REPUBLIEK SURINAME

MINISTRY OF PUBLIC WORKS
TRANSPORT AND COMMUNICATION

COASTAL RESILIENCE ASSESSMENT

PARAMARIBO, SURINAME
December, 2017

ACP-EU Natural Disaster Risk Reduction Program
An initiative of the African, Caribbean and Pacific Group, funded by the European Union and managed by GFDRR

GFDRR
Global Facility for Disaster Reduction and Recovery

WORLD BANK GROUP

Acknowledgements

Front page:

Photograph: NASA, true-color Terra MODIS image, September 19, 2002.

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Abbreviations

AAB	Annual Average Benefit
ACP-EU NDRR	Africa-Caribbean-Pacific EU Natural Disaster Risk Reduction Program
AAD	Annual Average Damages
AdKUS	Antom de Kom University of Suriname
AFD	Agence Francaise de Development
ARI	Annual Recurrence Interval
CBA	Cost-benefit analysis
CBR	Cost-benefit ratio (ratio of costs and benefits, each weighted according to discount rate)
CRA	Coastal Resilience Assessment
CCRIF	Caribbean Catastrophic Risk Insurance Facility
CELOS	Centre for Agricultural Research Suriname
CHARIM	Caribbean Handbook on Risk Information Management
CI	Conservation International
COP21	Conference of Parties 21
CPA	Coastal Protection Act
CPS	Country Partnership Strategy
DEM	Digital Elevation Model
DRM	Disaster Risk Management
DTM	Digital Terrain Model
EU	European Union
FRA	Flood Risk Assessment
GCM	Global Climate Model
GFDRR	Global Facility for Disaster Risk Reduction and Recovery
GLIS	Ground and Land Information System Management Institute
GoS	Government of Suriname
GPS	Global Positioning System
HEC-RAS	US Corp of Engineers Flood Modelling Software
HWM	High Water Mark
ICZM	Integrated Coastal Zone Management Plan (2010)
IDB	Inter-American Development Bank
IDF	Intensity-Duration-Frequency
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
JICA	Japan International Cooperation Agency
Km	Kilometer
LAC	Latin America and the Caribbean
LD	Local Datum
m	Meter
MAS	Maritime Authority of Suriname
MJO	Madden-Julian Oscillation
MoPW	Ministry of Public Works, Government of Suriname
MSL	Mean Sea Level

MUMA	Mixed Used Management Area
NAPAs	National Adaptation Programme of Actions
NCCR	National Coordination Centre for Disaster Preparedness
NIMOS	National Institute for Environment and Development in Suriname
NOAA	US-National Oceanic and Atmospheric Administration
NPV	Net Present Value
NSP	Normaal Surinaams Plein (national reference plane for Suriname)
PLP	Property Level Protection
RR	Required Return
SBB	Foundation for Forest Management and Housing, Government of Suriname
SHOM	French National Hydrographic Service
SOBEK	Deltares Flood Modelling Software
SRTM	Shuttle Radar Topography Mission
STU	Sediment Trapping Unit
TA	Technical Assistance
UFCOP	World Bank Urban Flood Community and Practice
UN	United Nations
UNDP	United Nations Development Programme
US$	United States Dollars
WB	World Bank
WWF	World Wildlife Fund
yr	year

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Photograph: Juliana Castaño-Isaza

Executive Summary for Coastal Resilience Assessment

Overview

A World Bank Technical Assistance, supported by the ACP-EU Natural Disaster Risk Reduction programme, has carried out a Coastal Resilience Assessment (CRA) as part of a strategic Flood Risk Assessment for the Greater Paramaribo area which is threatened by pluvial flooding and combined coastal flooding and erosion. The aim of the CRA is to provide evidence and tools to support the Government of Suriname to develop coastal management policies and interventions to address these hazards.

An evaluation of coastal dynamics and coastal flood risk was undertaken to determine the hazard extent and scope for mitigation actions. An assessment of effectiveness and an economic analysis showed that restoration of floodplain processes, including mangrove preservation and regrowth, is a crucial element of building coastal resilience for Paramaribo. However, the assessment also showed that ultimately flood mitigation through a mix of structural and non-structural interventions will be required.

Figure CRA-1. Remnant areas of mangroves north of Paramaribo

The Government of Suriname has been working towards improved management of disaster risks through development of a range of studies, plans and legislation. These recommended various physical interventions, with institutional and regulatory actions to reduce overall flood risk. Advances for coastal protection have included definition of coastal management areas and drafting of a Coastal Protection Act. However, recommended physical interventions (structural and nature-based) have not yet been implemented, partly due to a lack of evidence required to support sustainable solutions, and partly because detailed studies have reached opposing conclusions.

This CRA has provided an investigation focused on coastal flood and erosion risk for Greater Paramaribo. The study involved synthesis of previous studies, review of supporting data, some numerical modelling and an economic analysis of flood and erosion risk mitigation options.

Objectives of the CRA:

- To further improve the understanding of coastal flood and erosion risk, including the role that mangroves and other structural and non-structural interventions can play in mitigation.
- To provide new evidence and analytical tools to support the establishment of an appropriate coastal resilience strategy for Greater Paramaribo.

A Unique and Challenging Setting
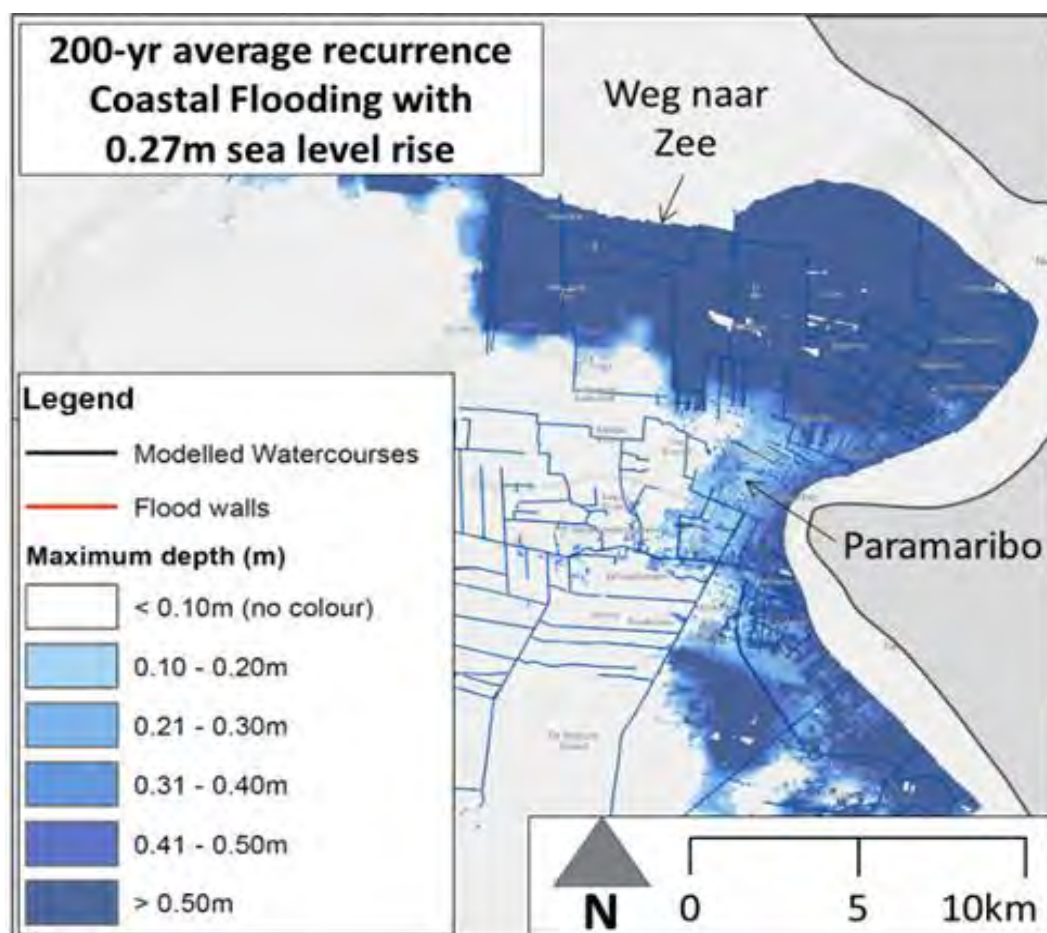
Figure CRA-2. Extent of potential coastal flooding hazard

An evaluation of coastal dynamics and coastal flooding has highlighted Suriname's unique oceanographic, ecological and geomorphic setting. Key points are:

- **The muddy coastline of Suriname is highly dynamic and transient.** The coastal margin moves by more than a kilometre over cycles of the order of 30 years, related to movement of vast migratory mudbanks generated from the Amazon River. Any intervention needs to consider these dominant coastal mechanics over relevant time-scales.

- **Low elevations occur across the coastal land north of Paramaribo, and are subject to high tide flooding.** Flooding for more than 2km landward of the shore has been observed during episodes of moderate surge coinciding with high tide. Potential coastal flood hazard extends to the urban margin of Paramaribo (Figure CRA-2).

- **Mature mangroves line the coast but in places removal has increased erosion stress.** The Suriname coastline is characterised by well-developed mangrove forests. However, areas of mangrove have been removed near the capital city of Paramaribo, increasing exposure to erosion and flood risk (Figure CRA-1, Figure CRA-3). Although mangrove regeneration efforts are underway, this process takes time and is hampered by erosion pressure during the present phase of the long-term coastal cycle.

- **Potential impacts associated with projected climate change are significant**. Flood risk will increase with sea-level rise.

Figure CRA-3. Coastal erosion north of Paramaribo

Coastal Hazard Mitigation

Under the CRA, a range of interventions to mitigate coastal hazard were evaluated, considering their effectiveness to (i) address long-term coastal change, (ii) reduce sensitivity to short-term coastal erosion pressure, and (iii) mitigate coastal flooding hazard. The assessment identified that no single intervention, on its own, can provide resilience against all three stresses in north Paramaribo.

- **Flood plain restoration:** Long-term coastal change can have large impact on activities in the coastal zone. Interventions protecting against this change need to be more robust, or replaced as the coast moves. Historic observations of Suriname's coast suggest that long-term coastal change, including erosion pressure due to mudbank migration, is best addressed through restoration of the coastal floodplain. Evaluation of tidal flooding extent and frequency suggests that the active floodplain should have a minimum width of 1.5km. Allowing the sediment floodplain to be active over this distance provides an equal "saving" of land by encouraging coastal stability. A wider floodplain will reduce the erosive impacts of projected sea level rise. Allowing the coastal plain to flood, supported by mangrove regeneration, is a key mechanism helping the coast to capture sediment, reducing the potential for long-term coastal retreat.

- **Mangrove restoration and preservation:** This was identified as a key activity for the coast north of Paramaribo. Combined with floodplain restoration, mangroves support longer-term coastal stability and they actively reduce short-term erosion. Mangrove preservation through planning regulations and on-ground management, is therefore required to secure existing coastal stability and ecosystem benefits. Previous efforts at mangrove stabilisation have demonstrated that there are challenges to achieve mangrove restoration. This is because establishing conditions suitable for mangrove regrowth in degraded areas requires more than simply planting seedlings. The approach of using sediment trapping units, trialled by the University of Anton de Kom and Conservation International, has been demonstrated as cost-effective where mangrove restoration is constrained by sediment mobility. Regeneration of mangroves has other important benefits such as enhancement of ecosystems, maintenance of dependent livelihoods, food supply, biodiversity and carbon sequestration. However, mangroves on their own do not provide a complete and timely solution to coastal hazards, with minor effect on flooding.

Mangrove and floodplain restoration will not entirely stop the process of coastal erosion, with mudbank migration continuing to drive the erosion-accretion cycle over a timescale of decades. However, creating a wide buffer will reduce coastline sensitivity to these cycles, help avoid long term net erosion, and support mangrove regeneration. Increased coastal stability developed through floodplain restoration enables other elements of the resilience strategy to be implemented in a more cost-effective manner than defence near the present-day shoreline. Further, it will help to establish and maintain floodplain storage north of the Greater Paramaribo Area, important for effective management of pluvial flooding.

Flood Mitigation

The risk of coastal flooding is high across the low-lying land north of Paramaribo. This exposure will increase as a function of sea-level rise, ultimately affecting the urban area of Paramaribo. In the long-term, a flood barrier will be required to protect the urban area. However, to support floodplain restoration, the barrier needs to be set back from the coast (Figure CRA-4).

Flood risk across the land between the coast and any barrier would require mitigation through a combination of: (i) structural measures: i.e. improvements to the drainage system; and limited land-raising for critical infrastructure such as utilities and emergency routes (although large-scale land-raising is not recommended); (ii) property-level protection (PLP): e.g. raised floor levels, flood stilts,

local flood barriers, door guards or other flood-proofing approaches; and (iii) non-structural measures e.g. development of flood forecasting, early warning systems and emergency response plans; implementation of institutional changes to support coordinated design, implementation and management of a holistic flood risk management strategy - this includes implementation of the Coastal Protection Act which aims at ensuring mangrove conservation and restoration; and planning / zoning to limit development on the most hazardous areas along the coast. This zoning may be implemented as part of the Coastal Protection Act and would need to recognise flood mitigation interventions. Enforcement of PLP should also be implemented for new buildings as part of development/building control.

Figure CRA-4. Flood mitigation zones

Flood-barrier Options

The effectiveness and cost-benefit of several different flood barrier options were considered for the Weg naar Zee coast, north of Paramaribo. Following mangrove removal, this area has suffered from erosion, and several short-lived flood barriers have been installed, but the area is still threatened by coastal inundation. Mangrove regeneration by sediment-trapping units is presently being trialled in the shallow coastal zone.

The CRA identified that the scale and cost of structural barriers vary depending on location. For example, a robust structure (e.g. a rock sea dyke) is required close to the coast, but various other options involving less robust structures (e.g. earth, timber or brush work) are increasingly viable away from the shore (Figure CRA-5).

- Structural barriers close to shore: Although in theory the construction of a sea dyke has the potential to provide protection from flooding, it is inconsistent with the parallel objective of managing coastal stability:
  - Erecting a solid structure on the coast conflicts with the coastal dynamics acting in the region.
  - This option would encourage development in an increasingly hazardous risk area.
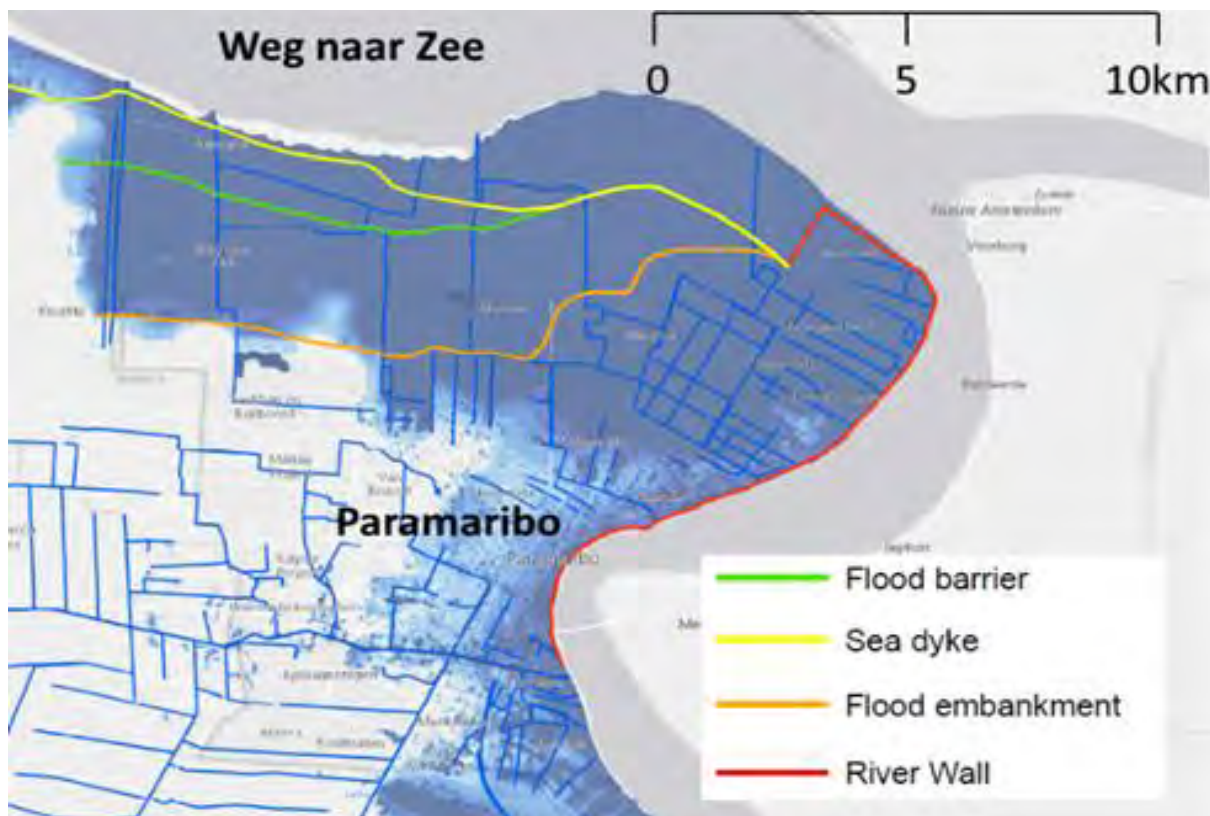
Figure CRA-5. Flood defence options north of Paramaribo

Therefore, construction of a sea dyke structure is not considered an appropriate solution for Paramaribo.

- Structural barrier further inland: A wider range of structural barriers can be used landwards, combined with floodplain restoration. The further landward that a flood barrier is constructed, the lower the capital and maintenance costs, and the greater the capacity for building coastal stability through floodplain restoration, including mangrove preservation and restoration. Construction of either a flood barrier or an embankment must be integrated with existing flood defences for the urban area of Paramaribo, the pluvial drainage network and road systems. Advantages of using this option rather than a sea dyke are:

o Use of mangroves provides a natural buffer to coastal erosion, gives substantial protection against waves, and encourages maintenance of flood storage.

o If appropriately combined with planning regulations, in line with the Coastal Protection Act, this approach will discourage further development along the coastal strip, seaward of the barrier, limiting increased investment and human exposure to flooding.

Cost-Benefit Considerations

Economic analysis of various approaches to coastal management highlighted that the substantial capital and maintenance costs of flood protection are largely offset by potential benefits associated with land improvement. Although other benefits, such as employment and ecosystem services (including fisheries, beekeeping, and carbon sequestration) have been considered, these are at least an order of magnitude smaller than the main costs and benefits.

There is a limited financial distinction between a small or a large coastal barrier setback inland if infrastructure costs, land improvement benefits and relocation of existing land-use are considered. The spatial distribution of land-value, which increases towards the city centre, provides greater imperative to protect areas close to the urban centre, rather than improving agricultural productivity. This means that any option can be made economically feasible, provided that an appropriate mix of land-uses is developed for the protected land. A substantial challenge remains for the Suriname Government to recover a suitable portion of the benefits to offset costs.

Summary and Recommendations

The recommended strategy for coastal hazard management includes preservation of remaining mangrove areas, reinforcement of existing flood defences along the Suriname River, designation of an active coastal floodplain area of more than 1.5km width, and installation of a flood barrier. Seaward of the flood barrier, flood-proofing of individual buildings, along with development of early-warning systems and evacuation plans is required to mitigate the coastal flood hazard.

Evaluation of costs and benefits associated with different barrier configurations indicated that financial viability depends on the capacity of the Government of Suriname to effectively use benefits as an offset to capital and maintenance costs. There is a high economic imperative for a barrier set back near the existing urban margin due to lower costs and higher land values. However, there is potentially lower direct return to the Government due to existing patterns of land-use and ownership.

Physical interventions need to be combined with policy and institutional changes to ensure a resilient coastal management strategy. Appropriate steps include refinement of existing coastal planning policy and strengthening of the disaster risk management authority.

1. Introduction

1.1 Background

Suriname is one of the most vulnerable countries in the world to the impact of sea-level rise due to climate change. Most of the population lives within a few meters above mean sea level, making coastal populations particularly susceptible to coastal erosion and flooding risks. Suriname is also prone to frequent river and surface water flooding, particularly when coincident with spring tides which limit drainage. Flood-risks in the capital city of Paramaribo (Figure 1-1), which contains the most substantially populated urban area on the Suriname coast, are particularly exacerbated by poor drainage-capacity due to either limited planning integration or insufficient maintenance.

The Government of Suriname (GoS) has been working towards improved management of disaster risks, through the development of a range of studies, plans and legislation. Both the 2001 Master Plan for the Drainage of Greater Paramaribo[1] and the 2010 Integrated Coastal Zone Management (ICZM)[2] recommended various physical interventions, and institutional and regulatory actions to reduce flood risk. Subsequent advances have also included the definition of coastal management areas and the drafting of a new Coastal Protection Act (CPA), which is under consideration by the GoS. However, the CPA and plans for physical interventions (recommended within these studies) have not been fully implemented. This is in large part due to a lack of funding and difficulties with respect to implementing the institutional changes required. However, it is also in part due to a lack of clear supporting evidence required to define appropriate, long-term sustainable solutions.

To support the GoS in its disaster risk reduction efforts, the World Bank coordinated a strategic level flood risk assessment for the city of Paramaribo, and surrounding area. The aim of this assessment is to provide the GoS new evidence and analytical tools to support the country in developing a program of interventions and policies to address recurrent flooding and the anticipated impacts resulting from climate change. This will strengthen the Government's understanding of coastal and urban drainage regimes leading to a subsequent investment plan designed to optimally reduce flood risk.

Figure 1-1: Location of Suriname and Paramaribo

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[1] Executive Summary, Masterplan Ontwatering Groot Paramaribo, Ministrie van Openbare Werken, Project UPO 08 – SR/002214 prepared by DHV-WLDelft-AMI-Sunecon, 15 June 2001
[2] ICZM (Integrated Coastal Zone Management) Plan Suriname: Coastal morphodynamics report prepared by Lievense Deltares, Oct 2009

1.2 The objectives of the Coastal Resilience Assessment

A key element of the assessment is an investigation focused on coastal flood and erosion risk in the greater Paramaribo area. Developing a better understanding of these risks, and working towards appropriate mitigation solutions is however, complex due to:

- The low, flat and muddy nature of the coastline, which results in complex hydrodynamics and sediment dynamics.
- Complex drainage systems within the city, which influence river, surface water and coastal flood risks.
- The legacy of previous coastal flood and erosion interventions, which have not always been implemented in a coordinated manner and have not been well maintained.
- Deforestation of mangroves and the impacts that this has had on increased erosion, flooding, and loss of land.
- The complex land ownership and increased density of infrastructure in the GPA, with high pressure for increased development of both residential and agricultural land.
- Uncertainty with respect to the potential impacts of climate change.

A key objective of this element of this assessment is to build upon the good work that has already been carried out on these topics over the years by the GoS and other organisations in order to:

- Further improve the understanding of coastal flood and erosion risk in the Greater Paramaribo Area, and the role that mangroves and other preventative interventions can play in future solutions.
- To provide new evidence and analytical tools which can be used, and built upon, by the GoS to establish and implement an appropriate coastal resilience strategy for the Greater Paramaribo Area.
- To inform decision-makers and donors on the role of mangroves in coastal protection, and additional benefits to coastal communities and the country as a whole.

To achieve these objectives, this study has involved the following key tasks:

- **Task 1: Local data collection and consultation.** This study has involved a comprehensive campaign of consultation with the GoS and other key stakeholders such as the Anton de Kom University of Suriname (AdKUS), Maritime Authority of Suriname (MAS), Centre for Agricultural Research Suriname (CELOS), National Institute for Environment and Development in Suriname (NIMOS), Foundation for Forest Management and Housing (SBB), Conservation International (CI), United Nations Development Programme (UNDP) and World Wildlife Foundation (WWF). All these organisations have provided invaluable local insight, understanding and data that has provided the foundations for the findings and recommendations of this assessment.
- **Task 2: Drivers of flood and erosion risk.** The Suriname coastline is highly dynamic and evolving and this will only increase with climate change. Any sustainable coastal resilience strategy must therefore recognise this feature and work with it. In this task, the complex nature of the process driving coastal flood and erosion risk in Suriname was reviewed to

provide the context required to work towards a sustainable coastal resilience strategy. This work is described in Chapter 2.

- **Task 3: Mangrove habitat status review.** Mangroves have potential to act as a natural form of flood and erosion risk control, reducing wave and surge heights and stabilising the coastline. While the Suriname coastline is characterised by the presence of mangroves, the coverage, density and health of these varies greatly and there has been significant loss of mangroves historically. In recent years, there has been a growing recognition of the value of mangroves in Suriname and promising regeneration efforts are underway in the Weg naar Zee area, on the coast, north of Paramaribo. This task involved an evaluation of the history of mangrove changes, the present status of mangroves and pressures upon them. This work, described in Chapter 3, was undertaken to provide further evidence to support the development of a sustainable coastal resilience strategy.
- **Task 4: Coastal protection services assessment.** Drawing on the results of Tasks 2 and 3, this task involved an evaluation of the relative opportunities provided by different coastal flood and erosion intervention methods, including the use of green infrastructure (e.g. mangrove regeneration), hard structures (e.g. dykes), soft structures (e.g. earthworks), non-structural (e.g. planning) and hybrid measures, combining elements of the other approaches. When considering a long-term, sustainable solution to flood risk, it is rarely ever one type of intervention that will provide the solution, but rather the objective is to identify a suite of solutions that work together to provide improved resilience. This work is described in Chapter
- **Task 5: Cost-effectiveness assessment.** When considering an appropriate solution to flood and coastal resilience, it is necessary to consider the balance of the costs of different intervention approaches with the benefits that these may afford (e.g. job creation, biodiversity, carbon sequestration). Furthermore, the costs and benefits for hard intervention and natural intervention approaches differ substantially and this is a key consideration of this assessment. In this task, the cost-effectiveness of different resilience strategies considered as part of Task 4 were evaluated based on available data and a range of assumptions. This work is described in Chapter 5.
- **Task 6: Development of recommendations.** As a result of the above tasks, this assessment has brought together new data, evidence and tools to support future decision making regarding development of a coastal resilience strategy for Suriname. While this work represents a significant step forward, it is important that this work is built upon by the GoS and other organisations to further refine the assumptions made and to undertake additional studies to define and implement a sustainable long-term coastal resilience strategy. To support this work, a set of key outcomes and recommendations from the study were developed, and are presented in Chapter 6.

2. Coastal flooding and erosion hazards

2.1 Introduction

Development of a sustainable coastal resilience strategy for the GPA requires an understanding of the local oceanographic and geomorphological processes at play. Understanding these processes is important because they drive the risk of flooding and erosion and because they in turn influence the practicality of possible coastal resilience interventions measures.

This chapter provides a synthesis and interpretation of available information on these important drivers, with a particular emphasis on the geomorphological dynamics of the coastline, which has a strong influence on the types of intervention measures that could be applied and the historical and future state of the mangroves.

2.2   Drivers of coastal flooding hazard

Sea-level variation
The primary factor controlling flood risks in Suriname is the way in which sea-levels fluctuate due to the combination of astronomical tides, storm surges and wave action. Each of these forces is introduced below.

Tides: The Suriname coast is characterised by semi-diurnal, micro-tidal conditions. This means that the coastline experiences approximately two high and two low tides per day (once every 12 hours and 25 minutes), and a moderate tidal range of the order of 2.8m (at maximum range). Despite this moderate tidal-range, it is well known that flood risk in Suriname is heavily influenced by astronomical tides. **For instance, flooding from river and surface water sources is often exacerbated if it coincides with high spring tides because the tides impede drainage of the flood water from the land**. Flooding of this nature has occurred in March 2009 affecting much of the farmland and housing across Weg naar Zee.

Storm surges: Although tropical cyclones (i.e. hurricanes) do not track near to the Suriname coast, trade wind variability and monsoonal storms do develop storm surges, which can result in coastal flooding when coincident with a high tide. Due to Suriname's tropical location, the magnitude of surges experienced is generally small, of the order of less than 0.4m, although it can be sustained for several days. Due to the low-lying nature of the coast, even the small contribution from a storm surge makes a large difference in flood area, with the additional effect that energetic wave conditions almost always occur simultaneous to a surge.

The term "extreme still water sea-level" is often used to describe the level that the sea reaches through combined astronomical tide and storm surge. This term is important for the purposes of this study, in part because flood modelling has been undertaken to inform the cost-benefit analysis described in Chapter 5.

Estimating reliable extreme still water sea-levels ideally requires accurate, long-term tide gauge records. Sea-level variations associated with tides and surges are measured in Suriname as part of a network of gauges managed by MAS. These gauges have historically been linked to port operations, and are therefore mostly situated in estuarine and riverine settings. This means that most are strongly influenced by riverine processes, making them unsuitable for refined extreme sea-level analysis. Analysis of extremes from these gauges is also complicated by frequent datum changes and data gaps. All these influences can be seen in the Paramaribo tide gauge records (Figure 2-).
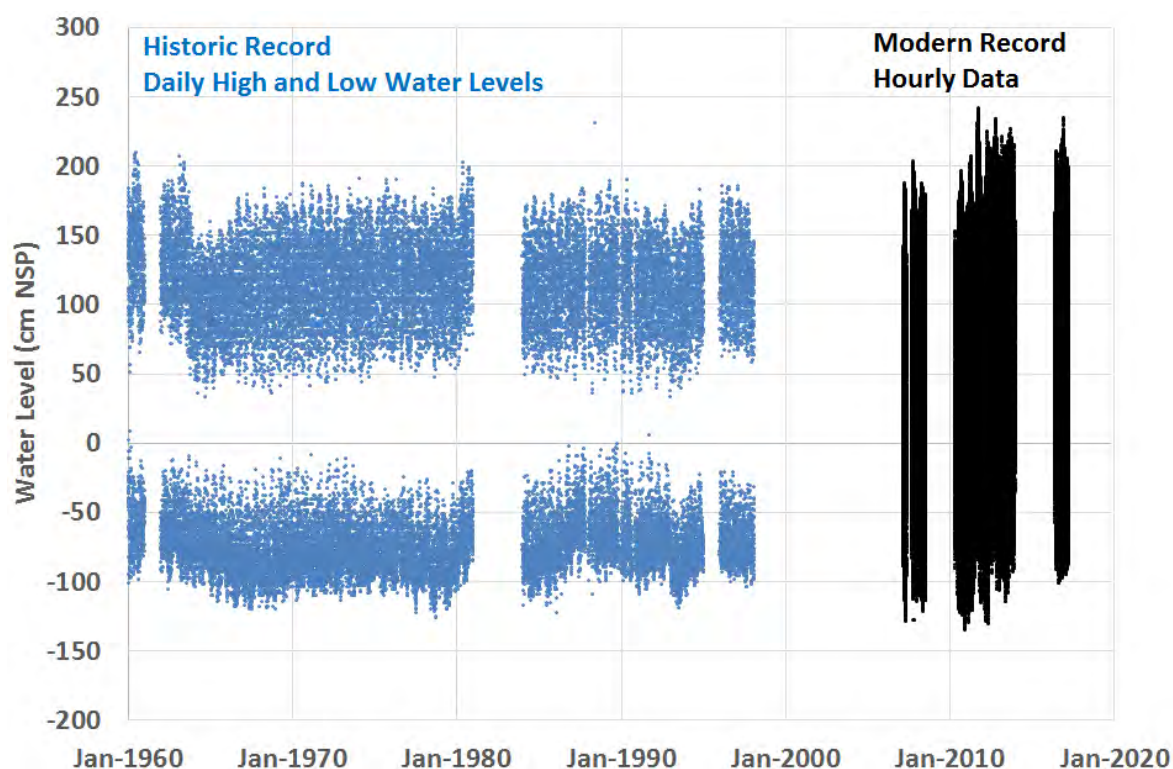
Figure 2-1: Reported water level data for Paramaribo. Data gaps, datum changes and the influence of river flow are illustrated.

Previous studies giving extreme sea-level estimates for the Greater Paramaribo Area were reviewed as part of this assessment. While these studies provide an indication of extreme sea-level conditions, the reliability of these estimates is questionable. For instance, a recent cost-benefit assessment undertaken by Burke & Ding (2016)[3] is based on an interpretation of the global DIVA[4] database (Hinkel 2005[5]), with no direct comparison made to observations or local datums. Sintec & Sunecon (2015)[6] also provides extreme sea-level estimates, developed as part of the detailed design of the proposed ring dyke at Weg naar Zee. For this assessment, the way historic and modern reference datums was resolved is unclear. Furthermore, the results are not consistent with the scale of surges observed in the region and additional analysis undertaken for this study (Appendix A). Sintec & Sunecon (2015) also referenced a previous extreme sea-level estimate prepared by the Ministry of Public Works (MoPW) and demonstrated its inadequacy based on recent observations, as the nominal 100-year extreme sea-level estimate has been frequently exceeded. Despite the difference in their origins, and the uncertainty associated with each, the Burke & Ding (2016) and Sintec & Sunecon (2015) extreme sea-level estimates are relatively close.

Review of the available data sets has been undertaken to determine the reliability of these extreme sea-level estimates, summarised in Appendix A. This review identified:

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[3] Burke & Ding. (2016) Valuation of Coastal Protection near Paramaribo, Suriname. Prepared for WWF Guianas.

4 DIVA is the Dynamic Interactive Vulnerability Assessment Model

[5] Hinkel, J. (2005). DIVA: an iterative method for building modular integrated models. In: *Advances in Geosciences* 4, pp. 45–50.

[6] Sintec & Sunecon (2015) Updated Ring-dyke Engineering Studies. {In Dutch}

- Published tidal planes substantially underestimate the tidal range (as discussed by Augustinus & Teunissen 2004[7]); and
- Surge levels implied by extreme distribution curve-fitting are above the scale observed in neighbouring French Guiana where better quality tide gauge records exist.

Due to these inconsistencies, new extreme sea-level estimates were derived from the historical record at Paramaribo (hydrometric station 6110), truncated to 1965-1998 to account for damming of the Suriname River, with a mean sea-level adjustment to match the observational record from 2009-2013 reported by Sintec & Sunecon (2015). This observational data displayed log-linear behaviour, which was extrapolated to estimate the recurrence of extremes.
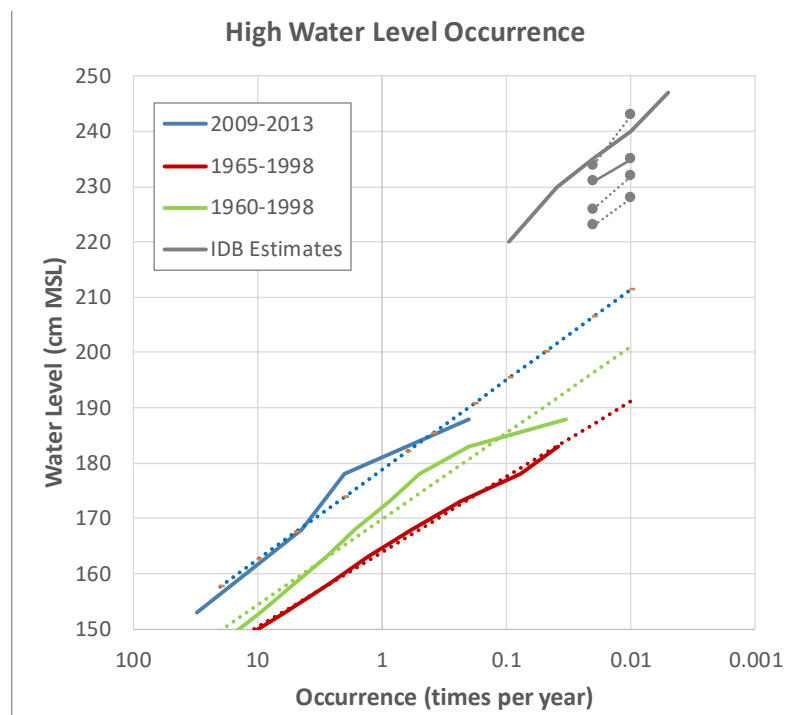
Figure 2-2: Extreme sea-level estimates derived from the historical record at Paramaribo (hydrometric station 6110). Estimates are truncated to 1965-1998 to account for damming of the Suriname River, with a mean sea-level adjustment to match the observational record from 2009-2013 reported by Sintec & Sunecon (2015). This observational data displayed log-linear behaviour, which was extrapolated to estimate the recurrence of extremes.

ARI (years)	1 yr	10 yr	25 yr	50 yr	100 yr	200 yr
Derived levels (MSL) *	1.82m	1.95m	2.02m	2.06m	2.11m	2.16m
Sintec & Sunecon (2015)				2.32m	2.35m	
Burke & Ding (2016)		2.20m	2.30m	2.35m	2.40m	2.47m
* Data referenced to Mean Sea Level (MSL). All water levels are presented to 2 decimal places for clarity, rather than as a reflection of accuracy. (ARI = Annual Recurrence Interval)						

Table 2-1: Extreme water level recurrence

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[7] Augustinus P & Teunissen P. (2004) Bank protection construction for the right bank of the Suriname River and the left bank of the Commewijne River. Morphological aspects and natural shoreline protection.

Differences between the 1965-1998 and 2009-2013 distributions were consistent with the mean sea-level change suggested by satellite altimetry (Willis *et al*. 2010[8]) and the tide gauge record in French Guiana, combined with the effect of inter-annual tidal variation (Haigh *et al*. 2011[9]). The extrapolated extreme water levels were in the order of 0.2-0.3m below those derived by Sintec & Sunecon (2015)[10]. This difference is considered to relate to incorporation of statistical uncertainty in the Sintec & Sunecon estimates, which is appropriate for structural design, but provides a high bias when assessing flood mitigation options.

Wave action: Wave action is a complex process controlled by several factors, including the meteorological origin, the pathway from generation to reaching the shore and the transition from deep water to shallow water. The way these factors combine determines the magnitude of any wave-induced flood or erosion impacts. Storm waves are generated in deep water, primarily through trade winds, and then propagate towards land. As they do so, they enter shallower water where wave transformation processes occur due to the interaction between the waves and the underlying sea-bed (and processes such as shoaling, refraction and diffraction).

The offshore wave climate, as reported from NOAA[11] oceanic wave buoys, ERA-40 (reanalysis model) altimetry analysis and Wavewatch III hindcast modelling, is moderate, with a seasonal peak from December through February. Across the region, wave heights exceeding 2m are relatively common (20-40% occurrence) with median wave periods around 8-10 seconds. Waves from the east-northeast are the most frequent, with an increasing onshore component from October through April.

In Suriname, and the Greater Paramaribo Area, waves approaching the coast are heavily influenced by the presence of large-scale migratory mud banks and smaller-scale inter-tidal flats, both of which are described in more detail further below. At a general level, these muddy structures act to dissipate the energy of waves before they reach the coastline; although the degree to which this dissipation occurs is highly localised - a function of the state of the mud banks offshore, the direction of the waves and the sea-level during an event.

Of importance to this study, it is important to note that the risk of flooding and erosion at any one location will not remain static because the coastal mud banks migrate through time. Currently, the mud banks in the Greater Paramaribo Area are at their lowest state, meaning wave penetration is the greatest it has been for 40 years. This migration has led to increased erosion is areas such as Coronie and Weg naar Zee, exacerbated by human activities.

In some locations in the Greater Paramaribo area, such as Weg naar Zee adjacent to the Hindu temple, dykes and walling have previously been erected (Figure 2-). In these locations, wave-induced flooding occurs through wave overtopping, a complex process controlled by the state of the sea (depth, wave properties) and the geometries of the intertidal zone and local flood defences.

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[8] Willis JK, Chambers DP, Kuo C-Y & Shum CK. (2010) Global Sea Level Rise. Recent progress and challenges for the decade to come. Oceanography, 23 (4). p26-35.
[9] Haigh ID, Eliot M & Pattiaratchi CB. (2011) Global influences of the 18.61 year nodal cycle and 8.85 year cycle of lunar perigee on high tidal levels. Journal of Geophysical Research: Oceans, 116(C6).
[10] Sintec & Sunecon (2015) Updated Ring-dyke Engineering Studies. {In Dutch}
[11] US-National Oceanographic and Atmospheric Administration

Figure 2-3: Dykes and walling in Weg naar Zee adjacent to the Hindu temple,

There is limited measurement of wave conditions along the Suriname coast, with most information derived from global wave modelling (Winterwerp & Augustinus 2009[12], Anthony 2015[13]).

Currents

Oceanic currents also influence coastal flood and erosion risk in Suriname, because they influence the dynamics of sediment movement and erosion/accretion processes. This in turn also affects the behaviour and stability of the mangroves. The two principle drivers of coastal currents are the trade winds and tides.

Suriname is located approximately where the Northeast trade winds and the Southeast trade winds, and their associated currents, converge. This convergence produces the persistent westward Guianas Current along the coast, which varies seasonally as the Inter-Tropical Convergence Zone (ITCZ) shifts. Tidal flows, on the other hand are almost orthogonal to the coast. These tidal flows interact with the Guianas Current as well as local features such as the mud banks, mangroves and wave-driven currents resulting in a complex current structure. **While the detail of this structure is not important here, it is important to recognize the complexities of these processes and their strong influence on the dynamics of the large-scale mud banks present along the Guianas coast, as** discussed further below.

Coastal Flooding

The overland area that may be potentially flooded during a high coastal water level event has been modelled using a 2D depth-averaged hydrodynamic model (TUFLOW), forced at the boundary by a hydrograph representing different amplitude flood events. Details of the numerical modelling process and outcomes are included in the Strategic Flood Risk Assessment for Suriname Report, which is associated with this assessment.

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[12] Winterwerp H & Augustinus P. (2009) *Coastal morphodynamics report. Physical description of the Suriname coastal system*. ICZM Plan Suriname.

[13] Anthony E. (2015) *Assessment of peri-urban coastal protection options in Paramaribo-Wanica, Suriname*. Prepared for WWF Guianas.

Modelling shows that the flood extent does not correspond to the topographic contours, which implies that the landward extent of coastal flooding is constrained by the flux and momentum of the floodwaters at the coastal boundary.

Much of the land north of Paramaribo is exposed to coastal flooding hazard, including frequent flooding of the low-lying Weg naar Zee area, with less frequent and shallow flooding of the suburbs of Rainville and Blauwgrond. The area inundated during a flood varies marginally with flood recurrence, which is a combined function of the small vertical difference between the 1-year and 100-year coastal flood events; and the brief period of several hours over which flooding can occur during the high tide window (Figure 2-).

The projected effect of sea level rise by 2050 has been represented by modelling of coastal flooding events with a 0.27m sea level rise (Figure 2-). Landward movement of flood hazard occurs across the Greater Paramaribo Area, with the potential to reach the dense urban margin of Paramaribo with a 10-yeear Annual Recurrence Interval (ARI) flood event.
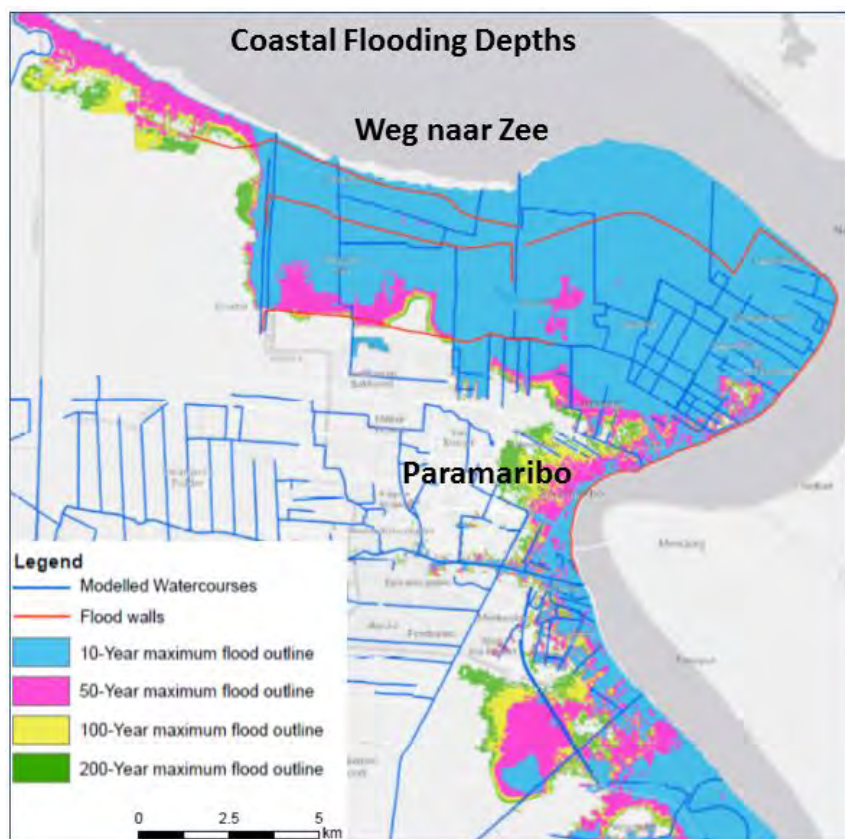
Figure 2-4: Modelled flood extents, present-day (no flood mitigation)
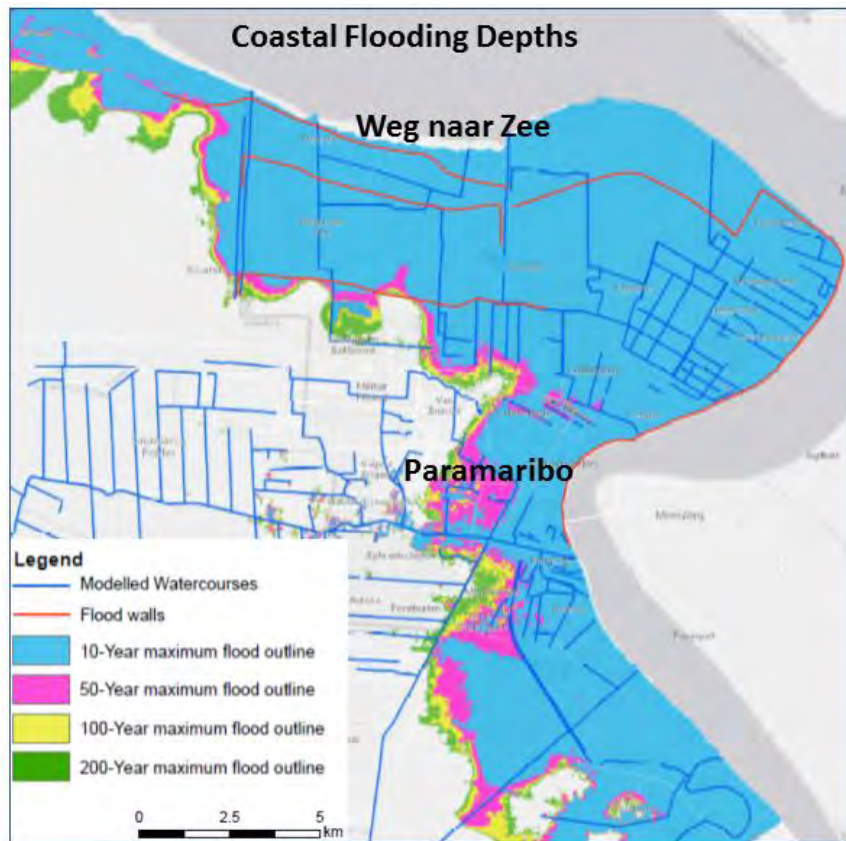
Figure 2-5: Modelled flood extents, with 0.27m sea-level rise (no flood mitigation)

2.3   Erosion and recession drivers

Regional geomorphology

The Guianas coast, from the mouth of the Amazon River, in Brazil, through to the mouth of the Amacuro River, in Venezuela, is scientifically unique. The enormous mass of mud released by the Amazon River, and the orientation of the coast relative to the prevailing trade winds, has enabled the development of a wide coastal zone over the late Holocene (last 6,000 years), formed almost entirely of mud, to a depth of tens of metres. The dynamics of this muddy coast have provided a setting for active research by coastal scientists since the 1950s (Vann 1959[14], Augustinus 1978[15]). **Furthermore, since the 1980s, the Guianas coast has been recognised as one of the global hotspots for potential sea-level rise impacts, due to this high coastal mobility as well as the low-lying nature of the coast**[16].

The Guianas floodplain is a chenier coastline, where cycles of coastal deposition and erosion across the floodplain produce ridges, swales, deposition fans, lagoons and tidal creeks. Most material supplied during accretion is mud, which is highly mobile, forming vast westward-migrating mudbanks, with large intertidal and subtidal area (Figure 2-). During erosion phases, finer material is washed

[14] Vann JH. (1959) The geomorphology of the Guiana coast. *Second Coastal Geography Conference*, Coastal Studies Institute, Louisiana State university, Washington DC, 153-187.

[15] Augustinus PGEF. (1978) *The changing shoreline of Suriname (South America)*, Doctoral dissertation, Utrecht University.

[16] Dasgupta S., Laplante B., Meisner C., Wheeler D., Yan J. 2009 The impact of sea level rise on developing countries: a comparative analysis. Climate Change 93, 379-388 doi: 10.1007/s10584-008-9499-5

away, leaving behind relict ridges of sand. In this setting, mangroves have been shown to help stabilise the mud coast, enhancing stability in both the erosive and accretive phases.

The most studied section of the Guianas coast is French Guiana, owing to its position as a French State, with strong connections to French academic institutions and coastal monitoring as part of the SHOM[17] network. This provides incidental information for the Suriname coast, including regional remote-sensing investigations and collation of offshore oceanographic information.

Scientific coverage of the Suriname coast has been less substantial, as coastal monitoring initiated during Suriname's period as a Dutch colony declined following independence from Netherlands in 1975, although post-colonial academic ties remain. Subsequent coastal assessment has generally been for the purposes of navigation through the MAS, academic research by AdKUS, intergovernmental projects assessing regional attributes, or non-government organisations including CI, UNDP and WWF.
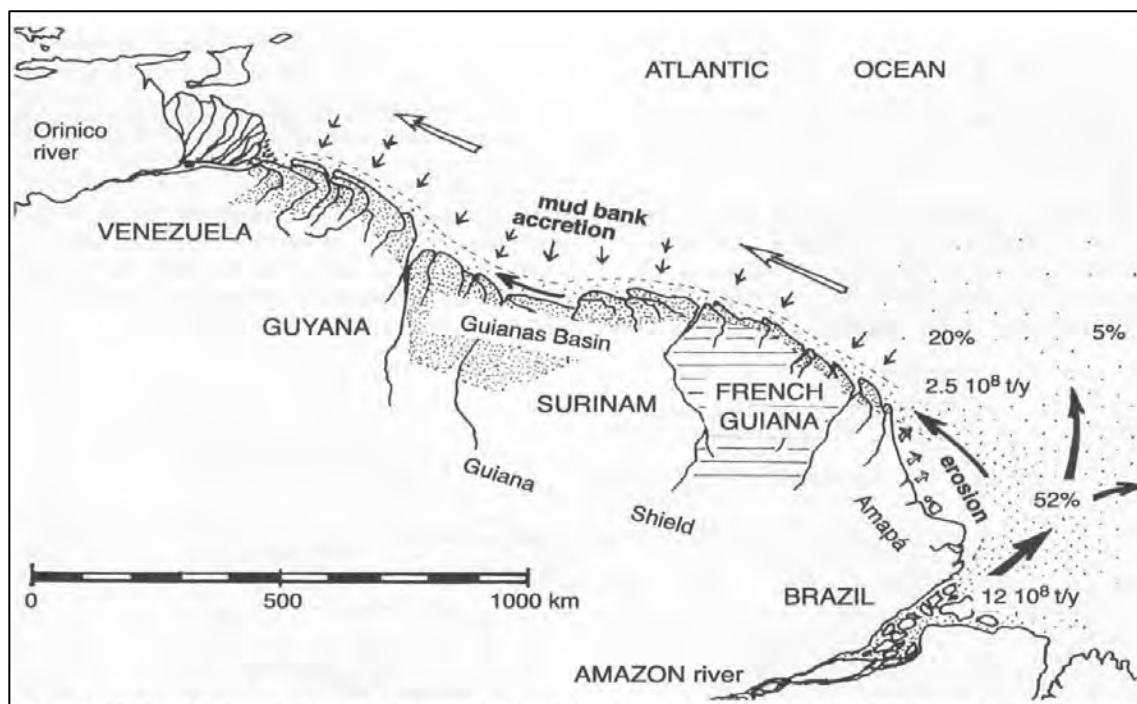
Figure 2-6: Regional coastal sediment transport (from Winterwerp & Augustinus 200918)

Suriname geomorphology

Suriname's muddy coast has developed as a function of the outpouring of mud from the Amazon River, of which a part is pushed westward along the coast by the northeast trade winds (through both waves and the Guianas Current). Over the late Holocene, the high supply of muddy sediment from the Amazon has caused an overall pattern of ongoing accretion (i.e. a build-up of sediment, Figure 2-), although there are periods of erosion and accretion within this general growth period. Other river systems along the Guianas, despite high seasonal rainfall and flow rates, do not provide a high sediment contribution to the coastal floodplain area.

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[17] French National Hydrographic Service
[18] Winterwerp H & Augustinus P. (2009) *Coastal morphodynamics report. Physical description of the Suriname coastal system*. ICZM Plan Suriname.

As indicated above, a very important feature of the Guianas coast to this study is the presence of large coastal mud banks, up to 60km in length, which extend up to 20km offshore (Figure 2-). These features are dynamic, moving westward at speeds that vary from 0.5-1.5 km/year, and with a spacing of approximately 30-40km along the Suriname coast. At a general level, this migration produces a long-term cycle of mud bank presence and absence at any given location (with a period of the order of 20-60 years). However, given the complexities involved, this description is somewhat simplified as mud bank dynamics are more complex, including mud bank mergers, growth, decline or initiation. This behaviour is described in greater detail in Appendix B.
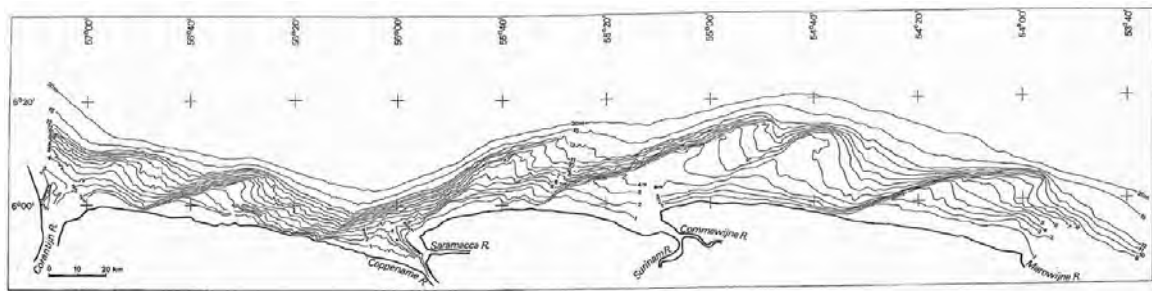
Figure 2-7: Depth contours off Suriname coast, showing large scale mud banks (from Winterwerp & Augustinus 200919, based on contours measured in 1960-1962)

In addition to the coastal mud banks, the nearshore region is characterised by a muddy inter-tidal flat; a feature that has also evolved over time. The width of this inter-tidal flat varies spatially (between about 1-2km) and in some locations, such as Weg naar Zee, has reduced by up to 400m over the past 30 years, as well as retreating (the front of the flat moved back by 1200m, and the shoreline by 800m). As shown in subsequent chapters, the muddy features of Suriname are also strongly inter-linked with mangrove dynamics.

Nearshore instability
The high mobility of muds along the Suriname coast determines that sediment is moved by both waves and flows, creating coastal morphology that results from a balance of disturbance and deposition (Figure 2-). Variation of the coastal texture (sediment type and vegetation) or the overall hydrodynamics (e.g. modifying drainage) adjusts this balance, and therefore will end up with a change in the coastal boundary. The most apparent shifts occur when loss of mangroves causes a much lower and flatter coastal gradient, or when erosion reaches sandy chenier deposits, allowing a steeper sandy beach to form.

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[19] Winterwerp H & Augustinus P. (2009) *Coastal morphodynamics report. Physical description of the Suriname coastal system*. ICZM Plan Suriname.
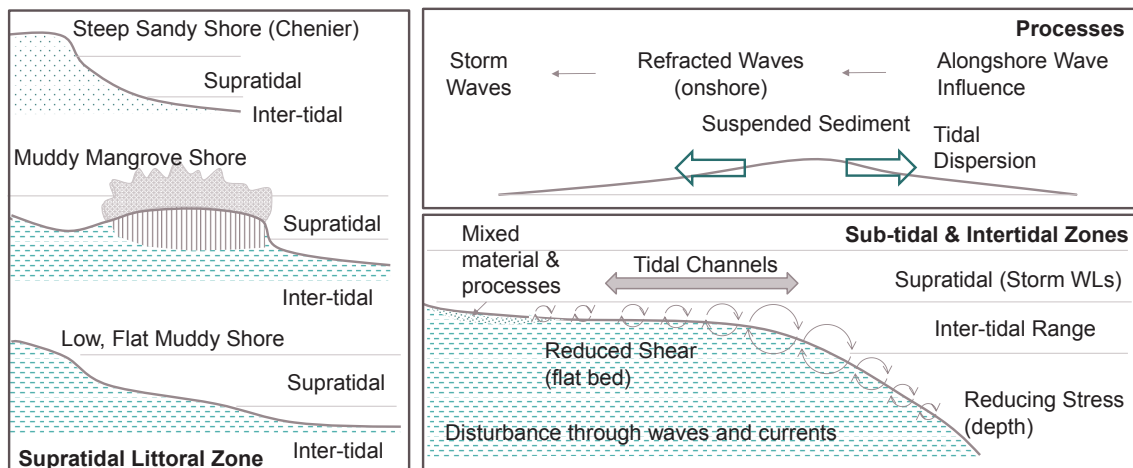
Mudbank profile results from a balance of disturbance and deposition

Figure 2-8: Coastal equilibrium concept

The regional cycle of erosion and accretion has been shown to have a slight bias towards net accretion in the long-term (Berrenstein 2010[20]). However, **in locations where the balance of erosion and accretion is tipped, the coast is capable of sustained long-term recession**, identified along the Coronie and Weg naar Zee coasts (Teunissen 2004[21]). Recession rates averaging 30 m/yr have been observed over more than one mudbank cycle, showing limited recovery during the normally accretive "mudbank" phase.

Local processes

Recession on the Weg naar Zee coast displays a characteristic sequence of salinisation, ponding, tidal creek incision and recession (Figure 2-). This sequence occurs on muddy coasts as a mechanism for change (Winn *et al*. 2006[22], d'Alpaos *et al*. 2005[23]), including adjustment to sea level.

The local erosion sequence is a small-scale response to broad-scale erosion drivers, and therefore it is not a wholly independent process. However, it suggests that existing practices using walls to segregate lots, or to "canalise" coastal land may act to accelerate the process of recession.

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[20] Berrenstein H. (2010) Coastal changes along the Suriname coast with emphasis on the changing coastline of Coronie from 1914 to 2007 and its influence on *Avicennia germinans L*. (Avicenniaceae). *Academic Journal of Suriname*, 1, 86-95.

[21] Teunissen P. (2004) *Project Studies for Construction of Coronie Foreshore. Natural and Artificial Coastal Change in the Coronie District*. {In Dutch}

[22] Winn KO, Saynor MJ, Eliot MJ & Eliot IG. (2006) Saltwater Intrusion and Morphological Change at the Mouth of the East Alligator River, Northern Territory. *Journal of Coastal Research*. 22 (1): 137-149.

[23] D'Alpaos A, Lanzoni S, Marani M, Fagherazzi S & Rinaldo A. (2005) Tidal network ontogeny: Channel initiation and early development. *Journal of Geophysical Research*, 110, F02001, doi:10.1029/2004JF000182.

Figure 2-9: Local erosion sequence

2.4   Summary and implications

This chapter has provided initial insight into the key factors driving coastal flood and erosion risk in Suriname and the greater Paramaribo area and has demonstrated the important link between the processes of tides, surges, waves, currents and coastal geomorphology.

Of most relevance to this study, this chapter has illustrated the highly dynamic nature of the muddy coastline, an important feature of Suriname that must be considered in detail with respect to potential coastal resilience intervention methods. Any intervention method implemented needs to consider the mechanics of the muddy coastline and the fact that there are ongoing cycles of change that will continue and may themselves change as the climate evolves. This means that a one-size-fits-all-places intervention method is unlikely to be effective and a range of adaptation approaches are likely to be required.

As will be illustrated in subsequent chapters, the story of flood and erosion risk in Suriname is also inter-linked with presence of mangroves, the pressures on these mangroves and other stressors associated with human activity and development. Subsequent chapters explore these factors further and build towards an understanding of how to increase resilience to flood and erosion in Suriname and the greater Paramaribo area.

3. Mangrove habitat status review

3.1 Introduction

It is now recognized globally that mangroves are an important asset with respect to coastal flood and erosion risk resilience, and this is indeed the case in Suriname and the greater Paramaribo area. The roots of mangroves reduce erosion and stabilize the shoreline. The trees and their roots attenuate (reduce) storm surges and wave action, reducing flood risk (Das & Vincent 2009[24]; Blankespoor *et al*. 2016[25]). The mangrove canopy decreases wind impacts. **Mangroves have also been shown to be relatively resilient to the impacts of rising sea-levels. If managed appropriately they can therefore form a crucial element of a sustainable coastal resilience strategy**.

Figure 3-1: Retention of sediment in mangrove root mass

Furthermore, the benefits associated with mangroves are not just about flood and erosion risk. **Mangroves provide diverse habitats, supporting strong ecosystems and associated agriculture and aquaculture benefits. Mangroves play an important carbon sequestration role, providing global benefits (Murdiyaso *et al*. 2015[26]). Mangrove restoration and management can also create jobs, providing local improvements to livelihoods**.

Of course, the degree that mangroves can form part of an effective coastal resilience strategy for Suriname and the greater Paramaribo area is strongly influenced by:

- The current state of the mangroves, and the pressures upon them.
- The natural and cyclical patterns of mudbank movements, which influence growth and retreat of mangroves through time.
- Institutional barriers to the promotion and sustainable management of mangrove forests.

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[24] Das S & Vincent J R (2009) Mangroves protected villages and reduced death toll during Indian super cyclone. *Proceedings of the National Academy of Sciences of the United States of America*, 106(18), 7357-7360.
[25] Blankespoor B, Dasgupta S, Lange GM (2016) Mangroves as a Protection from storm surges in a Changing Climate. *Ambio*, 46(4), 478-491.
[26] Murdiyarso D, Purbopuspito J, Kauffman JB, Warren MW, Sasmito SD, Donato DC, Manuri S, Krisnawati H, Taberima S & Kurnianto S. (2015). The potential of Indonesian mangrove forests for global climate change mitigation. *Nature Climate Change*, 5(12), pp.1089-1092.

This chapter explores the first two bullet points above to provide a context how mangroves can form part of a long-term sustainable coastal resilience strategy for the greater Paramaribo area. The influence of institutional barriers is discussed further in Chapter 6.

3.2   Mangrove status

The coastline of Suriname is, at a general level, characterized by the presence of extensive mangrove forests, with an area of 100,000 ha estimated (COCATRAM 2003[27], Figure 3-2). These forests form a broad band lining the coast, typically several kilometres wide. **While this coastal band has existed for many thousands of years, the location, width and characteristics of the mangroves has continuously changed; in large part due to mudbank dynamics, but also due to other stressors** discussed below.
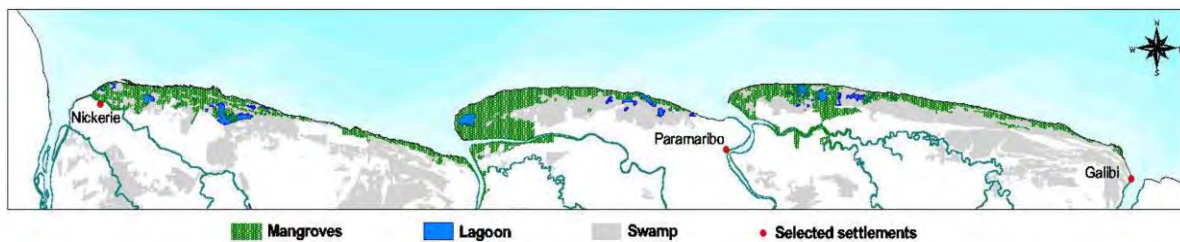
Figure 3-2: National coverage of mangrove forests and coastal swampland (From Tijon et al. 200828)

Unsurprisingly, the greater Paramaribo area is the area of greatest stress for Suriname's coastal mangroves. This is related to historical colonisation and the concentrated local population, but also the existing configuration of the large-scale coastal mudbanks, which is nearing the end of an extended "interbank" phase. This means it is at the most landward position of the erosion-accretion cycle, which is almost 1.2km landward of the shore position in the 1970s.

The present-day distribution of mangroves in the greater Paramaribo area are shown in Figure 3-3. While all coastal areas in the greater Paramaribo area have, at times, been characterised by mangroves, mangroves are no longer present in a significant manner along most of the Weg naar Zee coast and along most of the western bank of the Suriname River (adjacent to Paramaribo). These two areas were the subject of initial land clearing and development in late 18th Century (discussed further below). The two remaining substantial areas of mangrove forest are located along the Wanica coast, west of Weg naar Zee, and adjacent to the mouth of the Suriname River, near the suburbs of Rainville and Blauwgrond.

It is notable that **the Weg naar Zee mangrove community was primarily black mangrove, which has a shallower root system, whereas the two more stable areas of mangrove include a mixture of red, black and white mangroves**. One hypothesis for the differences in species range is the relative availability of fresh water during development of the more "stable" communities, although it should

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[27] COCATRAM. (2003) *Transfer of environmentally sound technologies for the sustainable management of mangrove forests: and overview*. Background document for the ad hoc expert group on finance and transfer of environmentally sound technologies. Secretariat of the United Nations Forum on Forests, Managua, March 2003.
[28] Tjon K, Wirjosentono J, Sabajo R, Jubitana H, Sewotaroeno M, Mol J, Babb Y, Evans G, Gangadien C, Parahoe M & Soetosenojo A. (2008) *Current Land Use and Improvement Needed for Sustainable Utilization*. Final Report on Biodiversity and Economic Valuation of Bigi Pan Multiple Use Management Area, Part III.

be recognised that the hydrology of the greater Paramaribo area has been substantially altered through drainage works.
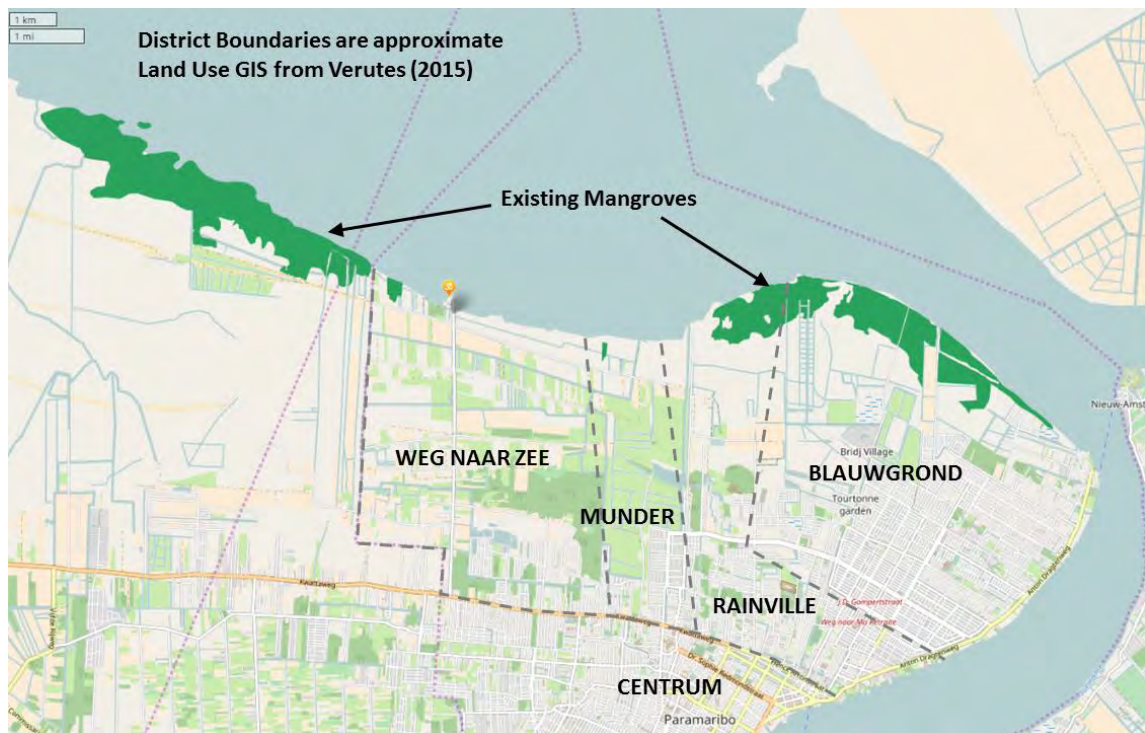
Figure 3-3: Greater Paramaribo urban extent and existing Mangrove forests (From Verutes 2015[29])

3.3   Mangrove stressors

There are a wide range of stressors acting on the mangroves in the greater Paramaribo area and disentangling these to highlight clear causes and effects is complicated. However, at a broad level, the key stressors influencing mangrove state are:

- Coastline change and the natural cycles of mudbank movements.
- Development pressures.
- Climate change.

Coastline change

Coastline change has created the greatest stress to mangrove forests in the greater Paramaribo area historically. The magnitude of this change is demonstrated by historical aerial imagery, which illustrates periods of coastal advance and retreat in Suriname since 1947 (Augustinus 1978[30], Gersie *et al.* 2016[31]). Change in the order of 1km has been observed on the coast, with an overall accretion trend for the whole Suriname coast of +5m/year (Berrenstein 2010[32]).

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[29] Verutes G. (2015) *Assessment of peri-urban coastal protection options*. http://www.geointerest.frih.org/Suriname/. WWF.

[30] Augustinus PGEF. (1978) *The changing shoreline of Suriname (South America)*, Doctoral dissertation, Utrecht University.

[31] Gersie K, Augustinus PGEF & Van Balen RT. (2016) Marine and anthropogenic controls on the estuary of the Suriname River over the past 50 years. *Netherlands Journal of Geosciences*, 95 (4), 419-428.

[32] Berrenstein H. (2010) Coastal changes along the Suriname coast with emphasis on the changing coastline of Coronie from 1914 to 2007 and its influence on Avicennia germinans L. (Avicenniaceae). *Academic Journal of Suriname*, 1, 86-95.

Behaviour along the greater Paramaribo coast represents a significant departure from the overall pattern of accretion, with significant coastal erosion occurring along the Weg naar Zee and Wanica coasts. Up to 1200m land loss has been identified for the Weg naar Zee and Wanica coasts (Figure 3-4). A portion of this retreat has been direct loss of "dry land", with mangrove retreat of up to 450m at Weg naar Zee and up to 600m along Wanica. The associated loss of mangroves is approximately 140 hectares. Most of this mangrove loss is from the Wanica coast, as most of the mangroves in the Weg naar Zee area had already been cleared following European colonization.
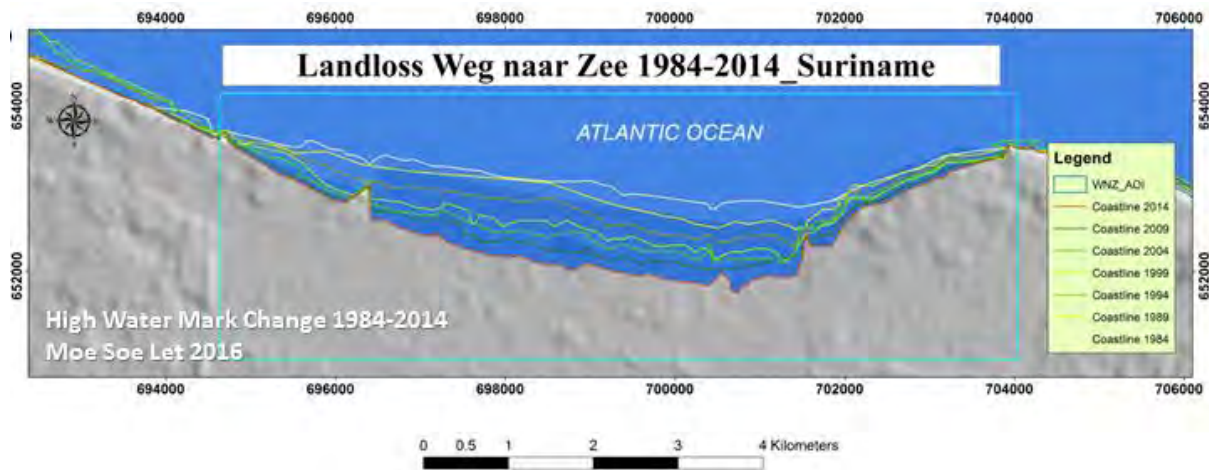
Figure 3-4: Retreat of Weg naar Zee coast 1984-2014 (from Moe Soe Let 2016[33])

This broad pattern of erosion is consistent with the movement of the large-scale mudbanks (Section 2.3). As discussed in Chapter 2, the westward movement of these mudbanks results in a cycle of accretion and erosion, with the greater Paramaribo area currently within a period of erosion. At a general level, it is therefore not surprising to have coastline change. **However, erosion that is currently being experienced is affecting areas that have been populated for more than a century. This implies that additional factors, or a coincidence of factors, are contributing to a greater retreat than has been observed historically as a function of mudbank dynamics**.

Review of shoreline change along the whole of Suriname coast highlights two areas showing a general trend of erosion at Coronie (near Totness) and at Weg naar Zee. These areas represent locations in which extensive rice polders were cultivated, effectively separating the shore from the floodplain, and reducing the capacity for the coast to "recover" during the mudbank phase. Simulation of erosion and recovery cycles based on observed rates of change and variability of the mudbank migration has suggested substantial long-term erosion can result from blocking coast-floodplain interaction (Appendix B).

A hierarchy of processes contributing to erosion on the Suriname coast has previously been postulated by Winterwerp & Augustinus (2009)[34]. This has since been supplemented by more recent studies from

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[33] Moe Soe Let V. (2016) *Study on the dynamics of the coastline of Suriname and the relationship to mangrove using Remote Sensing*. Antom de Kom University of Suriname, Faculty of Technology. Bachelor of Science Thesis.
[34] Winterwerp H & Augustinus P. (2009) *Coastal morphodynamics report. Physical description of the Suriname coastal system*. ICZM Plan Suriname.

Suriname and the Guianas (Anthony 2015[35], Gersie *et al*. 2016[36]) along with mechanisms identified that cause coastal change described for other mud coasts (Winn *et al*. 2006[37], Rossington *et al*. 2009[38], Townend *et al*. 2011[39]). Identified processes that may have contributed to increased erosion in greater Paramaribo are summarised by Table 3-1. Each of these is discussed further below.

Process	Scales
Mudbank dynamics (gross)	Large Scale (1-3km cycles over 30-50 years)
Changes to mudbank dynamics	Moderate (0.5-1km within unusual cycles)
Damming of Suriname River	Long-term (unquantified scale, over decades)
River channel migration	Moderate (not measured, 0.2-0.5km inferred)
Water courses / local drainage	Local scale (not measured, visually apparent)
Mangrove Loss/Removal	Local scale

Table 3-1: Processes contributing to erosion in greater Paramaribo.

Changes to mudbank dynamics

While movement of the mudbanks has been a constant, not all of the mudbanks are currently moving at the same rate and this may be exacerbating the scale of erosion currently experienced in parts of greater Paramaribo. In particular, the Coronie mudbank, located to the west has been the most rapidly moving mudbank along the Guianas coast (Gratiot 2011[40]). In contrast, the Commewijne mudbank, east of Paramaribo, has been the slowest moving mudbank. The result of this is an unusually long inter-bank period affecting area; a factor that may be leading to increased erosion in areas not seen historically.

Damming of the Suriname River

Installation of the Brokopondo Dam at the headwaters of the Suriname River has resulted in a substantial change to the hydrodynamics of the river estuary, shifting it from being dominated by seasonal flows, to being more strongly influenced by tidal exchange. **The consequent change in salinity provides direct stress on some mangroves, many of which require seasonal freshwater flushing** (Winterwerp *et al*. 2013)[41]. However, damming of the river may also affect sediment dynamics, with a local focus near the mouth of the river.

Global case examples of the response to damming rivers are diverse, with the most substantial impacts occurring when damming or water extraction cuts off riverine sediment supply, famously occurring at the Nile, Mississippi and Yellow Rivers. In situations where there is low riverine sediment supply reaching the coast, such as the Suriname River, impacts are largely related to a change in the estuarine hydrodynamics, with geomorphic responses of reducing the entrance cross-section and modifying the

[35] Anthony E. (2015) *Assessment of peri-urban coastal protection options in Paramaribo-Wanica, Suriname*. Prepared for WWF Guianas.

[36] Gersie K, Augustinus PGEF & Van Balen RT. (2016) Marine and anthropogenic controls on the estuary of the Suriname River over the past 50 years. *Netherlands Journal of Geosciences*, 95 (4), 419-428.

[37] Winn KO, Saynor MJ, Eliot MJ & Eliot IG. (2006) Saltwater Intrusion and Morphological Change at the Mouth of the East Alligator River, Northern Territory. *Journal of Coastal Research*. 22 (1): 137-149.

[38] Rossington, K., Whitehouse, R. J. S., & Spearman, J. (2009). Morphological modelling of intertidal profiles in estuaries with strong tidal currents. *Rivers, Coastal and Estuarine Morphodynamics*, 941-946.

[39] Townend I, Fletcher C, Knappen M & Rossington K. (2011). A review of salt marsh dynamics. *Water and Environment Journal*, 25(4), 477-488.

[40] Gratiot N. (2011) *Coastal erosion along the coast of Guiana*. Final report. MWH Consortium.

[41] Winterwerp JC, Erftemeijer PLA, Suryadiputra N, Van Eijk P & Zhang L. (2013) Defining eco-morphodynamic requirements for rehabilitating eroding mangrove-mud coasts. *Wetlands*, 33(3), 515-526.

structure of the ebb and flood sills. A wider geomorphic effect is to shift the estuary shape from that developed by "channel-forming floods" to instead take a tidal form, which has been described by an exponential relationship between the cross-sectional area and the distance upstream from the mouth (Woodroffe & Davies 2010)[42]. Although initial adjustment at the mouth can be rapid, within a decade or so, change to the wider estuary can be an extraordinarily slow process for a river with low fluvial sediment supply, as it requires material to be gradually moved upstream by the fraction of tidal flows capable of mobilising the bed.

The consequences of damming the Suriname River for estuarine and adjacent coastal morphology has not yet been explored in detail. Evaluation of changes to the channel cross-section in the first two decades was undertaken (van Heuvel 1983)[43], subsequently updated to include more recent change (Gersie *et al*. 2016)[44]. These assessments indicated relatively rapid change near the mouth of the River occurred initially (Figure 3-5), but that trend, although slowing, has not stopped, suggesting that adjustment to damming of the river may still be occurring. **Continued siltation of the estuarine channel potentially comes from river mouth sediments, with this movement contributing to the localised loss at Weg naar Zee**.
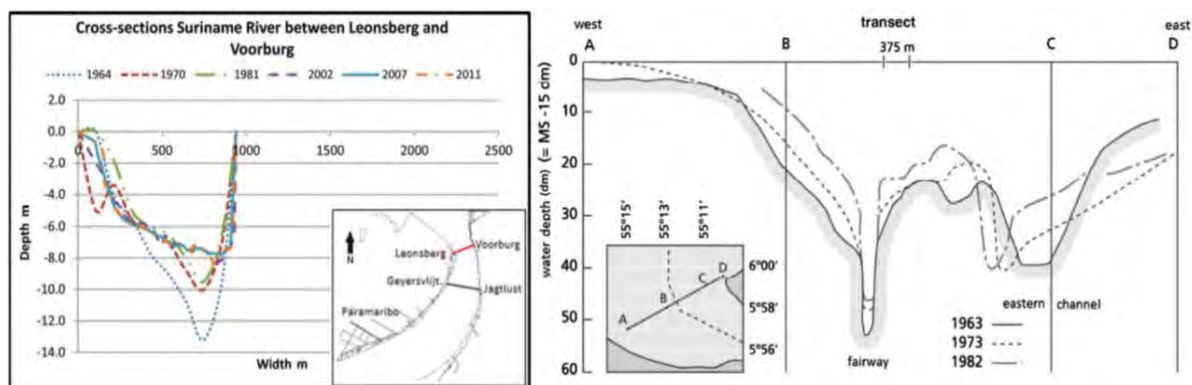
Figure 3-5: Changes to Suriname River entrance (from Gersie et al. 2016 following van Heuvel 1983)

Development pressure

The pressures on mangroves associated with development can broadly be characterised by (1) direct loss of mangroves through land clearing and (2) indirect impacts on mangroves associated with land-use change. Each of these categories of pressures are discussed below.

In situations where mangroves have been disturbed by a short, intense pressure (e.g. major storm damage, or a pollutant spill), restoration may be a relatively straightforward process, as the colonising and growth processes for mangroves are relatively rapid (Lugo 1998)[45]. However, **where loss occurs through sustained pressure, restoration of the coastal system towards its original state can be highly**

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[42] Davies G & Woodroffe CD. (2010) Tidal estuary width convergence: Theory and form in North Australian estuaries. *Earth Surface Processes and Landforms*, 35, 737-749.

[43] Van Heuvel T. (1983) Studie naar het gedrag van slib in en rond het estuarium van de Suriname rivier, in verband met de bevaarbaarhied van de toegangsgeul vanuit zee naar Paramaribo. Afstudeerwerk Technische Hogeschool Delft, Nederland, vakgoerp Kustwaterbouwkunde.

[44] Gersie K, Augustinus PGEF & Van Balen RT. (2016) Marine and anthropogenic controls on the estuary of the Suriname River over the past 50 years. *Netherlands Journal of Geosciences*, 95 (4), 419-428.

[45] Lugo AE. (1998) Mangrove forests: a Tough System to Invade but an Easy one to Rehabilitate. *Marine Pollution Bulletin*, 37 (8-12), 427-430.

challenging, with factors to be considered such as seed stock, hydrology, sediment supply, nutrients and bed stability (Gratiot 2011[46]; Winterwerp *et al* 2013[47]; Lewis *et al*. 2016[48]).

Direct impacts

The initial phase of land development along the coast in greater Paramaribo occurred in the 18th Century, largely involving the clearing of land for agricultural purposes. This development activity increased during a period of high immigration between the 1950s and 1970s (Nijbroek 2014[49]) with a focus on the development of rice plantations. In the 1980s, another phase of increased land development occurred due to a legal hiatus of land ownership following Suriname's transition through military rule; representing a period of squatting and tree felling for timber.

The cumulative effect of this development has been the removal of mangroves along most of the Weg naar Zee coast and most of the western bank of the Suriname River (adjacent to Paramaribo). As highlighted above, the two remaining substantial areas of mangrove forest occur along the Wanica coast, west of Weg naar Zee, and adjacent to the mouth of the Suriname River, near the suburbs of Rainville and Blauwgrond.

Since the 1980s, there has been considerable development pressure for northern Paramaribo. The opportunity for substantial increase in land values associated with improved flood management, either through increased agricultural productivity or residential use, has resulting in a strong imperative for existing land owners to seek development opportunities. Despite this pressure, major land clearing has been relatively rare, except developments at Rainville and Blauwgrond between 2009 and 2013 (Figure 3-6). As part of these developments, approximately 50 hectares of coastal mangrove were removed.

Figure 3-6: Residential development areas at Blauwgrond

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[46] Gratiot N. (2011) *Coastal erosion along the coast of Guiana*. Final report. MWH Consortium.

[47] Winterwerp JC, Erftemeijer PLA, Suryadiputra N, Van Eijk P & Zhang L. (2013) Defining eco-morphodynamic requirements for rehabilitating eroding mangrove-mud coasts. *Wetlands*, 33(3), 515-526.

[48] Lewis RR, Milbrandt EC, Brown B, Krauss KW, Rovai AS, Beever JW & Flynn LL. (2016) Stress in mangrove forests: Early detection and pre-emptive rehabilitation are essential for future successful worldwide mangrove forest management. *Marine Pollution Bulletin*, 109(2), pp.764-771.

[49] Nijbroek RP. (2014) *Mangroves, mudbanks and seawalls: Political Ecology of Adaptation to Sea Level Rise in Suriname*. PhD Thesis, University of South Florida.

Increased development density has also occurred closer to the coast, in the Weg naar Zee area. This area includes the Hindu Temple and its access via Henry Fernandesweg, which have been armoured and now project into the ocean.

The pattern of human activity to remove mangroves and develop infrastructure on the landward side is globally widespread. However, this reduces the potential for change to mangrove community width (habitat squeeze), either through sea-level variability or erosion cycles (Gilman *et al*. 2008[50]). Narrowing increases the fragility of the mangrove community, increasing the potential for tidal channels to cut through the mangroves and remove sediments. In situations where coastal squeeze causes local loss of mangroves, the absence of adult plants reduces resilience of the community, as there are no propagules. This may require artificial planting of seedlings or dispersion of mangrove propagules (Gratiot 2011[51]).

Indirect impacts

In addition to large scale clearing for development, the following factors have an influence on mangroves:

- **Drainage.** Development in greater Paramaribo has involved the construction of a network of drainage channels. These channels alter the hydrologic regime of the catchment, increasing the speed at which runoff is moved from the floodplain to the ocean. This causes a reduction of freshwater flow through the mangroves forest during periods of inundation, an important factor affecting the health and growth of mangroves.
  A secondary effect of drainage systems is to focus runoff flows. Where release to the ocean is uncontrolled, drainage channels scour the intertidal flats, increasing the export of sediment offshore.
- **Dykes.** A range of dykes and walling have been developed in and around Paramaribo to mitigate the risks of flooding (e.g. bank revetments and timber walls along the Suriname River, and a short-lived concrete dyke west of the Hindu temple). While these structures may provide local protection from flooding, like drainage channels they also impact the hydrologic regime of the catchment, influencing the supply of freshwater to the mangroves. Rainfall (or stream supply) on the landward side of the dyke must be managed to prevent runoff flooding, and therefore it is usually necessary for a dyke to include a drainage system. For earthen dykes, it is common for drainage channels outside and inside the dyke to provide borrow material for the bulk of the dyke. A new ring dyke and ring canal has been proposed for Weg naar Zee coast to reduce flooding (Proplan 2015[52]).
- **Minor clearing.** Minor clearing of mangroves for access tracks and drilling sites has occurred progressively as part of oil exploration activities. Harvesting of mangroves for firewood, fish-smoking and construction materials has been identified near urban areas, although this has been described as incidental, apart from phases of local land development through the 1950s to early 1980s.

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[50] Gilman EL, Ellison J, Duke NC & Field C. (2008) Threats to mangroves from climate change and adaptation options: a review. Aquatic Botany, 89(2), pp.237-250.
[51] Gratiot N. (2011) *Coastal erosion along the coast of Guiana*. Final report. MWH Consortium.
[52] Proplan (2015) *Feasibility Study Project Weg naar Zee coastal protection works for funding by the ISDB*. Prepared for Ministerie van Openbare Werken.

- **Dredging.** Potential impacts of dredging have been identified, although plans for navigational dredging (Augustinus 2006[53]) have not been active for some time.

Climate change and variability

Mangroves are specially adapted to a relatively narrow coastal habitat, mainly comprised of the upper part of the tidal range. Within this domain, mangrove species variation in root structure, pneumatophores ("breathing tubes") and mechanisms for salt shedding provide different degrees of sensitivity to bed movement, smothering or freshwater flow. Growth or loss of individual plants can be influenced by sensitivity at a very local scale (microhabitat), including the influence of adjacent plants. In general, the longer root systems of red mangroves are more tolerant to depth changes than black mangroves, which preferentially grow on the intertidal flats. Mangroves are particularly sensitive to smothering or erosion during the initial phase of establishment, which is a common reason it is difficult to re-establish a degraded mangrove bed.

The spatial distribution of species is often complex, indicating habitat changes over time, including changes to sediment, nutrient and freshwater supply (Alongi 2008[54]). This may include sequences of dieback and re-colonisation when conditions are not favourable to mangrove survival, such as closure of a tidal lagoon. Observationally, some resilience to changing conditions has been reported, including the effect of moderate rates of burial, which is sometimes cited as a basis for mangrove tolerance to sea level rise.

Information to describe broad-scale climate changes affecting the greater Paramaribo area mangroves has not been clearly identified. However, the role of microclimate variation has been anecdotally recorded, and there is substantial international literature indicating that an understanding of climate variability is essential to ensure rehabilitation for degraded sites (Lewis *et al*. 2016[55]).

Planning and management

A substantial positive change to regional management of Suriname's mangrove coast has been progressively brought forward through the introduction of coastal management plans (Teunissen 2000[56], 2004[57]) and subsequent definition of Mixed Use Management Areas and Nature Reserves along the coast (Figure 3-7).

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[53] Augustinus P. (2006) *Morphological Considerations in Relation to Channel Deepening in the Suriname River*. Suriname River Deepening Project (SRDP).

[54] Alongi D (2009) *The energetics of mangrove forests*. [Dordrecht]: Springer.

[55] Lewis RR, Milbrandt EC, Brown B, Krauss KW, Rovai AS, Beever JW & Flynn LL. (2016) Stress in mangrove forests: Early detection and pre-emptive rehabilitation are essential for future successful worldwide mangrove forest management. *Marine Pollution Bulletin*, 109(2), pp.764-771.

[56] Teunissen P. (2000) *Coastal Management Plan for the North Coronie Area in Suriname*. Republic of Suriname Ministry of Natural Resources (NH), Suriname Forest Service (LBB) and Nature Conservation Division (NB).

[57] Teunissen P. (2004) *Project Studies for Construction of Coronie Foreshore. Natural and Artificial Coastal Change in the Coronie District*. {In Dutch}

Figure 3-7: Suriname coastal Management Areas and Nature Reserves

Formalising of the management of the Suriname coast has been proposed through legislation, with the Coastal Protection Act (CPA) being subject to parliamentary discussion and negotiations. The CPA would provide a key regulatory framework for improved management of the coast. Corresponding institutional changes, including coordination of staff and funding sources, will be required to make the CPA functional.

3.4   Summary and implications

This chapter has provided insight into the status of mangroves in the greater Paramaribo area and the stressors acting on these (historical, current and future). **There are two main stressors that are arguably most important in this regard. The first of these is the natural, cyclical pattern of mudbank migration and the influence of these on mangroves. The second is development pressure**.

There is clear historical evidence to suggest that the distribution and characteristics of mangroves are directly linked to the movement of the mudbanks, with greater Paramaribo currently experiencing an extended period of coastal erosion. The erosion interbank phase, which typically lasts for approximately 20 years within the 30-year erosion-recovery cycle, has been sustained for more than 30 years, with another 5-20 years to go, based on the slow migration rate of the mudbank to the east.

Recognition of the influence of mudbank movement is essential with respect to developing a sustainable coastal resilience strategy because this strategy must work alongside the natural processes in the region. It is also important to recognise that the greater Paramaribo should again enter a period of sediment accretion associated with the arrival of the next mudbank. Clearly, this represents a strong opportunity for future mangrove regeneration; although it is important to recognise that mangrove regeneration takes time, limiting present day benefits, and that the presence of the mudbanks will only ever be temporary. Consideration of changing erosion pressure over time and its uncertainty is important.

Development control is also key to a sustainable coastal resilience strategy. It is clear that no one intervention will provide the solution to coastal flood and erosion risk in the greater Paramaribo area. A sustainable strategy will inevitably involve a range of interventions and zoning and development control are a key one. Development control will protect the mangroves and support regeneration activities. Development control will also help to reduce the population at risk of flooding. **The situation**

in Suriname and the greater Paramaribo area is such that there will always be a significant flood risk. While measure can be taken to limit this risk, the most effective strategy will be to limit the exposure of people and assets to this risk. **Implementation of the CPA and its institutional frameworks is key here.**

In the next chapter, the relative opportunities provided by different coastal flood and erosion intervention methods, including the use of mangroves and hard structures (e.g. dykes) is explored further.

4. Coastal protection services assessment

Consideration of coastal hazard mitigation options for the Suriname coast has previously resulted in several different recommended pathways for coastal management. These broadly correspond to either protection or hazard avoidance strategies, with an additional distinction of whether protection is developed through "hard" engineering or nature-based approaches.

- Nationwide, low development density in non-urban areas along the coast provides opportunity for hazard **avoidance** through use of coastal setbacks.
- At North Coronie, a coastal seawall was installed to provide **protection** to both the townsite of Totness and coastal access road to Nickerie, which had been subject to both inundation and erosion.
- For greater Paramaribo, existing development and human activity are subject to inundation hazard and erosion pressure, focused in the Weg naar Zee area. Evaluation based on flooding hazard recommended protection through a ring dyke and canal (Proplan 2015[58]). In contrast, evaluation based more heavily on erosion hazard recommended **mangrove reconstruction** supported by sediment trapping units (Burke & Ding 2016[59]). For the urban foreshore to the east, **protection** using a dyke was recommended based on cost-benefit evaluation.

The discrepancy between management strategies at a country scale and at more local scales is apparent. This has largely been determined by the differences in costs and benefits between largely rural and peri-urban settings, with protection being justified on a financial basis.

4.1   Country scale coastal hazard mitigation using setbacks

The planning approach of coastal setbacks requires definition of permissible land use activities within defined proximity to the coast, over a nominated period, typically in the order of 50 to 100 years. **Definition of an appropriate proximity to the coast requires consideration of longer-term coastal dynamics**. As this definition typically includes future changes to inundation or erosion patterns due to projected sea-level rise, the coastal setback zone commonly includes areas that are not under present-day threat from coastal hazards. For the Suriname coast, the challenge of balancing perceptions of present-day stability against the possibility of future hazard is also increased by the large-scale mudbank dynamics. **Balancing present day-use against future potential change provides a planning challenge**:

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[58] Proplan (2015) *Feasibility Study Project Weg naar Zee coastal protection works for funding by the ISDB*. Prepared for Ministerie van Openbare Werken.
[59] Burke & Ding. (2016) Valuation of Coastal Protection near Paramaribo, Suriname. Prepared for WWF Guianas.

- If no development is allowed in the fringe between present day and future hazard, then pressure for compensation by existing land-holders is likely, due to perceived opportunity cost.
- If "temporary" development is allowed, then unsteady transition from present day (low hazard) to future conditions with unacceptable hazard is likely to cause loss associated with occasional extreme events.
- If "permanent" development is allowed, installation of coastal defence systems or implementation of building floodproofing is likely to be required (i.e. using protection or tolerance strategies for flood hazard). Where defences are used, landward movements of the tidal zone will therefore "squeeze" coastal fringing mangroves against the defences, causing habitat loss (Gilman *et al*. 2007[60]).

Over recent decades, the GoS has progressively moved towards a planning framework that supports use of coastal setbacks to mitigate coastal hazards. Steps have included development of regional coastal management plans (Teunissen 2000[61], 2004[62]), definition of environmentally-based mixed used management areas (MUMAs) (Parahoe *et al*. 2008[63]) and most recently drafting of the CPA. Although the principal driver for this management framework is the sustainability of natural resources, including environmental productivity, the broad-scale approach to minimise disturbance of the coast is complementary to the use of coastal development setbacks, with "red-line" limits defined for each MUMA.

Techniques for the definition of coastal setback zones vary globally, but are typically based on approximation of the area likely to be dynamic over a 100-year time frame, considering extreme storms, coastal evolution and response to sea-level rise. Erftmeijer & Teunissen (2009) provided preliminary guidance for an appropriate setback for Suriname, based solely upon historic shoreline fluctuations, being in the order of 3-4km.

In the context of response to sea-level rise in the order of 0.5-1.0m over a time frame of 100 years, it is feasible that historic shoreline fluctuations will not provide an adequate indication of potential future coastal change. Estimates of the physical extent of potential coastal change may be provided by considering the vertical change to zones of geomorphic disturbance. Considering the present-day inter-tidal range, the *minimum* area of disturbance associated with a +1m sea-level rise is approximated by the +2.9m NSP contour, which covers almost the entirety of Paramaribo (see Section 4.2).

An acknowledged difficulty of applying broadscale coastal setbacks is the difficulty of introducing setbacks to a coast with existing land-use and infrastructure. In theory, this is most readily managed through phases of infrastructure renewal (Kousky 2014[64], NCCOE 2015[65]). However, except in the case

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[60] Gilman E, Ellison J and Coleman R (2007) Assessment of Mangrove Response to Projected Relative Sea-Level Rise and Recent Historical Reconstruction of Shoreline Position. *Environmental Monitoring and Assessment*, 124(1-3), 105-130.

[61] Teunissen P. (2000) *Coastal Management Plan for the North Coronie Area in Suriname*. Republic of Suriname Ministry of Natural Resources (NH), Suriname Forest Service (LBB) and Nature Conservation Division (NB).

[62] Teunissen P. (2004) *Project Studies for Construction of Coronie Foreshore. Natural and Artificial Coastal Change in the Coronie District.* {In Dutch}

[63] Parahoe M, Soetosenojo A, Jadhav Y & Wortel V. (2008) *Economic Valuation & Monitoring of MUMA*. Final Report on Biodiversity and Economic Valuation of Bigi Pan Multiple Use Management Area, Part IV.

[64] Kousky C. (2014) Managing shoreline retreat: a US perspective. Climatic Change, 1-12.

[65] National Committee for Coastal and Ocean Engineering: NCCOE. (2012) Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering. 3rd edition. Volume 1 of the NCCOE Coastal Engineering Guideline Series. Engineers Australia.

of large-scale disaster, the need for renewal typically occurs at a small scale, with the value of adjoining facilities, or connection to a wider network (e.g. the roadway at North Coronie) often used as a basis for valuation to justify replacement or reinforcement, rather than relocation.

Although large-scale disasters are sometimes identified as "opportunities" by planners, this does not preclude the need to avoid infrastructure and human loss. This concept does not represent a strategy, merely one aspect of post-disaster management. In many developing countries, this concept is constrained by limited budgets for retrofitting infrastructure after a disaster. As demonstrated following repeated flood disasters in Bangladesh, the high mobility of the population may also constrain targeted renewal, with resettlement of flooded areas before new infrastructure can be established.

4.2   Coastal hazard mitigation for the GPA

The two major coastal hazards experienced in the GPA are coastal inundation and erosion, which need to be considered simultaneously to determine the adequacy of mitigation options. Further, it has been demonstrated that on muddy coasts, although some forms of coastal defence can prevent erosion, they can also substantially reduce the capacity of the coast to naturally trap marine sediments, providing an important offset to potential erosion. Evaluation of hazard mitigation options has therefore been considered for:

- Flood dissipation.
- Erosion resistance.
- Effect on coastal recession.

Identification of erosion and inundation sources in Chapter 2 and 3 indicates that coastal hazards are developed through multiple sources. Some of these sources are developed at extremely large scales (e.g. mud-bank movements or global sea-level rise) and are therefore not easily managed. However, other sources, such as mangrove loss or wave overtopping, may potentially be managed at a local scale. The effectiveness of these local-scale interventions is greatest when near the coastal fringe, however, this also provides likelihood of being overwhelmed by larger-scale changes, particularly erosion.

Previous identifications of hazard mitigation options have used prioritisation of hazards as a basis for selection:

- Erftmeijer & Teunissen (2009), considered hazard management along the wider Suriname coast. They argued that the effects of walls to reduce onshore sediment retention, combined with scour due to wave reflection and compaction, made walling an inappropriate management strategy. Erftmeijer & Teunissen (2009)[66] undertook an assessment of hazard mitigation options with *sediment retention* as a priority;
- Sintec (2015)[67] considered hazard management on the Weg naar Zee coast. They argued that flood hazard was immediate and affected a larger area than erosion hazard. Protection using mangroves

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[66] Erftmeijer P & Teunissen P. (2009) *ICZM Plan Suriname - Mangrove Report. Analysis of problems and solutions for the management of mangrove forests along Suriname's 'wild coast'*. Lievense-Deltares.
[67] Sintec & Sunecon (2015) *Updated Ring-dyke Engineering Studies*. {In Dutch}

was deemed to be ineffectual for flood hazard prevention due to the low elevation of mangrove land. Use of a dyke structure was selected due to knowledge of existing structures for flood protection. Sintec (2015) used *flood protection* as a priority for selection of options.

- Burke & Ding (2016)[68] considered hazard management along the GPA coast, from Weg naar Zee through to Bluwgrond. Supported by a coastal change evaluation by Anthony (2016)[69], they developed a financial comparison of dyke structures and mangrove restoration on the assumption that either could provide effective coastal hazard mitigation at the time of installation. Overall, walling performance, particularly at Weg naar Zee, was simulated as extremely limited, following analysis of potential erosion stress. In effect, Burke & Ding (2016) used *erosion hazard* as a priority for selection of options. Performance of mangrove restoration was overestimated, and the area of land subject to flood hazard was substantially exaggerated.

For this evaluation, the potential solutions for the GPA were further considered, including non-structural measures, walling, mangrove restoration and flood plan restoration. Each of these solutions and their relative merits are discussed below.

Non-structural measures

Non-structural approaches towards hazard mitigation involve land-use planning, flood warning and evacuation systems to ensure that infrastructure risk and human safety are adequately mitigated. The opportunity for non-structural measures primarily occurs across the area which is flooded by infrequent, very high floods, but not frequent, lower floods. As shown by Figure 2- this represents only a narrow strip of land, which is substantially reduced for a projected sea level rise allowance of 0.27m (Figure 2-). In effect, **although the small amplitude of floods in greater Paramaribo suggests opportunity for use of non-structural measures, their viability is reduced by the substantial increase in flood recurrence due to only a small difference of depth**.

Property-level protection (PLP), although not strictly non-structural, provides strengthening of buildings at a very local scale that increases tolerance to flooding. Effective use of PLP requires incorporation of flood warning and evacuation systems. As with the use of planning measures, the key limitation of using PLP is that the viability of supporting adjacent land-use (e.g. agriculture) is substantially constrained by the frequency of flood recurrence.

Walling as a primary approach

Walling has been proposed as a primary means of achieving flood defence for greater Paramaribo (Proplan 2015[70]), with an 8.2km long rock dyke design proposed with a crest level of +5.85m NSP (i.e Normaal Surinaams Plein, the national reference plane for Suriname) and a toe level of 0.0m NSP (Sintec & Sunecon 2015). This is similar in design to the walling constructed for Totness, North Coronie (Figure 4-1). The walling is designed to tolerate a depth limited wave height, which means that erosion in front of the wall reduces its structural capacity, including scour that results from wall installation. **Bed lowering of approximately 1m would cause the design wave (being the conditions under which the dyke starts to experience damage) to shift from occurring once every 50 years on average, to once per year on average**. Based on approximate rates of change from 1984-2014 (Moe Soe Let

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[68] Burke & Ding. (2016) *Valuation of Coastal Protection near Paramaribo*, Suriname. Prepared for WWF Guianas.
[69] Anthony EJ. (2016) *Impacts of sand mining on beaches in Suriname*. WWF.
[70] Proplan (2015) *Feasibility Study Project Weg naar Zee coastal protection works for funding by the ISDB*. Prepared for Ministerie van Openbare Werken.

2016[71]), this would occur within a time frame of 10-15 years, providing an effective structural life of 15-25 years.

Figure 4-1: North Coronie Sea-Dyke and Canal (Public domain image from Panoramio TH22)

The proposed design includes a 50m wide buffer of planted mangroves. At historic rates of erosion (approximately 40m/yr), this buffer will last for approximately one year, which is insufficient time for mangroves to establish, and noting that the conditions may not be supportive for mangrove growth. It is understood that the 50m buffer has been incorporated as an offset to the effects of scour in front of the dyke, and therefore the time taken to erode does not add to the anticipated structural longevity. **Setting walling further landwards may provide greater longevity for walling**. However, the present layout has been based on the preservation of existing infrastructure, including Brantimakaweg and Oedayrajsingh Varmaweg roadway.

The need for walling to withstand progressive erosion, whether by increasing walling strength or setting it back further from the coast, will continue while the Weg naar Zee coast is in the interbank phase. Presently, the nearest approaching mudbank is approximately 15km from Braamspunt, near the mouth of the Suriname River (Anthony 2016[72]). The remaining length of the interbank phase is therefore suggested by its speed of movement along the Commewijne coast. Up to 2001, this mudbank had progressively slowed as it approached the Suriname River, to an estimated speed of 0.5km/yr along the coast (Augustinus 2006[73]; Gratiot 2011[74]). More recent measurements have demonstrated faster progress from 2009-2016 of up to 1.6km/yr, although this may be a short-term acceleration. Implicitly, this suggests the interbank phase at Weg naar Zee will conclude within 10 to 30 years.

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[71] Moe Soe Let V. (2016) *Study on the dynamics of the coastline of Suriname and the relationship to mangrove using Remote Sensing*. Anton de Kom University of Suriname, Faculty of Technology. Bachelor of Science Thesis.
[72] Anthony EJ. (2016) *Impacts of sand mining on beaches in Suriname*. WWF.
[73] Augustinus P. (2006) *Morphological Considerations in Relation to Channel Deepening in the Suriname River*. Suriname River Deepening Project (SRDP).
[74] Gratiot N. (2011) *Coastal erosion along the coast of Guiana*. Final report. MWH Consortium.

Projecting historic rates of erosion, the required setback for a dyke to avoid undermining pressure before the next mudbank phase is 400m to 1.2km. **In practical terms, a more substantial structure is required than proposed by Sintec & Sunecon (2015)[75] with larger rock armour and deeper scour embedment if placed on the coast, to cope with anticipated erosion pressure.**

In the longer-term, a key implication of using walling as the primary strategy for coastal hazard mitigation is the implication for reduced shoreline recovery during mudbank phases, due to disconnection from the adjacent floodplain. This local effect has contributed to local net erosion trends at Totness and Weg naar Zee. For Totness, this situation caused substantially reduced shoreline recovery during two mudbank phases around 1950 and 1990, with a net erosion trend of approximately 30m/yr from 1920 to 2008 (Winterwerp & Augustinus 2009[76]). This almost equals the 40m/yr rate of interbank erosion at Weg naar Zee from 1984-2014, and contrasts starkly with net average accretion of 5m/yr estimated for the whole Suriname coast from 1947-2007 (Berrenstein 2010[77]).

Estimates of the potential response to lagged mudbank arrival, or reduced shoreline recovery during the mudbank phase each have the capacity to cause approximately 1km of erosion over a single mudbank phase. This is consistent with stratigraphic measurement of coastal sediments along the Guianas coast. However, as the reduced shoreline recovery is largely a result of human activities since European colonisation, it is an additional factor to prehistoric change.

The constraint of the depth-limited design wave may be further complicated by the process of sea-level rise. Although it is understood that projected sea-level rise is moderate over the intended 50-year lifetime of the proposed rock dyke, it will further reduce the structure longevity due to increasing water depth and increasing rates of coastal erosion.

The potential for progressive erosion due to reduced shoreline recovery in the mudbank phase, combined with erosion due to sea-level rise, presents a significant challenge to use of walling as a primary strategy for coastal hazard mitigation. Appendix C provides an exploration of the mobility of the Suriname coast, built around the observations of coastal erosion and recovery cycles (Augustinus 1978[78]; Augustinus & Teunissen 2004[79]; Berrenstein 2010).

Under a scenario of using walls to defend a coast subject to sea-level rise, there is a need to recognise the relative risk associated with failure of the protection, either through a larger event than the wall is designed for, or the influence of progressive structural degradation (Hofstede *et al*. 2005[80]). In most locations where flood defences are installed, the belief in protection results in increasingly intense human activity, which further increases the residual risk associated with defence failure. This approach

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[75] Sintec & Sunecon (2015) *Updated Ring-dyke Engineering Studies*. {In Dutch}
[76] Winterwerp H & Augustinus P. (2009) *Coastal morphodynamics report. Physical description of the Suriname coastal system*. ICZM Plan Suriname.
[77] Berrenstein H. (2010) Coastal changes along the Suriname coast with emphasis on the changing coastline of Coronie from 1914 to 2007 and its influence on Avicennia germinans L. (Avicenniaceae). *Academic Journal of Suriname*, 1, 86-95.
[78] Augustinus PGEF. (1978) *The changing shoreline of Suriname (South America)*, Doctoral dissertation, Utrecht University.
[79] Augustinus P & Teunissen P. (2004) Bank protection construction for the right bank of the Suriname River and the left bank of the Commewijne River. Morphological aspects and natural shoreline protection.
[80] Hofstede J. (2005) COMRISK. Common Strategies to Reduce the Risk of Storm Floods in Coastal Lowlands. *Die Kuste* Special Edition, 70:

has usually required progressively increasing government investment in defence structure capital construction and maintenance.

To date, dykes have been considered as the most practical form of walling. This is due to experience with building such structures along the Suriname coast, due to the relatively narrow distance between the coast and existing infrastructure, the desired height of flood protection and the material life of structures. Alternative approaches to walling, including timber retaining walls or bioengineering techniques (e.g. brush-mattressing) have largely been ruled out before structural or financial evaluation.

It is noted that alternative forms of walling may be considered practical to enhance erosion resistance, rather than relying on the rock-dyke, as the functions of erosion and flood protection are not necessarily provided by a single structure. Sediment trapping units being trialled by the Anton de Kom University of Suriname at Weg naar Zee provide an example of bioengineering, with timber and brush walling structures providing a temporary protection that enhances the opportunity for mangrove restoration.

Figure 4-2: Alternative forms of walling (Guyana Seadyke from Anthony et al, 2012[81])

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[81] Anthony E, Gardel A and Gratiot N (2013) Fluvial sediment supply, mud banks, cheniers and the morphodynamics of the coast of South America between the Amazon and Orinoco river mouths. *Geological Society, London, Special Publications*, 388(1), 533-560.

Mangrove restoration

Mangrove restoration has been recommended as a preferred coastal management strategy to respond specifically to the hazard of erosion (Erftmeijer & Teunissen 2009[82]; Burke & Ding 2016[83]). The capacity to enhance restoration efforts has been demonstrated using sediment trapping units (Winterwerp *et al*. 2013[84]), including promising findings from their application in Suriname (Naipal & Fung-a-Loi 2016[85]). However, the value of mangrove restoration efforts is potentially constrained by:

- Mangroves have limited influence on flood hazard, particularly on the Suriname coast, where most floods are caused by high tides, rather than through short-term surge or wave energy.
- Time frame for habitat restoration is approximately 5-10 years, provided conditions are suitable.
- Complications of eco-hydrodynamic requirements, including freshwater needs and a limited domain of growth (Winterwerp *et al*. 2013).

Enhancement of mangrove restoration using bioengineering techniques has been promoted for the Guyana coast (Gratiot 2011[86]), ranging from artificial distribution of propagules to more structural alternatives, such as application of sediment trapping units.

A mangrove fringe provides perceptible slowing of coastal erosion during the interbank phase. This influence has been demonstrated at Weg naar Zee by the difference between movement of the high-water mark (HWM) (Moe Soe Let 2016[87]) and movement of coastal vegetation line, where the presence of a thin fringe of mangroves resisted change during a period of approximately 800m landward movement of the HWM.

Levels at which mangroves may provide coastal protection can be estimated by considering the zones in which species of mangroves are active and the relative heights of their aerial mass/undergrowth and root mass. For a fully developed fringe of black mangroves, this range is in the order of 0.2-2.2m NSP (Figure 4-3).

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[82] Erftmeijer P & Teunissen P. (2009) *ICZM Plan Suriname - Mangrove Report. Analysis of problems and solutions for the management of mangrove forests along Suriname's 'wild coast'*. Lievense-Deltares.

[83] Burke & Ding. (2016) Valuation of Coastal Protection near Paramaribo, Suriname. Prepared for WWF Guianas.

[84] Winterwerp JC, Erftemeijer PLA, Suryadiputra N, Van Eijk P & Zhang L. (2013) Defining eco-morphodynamic requirements for rehabilitating eroding mangrove-mud coasts. *Wetlands*, 33(3), 515-526.

[85] Naipal S & Fung-A-Loi C. (2015) *Mangrove rehabilitation Weg naar Zee with sediment trapping technique. An application to promote and enhance coastal resilience and mangrove restoration; An eco-based disaster risk reduction project*. {Presentation}

[86] Gratiot N. (2011) *Coastal erosion along the coast of Guiana*. Final report. MWH Consortium.

[87] Moe Soe Let V. (2016) *Study on the dynamics of the coastline of Suriname and the relationship to mangrove using Remote Sensing*. Anton de Kom University of Suriname, Faculty of Technology. Bachelor of Science Thesis.

Approximate levels at which mangroves may provide coastal protection

Typical bed levels for black mangroves	Range of levels over which mangroves may provide protection	
	2.2m NSP	
1.7m NSP	Flow baffling	
1.2m NSP	Erosion Resistance	
	0.2m NSP	

Canopy — 5-10m
Trunks
Undergrowth / Aerial Roots — 0.3-0.5m
Root Mass — 0.5-1.0m
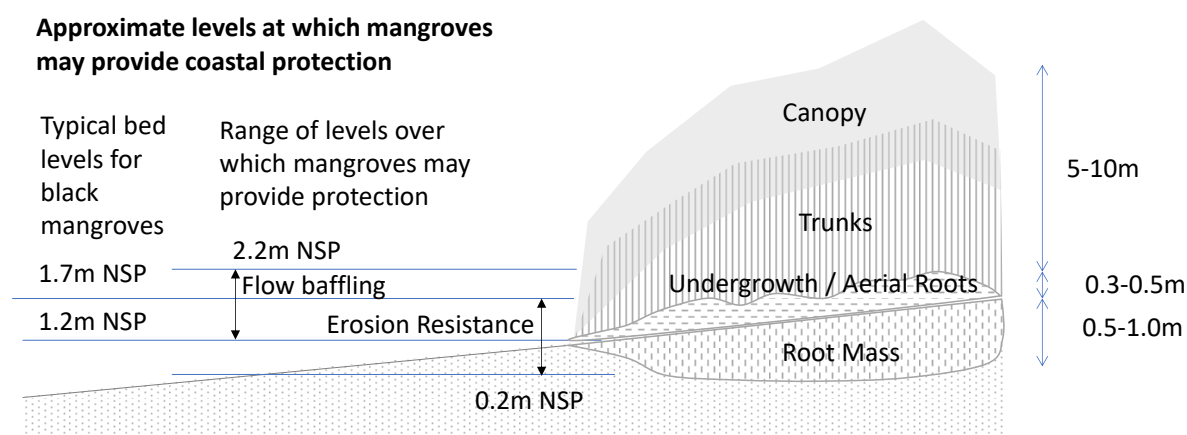
Figure 4-3: Levels for which black mangroves may provide protection

However, if the mangrove fringe is undermined, it provides limited subsequent retention and coastal erosion "catches up". From 2004 to 2014, the coastal vegetation line retreated approximately 600m, with the HWM retreating approximately 400m. In effect, this represents resistance of approximately half the erosion during the interbank phase, which demonstrates the value of a well-established coastal mangrove fringe.

For broad areas of coastal mangroves, the rapid damping of waves across tens of metres reduces the capacity of incoming water to carry sediment, and therefore may assist formation of discrete storm ridges, particularly sand and shell when they are available (Anthony 2015[88]). This capacity is substantially reduced for a narrow band of mangroves.

A similar process is considered to occur for muddy sediments, over decadal time scales, with the mangroves assisting in material capture. However, due to the relatively greater mobility of the mud compared with sand, the gradient of deposition is very flat, and strongly related to the consequent hydrodynamics, including formation of tidal channels (Wolanski 1992[89], Winterwerp *et al*. 2013[90]).

A narrow mangrove fringe, on its own, provides limited capture of muddy coastal sediments during the mudbank coastal phase. Consequently, there has been limited shoreline recovery for those areas in which the adjacent floodplain has been isolated from the coast, by polders, walling or roadways (as discussed in Section "Non structural measures" above).

Mangroves have historically demonstrated a substantial role for erosion resistance along the Suriname coast. However, their inability to provide substantial flooding protection determines that **mangrove restoration, on its own, does not provide a practical strategy for coastal hazard mitigation**.

Floodplain restoration

GPA is located on the low-lying Guianas region floodplain. Over thousands of years, this has gradually evolved with the passage of migrating mudbanks creating cycles of erosion and accretion, including overland sediment supply through high tides and floods. The low energy system has created a very

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[88] Anthony E. (2015) *Assessment of peri-urban coastal protection options in Paramaribo-Wanica, Suriname*. Prepared for WWF Guianas.

[89] Wolanski E. (1992) Hydrodynamics of mangrove swamps and their coastal waters. *Hydrobiologia*, 247: 141-161.

[90] Winterwerp JC, Erftemeijer PLA, Suryadiputra N, Van Eijk P & Zhang L. (2013) Defining eco-morphodynamic requirements for rehabilitating eroding mangrove-mud coasts. *Wetlands*, 33(3), 515-526

wide zone in which sediment exchange occurs, including the nearshore, intertidal area and on shore. **This "active zone" of the floodplain determines where sediment supply during the accretive mudbank phase is distributed. This has been modified since European colonisation of Suriname**:

- On the undisturbed parts of Suriname coast, the active zone of the floodplain includes extensive areas of mangrove, which allow water (and sediment) to flow through during flood events and high tides. This allows extensive onshore deposition of mud when the migratory mudbanks are located offshore, both throughout the mangroves and across the lagoons and flats further landward.
- On urban and peri-urban parts of the Suriname coast, barriers to flow, including roads and walling reduce movement of water and sediment to landward. This reduces the capacity for onshore deposition during the mudbank phase, and tips the balance of the erosion-accretion cycle from net accretion to erosion (Winterwerp & Augustinus 2009[91]).

The sharp difference in long-term behaviour between the undisturbed and modified coast is apparent at Weg naar Zee and Coronie (Berrenstein 2010[92]). Sustained recession at these locations provides a substantial challenge to the use of defensive structures, which will exacerbate the recession, despite the country-wide trend.

Effective management of the greater Paramaribo coast requires enhanced coastal stability, ensuring that recovery during the mudbank phase is commensurate with erosion during the interbank phases. Achieving this objective requires consideration of how the floodplain dynamics have been altered:

- The capacity of a mangrove fringe to enhance recovery is strongly influenced by the flooded area behind the coast which acts as a sediment trap, as well as the time over which floodwaters can drain out.
- Walling or roads may have cut off the flooded area and therefore reduced sediment capture;
- Artificial drainage systems accelerate the speed at which floodwaters recede, and therefore reduce sediment capture.

The linkage between walling, drainage and mangroves to recovery during mudbank phases requires deliberate scientific investigation. Although the effects of these factors have been demonstrated quantitatively through comparison with undisturbed sections of coast, there is yet no investigation of alternative measures. These may include using artificial wetlands as borrow pits behind a mangrove fringe, or creating sediment deposition areas using low level walling in a similar manner to the sediment trapping units.

An estimate of the active floodplain area has been developed by considering the area inundated during a flood event, over which incoming mud may be deposited. Combining the inundated area with relative occurrence (hours per year), the contribution of different flood levels and areas to potential deposition has been estimated (Figure 4-4). **This simplified evaluation indicates that approximately**

[91] Winterwerp H & Augustinus P. (2009) *Coastal morphodynamics report. Physical description of the Suriname coastal system*. ICZM Plan Suriname.
[92] Berrenstein H. (2010) Coastal changes along the Suriname coast with emphasis on the changing coastline of Coronie from 1914 to 2007 and its influence on *Avicennia germinans L*. (Avicenniaceae). *Academic Journal of Suriname*, 1, 86-95.

90% of floodplain sediment exchange will occur within 1.5km of the coast, suggesting an approximate minimum width for the floodplain to support coastal stability.
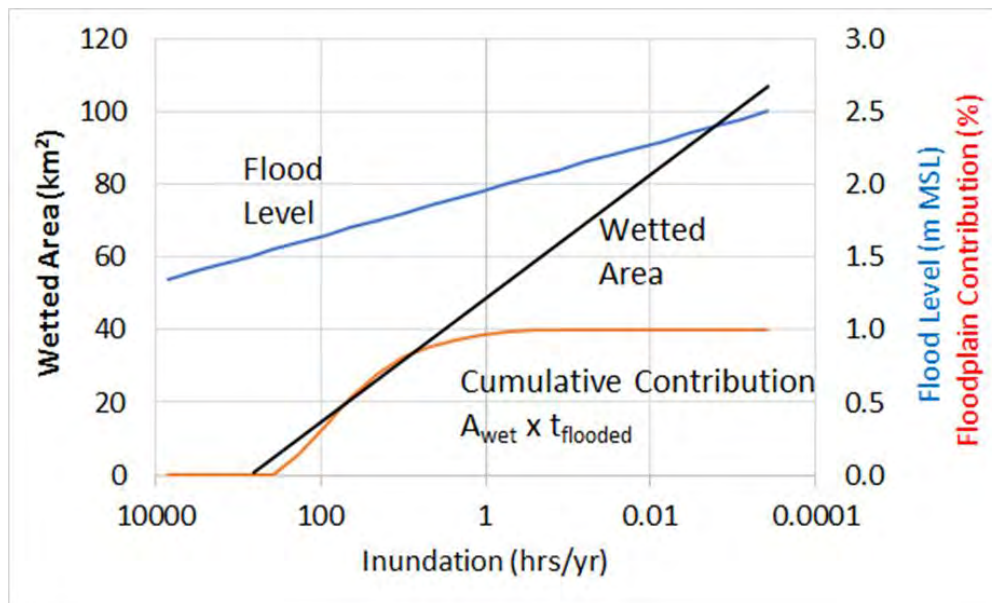
Figure 4-4: Simplified evaluation of active floodplain

4.3   Pathways forward for coastal hazard mitigation

This chapter has illustrated that no one mitigation approach will provide the level of protection required for greater Paramaribo. It is clear protection for the greater Paramaribo area will need to involve a mix of intervention approaches. This concept is further developed in the next chapter.

5. Cost-effectiveness of mitigation actions

Chapters 3 and 4 outlined the difficulty of using any one single strategy for coastal hazard mitigation, due to the difficulty of simultaneously dealing with coastal mobility, flooding hazard and long-term coastal stability. Each of the interventions considered provided a partial solution, and therefore there is a need to consider how a combination of actions may support coastal hazard management for greater Paramaribo. In this Chapter, the relative effectiveness of different interventions are considered, with economic analysis used to provide a basis for selecting the priority of potential actions.

Selecting a course of action where there are limited available resources requires a means of comparing the relative costs and benefits of different actions. **For greater Paramaribo, evaluation of coastal hazard mitigation actions involves a balance between the costs of mitigation and the benefits provided by the mitigation, typically related to the productivity of the land "saved" by intervention**. As discussed in Chapter 3, productivity may include direct financial returns, social benefits or environmental value.

The two key steps involved in determining the cost-effectiveness of coastal hazard mitigations are:

1. Determining the effectiveness of the proposed mitigation, relative to overall objectives. This may include partial risk reduction (e.g. only affecting low-moderate events), although it is a common objective to effectively eliminate risk up to a nominated hazard threshold.

2. Evaluating the relative cost of the proposed mitigation, compared to its effectiveness.

Section 5.1 outlines how each of the potential interventions addresses different flood events, and therefore how protection varies. The framework and basis for economic analysis is outlined in Section 5.2, with application to different types of flood mitigation considered in Section 5.3.

5.1   Effectiveness assessment of mitigation actions

Coastal hazards affecting Paramaribo include inundation due to coastal flooding, coastal erosion and long-term coastal instability (recession).

Coastal flooding exposure has been considered to occur across the range of events up to the 500-year Average Recurrent Interval (ARI) flood event (approximating the *probable maximum flood*), along with the allowance for sea-level rise. By 2050, this gives an estimated flood hazard range of up to 2.7m Normaal Surinaams Plein (NSP) (2.5m mean sea level (MSL)) which potentially includes parts of the existing urban area. Recurrence of flood exposure increases exponentially with decreasing level, such that a flood level of 1.5m NSP (1.3m MSL) occurs approximately a million times more often than a 2.7m NSP event. Despite this difference in occurrence, extreme sea-level events have significance, due to the much greater damage that may occur due to deeper flooding, including the risk to human life.

Following from Chapter 4, potential measures for mitigating flood hazard only (i.e. reducing the flooded area) include:

- Mangrove restoration and preservation, to create a buffer protecting against flow and waves, which may include the construction of sediment trapping units to support restoration. This is estimated to have minimal reduction on low level floods, as these are slow moving (tidal). The reduction on higher level events is influenced by the area flooded, with an estimated reduction of the 100-year ARI flood level of 0.22m towards the centre of Weg naar Zee and a reduction of 0.08m along the Blauwgrond and Rainville coast. In effect, mangrove restoration will not provide complete protection of the area potentially exposed to flooding, but will reduce the hazard area.
- The effectiveness of flood barriers (sea dyke, flood barrier or an embankment) is determined by the crest level of the barrier, its alongshore continuity, its distance to landward and its performance over the structural life cycle. It has been assumed that any walling will be designed to account for these factors, with the level specified to deal with flood level, wave action and settlement over time.
- An additional consideration for flood barriers is the potential interference of structures with coastal stability, including constraints to floodplain interaction and freshwater flow effects, which may destabilise mangroves or prevent their effective restoration. It is estimated that a setback of 1.5km is required to provide coastal stability and suitable hydrologic conditions for mangrove growth. The required area increases if projected sea level rise is considered, with a 3.6km width appropriate for 0.3m sea level rise if the floodplain were to remain unchanged. However, the effect of sea level rise can be directly offset by vertical accretion that is developed due to the floodplain restoration, and a smaller setback would be sufficient. For a barrier located within

1.5km of the existing shore, coastal instability caused by the structure should be incorporated in the "costs" as this represents degradation of the protection provided by mangroves and seabed in front of the barrier.

Non-structural measures to reduce flood risk include flood-proofing, flood forecasting, warning systems and identification of evacuation routes. These measures reduce the damages associated with flood events, rather than the flooded area.

- Flood-proofing (without warning systems) is applicable for buildings which are exposed to flooding, but remain suitable for evacuation during the probable maximum flood (i.e. less than 0.6m depth). For the present-day, this is applicable to land above +1.8m NSP, shifting to +2.1m NSP by 2050 due to projected sea level rise. Land above these levels also requires a safe evacuation route to be identified, which needs to consider the potential for concurrent runoff flooding.
- Flood warning systems provide increased opportunity for evacuation, and therefore may extend the depth to which flood-proofing may be effective. Further damage reduction can be achieved through any relocation of property or temporary protection measures (e.g. sand-bagging) that may be achieved given additional warning.

5.2 Economic assessment method and assumptions

The cost-effectiveness of mitigation options has been considered using economic analysis, evaluating the reduction of damages (benefits of protecting land) against the costs of intervention. Economic analysis is a tool to support decision-making. It has previously been used by the GoS to provide screening of coastal management decisions, including installation of a sea-dyke at Coronie, and is commonly used as supporting evidence when submitting applications for intergovernmental funding. The most widely applied technique is that of cost-benefit analysis (CBA), which involves weighing the relative balance of costs and benefits for a project.

A range of assessment techniques are available to support economic analysis of hazard mitigation or adaptation under changing conditions (Sayers *et al*. 2013[93,] Wise & Capon 2016[94]). Selection of an appropriate technique is broadly governed by whether the focus is on present-day action or future need for adaptation (Randall 2012[95]), although in many cases choice is constrained by available information or practitioner knowledge. **In this case, due to the familiarity of many practitioners and its simplicity, CBA was selected as a means of comparing the economic feasibility of coastal hazard mitigation options for the GPA**.

It is important to note that CBA is a tool to support broad decision-making. It is not a refined tool, can be quite subjective and contains several biases that make it difficult to apply to long-term assessment (>30 years) or situations of high uncertainty, particularly those involving adaptation.

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[93] Sayers P, Yuanyuan L, Galloway G, Penning-Rowsell E, Fuxin S, Kang W, Yiwei C & Le Quesne T. (2013) Flood risk management: A strategic approach.

[94] Wise R & Capon T. (2016) Assessing the costs and benefits of coastal climate adaptation. CoastAdapt Information Manual 4, National Climate Change Adaptation Research Facility, Gold Coast.

[95] Randall A, Capon T, Sanderson T, Merrett D & Hertzler G. (2012) Choosing a decision-making framework to manage uncertainty in climate adaptation decision-making: a practitioner's handbook. Report for the National Climate Change Adaptation Research Facility (NCCARF), Griffith University.

In recognition of the potential biases and uncertainties associated with CBA, three ways have been used to present cost-benefit. These are directly related:

- Net Present Value (NPV) is a summary of total costs and benefits, weighted according to a time-based discount rate, to account for the opportunity cost of capital expense. This presentation provides a bias towards large-scale, rather than efficient actions (Wise & Capon 2016).
- Cost Benefit Ratio (CBR) is the ratio of costs and benefits, each weighted according to discount rate. This presentation is intended to highlight efficient actions, which have a good return for the corresponding level of investment;
- Required Return (RR) indicates the benefits required for an action to break-even, or provide a positive financial outcome. This presentation is used for price-setting, or where the benefits have a substantial element of uncertainty, such as dependence on commodity prices, royalties or government tax income.

Previous Assessments

Two previous evaluations of coastal protection for the Weg naar Zee area have used cost-benefit assessment to support their recommendations. **Both studies used NPV assessment and came up with virtually opposite conclusions**:

- Proplan (2015)[96] undertook NPV assessment to demonstrate the economic feasibility of a hard sea-dyke, providing protection to 910ha of farmland or an equivalent structure protection a smaller area. The analysis was conducted over a 50-year plan period, with an opportunity cost for capital (discount rate) of 6%. The construction cost of US$95million was offset by assumed land productivity of US$9million per year.
- Burke & Ding (2016)[97] undertook NPV assessment to help justify the choice between an earthen dyke structure or mangrove regeneration as the primary strategy for coastal protection. The analysis was conducted over a 25-year plan period, with a discount rate of 3%. Estimated costs were based almost solely upon land acquisition, with an earth dyke cost of US$0.43million. Benefits were determined as protection of land value, and assigned as a proportion of land acquisition cost varying with flood depth for a nominal flood level of +5m (relative to MSL), giving up to US$36million per year "value" to complete protection.

These assessments were influenced by substantial underlying assumptions regarding effectiveness and structural life-cycles. The Proplan (2015) analysis assumed that the sea-dyke would be wholly effective for mitigation of coastal hazards (erosion and coastal flooding) for at least ten years. This effectively ignores the historic erosion trend and continuation of the present interbank erosion phase.

The Burke & Ding (2016) assessment assumed that mangrove restoration would provide complete protection within 10 years, and that the earthen dyke would largely have failed within 5 years. **This analysis overstates the area at risk and effectiveness of mangroves to provide protection** (i.e. it is too beneficial).

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[96] Proplan (2015) Feasibility Study Project Weg naar Zee coastal protection works for funding by the ISDB. Prepared for Ministerie van Openbare Werken.

[97] Burke & Ding. (2016) *Valuation of Coastal Protection near Paramaribo*, Suriname. Prepared for WWF Guianas.

In both studies, all accrued costs and benefits were considered, which fails to account for separation between the source of capital funding (Government) and ultimate beneficiaries (land owners).

Discount rates

Economic analysis methods typically use the concept of discount rate, which is a reduction of future values based upon the opportunity cost of using resources in the present. Discount rate is not directly related to inflation rate, although a high inflation may suggest it is appropriate to use increased discount rates, particularly if there is a high import cost component. The effect of discount rate weighting of costs over time, normally (with a positive discount rate) placing a lower financial significance on future actions than the present. For a 6% discount rate, this means by 50 years, the weighting is less than 5% of present-day values. All forms of economic analysis using discount rate (e.g. NPV, CBR or RR) are consequently generally limited tools for looking at long-term planning decisions, particularly where there is high uncertainty (Sayers *et al.* 2013[98]).
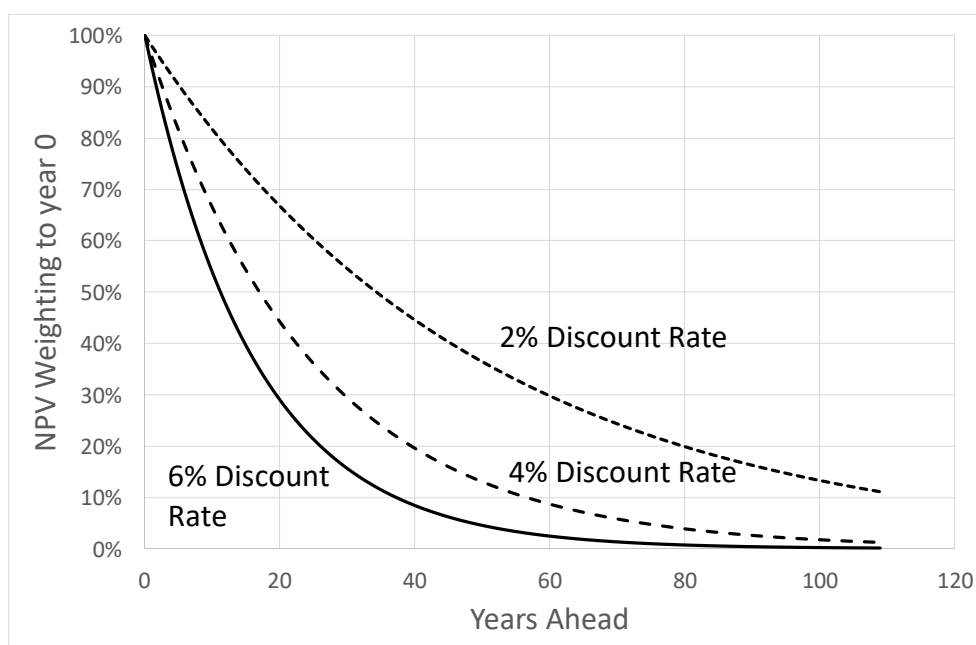
Figure 5-1: Influence of Time Frame on Net Present Value

Land values used

Land values may take various forms, including sale price, agricultural productivity, environmental or cultural value. Land value estimates for the GPA have been obtained from several sources:

- Land productivity estimates used for cost-benefit analysis for the Weg naar Zee sea-dyke financial justification (Proplan 2015[99]).
- Land acquisition costs used for cost-benefit analysis for the Paramaribo coastal protection analysis (Burke & Ding 2016[100]).

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[98] Sayers P, Yuanyuan L, Galloway G, Penning-Rowsell E, Fuxin S, Kang W, Yiwei C & Le Quesne T. (2013) Flood risk management: A strategic approach.
[99] Proplan (2015) *Feasibility Study Project Weg naar Zee coastal protection works for funding by the ISDB*. Prepared for Ministerie van Openbare Werken.
[100] Burke & Ding. (2016) Valuation of Coastal Protection near Paramaribo, Suriname. Prepared for WWF Guianas.

- Equivalent land value estimates from economic studies developed for Bigi Pan MUMA (Parahoe *et al*. 2008[101], Emanuels & Echeverria 2013[102]).

These estimates are summarised in Table 5-1. However, different approaches to valuation may give an extremely wide range of estimates, as demonstrated by Emanuels & Echeverria (2013) for Bigi Pan MUMA.

Classification	Valuation	Comment
Wetland / mangrove forest	US $230-$10,000 /ha/year	Low estimate is financial returns only. High estimate includes carbon sequestration value.
Agricultural land	US $10,000-$35,000 /ha/year	Estimates based on range of agricultural productivity and land acquisition costs
Residential land*	US $30,000-$250,000 /ha/year	Estimates based on range of land acquisition costs
* Land with a high cultural value, such as the Hindu temple at Weg naar Zee has not been valued.		

Table 5-1: Land value estimates

The substantial variation makes use of a fixed valuation potentially subjective. Consequently, economic evaluation has been presented in terms of Required Return (see Section 5.2).

The spatial distribution of land value is unequal across greater Paramaribo (Verutes 2015[103]). Between Wanica and Blauwground, where land is susceptible to flooding, land-value is spatially complex, affected by proximity to the city centre, cultural value, land ownership, topography, services, existing drainage and land productivity. However, in a broad sense, there is an increase in land value from the coast towards the city centre. **The importance of this pattern is that there is a substantially greater economic imperative towards urban expansion (or protection) than there is for increased agricultural productivity**. This supports a widely-used planning objective for compact urban development, implying mitigation focus near the existing urban area, rather than across a wide area.

Beneficiaries

Economic value varies according to who pays for mitigation and who benefits. Under existing land ownership patterns, the cost of any mitigation is likely to be met by the Government (including payment for Intergovernmental aid), whereas financial returns are primarily provided to land owners.

Planning tools associated with any form of costly intervention are required to ensure that there is a more even distribution of benefits. Commonly applied techniques for recovering costs from existing landowners include "special area" levies, co-contribution payments or compulsory purchase and re-sale following land improvement. These may accrue from 2-50% of the land valuation.

The complex pattern of land ownership across northern greater Paramaribo, much of which is related to historic subdivision, potentially makes selection of appropriate planning tools a challenging task. **More detailed evaluation of viable mitigation options requires an economic and legal assessment of**

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[101] Parahoe M, Soetosenojo A, Jadhav Y & Wortel V. (2008) *Economic Valuation & Monitoring of MUMA.* Final Report on Biodiversity and Economic Valuation of Bigi Pan Multiple Use Management Area, Part IV.

[102] Emanuels & Echeverria (2013) Monitoring & Evaluation Plan of Big Pan Multiple Use Management Area (MUMA).

[103] Verutes G. (2015) *Assessment of peri-urban coastal protection options.* http://www.geointerest.frih.org/Suriname/. WWF.

the Government of Suriname's capacity to implement the necessary steps. Should this assessment determine that implementation needs legislative change, an extended lead time is likely to be required.

5.3   Assessment of different approaches

The financial viability for different forms of coastal hazard mitigation are considered in this Section. For each intervention, the general question is whether the associated land-use value is sufficient to support the net cost of the intervention, i.e. considering the effects on existing assets and livelihoods. Due to the considerable uncertainty associated with land-use value and the ultimate destination of benefits, financial viability is presented as a Required Return (see Section 5.2).

Options considered for economic assessment include the regional coastal setback policy, mangrove restoration, sediment trapping units and installation of flood barriers. The viability of flood barriers has been considered across a wide spatial range, from near the existing shore, to the edge of the urban area.

Assessment of regional coastal setback policy

The limited presence of infrastructure and agricultural activities along Suriname's rural and non-urban coast provides an opportunity to avoid coastal hazards through formal development setbacks. A preliminary basis for setback has been applied to most of the Suriname coast, through the MUMA management framework, based on preservation of environmental values. The proposed CPA would provide a stronger legislative basis for this strategy, and include areas that are presently outside the MUMAs or Nature Reserves.

A physical allowance for floodplain processes includes the area subject to erosion and recovery during mudbank migration cycles (Erftmeijer & Teunissen 2009[104]) plus the active area effectively contributing to floodplain dynamics (Figure 4-4). This suggests a development buffer width of 3-5km, which approximately corresponds to the areas defined for the coastal MUMAs.

The relative benefit of preserving a coastal setback buffer is provided by the enhanced coastal stability. Comparing the net rate of accretion for the whole Suriname coast (5m/yr) with the recession rate where floodplain dynamics have been blocked (30m/yr), the equivalent benefit is from $800-$35,000 per kilometre, following the range of land value for coastal wetlands (Table 5-1). **Broadly, this implies that a regional coastal setback policy is financially viable**. However, as this range varies from direct financial returns through to value based upon carbon sequestration, **interpretation of an appropriate management cost for the coastal areas requires consideration of how the preserved value can be transferred to funding** (Tjon *et al*. 2008[105]).

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[104] Erftmeijer P & Teunissen P. (2009) *ICZM Plan Suriname - Mangrove Report. Analysis of problems and solutions for the management of mangrove forests along Suriname's 'wild coast'*. Lievense-Deltares.

[105] Tjon K, Wirjosentono J, Sabajo R, Jubitana H, Sewotaroeno M, Mol J, Babb Y, Evans G, Gangadien C, Parahoe M & Soetosenojo A. (2008) *Current Land Use and Improvement Needed for Sustainable Utilization*. Final Report on Biodiversity and Economic Valuation of Bigi Pan Multiple Use Management Area, Part III.

Assessment of mangrove restoration

Mangrove restoration costs have been estimated based on historical planting costs associated with the sediment trapping unit (STU) program (~US$1000/m, required every 5-10 years). **The value of mangrove restoration occurs due to the resistance to seabed lowering during the interbank phase of mudbank migration, the reduced flood area due to flow resistance and the enhancement of long-term coastal stability**. STUs, or other forms of bioengineering have been considered an integral part of the mangrove restoration program due to the demonstrated difficulty of re-establishing mangroves during the erosive interbank phase.

The capacity for fringing mangroves to resist erosion varies according to the species present, with residual black mangroves providing approximately 400m less landward movement than the high water mark at Weg naar Zee, which retreated by 1200m over a 30 year period. During the corresponding period, the area of mixed red and black mangroves along the Blauwgrond and Rainville coast provided effectively complete erosion resistance. It is noted that each species plays a different role, with the more deeply rooted red mangroves providing wave dissipation, whereas the shallow rooted black mangroves provide sediment retention. Using the wetland land values (Table 5-1), this gives a benefit range of US$300-$13,000 for restoration of black mangroves and US$900-$40,000 for restoration that can effectively combine red and black mangroves.

This benefit is further supported by improved coastal stability, equivalent to that considered for the wider Suriname coast (Section 5.3). **Simplistically, by allowing the sediment floodplain to be active over approximately 1,500m provides an equal "saving" of land by encouraging coastal stability**.

This combined benefit of erosion resistance and longer-term coastal stability relative to annual costs gives cost benefit ratios in the wide range of 5-500 (without considering the effect on flood area). Although this figure is effectively a meaningless CBR, **the potentially high benefits associated with mangrove restoration compared to costs are clearly demonstrated**. **However, the challenges of achieving mangrove restoration should not be underestimated, as establishing conditions suitable for mangrove regrowth in degraded areas requires more than simply planting** (Winterwerp *et al*. 2013[106]).

Assessment of sediment trapping units

Sediment trapping units (STUs) are one the approaches used to provide a suitable habitat for mangrove restoration in degraded areas. They provide three mechanisms for mitigation of coastal hazard:

- Providing a stable area for the establishment and growth of mangrove communities.
- Supporting a steeper seabed gradient in front of the mangroves, by capturing a sequence of levels within adjacent STUs.
- Providing the coastal mangroves for a greater tolerance to bed deepening on the seaward side.

Estimated costs for installation and maintenance of STUs are approximately double the cost of mangrove restoration. The major additional benefit associated with STUs above and beyond mangrove

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[106] Winterwerp JC, Erftemeijer PLA, Suryadiputra N, Van Eijk P & Zhang L. (2013) Defining eco-morphodynamic requirements for rehabilitating eroding mangrove-mud coasts. *Wetlands*, 33(3), 515-526.

restoration is the increased resistance to seabed lowering due to their capacity to extend to a greater depth. Consequently, if used effectively, STUs would provide equivalent to the "full protection" of a red and black mangrove community. This gives cost benefit ratios in the wide range of 4-400, without considering reduced flood area. The relative CBR is lower than for mangrove restoration. However, the analysis suggests that **STUs are likely to be a highly cost-effective option in situations where mangrove restoration is constrained by sediment mobility**. Use of STUs may achieve limited benefit if the degradation is caused by other forms of degradation, such as a lack of freshwater flow, unless the hydrological constraint is addressed separately.

Economic assessment of coastal defences

Installation of coastal defences against flood and erosion may occur (in a practical sense) across a wide spatial area, from the existing coastal margin to the urban fringe. The costs and effectiveness of barriers, including viable use of alternate materials, is strongly influenced by their proximity to the coast and the consequent wave climate (Figure 4-2). This economic assessment has been undertaken to evaluate appropriate locations and possible optimisations using alternative structure types.

Figure 5-2: Progression of structure types with wave climate

Factors considered in the economic assessment include:

- Capital cost
- Maintenance cost
- Land loss (coastal instability due to insufficient active floodplain)
- Structural degradation
- Relocation costs.

As illustrated by Figure 5-1, the length of assessment period may also affect economic analyses.

Due to the high cost-benefit ratio for mangrove restoration and STUs, and their potential to provide erosion protection and enhanced coastal stability, options to combine a separate flood barrier with mangrove restoration has also been considered. This is considered practical for a setback width of at least 1.5km, with increasing difficulty to maintaining a mangrove buffer for a barrier located further seaward.

Cost estimates and actual costs from sea dykes, earth dykes and STUs have been used to provide a spatially-varying cost continuum for different barrier structures.

- The cost of sea-dykes typically varies from US$1.5-$3.0 million per kilometre along the Guianas coast. Maintenance costs are relatively low with high design criteria (100+yr ARI) if the seabed in front of the wall does not lower. A typical lifetime is 10-40 years.
- Earth dyke costs vary from US$50,000-$500,000 per kilometre, with cost affected by the elevation and material availability. Maintenance costs are moderately high, and increase with inundation frequency. A typical lifetime is 5-25 years.
- Timber structures such as the sediment trapping units cost in the order of US$100,000-$200,000 per kilometre, with cost affected by accessibility and required depth of embedment. Maintenance costs are high, typically 10-20% per annum. A typical replacement cycle is approximately once every 15 years, although this mainly occurs through ongoing maintenance, rather than wholesale refurbishment. Maintenance of STUs may be able to be concluded if there is successful establishment of mangroves with suitable root depth.

Determination of change in wave climate from shore, including the effect of protection due to mangrove, has been used to assess how capital and maintenance costs are likely to vary depending on different barrier positions (Figure 5-3). These estimates highlight the high capital cost of rock structures and low maintenance cost, compared with the relatively lower capital cost and higher maintenance of earth or timber/brush structures.
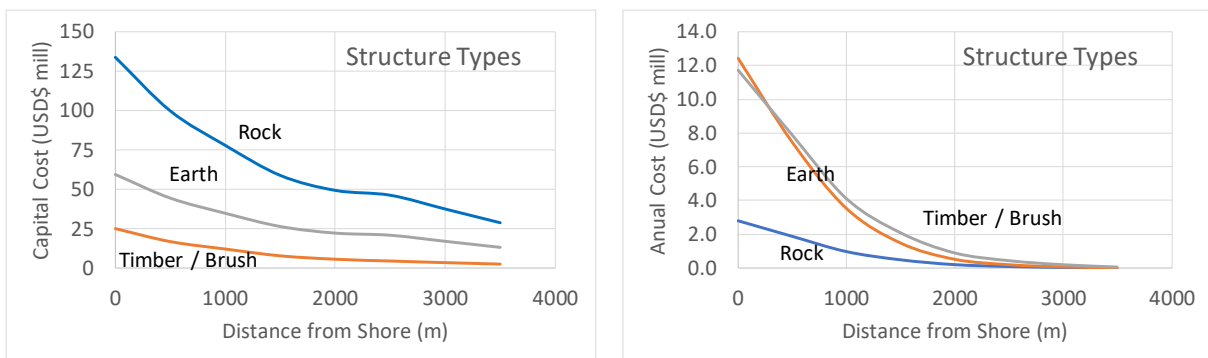
Figure 5-3: Capital and maintenance costs for material types with distance landward

The variation of capital cost due to increased sheltering from a 300m wide mangrove buffer is indicated by Figure 5-4. **This clearly indicates the substantial financial benefit of maintaining an adequate buffer in front of any flood barrier**, which is an extra contribution to the high cost-effectiveness considered in Sections 5.3.
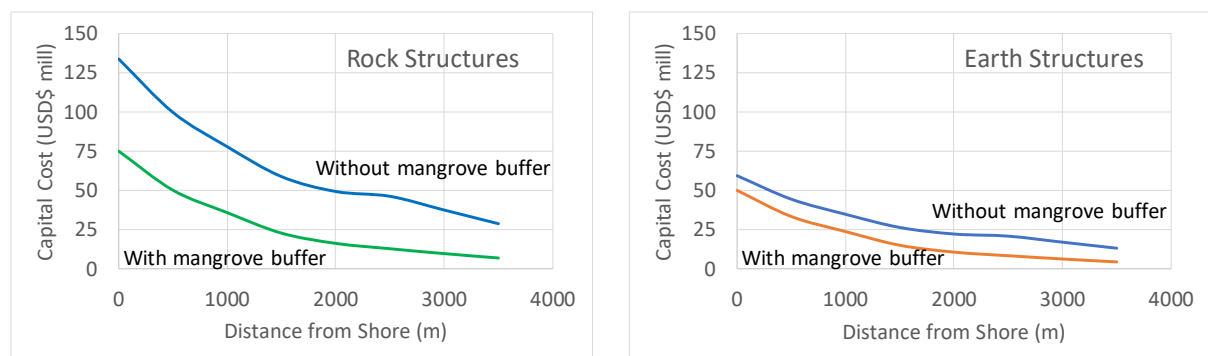
Figure 5-4: Capital Cost variation with distance landward

Incorporation of relocation costs has been based upon an estimate of US$98m for the Weg naar Zee area (Proplan 2015[107]), distributed across the coastal area. Combining capital, maintenance and relocation costs, variation of the total cost with barrier position indicates that the lowest direct monetary cost is achieved for a barrier located approximately 1.5km landward of the existing shoreline.
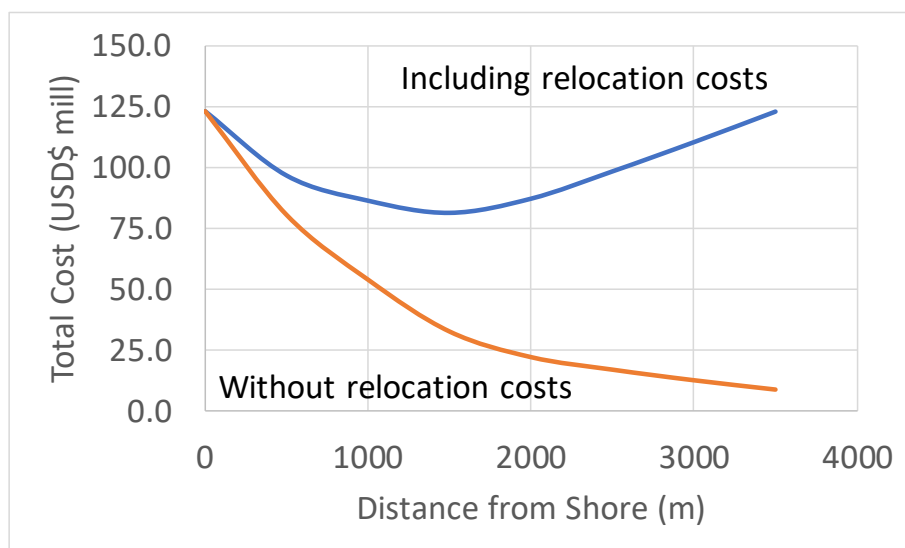
Figure 5-5: Consideration of rock structures, without effective mangrove buffer

Cost effectiveness of barrier options (material type and position) has been evaluated by considering the combination of monetary cost and land productivity. Non-monetary cost (due to coastal instability) requires consideration, but has not been included directly in the analysis. As the extremely high variation in land value (Table 5-1) makes use of a single value potentially misleading, the approach of "required return" has been used, which is the annual amount required to offset infrastructure costs associated with interventions. This can be compared with land values to determine the appropriate uses of the area sheltered by the barrier, accounting for the ability to recover costs from those benefitting directly.

Comparison of the required rate of return for different structure types, with or without a mangrove buffer, suggest that there is limited spatial variation in cost-effectiveness (Figure 5-6). The required rates of return suggest that the capital savings potentially provided by using a timber or brush structure offsets relocation costs for a barrier setback by about 2km. **For most of the spatial range considered, the required return is approximately US$2,000/ha/yr, which is comparable to land value estimates for wetland (non-monetary), a modest return from agricultural land value or a minor return from residential land value**. Further landward, the rapid rise of required return is partly offset by the greater land-value associated with proximity to the city centre.

The low required rate of return for barriers within 1.5km of the shore does not account for the reduced coastal stability that occurs if the active floodplain is interrupted.

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[107] Proplan (2015) Feasibility Study Project Weg naar Zee coastal protection works for funding by the ISDB. Prepared for Ministerie van Openbare Werken.
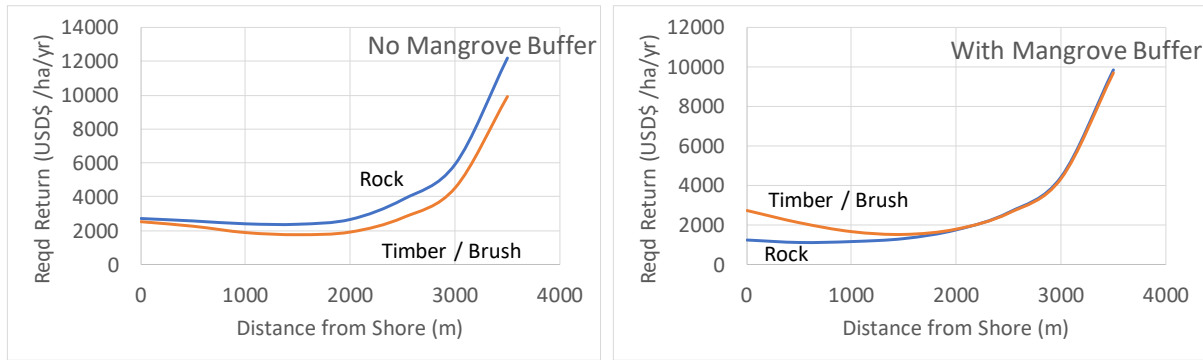
Figure 5-6: Required rate of return

Overall, the economic analysis suggests that any barrier position could be made financially viable through an appropriate mix of land-use. However, due to the higher density of land ownership and existing infrastructure, **there remains a substantial challenge for the government to ensure that a suitable proportion of benefits can effectively act as an offset to the capital and maintenance costs** (see Section 5.2).

6. Conclusions and recommendations

6.1 The flood and erosion risk

Development of a sustainable coastal resilience strategy for greater Paramaribo requires an understanding of both the local oceanographic and geomorphological processes at play. **Understanding these processes is important because they drive the risk of flooding and erosion and because they in turn influence the practicality of possible coastal resilience interventions measures.** Key points of note in this regard are:

- **The muddy coastline of Suriname is highly dynamic and transient**. Any intervention implemented needs to consider the mechanics of the muddy coastline and the fact that there are long-term cycles of substantial coastal change that will continue. Future dynamics are also likely to be altered by response to climate change and sea-level rise.

- **The status of the mangroves and the current and future stresses upon them**. While the Suriname coastline is characterised, in large part, by well-developed mangrove forests, this is no longer the case for the greater Paramaribo area. Large areas of mangroves have been removed for development, increasing risk to coastal erosion and flood risk. While efforts are underway to regenerate mangroves in Weg naar Zee, the process of mangrove regeneration will be slow. Current regeneration efforts are clearly hampered by the fact that greater Paramaribo is in an "interbank" phase within the mudbank cycle, meaning that the general trend is erosion, probably for the order of another 5 to 20 years. While the Paramaribo coast should again enter a period of sediment accretion, the timing of the arrival of the next mudbank is uncertain, and existing structural barriers are considered likely to reduce coastal recovery during the mudbank phase. Moreover, the presence of the mudbanks will only ever be temporary. Recognition that erosion pressure will change over time, particularly due to mudbank migration, is important when selecting interventions to manage coastal hazards. The potential uncertainty associated with this change suggests the need to use flexible and adaptable approaches, in general preference to treatments that are robust only up to a threshold. For both mangrove and floodplain restoration efforts, this may entail the use of redundancy, effectively allowing a rolling retreat within the area of restoration.

- **The impacts associated with climate change are significant**. Suriname and the Paramaribo coast are highly at risk of flooding from the sea. As illustrated in Figure 2-, there is an inevitability that this risk exposure will increase as a function of sea-level rise and climate change. While mangroves have a role to play in reducing this risk, mangroves on their own do not provide a complete and timely solution. Furthermore, the effectiveness of other structural solutions such as dykes and improvements to the drainage system have their limits and complications. In fact, no one intervention method will provide the level of resilience required for sustainable living in greater Paramaribo. **The area requires an integrated flood risk management strategy, involving a mix of natural, structural and non-structural interventions, combined with significant policy and institutional changes.** The sections below discuss the considerations further.

6.2   Recommended Strategy

Evaluation of cost-effectiveness for various forms of coastal hazard mitigation has indicated that mangrove and floodplain restoration (through a coastal setback) provide essential contributions to a long-term strategy for management of the coast, particularly for dealing with erosion and coastal stability. However, neither these interventions or non-structural (planning measures) provide adequate protection against severe coastal flooding. Consequently, a form of flood barrier is likely to be required, with the distance of any barrier from the coast affecting the mix of structural and non-structural interventions.

Financial considerations associated with different barrier positions are discussed in Section 5.3, which suggest that all options can be made viable, depending on the capacity of the GoS to obtain a sufficient return from the overall benefits to fund the capital and maintenance costs. In effect, the dependence of the financial viability upon revision and implementation of planning tools means that there is no clearly preferable option (from an economic perspective).

In the absence of a clear financial position, the ability to complement floodplain restoration and greater adaptive capacity suggest that a barrier setback from the coast is preferable. **The barrier should integrate with existing natural and artificial defences and provide spatial continuity - which means that mangrove conservation and connection to river walling are appropriate regardless of the flood barrier configuration**. Further discussion of relative consideration for barrier positions is included in Section 6.3. However, without developing the necessary planning tools, selection of a single setback distance remains uncertain.

Integration of floodplain restoration with a flood barrier setback from the coast creates three zones (Figure 6-1), each of which has a different suite of flood mitigation measures. Selection of suitable hazard management has been based upon relative depth and frequency of flooding, following generalised principles outlined in Appendix D:

- **Zone 1** (seaward): provides the main function of floodplain restoration. This zone should be at least 1.5km wide, with assets protected at a property level. Zoning and building development approvals are required to ensure that floodplain function is preserved. Land-use viability will be controlled by flood frequency, and it is recognised that agricultural use will become non-viable due to sea level rise.
- **Zone 2** (intermediate): occurs between the area of floodplain restoration and a flood barrier. This is a non-urban zone. Human safety should be managed through a combination of property level protection, evacuation planning and early warning systems. Land-use is expected to change over time, with the range of non-urban uses progressively reducing as sea level rise causes increased flooding frequency.
- **Zone 3** (landward): has flood protection provided by a barrier, and may be suitable for urban development, although planning provisions to control urban expansion in this zone may be used strategically to maximise longer-term capacity to adapt to erosion or sea level rise. An understanding of the barrier threshold and potential for failure should be incorporated into evacuation planning and structural design.

Figure 6-1: Coastal hazard mitigation zones

Components of coastal hazard mitigation

Creating resilience in greater Paramaribo should involve a mix of the following interventions:

Type	Location / Impact / Considerations
Structural	
Dykes/flood walls	**Location:** limited to critical infrastructure and emergency routes.
	Impact: Provision of flood and erosion protection for critical infrastructure and emergency response routes. It is typically practical for routes to be linked to flood-resistant infrastructure such as roads, bridges and sluices, provided that these facilities have been designed to withstand a severe flood event.
	Considerations: The erection of dykes should be limited to critical infrastructure and assets. The design of these structures should be considered within the wider context of coastal dynamics. It is important that the design of any structure does not disrupt the natural processes required to establish coastal stability. It is also important that the design of flood and erosion defences is adaptable to climate change to avoid the need for costly re-fits.
Mangrove regeneration and preservation	**Location:** Weg naar Zee, western bank of the Suriname River, Wanica and Rainville-Blauwgrond, if these areas become exposed to mangrove stress.
	Impact: Mangrove regeneration will help to enhance shoreline recovery during mudbank phases. Established mangroves will then provide a buffer to help resist erosion during subsequent inter-bank periods. Conservation of the existing mangrove communities is necessary for continued (relative) coastal stability of the coast to the east and west of Weg naar Zee, which is supported by the provisions of the proposed CPA.
	Considerations: Establishing best practice for mangrove regeneration and preservation requires research, testing and government support. Land-use policies are required to ensure that the mangrove regeneration and preservation supports active floodplain restoration, to enhance long-term coastal stability. Establishing appropriate approaches should be considered in combination with the design of grey infrastructure elements such as dykes and drainage.
Drainage	**Location: Northern part of greater Paramaribo (coastal floodplain)**
	Impact: Management of flood waters in the greater Paramaribo area, minimising impacts of flooding.
	Considerations: **The strategic Flood Risk Assessment has** identified improvements to the existing drainage system, including increasing the carrying capacity and efficiency of the existing drainage network, with expansion

		of the Saramacca Canal and desilting of channels. Design of these drainage improvements requires consideration impacts on coastal stability, including direct scour, freshwater supply to mangroves and potential to act as a barrier to floodplain processes. The opportunity to use floodplain restoration to provide stormwater storage volume should be evaluated.
	Property Level Protection (PLP)	**Location:** Property level (for infrastructure located between the coast and flood barrier). **Impact**: Use of raised floor levels, stilts, blow-out panels, water-resistant materials, raised electrical systems (FEMA 2005[108]). It is important to recognise that PLP does not reduce the probability of flooding on its own, but can reduce the cost of impacts. **Considerations**: Enforcement of PLP should be implemented for new building as part of development/building control. Retro-fitting existing properties is more difficult and will require incentivization and support. This may include dissemination of information about flood-proofing, publication of building guidelines, small building grants or tax reduction for flood-proofed properties. While PLP can provide safe havens during a flood, access to/from properties will be difficult during an emergency. Early warning system and detailed emergency response plans are therefore required to minimise impacts during a flood.
	Land raising	**Location:** Limited to critical infrastructure and emergency routes. **Impact**: Provision of flood and erosion protection for critical infrastructure and emergency response routes. **Considerations**: Use of land raising should be limited to small sections of the floodplain, to prevent obstruction of floodplain dynamics and consequently allow sediment delivery, supporting coastal stability. Land raising should not result in continuous barriers to flow in an east-west direction, with the number of north-south barriers to flow (e.g. roadways or sluices) minimised. The existing road layout, with a main north-south access route and several east-west distributing roads is not directly compatible with land raising to provide access routes. This road network is largely a result of historic land allocation and is therefore difficult to alter.
Non-structural		
	Planning / zoning	**Location: whole** floodplain **Impact**: Reduction of exposure to hazard.

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[108] Federal Emergency Management Authority. (2005) *FEMA Coastal Flood Hazard Analysis and Mapping Guidelines*. Focused Study Report.

	Considerations: Flood risk in greater Paramaribo is high and increasing. It is not possible to eliminate this risk, only to reduce it and put in practices to mitigate impacts. A key strategy in this regard is planning policy and land zonation. Ideally, the concept of using a coastal setback as a buffer to flood and erosion pressure which is intrinsic to the draft Coastal Protection Act should also be applied to the area. A minimum development setback of 1.5km is recommended, within which existing properties may use limited property-level protection. Between this setback and the existing urban margin, flood-proofing with warning and evacuation systems may be used effectively.
Early warning	**Location:** greater Paramaribo area **Impact**: Reduction of exposure to hazard. **Considerations**: Flood risk in greater Paramaribo often results as a function of the combination of sources of flooding and is significantly affected by the drainage network. The development of an early warning system that can account for this complexity will bring considerable benefit. In addition to the prediction of flooding, new institutional and communication frameworks will need to be established to manage operations ahead of an event (e.g. evacuations, preparation for emergency responders), ensure efficient and effective communication of warnings, and manage the aftermath of an event.
Emergency response	**Location:** greater Paramaribo area **Impact**: Reduction of exposure to hazard. **Considerations**: Effective emergency response requires detailed planning, training, the coordination of emergency services, the provision of specialist vehicles and equipment and the implementation of effective early warning and communications. Suitable shelter for those displaced during a flood event is required. Effective emergency response also requires the establishment of a lead disaster response and recovery agency. Steps towards establishing a disaster management agency are underway, but presently in the preliminary stages of institutional change.
Disaster risk financing	**Location:** greater Paramaribo area **Impact**: Implementation of fast and effective disaster response financing. This may include contingency funds held by Government, private insurance for businesses and households, and/or a national level insurance scheme. **Considerations**: Development of a disaster financing mechanism.

Institutional actions	**Impact**: Implementation of institutional actions to support coordinated design, implementation and management of a holistic flood risk management strategy.
	Considerations: Following from the above, key institutional changes required to establish effective risk management are:
	- Planning and development/building control. Requires effective development planning and control, with an objective to ensure that the financial benefits accrued through hazard mitigation provide offset to the capital and maintenance costs. Requires effective building control, particularly to support integration with flood management (i.e. not to block flood conveyance) and enhance the use of property flood-proofing. - Early warning. Requires the strengthening of the disaster risk management Agency for early warning and the development and implementation of tools and communications. The skills and technology suitable for early warning systems are available through the Hydromet section of Public Works. - Disaster response management. Requires the strengthening of the lead Agency responsible for the development and testing of disaster response plans and the coordination of emergency services during d after an event. - Disaster risk financing. Requires the Ministry of Finance to assess tools and institutional frameworks to support effective disaster risk financing, at national, private sector and household levels. - Forest/mangrove management. Regulatory changes proposed through the draft Coastal Protection Act require support through institutional change, to ensure that the CPA can be effectively implemented. The regulatory and institutional structures are co-dependent, and need to ensure that benefits afforded by these natural systems are used to offset the management costs. The promotion and execution of mangrove restoration and preservation activities, where necessary, may be part of the institutional role.

6.3 Flood Mitigation Options

The northern greater Paramaribo area is subject to frequent coastal flooding associated with high tides and moderate surges. The relative depth of flooding is comparatively small, which suggests opportunity for the use of non-structural measures (zoning / evacuation plans) or property level protection for non-urban land-use. However, in the longer-term, the potential for coastal flooding to reach the urban area of greater Paramaribo, particularly with the influence of projected sea level rise, determines that at some stage a more direct intervention to provide flood mitigation will be required.

Factors to be considered include:

- **Selection of an appropriate intervention requires spatial continuity**, to ensure that any form of barrier is not outflanked by floodwaters. For all barrier options, this involves connection to the existing walling and flood defences along the Suriname River.
- **Flood mitigation must be complementary to coastal stabilisation efforts**. For a flood barrier that does not support floodplain restoration (i.e. closer than 1.5km to the coast) then the barrier must also provide robust coastal protection and have limited effect on the stability of the adjacent coast, presently protected by mangroves. Mangrove preservation is essential for the stability of areas adjacent to Weg naar Zee.
- Provision of any flood barrier is expected to influence the pathway for urban expansion of Paramaribo. **Without incorporating suitable planning provisions, a smaller distance of the barrier from the coast will reduce the longer-term adaptive capacity of the area to tolerate both flooding and erosion**.

Contribution of natural interventions

The key asset for Suriname and greater Pararmaribo with respect to natural interventions and coastal resilience is the use of mangroves. As detailed in Chapter 3, **mangroves have a very significant role to play with respect to coastal resilience**. While the direct effect of mangroves on inundation extent during a flood event is limited, mangroves can substantially reduce the longer-term impacts of coastal erosion. Furthermore, regeneration of mangroves in the Weg naar Zee and Wanica areas will help to support coastline accretion. Over time, this accretion will help reinstate the mangroves in these areas and create an important buffer to help mitigate the effects of mudbank cycles. The mangroves will not entirely stop the process of coastal erosion, with mudbank migration continuing to drive the erosion-accretion cycle over decades. **However, creating a mangrove buffer will reduce coastline sensitivity to these cycles and help to avoid long term net erosion. This in turn will help to establish and maintain important floodplain storage north of Paramaribo**. Having this floodplain storage helps to protect the GPA and provides the space required to implement other elements of the resilience strategy, in a more cost-effective manner than direct defence near the present-day shoreline.

Structural options

While mangroves are a key component of coastal resilience for the area, mangroves on their own will not provide a level of resilience to flooding required. It is inevitable that some form of structural intervention will also be required to protect greater Paramaribo from inundation. In this study, three forms of structural intervention were considered, including:

- **Option 1**: A sea dyke (as per Sintec & Sunecon, 2015[109]) fronting the Weg naar Zee coastline, tying into higher land in Wanica and Blauwgrond (Figure 6-2). This option also assumes a connection to flood defences around the GPA, including walling along the river (Following Proplan 2015[110]). Conservation of the remaining areas of mangroves for Wanica and Rainville/Blauwgrond is considered essential, as loss of the mangroves would support accelerated erosion, similar to that experienced at Weg naar Zee once the mangrove fringe was undercut. The anticipated erosion distance is in the order of 1.5-2km, which is wider than the remaining fringe.

- **Options 2**: A flood barrier, extending approximately the same coastal length as the sea-dyke, but set back from the coastline by approximately 1.5km (Figure 6-3). The setback area includes mangrove regeneration works and conservation, with treatment of flood hazard through non-structural and asset-scale forms of hazard mitigation (i.e. "floodproofing"). As with Option 1, this option also assumes connection to flood defences around Paramaribo.

- **Option 3**: A smaller flood barrier, constructed near the existing urban boundary is proposed, to address the flood risk to existing densely populated areas. This option also requires connection to flood defences around the wider Paramaribo area, including flood walls along the river (Figure 6-4). Mangrove restoration in the Weg naar Zee area and conservation of the existing mangrove forest in Wanica and Rainville/Blauwgrond are essentail components of this option.

In the sections below, key considerations with respect to each of these options are summarised. Further detail is included in Chapter 4.

Option 1: Sea dyke with mangrove conservation

This option, which has already been considered in the Proplan (2015)[111] study and refined in the Sintec and Sunecon (2015)[112] design, involves erection of a sea dyke along the Weg naar Zee coastline. It relies on the continued stability of the coast to the east and west, which implicitly requires mangrove conservation for these areas. The proposed structure is a clay core dyke fronted by rock revetment; a structure similar to that erected in Coronie (Figure 4-1). An eastward extension of the proposed wall would also be required to connect to the existing flood defences along the Suriname River. Although this wall theoretically has the potential to provide protection from flooding, it is not considered to be an appropriate solution for Suriname and the greater Paramaribo area on the following basis:

- **Erecting a solid structure on the coast is in direct conflict with the natural processes acting in the region**. As highlighted above, the muddy coastline in this region is highly active and cyclical in nature. Erecting a sea dyke will eliminate potential for mangrove growth, meaning that the structure itself will be the front-line defence to the sea [113]. Unlike mangroves, a sea

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[109] Sintec & Sunecon (2015) Updated Ring-dyke Engineering Studies. {In Dutch}

[110] Proplan (2015) *Feasibility Study Project Weg naar Zee coastal protection works for funding by the ISDB*. Prepared for Ministerie van Openbare Werken.

[111] Proplan (2015) *Feasibility Study Project Weg naar Zee coastal protection works for funding by the ISDB*. Prepared for Ministerie van Openbare Werken.

[112] Sintec & Sunecon (2015) *Updated Ring-dyke Engineering Studies*. {In Dutch}

[113] The proposed design incorporates a narrow band of mangroves, which is intended to resist erosion and provide depth-limited wave conditions at the toe of the sea-dyke. However, it is considered unlikely that this mangrove fringe will provide this function, due to both continued erosion pressure during the present inter-bank phase, and the disruption of freshwater flows by the sea dyke, which contribute to mangrove health. Failure to establish this mangrove fringe would

dyke cannot naturally resist periods of erosion. In fact, a structure of this type will encourage and exacerbate erosion. Consequently, costly ongoing extension, maintenance and continuous adaptation will be required.
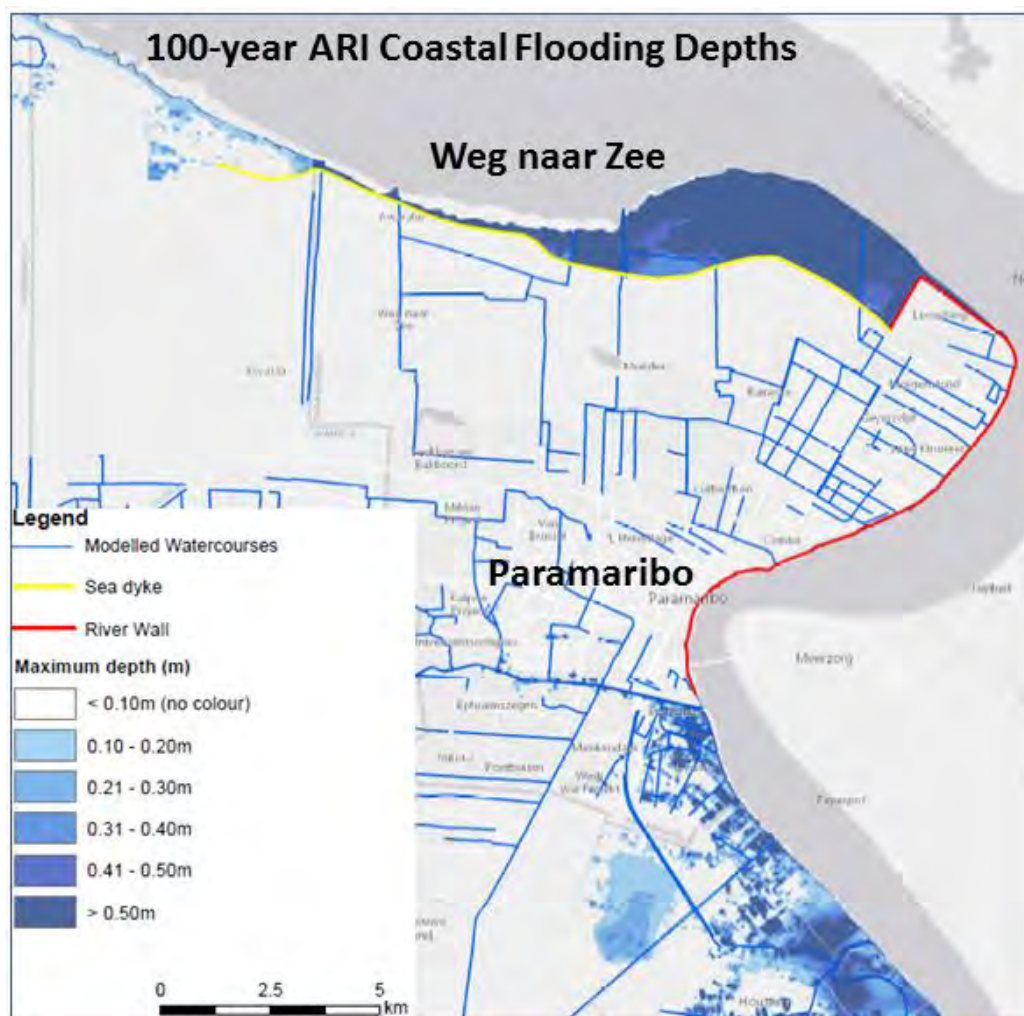
Figure 6-2: Flood and depth extents for sea-dyke option

- **This solution will encourage development in an increasingly hazardous risk area**. This solution has significant potential to encourage further development on the floodplain north of Paramaribo. This is a risky scenario for Suriname given the vulnerability of the sea dyke to erosion and breaching. During periods of flood, the sea dyke will be holding back immense volumes of water under high levels of pressure and under attack from waves. **The risk of a collapse of the structure is therefore high and consequential flooding will be rapid. This would impact public and private assets, with a genuine risk of loss to life in this scenario**.

Option 2: Set-back flood barrier with mangrove regeneration and conservation

In this option, a flood barrier would be erected approximately 1.5km inland from the coastline, extending from Wanica to Rainville (Figure 6-3). This landward location, and consequent substantially

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result in increased local scour due to wave reflection, and would require a more robust and expensive structure to provide the intended structural life.

reduced wave climate enables use of a wider range of structure type for the flood barriers, including bioengineering such as brush-mattressing or relatively low-cost hard-structures such as timber walling or rock pitching, which may be practically integrated into road systems. Erection of this flood barrier would be combined with mangrove regeneration along the Weg naar Zee shore and requires integration with flood defences around the wider area, including flood walls along the river. A 1.5km setback has been selected to provide the minimal volume of coast-floodplain tidal exchange to encourage coastal stability within the long-term erosion-accretion cycle.
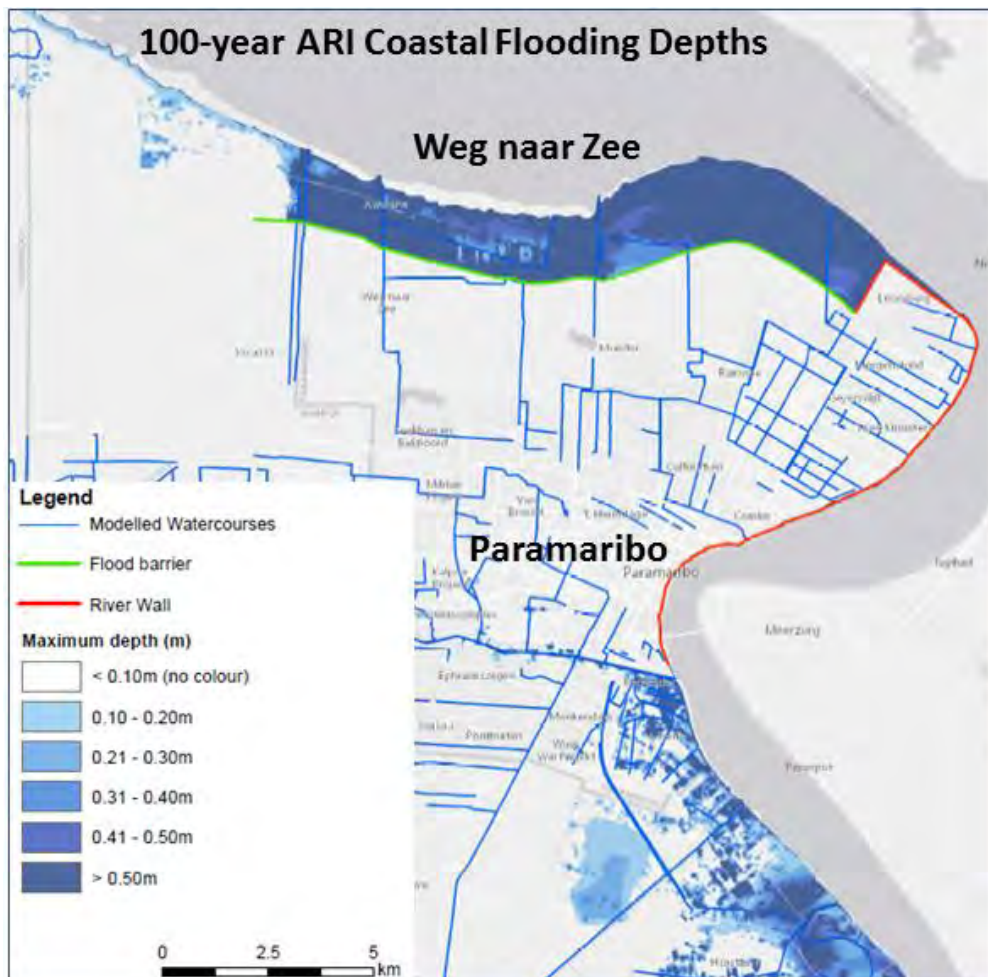
Figure 6-3: Flood extent and depths with 1.5km set-back flood barrier

The key advantages to this option versus a sea dyke are as follows:

- Use of mangroves provides a natural buffer to coastal erosion and encourages maintenance of flood storage north of the area. However, mangrove restoration will take time before it provides effective coastal protection, estimated as 5-10 years.
- Through the active use of mangroves and floodplain storage, the cost, size and extent of the flood barrier will be significantly less than a sea dyke. Furthermore, because the flood barrier is not in the front line to the sea, ongoing maintenance costs are expected to be less (although it will be very important to maintain this structure in a good repair).
- If appropriately combined with planning regulations, in line with the CPA, this approach will discourage further development along the coastal strip, seaward of the barrier, thereby minimising (although not eliminative) the exposure of people and assets to flooding hazards.

- Regeneration of mangroves clearly has other important benefits such as the enhancement of ecosystems, maintenance of dependent livelihoods, biodiversity and carbon sequestration.

The key disadvantages to this option are as follows:

- While this approach will discourage development in the coastal strip, it has the potential to encourage development directly landward of the flood barrier. As with the sea dyke, unless actively discouraged through planning, this may act to increase the number of people living in an area at risk of flooding through a collapse of the flood barrier under extreme conditions.
- One may argue that a key disadvantage of this option is that it limits the use of the coastal strip for development and farming. However, the use of this land for these purposes is simply untenable given the present day and future risks of flooding and erosion.

Option 3: Further set-back flood barrier with mangrove regeneration and conservation

- This option is similar to Option 2. However, the flood barrier is set back further and is smaller in scale, extending approximately along the line of Tiengieholoweg. This flood barrier would be rarely exposed to ocean water and therefore could be constructed as an earthwork bund, through low-cost timber walling, or pitching. As with Option 2, erection of this flood barrier would also be combined with mangrove regeneration and conservation and include flood walling along the river, where the urban margin is adjacent to the floodbank.
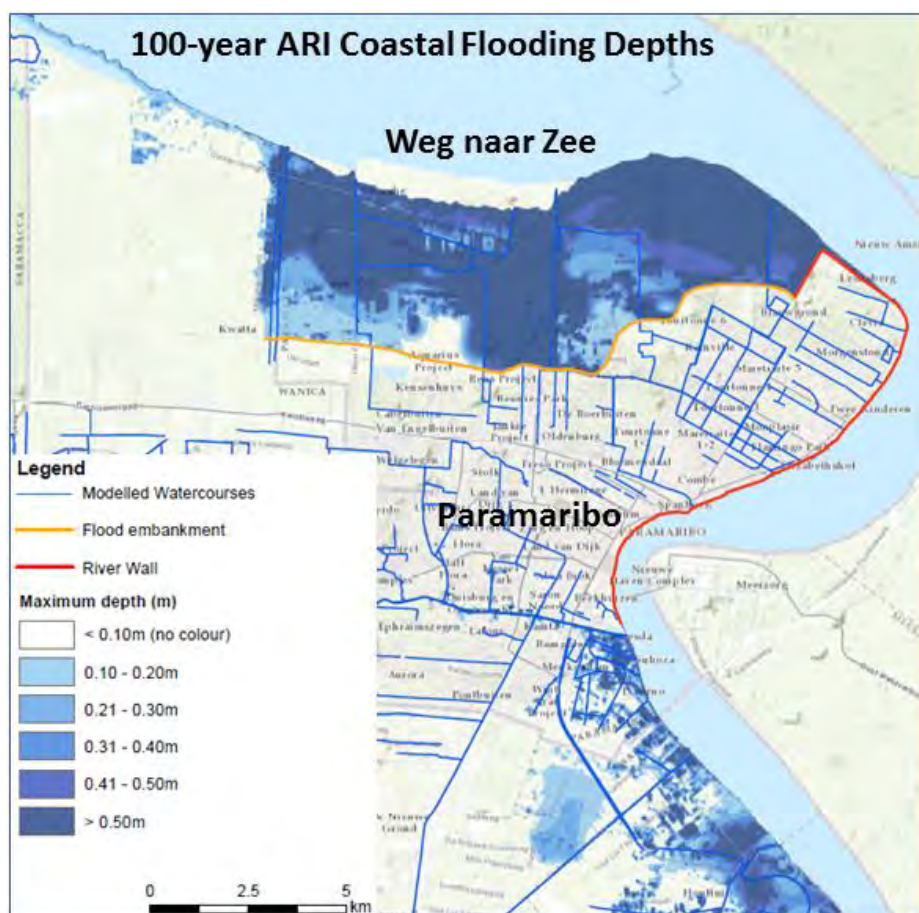

Figure 6-4: Flood extent and depths with urban flood barrier

The key advantages to this option versus Option 1 and 2:

- Key advantages associated with this Option over a sea dyke are similar to Option 2 in terms of the use of restored mangroves, the maintenance of floodplain storage, the discouragement of development in the coastal zone and the ecological benefits associated with mangrove regeneration.
- Additional benefits associated with this option over Option 2 are:
    - This approach allows for a larger sea-level rise before moderate-high density residential areas are likely to require defence from coastal flooding.
    - A larger floodplain is maintained, providing additional buffer and capacity to store flood water.
    - This approach, if combined with appropriate planning, would further discourage development in the floodplain, reducing the potential impacts of flooding.
    - Because the wall is set back further, it can be smaller and less extensive, reducing build and maintenance costs.

Key disadvantages to this option are as follows:

- As with Option 2, one may argue that a key disadvantage of this option is that it further limits the use of the area north of Paramaribo for development and farming. However, the use of this land for these purposes is untenable given present-day risks of flooding and erosion, which will increase over time due to sea-level rise. There is an additional cost associated with the progressive removal of existing assets, including roads and services.

Cost benefit considerations

Consideration of costs and benefits for the options above is dominated by infrastructure costs necessary to provide flood mitigation and the potential benefits associated with land improvement. Although other benefits have been considered in terms of fine-scale decision-making, particularly employment and ecosystem services, these are at least an order of magnitude smaller than the main costs and benefit factors.

Although all options may provide a positive net present value, this is strongly influenced by the area of defended land and associated benefits developed through land improvement. This potentially creates a false sense of economic value, as benefits and costs are not evenly distributed between landowners and government. This imbalance provides an important context for planning of the area north of Weg naar Zee. For Option 1 to be economically viable for the GoS (i.e. ignoring the practicalities of erosion hazard), the Government would need to obtain a significant part of the land improvement benefits. As the economic benefits are largely related to agricultural productivity, financial returns to the GoS are both indirect, and highly susceptible to market fluctuations. Securing the large capital funds for a sea defence would likely require land acquisition and resale following installation of defences. For Option 2, the smaller capital and maintenance costs make this constraint less substantial, and GoS financing may potentially be managed through less intrusive economic tools such as production tariffs and land taxes. For Option 3, there is a more direct connection to urban land improvement. This suggests that the relatively modest capital and maintenance costs may be recouped through direct contribution from private land owners, sale or lease of government owned land and ongoing land taxes.

6.4 CRA Limitations

Conclusions made regarding a pathway towards coastal hazard management for greater Paramaribo have been based upon the best available information at the time of preparation. However, there are several project aspects for which the quality of available information is inconsistent with their potential significance for project outcomes.

1. Topographic Data. Satellite derived topography has capacity for an estimated vertical error of 0.4m, which represents a substantial difference in terms of flood extent. Although performance of this dataset has been cross-checked, vertical error may vary spatially, and therefore may influence the flood assessment

2. Mangrove Stressors. Limited data was available to describe mangrove characteristics and stressors, including local-scale ecohydrology. Implementation of mangrove restoration and preservation techniques requires an increased depth of knowledge than applied to this assessment.

3. Coastal Flood Level Measurements. Information available to describe coastal flooding indicates datum instability and has been collected in a manner making it difficult to distinguish between oceanographic processes and effects of instrumentation. These limitations affect confidence in estimation of flood recurrence and projection of future flood hazard.

4. Coastal Mobility. Data describing coastal change has been largely extracted from aerial imagery, which is discrete in time and may respond to short-term perturbations including storm response. Additional information, including nearshore bathymetry, could support improved interpretation of driving processes, and therefore better inform appropriate interventions.

Analyses supporting the study that are built upon comparatively simple techniques include:

- Determination of the development setback necessary to support the active floodplain and enhance coastal stability.
- Economic analyses have used benefit-cost methods suitable for preliminary decision-making. Improved knowledge and more advanced forms of decision-making may be required for subsequent considerations.
- Evaluation of potential coastal change (Appendix C) is based on limited historic information regarding coastal trends. The "uncertainty-based" technique for projecting possible change reflects this constrained information. However, it is noted that none of the conclusions directly result from this assessment.

6.5   Conclusions and Recommendations

This evaluation has highlighted the importance of using mangrove regeneration and floodplain restoration to enhance long-term coastal stability. For the degraded area of Weg naar Zee, bioengineering is required to support mangrove restoration. It is recommended that a *minimum* development setback of 1.5km is established to support floodplain restoration, within which existing properties should consider property-level protection, or relocation.

Coastal flooding is a significant hazard to the area, with increased constraint likely to occur in response to projected sea level rise. In the immediate to short-term, coastal flooding provides a constraint to the agricultural land north of Paramaribo, with a risk of affecting the urban fringe by 2050. From an economic perspective, a flood barrier will be required in the long-term to protect this urban area. This must be integrated with existing protection and drainage systems to ensure effective protection.

Selection of an appropriate position for a flood barrier highly depends on the capacity for the Government of Suriname to develop planning tools that facilitate a more event distribution of benefits (i.e. offset the costs of building and maintaining a flood barrier). This will require refinement and implementation of planning regulations.

Flood hazards to the area between the development setback and urban fringe may be managed through emergency management systems, including forecasting, warning and evacuation. Flood-proofing of buildings in this area is required to limit potential flood damages. Development and implementation of emergency management systems requires investment to support a disaster risk management agency. This is presently in preliminary stages of institutional development.

Appendix A: Greater Paramaribo Water Levels

Objective

Evaluation of coastal flooding risk for Paramaribo requires a refined analysis of extreme water levels, incorporating the effects of projected sea level rise. To date, available estimates of extreme water level have either been derived from a limited data set of tide gauge observations (Sintec 2015[114]), or estimated from simplified global hazard assessments (Burke & Ding 2016[115]). In each case, the methodology used is considered likely to bias the coastal risk assessment for Greater Paramaribo.

Water Level Reference

Description of water levels for Paramaribo varies by source, with different reference systems commonly used (Figure 7-1):

- The national reference plane is the *Normaal Surinaams Plein* (NSP), typically used for terrestrial applications;
- A local datum (LD) is used for marine applications, approximately corresponding to low water level. This also approximates the Admiralty Tide Table reference level, which is based on the nearest standard port (Georgetown, Guyana);
- External data sources, including international databases, occasionally use mean sea level as a reference, which is approximately 0.22m above NSP.

+1.67m NSP   Highest Astronomic Tide

                                                                                    1.20m NSP

+1.52m NSP   Mean High Water Springs

                                                                                    1.03m NSP

+0.22m NSP   **Mean Sea Level**

Normaal Surinaams Peil (NSP) Datum

                                                                                    1.67m NSP

                                                                                    1.36m NSP

-1.28m NSP **Local Datum (LD)** Mean Low Water Springs

-1.43m NSP   Lowest Astronomic Tide

                                                                                    1.8m Spring ti
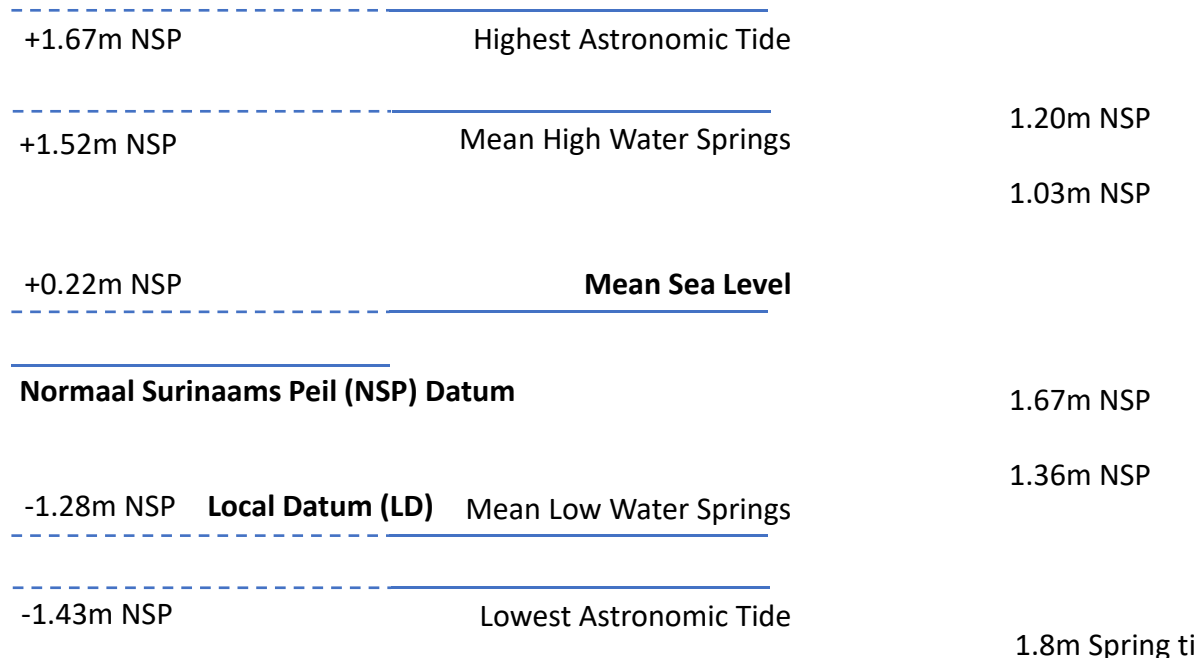
Figure AA-1: Paramaribo Tidal Planes and Common Vertical Datums

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[114] Sintec & Sunecon (2015) *Updated Ring-dyke Engineering Studies*. {In Dutch}
[115] Burke & Ding. (2016) *Valuation of Coastal Protection near Paramaribo*, Suriname. Prepared for WWF Guianas.

It is noted that tidal planes defined for Paramaribo are not considered reliable. They were derived from a short tide gauge deployment in 1965 (Augustinus & Teunissen 2004[116]). More recent observations of high water level events from 2009-2015, combined with a regional indication of small coastal surges from French Guiana, suggest that the tidal constituents, the vertical reference datum, or both, are inaccurate. Visual comparison of "spring high tide" from the 1960-1998 Paramaribo dataset with the MHWS tidal plane (Figure AA-1) suggest an underestimate of roughly 0.3m, which is consistent a shorter period of comparison to 2001 data (Augustinus & Teunissen 2004).

Water Level Observations

Observations of ocean water levels in Suriname are comparatively limited, with hydrometric measurements for the Suriname and Saramacca Rivers (Figure AA-2) being used for a mixture of navigational and hydrological purposes. A historic database from 1960 onwards is available, however, likely due to the practical constraints of interpreting tidally influenced river flow, the data has been stored as daily high and low water levels. There has also been some inconsistency in vertical reference datums, although most commonly it is either referenced to NSP or Local Datum (Figure AA-1).
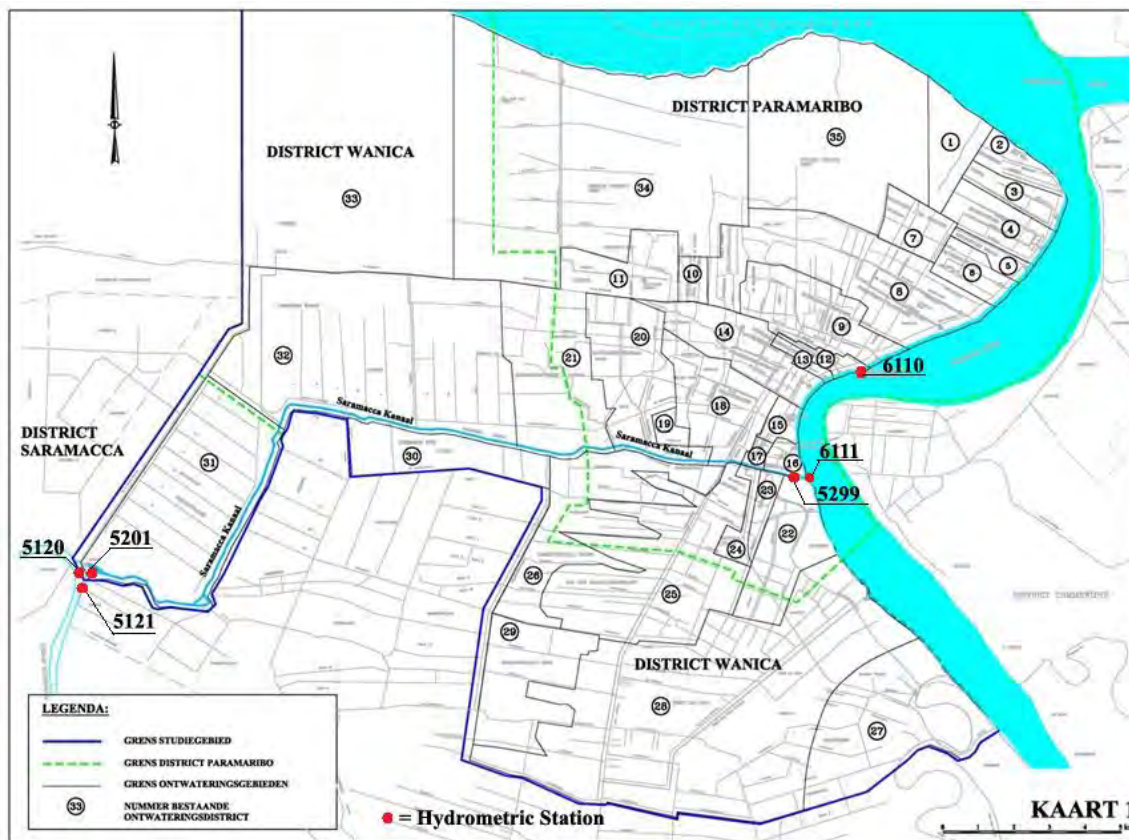

Figure AA-2: Hydrometric Stations near Paramaribo

[116] Augustinus P & Teunissen P. (2004) Bank protection construction for the right bank of the Suriname River and the left bank of the Commewijne River. Morphological aspects and natural shoreline protection.

Time series of the daily high and low water level records for Paramaribo (Figure AA-3) and Groningen, on the Saramacca River (Figure AA-4), including year-to-year comparisons (e.g. Figure AA-5) show several characteristics:

- The Paramaribo record shows the change in water level regime that occurred on the Suriname River following completion of Brokopondo Dam in 1964;
- The Groningen record shows a stronger seasonal pattern, particularly for the low daily water levels. This is highlighted on annual display, with low water levels being non-tidal from April to August, being a result of sustained runoff discharge;
- High water levels for both sites are characteristically tidal, with two peaks per month. Higher daily tide ranges occur around March and September, which is characteristic of semi-diurnal tides;
- The Paramaribo record displays greater amplitude of tidal response than the Groningen record;
- There is moderate year-to-year variability demonstrated in both records. Although some of this variability appears systematic (e.g. progressive change over several years), there is at most faint demonstration of either the 18.6 year lunar nodal cycle or the 4.4 year semi-harmonic of the cycle of lunar perigee (Haigh *et al.* 2011[117]).

Combined with sparse nature of the high and low water level data set, these characteristics constrain analysis of the long-term record for evaluation of mean sea level change, or identification of secondary mean sea level variability, including inter-annual and seasonal cycles.
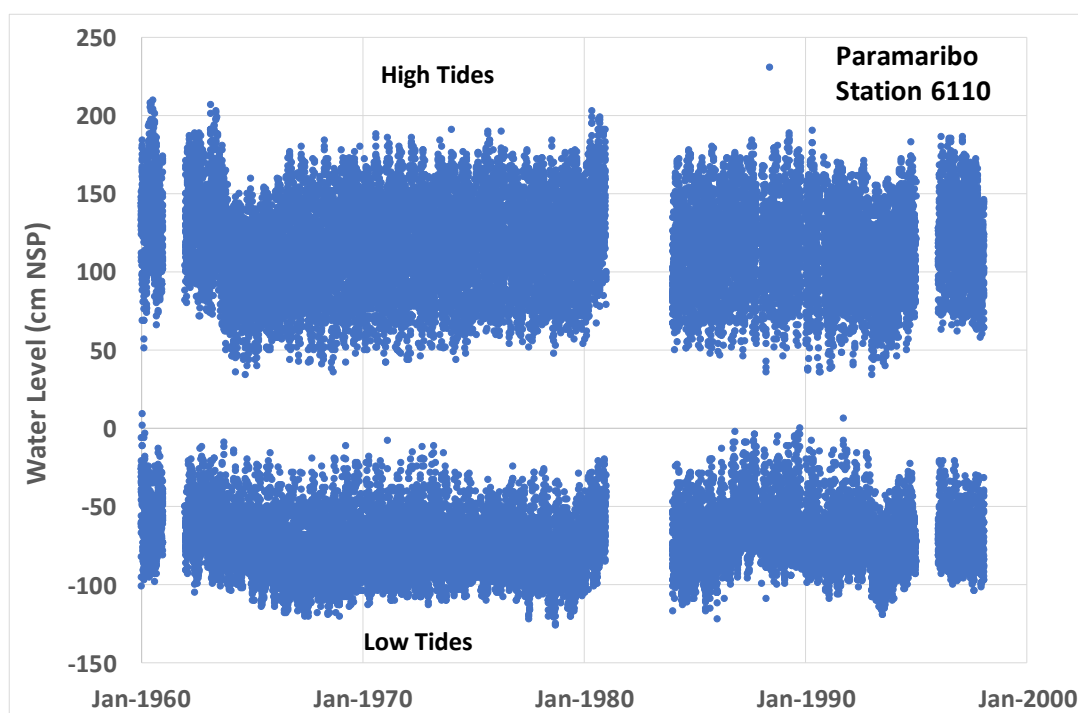
Figure AA-3: Time Series of High and Low Water Levels at Paramaribo hydrometric station on the Paramaribo River

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[117] Haigh ID, Eliot M & Pattiaratchi CB. (2011) Global influences of the 18.61 year nodal cycle and 8.85 year cycle of lunar perigee on high tidal levels. Journal of Geophysical Research: Oceans, 116(C6).

The average of high and low water levels for the Paramaribo hydrometric station from 1960-1998 is 0.21m, which is comparable to the difference between nominal mean sea level and NSP datum.
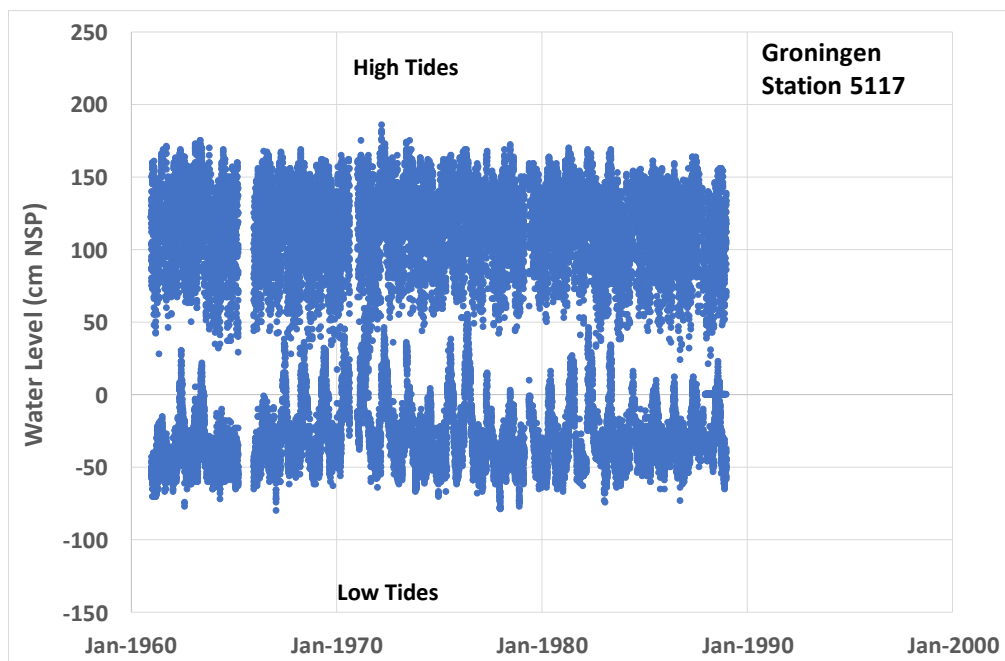
Figure AA-4: Time Series of High and Low Water Levels at Groningen hydrometric station on the Saramacca River
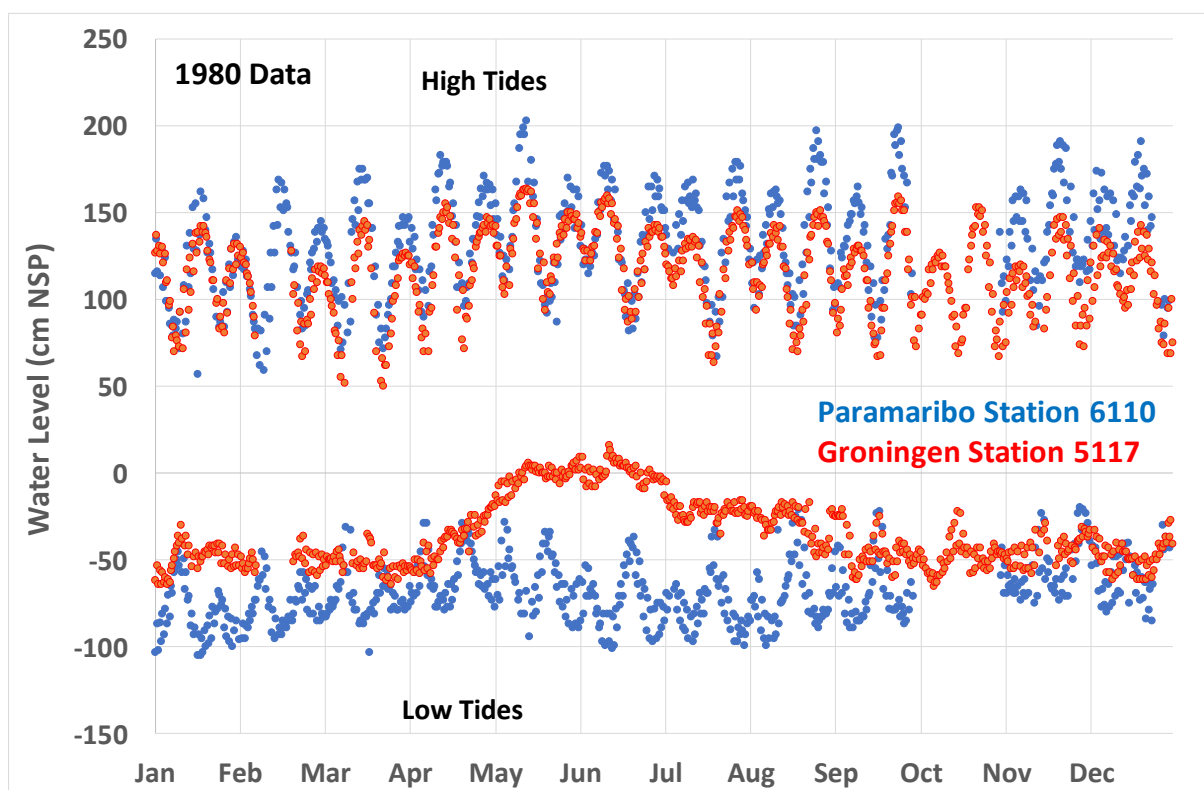
Figure AA-5: Comparison of 1980 High and Low Water Levels for Paramaribo and Groningen Hydrometric Stations

The high frequency (hourly) water level record from Ile Royale and Cayenne, French Guiana, provides a basis for evaluation of regional characteristics of sea level variability. It is worth noting that these sites are likely to be less influenced by seasonal river flooding than the Suriname record. A composite

water level signal has been decomposed into tidal, surge and mean sea level components (following Eliot 2010[118]), to examine the nature of surge and mean sea level variability (Figure AA-6).
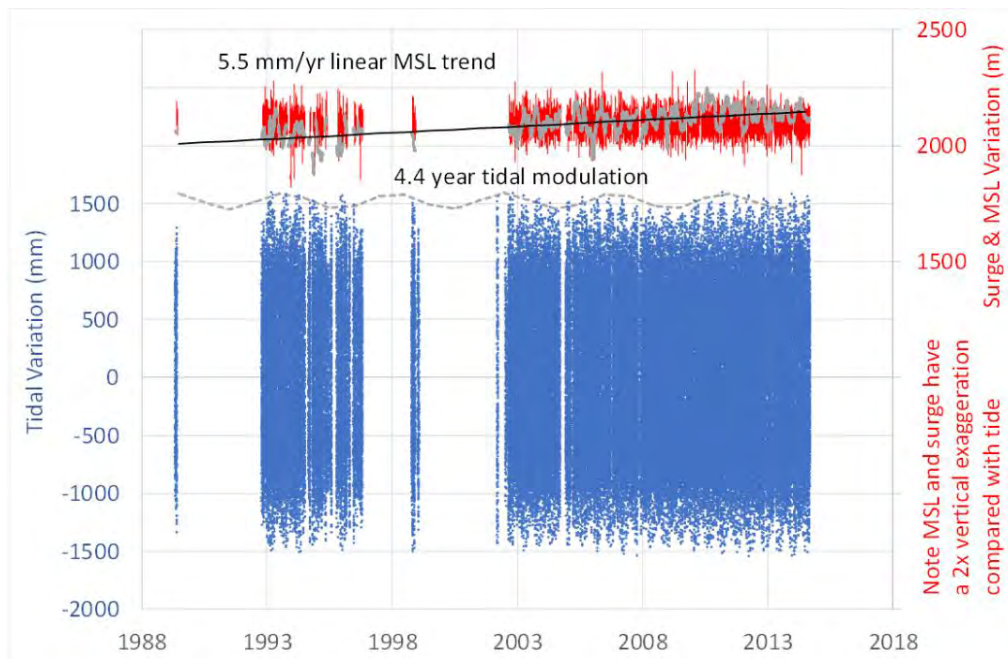
Figure AA-6: Decomposition of Cayenne Water Level Record

The sea level record from French Guiana provides some support for the estimates of sea level trend derived from satellite altimetry (Figure AA-7). However, it is important to note that the time scale over which both records are available does not allow separation of progressive sea level rise and decadal-scale sea level fluctuations. Consequently, the 5.5mm/yr rate derived from French Guiana should not be used for either long-term projection or back-casting.
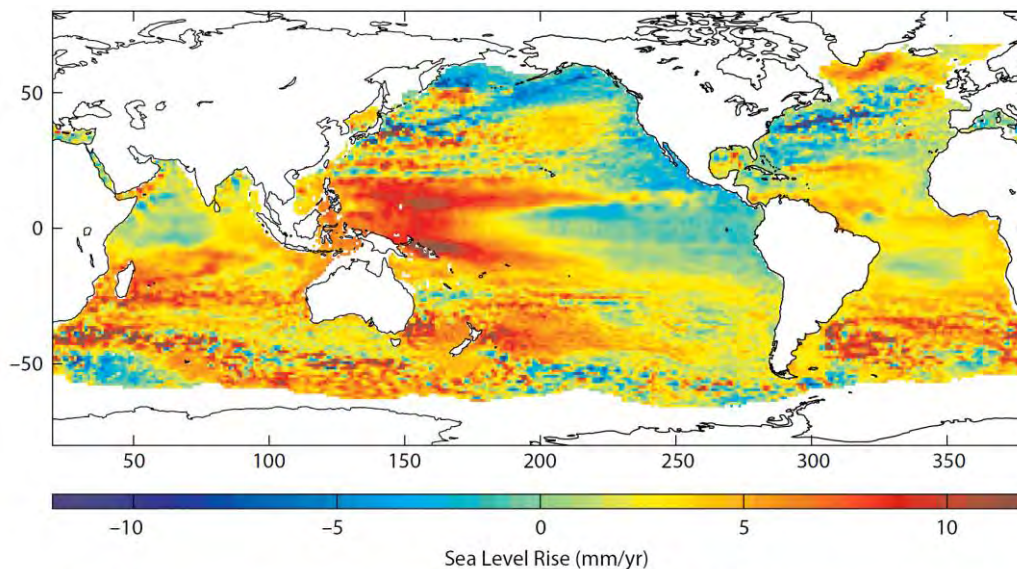
Figure AA-7: Sea Level Trend from Altimetry 1993-2009 (Extract from Willis et al 2010[116])

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[118] Eliot M. (2010) Influence of interannual tidal modulation on coastal flooding along the Western Australian coast. Journal of Geophysical Research: Oceans, 115(C11).

Decomposition of the French Guiana record also indicate the nature of tides and residuals (Figure AA-8). Tides clearly display seasonal attributes of a semi-diurnal regime, with peak spring tide range occurring around the equinoxes in March and September. The residual suggests three separate processes, including a seasonal variation (peaking around May) which is characteristic of inter-tropical convergence zone (ITCZ) movement and associated shift of trade winds; sustained weather-band influences, corresponding to a characteristic 30-60 days' time-scale of the Madden-Julian oscillation (MJO); and more rapid variability (1-30 days) typical of the weather band, including diurnal influences. Variability in the weather band is small, in the order of 0.25m, which is characteristic of storm surge.
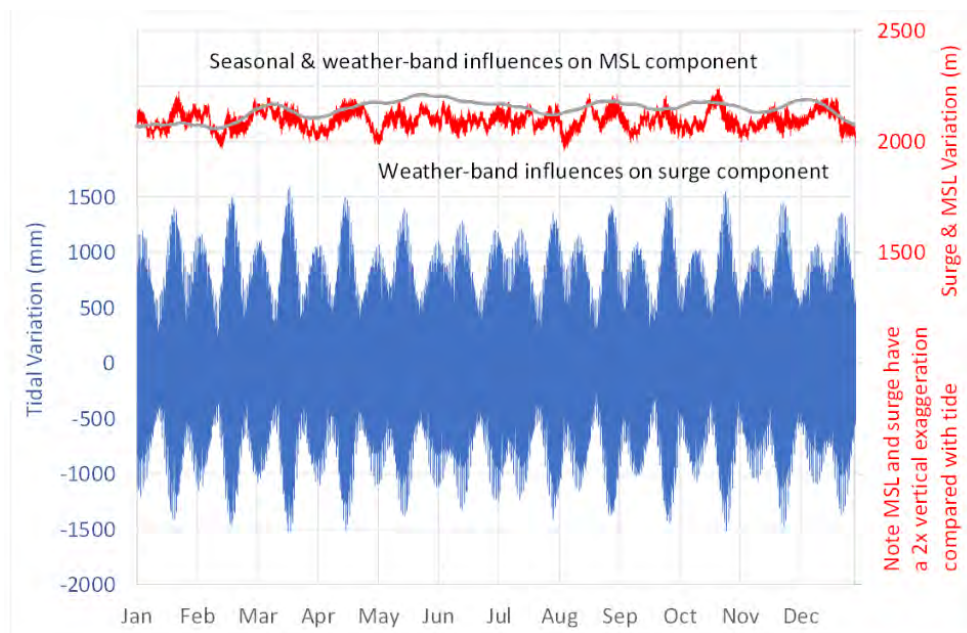

Figure AA-8: Cayenne Sea Level Decomposition for 2011

The inter-related nature of the processes contributing to residual (ITCZ, MJO, weather) makes it difficult to fully distinguish them from each other. Consequently, seasonal behaviour of tide and "residuals" has been evaluated (Figure AA-9), instead of assessing separate influences of mean sea level and surge components. The major outcome of the seasonal assessment is that peak tides are out of phase with the seasonal cycle of residuals. This creates separate opportunities for high water levels to occur either through high tides or through high surges, effectively extending the opportunity for high water level events across most of the year.
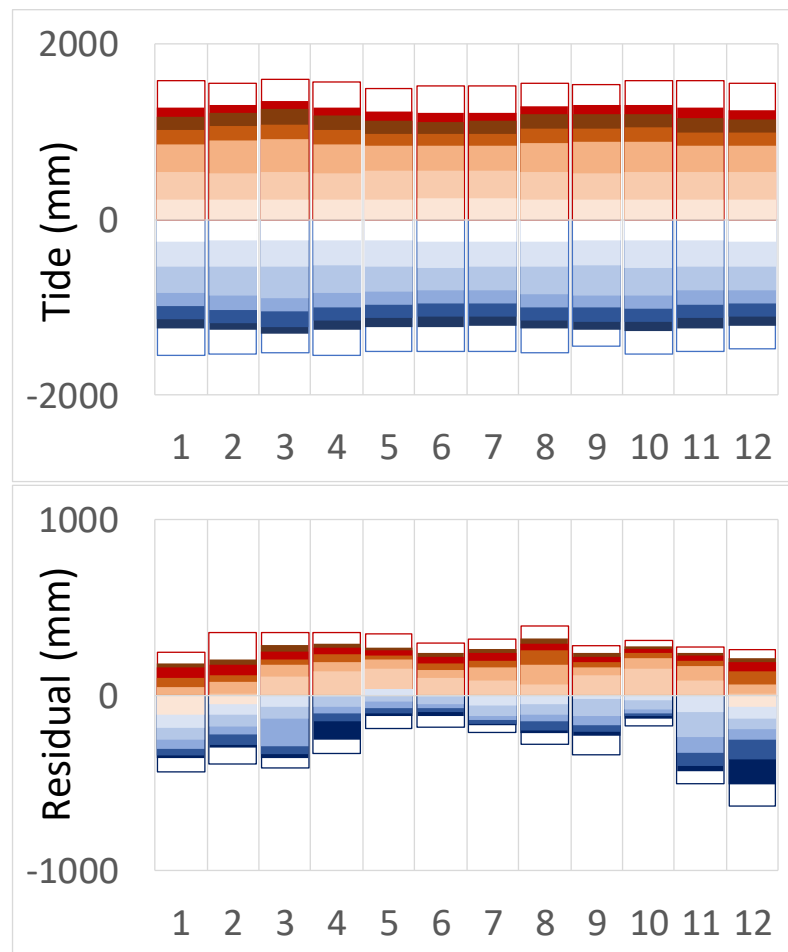
Figure AA-9: Seasonal Patterns of Tide and Residual
Note that higher residual variability in March & September may be related to tidal influence

Key findings of the decomposition of the French Guiana sea level record include:

- Tides are the dominant source of sea level variability;
- Non-tidal residuals provide a relatively small contribution to sea level variability, with the largest observed residual of approximately 0.4m (March 2009);
- There are contributions to the residual from ITCZ / trade-wind fluctuations, Madden-Julian oscillation and weather band. Direct storm surge, at the shortest end of the weather band, is small;
- A sea level rise of approximately 0.1m occurred from 1993-2014;
- Inter-annual tidal variability causes a range of the annual tidal maxima of approximately 0.14m, with a 4.4 year cycle. This peaked around 2010-2011 and again around 2015, which were anecdotally periods of coastal flooding pressure for Weg naar Zee;
- The seasonal patterns of tides and residuals are out of phase.

The most substantial implication for management of the Suriname coast is the relatively low amplitude of storm surges. Flooding is therefore more strongly affected by tidal and mean sea level fluctuations.

Event Typing

Examination of the nature of high water level events has been undertaken through three types of event "typing":

- Synoptic charts associated with high water level events identified from the Paramaribo data set or anecdotally (Sintec & Sunecon 2015[119]) have been examined (e.g. Figure AA-10);
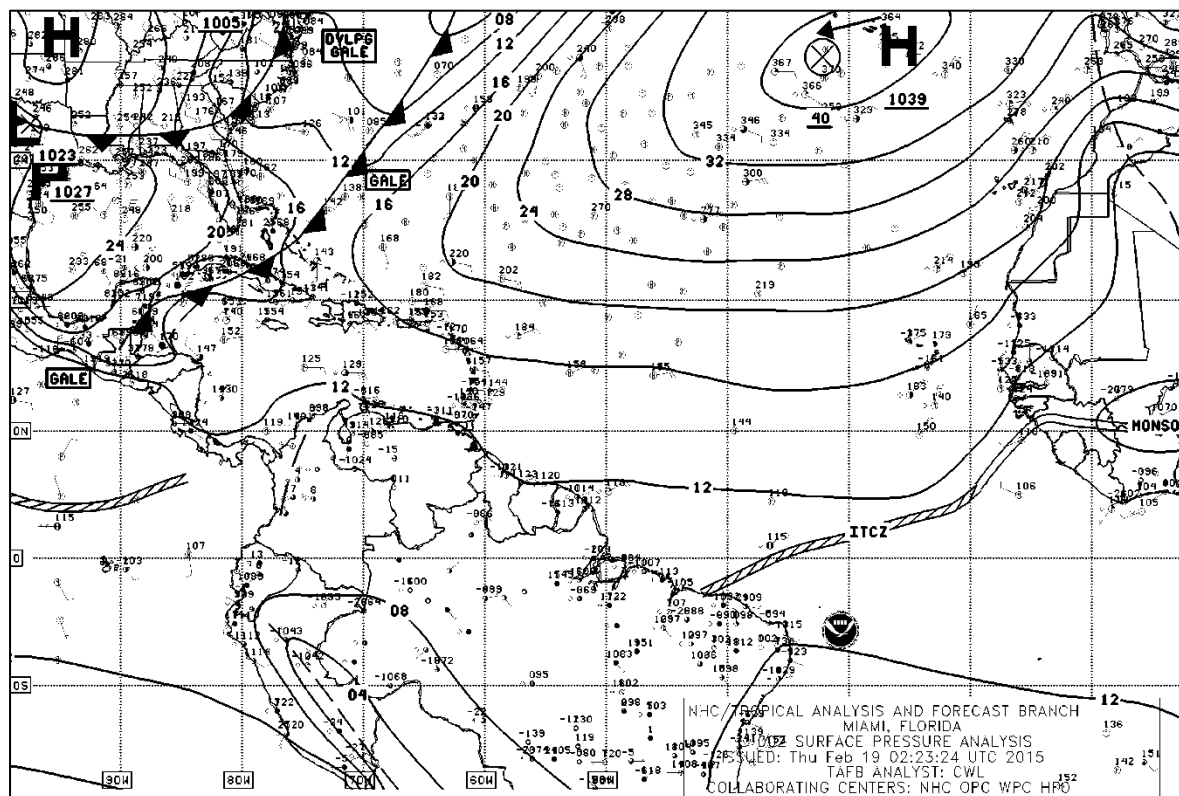
Figure AA-10: Synoptic Chart associated with recent extreme water level at Paramaribo

- The highest water level events observed in the French Guiana record have been assessed. For the highest 10 events, all were associated with large spring tides and moderate positive residuals (01-0.2m);
- Synoptic charts associated with larger surges within the French Guiana record were examined, to determine the synoptic nature of these events (Figure AA-11). Several different event types were apparent, including northward fluctuation of the ITCZ, remote tropical storm events (approximately 10% of high residuals), and rare local storms. It is notable that monsoon wind intensity, which is expected to contribute to sea level variability over time scales from seasonal down to the weather band, cannot be interpreted effectively from synoptic charts.

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[119] Sintec & Sunecon (2015) Updated Ring-dyke Engineering Studies. {In Dutch}
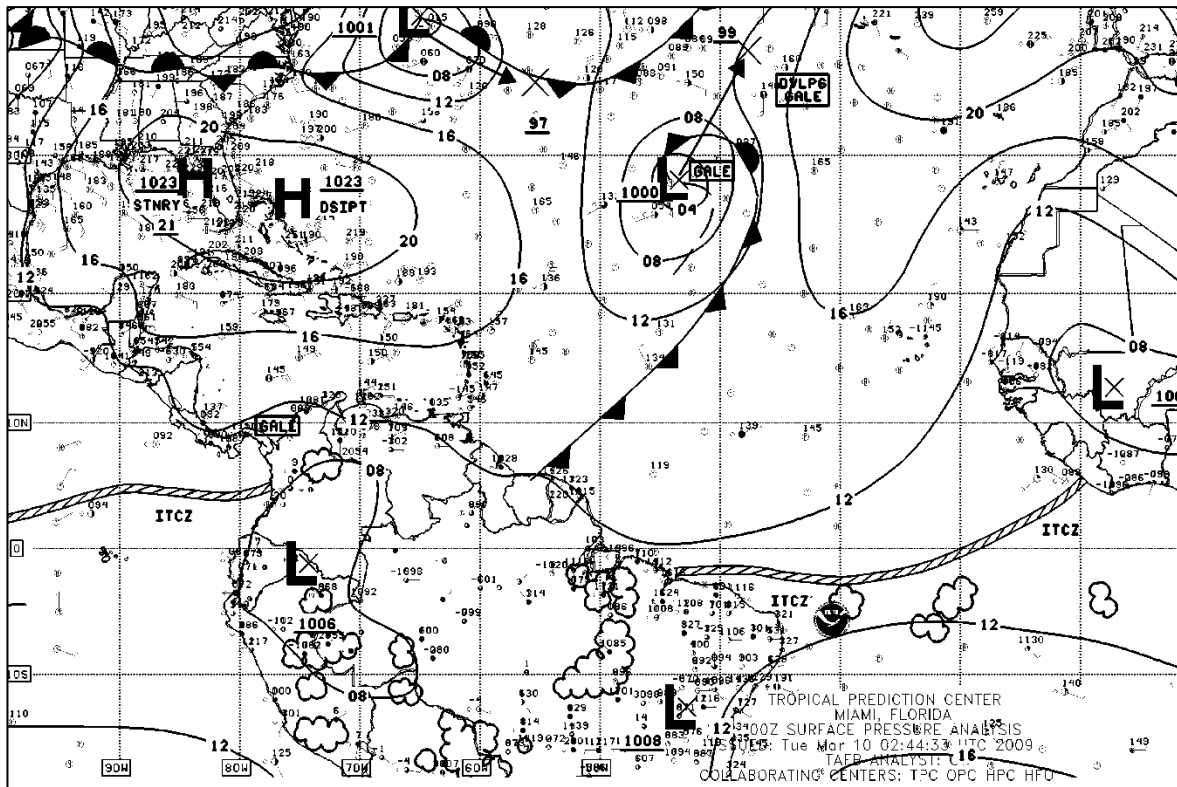
Figure AA-11: Synoptic Chart associated with highest observed surge in French Guiana record

High and Extreme Water Levels

Observation of high water level events for Paramaribo has been outlined for the period 2009-2013, with 9 events above +2.0m NSP reported (Sintec & Sunceon 2015[120]). This is greater than the incidence of high water level events recorded from 1960-1998, and substantially above the level implied by the reported tide range (Figure AA-1) and regional surge (Figure AA-6 & Figure AA-8). Comparison of the two observational data sets shows that the occurrence of high water level events from the 2009-2013 period would match the 1960-1998 data with a +0.1m mean sea level rise. This is consistent with both the French Guiana tide gauge record Figure AA-6) and global satellite altimetry (Figure AA-7).

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[120] Sintec & Sunecon (2015) Updated Ring-dyke Engineering Studies. {In Dutch}

	1960-1998 Data Set (30 years of data)		2009-2013 (5 years of observation)	
Water Level	Count	Occurrence	Count	Occurrence
2.3m NSP	1	0.03/yr		
2.2m NSP	1	0.03/yr		
2.1m NSP	2	0.07/yr		
2.0m NSP	15	0.5/yr	9	1.8/yr
1.9m NSP	50	1.7/yr	22	4.4/yr
1.8m NSP	154	5.1/yr		
1.75m NSP	288	9.6/yr	152	30/yr
1.7m NSP	546	18/yr		
1.65m NSP	913	30/yr		
1.6m NSP	1395	47/yr		
1.5m NSP	2726	91/yr		

Table AA-1: Observed count of recent high water level events

It is worth noting that high water level observations in the 1960-1998 were dominated by two phases of high water levels (1960-1963, 1980) with the highest water level record appearing as an outlier (27 May 1988). It is unclear whether the high-water level phases are associated with "real" phenomena, or are a response to imposed changes, including damming of the Suriname River in 1964.

Previous analyses of extreme water levels for Greater Paramaribo have been presented as part of the structural design for Weg naar Zee ring dyke (Sintec & Sunecon 2015[121]) and the cost-benefit assessment for coastal protection options (Burke & Ding 2016[122]). The latter has subsequently been further interpreted as part of the IDB flooding assessment.

Burke & Ding (2016) refer to the DIVA database, which estimates recurrence of surge above mean sea level and provides a classification of wave and tide range. A combination of tide, surge and wave was used to provide a preliminary estimate of flood hazard for the Suriname coast, which was subsequently revised to use a combination of surge and wave for estimation of coastal hazard. The basis for inclusion of these components, and their interaction, was not clearly described, although it was determined that the preliminary estimate (combining tide, surge and wave) suggested an extremely high incidence of flooding, which was not apparent. Subsequently, it has further been noted that very high wave dissipation occurs across the mudflats and wide intertidal areas, implying that "surge only" estimates are likely to be the best indicator of flood hazard.

[121] Sintec & Sunecon (2015) Updated Ring-dyke Engineering Studies. {In Dutch}
[122] Burke & Ding. (2016) Valuation of Coastal Protection near Paramaribo, Suriname. Prepared for WWF Guianas.

	Preliminary Estimate	Hazard Estimate	Inundation Hazard applied to calculate asset losses	
Components	Wave + Surge + Tide	Wave + Surge	Surge only	Wave + Surge
1 year ARI			2.2m NSP	
10 year ARI			2.4m NSP	
25 year ARI	5.5-9.1m NSP	3.3-5.6m NSP	2.4m NSP	5.2m NSP
100 year ARI			2.6m NSP	
Estimates have been converted from MSL reference to NSP by adding 0.2m				

Table AA-2: Extreme water level components used by Burke & Ding (2016)

Sintec & Sunecon (2015) outlined results of an extreme value analysis of the hydrometric station data from Niue Amsterdam, over the period 1966-1987. Comparison of the historic and modern reference datums was unclear and the set of extremes contributing to this assessment was not presented, limiting evaluation of the reliability of this analysis. A qualitative validation of the results was provided by comparison with recent observations of exceedance events, based on thresholds of +1.75m, +1.9m and +2.0m NSP, with a recent flood event of +2.09m NSP reported from 19 February 2015.

Outputs from extreme distribution fitting to the Niue Amsterdam data set are:

	Gumbel	Weibull	Log-Normal	Recommended
50 year ARI	2.56m NSP	2.48m NSP	2.45m NSP	2.53m NSP
100 year ARI	2.65m NSP	2.54m NSP	2.50m NSP	2.57m NSP

Table AA-3: Extreme water level components by Sintec & Sunecon (2015)

Sintec & Sunecon (2015) also refer to a previous definition of the 100yr ARI water level by MoPW, with a level of +1.90m NSP. This is refuted based on the frequent exceedance of this level between 2009 and 2015, with 22 occurrences above this level.

Due to uncertainty associated with stability of the Paramaribo hydrometric station, the 1960-1998 data set was not considered suitable for derivation of an extreme water level distribution. However, it is worth noting that applying the inverse of occurrence levels to the highest observations suggests approximately recurrence levels of 30, 14 and 2 years for +2.3, +2.1 and +2.0m NSP respectively, which is of similar scale to both the Sintec & Sunecon (2015) and Burke & Ding (2016) estimates, despite their highly dissimilar means of derivation. For this evaluation, we have chosen to use the Sintec & Sunecon (2015) estimates, although we consider that these are likely to provide a slight overestimate of flooding hazard, due to the statistical dependence on one or two observations.

Sea Level Rise

Analysis of sea level rise along the Guianas coast is partly constrained by limited available instrumentation, with satellite altimetry providing the most readily available measure of information for the region (Figure AA-7). Analyses of these records are largely focused on calculation of global

mean surface change (Nerem & Mitchum 2001[123]; Church & White 2006[124]; Willis *et al*. 2010[125]), although the most evident geographic patterns of change are more strongly related to decadal scale (or shorter) basin-scale hydrodynamics. These phenomena have the capacity to significantly bias interpretation of sea level trends from short to medium (<40 year) observational data sets, including interpretation of local rates of sea level rise.

Tide gauge data sets, or bench marks have occasionally been used as reference checks to altimetry (Pernaud 2014[126]). However, the associated data sets are rarely continuous, and therefore have potential for considerable bias either due to datum shift, or the influence of shorter-term mean sea level processes, such as related to El Niño-La Niña climate variability (Figure AA-12).
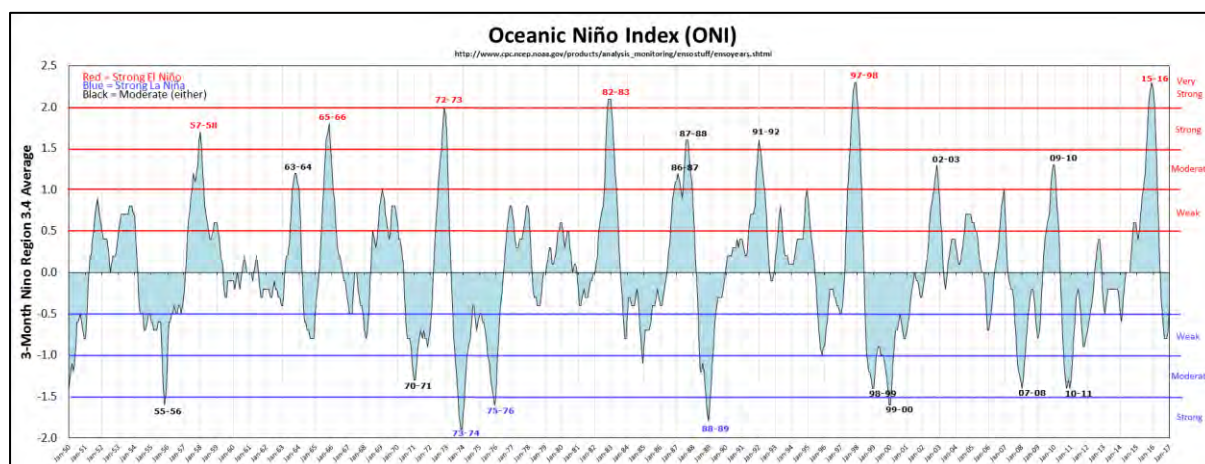

Figure AA-12: Oceanic Nino Index, which provides a simplified measure of inter annual climate drivers

Available water level data sets for Suriname and French Guiana do not provide a suitable basis for the evaluation of sea level rise. Although available altimetry and tide gauge information is reasonably coherent, it is not wholly practical to use observed rates of change over recent decades as a basis for long-term future projections.

Conclusions and Recommendations

Evaluation of local and regional data sets demonstrates:

- Most high-water level events in the region correspond to spring high tides, with small surge contributions from storm surge, Madden-Julian Oscillation and ITCZ / trade-wind variability;
- Mean sea level variation (0.1m rise since 1993) and inter-annual tidal modulations (4.4 year cycle) have both contributed to the changing occurrence of high water level events. In combination, these two processes account for approximately a +0.2m change to the

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[123] Nerem, R.S. and Mitchum, G.T., 2001. Observation of sea level change from satellite altimetry. International Geophysics, 75, pp.121-163.

[124] Church JA & White NJ. (2006) A 20th century acceleration in global sea-level rise. Geophysical Research Letters, 33, L01602.

[125] Willis JK, Chambers DP, Kuo C-Y & Shum CK. (2010) Global Sea Level Rise. Recent progress and challenges for the decade to come. Oceanography, 23 (4). p26-35.

[126] Pernaud ECR. (2014) Sea Level Rise and the Coastline of Guyana. University of Guyana. Powerpoint Presentation.

floodwaters with equivalent recurrence over the last 20 years (roughly changing the 10-year ARI level to an annual event);

- Existing tidal predictions for Paramaribo greatly underestimate the occurrence of high water levels;
- This divergence appears to be caused by inadequate definition of tidal constituents, with mean.

Comparison of available records suggests that the Sintec & Sunecon (2015)[127] extreme water level distributions provides a reasonable, possibly marginally conservative, estimate of coastal flooding recurrence within the present sea level regime.

It is recommended that a program of well controlled tide gauge deployments be undertaken, to revise the existing estimates of tidal constituents for Paramaribo.

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[127] Sintec & Sunecon (2015) Updated Ring-dyke Engineering Studies. {In Dutch}

Appendix B: Coastal Morphodynamics

Floodplain dynamics

Coastal floodplains occur in parts of the world where high sediment supply capable of building landforms is combined with intermittent marine or fluvial flood events capable of landform disturbance. Due to the relative stability of mean sea level over the late Holocene (within the last 6,000 years) coastal floodplains are mainly associated with areas that have accumulated in this modern geomorphic period.

For a floodplain that is built by marine sediment supply such as the Guianas coast, floodplain dynamics include cycles of accretion and erosion, in which both alongshore and cross-shore processes may be active. Flood events provide a significant role in coastal stability, with landforms built during prevailing events pushed landward during elevated conditions.

The comparatively simple concept of sediment supply being pushed along the coast by waves and landward during floods has a more complicated reality due to the influences of large scale mudbanks, chenier systems, mangroves and tidal channels. The contributions of these features to the highly dynamic nature of the Guianas coast has been explored in detail by a range of researchers. Some characteristics of these features are briefly summarised here.

Mudbank dynamics

The Guianas coast has extraordinary, vast, migrating coastal mudbanks, developed through the unique combination of mud supply from the Amazon, the tropical location and orientation of the northern South American coast. This combination provides large volumes of highly mobile mud, a relative absence of severe tropical storms and a sustained westward alongshore push due to the seasonal northeast and southeast trade winds.

The exact mechanics of mud bank movement have been theorised and studied in detail (Augustinus 1978[128], Plaziat & Augustinus 2004[129], Allison & Lee 2004[130], Gratiot *et al*. 2007[131], Anthony *et al*. 2008[132], Gardel *et al*. 2011[133]). This behaviour includes interactions of the moderately consolidated mud bank mass with the adjacent fluidised mud zone, which is held in suspension through tidal and wave hydrodynamics.

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[128] Augustinus PGEF. (1978) *The changing shoreline of Suriname (South America)*, Doctoral dissertation, Utrecht University.

[129] Plaziat JC & Augustinus PG. (2004) Evolution of progradation/erosion along the French Guiana mangrove coast: a comparison of mapped shorelines since the 18th century with Holocene data. *Marine Geology*, 208(2), pp.127-143.

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

[131] Gratiot N, Gardel A & Anthony E (2007) Trade-wind waves and mud dynamics on the French Guiana coast, South America: Input from ERA-40 wave data and field investigations. *Marine Geology,* 236(1-2), 15-26.

[132] Anthony EJ, Dolique F, Gardel A, Gratiot N, Proisy C & Polidori L. (2008) Nearshore intertidal topography and topographic-forcing mechanisms of an Amazon-derived mud bank in French Guiana. *Continental Shelf Research*, 28(6), 813-822.

[133] Gardel A, Gensac E, Anthony E.J, Lesourd S, Loisel H & Marin D (2011) Wave-formed mud bars: their morphodynamics and role in opportunistic mangrove colonization. *Journal of Coastal Research*, 64*,* 384-387.

The structure of a muddy coast is developed through a balance of sediment disturbance and deposition, with tidal hydrodynamics and bed structure being of equivalent importance to wave conditions (Figure AA-1). In this setting, the supratidal littoral shore (whether beach, mudflat or mangrove coast) and any tidal channels can play important roles to influence hydrodynamics, and therefore affect coastal structure. Mangroves provide both impedance of wave stresses and the flow of intertidal water and therefore may substantially support accretion in the presence of fluid mud. In the absence of intertidal mangroves, the mud bank width provides shelter from wave stress, but an intertidal "parting zone" is generated on the mud bank surface, causing deepening nearshore and producing a characteristic "concave" profile, with reduced shoreward sediment supply.
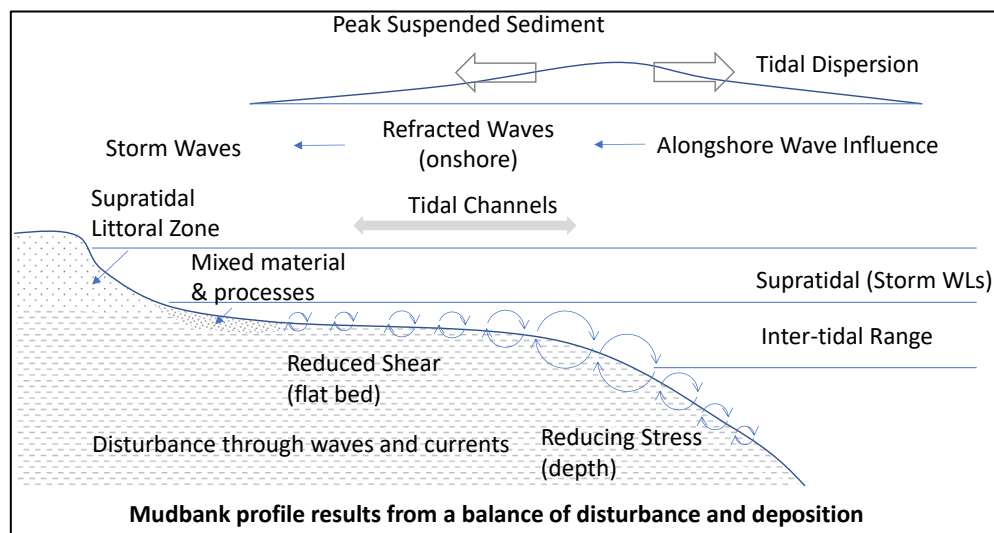

Figure AB-1. Conceptual basis for cross-shore structure.

The substantial difference in stable coastal structure due to the position of the mud bank, including the attached mass of fluid mud, determines that the mechanics of the coastal margin (the supratidal littoral zone) are very different behind the mud bank or for the "interbank" areas that are not sheltered by mud banks (Winterwerp & Augustinus 2009[134], Anthony *et al*. 2011[135], 2013[136]). On the leading side of the mud bank, mangroves support the capture of mud during the phase of high sediment availability. They can provide some resistance to wave action during the erosive interbank phase, but may be undermined if bed lowering reaches below their shallow root structure. Where mangroves have been lost, resistance to wave-driven coastal change is provided by the stability of the underlying material, with sands and shell fragments being inherently more stable than the finer muds or silts.

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[134] Winterwerp H & Augustinus P. (2009) *Coastal morphodynamics report. Physical description of the Suriname coastal system*. ICZM Plan Suriname.

[135] Anthony EJ, Gardel A, Dolique F & Marin D. (2011) The Amazon-influenced mud-bank coast of South America: an overview of short-to long-term morphodynamics of 'inter-bank' areas and chenier development. *Journal of Coastal Research*, (64), 25.

[136] Anthony E, Gardel A and Gratiot N (2013) Fluvial sediment supply, mud banks, cheniers and the morphodynamics of the coast of South America between the Amazon and Orinoco river mouths. *Geological Society, London, Special Publications*, 388(1), 533-560.

Sand cheniers

Sustained exposure to wave action along the coast may winnow the coastal sediments, developing ribbon-like lenses of coarser material, termed cheniers. On an exposed coast, these form beaches, which are subsequently surrounded by mud during accretionary phases. Generation and evolution of these features has been described for the Suriname and wider Guianas coasts (Augustinus 1980[137], Anthony *et al*. 2011[138]), including more detailed description of the Braamspunt shore and cape to the east of Paramaribo (Anthony 2016[139], Gersie *et al*. 2016[140]).

On other parts of the world, cheniers play a significant role to influence the configuration of more mobile coastal sediments (Woodroffe & Mulrennan 1993[141]). However, on the Guianas coast, the extremely fine fraction of coarse sediment available determines that their role is less substantial, albeit no less important, to provide a measure of stability during sustained periods of erosion.
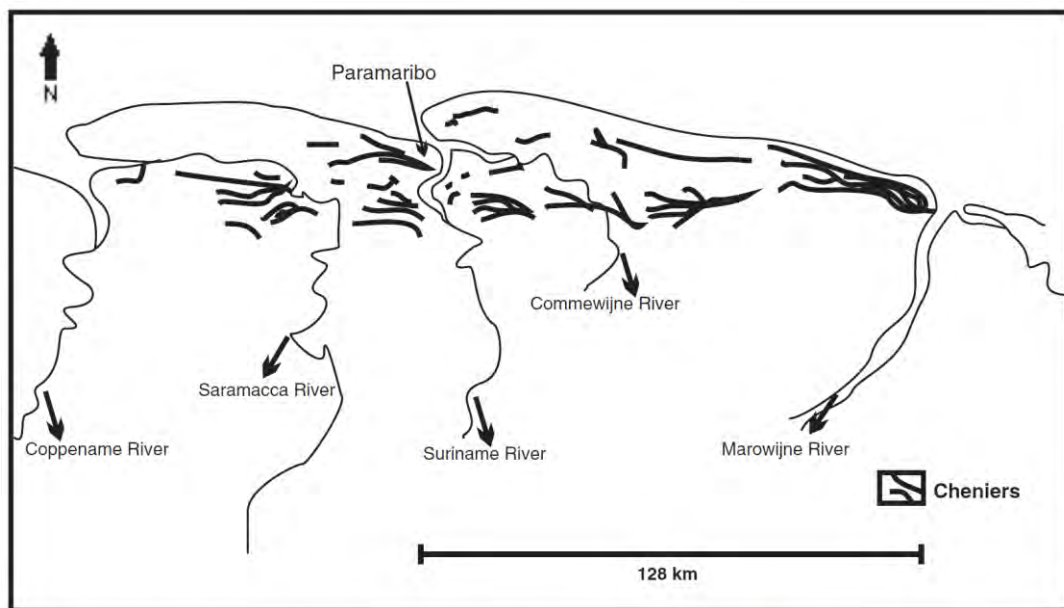
Figure AB-2. Identified Coastal Cheniers Near Paramaribo (From Gersie et al. 2016[142])

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[137] Augustinus, P (1980) Actual development of the chenier coast of suriname (South America). *Sedimentary Geology*, 26(1-3), 91-113.
[138] Anthony EJ, Gardel A, Dolique F & Marin D. (2011) The Amazon-influenced mud-bank coast of South America: an overview of short-to long-term morphodynamics of 'inter-bank' areas and chenier development. *Journal of Coastal Research*, (64), 25.
[139] Anthony EJ. (2016) *Impacts of sand mining on beaches in Suriname*. WWF.
[140] Gersie K, Augustinus PGEF & Van Balen RT. (2016) Marine and anthropogenic controls on the estuary of the Suriname River over the past 50 years. *Netherlands Journal of Geosciences*, 95 (4), 419-428.
[141] Woodroffe C, Mulrennan M and Chappell, J (1993). Estuarine infill and coastal progradation, southern van diemen gulf, northern Australia. *Sedimentary Geology*, 83(3-4), 257-275.
[142] Gersie K, Augustinus PGEF & Van Balen RT. (2016) Marine and anthropogenic controls on the estuary of the Suriname River over the past 50 years. *Netherlands Journal of Geosciences*, 95 (4), 419-428

Role of mangroves

The importance of coastal mangroves for dynamics of the Suriname coast has been explored by a range of researchers (Augustinus 1978[143], Winterwerp & Augustinus 2009[144], Anthony et al. 2011[145], 2013). This vegetation effectively provides a "skin" over muds, reducing their mobility due to waves or currents, and therefore playing a substantial role in coastal growth. Loss of the mangroves may expose the underlying mud to dispersion, contributing to erosion.

Tidal channels

Tidal channels occur along the fringing coastal margin of the Guianas coast. These features convey tidal waters and provide a significant mechanism for rapid local-scale sediment transfer, allowing adjustment to short-term variation in driving conditions (Perillo 2010[146]).

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[143] Augustinus PGEF. (1978) *The changing shoreline of Suriname (South America)*, Doctoral dissertation, Utrecht University.

[144] Winterwerp H & Augustinus P. (2009) *Coastal morphodynamics report. Physical description of the Suriname coastal system*. ICZM Plan Suriname.

[145] Anthony EJ, Gardel A, Dolique F & Marin D. (2011) The Amazon-influenced mud-bank coast of South America: an overview of short-to long-term morphodynamics of 'inter-bank' areas and chenier development. *Journal of Coastal Research*, (64), 25.

[146] Perillo, G and Syvitski, J (2010) Mechanisms of sediment retention in estuaries. *Estuarine, Coastal and Shelf Science*, 87(2), 175-176. **//** Pratolongo P, Perillo G and Piccolo M (2010) Combined effects of waves and plants on a mud deposition event at a mudflat-saltmarsh edge in the Bahía Blanca estuary. *Estuarine, Coastal and Shelf Science*, 87(2), 207-212

Appendix C: Paramaribo Coastal Change Scenarios

Introduction

This appendix provides a brief analysis of historic changes along the Suriname coast, used to derive potential coastal change scenarios for the City of Paramaribo. These scenarios will be used to support evaluation of coastal hazard management options for Paramaribo, as part of the Coastal Resilience Assessment by the World Bank.

Background

The coastal geomorphology of Suriname and the adjacent states of the Guianas coast is globally remarkable. Enormous quantities of fine mud released by the Amazon River are driven westward by equatorial trade winds, forming an extensive, low-lying coastal floodplain stretching more than 1500km (Noordam 2007[147]). The highly mobile nature of Amazon muds supports extensive presence of dynamic coastal features (Augustinus 1978[148], 2004[149]; Anthony et al. 2013[150]). These include:

- Extremely large-scale mudbanks extending to depths of 20m, up to 30km offshore. These migrate west along the Guianas coast at speeds from 0.5-1.5 km/year (Anthony et al. 2008[151]; Gersie et al. 2016[152]);
- Low lying coastal ridges, tidal lagoons and stranded lagoons, characteristic of variable phases of deposition;
- Linear cheniers, comprised of sand and shell, where sustained phases of erosion have produced lag deposits, subject to alongshore transport (Augustinus 1980[153]; Anthony et al. 2011; Anthony 2016[154]).

In this low-lying setting, interactions of the coast with mangrove communities are substantial. Mangroves help to stabilise the muddy shore, due to their capacity to resist wave action, and their

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[147] Noordam D. (2007) Sector: Geomorphology and soils. *Promotion of sustainable livelihood within the coastal zone of Suriname, with emphasis on Greater Paramaribo and the immediate region*, pp.1-41.

[148] Augustinus PGEF. (1978) *The changing shoreline of Suriname (South America)*, Doctoral dissertation, Utrecht University.

[149] Augustinus PG. (2004) The influence of the trade winds on the coastal development of the Guianas at various scale levels: a synthesis. *Marine Geology*, 208(2), 145-151.

[150] Perillo, G and Syvitski, J (2010) Mechanisms of sediment retention in estuaries. *Estuarine, Coastal and Shelf Science*, 87(2), 175-176. **//** Pratolongo P, Perillo G and Piccolo M (2010) Combined effects of waves and plants on a mud deposition event at a mudflat-saltmarsh edge in the Bahía Blanca estuary. *Estuarine, Coastal and Shelf Science*, 87(2), 207-212

[151] Anthony EJ, Dolique F, Gardel A, Gratiot N, Proisy C & Polidori L. (2008) Nearshore intertidal topography and topographic-forcing mechanisms of an Amazon-derived mud bank in French Guiana. *Continental Shelf Research*, 28(6), 813-822.

[152] Gersie K, Augustinus PGEF & Van Balen RT. (2016) Marine and anthropogenic controls on the estuary of the Suriname River over the past 50 years. *Netherlands Journal of Geosciences*, 95 (4), 419-428.

[153] Augustinus, P (1980) Actual development of the chenier coast of suriname (South America). *Sedimentary Geology*, 26(1-3), 91-113.

[154] Anthony EJ. (2016) *Impacts of sand mining on beaches in Suriname*. WWF.

role to dampen hydraulic exchange between the coast and the floodplain, which enhances the capacity for mud coast accretion.

Coastal Morphodynamics

Historic analysis of the Suriname coast (Augustinus 1978, 2004; Winterwerp & Augustinus 2009[155]; Berrenstein 2010[156]; Anthony 2015[157]) and wider region (Plaziat & Augustinus 2004[158]; Fromard *et al*. 2004[159]; Gratiot *et al*. 2007[160]; Anthony *et al*. 2008, 2010[161], ; Gratiot 2011[162]) has shown the highly dynamic nature of the Guianas coast is strongly dominated by movements of the large-scale mudbanks, driven by the wave and current regime developed by equatorial trade winds. Coastal change at any point along the coast tends to follow a cycle, with rapid shoreline accretion when the mudbank is located to seaward (the "mudbank phase") followed by sustained erosion when the mudbank is absent (the "interbank phase"). Over the long term (centuries) imbalance between the accretion and erosion phases has resulted in progressive growth of the Guianas coast, with the "Young" coastal plain of approximately 30-60km width estimated to have developed over the last 6000 years.

Observations of coastal change since European settlement have demonstrated that although the mudbanks are sustained coastal features, which may be tracked for decades, their characteristics are not entirely stable geographically or over time (Augustinus 1978[163], 2004[164]; Berrenstein 2010[165];

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[155] Winterwerp H & Augustinus P. (2009) *Coastal morphodynamics report. Physical description of the Suriname coastal system*. ICZM Plan Suriname.

[156] Berrenstein H. (2010) Coastal changes along the Suriname coast with emphasis on the changing coastline of Coronie from 1914 to 2007 and its influence on *Avicennia germinans L*. (Avicenniaceae). *Academic Journal of Suriname*, 1, 86-95.

[157] Anthony E. (2015) *Assessment of peri-urban coastal protection options in Paramaribo-Wanica, Suriname*. Prepared for WWF Guianas.

[158] Plaziat JC & Augustinus PG. (2004) Evolution of progradation/erosion along the French Guiana mangrove coast: a comparison of mapped shorelines since the 18th century with Holocene data. *Marine Geology*, 208(2), pp.127-143.

[159] Fromard F, Vega C & Proisy C. (2004) Half a century of dynamic coastal change affecting mangrove shorelines of French Guiana. A case study based on remote sensing data analyses and field surveys. *Marine Geology*, 208(2), 265-280.

[160] Gratiot N, Gardel A & Anthony EJ. (2007) Trade-wind waves and mud dynamics on the French Guiana coast, South America: input from ERA-40 wave data and field investigations. *Marine Geology*, 236(1), pp.15-26.

[161] Anthony E, Gardel A, Gratiot N, Proisy C, Allison, M., Dolique F and Fromard F (2010). The Amazon-influenced muddy coast of South America: A review of mud-bank–shoreline interactions. *Earth-Science Reviews*, 103(3-4), 99-121.

[162] Gratiot N. (2011) *Coastal erosion along the coast of Guiana*. Final report. MWH Consortium.

[163] Augustinus PGEF. (1978) *The changing shoreline of Suriname (South America)*, Doctoral dissertation, Utrecht University.

[164] Augustinus PG. (2004) The influence of the trade winds on the coastal development of the Guianas at various scale levels: a synthesis. *Marine Geology*, 208(2), 145-151.

[165] Berrenstein H. (2010) Coastal changes along the Suriname coast with emphasis on the changing coastline of Coronie from 1914 to 2007 and its influence on *Avicennia germinans L*. (Avicenniaceae). *Academic Journal of Suriname*, 1, 86-95.

Heijenk & de Jong 2016[166]; Anthony 2016[167]). Variable coastal behaviour has been attributed to different mechanisms including:

Trade-wind variability – identified inter-decadal variability of trade-winds has been attributed as a potential mechanism for change in mud-bank structure, and consequently the efficiency of mud delivery to the coast. This has been argued as a possible cause of the shift from country-wide net erosion from 1947-1966, to net accretion from 1966-2007 (Berrenstein 2010);

Impeded floodplain recovery – erosion and accretion cycles coincident with mudbank movement are apparent along most of the Suriname coast. Sustained erosion has been identified at Totness and Weg naar Zee, where the relative balance of the erosion and recovery cycle has been substantially altered. The key characteristic of these two locations which differentiates them from the remainder of the Suriname coast is the historical presence of extensive rice polders (Nijbroek 2012[168]). It is theorised that this effectively blocked mudbank-floodplain interaction during the mudbank phase, and therefore changed the balance of accretive and erosive phases;

Extended interbank phases – because the relative speeds of consecutive mudbanks is not always equal, an extended interbank phase may occur when the following mudbank is slower. This has occurred at Paramaribo, where the leading mudbank (presently along the Saramacca coast) has been moving west more than 1 km/year faster than the following mudbank (presently off the Commewijne coast);

Mean sea level change – sea level information from along the Guianas coast suggests a mean sea level rise exceeding the global average. This is supported by satellite altimetry, which shows a rise of approximately 0.1m between 1993 and 2009 (Willis *et al*. 2010[169]). Methods to derive mud coast response to sea level rise are less developed than for sandy coasts (Kirby 2000[170]; Rossington *et al*. 2009[171]) although in the long-term, sea level rise is expected to cause net erosion.

Coastal Change Model

A simple model of coastal change has been developed to provide a description of the potential sensitivity of Suriname shoreline to different mechanisms for change. The approach taken is to generate a Monte-Carlo model based on four inputs describing the interbank and mudbank phases:

- Duration of the mudbank phase (Tm) and average rate of accretion during this phase (Rm);
- Duration of the interbank phase (Ti) and average rate of erosion during this phase (Ri).

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[166] Heijenk R & de Jong S. (2016) *Mapping the dynamic Suriname Coast using satellite images*. https://vimeo.com/172752368. University of Utrecht.
[167] Anthony EJ. (2016) *Impacts of sand mining on beaches in Suriname*. WWF.
[168] Nijbroek RP. (2014) *Mangroves, mudbanks and seawalls: Political Ecology of Adaptation to Sea Level Rise in Suriname*. PhD Thesis, University of South Florida.
[169] Willis JK, Chambers DP, Kuo C-Y & Shum CK. (2010) Global Sea Level Rise. Recent progress and challenges for the decade to come. *Oceanography*, 23 (4). p26-35.
[170] Kirby R. (2000) Practical implications of tidal flat shape. *Continental Shelf Research*, 20(10), 1061-1077.
[171] Rossington, K., Whitehouse, R. J. S., & Spearman, J. (2009). Morphological modelling of intertidal profiles in estuaries with strong tidal currents. *Rivers, Coastal and Estuarine Morphodynamics*, 941-946.

For four different scenarios of change, a plausible range of these parameters was selected based on the historic coastal observations. For each scenario, 10,000 "futures" were determined, each one with a randomly selected set of parameters (Tm, Rm, Ti, Ri). Statistical analysis was used to determine the proportional occurrence of different coastal change outcomes from the 10,000 futures. Importantly, it is noted that this approach provides a relative measure of uncertainty associated with the different scenarios, rather than a likelihood of coastal change.

This approach provides a simplified version of the "probabilistic" method developed for long-term coastal change assessment (Woodroffe et al. 2012[172]).

Estimates of the coastal change parameters have been developed based on observations from the Suriname coast. Normal floodplain behaviour has been based upon erosion and accretion cycles measured across the wider Suriname coast, with median behaviour selected to match the long-term country-wide trend of 5m/yr accretion (Berrensetein 2010[173]). The median rate of erosion during the interbank phase was selected to match the rate of high water mark retreat observed at Weg naar Zee (Moe Soe Let 2016[174]).

The influence of impeded floodplain behaviour has been estimated based on the sequence observed at Totness from 1920 to 2008 (Winterwerp & Augustinus 2009[175]). The overall rate of erosion of 30 m/yr was developed through substantially reduced rates of accretion during the mudbank phase and moderately increased rates of erosion during the interbank phase, with a median rate of 60 m/yr selected to match observed shoreline retreat at Weg naar Zee following undermining of the coastal mangrove fringe.

The effect of extending the interbank phase was determined by doubling the median duration of the interbank phase. Average rates of erosion and accretion, and the length of the mudbank phase, where kept the same as the "normal" floodplain behaviour model.

An additional scenario was developed that combined the effects of an extended interbank phase and impeded recovery during the mudbank phase. The mudbank accretion rate of 60 m/yr was selected to provide a median net change over a single cycle that matched the 1200m erosion distance reported for Weg naar Zee (Moe Soe Let 2016).

[172] Woodroffe CD, Cowell PJ, Callaghan DP, Ranasinghe R, Jongejan R, Wainwright DJ, Barry S, Rogers K & Dougherty AJ. (2012) *Approaches to risk assessment on Australian coasts: a model framework for assessing risk and adaptation to climate change on Australian coasts*: final report.

[173] Berrenstein H. (2010) Coastal changes along the Suriname coast with emphasis on the changing coastline of Coronie from 1914 to 2007 and its influence on Avicennia germinans L. (Avicenniaceae). *Academic Journal of Suriname*, 1, 86-95.

[174] Moe Soe Let V. (2016) *Study on the dynamics of the coastline of Suriname and the relationship to mangrove using Remote Sensing*. Antom de Kom University of Suriname, Faculty of Technology. Bachelor of Science Thesis.

[175] Winterwerp H & Augustinus P. (2009) *Coastal morphodynamics report. Physical description of the Suriname coastal system*. ICZM Plan Suriname.

Scenario	Normal Floodplain Behaviour	Impeded Floodplain Recovery	Extended Interbank Phase	Extended Interbank & Impeded Recovery
Mudbank Phase	10 years	10 years	10 years	10 years
Duration Range	5-15 yrs	5-15 yrs	5-15 yrs	5-15 yrs
Mudbank Accretion	95 m/yr	30 m/yr	95 m/yr	60 m/yr
Accretion Range	45-145 m/yr	0-60 m/yr	45-145 m/yr	20-100 m/yr
Interbank Phase	20 years	20 years	40 years	30 years
Duration Range	10-30 yr	10-30 yr	30-50 yr	20-40 yrs
Interbank Erosion	40 m/yr	60 m/yr	40 m/yr	60 m/yr
Erosion Range	20-60 m/yr	40-80 m/yr	20-60 m/yr	40-80 m/yr

Table AC-1: Erosion and accretion parameters used for scenarios

Model Outputs

Monte Carlo simulations of 10,000 "futures" have been developed for each of the four scenarios, with the relative distribution amongst the futures evaluated for each forecast year. The resulting plots show the wide range of future possible outcomes that could be consistent with each scenario.

In each case, the model starts within the interbank phase, with at least 10 years remaining, based on the observed situation of the Commewijne mudbank, its' historic rate of movement (Winterwerp & Augustinus 2009[176]; Gersie et al. 2016[177]) and its' more recent speed (Anthony 2016[178]). This provides an initial dip for the plots associated with all scenarios.
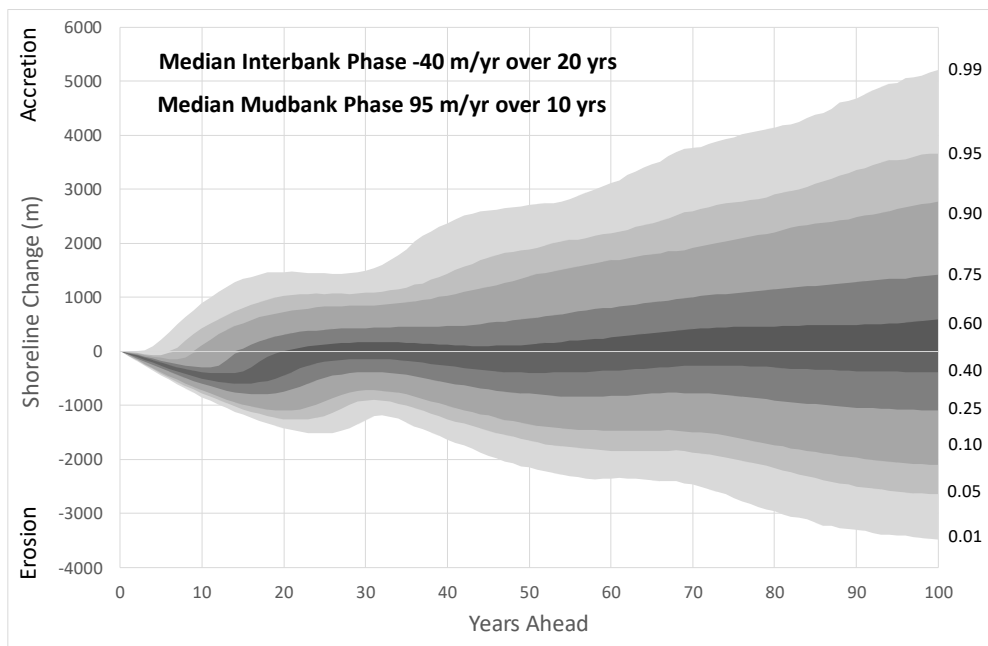
The model for normal floodplain behaviour (Figure 9-1) highlights the large scale of uncertainty relative to the small overall trend of accretion. However, it also suggests the significance of the present position within the interbank phase, with the initial dip providing erosion of more than 500m for approximately 50% of the modelled futures.

Each of the other scenarios increases the tendency for erosion. However, difficulty distinguishing between mechanisms is suggested by the initial similarity of the model outputs for impeded mudbank recovery (Figure 9-2) extended interbank phase (Figure 9-3) and the "combined" scenario (Figure 9-4).

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[176] Winterwerp H & Augustinus P. (2009) *Coastal morphodynamics report. Physical description of the Suriname coastal system*. ICZM Plan Suriname.
[177] Gersie K, Augustinus PGEF & Van Balen RT. (2016) Marine and anthropogenic controls on the estuary of the Suriname River over the past 50 years. *Netherlands Journal of Geosciences*, 95 (4), 419-428
[178] Anthony EJ. (2016) *Impacts of sand mining on beaches in Suriname*. WWF.

Figure AC-1. Coastal Change Futures for Normal Floodplain Behaviour.
Monte Carlo Model suggests uncertainty of futures under the scenario range of parameters.
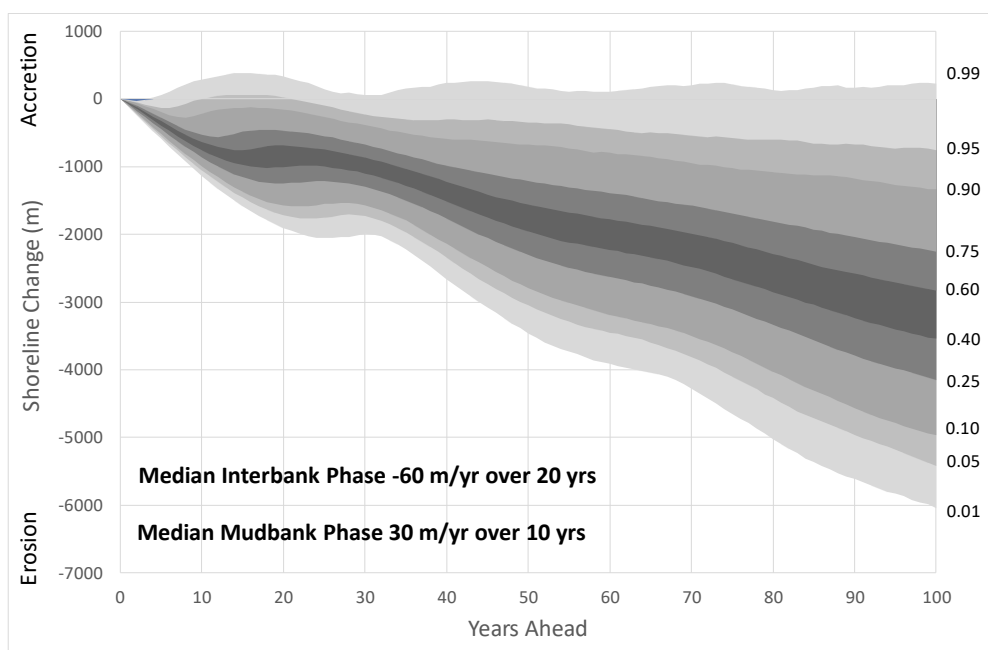
Figure AC-2. Coastal Change Futures for Impeded Floodplain Recovery.
Monte Carlo Model suggests uncertainty of futures under the scenario range of parameters

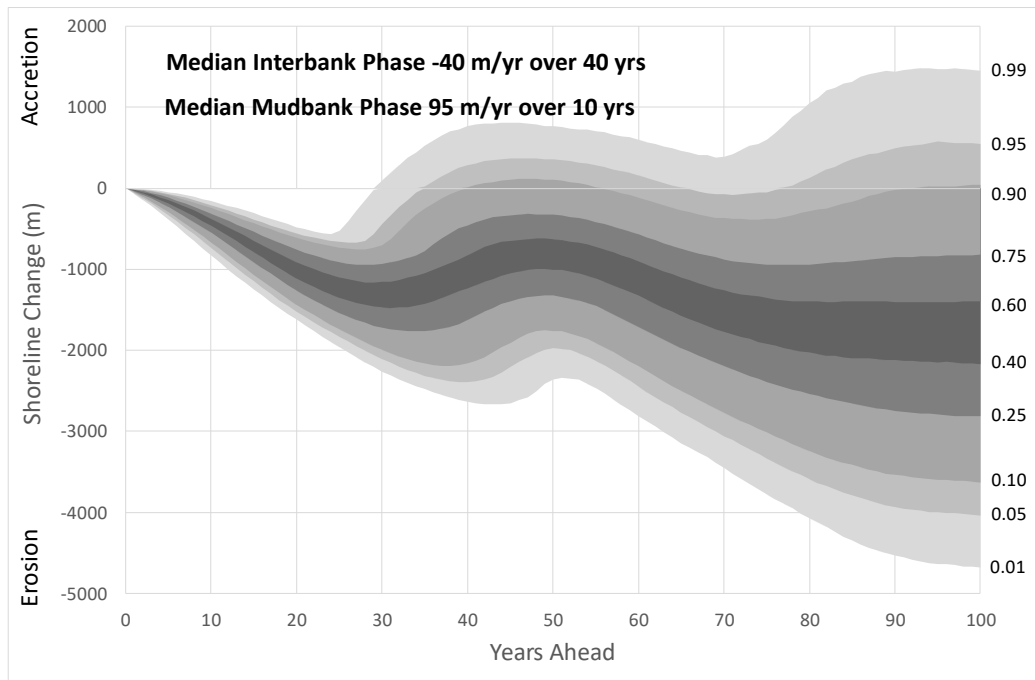*Figure AC-3. Coastal Change Futures for Extended Mudbank Phase.*
Monte Carlo Model suggests uncertainty of futures under the scenario range of parameters

A key modelling outcome is that the two scenarios with impeded floodplain recovery (scenarios 2 and 4) suggest the most substantial tendency towards erosion.
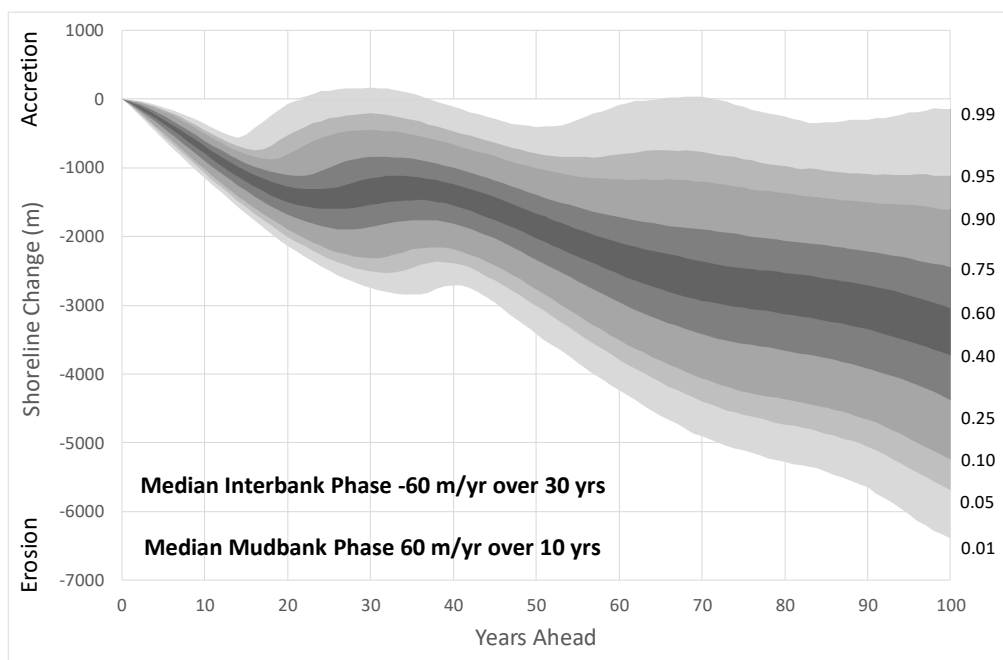
Figure AC-4. Coastal Change Futures for Extended Mudbank Phase and Reduced Floodplain Recovery.
Monte Carlo Model suggests uncertainty of futures under the scenario range of parameters

Application to Paramaribo

Proposed coastal management for Greater Paramaribo includes construction of a rock sea-dyke, to provide flood protection for the low-lying Weg naar Zee coastal plain (Proplan 2015[179]). The proposed design (Sintec 2015[180]) is based on depth limited wave conditions, and therefore coastal erosion provides a mechanism by which design conditions may be exceeded.

The existing design proposes a limited 50m buffer of planted mangroves on the seaward side of the dyke's toe. Based on comparison with historic rates of erosion during the interbank phase, this buffer is not expected to last long. Implicitly, either a more substantial structure (lower toe, larger armour) should be built, or the structure should be substantially set back from the present-day coast.

Application of the coastal change model scenarios highlights both the considerable uncertainty associated with projections based on available information, but also the importance of the concluding part of the present interbank phase. A further erosion distance in the order of 500m is considered likely within the next 20 years, even if the coastal behaviour is not influenced by either impeded floodplain recovery or further extension of the interbank phase (due to slowed mudbank movement).

The long-term importance of the two mechanisms for enhanced erosion (impeded recovery or extended interbank phase) is suggested by the coastal change modelling. This highlights the need for more detailed scientific assessment of these processes when establishing coastal setbacks suitable for long-term planning along the Suriname coast. In particular, the inclusion of observational uncertainty through the Monte Carlo modelling process demonstrates that extrapolation of historic trends does not provide an adequate representation of the range of potential coastal futures.

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[179] Proplan (2015) Feasibility Study Project Weg naar Zee coastal protection works for funding by the ISDB. Prepared for Ministerie van Openbare Werken.
[180] Sintec & Sunecon (2015) *Updated Ring-dyke Engineering Studies*. {In Dutch}

Appendix – D: Coastal Hazard Acceptance

Coastal hazards are typically irregular, occurring as a blend of frequent, limited impact events and infrequent, high impact events. This combination prompts use of a risk-management matrix (ISO 31000), which is typically constructed from hazard criteria at various levels of impact. For flooding, this may include thresholds for: human safety, structural failure, initiation of damage or frequency of inundation (e.g. crop salinization). For erosion, thresholds are usually associated with the amount of warning time, from areas subject to potential erosion hazard, through forecast erosion (over years) to imminent risk, where hazard is related to the likelihood of a sufficiently intense storm to cause damage due to erosion. Hazard thresholds vary between nations, and sometimes between agencies (Dekker *et al.* 2005[181], IWR 2011[182]). No documented flooding or erosion thresholds have been identified for Suriname, although the design for Weg naar Zee sea dyke suggests a 50-year ARI threshold for structural failure of defences (Sintec & Sunecon 2015[183]).

Choosing whether a level of hazard is unacceptable typically considers upper or lower thresholds, corresponding to low frequency or low cost respectively (Figure AD-1). In practice, use of upper thresholds is usually associated with regulatory agencies, setting safety standards for buildings or development setbacks, with more severe events neglected due to their infrequency (the accepted risk). Lower thresholds are informally used by owners to determine infrastructure or land-use viability, with less severe events neglected as a nuisance only. Intermediate levels represent situations which may be viable, but for which hazard is not negligible, and may require management.
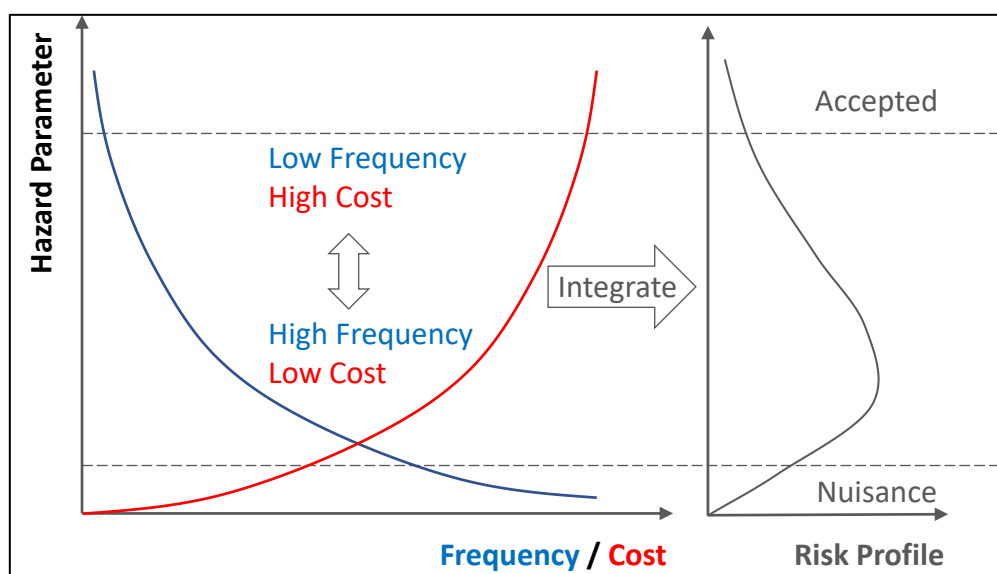
Figure AD-1. Development of risk profile from hazard frequency and cost

A measure of risk can be developed by integrating likelihood and costs of a hazard, giving an overall economic risk profile (Figure AD-1). Effective combinations of mitigation actions can be selected

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[181] Dekker J, Wolters A, den Heijer F & Fraikin S. (2005) Hydraulic Boundary Conditions for Coastal Risk Management – COMRISK Subproject 5. In: (Ed) Hofstede J. (2005) *COMRISK. Common Strategies to Reduce the Risk of Storm Floods in Coastal Lowlands*. Die Kuste Special Edition, 70: 151-172.

[182] IWR (2011) *Flood Risk Management Approaches as being practices in Japan, Netherlands, United Kingdom and United States*. IWR Report No: 2011-R-08.

[183] Sintec & Sunecon (2015) *Updated Ring-dyke Engineering Studies*. {In Dutch}

through consideration of the total risk profile (Oumeraci 2005[184]). However, selecting the best economic outcome does not necessarily address the needs for human safety. A "minimum safety standard" is often defined by regulation, that refers to a recurrence likelihood of either damage to a coastal defence, or extent of coastal development setback, typically in the range of 0.2-2% likelihood per year.

Techniques for defining flood hazard criteria vary substantially, according to the receptor[185] and flooding pathway. Flood depth, rate of rise, flow velocity and wave height may each contribute to hazard (FEMA 2005[186], McLuckie 2013[187]), with an example provided by Figure AD-2, although economic costs are often simply related to depth, through depth-damage relationships (Table AD-1).
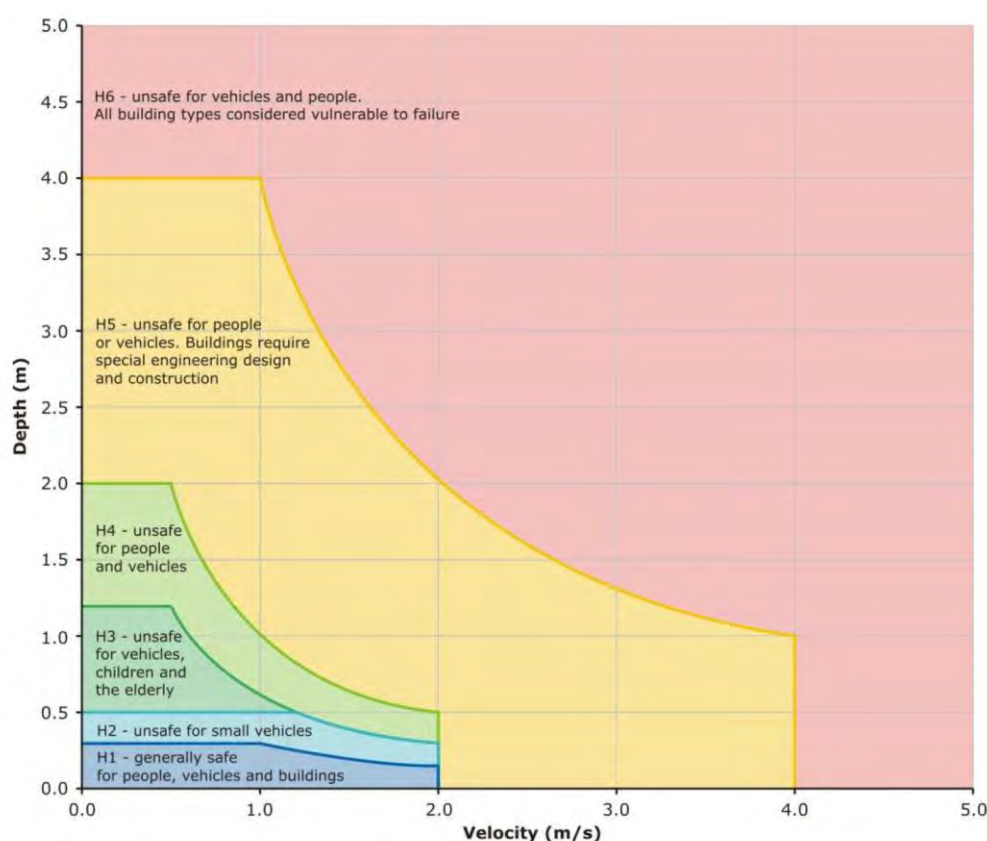
Figure AD-2. Flood hazard criteria incorporating depth and velocity From Smith & McLuckie (2015)[188]

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[184] Oumeraci H. (2005) Integrated Risk-Based Design and Management of Coastal Flood Defences. In: (Ed) Hofstede J. (2005) *COMRISK. Common Strategies to Reduce the Risk of Storm Floods in Coastal Lowlands*. Die Kuste Special Edition, 70: 151-172.
[185] 'Object' affected by flooding, which may be people, livestock, infrastructure, ecosystem, or other.

[186] Federal Emergency Management Authority. (2005) *FEMA Coastal Flood Hazard Analysis and Mapping Guidelines*. Focused Study Report
[187] McLuckie D. (2013) *Managing the floodplain: a guide to best practice in flood risk management in Australia*, Australian Emergency Management Institute, Handbook 7, Commonwealth of Australia.
[188] Smith & McLuckie D. (2015) Delineating hazardous flood conditions to people and property. Floodplain Management Australia Conference, Brisbane, 19-22 May 2015.

| Flood Depth	Human Safety	Structural Issues
< 0.3m	Can typically be tolerated	Minor damage to fittings
0.3-0.6m	Tolerable for low flow / waves	Minor damage to structures
0.6-1.2m	Tolerable for negligible flow	Structural failure possible
> 1.2m	Is typically unsafe for humans	Requires purpose-built structures

Table AD-1: Simplified depth-damage relationship

In general, low depths of flooding can be tolerated with moderately high frequency, with greater opportunities for land-use if moderate or deep flooding occurs increasingly rarely. Typically, the water level reached around once per year represents a level above which land-use may become viable, and the depth of flooding occurring around once per hundred years (say 50-500 year range) determines an appropriate degree of flood hazard mitigation, through hazard avoidance, tolerance or protection. The opportunity to use non-structural measures for flood hazard mitigation (e.g. choosing an appropriate land-use to tolerate moderate flooding) is broadly indicated by the area between the 1-year and 100-year flood limits. Mapping of the associated flood area shows that substantial areas north of Paramaribo, including Weg naar Zee, Rainville and Blauwgrond are subject to inundation during 1-year to 10-year ARI floods (Figure AD-3), and suggests only a narrow strip of land is potentially suitable for non-structural measures (on their own).
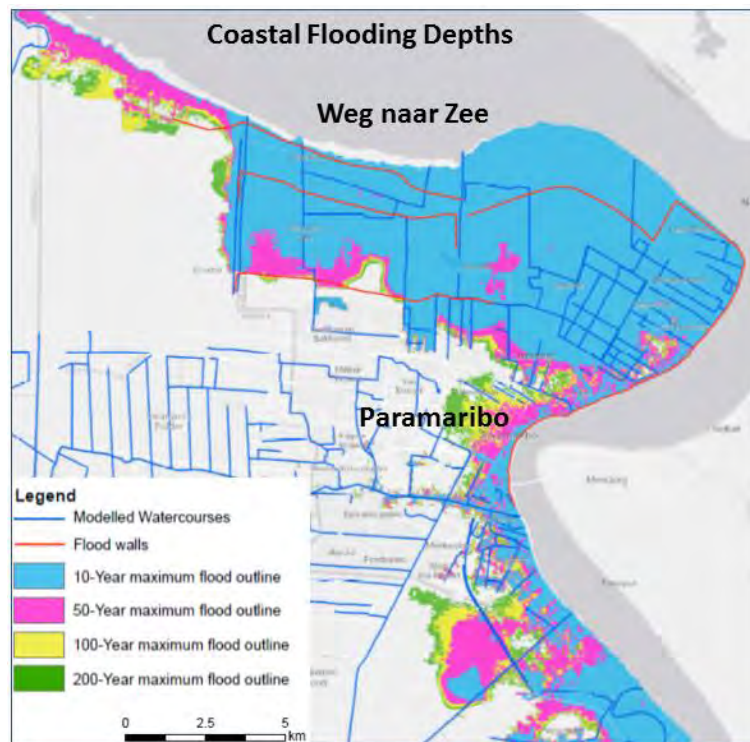
Figure AD-3. Present-day flood hazard mapping

Flood mapping may be used to define hazard zones based on a lower limit (land-use viability), an upper limit (accepted hazard) and the depth of flooding which occurs during the upper limit event. Using the

1-year and 500-year [189] ARI floods as the lower and upper limits respectively, it is notable that there is only ~0.5m vertical difference between the two. Consideration of depth-damage relationships suggests four flood hazard zones:

- Land below 1-year ARI is not viable for typical land-use activities without land improvement, although it may be suitable for coastally dependent activities;
- Land between 1-year and 500-year ARI floods that experiences more than 0.3m flood depth during the 500-year ARI event may be suitable for limited land-use, but may be unsafe for evacuation. Residences should generally be discouraged, although may be viable with suitable property-level protection plus definition / construction of safe evacuation routes;
- Land between 1-year and 500-year ARI floods, which experiences less than 0.3m flood depth during the 500-year ARI event is likely to be suitable for a wider range of land-uses. Evacuation is plausible, and therefore residences with low property-level protection (e.g. flood proofing) may be viable, although safe evacuation routes need to be identified.
- Above the 500-year ARI flood, most forms of land-use may be considered viable. Essential services (e.g. power, water, hospitals or evacuation shelters) should typically be located well above the 500-year level, with due consideration of access required during a flood.

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[189] It is common practice to incorporate an allowance for sea level rise into the upper flood limit.

Appendix – E: References

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December, 2017