

MSc Thesis

Feasibility of Beneficial Reuse of Sediment for Mangrove Rehabilitation in Paramaribo, Suriname

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Delft University of Technology

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Feasibility of Beneficial Reuse of Sediment for Mangrove Rehabilitation in Paramaribo, Suriname

by

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Preface

This report contains my MSc thesis, my graduation project for the master's program in Hydraulic Engineering at Delft University of Technology's Faculty of Civil Engineering. In this thesis, I assess the viability of repurposing dredged sediment to restore the growth of mangrove forests on the Weg naar Zee coast in Suriname, through the implementation of sediment nourishment.

I would like to express my gratitude to Boskalis and Deltares for providing me with the opportunity to work on this diverse and intriguing project. It has allowed me to develop several critical skills and gain a comprehensive understanding of the aspects of this real-world problem, which will undoubtedly benefit me throughout my career. I would like to thank the Hydronamic and Deltares teams for their encouragement and engagement throughout the process.

A highlight of my graduation period was the visit to Paramaribo in March. It was an enriching experience to visit the project site and interact with all the team members working on the project at that time. I appreciate Boskalis facilitating my visit to the project at such an early stage. This experience was instrumental in familiarizing myself with all aspects of the research and its beautiful location. A special thank you goes out to Vishay for guiding me throughout the entire week and enabling me to achieve all my goals for the visit.

I am grateful to all committee members for their input during the research. I consider myself fortunate to have had a group of professionals with such expertise on board, who were always eager to assist me with the challenges I encountered. The fact that not a single meeting was held without the entire committee present speaks volumes. Thomas, thank you for your continuous support during the research. I enjoyed our brainstorming sessions, your enthusiasm for problem-solving was genuinely contagious. Bob, thank you for guiding me in the relatively new field of numerical modelling. Your guidance made it an enjoyable process from which I learned a great deal. Han, thank you for bringing so much knowledge to every meeting. I learned a lot from your input and advice. Bram, thank you for helping me focus on the bigger picture and guiding me in the right direction. Wouter, thank you for joining the committee at a later stage with such enthusiasm for my research progress.

*Jeroen Pröpper
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Abstract

In response to the escalating coastal erosion at the Weg naar Zee region in Suriname, this study explores the beneficial reuse of dredged sediment from the Suriname River. The integral question is, "What is the feasibility of the beneficial reuse of dredged sediment through sediment nourishment to rehabilitate the growth of mangrove forest on the Weg naar Zee, Suriname coast?" To address this, literature research provides a basis for understanding imperative areas related to mud coast dynamics, sediment dynamics, mangroves, and the Suriname coastal system. This culminates in a system analysis and develops into a conceptual model of the Suriname River Estuary's dynamics. Further development of a hydrodynamic numerical Delft 3D model of the Suriname River Estuary system ensues. This analysis forms the foundation for further assessment of potential sediment input locations throughout the estuary.

Simulations are utilized to verify the sediment transport mechanisms, primarily focusing on two transport types: initial transport through the water column as suspended particulate matter (SPM), and migration over the bed influenced by wave forcing. These simulations offer valuable data on the impact of timing and placement of sediment input on the transport and deposition process. Employing recent survey data of the Weg naar Zee shoreline's foreshore, a schematisation was established to ascertain the total infill volume necessary for a convex-up profile favourable for mangrove rehabilitation conditions.

The results demonstrate the feasibility of achieving this profile by strategically inputting sediment, hence, capitalising on both transport types in the estuary. The study concludes by reiterating that the strategic placement of sediment nourishments can be a viable means of restoring the Weg naar Zee coastline. Finally, possible subsequent studies to address the existing uncertainties and streamline the implementation strategy are discussed.

Summary

Suriname is a country located on the north coast of South America. Its coastline is dynamic and experiences alternating phases of accretion and retreat. This is due to the migration of mudbanks from the Amazon River. Unfortunately, agricultural and urban activities have resulted in the removal of mangrove forests. As a result, certain coastal areas have undergone high levels of erosion. The Weg naar Zee region, one of twelve regions in the Paramaribo district, has been particularly affected due to mangrove deforestation for agricultural activities. The imbalance between erosion and sedimentation has led to a net increase in erosion, highlighting the urgent need for sustainable solutions.

A small-scale project was initiated in 2016 to artificially promote the siltation and growth of mangroves by constructing a permeable dam known as sediment trapping units (STUs). This project signifies Suriname's desire to restore the coastal mangrove forests, which help protect its largest city.

Amidst such efforts, exploring other Building with Nature-type concepts becomes essential. The erosion in the Weg naar Zee region and the dredging of the Suriname River, necessary for safe navigation and economic vitality, presents a distinct opportunity. The erosion problem can be mitigated by the beneficial use of dredged sediment, which could provide a sustainable and cost-effective solution to areas facing severe erosion problems. The dredging process yields sediment, which is currently being discarded offshore. However, this sediment can be repurposed through a method known as sediment nourishment. This innovative approach aims to mitigate the erosion issue, transforming a byproduct of a necessary process into a valuable resource for environmental restoration. This thesis focuses on the potential for benefiting from sediment reuse, particularly in the Weg naar Zee area. This approach, coupled with a deeper understanding of the Suriname coastline, sediment dynamics, mangrove species, and their growth conditions, can offer a scientifically and ecologically sustainable solution to the persistent erosion problem along the Suriname coast.

Despite the potential benefits, the feasibility of sediment nourishment is yet to be determined. The primary motivation of this thesis, therefore, centres on researching the beneficial reuse of dredged sediment from the Suriname River. This solution might not only restore the coastal conditions conducive to mangrove growth at Weg naar Zee but could also potentially render future dredging works more sustainable.

Therefore, the main research question of this thesis is: *Can dredged sediment from the Suriname River be used to rehabilitate the Mangrove forest on the Weg naar Zee coast?* Key sub-research questions aim to uncover the necessary local coastal conditions, the effect of the placement of dredged sediment within the Suriname River Estuary and the required amount of sediment needed to restore ideal conditions.

In line with the research question, the study will be conducted in several stages. The initial phase involves a comprehensive literature review to understand key topics, including mud coast dynamics, sediment dynamics, mangroves, and the Suriname coastal system. A system analysis focusing on the main processes influencing the Suriname estuary was then conducted using this information. This resulted in a conceptual model of the Suriname River Estuary dynamics, which was used to further develop an existing numerical model in Delft 3D.

Using recent survey data of the foreshore of the Weg naar Zee shoreline, a schematisation was made to determine the total volume necessary to build up the profile as required for the mangrove rehabilitation conditions. A healthy mangrove fringe of 300 m extending to MHW (mean high water), with a slope of 1:1000 of 200 m, plus a convex-up profile, were used as boundary conditions for this required profile.

The model was used to analyse the system's hydrodynamics, providing insights into critical parameters for understanding sediment dynamics in the Suriname Estuary. The model's simulations revealed the

effects of various factors on wave height, dissipation, and direction, as well as the occurring bed shear stress. It identified areas prone to sediment displacement based on flow velocity and patterns throughout the tidal cycle. This analysis resulted in several areas being deemed as potential for sediment input.

Simulations were run to test sediment input in these potential areas. This was done for two distinct transport types. The first transport type (TT1) focused on sediment transport as suspended particulate matter (SPM) directly after being brought into the system. Significant factors were, therefore, timing the input at distinct moments of the tidal cycle. Five locations were selected, and multiple simulations at different tidal cycle phases were run. The simulation results were analysed for two areas: the Weg naar Zee coastline, where the STUs are present, and the adjacent intertidal foreshore, extending to the deeper tidal flow channel.

The simulations for transport type 1 (TT1) confirmed that timing in the tidal cycle is crucial, as evidenced by the significant variation in results for a single location at different moments. The absolute quantity of sediment reaching the Weg naar Zee was lower than expected, as only 0.01% of the initially brought-in sediment reached Weg naar Zee, taken as an average over the simulations showing potential. Nevertheless, this could still be of significant influence, as a small quantity to the gross sediment balance can result in the net balance becoming positive instead of negative.

The second transport type (TT2) simulated using the model was sediment transport over the bed under the influence of wave forcing. A set volume of sediment was placed on the bed, and its dispersal was analysed. This was done for three locations showing promise due to their relative position to Weg naar Zee and locally occurring bed shear stress due to the perpendicularly approaching waves. Results were analysed by comparing the sediment quantity that migrated over the intertidal foreshore towards Weg naar Zee, to the amount of sediment still at the dumping location and the amount lost to the rest of the domain. Simulations showed that if a volume corresponding to 5 loads is subjected to an entire spring-neap tidal cycle, 24% contributes to the intertidal flat for the most promising location, which is the centrally located location #2 ("Centre").

A strategy was made to build up the foreshore using the two transport types that were researched. For the first 500m, STUs are used to trap sediments. This sediment is partly supplied by TT1 due to its capability of reaching the shoreline. The rest of the profile would be filled in by TT2, enabling the sediment to spread out over the foreshore. Projections for the total duration of infilling were made. The first section would most likely take almost ten years to be completed by transport type 1 alone. The rest of the profile would most likely take more than two years to complete. The possible overlap of the two transport types and the possible decreased duration due to the approaching mudbank complex were not considered. Also, for the first part of the profile, projections done with side-casting as an input technique showed promise with a likely duration of more than two years. However, this would affect the dredging project due to longer unloading times.

The results affirm that the strategic placement of sediment nourishments is a viable method for restoring the coastline of Weg naar Zee. However, this conclusion rests on certain assumptions, which occasion several recommendations for further research. These are aimed at reducing uncertainties around feasibility and refining the implementation strategy. Key suggestions for enhancing the current model include lengthening the simulation period, scrutinising uncertain model settings, and strengthening event-driven transport research.

Regarding system analysis, expanding field monitoring and data collection is recommended, focusing on evaluating sediment retention levels in Sediment Transport Units (STUs) and intertidal flat areas. The impact of mudbanks, especially their wave attenuation properties and sedimentation increments, presents a new area for exploration. Further refinements to the Delft3D model could involve collecting more comprehensive field data for validation and improvements to grid refinement and bathymetry. Future studies could consider the implications of different dredging vessels and sediment deposition patterns. A broader investigation of the Suriname River Estuary system should also consider social and economic aspects of mangrove restoration and analysis of sediment dispersal.

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Nomenclature

Abbreviations

Abbreviation	Definition
AdeKUS	Anton de Kom University of Suriname
BSS	Bed shear stress
CSD	Cutter suction dredger
EVA	Extreme value analysis
GMP	Good modelling practice
HCMS	High concentrated mud suspension
ICZM	Integrated coastal zone management
ITC	Intertropical convergence zone
ITF	Intertidal flat
LW	Low water line
LWS	Low water spring
MAS	Maritime Authority Suriname (Dutch: Maritieme Autoriteit Suriname)
MSL	Mean sea level
NDVI	Normalised difference vegetation index
NSP	Normaal Surinaams Peil
SPM	Suspended particulate matter
STU	Sediment trapping unit
SWAN	Simulating Waves Nearshore
TSHD	Trailing suction hopper dredger
TT1	Transport type 1 (SPM transport)
TT2	Transport type 2 (Bed Transport)
WID	Water injection dredger
WnZ	Weg naar Zee

Glossary

Term	Definition
Mudflat	The visible intertidal section of the mudbank complex, consisting of fluid mud, serves as a habitat for mangroves.
Mudbank	The submerged and separated segment of the mudbank complex, mainly not visible
Mudbank complex	The mudbank and the mudflat make up the mudbank complex together

1

Introduction

1.1. Project Area



Figure 1.1: Overview of Weg naar Zee in the greater Paramaribo area (WWF, Verutes, 2015)

Suriname is located on the northeast coast of South America, north of the Amazon River delta. Guyana, French Guiana, and Brazil are the neighbouring nations. It has about 600 000 inhabitants, nearly half of whom live in the capital, Paramaribo. The coast of Suriname is part of the same coastal system as Guyana and French Guiana. The coast is highly dynamic, mainly caused by migrating mudbanks. These mudbanks consist of sediment which originates from the Amazon River. They have an estimated average sediment yield of $1.2 \times 10^9 \text{ t yr}^{-1}$ (Anthony, Gardel, Proisy, et al. 2013).

The Suriname coast undergoes a dynamic process of alternately accreting and retreating due to the migration of these vast mudbanks along the coastline (Winterwerp, Albers, et al. 2020). With a periodicity of approximately 30 years, this migration leads to significant changes in the coastal landscape. When a mudbank protects the coast, it experiences accretion, while during the interbank phases, it retreats landward. During the presence of mudbanks, mangroves can thrive on mudflats along the coast. Mangroves, in turn, play a vital role in protecting the coast during interbank phases by attenuating wave impact and facilitating sedimentation. The majority of the coast undergoes net accretion over a long time scale. However, specific coastal stretches face problematic levels of erosion, particularly in areas where mangroves have been removed to make way for agricultural and urban activities.

A large number of mangroves populate the Suriname coastline. Suriname has an estimated 100,000 ha of mangroves. Mangroves are coastal forests in the (sub)tropics along protected bays, estuaries,

and inlets. They perform several services that benefit both the environment and society. They serve as a carbon sink, a system for purifying water, a fish habitat, and a source of timber (Barbier et al. 2011). Mangroves also serve as natural coastal protection. The mangroves attenuate waves and cause sedimentation of sediment, helping to prevent coastal erosion (Winterwerp, Albers, et al. 2020).

Although two-thirds of Suriname's mangroves and other coastal wetlands are protected or managed responsibly, and environmental laws and regulations are in place, mangrove resource management faces significant hurdles. In South America, a net loss of 2.9% of the total mangrove area was found between 1996 and 2016 (Worthington and Mark Spalding 2018). There are several reasons for the loss of mangrove forests. Mainly: pollution, deforestation and conversion to aquaculture and agriculture (Friess et al. 2019) (Erftemeijer and Teunissen 2009). In Suriname, the main reasons are cutting trees for agriculture, land use and constructing reflective seawalls too close to the waterline. Many species, including birds, fish, and crustaceans, lose their habitat due to clearing mangrove forests. Mangrove forests and their native species can be harmed by pollution from industrial and agricultural activities.

Weg naar Zee is one of twelve regions in the Paramaribo district. The land in the Weg naar Zee region is used for several reasons, including agriculture, fisheries and urbanisation (Anthony 2015). In the past, this stretch of coast was naturally protected by mangroves. These mangroves have been removed to make way for coconut palm agriculture. This has caused local coastal erosion and increased flood risk at Weg naar Zee. Small ad-hoc structures have been placed to mitigate this risk (Erftemeijer and Teunissen 2009). Because of the importance of mangroves to Weg naar Zee, promising regeneration initiatives are underway in the region. This task entails assessing the current state of the mangroves, historical changes, and external pressures. (Armando Guzman et al. 2017).

The rehabilitation of mangrove forests has been the subject of research for decades due to the benefits mangroves provide and the high rate of decline they experience globally. Rehabilitation is defined as the action of restoring something that has been damaged to its former condition. Several techniques have been developed to rehabilitate mangrove coasts worldwide. Restoring the local sediment balance along eroding coastlines is the basic tenet of restoring mangrove habitat. The rehabilitation projects worldwide had varying degrees of success (Winterwerp, Albers, et al. 2020).

The Suriname River is an important transport route for Suriname. Refer to Figure 1.1 for an overview of Paramaribo's location relative to the Suriname River and Estuary. It connects the ports of Paramaribo and Paranam to the Atlantic Ocean. The Paramaribo port is mainly used for the import/export of general cargo and containers. The Paranam port exports Alumina/Aluminium Oxide (Loose 2008). However, siltation poses a challenge by limiting the draught, preventing fully loaded ships from entering or making them tide-dependent.

Due to its significant economic importance, particularly for the expected future growth of the oil and gas industry, the fairway must be dredged to ensure safe ship navigation (Baggerbedrijf de Boer 2023). Suriname has, therefore, initiated a dredging project for the Suriname River fairway. The capital dredging project started in 2021, undertaken by the Joint Venture Baggerbedrijf De Boer B.V. – Boskalis B.V., and was completed in September 2023. Following this project, the maintenance dredging phase lasts two years. Baggerbedrijf De Boer will execute this. Although the dredged material is currently disposed of in offshore areas, there is a potential for beneficial sediment reuse. Notably, the sediment dredged during the maintenance phase has settled for only a year, indicating its likely uncontaminated nature and suitability for reuse. The reuse of dredged sediment is a generally known technique, and several case studies have been executed (Central Dredging Association – CEDA 2019). An interesting case study is the "Mud Motor" project, which was executed at the Port of Harlingen-Koehoal. In this project, sediment was deposited at a specific location and then transported to a target location, a nearby marsh, using natural hydrodynamics. This method has not been used in the Suriname Estuary before.

1.2. Problem analysis

Due to research conducted in the past, the erosion and sedimentation levels along the Suriname coast have been quantified. Using satellite images between 2000 and 2018, an assessment was made by de Jong et al. (2021). An algorithm used these satellite images to assess the locations of mangrove erosion, colonisation, surface areas of change and settlement patterns. The results confirm the overall westward migration of the mangroves, which is linked to the mudbank migration as expected. It also showed sizeable local variability. Some locations show coastal erosion up to 50 m yr^{-1} . Weg naar Zee is one of the locations which is a hotspot of coastal erosion and mangrove loss.

Another study, by de Vries et al. (2022) uses remote sensing and data analysis techniques to quantify the influence of mudbank dynamics on coastal variability along the Suriname coast. It shows there are 6 to 8 mudbanks, generally accounting for 32 m yr^{-1} accretion during their presence. An erosion rate of 4 m yr^{-1} is found during the absence of mudbanks. Weg naar Zee is one of the locations where these rates do not apply locally, and erosion is more significant than accretion.

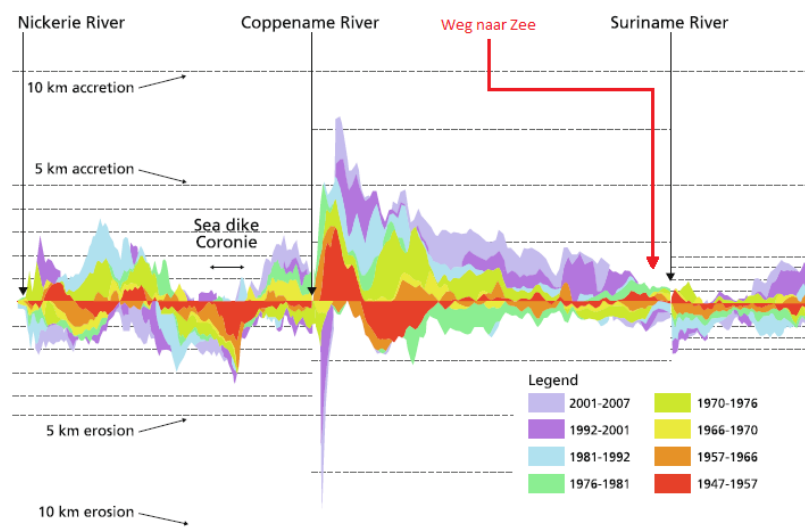


Figure 1.2: Coastal erosion and accretion between 1947 and 2007 along the entire Suriname coast as surveyed by Augustinus (Wong et al., 2017). Focusing on the Weg naar Zee location, it can be seen that the last period of accretion was up to 1981. Hereafter, only periods of erosion were surveyed.

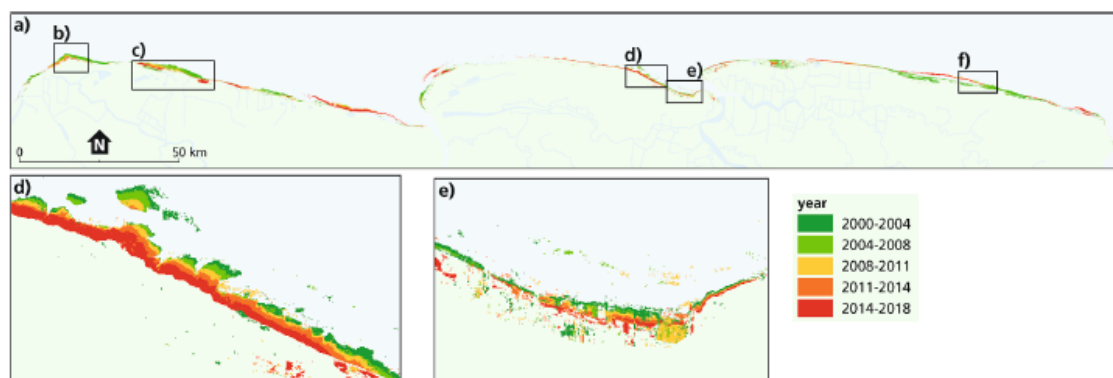


Figure 1.3: Decreases in Normalised Difference Vegetation Index (NDVI) values indicate a loss of mangrove coverage. This image shows that certain stretches of coastline have experienced a decline in mangrove growth since at least the year 2000. An overview map highlights selected locations: (d) Weg-naar-Zee west and (e) Weg naar Zee, which is the primary focus of this research. (Jong et al. 2021)

Human activities at Weg naar Zee have had a local negative impact. Mangroves have been removed for fishing and agricultural purposes. Also, the coastal squeeze has increased due to agricultural activities close to the coastline. Locally, the floodplain has decreased drastically. These influences have caused erosion to increase locally. The balance of erosion and sedimentation caused by the mudbank cycle has been affected. Weg naar Zee is experiencing net erosion instead of net sedimentation over more extended periods. As Winterwerp et al. (2013) suggested that hard sea dykes exacerbate the issue, a need for sustainable alternatives has grown.

The flowchart in Figure 1.4 explains the leading causes of net erosion at Weg naar Zee. Firstly, the survival of the coastal environment, including the mangroves, depends on the coastal buffer zone. The coastal buffer zone is the region between populated land and the sea. This region is inundated periodically due to the tidal flows and serves as a habitat for breeding. A reduction in the coastal buffer zone may be brought on by urbanisation along the shore. As a result, the sea has less space. This drop results in a decreased tidal range, a disruption of the sediment balance, and a reduction in onshore sediment supply.

A more reflecting shoreline also contributes to increasing the wave forcing. Hence, extensive land close to the coast (coastal squeeze) can result in increased wave force and decreased onshore sediment flow, which are significant drivers of erosion. The foreshore profile becomes concave-up. In Figure 1.5, the concave-up shape is represented by the bathymetry as it was in 2013. Further intensified wave activity and reduced onshore sediment transport due to this change can increase erosion. This causes a snowball effect and results in an imbalance in the cycle of erosion and sedimentation of the shoreline (Winterwerp, Erftemeijer, et al. 2013).

In conclusion, on the Surinamese coast, increased wave action is caused by excessive land usage, the destruction of mangroves, climate change, and the sporadic interbank phases of the mudbank system. The destruction of mangroves further exacerbates this coastal erosion snowball effect. Current conditions are thus causing a further increase in erosion and do not facilitate the rise of mangrove numbers. The main conditions causing the problem are:

- The coastline has a steep and concave upward slope profile, which enhances wave forcing.
- The coastline is retreating, resulting in a smaller buffer zone and, consequently, a smaller intertidal zone suitable for mangroves.
- The loss of mangrove forests causes a decrease in sediment retention or sedimentation, thus increasing net erosion.

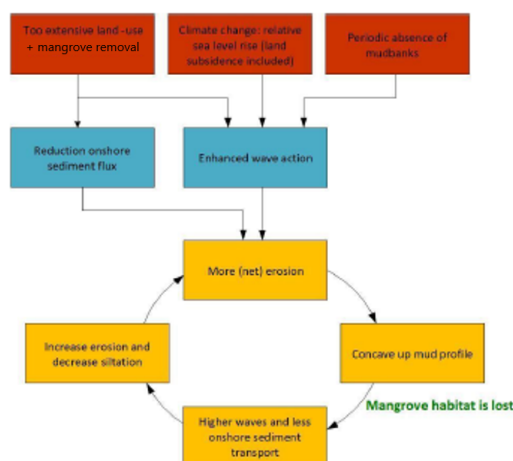


Figure 1.4: Erosion problem explained in flow chart for Weg naar Zee (adaptation of figure from Winterwerp, Erftemeijer, et al. 2013 by Çete et al. 2018)

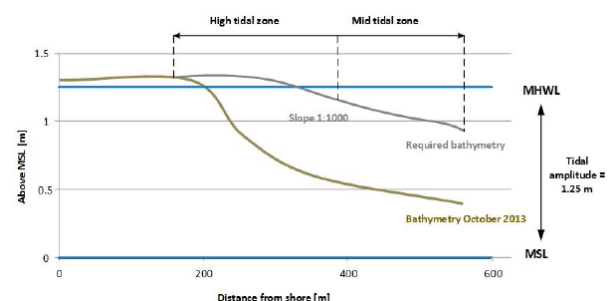


Figure 1.5: Slope profile difference between the required slope and the slope according to the 2013 bathymetry, according to Prof. Naipal

Sediment Trapping Units - In 2016, Professor Naipal of the Anton de Kom University (AdeKUS) initiated a small-scale project in Weg naar Zee. The project aimed to artificially enhance the siltation of sediment and the growth of mangroves by constructing permeable dams. A dam, 200 m in length, 2 m in height, and 0.5 m in depth, was built using wallaba poles and bamboo padding. The dam allows water to flow through it, but it reduces the flow velocity sufficiently to encourage siltation and prevent the silt from being swept back to the sea. This environment enables mangroves to root in the silt, reinforcing the dam's protective effect. This concept has been previously implemented in Java, Indonesia, and is similar to the salt marsh works in the Netherlands (Winterwerp, Albers, et al. 2020). Naipal's project served as the foundation for the "Mangrove Rehabilitation Project Weg naar Zee," officially inaugurated by President Santokhi in July 2022. The project, a collaboration between AdeKUS and the Ministry of the Public Domain, will run from 2022 to 2025. In addition to the rehabilitation efforts, a small-scale replanting initiative was carried out in 2018, although this initiative was not systematically monitored.



Figure 1.6: Picture showing the rows of permeable dams that make up the STUs constructed at Weg naar Zee

Rehabilitating Mangroves Weg naar Zee - The construction of the STUs at Weg naar Zee is the first attempt at rehabilitating mangroves in the area since 2015. The results of the first STUs showed enough promise to announce the desire to expand to 12 extra STUs. Due to the progress of this project and the growing desire of Suriname to rehabilitate its coastal mangrove forests, other options have been considered. These Building with Nature-type concepts have the same goal as the currently implemented STUs: restoring the necessary conditions for the growth of mangroves.

One of the suggested approaches, described in a report by Erftemeijer and Teunissen in light of the ICZM (Integrated Coastal Zone Management) of Suriname, is agitation dredging (also called a 'mud nourishment') (Erftemeijer and Teunissen 2009). They state that in regions where mangroves have been destroyed, the flow of fine sediment towards the coast should be increased artificially by raising the sediment concentration of the coastward transport (Erftemeijer and Teunissen 2009, Winterwerp and Augustinus 2009). The increase of the sediment influx towards the coast is done by, for example, agitation dredging (Winterwerp and Augustinus 2009). Erftemeijer and Teunissen state: "Such an intervention could prove to provide a long-lasting, cost-effective and sustainable solution (especially if accompanied by mangrove restoration) at areas facing serious erosion problems and may be substantially cheaper than the construction of coastal defence structures (such as the coastal dyke currently under construction at Coronie)."

The material necessary for the mud nourishment could originate from the dredging works in the Suriname River. In 2023-2025, maintenance dredging works will be executed by Baggerbedrijf De Boer. It is expected that in the following years, new dredging works will be necessary. Currently, the sediment is disposed of at allocated offshore areas. The beneficial reuse of sediment through sediment input can play a part in applying the Building with Nature principle to rehabilitate the Weg naar Zee mangrove belt. To enhance the circularity of the dredging works, it is possible to positively influence the Weg naar Zee coastal region by retaining the sediment within the system.

Mud nourishment is not straightforward engineering work. A thorough understanding of the coastal system is needed to execute such a project. The morphological, hydrodynamic and ecological elements of the system must be considered. A general knowledge of the coastal processes and sediment dynamics is necessary. Furthermore, to eventually rehabilitate the mangroves, the native local mangrove species and the conditions required for their growth and resilience must be known.

It is vital to evaluate the natural system and the executability of mud nourishment. A disposal strategy must be formed: will the nourishment be at once or several over a more extended period? The availability and properties of the sediment must be considered. What dredging equipment can be used, considering the vessel's draught and the project area's bathymetry? How will the sediment be nourished?

1.3. Opportunity

Weg naar Zee has experienced significant erosion, likely due to the destruction of mangroves to make way for agricultural and urban activity. Additionally, dredging of the Suriname River is necessary for safe ship navigation, which is economically significant. Dredging is expected to continue for many years, with dredged sediment now disposed of in offshore disposal areas. Building with nature concepts has been considered in light of the need to restore Suriname's coastal mangrove forests.

Erosion is caused by a disruption in sediment balance, emphasising the importance of sediment influx to the coast in restoring balance. Reusing dredged sediment through mud nourishment to augment the sediment flux at Weg naar Zee presents a promising solution to the erosion problem. This method can potentially restore the necessary coastal conditions for mangrove regeneration, reducing the impact of erosion. Despite the potential benefits of mud nourishment, the feasibility of this method is unknown. As a result, additional research is required to assess this intervention's feasibility to manage coastal erosion fully.

Therefore, the motivation for this thesis is to research the feasibility and potential implementation of the beneficial use of dredged sediment from the Suriname River. This could be part of the solution to restoring the coastal conditions of Weg naar Zee. This would restore the mangrove habitat locally. This could make the dredging works more sustainable by positively influencing the coast and the region. This solution could be pivotal in shaping a rehabilitation method for Suriname's mangrove forests and help safeguard the coastline for future generations.

1.4. Research questions

To explore the potential of this opportunity, the primary research question for this thesis has been formulated as follows:

"What is the feasibility of the beneficial reuse of dredged sediment through sediment nourishment to rehabilitate the growth of Mangrove forest on the Weg naar Zee, Suriname coast?"

To answer this research question, the following sub-research questions have been formulated:

1. What are the necessary abiotic conditions, considering the local coastal conditions and driving processes of the coastal system, for successful mangrove forest rehabilitation on the Weg naar Zee, Suriname coast?
2. Can sediment input be effectively utilised in the Suriname River Estuary to positively impact the conditions required for successful mangrove forest rehabilitation on the coast of Weg naar Zee?
3. What is the necessary amount of sediment required for these given conditions, and to what extent can strategic input through the beneficial reuse of sediment contribute to the reestablishment of these conditions

1.5. Research Approach

The objectives of the sub-research questions are:

1. To identify the necessary abiotic conditions required for successful mangrove forest rehabilitation on the coast of Weg naar Zee, Suriname, by conducting a literature review on the subjects of mud coast dynamics, sediment dynamics, mangroves, and the Suriname coastal system and analysing the influence of the coastal system, specifically mudbanks, on the necessary bed elevation, bed slope, and hydrodynamic conditions. Also, to identify the driving processes of the coastal system of Weg naar Zee and their impact on the necessary coastal conditions for mangrove forest rehabilitation by performing a system analysis focused on the hydrodynamic and sedimentological aspects of the Suriname estuary.
2. To analyse the efficiency levels of sediment input in the Suriname Estuary, considering the hydrodynamic and sediment dynamic processes and the greater coastal dynamics, such as the mudbank migration.
3. To analyse the necessary sediment volume to achieve the mangrove rehabilitation conditions. Then, to develop a concept nourishment strategy considering the results of previous sub-questions to provide this necessary sediment volume.

A research method consisting of several steps was executed to achieve the objectives and answer the research questions.

Firstly, literature research was conducted to gain a general understanding of the main subjects, including mud coast dynamics, sediment dynamics, mangroves, and the Suriname coastal system. This information was necessary to determine the conditions of the coastline for rehabilitating mangroves at Weg naar Zee. This mainly concerned the bed elevation, bed slope and hydrodynamic conditions required to restore the balance of sedimentation and erosion. The functioning of the Suriname coastal system and the influence of this system on these necessary conditions of the Weg naar Zee coast were analysed, mainly concerning the dynamics of mudbanks and their impact on the coastline. The research focused on the abiotic aspects necessary for rehabilitating mangroves, as the hypothesis was that these were limiting the mangrove growth at Weg naar Zee.

Next, a system analysis focused on the main processes influencing the Suriname estuary. The hydrodynamic and sedimentological aspects influencing the Weg naar Zee coastal morphology were analysed. Tidal ranges, the direction and amplitude of tidal and residual currents, the period and height of waves, and their recurrence were all collected, coastal geometry and bathymetry, and the origins and attributes of fine sediment.

A conceptual model was developed, incorporating both textual descriptions and visual representations for enhanced clarity. This model focused on discussing the main processes and their influence on the feasibility of mud nourishment. Furthermore, addressing how these processes could be accurately translated and incorporated into the model is crucial. This approach ensured a better understanding and evaluation of the feasibility of sediment input as a restoration method.

A Delft3D model was developed using the gathered information to test various nourishment locations. Several promising nourishment locations were selected based on the hydrodynamic processes. For these locations, concept nourishment configurations were chosen. The constructed model was adjusted and utilised to simulate the spreading patterns of nourishment at these locations. In this way, the working of mud nourishment at different locations in the coastal system, influenced by the driving hydrodynamic and sedimentological processes, was researched. The influence of these nourishments on the coastline of Weg naar Zee was researched. This was done by assessing the ability of the sediment to reach the Weg naar Zee coast.

A feasibility analysis was done based on survey data and the model results. A schematic analysis of the total sediment quantity required for a healthier foreshore profile was conducted. The sediment input strategy was tested against this quantity, and the entire project duration was estimated accordingly.

1.6. Report Structure

A brief description of the chapters in this thesis is given below:

- CH2 - Theoretical Background:** This chapter provides an overview of the main subjects through literature research, which includes mud coast dynamics, sediment dynamics, mangroves, and the Suriname coastal system. It evaluates the conditions required for mangrove rehabilitation at Weg naar Zee.
- CH3 - Suriname River Estuary System Analysis:** In this chapter, a system analysis is conducted to understand the main influences on the Suriname estuary. Emphasis is put on the hydrodynamic and sedimentological aspects affecting the Weg naar Zee coastal morphology.
- CH4 - Suriname River Estuary Model Set-up:** Here, a Delft3D model based on the gathered information is developed. The model tests various nourishment locations and their impact on the Weg naar Zee coastline.
- CH5 - Hydrodynamic Model Results:** This chapter presents the results from the Delft3D model simulation, highlighting the impact of hydrodynamic processes on the spreading patterns of nourishment.
- CH6 - Sediment Model Results:** This section focuses on the sedimentological outcomes of the Delft3D model simulations. It investigates the ability of the sediment to reach the Weg naar Zee coast, which affects the overall efficacy of the restoration method.
- CH7 - Feasibility Analysis:** A feasibility analysis based on model results, focusing on the required total sediment quantity and project duration, thus assessing the feasibility of the sediment input strategy.
- CH8 - Discussion:** The findings and outcomes from the previous chapters are discussed in this chapter. Potential implications of the research findings are explored.
- CH9 - Conclusion & Recommendations:** The final chapter concludes the thesis, summarising the findings and providing recommendations for future studies on mangrove rehabilitation.

2

Theoretical background

This chapter delves into the theoretical background of the Suriname coastal system, focusing on the Guiana Coastal System, the services provided by mangrove forests, and the rehabilitation of these ecosystems. It provides a comprehensive overview of the dynamics of mud coasts, sediment, and mangroves, and how these elements interact within the Suriname coastal system. The chapter also discusses the impact of human activities on these ecosystems and the efforts to restore and preserve them. The information presented in this chapter forms the foundation for understanding the subsequent analysis and discussions in this thesis.

This chapter presents theoretical insights regarding:

- 2.1 - The Guiana's coastal system
- 2.2 - Mangrove forest services
- 2.3 - Rehabilitation of mangroves

2.1. The Guiana Coastal System

The Suriname coastline is part of the larger 1600 km long Guiana Coast (see Figure 2.1). The Guiana coastal system consists of the coastline starting east at the mouth of the Amazon River in Brazil and stretching west up to the Orinoco River delta in Venezuela. The coastlines of Guyana and French Guiana, the neighbouring countries of Suriname, are also part of this system. This system is primarily supplied by Amazon River sediment, with 52% of the sediment moved westward (alongshore) by a combination of currents and waves. Four major depositional eras, interspersed with periods of erosion, have formed the coastal terrain over time. Most of the sediment is deposited in intertidal and subtidal settings, and rarely in supratidal settings, at or near mean sea level during the present Comowine phase. This deposition allows for the growth of intertidal vegetation. The Amazon River sediment is transported westward alongshore in the form of vast, wave-like mudbanks and in suspension, with the total sediment transport estimated to be between 150 Mt yr^{-1} to 200 Mt yr^{-1} . It is estimated that 50 Mt yr^{-1} to 100 Mt yr^{-1} per year is moved within a migrating mudbank, with the remaining capable of travelling distances beyond a single mudbank. The wavelength of the mudbanks along the Guiana Coast ranges from 25 km to 50 km, with an average of roughly 40 km (Allison, Nittrouer, and Kineke 1995, Eisma and van der Marel H.W. 1971). A smaller bank with a similar structure can occasionally be seen between two larger ones. Because of the cyclic nature of sediment deposition, the coastline and associated subtidal areas change rapidly, with cycles lasting around 30 years. During the inter-bank phase, erosion occurs, whereas accretion happens during the passage of a mudbank, which travels along the coast at a rate of 1 km yr^{-1} to 3 km yr^{-1} . Erosion characterises the inter-bank phase, which occurs between the mudbanks.

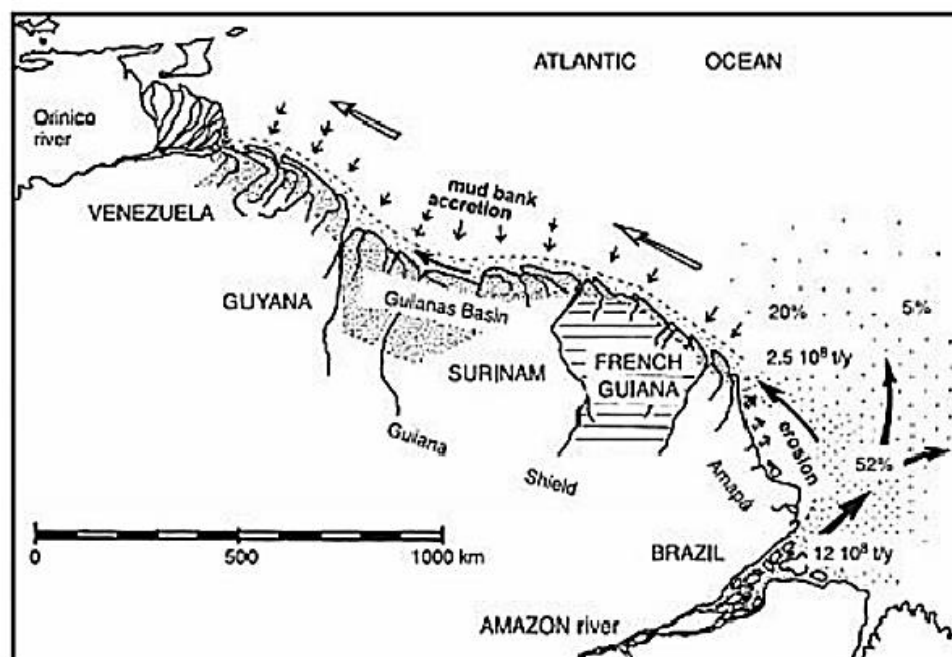


Figure 2.1: Map of the Guiana Coastal System (Froidefond et al., 1988). The Orinoco River is found in the North-West (NW) corner, while the Amazon River is found in the South-East (SE) corner. The area between the Orinoco and the Amazon Rivers is called the Guiana Coastal System. The arrows in the SE show the total river outflow from Amazon of $12 \times 10^8 \text{ ty}^{-1}$. The arrows along the Guiana coast represent the Guiana current, which carries about 20 % of the Amazon River outflow sediment in the form of mudbanks.

Sediment - The Amazon River is the source of the majority of the fine cohesive silt (mud) of the Guianas coastal system. Plaziat and Augustinus 2004 assert that the Guyana coastal system is part of the larger Amazon delta with extensive old and recent fine sediment deposits. Martinez et al. 2009 estimate that the mean annual fine sediment supply by the Amazon River is approximately $8 \times 10^8 \text{ ty}^{-1}$, with 20 % deflected to the North and entering the Guianas coastal system. About 40 % of this load is stored in migrating mudbanks (Eisma and van der Marel H.W. 1971, Eisma, Augustinus, and Alexander 1991), implying the transport of about 100 Mt in suspension along the coast. These estimates, although not recent and subject to change, suggest that substantial amounts of fines are transported along the coast in suspension.

Suspended Sediment Load - Due to the temporary storage of fines in mudbanks and coastal accretion, followed by their release during migration and erosion, the coastal system of the Guianas exhibits high turbidity. Large spatial and temporal variations in the concentrations of suspended fine sediment are the result. A background concentration of 50 mg L^{-1} to 100 mg L^{-1} is assumed, and previous literature reports suspended fine sediment concentrations up to 500 mg L^{-1} . Although the precise value of this background concentration is unknown, it is not critical.

Phenomenological Description of Mudbanks - The Guiana Coastline is distinguished by a wide variety of mudbanks, with 15 to 25 larger and smaller ones present at any given time, according to Anthony, Gardel, Gratiot, et al. 2010. The Delft Hydraulics Laboratory first looked at these mudbanks in 1962, and later studies were done by NEDECO 1968, Augustinus 1978, Allison and Lee 2004, and Anthony, Gardel, Gratiot, et al. 2010. In Suriname at the end of the 20th century, these mudbanks' longshore dimensions typically ranged from tens of kilometres to up to 60 km, with a decrease since then (Augustinus 2004c). These banks typically measure 10 km to 20 km in width and 5 m to 10 m in thickness, and they range in a vertical position from the 10 m to 12 m isobath (Anthony, Gardel, Gratiot, et al. 2010) to the 20 m isobath in Suriname and Guyana (Augustinus 1978 and NEDECO 1968). The mudbanks' varied orientation with respect to the shoreline and, as a result, their apparent length are caused by their general orientation towards the Trade Winds, which are more or less NE.

Because the mudbank is detached from the shore and sediment is transported onto the upper intertidal zone by flowing mud, the shoreline accretes during times of coastal setup and flood tide. When the tide is going out or during large flows, some of this sediment might be carried back offshore. The diagram's arrows show the proportion of sediment that was supplied to the deposition at the inner mudbank's leading edge. The trailing edge mangrove fringe is where the majority of sediment is eroded, with additional material coming from updrift mudbanks, the Amazon River, and erosion of the trailing edge mudflat and interbank intertidal-subtidal surface. This image suggests that mud banks not be attached to the mudbanks and the shore, and soft, fluid mud pools may develop in this area.

The difference between mudbanks and mudflats must be made. The mudflats are the visible intertidal portion of the mudbank complex. They consist of fluid mud and provide habitat for mangroves. Conversely, mudbanks are mostly invisible, disconnected, and submerged parts of the mudbank complex. The interbank region is the space between two mudbanks. The shoreline can accrete behind a mudbank due to the mild hydrodynamic conditions there, whereas the interbank area's coastline is directly exposed to ocean waves and erodes as a result.

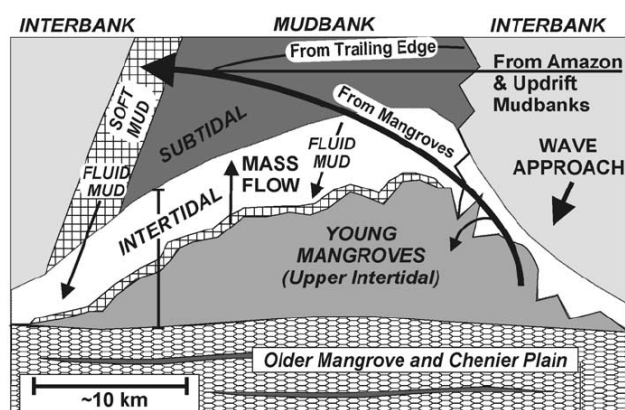


Figure 2.2: A diagram showing the inner mudbank-shoreline as explained in Allison and Lee 2004. The shoreline and the mudbank are separated here. During times of coastal setup and flood tide, fluid muds are driven onshore, causing sediment to reach the upper intertidal and produce shoreline accretion. During the ebb tide, some of this sediment may return offshore due to mass flows or fluid mud transport. The proportional size of the sediment supply to the leading edge deposition on the inner mudbank is indicated by arrows. The majority of the material comes from the erosion of the trailing edge mangrove fringe, with extra material also coming from up drift mudbanks, the Amazon River, and erosion of the interbank intertidal-subtidal surface.

Fluid Mud - Mud concentrations in coastal waters range between 100 mg L^{-1} and 10 g L^{-1} , with the mud particles suspended in a flocculated condition. The flocs start to agglomerate and form a gel once the concentration reaches a particular threshold value, which causes the gel to settle as a whole and release water through voids. This gel, also referred to as fluid mud, can reduce the motion of waves. As sedimentation occurs quickly, fluid mud may occasionally form along the northwest sides of mud banks. Fluid mud typically has a density of 1100 kg m^{-3} to 1250 kg m^{-3} . These findings have been documented by various sources, including Delft Hydraulics (1962), Diephuis 1966, and NEDECO 1968.

Mudbank Migration - Large wave-like migrating mudbanks characterize the westward alongshore movement originating from the Amazon. The processes that create the mudbanks and preserve their structure as they erode and migrate are not mechanistically explained. Overall, migration rates have remained pretty consistent. Even though the mechanisms underlying this are not well understood, it has been observed that migration speeds are getting increasingly variable.

With a periodicity of roughly 30 years and a yearly migration distance spanning from 1 to 3 km, Brunier et al. (2019) detects a consistent migration trend for Suriname mudbanks. Migration and stormy weather are strongly correlated, according to Augustinus 1978, underscoring the phenomenon's event-driven character. In support of these findings, Augustinus 2004c notes that during easterly winds, notably in the E-NE direction, Suriname mudbank movement velocities increase, causing banks to grow. According to a 2005 study by Gardel and Gratiot along the coast of French Guiana, migration velocities increased from 0.2 to 1.8 km/yr in the 1980s to 1.8 to 3.0 km/yr between 1990 and 2005, with the

strength and direction of the wind being a key factor. These studies show that migratory velocities are positively associated with wind speed and direction, even though easterly winds often lead to milder wave climates.

Mudbank movement is predominantly driven by waves that originate in the NEN-ENE region due to Trade Winds. The waves are refracted towards the crest of the mudbanks as they approach, resulting in their unique direction. Energetic waves can induce erosion on the windward and perhaps leeward sides of the banks. The windward-side eroded sediment is carried in suspension by zigzag currents, which accelerate towards the mudbank's crest and combine with the background suspended fine sediment. The suspended silt is moved towards the coast by flow-induced advection as the tide rises. Fine sediment from the leeward side may also contribute to the suspension beyond the mudbank crest.

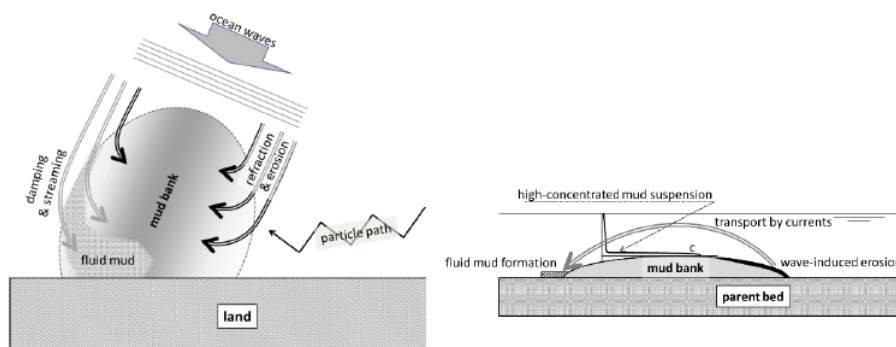


Figure 2.3: The driving forces behind mudbank migration are depicted in a schematic, including flows and waves surrounding the mudbank, as well as fine sediment transport (Smits, Winterwerp, and Best U 2022)

The flow slows down over the peak of the mudbank, causing the suspension to stratify into a High-Concentrated Mud Suspension (HCMS). According to Winterwerp (2001) and Winterwerp, Kessel, et al. (2021), this type of suspension is characterised by a decrease in the vertical turbulent mixing of suspended material. HCMS can be transported by turbulent flow, but if the concentrations of suspended fine sediment rise over a certain point, the flow cannot support the suspension, which results in the creation of fluid mud layers. Wells and Kemp (1986) and Winterwerp, Graaff, et al. (2007) have noted that these fluid mud layers have the capacity to dampen incoming waves by viscous dissipation within the viscous fluid mud.

The mud is subjected to radiation stress by the waves, producing a force that is directed in the direction of the waves and is known as "streaming." The horizontal recirculation cells (2.3) created by streaming can move large amounts of particles towards the coast. This results in the soft, fluid mud layers that are frequently seen behind mudbanks. These recirculation cells can be compared to rip currents occurring along sandy beaches. (Winterwerp, Kessel, et al. 2021).

Fluid mud is also pushed towards the coast under the influence of streaming-induced stresses. These stresses are lower than the stresses in the water column. However, due to the high sediment concentration in the fluid mud layer, the transport quantity remains significant. The fluid mud layers experience shear stress throughout their depth due to bottom friction, leading to densification. This densification can even result in over-consolidation. Consequently, the mud can become stagnant. Stagnation also occurs when the radiation stresses are not sufficiently high.

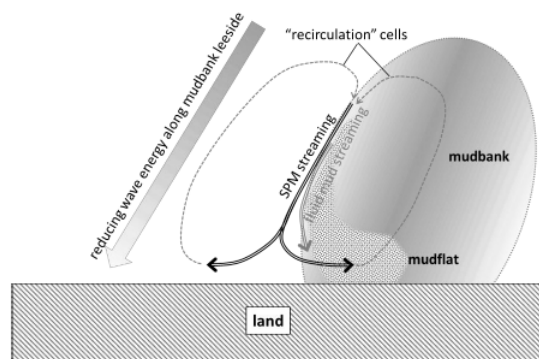


Figure 2.4: The schematic illustrates recirculation cells generated by wave-induced streaming, causing damping and resulting in onshore flux of suspended fine sediment (SPM). (Smits, Winterwerp, and Best U 2022)

Without fluid mud, waves will still dampen, albeit less, and streaming-induced onshore sediment transfer will be constrained. In these circumstances, advective transport, aided by the rising tide, is probably the main sediment transport mechanism. As a result, mudflats still gradually develop during moderate wave conditions, though at a slower rate than it does during more intense storm occurrences.

Hence, the creation of intertidal mudflats as a result of mudbank migration is referred to as an event-driven phenomenon. Significant amounts of mud can be dumped on the shore in a single occurrence, which causes mangroves to quickly colonise mudflats. To establish the best habitat conditions, however, the colonisation process may take several years in some places. The interbank coastline will likely be eroded by waves of all sizes since the fine sediments are soft.

Cheniers - Cheniers are sandy lenses found atop a muddy substrate in the Guianas' coastal system. While local rivers are the main supply of sand, some fine sand can also be produced by sorting of the Amazonian sediment. Sand is concentrated by waves between banks where there is less dissipation, creating cheniers (Augustinus 1978). Only during high tide, when wave-energy dissipation is minimised, are these processes conceivable. Sand overwashing muddy, degraded, and frequently organic-rich substrates is the main force behind Chenier growth. Cheniers emerge along the coast and travel westward by the mechanism of traditional littoral transport during calm times, propelled by residual wave forces. In the interbank areas, these cheniers act as natural sea walls, reducing coastline erosion and absorbing incoming wave energy. Yet, during episodic episodes, a chenier may have a portion covered with sediment deposits, preventing the down drift chenier from accessing sand and potentially leading to a breach due to thinning. It is significant to notice that breaching and inundations take place in front of, not behind, the migrating mudbank.

Conclusion - Due to optimal oceanographic parameters and a large supply of mud from the Amazon source, the 1500 km of coastline in the Guianas is a prime area for the development of mudbanks along the shoreface and coastal plain between the Amazon and the Orinoco Rivers. The Amazon River's discharge of suspended sediment is stored on the seafloor by the interactions of fresh- and saltwater along the shoreface, resulting in fluid-mud concentrations that eventually give rise to mud banks. In Brazil, the pressure gradient caused by interacting onshore trade winds and wave and tidal pressures can contribute to the creation of mud banks. Then, when these mud banks move along the Guianas' shores, muddy sediments and chenier sands are moved and redistributed over an extended period of years as a result of alternating phases of banks and inter-banks. Especially during strong wave-energy seasons like El Niño years, the coastal stratigraphic package is partially or rarely entirely removed during inter-bank phases, leading to net coastal-plain development with each cycle. Individual cheniers or bands of cheniers are integrated into the prograded coastal plain in sand-rich environments.

2.2. Mangrove forest services

According to Blasco, Saenger, and Janodet 1996, the term "mangrove" refers to a diverse assemblage of trees and shrubs that form the dominant plant communities in intertidal areas and saline wetlands along sheltered (sub)tropical coasts. This ecological classification includes numerous plant genera and families that have a variety of morphological, physiological, and reproductive adaptations that allow them to thrive in the dynamic and salty environment of the intertidal zone. Among these adaptations, the development of a specialised root system is critical for maintaining stability in the anaerobic mud subsoil and facilitating oxygen uptake from the atmosphere (Lewis III 2005).

Mangroves are a valuable resource for the region's ecological system and coastal dynamics because they grow where the sea and the land converge. Four major groups can be used to categorise these services, three of which are connected to coastal dynamics. The first category is force reduction, followed by shoreline stabilisation and wind reduction. Ecological services make up the fourth category of mangrove services.

Hydraulic force reduction - Although the extent of this reduction depends on the width and density of the forest, mangroves have the power to lower wave height and flow velocities. The trunk, roots, and branches of the mangroves work together to reduce the incoming forces. The transmission of the trunk operates throughout the entire water column and is independent of water depth. Longer waves, like those from cyclones, tsunamis, and swells, can pierce the mangrove forest more than shorter waves. Wave transmission is affected differently by the root system, with transmission increasing with water depth. Since the reducing effect of the roots diminishes with increasing water depth, damping is most effective in shallow water depths. According to Schiereck & Booij (1995), the roots are more effective in transmitting waves than the trunk. Within the first 100 metres of the mangrove forest, there may be a noticeable reduction in wave height, and within 500 metres of the forest, it may reach up to 50-99% (McIvor et al. 2012). Mangroves, however, can usually not serve as a standalone breakwater or a complete measure of protection for the hinterland. Additionally, they are not strong enough to withstand waves higher than a certain height, such as those produced by cyclones or tsunamis, which can cause the mangroves to collapse and even destroy the forest (Dahdouh-Guebas et al. 2005). Kilometres of mangroves may be required to significantly reduce the effects of flooding brought on by storm surges, cyclones, typhoons, or hurricanes (Tonneijck et al. 2015).

Shoreline stabilisation - Tidal currents carry flocs of cohesive sediment into the mangrove forest. The turbulence created by the flow around the mangrove roots helps to suspend them. The sediment settles during high water slack (HWS) because the lower ebb currents are too weak to re-entrain it (Furukawa and Wolanski 1996). This procedure improves the settling conditions in the nearby mangrove area and increases the flux of onshore sediment. The availability of sediment and the local environment have a major impact on the sedimentation rate. Sedimentation rates typically range from 1 to 10 millimetres per year (Tonneijck et al. 2015). Additionally, less sediment is eroded when waves are attenuated. Roots increase the soil's shear strength, which in turn prevents the soil layer from being washed away (Scoffin 1970). The study by McIvor et al. (2012) found that due to processes like sediment supply and sub-surface root growth rate, some mangrove forests were able to withstand sea level rise over thousands of years. However, the equilibrium of a net accreting coast changes to a net eroding coast when the sediment supply becomes insufficient and the net sediment balance turns negative (sedimentation - erosion < 0). The mangroves' stability is compromised and they may collapse as a result of the convex to concave change in the shape of the coastal foreshore. Additionally, the mangroves' destabilisation is initiated due to the increased load placed on them as a result of the foreshore waves' height remaining unchanged. (Winterwerp, Erftemeijer, et al. 2013).

Wind reduction - Mangrove forests nearby could provide wind protection for villages. According to research, mangrove belts along the coast can slow wind speeds within a circle that is 20 to 30 times the height of the trees. Given that mangroves are only 10 metres or so tall, their influence on wind velocity is most likely limited to a region that is 0.25 kilometres in size. However, tall trees may be vulnerable to bending, breaking, or uprooting during extreme weather conditions like cyclones, which reduces their ability to function as reliable windbreakers (Marchand 2008).

Ecological services - Mangroves provide a wide range of ecosystem services to local communities, including food production, timber production, and tourism. Additionally, because of their high carbon content, these forests act as a significant carbon sink, controlling the levels of carbon dioxide in the atmosphere (Donato et al. 2011). Additionally, they improve soil fertility by causing sedimentation through the production of organic matter while filtering pollutants and nutrients from the water (Thongjoo, Choosak, and Chaichana 2018). Additionally, mangroves serve as a natural defence against saltwater intrusion, which can harm freshwater resources. Finally, they serve as crucial breeding, feeding, and nursery grounds for various forms of marine and coastal biodiversity.

2.3. Rehabilitation of Mangroves

According to Winterwerp, Albers, et al. 2020, a number of factors, including their conversion to fishponds, logging for timber, infrastructure development, urbanisation, and groundwater extraction that causes land subsidence, are to blame for the loss of mangrove forests worldwide. Although there have been numerous attempts to restore these forests, planting campaigns have had disappointingly little success Primavera and Esteban 2008. Bijsterveldt et al. 2022 recommend opposed to actively planting propagules or seedlings to restore the mangrove habitats to promote natural recruitment. Lewis III 2005 and Winterwerp, Erftemeijer, et al. 2013 contend that experts have overlooked the state of the mangrove habitat because a natural revival that fails to take place indicates a problem with the habitat's essential elements, which must be corrected first. In line with earlier restoration efforts, they suggest a set of five guiding principles that take into account the natural ecology and dynamics of mangrove systems.

1. "Understand the ecology of the mangrove species at the site, in particular the patterns of reproduction, propagule distribution, and successful seedling establishment."
2. "Understand the hydrological patterns (in particular the depth, duration and frequency of tidal inundation) that control the distribution and successful establishment and growth of (targeted) mangrove species."
3. "Assess modifications of the original mangrove environment that currently prevent natural regeneration (recovery after damage)."
4. "Restore hydrology and other environmental conditions that encourage natural recruitment of mangrove propagules and successful plant establishment."
5. "Only consider actual planting of propagules, collected seedlings, or cultivated seedlings after determining (through steps 1–4) that natural recruitment will not provide the quantity of successfully established seedlings, rate of stabilization, or rate of growth of saplings established as objectives for the restoration project." species.

For agricultural purposes, building dams, buildings, or bunds close to or inside of mangrove forests upsets the delicate balance of fine sediment in the nearby mangrove-mud regions. A decrease in on-shore water flow, which results in a reduction in the flux of on-shore fine sediment, and an increase in wave height close to the structures, which results in local scour in front of the structure, are the sources of this disturbance. Due to this imbalance, the mudflat gradually becomes more concave-up, which intensifies wave effects. A five-step plan has been proposed to restore eroding mangrove-mud coasts in response to an analysis of the situation and recommendations by Lewis III 2005 and Winterwerp, Borst, and De Vries 2005. The plan takes into account morphodynamic specifications and calls for a "building with nature" strategy that combines engineering techniques with ecological processes.

1. Restore the intertidal zone by creating a well-regulated buffer zone spanning several hundred metres to restore the movement of fine sediment towards the shore. The removal of any obstacles therein would be necessary to facilitate unhindered tidal flow within the designated area.
2. Implementing "salt marsh works" is an efficient way to improve the natural retention of fine sediment on the mudflat. These entail building porous groynes in the intertidal zone with materials that are readily available locally to encourage sediment accretion. These structures also provide the additional advantage of locally reducing long-shore currents, which reduces the movement of fine sediments away from the restoration site (Bakker et al. 2002). In various works of literature, these structures are known as sediment trapping units (STUs).

3. Reduce wave heights by using the porous groynes mentioned in the previous point to reduce reflections off of structures in the mangrove forest or near the water's edge.
4. Restoring the disturbed hydrological conditions by rehabilitating creeks or removing small dams further inland is necessary to maintain the health of mangroves and ensure appropriate tidal inundation and freshwater flow (Lewis III 2005). Mangroves that have been turned into aquaculture ponds because of human activity should be considered for hydrological restoration in order to return them to their original state. Additionally, this would protect against erosion from storm waves and aid in coastal stabilisation (Stevenson, Lewis, and Burbridge 1999; Lewis et al. 2006).
5. Plant the appropriate mangrove species at suitable locations (above MHW) within the suggested "window of opportunity" in areas where the natural propagule supply is constrained (Balke et al. 2011). Replanting might not be required, though, if enough propagules are available.

Rehabilitation by STU - Net erosion is a major problem in coastal areas where mangroves have been removed. This issue can be lessened through the artificial facilitation of fine sediment settling, especially when mudbanks are passing in front of these locations. The installation of permeable groynes perpendicular to the coast, similar to the Dutch "salt marsh works," is one method that has been employed successfully for this purpose. These groynes, which are made up of permeable fences made of brushwood wedged between rows of parallel wooden poles, lower the wave energy and tidal current velocities, resulting in a low-energy environment that promotes the sedimentation of suspended material and prevents the erosion of accumulated sediment. As a result, the shore accretes more quickly, which speeds up the natural (re-)colonisation of mangroves through seed dispersal and seedling establishment. This action may eventually lead to the restoration of a mangrove forest buffer, which will lower erosion rates when there are no mudbanks present. An environmentally friendly method of coastal defence contributes to the necessary degree of safety and protection while having minimal effects on the natural system.

3

Suriname River Estuary System Analysis

3.1. Geography

Suriname covers 163,800 square kilometres and has a 386-kilometre coastline along South America's northern coast. A sizeable coastal plain exists, much of it below 5 meters. According to geology, the nation is underlain by igneous and metamorphic rocks that are part of the Guyana Shield. Sands and silts, which make up the coastal plain and are home to 85% of the people, are deposited on top of these rocks. Almost 500 thousand people are living there as of 2009.

Within the Paramaribo district, one of its twelve areas is called Weg naar Zee. The National Statistics Office of Suriname estimates that around 14,000 people reside in the Weg naar Zee area, with a population density of 390 persons per square kilometre. The site spans approximately 41 square kilometres. Today, the land in this area is utilized for various purposes, including urbanisation, animal husbandry, and agriculture. Agriculture serves as the primary source of income and is extensively practised. The Atlantic Ocean forms the northern boundary of the region.

The direct hinterland of the coast of Weg naar Zee is used for agricultural activities. The coast is currently protected only by a temporary man-made clay dyke, as locally, the mangroves have been lost. As the hinterland is relatively low-lying, it is prone to floods. The main drivers of this coastal flooding hazard are storm surges, wave action and sea level rise.



Figure 3.1: Map of Suriname, Source: WorldAtlas Website (2023)

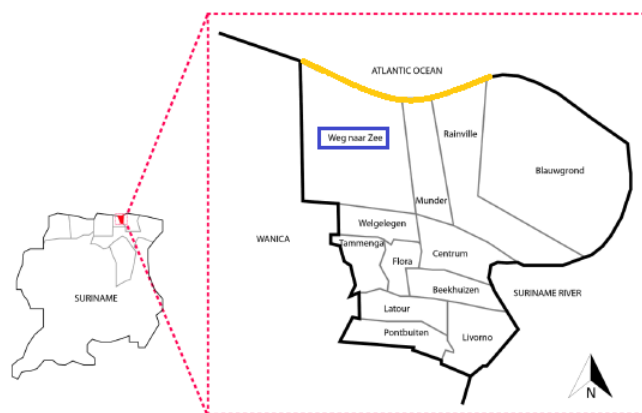


Figure 3.2: Weg naar Zee overview map showing the coastline schematically (Çete et al. 2018)

3.2. Climate Conditions

Suriname has a tropical climate with heavy rainfall, constant temperatures, and high humidity. The Inter Tropical Convergence Zone (ITCZ) mainly influences the Suriname climate conditions. This zone comprises the North East and South East Trade Winds. Suriname experiences four periods of different climates: a long dry and wet period plus a short dry and wet period. The position of the ITCZ influences these periods (Augustinus 1978). The duration of these four periods is listed in Table 3.1.

Period	First Month	Last Month
short rain period	December	February
short dry period	March	March
long rainy period	April	July
long dry period	August	November

Table 3.1: Table listing the four periods of rainfall in Suriname

Suriname experiences seasonally changing wind frequencies. The wind mainly comes from the NE and ENE directions throughout the year (Augustinus 1978). The wind direction is influenced strongly by the ITCZ position. The winds are more easterly during the long dry period (Aug. - Nov.). The NE trade winds have a higher speed and are more influential on the coastline. These higher speeds (5.5 - 7 m/s) occur in the colder winter months. In the warmer summer months, lower speeds occur (4.5 - 5.5 m/s). (Persaud, Flynn, and Fox 1999). For the full monthly values of wind speeds, see appendix B for the monthly wind roses. In Figure 3.3, the wind and precipitation seasons have been summarised visually.

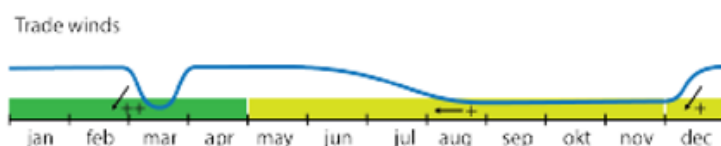


Figure 3.3: This diagram represents the frequency and duration of dry and rainy periods, as well as the speed and direction of the wind. The blue line indicates periods with higher and lower precipitation, while the green and yellow lines show periods of higher and lower wind speeds, respectively. The arrows indicate the direction of the wind, either East or Northeast. (Gerritsma et al. 2020).

3.3. Hydrodynamics

3.3.1. Tides

The Suriname River estuary can be classified as tide-dominated. According to Ali (2016), the tidal range in the Guiana Coast varies alongshore and is affected by location. Due to a semi-diurnal tide system, there are two high tides and two low tides per day along the Suriname Coast (Bosboom et al., 2015). The average tidal range of the semi-diurnal tide is 1.8 metres Augustinus 2004c. The average tidal range at spring tide is 2.8 m, whereas that at neap tide is 1.0 m (Nedeco, 1968). The Suriname Estuary is now categorised by Davies (1964) and Dyer (1997) as a mesotidal estuary.

Tidal velocities are relatively low, typically around 0.1 to 0.2 meters per second, and generally flow perpendicular to the coastline. The tidal range is relatively uniform along the coast, and the tidal filling and emptying of the Guyana coastal system occurs more or less perpendicular to the coast. Therefore, the tide rarely causes longshore currents. (van Ledden et al., 2009). The tidal current causes a reversal twice daily of the flow direction. The flood current is stronger than the river discharge. The speed at which water flows inland during high tide flows depends on its position in the tidal cycle and the river discharge.

The Suriname River's tidal wave's amplitude drastically decreases at Berg en Dal (164 river kilometres). As a result, the tide effect is no longer noticeable there. A longitudinal salinity gradient is produced by the tide's movement in the river and extends up to 50 km land inwards from the river's mouth (Zwol 2008).

3.3.2. Waves

Offshore waves come from a variety of directions that vary from North to East. However, the majority of waves, over 90%, typically propagate from directions between 20°N and 100°N, whereas just 45% do so from between 50°N and 70°N. In the tropical region of the North Atlantic Ocean, trade winds display a high link with the sea and swell height and direction (NEDECO 1968).

Typically, between December and March, the winter season is when the largest waves occur. Wave periods in deep waters range from 5 to 13 seconds, with an average major wave height of about 1.6 m. The significant wave height in deep seas during winter, however, rises to about 3.0 m for a 10% exceedance probability. In contrast, August and September are normally when the waves are at their lowest. During the summer, deep waters typically see waves with a substantial height of 0.8 m and periods of 3 to 11 seconds. The significant wave height in deep seas during the summer, however, rises to about 1.6 m for a 10% exceedance probability (NEDECO 1968).

Wave heights are reduced to between 85 and 30 % of their initial height as they approach the beach from deep oceans due to wave refraction, wave energy dissipation, and wave transformation. As the waves travel from deeper to shallower seas in the Suriname estuary, they refract in a direction perpendicular to the Warappa and Vissersbanks, transforming into solitary waves that do not break but rather dampen when they reach the muddy seabed (Zwol 2008).

3.3.3. Currents

Suriname is located close to where the northeast trade winds and associated currents meet the south-east trade winds. The ITCZ, which results from this convergence, generates the steady Guianas Current along the coast (Armando Guzman et al. 2017). The westward coastal current has a maximum velocity of 1 m s^{-1} at the surface and 0.10 to 0.35 m s^{-1} near the bottom. Shore-normal tidal currents along the Guianas coast can locally reach 0.45 m s^{-1} (Bourret et al., 2008). Tidal currents are most significant at the river mouth (Augustinus 2004c).

3.3.4. Stratification

The Suspended Particulate Matter (SPM) dynamics within the estuary are affected by its stratification. This stratification can be linked to the longitudinal salinity gradient, which is a result of the tidal range. This implies that the tide directly impacts the distribution of salinity in the water. In particular, the reach of saltwater from the tide is approximately 50 km upstream from the mouth of the river. The Afobaka dam regulates the river discharge, controlling the inflow of freshwater. Interestingly, this freshwater influx is not constant: the wet and dry seasons bring about an annual variation that impacts the estuary's stratification. Onshore winds also play a significant role, helping to keep the freshwater near the coast. This helps to explain the variations in the salt content observed at the river estuary. These changes are primarily a result of the tide-driven currents that cause saltwater to flow in and out of the estuary, along with the outflow of freshwater from the Suriname and Commewijne Rivers. Historic measurements provide a critical context for this discussion. Nedeco's study in 1968, for example, calculated the salt content of the water at the estuary NEDECO 1968. Their research showed that during high tide, the salty waterfront advances until Domburg (km 70), whereas the lowest salt concentrations pull back to Paramaribo (km 50) during low tide. This salinity fluctuation is particularly pronounced between Leonsberg (km 43) and Paramaribo (km 52), where significant variations in salt content are seen both at the surface and the river bed Heuvel 1983. These variations suggest considerable salt stratification occurs between these two points.

3.3.5. Sea Level Rise

According to the projections, sea level rise is anticipated to occur at an average rate of 3.1 mm yr^{-1} along the Suriname coast, which is consistent with global averages. Suriname faces a significant risk of floods and salt intrusion due to rising sea levels, with vulnerable sectors including infrastructure, GDP, and tourism. The agricultural industry, mainly located in low-lying polders, is particularly susceptible to the impacts of salt intrusion caused by climate change. (Scott and Simpson 2009)

3.4. Morphology

3.4.1. Bathymetry and profiles

According to Nom (1967), the continental shelf northwards of Suriname is 150 km wide and has an average slope of 1:1600 up to approximately 100 m. The shelf of Suriname can be divided into two parts: divided by the 20 m isobath (NEDECO 1968, Augustinus 1978). The mudflats and troughs in between have a more gentle slope closer to 1:3000. The northwest flanks of the mudflats have a steeper slope (averaging 1:500) (NEDECO 1968, Allersma 1968). Available data indicate that the course of the Suriname River estuary in the lower reach is very stable. Possible local erosion or accretion of the river banks is insignificant. Also, the positions of the deeper channels in the estuary have not changed considerably. (NEDECO 1968).

3.4.2. River Discharge

The four main rivers of Suriname that flow out into the sea, from east to west, are the Nickerie, Coppename, Saramacca, and Suriname Rivers. Table 3.2 provides each river's annual (or average) discharge and corresponding annual sediment load.

	Saramacca	Coppename	Nickerie	Suriname
Catchment Area ($\text{km}^2 \times 10^3$)	12	20	10	16.5
Discharge ($\text{m}^3 \text{yr}^{-1} \times 10^8$)	8	14	6	
Average Discharge ($\text{m}^3 \text{s}^{-1}$)				440
Sediment Load ($\text{t yr}^{-1} \times 10^6$)	0.2	0.4	0.2	0.25

Table 3.2: The different values for the river discharge (load) for the four main rivers outflowing at the Suriname coastline (Gersie, Augustinus, and Van Balen 2016 Smits, Winterwerp, and Best U 2022)

3.4.3. Sediment

The NEDECO study (1968) involved an investigation into the composition of the Suriname Estuary subsoil by collecting a significant number of borings. Analysis revealed that north of Braamspunt, the outer bar was comprised predominantly of silt and clay, with localised occurrences of sand and shells. The mud present in the subsoil was found to have a water content of approximately 50%, with a corresponding density of roughly 1450 kg m^{-3} . The sand particles detected exhibited an average diameter of no greater than 300 microns.

The Guiana Coastal System is characterised by an exceptionally high level of turbidity, with the concentration of suspended fine sediment varying significantly both spatially and temporally. The suspended sediment concentration within the Guiana Coastal System typically registers at a few hundred milligrams per litre, though local readings can be substantially higher. These sediments are transported by a combination of tidal flows, the Guiana Current, and fresh water-induced gravitational circulation, following a zigzag path from west to east (Augustinus 1978). This sediment suspension is the foundational source of fine sediment in the region's coastal waters, with minimal contributions from local rivers. Due to a lack of comprehensive data, we must assume a background concentration of suspended fine sediment ranging from 50-100 mg/L within the coastal zone of Suriname. This value is speculative but serves as a plausible estimate for the mean concentration of fines present in the area. Because the maximum suspended fine sediment concentration in the Guianas coastal waters is limited by the so-called carrying capacity of the turbulent water flow (e.g. Winterwerp 2001; Winterwerp, Kessel, et al. 2021), this value assumption is valid. Several significant sediment phenomena occur in the system for different sediment concentrations:

- 0.1 - 10 g/l** A phenomenon known as flocculation occurs, wherein the sedimentation rate progressively rises with higher initial concentrations.
- 5 - 200 g/l** The characteristic fall velocity decreases as concentration levels rise because settling is hampered. There are some localised areas where the concentration can be so high that fluid mud with a density of 1100 to 1200 kg m^{-2} forms as a result. As a result, this mud gathers in the fairway's lower portions of the ocean floor.
- > 200 g/l** Fluid mud can develop, and the accumulated mud undergoes a process of consolidation,

transforming into a solid bottom in the absence of erosive influences, resulting in the formation of a layer

3.4.4. Sediment origin and budget

The sediment present in the Suriname River Estuary, as well as the broader Guiana Coastal System, can be traced back to its source in the Amazon River. This assertion is supported by two key pieces of evidence: Firstly, measurements taken by Allison and Lee (2004) revealed that the rivers comprising the Guiana System transport minimal quantities of fine sediment, typically ranging between 1 mg L^{-1} to 10 mg L^{-1} . Secondly, research conducted by NEDECO (1968) indicates that the sediment found in Suriname's coastal regions shares a comparable composition to the original sediment present in the Amazon River. Furthermore, Augustinus (1978) found that the uncommon fine sands found within the Guiana Coastal System bear a chemical signature that is consistent with sand originating from the Amazon River.

The sediment dynamics along the Suriname Coast are, therefore, primarily governed by the fluxes of mud originating from the Amazon delta. This sediment is composed of both sand and fine, cohesive particles. The Amazon River system discharges approximately 1200 Mt of silt and clay annually, in addition to 30 Mt to 80 Mt of sand and other fines, which constitute approximately 5 % of the total output (Eisma, Augustinus, and Alexander 1991). The dispersion of sediment within the Amazon system is influenced by tides, waves, the North Brazil and Guiana Currents, as well as estuarine circulation. Of the entire sediment output, approximately $52\% \pm 16\%$ remains on the Amazon River shelf, while 20 % (220 Mt yr^{-1} to 260 Mt yr^{-1}) is transported in a northwesterly direction along the Guiana Coast, some of which takes the form of mudbanks. Roughly 0.4 % to 0.5 % of the total Amazon sediment output is deposited along the coast of the Guiana Coastal System, with a significantly larger proportion deposited along the Suriname Coast than in adjacent countries (Eisma, Augustinus, and Alexander 1991). The remainder of the sediment ultimately reaches the Orinoco Delta in Venezuela.

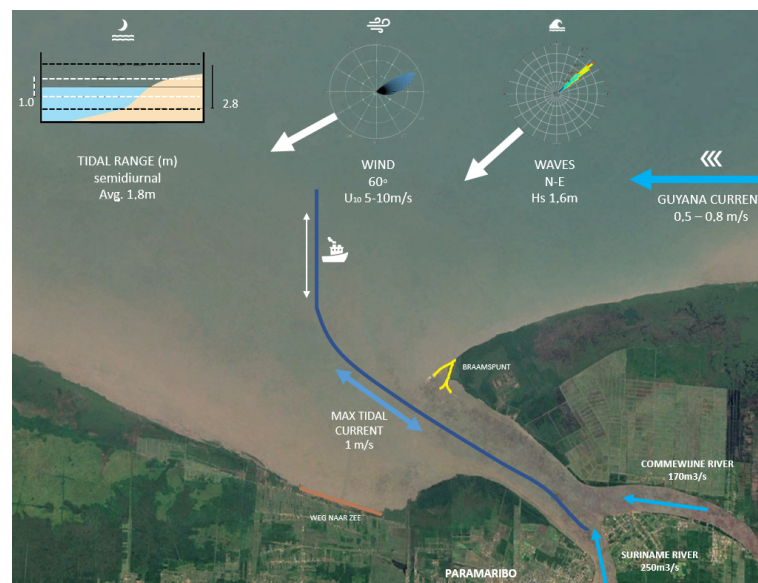


Figure 3.4: Schematisation of the Suriname Estuary showing the main hydrodynamic processes influencing the estuary dynamics. The locations of Weg naar Zee, Braamspunt and the shipping lane are also depicted in the diagram.

3.4.5. Mudcape Dynamics

In recent geological history, some eastern estuarine banks have transformed into elongated headlands referred to as "mudcapes" in the literature (Allison, Nittrouer, and Kineke 1995). During their development, these mud banks redirect south-north running rivers to the west. This causes a westward deflection of smaller river mouths along the coast, leading to the formation of mudcapes due to the accumulation of Amazon mud. Mudcapes, along with cheniers, offer protection to coastal areas westward from northeast ocean waves. Notable examples in Suriname of these redirected rivers are the

Saramacca and Commewijne rivers. Paramaribo is located on the western bank of such a cape deflection at the mouth of the Suriname River (Anthony 2016).

For larger rivers like the Maroni and Corantijn rivers, located on the border of Suriname, this deflection is counteracted by a phenomenon known as the 'hydraulic-groyne effect' (Anthony, Gardel, Proisy, et al. 2013, Gensac et al. 2016). This effect is caused by the greater liquid discharge of these rivers compared to smaller inland rivers such as the Suriname River.

In the case of smaller rivers with limited sand supply, such as the Suriname River's mouth, where fluvial sand remains confined within the estuary, prolonged erosion can occur in downstream coastal areas like the Weg naar Zee region north of Paramaribo, on the western bank of the Suriname River's mouth. According to Anthony (2016), shoreline retreat has persistently affected this area, although the trend has diminished from 2009 to 2015. Erosion hotspots seem to coincide with areas where the river's fluvial jet outflow hinders the firm attachment of mud to the shoreline.

Increased E-NE winds, together with the resulting waves, are causing the mudbanks to expand (Augustinus 1986, 2004b). Consequently, coastal accretion is increasing. The currently approaching mudbank at Braamspunt is significant, stretching over seventy kilometres (Augustinus 2004b). In the future, the western flank of the bank will reach Braamspunt, and at that point, it will supply fluid mud to the area.

Since the construction of the Afobaka dam, the outflow of the Suriname River has been regulated, and peak discharges to cleanse the estuary and flush it clean no longer occur. As a result, there is a possibility that Braamspunt may develop into a mudcape, leading to a westward shift of the estuary. This shift could have significant implications for the navigability of the Suriname estuary.

3.4.6. (Historic)dredging and sand mining activities

Historically, the present-day navigation channel was nothing more than a furrow across the 'talweg' of the lower reaches and across the outlying mobile mud flat. This fairway has been kept at depth for years by the agitation of shipping, a 'laissez faire' policy. Here, loaded vessels are skilfully piloted through the marked groove with low keel clearance. Dredging work has been a rare activity. The following timeline shows the major changes in the Suriname River channel (Sources: Hydronamic and Sescon Group 1992, Quist and Plooy 2008).

- 1940 - Due to the rapidly increasing demand for bauxite in 1940, the outer channel was deepened for the first time through experimental agitation. Many ships, from Alcoa (Suralco) in particular, sailed with reduced keel clearance. In addition, a tug with a trailing plough was used.
- 1942 - The trench was deepened and maintained to about 5.5 m-CD by two full-time trailing suction dredgers from CAC (USA).
- 1944 - Maintenance dredging was ceased.
- 1945 - From this year, the depth of the outer channel was maintained as much as possible by the agitating action of the large, partly purpose-built, bauxite ships, loaded to virtually no keel clearance at the channel's site.
- 1959 - Gully barriers at the site of Dijkveld, Jagtlut, Commewijne inlet and Resolution by means of a cutter suction dredger and a crane pontoon, both from Alcoa, deepened to about 5 m-CD.
- 1960 - Outside fairway filled to about 4.3 m-CD this year due to passing easterly mudbank between 1945-1965, caused by the fluid mud-rich western flank.
- 1965 - The discharge and silt regime of the Suriname River has changed dramatically with the construction of the Afobaka dam (km 194).
- 1970 - Braamspunt sand spit enlarged, likely due to the passing of the northerly mudbank
- 1992 - Fluid mud found again in the outer fairway. Hydronamic, in collaboration with Sescon Group, wrote a report that concluded the current policy is not viable for maintaining the fairway depth in the long run. They recommended deepening the fairway to 5.5 m-CD and changing the width to 85m. However, this advice was not followed at the time.
- 2008 - Lievense consultants designed a possible dredging project at the request of Suralco / BHP and Staatsolie. In light of this design, a Delft3D model of the Suriname River & Estuary was produced. However, the design was not implemented.

2021 - The joint venture Baggerbedrijf De Boer B.V. - Boskalis B.V. began the first dredging works. They will perform capital dredging to 4.75 m-CD, followed by two years of maintenance dredging.

3.5. Conceptual System Understanding

An understanding of the main processes in the estuarine system, and their influence on the sediment dynamics and thus mud nourishments, is vital for this research. In this section, these processes will be described. In the next chapter, it will be explained what the model requirements are to satisfactorily simulate these processes.

There are several processes that have a significant influence on the dynamics of SPM (Suspended Particulate Matter) in the Guiana System coastal waters. The wind speed and direction of the wind, governed by the Trade Winds, influence both the swell waves and the longshore Guiana Current. In conjunction with these processes, the tide and stratification of the estuary are the main drivers of SPM dynamics.

The Trade Winds have a yearly persistent NE direction, with only slight yearly variation. The Suriname Coast is therefore affected by mainly swell waves originating from the NE direction. Short sea waves are not dominant on the Suriname coast. The Guyana Current induces longshore currents resulting in SPM transport to the west. The wind-induced flow and setup itself are not dominant driving forces on the fine sediment dynamics in these waters (NEDECO 1968).

The swell waves themselves have their influence on the SPM dynamics in the estuary. Waves increase bed shear stress, which causes erosion. The waves mobilise the fine sediment from the muddy bed, resulting in high concentrations of SPM. Refraction causes them to rotate, so that close to the coast they end up entering almost perpendicular. They tend to have, especially in sedimentation areas, the characteristics of solitary waves (Wells and Coleman 1981). The waves dissipate most of their energy in the soft mud layer covering most of the nearshore area. They do not break due to shallow water but are damped by viscous dissipation. The waves are accountable for a large portion of the nearshore transport of sediment (Wells and Coleman 1981).

The eastern mudcape, with the Braamspunt sand spit as its most westerly point, protects the Suriname Estuary from direct NE wave action. Waves entering the Suriname River estuary are further refracted around Braamspunt, which is the westward-projecting east bank of the estuary (see Figure 3.5). On top of that, due to the vertical tide, wave action affects the banks of the estuary in ever-changing places. This further lowers the erosive influence of waves in the estuary. For generating local wind waves of any importance in the estuary, the fetch length is too short (Augustinus 2004a).

Sediment supply is almost entirely tidally determined in the estuary. Sediment is transported westward by the current along the coast and is carried into the estuary Gersie, Augustinus, and Van Balen 2016. During low tide, it is discharged back to sea. Due to the nature of the sediment, transport mainly takes place in suspension. Locally, the SPM concentration can become so high that fluid mud arises. This will collect in the lower parts of the bed, including in the fairway channel.

The Guiana Current has low velocities and is therefore just able to transport silt and fine sand (Augustinus 1978). It further influences the current patterns along the mouth of the estuary. During flood, the flow pattern at the mouth of the Suriname River (km 0 - km 30) changes due to the Guiana wind-driven current. This causes a saltwater flux to enter through the eastern channel of the estuary. During ebb, water flows to the sea through the main channel on the west side of the estuary. The Guiana Current also interacts with the tidal cross-shore currents, creating a zigzag pattern that the suspended sediments follow westwards (see Figure 3.5). This flow pattern also occurs in Guyana, driven by the same processes (Smits, Winterwerp, and Best U 2022). These flow patterns influence the SPM transport patterns in the estuary.

Due to the baroclinic pressure gradient, an offshore surface current & onshore undertow occur. Due to the gravitational circulation, the sediment remains on the foreshore. This could prove beneficial for

mud nourishment, as it would be positive if the sediment is kept close to shore.

Not only do these hydrodynamic forces drive the sediment dynamics in the Suriname Estuary and thus affect the functioning of mud nourishment, but the sediment properties and quantities in the system also play a crucial role in determining its effectiveness, see 3.4.3. A significant sediment phenomenon that could affect mud nourishment feasibility, concerning fluid mud, is mud streaming (Augustinus 1978) (Wells and Coleman 1981). The streaming has been observed at the currently placed STUs at Weg naar Zee. Sedimentation of fine sediments takes place here in front of the trapping units, instead of behind them (H.Winterwerp, personal communication, May 2023).

A westerly migrating mudbank is currently approaching Braamspunt and will cross the estuary entrance channel in about 5 years (For reference to the in-depth explanation of the Guiana Systems mudbank dynamics, see section 2.1). This will cause a situation change for the estuarine system, which is currently in an interbank situation. The mudbank will affect both the hydrodynamic forcing and the sediment dynamics in the estuary. See Figure 3.6 for a schematisation of this future situation.

The exact migration process of the mudbank complex across the Suriname Estuary remains unknown. However, it is understood that mudbanks migrating westward in front of an estuary maintain a certain distance from the coast due to river discharge (Delft Hydraulics Laboratory 1962). Typically, the mudbank complex consists of two parts, namely the freely migrating seaward part consisting mainly of fluid mud and the landward part connected to the coast. The landward part, sheltered from currents and waves by the seaward part, consists of deposited mud (Allison and Lee 2004). In the presence of an estuary, this connected landward section does not form due to the turbulence caused by the inflow and outflow of water (Gersie, Augustinus, and Van Balen 2016). This effect is the hydraulic groyne effect (see paragraph 3.4.5).

As the migration will occur in the (near)future, this situation should also be considered in the model study. The focus should be on the influence the migrating mudbank has on the short-timescale dynamics, as this influences the nourishment's effect in the estuary. An example of these short-timescale dynamics is the change of the hydrodynamic forcing in the estuary. Mainly, the wave dynamics will change. It is expected that the mudbank and the fluid mud layers surrounding it will attenuate the waves. Lower waves reaching the coast will result in locally reduced bed shear stress. Consequently, this leads to less sediment mobilisation and decreased coastal erosion caused by wave action.

The migrating mudbank will supply the Suriname River's entrance channel with increasing amounts of fine sediments as the mudbank moves further across the estuary. This will play a part in the increase of sedimentation along the coastline of the estuary. The entrance channel could close off if the Suriname River's discharge capacity is insufficient. High maintenance dredging rates would be required. If the entrance channel bathymetry changes, this could influence hydrodynamic forcing in the estuary. The wave propagation direction could change, thus causing a different wave pattern in the estuary.

Fluid mud is formed in the lee side zone of the mud banks. Waves, transformed into solitary waves when approaching the shore over the mud bank, bring the fluid mud shoreward due to radiation stresses. This is the mud streaming effect discussed in 2.1. Normally, this streaming effect creates an influx of sediment, which forms mudflats at the coastal lee side of the mudbanks. Now, this streaming effect could be an added sediment source for Weg naar Zee, as the mudbank is migrating across the estuary.

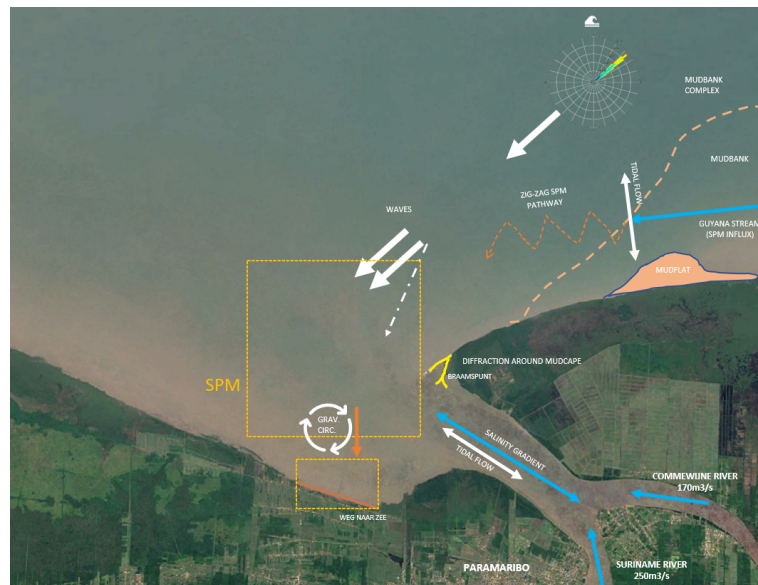


Figure 3.5: Schematisation of the Suriname Estuary illustrates the current situation, where the mudbank complex is situated eastwards of Braampunt, off the coast of the eastern mudcape. The schematisation highlights the main processes discussed in the referenced material. The Guyana Stream, in conjunction with the cross-shore tidal flows, generates a zig-zag flow pattern. This pattern is subsequently followed by the Suspended Particulate Matter (SPM) influx, which is the primary influx of SPM. The SPM is transported towards the coast by waves, tide, and gravitational circulation, determining the SPM levels observed at Weg naar Zee.

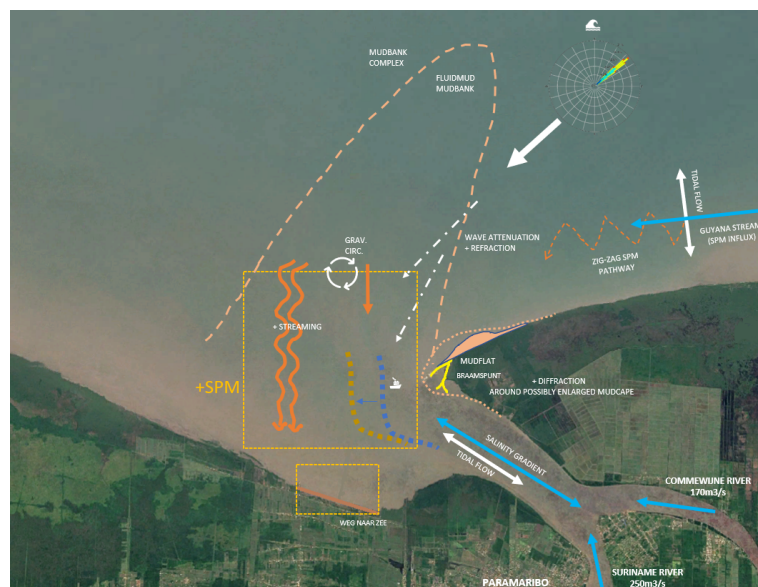


Figure 3.6: Compared to the situation depicted in 3.5, this schematisation now illustrates the future scenario where the mudbank complex migrates across the Suriname Estuary, impacting both hydrodynamics and sediment dynamics. The mudbank attenuates incoming waves and enhances refraction into the estuary. The flow of fluid mud is now directed into the estuary along the western side of the mudbank, leading to an increase in Suspended Particulate Matter (SPM) levels within the estuary. The potential expansion of the eastern mudcape, along with the western relocation of the shipping channel, is also incorporated into the schematisation.

This research aims to assess the feasibility of targeted sediment influx in the system to rehabilitate the Weg naar Zee coastline for Mangrove rehabilitation. This feasibility depends on the relative increase of sediment influx at the Weg naar Zee coastline due to the nourishment in the system. To be able to determine this influx, a closer look at the situation at Weg naar Zee should be taken.

Currently, tidal flow and wave action serve as the principal hydrodynamic forces (see Figure 3.7). The mudbank complex has not yet begun migrating across the estuary, so waves are at a high level. The waves and tide bring in sediment onto the intertidal flat at Weg naar Zee's foreshore. The coastline is experiencing erosion, thus more sediment is leaving this coastal cell than is being retained. This is despite the STU structures currently in place in the westerly part of the coast.

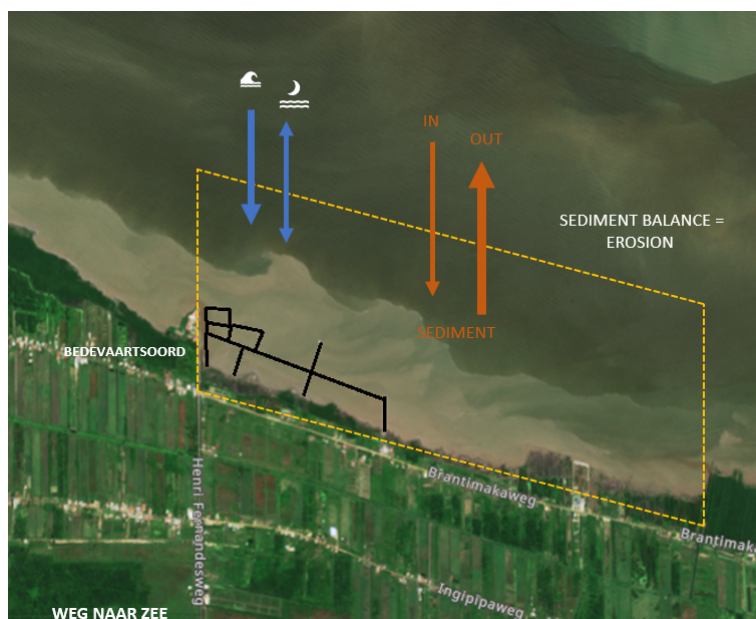


Figure 3.7: The situation at Weg naar Zee where the mudbank has not started migrating across the estuary, the STUs have not been extended across the entire coast and there is no sediment influx in place

Now, if we consider the desired situation without the migrating mudbank (see Figure 3.8); A sediment influx strategy is being executed, thus increasing the influx of sediment in the cell. The STUs have been extended, and we assume these are working effectively by retaining the increased sediment influx. The coastal cell now retains more sediment than it loses and sedimentation occurs.

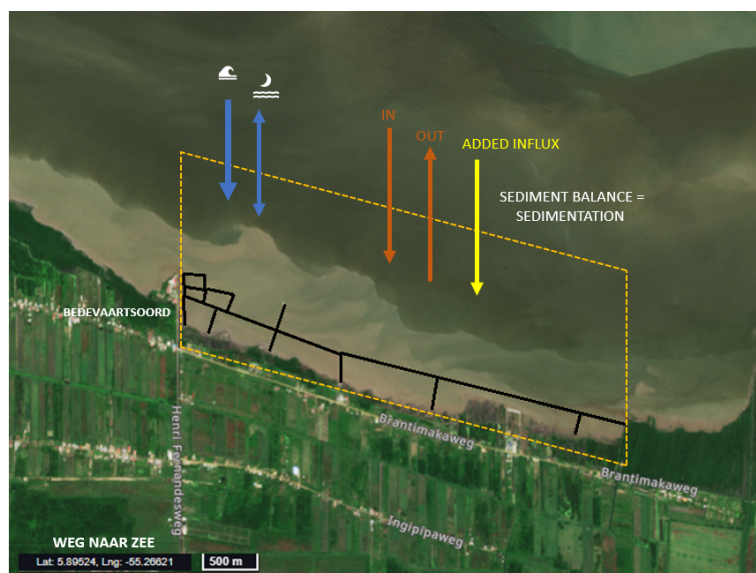


Figure 3.8: The situation at Weg naar Zee where the mudbank has not started migrating across the estuary, the STUs have been extended across the entire coast and there is a sediment influx in place

If at a later stage, the mudbank complex has started to migrate across the estuary, the situation changes (see Figure 3.9). The wave action decreases, as the mudbank attenuates the waves. This decreases the amount of sediment that reaches the coast. However, due to the increase of SPM in the water induced by the mudbank, an increased amount of sediment reaches the coast. If, hypothetically, more sediment reaches the coast than in the previous situation, less sediment influx is necessary to keep the coast in a state of sedimentation

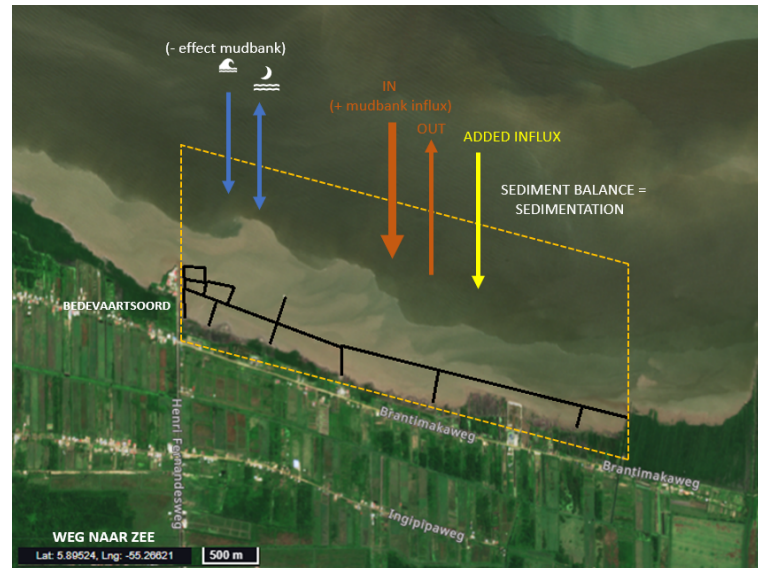


Figure 3.9: The situation at Weg naar Zee where the mudbank has started migrating across the estuary, the STUs have been extended across the entire coast and there is a sediment influx in place

4

Suriname River Estuary Model Set-up

This chapter explains the setup process for the model used in this research. Firstly, it explains the choice of the process-based model, Delft3D. The model used in this research was developed by Alkyon & Lievense up until 2008 and was later modified by M. Loose in the same year. The capabilities of this model are then elaborated upon. Subsequently, the setup process for developing the model for the current research is described. Hereafter, the general layout of the updated model and the processes it simulates are listed and explained. Finally, the different scenarios that are simulated are addressed, concerning the mudbank location and the hydrodynamic forcing due to seasonal variations.

4.1. Model purpose & requirements

Establishing a conceptual framework, that qualitatively distinguishes the main influencing forces, is a necessary first step. This conceptual model is a prerequisite for clarifying assumptions, both implicit and explicit, and for effectively communicating and debating conclusions. All of these activities take place within the broad framework of the research. In the previous chapter 3 different processes occurring in the Suriname Estuary were discussed. The conceptual model showed the occurring phenomena that should be considered. These include the influence of waves in combination with the tide, the influence of the mudbank location on the waves, the flow patterns and the sediment dynamics in the estuary. And lastly, the effect of the balance between fresh and saline water in the estuary, driven by the tidal flow and freshwater influx. This paragraph addresses what the model requirements are to effectively simulate the estuary considering these processes.

Purpose - The purpose of studying the Suriname Estuary through modelling is to assess the viability of mud nourishments within the estuary. The model enables the simulation of the key processes that influence nourishment dynamics within the estuarine system, focusing on a short-term scale of approximately one spring-neap tidal cycle. Through these simulations, the behaviour of the nourished sediment can be observed and analysed.

To enable a thorough assessment of the feasibility of the nourishment under various circumstances, the simulation scenarios should include both large- and small-scale system dynamics. This method makes it easier to compare various scenarios, such as applying nourishment under normal hydrodynamic conditions versus under extreme weather conditions. It also permits testing the effectiveness of the nourishment during an interbank phase or when a mudbank is present and crossing the estuary.

The primary objective is to quantify the amount of sediment reaching the coastline of Weg naar Zee, thereby determining the extent to which nourishment can potentially enhance onshore sedimentation. This analysis allows for an assessment of the potential positive impacts of the nourishment project in increasing sediment deposition along the shoreline.

Requirements - The research (sub)questions to be addressed and an understanding of the procedures necessary to answer those questions determine the numerical model's configuration. The following re-

quirements are as a result necessary:

1. The model grid needs to encompass a sufficiently large offshore area of the estuary. This ensures accurate simulation of hydrodynamic forcing, including the effects of the mudbank, if applicable.
2. The hydrodynamic forcing of the model should account for seasonal variations, such as summer and winter conditions. A yearly statistical average value should be used to account for these variations. By using a yearly average, the forcing will be representative of conditions year-round. A higher second condition can also be applied to show the influence of stormy conditions.
3. Boundary conditions for the model should include the tidal regime of the ocean, the Guyana current, sediment influx, and river discharge.
4. The model should be capable of simulating hydrodynamic and morphodynamic processes in three dimensions. This is essential due to the stratified conditions of salt and sediment in the estuary, which cause flow differences between the bed and surface, as well as cross-channel flow differences. Sufficient vertical resolution is necessary to capture the effects of vertical stratification and residual flows (gravitational circulation). A distribution over 10 sigma layers should be sufficient.
5. The simulation period should cover a complete spring neap tidal cycle.
6. A model-specific wave module is necessary. This is mainly because the waves induce bed shear stresses. Wave conditions therefore primarily serve to stir up sediment, which is then transported by currents. The wave-driven currents have a minor contribution to sediment transport in this area.
7. A simulation should be constructed for the situation where the mudbank is present in the estuary from the coast to the -10 m isobath
8. To account for sediment processes and accurately simulate the suspended particulate matter (SPM) dynamics, the following aspects should be considered:
 - The influence of sediment on fluid density. This is crucial in the Suriname River Estuary due to its high sediment concentrations.
 - The suspended transport of muddy sediment load can be modelled using the 3D advection-diffusion equation.
 - Hindered settling should be considered in the model. This helps capture the realistic behaviour of sediment particles in the estuary.
 - Erosion and deposition processes can be simulated in Delft3D-FLOW using the Partheniades-Krone formulations.
 - The density of the fluid mixture. The density influences the vertical stratification and circulation patterns within the estuary.

4.2. Delft3D

Delft3D, developed by Deltares, is a process-based software package utilized for constructing the schematic representation of coastal areas. Delft3D offers a wide range of simulation capabilities, including hydrodynamics, sediment transport, wave dynamics, and morphodynamic processes. The software is composed of various modules that can be used either independently or in combination. Specifically, the module required for conducting flow calculations is referred to as Delft3D-FLOW, while the one dedicated to wave calculations is denoted as Delft3D-WAVE.

The flow module within Delft3D is a hydrodynamic and sediment transport simulation program capable of handling two-dimensional (2D) or three-dimensional (3D) scenarios. It can compute non-steady flow and transport phenomena. Non-steady flow conditions can arise due to various factors, including meteorological influences like wind and tides. Additionally, forcing can originate from pressure gradients resulting from variations in the free surface or density gradients. The calculations are performed on a grid that is fitted to the boundaries of the system (Deltares, 2021a). Delft3D-FLOW effectively determines the flow and transport processes by solving the horizontal equations of motion, the continuity equation, and the transport equation for conservative constituents. The flow is computed using the one-dimensional shallow water equations, which accurately represent the dynamics of fluid flow in a wide range of coastal and estuarine environments.

Delft3D-SED is a module incorporated in FLOW for sediment transport calculations. Sediment transport in Delft3D can be modelled for cohesive and non-cohesive sediment types. As this concerns a mud coast, cohesive sediment is selected. Cohesive sediment transport is based on the Partheniades-Krone formula. It compares computed bed shear stresses versus critical bed shear stress to calculate erosion fluxes. The deposition is calculated using the concentration, settling velocity, and a dimensionless reduction factor (Deltares, 2021a).

The wave module in Delft3D is based on the SWAN (Simulating Waves Nearshore) model, developed by the TU Delft, in which waves are described using a two-dimensional wave action density spectrum. The wave action density is the wave energy density divided by relative frequency. It seems possible to predict waves with reasonable accuracy using the spectral distribution of the second-order moment of the waves, albeit not sufficient to fully describe the waves statistically (Deltares, 2021b). The spectral action balance equation describes the evolution of the wave spectrum. In SWAN, waves are generated by wind. Dissipation of waves occurs by white capping, bottom friction and depth-induced breaking. Furthermore, wave energy is shifted between frequencies by non-linear wave-wave interactions, i.e. as triads. These processes are all included in the SWAN model:

- wave generation by the action of the wind
- refraction over a bottom of variable depth and a spatially varying ambient current
- wave blocking by currents
- dissipation by white capping/ wave breaking/ bottom friction
- non-linear wave interactions
- partial wave transmission and reflection

4.3. Original Model Functionality

Alkyon set up a 2D flow model to simulate the tidal regime of the Suriname River and Estuary and compared simulations with existing data. The model simulates the flow regime between the 10 m depth contour (offshore), 10 km upstream of Paranam and the first 10 km of the Commewijne River. The model was provided with a rectangular water buffer area, representing the upstream tidal storage capacities, which were adjusted to calibrate the propagation and attenuation of the tidal wave. The river discharges have been set to an average value for the discharge in the Suriname River and the Commewijne River. The Guyana current was set as one of the boundary conditions to calibrate the total flow regime of the Suriname River Estuary. The tidal movement has been reproduced quite well; however, the flow velocities show some difference with the measurements

Alkyon also made a 3D model to study sediment transport and to determine the future sedimentation volume and the required maintenance dredging in the fairway channel. The 2D flow model has been used to determine the upstream boundary conditions for the 3D model. The grid is distributed in 10 horizontal sigma layers. Loose (2008) altered the Alkyon model during his thesis research. Alkyon was focused on the correct simulation of erosion and sedimentation in the river. Loose wanted to focus on the correct simulation of the main hydrodynamic processes in the system: gravitational circulation, tidal asymmetry, and damped turbulence. Loose his adjustments were enabling erosion and deposition in the Alkyon model. He calibrated the sediment concentrations by adjustments of the critical bed shear stress for erosion and deposition.

The model Loose used for his study serves as a starting point for this modelling study. The main layout and capability of the model used by Loose are listed here. For the full model overview, see appendix D.

Processes

- Salinity included
- Sediment included, only one mean diameter fraction used
- Wind, waves, secondary flow not included

Bathymetry & Grid

- Based on survey data from MAS 2002-2004
- 3D-grid contains rectangular cells with varying widths/lengths
- Horizontal grid resolution: approx. 30 x 30 m at fairway alignment; Ocean cells at approx. 200 x 200 m
- 10 sigma layers per horizontal grid cell
- Constant distribution of layer thickness in the vertical direction

Timeframe, Boundary and Initial Conditions

- Simulation period: 15 d (cover 29 tidal cycles, including spring and neap tides)
- Boundary flow conditions:
 - Tidal forcing: Ocean north and west boundaries divided into 5 sections
 - Current forcing: east boundary, 0.2 m s^{-1} at ocean side and 0.1 m s^{-1} at coast
 - Discharge condition: Suriname and Commewijne Rivers as time-series
- Boundary transport conditions:
 - Salt influx: Ocean boundary there is an influx of water of 32‰, Commewijne River boundary it is set as 16‰ and at the Suriname River boundary it is set as 0.1‰.
 - Sediment influx: Ocean boundary east influx of 0.2 kg m^{-3}
- Initial conditions:
 - Condition file containing water levels, velocities, salinity concentrations and sediment concentrations in every grid cell
 - Sediment concentration of the fluid mixture for all cells 0.5 kg m^{-3}
 - Bed layer thickness 0.1 m

Non-default physical Parameters

- Roughness: $k_s = 0.003 \text{ m}$ to 0.004 m for the ocean and river mouth area, $k_s = 0.001 \text{ m}$ to 0.002 m for the study area and a higher $k_s = 0.01 \text{ m}$ for the upstream part of the study area where the sediment diameter of the river bed is larger.
- Viscosity: k-epsilon model for the vertical turbulent eddy viscosity and the vertical eddy diffusivity additional to the background values.
- Sediment parameters:
 - Specific density = 2650 kg m^{-3}
 - Dry bed density = 500 kg m^{-3}
 - Sediment erosion rate = $1 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$
 - Reference density for hindered settling (C_{gel}) = 50 kg m^{-3}
 - Settling velocity = 0.5 mm s^{-1}
 - Critical bed shear stress erosion = 0.2 N m^{-2}
 - Critical bed shear stress deposition = 0.1 N m^{-2}
- Morphology settings: no updated bed changes, effect sediment density fluid mixture included, morphological scale factor = 1

Simulating physical processes in Delft3D

Sediment transport - Muddy sediments are transported in a suspended state. The transport of suspended substances is modelled in Delft3D-FLOW by a 3D advection-diffusion equation. Thus, transport is determined by the concentrations in the fluid mixture and the discharge. Bed-load transport in the Suriname Estuary is in the form of density currents of fluid mud. The simulation of fluid mud is complex in the base version of Delft3D-FLOW and is thus not included as a physical process.

Hindered settling - Hindered settling is implemented in Delft3D-FLOW to account for high sediment concentration impacts on sediment movement. It depends on mean fall velocity, hindered settling concentration, and sediment concentration.

Erosion and deposition - Erosion and deposition are modelled using Partheniades-Krone formulations. Erosion depends on a default erosion parameter, critical bed shear stress for erosion, and occurring bed shear stress calculated with hydrodynamic equations. Deposition depends on mean fall velocity, occurring sediment concentration, and the relation of critical bed shear stress for deposition with calculated bed shear stress.

The density of the fluid mixture - Sediment content in the fluid mixture impacts its density, which is modelled as a function of sediment concentration and the density difference between water and sediments. This enables the effect of density currents.

The model boundary condition for transport - Boundary conditions for transport define concentrations of salt and sediment at the edges of the simulated estuary. A smooth transition of concentrations follows a Thatcher-Harleman half-cosine condition. Boundary values remain constant until outward flow begins.

Consolidation and settling - Delft3D-FLOW can not simulate sediment consolidation. Consolidation has an impact on the erodibility of the bed. Consolidation occurs as sediment particles settle and densify, making denser layers less erodible. Limitations in simulating consolidation stem from the inability to establish sediment bed layers with increasing density in-depth and considering time-dependent density changes. To address this, the study model uses a 0.1 m top layer with low critical bed shear stress, representing easily erodable muddy sediment, with no erodable sediment beneath it.

Stratification in Delft3D model The simulations begin with initial conditions defined in a file that specifies salinity levels in each grid cell, data derived from the output of a pre-existing 2D model. Boundary conditions for various sections of the grid are set to account for the salt transport conditions of each location, using standard values from the Alkyon model. For instance, the Ocean boundary experiences water influx with a salinity of 32 ‰, while the salinity levels are 16 ‰ and 0.1 ‰ for the Commewijne River and Suriname River boundaries, respectively (Zwol, Quist, and P.J. Plooy 2008; Loose 2008). Additionally, due to the short length of the Commewijne River in the model, salt intrusion occurs further upstream from the set boundary. Reaching an equilibrium stage for the finest sediments and salt intrusion into the entire bay requires considerable time and cannot be achieved within the simulation period. Thus, a restart file with initial conditions from previous runs facilitates equilibrium in salinity during calibration. Saltwater intrusion from the Atlantic Ocean into the Suriname River is a critical factor that substantially affects the sedimentation processes due to salinity differences leading to sediment flocculation. Therefore, Alkyon dedicated extra effort to correctly calibrate the salinity intrusion, and the model was run until an equilibrium situation was reached. This equilibrium initial conditions file is used for the salinity in the model in this research.

Sediment in Delft3D model From the start of the simulation, a single fraction of sediment is present in the system. This sediment is found in different forms: primarily within a 0.1m bed layer that covers the entire domain, and secondarily through sediment concentrations included in the initial conditions file. The initial conditions file, used at the start of the computations, specifies the sediment concentrations in every grid cell. It is derived from the output of a 2D model, at the same simulation time as the start of the 3D simulation.

Additionally, the boundary conditions determine the sediment concentration entering the domain. These conditions are set at the same boundaries as the grid model. Specifically, the Ocean boundary is defined as a yearly mean value of 0.2 kg/m³ for all sections, an estimate representative of the mean sediment influx in the model area. Both river boundary conditions are set as zero, based on the assumption that sediment transport from upstream is negligible. Literature supports this, stating that little sediments from the landside (approximately 0.02 kg/m³ at Suriname River, according to Nedeco, 1986) are transported into the river and that these sediments are primarily sand particles, not mud. Finally, a Thatcher-Harleman boundary condition is established for all transport boundaries, set at 180 minutes.

4.4. Adjustments Hydrodynamic Model

Considering the model requirements, discussed in 4.1, several hydrodynamic processes are included in the original model. The model can accurately simulate a complete tidal cycle. Hydrodynamic boundary conditions, such as the Guyana Current and the River Discharges, are set up. Stratification is simulated in the estuary due to the 10-layer 3D model. This causes gravitational circulation which is also simulated by the model.

The main processes not included in the original model, which are necessary (see section 3.5) are wind and waves. Also, a change to the bathymetry is necessary for the future situation where the mud-bank migrates across the estuary. The reason why these processes are necessary, and how they are implemented, is discussed in this section.

4.4.1. Wind and Waves

The effect of waves is an important process because of the stirring-up of sediment they induce. Their effect on the bed shear stress is the main reason wave conditions must be included. The waves also induce currents, but these are of less importance. The sediment stirred up by the waves is transported by other currents in the system. The currents induced by waves have a far smaller effect on sediment transport. This means the wave direction is of smaller importance for the sediment transport study.

In this case, the FLOW and WAVE modules are coupled and thus influence each other. The WAVE module is updated every 30 minutes by the FLOW module. Because the model is run coupled, the WAVE module can use up-to-date water levels. The effect of the tidal range on the penetration of waves into the system is therefore simulated. During higher water levels, waves penetrate further into the estuary.

An average yearly wave condition is used as forcing on the northern boundary of the model. The wave conditions vary yearly, mainly between the summer and winter periods. Therefore, a normative wave condition was chosen. An extreme value analysis (EVA) of the wave and wind climate was used as the basis of this decision (see appendix A). The yearly normative wave height is 1.5 m with a period of 6.9 sec and a nautical direction of 64 deg. To account for some variation in the direction a directional spreading of 4 degrees is set. This wave condition is imposed on the northern boundary of the grid during the entire period.

A new grid and bathymetry file were constructed for the WAVE module 4.1. By only imposing the wave condition on the northern boundary, part of the eastern side of the domain is not subjected to wave. This is due to the wave direction causing a shadow effect. This was solved by extending the original FLOW grid by 12.5 km towards the east. The original bathymetry was extended to create a new file for the WAVE module. It was assumed the variation on this side would be minimal.

For the wind, a year-average condition is considered in the model (7.5 m/s). As the wind blows constantly from the east/northeast, a direction of 70 degrees is used.

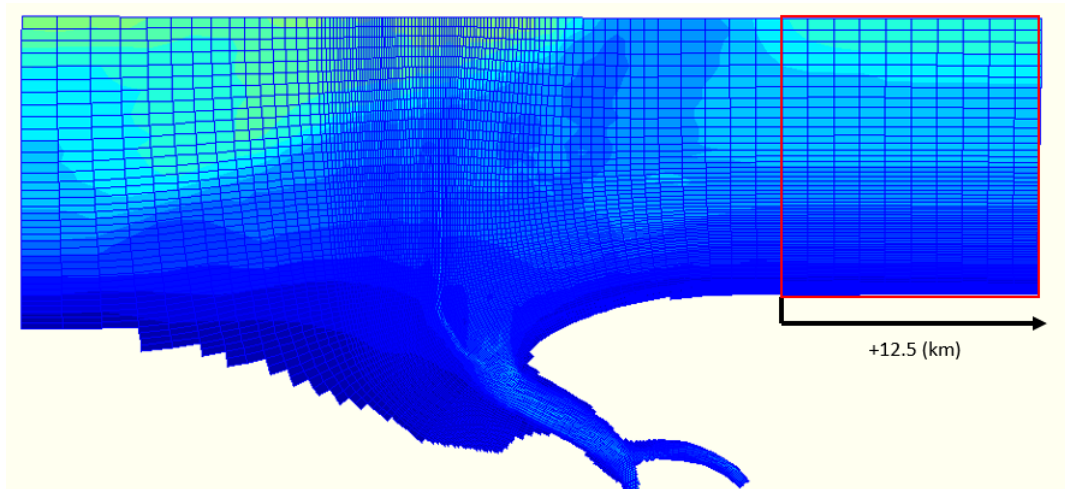


Figure 4.1: The new WAVE grid, showing the extended stretch on the east border of 12.5km, including the extrapolated bathymetry file.

4.4.2. Bathymetry

A mudbank complex is currently situated on the eastern mudcape of the Suriname Estuary. It is expected that in five to ten years, this mudbank will migrate across the estuary. As was discussed in 3.5, this will have a significant influence on the hydrodynamic and sediment processes in the estuary. Therefore, it will likely have a significant influence on the feasibility of mud nourishment.

To research the impact of the mudbank, this situation will be simulated using the Delft3D model. The main hydrodynamic processes influenced by the migrating mudbank are waves. It is expected that the waves will refract and attenuate due to the smaller depth over the mudbank. To incorporate this effect in the hydrodynamic model, the bathymetry will be adjusted to include the mudbank feature.

It is unknown what the exact dimensions and shape of the mudbank will be during migration. Also, the difference between fluid mud and a bathymetric feature of the mudbank is not known. For these reasons, a schematisation must be made. Past research, in which the mudbank complex size was determined, was used to make this schematisation (Chevalier, Froidefond, and Devenon 2008, NEDECO 1968). The dimensions were mainly based on the main contour lines, the orientation and the fact that they stretch out to the -10 isobath.

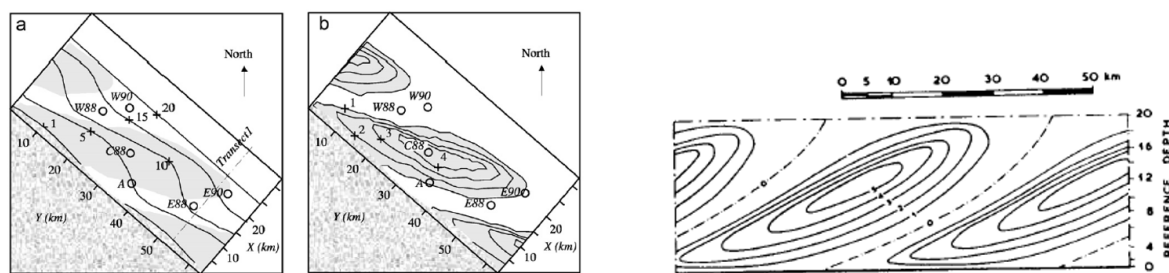


Figure 4.2: Left & Centre: Schematisation by Chevalier, Froidefond, and Devenon 2008 showing extension offshore, orientation and contour lines. Right: Schematisation by NEDECO 1968 showing length and contour lines.

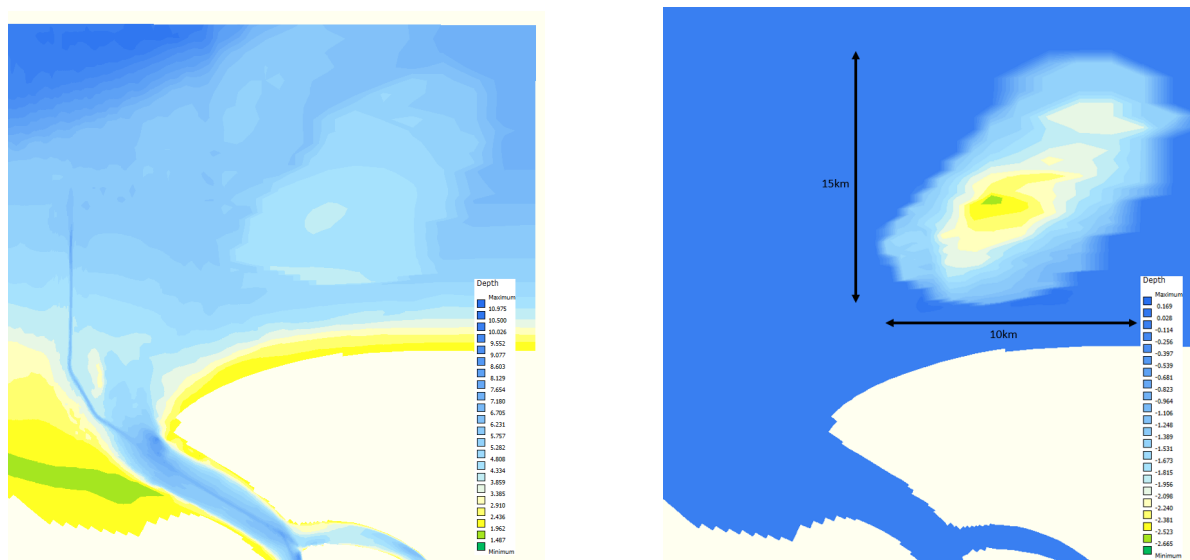


Figure 4.3: **Left:** The bathymetry file developed for simulations where a mudbank is present to the east of the estuary, showing the absolute depths. **Right:** Here, the depth of the mudbank is presented separately, showing the absolute difference compared to the original bathymetry. Here, the shape and contour lines are more visible.

4.4.3. Grid Refinement

Originally, the model was engineered to facilitate analysis of sedimentation within the river fairway, resulting in a higher resolution in that specific area. However, the model's objective has shifted towards examining sediment dynamics in other areas such as the mouth of the estuary, the intertidal flat, and the Weg naar Zee coast. Consequently, these areas necessitate an enhancement in resolution.

In response, the resolution in these areas was boosted by 33%. Conversely, due to the need for more efficient calculation times, the resolution of the river fairway was reduced by 33%.

To enable grid alteration, components of the Delft3D model, specifically various sub-files, required modifications. Not all were significant as they didn't impact the functionality of the model. Nevertheless, one notable change was made to the initial conditions file.

Previously, bed roughness was detailed for designated areas, due to the requirements of the older model's purpose. In contrast, the current model employs a universal k_s roughness value of 0.0035 throughout the entire domain. This choice is justified by the fact that this was the value initially assigned to the river and estuary mouth.

4.5. Adjustments Sediment Model

To facilitate the new purpose of the model, several changes had to be made. These changes are addressed in this paragraph.

Extra Sediment Fraction

Currently, a single sediment fraction is applied throughout the model domain. This fraction is named "Sediment Silt". To distinguish this background sediment from the inputted sediment and second fraction is added to the model, namely "Sediment Nourishment". The fractions both have the same characteristics. In a later stage, if alterations are made to the "Sediment Nourishment" fraction, these will be addressed. The initial conditions for the background "Sediment Silt" remain the same as listed in 4.3.

5

Hydrodynamic Model Results

To be able to make an informed decision on where sediment should be introduced into the system, it is necessary to have an understanding of the hydrodynamics. Furthermore, the hydrodynamic model should accurately replicate the real-life processes described in the conceptual model. If this is the case, the hydrodynamic model can be utilized to simulate sediment dynamics, serving as a research method to assess the feasibility of nourishment.

For this reason, model output, which is generated for several key hydrodynamic parameters, is displayed and analysed in this chapter. The main parameters we are interested in are listed below, including the section in which they are discussed. For each parameter, key plots are discussed for the different scenarios. The key takeaways for each parameter are elaborated.

1. Wave height [m] and -dissipation [W m^{-2}]
2. Wave direction and spreading [°]
3. Bed shear stress [Pa]
4. Flow velocity [m s^{-1}] and patterns

The chapter concludes with a conclusion, joining the key findings. Here, the consequences of the findings for the possible sediment input locations and timing are explained. These will be formulated in a map showing the main promising areas. This information will be key for the coming chapters, in which the sediment modelling will be discussed.

5.1. Hydrodynamic Model Scenarios

To research the system's hydrodynamics, several scenarios are simulated to assess different occurring parameters. As discussed earlier, the seasonality of the Suriname Estuary plays a minor role. For this reason, it is chosen only to analyse two wave climates: normal and storm conditions (see paragraph 4.4.1 for further explanation). Another scenario change is the mudbank complex approaching the estuary (see paragraph 4.4.2 for further explanation). This results in four scenarios, displayed in Figure 5.1 earth

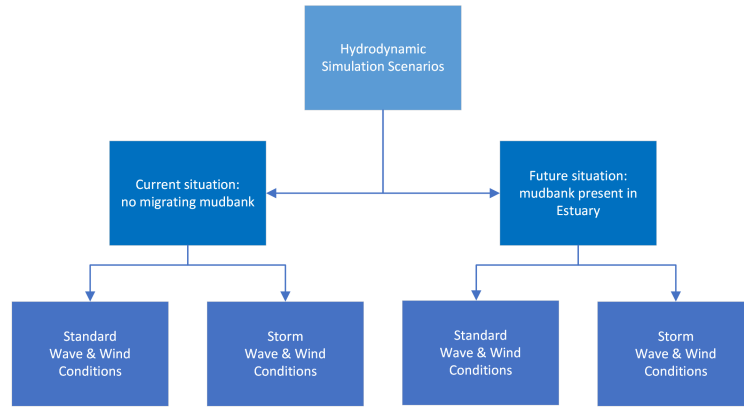


Figure 5.1: This flowchart breaks down the scenarios executed for the hydrodynamic analysis. It mainly distinguishes between situations where a mudbank is present or not, as well as scenarios with standard and storm wave/wind conditions.

5.2. Wave height and dissipation

As discussed in the previous chapter, the WAVE module was added to the Delft3D model to account for the influence of waves in the estuary. The wave height and the influence the bathymetry has on this height are expected to differ for the different scenarios. To display this Figure 5.2 shows the wave height (m) and dissipation (W m^{-2}) throughout the domain.

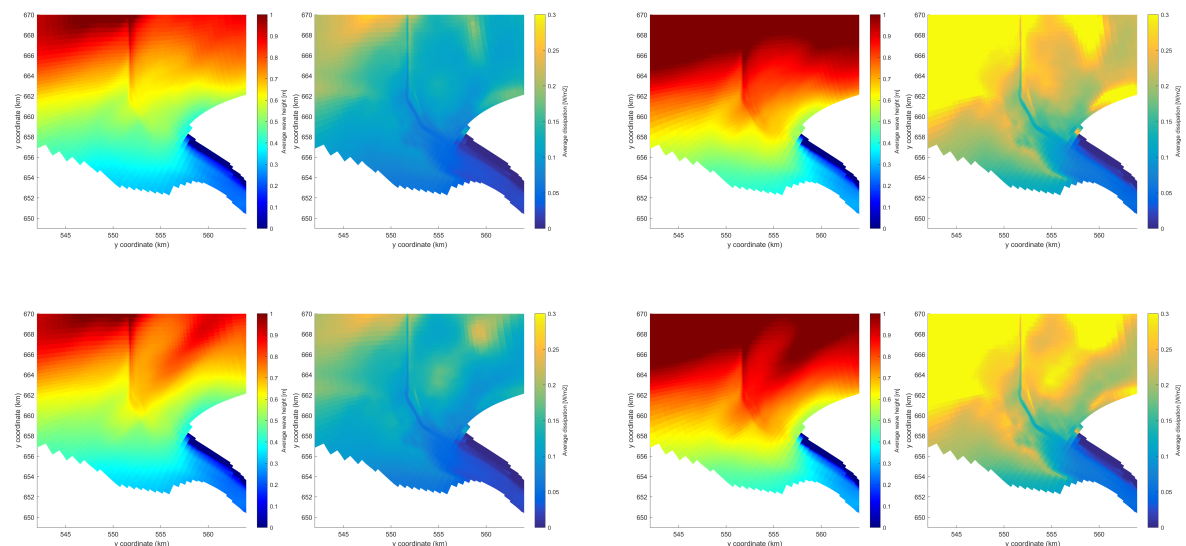


Figure 5.2: Top row: These are the simulations without a mudbank present. The two figures left are the average wave height and dissipation for normal conditions. The two figures to the right are for storm conditions. **Bottom row:** These are the simulations with a mudbank present. The two figures left are the average wave height and dissipation for normal conditions. The two figures to the right are for storm conditions.

The waves during the storm scenarios penetrate further into the estuary. The average wave height on the intertidal flat in front of Weg naar Zee is approximately 0.5 m, while in the normal scenario, this is around 0.3 m. As expected, the average dissipation is higher for the storm scenario, as higher waves penetrate further onto the same bathymetry. An observation is that the average dissipation on the border of the inter-tidal flat is only around 0.1 W m^{-2} in the normal situation. During storm conditions, the average dissipation is 0.2 W m^{-2} .

For both scenarios, the presence of the mudbank does not seem to change the situation at the intertidal flat and Weg naar Zee. At the mudbank location itself, some variation in wave height and dissipation can be seen, but it seems to have little influence further in the estuary.

5.3. Wave direction and spreading

Alongside the wave height and dissipation, the wave direction throughout the estuary is important. In Figure 5.3 the average wave direction (as vectors) and directional spreading of the waves (deg) are shown. The spreading is an indicator of wave refraction due to bathymetric change.

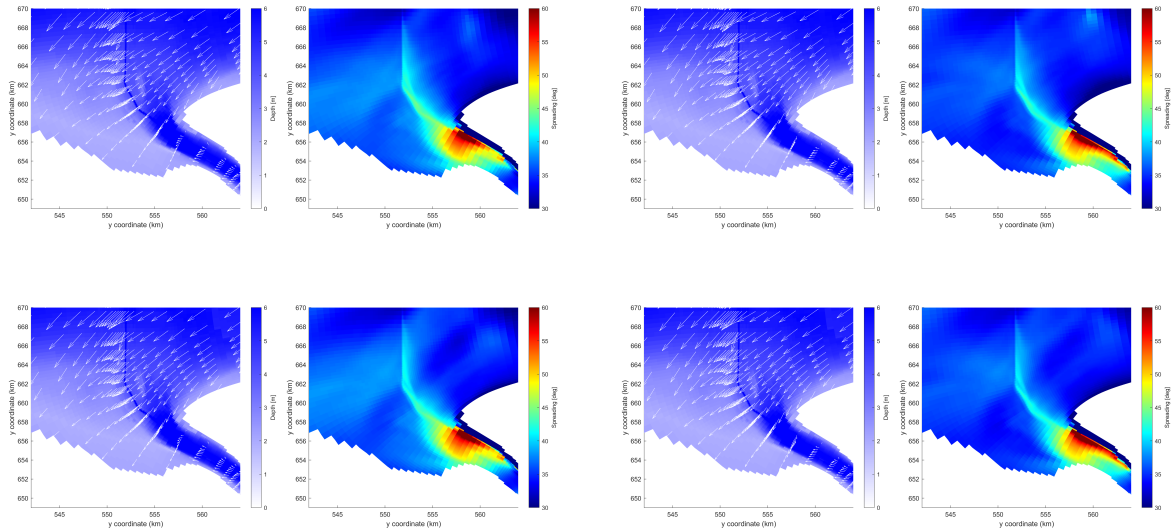


Figure 5.3: **Top row:** These are the simulations without a mudbank present. The two figures left are the average wave height and dissipation for normal conditions. The two figures to the right are for storm conditions. **Bottom row:** These are the simulations with a mudbank present. The two figures left are the average wave height and dissipation for normal conditions. The two figures to the right are for storm conditions.

The plots demonstrate a low influence from the wave climates and the mudbank on the average wave direction. For all scenarios, the waves approach Weg naar Zee and the intertidal bank in front of it in a perpendicular fashion. During the storm conditions the higher values of wave directional spreading are found deeper in the estuary mouth. That shows the waves refract further into the estuary mouth around the Braamspunt cape.

5.4. Bed shear stress

The hydrodynamic factors such as tidal flows, currents, and waves play a significant role in shaping the bed of the domain. Bed shear stress (BSS), an important byproduct of these factors, tends to be higher in areas experiencing higher flows and wave activity combined with lower water levels. The occurrence of these stresses significantly influences the erosion and subsequent displacement of sediment from the estuary bed. Therefore, it becomes important to pinpoint the locations where such stresses are most likely to occur during the simulation period. It is in these locations that sediment displacement will be at its peak, thus preventing the sediment from remaining deposited on the estuary bed.

Instead, the eroded sediment is likely to be swept along, and suspended in the water column as SPM. This highlights the importance of analysing the occurrence of bed shear stress across the domain, in order to properly comprehend and predict sedimentary dynamics.

The impact of tidal flows and currents, as well as wave energy on bed shear stress, can be differentiated through Figure 5.4. This Figure presents a comparison of the average bed shear stress during the entire simulation period. On the right, the occurring bed shear stress applies only to the FLOW module. On the left, the situation shows when both the WAVE and FLOW models are operating.

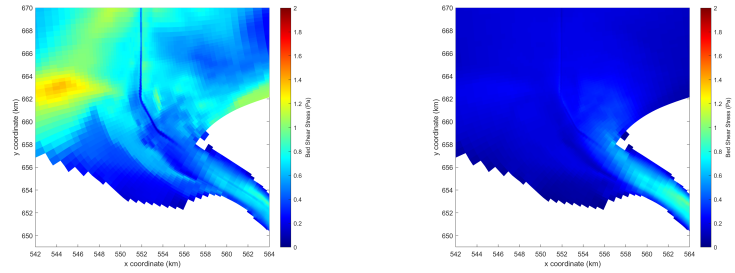


Figure 5.4: **Left:** This section presents the mean bed shear stress (Pa) over the entire simulation period (spring-neap tidal cycle), occurring within a specific domain of the Suriname Estuary, based on a coupled model. This model incorporates the combined influences of both FLOW and WAVE modules. **Right:** This plot reflects the same area, yet considers a non-coupled model that is solely influenced by the FLOW module.

Clearly, the influence of waves on the bed shear stresses that occur is of great importance. When only the FLOW module is used, it primarily generates bed shear stresses in the deeper gully of the estuary mouth. This is due to the higher flow velocities produced by tidal flows. In the rest of the estuary, waves are the main generators of bed shear stress. The beneficially reused sediment will be unloaded at the borders of the deeper gully and the foreshore of the intertidal flat. These areas only exhibit bed shear stresses caused by wave influence. Therefore, waves will play a significant role in generating bed shear stresses in the areas where the sediment will be introduced into the system.

Further diving into the average bed shear stresses occurring for different situations, we can compare the situation with and without the mudbank complex present, and with normal or storm conditions. These four situations, with the average bed shear stress over the entire simulation period, are plotted in Figure 5.5.

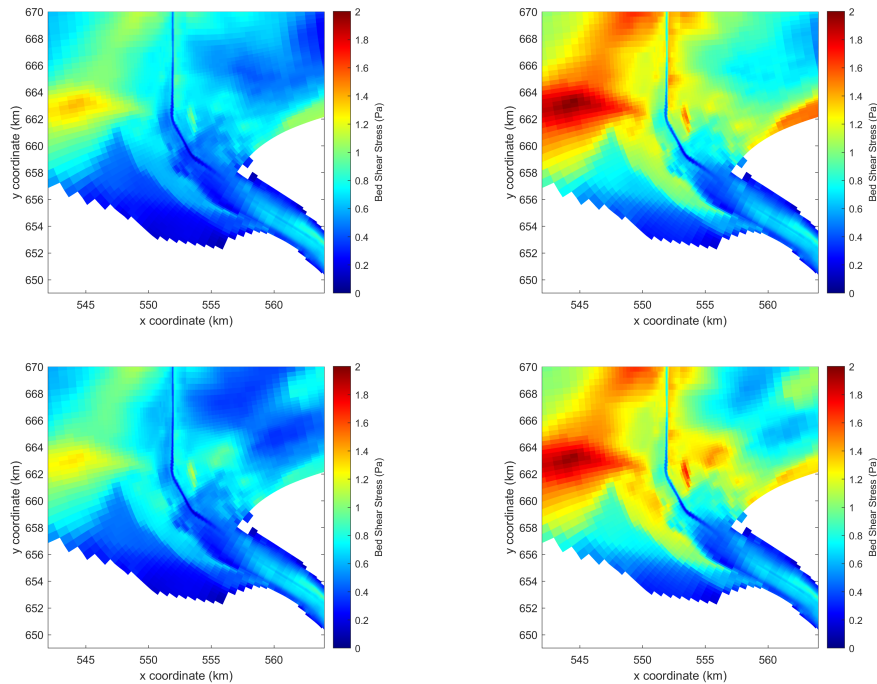


Figure 5.5: Images depicting average BSS levels over the entire simulation period. Top row: Simulations without a mudbank. The figure on the top left shows the average bed shear stress under normal conditions, while the figure on the top right shows the same under storm conditions. Bottom row: Simulations with a mudbank. The figure on the bottom left shows the average bed shear stress under normal conditions, and the figure on the bottom right shows the same under storm conditions.

As expected, based on earlier results regarding wave influence, the schematised mudbank has a minor influence on the bed shear stresses occurring in the estuary near Weg naar Zee. Some minor differences can be observed at the mudbank's location. However, the wave conditions have a far larger influence, particularly on the transitional area between the deeper channel of the estuary and the intertidal area in front of the Weg naar Zee coastline.

Up to now, we've only taken into account average values spanning the entire simulation period. To gain a more detailed perspective, it's important to distinguish between spring and neap tidal cycles. The broader range of water levels throughout these cycles undoubtedly influences the bed shear stresses exerted on the estuary bed. The influence of the mudbank is now left out. The generated plots can be seen in Figure 5.6.

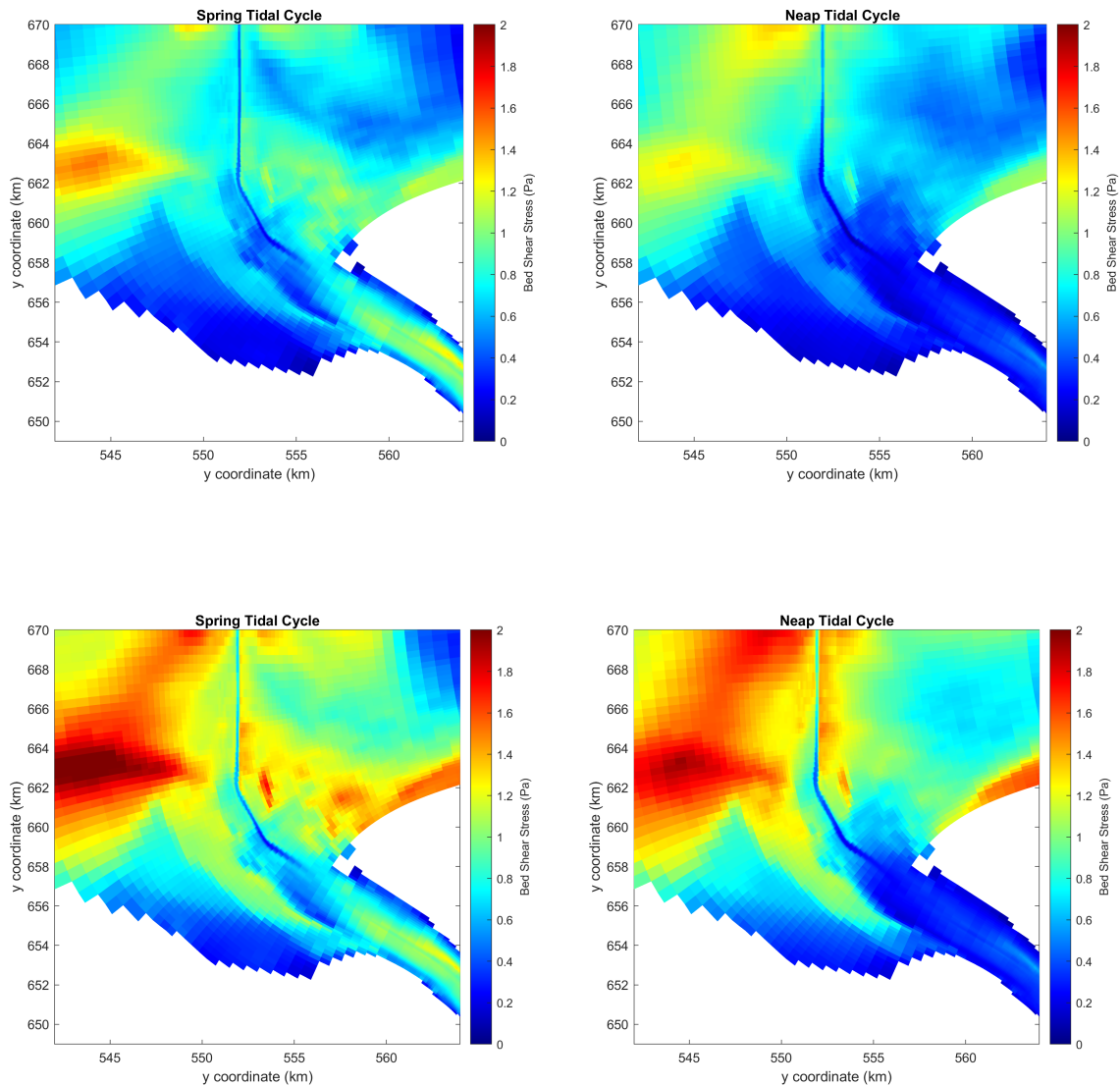


Figure 5.6: These are all simulations without a mudbank present. The top row shows a simulation with normal conditions. The bottom row shows a simulation with storm conditions. The images to the left show the average BBS over a spring tidal cycle, and to the right over a neap tidal cycle.

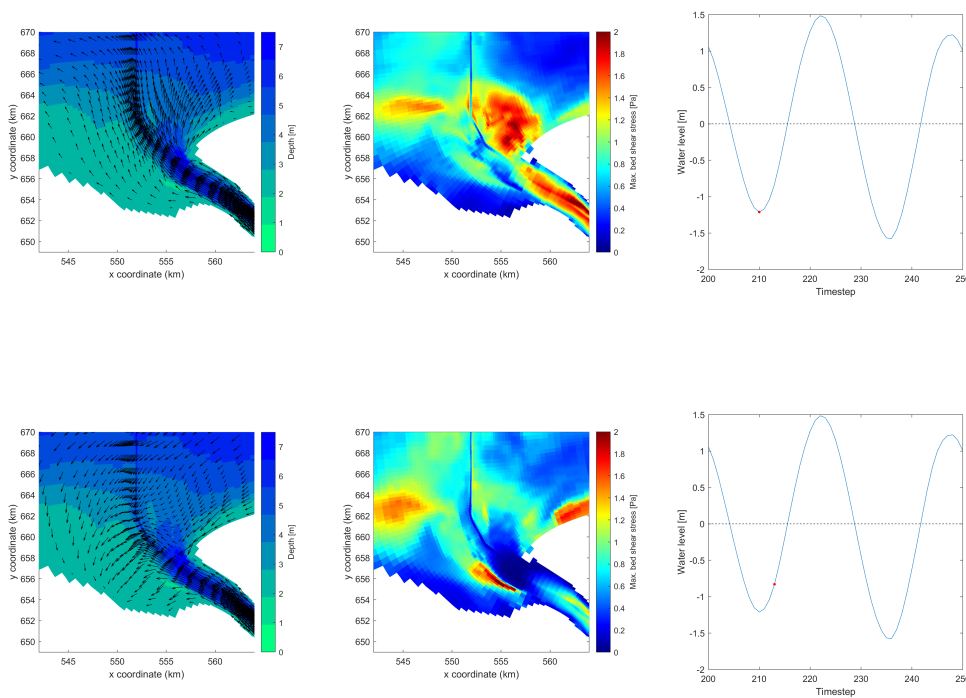
Based on these plots, we can conclude that the spring tidal cycle, with its larger water level range, generates higher average bed shear stresses. While this is generally true, the differences on the intertidal flat in front of Weg naar Zee are relatively small, with the difference between the average values during normal conditions being around 0.1 Pa. Interestingly, during storm conditions, the average BSS values in this area are almost identical.

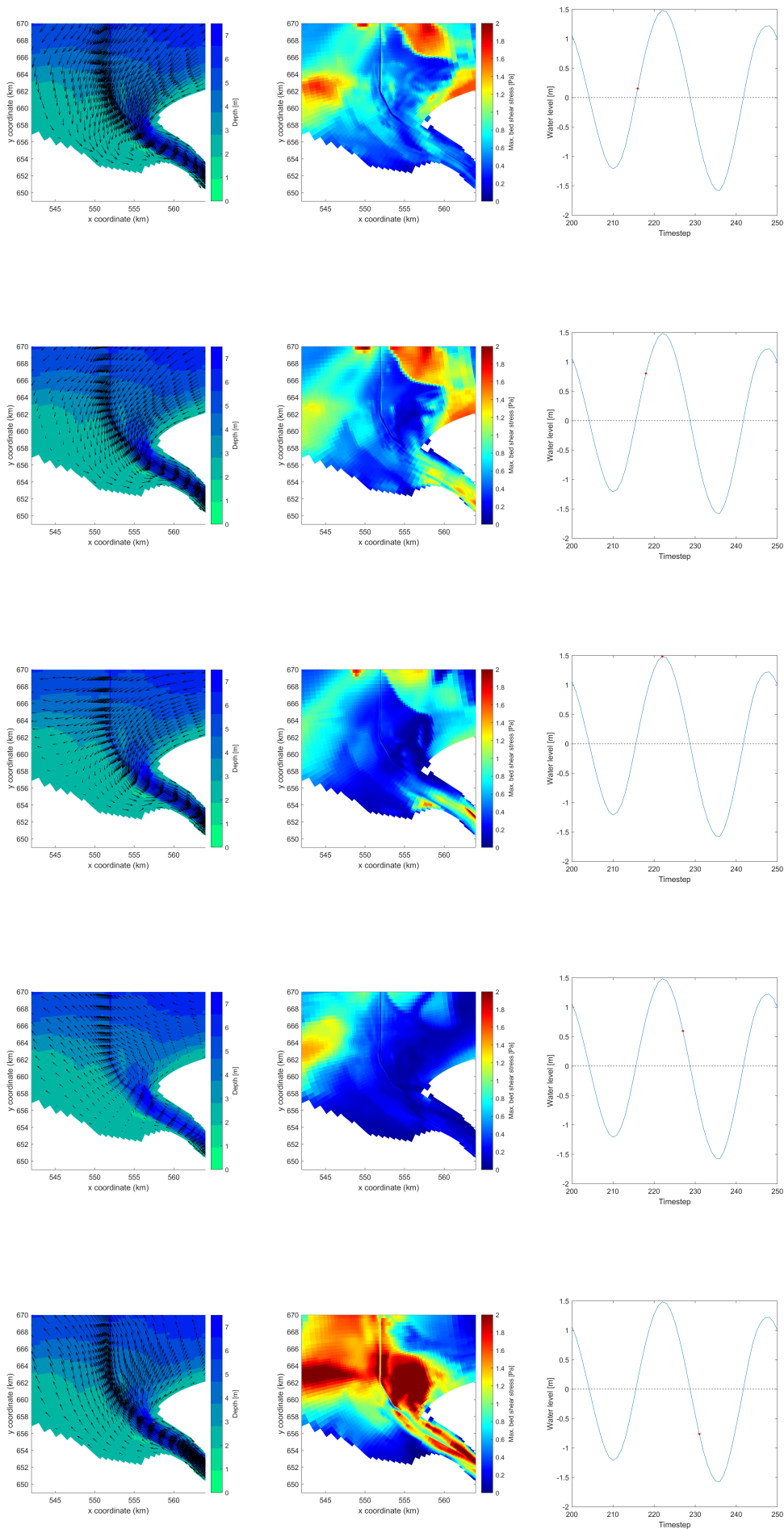
5.5. Flow velocity and patterns

For a full understanding of the dynamics during the simulation, analysing a single tidal cycle becomes essential. The focus here is on the variations in flow velocities and direction throughout this cycle. Bed shear stress, which occurs during this cycle, marks the spots where sediment could be drawn into the flow. To illustrate this, we consider a tidal cycle for a situation without a mudbank under normal wave- and wind conditions. A spring tidal cycle is selected for this analysis due to its highest range and, as observed earlier, highest bed shear stress values.

The sequence begins at low tide, with water continuing to out-flow in the estuary. This low water level gives rise to increased wave influence on the sea bed and thus increased bed shear stresses. The images that follow, right up to high water, reveal a shift in the flow pattern. Now, the flow creates a circular movement over the intertidal flat and towards the estuary mouth, flowing in line with Weg naar Zee.

Once we reach high water, the bed shear stresses decrease. After high water, the pattern adjusts back to outflowing, with the water following the same circular route, but now directed westwards. During this phase, the bed shear stresses are noticeably high in the deeper gully and on the edges of the intertidal flat. These patterns will be instrumental in pinpointing potential sediment input areas.





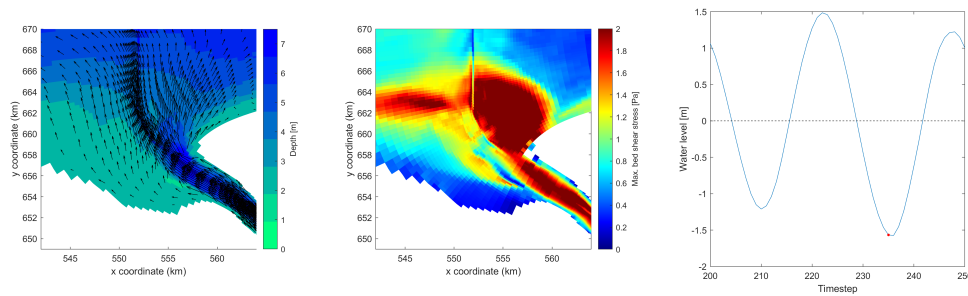


Figure 5.7: This series of eight snapshots spans a spring tidal cycle, starting and ending at low water. This represents the situation without a mudbank under normal conditions. LEFT: flow velocity vectors and bathymetry are shown. CENTRE: shows the current maximum BSS values, which range up to 2 Pa. RIGHT: the current water level throughout the tidal range is displayed.

5.6. Conclusion

This chapter delves into the results of the hydrodynamic model, a critical tool for understanding sediment dynamics and evaluating the feasibility of sediment nourishment. The model successfully simulated several dynamic processes within the Suriname Estuary, giving insight into various essential hydrodynamic parameters. The key hydrodynamic parameters examined in this chapter were:

1. Wave height [m] and wave dissipation [W m^{-2}]: The simulations showcased the differences in wave height and dissipation for normal and storm conditions, both with and without the presence of a mudbank. While the presence of the mudbank had little influence, storm conditions resulted in higher wave heights and dissipation, especially deeper into the estuary.
2. Wave direction and spreading [deg]: The wave direction throughout the estuary was analysed, along with the directional spreading, which indicates wave refraction due to bathymetric changes. The simulations revealed that wave direction remained relatively consistent across scenarios, approaching the coast in a perpendicular fashion.
3. Bed shear stress: Bed shear stress, generated by tidal flows, currents, and waves, plays a significant role in shaping the estuary bed. The simulations showcased the occurrence of bed shear stress across the domain, highlighting areas of higher flow velocity and wave activity combined with lower water levels. These areas are prone to sediment displacement, indicating potential sediment input locations.
4. Flow velocity and patterns: Analysing flow velocities and patterns during a tidal cycle provided insights into the dynamics of sediment transport. The simulations illustrated the variation in flow patterns throughout the cycle, emphasising the circular movement over the intertidal flat and towards the estuary mouth. These flow patterns correspond to high bed shear stresses and may serve as key areas for sediment input.

Based on the analysis of these hydrodynamic parameters, promising areas for sediment input were identified. These areas consider flow patterns, occurring bed shear stress, and wave influence. A map highlighting the potential sediment input locations, depicted by green areas, was included to support this conclusion.

It is important to note that the findings from this chapter form the basis for the following chapter. These chapters delve into sediment modelling. The information gathered here will serve as a basis for further exploration of the feasibility and effectiveness of sediment nourishment in the identified promising areas.

Area 2, highlighted in green on the map in Figure 5.8, represents the most promising location for sediment input, taking into account flow patterns, wave influence, and proximity to the shoreline. The flow pattern, as shown in Figure 5.7, indicates that any input in this area would follow transport paths towards the coast during rising tide. BSS levels are significant, suggesting that sediment would be stirred

up off the bed in this area. Additionally, this area is relatively close to the shore.

Areas 1 and 3 also show promise, but they have certain drawbacks. Area 1 has favourable flow patterns but is not close to the shore. Area 3 is closer to the shore but lacks higher BSS levels and has less pronounced flow patterns. However, this area shows promise during falling tides.

On the other hand, areas marked in red are deemed unsuitable for sediment input. These areas are inaccessible or do not exhibit the promising factors seen in Areas 1 to 3. Overall, the results from the hydrodynamic model have provided valuable insights into the system's dynamics, which will help inform future decision-making regarding sediment input in the Suriname Estuary.

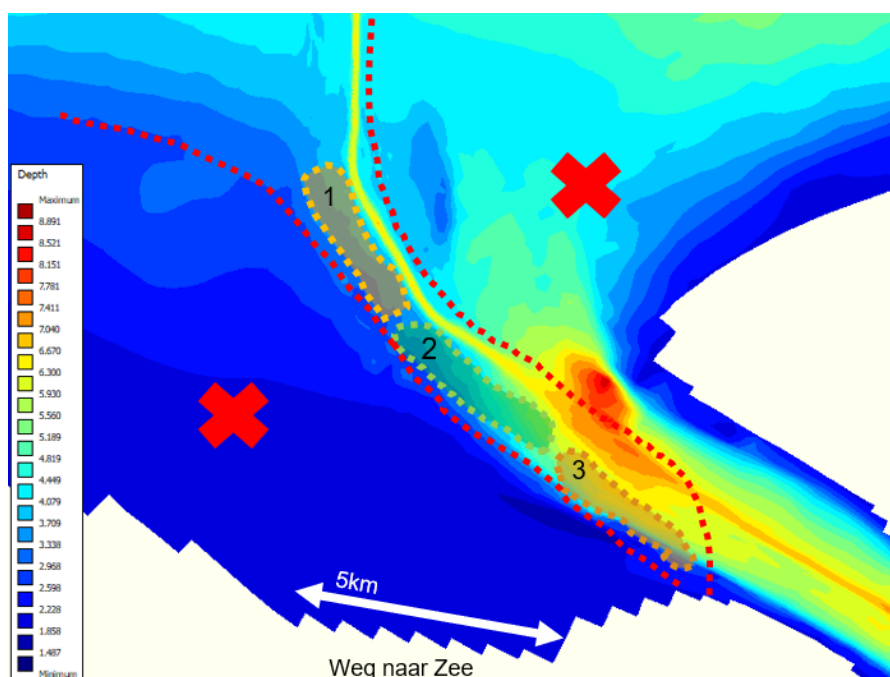


Figure 5.8: The Figure below illustrates potential locations for sediment input, as determined by the hydrodynamic analysis. The area highlighted in green is considered the area with the highest potential due to the flow patterns, wave influence, and proximity to the shore. Areas in orange show promise but less than the green area. Conversely, the areas marked in red are deemed unsuitable for sediment input.

6

Sediment Model Results

The previous chapter elaborates on the hydrodynamics of the Suriname River Estuary during a spring-neap tidal cycle. This information is necessary to investigate further one of the sub-research questions: What is the potential effectiveness of sediment input in the estuary? Using the insights from the last chapter, the focus can be placed on several promising input locations. A suitable input time in the tidal cycle can be determined for these locations. The sediment input should also be adequately modelled in the simulation to reflect real-life input techniques accurately. Two types of sediment transport will be considered in this study.

This chapter will discuss various aspects related to the effectiveness of sediment input. Firstly, the plan of approach for determining the sediment input effectiveness will be explained in the next section. Then, the selection criteria for testing locations and times will be elaborated for two transport types. The method of simulating sediment input in the estuary will be explained subsequently. After that, the initial test results will be described. Finally, the changes made to the model based on the initial results and the improvements achieved with the new model will be discussed.

6.1. Approach for Sediment Modelling

The potential effectiveness of sediment input can be determined by considering two types of transport. The first type involves the sediment transport in the water column, known as plume dispersion. The second refers to the sediment transport across the estuary bed under the influence of wave forcing. Each transport type will be modelled and assessed separately. This enables the results to be distinguished accurately.

A step-by-step approach has been outlined for modelling both transport types. The aim is to continuously refine these steps and adjustments to arrive at final results that accurately depict the real-life scenario. The steps for modelling plume dispersion will be discussed first, followed by the steps for modelling bed transport. The approach for the modelling of initial plume dispersion is as follows:

1. The hydrodynamic model results from the previous chapter are interpreted to select sediment input locations. Five locations are selected, thereby not creating too many simulations but still being able to differentiate the workings of the locations. The locations are based on occurring bed shear stress, wave action, and (tidal) flow patterns. Another factor which is acknowledged, not considered in the previous chapter, is ship navigability.
2. Suitable times for sediment input throughout the tidal cycle are selected for each location. This timing is based on the tidal cycle. For example, a location could be more effective during a rising tide, while another works mainly during a falling tide. Locations are tested during an average tidal cycle early in the simulation, thus being able to simulate sediment transport during the entire simulation.
3. Sediment is brought in once to be representative of a single barge load of sediment in the field. The sediment characteristics and the dredging equipment used determine model settings. Also,

inserting the sediment into the system represents the unloading times and techniques used in the field.

4. The representative load is simulated for the input locations and their corresponding timing. A single load is simulated, so the spreading of a singular load can be assessed. A single load does not resemble a realistic situation, as multiple loads will be inputted. Therefore, the results of a single load are scaled up accordingly.
5. The results of the different simulations are analysed. The spread of the plume and the percentage that reaches Weg naar Zee (WnZ) and the adjacent intertidal zone are important factors to

Approach for modelling of wave-influenced bed transport:

1. The locations for sediment input are determined based on two important factors. The first factor to consider is the levels of BSS observed throughout the simulation phase. The second factor involves practical considerations, specifically the accessibility of the location to vessels and its low slope levels. Three locations spread over the promising area where input is deemed promising are considered. Unlike the plume dispersion transport type, timing isn't anticipated to be as critical. All input occurs at the beginning of the simulation, and the analysis is conducted over the entirety of the simulation's duration.
2. In a fixed area of 2x2 grid cells, a volume of sediment is included in the initial model conditions. This volume represents a fixed number of barge loads. The surface area varies slightly for the three locations and has an average value of 13.9 ha. In contrast to the plume dispersion transport type, multiple amounts of barges are now considered. Assuming all sediment stays on the bed within this allocated area, the height of the sediment mound can be determined. This height is modelled in the bathymetry, thus accounting for the increased wave influence caused by the mound on the bed. The sediment is initially present in the model and thus undergoes the influence of wave and flow forcing throughout the entire simulation.
3. The simulations of the chosen locations are analysed. A balance of the spread of sediment throughout the simulation is made. The initial volume of sediment in the area covered by the 2x2 grid cells is expected to have decreased drastically. The focus is on what percentage is found in several key areas. These areas include the intertidal flat, indicating the sediment directed towards WnZ, the sediment already reaching the WnZ coastline, and the sediment untraceable to these regions or the initial area, hence considered lost.
4. Using these results, the efficiency levels of the different locations are compared. The reasons for the differences in the results are discussed.
5. A sensitivity analysis is done for critical parameters of which the specific value is not known precisely. This shows the influence changing this parameter within its range of uncertainty has on the results.

6.2. Transport Type 1: Plume Dispersion

This section discusses the modelling work conducted to evaluate the feasibility of transporting sediment in the form of Suspended Particulate Matter (SPM). This sediment was modelled as a plume moving through the water column towards the Weg naar Zee coastline, driven by hydrodynamic processes.

6.2.1. Selection of Sediment Input Location and Timing

Five test locations for the sediment input are selected based on the factors discussed in 6.1. Location 1 (North), Location 2 (North-Centre), Location 3 (Centre), Location 4 (centre-South) and Location 5 (South). See Figure 6.1 for an overview of these locations. Each location has positive and negative characteristics that will determine the efficiency of inputting sediment at that location. Also, different input times in the tidal cycle are necessary due to the various locations in the estuary. For each site, these characteristics and input times will be discussed here.

Location 1 (North) is furthest from the Weg naar Zee coast and the estuary mouth. It is at the reachable transition between the shipping lane and the intertidal flat. Waves have been attenuated less than for the other locations and have a higher impact. This location uses the flow patterns associated with the incoming water of rising tide. Thus, two input times are selected: low tide and mid tide (rising).

Location 2 (North-Centre) is fairly close to the North location but has the added advantage of being closer to the estuary’s active centre. This location offers a balance between wave attenuation and impact. Suitable input times for this location likely include low tide and mid tide (rising), using the same flow patterns as location 1 (north).

Location 3 (Centre) is located centrally between the mouth of the estuary and the start of the outer shipping lane. It is situated in the transition between the inter-tidal flat and the area reachable by vessels. At this location, waves impact the intertidal flat perpendicularly due to refraction around Braamspunt and thus have a high impact. This location has a less clear favourable input time, so four input times will be tested. Low tide, high tide and mid tide (rising and falling).

Location 4 (Centre-South) is further down than the Centre, nearing the southern part of the estuary. This location offers a different dynamic as it is closer to the estuary mouth while still being significantly influenced by the intertidal flat. Being in the transitional area between the intertidal flat and the shipping lane, it experiences a fair degree of wave impact. The input times for this location would be high tide and mid tide (falling) due to the opportunity for efficient sediment distribution as the tide recedes.

Location 5 (South) is located at the estuary mouth and is closest to Weg naar Zee. It is located next to the shipping lane at the narrow transition between the intertidal flat and the area reachable for vessels. It is less reachable by waves and is more sheltered than the other locations. Only during falling and thus outflowing tide, this location is promising. Therefore, two input times are selected: high tide and mid tide (falling).

Timestep	Start	End	Tidal cycle
13	09:00:00	09:05:12	Low
17	10:50:00	10:55:12	Mid (rising)
23	13:40:00	13:45:12	High
30	17:30:00	17:35:12	Mid (falling)

Table 6.1: Timing information for each timestep

Loc #	Timesteps	M (grid)	N
1	(13, 17)	55	58
2	(13, 17, 23)	56	63
3	(13, 17, 23, 30)	58	70
4	(13, 17, 23)	59	80
5	(17, 23, 30)	59	90

Table 6.2: Location data for each timestep

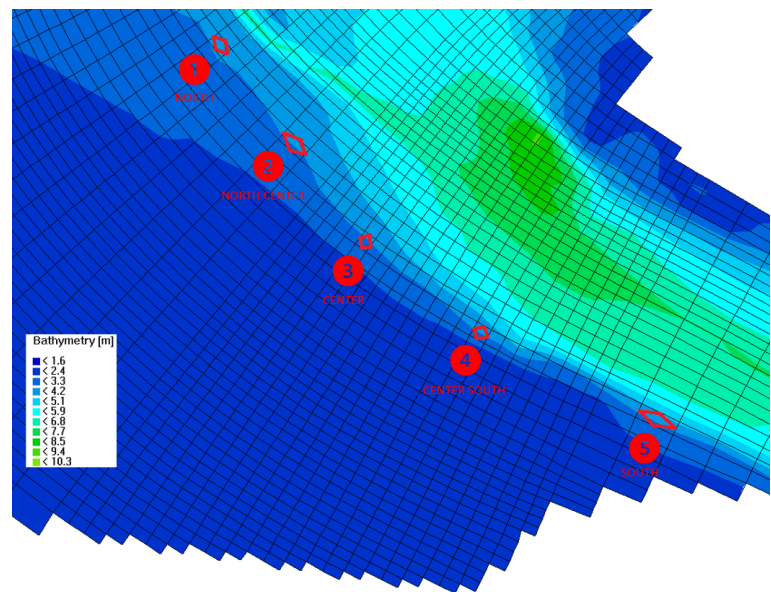


Figure 6.1: In this chapter, we discuss the sediment transport testing carried out at five locations, shown in this figure.

6.2.2. Modelling of Sediment Input Volume

The capital and maintenance dredging of the Suriname River is mainly executed by trailing suction hopper dredgers (TSHD). The different dredgers that are used for the project have varying capacities. The deposition techniques are the same for all vessels: deposition through doors or valves under the vessel, pumping the liquefied material through pumps and jets, and rainbowing. This modelling phase focuses on deposits through the doors under the vessel.

The model should accurately simulate the actual deposition process through the under-hull doors of the TSHD, mirroring its real-world application. The Boskalis Workability team, who worked on the Suriname Dredging Project, provided critical data representing a single dumping event within the Delft3D modelling environment. This was achieved using the "operation" functionality within Delft3D's FLOW module (see Table 6.3).

	Value	Unit
Dump time	312	s
Capacity hopper	3000	m ³
Flow	9.61	m ³ s ⁻¹
Density	1300	kg m ⁻³
Total sediment	3898	ton

Table 6.3: The model settings used for the operation modelled in the FLOW module to simulate a single barge load

These values are almost satisfactory for input in the "operations" functionality of FLOW. The final input variable is the input distribution over the ten layers of the 3D model. The selected input technique is to make distribution over top layer one and the bottom layers five up to 10, which account for approximately 33% of the water column. This simulates the sudden drop of the material, as it quickly drops to the bottom of the water column if it is dropped at once. The distribution thus is as depicted in Table 6.4.

z layer	water depth (%)	distribution (%)	input (kg)	density (kg m ⁻³)	time (sec)	input (m ³)	input debit (m ³ s ⁻¹)
1	20	10	3.90×10^5	1300	312	3.00×10^2	0.96
2	20	0	0	0	0	0	0
3	15	0	0	0	0	0	0
4	12	0	0	0	0	0	0
5	10	27	1.06×10^6	1300	312	8.18×10^2	2.62
6	8	22	8.50×10^5	1300	312	6.54×10^2	2.10
7	6	16	6.38×10^5	1300	312	4.91×10^2	1.57
8	4	11	4.25×10^5	1300	312	3.27×10^2	1.05
9	3	8	3.19×10^5	1300	312	2.45×10^2	0.79
10	2	5	2.13×10^5	1300	312	1.64×10^2	0.52
SUM	100	100	3.90×10^6			3×10^3	9.61

Table 6.4: Breakdown of sediment input distribution over the water column. The distribution spans from the top layer (1) to the bottom layers (5-10), with a weighted average applied to layers 5 to 10. The total input is then translated from kilograms to an input debit per layer (m³ s⁻¹), serving as the model input.

Each simulation was executed over an entire spring-neap tidal cycle. The results demonstrate how sediment from a single Trailing Suction Hopper Dredger (TSHD) barge load would disperse throughout the system. Points of interest include this plume dispersion and the rate at which it dissipates. It is also interesting to examine if and to what extent this sediment would reach the Weg naar Zee coastline. If the efficiency of a single barge loading could be determined, these metrics could be contrasted across different locations and timings. Hence, using this information, the settings demonstrating the highest success rate could be subject to in-depth study, limiting the number of required simulations.

To achieve this goal, two areas near the Weg naar Zee coast were selected for analysis. The focus would be on the total kilograms of sediment flux that enters and exits the grid cells in this region. The first area is the shoreline of Weg naar Zee (left Figure 6.2). Assuming that a certain sediment quantity would be retained by the Sediment Trapping Units (STU) located at Weg naar Zee, this sediment level could gauge the input locations' effectiveness. The second area is the adjacent inter-tidal flat, the foreshore of Weg naar Zee, stretching up and till the deeper tidal channel (right Figure 6.2).

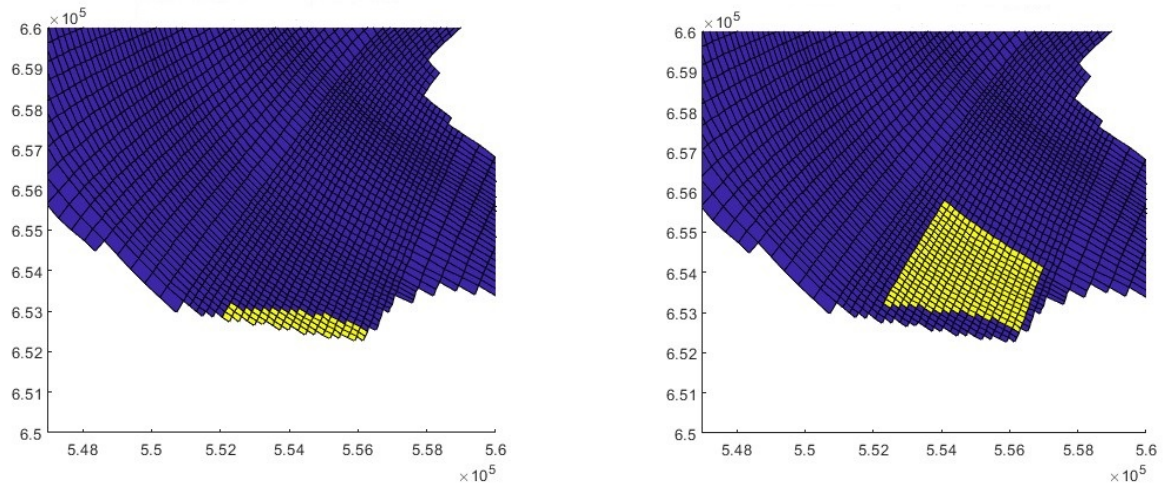


Figure 6.2: Left Figure: The selected grid cells, highlighted in yellow, represent the Weg naar Zee shoreline. This area, totalling 161 hectares, was used for the forthcoming analysis. Right Figure: The selected grid cells represent the inter-tidal flat, the foreshore of the Weg naar Zee coastline. Highlighted in yellow, it encompasses a total area of 820 hectares.

6.2.3. Model Simulation Settings

The model settings have not changed compared to the settings discussed in chapter 4. The forcing conditions of the wind- and wave are the same as discussed in paragraph 4.4.1. The sediment input parameters for the input sediment are as follows:

Parameter	Value	Unit
Sediment specific density	2650	kg/m ³
Dry bed density	500	kg/m ³
Erosion parameter	0.0001	kg/m ² /s
Fresh settling velocity	0.25	mm/s
Saline settling velocity	0.25	mm/s
Critical bed shear sed	1000	N/m ²
Critical bed shear ero	0.2	N/m ²
Initial bed layer thickness	0	m

Table 6.5: Input sediment parameters

6.2.4. Modelling Results

The first results were found using the input settings and analysis technique discussed earlier. Table 6.6 displays values from the max value of sediment, which reaches the Weg naar Zee coastline soon after introducing the sediment load. These values are expressed in total tons and as a percentage of the initially inputted load. Moreover, Table 6.6 provides data on the ratio between this volume of sediment and the background sediment present in this area. The data represents the total sediment in the ten z layers of the water column.

Loc #	Test	Timestep	Tidal cycle	Max ton	Max %	% vs silt	Location Max
1	L1.1	T13	Low	0.06	0.002	0.45	x
1	L1.2	T17	Midpoint (rising)	0.03	0.001	0.48	
2	L2.1	T13	Low	0.86	0.022	7.295	x
2	L2.2	T17	Midpoint (rising)	0.85	0.022	6.607	
2	L2.3	T23	High	0.01	0.000	0.00	
3	L3.1	T13	Low	0.78	0.020	1.30	x
3	L3.2	T17	Midpoint (rising)	0.61	0.016	1.01	
3	L3.3	T23	High	0.02	0.001	0.00	
3	L3.4	T30	Midpoint (falling)	0.00	0.000	0.00	
4	L4.1	T13	Low	0.13	0.003	0.11	
4	L4.2	T17	Midpoint (rising)	0.15	0.004	0.13	
4	L4.3	T23	High	0.29	0.007	0.58	x
5	L5.1	T17	Midpoint (rising)	0.11	0.003	0.06	
5	L5.2	T23	High	0.28	0.007	0.20	x
5	L5.3	T30	Midpoint (falling)	0.25	0.006	0.180	

Table 6.6: The table presents the results of the sediment plume modelling conducted for all the run simulations. To initiate the sediment input, several timesteps have been chosen per location. The table shows the maximum sediment value in the assigned Weg naar Zee coastal area per simulation. This value is expressed both in absolute tons and as a percentage compared to the original total weight of sediment inputted. Additionally, the table provides the ratio between input sediment and background sediment at the maximum value timestep. The simulations per location with the highest max value are marked with an 'x'.

The data gives valuable insights into the feasibility of this transport type contributing to the growth of the WnZ coastline. First of all, the results are generally low. At one timestep, the highest value of nourished sediment found in the area at WnZ is 0.85 tons. This is 0.022% of the total volume of sediment brought into the system; in the sediment distribution during input, 10% of the total contributes to layer 1. One five-hundredth of this volume is transported by (current) flow towards Weg naar Zee, which is lower than expected.

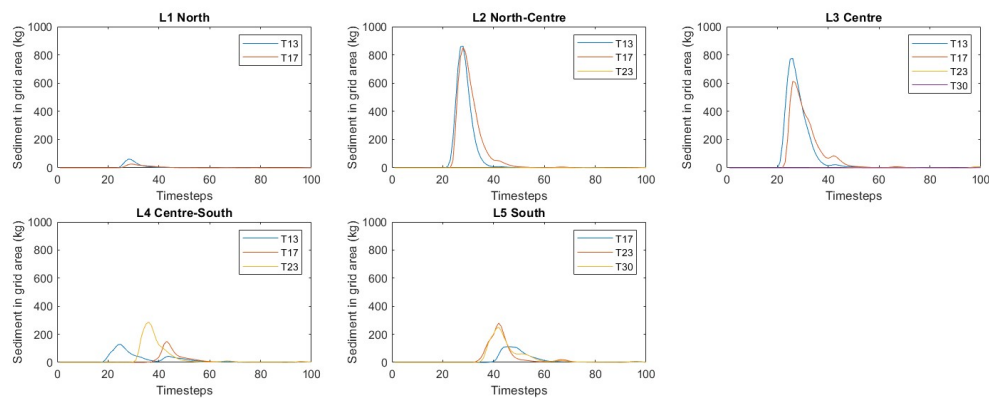


Figure 6.3: Graphs showing the sediment total weight (kg) which is present in the Weg naar Zee coastal area (see Figure 6.1 for all five locations).

Despite the low values, the differences between the results effectively represent the expected functioning of this transport type. The outcomes, which are associated with the timing of the input and the occurrence of maximum values, align with expectations. For instance, consider location 2 (North-Centre). It was initially hypothesised that sediment should be introduced during low or rising tides. Under these conditions, tidal flow patterns would likely transport the sediment towards Weg naar Zee. The attained results substantiate this hypothesis. Both low and rising tide inputs yield similar results, while input at high tide leads to noticeably lower outcomes. The same observation applies to locations 4 (Centre-South) and 5 (South), where the initial hypothesis suggested sediment input should occur

during high tide. Indeed, the resulting data corresponds with this supposition.

Even though only a minimal fraction of the nourished sediment reaches Weg naar Zee, the proportion between the nourished and background sediment within the observed area may nevertheless be significant. A ratio of 1 to 0.073 was identified during simulation L2.2. This indicates that even with low absolute values, the sediment introduced can still exert influence compared to the sediment already located near the Weg naar Zee shoreline.

The impact of the settling velocity on plume dispersion and sediment spread was a significant point of interest. Expectations were that the sediment would remain suspended long enough to be transported by wave and flow forcing. The simulations, however, indicate that a high proportion of the sediment remains deposited at the dumping site. The sediment remains at this location throughout the simulation. See the paragraph 6.8 for more insights on the sensitivity of the fall velocity in the simulations.

The same analysis has been done for the sediment entering the inter-tidal area. It's important to note that the assumption of a large portion of the sediment being retained due to STUs is not necessarily applicable here. Nevertheless, a significant quantity of sediment could add to the sedimentation of this area. Consequently, a representation of sediment entering this area as SPM is shown in Table 6.7.

Loc #	Test	Timestep	Tidal cycle	Max ton	Max %	% vs silt	Location Max
1	L1.1	T13	Low	23.5	0.6	1.4	
1	L1.2	T17	Midpoint (rising)	72.0	1.8	4.2	x
2	L2.1	T13	Low	75.7	1.9	3.5	
2	L2.2	T17	Midpoint (rising)	134.5	3.4	5.5	x
2	L2.3	T23	High	1.0	0.03	0.01	
3	L3.1	T13	Low	115.8	3.0	7.8	x
3	L3.2	T17	Midpoint (rising)	75.0	1.9	3.1	
3	L3.3	T23	High	9.8	0.3	6.0	
3	L3.4	T30	Midpoint (falling)	0.3	0.01	0.004	
4	L4.1	T13	Low	104.2	2.7	6.5	x
4	L4.2	T17	Midpoint (rising)	50.7	1.3	2.8	
4	L4.3	T23	High	42.0	1.1	5.9	
5	L5.1	T17	Midpoint (rising)	17.1	0.4	0.7	
5	L5.2	T23	High	16.4	0.4	2.8	
5	L5.3	T30	Midpoint (falling)	40.9	1.0	7.2	x

Table 6.7: Additional results of sediment plume modelling, now concerning the inter-tidal flat area instead of the Weg naar Zee coastline. See Figure 6.5 for an image showing this area.

The data provides valuable insights into the feasibility of this transport type contributing to the potential growth of the intertidal area. The initial observation reveals that, as expected, the maximum values of tons of sediment are higher than those in the previous table. This aligns with expectations, given that the observation area is more extensive and closer to the input locations.

Current simulations are promising, indicating that the area contains around 1.0 to 3.4 % of the original input at the timestep with the highest sediment level. These are significant values, demonstrating that a single barge load can have a noticeable impact. In these simulations, the ratio between these values and the background sediment values that occur ranges between 4.2 to 7.8 %, which are also significant levels.

Interestingly, the most promising timing per location does not align with the previous analysis which concerned the Weg naar Zee coastline area (see Table 6.6). For instance, focusing on the unloading locations 1 (North) and 2 (North-Centre), low tide (timestep 13) is the optimal moment for input to maximise transport to the Weg naar Zee coast. However, when considering transport to the intertidal flat, the rising tide (timestep 17) presents higher maximum values for locations 1 and 2 (see Table 6.7).

The optimum input time for location 4 (Centre-South) transitions from high tide for the Weg naar Zee coast to low tide for the intertidal flat, completely reversing the optimum flow dynamics between inflowing and outflowing water in the estuary. This due to location 4 being situated in an area where transport directions change quickly during the tidal cycle.

6.3. Transport Type 2: over bed influenced by waves

Sediment transport occurs not only as Suspended Particulate Matter (SPM) in a plume through the water column, but also across the seabed. This seabed transport is mainly driven by bed shear stress (BSS) from wave action. It is expected that the wave action, primarily directed at Weg naar Zee, could potentially increase sedimentation levels on the Weg naar Zee coastline.

A large portion of the sediment brought in by dredging vessels is immediately deposited on the estuary bed. Given this amount of sediment, the main questions arise: 'How much sediment is transported towards Weg naar Zee, and after how long?' and 'What is the best location in the estuary to introduce sediment?'. These questions will be addressed in the following discussion. Several simulations were run to assess the potential and effectiveness of this type of transport within the Suriname River Estuary.

6.3.1. Selection of Sediment Input Locations

A set of unique locations was selected to investigate the impact of Transport Type 2 (TT2), distinct from the five sites chosen for analysing plume dispersion transport. Three locations were selected, deemed sufficient to encompass the complete area considered appropriate for this mode of transport. The suitability of this designated area hinges on several contributing factors. A consistently high bed shear stress (BSS) level throughout the simulation timeline is required, as it is instrumental for sediment displacement. The chosen sites should also be easily accessible from the shipping lane for logistical convenience. Lastly, locations with a slope were excluded to avoid destabilising the sediment volume on the bed.

Figure 6.4 depicts the three selected locations. Location 1 (North), 2 (Centre) and 3 (South) are spread out over the edge of the inter-tidal flat. They are situated just before the run-off towards the deeper tidal channel and shipping lane. They are spread out over the area where the wave action is directed towards Weg naar Zee and thus where BSS levels are highest (see Chapter 5 for figures justifying this).

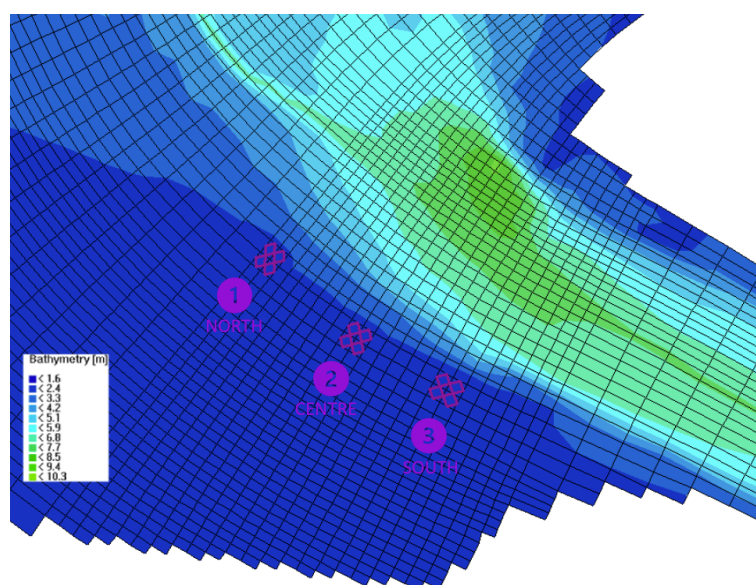


Figure 6.4: In this paragraph, we discuss the sediment transport over the bed carried out at three locations, shown in this figure. Location 1 (North), location 2 (Centre), location 3 (South).

6.3.2. Modelling of Sediment Input Volume

The goal was to simulate a volume of sediment deposited on the bottom, representing a certain number of barge loads. The same volume of sediment would be used for each location, making it possible to compare the results of the three chosen locations. However, the area of the three chosen locations varied slightly. For each location, an area encompassed by 2x2 grid cells was selected. The volume of sediment, supplied by five barge loads, if entirely deposited in the 2x2 grid cell areas, would have different heights from the bed on up.

A significant unknown is the degree of compaction the sediment experiences during deposition and while remaining on the bed. Likely, the sediment will not retain the same density as during the initial input. Therefore, the original value of 1300 kg m^{-3} may not be appropriate. An assumption is made, stating that the sediment volume on the bed now possesses a density of 1400 kg m^{-3} . This implies that it comprises 25 % dry density and 75 % water/pores. In contrast, during the sediment's input, this ratio was approximately 80 % pores or water. The dry bed density is now 650 kg m^{-3} . The results of calculating these heights and the total volume of sediment are displayed in Tables 6.8 and 6.9.

Data type	Value	Unit
Single load	3.90×10^6	t
Number of loads	5	-
Multiple loads	1.95×10^7	kg
Density bed	1400	kg m^{-3}
Dry bed density	650	kg m^{-3}
Volume bed 1 load	5997	m^3
Volume bed 5 loads	29983	m^3
Total sediment bed	1.95×10^7	kg

Table 6.8: Table showing the process used to determine the total volume of sediment situated on the seabed, following the input of 15 distinct sediment loads.

	L1 North	L2 Centre	L3 South
Area 2x2 grid cells	$125\,640 \text{ m}^2$	$138\,770 \text{ m}^2$	$154\,511 \text{ m}^2$
LxB	354 m	373 m	393 m
Height in 2x2 area	0.24 m	0.22 m	0.19 m
Volume in 2x2 area	$29\,983 \text{ m}^3$	$29\,983 \text{ m}^3$	$29\,983 \text{ m}^3$

Table 6.9: The total area and the total height of sediment within that area, for the three distinctive locations, North/Centre/South

Now that the heights per location have been determined, they can be used to incorporate the sediment volume into the model. The sediment volume will be considered in the model in two ways.

First, by adding the height of the sediment volume to the bathymetry depth file, the model accounts for the additional height caused by the sediment mound on the bed. This adjustment increases the influence of the wave forcing, leading to higher bed shear stress levels and thereby enhancing sediment transport.

Secondly, the sediment volume is included in the initial condition file. Consequently, at the onset of the simulation, the sediment is already present on the bed. Throughout the simulation, this sediment volume is subjected to forcing. Thus, the model portrays how the sediment would relocate during a complete spring-neap tidal cycle, given that this is the duration modelled.

6.3.3. Model Simulation Settings

- Normal wave- and wind conditions were used for the simulations; see section 4.4.1 for the wave- and wind conditions settings.
- Wave parameters were kept the same as in 4. The only adjustment was a lower friction factor (value now 0.019); see 6.4.3 for clarification.
- Sediment characteristics are the same as in section 6.2.3.

6.3.4. Modelling Results

The purpose of modelling Transport Type 2 (TT2) was to discern whether and where sediment dispersion occurs during the simulation period. The investigation aimed to determine if the sediment would principally migrate toward the coastline or if alternate dispersion patterns were also present. Another essential aspect was quantifying the amount of sediment remaining in the original 2x2 grid cell area compared to other regions. The rate at which sediment decreases in this area could yield insights into the time taken for complete sediment transport. To ascertain these factors, an analysis was performed.

For each location, a specific region was identified and marked as the zone where sediment contributes to the expansion of the inter-tidal flat, and ultimately, Weg naar Zee. It's assumed that the sediment present in this region during the simulation migrates towards the coastline. This zone is between the Weg naar Zee coastline and the original deposit zone. The three distinct areas chosen for each location are depicted in Figures 6.5.

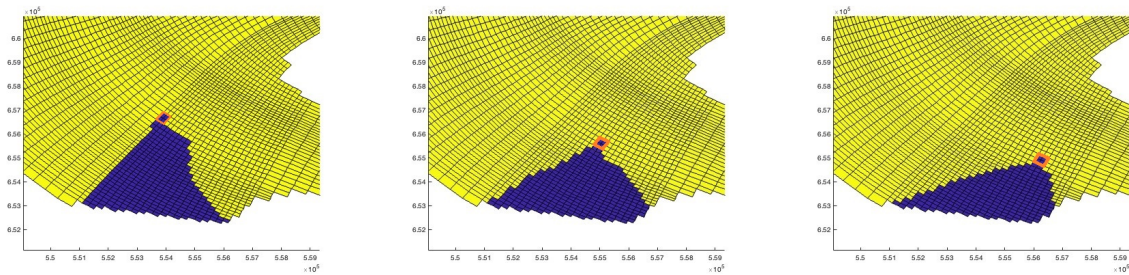


Figure 6.5: Selected area for the inter-tidal flat (ITF) for each location, from left to right: Location 1 (North), Location 2 (Centre), Location 3 (South). The orange section depicts the input area for the three locations. Location 1 (North) has a total size of 1037 ha, Location 2 (Centre) of 974 ha, and Location 3 (South) of 821 ha.

The sediment spread is analysed within three distinct areas throughout the simulation. The first area refers to the original 2x2 grid cell area where the volume of the sediment was present at the beginning of the simulation. The second area is the 'blue area', also known as the intertidal flat (ITF), as depicted in Figure 6.5. This area encompasses the intertidal flat located between the initial sediment input area and Weg naar Zee. Area 3 is part of Area 2, covering only the Weg naar Zee shoreline. The final area constitutes the remaining section of the model domain that is not included in the first two areas. Any sediment transported to this area is considered lost or removed from the system. Table 6.10 summarises the simulated outcomes for these three distinct locations.

		North	Center	South
Area 1: Original	Initial (kt)	19.6	19.8	19.0
	Final (kt)	0.507	0.961	1.38
	(%)	2.6%	4.9%	7.3%
Area 2: ITF	Final (kt)	4.48	4.77	3.85
	(%)	22.7%	23.97%	20.3%
Area 3: Domain	Final (kt)	14.6	14.0	13.7
	(%)	74.3%	70.8%	72.3%
Area 4: WNZ	Final (kt)	0.033	0.0288	0.0288
	(%)	0.17%	0.15%	0.15%
Area 5: Rest	(%)	0.27%	0.21%	0.05%
Total(%)		100.0%	100.0%	100.0%

Table 6.10: Results of the simulation run for locations 1 to 3, or North/Centre/South, showing sediment spread throughout the domain, linked to distinctive areas. The simulations were run under normal wave and wind conditions.

The first observation is that there exists a difference in the total initial kg per location. Contrary to the approach discussed earlier, this should not be the case, as both the volume and density are set to be equal at all locations. This discrepancy is caused by an inaccuracy in programming the sediment height in the model. However, it was not sensitive enough to achieve the same total sediment weight or volume for all three locations. This, nevertheless, is not an issue, as the focus will primarily be on comparing the ratio of sediment in different areas. Even a slight difference in sediment volume wouldn't drastically impact the ratio.

The second point of attention is the overall sediment distribution at the end of the simulation. Across all simulations, it is clear that a maximum of 7.3% of the total sediment is still present in its original area. Around 22% has migrated towards the Weg naar Zee coast and is deposited in the areas depicted in Figure 6.5, covering the inter-tidal flat. The results indicate that at least 20% will contribute to the build-up of the inter-tidal flat and eventually Weg naar Zee. A small fraction of the total, around 0.15%, has already reached the Weg naar Zee shoreline. However, a sizeable portion of the initial sediment has been carried in less favourable directions for the intended objective, with a minimum of 70.8% of the original sediment volume lost to the rest of the domain.

The three locations show differences in the ratio of sediment. The northern location has the least sediment left in the original area. This was expected, as this location is subjected to higher forcing than the other two. The average bed shear stress level for location 1 (north) is 1.22 (Pa) throughout the entire simulation, while location 2 (centre) has an average of 1.07 (Pa) and south has an average of 0.76 (Pa). This difference is caused mainly by where the 2x2 grid-cell areas are located in the domain and the difference in added height to the bathymetry resembling the volume of sediment on the bed. The differences in transport direction and patterns can be seen clearly in Figure 6.6.

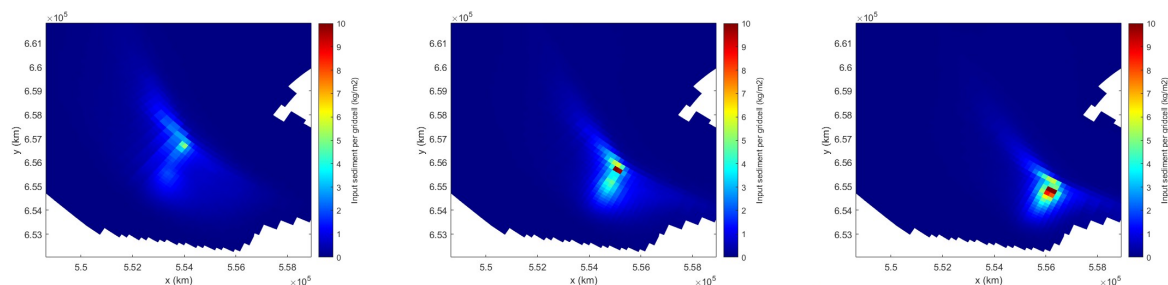


Figure 6.6: Visual depiction of the distribution of sediments after a simulation run for three locations: North (Location 1), Central (Location 2), and South (Location 3). The images reveal distinct sediment spread patterns per location post-simulation.

Focusing on the volume of sediment transported out of the original area, what would be the ratio between the positively contributing sediment (situated in Area 2, inter-tidal flat) and the negatively contributing sediment (situated in Area 3, the rest of the domain)? The ratio is the best for the central location, with 75% being lost and 25% still contributing. The northern, with 76% to 24%, comes in second. This ratio is less favourable for the southern location, with only 22% contributing and 78% being lost.

An interesting second analysis is to do the same simulation but with higher wave conditions. See 4.4.1 for the conditions. Would higher waves change the distribution between Area 2 and 4 (ITF + WnZ) and Area 3 (the rest of the domain)? And how much would remain in the original 2x2 grid cell area compared to the standard wave conditions displayed in the previous analysis? The results of this simulation can be seen in Table 6.11.

		North	Centre	South
Area 1: Original	Initial (kt)	19.6	19.8	19.0
	Final (kt)	0.117	0.238	0.552
	(%)	0.6%	1.2%	2.9%
Area 2: ITF	Final (kt)	4.17	4.23	3.37
	(%)	21.0%	21.21%	17.7%
Area 3: Domain	Final (kt)	15.2	15.3	15.1
	(%)	77.7%	77.1%	79.2%
Area 4: WNZ	Final (kt)	0.0397	0.0298	0.0269
	(%)	0.2%	0.15%	0.14%
Area 5: Rest	(%)	0.47%	0.34%	0.10%
Total(%)		100.0%	100.0%	100.0%

Table 6.11: Results of the simulation run for locations 1 to 3, or North/Centre/South, showing sediment spread throughout the domain, linked to distinctive areas. The simulations were run under higher wave and wind conditions.

In Area 1, the original input area, the total remaining sediment is significantly reduced. Under normal conditions, around 2 to 7% of the sediment input remained during the simulation. However, elevated wave conditions result in only around 0.5 to 3% of sediment left. This outcome aligns with expectations, given that higher wave conditions increase bed shear stress, facilitating heightened sediment transport and transport through the domain.

Reexamining the sediment that has moved from the original Area 1, the question arises: what is the proportion between the sediment contributing and the sediment lost? Compared to the simulation under normal conditions, the ratio is less favourable. This implies that the additional sediment transport contributes more significantly to the rest of the domain (Area 3) than to the positive side of the ITF (Area 2). This can be seen in the graphs in 6.7. Should the simulation under normal conditions have been extended, there is a likelihood that the ratios would closely resemble those recorded after the simulation under elevated wave conditions.

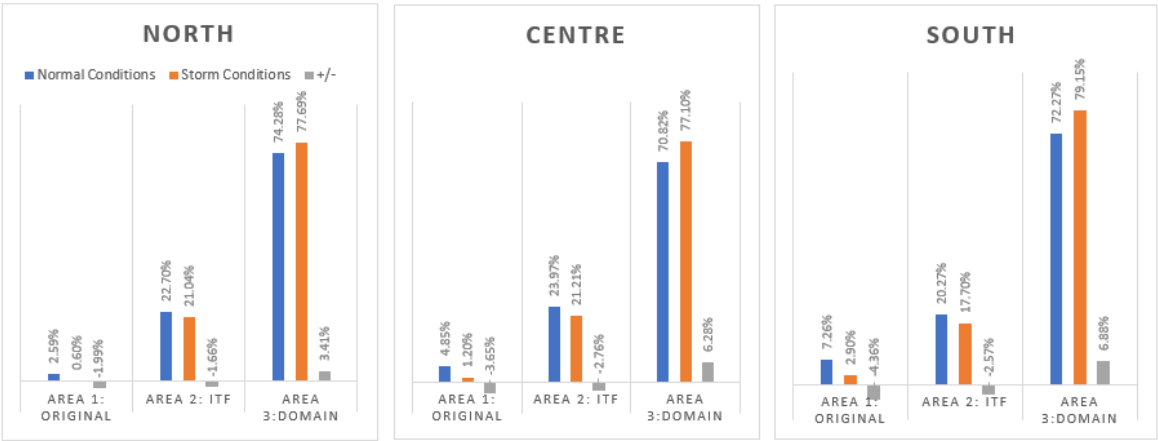


Figure 6.7: Graphs comparing sediment spread per area for the simulations run with normal vs. higher wave and wind conditions.

	Loc. 1 (North)	Loc. 2 (Centre)	Loc. 3 (South)
Normal conditions	3.27	2.96	3.57
Higher wave/wind conditions	3.69	3.64	4.47

Table 6.12: This table displays the ratios of end sediment quantities in two areas—Area 2: ITF and Area 3: Domain—across various scenarios. Among the scenarios, Location 2 (centre) under normal conditions results in the most favourable sediment distribution.

6.4. Sensitivity Analysis

The sensitivity analysis section provides an in-depth exploration of the effects of variations in key parameters on simulation results. These parameters are integral to the previous simulations and contain elements of potential uncertainty. The analysis comprises four parameters or model settings: fall velocity of input sediment, input technique, and wave parameters (breaking index and friction factor).

6.4.1. Fall velocity of input sediment

The fall velocity parameter is significant for Transport Type 1, the Plume Transport system. In the simulation executed for Location 3 Number 2 (T17), the fall velocity was set at 0.25 mm/s, corresponding to above-average outcomes. To gauge the sensitivity of the result to changes in fall velocity, this value was increased to 0.5 mm/s, bringing it in line with the typical value for background sediment.

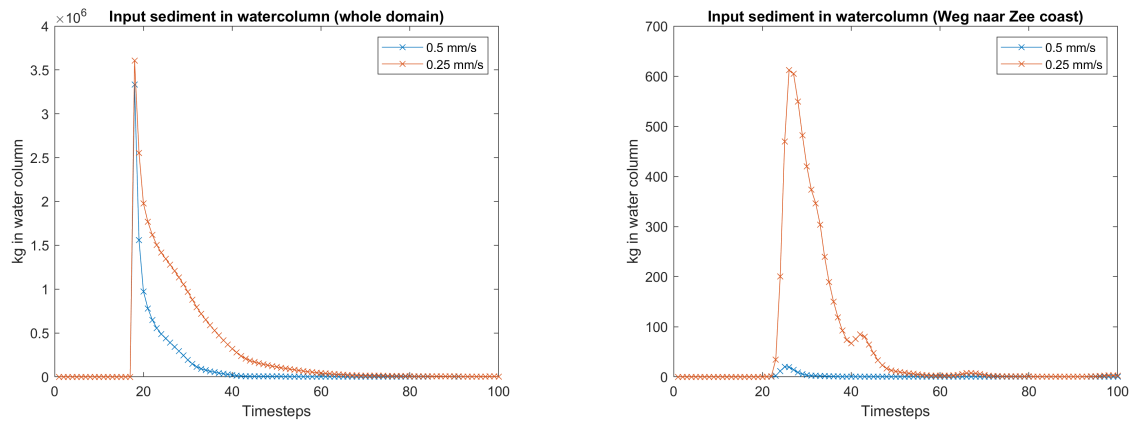


Figure 6.8: Left: Plot of the first 100 timesteps (50 hours) of the simulation. It shows the total quantity (kg) of sediment suspended in the water column throughout the domain for two different fall velocities.
Right: The same plot but now only for the Weg naar Zee grid cell area shown in 6.2 (left figure).

In the left Figure 6.8, the effects of the change in fall velocity of the input sediment are presented. These represent the total weight of sediment suspended in the water column at each timestep. The sudden increase is due to a single sediment load input at timestep 17. Initially, the SPM, due to the input, stays suspended partly till T70, so for 28.5 hours. With double the fall velocity, the initial SPM weight in the water column is lower due to higher initial deposition. A decrease of 8% in the initial suspended weight of sediment is observed. Also, due to the higher fall velocity, all sediment deposits at around T45, so after 14 hours, twice as fast as expected for the double fall velocity.

The right Figure 6.8 shows the repercussions for the simulation results. This Figure shows sediment values in the Weg naar Zee grid cell area. An adjustment in fall velocity by 50% led to a significant drop in the maximum values of sediment reaching the Weg naar Zee region. Specifically, the values plunged 40-fold, emphasising the high sensitivity of plume transport towards the Weg naar Zee coast due to the increase in sediment fall velocity.

6.4.2. Input Technique

This sensitivity analysis revolves around Transport Type 1 and Plume Transport and explores the implications of adopting different input techniques. In contrast to the initial technique, an alternative technique known as "side casting" was modelled. Side casting at the dumping site is done by pumping sediment from the hopper into the water column at the disposal site; submerged or emerged methods can be used. Here, submerged is considered. This technique necessitates a longer duration for sediment input and confines all sediment to the top two layers.

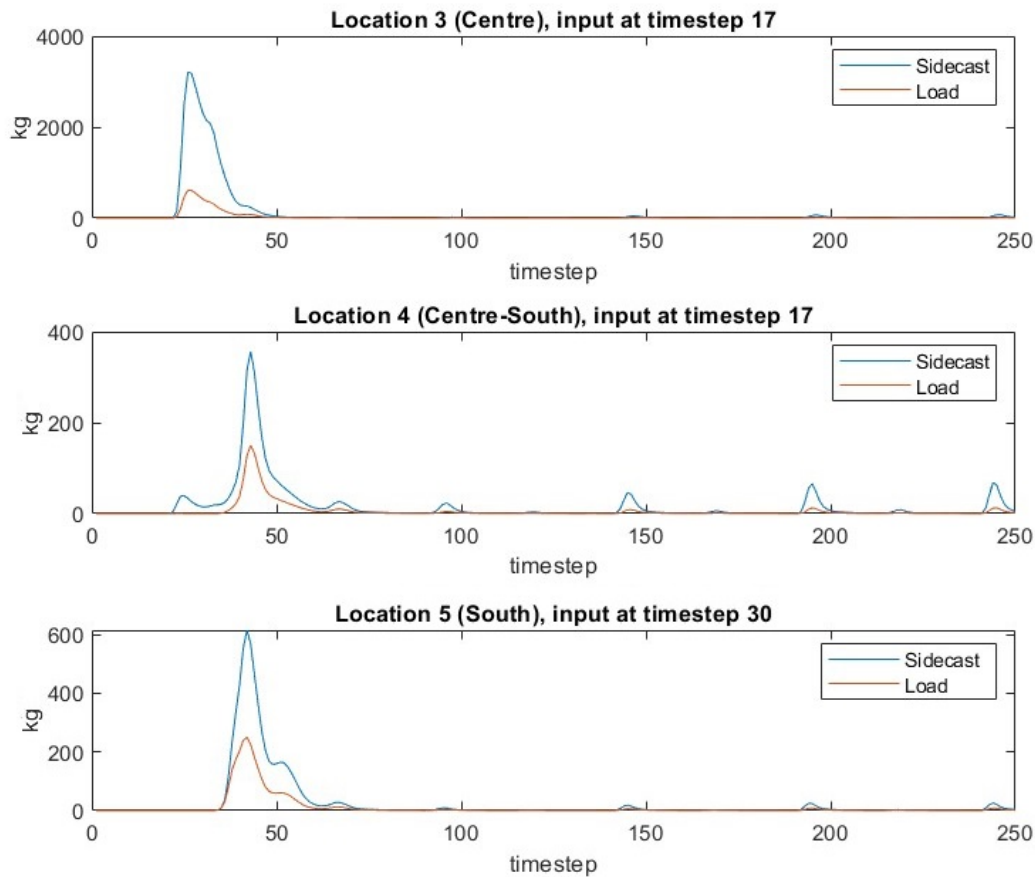


Figure 6.9: Top to bottom: plots showing total sediment quantity (kg) in the water column in the Weg naar Zee grid cell area shown in 6.2 (left figure). Comparison is between normal and side casting input methods for three different input locations.

Figure 6.9 shows the results of the original simulation, plus the simulation using the side casting method, for three simulations. The modification increased maximum values at the maximum timestep, going up by a factor of 3 to 6. Therefore, considering only transport type 1, this method shows better results than the original input technique discussed in 6.2.2. Nonetheless, it's crucial to consider the operational implications; longer input times mean extended idle times for the vessels, impacting efficiency and operational costs for the maintenance dredging works.

6.4.3. Wave Parameters

The third sensitivity analysis examines the wave parameters — breaking index and friction factor — and their impact on Transport Type 2 (Bed Transport). A simulation with normal conditions, just as in 6.3.4, is compared to a simulation with altered wave parameters.

It is important to note that an adjustment to the total sediment quantity in the original 2 x 2 area has been made for these calculations. The amount now equates to 15 loads, resulting in 5.85×10^7 kg of sediment. This modification ensures that the quantity is not replenished throughout the simulation, thus facilitating the comparison of the two executed simulations.

Breaker parameter

The initial simulation utilised a breaker parameter of 0.73, the default value in SWAN. This parameter determines the maximum height of waves before breaking in the Battjes & Janssen model (1978) used by SWAN. This value was reduced to 0.5 to assess sensitivity, significantly altering the waves' breaking behaviour within the domain. Waves now break earlier in the domain, as smaller depths are necessary to reach the maximum wave height.

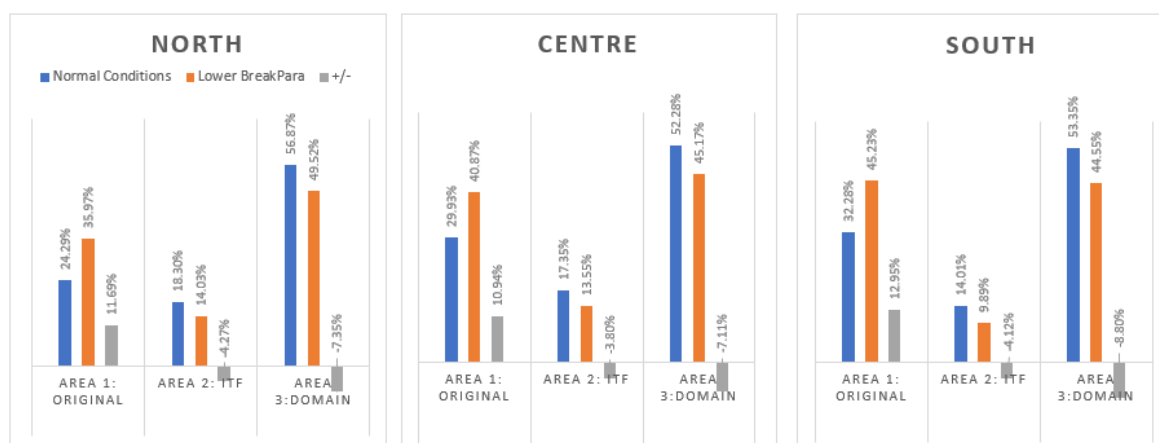


Figure 6.10: Graphs comparing sediment spread per area for the simulations run with normal vs. lower breaker parameter (0.5) conditions.

	Loc. 1 (North)	Loc. 2 (Centre)	Loc. 3 (South)
Normal conditions	3.11	3.01	3.81
Lower Breaker Parameter (0.5)	3.53	3.33	4.50

Table 6.13: This table displays the ratios of end sediment quantities in two areas—Area 2: ITF and Area 3: Domain—across various scenarios. Among the scenarios, Location 2 (centre) under normal conditions results in the most favourable sediment distribution.

The immediate impact of this change was a decrease in the overall proportion of sediment transported. The other observation is a change in how the transported sediment is distributed over Area 2 (ITF) and Area 3 (the rest of the domain). Compared to the original results, this setting of the breaker parameter shows worse results for all locations. The ratio between sediment contributing to the ITF and the rest of the domain is higher for all locations than the original results.

Friction factor

A similar methodology was adopted to test the sensitivity of the simulation to changes in the friction factor. Increasing the friction factor from 0.019 to 0.038 implied an enhanced interaction between the waves and the bed, translating to quicker wave attenuation.

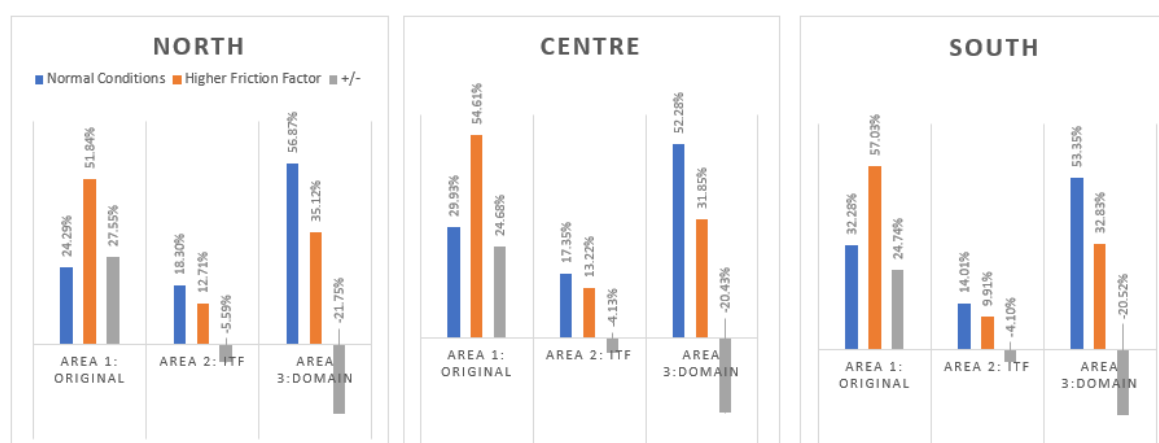


Figure 6.11: Graphs comparing sediment spread per area for the simulations run with normal vs. higher friction factor (0.038) conditions.

	Loc. 1 (North)	Loc. 2 (Centre)	Loc. 3 (South)
Normal conditions	3.11	3.01	3.81
Higher friction factor (0.038)	2.76	2.41	3.31

Table 6.14: This table displays the ratios of end sediment quantities in two areas — Area 2: ITF and Area 3: Domain — across various scenarios. Among the scenarios, Location 2 (centre), with a higher friction factor (0.038), results in the most favourable sediment distribution.

The overall transported sediment witnessed a reduction, aligning with initial expectations. If we now focus on the distribution between ITF and domain, a different result can be compared to the breaker parameter. More positive distributions of sediment occur compared to the original situation. Table 6.14 shows that the ratios are lower for each location, offering the best results for location 2 (centre).

6.5. Conclusion

This chapter discusses the simulation results for two types of transport: Transport Type 1 (TT1), which involves the transport of SPM through the water column, and Transport Type 2 (TT2), which involves the transport of sediment over the bed under the influence of wave forcing. Since both types are treated separately, their results will also be considered separately.

TT1 was simulated at five possible locations, at various moments throughout the tidal cycle. As expected, timing proved crucial for achieving higher efficiency levels. The higher efficiency levels coincided with moments in the tidal cycle that were initially expected, indicating that the simulations produced logical results. The highest efficiency level for transport towards the Weg naar Zee coast was found for location 2 "north-centre" at slightly more than 0.02%. Efficiency levels towards the intertidal flat were generally higher, which is logical as this area is larger and closer to the input locations. Here, the highest level found was 3.4%, also for location 2 "north-centre".

TT2 was simulated at three possible locations, with similar results for each location. The efficiency of transport over the intertidal flat, spreading out towards Weg naar Zee, ranged between 20.3% and 24%. Location 2 "Central" showed the highest efficiency levels, which was expected due to its central location relative to the coast. This location had a ratio of 1:2.96 between positively contributing sediment and sediment that is lost to the domain. Simulations with higher wave and wind conditions showed less positive ratios across all locations.

The results discussed in this chapter detail the differences between transport levels, influenced by location, tidal levels, wave and wind conditions, and transport type. But what levels should be used for subsequent analysis? In practice, it's not possible to unload sediment at the most efficient moment and location every time. Therefore, having efficiency levels for all these different scenarios is highly valuable. If an unloading strategy for the execution of the beneficial reuse of dredged sediment is developed in the future, these results can help choose the best possible location at that time in the tidal cycle. For upcoming analysis, an average value will suffice to account for the variability of location and timing. For TT1, an average value over the highest efficiency levels for the four moments chosen in the tidal cycle (low to high water) is suitable. For TT2, an average of the efficiency levels of the three locations is suitable."

7

Feasibility Analysis

The previous chapter 6 discusses modelling research into placing fine sediment in the Suriname River Estuary. This research assessed the efficiency levels of two transport types, investigating varying placement locations and timings. The findings allow an evaluation of the impact of these inputs on the overarching objective, which is to address the question: How much material is required at WnZ and on the inter-tidal flat to form a stable-dynamic mangrove green belt of 300m width? This chapter aims to help answer this question.

In the first part of this chapter, we process and analyse recent data on the bed level of the inter-tidal flat. Using this data, we create a schematisation to estimate the volume necessary to restore the foreshore to its estimated historical profile. This profile represents an estimate of the foreshore's state when the coast was healthy and non-erosive, characterised by a convex-up shape along the entire cross-shore transect.

In the following section, the feasibility of nourishing sediment to complete this profile is explored, using the calculated volume as a reference. The effect of depositing fine sediment using the two transport types, either in isolation or combined, is discussed. The range of the parameters determining the final project duration are used to determine a bandwidth project duration. Based on the results, the feasibility of employing this technique is assessed.

7.1. Analysis necessary volume inter-tidal flat and WnZ

The hydrographic survey was systematically conducted using a Ceescope single-beam echo-sounder with frequencies of 200 kHz and 33 kHz on a small vessel by the Maritime Authority Suriname (MAS). The Vertical Datum was based on the Low Water Spring (LWS), Normale Surinaamse peil (NSP), with tide measurements taken every 10 minutes. The data was processed and calibrated using Hypack 2014-2023. However, full-area seafloor coverage was not achieved due to accessibility issues for the vessel. See Figure 7.1 for an overview of the survey data.

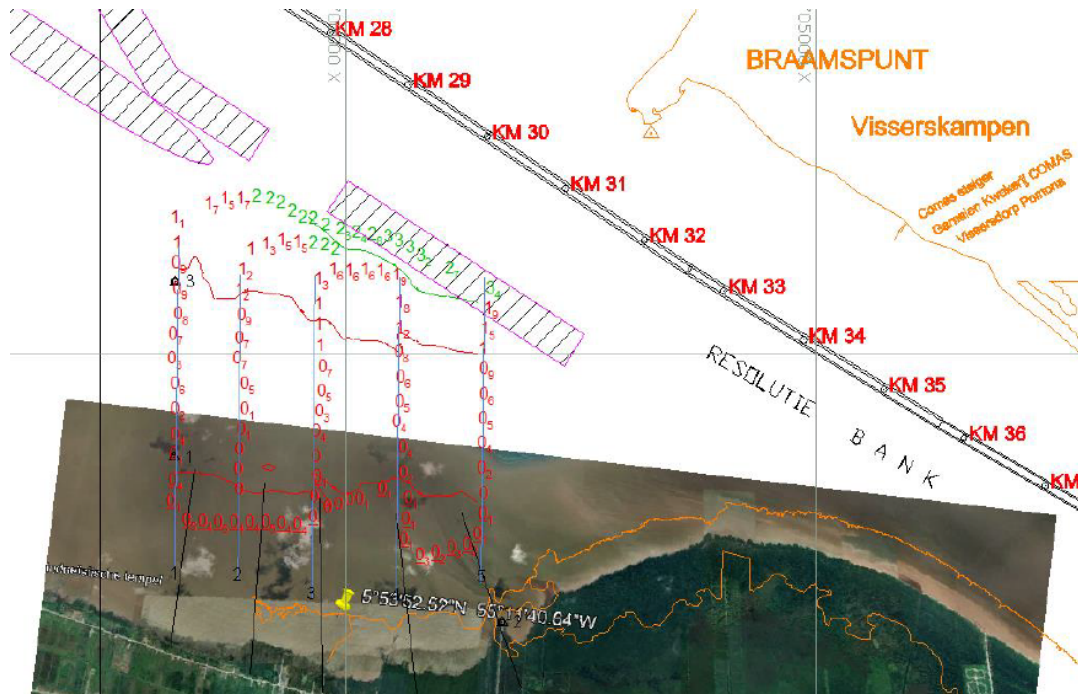


Figure 7.1: Overview of survey data, showing its location in the domain and the depths of the intertidal flat. Levels are with respect to low water spring (LWS).

Not all data points obtained for the survey are necessary for this analysis. In Figure 7.1 and 7.2, the entire path the survey vessel sailed and surveyed is visible. The five lines were the initially requested survey lines by Boskalis. The data obtained along these five lines will be used for this analysis. The data of these lines was thus extracted and separated for further review.

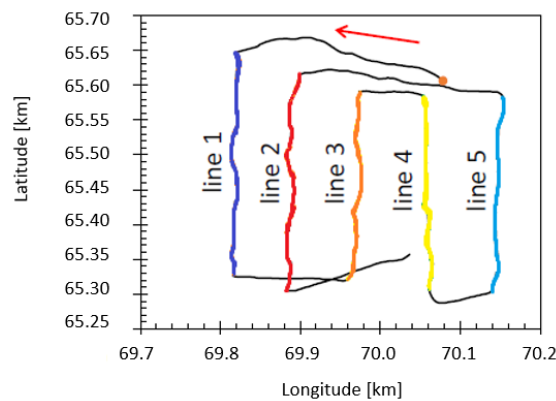


Figure 7.2: An overview of the survey data and the path the survey vessel covered. The lines extracted from the data for further analysis are indicated (1 to 5).

The separate profiles have been displayed in Figure 7.3. The data are w.r.t. LWS (low water spring), i.e. well below MSL (mean sea level). A simple second-degree polynomial fit was done for each profile to analyse the shape. Profile 1 shows a concave-up profile typical for erosive conditions and was thus initially expected. Profile 2 shows a more convex-up profile and, therefore, a more desired profile. The foreshore profiles shift more towards convex-up, moving from 2 to 5, so more towards the river mouth.

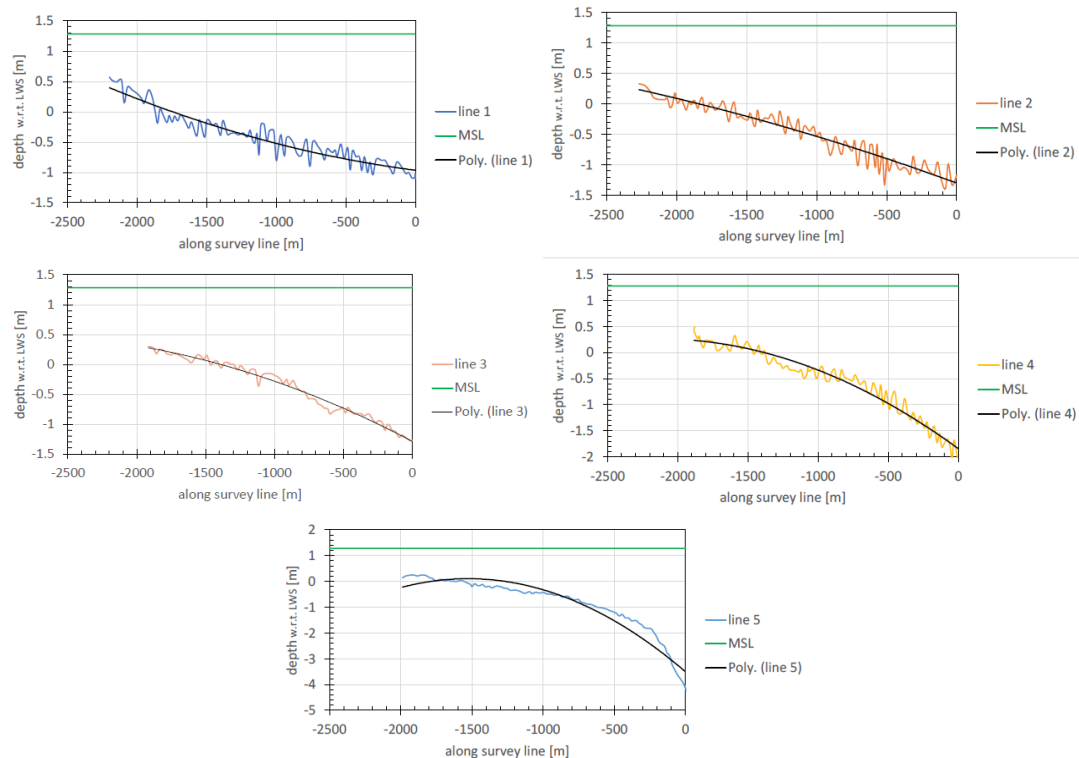


Figure 7.3: The five lines of depth data, extracted from the complete set illustrated in Figure 7.1, are represented along with a polynomial trend line.

Survey data does not extend to the Weg naar Zee shoreline, which makes determining the required volume difficult. Consequently, an extrapolation of profile data towards the shoreline was necessary to estimate the current profile. With the current profiles established, the estimated historic profile was determined. Ideally, this should create a convex-up profile with the corresponding shore and the toe slopes. To be able to extrapolate the data towards the shore, some assumptions had to be made. The approach involved the following steps:

1. The distance between the current shoreline and the most shoreward obtained data point was measured using Google Earth. This is the distance over which the shorewards extrapolation was done.
2. It was assumed that the road running parallel to the Weg naar Zee coast is located at approximately the Mean Highest High Water (MHHW) level (2.9 m+CD). The shoreline of the historic mangroves location, as seen in Google Earth, is presumed to be at the Mean High Water (MHW) level (2.5 m+CD). This shoreline location, assumed to coincide with the MHW level, is used to fit both the current and estimated historic profiles.
3. Using the historic mangrove belt shoreline location, the current profile was completed. The extrapolation between the survey data of the actual profile and the assumed shoreline point at MHW is represented by the purple line, labelled 'extrapolation to shore', in Figure 7.4.
4. Using a polynomial fit through this point and the survey data, a profile for the current situation was schematised. In Figure 7.4 this fit is represented by an orange line, the "fit of survey data".
5. An extension of the future mangrove fringe, 300 m offshore, is assumed. This is an average length of mangrove fringe necessary for rehabilitation. This fringe extends offshore from the shoreline point of the historic mangrove location, which was found in step 2 and assumed to be at MHW height. This is the outer left point in the plots in Figure 7.4. A further 200 m of profile, with a 1:1000 slope, is added to this 300m extension of the coast for a smooth transition.
6. From this extended point, now a total distance of 500m from the original shoreline, a polynomial fit (3rd or 4th degree, depending on the survey data) is made to the most offshore obtained survey data point. The toe of the profile, located at this point, is assumed to have the same slope as the

original data and is about 1:1000. This assumption is used to fit the data between the coastal extension of 500 m and the toe of the profile. This polynomial fit provides the profile of the desired foreshore, and is represented in Figure 7.4 by the green line, labelled "fit historic profile".

7. Figure 7.4 demonstrates all the five profiles determined by this approach.

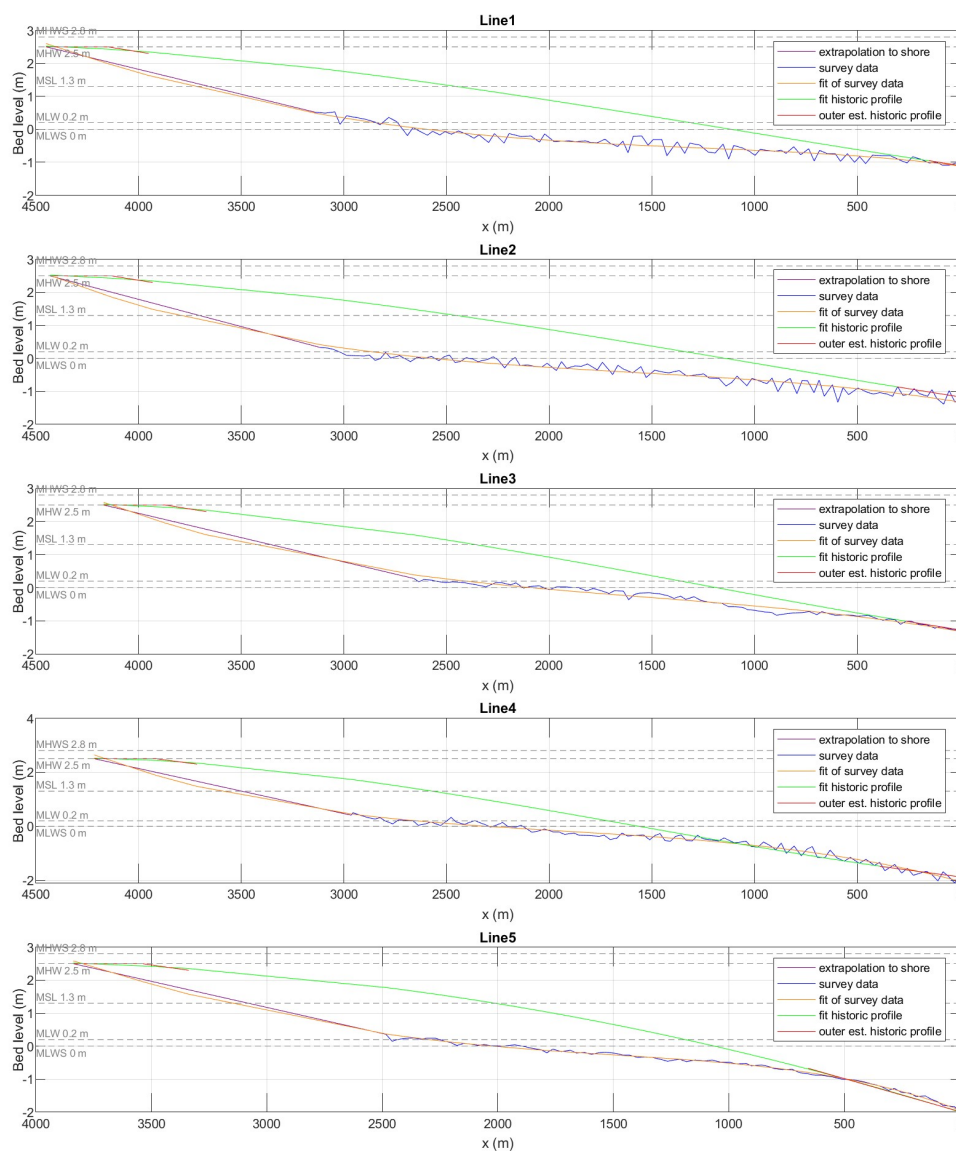


Figure 7.4: Five plots showing the survey data, the extrapolation of the survey data to the shore and the constructed desired profile for the five lines depicted in Figure 7.2

Now that a clear profile for the current and desired situations has been established, the necessary infilling per meter width of the foreshore can be determined. For each line, an integration technique is employed to calculate the area enclosed by the current and the estimated historic profile. With the x-coordinates of the lines, this total area can be translated into a volume. Figure 7.5 provides a schematic illustration of this technique. The final results are presented in Table 7.1. Based on these calculations, the total volume necessary to achieve the estimated historic profile for the inter-tidal flat of the foreshore requires approximately $1.08 \times 10^7 \text{ m}^3$ of material.

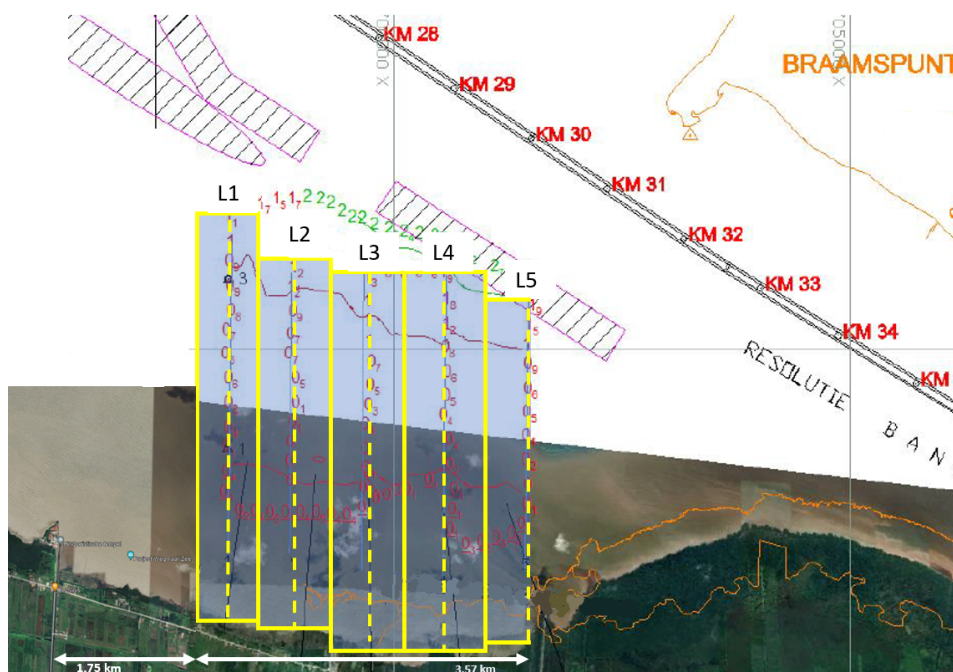


Figure 7.5: The used schematisation for determining the total infill volume is drawn into the survey overview chart. Line 5 has a single section. Lines 1/2/3/4 are split into two sections, named A and B. The volume calculation is listed in Table 7.1

	x coordinate [m]	width line to line [m]	width 1/2 line to line [m]	area profile [$\text{m}^3 \text{ m}^{-1}$]	volume [m^3]
Line1A	698136	695	348	3631	1.26×10^6
Line1B	698136	695	348	3631	1.26×10^6
Line2A	698831	695	348	3798	1.32×10^6
Line2B	698831	795	397	3798	1.51×10^6
Line3A	699626	795	397	2637	1.05×10^6
Line3B	699626	1108	554	2637	1.46×10^6
Line4A	700734	1108	554	2315	1.28×10^6
Line4B	700734	650	325	2315	7.52×10^5
Line5	701384	650	325	2721	8.84×10^5
Total			3569		1.08×10^7

Table 7.1: The used schematisation for determining the total infill volume is included in this Table. The area per running meter is used to determine the total volume for each section, visible in Figure 7.5.

It is important to note that the current analysis only accounts for the foreshore extending from the surveyed area. This area is depicted Figure 7.5 and corresponds to 3.57 km of the eastern part of Weg naar Zee. In this Figure, it is clear that 1.75 km of the western Weg naar Zee shoreline is not included. It is assumed that this section has a similar convex-up foreshore profile to line 1. Extending this profile westwards for 1.75 kilometres and adding the resulting volume gives a total volume of $1.71 \times 10^7 \text{ m}^3$. This is around 60% higher than without this area.

However, the 1.75 km on the east side of the area in Figure 7.5 corresponds to the shoreline where the mangrove fringe is recovering naturally. Therefore, this area could possibly be excluded from this analysis, as the focus is on the Weg naar Zee shoreline where this natural recovery is not possible, i.e., the westward side. Excluding the easterly 1.75 km of the profile results in a total volume of $1.28 \times 10^7 \text{ m}^3$. This volume is used in the subsequent analysis.

This volume corresponds to the total volume of the entire foreshore for the difference between the current situation and the estimated historic profile. However, in reality, the profile will be suitable for the rehabilitation of mangroves before the historic profile is fully recovered. Favourable conditions due to a less concave-up shape and more suitable habitat at the shoreline for a mangrove fringe can be achieved with a lower total volume. These considerations concerning the total volume will be taken into consideration in 7.3 where the duration for the profile build-up through nourishment is assessed.

7.2. Projected Maintenance Dredging Volumes

A first analysis of the necessary infill volume is done for the foreshore of Weg naar Zee; the results can be used to deduce what impact can be made in creating a healthy foreshore. However, it is important to consider what the annual maintenance dredging volumes are expected to be. This volume determines the maximum yearly sediment input through nourishment, as the dredged sediment during the maintenance works is solely used for the input. Several researches have been done on the annual maintenance volume for the Suriname River.

Year	Company	Notes	Volume ($\text{m}^3 \text{ yr}^{-1}$ in-situ)	Reference
1982	USACE	depth (m-CD) = 5.0 m	0.4×10^6	United States Army Corps of Engineers (USACE) (1982)
1992	Boskalis	depth (m-CD) = 5.0 m	1.1×10^6	Hydronamic (1992)
		depth (m-CD) = 5.5 m	2.1×10^6	
		depth (m-CD) = 6.0 m	3.7×10^6	
		depth (m-CD) = 7.0 m	7.9×10^6	
2008	Lievense	depth (m-CD) = 6.45 m	3.4×10^6	Zwol (2008)

Table 7.2: Overview of companies who researched the yearly maintenance dredging total volumes, with the years, notes, and total volumes

The study by Lievense is the only one grounded in modelling studies, and considering its similarity to the average value yielded from the Boskalis research, the annual dredging maintenance volume (in situ) is assumed to be 3.4 million cubic meters.

7.3. Analysis feasibility input fine sediment

In this section, we aim to analyse the feasibility of fine sediment input. We start by revisiting the results from earlier discussions and consider the possibilities of infilling with nourishment. We consider various scenarios, including using only TT1 (plume dispersion), only TT2 (bed transport), a combination of both, and other input techniques. We also consider these variations' potential impacts in light of sensitivity analysis. Constructability considerations such as sailing times are included in the analysis.

Concerning the total volume of material determined in section 7.1, we now analyse how this can be linked to the input efficiencies found in chapter 6. This raises several important questions, including the composition of sediment deposited on the inter-tidal flat, the density of the material, and the amount of sediment retained in the area. This amount is based on the input volume, transport types 1 and 2, and the quantity of sediment reaching the area. This last aspect leads us to consider what input techniques

and transport types are being used and the frequency of sediment input.

It is important to note that no final answers can be provided to these questions, as they are based on various assumptions. For this analysis, we will use variability assumptions to understand the potential timescale needed to build up the foreshore purely with the inputted sediment. The assumptions include:

- The required volume will be completely filled by the beneficially used dredged sediment which is inputted into the system.
- The composition of the necessary volume is comprised entirely (*i.e.*, 100%) of the infilled sediment fraction
- The density of the accreted bed volume is 1400 kg/m^3 (dry bed 650 kg/m^3) and the maximum amount of sediment reaching the required area is entirely (100%) retained
- For Transport Type 2 (TT2), it is presupposed that the sediment on the inter-tidal flat will eventually spread across the flat towards the Weg naar Zee coastline
- The sailing and unloading time stands at 3 hours; hence, there would be eight inputs daily at full (100%) capacity with one vessel operational. This is in compliance with past project execution.
- The wet in-situ accreted maintenance sediment has a density of 1300 kg m^{-3} as per the references: (Hydronamic and Sescon Group 1992; Zwol, Quist, and P.J. Plooy 2008)

Due to the variability of parameters used for this analysis, a Monte Carlo analysis is applied. This analysis technique not only shows the project duration with the highest probability but also the range of possible durations. The calculations are run ten thousand times to determine the probability distribution of outcomes. Not all parameters are assigned a distribution; some are fixed values or averages of past results. In the following section, the analysis will be discussed separately for the two types of transport. The analysis, along with the selection of input parameters, is discussed in the following sections.

7.3.1. Contribution of Transport Type 1: Plume Dispersion

The first transport type (TT1) has mainly been evaluated in light of increasing the sediment influx to the Weg naar Zee coastline. The Suriname Estuary coastline is a dynamic area. The cross-shore profile of this muddy coast is dynamic since the tidal currents carry a net sediment transport towards the coast by tidal filling, while the waves erode the bed by stirring up the sediment. The theory is that gross sediment transport at this coast, which has an abundance of fine sediments, is extensive in relation to the net sediment transport. Small changes in gross sediment transport can thus result in a relatively large change in the net sediment transport and sometimes reverse the direction of the net transport (Winterwerp and Kesteren 2004).

Despite low transport values of input sediment to Weg naar Zee as SPM (see chapter 6), small changes in the gross sediment transport can thus significantly impact and reverse the direction of net transport. Implementing the STUs (sediment trapping units) would also contribute to the increase of net retained sediment, thus helping change the direction of net transport to a more accretive state.

Determining how much influence this transport type has on the accretion of the coastline is currently difficult. More information is necessary about current erosion/sedimentation levels, plus the retention levels of the STUs need to be researched. Such an analysis could likely only be done correctly by doing a modelling study, which also models the STUs at the Weg naar Zee shore. The model would have to be more precise and developed for smaller-scale analysis than the model used for this study.

But still, a schematic analysis can be done, showing the scale of the necessary build-up of the coast. The estimated historic profiles are used for this analysis, determined in paragraph 7.1. Here, we only consider the added 500m of coast extension for the mangrove fringe, as this is the stretch of coast the STUs must build out. The rest of the profile will be considered in the following section, discussing the transport type 2 (TT2) contribution. The calculation used for this volume is the same as shown in Section 7.1. The total volumes for the 500m mangrove fringe are listed in Table 7.3. The total volume of $4.93 \times 10^5 \text{ m}^3$ accounts for 5% of the total volume. This ratio, between the 500m coastal stretch and the rest of the foreshore, will be used in the subsequent analyses.

Line number	Value
Line 1	115 (m ³ m ⁻¹)
Line 2	231 (m ³ m ⁻¹)
Line 3	122 (m ³ m ⁻¹)
Line 4	141 (m ³ m ⁻¹)
Line 5	125 (m ³ m ⁻¹)
Total Volume	4.93E+05 (m ³)

Table 7.3: The results of the area profile for the first 500m of the profile for the five lines, plus the total volume this comes to if the same calculation is done as in 7.1

The analysis thus considers how long it takes to fill in 5% of the total volume of sediment, determined in 7.1, by sediment supplied by TT1. This sediment is retained fully by the STUs in place. The input sediment contributes to 5% of the total volume compared to the naturally present background sediment. The 5% corresponds to the average ratio between input and background sediment found in section 6.2.4.

The volume that reaches the Weg naar Zee coastline is based on the modelling results for TT1, discussed in section 6.2.4. Taking the maximum value is not realistic, as the unloading can not only be executed at that location and at that time in the tidal cycle. To account for the variability of input timing and location, the average value of the highest found volumes per timing in the tidal cycle is used for the analysis. The results of location north-centre (timestep 13 and 17) and location south (timestep 23 and 30) are used. This comes to an average value of 0.57 tons.

The variability of parameters is accounted for in the Monte Carlo simulation as follows:

- Total necessary volume - As discussed at the end of Section 7.1, the exact necessary infill volume is not known. The schematised analysis comes to $1.28 \times 10^7 \text{ m}^3$ as an estimate. However, it's also suggested that the coast could be suitable for mangrove rehabilitation at an earlier stage. Therefore, this parameter is modelled as a normal distribution. A mean of 75% of this volume, or $0.96 \times 10^7 \text{ m}^3$, is used with a standard deviation of 0.1×10^7 . This approach accounts for the possibilities that only 50% or 100% of the volume is necessary, assigning them lower probabilities. The highest probability is that the required volume will fall between these values.
- Percentual contribution - The 5% contribution of the input sediment with respect to the background sediment is uncertain, as a mean value of model results is used. Therefore a slight variability is accounted for by using a normal distribution. A mean of 0.05 and a standard deviation of 0.01 is used.
- Sailing time - The average sailing, plus unloading time, is 3 hours according to the past project data. Due to various factors, this value is variable. This parameter is therefore included with a normal distribution with a mean of 3 hr and a standard deviation of 0.1 hr.
- Daily operational time - The average value of operational hours throughout the project is variable due to unforeseen events, such as breakdowns and workability issues. To account for this variability this parameter is included as a normal distribution with a mean of 23 hr and a standard deviation of 0.1 hr.

The above parameters were used to analyse the total duration to infill the volume purely by means of the contribution of TT1. The total sediment weight necessary is the "Total volume first 500 m" multiplied by the "Sediment necessary (dry bed density)". How many loads are necessary is determined by dividing this value by the "Retained value due to input 1 load" divided by "Percentual contribution". The time this takes is determined by the "operational daily hours" divided by the "sailing time + unloading".

In Table 7.4 the different parameters and the final results of the Monte Carlo analysis are displayed. On one side the total necessary volume is determined, on the other end, the total time it takes for TT1 to supply this sediment is determined.

	Value / Mean Value	Distribution	St.Dev.	Unit
Necessary volume				
Total necessary volume profile	0.96×10^7	Normal	0.1×10^7	m3
Total volume first 500m	5% of above	-	-	-
Density in-situ	1400	Constant	-	kg/m3
Water content	75	Constant	-	%
TT1 - contribution				
Retained value due to input 1 load	0.57	Constant	-	ton
Percentual contribution	5	Normal	1	%
Sailing time + unloading	3	Normal	0.1	hr
Daily operational time	23	Normal	0.1	hr
Average years necessary	9.7			yr
80% confidence interval	7 to 12.6			yr

Table 7.4: The calculation done for the total infilling duration of the first 500m of the profile using transport type 1 (TT1)

Considering the side-casting method, tested in the sensitivity analysis discussed in Section 6.9, we could multiply the "Retained value due to input 1 load" by 4.5 to 2.6 tons. Input time would increase from 5 to 30 minutes, causing the number of daily loads to drop to an average value of 6.8. Doing the same analysis, we would now have an average duration of 2.4 years with an 80% confidence interval of 1.7 to 3.2 years. This change in sailing time would have great negative impact on the dredging project duration and costs. Also, by inputting sediment in this way, a combination of TT1 and TT2 is changed as less sediment falls to the bed at the unloading location.

7.3.2. Contribution of Transport Type 2: Bed Transport

A different approach is necessary for the second transport type (TT2). This transport primarily contributes to the build-up of the intertidal flat and foreshore of the Weg naar Zee coastline. Sediment is input at the boundary of the foreshore, and due to wave forcing, it migrates shorewards. Eventually, a part will reach Weg naar Zee. However, the bulk of the volume is expected to remain on the foreshore. Therefore, we will consider this separately.

In the previous section 7.3.1, an analysis was done for the duration to fill 5% of the total volume, corresponding to the first 500m of the profile. Now, 95% of the profile is considered. This results in the volume necessary to achieve the desired foreshore concave profile. The same consideration as in the previous section is made for the variability of the total volume.

The model results of the TT2 simulations, discussed in 6.3.4, were used for this analysis. The average of the results found for the three locations was used. By this means variation in unloading location is accounted for. The average of the simulation results showed that 22.3% of the sediment transports over the intertidal flat towards Weg naar Zee, so this percentage was used as a contribution in the calculations. To account for variability of this value, a normal distribution with a standard deviation of 0.5% is used. It is assumed that 100% of this sediment contributes to the build-up of the desired profile. The same variability considerations for the sailing + unloading times and the operational daily hours apply here as in the previous section. The analysis is listed in Table 7.5.

	Value / Mean Value	Distribution	St.Dev.	Unit
Necessary volume				
Total necessary volume profile	0.96×10^7	Normal	0.1×10^7	m3
Total volume TT2 contribution	95% of above	-	-	-
Density in-situ	1400	Constant	-	kg/m3
Water content	75	Constant	-	%
TT2 - contribution				
Total start sediment (5 loads)	19.8	Constant	-	kton
Percentage travelled towards WnZ	22.3	Normal	0.5	%
Sailing time + unloading	3	Normal	0.1	hr
Daily operational time	23	Normal	0.1	hr
Average years necessary	2.3			yr
80% confidence interval	2.0 to 2.6			yr

Table 7.5: The calculation done for the total infilling duration of the profile through transport type 2 (TT2). This does not include the first 500m of the shore (5% of the total) as this is filled in by transport type 1 (TT1)

7.3.3. Combination of both Transport Types

The two transport types have been analysed separately. In reality, implementing sediment input would be a joint effort between the two. Considerations are:

- When sediment is placed on the bed for eventual transport via TT2, part of the load will be transported via the water column by TT1. In this way, a combination of both can be achieved if the sediment is offloaded strategically for TT2 and at the right timing to transport to the Weg naar Zee coastline by TT1.
- In the analysis done in section 7.3, the sediment of TT2 only contributes to the foreshore development, but in reality, a percentage will likely migrate to the shoreline, and thus also contribute to the development of the Weg naar Zee volume.
- When the side-casting method is implemented, a minor part will be deposited on the bed. Using this method will, therefore, increase the efficiency of TT1 but contribute less to TT2. This must be considered if an eventual strategy is further worked out.

8

Discussion

This section delves into the findings of the research. The discussion begins with the results and their implications. This is followed by an exploration of key considerations related to system dynamics and constructability. Attention then turns to important aspects of the model's functionality. Subsequently, the accuracy of the feasibility analysis conducted is evaluated. Finally, the broader applicability of the research findings is considered.

8.1. General Results

Previous Chapters 6 and 7 focused on utilising the model and analysing the results. But what do these results imply for the potential execution of beneficial reuse of dredged sediment during future maintenance dredging projects?

Firstly, the results of Chapter 6 concerning transport type 1 provide a clear understanding of the most suitable locations within the domain for input and the most efficient timing. This knowledge enables project planning to optimize input locations during the tidal cycle. However, aligning the arrival of the loaded vessel with the ideal moment in the tidal cycle can be challenging during actual dredging works. Therefore, knowing the best location at all times is crucial. The results also indicate that side casting is more efficient for transport by TT1 towards Weg naar Zee, which could be beneficial when vessels have extra unloading time.

The results show a generally low ratio between inputted sediment and the sediment that reaches the Weg naar Zee shore for TT1. TT2 shows higher efficiency levels, but due to its unloading at the edge of the intertidal flat, it has more difficulty reaching the shoreline itself. This highlights the importance of combining these two transport types efficiently. The analysis in Chapter 7 separates the two to enable comparison of the results. In reality, a combination of TT1 and TT2 will yield the best results. The placement of sediment for TT2 will result in a percentage of the total load in the water column, which could result in transport towards the shore using TT1, if placed at the right time and location.

The results of Chapter 7 provide an initial indication of the project duration. Assuming the analysis is accurate, the extension of the shoreline by TT1 would take between seven and thirteen years, with the highest probability of a duration of around ten years. Ten years may seem long, but it should be considered in the context of the Weg naar Zee coast, which has been in decay for the past 50 years. If a relatively low-effort project can solve this problem in 10 years, this duration would not be too long.

This assumes the separate influences of TT1 to the first 500m and TT2 to the rest of the profile. In reality, TT2 will likely contribute to the build-up of the shoreline as well. This would increase the duration length of TT2, which is most likely around 2 years according to Chapter 7, but greatly decrease the duration of TT1. This would mean the total duration would be less than 10 years, making this technique even more attractive.

The project can be considered 'low effort' for several reasons. After using this research as a basis to develop a complete execution strategy, the execution itself is low effort. The sediment is already dredged and transported offshore. If only the unloading of sediment is relocated to the locations analysed in this research, and efficiently timed during the tidal cycle, this approach could greatly benefit the Weg naar Zee coastline. This would likely also decrease project costs due to the reduced sailing times compared to the original journey offshore. This technique not only has incentives for the Suriname coastal management representatives but also for the dredging companies executing the maintenance works in the future

8.2. System and constructability

This section discusses key considerations related to system dynamics and constructability. These points are crucial for understanding the implications of the model and feasibility analysis results. While some of these considerations may positively impact the feasibility results, others could complicate the execution of the project.

8.2.1. Influence of Mudbank

The impact of the approaching mudbank, emanating from the eastern seaboard and currently moving towards the Suriname River estuary, is primarily accounted for in the hydrodynamic analysis. This impact is simulated by incorporating its bathymetric features into the model. However, this approach does not encapsulate fully all the potential effects that the mudbank could have on the estuary. In reality, the mudbank will not only attenuate waves but also lead to increased sediment concentrations. This is further increased by the flow of fluid mud on the western side of the mudbank complex, resulting in even higher sediment levels within the estuary. This phenomenon could significantly influence the ratio of input sediment to background sediment. Moreover, changes in hydrodynamic conditions, such as wave height and direction, along with altered flow patterns induced by the mudbank, are likely to yield different results in the feasibility analysis. Acknowledging these potential changes is crucial when utilising this analysis in practice, particularly given the imminent arrival of the mudbank complex at the estuary.

Consider, for example, the functioning of Transport Type 2 (TT2), which is primarily driven by wave forcing. The presence of a mudbank would significantly influence wave propagation towards the unloading location for TT2. Wave attenuation, caused by the mudbank in the estuary, is expected to decrease the efficiency of TT2. However, the mudbank would also increase sediment concentrations in the estuary. As a result, the Weg naar Zee would experience less coastal stress due to the natural shelter provided by the mudbank. This, combined with increased sediment retention from the STUs and potentially mangrove trees, highlights the importance of considering the timeline of implementation. The key question is: how much should the coastal conditions have recovered by the time the mudbank starts migrating across the estuary? It's possible that by this time, the coastline could have been brought to a state where it can continue to develop under the conditions created by the mudbank, without sediment input.

8.2.2. Refilling dredged channel

The research findings indicate that a significant portion of the sediment introduced into the system is unintentionally lost to areas where it was not intended to be transported. A fraction of this sediment returns to the shipping channel from where it was initially dredged. This could potentially lead to negative implications for future maintenance dredging operations. As it stands, only the deposition locations can be ascertained from the simulation result plots; the precise volume of sediment that ends up back in the shipping channel remains uncertain. This specific quantity can be investigated in future studies using the same model.

8.2.3. Nourishment Options

Dredging vessel Type

Trailing Suction Hopper Dredger (TSHD) – The modelling studies performed in this research currently rely on a TSHD. The sediment input is based on a TSHD with a predetermined volume and draught, reflecting a mid-sized TSHD. The vessel's capacity significantly affects the feasibility calculations elab-

orated in Chapter 7. The study presumes that all sediment is offloaded through the under-hull doors, conditioning the offload position to the vessel's under-hull clearance. An alternative method worth exploring is rainbowing the sediment onto the deposition site. Although this method compromises accuracy, it enhances the % of input sediment in the water column, potentially benefiting transport type 1. Another potential strategy is pipelines, which could facilitate nourishment closer to WnZ but may significantly inflate execution costs. Moreover, the agitation method, as indicated by the sensitivity analysis, holds promise. The TSHD can operate by maintaining a continuous overflow of sediment from the ship's hold or reintroducing the sediment into the water column with a pump. However, to achieve a sufficient level of SPM reaching WnZ, the TSHD would need to sail to specific input locations.

Water Injection Dredger (WID) – Hydrodynamic dredging includes all dredging techniques that lead to the suspension or re-suspension of bed material. These techniques use natural processes, such as tidal currents, to move the suspended material. Understanding the local dynamics of water movement from this study could be helpful for further investigating the feasibility of this technique. A WID works by injecting water into the sediment layer using a low-pressure water jet, leading to the suspension of sediment and creating a density current. A powerful water jet stirs the sediment from the bed (Sigwald, Ledoux, & Spencer, 2015). Some projects that have used this method show promise, but they have been more suited for tasks such as port and waterway maintenance (Spearman and Benson 2023).

Cutter Suction Hopper Dredger (CSD) – Utilising pipelines to deposit the sediment closer to the WnZ shore could boost efficiency for transport type 2. Regarding draught clearances, the CSD has a distinct advantage over the TSHD, making access less challenging. Due to long distances to the shore, pipelines would bring substantial costs to the project. The idea of no extra costs and only bringing extra value by utilising the nourishments would be lost. Also, due to the long distances from the maintenance dredging works to Weg naar Zee, using CSD for this type of work is not possible.

Accessibility of Input Location

Concerning TT1: The locations assessed for this transport type typically have fewer accessibility issues due to an average depth of 6 meters. These locations can mostly be accessed during at least half of the tidal range.

Concerning TT2: There is less depth available at the locations tested for this transport type, due to the requirement for sediments to reside on nearly flat terrains to prevent gravitational transportation into deeper channels. Therefore, a higher water level is crucial here, constricting the opportunity window as only a portion of the tidal range permits vessel access. This implies that not all fully loaded vessels may be able to offload at the three tested locations for this transport type at all times.

8.3. Model Functionality

This section discusses the functionality of the Delft3D model, which facilitated the feasibility analysis. The model's functionality is crucial for the end results. The major points of discussion related to the model are detailed below:

8.3.1. Data and Validation

In earlier modelling studies such as Loeff et al. (2022) and Maria Eirini Tzampazidou et al. (2020), it was noted that a lack of data from the coastal region of Suriname makes it difficult to calibrate and validate numerical models set up for this area. Because accurate and extensive data-sets can't entirely confirm the results of these models, expert judgement is used to verify the outcomes. The basic model used in this research, created by Alkyon and modified by Loose (2008), was validated using water level, flow velocity, salinity distribution, and background sediment concentration data collected from the region. The model was expanded during this research by adding a WAVE model to the already calibrated and validated FLOW model. However, because of missing data from the coastal area of Suriname, this WAVE model couldn't be validated using wave data and so was confirmed by expert judgement instead. The absence of field measurements of wave environments in this coastal region highlights an area for future research. If more modelling work is planned for the coast of Suriname, it is essential to collect more field data, such as wave data over a mud layer traverse and the current situation, to allow for a more thorough comparison.

8.3.2. Fluid Mud Layers

The simulation of fluid mud layers is a complex process. These dense fluids act as individual layers on the bottom of the bed, mainly in the deeper tidal channel and river. These layers can not be accounted for in the current Delft 3D model Quist and Plooy 2008. In a different research, the wave-damping effects in the Suriname Estuary were analysed by Loef et al. (2022) using SWAN mud. However, this research diverges by utilising wave conditions determined through EVA analysis of offshore waves that are subsequently transformed into shore conditions. In this study, the effects of the mudbank were attempted to be simulated during the hydrodynamic analysis only by means of bathymetric changes. For a comprehensive representation of these fluid mud layers, which are present due to migrating mudbanks, it is suggested to incorporate a SWAN mud model into the WAVE model. Notably, nourishment's feasibility could be drastically altered, especially when a mudbank is present. This is attributed to the change in wave attenuation over the fluid mud layers present in that specific scenario.

8.3.3. Grid Resolution & Bathymetry

In section 4.4, it was explained that the grid underwent a refinement process to study the transport at the Weg naar Zee shoreline up to the tidal channel. However, the inability to refine the shoreline resulted in a step-wise grid pattern instead of a smoother one, which may have caused minor side effects on the model outcome. Nevertheless, the effects were minimal as the transport along the coast was insignificant, as demonstrated by the transport type 1 results.

The bathymetry underwent minor changes due to extension towards the east for the wave model. The research area observed no changes, and likely, the bathymetry does not represent the current situation perfectly. Acquiring more survey data may alter the model's bathymetry, enhancing the results positively. Further, there is little data on the thickness and location of fluid mud layers. The probable reason for this is that the thickness of these mud layers is difficult to measure. These layers could affect the bathymetry, which would affect the model results.

8.3.4. Functionality of Settling

The settling velocity is crucial in the model, especially for transport type 1 (plume). A sensitivity analysis was conducted for settling velocity, which revealed its importance. The Delft3D-FLOW version includes the hindered settling process, which affects sediment input. High sediment concentrations are present in the input gridcells, particularly in the layers where sediment is brought in. The hindered settling reference density is currently set at C_{gel} 50kg/m³. The hindered settling process is a function of the mean fall velocity and a ratio of the hindered settling concentration ($CSOIL$) to the occurring sediment concentration. For the input sediment, the settling velocity is set at 0.25 mm/s. Although no further calibration has been conducted, it is possible that more positive results could be obtained if more hindered settling were to occur. This could cause more sediment to remain in the water column for a longer period, resulting in more transport in the direction of Weg naar Zee.

8.3.5. Modelling of Input Sediment in the Model

To be able to model the input of sediment for analysing the spread of sediment, several assumptions and schematisations were made. In the first place for transport type 1, transport through the water column under the influence of flow pathways caused by tidal flows. In the second place for transport type 2, the transport of sediment migrating over the bed under the influence of wave forces. Based on the unique limitations and assumptions, this section explores the modelling of input sediment in the model for transport types 1 and 2.

Transport Type 1

It is assumed that all sediment dredged during maintenance work is the "Guyana Mud" sediment with the same characteristics as the background sediment in the model. However, it's possible that sand or other sediment types could also be present, especially since maintenance dredging primarily involves sediment recently deposited in the shipping channel. This sediment mostly consists of the imported Guyana Sediment, but the percentage of other sediment types could be significant. Additionally, the capacity of the TSHD used to transport sediment is currently fixed at 3000 m³, but this value could be smaller or larger depending on the vessel used for the project. Finally, how sediment is distributed during input is also fixed, but this could vary depending on vessel size, local water depth, and the specific sediment load being transported. All of these assumptions determine the total weight of suitable

sediment that will be transported to the Weg naar Zee area and thus impact the efficiency of this transport mode. Providing more specific information about these assumptions would reduce uncertainty and provide a clearer picture of the total sediment weight being transported.

Transport Type 2

For Transport Type 2's sediment input modelling, the principal schematisation involves the sediment distribution on the seabed. In the current model, the sediment is evenly spread across the domain covered by the 2x2 grid cells. In contrast, in the real world, the deposition of 5 loads of sediment would result in a more mound-like formation, with a higher elevation at the centre that tapers off towards the edges. Consequently, the central part of the mound would experience a greater wave forcing, leading to a faster sediment transport rate compared to what is currently modelled. According to the sensitivity analysis performed for wave influence, this discrepancy would have a minor effect on the distribution of the transport direction. The primary influence would instead be noticeable in the total time required for the sediment to spread out.

A secondary assumption in the model is that all the dumped sediment remains within the original deposit area during the discharge of 5 loads. In reality, the sediment would be exposed to wave forcing and disperse as soon as the initial load is deposited on the bed. However, similar to the previous consideration, this factor would primarily alter the transport times and would not significantly affect the distribution of transport direction.

8.4. Accuracy of Feasibility Analysis

Chapter 7 discusses the schematisation of the total required volume, and the associated relationship between this total volume and the ability of the sediment nourishment to "fill up" the volume. The analysis provided in this chapter offers useful insights, but it was necessary to make some assumptions to reach the final conclusion. These assumptions are listed and discussed below:

- To find out the total required volume, some assumptions had to be made because the survey data lacks information about the crucial area between the inter-tidal flat and the Weg naar Zee coast. Currently, an extrapolated estimate is used to find the necessary elevation required for a healthy mangrove fringe, but this method isn't completely reliable. Having exact profile data up to the coast would reduce this uncertainty.
- At present, how much sediment input can "fill up" this volume is purely speculative. It's unknown how much sediment actually stays in the system. It's possible that all sediment at Weg naar Zee is retained by the existing STUs, but this isn't certain. Similarly, the amount of sediment retained on the intertidal flat is unknown. Nevertheless, satellite images over the previous years show that coastal stretches where mangroves have resettled are built out. This further proves the ability of the coastline to retain sediment, if mangroves are rehabilitated. Since restoring the Mangrove fringe is essential for rehabilitation, any sediment that makes its way to Weg naar Zee improves the situation. However, it's not yet possible to accurately say how long it would take to restore a healthy profile.

8.5. General Applicability

This case study could become a model for "Building with Nature", helping other similar projects in the future. The research gives a broad understanding of how "mud nourishments" can be used, especially in the lively environment of the Suriname Estuary. It provides a deeper insight into the coastal system and sediment routes, which can be used to improve restoration strategies using Suriname as an example. This knowledge could be used in other places too, although we would need to consider local variations. But what can future projects in places with muddy coasts learn from this?

Restoring mangrove trees using structures that can catch sediment is mainly suggested for places with a wide tidal range and a lot of sediment (Balke and Friess, 2016). We selected two examples of mangrove coasts to compare to Suriname due to similar levels of erosion (Deltares, 2022b). Guinea's coast could be a place where this method could work. Though the tidal range there is like Suriname, other conditions differ as it is a muddy and low-energy place affected by wind and tide currents with a few small rivers. Ghana, also on Africa's West coast, faces more wave-influenced conditions, sand

sediments, and two major rivers. As these conditions will be significant, this research may have similarities to Ghana.

Strong knowledge of both the physical and ecological systems is crucial for successful mangrove restoration. However, without an understanding of the social and economic aspects, restoration efforts may not succeed. Many mangrove coasts, similar to Weg naar Zee, face challenges, which can result in harmful effects on local communities. In some past cases, the value of mangrove trees has been underestimated. Also, subsidence problems caused by groundwater extraction, common in Demak (Gijón Mancheño, 2022), are often poorly understood. The success of mangrove restoration efforts relies on a broader understanding and awareness among local communities regarding the importance of mangrove protection and the possible impacts on these ecosystems. Collaborating with local people is crucial in restoring the mangrove coastal system. Therefore, it is essential to prioritise the creation of local awareness.

Conclusion & Recommendations

9.1. Conclusion

The main question that was sought to be answered during this study is the following:

"What is the feasibility of the beneficial reuse of dredged sediment by means of sediment input to rehabilitate the growth of Mangrove forest on the coast of Weg naar Zee, Suriname?"

To answer this question, the three subquestions will be further elaborated on:

1 - What are the necessary abiotic conditions, considering the local coastal conditions and driving processes of the coastal system, for successful mangrove forest rehabilitation on the coast of Weg naar Zee, Suriname?

Although the Suriname coast is largely in a healthy and dynamic balance, it is highly dynamic due to the passing of mudbanks originating from the Amazon River. The transit of these mudbanks results in coastal accretion. However, following the passage of the mudbank, an inevitable coastal retreat occurs during the interbank phase. This process maintains a delicate balance.

Currently, the balance of the Weg naar Zee coastline is disrupted, resulting in an overall erosive state. This coastline is located within the Suriname River Estuary and remains somewhat removed from the mudbanks, rendering the accretion-retreat cycle inapplicable to this region.

The removal of mangroves, coupled with prolonged exposure to large wave forcing, has transformed the foreshore profile from a healthy, convex-up shape to a more concave-up shape. This alteration results in a reduced intertidal area, amplified wave height, and a decreased external sediment supply. An outcome of these changes is a net seaward sediment transport, which contributes to shoreline erosion.

For mangrove rehabilitation to occur, it is crucial to restore a healthy, convex-up foreshore profile. Ideally, an elongation of the shore of approximately 300 meters, at the level of Mean High Water (MHW), followed by a convex-up profile extending towards the deeper tidal channel, should be targeted. These alterations would lead to an increased tidal range, diminished wave height, and enhanced external sediment supply. Such conditions would nurture a net shoreward sediment transport, necessary to transition the Weg naar Zee shoreline from an erosive to an accretive state. Historic satellite images of neighbouring coastal stretches show that, when rehabilitated, mangroves can quickly develop a healthy coastal fringe and help build out the coast.

By fostering milder hydrodynamic conditions, mangrove propagules are granted the opportunity to settle and regrow on the Weg naar Zee shore. Thus, conditions could be restored to a previous state where the mangroves thrived. It is essential to minimize human interference, as excessive human intervention significantly contributed to the initial disappearance of the mangroves.

2 - Can sediment input be effectively utilised in the Suriname River Estuary to positively impact the conditions required for successful mangrove forest rehabilitation on the coast of Weg naar Zee?

The analysis conducted in Chapter 5, using the developed Delft3D model, provided insights into the main hydrodynamic processes in the system. The results indicated favourable conditions for inputting sediment to transport it towards Weg naar Zee. Firstly, flow velocities and transport pathways at particular moments in the tidal cycle suggested that transporting Suspended Particulate Matter (SPM) towards the Weg naar Zee coast after its introduction is possible. Secondly, significant bed shear stress triggered by both regular and higher than average wave conditions, at locations where input could be added, suggested that bed transport towards Weg naar Zee under wave influence was likely, indicating that SPM plume dispersion towards Weg naar Zee (TT1) and transport via migration over the bed (TT2) are viable options the estuary presents.

Both transport types were tested separately, yielding promising results. Transport type 1 represents sediment transport towards the Weg naar Zee coast after inputting sediment into the water column. Though the sediment quantities might seem small compared to the original input, they can still significantly increase the gross sediment quantities at Weg naar Zee. This increase could lead to a flip of net sediment export towards input. Besides, it was shown that the side-casting method could multiply the sediment quantities by a factor ranging from 3 to 6. This shows its promise as a technique for implementing sediment nourishment in the system.

For Transport type 2, it was observed that a substantial percentage of sediment would indeed migrate towards the Weg naar Zee coastline, originating from 3 different locations. Although the simulation times were not long enough to show final transport quantities, positive results revealed a contribution of 24% sediment for the most favourable location. With a longer simulation period, this percentage could become even higher, as 5% of the sediment is still in the original area.

The results solidify the potential to cleverly use the estuary system's hydrodynamic processes to transport sediment from farther distances towards the Weg naar Zee coast, thereby positively affecting the coastal conditions.

3 - What is the necessary amount of sediment required for these given conditions, and to what extent can strategic input through the beneficial reuse of sediment contribute to reestablishing these conditions?

Based on the foreshore survey data, a schematisation of the total infill volume was made in Chapter 7. The extrapolation from five transects revealed that an infill volume of roughly 13 million m³ would be needed to bring the foreshore to the level of the estimated historic profile.

By applying the results obtained for the two transport methods, it was possible to estimate the impact on the system of inputting a set sediment quantity. For the Weg naar Zee coastline, considering the impact of the first transport type, the most likely estimate is approximately 9.7 years. However, there is an 80% confidence interval, suggesting that the actual timeframe could fall between 7 and 12.6 yr. For the rest of the foreshore, taking into account the impact of the second transport type, it would require around 2.3 years, with an 80% confidence interval between 2.0 and 2.6 yr. However, this schematisation only factors in direct influences of the separate sediment inputs. The reality is that sediment already present in the system would also contribute. Also, efficiently combining both transport types could decrease the total duration. Further analysis would be necessary to obtain a more reliable value.

Additionally, this timeline does not consider the influence of the approaching mudbank complex. It's anticipated that the large amount of sediment brought by the mudbank complex, along with processes like mud streaming, could significantly expedite the restoration of the Weg naar Zee coastline. Therefore, the actual duration could be shorter than the determined period.

9.2. Recommendations

This study serves as a solid foundation for exploring the implementation of sediment input in the Suriname Estuary. Further points for subsequent research are presented in this section. These could potentially be incorporated into the ongoing "Partners voor Water" project on this topic. Boskalis and Deltares, among others, carry out this project.

Further Research on the Suriname River Estuary :

- **Mudbank Influence:**
The advancing mudbank from the eastern seaboard offers a compelling area of research. Besides attenuating waves, the mudbank could potentially lead to increased sediment concentrations that must be incorporated into future hydrodynamic analysis.
- **Analysis of Dredged Channel Refilling:**
Conduct a detailed study into the inadvertent loss of re-inputted sediment back into the initial dredging zone. This could facilitate more accurate estimation of maintenance dredging volume and improve operational plans. The model used for this research could be used for this purpose, given its original intent of quantifying sedimentation in the shipping channel. Necessary modifications would include extending the simulation time and incorporating multiple sediment inputs to simulate the effects of large-scale sediment unloading.
- **Examination of Dredging Vessel Types:**
Detailed examination of the usage of different types of dredging vessels, such as TSHDs, WIDs, and CSDs, and their effects on the coastal ecosystem could prove beneficial. Constructability and cost scenarios for each vessel type can also be explored. Exploring different scenarios concerning total loads and corresponding draughts, compared to real-time tidal levels, could be useful for researching the accessibility of the input locations throughout the tidal cycle.
- **Social and Economic Aspects:**
Further research on the social and economic aspects of mangrove restoration, engaging local communities and developing their understanding of the long-term value these ecosystems hold, is also recommended.
- **Comparisons with Similar Ecosystems:**
Using the research developed in this project as a benchmark for 'Building with Nature' projects, similar scenarios in comparable ecosystems could be studied for further insights or validation of the current project's findings. Mainly focussing on upscaling possibilities in other rivers/estuaries in Suriname, and its neighbouring country Guyana, as system conditions are comparable here. Countries with similar coastal conditions, such as Guinea or Ghana, could benefit from this technique (see Section 8.5).

Adjustments to the Delft3D Model:

- **Data Collection for Validation:**
Collecting more comprehensive field data, such as wave data, could help validate and calibrate the enhanced version of the Delft3D model applied to Suriname's coast. Wave data, particularly from the start of the intertidal flat where sediment input locations are chosen in this research, would be beneficial. This data could validate the wave results from the hydrodynamic model, which are crucial for the TT2 efficiency results.
- **Simulation of Fluid Mud Layers:**
Future research could focus on incorporating a SWAN mud model into the WAVE model of the Delft3D system. This could significantly improve the representation of fluid mud layers and possibly render radically different outcomes for nourishment feasibility.
- **Increase the model simulation period:**
Mainly important for transport type 2, as sediment is not fully distributed at the end of the simulation. For transport type 1, it is sufficient as the transport has fully died out for that single load. Combinations of loads and their effects during longer simulations could be researched if the model simulates a longer period.
- **Grid Refinement & Bathymetry:**
Further refinements toward a smoother grid system could be beneficial. Additionally, more accurate and updated bathymetric data might enhance model results.

- **Modelling of Settling and Input Sediment:**
For future research, it is recommended to confirm the settings of sediment parameters or make more accurate assumptions about the sediment type. This can be done by more extensive sensitivity testing and validating with field observations. The properties to focus on include critical shear stress for erosion, erosion rate, deposition efficiency, and settling velocity.

Further Analysis Feasibility

- As mentioned in Section 8.4, the analysis carries a degree of uncertainty due to insufficient data on the foreshore. Further surveys on the foreshore could reduce this uncertainty, leading to more accurate foreshore profile estimates and a more precise feasibility analysis. Therefore, it would be beneficial to survey the area between the current data and the shoreline. Additionally, obtaining data on the profile at the western end of Weg naar Zee, which is currently missing, would further enhance the accuracy of the analysis.
- Further detail how much-nourished sediment is sustained on the foreshore or at the Weg naar Zee coast. A detailed analysis of the deposition of the input sediment, taking into account the actual volume of sediment retained in the system, can provide more accurate estimates of the duration required to restore the foreshore profile to the conditions necessary.
- Further detail the working of the STUs. As they are already in place, a way of quantifying how much sediment is being retained by the structures should be chosen. If available, using data already measured in the field in previous years. Or by acquiring data by setting up a monitoring plan in the field. If the accurate sediment retention capability of the STUs is known, this will make the feasibility analysis in Chapter 7 more accurate.

Implementation Pilot Project

- If results, after further refinement of the feasibility analysis, continue to show promise for this technique, a pilot project could be executed in the field. This could take place during the "Partners for Water" project, which will utilise and build upon the research conducted in this thesis. The pilot project would aim to validate the results shown in the model simulations. One potential technique for the pilot project could be a tracer study, similar to the method used in the Mud Motor project (Vroom et al. 2017). Tracer sediment could be introduced into the system at specific moments during the tidal cycle. By analysing the quantity of the tracer found in samples taken from the shoreline at low water, the efficiency of different input locations can be tested. This could serve as a validation of the model results.

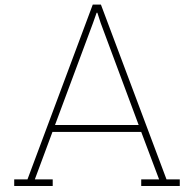
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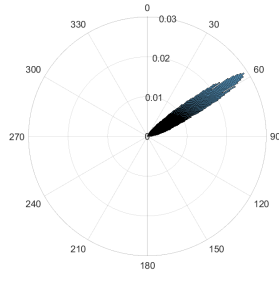
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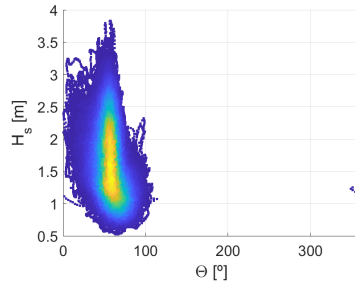


Wave & Wind EVA

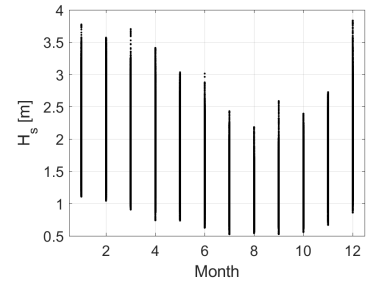
The data is obtained from Aktis Hydraulics and transformed to nearshore conditions using SWAN. The offshore data is hindcast and has been calibrated by Aktis Hydraulics against altimeter data. The used location is at Lon -53.9998°E, Lat 7.0006°N, at a depth of 86.19m. The time series consists of 1-hourly data over a period of 43 years of data (1979-2021). The series includes significant wave height (H_s), associated spectral peak period (T_p), zero-crossing period (T_z) and incoming directions for the total sea state, swell and wind sea separated. Also, wind speed and direction at 10m height (U_{10}) are included. The graphs present density plots, where the colour intensity represents the concentration of data points. A more intense yellow colour indicates areas with a higher density of data points, signifying regions of the parameter space where combinations are more frequently observed.



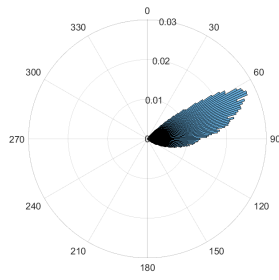
(a) Wave rose



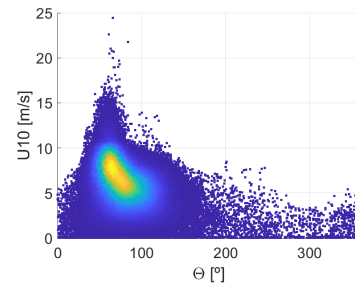
(b) Wave direction vs. H_s



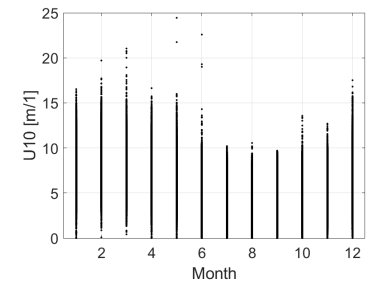
(c) Month vs. H_s



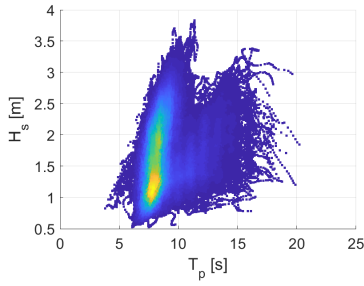
(a) Wind rose



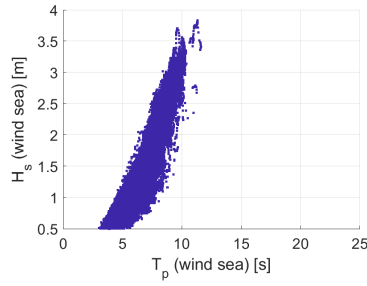
(b) Wind direction vs. U_{10}



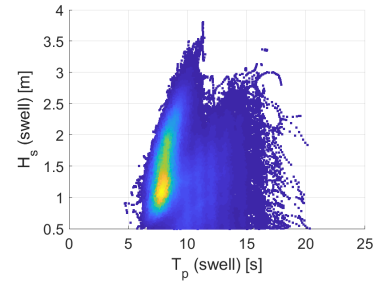
(c) Month vs. U_{10}



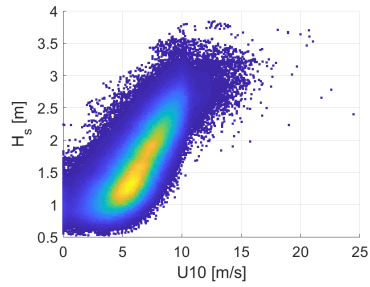
(a) Total sea state H_s vs T_p



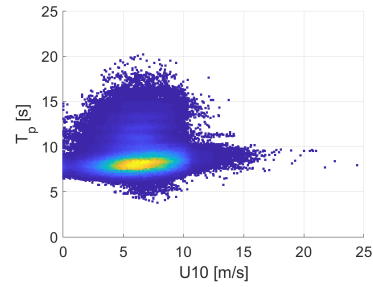
(b) Wind sea H_s vs T_p



(c) Swell H_s vs T_p



(a) H_s vs. U_{10}



(b) T_p vs. U_{10}

B

Wave- and Windroses

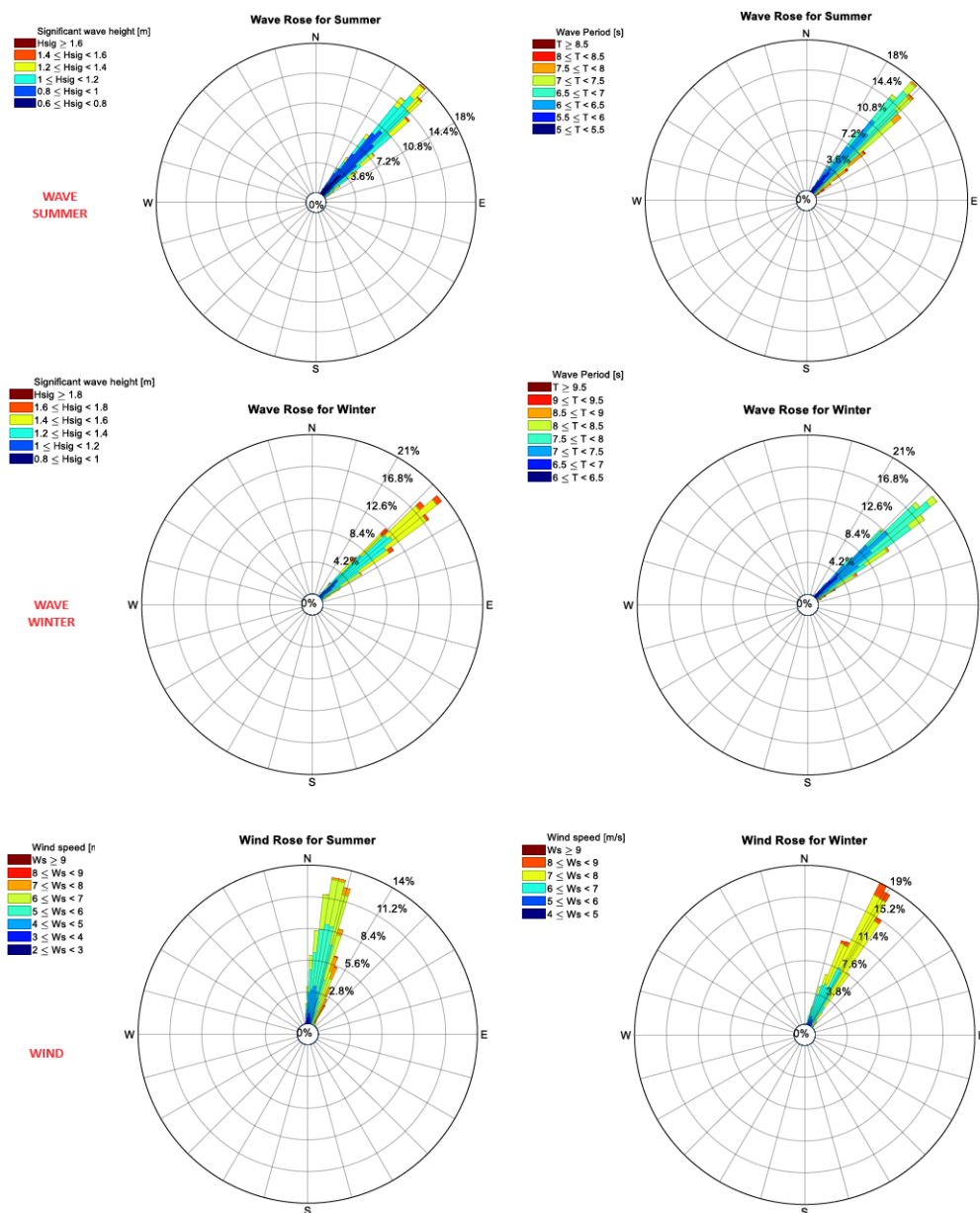


Figure B.1: **Top Row:** Offshore wave roses for the summer conditions, the top is the significant wave height (m) and the bottom is the wave period (s) **Middle Row:** Offshore wave roses for the winter conditions, the top is the significant wave height (m) and the bottom is the wave period (s) **Bottom Row:** Wind roses, the top is the wind speed in the summer period (m/s) and the bottom is the wind speed in the winter period (m/s)

C

Theoretical Background

Sections C.1 and C.2 are fully based on the lectures of the course Sediment Dynamics (CIE4308) at the Delft University of Technology, the book 'Introduction to the Physics of Cohesive Sediment Dynamics in the Marine Environment' from Winterwerp and van Kesteren (2004) and the book 'Coastal Dynamics' from Bosboom and Stive (2021)

C.1. Fine Sediment Dynamics

Classes / Composition - Marine sediment is a mixture of fine particles (silt and clay below 63 micrometres), sand, organic matter and water. The sand and silt are spheres and form a granular skeleton. The clay content in the mud mixture is more plate-like and has cohesive properties, which means they attract to each other coherence. The water content is important for classifying the bed type, plastic or liquid.

Flocculation - Cohesive particles can join and create flocs through a dynamic process called flocculation, which is influenced by several variables, including the organic composition, the spatial and temporal dimensions, and other variables. Small sediment particles can naturally aggregate into larger flocs in aquatic environments, made possible by natural flocculants like microorganisms or organic matter. In contrast, adding salt can also cause flocculation. A loose structure, high water content (>95%), and a typical size of several hundred micrometres are the characteristics of flocs. Small particle buildup in flocs causes low permeability and can cause liquefaction by quickly raising water pressure, which weakens the soil. The soil becomes "liquid" due to this loss of bearing capacity.

Settling - Due to variations in settling velocity, the settling behaviour of fine cohesive sediment (clay and silt) differs from that of coarse non-cohesive sediment (sand). Stokes' traditional settling law holds true for sand particles but not for non-Euclidean mud flocs. Because coarse sediment settles more quickly than fine sediment, sediment sorting happens in mixtures of coarse and fine sediment. Additionally, flocculation has an impact on the settling velocity and behaviour. The settling velocity of flocs is influenced by their size and density, with larger and denser flocs settling faster and closer to the source of the sediment. Although increasing the amount of suspended sediment improves flocculation, the effect is limited by slowed settling brought on by sediment blockage. Near the bottom, where sediment is stirred up from the fluffy bed layer, are the highest volumetric concentrations. A shock wave known as the lutocline results from sediment blockage near the bottom when the critical concentration is exceeded. The composition of the bed is arranged according to settling velocity as a result of sediment sorting, with the smaller settling velocity particles forming the top, fine, and erodible "fluffy layer" and the larger settling velocity particles forming the lower, "consolidated layer." Fine sediment interactions, flocculation, and hindered settling all interact to cause the settling velocity to be complex and irregular.

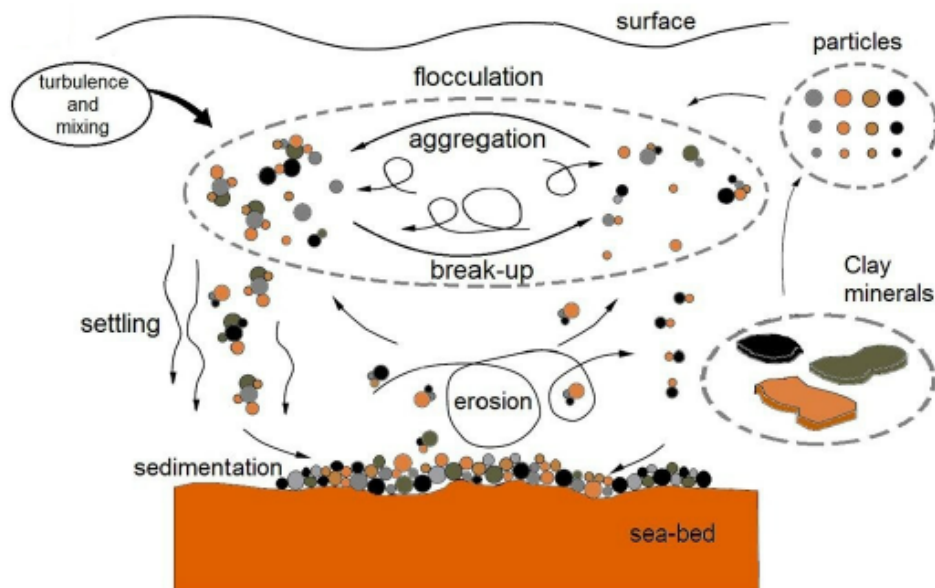


Figure C.1: Figure showing the cycle of deposition and resuspension of cohesive sediment including the flocculation process, influenced by turbulence and mixing, composed of aggregation and break-up (Source: Wang X.H. and Andutta F.P. 2013)

Transport and erosion - Hydrodynamic forcing, settling velocities, and bed quality all play a role in the

transfer of fine sediment between the bed and the water column. The energy needed to keep cohesive fine sediments suspended is much smaller than the energy needed to remove these particles from the bed. In essence, above a predetermined forcing threshold, fine sediments are dislodged and remain in the water column even under light-forcing conditions.

The dynamics of mud coasts and the erosion of fine sediment are both significantly influenced by waves. Particularly, wave forcing disturbs the bed, causing fine sediment to become suspended. Additionally, waves encourage mixing brought about by flow and may reduce the strength of the soil by oscillatory stresses. Wave-induced transport is not significant because it would prevent the accumulation of fine sediment. Theoretically, currents mix and move the sediment, while waves mobilize it. The effect of waves on the flow boundary affects the amount of vertical mixing. The behaviour is distinct in the turbulent breaker zone, where radiation shear stresses predominate in long-shore transport.

State of bed - Cohesive and non-cohesive sediment, as well as consolidated and fluffy bed layers, make up the bed state. A "starved bed" condition, specifically for fine sediment, is a possibility in conditions where sediment availability is constrained. Entrainment functions, as opposed to transport formulae used for alluvial bed conditions where sediment availability is not a limiting factor, are the approach that is most appropriate to use in this scenario. It is crucial to remember that the entrainment function mainly concentrates on pick-up and that its applicability is limited to grains with diameters between 0.1 and 1.0 millimetres.

Erosion modes - The overall amount of sediment removed from the bed is referred to as erosion. Entrainment, floc erosion, surface erosion, and mass erosion are the four erosion modes that can be distinguished for muddy beds. Particles are suspended from the bed by turbulent vertical mixing, which leads to entrainment. When shear stresses from peaks resulting from turbulence or waves exceed the drained strength of unconsolidated flocs, floc erosion occurs when individual sediment flocs rupture from the bed. Horizontal floc layers are eroded layer by layer when there is surface erosion. As water permeates the layer and replaces the flocs of sediment, the permeability of the bed is crucial to this process. On the other hand, mass erosion happens when water cannot reach the inside of the chunks, prohibiting surface erosion. Larger flow-induced shear stresses that are greater than the strength of the undrained bed may cause the overly-consolidated bed to erode. Mass erosion is a result of bed failure brought on by the development of cracks.

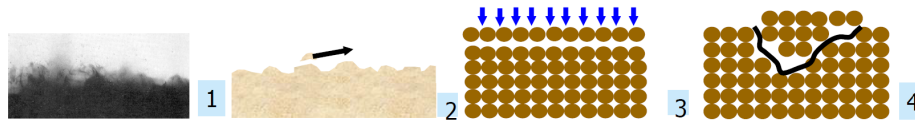


Figure C.2: The four erosion modes: [1] Entrainment, [2] Floc erosion, [3] Surface erosion, [4] Mass erosion (Source: Course CIE4308 Sediment Dynamics)

Erosion and deposition model and formula - In the scientific community, the Partheniades-Krone formulation, which takes erosion and deposition into account, is frequently used. Named after Partheniades, who first proposed it in 1965, this specific model relates to fine sediment. According to the model, erosion depends on three variables: the erosion parameter (M), the ambient shear stress (τ_b), and the critical shear stress for erosion (τ_c). This model is applicable to consolidated and homogenous beds. The ambient shear stress needs to be higher than the necessary shear stress for erosion to take place. On the other hand, Krone developed the deposition model for fine sediment, which is dependent on four variables: the fall velocity (w_s), the concentration (c), the ambient shear stress (τ_b), and the critical shear stress for erosion (τ_c). The concentration, fall velocity, and ambient shear stress all affect how much is deposited.

$$E = M \left(\frac{\tau_b}{\tau_c} - 1 \right) \quad (C.1)$$

$$D = w_s c \left(1 - \frac{\tau_b}{\tau_c} \right) \quad (C.2)$$

The Partheniades-Krone model, which is single-layer and cannot account for steady or gradually changing flow because the critical shear stress for erosion is fixed, has some limitations. If the threshold is not exceeded, this can lead to unlimited deposition, and if it is, it can also lead to unlimited erosion. Van Kessel et al. created a more recent model in 2011, which is a two-layer system, to overcome this limitation. Based on physical and biological processes, the upper layer and the layer below function independently. On short-time scales, the upper layer is active, whereas the lower layer is active on long-time scales. This corresponds to the "fluffy layer" and the "consolidated layer," and allows for the reasonably accurate modelling of spatial and temporal variability.

C.2. General Mud Coast Dynamics

A “muddy coast” is a coastline that consists of mainly fine and cohesive sediment types. These coasts are also generally populated by a large quantity of (mangrove) vegetation. The muddy coasts are generally low-energy environments, as fine sediment can only remain nearshore in mild conditions. Therefore, the foreshore is mildly sloping, in the order of 1:1000 or 1:1500. Muddy coasts are mainly found in the tropic areas worldwide, due to high precipitation and chemical weathering of the sediment. The moderate slope of the foreshore causes waves and tidal velocities to refract as they reach the shoreline. The wave energy is diminished as it travels towards the coast, mostly through dissipation and less through wave-breaking. As a result, long-shore currents are small due to the shallow water, and sediment is primarily transported perpendicular to the coast. The only factors influencing the cross-shore movement of sediments in the foreshore are nearby wind-driven currents and waves. The variables influencing the availability of sediment along the coast include the interaction of waves stirring up sediment in the shoreline and the tide transporting it. Tidal filling refers to the conveyance, which is made towards the direction of the coast during a rising tide. The transportation is directed offshore during a lowering tide.

Sediment at the shoreline is stirred up mostly by larger waves. The eroding pressures on the coast that smaller waves produce are larger than the sediment availability they produce. Bigger waves are thought to have a beneficial net effect since sediment availability outweighs coastal erosion. As a result, it is thought that the smaller waves are mainly to blame for coastal retreat.

The undertow's seasonality is essential for the movement of sediment. Freshwater flows into the sea during the rainy season as a result of precipitation, and the wind pushes the water in that direction. An onshore undertow is produced when salt water moves in the direction of the coast due to the difference in pressure between the layers of salt and freshwater. While the undertow pulls sediment-rich water in the opposite direction, towards the coast, depositing sediment in the foreshore, the surface current flows in the opposite direction, offshore.

The flow of freshwater declines during the dry season, leaving only the wind to push water towards the coast. This causes a setup with an offshore undertow and an onshore surface current that is directed towards the coast. This time, the undertow moves the heavy sediment concentrations offshore. Coastal accretion or retreat, which has a small net effect, is determined by the balance between two major gross effects: sedimentation and erosion. Even minor fluctuations in these rates can have a significant impact on the overall balance, resulting in either accretion or retreat. As a result, mangrove muddy coasts are highly dynamic.

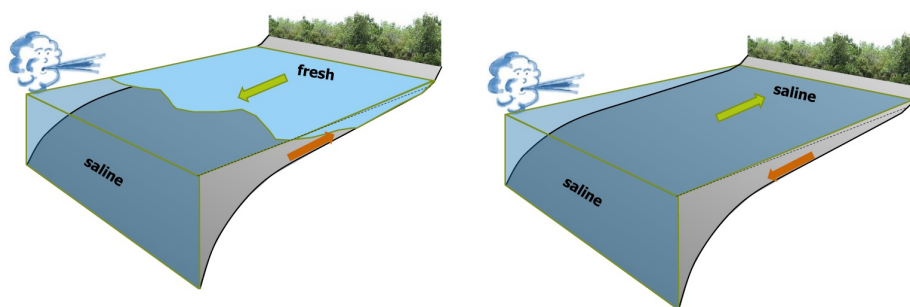


Figure C.3: Left: the estuarine circulation in the wet season caused by a baroclinic pressure gradient, Right: the offshore undertow in the dry season caused by a wind induced setup towards the coast (Source: Course CIE4308 Sediment Dynamics)

C.3. Mangrove Locations worldwide

Mangrove distribution varies significantly across the globe in both longitudinal and latitudinal directions. In terms of latitude, the distribution is limited to 30° in the Northern Hemisphere and 30° in the Southern Hemisphere. On the other hand, there is a significant difference in the diversity of mangrove species along the length of the continent, with Asia having the most variety and Africa and America having the least (Balke et al. 2011). Mangrove systems emerge as a result of a combination of climate, hydrological, and geomorphological factors.

For starters, mangroves are strongly linked to seawater temperature, with a lower temperature limit of 20 °C. Mangrove growth is aided by warm ocean currents and hampered by cold ocean currents. Second, because mangroves are frost-intolerant, the air temperature has a significant impact on their survival (Mitsch et al. 2009). Thirdly, mangroves favour locations with high tidal ranges because they can withstand brief inundation, giving them an advantage over freshwater trees in the intertidal zone. The tidal range is also necessary for mangrove propagation by floating propagules (movement). Wave exposure also affects the growth of mangrove systems because powerful wave activity prevents propagules from anchoring and stresses young mangrove trees, which lowers their survivability. In low-energy hydraulic conditions, such as broad mudflats where wave energy is dissipated, mangroves thrive. Mangroves can also be found in saltwater environments, where they thrive because of their high level of saltwater tolerance (they are halophytes), and because they need to be periodically flooded with freshwater from rainfall, rivers, and groundwater in order to lower salinity and provide nutrients. The intertidal zone along the coast, where both saltwater and freshwater are present, is where mangroves grow to their greatest extent.

The development of mangroves is significantly influenced by the characteristics of the soil. Though they can grow on a variety of soil types, mangroves prefer muddy or silty substrates, though they can also be found on rocky soils. The substrate must have enough nutrients, space for root attachment, and drainage otherwise the mangrove will not be rooted securely, will not be able to collect enough nutrients, or will not have good aeration (Balke et al. 2011, Kjerfve 1990).

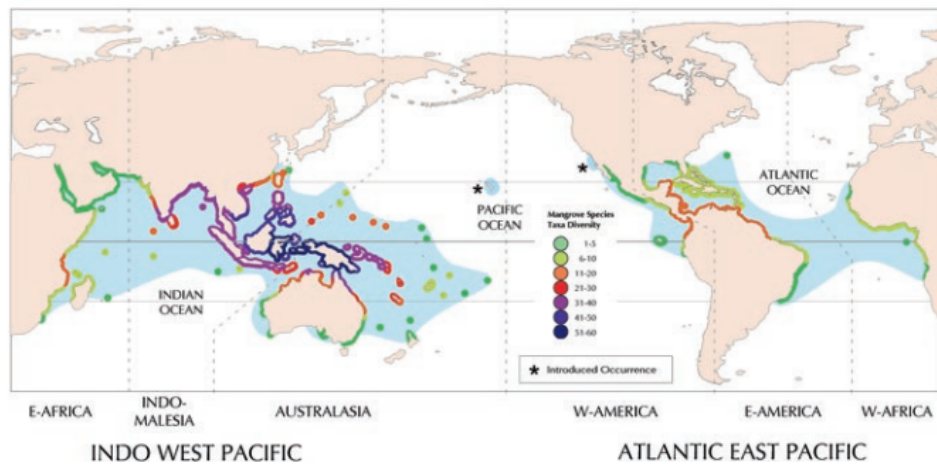


Figure C.4: The distribution of mangroves (shown in blue) illustrates the variety of distinct species and hybrids. The world's bioregions are clearly divided into the eastern and western hemispheres, with two hotspots of diversity: a dominant one in the Indo-Australian Archipelago region to the north of Australia and a much smaller one in the Caribbean American Isthmus region to the northwest of South America.(Duke 2017)

C.4. Mangroves on Suriname's coast

The Surinamese coast is made up of a variety of habitats, such as shallow saline and brackish lagoons and swamps inland, intertidal mudflats, sand and shell beaches, and vast mangrove swamps. Further inland, marshes become fresh, and swamp forests and mixed dryland forests grow on sandy ridges (Augustinus 1978). Some of the most productive ecosystems on the continent can be found in the mangrove forests and mudflats that line Guiana's coastal system (Marc Spalding, Blasco, and Field 1997).

Mangrove forests are found as a fringe along nearly the entire 375 km of Suriname's coastline, with an average width of about 3 km. However, this can vary greatly (0–8 km) depending on the local conditions for erosion and accretion. Mangroves can be found from the estuaries upstream to brackish regions along the major rivers and tidal creeks. In addition, the brackish swamps behind the mangroves contain sporadic pockets of mangrove vegetation.

The three main varieties of mangroves found in Suriname are Parwa, Akira, and Mangro.

- Black Mangrove (*Avicennia germinans*), also known as "parwa," makes up almost the entire mangrove forest that borders the coast. The mangrove-zone that surrounds rivers' lower reaches also contains this kind of mangrove.
- "Akira," or White Mangrove (*Laguncularia racemosa*), is a type of mangrove that grows along the muddy banks of tidal creeks and levees.
- Red Mangrove (*Rhizophora mangle*), locally known as "mangro," dominates the Mangro vegetation, which is primarily found on the thin mudbanks along the lower reaches of rivers in Suriname.

The dominant species along the coast, *Avicennia germinans* (parwa), should be given priority in mangrove rehabilitation efforts, according to the ICZM report. It is not advised to plant Mangro or Akira along the coast because these species do not naturally occur here. *Avicennia germinans* (parwa) probably do not need to be manually planted because their propagules are readily available and widely dispersed.

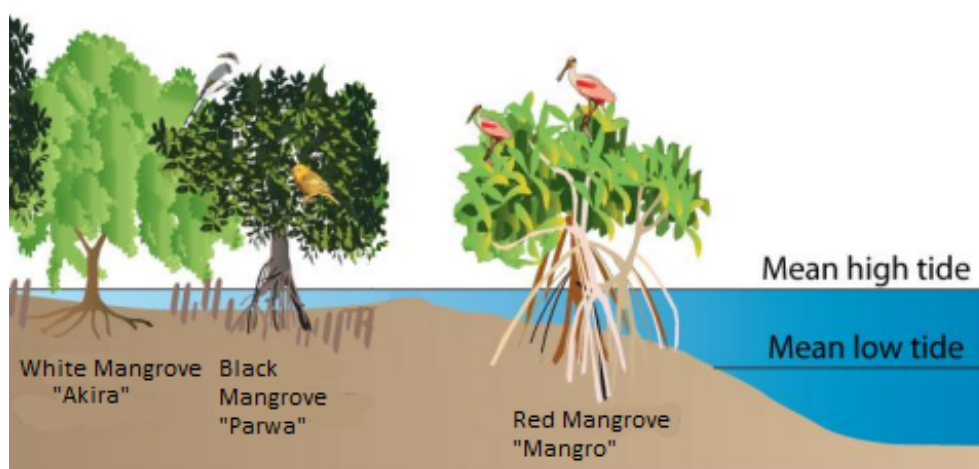
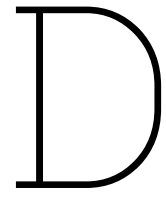


Figure C.5: Diagram showing the three Suriname Mangrove types, including their relative location to the water and the tidal range (Source: Kruczynski, W. L., & Fletcher, P. J. (2012). "Tropical connections", University of Maryland Center for Environmental Science.



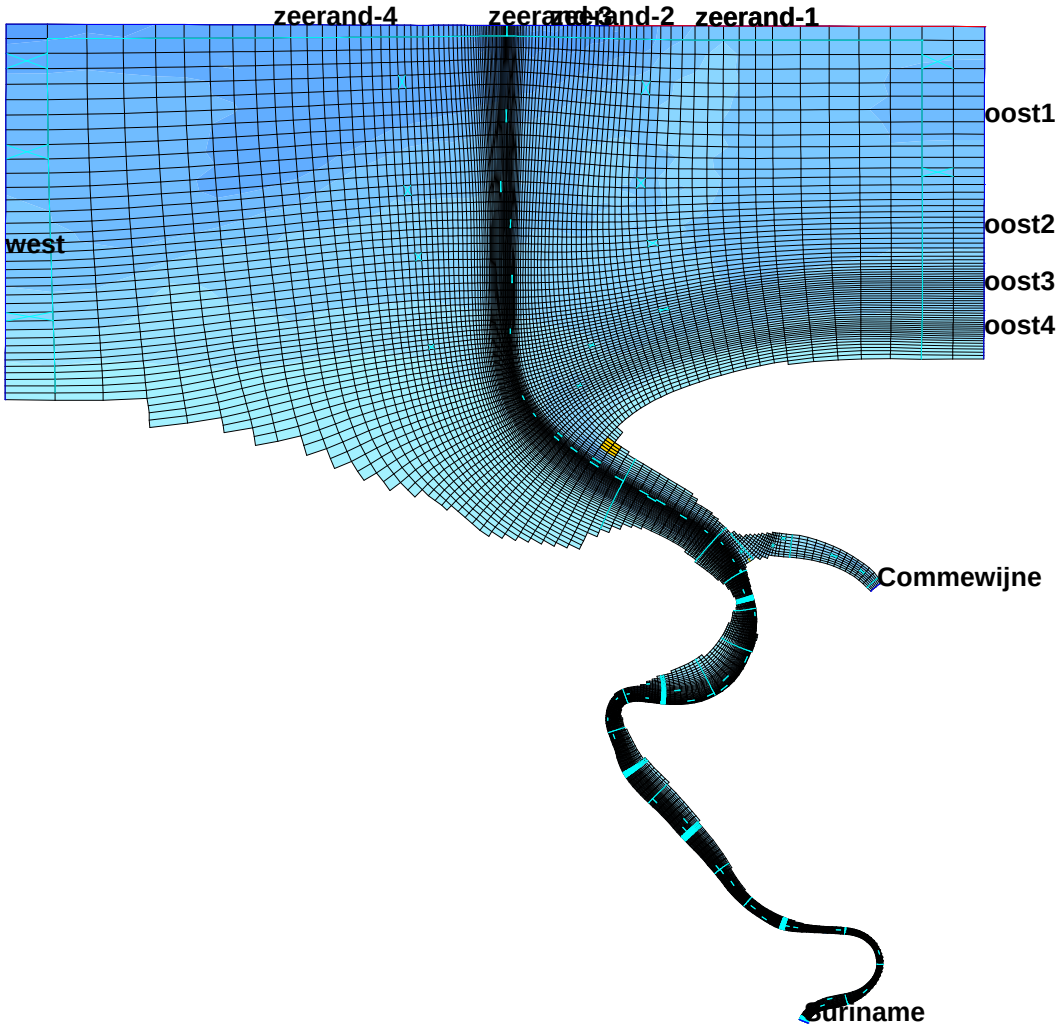
Original and Adjusted Model Grid

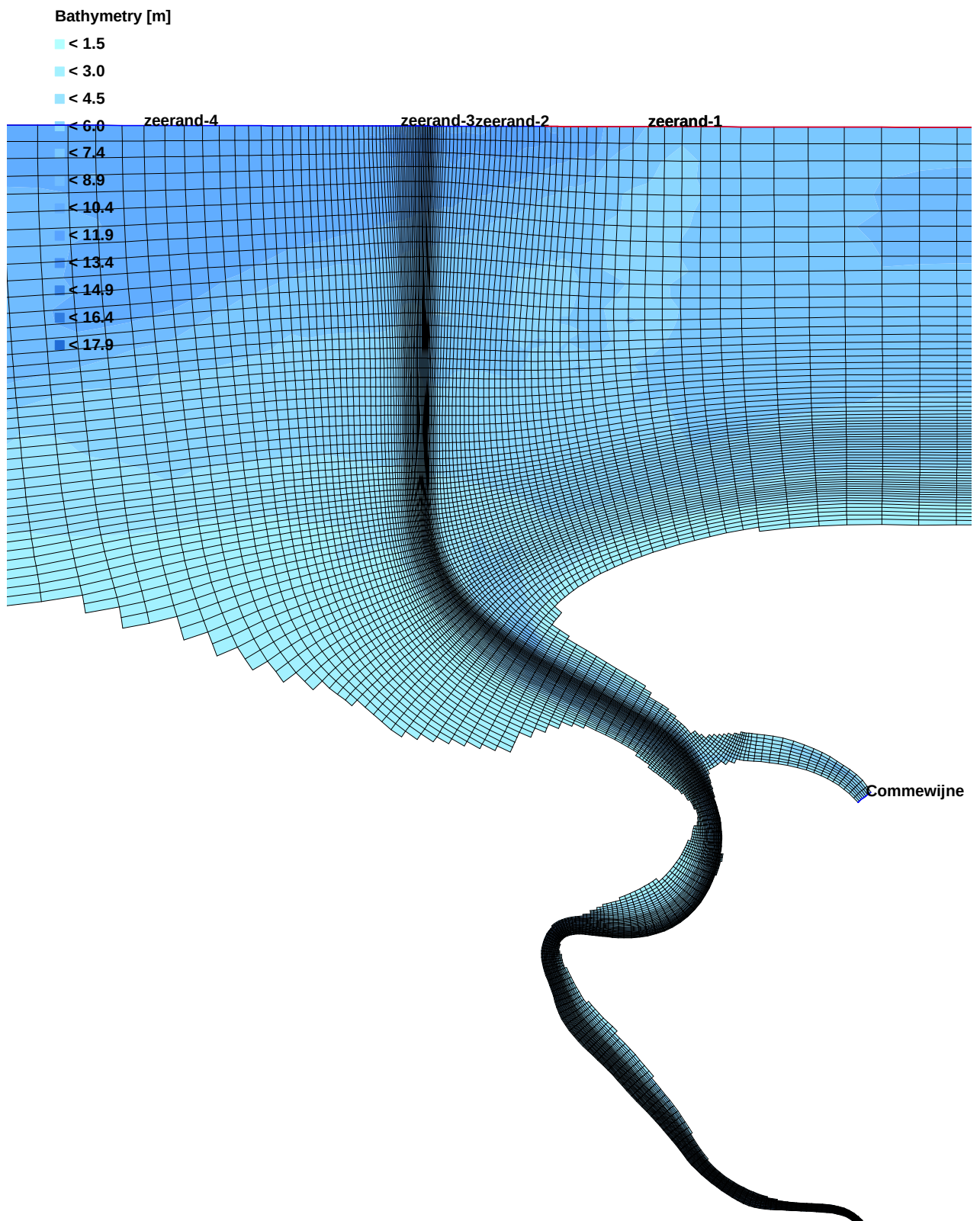
Following pages:

- 1 - The original model grid developed by Alkyon Zwol, Quist, and P.J. Plooy 2008 and used by M.Loose Loose 2008.
- 2 - Zoomed-in image of this model showing the grid structure.
- 3 - The adjusted model grid with changes to the structure used for this research.
- 4 - Zoomed-in image of this model showing the grid structure.

Bathymetry [m]

- < 1.5
- < 3.0
- < 4.5
- < 6.0
- < 7.4
- < 8.9
- < 10.4
- < 11.9
- < 13.4
- < 14.9
- < 16.4
- < 17.9





Bathymetry [m]

- < 1.5
- < 2.3
- < 3.2
- < 4.1
- < 5.0
- < 5.8
- < 6.7
- < 7.6
- < 8.5
- < 9.4
- < 10.2
- < 11.1
- < 12.0
- < 12.9
- < 13.7
- < 14.6
- < 15.5
- < 16.4
- < 17.3
- < 18.1

