Morphological Response of the Dutch Sandy Coast to Accelerated Sea Level Rise

A process-based modelling approach using Delft3D, applied to the Delfland coast

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MORPHOLOGICAL RESPONSE OF THE DUTCH SANDY COAST TO ACCELERATED SEA LEVEL RISE

A process-based modelling approach using Delft3D, applied to the Delfland coast

Delft University of Technology
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Ingrid Lambert

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ABSTRACT

Accelerated sea level rise (SLR) is predicted to have multiple adverse impacts on the coastal zone, aggravating phenomena such as coastal erosion on sandy coasts. For climate change adaptation planning and informing policy, morphodynamic changes occurring at coastlines are becoming increasingly important.

In this study, a calibrated Delft3D model forced by real-time wave conditions, was applied to simulate and assess the morphological behaviour of the Delfland coast in response to accelerated SLR over a 30-year time period. The calibrated Delft3D model uses a novel acceleration technique called brute-force merged (BFM) proposed by Luijendijk et al. (2019), which enables the modelling of multi-decadal predictions, with significant gain in computational effort. Evaluating the added value of Delft3D as a coastal impact model is another objective of the study. An assumption of the study was that no nourishments take place, i.e. no additional sediment supply. The Sand Engine (*Zand Motor* in Dutch), currently located along this coast was also excluded from the model, thereby assuming a straight unnourished coastline.

A selection of six SLR scenarios was simulated, including a no SLR scenario used as the reference case. The chosen scenarios covered the full bandwidth of accelerated SLR projections translated for the Dutch coast up to 2100, assuming increased mass loss from the Antarctic ice sheet, a hypothesis proposed by DeConto and Pollard (2016). These projections therefore exceed those presented in the IPCC AR5. Based on the recent literature, the SLR rates selected, ranging from 3 mm/year to 120 mm/year, are assumed plausible and useful for the modelling study. SLR was simulated, increasing linearly from zero by a constant rate, instead of an instantaneous absolute increase in water level. This was to maintain a (dynamic) equilibrium state, and keep initial bathymetry constant across the simulation runs.
The increasing SLR rise was added to the surge time series. The surge itself remained unaltered from the calibrated model, as did the other input parameters, including the wave climate. All forcings, except the increasing water level were kept constant across the simulations, thereby simulating only the SLR-induced morphological changes, and providing intercomparable results.

Model outputs that are assessed include erosion and sedimentation plots, and volume changes, particularly erosion volumes. Analysis shows that no major change to the general coastal system behaviour occurs due to accelerated SLR; erosive sections in the south remain erosive and accretive regions in the northern part remain accretive. This is influenced mainly by gradients in alongshore sediment transport and presence of structures. Erosion volumes increase with higher SLR rates, indicating an increase in erosion rate due to accelerated SLR. Volume changes were calculated in different alongshore sections and in different depth/elevation zones in the cross-shore direction in order to identify regions more vulnerable to accelerated SLR. It is determined that the southern section is most impacted by SLR causing increased erosion, particularly in the subtidal zone. Processes driving the observations and trends are discussed in the study. With significant SLR, dune erosion also occurs due to water levels and waves being able to reach higher elevations. The dunes along the Delfland coast are the primary sea defence which protects the hinterland from flooding, therefore it is critical to consider potential dune erosion due to accelerated SLR. Implications of the model study's findings are briefly discussed, in the context of coastal maintenance policy and implementation of nourishments.

Delft3D shows a number of benefits, including detailed analysis at multiple spatio-temporal scales. Another is the inclusion of transport processes in both alongshore and cross-shore directions, which is not the case for the Bruun Rule or 1-D coastline models. A limitation of Delft3D is that it does not include aeolian transport processes, and so dune growth cannot be simulated.

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A special thank you to my CoMEM classmates, this journey would not have been the same without you. Boys, thanks that we could feel like a family and for the lasting memories, it's been great fun! To all my friends back home and new friends all over Europe, thank you for the motivation to finish during this last stretch.

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Ingrid Lambert
Delft, July 2019

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LIST OF ABBREVIATIONS AND SYMBOLS

BCL	Basal Coastline
BF	Brute Force
BFM	Brute Force Merged
DoC	Depth of closure
D_{50}	Median grain size diameter
GHG	Greenhouse gas
GMSL	Global Mean Sea Level
H_s	Significant wave height
IPCC	Intergovernmental Panel on Climate Change
km	Kilometers
KNMI	'Koninklijk Nederlands Meteorologisch Instituut' (Translation: Royal Netherlands Meteorological Institute)
LST	Longshore sediment transport
m	Metres
mm/year	Millimeters per year
Mm^3	Million cubic meters
MICI	Marine ice cliff instability
MCL	Momentary Coastline: translation of 'Momentane Kustlijn' (MKL)
MLWL	Mean Low Water Level
MHWL	Mean High Water Level
MORFAC	Morphological Acceleration Factor
MSL	Mean Sea Level
NAP	Normaal Amsterdams Peil
PCR	Probabilistic Coastline Recession
RCP	Representative concentration pathway
SLR	Sea Level Rise

1

INTRODUCTION

In the face of global sea level rise, understanding morphodynamic changes that occur at coastlines are becoming increasingly important to plan for and inform policy. In this thesis, morphological simulation runs are carried out using a calibrated Delft3D model in an attempt to assess the impact of SLR on a case study site along the Dutch coast. This chapter provides context to the problem, and presents the objectives, research questions and motivation behind the study.

1.1 Background

Climate change is a major global challenge we face today and will continue to face for decades to come. From a coastal perspective, rising sea levels, changes in wave climate, and more intense and frequent storm surges, could mean that many coastlines will change significantly over the next century. The world's coastlines are shaped by mean sea level (MSL), wave conditions, storm surge and river flows. With this, Ranasinghe (2016) states that any variability in these environmental forcings due to climate change, will inevitably impact the coastal zone. Consequences of climate change, such as rising sea levels, make coastlines more vulnerable to erosion and flooding (Ranasinghe & Jongejan, 2018). Where coastal erosion and flooding is already a concern in many areas, the consequences of accelerated sea level rise (SLR) are likely to worsen the effect and/or extent of these phenomena in future decades, leading to a range of adverse impacts, and thereby exposing the coastal zone to greater risks (Nicholls et al., 2007; Le Cozannet et al., 2014; Ranasinghe, 2016). This will increase the pressures on coastal habitats, ecosystems and coastal towns or cities, especially considering the increasing population densities in coastal areas (Villatoro et al., 2014; Brown et al., 2016). This is the case for many sandy coasts around the world, often highly developed and densely populated due to the variety of social and economic opportunities provided.

Sandy coasts constitute a substantial part of the world's coastline, i.e. quantified as approximately 31% of the world' s ice-free shorelines (Luijendijk et al., 2018). In the same report, through analysis of satellite derived shoreline data, it is estimated that approximately 24% of sandy beaches are eroding at rates exceeding 0.5 m/year. Global occurrence of erosion (and accretion) hotspots are shown in Figure 1-1. Coastal erosion, which can occur over varying time and spatial scales, is driven by the action of wind, waves, and storms, but can also be caused by human intervention. Sandy beach morphology can be highly dynamic in both space and time (Luijendijk et al., 2018), continually adjusting to changes in hydrodynamic forcing, generally over the long-term. However, rapid changes occurring under high wave-energy conditions, i.e. extreme storm events, can also affect the long-term trends of coastal change (Luijendijk et al., 2019). With climate change influencing the hydrodynamic conditions at many of the world's sandy coasts, the morphodynamics of the coastal system may change, thus affecting long-term erosion and sedimentation patterns.

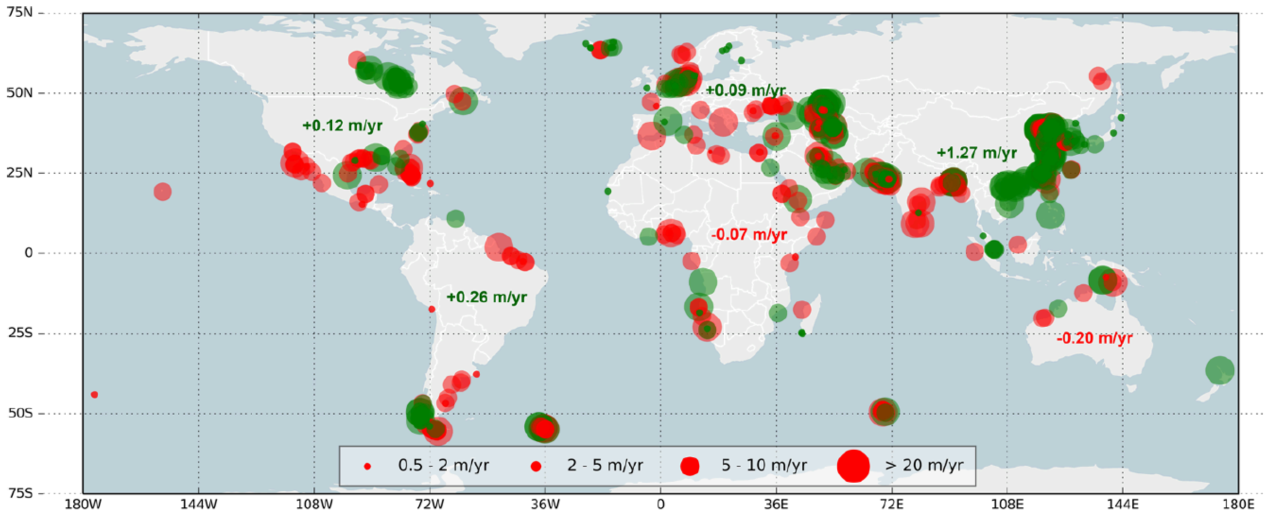


Figure 1-1: Global hotspots of beach erosion (red) and accretion (green) (Luijendijk et al., 2018)

It is expected that sandy coastlines will retreat due to a rise in sea levels (Nicholls et al., 2007; Figueiredo et al., 2018). Other than the related physical, environmental and ecological impacts, coastline retreat could have massive negative socio-economic implications affecting population, infrastructure, assets, and also activities related to tourism and recreation (Nicholls et al., 2010; Rodríguez et al., 2017). These socio-economic impacts could reach a global scale, and it is important to account for the rapid urban growth in coastal areas; millions of people living in low-lying areas around the world will be affected (Bosello & De Cian, 2013). Low-lying coastal areas and hinterlands, such as the Netherlands (where almost one-third of the country is below MSL (Stive et al., 2013a)), are particularly vulnerable to coastal climate change effects, and are classified amongst the regions at highest risk to SLR (IPCC, 2007a).

In this thesis, the sandy coastal stretch between Hook of Holland and Scheveningen, named the Delfland coast, has been selected as a case study site. The dunes in this region are the primary sea defence, protecting the inland areas from potential flooding (Mulder & Tonnon, 2011), but coastal erosion could threaten the strength of the dunes and lead to inundation of the hinterland. Being a region subject to chronic erosion (van Rijn, 1997), periodic sand nourishments have taken place to compensate for the ongoing coastal erosion; this forms part of a coastal maintenance strategy referred to as Dynamic Preservation, which was implemented into Dutch law in 1990 (Stronkhorst et al., 2000; Borsje, 2017). Today, the Delfland coast is commonly known for the Sand Engine (*Zand Motor* in Dutch), a mega-nourishment of unprecedented size, implemented along this coastal stretch in 2011 (Mulder & Tonnon, 2011).

To account for accelerated SLR, expectations are that nourishment volumes for the Dutch coast will need to increase in the future. Future projections of SLR remain uncertain (Nicholls & Cazenave, 2010) due to the dependency predominantly on future greenhouse gas (GHG) emissions, related thermal expansion of seawater, and the mass loss of ice sheets and glaciers. Despite this uncertainty, impacts of accelerated SLR to the coastal system need to be explored so that society can be better prepared for the future and alternative climate change adaptation measures implemented to improve the resilience of the coast.

1.2 Problem Statement

Climate change impacts are predicted to exacerbate problems within the coastal zone which is already stressed by human activity. This includes accelerated SLR, predicted to cause unprecedented coastal recession in the 21st century, which may compromise coastal safety (Ranasinghe et al., 2012). This is especially relevant to the Netherlands, where the hinterland is densely populated and low-lying. Furthermore, along the Holland coast, the sandy beach and dunes form the first line of defence, thus any retreat in the coastline could threaten the strength of the dunes and hence its functionality as a sea defence.

Recent studies indicate a possible additional acceleration of global mean SLR, largely associated to new scientific insights of the potential breakup and increased mass loss of the Antarctic ice sheet due to ice cliff instability and collapse (DeConto & Pollard, 2016; Bamber et al., 2019). Should such increased mass loss occur, this will greatly contribute to the acceleration of future SLR. New insights suggest that SLR could quickly accelerate after 2050. This could result in sea levels towards the end of the century being much higher than what has previously been projected by the Intergovernmental Panel on Climate Change (IPCC). To date, the highest likely range concluded by the IPCC for globally averaged SLR in the year 2100 is 0.52 m to 0.98 m (Church et al., 2013), however recent studies explore SLR beyond the likely range, indicating more extreme global estimates in the range of 2.0 m to 3.0 m in 2100. These higher values would mean greater sea levels than what has been assumed thus far by policymakers for coastal zone management, also in the Delta Programme[1] of the Netherlands which currently assumes a SLR of up to approximately 1.0 m by 2100.

Coastal risk management and adaptation will become a critical issue for numerous coastal communities and related economic activities due to accelerated SLR. The more extreme SLR projections call for sound knowledge of the physical impacts of accelerated SLR to the coastal zone. In the context of morphology of sandy coasts, such as the Holland coast, increased erosion and coastline retreat may be of critical concern. Impact analysis is required to understand the morphological behaviour of sandy coasts in response to accelerated SLR. Modelling of SLR impacts on shoreline and beach morphology is an active, yet relatively underdeveloped field of research. This is due to difficulties in observing, understanding, and accurately modelling the wide range of complex physical processes in the coastal zone.

1.3 Research Objectives and Questions

Following the problem statement, the overarching aim of this thesis is as follows:

To investigate the influence of accelerated SLR on the morphological behaviour of a sandy coastal stretch by conducting multi-decadal predictions using a calibrated Delft3D model forced by real-time wave conditions. The Delfland coast is selected as a case study to highlight the added value of applying such real-time process-based model predictions for studying alongshore and cross-shore behaviour of the sandy coast.

[1] The Delta Programme is a national programme aimed at protecting the Netherlands from flooding, ensuring sufficient fresh water supply, and climate-proofing the country (Ministry of Infrastructure and the Environment, 2017).

1.3.1 Research questions

This study attempts to answer the following main research questions:

(1) What are the effects of accelerated rates of SLR on the morphodynamics of the Delfland coast, should no adaptation/mitigation measures be implemented in the future?

(2) What is the added value of using a process-based area model, such as Delft3D, in assessing SLR impacts on the morphodynamic changes and beach-dune evolution of sandy coasts, compared to e.g. the Bruun Rule?

A number of auxiliary questions which help to achieve the aim of the study are presented:

- How can an acceleration in SLR be simulated in Delft3D?
- What time period is necessary to be simluated to effectively account for the impacts of SLR?
- What is the future behaviour of the Delfland coast considering a range of SLR rates?
  - How does the morphodynamic behaviour change over different time and spatial scales?
  - Are there changes to the general erosion and sedimentation patterns?
  - Does an increase in SLR rate lead to more erosion of the coast?
  - What is the difference in volume change for a SLR scenario compared to that if no SLR occurs?
- What are the benefits and limitations of using a Delft3D model for SLR impact analysis?

1.3.2 Research approach

The basic research approach is outlined in the flowchart shown in Figure 1-2 below.

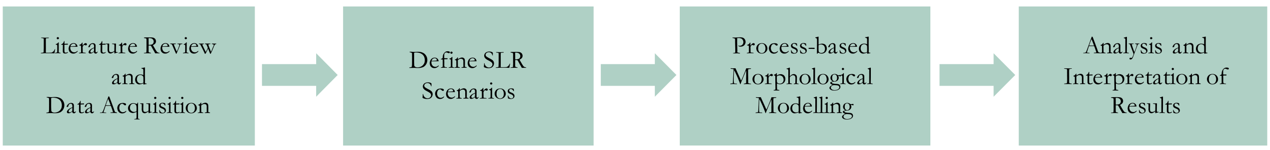


Figure 1-2: Flowchart presenting the research approach followed.

To meet the objectives of this study, a calibrated Delft3D model which uses a new acceleration technique proposed by Luijendijk et al. (2019), is used. Simulations are run for a period of 30 years, in order to assess the morphological behaviour of the Delfland coast under different SLR scenarios (represented by a range of SLR rates) over the mid- to long-term, i.e. 5 to 30 years.

1.4 Motivation and Research Significance

1.4.1 Knowledge gap and research focus

For the Dutch coast, exact consequences of accelerated SLR and possible adaptation measures which would be successful are still largely unknown across the many disciplines impacted by SLR, such as flood protection and water management (Deltares, 2017). From a coastal morphodynamics perspective, SLR changes the necessary sand volume to stabilize the coastal area, and there is still much uncertainty about the way in which accelerated SLR has an effect on sediment transport along the Dutch coast. This, together with the fact that the current preferential strategy of the Delta Program for coastal defence and maintenance, is sand nourishments, leads to the need for better understanding of the morphological behaviour of sandy coasts in response to increased sea levels. Hence the aim of this study is in line with the knowledge gap there currently is.

1.4.2 Research significance

Behaviour of coastal systems and the expected beach morphodynamics in response to accelerated SLR, and other climate-induced impacts, need to be understood to be able to make adequate and sustainable coastal management decisions. Knowing how fast SLR impacts will manifest under different possible future climate change scenarios is crucial both for adaptation planning and implementation of measures to reduce the risk of coastal erosion and flooding.
Improved understanding of the morphological behaviour of sandy coasts under the influence of SLR, could help in planning requirements for sand nourishments, and climate change adaption strategies.
Accelerated SLR may require a transformative change in coastal management policy, beyond upscaling the present-day solutions (Deltares, 2017). A lot of time is needed to plan and implement any such large-scale measures, and so early action for development of climate change adaptation strategies is needed. This will also help prevent more radical choices that may come at a greater expense later in time.

Furthermore, with the Netherlands being especially vulnerable to accelerated SLR, more dramatic climate change scenarios are to be considered for planning purposes. Knowing the major consequences of such extreme climate scenarios, may in turn help motivate for further reduction of GHG emissions, and hold governments and industry accountable.

Due to the complexity in projecting long-term morphology incorporating the stochastic nature of processes and dynamic interactions involved, there is no reliable universal model that can accurately predict the impacts of SLR on a variety of coastlines (FitzGerald et al., 2008; Passeri et al., 2015).
The varied number of models that have been used to predict coastal impacts of SLR, are each limited in the information they provide due to assumptions.
Understanding morphological model results could help coastal engineers and scientists to develop new methods in numerical modelling of morphodynamics and SLR, in order to produce more accurate and reliable predictions for the long-term (i.e. robust and stable results).

1.5 Thesis Layout

The report follows with a literature study presented in Chapter 2, comprising relevant background information on the morphodynamics of sandy coasts in general, the physical impacts of SLR to sandy coasts, and global projections of accelerated SLR. Chapter 3 is a continuation of the literature study, focused on the study area of the thesis, i.e. the Delfland coast in the Netherlands.

Chapter 4 presents the modelling approach in which a description is given of the calibrated Delft3D model used in the study, the selection of simulated SLR scenarios, and the model setup. The model outputs and findings are presented mainly in the form of graphs in Chapter 5, with an additional discussion in Chapter 6 explaining the physical processes driving the morphological changes and trends. Chapter 7 concludes with answers to the research questions and recommendations for further research.

2

LITERATURE REVIEW

This chapter presents a review of published literature collected on themes relevant to the main research topics of sandy coasts and accelerated SLR. Section 2.1 provides general theoretical knowledge on sandy coasts, and processes driving morphological change, particularly coastal erosion. The basic physical science of SLR and impacts thereof to the coastal zone is introduced in Section 2.2, and is followed by Section 2.3 in which an overview of methods used to assess and/or model coastal impacts of SLR is given. The chapter concludes with a critical evaluation of global SLR projections in Section 2.4.

2.1 Sandy Coasts

2.1.1 Introduction

Sandy coasts comprise a significant proportion of the world's beaches (Bird, 1996), the global occurrence thereof most recently quantified by Luijendijk et al. (2018) as 31% of the world's ice-free shorelines. Sandy beach ecosystems are extremely valuable (Ranasinghe, 2016), not only for the economic and recreational features or aesthetic value that they provide, but also as a first line of defence against coastal storm impacts, for the ecological habitats they host and for drinking water supply (Mulder & Tonnon, 2011). However, erosion of sandy coasts are negatively impacting the functions and values of sandy beaches.

Sandy beaches and coastal foredunes form part of a dynamic sediment sharing system (Psuty, 2008). Sand can be exchanged in both the offshore and onshore direction (i.e. cross-shore sediment transport), or moved alongshore, parallel to the coast, to supply adjacent beach and barrier systems. These processes are described in the subsections below.

2.1.2 Understanding the terminology

The schematic diagram shown in Figure 2-1 presents the generic structure of a beach across the coastal zone, the interface between land and sea. Typical terminology of a sandy coast is explained here.

The cross-shore coastal profile is dynamic and influenced by tides, currents, waves and wind. Of key importance is the shoreface profile, which extends up to the depth of closure (DoC), below which limited morphological activity occurs i.e. the seaward limit or depth where the seabed is no longer influenced by waves and cross-shore sediment transport is insignificant. Therefore, the DoC delineates the nearshore from the offshore zone (Passeri et al., 2015)

The upper part of the shoreface consists of the surf zone and extends across to the first dune row or cliff face (Bosboom & Stive, 2015). This includes the beach (sub-aerial) and the inter-tidal zone which lies between low and high water, at the transition between the surf zone and the beach. The surf zone is also called the breaker zone or littoral zone; this is where waves are breaking and most changes take place. The lower shoreface is called the shoaling zone, where waves travel from deep to shallow water and amplify before breaking.

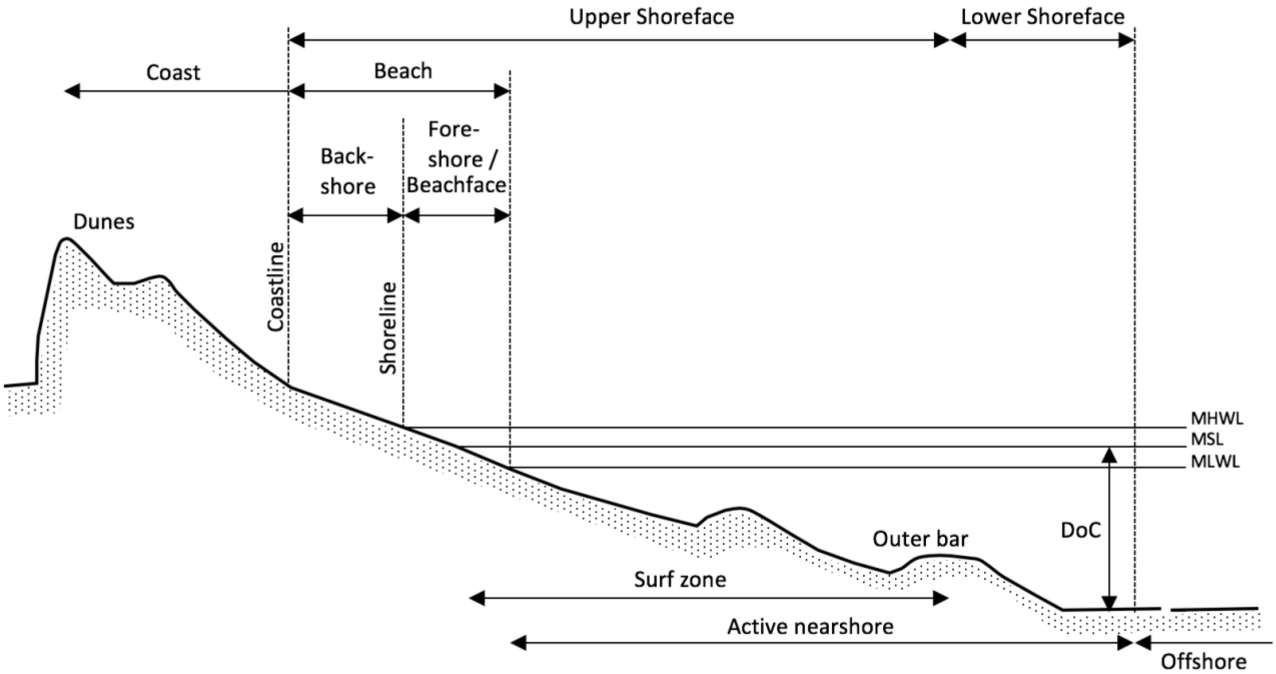


Figure 2-1: The coastal zone (Adapted from: CERC, 1984)

Observations of beach profiles led to the characterization of the dynamic equilibrium beach profile concept, first introduced by Bruun (1954). The concept assumes that a beach profile maintains an average constant shape as it continuously oscillates in response to varying forcing. Woodroffe (2003; 2007) explains if the boundary conditions that affect a beach remained constant then the shape of the beach would not be expected to change. However, in nature external conditions (waves and water levels) do change and the landscape continuously evolves to adjust to the new boundary conditions, and so a dynamic equilibrium occurs.

2.1.3 Morphodynamics of sandy coasts

Time and spatial scales

Processes linked to shore and shoreline evolution do not only vary over time, but also over a wide range of spatial scales. The various time- and spatial-scales over which relevant coastal processes occur, are indicated in Figure 2-2 below. The shoreface profile shows a cross-shore gradient where timescale increases with depth. Storms and cross-shore processes are dominant over short time-scales, typically hours to months or years. In this case, the lower shoreface shows negligible activity compared to the upper shoreface which shows highly dynamic variations.

For the medium-term, over which years to decades are considered, and a spatial scale of 1 to 5 km, variations in wave climate and extreme events are relevant. Relative sea level changes and regional climate variations occur over longer time-scales of decades to millennia, and affect regions of 10 to 100 km (Stive et al., 2002). Alongshore processes are more important on open coasts and cover longer time-scales.

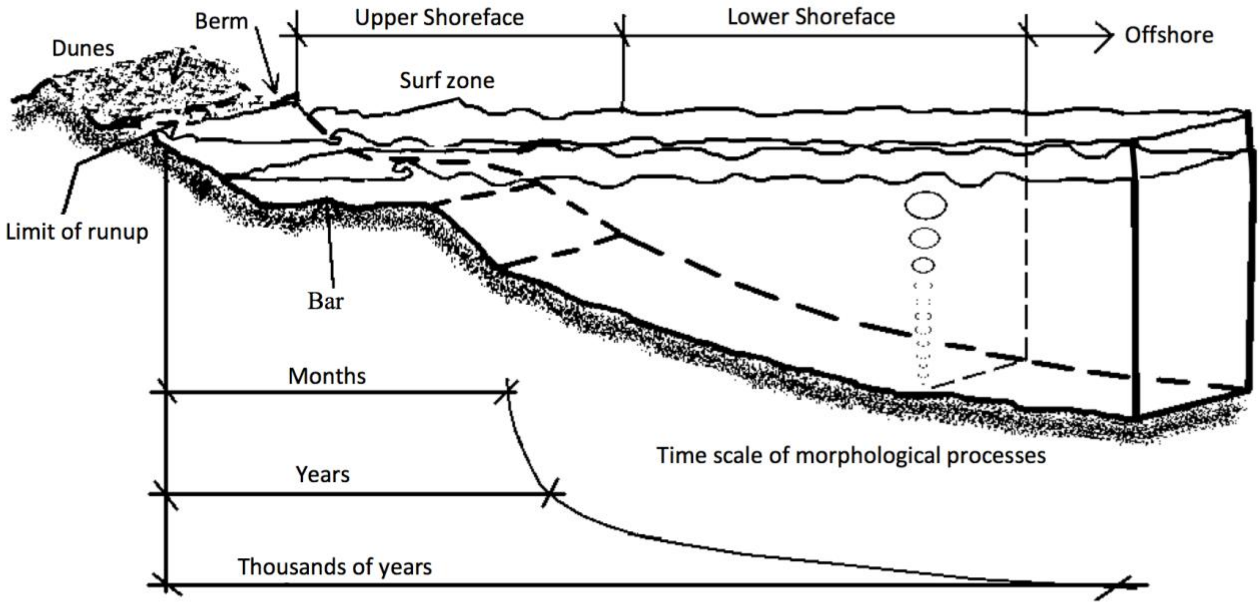


Figure 2-2: Time scale of morphological processes (Adapted from: Cowell et al., 1999)

Coastal erosion

Coastal erosion can be driven by natural processes, i.e. by the action of waves, wind, tides and nearshore currents. Erosion processes can also be caused by human activities and intervention, most commonly by the construction of hard structures such as coastal defences which interrupt the transport of sand, e.g. groynes or seawalls.

Long-term erosion, termed structural erosion, is differentiated from storm damage (episodic erosion) to dunes. During storm surges, the high surge level and waves can reach and attack the dune face causing erosion (Bosboom & Stive, 2015); eroded sand from the dunes is then transported to the beach and shallow shoreface. Sediment transport in the offshore-direction is caused by a strong undertow, defined as a wave-induced return current in the surf zone. As the sediment deposits to form a new coastal profile in the foreshore, more energy from incoming waves are dissipated, and consequently dune erosion rates decrease over time as the storm progresses. The beach (should) naturally recover during periods when the weather is calm, with waves and swell returning sediment shoreward. This is because with low, non-breaking waves, onshore-directed transport processes related to wave asymmetry and wave-induced streaming are dominant. This leads to accretion processes in the beach zone.
Storms causing episodic erosion are therefore said to generally only redistribute sand, i.e. the amount of sediment in the entire active zone from the first dune to just offshore of the surf zone (upper part of the lower shoreface), remains constant if assuming no alongshore sediment transport gradients exist.

Structural erosion on the other hand, is characterised as ongoing (long-term) erosion of the coastline, in which sand disappears from the system and is no longer available, i.e. structural losses, meaning the amount of sediment in the active zone does not remain constant. This is due to gradients in sediment transport causing long-term morphologic changes in the coastline. Changes in longshore sediment transport (LST) magnitudes, can lead to long-term erosion and accretion making the shoreline either retreat or advance.

Sediment budget

The sediment budget can be defined as the balance between changes in the volume of sediment stored in the system and the sum of the volumes of sediment entering (i.e. source) or leaving the system (i.e. sink) (List, 2005). Any process that results in a net gain in sediment is a source, alternately a sink represents a net loss of sediment in the system within defined boundaries.
Examples include dune or backshore erosion which is considered a source to the beach, whereas aeolian loss from the beach to the dunes is classified as a sink.

2.2 Sea Level Rise Impacts on Sandy Coasts

Without considering climate change impacts, the coastal zone already faces problems such as erosion due to natural processes and human intervention. Bird (1996) stated that if sea levels increase, there will be an acceleration of existing beach erosion, and erosion will begin on many beaches that are now (previously) stable or growing. Therefore, SLR in response to continuing global warming, will only accentuate problems in the coastal zone (Cazenave & Le Cozannet, 2014), undermining coastal safety of the growing populations living in coastal areas.

This section serves as an introduction to understanding SLR and its impacts in the context of morphology of sandy coasts, and is followed by typical methods used to assess these coastal impacts.

2.2.1 Background on sea level rise

Global warming, a result of the accumulation of human-induced greenhouse gases (GHG) in the atmosphere, contributes to globally averaged SLR through (1) thermal expansion of sea water, i.e. as the water warms, the oceanic water volume increases; and (2) widespread mass loss of land ice, including melting of ice sheets, and smaller ice caps and glaciers (IPCC, 2007b; Nicholls & Cazenave, 2010). Estimated magnitudes and rates of SLR however remain uncertain according to Nicholls and Cazenave (2010); key uncertainties being related to the behaviour and melting of the Greenland and West Antarctic ice sheets, and the amplitude of regional changes in sea level.

Regional differences in SLR are attributed to physical processes redistributing the water around oceans; this can be due to mass redistribution in the Earth's system, the effect of the Earth's rotation on the ocean surface and dynamic changes in ocean circulation, amongst other mechanisms (Stocker et al., 2013; Le Bars et al., 2019). Furthermore, according to Stocker et al. (2013), change in sea level relative to the land (i.e. relative sea level) can be significantly different from the GMSL. Land subsidence, a non-climatic component of relative SLR, amplifies the local vulnerability to a rise in sea levels. Subsidence is defined as a vertical land movement, either due to natural causes (e.g. sediment loading in river deltas), but mainly because of human activities such as ground water mining and oil/gas extraction (Cazenave & Le Cozannet, 2014).

As researched by Nicholls and Cazenave (2010), subsidence and other human-induced changes to coastal areas (e.g. coastal defences, port and harbour works, reduced sediment supply due to dams) have obscured the impacts of climate-induced SLR during the 20th century. However, it is assumed that globally, coastal beaches have experienced net erosion during the last century because of rising sea levels (IPCC, 2013). Due to global warming-induced climate change, the rise in sea level is expected to continue increasing through the 21st century and beyond 2100, with its impacts on coastal areas predicted to worsen in the coming decades (Church et al., 2013).

2.2.2 Description of sea level rise impacts

As sea levels rise, coastal morphology strives to achieve equilibrium (Passeri et al., 2015). The increased water volume induces an increase in sediment demand, amplifying the phenomenon of coastal erosion which may significantly reshape the coastal landscape. The coastline position is affected due to erosion and accretion processes depending on the local geometry and geomorphology. Additionally, the beach profile also evolves in response to storms, moderate wave conditions and SLR causing changes in the beach morphology (Rodríguez et al., 2017).

FitzGerald et al. (2008) explains that unlike infrequent large-magnitude storms that can reshape the coast in a few hours, the impacts attributed solely to SLR are typically slow, repetitive and cumulative. Due to this slow nature of SLR, Ranasinghe (2016) states that SLR driven physical impacts will manifest themselves as long-term impacts over a timescale of ~50-100 years.

Physical impacts of accelerated SLR include submersion, erosion, and increased vulnerability to extreme marine events. These impacts, specific to sandy coasts, are elaborated on below:

- Immediate effects include submergence and increased flooding of coastal land, and saltwater intrusion of surface waters. If low-lying land is unprotected, permanent inundation is likely (Ranasinghe, 2016).
- Longer-term impacts, as coastal morphology adjusts to new conditions, include increased erosion and coastline retreat, also saltwater intrusion into ground water.

Other impacts are related to the combined effect of SLR causing increased water levels and subsequent wave attack:

- Larger water depths in front of the coast, and conseqently reduced bottom friction and breaking, cause waves propagating towards the coast in the nearshore to lose less energy. This results in a greater wave attack.
- SLR allows waves to attack dunes at a higher level and more landward. Hence SLR also affects dune erosion (de Winter & Ruessink, 2017).
- Zhang et al. (2004) states that it is likely that long-term enduring increases of sea level will monotonically increase long-term erosion rates. This is a reasonable hypothesis because of the crucial role in erosion played by elevated water level during coastal storms.

The physical impacts of SLR can in turn have both direct and indirect socioeconomic impacts, locally and on a global scale (IPCC, 2007a).

2.3 Assessing the Impacts of Sea Level Rise

Global sea levels are increasing, yet our ability to predict SLR impacts to coastal systems is complicated by variability in the factors driving SLR and system response. The precise role of SLR is difficult to determine due to considerable regional and local variations (IPCC, 2007b), in particular land subsidence and coastal changes due to human intervention, as discussed in Section 2.2.1.

2.3.1 *The Bruun Rule*

The most widely used method to assess the impact of SLR on a coastline is the Bruun Rule (Bruun, 1962). This is based on a simple 2-dimensional mass conservation principle by which a landward and upward shift of a cross-shore shoreface profile, assumed in equilibrium state, is estimated in response to a rise in the MSL.

To maintain the equilibrium profile, material eroded from the beach foreshore and backshore is moved and deposited on the lower surf zone in deeper water., i.e. an assumption is made that the eroded volume is equal to the volume deposited (Ranasinghe et al., 2007). This results in the shoreline retreating (horizontal translation); at the new shoreline position, a new equilibrium profile forms maintaining the profile shape.

The Bruun Rule, can be used to estimate the horizontal extent of coastal recession (i.e. retreat distance, R), is expressed in equation 1 below and by means of the schematic diagram shown in Figure 2-3.

$$R = LS/(B + h) \qquad [1]$$

where B is the dune height, h the maximum depth up to where exchange of material between the nearshore and offshore takes place, and L is the length over which the erosion and sedimentation takes place, i.e. horizontal distance from the shoreline to depth h. The rise in sea level above MSL is symbolized by S.

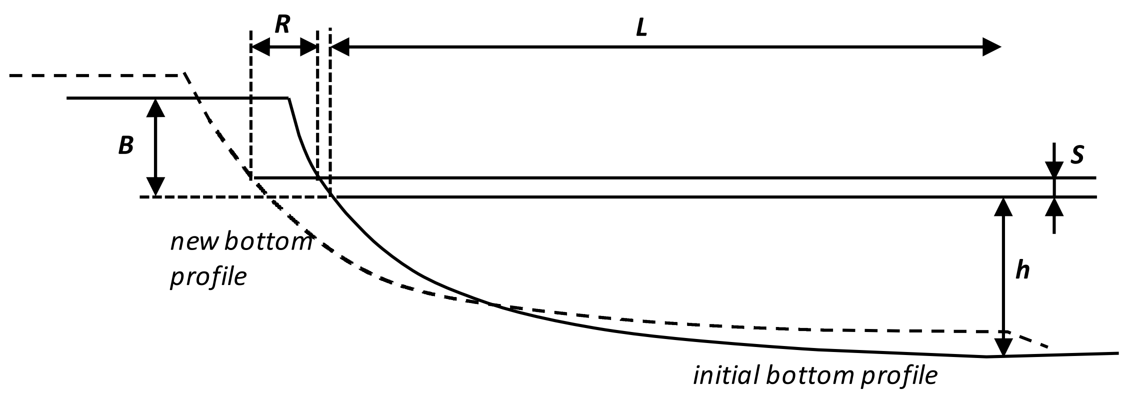


Figure 2-3: Geometric response of nearshore profile to SLR according to Bruun (1962)

A retreat distance in the range of 50 to 200 times the rise in relative sea level is predicted by the Bruun Rule (Bruun, 1962; Nicholls et al., 2007)

Although this simple deterministic method gives qualitative insight into profile response to SLR, critical reviews have been made against this method (Pilkey & Cooper, 2004; Cooper & Pilkey, 2004; Ranasinghe & Stive, 2009). It is stated that the Bruun Rule is unsuitable to be used to obtain reliable estimates for local scale assessments, and that due to its oversimplifications, it cannot be considered a valid model (Ranasinghe et al., 2012). An example is the neglect of time needed to establish an equilibrium profile, and the impact of storms on dune erosion.

Davidson-Arnott (2005) comments that "the assumption of net sand transfer to the nearshore profile and deposition of a thickness of sediment equal to the rise in sea level is probably incorrect." Omission of the dune sediment budget and the processes associated with beach-dune interaction is another shortcoming of the conceptual model proposed in the Bruun Rule. A proposed model incorporating consideration of the dune-sediment budget and foredune dynamics, is arguably a better starting point for developing more realistic models of shoreline response to SLR according to Davidson-Arnott (2005). Such a model predicts no net transfer of sediment to the nearshore profile and preservation of the foredune through landward migration.

2.3.2 *Alternative modelling methods*

For long-term coastal impact assessment, analytical coastline models are commonly used as they can be applied over length scales of up to 100 km and longer time scales (decades to centuries), e.g. UNIBEST-CL and GENESIS. Such models are based on the one-line theory, attributing shoreline change to longshore sediment transport differentials, whereas cross-shore transport is assumed to cancel out over the long-term. This allows for fast computations computing coastline retreat in planform. However, these models are limited in output information, e.g. due to the use of a constant profile and the lack of cross-shore transport.

An alternative approach is using a probabilistic coastline recession (PCR) model which provides probabilistic estimates of SLR driven coastal recession. As proposed by Ranasinghe et al. (2012), this is a more appropriate method for planning purposes than the deterministic, single value estimate derived from the traditional Bruun Rule.

X-Beach, a process-based model (Roelvink et al., 2009) commonly used to assess storm impacts on dune erosion (short time-scale), has also been used to quantify the impact of SLR on the magnitude of future dune erosion (de Winter & Ruessink, 2017). This is an improvement compared to dune erosion studies in which impacts are assumed to be in the cross-shore direction only (e.g. Li et al., 2013).

Ranasinghe (2016) describes an ideal model used for comprehensive climate change assessments, as one that would be a multi-scale coastal impact model; a coastal area model with at least quasi-3D hydrodynamics to incorporate both cross-shore and longshore hydrodynamics relevant for episodic, medium-term and long-term morphodynamics. This is to correctly simulate the numerous physical processes occurring at different spatio-temporal scales, including inter-scale morphodynamics.

2.4 Global Projections of Accelerated Sea Level Rise

2.4.1 *Introduction*

With the release of the latest Fifth Assessment Report (AR5) by the IPCC (2013), the following key findings can be summarised regarding the rise in sea levels:

(1) global mean sea level (GMSL) is rising

(2) the rate of GMSL rise has likely increased since the early 20th century

(3) GMSL will continue to rise during the 21st century and well beyond 2100, the rate thereof very likely to exceed previous observed rates

(4) i.e. it may accelerate further in this century

It is reported that the GMSL had risen at an average rate of 1.7 to 1.8 mm/year during the 20th century, indicated by tide gauge measurements (IPCC, 2007a). However, over the period from 1993 to 2010, the mean rate of SLR increased to 3.2 mm/year, suggesting it is likely that the rate of SLR has accelerated since the early 1990s, relative to the long-term average (Church et al., 2013; Nicholls & Cazenave, 2010).

In general, projecting future SLR is complex and uncertainty remains (Bakker et al., 2017). Varying estimations have been made in the past and are continually updated over time as scientists develop a better understanding of the atmosphere, related ocean warming and ice sheet dynamics (Church et al., 2013); and as new information is gained from improved climate and numerical ice sheet models (Ritz et al., 2015).

2.4.2 Projections of global mean sea level rise by IPCC

In the IPCC AR5, a set of climate scenarios, defined as Representative Concentration Pathways (RCPs[2]), are used in climate model simulations to represent a range of future scenarios, indicative of an increase of cumulative GHG emissions and other climate drivers to the atmosphere during the 21st century.

According to projected levels of GMSL rise reported in AR5 (IPCC, 2013), a *likely* range of 0.26 to 0.55 m is estimated for RCP2.6, and 0.45 to 0.82 m for RCP8.5 in the time period 2081-2100 relative to 1986-2005. The full range of projections for all four RCP scenarios are summarized in Table 2-1, corresponding to projected changes in global mean surface air temperature (°C) as shown.

Table 2-1: IPCC AR5 projections of GMSL rise (m) for the mid- and late 21st century.

Scenario	2046-2065*			2081-2100*		
	Mean Temperature (°C)	GMSL rise (m)		Mean Temperature (°C)	GMSL rise (m)	
		Median	Likely Range		Median	Likely Range
RCP2.6	1.0	0.24	0.17 – 0.32	1.0	0.4	0.26 – 0.55
RCP4.5	1.4	0.26	0.19 – 0.33	1.8	0.47	0.32 – 0.63
RCP6.0	1.3	0.25	0.18 – 0.32	2.2	0.48	0.33 – 0.63
RCP8.5	2.0	0.30	0.22 – 0.38	3.7	0.63	0.45 – 0.82

* relative to the reference period of 1986-2005

Figure 2-4 depicts the time series of the above-mentioned projections for RCP2.6 and RCP8.5, with blue and red shading showing the assessed likely range for the respective RCP scenarios. For RCP2.6, the likely range for GMSL rise *by the year 2100* ranges from 0.28 to 0.61 m, and for RCP8.5, from 0.52 to 0.98 m. The coloured vertical bars show the likely ranges for all RCP scenarios, with the corresponding median value indicated by the horizontal line.

[2] RCPs can be summarised as one scenario with a very low radiative forcing level due to mitigation, i.e. emissions decline after 2020 (RCP2.6), two stabilization scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions, i.e. a continued rise of GHG emissions throughout (RCP8.5) (IPCC, 2013; Vermeersen et al., 2018).

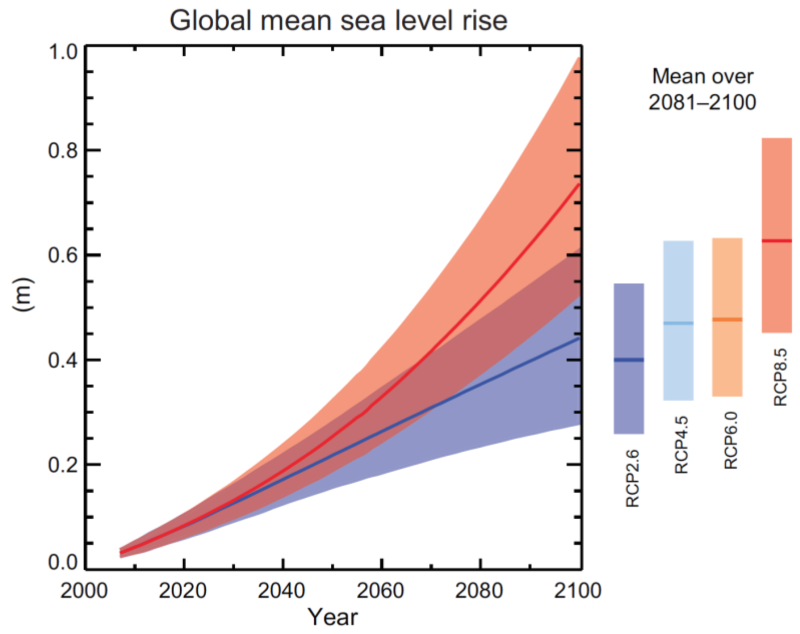


Figure 2-4: Global mean SLR relative to 1986-2005 (IPCC, 2013)

Furthermore, the estimated rates of GMSL in mm/year during the period 2081 to 2100 are presented in Table 2-2. These rates are associated with contributions from the Greenland and Antarctic ice sheets, and rapid changes in ice sheet dynamics.

Table 2-2: IPCC AR5 projections of GMSL rise rates (mm/year) in 2081-2100

Scenario	2081-2100*	
	Median	Likely Range
RCP2.6	4.4	2.0 – 6.8
RCP4.5	6.1	3.5 – 8.8
RCP6.0	7.4	4.7 – 10.3
RCP8.5	11.2	7.5 – 15.7

* relative to 1986-2005

Based on observations, physical understanding and modelling capabilities at the time, the following statement was made in AR5:

> Only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the likely range during the 21st century. There is medium confidence that this additional contribution would not exceed several tenths of a meter of SLR during the 21st century. (IPCC, 2013)

However, more recent studies on the contribution of and possible increased and more rapid ice melting in Antarctica, show that sea level is not only rising, but the rate of that rise could potentially be much faster in coming decades.

2.4.3 Additional insights into accelerated sea level rise

A study based on precision satellite altimeter data that has been collected since 1993, confirms the acceleration of global average sea levels in recent decades (Nerem et al., 2018). This 25-year time-series of sea level change data measured a rise in GMSL of ~3 ± 0.4 mm/year. Moreover, it has allowed for first estimates of a climate change driven *acceleration rate* of GMSL, a final value estimated as 0.084 ± 0.025 mm/year^2. Although still difficult to detect acceleration from this sample data of a relatively short time-series, and results may be sensitive to methods of interpretation applied, it is considered to allow more precise quantification than tide gauge data, or at least a sufficient alternative.

Considering a current rate of SLR of approximately 3 mm/year, in combination with the altimeter-based acceleration estimate, a SLR of around 0.65 m by 2100 relative to 2005 is predicted. This is in line with projections in the IPCC AR5 (refer to Table 2-1). This stresses the fact that the observed acceleration will more than double the amount of SLR towards the end of the 21st century compared with a constant rate per year. According to this study, it is also known that Greenland and Antarctica account for most of the observed GMSL acceleration. Major uncertainties still exist regarding the potential contributions of the polar ice sheets to future SLR and projections thereof, in particular that due to mass loss from the Antarctic. Predictions thereof from process-based models vary widely, ranging from 0.0 to more than 1.0 m contributions to GMSL rise this century (Edwards et al., 2019).

Scientists have studied the rate of melting from the Antarctic ice sheet and concluded that it has accelerated threefold in the last five years (Shepherd et al., 2018). It is projected that parts of the Antarctic ice sheet could be more unstable than previously thought; losing more mass during the 21st century. A climate model study by DeConto and Pollard (2016), predicts that a continued increase in GHG emissions over the next several decades could trigger the collapse of parts of Antarctica's ice sheet, in turn causing an additional rise in sea levels of more than 1.0 m by 2100. This is mainly due to the processes simulated by the model which increases ice loss; processes that may not necessarily arise in the future, but which cannot be disregarded either. This includes the possibility of surface meltwater which could make ice cliffs unstable and collapse under their own weight after ice sheets disintegrate, an unstoppable process once it is underway.

Edwards et al. (2019) disagrees with the possibility of such rapid collapse of coastal ice cliffs, and argues that previous projections of the marine ice cliff instability (MICI) hypothesis, which drives the highest predictions of Antarctic sea level contributions of ~1.0 m within this century, are over-estimated.

However, in a more recent study based on structured expert judgment, Bamber et al. (2019) also finds relatively high estimates for ice sheet contributions by 2100. For a temperature scenario based on GHG emission reductions in line with the Paris Agreement, a 95th percentile value of 0.81 m is obtained, increasing to 1.78 m for unchecked emissions growth. With the inclusion of thermal expansion and glacier contributions, global total SLR estimates exceed 2.0 m by 2100 for the 95th percentile ice sheet contribution. Findings of this study support the use of such high-end global SLR scenarios exceeding 2.0 m for planning purposes within the 21st century.

These recent studies that explore SLR beyond the current 'likely range' and which found higher values, indicate that the additional contribution due to a partial collapse of the West Antarctic ice sheet, as referred to in the extract from the IPCC AR5 in section 2.4.2, may be more significant than previously thought.

According to Le Bars et al. (2017), the increased mass loss from the Antarctic ice sheet (and hence the total magnitude of SLR towards the end of the century and beyond 2100), is strongly dependent on the concentration of future GHG emissions, and thereby global temperature change affecting the polar ice sheets. If emissions are not reduced, risk of faster SLR increases significantly.

3

THE DUTCH AND DELFLAND COAST

This chapter addresses relevant literature related to the Dutch coast, and in particular the Delfland coastal stretch which is selected as a case study in this thesis. Following the global projections of SLR presented in Section 2.4.2 and Section 2.4.3, SLR projections for the Dutch coast are provided in Section 3.1. The coastal setting of the Delfland coast is described in Section 3.2. Subsequent sections (3.4 to 3.7) give attention to the coastal management policy of the Netherlands, and related information on sand nourishments which have previously been implemented along the Delfland coast. Section 3.8 briefly discusses adaptation planning in the Netherlands, focusing on the nourishment strategy.

3.1 Sea Level Rise for the Dutch Coast

3.1.1 Delta Scenarios

At present, SLR along the Dutch coast is said to be approximately 2 mm/year, although local variations may occur along the coast. This rate, assumed to lead to a 0.2 m SLR per century (if continuing unchanged) is generally used for coastal maintenance and the design of structures with a short lifespan (Deltares, 2018). According to Mulder and Tonnon (2011), 2mm/year in policy is (was at the time) generally regarded as a good approximation of actual SLR.

The so-called Delta Scenarios are based on the KNMI'14 climate change scenarios for the Netherlands, as calculated by the Royal Netherlands Meteorological Institute (KNMI, 2014) on behalf of the Delta Committee. The KNMI'14 scenarios are in turn based on the GMSL projections published in the IPCC AR5 (refer to Table 2-1). The Delta Scenarios currently consider a maximum SLR of 0.4 m in 2050, and approximately 1.0 m in 2100, relative to 1995. However, in the Delta Report 2008, the Delta Committee did recommend that a worst-case regional SLR of 1.3 m by 2100, and 2 to 4 m by 2200, should be considered (Veerman, 2008).

3.1.2 Accelerated regional SLR projections

From the global SLR projections, it is evident that GMSL is rising (refer to Section 2.4.1), however Lombard et al. (2005) reveals important regional variability. A number of the physical processes causing differences between global and local sea level changes are mentioned in Section 2.2.1. One such reason is due to changes in the gravity field of the earth, which causes SLR to generally be larger further away from the region where the land ice melts. This is a counterintuitive rule of thumb, as discussed by Le Bars et al. (2019). He states that it is for this reason that the future of Antarctica is more important for the Netherlands than the melting of the Greenland ice sheet, e.g. the opposite is true for Chile.

In response to the new scientific insights regarding the possible accelerated breaking down and melting of land ice on Antarctica, as proposed by DeConto and Pollard (2016) (refer to Section 2.4.3), investigations of the possible consequences thereof for the Netherlands (it being sensitive to a melt of Antarctica) had been initiated (Deltares, 2017; Haasnoot et al., 2018).

Figure 3-1 presents SLR projections which account for the extreme Antarctic ice sheet contributions up to the year 2100, converted specifically for the Dutch coast by Le Bars et al. (2017). These estimates are compared to the current Delta Scenarios for which no inclusion of extra accelerated SLR is made. On the left, the absolute SLR projections are shown, and corresponding rates of SLR are to the right. Appendix A presents the same figures, but includes vertical bars to show the range and median values at different time periods up to 2100. For both the absolute SLR and the rates, ranges of projected values are tabulated in Table 3-1 and Table 3-2 respectively, and discussed in more detail below.

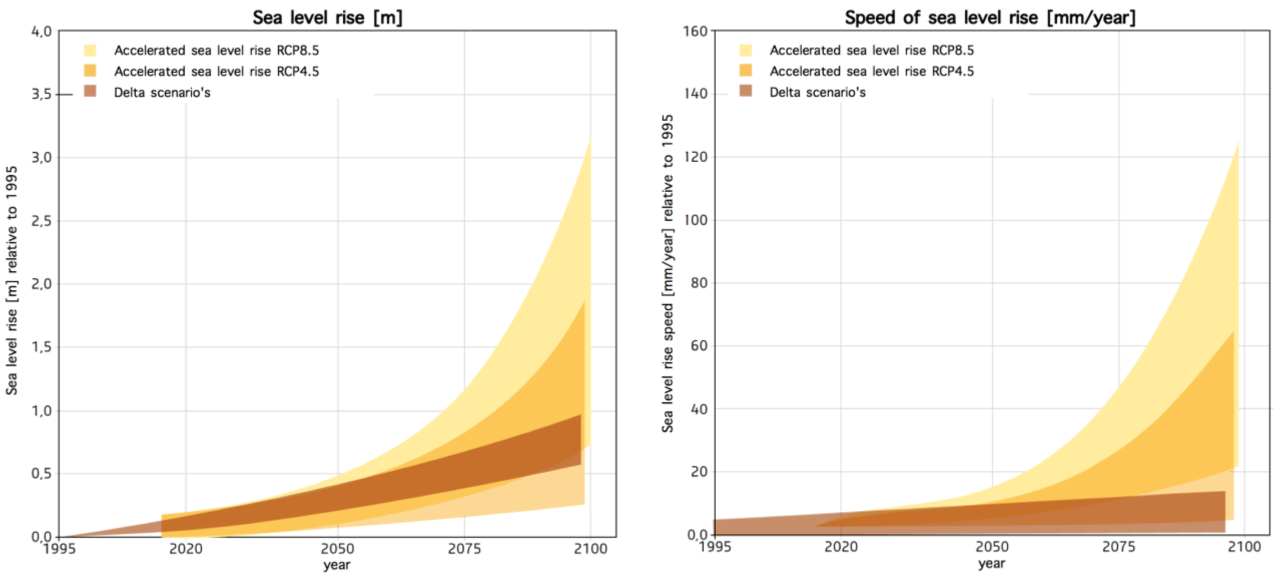


Figure 3-1: SLR projections for the Dutch coast (Haasnoot et al., 2018)

These results were used as the starting point for the purposes of an exploratory study by Deltares research institute (Haasnoot et al., 2018), in provision of a background document to the Delta Progamme 2019 report, to investigate the potential impacts of accelerated SLR on the preferential strategies for safety management stipulated in the Delta Programme. The Delta Scenarios will, just as the previous scenarios, be updated in line with the upcoming IPCC AR6 report, due to be published in 2021.

Table 3-1 presents the SLR projections as shown in Figure 3-1 (left). Column 1 contains the current Delta Scenarios and projections for accelerated SLR are updated for the RCP4.5 (column 2) and RCP8.5 (column 3) emission scenarios, approximately representative of a 2°C and 4°C rise in global temperatures respectively, as defined in the IPCC AR5.

Table 3-1: SLR projections including additional acceleration (m) for the Dutch coast

Year	Delta Scenarios		Accelerated SLR RCP4.5			Accelerated SLR RCP8.5		
	Low	Upper	Low	Middle	Upper	Low	Middle	Upper
2020	0.09	0.18	0.00	0.15	0.20	0.00	0.15	0.20
2050	0.20	0.40	0.07	0.24	0.41	0.09	0.29	0.47
2070	0.35	0.60	0.15	0.43	0.70	0.29	0.65	1.00
2100	0.55	0.90	0.29	1.08	1.92	0.75	1.95	3.17

A 2°C warming would be in accordance with the successful reduction of GHG emissions stipulated in the Paris Agreement. Although Dutch policy is aimed at achieving the 2°C objective, a 4°C scenario (i.e. unmitigated future increase in GHG emissions) is also considered as there is a chance that the international climate objective is not achieved in time (Haasnoot et al., 2018).

According to Haasnoot et al. (2018), it is expected that the extra acceleration in SLR will manifest at the earliest from 2050. Therefore, Table 3-1 shows that the maximum values of the new projections with accelerated SLR do not significantly differ from that of the Delta Scenarios up to 2050. After 2050, differences become more visible, with the new projections strongly deviating from the Delta Scenarios as SLR could potentially accelerate rapidly in the second half of the century.

Towards the end of the century (2070-2100), the Delta Scenarios assume an increase of between 0.35 and roughly 1.0 m. However, the adjusted RCP4.5 projection shows that sea level may rise between 1.0 and 2.0 m by 2100 as indicated by the middle and upper values respectively. For the extreme scenario, this can go up to approximately 2.0 m (middle value) and a maximum of 3.0 m (upper value) in 2100. The magnitude and range of these new projections are significantly greater than earlier assessments and so, uncertainty is also increased, especially concerning the upper values.

The potential absolute increase in sea level is not the only estimate important for evaluating future SLR, but also the rate at which this increase could occur. Table 3-2 below summarises projected speeds for SLR, corresponding to the graph shown in Figure 3-1 (right). For the Delta Scenarios, the rate is assumed to increase up to 10 mm/year around 2050, and a maximum of 14 mm/year in 2100. With the extra accelerated SLR, this maximum value could already be reached by 2050, and increase further reaching 20 to 35 mm/year around 2070 and even 60 mm/year or much more at the end of the century.

Table 3-2: Speed of accelerated SLR (mm/year) for the Dutch coast

Year	Delta Scenarios		Accelerated SLR RCP4.5		Accelerated SLR RCP8.5	
	Low	Upper	Low	Upper	Low	Upper
2020	0.00	7.00	2.00	5.00	2.00	7.00
2050	0.00	10.00	2.00	12.00	6.00	15.00
2070	0.00	12.00	3.00	20.00	10.00	35.00
2100	0.50	14.00	5.00	65.00	20.00	120.00

3.2 Coastal Description of the Study Area

The Dutch coast, which faces the southeast part of the North Sea, is typically divided into three regions or subsystems: (1) the Southern Delta coast, (2) the central Holland coast and (3) the Wadden coast in the north (EUCC-D, 2004-2019). This division is based on differences in morphological appearances and underlying physical processes. Of interest in this thesis, is the Holland coast along which the Delfland coast and study area is located, as shown in Figure 3-2. Almost the entire Holland coast, 118 km in length, is made up of and protected by sandy beaches and wind-blown dunes (de Winter, 2014), only interrupted by the IJmuiden and Scheveningen harbour moles. Together, the shoreface, beach and vegetated dunes offer a natural, sandy defence to protect the low-lying hinterland of the Netherlands against flooding; this is the primary function of the coast (Min V&W, 1996; Mulder & Tonnon, 2011).

The Delfland coast makes up the approximately 16.5 km long sandy beach stretch between Hoek of Holland and the harbour of Scheveningen, i.e. the southern section of the Holland coast (see Figure 3-2). This is the most densely populated coastal region in the Netherlands, with cities near the sea. The dunes are therefore essential in the prevention of flooding of the low-lying hinterland which is of high economic value.

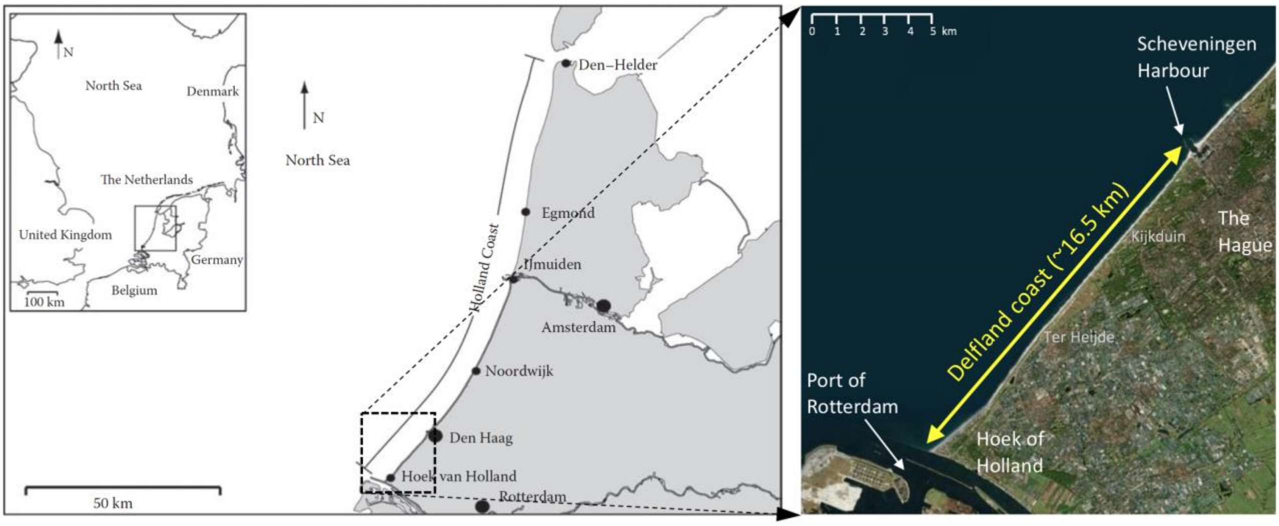


Figure 3-2: Overview of the Holland coast (Borsje, 2017) (left) and location of the study area – the Delfland coast (right)

In general, the Holland coast is described as an 'inlet-free, sandy, micro-tidal and wave-dominated' coast (Wijnberg & Terwindt, 1995). The sandy beaches and surf zone of the Delfland coast consists of non-cohesive sediment, with grain sizes in the range of fine to medium sand (i.e. median grain size diameter D_{50} = 240 μm), coarsest at the shoreline and fine seaward. The nearshore zone is characterised by a mildly sloping beach profile with possibly one or two bars, and varying only gradually alongshore, i.e. rather uniform (Luijendijk et al., 2017). That is, prior to the implementation of the Sand Engine mega-nourishment in 2011 (refer to section 3.7).

The beach width varies along the Delfland coast, as does the width of the dune area from the dune foot, typically from narrow, ranging between 150 to 250 m in the central section, to very wide at Hoek of Holland, approximately 500 m. The dune height is generally between +10 m NAP[3] to +15 m NAP; locally, dunes can reach over +20 m NAP.

Tides are semi-diurnal (Wijnberg, 2002), and at Scheveningen the tide has a spring/neap tidal amplitude of 1.98/1.48 m (Luijendijk et al., 2017). The asymmetric tide with longer falling period than rising period (8 hours and 4.35 hours respectively), causes asymmetric alongshore velocities. The flood tidal currents peak at 0.7 m/s in a northeasterly direction, while the maximum ebb tidal currents reach 0.5 m/s, directed to the southwest.

In general, the prevailing wind direction from the North Sea is southwest, however storm winds originate from the northwest. This results in the highest offshore significant wave heights (H_s), greater than 4.5 m, to originate from the west and northwest. Small waves (H_s < 1 m) also predominantly come from the northwest, whereas average waves (1.5 m < H_s < 3.5 m) come from both the southwest and the northwest. The wave climate is further characterised by a distinct seasonal signal; waves in winter reach average heights (H_s) of 1.7 m, whilst in summer they decrease to approximately 1 m. The 1-year return period offshore significant wave height (H_s) is 4 m, and the 1-year return period surge level at Hoek of Holland is 2.35 m (Luijendijk et al., 2017).

3.3 Sediment Transport along the Delfland Coast

A number of studies provide a detailed sediment budget analysis for the entire coast of the Netherlands, presenting information on alongshore and cross-shore transport rates (van Rijn, 1995; van Rijn, 1997; Van der Spek & Lodder, 2015). Sediment transport along the Holland coast is dominated by wave-induced longshore sediment transport (LST) processes (Bosboom & Stive, 2015) which is mostly northward directed. Yearly net rates thereof are estimated between 50 000 and 170 000 m^3/year for the region of the Delfland coast, dependent on the wave climate (van Rijn, 1995; Van de Rest, 2004); a value of 175 000 m^3/year is estimated by van Rijn (1997).

Luijendijk et al. (2019) reconstructs 30 annual LST curves for the Delfland coast from morphostatic (no bed level updating) transport computations for 214 wave conditions covering the full extent of the wave climate at the Delfland coast, and the probability of occurrence calculated per wave condition, per year. The envelope of the alongshore distribution of the simulated LST is shown in Figure 3-3; the black line indicates the longshore transports based on a reduced set of 10 wave conditions. Here, the net LST is said to reach a maximum average of approximately 200 000 m^3/year.

The Delfland coast is bounded in the south by a long groyne at Hoek of Holland, which allows ships to access the Port of Rotterdam (Stronkhorst et al., 2018). Extending beyond the surf zone up to 4.2 km into sea (Luijendijk et al., 2017), the groyne blocks alongshore sediment transport, hence the LST is zero at this southern boundary, as shown in Figure 3-3. At the smaller Scheveningen harbour mole, which forms the northern boundary of the Delfland coast cell, some sediment bypassing in the order of 150 000 m^3/year occurs (Luijendijk et al., 2019). The Delfland coast therefore forms a more or less closed coastal cell (ref).

[3] Normaal Amsterdams Peil: local vertical datum used for height measurements in the Netherlands; 0 m NAP is approximately equal to mean sea level (MSL).

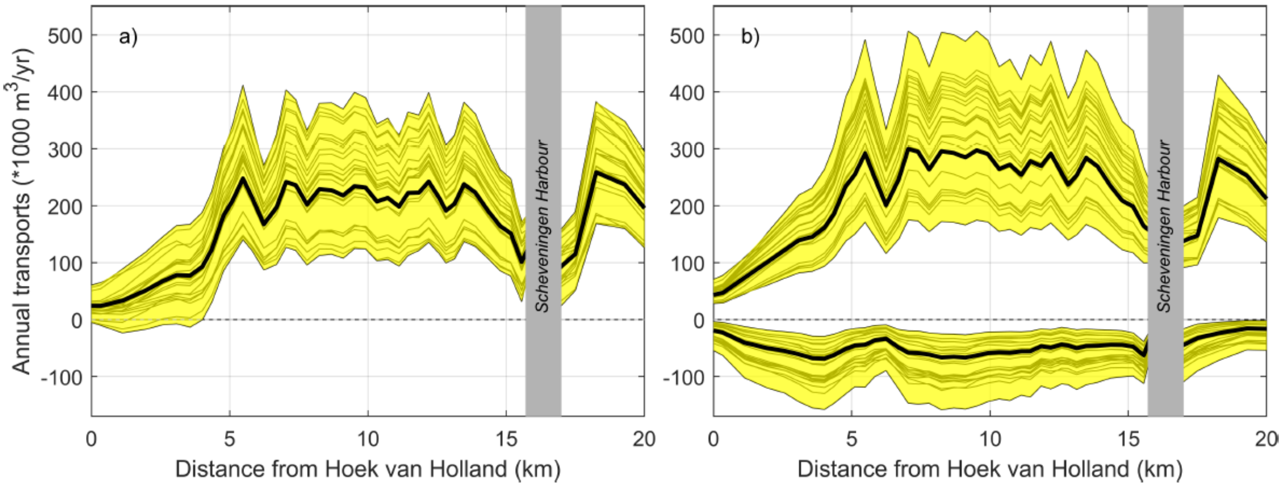


Figure 3-3: Envelope of the alongshore distribution of the annual (a) net and (b) gross longshore transports for the years 1985–2015 (Luijendijk et al., 2019).

Varying depths of closure (DoC) have been reported in previous literature. Van Rijn (1997) uses two values: -5.5 m and -8 m NAP (~ MSL), saying the location of closure depth is not well defined, but that the latter value roughly represents the edge of the surf zone along the Holland coast. This earlier assessment of the closure depth at this coast was later confirmed as -8 m NAP by De Vries et al. (2018). Tonnon et al. (2018) refers to the lower shoreface between -6 m and -10 m MSL and depth of closure as the dynamic boundary at an optimal water depth of 6.3 m, specific to the Sand Engine case along Delfland.

The coastal system of the Holland coast (including Delfland) is generally characterised by an erosive trend (Borsje, 2017). This is due to the natural supply of sediment to the coast being limited and resulting in a retreating coastline (Stronkhorst et al., 2018). Increasing the sediment volume by artificial sand nourishments over the last few decades, has changed the generally erosive trends into generally accretive trends in the shallow coastal zone between -8 m MSL and the landward side of the frontal dune row according to Van der Spek and Lodder (2015). This is discussed in more detail in the subsequent sections.

3.4 Dutch Coastal Defence Policy

The Netherlands is unique in that management of flood protection and coastal maintenance is stipulated in policy for the interest of national safety. In the past, groynes, dikes and seawalls were built to compensate for the ongoing coastal erosion, i.e. prior to 1960 (van Rijn, 1997).

The Dutch coastal defence policy as it is today, first became formalised in 1990. In a decision to stop any further structural erosion and prevent the coastline from moving inland, it was decided that sand was to be added to the coast through artificial sand nourishments, rather than building hard structures (if/where possible). The Dutch government adopted the 'Dynamic Preservation' policy in which the coastline would be maintained at its 1990 position, termed the basal coastline (Min V&W, 1996).

Keeping the coastline in place is essential for protection of the low-lying hinterland from coastal floods. This coastal policy was therefore first aimed at sustainable preservation of coastal flood protection and of functions in the dune area. The policy was later extended to a larger scale to ensure sustainable preservation of safety and of functions in the entire *coastal zone,* from the dune area across to, and including, the lower shoreface, (Mulder & Tonnon, 2011). Hence, the policy is summarized by three main objectives:

1. Maintain the minimum dune strength.
2. Maintain the reference coastline.
3. Maintain the sand volume in the coastal foundation.

The principle intervention procedure is sand, allowing optimal use of and providing optimal space for natural processes and dynamics along the coast (Stronkhorst et al., 2000). 'Dynamic Preservation' to maintain the coastline has been put into practice through the 'soft approach' and preferred intervention of nourishing the coast at regular intervals with small volumes of sand dredged from the North Sea. Sand is extracted seaward of the -20 m MSL depth contour which is considered the long-term lower boundary of the coastal system of the Netherlands (Van der Spek & Lodder, 2015).

The volume of sand needed in 1990 was approximately 6 million m^3, supplied mainly as beach nourishments. In 2001, this annual sand nourishment volume doubled to an average of 12 million m^3 to nourish the entire Netherlands coast, with an increase in shoreface nourishments. This volume was largely successful in maintaining the position of the coastline, but was deemed insufficient to maintain the total active sand volume of the system when an update of the sediment budget showed a negative total of roughly 20 million m^3 (De Ronde, 2008; Mulder & Tonnon, 2011).

The Delta Programme 2008 report (Veerman, 2008) included potential accelerated SLR and climate change as factors against which flood protection needs to be ensured. Accordingly, the Delta Commission recommended the raise in yearly nourishment budget from 12 to 20 million m^3 per year for an estimated SLR of 2 mm/year. A further raise of up to 85 million m^3/year until 2050, has been suggested to accommodate an extreme SLR rate of 12 mm/year (or a worst-case scenario of 1.3 m SLR in 2100).

Giardino et al. (2011) states that higher sand nourishment volumes will be necessary in the future to accommodate more severe SLR scenarios predicted.

3.5 Sand nourishments

3.5.1 Concept of the Momentary Coastline

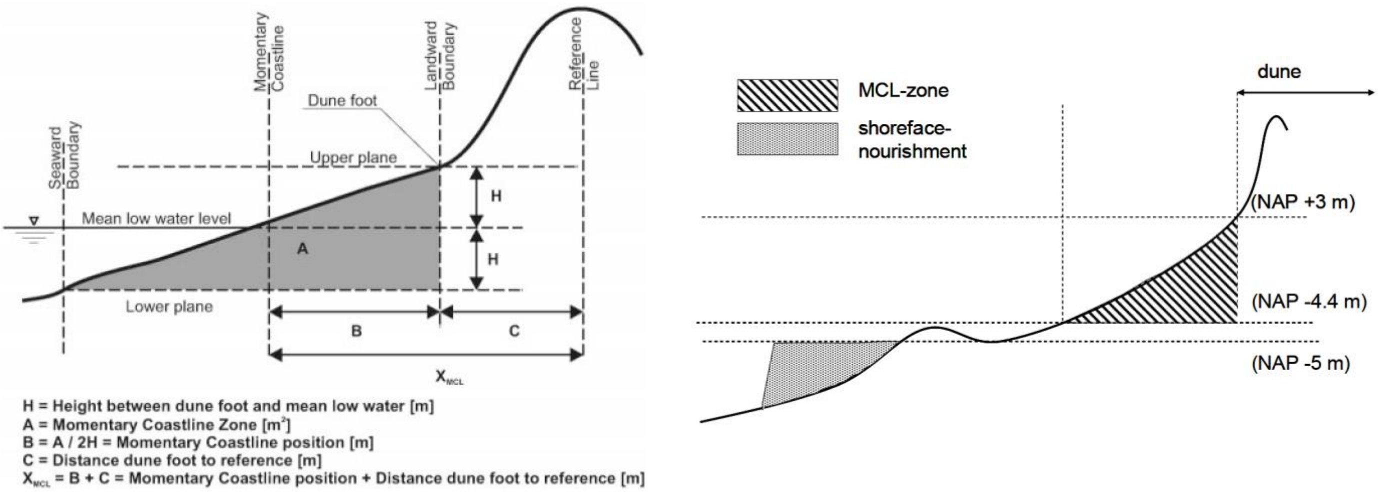
Sand nourishments are a common coastal maintenance strategy in the Netherlands, and elsewhere, used as a measure to mitigate coastal erosion along sandy beaches, and hence stabilize the shoreline and enhance coastal safety and beach width (Luijendijk et al., 2017; Stronkhorst et al., 2018).

The nourishment requirement in the Netherlands, and distribution thereof, is governed by the definition of the basal coastline (BCL), i.e. the 1990 reference position of the coastline. Periodically, the position of the coastline is assessed by means of surveying cross-shore profiles at fixed transects; if the reference standard is likely to be breached by ongoing coastal erosion, sand nourishments are carried out as a preventative measure/adaptive management method at the erosive stretches along the coast (Briere et al., 2017).

This is determined through the concept of the Momentary Coastline (MCL), in Dutch 'Momentane Kustlijn' (MKL), which defines the coastline position as a function of the volume in the nearshore zone (van Koningsveld & Mulder, 2004). This means that for any given cross-shore profile, the MCL is calculated based on the area (or volume per unit length) of sand between two horizontal planes (Min V&W, 1991) as shown in Figure 3-4 (a) and the equation below.

$$X_{MCL} = \frac{A}{2H} + C \qquad [2]$$

In Figure 3-4 (b), the MCL-zone is defined as lying between the landward boundary at +3 m MSL (i.e. dune foot) and a seaward boundary of -4.4 m MSL. If the sand volume in this vertical section is smaller than the reference volume, the cross-section qualifies for nourishment (Van der Spek & Lodder, 2015). At the proposed erosive locations, shoreface nourishments are generally implemented at a depth of -5 m, with a volume equal to twice the calculated loss in the MCL-zone¸ according to van Koningsveld and Mulder (2004).



(a) Calculation of MCL position
(Source: Min V&W, 1991)

(**b) Schematic diagram of volume loss in the MCL-zone and required shoreface nourishment**
(Source: van Koningsveld & Mulder, 2004)

Figure 3-4: Momentary Coastline (MCL) definition

3.5.2 Historical sand nourishments along the Delfland coast

The Holland coast, characterised by an eroding trend as discussed in Section 3.3, is further described as being predominantly erosive in the northernmost and southernmost sections (Stronkhorst et al., 2018). The southernmost section which forms part of the Delfland coast, is prone to chronic erosion; according to Luijendijk et al. (2017) due to the presence of the nearby Rhine-Meuse estuary which acts as a sink for marine sediments as sediment supply from the rivers has substantially reduced over the last centuries.

It is recorded that the total nourishment volume to maintain the coastal foundation of the Delfland coast (at a present SLR rate of 2 mm/year) is approximately 1.1 million m^3 per year (Mulder & Tonnon, 2011).

A historical inventory of all beach, shoreface and dune nourishments implemented along the Delfland coast between the years 1988 and 2013 is presented in Table B-1 in Appendix B (refer to Figure 3-2 for approximate locations). Between 1988 and 2007, approximately 15 million m^3 of sand was replenished between Hoek of Holland and Scheveningen; yearly totals are shown in Figure 3-5, along with average volumes calculated for different time periods: 1991-2000, 1998-2007, and 2001-2007 (also see Table B-2). In the early 1990s, common practice was to implement beach nourishments. Later, the total volume of shoreface nourishments increased, due to benefits such as lower cost in comparison to beach nourishments, and less negative impacts to the coastal environment and biodiversity (Giardino, 2019). Yearly shoreface nourishments typically range in size from 200 to 400 m³/m.

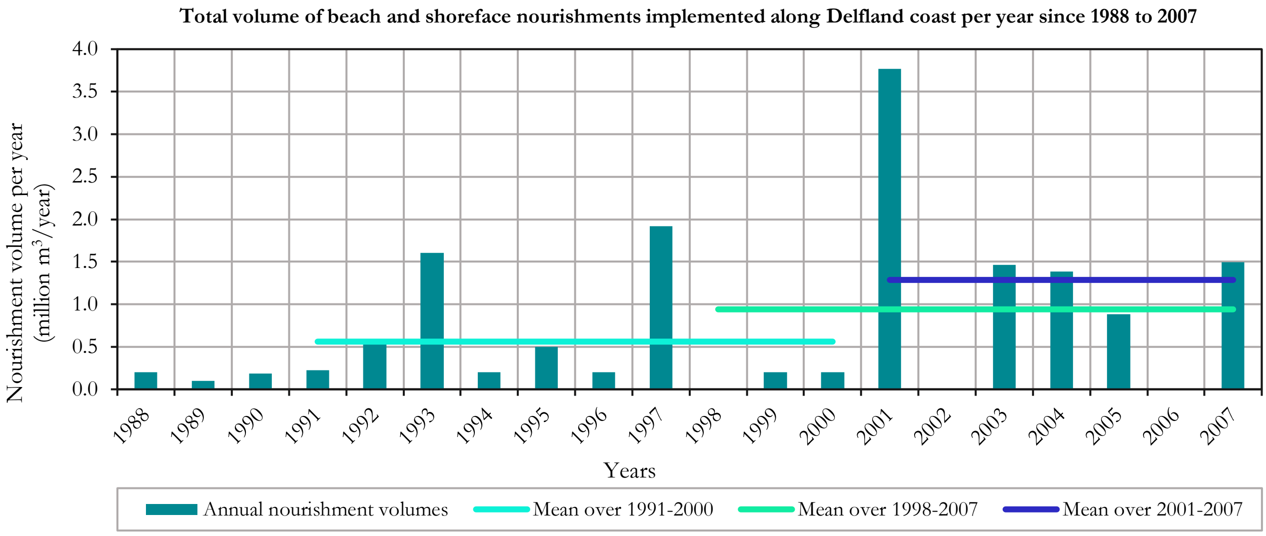


Figure 3-5: Nourishment volumes (millions m³/year) at Delfland coast for 1988-2007.

According to Van der Spek and Lodder (2017), much has changed in the Defland coastal section after 2007. The larger nourishment volumes applied in the years 2009 to 2010 specifically (refer to Table B-1), included beach widening between Ter Heijde and Hoek of Holland and artificial dune construction for the compensation of the Maasvlakte 2 expansion at the Port of Rotterdam. Ter Heijde and Kijkduin were strengthened as these areas are particular weak links. In 2011, the Sand Engine was implemented; refer to Section 3.7 for more information regarding this mega-nourishment.

3.6 Sediment Budgets at Delfland Coast

3.6.1 The effect of sand nourishments on the sediment budget

The effect of nourishing the Dutch coast has thus far been successful by achieving the aim of the Dynamic Preservation policy to stop coastal recession. According to Van der Spek and Lodder (2015), the first 15 years of nourishing the coast (1990-2005) has resulted in the sediment budget showing a positive accretionary status for the upper shoreface, beach and frontal dunes.

This is depicted in Figure 3-6 for different zones along the Holland coast. Where nearshore zones in (a) are largely classified as erosive or more or less stable (blue/green) with volume changes in the range of -1 to -5/-1 to +1 million m³ respectively (assuming trends without nourishment), most of these zones change to orange in (b), an indication of accretive volumes of +5 million m³ or more due to the sand nourishments implemented over the 15-year time period. The deeper shoreface zones in (b) are seen to still erode. Overall, the net sediment budget of the Dutch coast therefore remains negative due to erosion of the lower shoreface and ebb-tidal deltas (Van der Spek & Lodder, 2015).

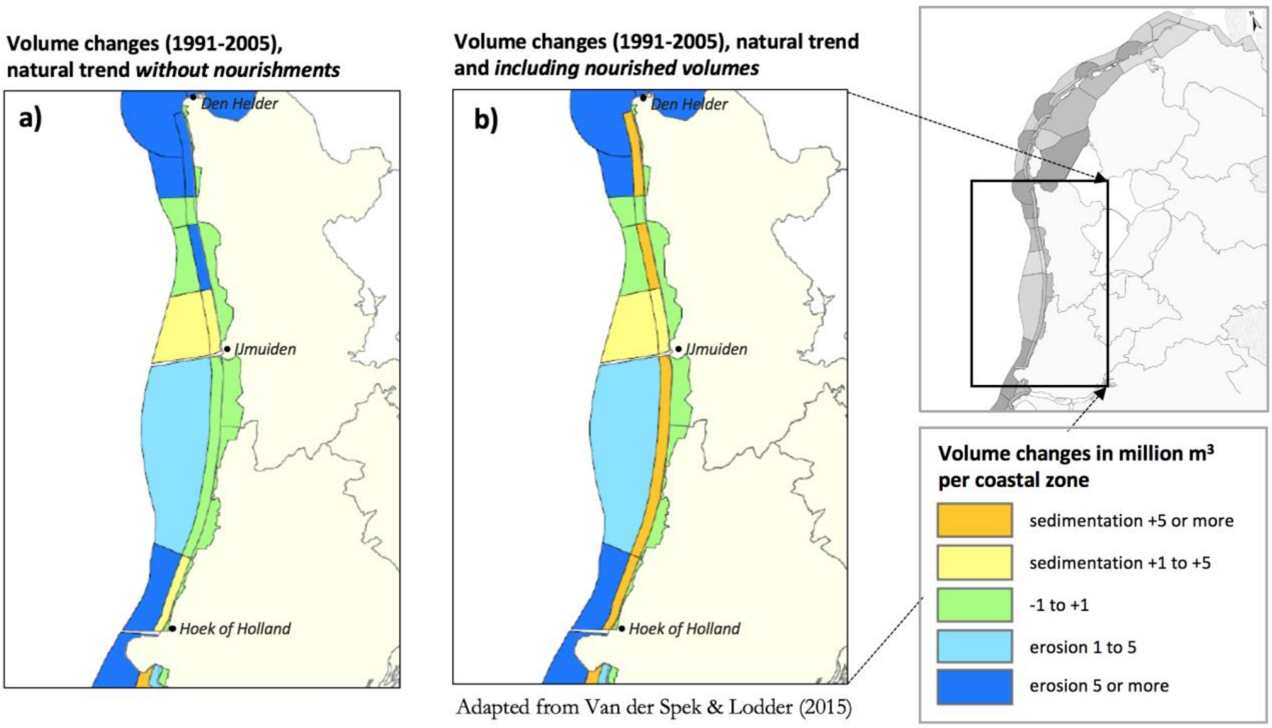


Figure 3-6: Volume changes for Delfland coast over 1991-2005, natural trend (a) without and (b) with nourishments

The volume changes of the dunes landward of the frontal dune row, are said to not be included in the sediment budget calculations above. This is because the dunes catch almost all aeolian sand transport.

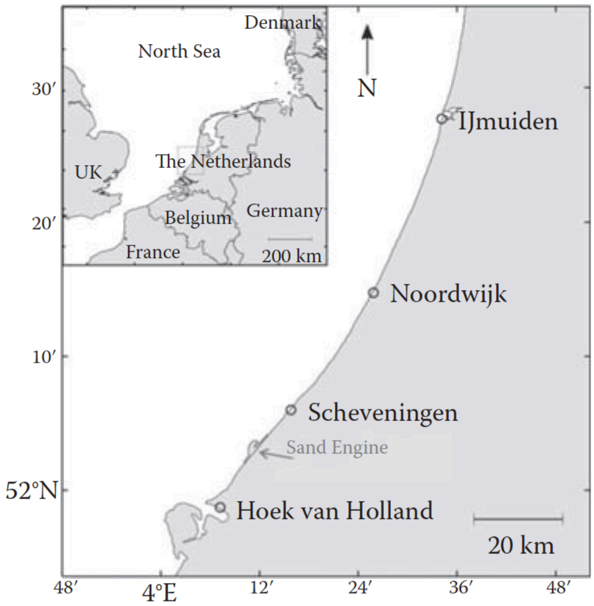
3.6.2 Estimates of dune erosion

Previous studies give an indication of dune erosion to storm impact and SLR (e.g. de Winter & Ruessink, 2017). Present-day safety standards in Dutch coastal policy require dunes to not breach during a 1:10 000-year storm event, i.e. a surge level greater than 5 m, a wave height H_{m0} between 8 to 9 m, and wave period T_p of approximately 14-16 s. Projected dune erosion volumes under such extreme storm conditions, and without SLR, are 350 m^3/m and 230 m^3/m, determined for two sites along the Holland coast, but north of Scheveningen, namely Egmond and Noordwijk (de Winter & Ruessink, 2017). With SLR, this increases to a range of 350 to 540 m^3/m and 230 to 380 m^3/m respectively. A linear relation between dune erosion volume and SLR is found by de Winter and Ruessink (2017). This amounts to 80 m^3/m per m SLR and 52 m^3/m per m SLR for Egmond and Noordwijk respectively.

3.7 The Sand Engine

The need to upscale the yearly nourishments considering SLR projections, and the Delta Commission's recommendation to increase the annual nourishment budget up to 2050, were amongst the motives which led to the innovative Sand Engine (*Zand Motor* in Dutch) pilot project being built in 2011.

The Sand Engine, located along the Delfland coast as shown in Figure 3-7, is a single mega-nourishment consisting of 21.5 million m^3 of supplied sand that was placed on the foreshore of the coast to form a large man-made peninsula (Mulder & Tonnon, 2011).



(Source: Borsje, 2017)

(Source: Luijendijk & van Oudenhoven, 2019)

Figure 3-7: Location of Sand Engine (left) and aerial photograph of Sand Engine in year 2013 (right).

Natural coastal processes are redistributing the deposited sand along the Delfland coast, as has already been observed in the time since construction. This helps strengthen the coastline as a flood defence. It is expected that for more than 20 years this mega-nourishment will provide the coast with sufficient sand for coastal protection (Mulder & Tonnon, 2011; Luijendijk et al., 2017; Luijendijk et al., 2019). This reduces the requirement of regular nourishment operations for the maintenance of the Delfland coast, whilst the Sand Engine provides added benefits such as nature development, and promoting recreation. Overall, it is believed that such a larger-scale single nourishment is more efficient, economical and environmentally friendly in the long-term than traditional beach and shoreface nourishments being implemented every three to five years (Stive et al., 2013a).

Being a pilot project, this local mega-nourishment is tested as a measure to account for the anticipated increased coastal recession during this century due to SLR (Stive et al., 2013b). According to Briere et al. (2017), the large volume of sand deposited in one location to form the Sand Engine is said to have a positive impact on coastal protection, based on monitoring data thus far.

Inspired by the 'Building with Nature' concept, this unique and innovative mega-nourishment strategy is an example of future large-scale solutions which can potentially be implemented as climate change adaptation strategies to counteract coastal erosion and inundation caused by SLR on open coasts.
Numerous studies monitoring and testing the effectiveness and efficiency of the Sand Engine as such a measure are still underway; if proven successful, it could potentially become a generic solution applied at more sandy coasts across the globe which are vulnerable to SLR-driven coastal recession.

However, with the latest SLR projections being much higher than what was predicted at the time during which the Sand Engine was designed and implemented, SLR along the Dutch coast could be more extreme than previously anticipated. This could lead to a massive increase in the annual nourishment volume needed (discussed further in Section 3.8). This raises the question of whether another Sand Engine should be built along the Dutch coast or whether more nourishments of the Sand Motor type are a solution? And if so, how the required sand volume and placement in the nearshore could be optimized? Such questions and concerns, amongst others, are expressed in a recently published book *The Sand Motor: A Nature-Based Response to Climate Change,* as part of the NatureCoast research program (Luijendijk & van Oudenhoven, 2019).

This book largely documents the findings, reflections, and lessons learnt from many researchers directly involved in the research and monitoring of the Sand Engine pilot project, not only from the coastal morphodynamics and coastal safety perspective, but across the interdisciplinary field thereof, such as ecology and governance, and comments from end-users.

3.8 Need for Adaptive Planning

The recent insights to possible additional acceleration in the rate of SLR has already motivated exploratory studies in the Netherlands regarding the consequences thereof for the Netherlands, and possible short- and long-term mitigating strategies. This is briefly discussed below, further adding to the motivation for this thesis and the need to understand morphological behaviour of sandy coasts due to accelerated SLR.

A Policy Hackathon was held by Deltares research institute on 8 November 2016 (Deltares, 2017) in which the consequences of accelerated and extreme SLR for the Netherlands was discussed in response to DeConto and Pollard's findings (2016). Results of the hackathon give a first indication of what could possibly happen in such a future. This is in relation to possible limits to adaptation across several disciplines linked to water management and flood protection, i.e. in a broad context.
Another exploratory study, also by Deltares (Haasnoot et al., 2018) and which uses the new converted SLR projections for the Dutch coast (refer to Figure 3-1) gives focus to impacts for the coastal foundation, flood risk management and freshwater supply in the Netherlands, and what implications any consequences would have for the preferential strategies of the Delta Programme.

In terms of the current nourishment policy, accelerated SLR will result in an increase in sand volume requirement. The question remains up to what point (in time) or at which anticipated magnitude or rate in SLR would the current nourishment strategy for the Netherlands be sufficient? Is a strategic shift in policy, beyond upscaling present-day strategies required and when? Examples of possible limitations include: the volume of sand nourishment is too large, availability of sand is reduced (demand vs. supply), implementation costs are too high, and negative effects to the ecology or recreation values of the coast.

The Delta Committee (Veerman, 2008) recommended that the nourishment budget be upscaled to 85 m^3/year until 2050, and stated that for every millimeter of SLR, 7 million m^3 of sand will be required. For SLR rates between 6 – 12 mm/year, 40 to 85 million m^3 of sand would be required every year.

The coastal foundation is assumed as the area between the dunes and the 20 m depth. For the entire coast of the Netherlands this equates to an area of approximately 4000 km^2. Column 2 in Table 3-3 presents estimated sand volumes required for the entire Dutch coast based on accelerated SLR rates (Haasnoot et al., 2018). This is a simple calculation in which the amount of sand required is equal to the water volume increase due to SLR. Column 3 shows values converted for only the Delfland coast with an approximate coastal foundation of 145 km^2.

Table 3-3: Estimated sand nourishment volumes for accelerated SLR – Dutch coast

SLR speed (mm/year)	**Volume (Mm^3/year)**	
	Dutch coast	**Delfland (~16.5 km)**
2	8	0.3
3	12	0.4
5	20	0.7
12.5	50	1.8
30	120	4.4
40	160	5.8
60	240	8.7

The values in Column 3 give an indication that nourishment volumes applied to the Delfland coast have been much larger than necessarily required (based on this simple calculation). Hence the reason why the sediment budget for the coast shows an accretive trend as discussed in 3.6.1.

It is presumably expected that the preferential strategies of the Delta Program would be sufficient until 2050 to keep the Netherlands livable and habitable. However, the larger uncertainties make it difficult to know what to prepare for. There is a need for a flexible adaptation strategy that can be applied to the changing views concerning the severity of impacts of climate change.

4

MODELLING APPROACH

Following the research approach introduced in Section 1.3.2, this chapter sets out the modelling methodology for simulating the morphological behaviour of the Delfland coast to accelerated SLR using a calibrated Delft3D model. Section 4.1 first provides an overview of Delft3D in general, and shortly describes the state-of-the-art calibrated model used in the study. Key aspects of the modelling approach and required model outputs are also introduced. The selection of SLR scenarios that were simulated is discussed in Section 4.2, followed by technical details related to the model setup in Section 4.3. Assumptions relevant to the modelling study are listed in Section 4.4.

4.1 Modelling Framework

4.1.1 Delft3D model structure

The processed-based numerical model Delft3D (Lesser et al., 2004) is commonly used to compute hydrodynamics, waves, sediment transport and morphological changes under the influence of tidal, wind-driven and wave-driven currents (Luijendijk et al., 2017). The morphological feedback loop used in Delft3D is presented in Figure 4-1.

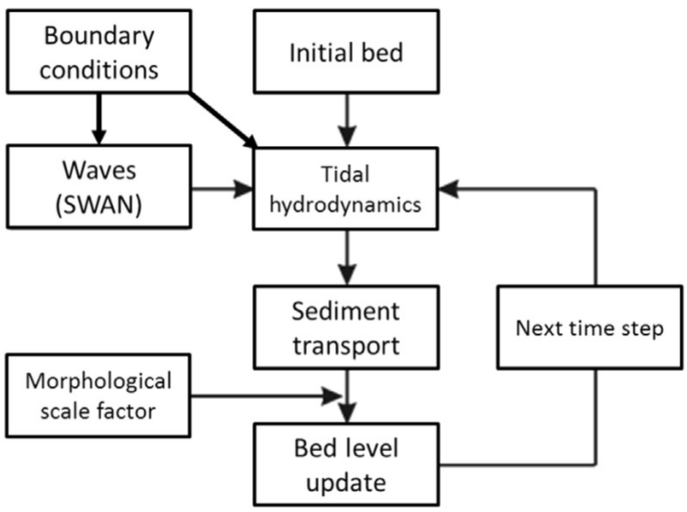


Figure 4-1: Morphodynamic feedback loop applied in Delft3D (Luijendijk et al., 2017)

Delft3D is therefore able to simulate morphological changes due the combined effect of tides, waves and currents (Lesser, 2009; Ranasinghe, 2016), and is most commonly applied for spatio-temporal scales covering areas from ~10 m to 10's of km, and periods of a tidal cycle up to decades (Luijendijk et al., 2011).

Delft3D is generally considered computationally expensive, and requires techniques like input reduction or a morphological acceleration factor (i.e. MORFAC) to speed up morphodynamic simulations within a realistic timeframe. Input reduction aims to lessen the computational effort by reducing hydrodynamical forcing conditions to a limited set of conditions representative of a longer-term signal (e.g. schematized wave climate). The MORFAC approach allows simulated morphology to be accelerated by multiplying calculated bed changes with a constant factor.

4.1.2 Calibrated Delft3D model

The Delft3D model used in the present study was one that has been calibrated and validated in a previous study. This is a Delft3D model of the Sand Engine which makes use of a new acceleration technique called 'brute-force merged' (BFM) (Luijendijk et al., 2019); the model domain thereof covering the same southern section of the Holland coast, i.e. Delfland which forms the study area in this thesis.

The BFM technique uses the standard version of Delft3D (Lesser et al., 2004), and mimics an unfiltered real-time (brute force) simulation well, yet with significant gain in computational cost. In short, this is done through a combination of the compressed brute force technique (MORFAC > 1) and parallel online method, similar to the 'mormerge' procedure (Roelvink, 2006).
In this way, because the brute force time series are applied, gross transport components are inherently included. Moreover, it allows for seasonal variations and incorporates full variability of the wave climate (wave directions and heights), including storm events (1:5 year) and also potential beach recovery periods. This state-of -the-art technique can therefore be used to predict morphological evolution of sandy coasts at time scales from hours to decades. This is an improvement to wave schematized techniques which do not fully represent the range and variability in wave heights, direction and surge levels, and as such are deemed not capable of accurately reproducing morphological response at short time scales, in particular erosion of the upper profile.

According to Luijendijk et al. (2019) the BFM acceleration technique provides the optimal combination of phenomenological accuracy and computational efficiency at both short to medium, and long timescales. In this previous study a one-year brute force (BF) simulation took 331 hours (~2 weeks) to complete, whereas the BFM simulation required only 4.5% of the computational time of the BF simulation.
As it allows morphological modelling over longer time-scales covering decades with a significant reduction in computational effort, this novel technique is viewed as an attractive method for assessing impacts of SLR, considering the slow nature thereof.

For a more detailed account on the calibration and validation, refer to the studies by Luijendijk et al. (2019; 2017).

4.1.3 Methodology

The following text introduces aspects that were integral to the modelling study in this thesis.

<u>Simulated time period:</u>
For the purpose of this study, a time period of 30 years was chosen to be simulated. This choice was viewed as a trade-off between the time necessary to effectively assess the impacts of SLR, knowing that SLR impacts would be more visible over the longer-term (i.e. decades to centuries), and the computational effort and efficiency associated with Delft3D. A 30-year period is assumed sufficiently long to obtain the required

results for assessment of morphological changes over the medium- to long-term (5 to 20-30 years). Using the BFM acceleration technique allows such a simulation to run for approximately 20 days.

Exclusion of the Sand Engine:
To assess the impact of SLR only, possible interference from the morphological development and dispersion of sand from the Sand Engine were to be excluded. Therefore, the initial bathymetry used in the new model setup was that of the Delfland coast prior to the implementation of the large-scale nourishment currently present at this coast, i.e. before the year 2011. Through this action, an almost straight, unnourished beach was obtained for the purpose of this thesis. This is in line with the objectives to assess SLR impacts on a sandy coast should no adaptation/mitigation measures take place.

Selection of SLR scenarios:
SLR scenarios simulated in the Delft3D model were defined from available literature presented in Section 3.1. The desktop study provided insight into defining a range of useful and plausible SLR scenarios for the Dutch coast, with higher rates of SLR assuming the potential collapse of the Antarctic ice sheet as proposed by DeConto and Pollard (2016). The selection of SLR scenarios is provided in Section 4.2.

Model outputs:
The target of the model simulations was to obtain the following outputs for each SLR scenario over time:

- Computed erosion and sedimentation patterns in the nearshore zone of the study area, and
- Magnitude of volume changes, with a focus on erosion.

These model outputs were studied in order to understand the behaviour of the coastal system under changing water level conditions, and to discuss trends representing the long-term erosional behaviour of the coast in response to different rates of SLR.

4.2 Simulated Sea Level Rise Scenarios

The Delta Scenarios and accelerated SLR projections translated for the Dutch coast (Le Bars et al., 2017), as presented in Section 3.1.2, form the basis for the SLR scenarios in the model simulations. These projections have therefore been further simplified and are summarised in Table 4-1 below, categorized into minimum, high and extreme values.

Table 4-1: Summarised accelerated SLR: Absolute SLR values in m (left). SLR rates in mm/year (right).

Year	SLR (m)		
	Min	High	Extreme
2020	0.00	0.15	0.20
2050	0.2-0.3	0.40	0.47
2070	0.35-0.4	0.70	1.00
2100	1.00	2.00	3.00

Year	Speed of SLR (mm/year)		
	Min	High	Extreme
2020	0	3	6
2050	10	12	15
2070	12	20	35
2100	15-35	60	120

For the morphodynamic simulations, assessing the different rates of SLR (in mm/year) was considered more important and relevant than the absolute SLR values (i.e. total water level elevations). This is because the coast would no longer be in a (dynamic) equilibrium state if absolute sea level changes are simulated. Such a simulation would mainly represent 'immediate' coastal flood inundation due the instantaneous increase in water levels, and not consider the morphological changes that happen over time as a result of the slow or accelerated rise in sea levels. Furthermore, initial bathymetry is required to be kept constant across the different simulation runs for intercomparable results.

Rates of SLR that were selected to simulated in the modelling study represent the full range of those projected, i.e. between a minimum value approximately equal to the current GMSL rise of 3 mm/year (slightly higher than the current rate of SLR along the Dutch coast), and the most extreme scenario predicted for 2100 (or beyond). The following six rates were chosen to each represent different SLR scenarios, including one with no rise in sea level, i.e. the reference case:

1. 0 mm/year
2. 3 mm/year
3. 15 mm/year
4. 30 mm/year
5. 60 mm/year
6. 120 mm/year

As it is not known for certain when exactly in the second half of the century the much higher rates of SLR may occur, these values should not be seen as synonymous with a particular period of time in the future, e.g. a rate of 15 mm/year could potentially occur during any time period from 2050 as it lies within all estimated speed ranges, even for the year 2100 (assuming the projections are correct). To some extent this makes 15 mm/year the most likely approximate rate of SLR to be reached within the 21st century, yet it is a high enough value that differences in model outputs should be visible compared to a no SLR scenario (or at least a bigger difference than would be expected for a rate of 3 mm/year).

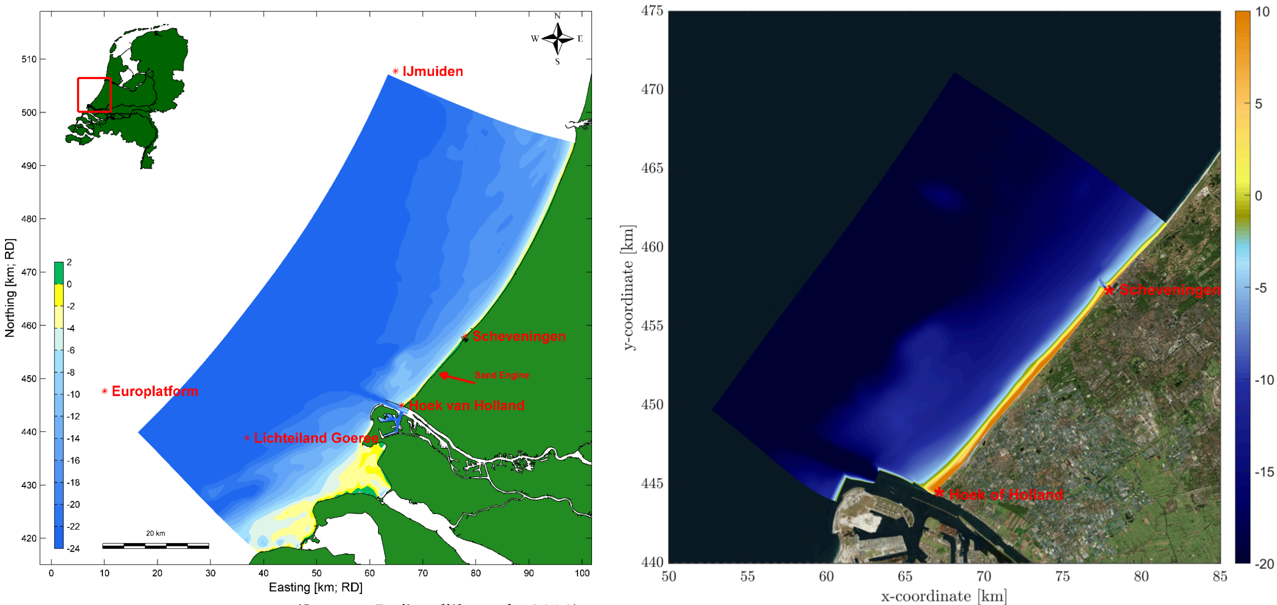
The 60 and 120 mm/year scenarios are in effect even higher than what was considered in a previous study for the Netherlands, a hypothetical case starting in 2030, with sea level rising to a level of 5 m after 100 years (Olsthoorn et al., 2008) and a global study (Tol et al., 2006). It should be noted that these extreme cases are high-end scenarios for the year 2100, and so may only occur within the next century. Nevertheless, these are chosen to be modelled to cover the full bandwidth of projected SLR rates, with the extreme scenarios still regarded as informative in terms of analyzing trends for higher SLR rates.

4.3 Model Setup

4.3.1 Grid and bathymetry

For the present study, the model domain and grid remain the same as that which is used in the aforementioned calibrated model of the Sand Engine (Luijendijk et al., 2019). A brief summary of the model parameters and settings is presented below.

The Delfland coast, between Hoek of Holland and Scheveningen, is shown in Figure 4-2, as well as the initial bathymetry used in the model simulations of the present study (on the right side of the figure), i.e. the straight-lined sandy coast without the Sand Engine. The bathymetry and subaerial topography of the calibrated model is replaced with the bathymetry from the year 2010, prior to the implementation of the Sand Engine. The bathymetry is based on echo-sounding surveys conducted by Rijkswaterstaat. First, a simulation is run for 5 years (computational time of 3.2 days) with no SLR to obtain a more equilibrium beach state. The bed level output of this run is used as the initial bathymetry in all subsequent runs, for the no SLR scenario and the remaining five which represent varying accelerated SLR rates.



(Source: Luijendijk et al., 2019)

Figure 4-2: Geographical setting of the Delfland coast and larger-scale wave model domain in calibrated model (left). Model domain with initial bed elevations in meters (right).

The domain of the Delfland coast was schematized with a curvilinear computational grid. The grid covers an area of 26 km in the alongshore direction and 15 km in the cross-shore direction, with water depth of approximately 21 m at the offshore boundary. The grid consists of 221 by 83 cells, with resolution varying from 35 m to 500 m.

4.3.2 Boundary conditions

Time series of the wave, wind and surge, are based on measured data from 2011-2016 (used in the calibrated model), and repeated every five years for the 30-year simulation. An example of the 5-year wave and surge time series is shown in Figure 4-3; the highest wave occurrence in years 4 and 5, almost reaching 5 m.

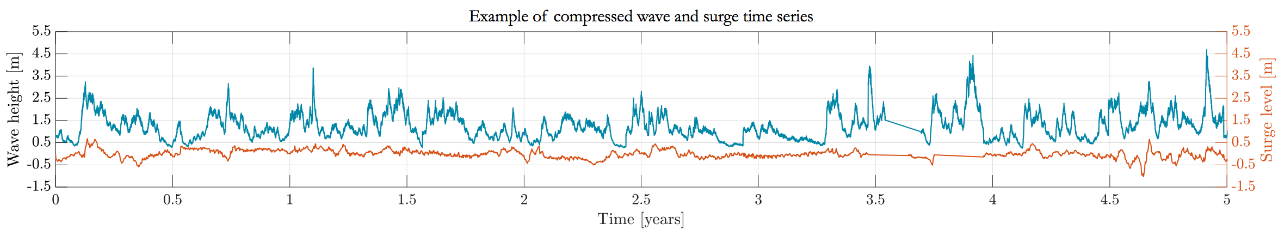


Figure 4-3: Example of compressed wave and surge time series in the calibrated model

These boundary conditions are kept the same as in the calibrated model, i.e. not projected to differ from the 2011-2016 measurements. Keeping the future wave heights and periods, as well as the storm surges, unaltered is in line with assumptions made by de Winter and Ruessink (2017). Although this is not entirely representative of a future wave climate, in this way additional uncertainty that forecasting a future wave climate will bring is controlled. Furthermore, this limits misinterpretation of coastal change which may occur due to a combination of the various forcing factors. In an attempt to isolate the effect of SLR, only the surge time series differs in each simulation to account for SLR (surge itself remain unchanged); other input parameters are kept constant. This thereby simulates only the sea level variations and consequent morphological response, i.e. SLR-induced morphological change.

The sediment transport settings are similar to that of Luijendijk et al. (2017), in which the formula of van Rijn is used (van Rijn, 2007).

4.3.3 Water level adjustment accounting for sea level rise

Figure 4-4 below presents the adjustment of the surge time series in the Delft3D model to add SLR over a 30-year period. The first plot shows an example surge time series from the model inputs; these values are assumed to remain unaltered. The SLR scenarios represented by a range of SLR rates are assumed to increase linearly from zero by a constant rate per year. This linear increase is shown in subplot 2 (3 mm/year not shown in the figure), with the corresponding absolute water level increases at certain time intervals shown in Table 4-2. Subplot 3 shows the final modified time series used as input to the model simulations; a summation of the surge time series and the rise in sea level.

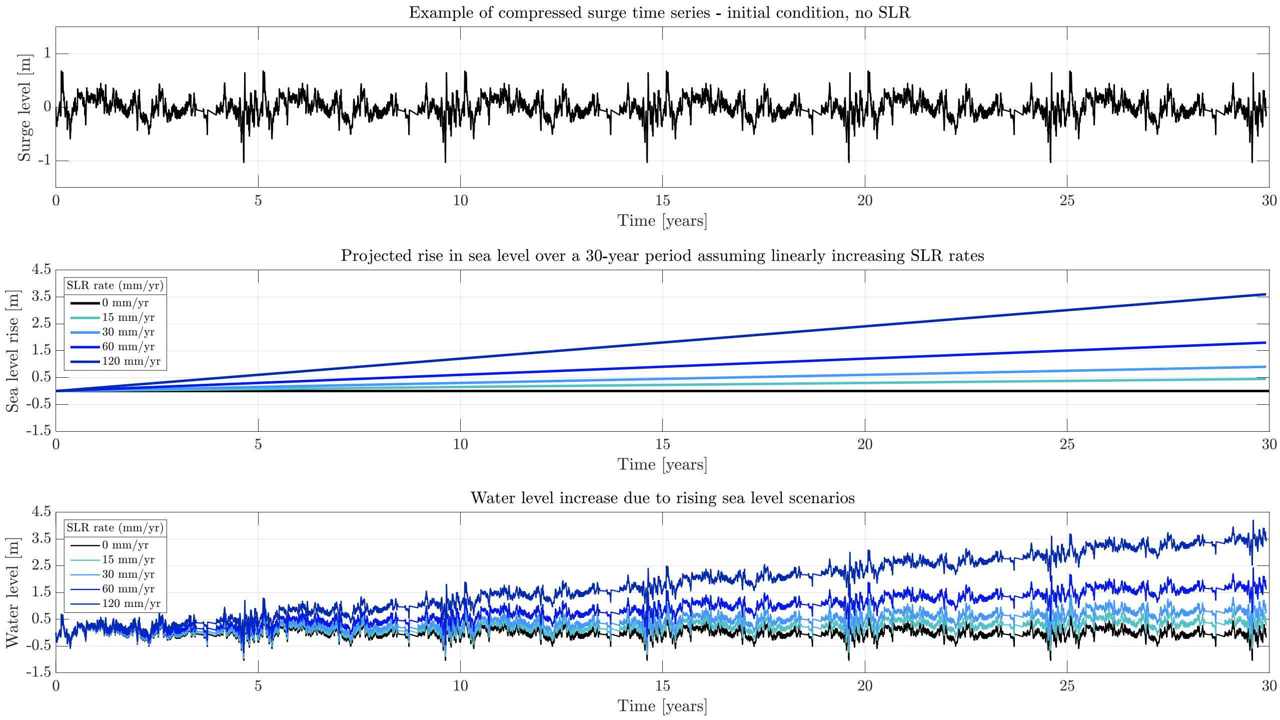


Figure 4-4: Water level adjustment to account for SLR

Table 4-2: Absolute rise in sea level (m) corresponding to simulated SLR rates over time.

Time interval [years]	Simulation run: Sea level rise scenario					
	0 mm/yr	3 mm/yr	15 mm/yr	30 mm/yr	60 mm/yr	120 mm/yr
5	0.00	0.02	0.08	0.15	0.30	0.60
10	0.00	0.03	0.15	0.30	0.60	1.20
15	0.00	0.05	0.23	0.45	0.90	1.80
20	0.00	0.06	0.30	0.60	1.20	2.40
25	0.00	0.08	0.38	0.75	1.50	3.00
30	0.00	0.09	0.45	0.90	1.80	3.60

4.4 Assumptions and Limitations

4.4.1 Summary of assumptions

The following assumptions are made in the modelling study:

- All scenarios assume an unnourished straight coastline, i.e no additional sediment input.
  - In reality, and under current policy, sand nourishments would be executed to 'help' the coastal foundation keep pace with SLR.
- Initial bathymetry (2010) is first modelled to retrieve an 'equilibrium profile'.
- Potential land subsidence, and hence relative SLR , is not considered.
- SLR is assumed to increase linearly during the simulated 30-year period.
  - This does not represent a fixed 30-year time period in the future, e.g. a rate of ~3 mm/year for the Dutch coast is more likely in the next few decades, whereas the extreme scenarios of 60 and 120 mm/year are only projected to occur towards the end of the 21st century.
  - This emphasises the hypothetical nature of the study.
- The future wave climate is kept unchanged from the calibrated model.

4.4.2 Limitations

The Delft3D model does not include aeolian transport processes and so cannot accurately simulate the *full* coastal system.

5

ANALYSIS OF RESULTS

The model outputs and results processed therefrom are provided in this chapter. First, erosion and sedimentation plots derived from bed level changes to the initial bathymetry are shown in Section 5.1. The plots are used to explain the overall morphodynamic behaviour of the Delfland coast as simulated in the Delft3D model, under the different climate scenarios (i.e. varying SLR rates) with all simulations assuming an unnourished coast. In Section 5.2, a detailed description of the approach taken to obtain and analyse quantitative sediment volume changes is provided. The resultant erosion and accretion volumes, and alongshore differences, are presented in the form of graphs in the subsequent sections (5.3 to 5.5). Trends are analysed and observations described; reasons and interpretation of this analysis is explained in Chapter 6.

5.1 Coastal System Behaviour

Figure 5-1 presents a selection of plots showing modelled bed level changes extending to the nearshore zone of the Delfland coast, between Hoek of Holland (located at 0 km) and Scheveningen harbour (at ~16.5 km). This provides a visual comparison of the typical erosion (blue) and sedimentation (red) patterns in the study area. On the left side (a-c), snapshots at 10-, 20- and 30-year time intervals are shown for the no SLR scenario (i.e. reference case). The right side (d-f) shows snapshots for three of the simluated SLR scenarios, all at the 20-year time interval.

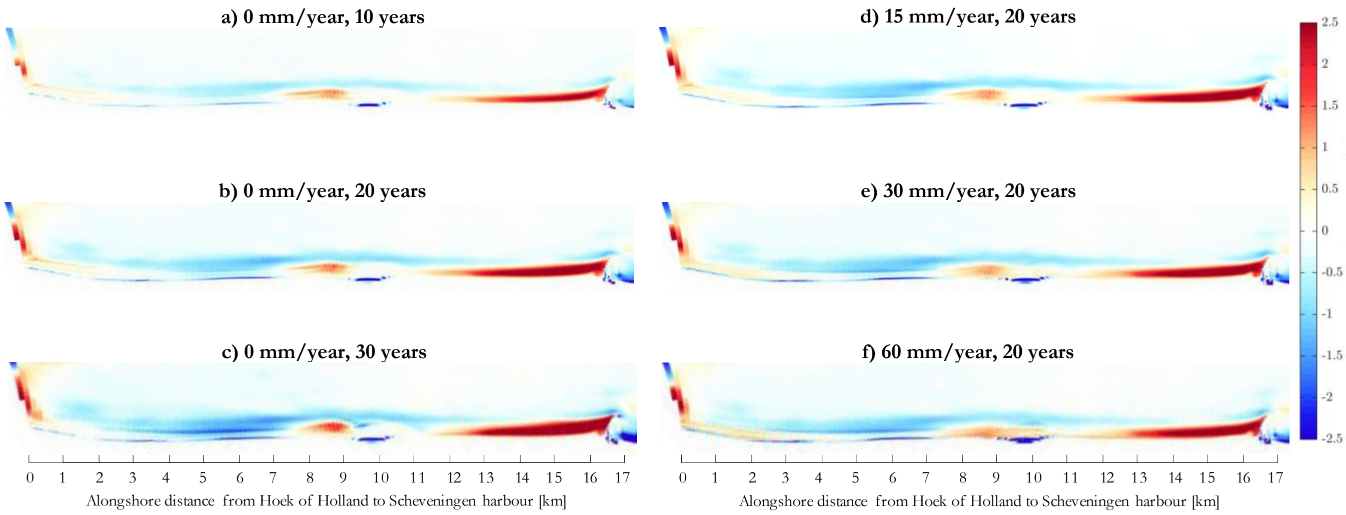


Figure 5-1: Computed bed level changes: no SLR scenario over time (left), increasing SLR rates at the 20-year time interval (right).

From these model outputs, one can generally see that erosion is common in the south, closest to Hoek of Holland, and increases in magnitude with distance from 0 km up to approximately 7 km alongshore where the shaded areas are darker blue. Accretion occurs in the northern section of the Delfland coast, with sediments accumulating just south of the harbour mole at Scheveningen, as is evident from the dark red shading. Some accretion is also seen at 0 km, this is alongside the long groyne at the entrance of the Port of Rotterdam. For context, these structures are indicated in yellow in Figure 5-2 below.

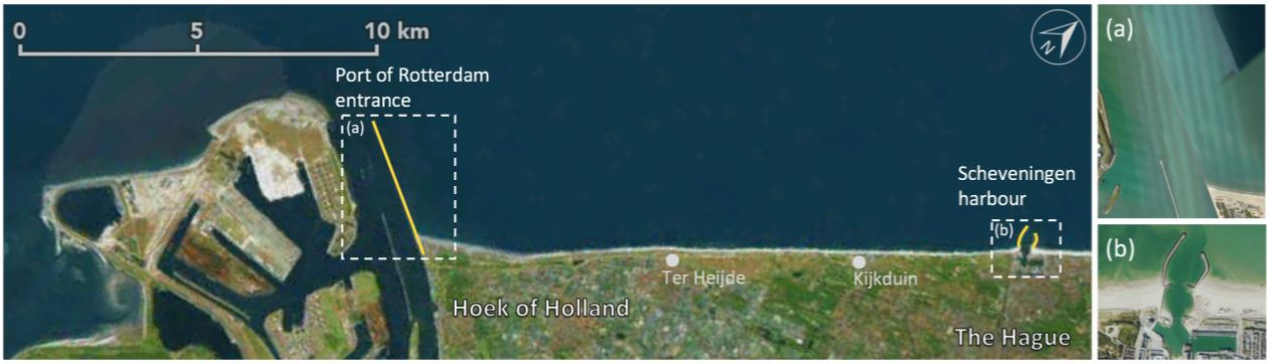


Figure 5-2: Study area showing position of harbour structures (Adapted from © 2012-2015 Apple Inc.)

Referring back to Section 2.1.3 and Section 3.3, due to the presence of structures blocking the LST process, LST is zero at the Hoek of Holland domain boundary (see Figure 3-3). The transport gradient increases in the southern section nearest to Hoek of Holland (~ first 5 km), hence the significant erosion, until a more or less stable point is reached. Net sediment transport occurs in a northerly direction along the coast, and as the transport gradient decreases again, deposition of the eroded sand occurs towards the northern section of the coast. Sediments are ultimately trapped by the Scheveningen harbour mole, but some bypassing does occur.

In general, these results are in line with the expected natural dynamics of such a coastal system bounded by structures, taking into account the northerly directed LST at the Delfland coast. It is also known that locations near Ter Heijde and Kijkduin are considered weak links (refer to Section 3.5.2); this may be represented by the significant erosion visible at 7 km and near 9-10 km respectively. The sedimentation behaviour between 8-9 km is less expected, however bed level changes here are relatively small in magnitude, and as such are not considered a major issue in the reliability of the model results as a whole. This local effect could be caused by the curvilinear grid at this region which is the same area as where the Sand Engine is located in the original calibrated model.

Comparing the erosion and sedimentation patterns over time, i.e. left side of Figure 5-1 (a-c), differences can be seen, with erosion and accretion increasing in area and magnitude in the time from 10 to 30 years. On the other hand, differences between the plots for varying SLR rates at the same time interval, i.e. right side of Figure 5-1 (d-f), are not as easily distinguishable. Therefore, the model outputs indicate that varying SLR rates have subtle effects on the overall morphodynamics of the coastal system, with no visual indication (at this scale) of major changes to the natural dynamics, or what can be considered the 'normal' coastal evolution of the Delfland coast, assuming no nourishments take place.

For a more detalied account of morphodynamic changes under the different SLR scenarios, further analysis focuses on the magnitude of sediment volume changes and differences relative to the reference case which represents a no SLR scenario.

5.2 Method of Analysis

The morphodynamics of the sandy beach can be explained in temporal and spatial terms by examining the impact of the variable rates of SLR on erosion over time and within different regions (i.e. control areas) in the nearshore zone. With SLR, it is expected that erosion volumes will increase (refer to Section 2.2.2). The extent of this hypothesis, and the effect under increasing rates of SLR (representing an acceleration in SLR), is analysed in the subseqent sections. First the method to calculate the sediment volume changes is explained below.

Figure 5-3 shows a schematic diagram of bed level changes to a beach profile under no SLR (dotted line) compared to with SLR (dashed line). With significant SLR, water levels and waves can reach the higher dunes. Wave attack occuring higher up in the shoreface profile, where the water level did not reach before, causes more erosion. The shaded area indicates the potential additional erosion volume due to SLR which is of interest in the analysis.

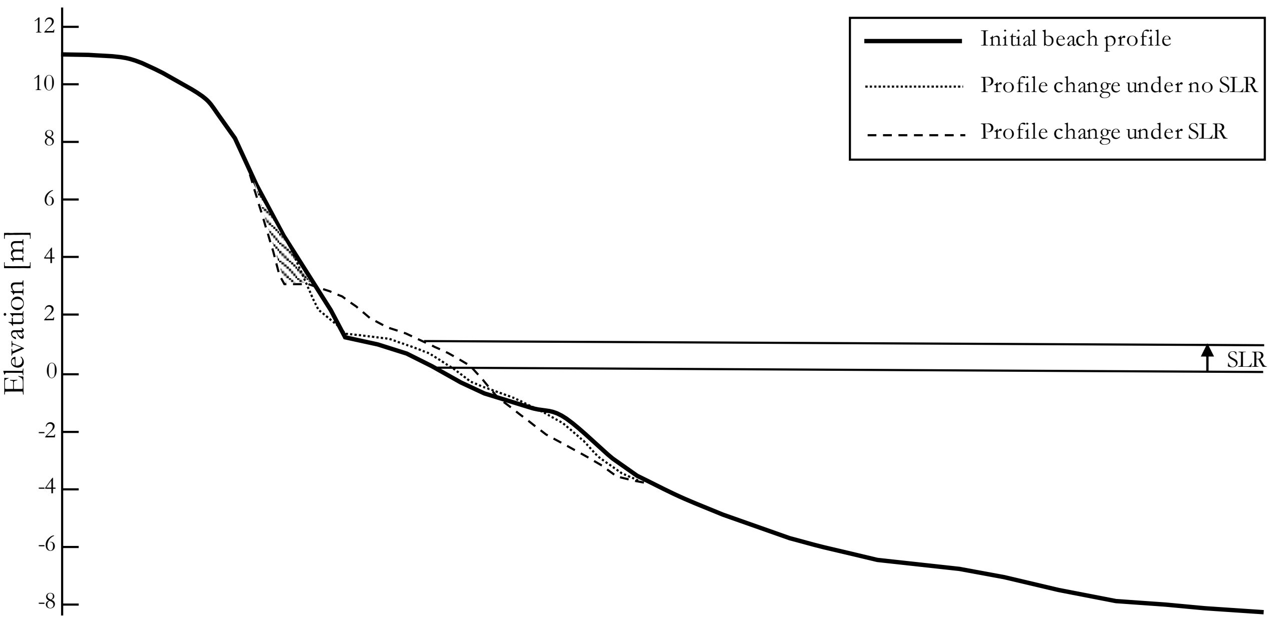


Figure 5-3: Schematic diagram showing beach profile changes and additional erosion due to SLR

Bed elevation changes are multiplied by the surface area (on a cell-by-cell basis), and summed to derive the cumulative volume change in each year. Erosion is defined as the negative volume, accretion as positive. This is presented in the equations below and diagrammatically shown in Figure 5-4.

$$Depth\ change = Bed\ level_{new} - Bed\ level_{initial} \quad [3]$$

$$Total\ volume\ change = \sum[(Depth\ change) \cdot (Surface\ area)] \quad [4]$$

for depth change < 0 → Erosion volume
for depth change > 0 → Accretion volume

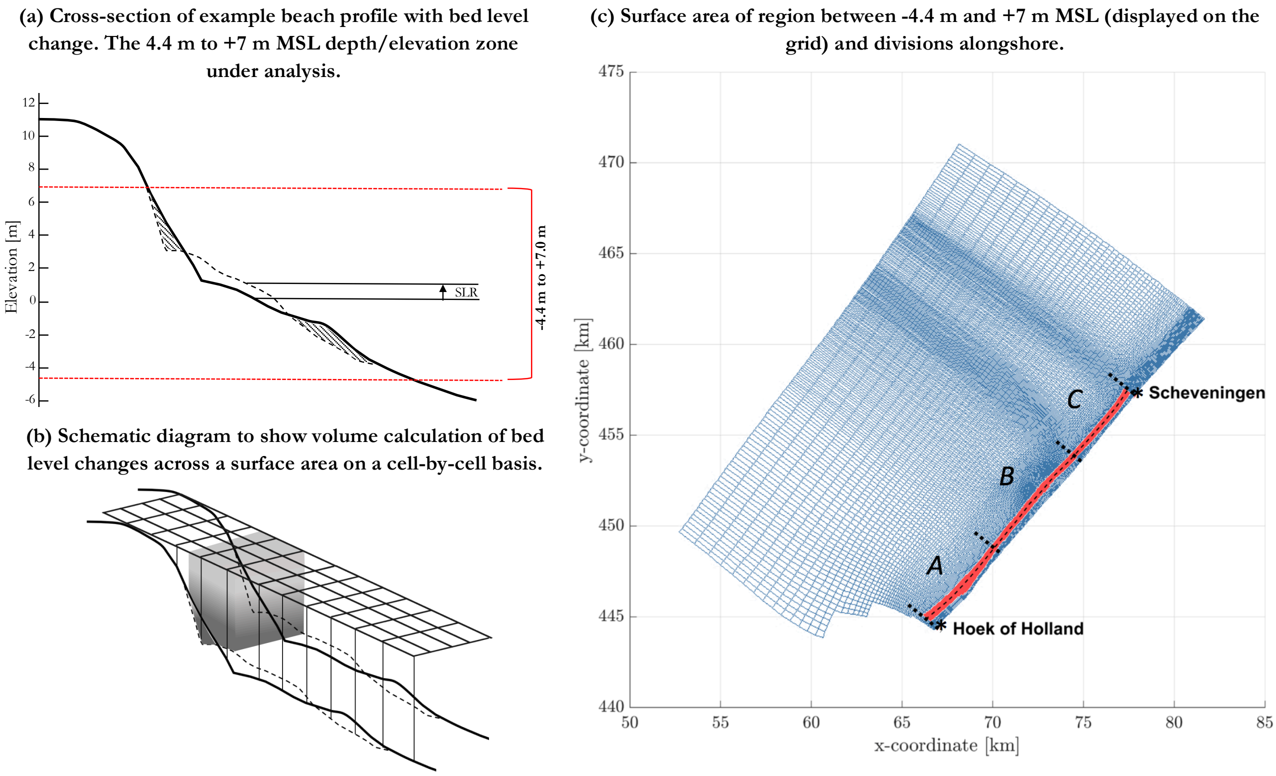


Figure 5-4: Calculation of volume changes

Figure 5-4 (a) shows two horizontal planes, -4.4 m MSL and +7 m MSL, between which bed level changes were considered. The coloured red region in Figure 5-4 (c) represents the grid cells lying between these contours over which the volume changes were calculated; for the entire length of the Delfland coast (~16.5 km), this region has a surface area of approximately 7.64 km^2.
To facilitate a more detailed analysis, the study area was also subdivided into 3 sections alongshore, as indicated in Figure 5-4 (c): section A (length ~5 km), section B (length ~6.7 km) and section C (length ~4.8 km).

The -4.4/+7 m MSL depth/elevation zone represents the subtidal, beach and dune region. Volume changes within two other depth/elevation zones were also calculated as follows:

- -1 m to +7 m MSL: Represents the cross-shore region extending from the intertidal zone (i.e. foreshore) up to the dunes, and
- -4.4 m to +3 m MSL: Equal to the MCL-zone extending up to the dune foot (see section 3.5.1).

Due to the fact that Delft3D lacks the ability to perform reliable morphological results in the lower shoreface, only the upper shoreface with a seaward boundary of less than a depth of 5 m MSL was considered in all depth/elevation zones.

For all depth/elevation zones and beach sections alongshore, volume changes were primarily calculated at 5-yearly intervals over the 30-year simulation period. Intervals of approximately 5 years are assumed representative of the longer-term fluctuations.

5.3 Erosion Volumes

In the following subsections, the findings of the erosion volume change results are presented. Focus is given to results pertaining to the depth/elevation zone which includes the dune area, i.e. the subtidal and dune region (-4.4 m to +7 m MSL zone), and the intertidal and dune region (-1 m to +7 m MSL), with supplementary results for each attached in Appendix C1 and C2 respectively. Where applicable, reference is made to the results calculated for the MCL-zone (-4.4. m to +3 m MSL); results thereof are attached in Appendix C3.

5.3.1 Temporal behaviour of erosion for the full Delfland coast

For each of the six simulations, the erosional volume changes were calculated, as described in Section 5.2, for each timestep (i.e. 300) over the simulated 30-year time period, providing results for approximately every month. Figure 5-5 graphically presents these cumulative erosion volumes (in 1000 m^3) for the subtidal and dune region, i.e. -4.4 m to +7 m MSL, across the entire Delfland coast (length ~16.5 m, area of 7.64 km^2). Due to unreliable results being obtained in the last simulation year, most likely caused by imperfect boundary conditions, volume changes are plotted only up to 28 years. Instabilities in the model also occurred during the 120 mm/year simulation run, hence the shorter time series showing volume changes up to almost 23 years.

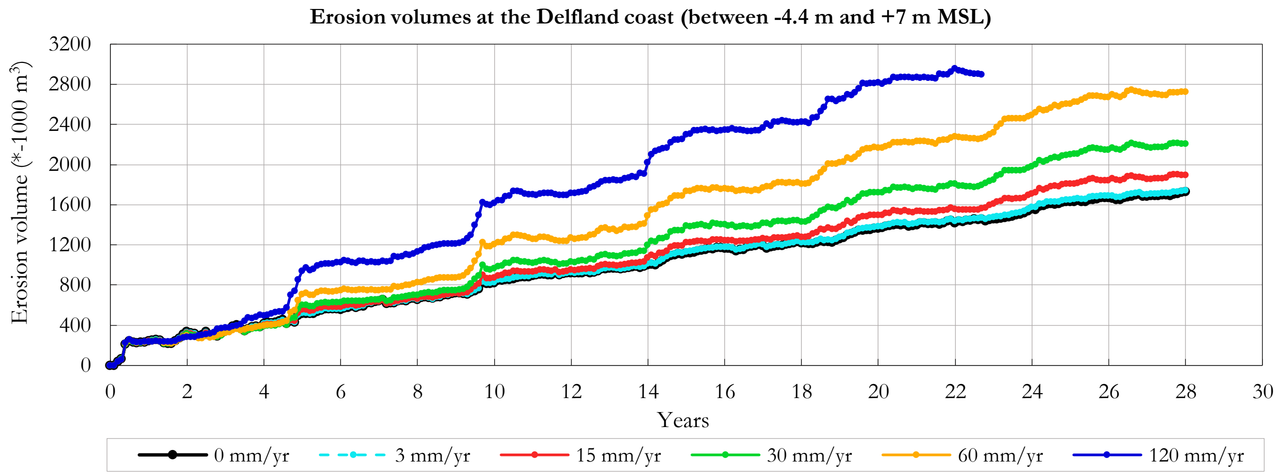


Figure 5-5: Cumulative erosion volumes plotted per timestep for each SLR scenario at the Delfland coast (between -4.4 m and +7 m MSL)

From Figure 5-5, it is seen that the two highest SLR scenarios (extreme cases of 60 and 120 mm/year, depicted by the yellow and blue lines respectively) show the largest deviation from the erosion trend of the no SLR scenario (i.e. rate of 0 mm/year, represented by the black line). Results from the 3 mm/year scenario (turquoise dashed line) is more or less identical to that of the no SLR scenario. A jump in erosion volumes, approximately every 4-5 years, is also visible for the two highest SLR scenarios. This likely corresponds to the occurrence of the highest wave condition in the wave input time series (see Figure 4-3).

For analysis purposes, the above plot is simplified to show only cumulative erosion volumes every 5 consecutive years, with the exception of the last timestep which is taken at 28 years instead of at 30 years. This is shown in Figure 5-6, with corresponding values (rounded to the nearest 10 000 m^3) tabulated in Table 5-1.

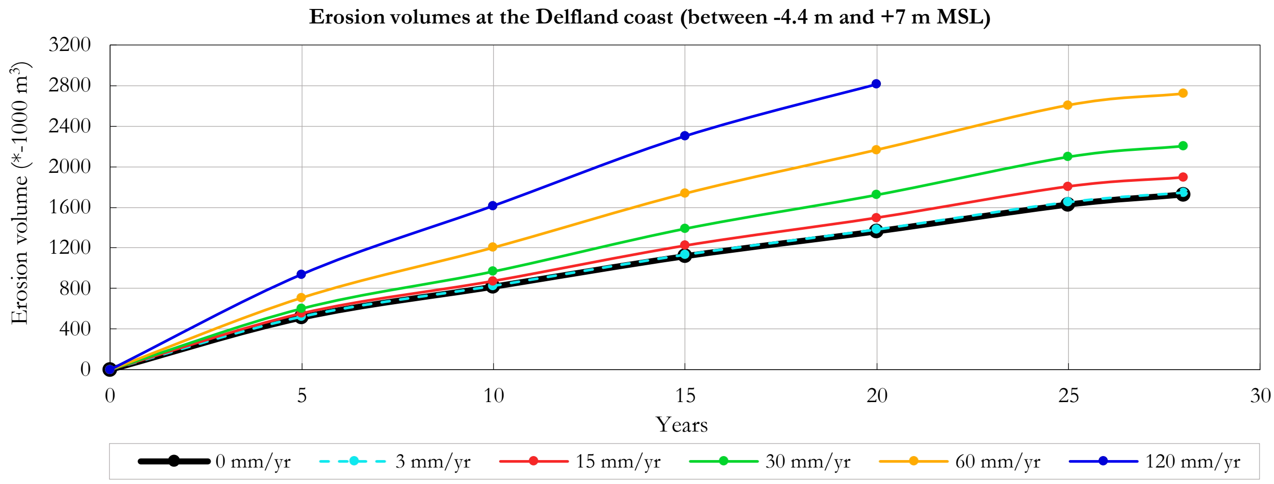


Figure 5-6: Change in erosion volumes over time for increasing SLR rates at the Delfland coast (between -4.4 m and +7 m MSL)

Table 5-1: Aggregated erosion volumes (in m³) over time for increasing SLR rates at the Delfland coast (between -4.4 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	-510 000	-520 000	-560 000	-600 000	-710 000	-940 000
10	-820 000	-830 000	-870 000	-970 000	-1 200 000	-1 620 000
15	-1 120 000	-1 130 000	-1 220 000	-1 390 000	-1 740 000	-2 300 000
20	-1 360 000	-1 380 000	-1 500 000	-1 720 000	-2 170 000	-2 810 000
25	-1 630 000	-1 650 000	-1 810 000	-2 100 000	-2 610 000	
28	-1 730 000	-1 750 000	-1 900 000	-2 200 000	-2 720 000	

Figure 5-6 shows that for the no SLR scenario, cumulative erosion increases over time, but the erosion rate (per 5-year period) decreases over time, at least up to 20 years. This is to be expected as the morphology and beach profile shape adjusts over time. All other scenarios follow a similar trend, with a slight flattening of the curves visible towards the end of the simulation period, but prior to that, the steeper slopes represent an increase in erosion rates. In terms of the magnitude of erosion, the 3 mm/year scenario is almost no different from the no SLR scenario, as indicated by the overlapping turquoise and black lines, and differences between the two ranging from 10 000 – 20 000 m³ (refer to Table 5-1). Relative differences are also small for the 15 mm/year scenario compared to the no SLR scenario, increasing however to the order of 100 000 m³ from 15 years. This relative difference is already reached after just more than 5 years for the 30 mm/year scenario. For the higher rates of SLR, bigger deviations from the no SLR scenario occurs, with larger increases in erosion volume already in the initial years, as indicated by the steeper slopes present for the 60 and 120 mm/year scenarios.

A relative difference in the order of magnitude of 1 million m³ is reached at the end of the simulation for the 60 mm/year scenario, and already before 15 years for the 120 mm/year scenario. Furthermore, the approximate amount of erosion that occurs over 28 years (without nourishments) assuming no SLR (or 3 mm/year) is reached after 20 years for a 30 mm/year case, and 15 years or less for the 60 mm/year and 120 mm/year scenarios respectively.

5.3.2 *Spatial similarities and differences*

Here below, a more detailed analysis is executed than the one of aggregated erosion volumes over the entire Delfland coast (Section 5.3.1). Following the division of the coast into three sections alongshore as shown in Figure 5-4 (c) and described below, the cumulative erosion volumes from Table 5-1 are recalculated for each of the three sections; refer to the tables attached in Appendix C1.

Section A represents the southern coastal section from Hoek of Holland to approximately 5 km alongshore (refer to Figure 5-2); between the horizontal planes -4.4 m to +7 m MSL, this covers a surface area of 2.74 km². Section B is the central section, from 5 km to approximately 11.7 km, with a surface area of 2.91 km². Section C is the northern section of the coast, from 11.7 km up to Scheveningen harbour (at ~16.5 km), with a surface area of 1.99 km².

Most of the erosion occurs in the southern and central beach stretches (sections A and B); the addition of the erosion volumes in these sections (see tabulated results in Appendix C1) approximately equal to the aggregated values in Table 5-1 calculated for the entire Delfland coast. On the other hand, the northern section (i.e. section C) experiences relatively minimal erosion, if any it can be assumed negligible. This is in line with the erosion and sedimentation plots shown in Figure 5-1, where the northern section is mainly subject to sediments accumulating south of the Scheveningen harbour mole.

Results are plotted for section A, B and C, in Figure 5-7, Figure 5-8, Figure 5-9 respectively.

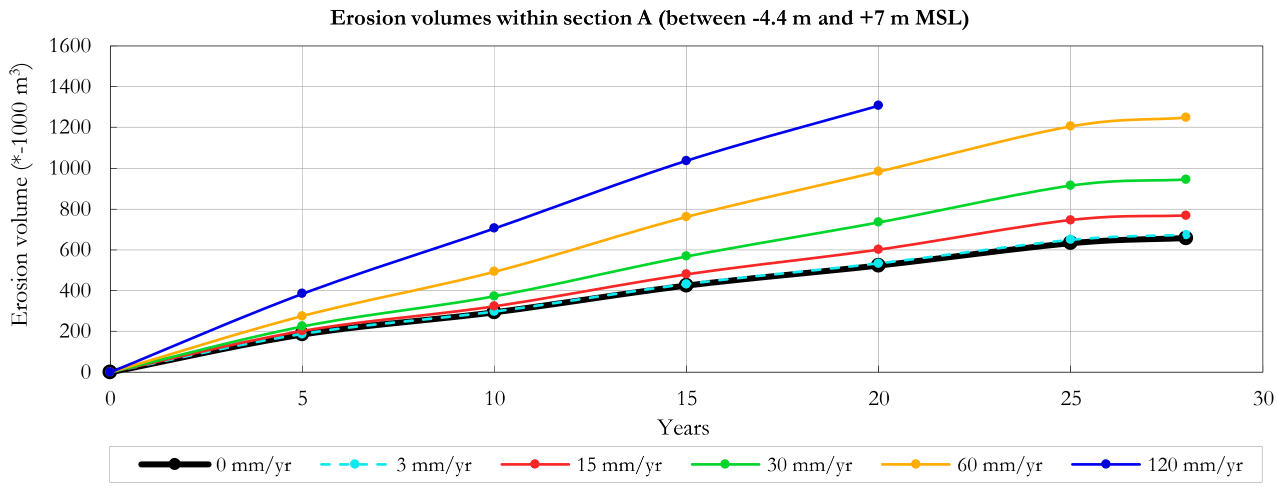


Figure 5-7: Change in erosion volumes over time for increasing SLR rates within the southern section, A (between - 4.4 m and +7 m MSL)

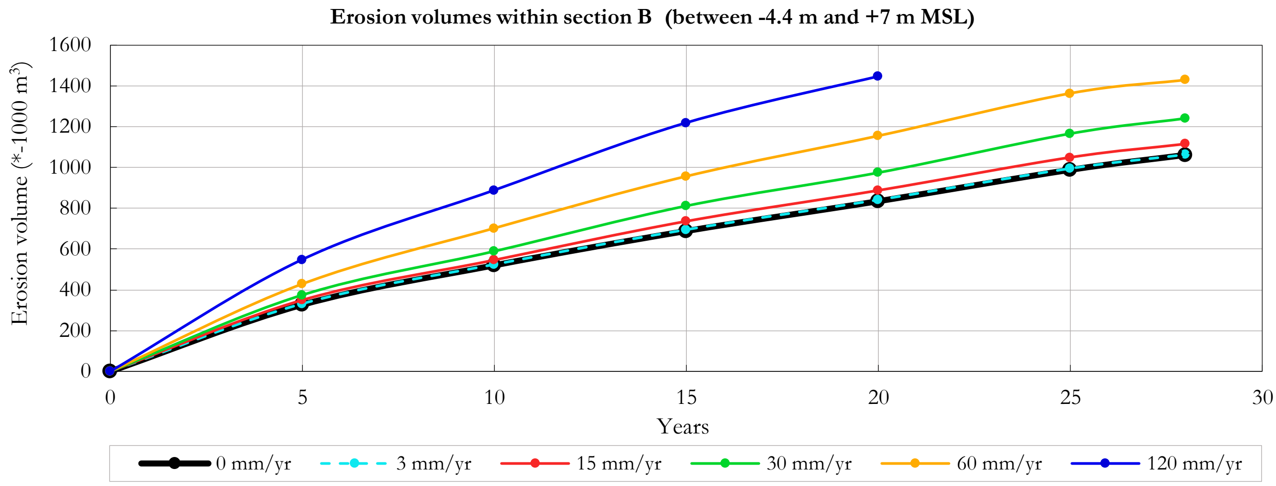


Figure 5-8: Change in erosion volumes over time for increasing SLR rates within the central section, B (between - 4.4 m and +7 m MSL)

Erosion in the southern and central sections of Delfland coast follow a similar/same trend as that of the aggregated volumes plotted in Figure 5-6. The key difference between section A (Figure 5-7) and B (Figure 5-8) within the -4.4 m to +7 m MSL zone, is that B (central section) experiences more erosion, also for the no SLR scenario. The steeper slopes present for all scenarios in Figure 5-8 indicate this, whereas the increase in erosion for the reference case in Figure 5-7 is more gradual. By comparing these two graphs to those of section A and B within the MCL-zone (refer to Appendix C3), the additional erosion in section B can be interpreted predominantly as more dune erosion. This is because in the lower coastal profile, between -4.4 m and +3 m MSL, the erosion volumes for the reference case calculated in sections A and B are more similar, almost equal in magnitude. Upon close inspection, the erosion in Section B (Figure 5-8) tends to decrease over time, with curves more or less flattening up to 20 years. Steeper slopes plotted in section A, show a rather increasing trend in erosion.

In the northern section (C), magnitudes of calculated erosion volumes are two to three orders of magnitude smaller than that in sections A and B. Erosion in section C can therefore generally be neglected, but is nevertheless shown in Figure 5-9 (the y-axis is kept the same as previously for comparative reasons).

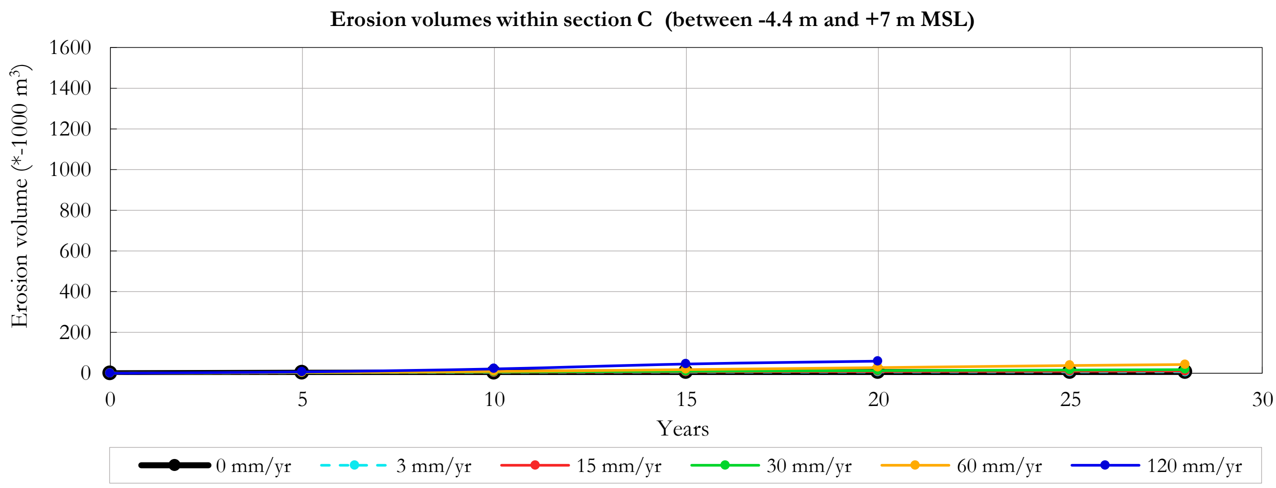


Figure 5-9: Change in erosion volumes over time for increasing SLR rates within the northern section, C (between - 4.4 m and +7 m MSL)

5.3.3 Erosion volume relative to no SLR scenario (%) – for - 4.4 m and +7 m MSL

The graphs presented in Section 5.3.2 can also be analysed in terms of the difference in erosion volume relative to the reference case, i.e. no SLR scenario. Tabulated results are attached in Appendix C1 for the -4.4 m to +7 m MSL zone, with corresponding graphs shown for beach sections A and B in Figure 5-10 and Figure 5-11 respectively, and discussed there below.

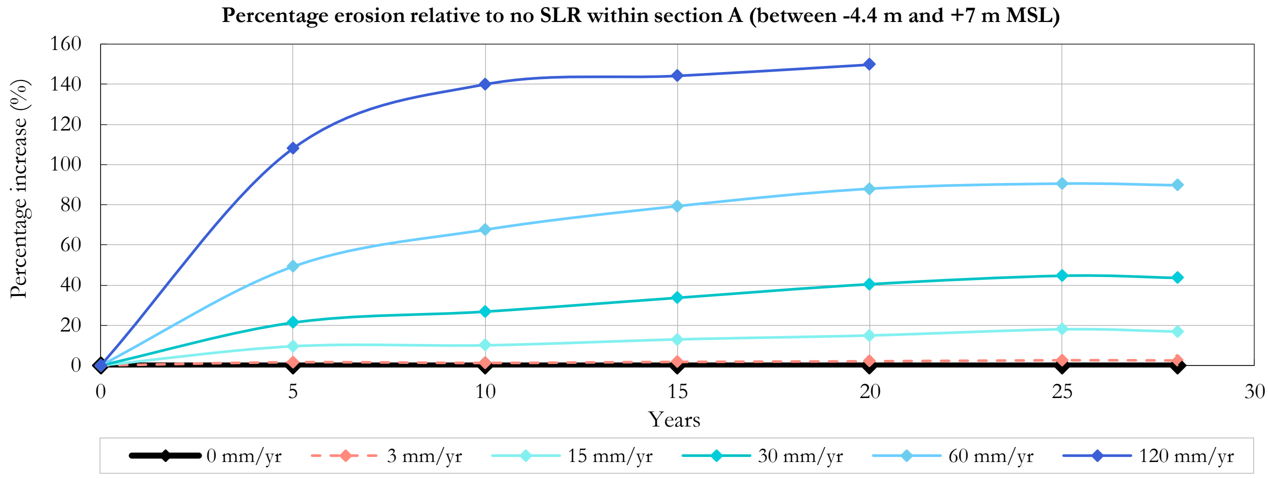


Figure 5-10: Erosion relative to no SLR (%) for increasing SLR rates within the southern section, A (between -4.4 m and +7 m MSL)

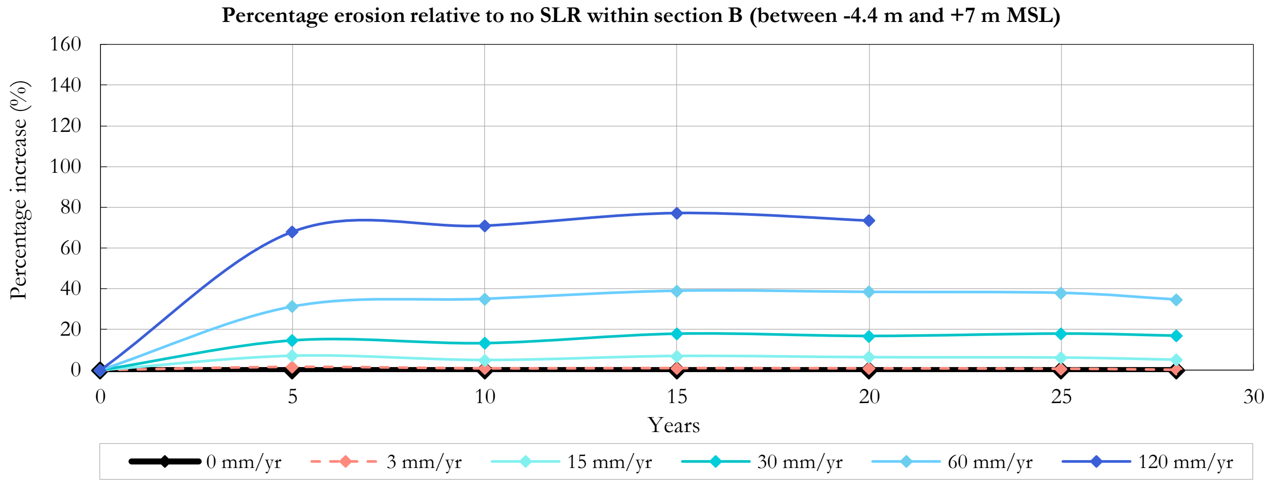


Figure 5-11: Erosion relative to no SLR (%) for increasing SLR rates within the central section, B (between -4.4 m and +7 m MSL)

Plotted against the same y-axis (% increase relative to the reference case), Figure 5-10 shows percentages approximately double in value to that in Figure 5-11 for each SLR scenario. This means that in the southern beach section (A), the amount of erosion that is caused by the different SLR rates is almost double compared to that in the central section (B). The lower percentage differences for section B can be explained with reference to its corresponding erosion plot in Figure 5-8. Due to the erosion volume also significantly increasing for the no SLR scenario in the central beach section (B), but the varying SLR rates having similar impacts on the total magnitude of erosion within both sections A and B, the percentage increase is not as significant as it is in section A. Therefore, it can be understood that SLR has a greater impact on erosion in section A. This can be attributed to the significant transport gradient in the southern beach section of the Delfland coast, discussed in more detail in Chapter 6.

Furthermore, in section A, trends are increasing up to 25 years for all SLR rates. Whereas in section B, the percentage differences tend to stabilize or remain constant after 10 years, meaning that additional erosion over time remains constant relative to the increase in erosion for the no SLR scenario. In other words, higher SLR rates does indeed increase the amount of erosion compared to the reference case, but over time this relative difference becomes approximately constant, not additionally increasing over time as well, like in Section A. This is also addressed in Chapter 6.

5.3.4 Erosion volume relative to no SLR scenario (%) – for - 1 m and +7 m MSL

Analysing the results calculated within the -1 to +7 m MSL zone, i.e. excluding the subtidal region, the percentage difference graphs provide slightly different trends. Interesting to note is that the results are more or less the same for the first 5 years for both the southern section (Figure 5-12) and central section (Figure 5-13). Thereafter, in the southern section (A), the increasing trend in erosion between 10 and 20 years is more pronounced for the highest SLR rate of 120 mm/year than it is in Figure 5-10. The overall trend in Figure 5-13 for section B, remains somewhat constant (and 120 mm/year decreases), similar to that in Figure 5-11.

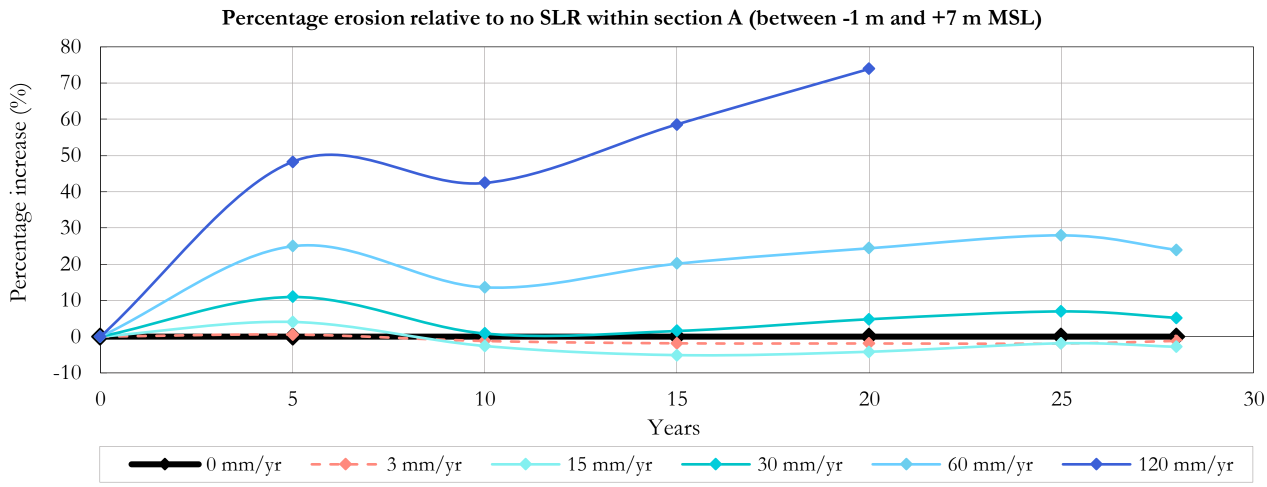


Figure 5-12: Erosion relative to no SLR (%) for increasing SLR rates within the southern section, A (between -1 m and +7 m MSL)

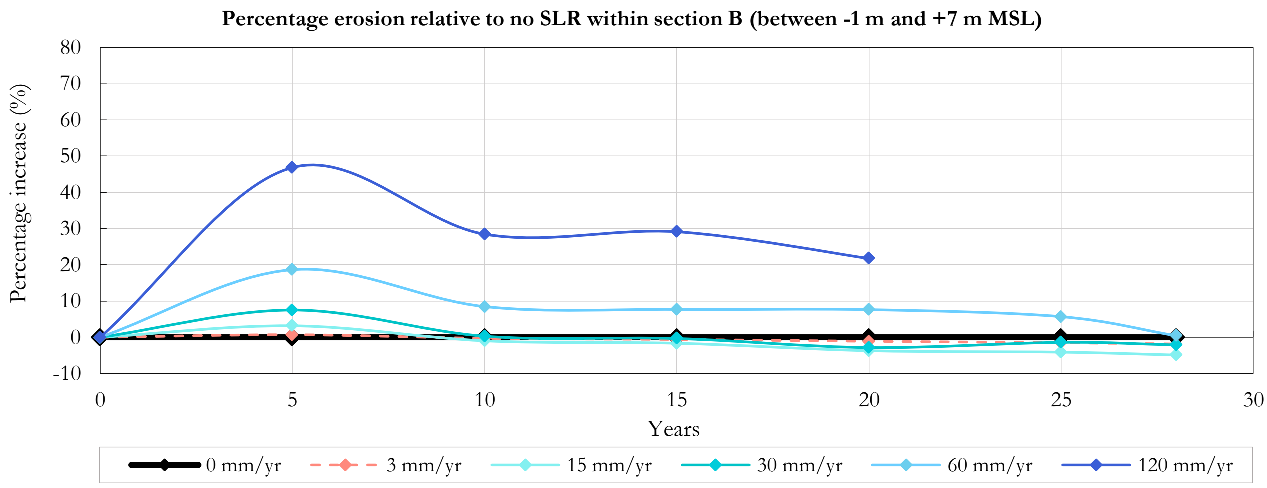


Figure 5-13: Erosion relative to no SLR (%) for increasing SLR rates within the central section, B (between -1 m and +7 m MSL)

The smaller percentage increases within the -1 m to +7 m MSL zone, i.e. more than half of that in the - 4.4 m to +7 m MSL zone, (especially for section A, compare Figure 5-10 and Figure 5-12), indicate that SLR may have a more significant impact on the subtidal region. This is discussed in Chapter 6.

5.3.5 Erosion volume relative to no SLR scenario (%) – northern beach section (C)

Although it has been analysed that erosion volumes in the northern section (C) can be neglected due to the smaller magnitudes of erosion in comparison to that in the other two beach sections, the percentage difference graphs lead to other observations. This is shown in Figure 5-14 and Figure 5-15 for the different depth/elevation zones as titled.

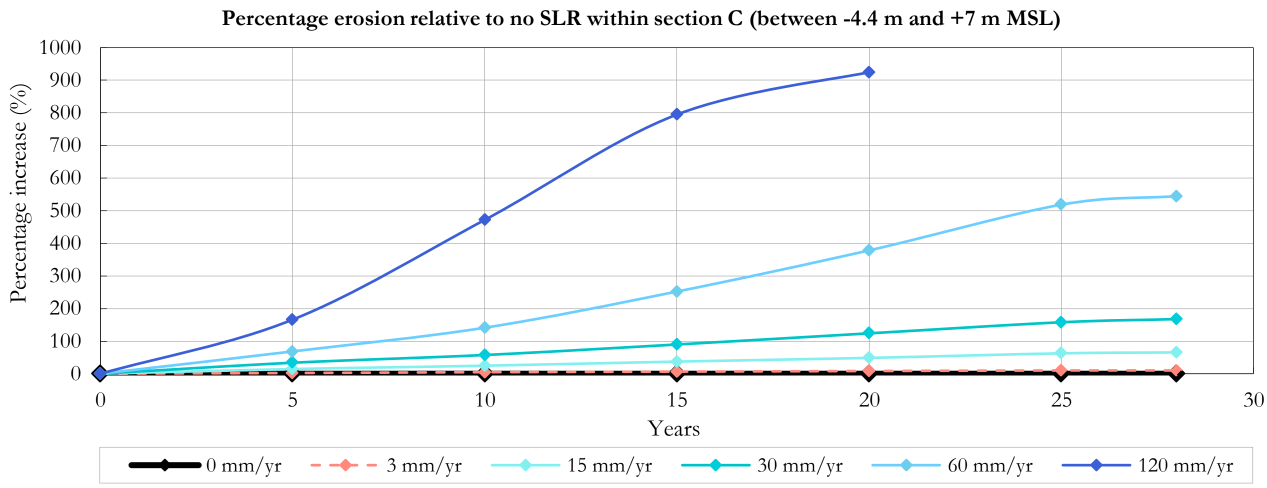


Figure 5-14: Erosion relative to no SLR (%) for increasing SLR rates within the northern section, C (between -4.4 m and +7 m MSL)

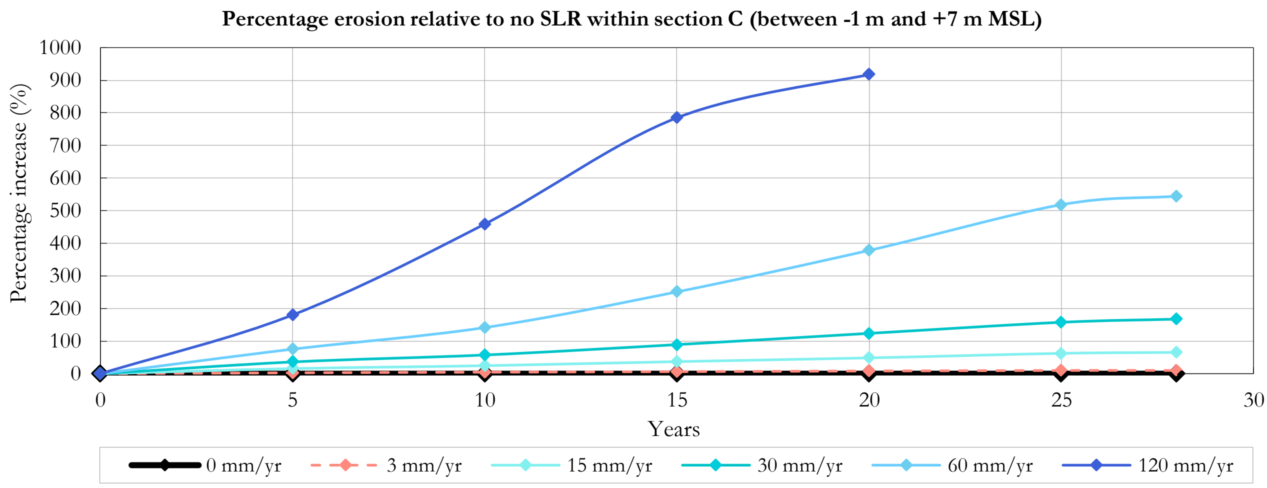


Figure 5-15: Erosion relative to no SLR (%) for increasing SLR rates within the northern section, C (between -1 m and +7 m MSL)

Firstly, percentage results in the two zones are more or less identical (refer to the Section C tables in Appendix C1 and C2 for specific percentage values), leading to the conclusion that the small amount of erosion that does occur in the northern part of Delfland coast is within the upper coastal profile or dune region, not in the subtidal zone, i.e. not below -1 m MSL. Next, the percentage difference values extend up to values between maximums of 500 to 900% for the 60 and 120 mm/year scenarios respectively. A 100% is reached after 15 years for the 30 mm/year SLR rate, and already between 5 to 10 years for the 60 mm/year SLR rate.

From these two graphs, it can be interpreted that higher SLR rates will cause a relatively large impact on dune erosion in the northern section, despite the magnitude of erosion here being much smaller in comparison to the rest of the Delfland coast.

5.4 Accretion volumes

A look at accretion volumes, calculated for the entire Delfland coast (refer to Appendix D1, D2 and D3 for results of the three different depth/elevation zones), shows that in general, the higher the SLR rate, the greater the accretion volume as well.

A comparison between results from the -4.4 m to +7 m MSL zone (Appendix D1) and the -4.4 m to +3 m MSL zone (Appendix D3), shows almost identical results. This is logical as any eroded material from the dunes would most likely be deposited below the dune foot at + 3 m MSL.
In the -1 m to +7 m MSL zone (Appendix D2), the accretion volume for the no SLR scenario (and 3 mm/year) remains constant after 5 years, i.e. no additional accretion over time. Hence for no or minimal SLR, most of the accretion occurs below -1 m MSL in the subtidal region. For the higher SLR rates, steep increases in accretion are seen. The corresponding percentage difference graph for the -1 m to +7 m MSL zone shows a relative increase up to almost 250% for the highest SLR rate at 20 years. In part, this is due to the additional erosion of dunes at higher elevations; material will also be deposited higher up in the beach profile.

5.5 Alongshore distribution of volume change

The erosion and accretion volumes were also adjusted to values per metre alongshore, examples are shown in Figure 5-16 and Figure 5-17 (for each: accretion on top, erosion below). This allows for an alternative method of analysis in both space and time. Spatially, these graphs closely resemble the erosion and sedimentation plots seen in Figure 5-1, but aggregated for all SLR scenarios at the 20 year time interval. The various beach sections can be described as follows based on this visual aid:

- An erosive section in the first 5 km (i.e. southern section, A), with erosion volumes increasing alongshore (see large erosion volumes in particular for the -4.4 m to +7 m MSL zone, Figure 5-16).
- A more or less stable section in the middle (central section, B) with both erosion and accretion. Significant erosion continues up to approximtaley 7 km and a weak link is present at 9-10 km. However, results between 8-10 km may be sensitive to the curvilinear grid as previously mentioned.
- An accretive section south of the Scheveningen harbor (northern Delfland section, C), where erosion can be neglected. Sediment accumulates updrift of the harbour mole which partially blocks the LST.

The impact of varying SLR rates are visible from the difference in magnitude of volume change ($m^3/m/year$) between the respective coloured lines and the black line representing the no SLR scenario, most notably for the erosion occurring up to 7 km. In the -1 m to +7 m MSL zone (Figure 5-17), a significant difference in accretion volumes for the higher SLR rates is noticed, in particular in section C. This might relate to the high percentage increases for accretion volumes, first indicated in Section 5.4 above. As erosion in this beach stretch can be considered mostly negligible, the significant accretion is interpreted as sediments being transported alongshore and deposited here (due to the decreasing LST gradient), rather than cross-shore movement of sediments from dune erosion. This gives an indication that with higher SLR rates, and hence greater water levels nearer to the shore, alongshore sediment transport and deposition could occur higher up in the beach profile.

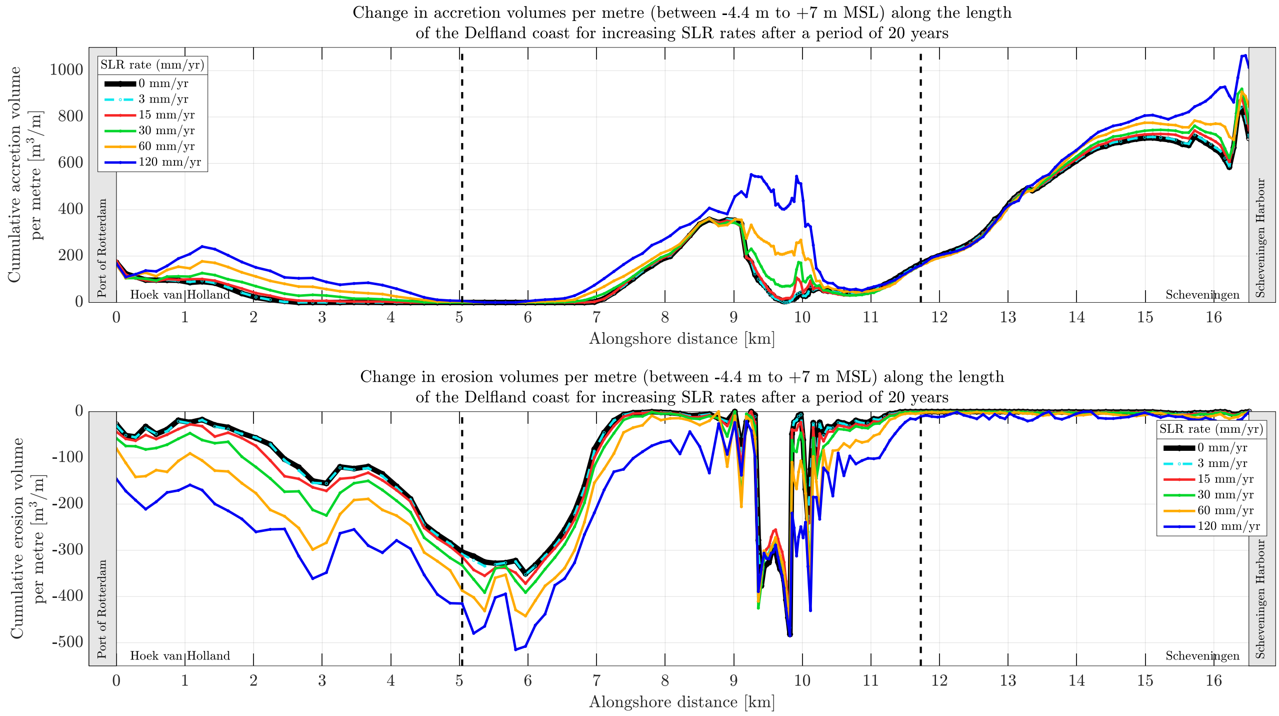


Figure 5-16: Alongshore distribution of volume change (m^3/m/year) at 20 years, between -4.4 m and +7 m MSL

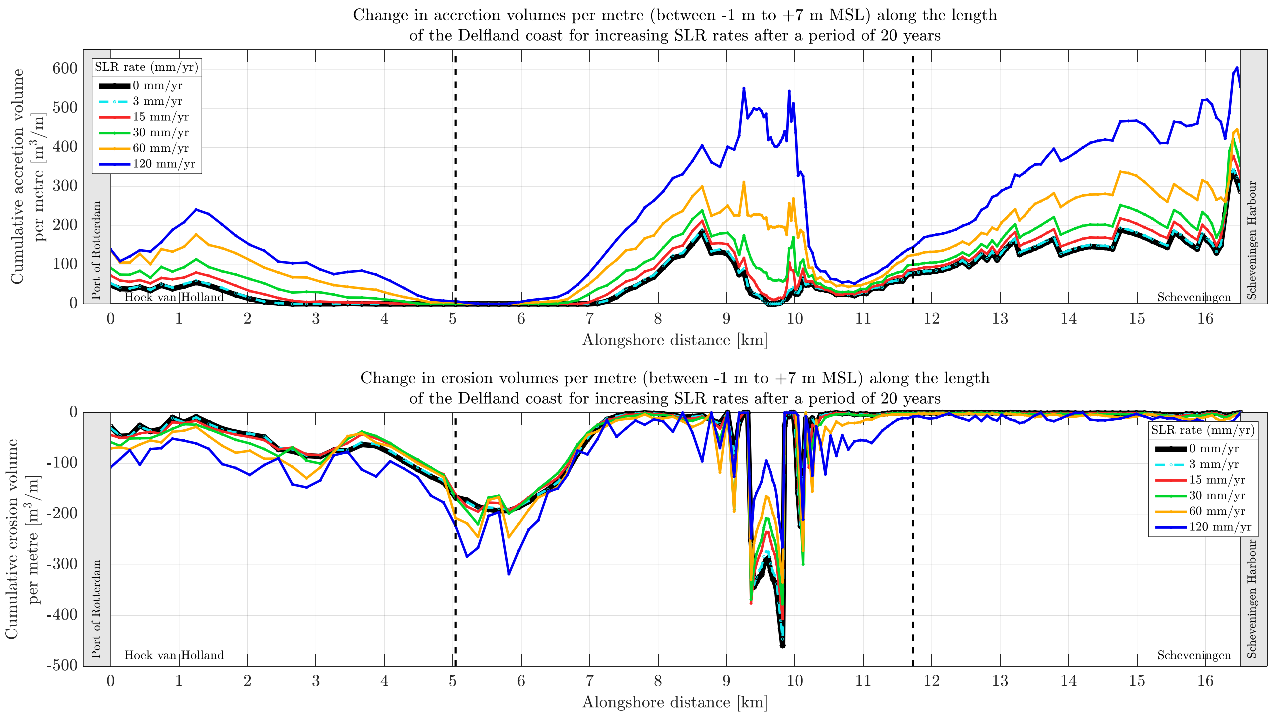


Figure 5-17: Alongshore distribution of volume change (m^3/m/year) at 20 years, between -1 m and +7 m MSL

6

DISCUSSION

This chapter provides further interpretation of the results presented in Chapter 5. A summary of the key findings and physical processes behind the observations and trends are given in Section 6.1. In Section 6.2, comments on the accuracy of the results are provided, based on previous studies. And in Section 6.3, important limitations of the modelling study are discussed. The chapter concludes with implications of the results in the broader context in Section 6.4.

6.1 Key Findings and Driving Processes

6.1.1 Summary of key findings

From the analysis of results in the previous chapter, it is evident that there are differences in both alongshore and cross-shore spatial behaviour of the coast due to SLR and its impact on erosion. The main findings can be summarised as follows:

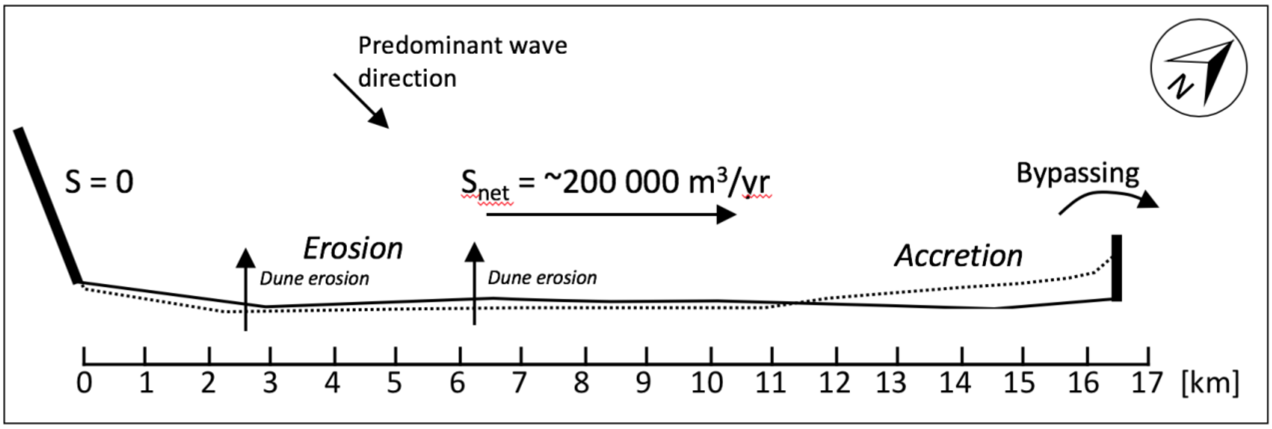
1) Erosion predominantly occurs in the southern and central beach sections, the same as for the no SLR scenario. Therefore, SLR has no major impact on the overall erosion and sedimentation patterns of the Delfland coast, i.e. erosive sections remain erosive, and the northern section remains accretive. However, sediment volume changes increase in magnitude due to SLR.
2) SLR has a larger impact on erosion volume changes in the southern beach section (A) nearest to Hoek of Holland than on the central section (B), particularly in the subtidal region.
3) The southern section (A) shows an increasing trend in erosion for increasing SLR rates compared to the central section (B) where relative differences become constant over time.

6.1.2 Reasons for changes in morphodynamic behaviour

The above findings are elaborated on below with the use of diagrams where applicable.

<u>Coastal System Behaviour, increase in erosion and accretion volumes:</u>

In terms of alongshore differences, erosion mainly occurs in the southern and central sections of the Delfland coast, whereas the northern section shows an accretive trend. This is due to the presence of the harbour moles at either boundary and gradients in LST (see description in 5.1), and is considered the normal evolution of the Delfland coast under present conditions, should no nourishments take place. Therefore, from the simulation results, it is assumed that accelerated SLR has no major influence on the overall system dynamics of the Delfland coast, but increases both the erosion and accretion volumes. Figure 6-1 shows a schematic diagram to summarize this. The steeper slopes presented in the erosion volume plots indicate that erosion rates increase with higher SLR rates, as suggested by Zhang (2004) (refer to Section 2.2.2).



* Note: the dotted line does not represent the coastline position

Figure 6-1: Alongshore coastal system behaviour of the Delfland coast

Reasons for the increased erosion is explained as follows: with higher sea levels, the water level and waves are able to reach areas more landward and eventually with large SLR the dunes as well, allowing waves to attack regions of higher elevation in the upper coastal profile. A larger part of the active coastal profile will be mobilized, thus increasing the erosion volume. This is in line with expected SLR impacts on sandy coasts as introduced in Section 2.2.2 and explained by de Winter & Ruessink (2017). Another reason linked to the increased beach and dune erosion could be because of a decrease in the available recovery time of the beach as a result of an increasing frequency of high water levels as a result of the accelerated rates of SLR.
In turn, the eroded material will be deposited in the shallow shoreface (before transported further offshore by cross-shore processes or alongshore), hence the Delft3D model shows additional accretion volumes (of redistributed sand) in the foreshore and upper surf zone.

With higher SLR rates and hence greater water levels, material eroded from the dunes may also be deposited higher up in the coastal profile, essentially the backshore region (refer to Section 5.4 and Figure 2-1 for the definition of coastal zones). This is schematically shown in Figure 6-2 for an example profile.

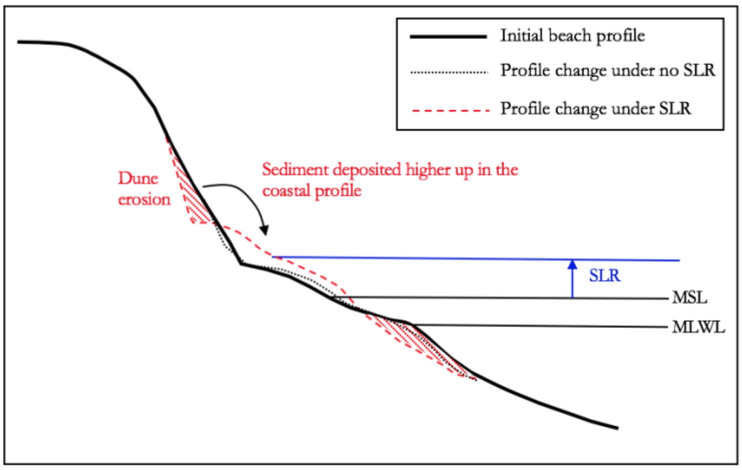
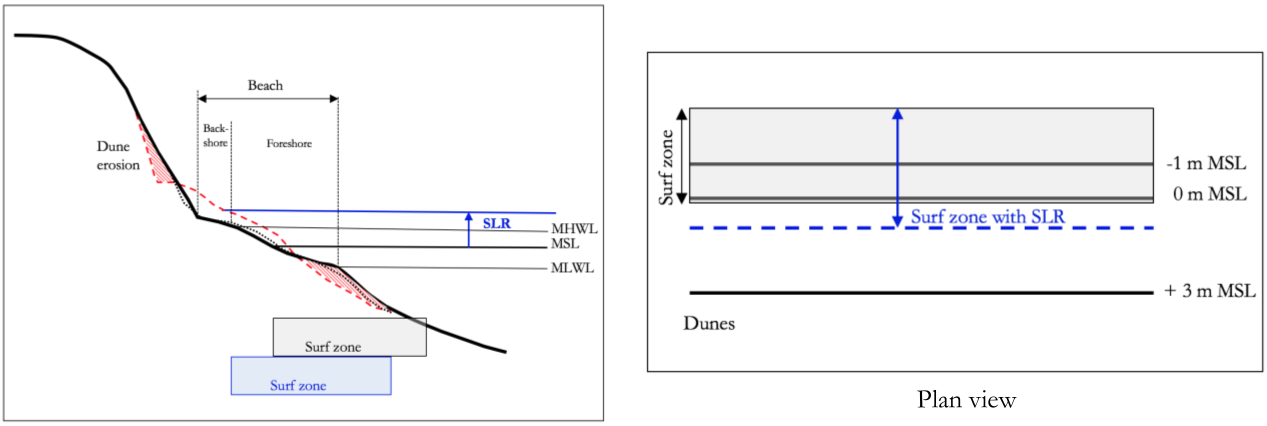


Figure 6-2: Cross-shore erosion and deposition due to SLR

<u>SLR has a larger impact on erosion volume changes in the southern beach section (A) than on the central section (B), particularly in the subtidal region:</u>

This alongshore difference is shown by the larger percentage changes in erosion volumes (relative to the no SLR scenario) for section A compared to in section B (see Figure 5-10 and Figure 5-11). The southern beach stretch is therefore more vulnerable to increasing rates of SLR in general, and particularly in the subtidal region (i.e. cross-shore difference, discussed in Section 5.3.4). Reasons for this is related to the increasing LST rates in the first ~5 km from Hoek of Holland as discussed in Section 3.3 (refer to Figure 3-3). The large gradient in LST from zero up to approximately 175 000 – 200 000 m^3/year induces erosion in this section. With larger water levels due to SLR, the region in which this sediment transport (littoral drift) occurs, i.e. the surf zone, could potentially shift more landward, and as such increases the amount of erosion. Figure 6-3 shows this in cross-shore and plan view.



Plan view

Cross-shore view

Figure 6-3: Landwards shift of the surf zone

Any eroded material from the upper beach zone or dune region is transported seaward, but once in the surf zone, the wave-driven long-shore currents pick up the sediments and move it in a northerly direction along the coast. Sediment from section A therefore does not remain in the foreshore or subtidal zone of section A, but is transported to section B and ultimately section C, where the material accumulates. Should a landwards shift of the surf zone occur, deposition in the northern coastal stretch (section C) will be affected as more sediment is blocked by the harbour mole at Scheveningen (refer to Section 5.4).

An alternative reason for the increased erosion in the subtidal zone of section A could be that the alongshore gradient in wave energy differs with increasing water level. Waves could start to refract differently with an increasing water depth.

<u>Dune erosion in section B and differing erosion trends:</u>

In the central section, more dune erosion occurs, even without SLR. This could be due to the steeper dunes present along the central section (B), compared to in section A, see Figure 6-4 below. Another reason could be larger wave impact experienced in this open beach stretch, whereas the southern section is somewhat sheltered from SW waves by the Maasvlakte 2 and the long groyne at Hoek of Holland.

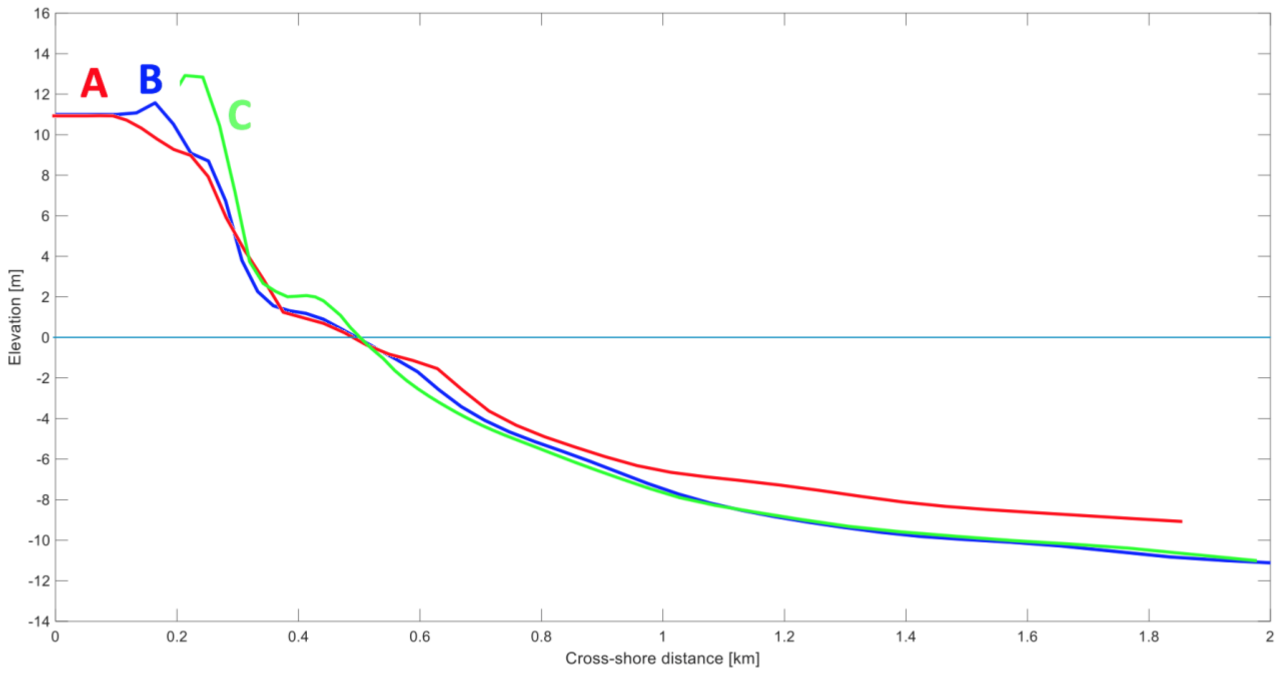


Figure 6-4: Representative profiles for each beach section along Delfland coast

Figure 5-11 showed a stabilizing trend in the amount of erosion over time relative to the no SLR scenario for section B. This is further investigated by calculating erosion volumes in an additional depth/elevation zone from -4.4 m to +10 m MSL, i.e. to the top of the dunes approximately. Figure 6-5 presents the results for section B, showing a different trend, one that also slightly increases, and more so for the highest 120 mm/year scenario. Hence, dune erosion higher than +7 m MSL occurs in the central section of Delfland, whereas for the same analysis in section A, results are identical to that of the -4.4 m to + 7 m MSL zone. This means that at the same increased water level, +7 m MSL is the maximum elevation at which the dunes in section A are eroded, whereas in section B, dune erosion occurs higher than that.

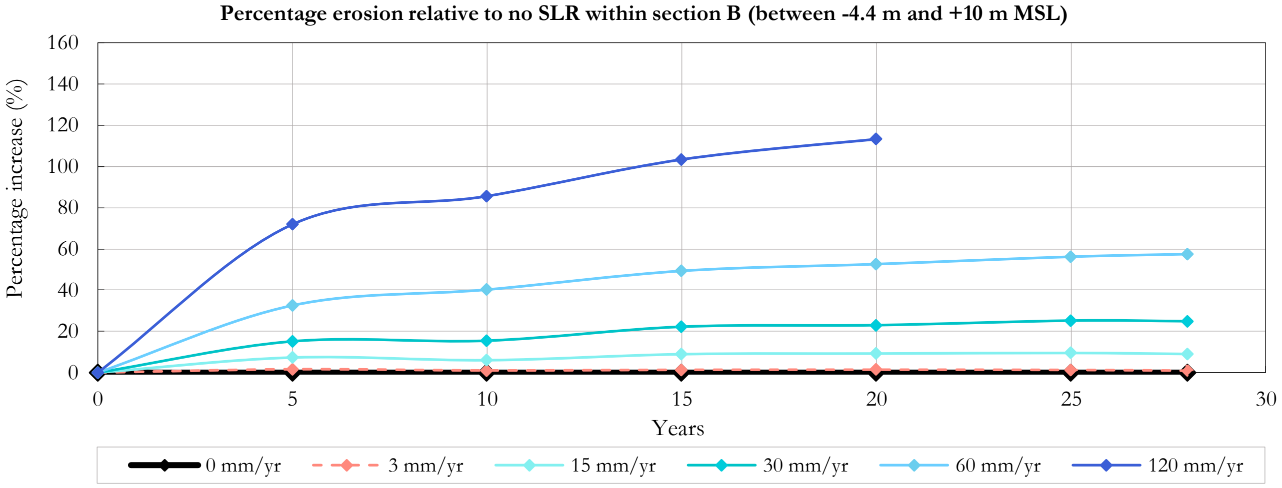


Figure 6-5: Erosion relative to no SLR (%) for increasing SLR rates within the central section, B (between -4.4 m and +10 m MSL)

The larger water depth created in section B, leads to wave energy being dissipated closer to the dunes, leading to more erosion higher up along this steep dune section. Over time the vulnerability of the dunes becomes more important. It is also noted that sand nourishments that have previously taken place in the central beach section, near Ter Heijde and Kuijkduin, may also affect these results.

6.2 Relevance of model results

The volume change results can be compared to findings in previous studies. Based on the sediment budget study reviewed in Section 3.6.1, erosion volume changes for an unnourished Central Holland coast are roughly in the order of 1 million m^3 over a period of 15 years, i.e. erosion volumes in the upper shoreface, beach and fore dunes, (Van der Spek & Lodder, 2015). From the simulated scenarios in this study, for the entire Delfland coast after a 15-year period with no SLR (and the 3 mm/year scenario), cumulative erosion volumes range between roughly 0.7 and 1.1 million m^3 for the subtidal and dune region (refer to tables in Appendix C1 and C2). These values are assumed to be reasonable as the sediment budget analysis referred to could have accounted for erosion volumes extending to a greater depth than the -4.4 m MSL which was used as the seaward limit for the model results. Should the values be slightly underpredicted, the relation between the varying SLR rates is believed to be correct.

Furthermore, the results show the sensitivity to higher waves during a storm event, with the jump in erosion volumes every 4-5 years as shown in Figure 5-5. Luijendijk et al. (2017) found that the dominant forcing mechanism driving the initial morphological response of the Sand Engine is waves. Considering a combination of SLR and storm waves, the Delft3D results give an indication of the relative importance of the wave climate in comparison to SLR.

Erosion volumes within the dune region calculated in this modelling study seem to be small in relation to the total dune erosion volumes modelled by de Winter and Ruessink (2017) as discussed in Section 3.6.2. This is to be expected as the input data accounts for a 1:5-year storm compared to a 1:10 000 storm event. However, if a dune erosion estimate in the range of 52-80 m^3/m per m SLR is considered, an approximate comparison can be made. Based on results erosive volume results in section A and B from the -1 to +7 m MSL zone (Appendix C3), ranges of 67-85 m^3/m per m SLR, and 64-77 m^3/m per m SLR are estimated for the 30 mm/year and 60 mm/year scenario respectively. This can be used to justify the validity of the dune erosion volumes modelled by the calibrated Delft3D model under the impact of SLR.

6.3 Limitations

Some limitations to the modelling study carried out are listed and discussed below.

<u>Exclusion of aeolian transport:</u>
An important limitation of this study is that the Delft3D model does not include aeolian transport processes. This is a drawback of the study as the full coastal system cannot be accurately simulated. Aeolian transport is an important physical process that needs to be taken into account to assess the potential dune growth which affects the functionality of the dunes as a sea defence. Typical transport rates are in the order of 10 to 20 $m^3/m/year$. However, as this is dependent on the type of coast, whether accretive or erosive, as well as the beach width, SLR could have a large impact on the aeolian transport capacity should the beach width decrease due to increasing water levels.

Change in future wave climate:
Another key limitation of this modelling study is that other climate change impacts changing the hydrodynamic boundary conditions were not considered. Example include the increased frequency and intensity of storms in the future, or a change in wave direction. Although beneficial to attempt to model the isolated the effect of accelerated SLR, other climate change impacts may in fact override the SLR impact on coasts.

Unnourished coast:
Due to the focus of this thesis being limited to the process-based modelling of SLR-driven morphodynamic changes on an unnourished coast, the study did not investigate potential adaption strategies. Hence, the thesis does not aim to answer questions related to the feasibility of nourishments in the future or whether a shift in policy is required (refer to Section 3.8). Such adaptation planning to climate change should ideally follow an integrated approach, especially because factors such as the demand for sand and its availability, sustainable methods of dredging and nourishing the coast, and beach use or spatial adaptation, also need to be considered.

Site-specific:
Lastly, the Delft3D model is calibrated for the Delfland coast. Although the findings can to some extent be representative of SLR-induced morphological response of sandy coasts in general, behaviour of other coastal stretches may also be very different. Such a Delft3D model would need to be calibrated and validated for site-specific conditions, and account for different local SLR projections, potential land subsidence, and most importantly the regional wave and wind climate driving the physical processes.
Furthermore, the time series in this modelling study is based only on 5-year data. For more accurate predictions of the coastal evolution, extensive historical observations are required.

6.4 Implications

Erosion volumes calculated in such a Delft3D could potentially be used in the aid of sediment budget analyses. On the other hand, coastline or dune foot retreat (in m/year), a parameter which is more commonly calculated to predict coastal recession due to SLR, is not as easily distinguishable in the model results due to the increasing water levels over time.

Implications in the broader context are related to coastal maintenance policy and implementation of nourishments. In Section 3.5.1, the method of determining whether sand nourishments are required was discussed, i.e. based on the MCL position. However, because of the increased water level in the nearshore due to SLR, a more dynamic approach in the future would be required. The subtidal zone often shows an accretive trend, due to the deposition of material from the eroded beach and dunes. Hence, continued use of the MCL-method would not suffice in showing where significant erosion takes place. The full coastal profile from the dunes to the surf zone may be an alternative approach.

Based on the simulations showing variability in cross-shore and alongshore erosion and sediment transport due to SLR, the location of sand nourishments may become more important. The current Dutch policy towards SLR is to add sediment volume to the profile as the water increases so that the bed level can keep pace with SLR. This is based on the calculations of the coastal foundation. However, these estimates do not account for additional erosion caused by accelerated SLR, and so dune erosion is excluded. With accelerated SLR, the need for dune strengthening may become more imminent. This is in line with the findings of de Winter and Ruessink (2017), who state that dune strengthening may be more effective, in the case of large SLR.

Beach-dune interactions and in particular dune erosion at higher elevations becomes more critical with increased rates of SLR. As this is a sediment-sharing system, the beach and dune sediment budgets may need to be jointly considered.

7

CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes the outcomes of this study in the context of answers to the research questions set in Section 1.3.1. Additionally, recommendations for further research are provided.

7.1 Conclusions

This thesis concludes a first assessment of modelling the effects of climate change-induced accelerated SLR on the morphological behaviour of a sandy coastal stretch in a process-based Delft3D model.
The Delfland coast in the Netherlands was selected as a case study. Here, the sandy dunes are the primary sea defence. Coastal erosion due to accelerated SLR could endanger the strength of the dunes and put the low-lying hinterland (densely populated and of high socio-economic value) at greater risk of flooding.

Morphodynamic simulations were carried out through application of a calibrated Delft3D model (Luijendijk et al., 2019), which is forced by real-time wave conditions. This is a novel acceleration technique called brute-force merged (BFM), which allows for more accurate representation of morphological changes over short, medium- and long-term timescales. A 30-year time period was selected to simulate and asses the morphological behaviour of the Delfland sandy coast (16.5 km in length) in response to accelerated SLR, the water level being the only forcing factor that changes across the different simulations.

Two main research questions were set and concluding remarks to each are discussed below:

(1) What are the effects of accelerated rates of SLR on the morphodynamics of the Delfland coast, should no adaptation/mitigation measures be implemented in the future?

Overall, the long-term morphological evolution shows an increase in erosion volumes for the no SLR scenario, assuming no sand nourishments take place; results of the increasing SLR rates are shown to follow a similar trend in most cases. In general, for the no SLR scenario, erosion rates (assessed per 5-year period) decrease over time up to 20 years, whereas higher SLR rates result in larger volume changes and/or deviations from the normal trend. Steeper increases in erosion over time represent increasing long-term erosion rates, which is different from the no SLR scenario.

Computed results are dependent on the method used to spatially analyse model outputs in terms of the division of the coast into subsections alongshore, and depth/elevation zones representing different cross-shore sections of the coastal profile. Alongshore distribution of volume changes shows that erosion mostly occurs in the southern and central sections of the coast, i.e. up to approximately 7 km from the Hoek of Holland. Negligible erosion occurs in the northern section, characterized predominantly an accretive zone, due to sediments moved by northerly-directed LST and depositing updrift of the harbour mole at Scheveningen harbour. These overall system dynamics describing alongshore variability in the morphodynamic behaviour remain the same under varying SLR scenarios. Erosive stretches show increasing erosion with higher SLR rates, and accretive sections remain accretive with increased sedimentation.

Different depth/elevation zones also show different cross-shore responses to accelerating SLR. The foreshore and sub-tidal region in the southern section, nearest to Hoek of Holland, is susceptible to increasing erosion caused by higher rates of SLR. Reasons for this include the large gradient in LST rates and a potential landwards shift of the surf zone as water depths nearer to the shore increase. Alternatively, if waves refract differently with an increasing water depth, the alongshore gradient in wave energy could be the cause of increased erosion.

The higher the SLR rate, the more critical the erosion of the dunes become, due to the water level and waves reaching higher elevations and subsequent wave attack causing erosion. Steeper dunes in the central part of the coast, are also locally more vulnerable to erosion at their highest elevations.

In relation to other sandy coasts, a general hypothesis according to Bird (1996) is that if sea levels increase, there will be an acceleration of existing beach erosion, and erosion will begin on many beaches that are now (previously) stable or growing. Using the Delfland coast as a case study site shows that existing beach erosion is indeed accelerated, more over that dune erosion becomes critical under high-end accelerated SLR projections. The stable and accretive coastal stretches are not influenced by SLR-induced beach erosion, or it may take a much longer time. This however is site-specific mainly as a result of alongshore sediment transport and geometry of structures. Other stable or growing sandy beaches may behave differently due to local conditions.

(2) What is the added value of using a process-based area model, such as Delft3D, in assessing SLR impacts on the morphodynamic changes and beach-dune evolution of sandy coasts, compared to e.g. the Bruun Rule?

Assessing the added value of Delft3D, the following conclusions can be drawn, in comparison to other coastal impact models:

- Delft3D successfully offers the ability to assess both the temporal and spatial behaviour of volume changes. This allows for a more detailed analysis at multiple spatio-temporal scales, instead of calculating a single, determinstic value estimate such as the Bruun Rule does.
- Delft3D allows for both alongshore and crosshore transport processes. The inclusion of alongshore transport gradients is in contrast to the Bruun Rule which assumes no alongshore gradients in net longshore transport, and thus net sediment transport occurs perpendicular to the coast. This is also an improvement to 1-D coastline models in which no cross-shore transport is considered.
- Delft3D allows for alongshore and cross-shore variability in the beach and profile shapes. This is instead of assuming a representative cross-shore profile and an alongshore uniform coast, as applied commonly in X-Beach and 1-D coastline models. The helps to assess spatial differences in the coastal behaviour, and determine where the effects of SLR may be largest, if the impact is not constant across the entire beach.

- The calibrated Delft3D model can adequately account for dune erosion processes due to accelerated SLR. With accelerating SLR, the vulnerabliity of the dunes increase and so volume changes in the dune sediment budget becomes of greater importance in the sand-sharing system in the long-term. This is compared to the Bruuun Rule in which sand supply from other sources and sand losses are not considered. This allows coastal profile changes in Delft3D, inclduing with significant steepening, which is not the case for the Bruun Rule where the new equilibrium profile maintains a constant profile shape.
  - A disadvantage of Delft3D, similar to the Bruun Rule is that aeolian transport (sand loss) is not modelled.

The added value particular to the BFM acceleration technique used in the calibrated model, is that it incorporates full variability of the wave climate, and not only a maximum schematized wave climate:

- In this way, normal conditions are included which allow for beach recovery after a storm event. Correctly simulating morphodynamic processes over episodic to long-term timescales is in line with an 'ideal' multi-scale coastal impact as proposed by Ranasinghe (2016).

Additional added benefits of Delft3D which have not been assessed in this modelling study include:

- Quantifying the differences in alongshore gradient of wave energy/wave progagation with increasing sea level.
- Quanitifying the impact of increasing water depths on the tidal propagation and the corresponding tidal currents.

7.2 Recommendations for Further Research

A number of recommendations to build on the modelling study presented in this thesis, as well as points of interest for further research have been identified and are listed below.

For improvement to the current modelling study and results thereof:

- Further work needs to be carried out in order to accuratley validate the volume change results of this modeling study, e.g. sediment budget analysis under accelerated SLR scenarios, compare dune erosion results an X-Beach simulation for the Defland coast.
- Adjust the grid and mesh to improve local results at 9-10 km alongshore.
- Estimate coastline and dune-foot positions and compare with 1-D coastline model predictions.

Further research:

- Repeat simulations with adaptation measures in the form of beach and shoreface nourishments to assess the feasibility of such solutions in reducing the amount of erosion with increasing SLR rates. One can assess the sand volume required and whether the nourishments help the coastal foundation to keep pace with SLR, or wehther dune erosion is still critical and at which rate of SLR. This can also test the importance of nourishment placement.
- Couple Delft3D and Aeolis, to incorporate aeolian transport for dune growth.
- Determine the relative importance of accelerated SLR, in comparison to other climate change-induced changes/forcing factors. Therefore, simuate a change in wave direction or more frequent storms (or

longer duration). Also simulate the combined effect of SLR and e.g. a change in wave direction. In this way a sensitivity analysis can be done.

- Assess the accelerated SLR impact on a sample of sandy coasts in order to analyse the coastal sensitivity and assess impacts of SLR on sandy beaches in general. Note new models need to be calibrated to the site-specific conditions.

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APPENDICES

APPENDIX A

SLR Projections for the Dutch Coast

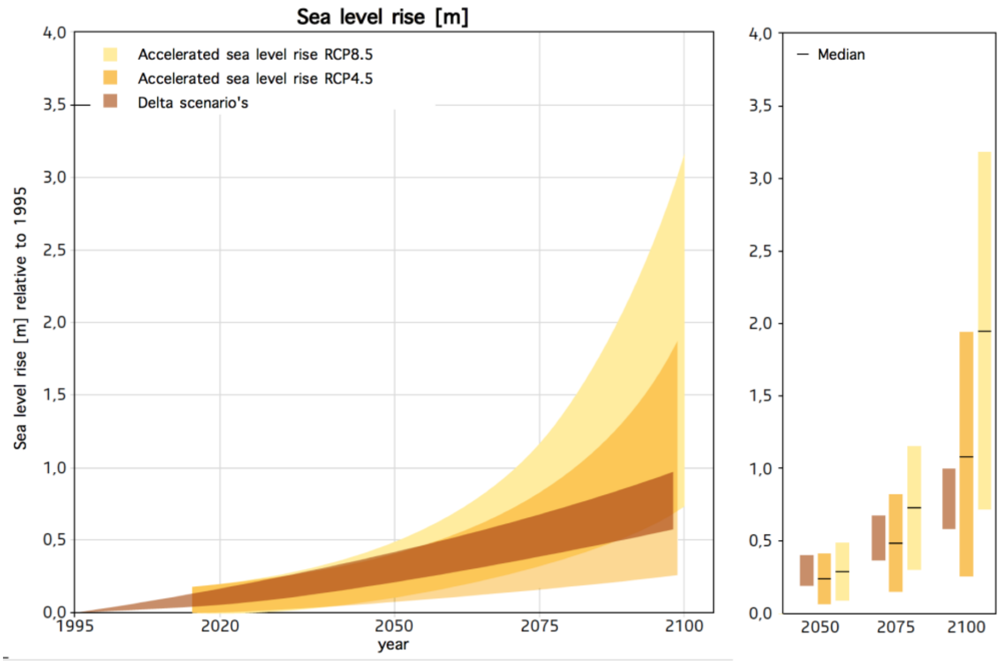


Figure A-1: SLR projections including additional acceleration (m) for the Dutch coast

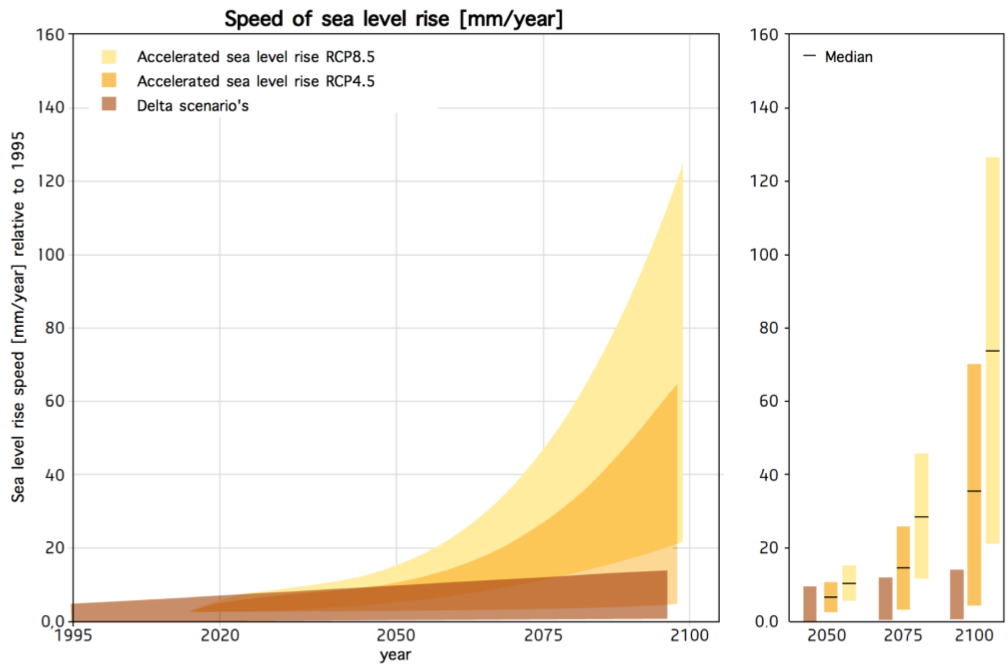


Figure A-2: Speed of accelerated SLR (mm/year) for the Dutch coast

(Source: Haasnoot et al., 2018)

APPENDIX B
Historical Nourishments

Table B-1: Nourishments along the Delfland coast listed by year of implementation from 1988 to 2013

Year	Volume (million m³)	Volume per metre (m³/m)	Type of nourishment	Approximate location
1988	0.20	400	Beach	Hoek of Holland
1989	0.10	133	Beach	Hoek of Holland
1990	0.18	183	Beach	Hoek of Holland
1991	0.22	223	Beach	Hoek of Holland
1992	0.56	560	Beach	Hoek of Holland
1993	0.46	97	Beach	Hoek of Holland
1993	1.14	191	Beach	Ter Heijde
1994	0.20	200	Beach	Hoek of Holland
1995	0.20	200	Beach	Hoek of Holland
1995	0.30	131	Beach	Ter Heijde
1996	0.20	200	Beach	Hoek of Holland
1997	0.20	200	Beach	Hoek of Holland
1997	0.88	519	Shoreface	Ter Heijde
1997	0.83	166	Beach	Ter Heijde
1999	0.20	267	Beach	Hoek of Holland
2000	0.20	200	Beach	Hoek of Holland
2001	2.97	582	Shoreface	Ter Heijde
2001	0.80	200	Beach	Ter Heijde
2003	0.21	213	Beach	Hoek of Holland
2003	1.25	229	Beach	Ter Heijde
2004	0.23	231	Beach	Hoek of Holland
2004	1.16	211	Beach	Ter Heijde
2005	0.88	200	Shoreface	Ter Heijde
2007	0.74	513	Beach	Hoek of Holland
2007	0.75	150	Shoreface	Hoek of Holland
2008	3.00	1315	Beach - Dune	Ter Heijde
2009	4.50	2093	Beach	Hoek of Holland
2009	3.00	1923	Beach - Dune	Kijkduin
2010	5.00	909	Beach - Dune	Ter Heijde
2010	2.50	814	Beach - Dune	Kijkduin
2011	2.00	917	Shoreface - Sand Engine	Ter Heijde
2011	17.00	8994	Beach - Sand Engine	Ter Heijde
2011	0.50	231	Shoreface - Sand Engine	Kijkduin
2013	1.50	375	Shoreface	Hoek of Holland

Source: http://kml.deltares.nl/kml/rijkswaterstaat/suppleties/

Table B-2: Mean annual nourishment volumes at Delfland coast

Period over which average is calculated	Volume (Mm^3/year)
10-year average (1991 – 2000)	0.6
10-year average (1996 – 2005)	1.0
10-year average (1998 – 2007)	0.9
7-year average (2001 – 2007)	1.3
15-year average (1994 – 2008)	1.0
20-year average (1989 – 2008)	0.9

APPENDIX C

Model Results - Erosion

C1: Erosion in the -4.4/+7 m MSL depth/elevation zone

Erosion volumes (m³) over time, calculated in the -4.4/+7 m MSL zone: (rounded values)

Southern section (A): 2.74 km²

Erosion volumes (in m³) over time for increasing SLR rates within the southern section, A (between -4.4 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	-180 000	-190 000	-200 000	-220 000	-280 000	-380 000
10	-290 000	-300 000	-320 000	-370 000	-490 000	-710 000
15	-420 000	-430 000	-480 000	-570 000	-760 000	-1 040 000
20	-520 000	-530 000	-600 000	-730 000	-980 000	-1 310 000
25	-630 000	-650 000	-750 000	-910 000	-1 210 000	
28	-660 000	-670 000	-770 000	-940 000	-1 250 000	

Central section (B): 2.91 km²

Erosion volumes (in m³) over time for increasing SLR rates within the central section, B (between -4.4 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	-330 000	-330 000	-350 000	-370 000	-430 000	-550 000
10	-520 000	-520 000	-550 000	-590 000	-700 000	-890 000
15	-690 000	-700 000	-740 000	-810 000	-960 000	-1 220 000
20	-830 000	-840 000	-890 000	-970 000	-1 160 000	-1 450 000
25	-990 000	-1 000 000	-1 050 000	-1 170 000	-1 360 000	
28	-1 060 000	-1 060 000	-1 120 000	-1 240 000	-1 430 000	

Northern section (C): 1.99 km²

Erosion volumes (in m³) over time for increasing SLR rates within the northern section, C (between -4.4 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	-3 000	-3 000	-3 000	-3 000	-4 000	-7 000
10	-4 000	-4 000	-5 000	-6 000	-9 000	-21 000
15	-5 000	-5 000	-7 000	-10 000	-18 000	-45 000
20	-6 000	-6 000	-9 000	-13 000	-28 000	-59 000
25	-6 000	-7 000	-10 000	-16 000	-38 000	
28	-7 000	-7 000	-11 000	-18 000	-43 000	

Percentage increase in erosion per year relative to no SLR, calculated in the -4.4/+7 m MSL zone:
(based on exact erosion volumes, not rounded values as tabulated above)

<u>Southern section (A):</u> 2.74 km²

Erosion relative to no SLR (%) for increasing SLR rates within the southern section, A (between -4.4 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	0.0	1.6	9.6	21	49	108
10	0.0	1.2	10	27	68	140
15	0.0	1.8	13	34	79	144
20	0.0	2.1	15	40	88	150
25	0.0	2.6	18	45	91	
28	0.0	2.5	17	44	90	

<u>Central section (B):</u> 2.91 km²

Erosion relative to no SLR (%) for increasing SLR rates within the central section, B (between -4.4 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	0.0	1.6	7.1	15	31	68
10	0.0	0.8	5.0	13	35	71
15	0.0	1.0	7.0	18	39	77
20	0.0	0.8	6.4	17	38	73
25	0.0	0.7	6.2	18	38	
28	0.0	0.2	5.1	17	35	

<u>Northern section (C):</u> 1.99 km²

Erosion relative to no SLR (%) for increasing SLR rates within the northern section, C (between -4.4 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	0.0	2.2	14	34	68	166
10	0.0	4.7	25	57	141	472
15	0.0	6.4	37	90	252	795
20	0.0	8.3	49	124	378	925
25	0.0	10	63	158	518	
28	0.0	10	65	167	545	

C2: Erosion in the -1/+7 m MSL depth/elevation zone

Erosion volumes (m³) over time, calculated in the -1/+7 m MSL zone:
(rounded values)

Southern section (A): 1.83 km²

Erosion volumes (in m³) over time for increasing SLR rates within the southern section, A (between -1 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	-80 000	-80 000	-80 000	-90 000	-100 000	-120 000
10	-170 000	-170 000	-160 000	-170 000	-190 000	-240 000
15	-240 000	-230 000	-230 000	-240 000	-290 000	-380 000
20	-300 000	-300 000	-290 000	-320 000	-370 000	-520 000
25	-370 000	-370 000	-370 000	-400 000	-480 000	
28	-420 000	-410 000	-400 000	-440 000	-520 000	

Central section (B): 1.75 km²

Erosion volumes (in m³) over time for increasing SLR rates within the central section, B (between -1 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	-170 000	-170 000	-170 000	-180 000	-200 000	-250 000
10	-340 000	-330 000	-330 000	-340 000	-360 000	-430 000
15	-440 000	-430 000	-430 000	-430 000	-470 000	-560 000
20	-540 000	-530 000	-520 000	-520 000	-580 000	-660 000
25	-640 000	-630 000	-610 000	-630 000	-680 000	
28	-710 000	-690 000	-670 000	-690 000	-710 000	

Northern section (C): 1.21 km²

Erosion volumes (in m³) over time for increasing SLR rates within the northern section, C

(between -1 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	-2 000	-2 000	-3 000	-3 000	-4 000	-6 000
10	-4 000	-4 000	-5 000	-6 000	-9 000	-21 000
15	-5 000	-5 000	-7 000	-10 000	-18 000	-45 000
20	-6 000	-6 000	-9 000	-13 000	-28 000	-59 000
25	-6 000	-7 000	-10 000	-16 000	-38 000	
28	-7 000	-7 000	-11 000	-18 000	-43 000	

Percentage increase in erosion per year relative to no SLR, calculated in the -1/+7 m MSL zone:
(based on exact erosion volumes, not rounded values as tabulated above)

Southern section (A): 1.83 km²

Erosion relative to no SLR (%) for increasing SLR rates within the southern section, A
(between -1 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	3 mm/yr	15 mm/yr	30 mm/yr	60 mm/yr	120 mm/yr
5	0.0	0.6	4.1	11	25	48
10	0.0	-1.2	-2.6	0.9	14	42
15	0.0	-1.8	-5.1	1.6	20	59
20	0.0	-1.9	-4.2	4.8	24	74
25	0.0	-1.9	-1.8	7.0	28	
28	0.0	-1.2	-2.8	5.2	24	

Central section (B): 1.75 km²

Erosion relative to no SLR (%) for increasing SLR rates within the central section, B
(between -1 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	3 mm/yr	15 mm/yr	30 mm/yr	60 mm/yr	120 mm/yr
5	0.0	0.7	3.2	7.5	19	47
10	0.0	-0.3	-1.0	0.3	8.5	29
15	0.0	-0.6	-1.6	-0.3	7.7	29
20	0.0	-1.1	-3.7	-2.8	7.6	22
25	0.0	-1.5	-4.1	-1.4	5.7	
28	0.0	-1.9	-4.9	-2.1	0.4	

Northern section (C): 1.21 km²

Erosion relative to no SLR (%) for increasing SLR rates within the northern section, C
(between -1 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	3 mm/yr	15 mm/yr	30 mm/yr	60 mm/yr	120 mm/yr
5	0.0	2.8	16	36	75	180
10	0.0	4.7	25	58	142	459
15	0.0	6.4	37	89	251	785
20	0.0	8.3	49	124	378	918
25	0.0	10	63	158	518	
28	0.0	10	65	167	545	

C3: Erosion in the -4.4/+3 m MSL depth/elevation zone (~ MCL-zone)

Erosion volumes (m³) over time, calculated in the -4.4/+3 m MSL zone:
(rounded values)

Southern section (A): 2.09 km²

Erosion volumes (in m³) over time for increasing SLR rates within the southern section, A
(between -4.4 m and +3 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	-170 000	-170 000	-180 000	-200 000	-240 000	-320 000
10	-250 000	-250 000	-270 000	-300 000	-380 000	-520 000
15	-360 000	-360 000	-380 000	-440 000	-560 000	-750 000
20	-430 000	-440 000	-460 000	-540 000	-700 000	-970 000
25	-520 000	-520 000	-570 000	-670 000	-850 000	
28	-530 000	-530 000	-570 000	-660 000	-850 000	

Central section (B): 2.63 km²

Erosion volumes (in m³) over time for increasing SLR rates within the central section, B
(between -4.4 m and +3 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	-210 000	-220 000	-230 000	-240 000	-270 000	-350 000
10	-310 000	-310 000	-320 000	-340 000	-420 000	-570 000
15	-410 000	-410 000	-430 000	-490 000	-600 000	-840 000
20	-510 000	-510 000	-540 000	-600 000	-730 000	-1 060 000
25	-630 000	-630 000	-660 000	-730 000	-910 000	
28	-690 000	-680 000	-690 000	-780 000	-960 000	

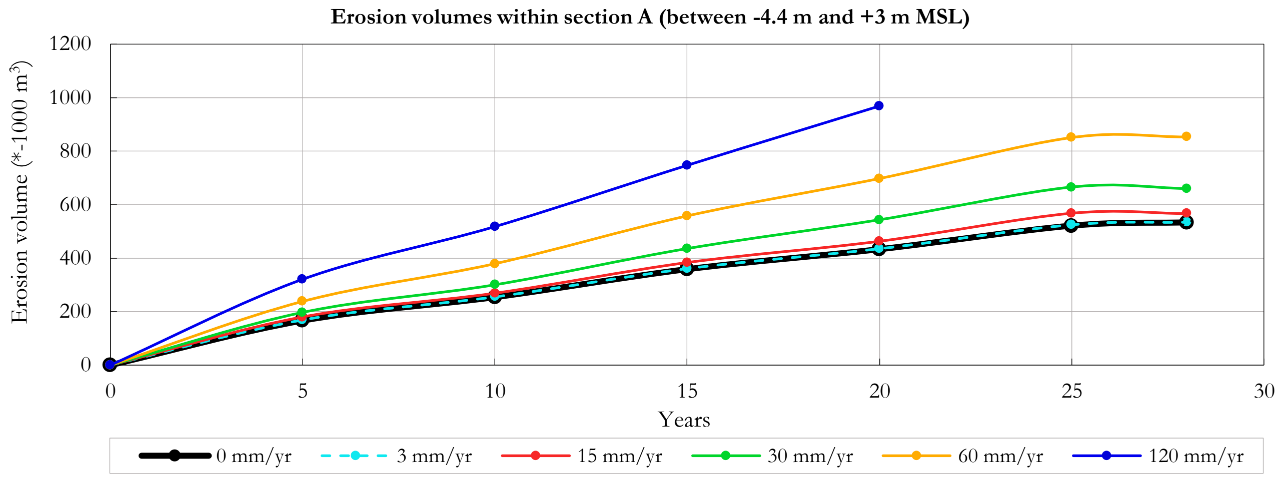
Northern section (C): 1.82 km²

Erosion volumes (in m³) over time for increasing SLR rates within the northern section, C
(between -4.4 m and +3 m MSL)

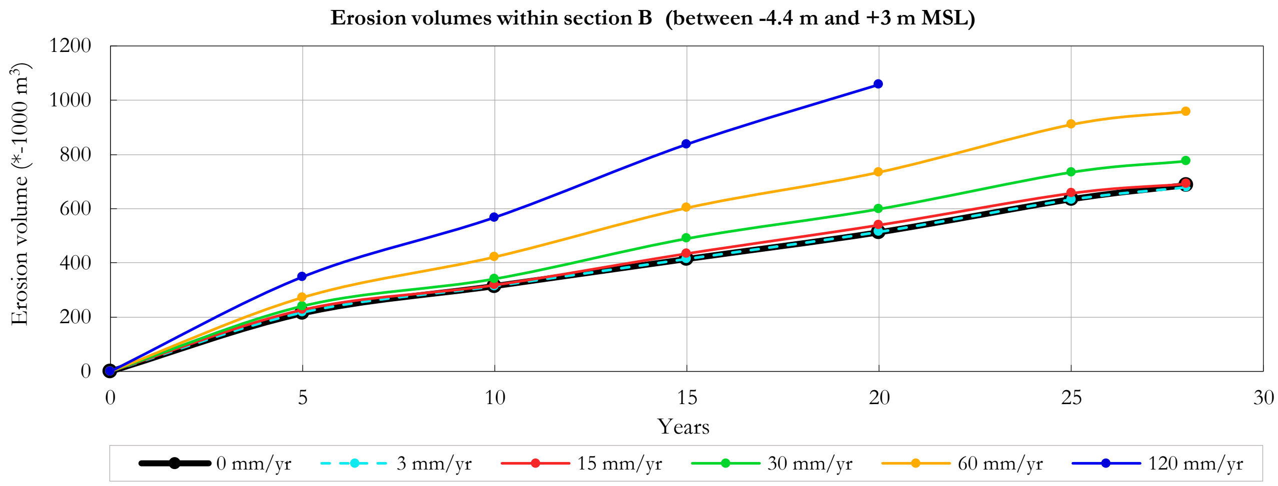
Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	-1 000	-1 000	-2 000	-2 000	-2 000	-2 000
10	-1 000	-1 000	-2 000	-2 000	-2 000	-2 000
15	-2 000	-2 000	-2 000	-2 000	-1 000	-2 000
20	-2 000	-2 000	-2 000	-2 000	-1 000	-1 000
25	-2 000	-2 000	-3 000	-2 000	-1 000	
28	-2 000	-2 000	-2 000	-2 000	-1 000	

Graphs showing erosion volumes (* -1000 m³) over time, calculated in the -4.4/+3 m MSL zone

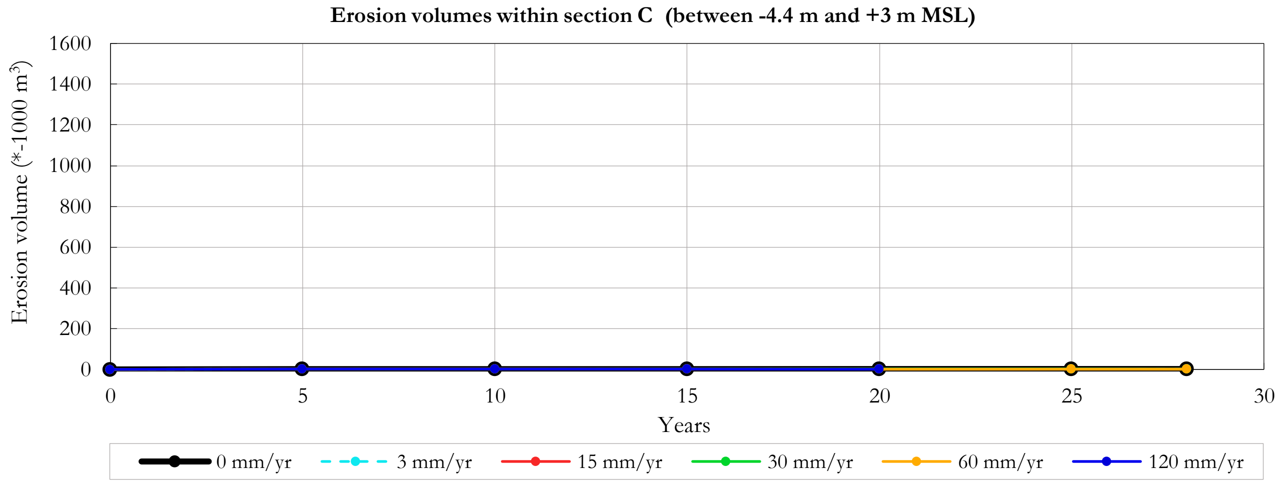
Southern section (A): 2.09 km²



Central section (B): 2.63 km²



Northern section (C): 1.82 km²



Percentage increase in erosion per year relative to no SLR, calculated in the -4.4/+3 m MSL zone:
(based on exact erosion volumes, not rounded values as tabulated above)

Southern section (A): 2.09 km²

Erosion relative to no SLR (%) for increasing SLR rates within the southern section, A
(between -4.4 m and +3 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	3 mm/yr	15 mm/yr	30 mm/yr	60 mm/yr	120 mm/yr
5	0.0	1.3	8.2	18	43	93
10	0.0	0.4	5.8	18	49	104
15	0.0	0.6	6.9	22	56	108
20	0.0	0.4	6.9	25	61	124
25	0.0	0.6	8.9	28	63	
28	0.0	0.1	6.1	24	60	

Central section (B): 2.63 km²

Erosion relative to no SLR (%) for increasing SLR rates within the central section, B
(between -4.4 m and +3 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	3 mm/yr	15 mm/yr	30 mm/yr	60 mm/yr	120 mm/yr
5	0.0	1.4	5.9	12	27	63
10	0.0	-0.1	1.1	18.1	34	81
15	0.0	0.0	4.8	18	45	102
20	0.0	0.2	5.1	17	43	106
25	0.0	-0.2	3.4	16	43	
28	0.0	-1.2	0.6	13	40	

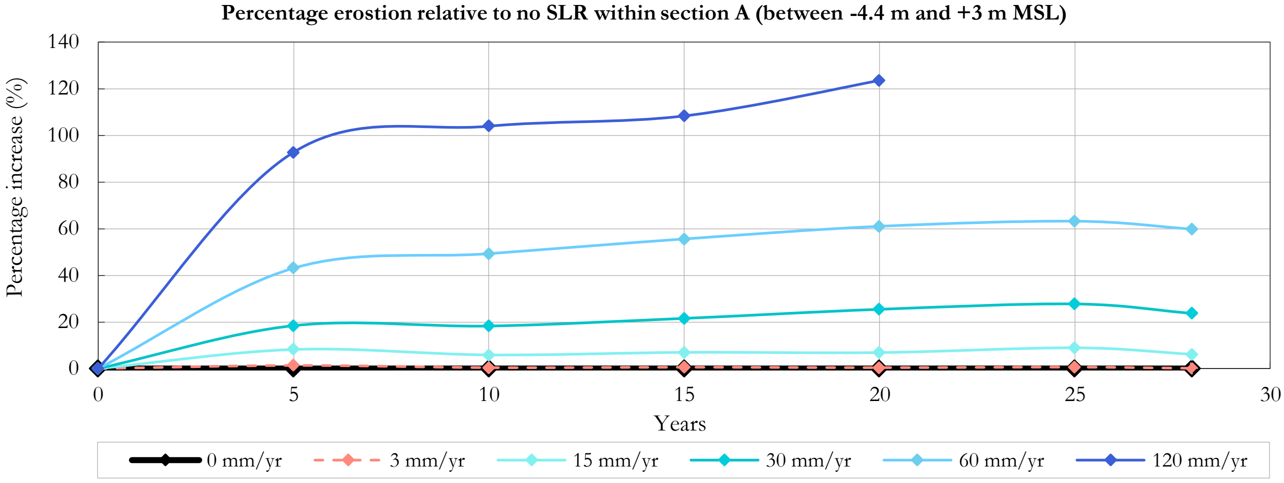
Northern section (C): 1 .82 km²

Erosion relative to no SLR (%) for increasing SLR rates within the northern section, C
(between -4.4 m and +3 m MSL)

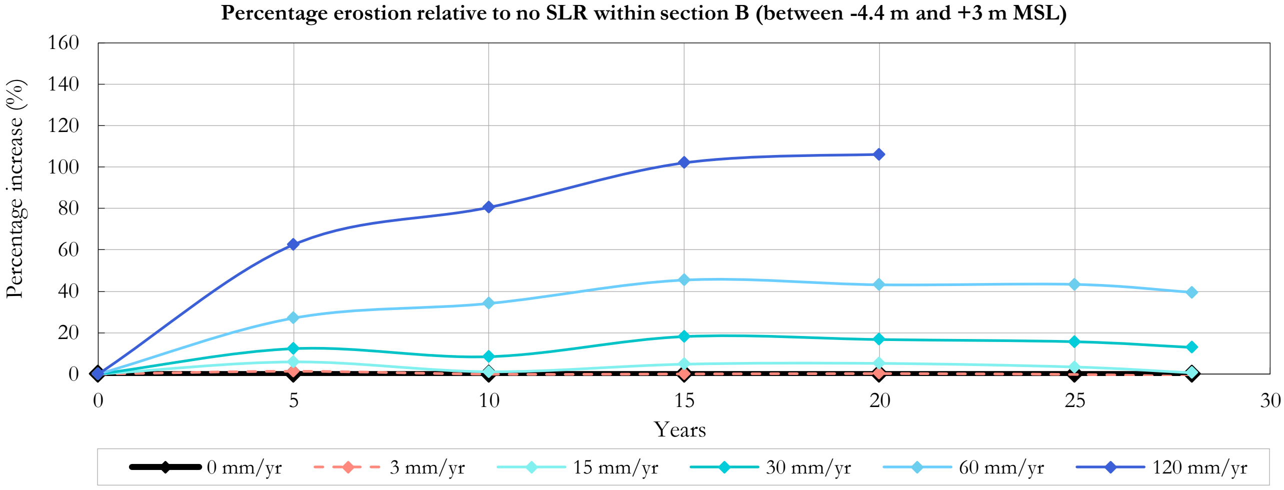
Year	Simulation run: Sea level rise scenario					
	0 mm/yr	3 mm/yr	15 mm/yr	30 mm/yr	60 mm/yr	120 mm/yr
5	0.0	1.4	10	19	36	33
10	0.0	4.4	20	38	59	41
15	0.0	5.4	23	33	-18	10
20	0.0	7.3	23	26	-53	-52
25	0.0	10	38	19	-51	
28	0.0	6.9	24	-15	-55	

Graphs showing percentage increase in erosion per year relative to no SLR, calculated in the - 4.4/+3 m MSL zone:

<u>Southern section (A):</u> 2.09 km²



<u>Central section (B):</u> 2.63 km²



<u>Northern section (C):</u> 1 .82 km²

- Negligible

APPENDIX D

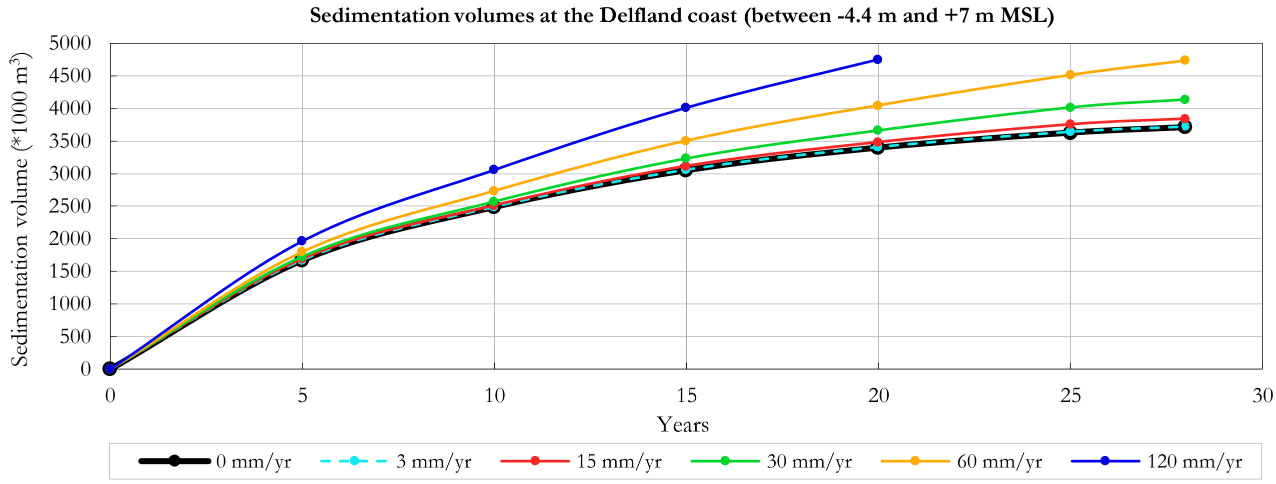
Model Results - Accretion

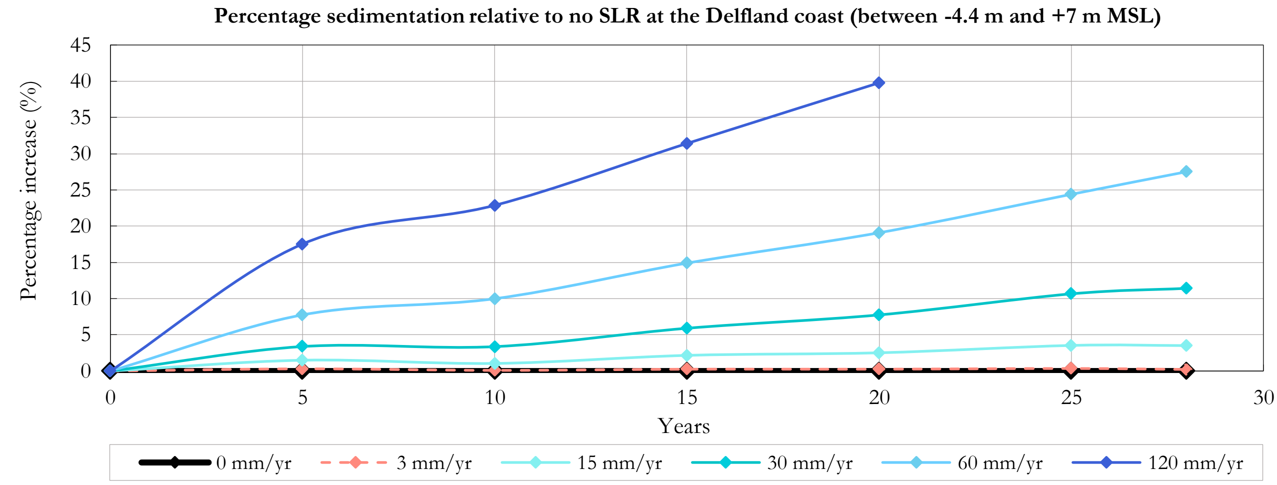
D1: Accretion in the -4.4/+7 m MSL depth/elevation zone

Full Delfland coast: 7.64 km²

Aggregated accretion volumes (in m³) over time for increasing SLR rates at the Delfland coast (between -4.4 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	3 mm/yr	15 mm/yr	30 mm/yr	60 mm/yr	120 mm/yr
5	1 670 000	1 680 000	1 700 000	1 730 000	1 800 000	1 960 000
10	2 490 000	2 490 000	2 510 000	2 570 000	2 740 000	3 060 000
15	3 050 000	3 060 000	3 120 000	3 230 000	3 510 000	4 010 000
20	3 400 000	3 410 000	3 490 000	3 660 000	4 050 000	4 750 000
25	3 630 000	3 640 000	3 760 000	4 020 000	4 520 000	
28	3 710 000	3 720 000	3 850 000	4 140 000	4 740 000	



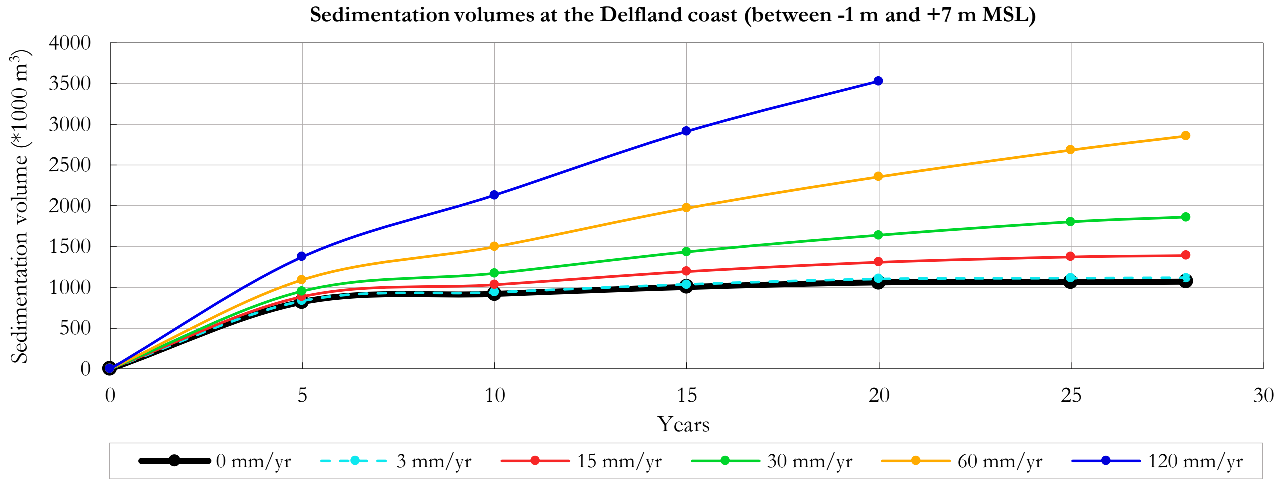


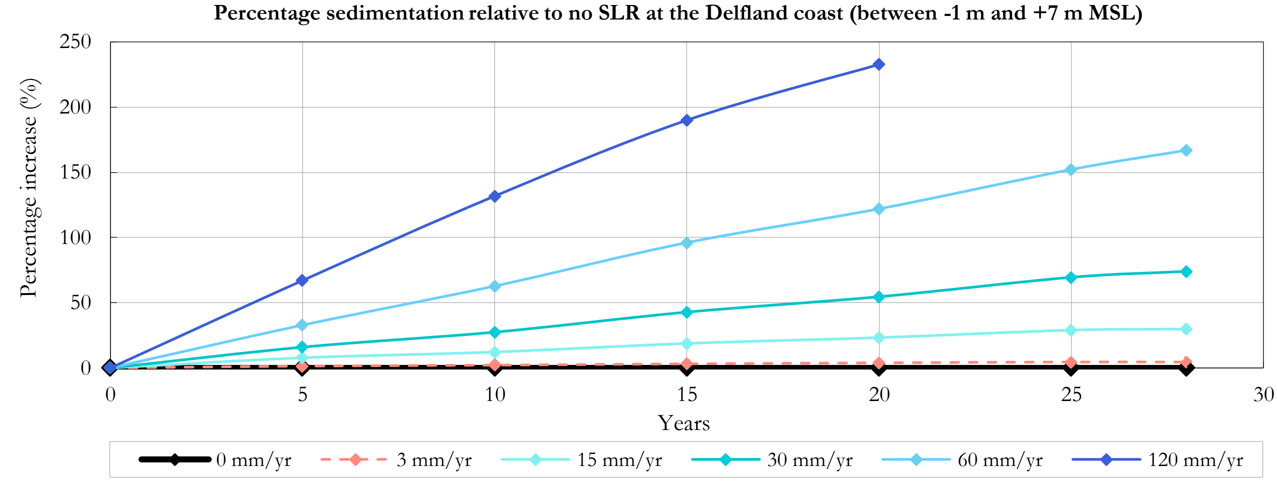
D2: Accretion in the -1/+7 m MSL depth/elevation zone

Fulll Delfland coast 4.80 km²

Aggregated accretion volumes (in m³) over time for increasing SLR rates at the Delfland coast (between -1 m and +7 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	3 mm/yr	15 mm/yr	30 mm/yr	60 mm/yr	120 mm/yr
5	820 000	830 000	890 000	950 000	1 090 000	1 370 000
10	920 000	940 000	1 030 000	1 170 000	1 500 000	2 130 000
15	1 000 000	1 040 000	1 190 000	1 430 000	1 970 000	2 910 000
20	1 060 000	1 100 000	1 310 000	1 640 000	2 360 000	3 530 000
25	1 060 000	1 110 000	1 370 000	1 800 000	2 680 000	
28	1 070 000	1 120 000	1 390 000	1 860 000	2 860 000	





D3: Accretion in the -4.4/+3 m MSL depth/elevation zone (~ MCL-zone)

Full Delfland coast: 6.54 km²

Aggregated accretion volumes (in m³) over time for increasing SLR rates at the Delfland coast (between -4.4 m and +3 m MSL)

Year	Simulation run: Sea level rise scenario					
	0 mm/yr	**3 mm/yr**	**15 mm/yr**	**30 mm/yr**	**60 mm/yr**	**120 mm/yr**
5	1 670 000	1 680 000	1 700 000	1 730 000	1 800 000	1 960 000
10	2 490 000	2 490 000	2 510 000	2 570 000	2 740 000	3 050 000
15	3 050 000	3 060 000	3 120 000	3 230 000	3 500 000	4 000 000
20	3 400 000	3 410 000	3 490 000	3 660 000	4 050 000	4 710 000
25	3 630 000	3 640 000	3 760 000	4 020 000	4 510 000	
28	3 710 000	3 720 000	3 840 000	4 140 000	4 730 000