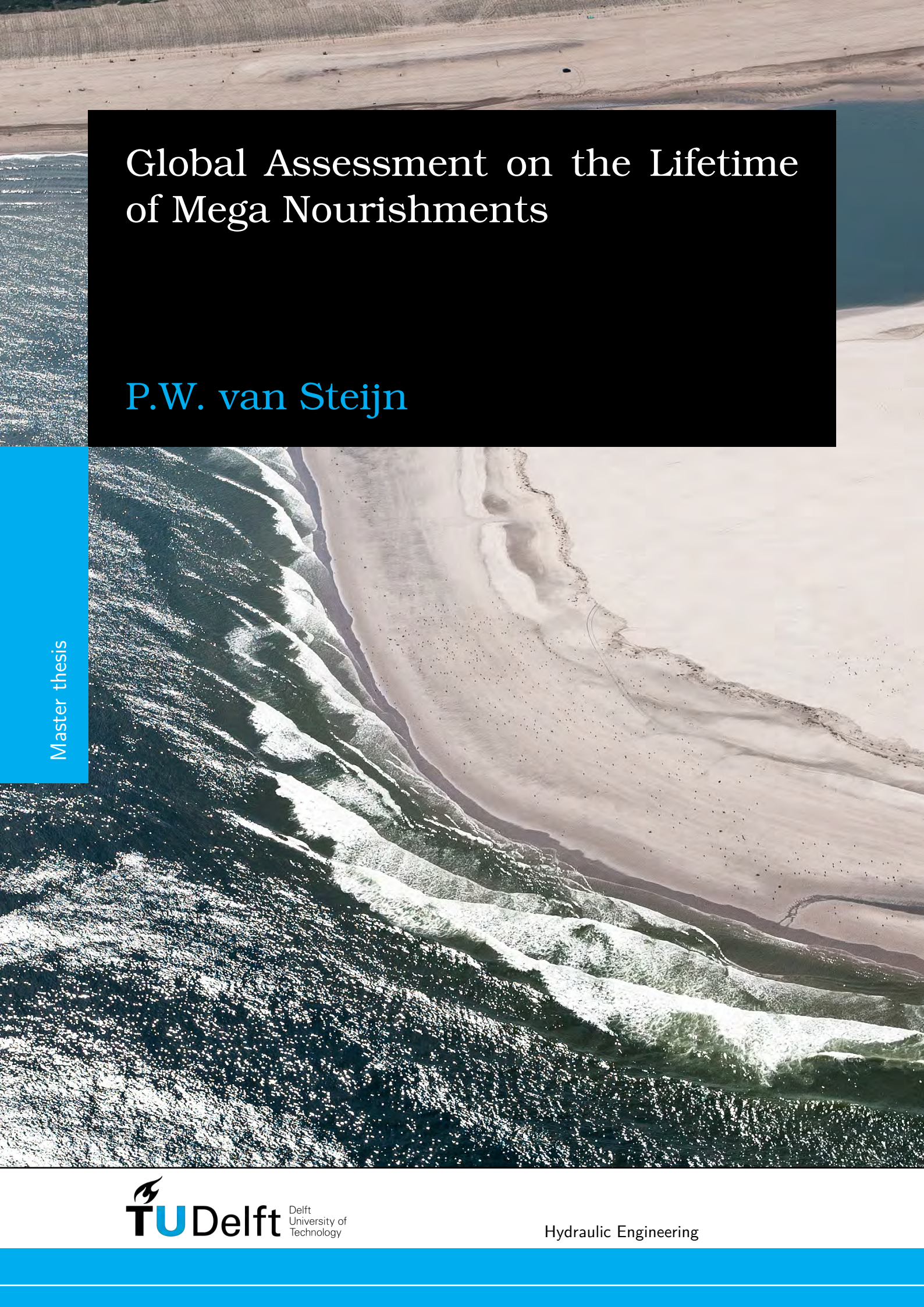




# Global Assessment on the Lifetime of Mega Nourishments

P.W. van Steijn

Master thesis

Front cover: Aerial photograph of the Sand Engine made from an altitude of 438 m on the 5<sup>th</sup> of July 2011 by Joop van Houdt, Rijkswaterstaat, <https://beeldbank.rws.nl/MediaObject/Details/405312>

# Global Assessment on the Lifetime of Mega Nourishments

MASTER THESIS

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February 13, 2015

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# Abstract

Recently an innovative nourishment method has been applied as a counter measure for coastal recession in the Netherlands. This soft engineering solution, also known as the Sand Engine, consists of a shoreline perturbation of 21.5 Mm<sup>3</sup> sand which will be redistributed along the shore by the natural forces of waves, tides and winds over a stretch of 10 km to prevent coastal retreat. It is expected that this multifunctional 'building with nature' solution has several economical, ecological and recreational advantages compared to the traditional nourishment approaches. The mega nourishment intervention may therefore become one of the common nourishment methods to combat beach erosion. The international potential is assessed by determining the relative influence of wave climate parameters and nourishment dimensions on the lifetime of a mega nourishment for a straight alongshore uniform sandy shore.

The Mega Nourishment tool has been developed to obtain a first estimate of the lifetime for a geographical location in the world by computing the nourishment redistribution and the cross shore erosion of the shore using wave climates from two global wave models. The redistribution of the nourishment is caused by gradients in the Longshore Sediment Transport (LST) and is simulated with the Unibest-CL+ coastline model. For the coastal erosion two process are taken into account: The erosion due to a rising sea level and the landward directed sediment loss during a storm simulated with a 1D Xbeach model.

A comparison has been made between the tool results and an other model simulation of the Sand Engine. All simulations estimated different redistribution rates for the Sand Engine depending on the wave climate used. The lifetime predictions for the simulations were however similar. The Sand Engine is estimated to be sufficient to protect 10 km of coast for a period of about 50 years.

The tool is furthermore used to simulate many cases with different wave climates, nourishment dimensions, cross shore profile shapes and sediment sizes. Using these results several conclusions are drawn. The redistribution rate is predominantly determined by the wave energy. A larger directional spreading and wave steepness also slightly increases the redistribution rate. The spreading of the nourishment is found to be less sensitive to different shapes of the cross shore profile and grain sizes larger than 250  $\mu\text{m}$ . For smaller grain sizes the redistribution however rapidly increases. The erosion rate calculated by the tool can only be used as an indicative estimate. Based on the model results several empirical relations and a design graph are derived to estimate the redistribution and the lifetime of a mega nourishment. These equations can be used for an initial design of a mega nourishment. To obtain an accurate lifetime prediction it is recommended to pay sufficient attention to the quality of the wave data and the estimation of the shoreline erosion.



---

# Preface

This thesis concludes the double degree master program "Hydraulic Engineering and Water Resources Managements" at the Delft University of Technology and the National University of Singapore. The research was conducted in cooperation with the group "Hydrodynamics and morphology" as part of "Witteveen+Bos", an engineering and consultancy company.

The initial idea for the topic of my thesis was about the application of a "building with nature" solution (like the Sand Engine) to prevent further coastal retreat in Da Nang Bay, Vietnam. A proposal was already made by Witteveen+Bos but unfortunately the project was cancelled just before the start of my graduation work. From that moment on the choice was made to follow a more general approach for my research by focussing on the international potential of the mega nourishment concept as a new coastal protection measure. This very broad and general topic was further specified by considering the influence of different wave climate conditions and nourishments shapes on the lifetime of this soft engineering solution.

First of all I would like to thank my graduation committee for their help during the graduation period. This thesis work would not be as successful without the help from my main supervisors, Daniël Dusseljee and Arjen Luijendijk. I would like to thank them for their enthusiasm, inspiring ideas and useful feedback during the frequent meetings we had. I'm also grateful for the help of Marion Tissier for her ideas and thorough review of my report; Bas Huisman for sharing his expertise, thoughts and feedback; and Marcel Stive for his input during the committee meetings. Special thanks go also to Gerwin Stam whose thesis work about beach extensions at the Dutch coasts and model set-up was a good starting point and inspiration for my own work.

During my graduation work I had a great time at Witteveen+Bos during working hours, the drinks and the outings organised by the company. I would like to thank my colleagues and fellow graduate students for their interest in my work, their willingness to help and for the enjoyable time.

Finally I would like to thank my parents who gave me the possibility to study and always supported me during my studies and my girlfriend for her care and unconditional love. Finally many thanks to my family and friends for their support, encouragement and interest in my studies.



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# Nomenclature

|               |                                                                               |
|---------------|-------------------------------------------------------------------------------|
| $\beta$       | Beach slope [°]                                                               |
| $\theta_c$    | Coastline angle [°]                                                           |
| $\theta_{eq}$ | Equilibrium coastline angle for which $Q_s$ is zero [°]                       |
| $\theta_r$    | Coastline angle relative to the angle of equilibrium: $\theta - \theta_e$ [°] |
| $\rho_s$      | Sediment density [kg/m <sup>3</sup> ]                                         |
| $\theta_w$    | Wave direction relative to shore normal [°]                                   |
| $c$           | Wave velocity [m/s]                                                           |
| $c_1$         | Coefficient of the S- $\phi$ curve [m <sup>3</sup> /yr]                       |
| $c_2$         | Coefficient of the S- $\phi$ curve [-]                                        |
| $c_g$         | Wave group velocity [m/s]                                                     |
| $D_{10}$      | Grain size for which 10% of the particles is finer [ $\mu$ m]                 |
| $D_{50}$      | Median grain size diameter [ $\mu$ m]                                         |
| $D_{90}$      | Grain size for which 90% of the particles is finer [ $\mu$ m]                 |
| $DoC$         | Depth of Closure [m]                                                          |
| $DoI$         | Distance of Influence [m]                                                     |
| $E$           | Erosion rate [m/yr]                                                           |
| $E_w$         | Wave energy [J/m <sup>2</sup> ]                                               |
| $f_w$         | Friction coefficient [-]                                                      |
| $g$           | Gravitational acceleration [m/s <sup>2</sup> ]                                |
| $h$           | Water depth [m]                                                               |
| $H_0$         | Deep water wave height [m]                                                    |
| $h_d$         | Elevation of the dune/berm above Mean Sea Level (MSL) [m]                     |
| $h_{db}$      | Water depth at dynamic boundary [m]                                           |
| $h_p$         | Height of the active profile [m]                                              |
| $H_s$         | Significant wave height [m]                                                   |
| $K$           | Diffusion coefficient [m <sup>2</sup> /yr]                                    |
| $k_b$         | Bottom roughness [m]                                                          |
| $L_0$         | Deep water wave length [m]                                                    |
| $L_{DoC}$     | Cross shore distance between the water line and the $DoC$ location [m]        |
| $L_{mn}$      | Alongshore length mega nourishment [m]                                        |
| $p$           | Porosity [-]                                                                  |

|            |                                                                  |
|------------|------------------------------------------------------------------|
| $Q_s$      | Sediment transport [ $\text{m}^3/\text{yr}$ ]                    |
| $q_s$      | Sediment transport rate per unit width [ $\text{m}^2/\text{s}$ ] |
| $R$        | Coastal retreat [m]                                              |
| $s$        | Wave steepness [-]                                               |
| $SLR$      | Sea level rise [m]                                               |
| $T_{50\%}$ | Nourishment half-time [yr]                                       |
| $T_L$      | Lifetime of a mega nourishment [yr]                              |
| $T_p$      | Wave peak period [s]                                             |
| $T_s$      | Significant wave period [s]                                      |
| $u$        | Flow velocity [m/s]                                              |
| $V_{mn}$   | Volume mega nourishment [ $\text{m}^3$ ]                         |
| $W_{mn}$   | Cross shore width mega nourishment [m]                           |
| $w_s$      | Sediment fall velocity [m/s]                                     |
| $y$        | Cross shore coastline position [m]                               |
| $y_{db}$   | Offshore location of dynamic boundary [m]                        |
| $z_b$      | Bed level [m]                                                    |

---

# Abbreviations

|              |                                                    |
|--------------|----------------------------------------------------|
| <b>DMW</b>   | Dean-Moore-Wiegel                                  |
| <b>DoC</b>   | Depth of Closure                                   |
| <b>DoI</b>   | Distance of Influence                              |
| <b>ECMWF</b> | European Centre for Medium-Range Weather Forecasts |
| <b>GEBCO</b> | General Bathymetric Chart of the Oceans            |
| <b>GP</b>    | Generalised Pareto                                 |
| <b>IFS</b>   | Integrated Forecast System                         |
| <b>IPCC</b>  | Intergovernmental Panel on Climate Change          |
| <b>LST</b>   | Longshore Sediment Transport                       |
| <b>MHW</b>   | Mean High Water                                    |
| <b>MLW</b>   | Mean Low Water                                     |
| <b>MSL</b>   | Mean Sea Level                                     |
| <b>MSTR</b>  | Mean Spring Tidal Range                            |
| <b>NOAA</b>  | National Oceanic and Atmospheric Administration    |
| <b>RCP</b>   | Representative Concentration Pathway               |
| <b>RMS</b>   | Root Mean Square                                   |
| <b>RTR</b>   | Relative Tidal Range                               |
| <b>SLR</b>   | Sea Level Rise                                     |



---

# Chapter 1

---

## Introduction

About 20 to 40% of the coasts around the world are backed by beaches and other sandy deposits (Bird, 1996, 1985). World-wide evidence on beach erosion, assembled between 1976 and 1984 by the Commission on the Coastal Environment, showed that more than 70% of these sandy shores eroded in this period. (Bird, 1985). Besides this, coastal utilisation has tremendously increased since the 20<sup>th</sup> century and is expected to increase even further. Currently 23% of the world's population and 60% of the 39 largest cities in the world with 5 million inhabitants or more are located within a distance of 100 km from the shore (Nicholls et al., 2007). The increase in human utilisation squeezes the coastal system and results in a lack of space for the beach to move landward as it would naturally do. Buildings, infrastructure and other human functions in the coastal area are now threatened by shore retreat. The combination of an expected long term coastal erosion trend and further increase in human pressure on the coastal system will amplify the human vulnerability and will enlarge the severity and quantity of coastal erosion problems around the world.

Different solutions have been used to combat coastal erosion varying from 'hard' solutions such as groins, offshore breakwaters and revetments till 'soft' solutions like beach and foreshore nourishments. In the Netherlands coastal erosion has successfully been mitigated by nourishments along the 350 km long sandy shoreline since 1990. A predicted acceleration in sea level rise however would require larger nourishment volumes to keep the shoreline at its current position. An innovative solution was therefore developed and executed in a pilot project in the Netherlands to nourish larger amounts of sands: the "Sand Engine". This concept, also known under the term "Mega nourishment", consists of a local sandy perturbation of the coast that will be redistributed alongshore by the forces of the sea to supply sediments to the adjacent coast. As mentioned by Stive et al. (2013), elements of this sandy strategy could be applied in other coastal areas around the world that suffer from beach retreat. It is however unknown how quickly such a nourishment will redistribute along other types of beaches and how often such a measure needs to be applied to obviate shoreline retreat. In this graduation research a tool is therefore developed to investigate how the wave climate and the nourishment dimensions influence the redistribution and lifetime of a mega nourishment.

### 1-1 The problem of beach erosion

Seaward and landward movement of the shoreline is a natural process which has always been present and is not necessarily a problem in itself. According to Pilkey et al. (2011) the greatest threat for the world's beaches is therefore not only caused by the forces of nature such as storms and a rising sea level. The threat mainly comes from the human population itself that urbanised the area close to the shore, squeezed the coastal system and now attempts to control the beach position instead of allowing the shore to move landward as it naturally would. Since the Second World War humans have replaced many natural dune systems by buildings close to the shore (Schwartz, 2006). This utilisation considerably increased over

the past century and lead to an aggravation of coastal erosion problems. For the 21<sup>st</sup> century a further increase in human population in the coastal area is expected by Nicholls et al. (2007). They presented several scenarios in which the coastal population of 1.2 billion people of 1990 could increase to 1.8 - 5.2 billion in 2080. With this it was concluded with very high confidence that the consequences of climate changes on the coastal areas will exacerbate due to the increase in human pressure on the coastal area.

From the above it becomes clear that a coastal erosion problem is always a combination of 1) the erosional processes that cause a shore to retreat and 2) the presence of human functions close to the sea that are threatened by this retreat. For these functions one could for example think of living, recreation, nature development, flood safety of the hinterland and agriculture. Figure 1-1 is a good example that illustrates this existence of an erosion problem: a retreating beach that is threatening a residential area. This research searches for an efficient method to estimate the lifetime of a sandy solution as a mitigation measure for these coastal erosion problems.



**Figure 1-1:** Example of an erosion problem which is a combination of shoreline retreat and human functions that are at risk (Source: Barringer)

## 1-2 Mega nourishments

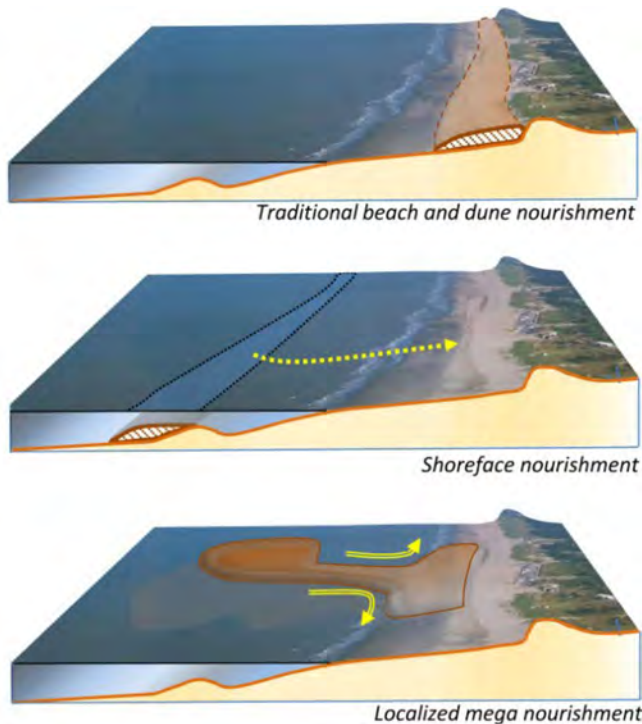
A mega nourishment is a recently developed innovative sandy solution to obviate coastal erosion problems. It is a *large, local, salient shaped nourishment* of sand in front of the coasts that is redistributed alongshore by the ocean forces (waves and tides) to supply sediments to the adjacent coast. It serves as a *multifunctional and long term solution* for a coastal erosion problem.

A visualisation from Stive et al. (2013) is presented in Figure 1-2 to illustrate how this innovative concept differs from the more traditional nourishment strategies applied on the beach, dune and foreshore. The main difference between these nourishment concepts is related to the redistribution processes that are favoured. For a traditional dune and beach nourishment the erosion by natural processes is undesired and should be minimized to keep the beach in place as long as possible. A shore face nourishment however uses these natural processes to redistribute the sand in cross shore direction. The mega nourishment concept goes a step further by also using the natural processes to redistribute the nourishment in alongshore direction. This type of nourishment is therefore only placed on part of the beach and has a larger volume per meter shore.

A mega nourishment can be seen as a total coastal management system that combines coastal engineering with environmental, ecological and social functions of the coastal area (Stive et al., 2013). It has several advantages in comparison to the traditional beach and foreshore nourishments. First of all such a nourishment has an advantage of scale which makes it a more economical solution. Besides, it reduces the nourishment frequency which is beneficial in the light of the expected increase in the severity of coastal erosion. The nourishment concept furthermore only has to be executed on a small stretch of coasts. This local character in combination with a reduced frequency results in less disturbance of the coastal area

and therefore reduces the ecological stress on the coast. Finally the large perturbation provides space for recreation and nature development which makes it a multifunctional solution for coastal erosion.

Currently the mega nourishment concept has only been applied ones in the Sand Engine pilot project (see Section 1-3). It could however become a more common alternative to solve erosion problems. A start has already been made to investigate the application of this concept at other locations in the world. In Southern Sweden and Lima (Peru) for example several parties already showed their interest in this innovative concept. Witteveen+Bos furthermore proposed to investigate whether a mega nourishment is applicable to solve an erosion problem at the coast of Da Nang (Vietnam). From this it becomes clear that the mega nourishment concept has an international potential to solve current and future erosion problems around the world.



**Figure 1-2:** Visualisation of nourishment strategies. (a) traditional beach and dune nourishment, (b) a shoreface nourishment that will be distributed by marine processes in cross-shore directions and (c) a localised mega nourishment that will be distributed by marine and aeolian processes in cross-shore and long-shore direction (Source: Stive et al., 2013)

### 1-3 The Sand Engine

Recently the mega nourishment concept was executed in a pilot project, called "the Sand Engine", to combat coastal erosion in the Netherlands, a low-lying country of which more than 50% of the land lies below mean sea level. This country is primarily protected by beaches and dunes along the 350 km North-sea coastline to prevent flooding from the sea. Due to a reduction in sediment supply from the rivers and a rising sea level the Dutch coast is eroding over the past centuries (Pranzini and Williams, 2013). After years in which coastal erosion was primarily mitigated by hard constructions, the government decided in 1990 to implement a new nourishment policy, named 'dynamic preservation'. According to this policy the coastline should be kept at its 1990 position by means of sandy solutions. Since then the Dutch have gained over 20 years of experience with beach and foreshore nourishments and executed around 300 nourishments at more than 60 different locations. Such a foreshore nourishment typically has a length of approximately 2 to 5 km, a total volume of 1-2 Mm<sup>3</sup> of sand (300-500 m<sup>3</sup>/m) and a lifetime of 3-5 years (Stive et al., 2013; Bosboom and Stive, 2012).

Currently 12 Mm<sup>3</sup> of sand is nourished every year on the Dutch coasts. Mulder and Tonnon (2011) expect however that the current yearly nourishment volume will increase to 85 Mm<sup>3</sup> per year by 2050 to prevent shoreline retreat. In this context the idea was born to nourish one large volume of sand to protect the Delfland coast for a period of 20 years. This idea was eventually executed in a pilot project at Kijkduin called the 'Sand Engine'. This example of a mega nourishment consists of a shoreline perturbation with a



**Figure 1-3:** The Sand Engine in September 2011 (left) and September 2013 (right)  
(©Rijkswaterstaat/Joop van Houdt)

volume of  $21 \text{ Mm}^3$  (approximately  $10,000 \text{ m}^3/\text{m}$ ). It is an example of "building with nature" where the natural forces of waves and tides rework the sediments to feed the adjacent coastline over a stretch of 10 to 20 km for a period of 20 years, creating 35 ha of new beach. After construction the Sand Engine had an area of 128 ha, stretched 2.4 km of coastline and extended 1 km offshore. Several salient shapes were considered in the design and eventually a hook-shaped mega nourishment was preferred.

Figure 1-3 shows the initial shape of the sand engine a few months after construction (left) and after two years (right). The figure shows that the Sand Engine already spread towards the north and the south in the two years after construction. Currently research is going on to monitor the morphology and to better understand the coastal processes that play a role. This research will continue until 2021 and the first official results will be available in 2016. For more information about the Sand Engine reference is made to Appendix A.

## 1-4 Research objective

The idea of the Sand Engine could be exported to other beaches in the world to make the mega nourishment concept one of the standard soft engineering strategies to mitigate coastal erosion. Until now it has however not been researched how quickly a mega nourishment will redistribute and how often such a measure needs to be applied at other sandy shores in the world that suffer from erosion. One main objective is therefore defined:

*Determine the relative influence of **wave climate parameters** and **nourishment dimensions** on the **lifetime** of a mega nourishment for a straight alongshore uniform sandy coast using data from global wave models*

The **lifetime** is defined as the time for which the coastline position remains seaward of its initial position before executing the mega nourishment. Its definition is further explained in Section 3-1. It is explicitly chosen to use global wave data sources to enable the possibility to make a quick first assessment of the redistribution rate and lifetime of a mega nourishment at a geographical location in the world. This serves an important sub-objective to make this research also useful for engineering practices.

The overall objective will be reached by following an approach that consists of three steps:

1. *Identify the sediment transport processes that affect the redistribution rate and the lifetime of a mega nourishment*

2. *Set up a modelling framework that incorporates these coastal processes to simulate the coastline evolution in time*
3. *Quantify the relation between environmental parameters (e.g. wave climates and nourishment dimensions), redistribution and lifetime of a mega nourishment*

## 1-5 Scope

The coast is a very complex system that shows a large variability. This makes it impossible to assess the lifetime of a mega nourishment for all coastal configurations. The choice is therefore made to focus on the following parameters only:

- *Wave climate parameters (from global wave data sources): Height, direction and steepness*
- *Size and shape of a mega nourishment*
- *Sea Level Rise (SLR)*
- *Potential storm impact*

A sensitivity analysis is performed for the effect of different uniform sediment sizes and exponential cross shore profile shapes. Sediment transport by wind and tidal flow will not be considered. This thesis will furthermore not deal with complex coastline forms such as bays and river deltas. Also the effect of spatial variations in offshore bathymetry such as islands and offshore canyons in front of the shore are not considered. The coastline will be assumed to be straight and alongshore uniform.

## 1-6 Report outline

The next chapter will identify the sediment transport processes that are relevant for a mega nourishment. These processes are included in the MN-tool which is described in chapter 3. This chapter starts with a description of the modelling approach and the definition of lifetime. Subsequently a detailed description is included about the tool. The chapter ends with a specification of the different model parameters and runs that will be performed to assess the relative influence of the wave climate parameters and nourishment dimensions. A comparison between the tool predictions, other model results and measurements for the Sand Engine is made in chapter 4. Chapter 5 continues with a presentation of the model results for the redistribution of the nourishment, the erosion of the autonomous shore and finally the lifetime. In this chapter several empirical relations will be presented. The results are followed by a discussion chapter that elaborates on the exclusion of physical processes, the consequence of the model assumptions and the practical issues for applying the tool for a mega nourishment design. Chapter 8 includes the main conclusions and recommendations for further research.

This document includes four appendices. Appendix A provide more background information regarding the Sand Engine. Appendix B elaborates on the model background and underlying equations. A more detailed description about the model parameters and wave climates is included in Appendix C. Finally Appendix D discusses some of the famous coastal classification schemes.

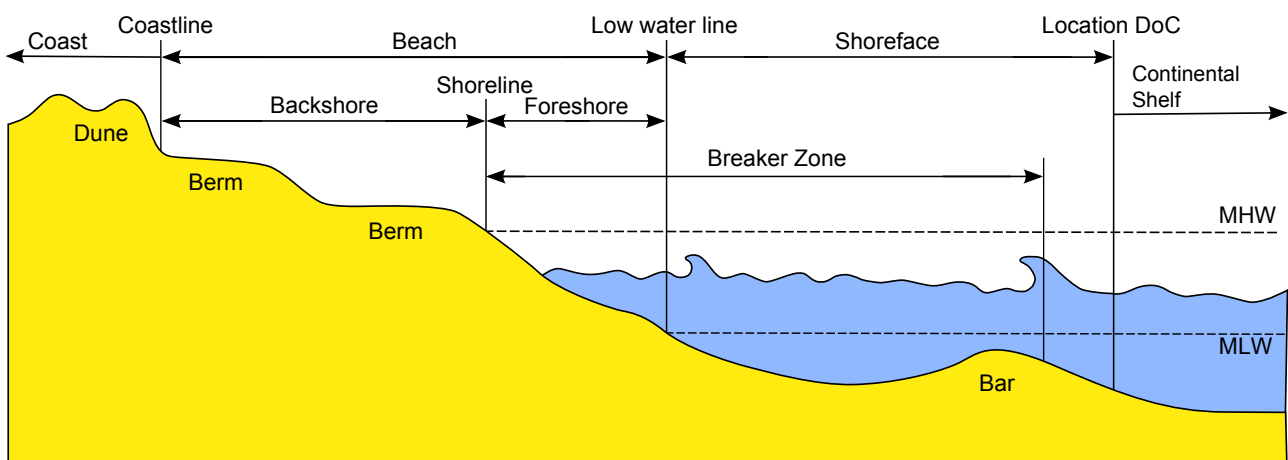


## Identification of processes and parameters

In this chapter the coastal processes are identified that influence the redistribution rate and lifetime of a mega nourishment. It starts with a general terminology of the coastal zone. Subsequently Section 2-2 deals with the sediment transport processes that influence the nourishment redistribution and the coastal erosion.

### 2-1 Coastal terminology

The *coastal zone* is the transition zone between land and sea and is schematically visualised in Figure 2-1. It consists of four zones: Coast, beach, shoreface and continental shelf. The *beach* reaches from the Mean Low Water (MLW) line till the landward limit that is affected by storm waves. The *shoreface* extends from the MLW line till a depth of about 10 to 20 meters where the bottom profile is not affected by wave action (Bosboom and Stive, 2012). The area landward of the beach till the first major topographical change is defined as the *coasts*. Seaward of the shoreface the *continental shelf* begins, a shallow area that surrounds a continent. The beach consists of the *foreshore* (the area between the MLW line and the Mean High Water (MHW) line) and the *backshore* (the part of the beach that is usually dry). The boundaries of the breaker zone are varying as the wave conditions change. This zone reaches from the offshore location where the waves start to break till the shoreline which is located at the MHW line.



**Figure 2-1:** Definitions in the coastal zone (adapted from US Army Corps Of Engineers, 2002)

The Depth of Closure (DoC) is the seaward limit of the shoreface and is defined as the water depth at which the bed level show no significant changes over a certain period of time. Extending a mega nourishment

beyond the DoC implies that part of the nourished volume will never be transported by the waves. The DoC is also required to estimate the erosion caused by SLR (see Section 2-2-3).

Hallermeier (1981) proposed an empirical formulation for the annual value of the DoC. According to Nicholls et al. (1998) this formulation can also be written in generalized time-dependent form as:

$$DoC = 2.28H_{s,t} - 68.5 \frac{H_{s,t}^2}{gT_{s,t}^2} \quad (2-1)$$

The symbol  $t$  stands for the time scale that is considered.  $H_{s,t}$  is the non-breaking significant wave height that is exceeded 12 hours per 't' years with corresponding significant wave period  $T_{s,t}$ .  $g$  is the gravitational acceleration.

In 1985 Birkemeier modified the equation of Hallermeier by adjusting the coefficients to 1.75 and 57.9 based on other site specific measurement surveys conducted at Duck, North Carolina. His equation results in a smaller DoC. According to Kraus et al. (1998) it is recommended to use the DoC formulation of Hallermeier for beach fill design because it provides a conservative estimate.

## 2-2 Sediment transport processes

This section first introduces the notion of sediment transport. Subsequently both longshore and cross shore sediment transport processes are described including the important parameters that influence these processes.

### 2-2-1 Sediment transport

According to Bosboom and Stive (2012) sediment transport is defined as the movement of particles over a certain period of time through a well-defined plane. It can be classified based on the transport mechanism: Bed load transport (described as the rolling and sliding of material close to the bed) and suspended transport (the transport of sediments that are in suspension). The total sediment transport is the sum of both mechanisms.

Gradients in sediment transport result in bed level changes. This is described by the Exner equation, a continuity equation that relates the bed level  $z_b$  to the transport of sediment  $Q_s$  in  $x$  and  $y$  direction:

$$(1 - p) * \frac{\partial z_b}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \quad (2-2)$$

In general the total sediment transport can be calculated with Equation 2-3 by integrating the flow velocity  $u(z)$  multiplied by the sediment concentration  $c(z)$  over the water depth  $h$ . In this equation the parameter  $a$  represents the thickness of the bed load transport layer.

$$q = q_b + q_s = \int_0^a u(z)c(z)dz + \int_a^h u(z)c(z)dz \quad (2-3)$$

The transport of sediments is a very complex process for which only empirical relations exist that relate the transport to the hydrodynamic forcing and the sediment characteristics. Along a coast sediment transport is often driven by a combined motion of waves and currents. The oscillatory near bed velocity caused by waves generally stirs up the sediments from the bed. The (wave induced) currents cause the net movement of the mobilized particles.

In sediment transport formulations several characteristic sediment properties are used. One of the most commonly used is the median grain size  $D_{50}$ . To describe the grading of the sediments the ratio of  $D_{10}/D_{90}$  is often used with  $D_x$  defined as the diameter for which  $x\%$  of the particles is finer. Other important parameters are the porosity  $p$  and the density of the material  $\rho_s$ .

### 2-2-2 Longshore transport

When waves approach the beach under an angle a current is generated by a longshore directed wave force. This current has a certain transport capacity by which sediments can be moved. Its magnitude mainly depends on the hydrodynamic forces in the surf zone and the resistance of the sediment particles (Bosboom and Stive, 2012). The turbulence of the breaking waves stirs up sediment from the bed. These suspended sediments are transported along the coast by the wave induced longshore current. Spatial gradients in the LST cause a net movement of sediments which results in coastline changes.

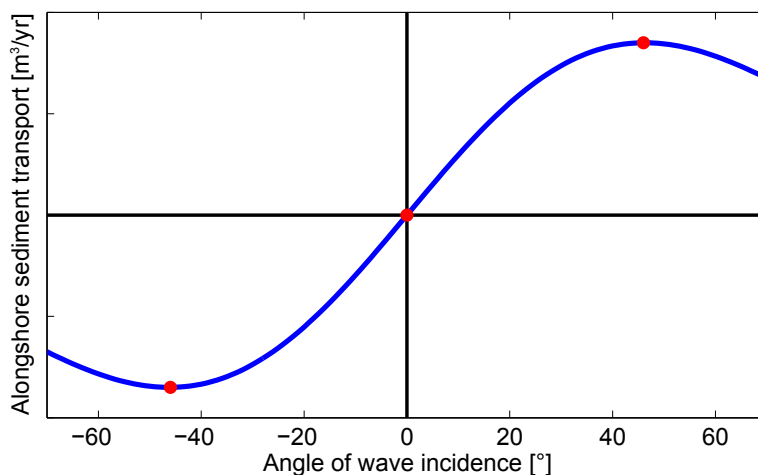
#### Transport models

The LST can be estimated by bulk transport formulas and process based models (Mil-Homens et al., 2012). Bulk transport formulas are empirical and quantify the total transport over the entire surfzone. These simplified formulas are dependent on a small number of input parameters and are easy to apply. However without calibration these different formulas can easily give a transport estimates that differs by a factor 10 (Bosboom and Stive, 2012). Different bulk transport formulas are proposed in literature such as the CERC formula and the formulation of Kamphuis (1991). In the CERC formulation the LST only depends on wave height, angle of wave incidence and the immersed mass of sediments. This formulation generally gives an overestimation of the LST. In the Kamphuis formulation the LST is a function of wave parameters (height, period and angle of incidence), sediment properties (grain size and immersed mass) and beach slope.

Process based LST models are based on balance equations and calculate the cross shore distribution of the longshore current. The near bed velocities that follow from this calculation are used in empirical sediment transport formulation (such as the formulation of Van Rijn et al. (2004)) to compute the LST. The Unibest model is an example that calculates the LST using a process based approach (see Section 3-2 for more information).

#### S- $\theta$ curve

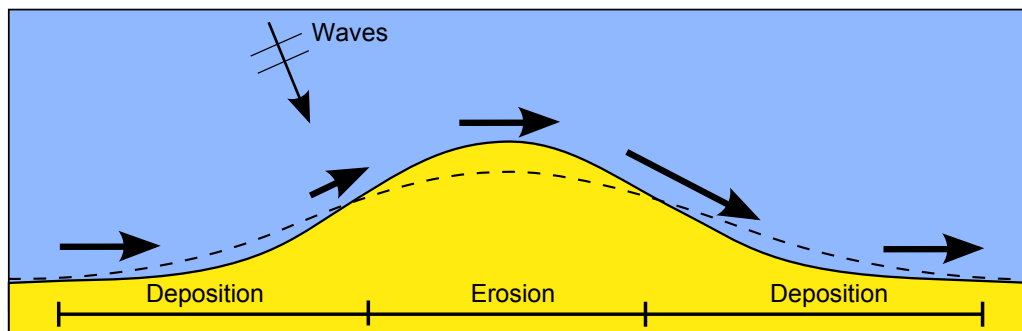
The magnitude of the LST rate is a function of the wave angle. In literature this relation is often expressed in an "S- $\varphi$  curve". Because all angles in this theses are denoted by  $\theta$  it is called the "S- $\theta$ " curve where S refers to the sediment transport and  $\theta$  to the angle of wave incidence (see Figure 2-2). The LST is zero for normal incident waves with an angle of  $0^\circ$ . The maximum LST occurs for a wave angle of about  $45^\circ$ . For wave angles of  $\pm 30^\circ$  the relation between transport and wave angle is almost linear. The local slope of this curve represent the LST gradient. The S- $\theta$  curve will be a central concept throughout this report.



**Figure 2-2:** Example of an S- $\theta$  curve which shows the relation between the LST and the angle of wave incidence. The red dots indicate the angles of wave incidence that correspond to the maximum and minimum LST

### Effect on a mega nourishment

The longshore redistribution of a mega nourishment is caused by gradients in LST. The coastline along a mega nourishment can be seen as a local disturbance of the "equilibrium" shoreline orientation. This curvature gives rise to gradients in the LST resulting in the redistribution of a mega nourishment and a restoration of the original (in this case straight) coastline. Figure 2-3 visualises the changes in LST by means of black arrows along a mega nourishment. The size of the arrow represents the magnitude of the LST. The figure furthermore shows the corresponding locations of erosion and deposition. This situation is valid for waves with a relative angle of incidence smaller than  $45^\circ$ .



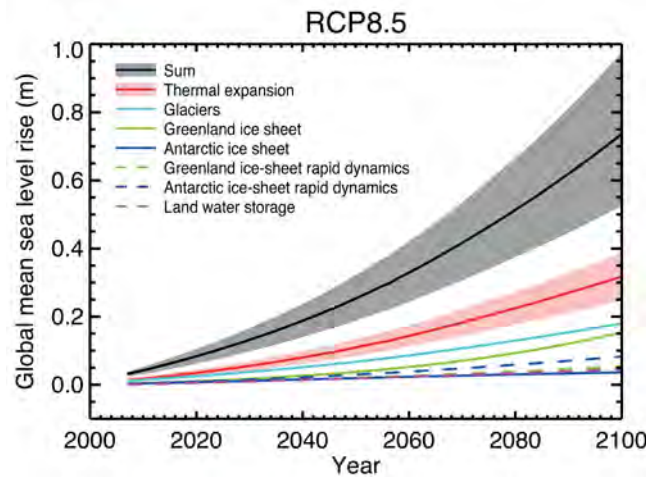
**Figure 2-3:** LST gradients around a mega nourishment for waves with a relative angle of incidence smaller than  $45^\circ$  and the corresponding erosion and deposition pattern (adapted from Ashton and Murray, 2006)

### 2-2-3 Cross shore transport

The lifetime of a mega nourishment depends on the cross shore erosion of the coast. For a straight alongshore uniform coast there are no LST gradients. The erosion is therefore only caused by sediment transport processes in cross shore direction. The erosional processes that are taken into account in this thesis are discussed below: The retreat due to SLR and storm erosion.

### Sea level rise and coastal retreat

SLR is one of the main threats for the coastal systems in the world and is therefore extensively discussed in literature. According to the latest report of the Intergovernmental Panel on Climate Change (IPCC) it is considered very likely that the rate of SLR will increase in the 21st century. Predictions on global mean SLR for different climate scenarios range from 0.26 m to 0.98 m by 2081 - 2100 relative to 1986 - 2005. Figure 2-4 shows the SLR prediction following the most extreme Representative Concentration Pathway (RCP) scenario leading to a total radiative forcing of  $8.5 \text{ W/m}^2$  in 2100. For these scenarios the rate of SLR is expected to increase from 3.2 mm per year in 1993 - 2010 to 8 - 16 mm per year in 2081 - 2100 (Church et al., 2013). The IPCC report states that SLR will most probably show a strong spatial variation. Along 70% of the coast the predicted SLR is expected to be within 20% of the global mean.



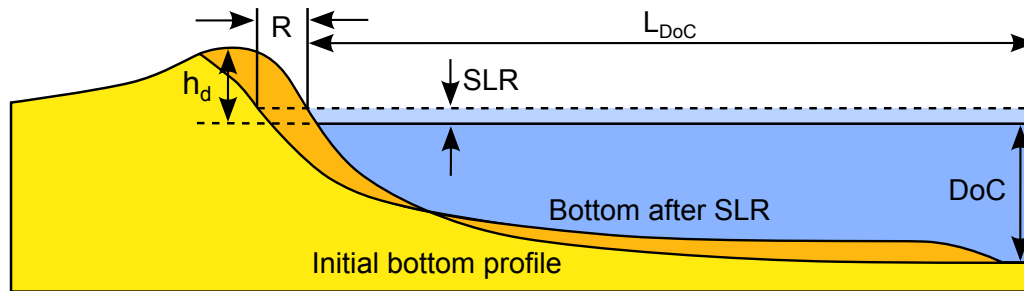
**Figure 2-4:** Prediction of global mean SLR relative to 1986-2005 as function of time for the RCP8.5 scenario (Source: Church et al., 2013)

The rise in sea level will have a negative effect on the sediment budgets of the world's coastlines. There are however numerous factors that cause a change in the coastal sediment balance which makes it very hard to discern and quantify the impact of SLR. The Bruun rule is the most widely used method to estimate the relation between SLR and coastal retreat, a simplified 2D cross-shore mass conservation model (Bruun, 1962). The model of Bruun showed that the shoreline response to SLR is not just a movement of the waterline but rather a landward and upward change of the whole coastal profile (Cooper and Pilkey, 2004). Bruun assumed an equilibrium between the cross shore profile and the hydrodynamic forcing (Bosboom and Stive, 2012). When sea level rises, the foreshore becomes deeper and less effective in dissipating the wave energy. Higher waves will therefore reach further up the shore and move sediments offshore. The equilibrium profile is restored by filling the cross-shore profile with sediments originated from the upper beach (see Figure 2-5). This process is quantified by the Bruun rule which is expressed as:

$$R = \frac{L_{DoC}}{h_d + DoC} SLR = \frac{1}{\tan \alpha} SLR \quad (2-4)$$

The shoreline retreat ( $R$ ) is a function of the cross-shore distance ( $L_{DoC}$ ), the closure depth ( $DoC$ ), the rise in sea level ( $S$ ) and the elevation of the dune above MSL ( $h_d$ ). For small values of the average bottom slope  $\tan \alpha$  (e.g. 0.01 to 0.02) the retreat is approximately 50 to 100 times the rate of SLR (FitzGerald et al., 2008).

It should be emphasised that the Bruun rule has its limitations and shortcomings. The formula does not include the real physical process of waves that erode sediments offshore. It furthermore requires several input parameters that have a major uncertainty such as the DoC. Ranasinghe and Stive (2009) concluded that the equation is therefore only suitable to obtain an indicative estimate of the coastal retreat. There are however no other methods available to quickly estimate the impact of SLR.

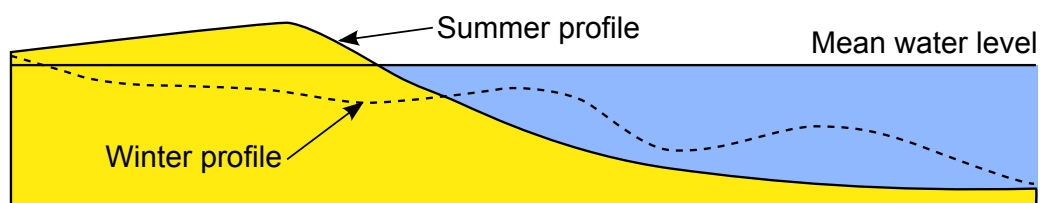


**Figure 2-5:** Coastal response towards a rise in sea level according to the Bruun rule. The coast retreats with SLR by moving sediments offshore (adapted from FitzGerald et al., 2008)

### Profile variability by seasonal wave climate variations

Seasonal wave climate variations cause cross shore beach profile variability. This is explained by the typical 'summer' and 'winter' profile (see Figure 2-6). In winter the profile slope is generally milder to better dissipate the higher wave energy. This milder slope is caused by the strong wave undertow which causes sediments to move offshore. In summer sediments are transported onshore predominantly due to short wave skewness of the lower waves (Bosboom and Stive, 2012). This seasonal variation in wave climates continuously redistribute sediments in the littoral zone resulting in an oscillating water line position. This oscillating movement can be seen as the "breathing space" of the beach. As long as the wave climate does not intensify there is no net loss of sand from the beach. When storm intensity and frequency however increases, more sediments are eroded offshore to a larger water depth. When the recovery time of the beach during the milder 'summer' waves becomes insufficient to restore the original coastline position, the beach shows a net eroding trend. The process induced by an intensified wave climate is comparable to the effect of SLR. For coasts along a narrow continental shelf where submarine canyons can reach the littoral zone (mainly along leading edge coasts) more sediments can permanently be lost to deeper water by this cross shore sediment transport process. The width of the relatively shallow area is therefore an important parameter that determines the accommodation space for a mega nourishment.

Unfortunately no reliable estimates are available for predictions on wave climate intensification. Furthermore the estimate of the coastal retreat due to an intensification of the wave climate is already a research in itself. Therefore the impact of an intensified wave climate on the coastal profile will not be considered in this thesis.



**Figure 2-6:** Changes in beach profiles due to seasonal variation in wave climate: Summer and winter profiles (adapted from Schwartz, 2006)

### Landward sediment loss in storms

Besides offshore directed transport, sediments can also be lost from the shore in landward direction when the beach is attacked by a storm, cyclone or hurricane. This process is especially important when the height of the backshore and dunes is relatively low compared to the sea water level. Sallenger (2000) defined four different storm regimes to categorise the storm impact on barrier island:

- Swash regime: wave run-up is confined to the foreshore
- Collision regime: wave run-up reaches the dune base and starts eroding the dune

- Overwash regime: wave run-up is larger than the dune height and overtopping of the dunes take place
- Inundation regime: The coastal profile is submerged and water flows over the dune

In the overwash and inundation regime waves transport sediments to the hinterland which is a permanent sediment loss. This process is expected to be very sensitive to the height of the profile relative to the storm surge level and the storm wave energy. The amount of sediments that are lost can furthermore be dependent on the shape of the profile, the duration of the storm and the sediment properties.

## 2-3 Summary

The redistribution of the nourishment in alongshore direction is caused by gradients in LST. The magnitude of these gradients depends on the wave climate, the sediment size, the coastline gradient and the slope of the cross shore profile. The erosion is determined by sediment transport processes in cross shore direction. The erosional processes that will be considered are SLR and the sediment loss in landward direction during storms. Important parameters that influence these processes are expected to be the shape of the cross shore profile, the wave climate and the sediment properties.

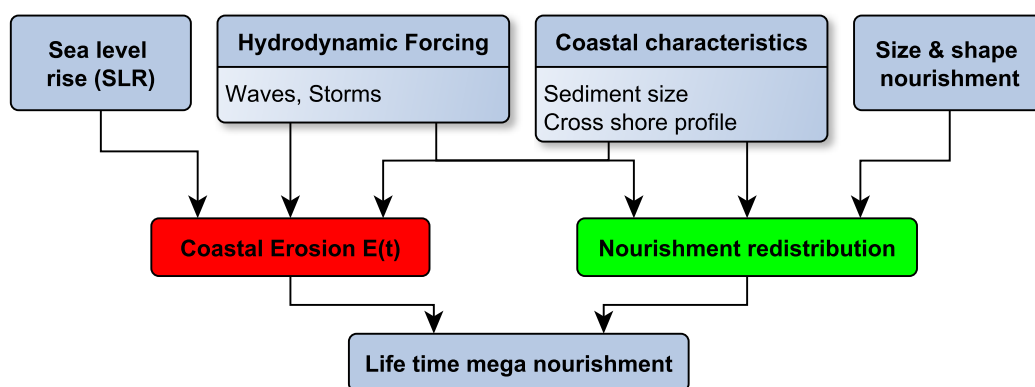


## Mega Nourishment tool

An approach is explained in the first section to quantify the lifetime of a mega nourishment. The second sections describes the numerical models that are used to estimate the redistribution of the nourishment and the erosion of the shore. The approach is subsequently reflected in a self-developed tool to calculates the lifetime of the mega nourishment. This tool is called "The Mega Nourishment tool" abbreviated as the "*MN-tool*". An overview of the MN-tool and a detailed description of the individual parts in provided in Section 3-3. The chapter ends with a description of the model strategy and parameters.

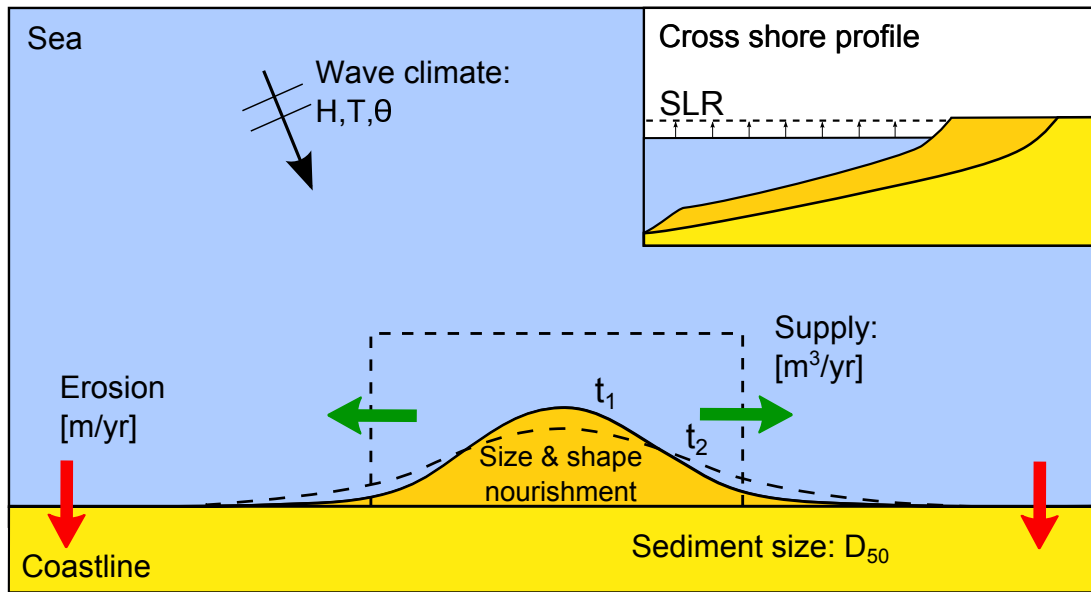
### 3-1 Model approach

The model approach is summarised in a flow chart presented in Figure 3-1. The final aim of this approach is to estimate the *lifetime* of a mega nourishment. This lifetime is determined by 1) the expected erosion of the shore and 2) the supply rate of sediments due to the redistribution of a mega nourishment. the *coastal erosion* and the *nourishment redistribution* are caused by sediment transport processes in cross shore and longshore direction. As described in Section 2-2 these processes are a function of different coastal parameters (see the top row of the flow chart in Figure 3-1).



**Figure 3-1:** Modelling approach: Estimation of the lifetime by quantifying the coastal erosion and the nourishment redistribution

Figure 3-2 visualises the approach using a top view of the mega nourishment area. A virtual box is drawn around the initial shape of the nourishment. The redistribution of the nourishment is represented by the green arrows that represent the sediment supply to the adjacent coast. This supply of sediments should compensate the erosion of a coastal stretch (visualised by the red arrows) to prevent shoreline retreat.



**Figure 3-2:** Model schematisation: Top view and cross section (top right) of the coasts including the different parameters that influence the morphological development of a mega nourishment. The green and red arrows indicated the sediment supply from the nourishment and the erosion of the shoreline respectively

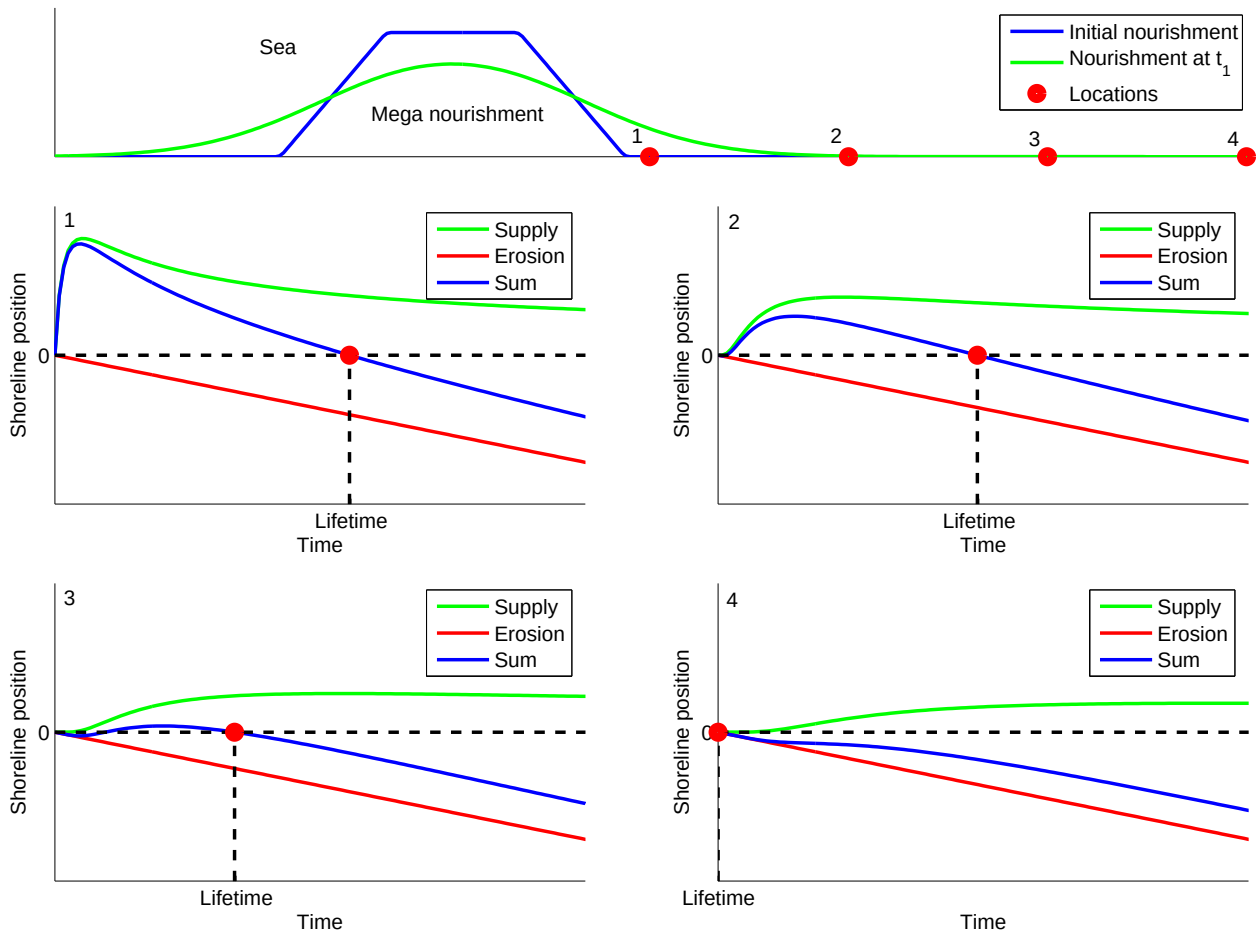
The lifetime of a mega nourishment is defined as the time for which the coastline position remains seaward of its initial position (before executing the nourishment) and can be described by Equation 3-1. It is a function of:

1. The *redistribution* of the nourishment supplying sediments to the coast
2. The *erosion* of the autonomous shore
3. The longshore *distance* from the center of the nourishment

$$Lifetime = f(Redistribution, Erosion, Distance) \quad (3-1)$$

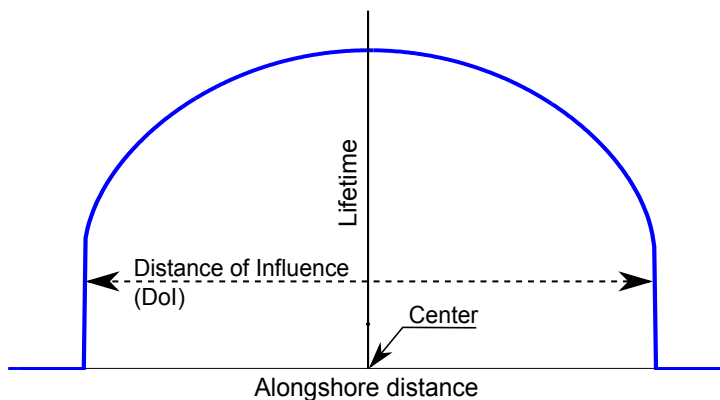
The concept of lifetime is further clarified using conceptual visualisations presented in Figure 3-3. The top of this figure shows a plan view of the initial mega nourishment shape and at a later time level  $t_1$ . The red dots indicate 4 different locations alongshore for which the shoreline development is given as function of time. In these plots the shoreline position (blue line) is defined by the sum of the sediment supply due to the nourishment *redistribution* (green line) and the cross shore *erosion* of the shore (red line). The lifetime of the mega nourishment is visualised with a red dot that corresponds to the moment at which the shoreline (blue line) reaches its initial position (black dotted line).

Location 1 in Figure 3-3 is closer the nourishment compared to location 2 resulting in a slightly longer lifetime. At location 3 the nourishment supply is at first not sufficient to prevent coastal retreat. On the long term the erosion is however still compensated. The lifetime is in this case defined as the latest moment when the shoreline position is equal to the initial position. At location 4 the shoreline starts to erode but this erosion is slowed down due to the nourishment redistribution. However the shoreline position (blue line) will never reach its initial location (black dashed line) and the lifetime has therefore suddenly dropped to zero. In this case the effect of the nourishment is still noticeable but additional coastal protection measures are required to prevent shoreline retreat.



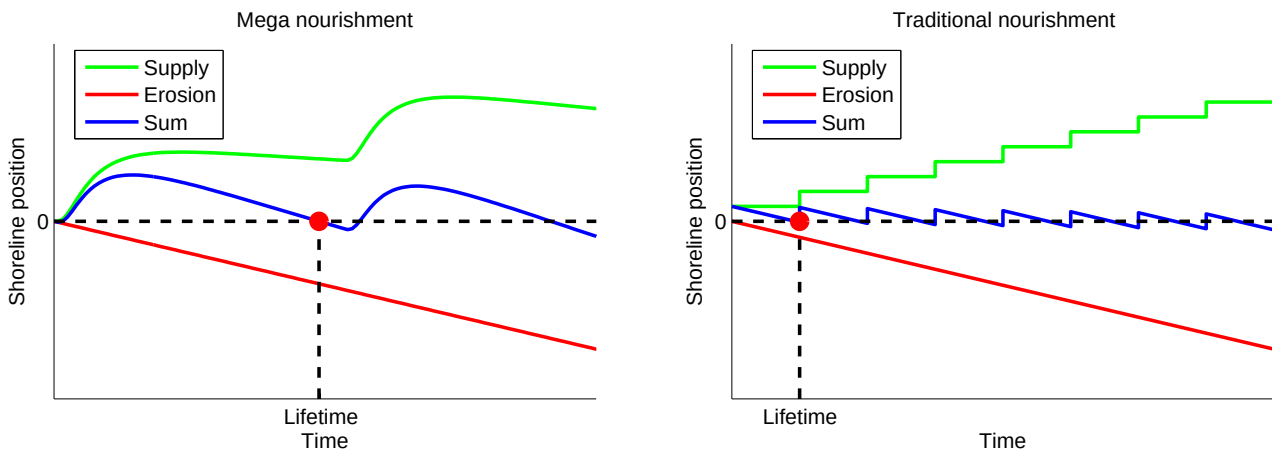
**Figure 3-3:** Conceptual visualisation of the shoreline position as function of time for different locations along the shore. Top sub figure shows the top view of the nourishment and the different locations 1 to 4. The other sub figures show the accretion of the shoreline (green) due to the nourishment redistribution, the erosion of the shoreline (red) and the sum of both (blue) representing the coastline position in time

A measure is introduced to quantify the alongshore length over which the nourishment lifetime is larger than zero: the Distance of Influence (DoI). Figure 3-4 illustrates this definition with a conceptual plot of the lifetime against the distance from the nourishment center. It shows a sudden drop of the lifetime just before the DoI is reached which is a consequence of the lifetime definition. Beyond the DoI the redistribution of the nourishment is insufficient to fully compensate the shoreline erosion. There is however still a noticeable effect from the nourishment but additional measures are required to keep the coastline seaward of its initial location.



**Figure 3-4:** Conceptual relation between the lifetime and the alongshore distance from the mega nourishment center. The lifetime of the nourishments becomes shorter with increasing distance. The length of the shore for which the lifetime is larger than zero is defined as the Distance of Influence (DoI)

The difference between a mega nourishment and a traditional nourishment is explained by plotting the shoreline position as function of time. This is done in Figure 3-5 for two beaches: one on which two successive mega nourishments are applied and one beach that is nourished eight times over its entire length.



**Figure 3-5:** Shoreline position as function of time: Conceptual Comparison between mega nourishment and traditional nourishment. Left sub figure shows the coastline position in time when 2 mega nourishments are applied. Right sub figure shows the coastline position in time when 8 traditional nourishments are applied

## 3-2 Numerical models

Longshore and cross shore sediment transport are the two main processes that determine the redistribution rate of the nourishment and the erosion rate of the shore. These two processes will be considered by means of two numerical models to model the complex interactions between the coastal parameters and the morphological development of the shore. The numerical models that are used are: A coastline model "Unibest-CL+" to simulate the longshore redistribution of the mega nourishment and a 1 dimensional "Xbeach" model to estimate the cross shore landward sediment losses during storms. A short description on the numerical model concepts, the main assumptions and the limitations is provided below.

### 3-2-1 Unibest-CL+ model

A behaviour oriented model "Unibest-CL+" is used to model the alongshore redistribution of the mega nourishment. This widely applied model in coastal engineering is based on single line theory and calculates the longshore sediment transport under the influence of wave action and tidal flow. It is able to quickly simulate long term coastline evolution and to estimate large scale sediment budgets. These properties makes the model perfectly suitable for an initial estimate of the nourishment redistribution rate. The model consists of two modules:

- The Longshore Transport module: *LT-module*
- The Coast Line module: *CL-module*

The *LT-module* calculates the LST for different wave conditions and shoreline orientations (Deltares, 2010). It contains a 1D wave propagation and decay model that transforms offshore wave data to the shore. The wave and tide induced flow velocities are calculated for an arbitrary beach profile by solving the wave action balance, the equation for wave set-up and the alongshore momentum equation. The velocities that are solved by these equations in combination with other sediment transport parameters are used in one of the integrated sediment transport models to calculate the LST. The output of the LT module is a

yearly averaged  $S$ - $\theta$  curve that follows from a weighted average of the LST rates for all wave and current conditions for a number of coastline orientations. In this yearly averaged curve the orientation of the shore is plotted against the LST rate. The coastline orientation that corresponds to a LST rate of zero is called the equilibrium coastline angle  $\theta_{eq}$ . More information regarding the underlying equation of the LT-module can be found in Appendix B.

The LT-module includes one unique parameter which makes the Unibest model different from other coastline models: The dynamic boundary which is the offshore distance till which the LST is computed. The cross shore profile located landward of this boundary rotates in the same way as the coastline while the orientation at the offshore side is kept constant (see also Figure 3-12). This affects the refraction of the waves and generally enhances the LST rates for a mega nourishment.

The shape of the  $S$ - $\theta$  curve is described by an exponential function (Equation 3-2) that is fitted on the averaged LST rates for different coastline orientation by using the least-square method. In this equation the sediment transport  $Q_s$  in  $[m^3/yr]$  is a function of the relative coastline angle  $\theta_r$  which equals the coastline orientation minus the equilibrium coastline angle:  $\theta_r = \theta_c - \theta_{eq}$ . This equation uses two fitting coefficients:  $c_1$  and  $c_2$ . From the derivative of  $Q_s$  it follows that  $c_1$  represents the gradient of the  $S$ - $\theta$  curve at  $\theta_c = \theta_{eq}$  (Equation 3-3). It can furthermore be shown that the coastline angle of maximum sediment transport  $\theta_{max}$  only depends on the coefficient  $c_2$  (Equation 3-4). Finally the value of maximum transport  $Q_{s,max}$  is determined by both  $c_1$  and  $c_2$  according to Equation 3-5.

$$Q_s(\theta_c) = c_1 \theta_r e^{-(c_2 \theta_r)^2} \quad (3-2)$$

$$\frac{dQ_s}{d\theta_c}(\theta_c = \theta_{eq}) = c_1 \quad (3-3)$$

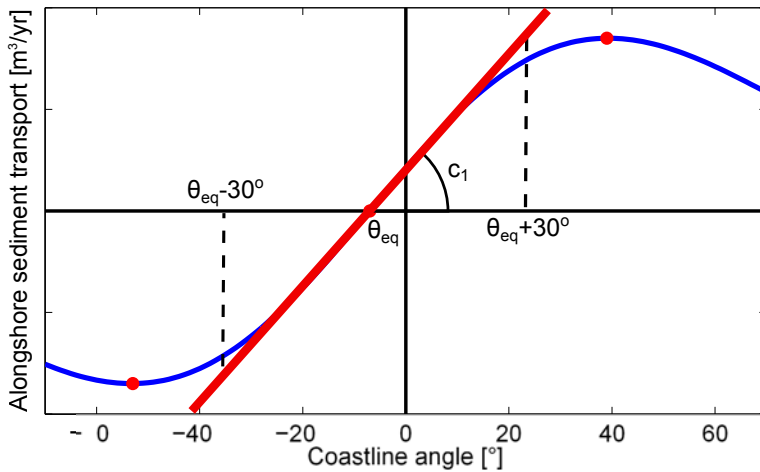
$$\frac{dQ_s}{d\theta_c} = 0 \quad \text{gives} \quad \theta_{max} = \pm \frac{1}{c_2} \sqrt{\frac{1}{2}} \quad (3-4)$$

$$Q_{s,max} = Q_s(\theta_{max}) = \frac{c_1}{c_2} \sqrt{\frac{1}{2}} e^{-\frac{1}{2}} \quad (3-5)$$

The *CL-module* simulates the coastline evolution based on the gradients in LST. It is based on single-line theory which was introduced by Pelnard-Considere (1956). This theory assumes a constant equilibrium cross shore profile which can move seaward or landward over its entire active height. Beyond the active height, the profile does not change. To simulate the coastal changes a continuity equation together with an equation of motion are solved by the CL-module for a set of initial and boundary conditions. When combining these two equations and performing a first order Taylor expansion of  $Q_s$  at  $\theta_c = \theta_{eq}$  the well known diffusion equation is obtained:

$$\frac{\partial y}{\partial t} = -\frac{c_1}{h_p} \frac{\partial^2 y}{\partial x^2} \quad (3-6)$$

The above equation assumes a linear  $S$ - $\theta$  curve which is a valid assumption as long as the coastline angles remain relatively small. For angles larger than  $\theta_{eq} + 30^\circ$  the  $S$ - $\theta$  curve deviates significantly from this linear line. In this case Equation 3-6 is inappropriate to describe the coastline evolution. In Equation 3-6 the ratio of  $c_1$   $[m^3/yr/^\circ]$  over the active height  $h_p$   $[m]$  (defined in Figure 3-12) determines the speed of the nourishment diffusion. In the remainder of this thesis  $c_1$  will be referred as the diffusion coefficient per unit of profile height ( $h_p$ ).



**Figure 3-6:** Linearised approximation of the  $S-\theta$  curve (in red) which is approximately valid for  $-30^\circ < \theta_{eq} < 30^\circ$ . The gradient of the linear  $S-\theta$  curve is equal to  $c_1$  which will be referred to as the diffusion coefficient of a mega nourishment

### Assumptions and limitations

The model is based on single line theory and always assumes an equilibrium cross shore profile. This means that the effect of (seasonal) cross shore profile variations on the LST are not taken into account.

The LT-module is furthermore fully based on linear wave theory to calculate the wave energy and the wave orbital velocity near the bottom. The only parameters that can be specified for a wave condition are the significant wave height  $H_s$ , the wave peak period  $T_p$  and the mean wave direction  $\theta_w$ . The shape and transformation of the wave energy density spectrum are not considered in this model.

Quasi steady sediment transport is assumed meaning that the sediment transport is always equal to the transport capacity. The sediments will therefore instantaneously respond to the flow conditions. This quasi steady assumption is valid if the adjustment length scale of the sediment transport process is smaller than the grid size that is applied in the Unibest model.

The model does not update the coastline position based on each individual wave condition. It calculates a yearly averaged  $S-\theta$  curve based on the entire wave climate.

Unibest-CL+ can furthermore not cope with a strongly curved coastline. A growth of the shoreline and the development of spits that occur for angles of wave incidence that exceed  $\theta_{eq} \pm 45^\circ$  cannot be modelled with Unibest.

The transformation of wave from the offshore to the near shore is calculated in 1D. In this model the coastline is considered to be uniform in longshore direction with straight and parallel depth contours offshore of the dynamic boundary. This schematisation become however invalid for strongly curved coastlines such as bays and locations with a complex offshore asymmetry.

### 3-2-2 Xbeach model

The Xbeach model is developed to simulate the coastal response during storm conditions and includes the process of dune erosion, overwash and breaching (Roelvink et al., 2010). It is a two-dimensional depth averaged model that describes the propagation of waves and waves groups by solving a time-varying wave action balance including shoaling, refraction, current refraction and wave breaking. The Soulsby - Van Rijn formulation has been implemented to calculate the equilibrium sediment concentration. This concentration is used in a depth-averaged advection diffusion equation to compute the actual sediment concentration and the sediment transport rates. For bed slopes steeper than a user defined critical value the transport of sediments is calculated with an avalanching equation for the simulation of dune erosion. For more information regarding the physical processes and underlying equations reference is made to the Xbeach manual (Roelvink et al., 2010).

The process based Xbeach model can easily become rather complex and computational expensive, especially when it is used 2D mode. In the tool that assumes an alongshore uniform coast the Xbeach model can however be used in 1D mode which makes it possible to simulate one storm event in about 10 minutes.

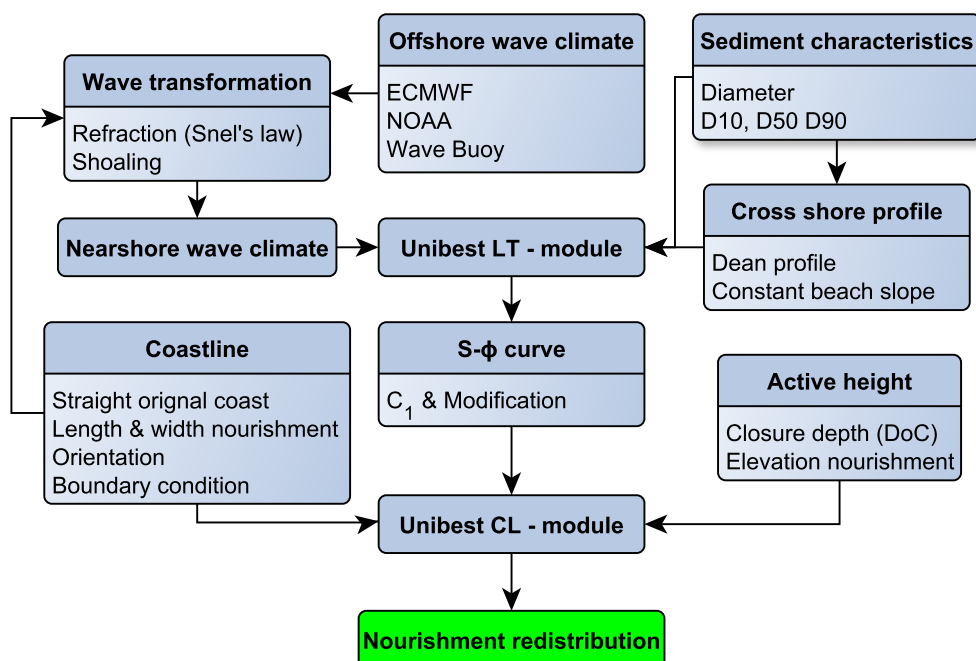
### 3-3 Tool overview

The tool is divided into a longshore and a cross shore part. First a flow chart of both the longshore and the cross shore part of the tool are shown and explained. These charts are an elaboration of the model approach of Figure 3-1. Subsequently the individual boxes of the flow charts are discussed in more detail.

#### 3-3-1 Longshore part

The first part of the tool is used to calculate the redistribution of the mega nourishment. A flowchart of this tool is given in Figure 3-7 which incorporates both modules of the Unibest-CL+ model. For the LT-module several parameters needs to be specified: the wave climate, the tidal flow velocity, the cross shore profile and the sediment characteristics. An offshore wave climate can be used from either global wave models or from a wave buoy. The climate is transformed to nearshore by taking into account wave refraction, shoaling and the coastline orientation. It is assumed that the shape of the cross shore profile fully depends on the sediment size according to the so called Dean-Moore-Wiegel (DMW) profile (see Section 3-3-4). For the sediment characteristics several size parameters can be specified. For other sediment transport parameters the default model values are used. The tidal flow can be added by defining a couple of conditions of water level and tidal flow velocity.

The output of the LT-computation is the  $S-\theta$  curve and the diffusion coefficient. This curve is used by the CL-module together with the coastline position, the active height of the profile and the boundary condition of the coastline. In the tool only a straight coast can be defined with in the middle of the model domain a local perturbation with a certain width and length. A constant coastline angle is prescribed at the boundaries.



**Figure 3-7:** Longshore part of the MN-tool to calculate the nourishment redistribution

### 3-3-2 Cross shore part

The cross shore part of the tool estimates the erosion of the shore. This part of the tool, visualised in Figure 3-8, uses a 1D Xbeach model to estimate the cross shore sediment loss due to overwash. It furthermore estimates the impact of SLR by means of the Bruun rule. Part of the boxes in the flow chart are identical to the ones from the longshore part of the tool (Figure 3-7). An important addition to this scheme is the extreme value analysis which calculates the wave height, wave period and duration for a storm with a specific return period. For the cross shore profile the crest level needs to be specified. For the sediment characteristics the  $D_{10}$  cannot be specified because this variable is not included in the transport formulation used in Xbeach. Furthermore a storm surge value can be entered by the user or estimated by means of a 1D water level set-up calculation which makes use of bathymetry data from a General Bathymetric Chart of the Oceans (GEBCO).

The Xbeach model uses the output of the extreme value analysis, the cross shore profile, the sediment characteristics and the storm surge level to estimate the overwash volume during a single storm event. The retreat distance as a result of SLR is calculated by means of the Bruun rule (see Section 2-2-3) which requires the DoC, a prediction for the rise in sea level and the shape of the cross shore profile. The depth of closure is calculated according to the equation of Hallermeier (see Section 2-1). In the end of the flow chart the coastal erosion in [m/yr] is estimated by summing the losses due to storm overwash, SLR. A uses values for the erosion rate can be added to include other erosional processes.

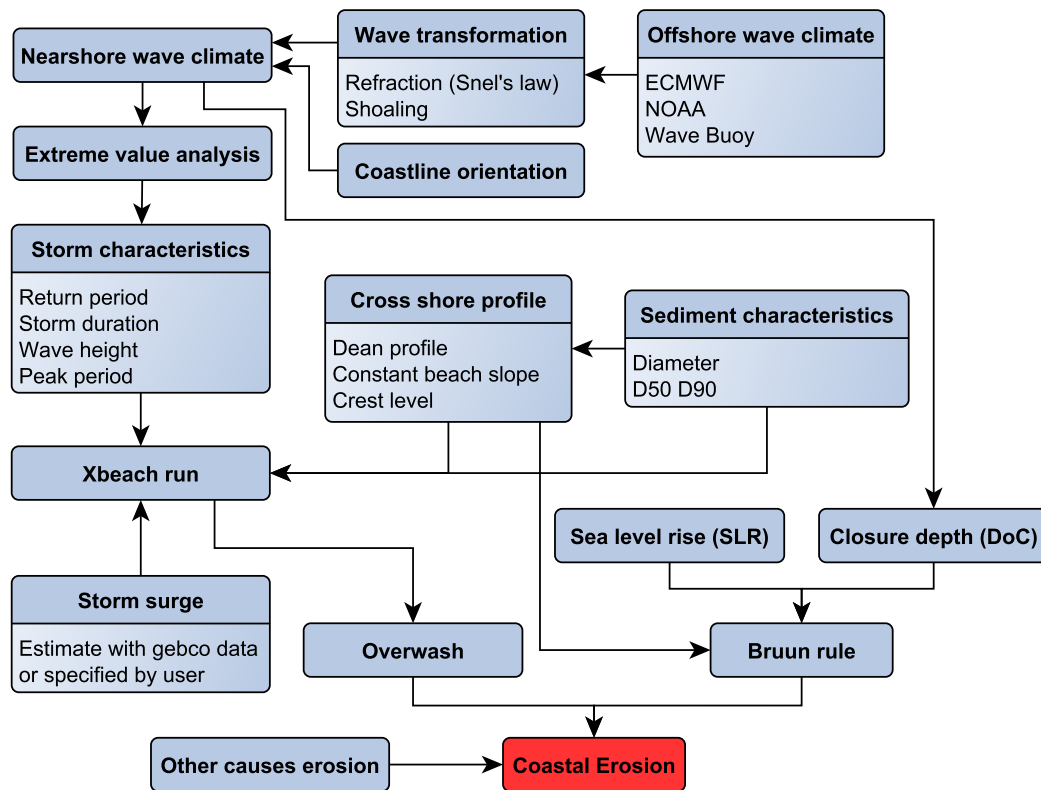


Figure 3-8: Cross shore part of the tool to estimate coastal erosion

### 3-3-3 Tool assumptions and simplification

Several assumptions and simplifications are made for the schematisation of the coastal area and the calculation of the sediment transport rates. These assumptions are listed here and discussed in more detail in the remainder of this chapter.

- The shape of the cross shore profile is assumed to depend only on the sediment diameter. Secondary bed forms and variations in profile shape over time are not considered
- For wave transformation parallel depth contours are assumed and only refraction and shoaling are accounted for
- The coastline is modelled straight and longshore uniform. No complex coastline shapes are considered
- The water depth at the dynamic boundary ( $h_{db}$ ) is equal to the DoC according to the equation of Hallermeier (1981)

### 3-3-4 Detailed tool description

#### Offshore wave data

Waves are the main forcing mechanism that drive coastal sediment transport processes. Site specific long term wave data is therefore an essential input parameter for the modelling of the mega nourishment evolution. For the tool, data is used from global atmospheric models that performed a reanalysis of waves and wind on the open ocean. This has the advantage that the morphological evolution of a mega nourishment can easily be assessed for a wide range of location in the world. A clear disadvantage of the use of these models is the unknown and spatially varying data reliability. When using this model tool for a certain case, it is preferred to use site specific wave data measured by for example wave buoys to improve the prediction of the nourishment redistribution rate. Site specific buoy data is for example used for the comparison between the tool prediction and the Sand Engine pilot (see Section 4-1).

Two different sources of global wave model data are used for the modelling: data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and from the National Oceanic and Atmospheric Administration (NOAA). NOAA performed a wave hindcast reanalysis with the WAVEWATCH III model (version 2.22) and a GFS wind analysis covering a 9 year period with a 3 hour time interval between two successive output points (NOAA, 2014). It covers the period from February 2005 till January 2014 and provides model output on a 30 arc-minute global grid (grid size of approximately 56x56 km on the equator). The wave output from ECMWF is taken from the ERA-Interim reanalysis that is produced with the Integrated Forecast System (IFS) (Dee et al., 2011). This IFS incorporates three components for atmosphere, land surface and ocean waves that are fully coupled. The ocean wave component in the IFS is based on the WAM approach. It contains model output on a 6 hourly interval from 1979 till 2013 on a spatial rectangular grid of 1.5 degrees (approximately 165x165 km on the equator). Figure 3-9 shows the wave data grids of both wave models including the wave height at an arbitrary moment in time.

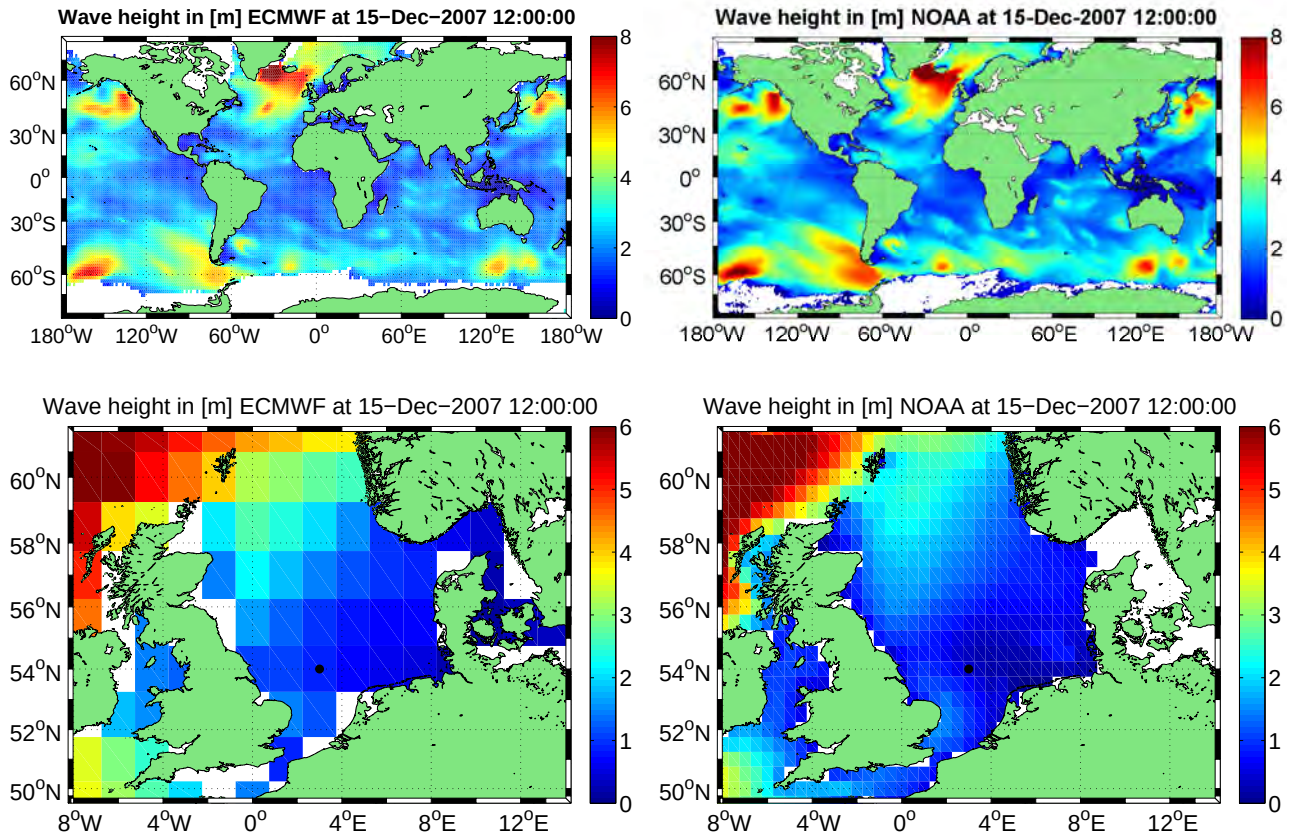
Both wave models, WAVEWATCH III and WAM, are third generation wave models. These type of models solve the spectral energy balance equation (see Equation 3-7) for all wave components at all model grid cells for each moment in time (Holthuijsen, 2007). In these models the shape of the wave energy spectrum can freely develop and is not prescribed beforehand. The source term ( $S$ ) in Equation 3-7 is a sum of terms given in Equation 3-8:  $S_{in}$ ,  $S_{nl4}$  and  $S_{wc}$  represent the processes of wave generation by wind, quadruplet wave-wave interactions and energy dissipation due to white capping.

$$\frac{\partial E(f, \theta_w; x, y, t)}{\partial t} + \frac{\partial c_{g,x} E(f, \theta_w; x, y, t)}{\partial x} + \frac{\partial c_{g,y} E(f, \theta_w; x, y, t)}{\partial y} = S(f, \theta_w; x, y, t) \quad (3-7)$$

$$S = S_{in} + S_{nl4} + S_{wc} \quad (3-8)$$

Both wave models provide three parameters for each time step over the entire spatial domain which are derived from the wave energy density spectrum:

- $H_s$  the significant wave height [m]
- $T_p$  the wave peak period [s] for NOAA and  $T_{mean}$  the mean wave period [s] for ECMWF



**Figure 3-9:** Wave data grid of ECMWF and NOAA wave models for the world and the North Sea. The colors show the height of the waves on 15 December 2007 at 12 o'clock

- $\theta_w$  the mean wave direction at the peak period

In the Unibest LT-module the wave peak period  $T_p$  needs to be prescribed. However the ECMWF wave model output only provides the mean wave period  $T_{mean}$ . The relation between mean period and peak period depends on the shape of the wave spectrum and values has been found for  $T_m/T_p$  of 0.7 – 0.9 (Schierack, 2003). A correction factor for the mean period of the ECMWF data can be entered in the tool. For the aim of this thesis this correction factor is not used because the difference between mean and peak period depends on the spectral shape which is unknown. For a swell wave climate this difference is generally much smaller compared to a wind wave climate. Applying one single factor for all climates is therefore unrealistic.

### Wave transformation & nearshore wave climate

In the tool the wave climate is transformed from offshore to nearshore by taking into account analytical expressions for wave refraction and shoaling for a alongshore uniform coast with parallel depth contours. The waves are transformed till the DoC according to Hallermeier (1981). At this depth depth limited wave breaking hardly occurs. An example of a transformed climate is included in figure 3-10 that shows the offshore wave rose and the transformed wave climate near the shore. The final transformation of the waves till the shore is taken over by the Unibest LT-module which also includes the process of wave energy dissipation due to wave breaking and bottom friction in the wave energy balance.

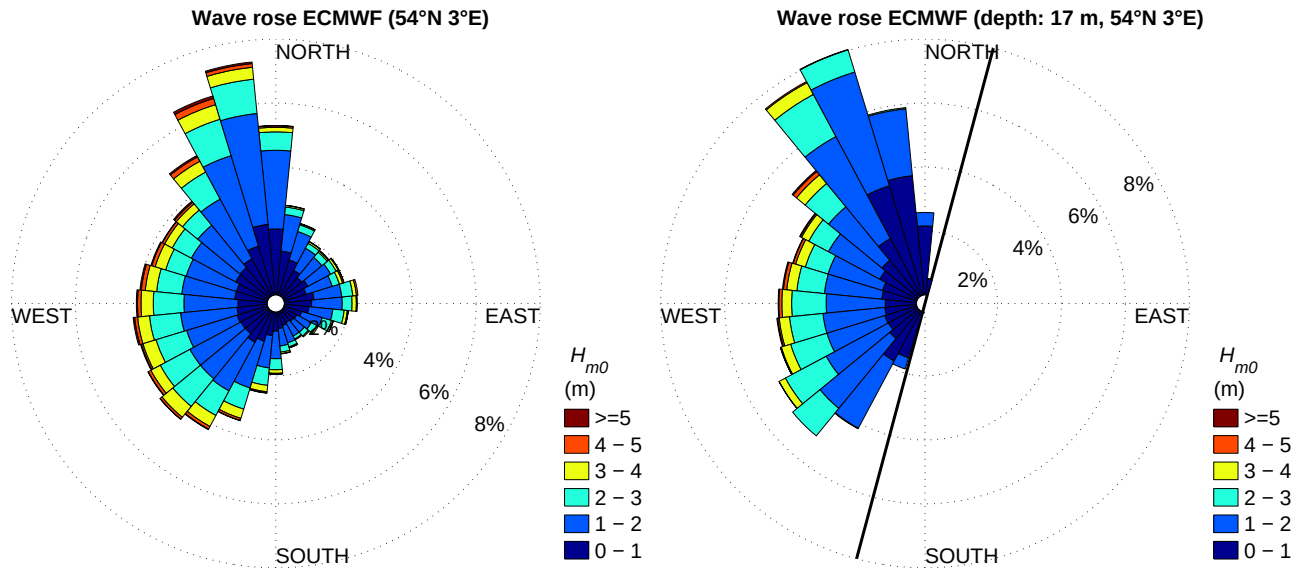
The wave angle at the nearshore depth  $\theta_{w,1}$  is calculated according to snel's law:

$$\frac{\sin \theta_w}{c} = \text{constant} \quad \text{gives} \quad \sin \theta_{w,1} = \frac{c_1}{c_0} \sin \theta_{w,0} \quad (3-9)$$

The wave height at the nearshore depth  $H_1$  is calculated by multiplying the offshore wave height  $H_0$  with the shoaling coefficient  $K_s$  and the refraction coefficient  $K_r$ :

$$H_1 = H_0 K_s K_r \quad \text{with} \quad K_s = \sqrt{\frac{c_0}{2c_{g1}}} \quad \text{and} \quad K_r = \sqrt{\frac{\cos\theta_{w,0}}{\cos\theta_{w,1}}} \quad (3-10)$$

When the angle between the direction of wave propagation and the coastal normal is larger than  $90^\circ$  the wave height and wave period are set to zero.



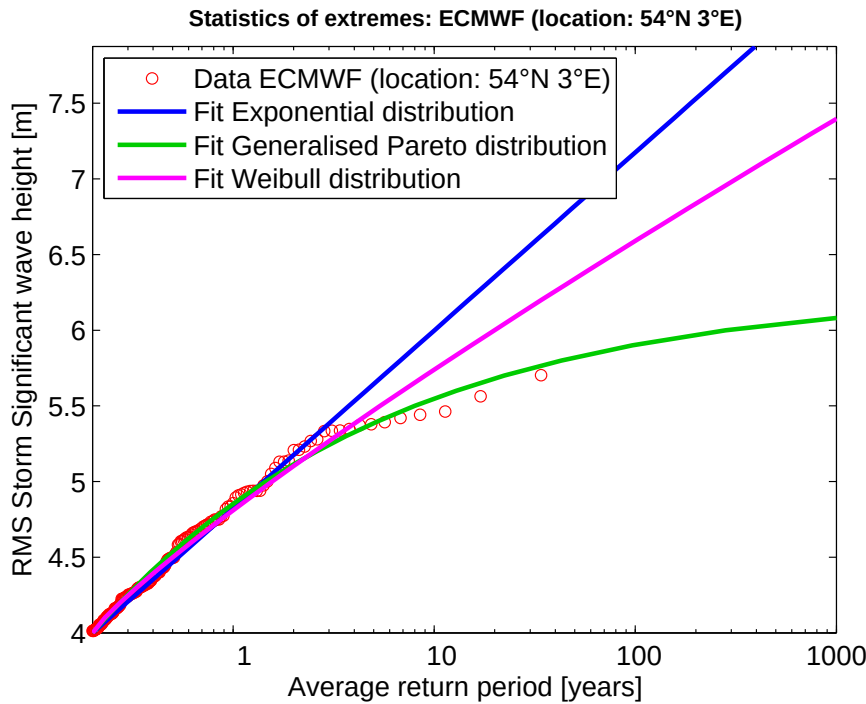
**Figure 3-10:** Wave rose of the offshore wave climate in the North Sea from the ECMWF wave model and the transformed wave climate at 17 m water depth with an orientation of the coastal normal of  $285^\circ$

For the computation in the LT-module a maximum of thousand conditions can be entered. The amount of wave conditions in the transformed climate is therefore reduced by categorising all wave conditions in bins with equal wave height, period and direction. Subsequently the number of conditions per bin are counted to obtain a percentage of occurrence for each condition. The amount of bins is iteratively defined by imposing a maximum amount of allowable wave conditions. It has been found that an amount of 200 wave conditions is sufficient for the wave climate schematisation. This amount has almost the same averaged wave climate characteristics compared to the entire climate (e.g. mean significant wave height and peak period) and provides almost the same S- $\theta$  curve compared to a model run with more conditions.

### Extreme value analysis

The characteristics of a storm needs to be defined to estimate the sediment loss toward the hinterland. This can automatically be done in the tool by performing an extreme value analysis based on the peak-over-threshold approach. For this approach a return period and a threshold value needs to be specified which are used by the tool to determine the probability distribution of the significant wave heights that exceed the threshold value. According to the extreme value theory this distribution is best described by the Generalised Pareto (GP) distribution (Holthuijsen, 2007). A fit is therefore made between this GP distribution and the extreme wave height distribution. Because the GP distribution does not fit well for all wave climate, fits are also made with the exponential and weibull distribution. The user can check which fit result in the best approximation of the storm wave height. The significant wave height that corresponds to the specified return period is calculated by solving Equation 3-11. An example of an extreme value analysis using the tool is included in Figure 3-11. In this case the GP distribution provides the best fit.

$$RP_{\underline{H}_{s,peak} > H_{s,peak}} = \frac{\Delta T_{storm}}{1 - P(\underline{H}_{s,peak} \leq H_{s,peak})_{threshold}} \quad (3-11)$$



**Figure 3-11:** Example of an extreme value analysis of the transformed climate of Figure 3-10 Showing the ECMWF) storm wave height

For the Xbeach model a storm is schematised by a significant wave height with corresponding peak period and a storm duration. The maximum significant wave height in a storm is however an overestimation for the wave energy during the entire storm. It is chosen to use the Root Mean Square (RMS) significant wave height  $H_{s,rms}$  of a storm as representative because the wave energy is proportional to  $H_s^2$ . The extreme value analysis is therefore performed on the extremes of  $H_{s,rms}$ . This storm duration is estimated by averaging the duration of all storms with a higher wave height.

### Sediment characteristics

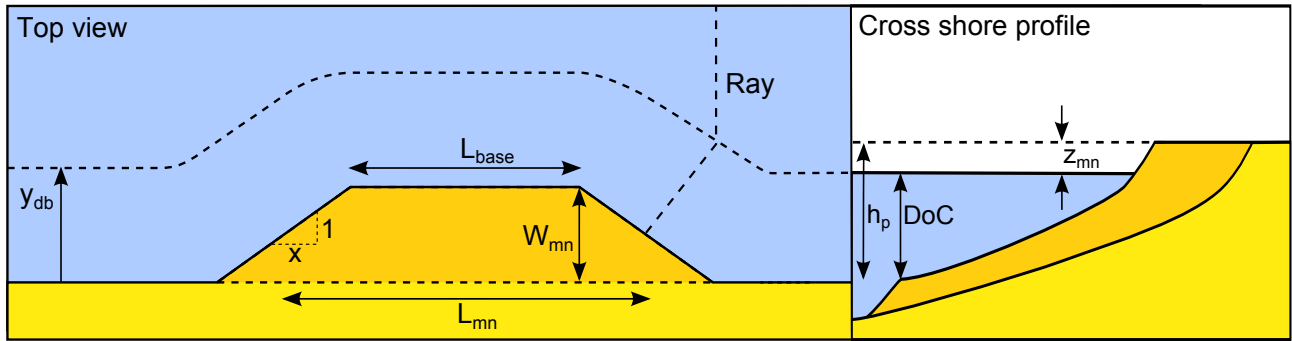
For the longshore part different sediment transport formulations can be used which require different input parameters. The most advanced transport formulation implemented in the LT module, the TR2004 formulation for non-cohesive sediment developed by Van Rijn et al. (2004), is used as default in the tool. This formulation takes into account both suspended and bed load transport under currents and waves. It has been improved compared to the previous transport formulations by implementing predictors for the bed roughness and the size of the suspended sediment size. Three values for the sediment size needs to be specified in this equation: the median sediment diameter  $D_{50}$ , the diameter for which 10% of the grains is finer  $D_{10}$  and the  $D_{90}$ . For all other sediment transport parameters and calibration coefficients the default values are used.

### Schematisation coast and nourishment

For the Unibest CL-module a straight coastline is prescribed with in the middle a local perturbation which represents the mega nourishment. The length of the straight coastline is chosen sufficiently long to prevent any effects from the model boundary. At the boundaries of the longshore model domain a constant coastline angle is assumed. The grid size of the model in varying from 500 m at the model boundaries till 50 m in the area of interest for sufficient model resolution.

Figure 3-12 shows the mega nourishment schematisation. The volume of sand depends on the active profile height ( $h_p$ ), the alongshore length ( $L_{mn}$ ), the cross shore width ( $W_{mn}$ ) and the orientation of the outer ends of the nourishment ( $1 : x$ ). The active profile height is the vertical distance over which the cross shore profile moves seaward or landward. It is assumed that this height is equal to the sum of the annual closure depth DoC and the nourishment elevation above MSL ( $z_{mn}$ ). The Unibest CL-module assumes that the coastal profile shape is constant and can move seaward or landward over its active height  $h_p$ . Therefore the sediment volume of a mega nourishment can be computed by multiplying the nourishment area by the active profile height  $h_p$  according to Equation 3-12.

$$V = L_{mn} W_{mn} h_p = (L_{base} + x W_{mn}) W_{mn} h_p \quad \text{with} \quad h_p = DoC + z_{mn} \quad (3-12)$$



**Figure 3-12:** Schematisation of a mega nourishment: the dynamic boundary  $y_{db}$  is located at the DoC. The dynamic boundary results in a bend in the cross shore ray which influences the refraction pattern of the waves.

Figure 3-12 furthermore shows the location of the dynamic boundary ( $y_{db}$ ) which is the offshore distance till which the LST is computed. The cross shore profile located landward of this boundary rotates in the same way as the coastline while the orientation offshore of this boundary is kept constant. This results in a sudden bend in the cross shore ray which has a large influence on the refraction pattern of the waves (see the dashed ray in Figure 3-12). In the tool the location of this boundary is assumed to be equal to the offshore location of the DoC according to Hallermeier (1981).

For the cross shore profile an equilibrium DMW-profile is used which was introduced by Stive et al. (1992). This profile consists of an offshore part which is defined by a power law function that relates the water depth  $h$  and the offshore distance  $x$  (Equation 3-13). Near the waterline the profile goes over into a beach with constant slope  $\beta$  according to Equation 3-14. In this equation the parameters  $x^*$  and  $h^*$  are evaluated at the water depth that fulfils the condition  $dh/dx = \tan\beta$ .

$$h = A(x)^{\frac{2}{3}} \quad \text{for} \quad \frac{dh}{dx} \leq \tan\beta \quad (3-13)$$

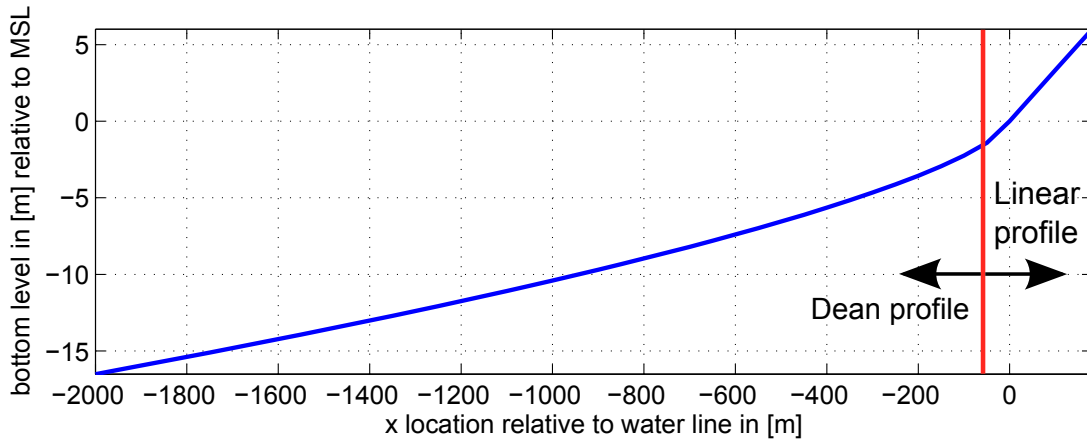
$$h = h^* - \tan\beta(x^* - x) \quad \text{for} \quad \frac{dh}{dx} > \tan\beta \quad (3-14)$$

Dean (1987) showed that the coefficient  $A$  in Equation 3-13 could be expressed as a function of the sediment fall velocity  $w_s$ :

$$A = 0.5w_s^{0.44} \quad (3-15)$$

The fall velocity  $w_s$  is computed according to the formulation by Van Rijn (1993) and only depends on the median grain size ( $D_{50}$ ). The cross shore profile is assumed to be constant in time and space. This implies that all variation in the cross shore profile, such as an initially steeper profile of the nourishment and

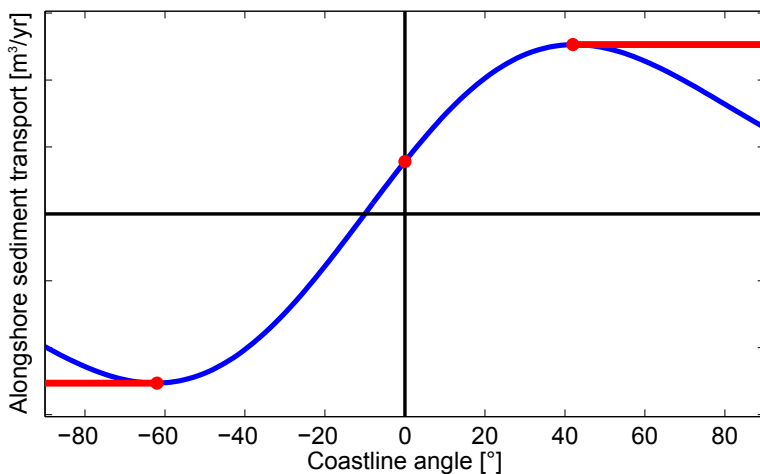
variations due to different wave conditions, are not considered in the tool. The cross shore beach profile for a median sediment diameter of  $250\ \mu\text{m}$  and a beach slope of 1 in 30 is given in Figure 3-13.



**Figure 3-13:** Cross shore beach profile for  $D_{50} = 250\mu\text{m}$  and a beach slope of 1:30

### Modification S- $\theta$ curve

Since 2014 the Unibest-CL+ model contains an option to prevent model instabilities and excessive growth of the mega nourishment which includes a slight modification of the S- $\theta$  curve (see also Stam, 2014). In the model the alongshore sediment transport increases with an increasing relative angle of wave incidence. Maximum transports are generally reached when waves approach the shore under an angle of about 45 degrees. For larger angles however this alongshore sediment transport reduces. Model instabilities and a growth of the mega nourishment therefore occur due to the strong coastline gradients at the edges of the mega nourishment. To prevent this issue the alongshore sediment transport is maximised for all coastline angles that fall outside the interval of  $-45^\circ < \theta_{eq} < 45^\circ$ . This maximisation is visualised with red lines in Figure 3-14.



**Figure 3-14:** S- $\theta$  curve with maximized alongshore sediment transport for coastline angles that fall outside the interval of  $-45^\circ < \theta_{eq} < 45^\circ$

### Storm surge

The amount of sediment loss in landward direction during storms strongly depends on the storm surge level. This level is varying all over the world. In the tool a storm surge level can be entered which is used in the Xbeach calculation. The tool also has the possibility to obtain a rough estimate of the surge level based on a simple water level set up calculation. This calculation requires the wind velocity components

$U_w$  and  $V_w$  at an elevation of 10 m which are available from the ECMWF model output. Furthermore a 1D bathymetry is used from GEBCO.

### Other causes erosion

The tool incorporates an estimation for coastal retreat due to SLR and overwash during storms. However other coastal erosion processes may cause a retreat of the shoreline such as illegal sand mining or sand losses into offshore canyons. These losses can be estimated and included as a alongshore uniform erosion value in m/yr.

## 3-4 Tool simulation strategy and parameters

The tool is used to assess the relative influence of the coastal parameters on the lifetime of a mega nourishment. This assessment is done by following a four step approach:

1. Determine the influence of the wave climate parameters on the nourishment *redistribution*
2. Estimate the influence of SLR and extreme wave conditions on the *erosion* of the autonomous shore
3. Quantify the lifetime of a mega nourishment based on different erosion rates, redistribution rates, and nourishment dimensions
4. Perform a sensitivity analysis to assess the influence of other parameters

Four *evaluation criteria* are used to quantify the relative influence of the different parameters:

- Diffusion coefficient,  $c_1$  [ $\text{m}^3/\text{yr}/^\circ$ ]: Gradient of S- $\theta$  curve which quantifies the redistribution rate
- Half-time,  $T_{50\%}$  [yr]: Time to reduce sand volume within the initial area of the nourishment by 50%
- Lifetime,  $T_L$  [yr]: Time for which the coastline position remains seaward of its initial position
- Distance of Influence,  $DoI$  [m]: The alongshore length for which the lifetime is larger than zero

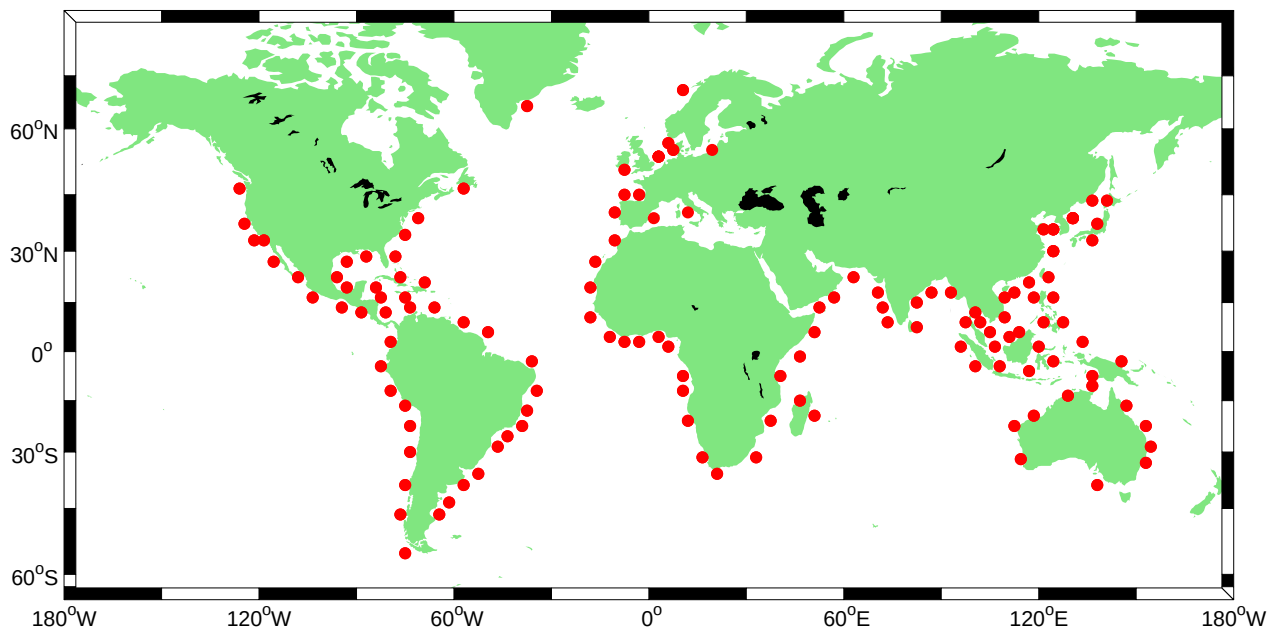
A *default model* set-up is defined as a starting point for this approach. For this model the most important parameters are:

- Sediment characteristics:  $D_{50} = 250\mu\text{m}$ ,  $D_{10} = 0.6D_{50} = 150\mu\text{m}$ ,  $D_{90} = 1.4D_{50} = 350\mu\text{m}$
- Beach slope:  $\beta = 1 : 40$
- Nourishment size:  $h_p = 7\text{m}$ ,  $W_{mn} = 700\text{m}$ ,  $L_{mn} = 1700\text{m}$ ,  $x = 2$
- Dynamic boundary:  $h_{db} = DoC$  according to Hallermeier (1981)
- Bottom roughness:  $k_b = 0.01\text{m}$
- Bottom friction coefficient:  $f_w = 0.01$

The nourishment dimensions result in a volume of  $V_{mn} = 15 \text{ Mm}^3$  which is of the same order as the Sand Engine volume ( $16.5 \text{ Mm}^3$ ). The value for the bottom roughness is generally in the range between several centimetres and several decimetres. A value of 0.01 m is therefore used in the default model. For the bottom friction factor which is used in the wave energy balance equation a realistic value of 0.01 is chosen. Both values for the roughness and the friction factor are advised by the Unibest manual (Deltares, 2010).

To accomplish step 1 of the approach runs are performed using the default model parameters and a variety of wave climates. For this many different locations around the world are chosen to generate a dataset that include 272 different wave climates at 137 locations (see Figure 3-15). Figures are included in Appendix C

that visualise different wave climate parameters to show the large variety of wave climates that have been used for the tool simulations.



**Figure 3-15:** Selected locations for wave climates

To estimate the erosion rate of the autonomous shore (step 2), different storm conditions are imposed. These are specified in Appendix C. For the assessment of the nourishment lifetime (step 3) only the Unibest CL-module is executed. For these runs several diffusion coefficients are used that represent the nourishment redistribution. Furthermore the dimensions of the nourishment and the erosion rates of the shore are varied. In the sensitivity analysis (step 4) different model parameters are altered such as the sediment size, the bottom roughness and the location of the dynamic boundary. More information on the model set-up for each run is provided in Appendix C.

### 3-5 Summary

An approach is presented that relates the lifetime to the nourishment redistribution, the erosion of the shore and the longshore distance from the nourishment center. The Mega Nourishment tool has been developed to estimate the redistribution and the erosion to obtain a first estimate of the nourishment lifetime. This tool makes use of two numerical models: Unibest-CL+ to calculate the longshore sediment transport and Xbeach to estimate the cross shore sediment loss during a storm. Wave data from global wave models can be used in the tool to predict the lifetime of a mega nourishment for a location in the world. A simulation strategy of the tool is defined to quantify the relative influence of different parameters on the nourishment lifetime. A default model is defined as a starting point for the simulations.

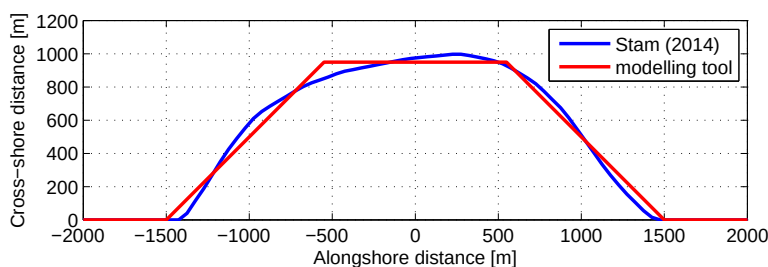
## Comparison tool & Sand Engine predictions

Recently a thesis project was done about the evolution of beach extensions for the Dutch coasts in which the morphological behaviour of the Sand Engine was modelled using Unibest-CL+ (Stam, 2014). This work concluded that the Sand Engine predictions from Unibest and Delft3D are very similar. Besides this the Unibest model of Stam showed a good correspondence with the measurement data of the Sand engine. The results of the MN-tool will therefore be compared with the Unibest-CL+ model prediction of Stam.

### 4-1 Model parameters

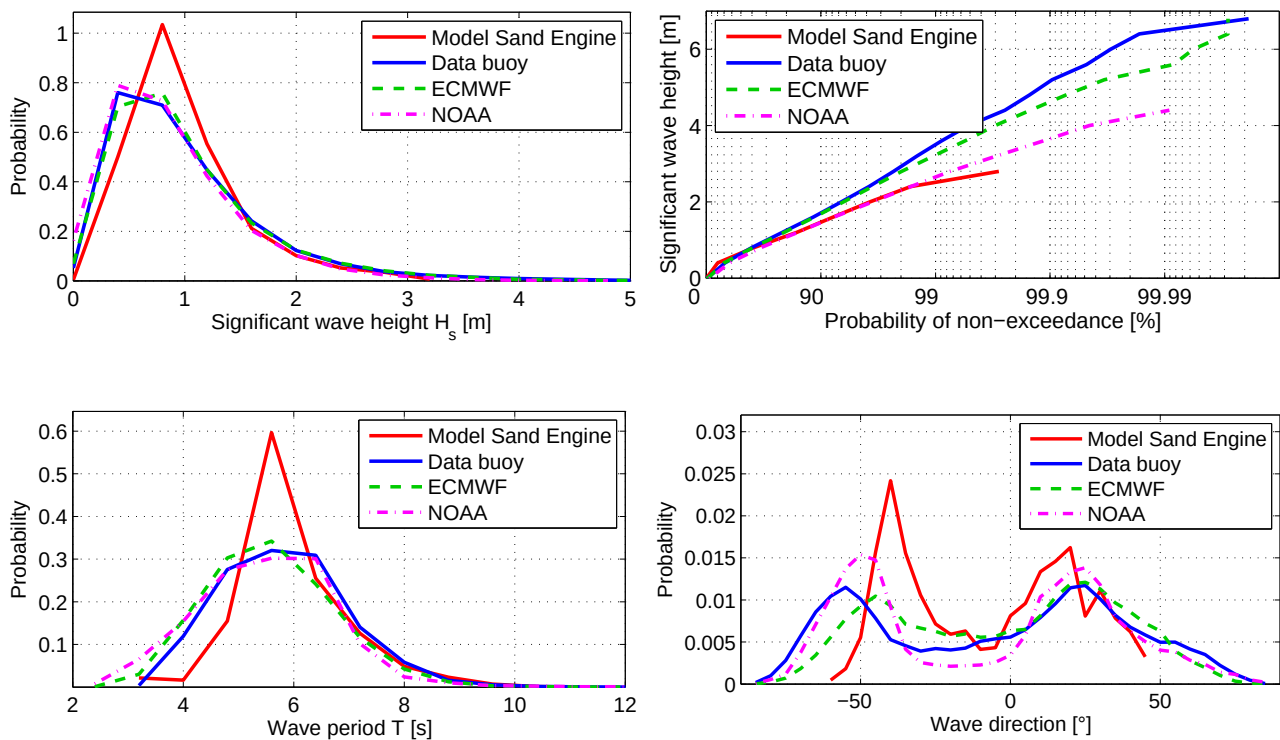
Stam (2014) made a schematisation of the Sand Engine with the Unibest-CL+ model (see Figure 4-1). His model incorporated a wave boundary condition file with a transformed wave climate near the location of the Sand Engine consisting of 269 wave conditions. Tidal currents were not considered in the model and the dynamic boundary was chosen at a water depth of  $h_{db} = 6.3$  m. The active height  $h_p$  of the Sand Engine was set to 8.5 m in order to obtain a nourishment volume of  $16.5 \text{ Mm}^3$ .

For the tool several parameters will differ from the model of Stam. First of all wave data will be used from the global wave models and an offshore wave buoy 'IJmuiden munitiestortplaat' located at  $52.55^\circ\text{N}$   $4.06^\circ\text{E}$ . For the sediment size the values from a measurement survey at the Sand Engine in June 2011 are used:  $D_{10} = 151 \mu\text{m}$   $D_{50} = 278 \mu\text{m}$   $D_{90} = 482 \mu\text{m}$ . The shape of the cross shore profile only depends on the sediment diameter  $D_{50}$ . Furthermore the dynamic boundary is set at the DoC which is calculated with the equation of Hallermeier (1981). This results in higher values for the dynamic boundary compared to the model of Stam (2014). The shape of the Sand Engine is defined using the model tool parameters: a cross shore width of  $W_{mn} = 950$  m, an alongshore length of  $L_{mn,base} = 1100$  m and a ratio of  $x = 1 : 1$  for the outer edges of the nourishment (see Figure 4-1). The active height was set to 8.47 m in order to conserve the Sand Engine's volume of  $16.5 \text{ Mm}^3$ .



**Figure 4-1:** Schematisation of the Sand Engine in the model of Stam (2014) and in the tool

Figure 4-2 shows the wave climate parameter distributions for the different wave data sources. These distributions are made for the transformed wave climates at a nearshore depth of 6.3 m taking into account the waves with a height larger than zero. At this depth part of the waves in the climate are already broken. Wave heights larger than 3 m can therefore be seen as unrealistic because the process of wave breaking is not incorporated in the wave climate transformation. In addition Table 4-1 shows some of the characteristic wave climate parameters: the percentage of the time without waves (caused by the 1D wave transformation described in Section 3-3-4), the averaged and RMS significant wave height, the averaged wave period and the directional spreading. It is found that the wave heights used in the model of Stam (2014) are larger compared to the other climates. The wave period distribution of the Sand Engine model by Stam is furthermore more peaked and has a larger average value. For the wave buoy 'IJmuiden Munitiestortplaats' only mean wave periods were available which leads to lower periods compared to the other data sources. The values of the wave period were therefore multiplied by a factor 1.25 to transform the mean periods to the peak periods. This factor is proposed by Schiereck (2003) as a first estimate for the factor between mean and peak period. For the directional spreading there is a difference of about  $20^\circ$  between the model of Stam (2014) and the tool data sources.

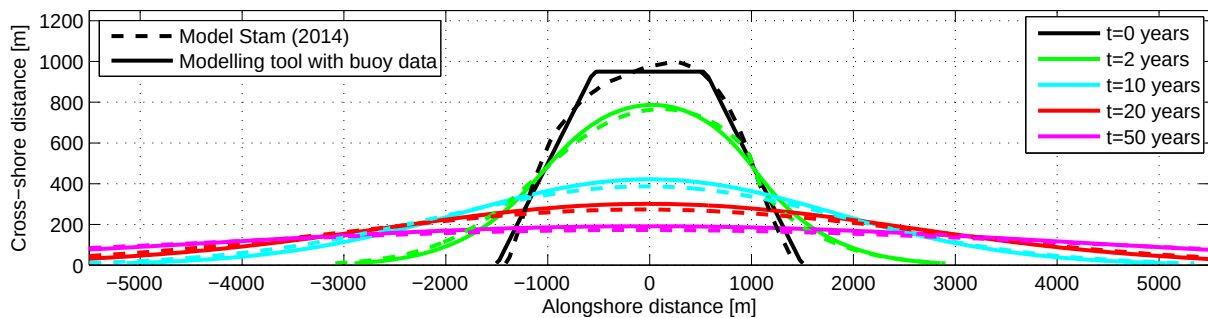


**Figure 4-2:** Distributions of wave climate parameters for different data sources: In red the data from the model of Stam, in blue the data from the wave buoy 'IJmuiden Munitiestortplaats', in green the data from the ECMWF wave model and in pink the data from the NOAA wave model

To make an estimate of the coastal erosion rate for the shore coast, data is used from the yearly report on the coastline development of the Netherlands (Rijkswaterstaat, 2011) which provides the trend for the coastline position based on a linear trend of the coastline position over the past ten years. An nett erosion value of 0.2 m in 2010 and 1.5 m in 2011 was found by spatially averaging the coastline position of the Delfland coast. With the expected acceleration in SLR for the 21<sup>st</sup> century this value will probably increase during the lifetime of the Sand Engine. For the estimation of the lifetime for the Sand Engine a value of 2 m/yr is therefore assumed.

## 4-2 Redistribution Sand Engine

Figure 4-3 shows the coastline development for the predictions made by the model of Stam (2014) (dashed lines) and the predictions according to the tool simulation using the wave buoy data at 'IJmuiden Munitiestortplaats' (solid lines). The similarity between both results is remarkable because of the considerable difference between the wave climates used in both simulation (see Figure 4-2 and Table 4-1). This would suggest that the almost perfect resemblance between the model results of Stam and the simulation with the wave buoy data is coincidence. Another interesting point is the symmetrical redistribution of the Sand Engine for both simulations. This symmetry is to a certain extend also observed in the morphological predictions by Stive et al. (2013) which are given in Appendix A and is explained by the almost constant gradient of the LST.



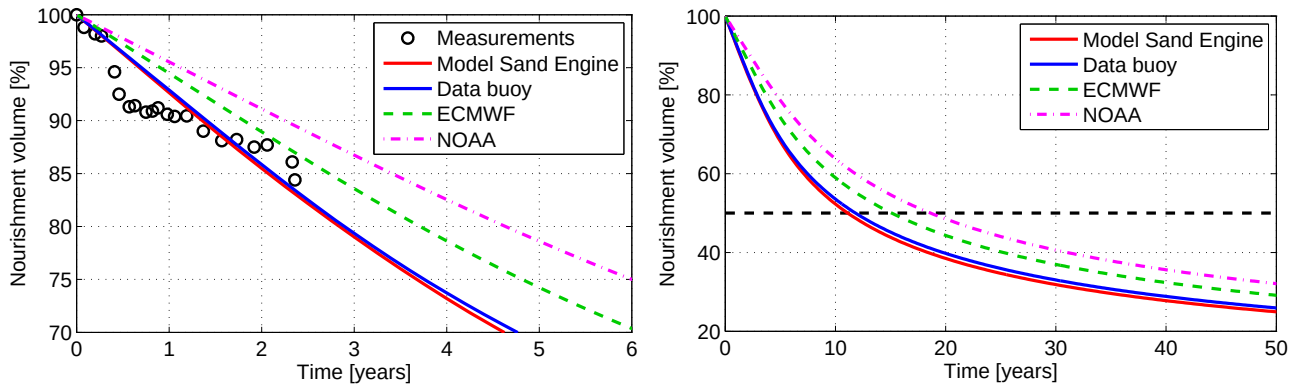
**Figure 4-3:** Comparison of the model results for the coastline development of the Sand Engine according to Stam (dashed lines) and the simulation with buoy data at 'IJmuiden Munitiestortplaats' (solid lines)

Figure 4-4 shows the volume decrease of the nourishment in time for all model simulations. The diffusion coefficients and half-times that correspond to these lines are presented in Table 4-1. The black circles in the left sub-plot correspond to the measured volume decrease of the Sand Engine in the first 2.5 years after construction. These show a varying rate of volume decrease over the year due to seasonal changes in the wave climate, an effect which is not observed in the model results that are based on a yearly averaged  $S-\theta$  curve. The results of Stam and the simulation with the buoy data show the best correspondence with the measurement. The measurement period is however too short to draw a quantitative conclusion regarding the future speed of redistribution.

The predictions of the tool for the global wave models predicts a considerable lower rate of volume decrease. These global models are specifically designed to model waves on the open ocean and are less suitable for an accurate description of the waves on the North Sea. Compared to the wave buoy data the wave models underestimate the wave heights in front of the Dutch coasts resulting in a significantly lower redistribution rate: The diffusion coefficient and half-time differ almost a factor 2 compared to the results of Stam. This difference endorses the importance of having a representative wave climate to estimate the redistribution rate.

|                   | $\overline{H_s}$ [m] | $\overline{H_s^{2\frac{1}{2}}}$ [m] | $T_p$ [s] | $ \overline{\theta_w} - \theta_{eq} $ [°] | $c_1$ [m <sup>3</sup> /yr] | $T_{50\%}$ [yr] |
|-------------------|----------------------|-------------------------------------|-----------|-------------------------------------------|----------------------------|-----------------|
| Model Sand Engine | 0.99                 | 1.11                                | 5.9       | 22                                        | 0.031                      | 11              |
| Data buoy         | 0.90                 | 1.19                                | 4.9       | 42                                        | 0.030                      | 12              |
| ECMWF             | 0.78                 | 1.08                                | 4         | 41                                        | 0.023                      | 15              |
| NOAA              | 0.79                 | 1.01                                | 4.6       | 45                                        | 0.020                      | 19              |

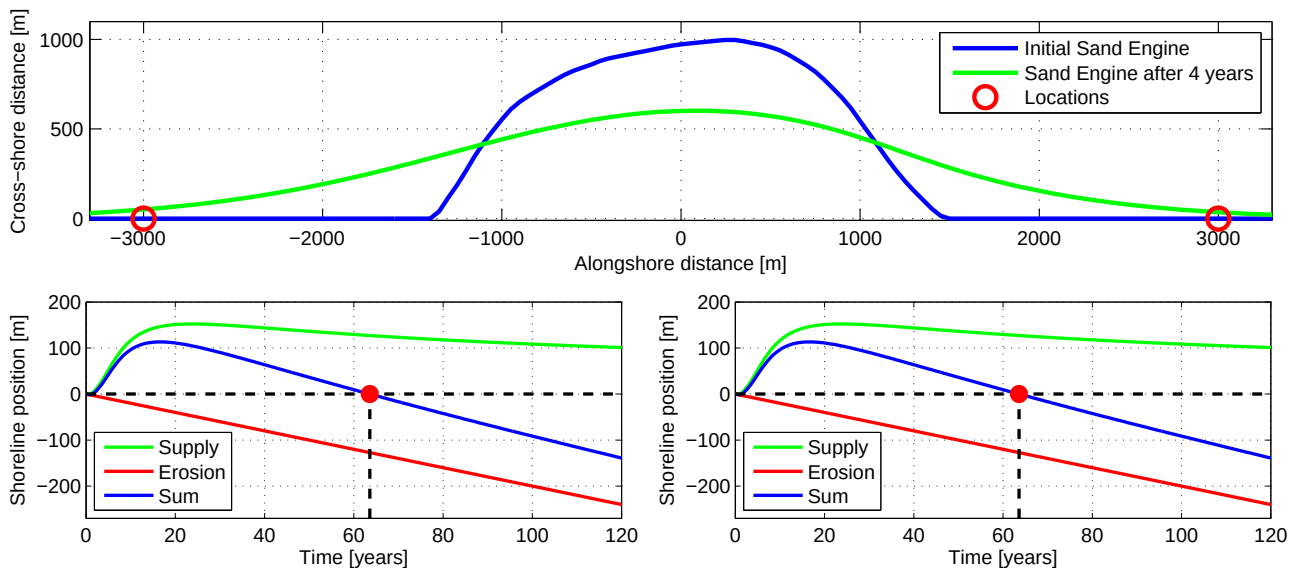
**Table 4-1:** Wave climate parameters and model results for the wave data sources: mean and RMS significant wave height, wave peak period, directional spreading, diffusion coefficient and half-time



**Figure 4-4:** Volume decrease of the Sand Engine for all model simulations. The predictions using the buoy data are similar to those of Stam

### 4-3 Lifetime Sand Engine

The results of Stam (2014) for the nourishment redistribution are used together with an assumed erosion rate of 2 m to estimate the lifetime of the Sand Engine. Figure 4-5 shows the coastline positions as function of time for two different alongshore locations. For each location the lifetime is indicated with a red dot. At a distance of 3 km from the center of the Sand Engine it is expected that no additional coastal protection measures are required for a period of about 65 years.

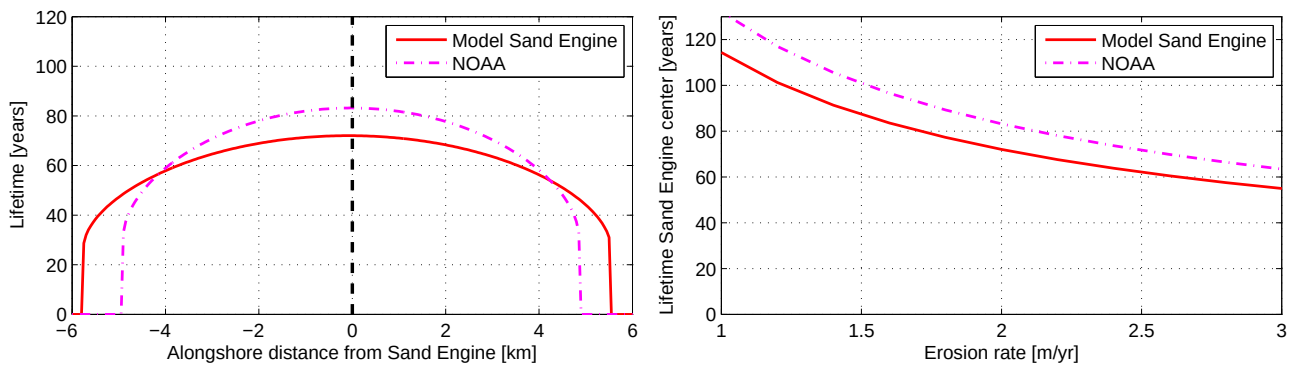


**Figure 4-5:** Coastline position as function of time for two locations adjacent to the Sand Engine. The lifetime is indicated with a red dot in the lower sub-plots

In 4-6 the lifetime is given as function of the distance from the center of the Sand Engine (left sub-plot) and as function of the erosion rate of the shore (right sub-plot). The two lines represent the predictions using the wave data sources that correspond to the smallest and the largest half-times: The predictions made by Stam (red solid line) and the predictions of the tool for the NOAA data (pink dashed line). The left sub-plot contains very steep gradients at the boundaries of the DoI where the lifetime suddenly drops to zero, which is a consequence of the lifetime definition (see also Section 3-1).

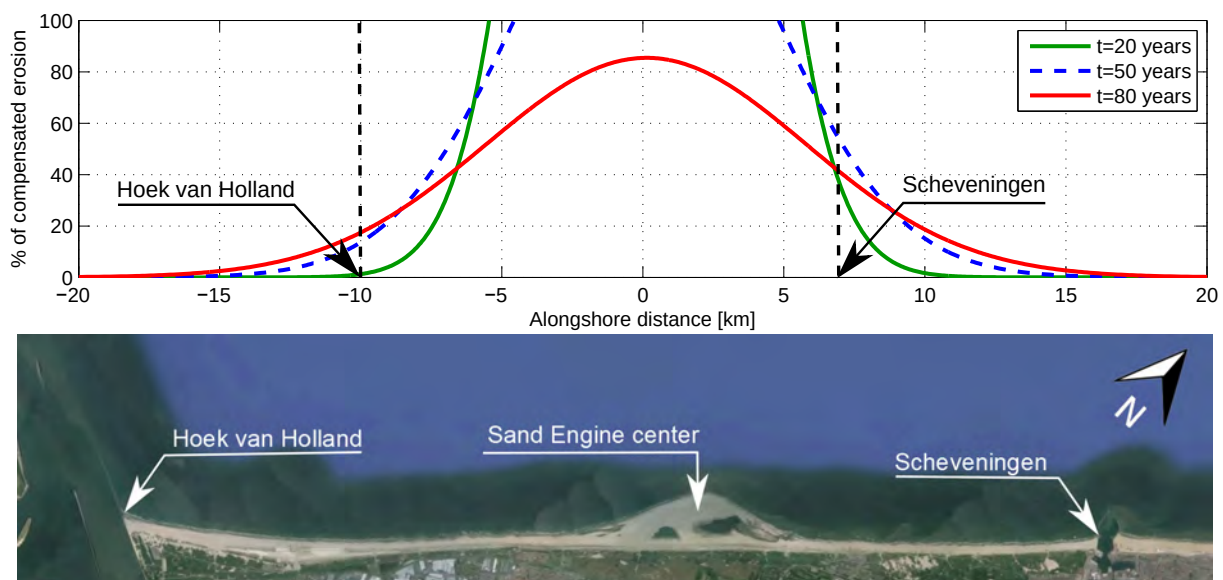
Interestingly, the estimates for the lifetime of the simulations differ less compared to those of the half time. A small difference in the wave climate therefore strongly influences the speed at which the shape of

the Sand Engine changes, while its influence on the lifetime is rather limited. Figure 4-6 shows that no coastal maintenance is required for a period of 50 years over an alongshore distance of about 10 km. The assumption of the erosion rate of the shore is found to be very important for an accurate estimate of the lifetime: The lifetime at the nourishment center differs about a factor 2 for erosion rates of 1 and 3 m/yr. Estimates for the Dol are in between 10 and 12 km. Beyond the Dol the effect of the nourishment is still considerable but additional measures are required to avoid shoreline retreat.



**Figure 4-6:** Left: lifetime of the Sand Engine as function of the alongshore distance relative to the center of the nourishment ( $x = 0$ ) assuming an erosion rate of 2 m/yr. Right: Lifetime at the center of the Sand Engine as function of the erosion rate

Also beyond the Dol the Sand Engine significantly reduces the need for coastal maintenance. This is expressed by Figure 4-7 that shows the percentage of compensated erosion as function of the alongshore distance at several moments in time for the results of Stam. After 50 years (blue dashed line) the Sand Engine fully compensated the coastal erosion over a stretch of almost 10 km. The red line shows that at a distance of  $\pm 10$  km from the center the average need for sand has reduced by 20% for a period of 80 years. A reduction in coastal maintenance is therefore expected for the entire Delfland coast of 17 km between 'Hoek van Holland' and 'Scheveningen'.



**Figure 4-7:** Percentage of compensated erosion as function of the alongshore distance. The bottom figure shows a satellite image with the boundaries of the Delfland coast: Hoek van Holland and Scheveningen (Source: Google Earth)

The results for the nourishment lifetime show that the Sand Engine is not sufficient to protect the Delfland

coast between 'Hoek van Holland' and 'Scheveningen' (17 km) for a period of 20 years. This is in correspondence to the additional nourishment volume that is predicted in the environmental impact assessment by DHV (2010). The assessment however expects a significant reduction in coastal maintenance till 30 to 40 years after construction which is in line with the results in Figure 4-7.

## 4-4 Summary

All model simulations predict an symmetrical redistribution of the Sand Engine because of the almost linear  $S-\theta$  curve. The averaged wave climate parameters of the different data sources show a substantial variation. These variations have a large effect on the rate of change of the nourishment shape: Estimations for the half-time and diffusion coefficient of the Sand Engine differ almost a factor two. It is therefore of high importance to obtain a representative wave climate for an accurate prediction of the coastline changes for the Sand Engine. The different wave climates however have a limited effect on the lifetime and the DoI. The Sand Engine is expected to be sufficient to protect 10 km of coastline for a period of about 50 years. The results furthermore predict a reduction in coastal maintenance along the entire Delfland coast. All lifetime predictions are based upon an assumed averaged erosion rate of 2 m/yr. This future erosion rate is found to be very important to obtain an accurate prediction of the nourishment lifetime.

# Redistribution, coastal erosion and lifetime of mega nourishments

This chapter presents the results of the MN-tool for the redistribution rate (section 5-1), the erosion of the autonomous shore (section 5-2) and the lifetime of a mega nourishment (section 5-3). For each section the results from different model runs are used. For more information regarding these runs and the parameters reference is made to appendix C. In this chapter several functions are fitted on the model results by using the method of non-linear least squares.

## 5-1 Results nourishment redistribution

The default model set-up is the starting point for the analysis of the mega nourishment redistribution rate. This model set-up is used in combination with a set of over 250 different wave climates from the global wave models of ECMWF and NOAA. These climates are chosen all over the world to cover the wide variability in wave heights, periods and directions of the wave climates around the world. In Appendix C a map of the wave climate locations is included together with a couple of figures that show the averaged wave climate parameters.

For each wave climate a model simulation is performed with the default model setup. Subsequently scatter plots are made to visualise the relations between different parameters. Two characteristic parameters are used to describe the redistribution of a mega nourishment:

- Diffusion coefficient,  $c_1$  [ $\text{m}^3/\text{yr}/^\circ$ ]: Gradient of  $S-\theta$  curve which quantifies the redistribution rate
- Half-time,  $T_{50\%}$  [yr]: Time to reduce sand volume within the initial area of the nourishment by 50%

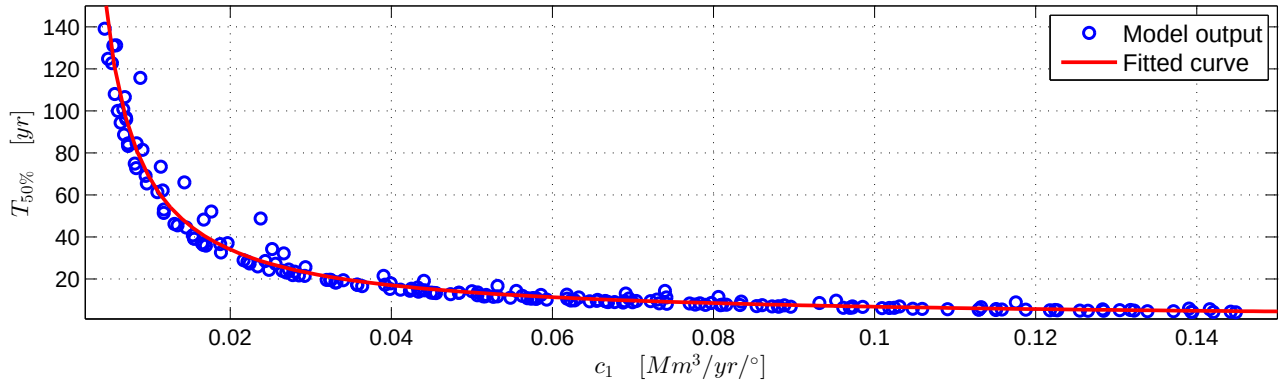
First the relation between diffusion coefficient and the half-time is presented. Subsequently the diffusion coefficient is related to different wave climate parameters.

### 5-1-1 Relation diffusion coefficient and half-time

The diffusion coefficient is a rather abstract parameter and from its value alone it is not directly clear how quickly a mega nourishment spreads along the shore. To illustrate its meaning, the parameter is related to the half-time for the default model with a nourishment volume of  $15 \text{ Mm}^3$ .

The relation between the diffusion coefficient and the half-time is shown in Figure 5-1. Each blue circle in this figure represents one model run with a different wave climate. The circles in the figure show that

the half-time is inversely related to the diffusion coefficient which is according to the expectations. This is illustrated by the fitted function of the form  $T_{50\%} = a/c_1$ . Some points however deviate from the fitted curve.

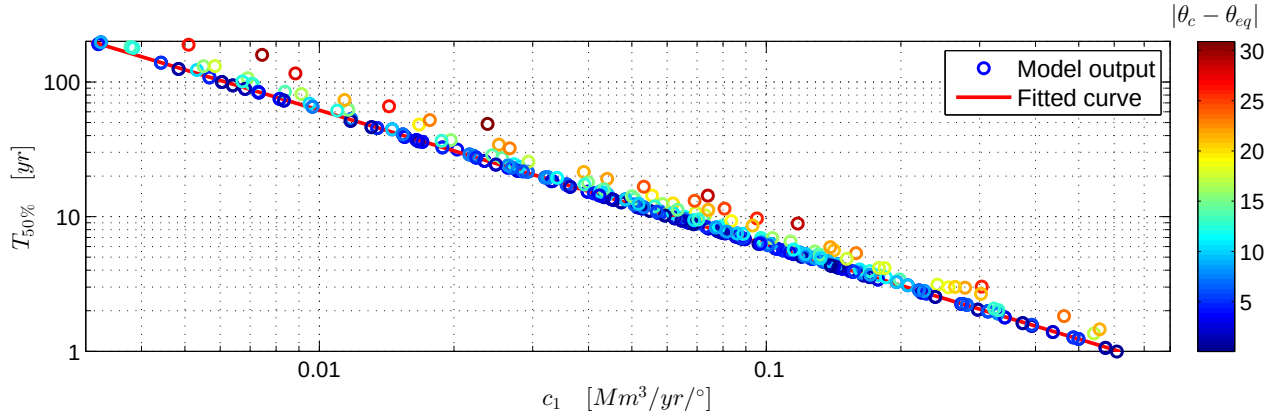


**Figure 5-1:** Nourishment half-time is inversely proportional to the diffusion coefficient. Fitted function  $T_{50\%} = 0.62/c_1$

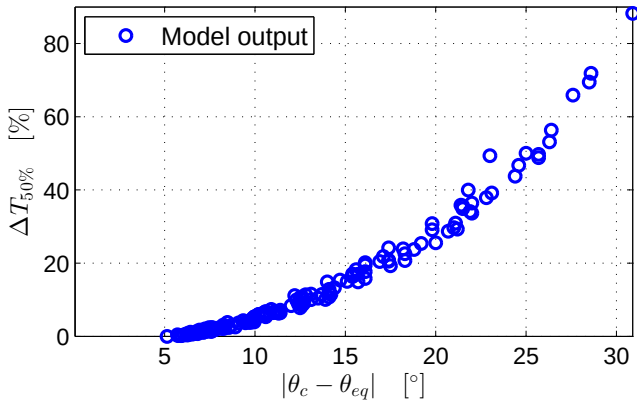
It has been found that the deviation from the inverse relation is related to the absolute difference between the actual and the equilibrium orientation of the coastline ( $|\theta_c - \theta_{eq}|$ ). This is illustrated in Figure 5-2 that shows a coloured scatter plot on double logarithmic axis (on these axis the inverse relation becomes a straight line). The colour scale, that represents the absolute difference between actual and equilibrium coastline orientation, shows that all outliers of the scatter correspond to large equilibrium coastline orientations, hence a coasts with a large nett alongshore sediment transport rate. This is explained by considering the gradient of the  $S-\theta$  which is decreasing for larger coastline angles relative to  $\theta_{eq}$ .

In Figure 5-2 an inverse function is fitted on the model output points that have an equilibrium coastline orientation smaller than  $5^\circ$ . Subsequently the relative deviation between the fitted line and the half-time ( $\Delta T_{50\%}$ ) is calculated for all points and plotted as function of the equilibrium coastline orientation in Figure 5-3. From this figure it is concluded that the error between the fit and the model output points is very small for values of  $|\theta_c - \theta_{eq}| < 10^\circ$ . For these cases the  $S-\theta$  curve can be approximated by a linear function.

The deviation of the half-time becomes more significant for angles larger than  $15^\circ$ . It is however expected that most of the coastlines in the world have small equilibrium angles. Along these sandy shores the wave climate already reworked the sediments for years resulting in a shoreline that approaches an equilibrium orientation. The results for larger values of  $|\theta_c - \theta_{eq}|$  are furthermore questionable because the Unibest model does not include the process of spit development that occurs for high angle wave climates. In the remainder of this thesis it is therefore assumed that the angle between the wave climate and the coastline has a negligible effect on the half-time and the diffusion coefficient. In other words the equilibrium angle is assumed to be zero for all cases.



**Figure 5-2:** Half time as function of the diffusion coefficient on double logarithmic axes. Inverse function is fitted through the data points that fulfil the condition  $|\theta_c - \theta_{eq}| < 5^\circ$ :  $T_{50\%} = 0.61/c_1$ . The colour scale shows that deviations from the fit correspond to model runs with a large relative equilibrium angle



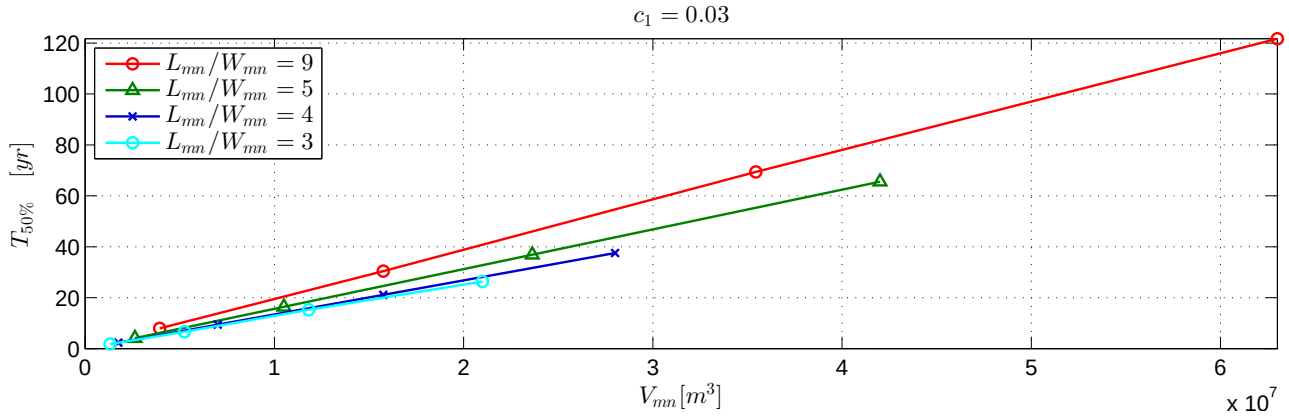
**Figure 5-3:** Deviation of  $T_{50\%}$  from the fitted curve of Figure 5-2 in percent as function of  $|\theta_c - \theta_{eq}|$ . Cases with a large  $|\theta_c - \theta_{eq}|$  show a larger deviation from the fitted curve

The above results for the relation between  $c_1$  and  $T_{50\%}$  are only valid for the nourishment dimensions of the default model. A more general relation for  $T_{50\%}$  was derived by running the Unibest CL-module for different values of the diffusion coefficient, the active height and the nourishment dimensions (for a more detailed model specification see Appendix C).

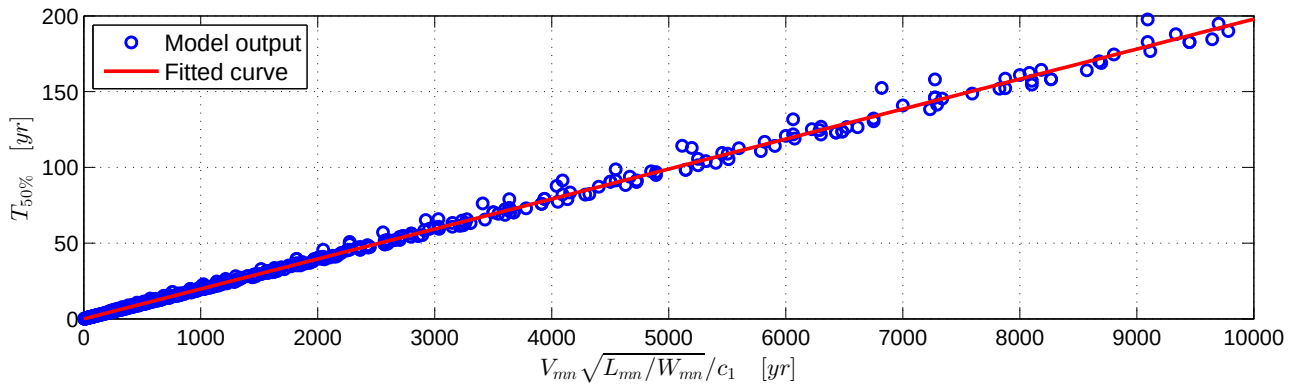
In Figure 5-4 the results of the runs with a diffusion coefficient of  $0.3 \text{ Mm}^3/\text{yr}/^\circ$  are shown. For all nourishments with a constant ratio of length over width ( $L/W$ ) the half-time is linearly related to the nourishment volume. The gradient of the linear relation however changes for different  $L/W$  ratios due to changing coastline gradients and a different alongshore length of the nourishment.

A more general relation between the half-time and the nourishment parameters has been found empirically. This relation is described by Equation 5-1 and relates the half-time with the nourishment volume, the active height, the  $L/W$  ratio and the diffusion coefficient. The empirical relation is visualised in Figure 5-5 which shows the half-time as function of different nourishment parameters. A linear relation is fitted in this figure which results in a mean relative difference with the model output points of only 6%.

$$T_{50\%} = 0.020 \frac{V}{c_1} \sqrt{L_{mn}/W_{mn}} \quad (5-1)$$



**Figure 5-4:** Linear relations between the half-time and the nourishment volume for different values of the LW-ratio



**Figure 5-5:** Half-time as function of the volume, the LW-ratio and the diffusion coefficient. Fitted function  $T_{50\%} = 0.020 V_{mn} \sqrt{L_{mn}/W_{mn}} / c_1$

### 5-1-2 Relation wave climate parameters and diffusion coefficient $c_1$

The previous section explained how the half-time of a mega nourishment is related to the diffusion coefficient  $c_1$ . This section discusses how the value of  $c_1$  is related to different wave climate parameters. For this a new parameter is introduced first: the scaled diffusion coefficient  $c_{1,s}$ .

The majority of the climates have a certain percentage of time without waves. This is caused by the wave transformation which sets the significant wave height and peak period to zero for all waves with an angle of wave incidence larger than  $90^\circ$ . Unfortunately the percentage of no waves is influencing the distributions of the wave climate parameters and the value for the diffusion coefficient. It is therefore chosen to neglect all waves in the climate with a height of zero for the calculation of the averaged wave climate parameters. The diffusion coefficient should therefore be scaled with the percentage of no waves. This scaling will result in a better comparison between the characteristics of the wave climate and the diffusion coefficient. Equation 5-2 shows the scaling of  $c_1$  based on the percentage of time without waves ( $p_{nowaves}$ ).

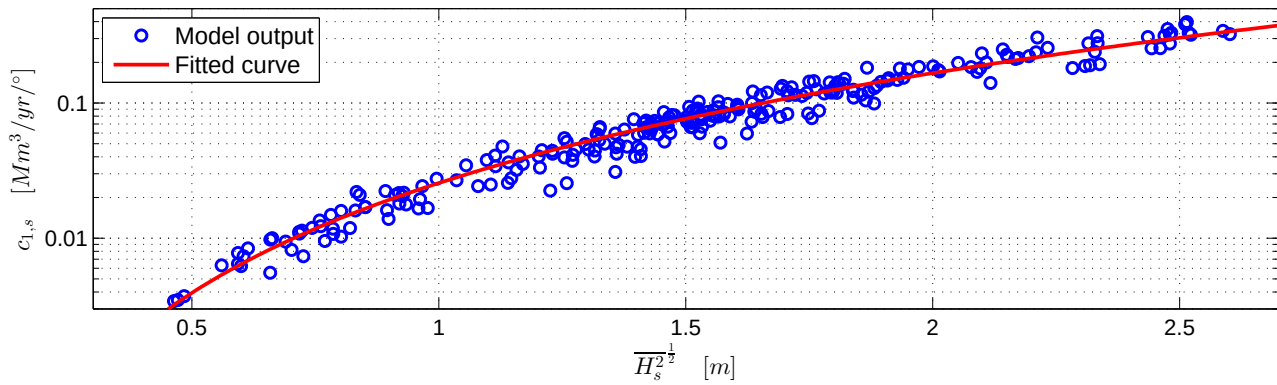
$$c_{1,s} = \frac{c_1}{1 - p_{nowaves}} \quad (5-2)$$

## Wave height

Different averaged wave height parameters were related to  $c_{1,s}$ :

- The average of all significant wave heights:  $\overline{H}_s$
- The average of the highest  $x$  percent of the significant wave heights:  $\overline{H}_{x\%}$
- The average of the significant wave height to the power  $x$ :  $\overline{H}_s^x$

From these parameters, the RMS of the significant wave height, defined as  $\overline{H}_s^{2\frac{1}{2}}$ , results in the smallest scatter with the scaled diffusion coefficient (see Figure 5-6). From linear wave theory it is known that the wave energy is proportional to the square of the wave height. It can therefore be concluded that the magnitude of the diffusion coefficient best relates to the wave energy of the climate. The RMS value accounts more for the higher waves which have a larger contribution to the diffusion coefficient. When putting even more emphasize on the higher waves in the climate the relation however becomes weaker. A best fit on the model output points was obtained by an exponential function, the red line in Figure 5-6.



**Figure 5-6:** Scaled diffusion coefficient as function of the RMS significant wave height. Fitted function:

$$c_{1,s} = 0.026(\overline{H}_s^{2\frac{1}{2}})^{2.70}$$

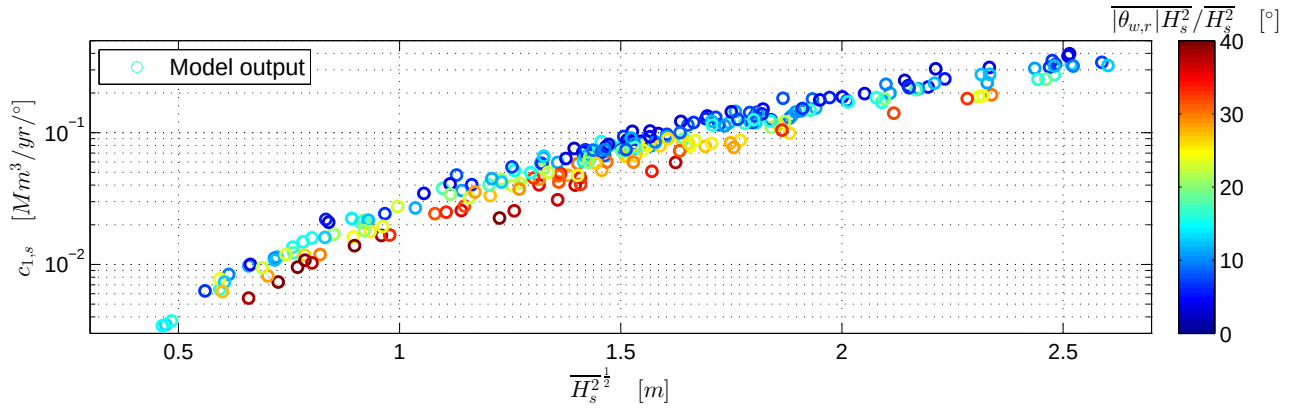
## Directional spreading

The remaining scatter between the RMS of the significant wave height and the diffusion coefficient is partly caused by the directional spreading of the wave climate. A parameter is defined that quantifies the directional spreading:

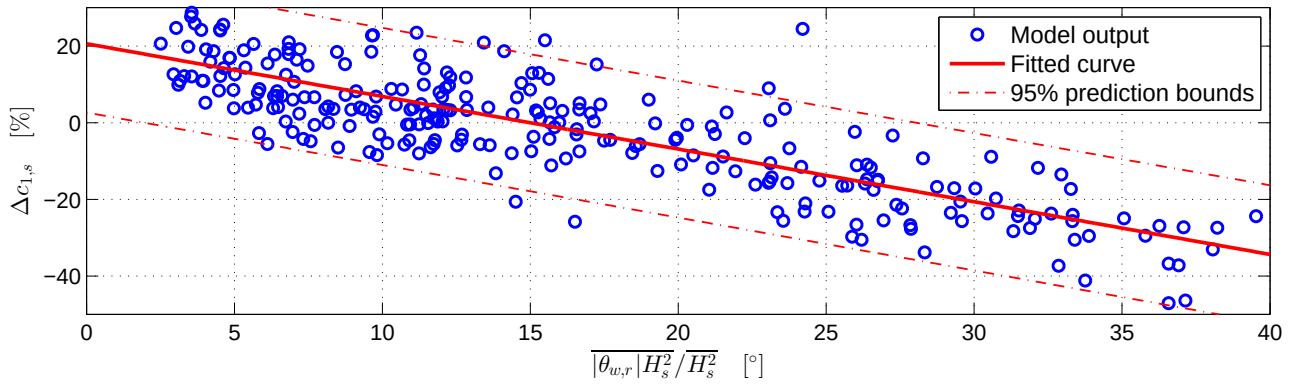
$$|\theta_{w,r}| \overline{H}_s^2 / \overline{H}_s^2 \quad \text{with} \quad \theta_{w,r} = \theta_w - \theta_{eq} \quad [-] \quad (5-3)$$

In Equation 5-3  $\theta_{w,r}$  represent the relative angle of wave incidence. The averaged directional spreading which is a measure for the width of the wave angle distribution is weighted by the significant wave height squared because the larger waves contribute more to the magnitude of the diffusion coefficient.

The directional spreading of the wave climates is visualised with a colour scale in Figure 5-7 that shows the RMS significant wave height as function of the diffusion coefficient. In this figure a clear sorting can be seen: The diffusion coefficient is generally smaller for wave climates with a larger directional spreading. This is supported by Figure 5-8 that shows the scatter between the directional spreading and the relative deviation of  $c_{1,s}$  from the exponential fit of Figure 5-7. A linear decreasing relation is found between both parameters. However the 95% prediction bounds of this equation still show a scatter of  $\pm 20\%$ .



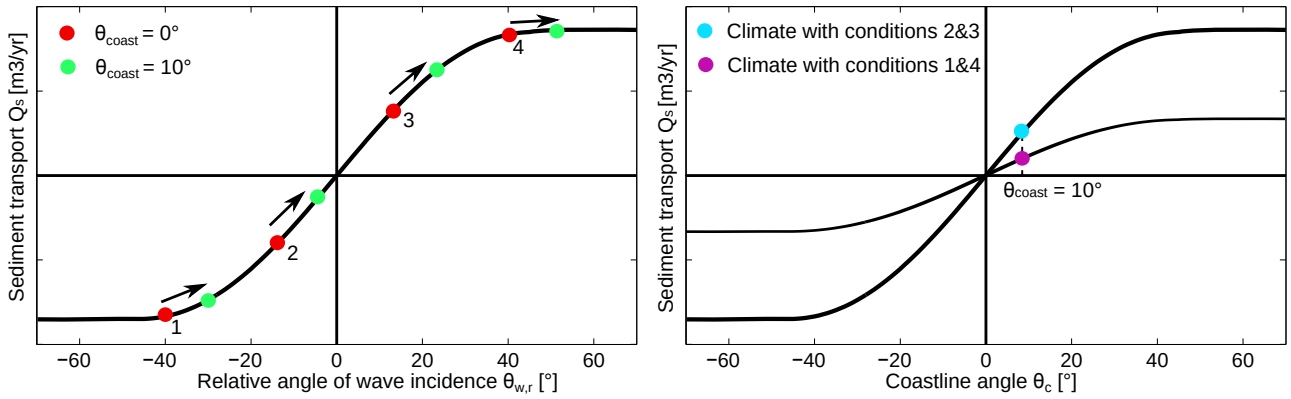
**Figure 5-7:** RMS significant wave height as function of the scaled diffusion coefficient. The colour scale shows the weighted directional spreading



**Figure 5-8:** Relative deviation of the scaled diffusion coefficient from the exponential fit of Figure 5-7 as function of the weighted averaged directional spreading. Fitted function:  $\Delta c_{1,s} = -1.37(|\theta_{w,r}| H_s^2 / H_s^2) + 20.59$

Physically the reduction in diffusion coefficient for climates with a large directional spreading is caused by a lower LST gradient. This reduction is illustrated in Figure 5-9 that shows the sediment transport  $Q_s$  as function of the relative angle of wave incidence  $\theta_{w,r}$ . The red dots in the figure corresponds to four wave conditions with the same height and period but with a different wave direction. These waves first approach a coastline with an orientation of  $0^\circ$ . This correspond to a LST value indicated by the red dots. When the coastline orientation is turned by  $10^\circ$ , the relative angles of wave incidence change resulting in a shift of the red dots. For the coastline orientation of  $10^\circ$  the LST changed for each wave conditions (from the red dots to the green dots).

Lets now consider two theoretical wave climates that consist of two wave conditions with the same duration: a climate with condition 2&3 and a climate with condition 1&4. The right sub-plot of Figure 5-9 shows the S- $\theta$  curve for both climates. This curve is created by averaging the sediment transport rates of both conditions. For a coastline orientation of  $10^\circ$  it can be seen that this average rate is considerably larger for the wave climate with condition 2&3. This is caused by the larger change in LST for a coastline rotation of  $10^\circ$ . This is the reason why a climate with a large directional spreading has a lower diffusion coefficient.



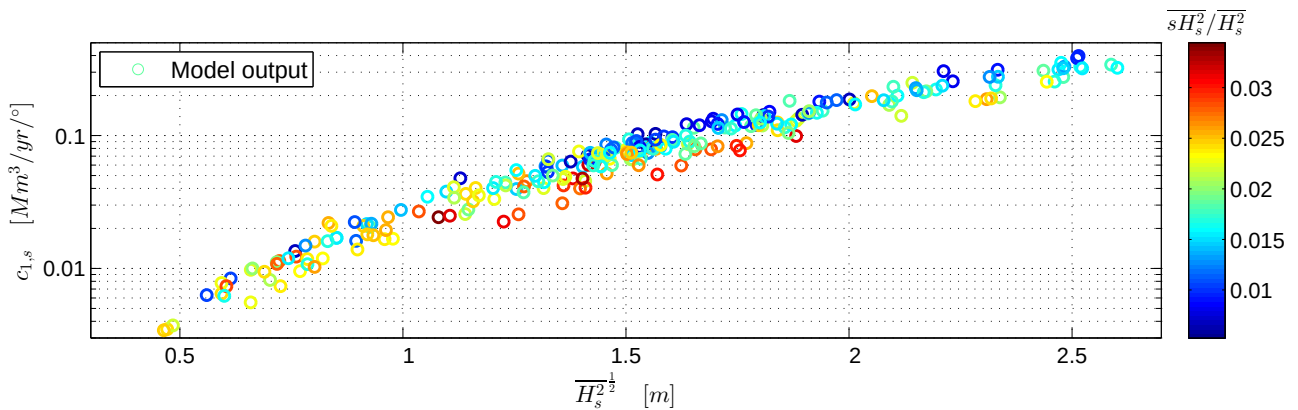
**Figure 5-9:** Physical explanation for lower diffusion of a climate with a large directional spreading. Left:  $S$ - $\theta$  curve with four different wave conditions and two coastline orientations. When the coastline rotates over  $10^\circ$  all points on the curve shift to the right (from red to green). Right: For a theoretical wave climate that consists of wave condition 2&3 the gradient of the  $S$ - $\theta$  curve is larger resulting in a larger diffusion coefficient. Climates with a large directional spreading therefore result in a lower diffusion coefficient.

### Wave steepness

The deep water wave steepness also has an influence on the magnitude of the diffusion coefficient. The weighted averaged deepwater wave steepness is defined in Equation 5-4. It is again chosen to weight this parameter with the square of the significant wave height to account more for the higher waves in the climate.

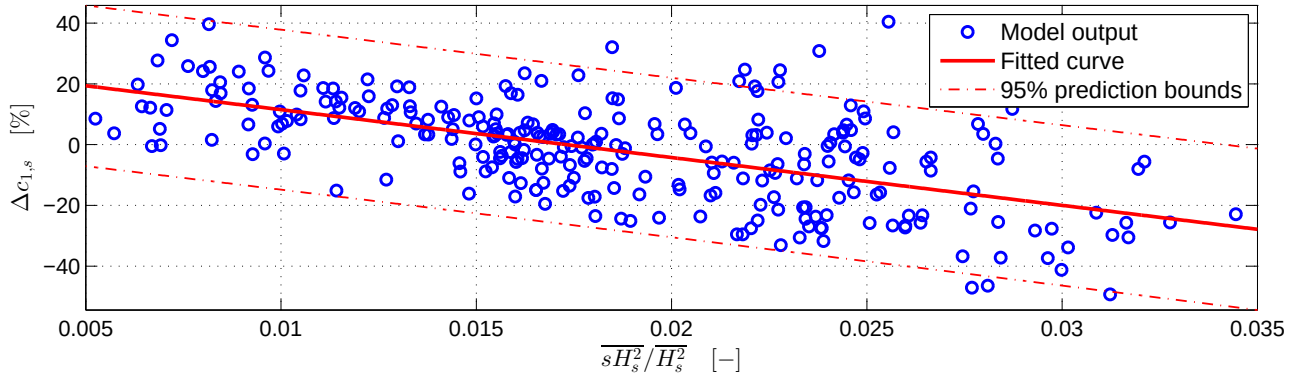
$$\frac{\overline{sH_s^2}}{H_s^2} \quad \text{with} \quad s = \frac{H_s}{L_0} = \frac{2\pi H_s}{gT_p^2} \quad [-] \quad (5-4)$$

A coloured scatter plot is made of the RMS significant wave height and the diffusion coefficient (see Figure 5-10). The colour scale in this figure shows the weighted averaged deepwater wave steepness. When looking at the sorting of the colours it can be concluded that waves with a larger steepness (wind waves) generally have a lower diffusion coefficient compared to waves with a low steepness (swell waves).



**Figure 5-10:** RMS significant wave height as function of the scaled diffusion coefficient. The colour scale shows the weighted averaged wave steepness

Figure 5-11 shows the averaged wave steepness as function of the relative deviation of  $c_{1,s}$  from the exponential fit of Figure 5-10. As for the directional spreading a linear decreasing relation is fitted on the model output with 95% prediction bounds of about  $\pm 20\%$ .



**Figure 5-11:** [Relative deviation of the scaled diffusion coefficient as function of the weighted averaged wave steepness. Fitted function:  $\Delta c_{1,s} = -1575(sH_s^2/H_s^2) + 27.25$

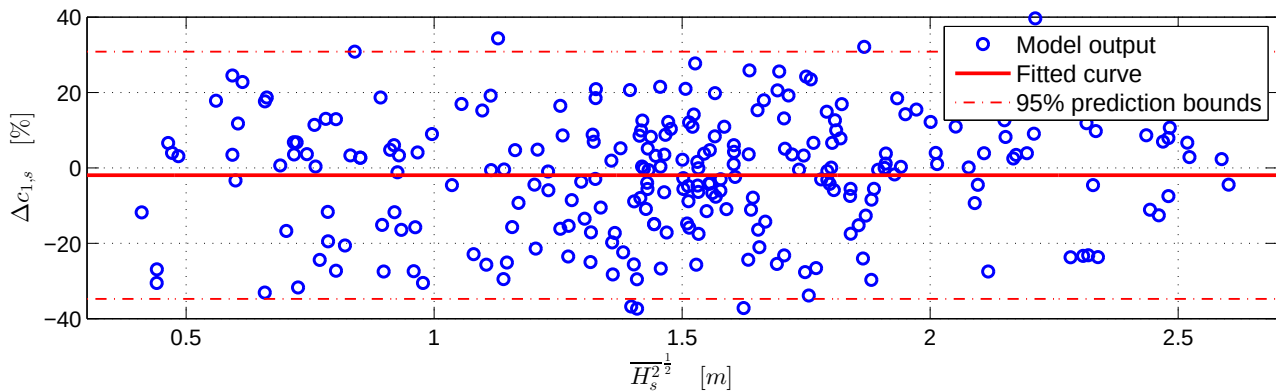
The effect of the wave steepness can be explained by the difference in wave energy transport ( $P$ ). Because wave energy is propagating with the wave group velocity the wave energy transport is defined as:  $P = E_w \cdot c_g$  in [J/m/s]. Waves with a larger period (thus a lower steepness) propagate faster resulting in a larger wave energy transport. The transport of wave energy is included in the wave energy balance of the LT-module (see Appendix B).

The refraction of longer waves has an opposite effect on the diffusion coefficient. Wave with a longer period refract more and will therefore approach the shore under a smaller angle causing a slight reduction in transport. This effect is however found to be negligible compared to the increase in wave energy transport.

### Empirical relations for $c_1$

Based on the previous results several empirical relations are derived that can reproduce the diffusion coefficient of the model results. These formulation differ in complexity and accuracy. The diffusion coefficient is expressed in Equation 5-5 by an exponential function that only includes the RMS significant wave height. This function is found by fitting an exponential expression on the model output results of Figure 5-6. The uncertainty of this relation compared to the model results is quantified by the prediction bounds in Figure 5-12: There is a 95% probability that the diffusion coefficient calculated with the Unibest LT-module deviates less than 35% from the equation.

$$c_{1,s} = 0.026 \cdot \overline{H_s^2}^{1.35} \quad (5-5)$$



**Figure 5-12:** Relative deviation of the scaled diffusion coefficient as function of the RMS significant wave height

The relation for  $c_{1,s}$  can be improved by applying a linear correction factor that depends on the directional spreading and the wave steepness. It is however found that both parameters are dependent: A large directional spreading is generally associated with a larger wave steepness while the opposite is true for a unidirectional climate. Directly using the gradients of the linear fits from Figures 5-8 and 5-11 would therefore result in an overcorrection of the diffusion coefficient. The diffusion coefficient is therefore corrected first by the linear relation for the directional spreading. Subsequently a second linear correction is made based on the wave steepness.

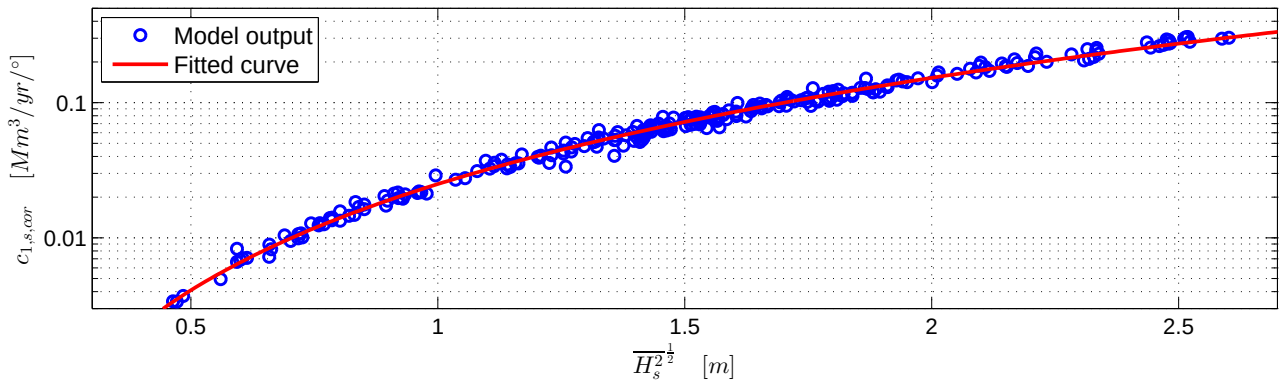
linear correction factors ( $\Delta c_{1,s}$ ) are derived based on the *weighted* (Equation 5-6) and the *non-weighted* (Equation 5-7) values of the directional spreading and the wave steepness. These correction factors for  $c_{1,s}$  are used in Equation 5-8 to obtain a new corrected value for the diffusion coefficient:  $c_{1,s,cor}$ .

$$\Delta c_{1,s} = -1.37 \cdot (\overline{|\theta_{w,r}|} \overline{H_s^2} / \overline{H_s^2}) - 733 \cdot (\overline{s} \overline{H_s^2} / \overline{H_s^2}) + 34.81 \quad (5-6)$$

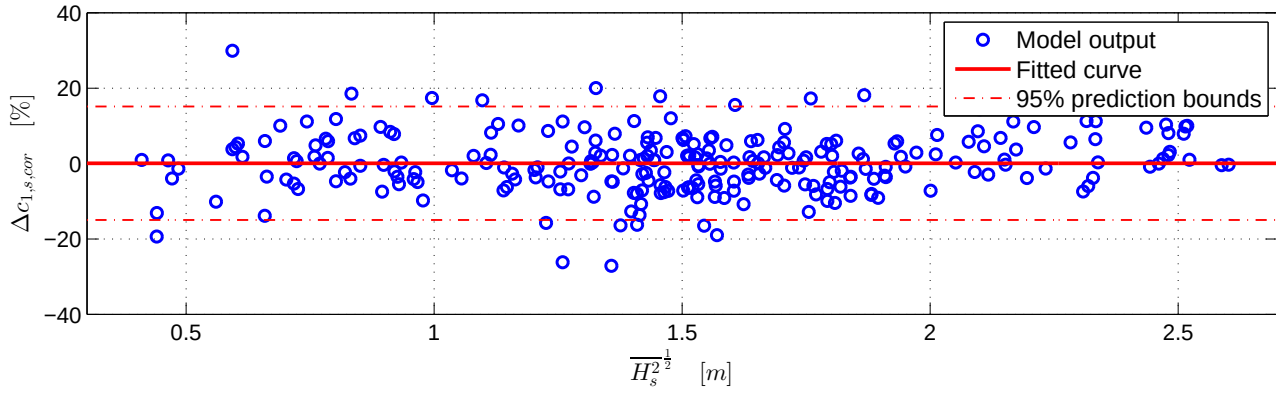
$$\Delta c_{1,s} = -1.03 \cdot \overline{|\theta_{w,r}|} - 1401 \cdot \overline{s} + 21.28 \quad (5-7)$$

$$c_{1,s,cor} = c_{1,s} - \frac{\Delta c_{1,s}}{100} c_{1,s} \quad (5-8)$$

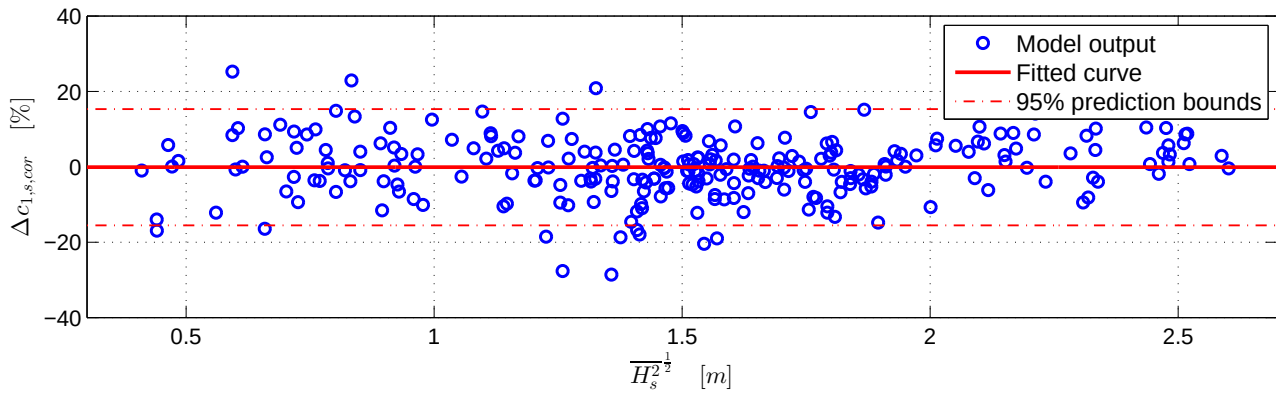
The linear correction results in a considerable reduction of the scatter between the RMS significant wave height and the diffusion coefficient which is illustrated in Figure 5-13 for the correction factor based on the weighted parameters. The scatter reduction can be quantified by the prediction bounds for  $\Delta c_{1,s,cor}$  which are visualised in Figure 5-14 for the weighted parameters and in Figure 5-15 for the non-weighted parameters. According to both figures there is a 95% probability that the model results deviate less than  $\pm 15\%$  from the empirical equation. This is a significant reduction compared to the 35% for Equation 5-12. For the accuracy of the empirical equations it makes no difference if the non-weighted or weighted parameters are used for the correction. It is therefore advised to use the non-weighted parameters for the ease of use.



**Figure 5-13:** Corrected scaled diffusion coefficient as function of the RMS significant wave height. The correction using the weighted values of the directional spreading and the wave steepness results in a significant reduction of the scatter compared to Figure 5-6



**Figure 5-14:** Relative deviation of scaled diffusion coefficient as function of the RMS significant wave height after a *weighted* linear correction of  $c_{1,s}$  according to Equation 5-6



**Figure 5-15:** Relative deviation of scaled diffusion coefficient as function of the RMS significant wave height after a *non-weighted* linear correction of  $c_{1,s}$  according to Equation 5-7

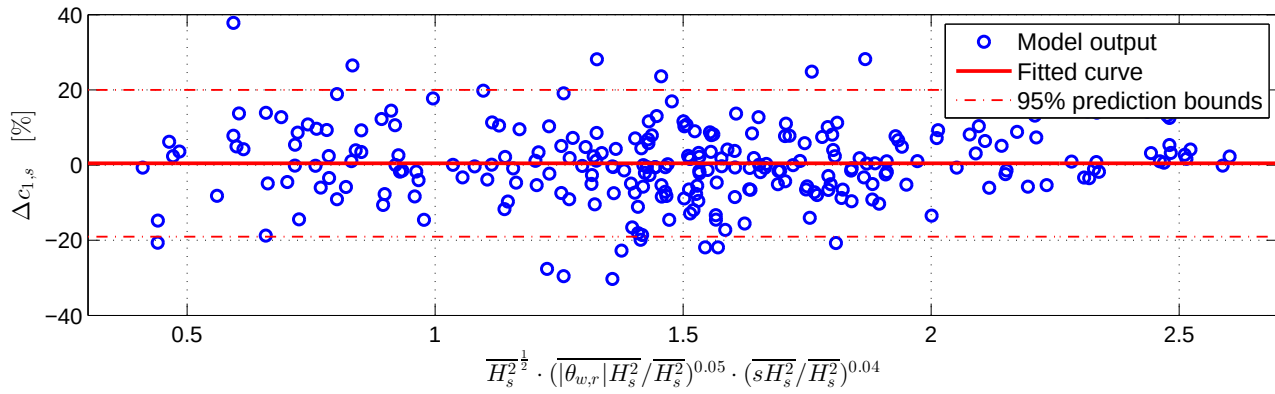
Two other empirical relations are derived that assume an exponential relation between the diffusion coefficient, the RMS significant wave height, the directional spreading and the steepness. Such an exponential relation provides a good indication of the relative influence of the wave climate parameters. The exponents in these equations are determined by searching for the minimum mean relative deviation of the diffusion coefficient ( $\overline{\Delta c_{1,s}}$ ).

The first relation given in Equation 5-9 includes the weighted parameters for the directional spreading and the wave steepness. Equation 5-10 uses the non weighted parameters and is therefore easier to use. However, the uncertainty of this equation is slightly larger. For Equation 5-10 there is a 95% probability that the model results differ less than  $\pm 22\%$ . Using the weighted parameters this percentage reduces to  $\pm 19\%$ . The relative deviation of the scaled diffusion coefficient is plotted for both exponential equations in Figures 5-16 and 5-17.

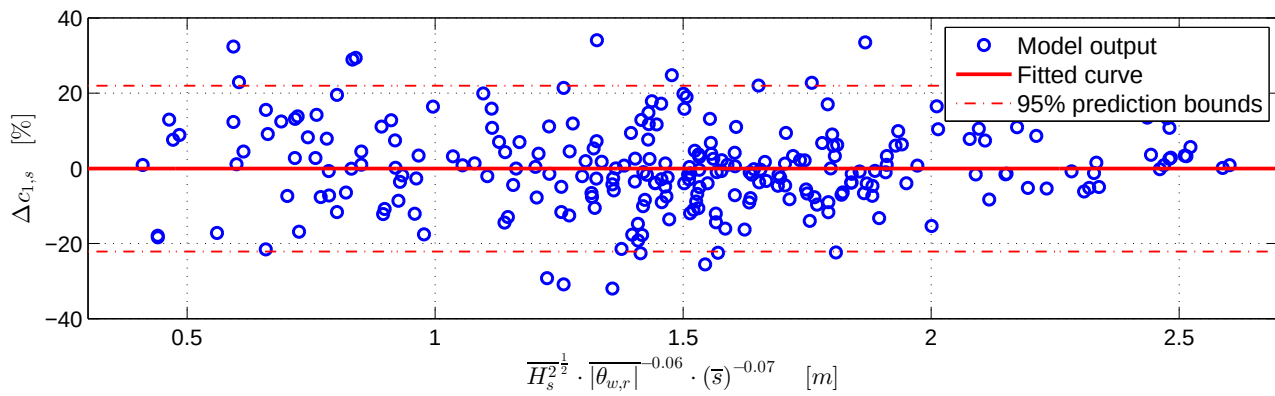
$$c_{1,s} = 0.024 \cdot \overline{H_s^2}^{1.33} \cdot (\overline{|\theta_{w,r}|} \overline{H_s^2} / \overline{H_s^2})^{-0.13} \cdot (\overline{sH_s^2} / \overline{H_s^2})^{-0.11} \quad (5-9)$$

$$c_{1,s} = 0.016 \cdot \overline{H_s^2}^{1.34} \cdot \overline{|\theta_{w,r}|}^{-0.12} \cdot (\overline{s})^{-0.19} \quad (5-10)$$

These final equations provide an indication for the relative influence of wave height, directional spreading and wave steepness. The wave height is by far the most dominant parameter for the estimation of the diffusion. A slight improvement can be made for the certainty of  $c_{1,s}$  by including the effect of the wave direction and steepness.



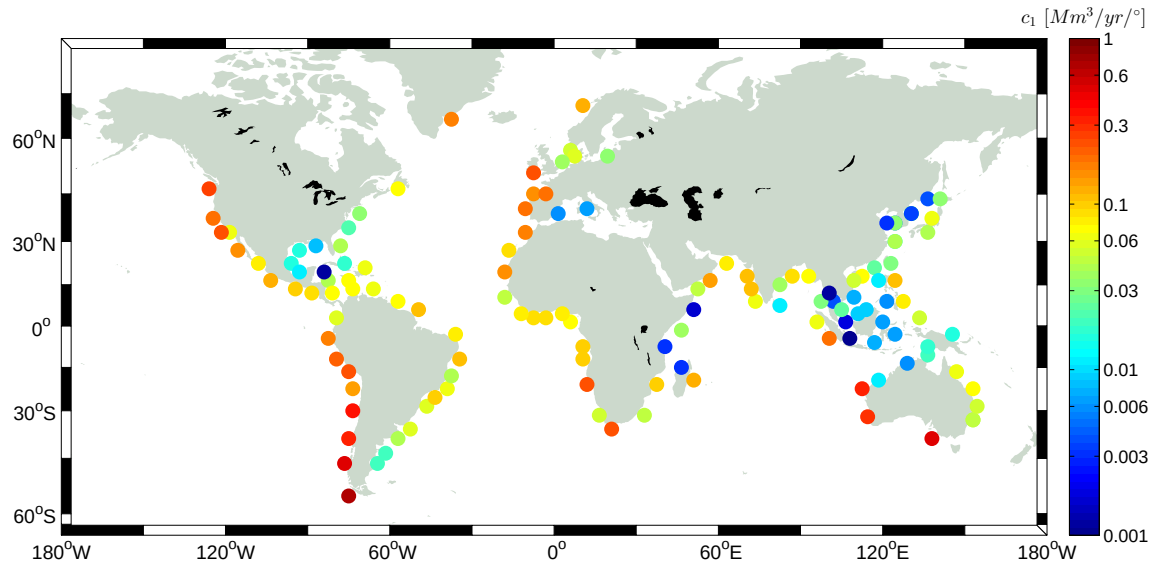
**Figure 5-16:** Relative deviation of the scaled diffusion coefficient as function of the significant wave height, the directional spreading and the wave steepness



**Figure 5-17:** Relative deviation of the scaled diffusion coefficient as function of the significant wave height, the directional spreading and the wave steepness

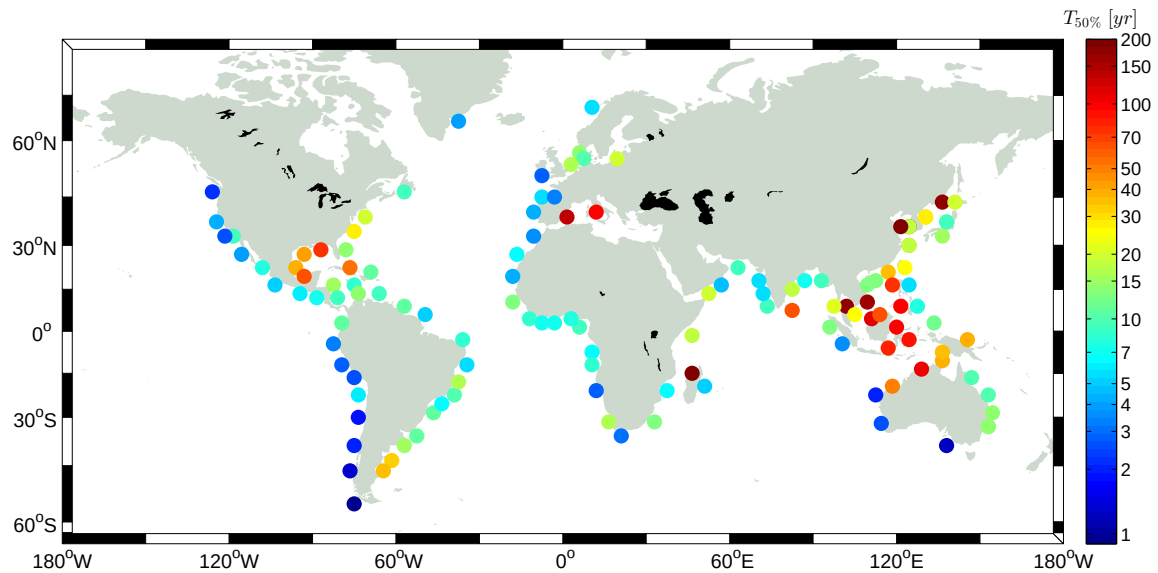
### Global variation of $c_1$ and $T_{50\%}$

137 different locations around the world were selected to compute the diffusion coefficient of a mega nourishment. The results for the diffusion coefficients calculated with the ECMWF wave model data are spatially presented on a global map in Figure 5-18. The dots in the figure corresponds to the chosen location and the dot's colour represents the value of the diffusion coefficient. This coefficient is generally large for the beaches that face the open ocean whereas the diffusion is small for coasts along the protected seas (e.g. in the Gulf of Mexico, the Mediterranean and south east Asia).



**Figure 5-18:** Global variation of the diffusion coefficient for all wave climates of the ECMWF wave model

Figure 5-19 shows a spatial representation of the half-times for the default nourishment of  $15 Mm^3$ . In this figure the color scale is logarithmic to visualise the differences in half-times. Along the majority of the world's coastline the half-time of the default model is between 1 and 15 years with the shortest half-times along the west coast of South America and Australia. Especially along these coasts the shape of a mega nourishment will disappear in a few years time. For the protected seas however the low diffusion coefficient results in half-times that go up to 150 years. At these locations the LST gradients are insufficient to diffuse the relatively large nourishment. A smaller mega nourishment would then be more suitable.



**Figure 5-19:** Global variation of the half-time for the default model with ECMWF wave climates

## 5-2 Results shoreline erosion

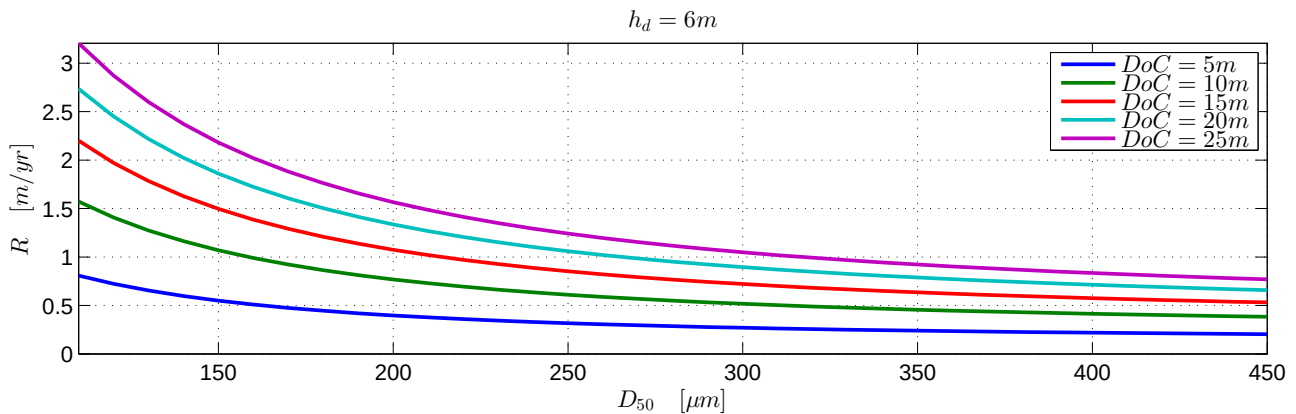
An estimation of the erosion of the shoreline is required to estimate the lifetime of a mega nourishment. This sections shows the results for the cross shore part of the MN-tool that aims at quantifying this erosion rate for a straight sandy shore. First of all the coastal retreat is quantified for a rise in sea level using the Bruun rule (see Section 2-2-3). Subsequently the coastal erosion during an episodic storm event is estimated 1D Xbeach simulation. For a detailed specification of the model runs reference is made to Appendix C.

### 5-2-1 Sea level rise

For the coastal response towards a rising sea level a simple 2D cross-shore mass conservation model as proposed by Bruun (1962) is used in the tool. This model assumes that the entire coastal profile move landward and upward in response to a rising sea level. The shoreline retreat  $R$  is a function of the cross-shore distance  $L_{DoC}$ , the closure depth  $DoC$ , the rise in sea level  $S$  and the elevation of the dune above MSL  $h_d$ . (see Section 2-2 for more information regarding the Bruun rule). The cross-shore distance is related to the shape of the cross shore profile which is assumed to depend only on the sediment diameter. The coastal retreat therefore also depends on the sediment diameter  $D_{50}$ .

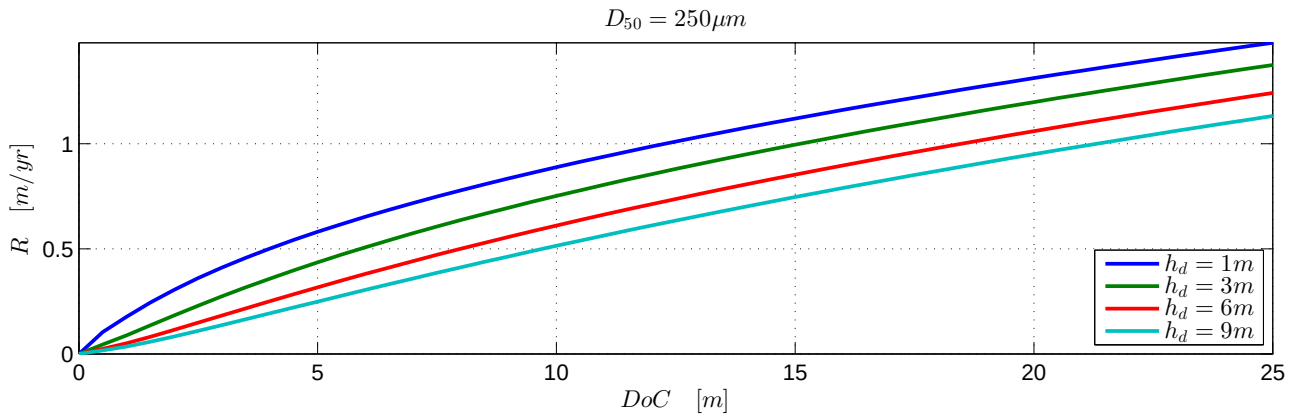
The upper bound of the IPCC predictions are used as an estimation for the expected SLR in 2100. This was found to be 0.98 m in 2100 relative to 2005 (see also Section 2-2-3). For simplicity the rise in sea level is assumed to be linear to obtain an estimation for the average yearly rate of coastal retreat.

In Figure 5-20 the coastal retreat is plotted against the sediment diameters for different values of the closure depth. It shows that for a larger median sediment diameter (hence a steeper profile) the coastal retreat reduces. One should notice that not all combinations of  $DoC$  and  $D_{50}$  are realistic. As shown in Appendix D-1 fine sediments generally occur along coast that are attacked by milder waves, so with a small  $DoC$ . Coarse sediment are often present along coasts that are attacked by larger waves. Retreat rates of Figure 5-20 above 1.5 m/yr are therefore expected to be rare.



**Figure 5-20:** Rate of coastal retreat as function of the sediment diameter for different values of the  $DoC$  for a dune crest level at MSL+6 m

Figure 5-21 shows the relation between the coastal retreat and the  $DoC$  for different values of the dune height  $h_d$ . For a low profile height ( $h_d = 1m$ ) the retreat is maximum. Again the high retreat values become more unrealistic because sediments are generally become coarser for larger closure depths (hence larger waves). It can therefore be stated that retreat rates above 1.5m/yr become more unrealistic.



**Figure 5-21:** Rate of coastal retreat as function of the DoC for different values of the dune crest level for a median sediment diameter of  $250 \mu m$

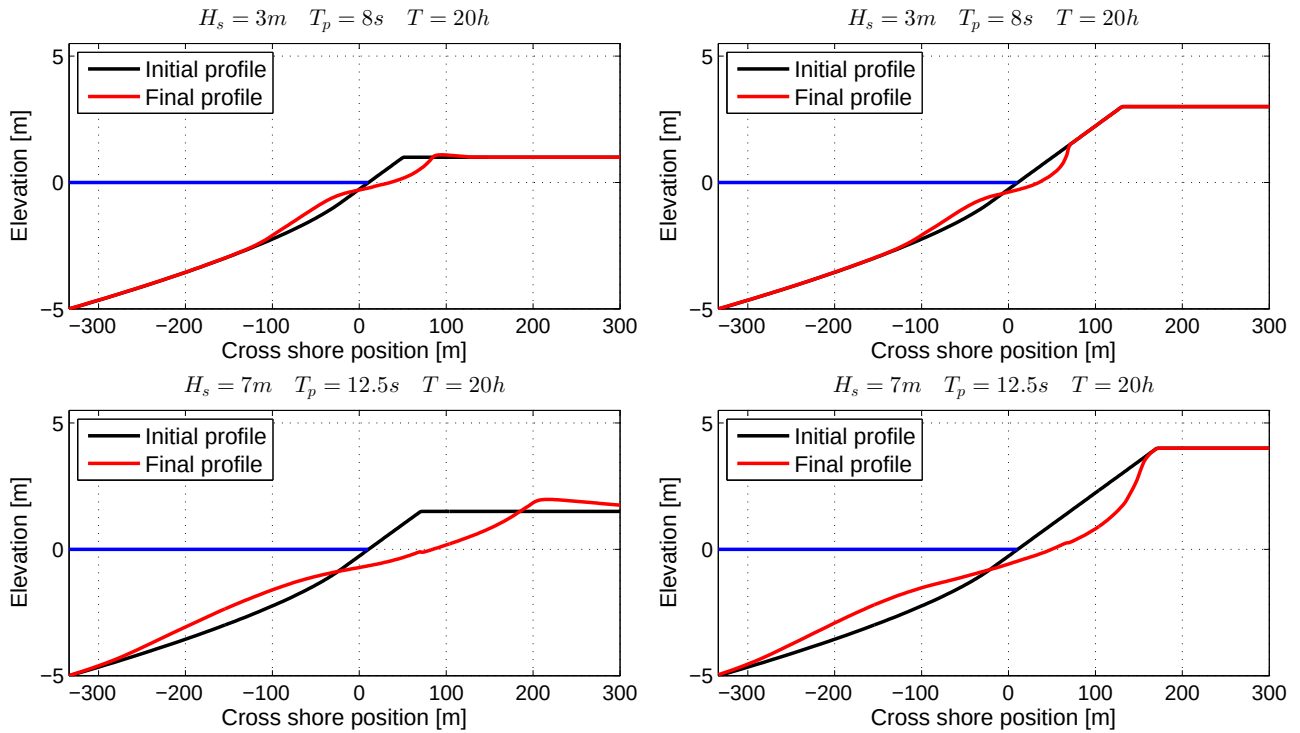
## 5-2-2 Landward erosion in storms

To assess the landward erosion during storm events a set of model runs were defined in Appendix C-3. The results of these simulations with a one dimensional Xbeach model are presented in this section. Figure 5-22 shows the response of the coastal profiles for four different runs. In the left two sub-plots in this figure sediment is washed over the profile by the storm waves while in the right sub plots the crest level of the profile is sufficiently high to prevent overwash. During a storm the profile shape adapts for the storm wave conditions to better dissipate the wave energy. This adaptation is shown in the results: Part of the sediments from the upper part of the foreshore are eroded and moved to deeper water. In the storm however these sediments are transported to relatively shallow water (depth of about 5 m below MSL) and therefore still remain in the active part of the coastal profile. These sediment are therefore not considered to be lost.

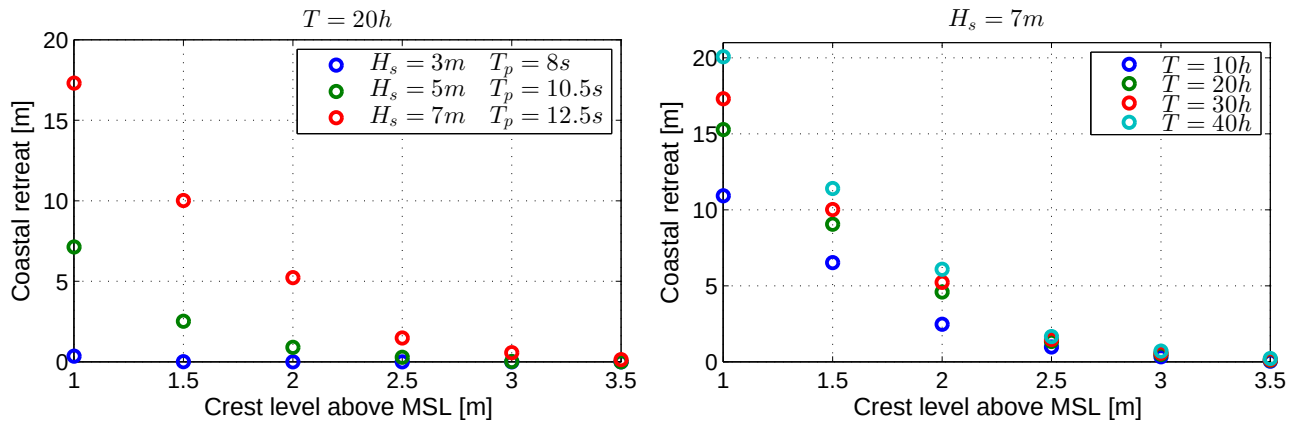
Sediments that are washed over the profile however will never be able to reach the beach again. These sediment are therefore considered to be lost. The amount of sediments that are washed over mainly depends on the storm characteristics and the crest level of the cross shore profile relative to the storm surge level. The retreat rate of the shoreline is therefore plotted as function of the crest level and the storm characteristics is Figure 5-23. These plots show that no overwash takes place as long as the profile is sufficiently high. However as soon as the crest level drops below a certain threshold value the retreat rate rapidly increases. The height of the profile for which no overwash takes place needs to be larger when the beach is attacked by a more severe storm with higher waves. It is furthermore found that the storm duration has only little influence on the rate of coastal retreat and the threshold value.

In Figure 5-24 the coastal retreat is plotted against the crest level for different sediment diameters. Interestingly the sediment diameter has a relatively small influence on the coastal erosion rates. For smaller median sediment diameters coastal retreat is even less compared to the larger sediments. For sediments sizes in between  $250 \mu m$  and  $350 \mu m$  the retreat rate is almost the same.

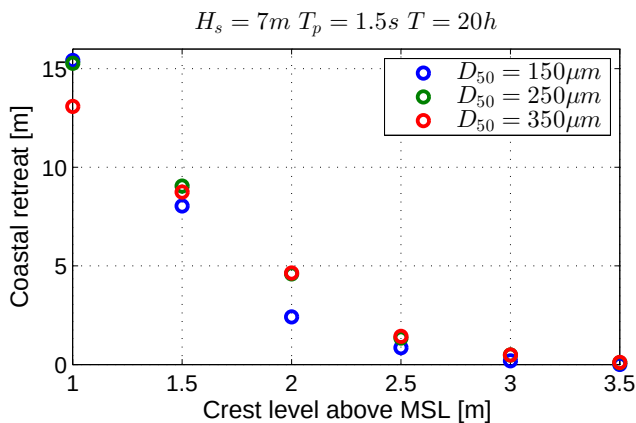
From these results it is concluded that the landward erosion during storms rapidly increases when the crest level of the profile comes below a threshold value. So for one storm the erosion can be negligible while for another storm with slightly higher waves the erosion can suddenly increase to over 5 m. This property makes it very difficult to translate the event driven erosion to a yearly averaged coastal retreat. Still this analysis can be used to provides an indication if this coastal erosion process is relevant for a specific case. As long as the backshore is sufficiently high this process does not need to be considered at all, while for a profile with a low crest level the overwash process should be dealt with in more detail.



**Figure 5-22:** Cross shore profile changes before and after a storm for different storm characteristics and crest levels for a 20 hour storm computed with a 1D Xbeach model. Overwash takes place in the left plots



**Figure 5-23:** Coastal retreat as function of the crest level of the profile above mean sea level for different storm characteristics. As soon as the crest level drops below a threshold the coastal retreat rapidly increases



**Figure 5-24:** Coastal retreat against the crest level for different median sediment diameters

### 5-3 Results nourishment lifetime

This section presents the results for the lifetime of a mega nourishment. It first shows the lifetime for three different cases. Subsequently general relations are presented for the lifetime at the nourishment center and the Distance of Influence (DoI). The results were obtained by running the Unibest CL-module for different diffusion coefficients, nourishment dimensions and active heights. For all these cases the coastline orientation is chosen equal to the equilibrium angle:  $\theta_c = \theta_{eq}$ . For more information regarding the model runs and parameters see Appendix C. The lifetime is calculated by analysing the coastline evolution in time which is determined by the coastline growth due to the redistribution of the mega nourishment and a linear constant erosion rate along the entire shore in m/yr (See also Section 3-1).

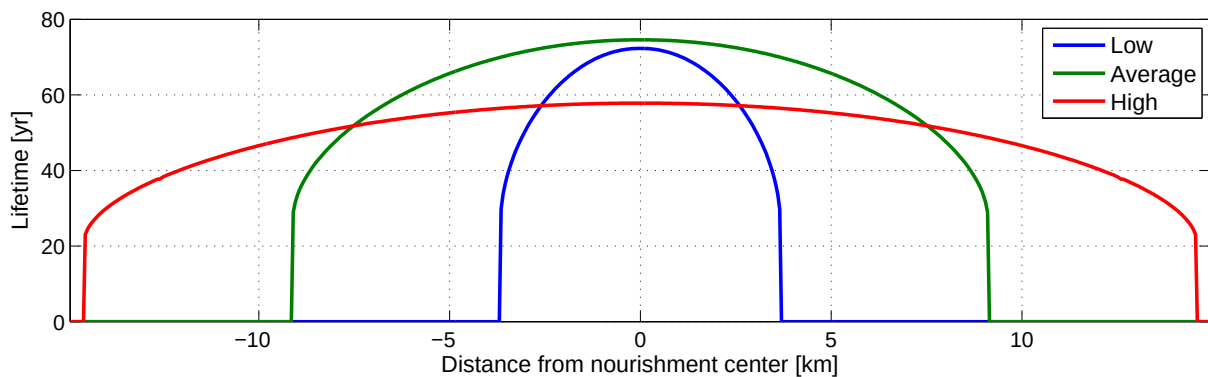
#### 5-3-1 Lifetime scenarios

For many sandy shores in the world the coastal parameters are often related to each other. For example a low diffusion coefficient implies a relatively mild wave climate. Coasts that are attacked by these mild waves generally show lower erosion rates and a lower value for the DoC which limits the maximum offshore extend of the nourishment. For high intensity wave climates however the diffusion coefficient and the erosion rates of the shore are generally higher. Because of these dependencies it is chosen to look first at a few scenarios for the assessment of lifetime. These scenarios include a beach attacked by a *low energy* wave climate, an *average energy* wave climate and a *high energy* wave climate. The chosen parameters are given in the table below:

**Table 5-1:** Scenarios for the lifetime analysis

| Climate intensity | $c_1$ | $[Mm^3/yr]$ | $E$ | $[m/yr]$ | $DoC$ | $[m]$ | $W_{mn}$ | $[m]$ | $L_{mn}$ | $[m]$ |
|-------------------|-------|-------------|-----|----------|-------|-------|----------|-------|----------|-------|
| Low               |       | 0.01        |     | 0.4      |       | 5     |          | 250   |          | 500   |
| Average           |       | 0.06        |     | 1.4      |       | 9     |          | 750   |          | 1500  |
| High              |       | 0.2         |     | 2        |       | 12    |          | 1000  |          | 2000  |

Figure 5-25 shows for each scenario (*low*, *average* and *high*) the lifetime as function of the distance from the nourishment center. The steep gradients at the boundaries of the DoI where the lifetime suddenly drops to zero are a consequence of the lifetime definition (see also Section 3-1 and Figure 3-3). The DoI logically increases with increasing wave climate intensity meaning that a larger stretch of coast can be protected. The lifetime at the nourishment center (at  $x = 0$ ) however reduces due to the more rapid alongshore redistribution and the increasing erosion rate of the shore. The three scenarios do unfortunately not provide insight into the influence of the coastal parameters on the nourishment lifetime and DoI. The next section therefore searches for a relation between the different parameters.



**Figure 5-25:** Lifetime as function of the alongshore distance from the nourishment center for three cases.

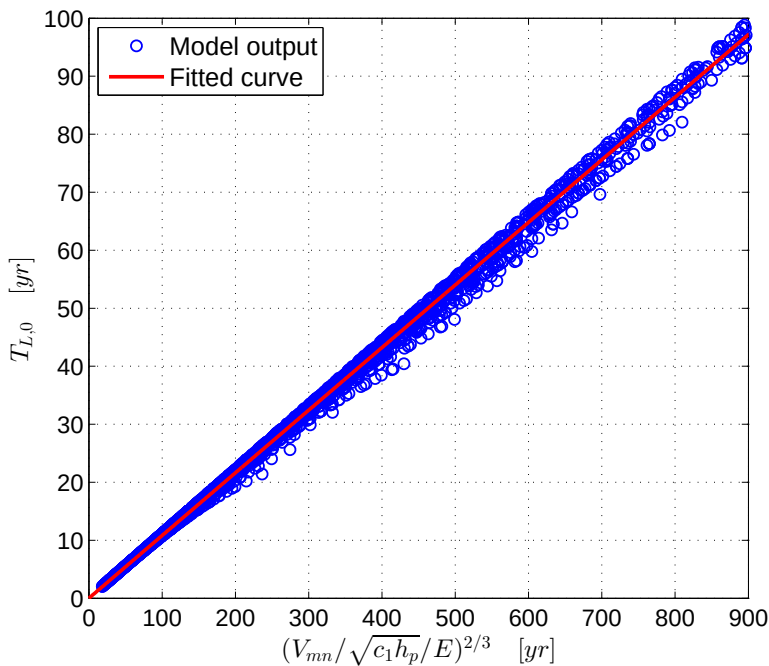
### 5-3-2 Empirical relations

When the net LST rate is zero the nourishment redistribution can be described by a diffusion equation which has a rather complicated exact solution. It is therefore chosen to search for two simple empirical relations for the lifetime and the DoI as function of the nourishment size, the diffusion coefficient and the erosion rate. These relations were found by analysing the Unibest CL-module results for the coastline evolution in time. This evolution is simulated for numerous cases with varying nourishment sizes, the diffusion coefficients, the active heights and the erosion rates (see appendix C for more information).

The first relation that is empirically found is presented in Equation 5-11 and gives an exponential relation for the lifetime at the nourishment center  $T_{L,0}$  [yr] which is a function of the nourishment volume  $V_{mn}$  [m<sup>3</sup>], the active height  $h_p$  [m], the diffusion coefficient  $c_1$  [m<sup>3</sup>/yr/°] and the erosion rate  $E$  [m/yr]. Note that the dimension on both sides of the equation are in years. In this equation the lifetime is proportional to the diffusion coefficient to the power -1/3 meaning that the influence of the diffusion coefficient on the lifetime is limited. A reduction of the diffusion coefficient by a factor two does reduce the lifetime by only 20%. This is also found for the Sand Engine case. The equation furthermore shows a strong dependency between lifetime and erosion rate which emphasises the need for an accurate prediction of the averaged yearly retreat rate. The lifetime at the nourishment center does furthermore not depend on the surface shape of the nourishment, but only on the volume.

$$T_{L,0} = 0.11 \left( \frac{V_{mn}}{\sqrt{c_1 h_p} E} \right)^{\frac{2}{3}} \quad (5-11)$$

Figure 5-26 includes a visualisation of the above equation together with all model output points. The red line in this figure represents a linear function with a gradient of 0.11 (corresponding to Equation 5-11) which was fitted on the model output (in blue). The empirical equation is able to reproduce the model results with a mean relative deviation from the fit of 2% and a maximum of 16%. The relative deviation between the model results and the fit in Figure 5-26 is larger for cases where the linear erosion of the shore becomes more important relative to the redistribution of the nourishment. This dominance starts to occur for relatively large erosion rates in combination with a large alongshore length and a relatively small diffusion coefficient.



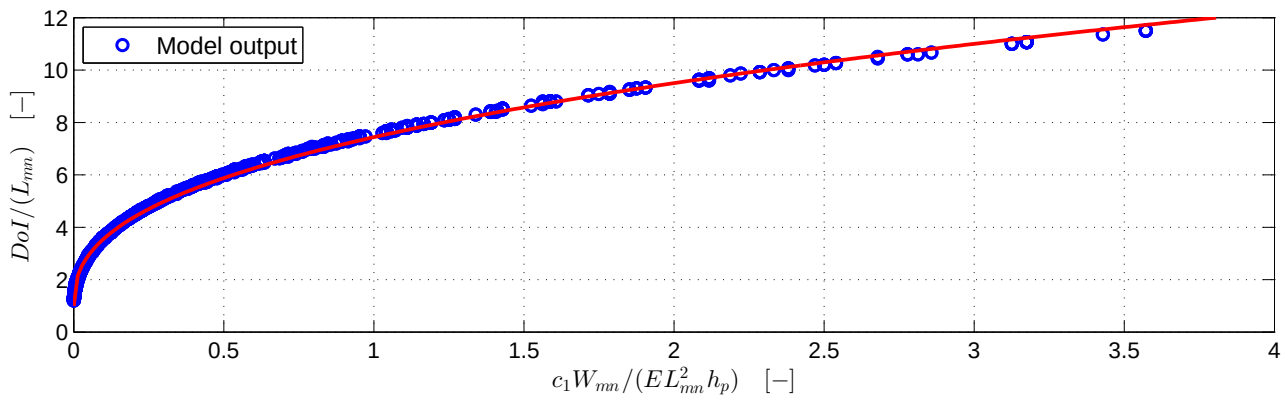
**Figure 5-26:** Lifetime as function of the diffusion coefficient, the nourishment size parameters and the erosion rate. Fitted function:  $T_{L,0} = 0.11 \left( \frac{V_{mn}}{\sqrt{c_1 h_p} E} \right)^{\frac{2}{3}}$

Besides the lifetime an empirical relation is presented in Equation 5-12 for the Distance of Influence (DoI)

which is defined in Section 3-1 as the alongshore length for which the lifetime of the nourishment is larger than zero. The left hand side of this equation includes the DoI divided by the length of the mega nourishment  $L_{mn}$ , a non-dimensional parameter. This ratio is an exponential function of a dimensionless combination of the diffusion coefficient  $c_1$ , the erosion rate  $E$  and the nourishment dimensions. '+1' is added at the right hand side because the DoI can never be smaller than the length of the mega nourishment itself, hence the right hand side of the equation should be by definition larger than one.

$$\frac{DoI}{L_{mn}} = 6.44 \left( \frac{c_1 W_{mn}}{E L_{mn}^2 h_p} \right)^{0.40} + 1 \quad (5-12)$$

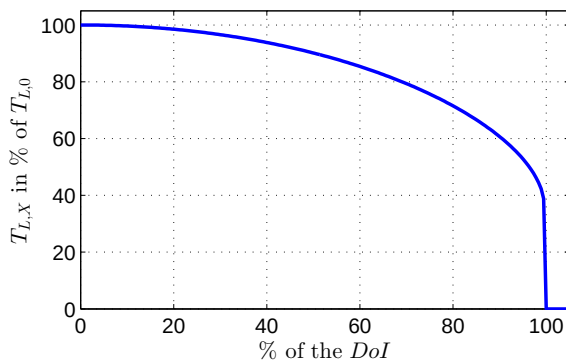
Equation 5-12 is shown together with the model results in Figure 5-27. Visually the fitted equation (in red) seems to result in a good fit for all model output points (in blue). The maximum deviation between the fit and the model points is in the order of 10%. The mean relative error between the fit and the model points is 3.6%.



**Figure 5-27:** DoI as function of the diffusion coefficient, the nourishment size parameters and the erosion rate. Fitted function  $DoI/L_{mn} = 6.44(c_1 W_{mn}/(E L_{mn}^2 h_p))^{0.40} + 1$

Note that beyond the DoI the mega nourishment still supplies sediment to the shore. At these location however the supply becomes insufficient to fully compensate the erosion of the shore. Additional measures are therefore required to prevent a retreat of the beach. This was already illustrated in Figure 3-3 which showed the conceptual plots for the lifetime of a mega nourishment.

Finally the lifetime as function of the alongshore distance is presented in a design graph in Figure 5-28. On both axis the variables are plotted as a percentage of the DoI (x-axis) and the lifetime at the nourishment center (y-axis). The shape of this graph with the relative parameters is found to be the same for all model runs. To use this graph the values for the lifetime and the DoI at the nourishment center  $T_{L,0}$  should be calculated first with Equation 5-11 and 5-12.



**Figure 5-28:** Design graph for the lifetime  $T_{L,X}$  in % of the lifetime at the nourishment center  $T_{L,0}$  (y-axis) as function of the percentage of the DoI

## 5-4 Summary

The results for a large number of tool simulations are presented in this chapter. For the nourishment redistribution the half-time is inversely related to the diffusion coefficient. An empirical relation is derived that relates the half-time to the diffusion coefficient, the nourishment volume and the length over width ratio of the mega nourishment. The diffusion coefficient is primarily related to the averaged wave energy of the climate. The directional spreading and the averaged wave steepness also influence the diffusion coefficient. However these effects are significantly smaller compared to the wave energy. Several empirical equations are derived that show the relative influence of the wave climate parameters on the diffusion coefficient.

For the shoreline erosion an indicative estimate is made for the retreat driven by SLR. In general retreat rates are expected to be smaller than 1.5 m/yr. However this value can only be used as an indicative estimate since the Bruun rule is strongly simplified and the exact properties of the shore may have an effect on the retreat rates. Landward storm erosion is especially relevant for beach profiles with a low dune height relative to the storm surge level. It is difficult to relate the event driven storm erosion to a yearly averaged coastal retreat. The tool can therefore only be used to obtain an indication whether this process should be taken into account to estimate the shoreline erosion.

Empirical relations and a design graphs are derived for the lifetime of a mega nourishment by analysing the results of the coastline evolution for several nourishment dimensions, erosion rates and diffusion coefficients. It is found that the lifetime at the nourishment center depends on the nourishment volume but not on the nourishment shape. Furthermore the erosion rate of the shore has a larger effect on the lifetime compared to the diffusion coefficient. The design graphs can be used to estimate the lifetime of the nourishment for other alongshore locations

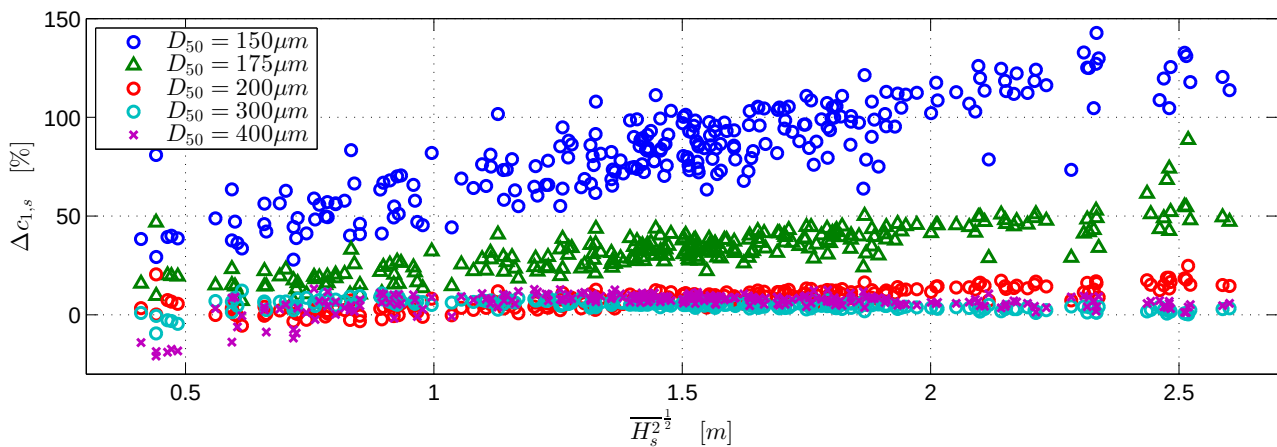


## Sensitivity analysis

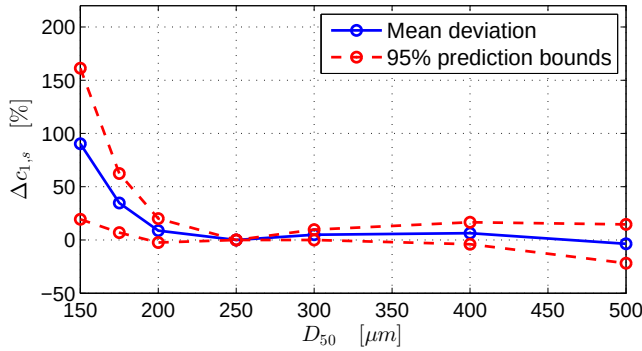
### 6-1 Median sediment size and profile shape

The median grain size is altered between  $150\ \mu\text{m}$  and  $500\ \mu\text{m}$  to assess the influence of the sediment size on the diffusion coefficient. Indirectly this also affects the shape of the cross shore profile due to the assumed exponential relation with the median grain size according to the Dean profile (see Section 3-3-4). The LT-module of the Unibest model is used to calculate the diffusion coefficient for all different wave climates and several median sediment diameters.

The results are included in Figure 6-1 that shows the change of the scaled diffusion coefficient in percent relative to the default model (with a median sediment size of  $250\ \mu\text{m}$ ) as function of the RMS significant wave height. The figure shows a large sensitivity for grain sizes smaller than  $200\ \mu\text{m}$  whereas the diffusion coefficient hardly changes for sediment sizes smaller than  $200\ \mu\text{m}$ . This is also illustrated by Figure 6-2 that shows the mean and the 95% prediction bounds for the deviation in  $c_{1,s}$  as function of the sediment size: For median grain sizes smaller than  $200\ \mu\text{m}$  the gradient in longshore sediment transport rapidly increases resulting in a mean deviation of about 90%. The linear correlation for small sediment sizes furthermore shows that the increase of the diffusion coefficient is larger for high energy wave climates. The 95% prediction bounds therefore show an increasing uncertainty for the percentual deviation in  $c_{1,s}$ .

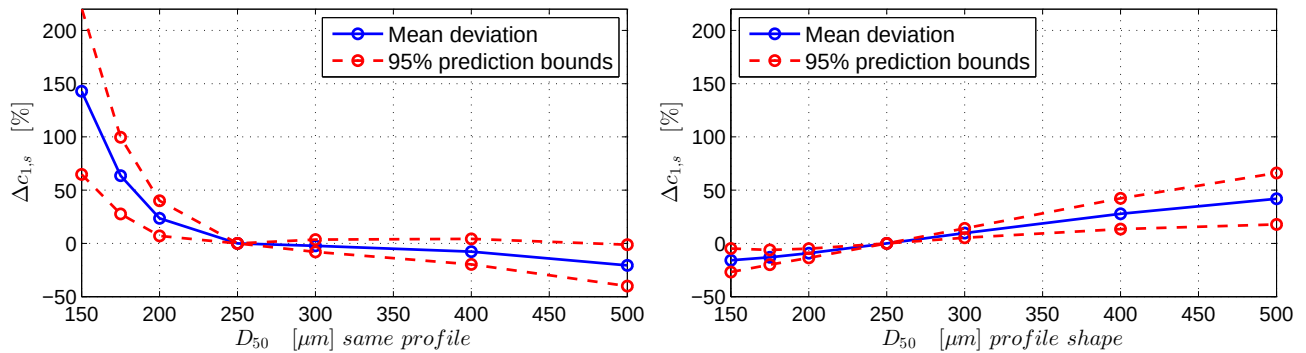


**Figure 6-1:** Relative change of the scaled diffusion coefficient compared to the default model (with  $D_{50} = 250\ \mu\text{m}$ ) for several sediment sizes as function of the RMS significant wave height

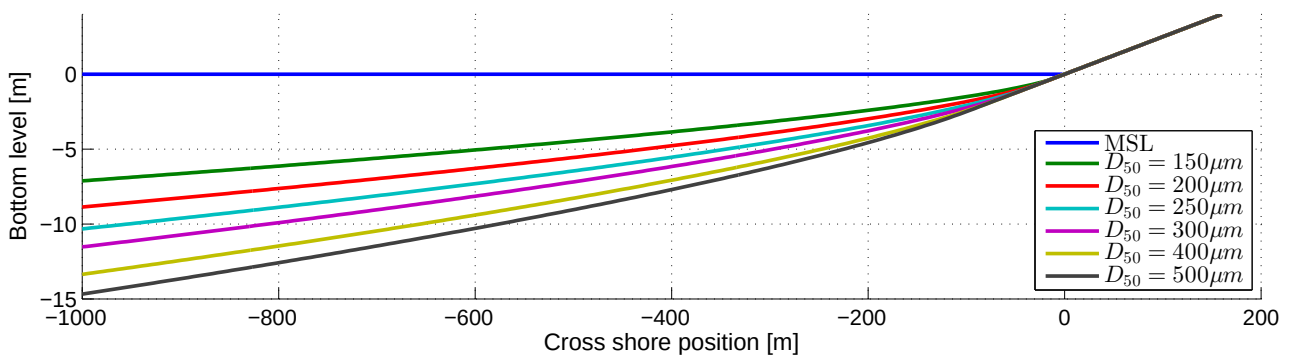


**Figure 6-2:** Mean and 95% prediction bounds for the relative change of the diffusion coefficient as function of the sediment size

The sensitivity against a different sediment size can physically be explained by two processes which counteract each other: The change in flow resistance of the sediment particles and the more intense wave breaking on a steeper cross shore profile. Both effects are visualised in Figure 6-3 which shows the mean and the 95% prediction bounds for the deviation in  $c_{1,s}$  relative to the default model. The results in the left plot are obtained by only altering the sediment size and keeping the cross shore profile constant while for the results in the right plot only the shape of the profile was altered (so the same sediment size of 250  $\mu\text{m}$ ). The profile shapes that have been used for the simulations are given in Figure 6-4. For relatively small grain sizes the increase of the diffusion coefficient due to the reduced flow velocity dominates over the decrease due to the milder cross shore profile. For larger sediments however both effects are of the same order of magnitude and cancel out each other.



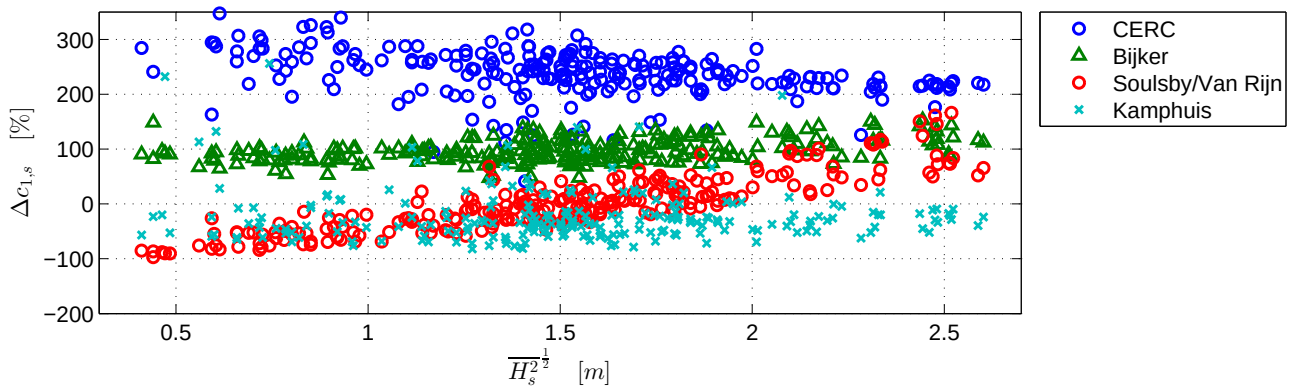
**Figure 6-3:** Mean and 95% prediction bounds for the relative change of the diffusion coefficient as function of the sediment size. In the left plot the profile is kept constant while in the right plot only the shape of the profile is varied



**Figure 6-4:** Cross shore profile shapes for different median sediment diameters

## 6-2 Sediment transport formulation

In the Unibest LT-module several sediment transport formulations can be chosen besides the formulation of Van Rijn et al. (2004). The diffusion coefficient has been calculated for four other formulations. These include two bulk longshore sediment transport formulas: The formulas of CERC and Kamphuis (1991). Besides this the transport formulations of Soulsby-Van Rijn and Bijker were used. The result of the different model runs are included in Figure 6-5 that shows the difference of  $c_1$  relative to the default model. The mean difference and its 95% prediction bounds are given for each formulation in table 6-1. The CERC formula is known to over predict the sediment transport rates which is clearly visible in the results. Also the Bijker formula results in much larger sediment transport rates. The Kamphuis formula shows the best correspondence with the default model which is remarkable because its formulations is very simple compared to the complexity of the transport model of Van Rijn et al.. The results for the formula of Soulsby-Van Rijn deviates especially for lower and higher waves. The diffusion coefficient can deviates in the order of  $\pm 100\%$  if a different transport formulation is used. This strong sensitivity shows that the estimations of the diffusion coefficient for a certain case can only be used as a first estimate.



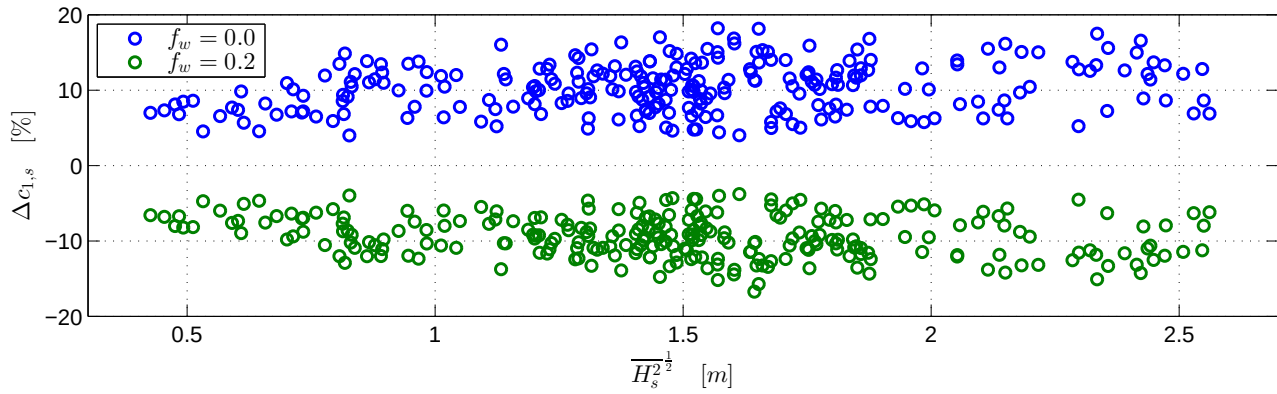
**Figure 6-5:** Relative deviation of the scaled diffusion coefficient for several sediment transport formulations as function of the RMS significant wave height

| Transport formulation | $\Delta c_{1,s}$ [%] |                       |     |
|-----------------------|----------------------|-----------------------|-----|
|                       | Mean                 | 95% prediction bounds |     |
| CERC                  | 151                  | 132                   | 319 |
| Bijker                | 99                   | 55                    | 143 |
| Soulsby-Van Rijn      | 6                    | -109                  | 122 |
| Kamphuis              | -22                  | -118                  | 75  |

**Table 6-1:** Mean and 95% prediction bounds for the change of the scaled diffusion coefficient for different transport formulations relative to the default model (that uses the sediment transport formulation of Van Rijn et al. (2004))

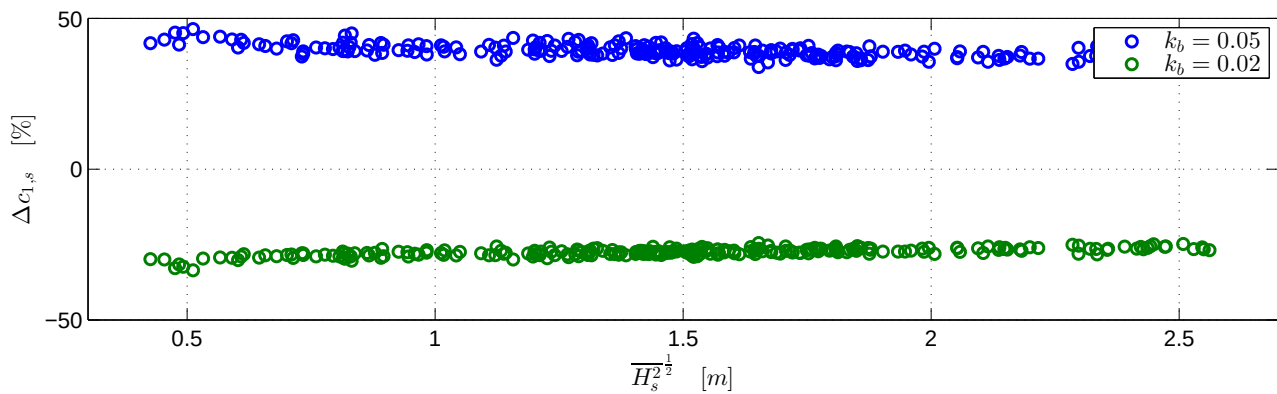
## 6-3 Bottom friction and roughness

The bottom friction and the bed roughness are two calibration parameters of the Unibest model. The friction coefficient is included in a dissipation term of the wave action balance and according to the Unibest manual a value of 0.01 is realistic. It is found that the sensitivity for this parameters is relatively small (see Figure 6-6). If the friction term is completely excluded of the wave energy balance ( $f_w = 0$ ), the diffusion coefficient only increases with about 10%. For a friction value of 0.02 the diffusion coefficient reduces by approximately 10%.



**Figure 6-6:** Relative change of the scaled diffusion coefficient for two friction coefficients as function of the RMS significant wave height

Figure 6-7 includes the result for a different bed roughness value which is by default 0.1 m. According to the Unibest manual this value can vary between several centimetres to a couple of decimetres. It is therefore chosen to test the sensitivity for roughness values of 5 and 20 cm which give rise to a difference of about 35% for the diffusion coefficient. Table 6-2 shows the mean and the 95% prediction bounds for the diffusion coefficient calculated with different friction and bed roughness values.



**Figure 6-7:** Relative change of the scaled diffusion coefficient for two bed roughness values as function of the RMS significant wave height

| Friction and bed roughness | $\Delta c_{1,s}$ [%] |                       |     |
|----------------------------|----------------------|-----------------------|-----|
|                            | Mean                 | 95% prediction bounds |     |
| $f_w = 0$                  | 10                   | 4                     | 17  |
| $f_w = 0.02$               | -9                   | -15                   | 4   |
| $k_b = 0.05$               | 39                   | 35                    | 43  |
| $k_b = 0.02$               | -27                  | -30                   | -25 |

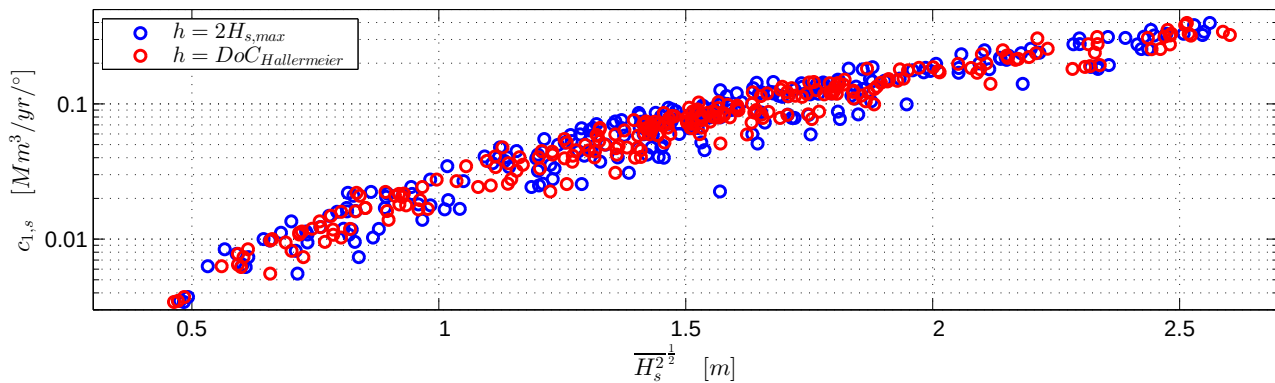
**Table 6-2:** Mean and 95% prediction bounds for the deviation of the scaled diffusion coefficient for different friction and bottom roughness coefficients relative to the default model

## 6-4 Location transformed wave climate

The magnitude of the averaged wave climate parameters depends on the offshore water depth at which these are calculated. This is illustrated in Figure 6-8 that shows the relation between the RMS significant wave height and the diffusion coefficient  $c_{1,s}$  evaluated at two different water depths: at the DoC and at a depth equal to 2 times the maximum wave height (at this depth no depth limited wave breaking occurs).

A significant smaller scatter is found in the results if the RMS significant wave height is computed at the DoC which is located closer to the shore compared to a depth of  $2H_{s,max}$ . At this smaller water depth the waves that approach the shore under an angle have refracted more. This refraction causes a reduction in wave height and a shift of the points in the scatter to the left. For the waves that approach the coast under a small angle, the wave height slightly increases with decreasing water depths due to shoaling. Evaluating these waves at a smaller water depth will therefore cause the points in the scatter to shift to the right. Both effects of refraction and shoaling cause a reduction in the scatter: The 95% prediction bounds of Equation 5-5 reduce from  $\pm 45\%$  to  $\pm 30\%$ .

If the water depth at which the wave climate parameters are compared is chosen too small, waves become unrealistically high because wave breaking is not included in the 1D wave transformation. The wave climate parameters should therefore be compared at a water depth where wave breaking hardly occurs. For this the DoC is a better choice compared to a depth of  $2H_{s,max}$ .



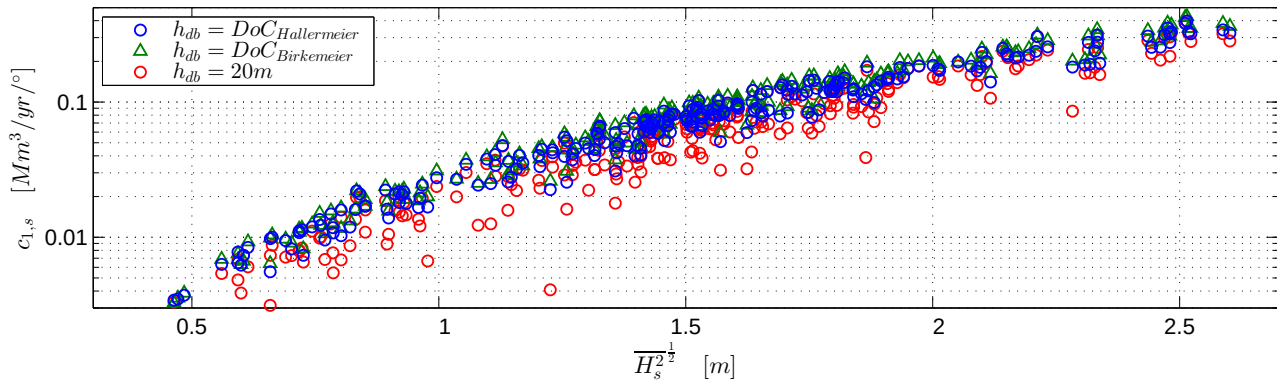
**Figure 6-8:** Scaled diffusion coefficient as function of the RMS significant wave height evaluated at different water depths.  $\overline{H}_s$  of the blue dots is taken from the transformed climate at a water depth of 2 times the maximum of  $H_s$ . The red dots represents the  $\overline{H}_s$  taken at a depth equal to the DoC according to Hallermeier

## 6-5 Dynamic boundary

The dynamic boundary is the offshore distance till which the LST is computed. The cross shore profile located landward of this boundary rotates in the same way as the coastline while the orientation at the offshore side is kept constant. The choice for this parameter therefore influences the refraction of the waves and therewith the LST rates. By default the dynamic boundary is located at the DoC according to the formulation of Hallermeier (1981). To analyse the sensitivity of this parameter two other locations of the dynamic boundary are used: At the DoC according to Birkemeier (1985) (which results in a smaller depth compared to Hallermeier) and at a depth of 20 m.

In Figure 6-9 the results of all model simulations are provided for the three ways of determining the location of the dynamic boundary. The model runs with a dynamic boundary at the DoC of Birkemeier show a slightly larger diffusion coefficient. For a dynamic boundary further offshore at a depth of 20 m the wave refract more which decreases the angle of wave incidence. This causes a reduction in the LST gradients and the diffusion coefficient. The sensitivities are quantified in Table 6-3 that shows the change of the diffusion coefficient relative to the default model including the 95% prediction bounds.

It is concluded that the effect on the diffusion coefficient is negligible for minor changes of the water depth at the dynamic boundary (about 1-2 m). The effect however becomes significant if the dynamic boundary is chosen far offshore (e.g. at 20 m). Other coastline models that do not include this parameter will therefore underestimate the LST rate and therewith the diffusion coefficient of a mega nourishment. The dynamic boundary is thus an essential parameter for a good estimate of the diffusion coefficient.



**Figure 6-9:** Scaled diffusion coefficient as function of the RMS significant wave height for different dynamic boundaries. The blue dots corresponds to the model result using a dynamic boundary at a water depth calculated using the DoC formulation of Hallermeier. Model results of the green dots are obtained by using the DoC formulation of Birkemeier. The red dots correspond to a dynamic boundary of 20 m

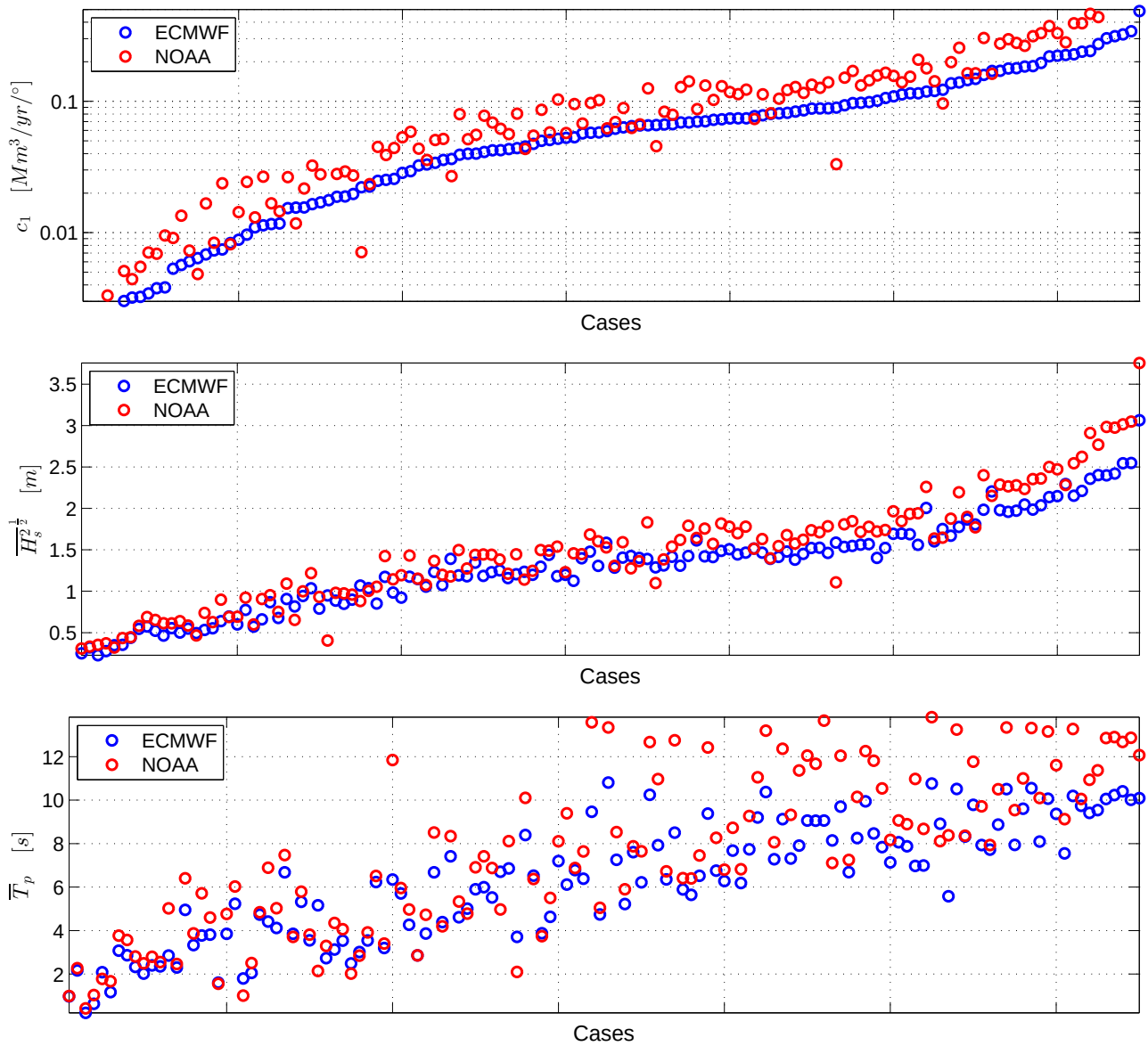
| Dynamic boundary            | $\Delta c_{1,s}$ [%] |                       |    |
|-----------------------------|----------------------|-----------------------|----|
|                             | Mean                 | 95% prediction bounds |    |
| $h_{db} = DoC_{Birkemeier}$ | 9                    | 1                     | 18 |
| $h_{db} = 20m$              | -18                  | -44                   | 8  |

**Table 6-3:** Mean and 95% prediction bounds for the change of the scaled diffusion coefficient for different dynamic boundaries relative to the default model

## 6-6 Choice of global wave model

At each location a wave climate is taken from the ECMWF and from the NOAA wave model. The choice for either of these models has a considerable effect on the estimate of the diffusion coefficient. This is visualised in Figure 6-10 that shows three characteristic parameters for each case:  $c_1$ ,  $\overline{H}_s$  and  $\overline{T}_p$ . The locations are sorted based on an *ascended* value of  $c_1$  for the simulations using the ECMWF wave model data. The colours of the dots correspond to the wave model: the blue dots represent the simulations with ECMWF data and the red dots the simulations with NOAA data.

Table 6-4 shows the mean and the maximum percentual differences between the three parameters relative to the ECMWF results. In general the NOAA wave data includes on average 15% higher waves with 23% longer periods. As a consequence the simulations with the NOAA wave model data therefore calculate an on average 55% larger diffusion coefficient. This difference stresses the importance of having a representative wave climate for an accurate estimate of the diffusion coefficient.

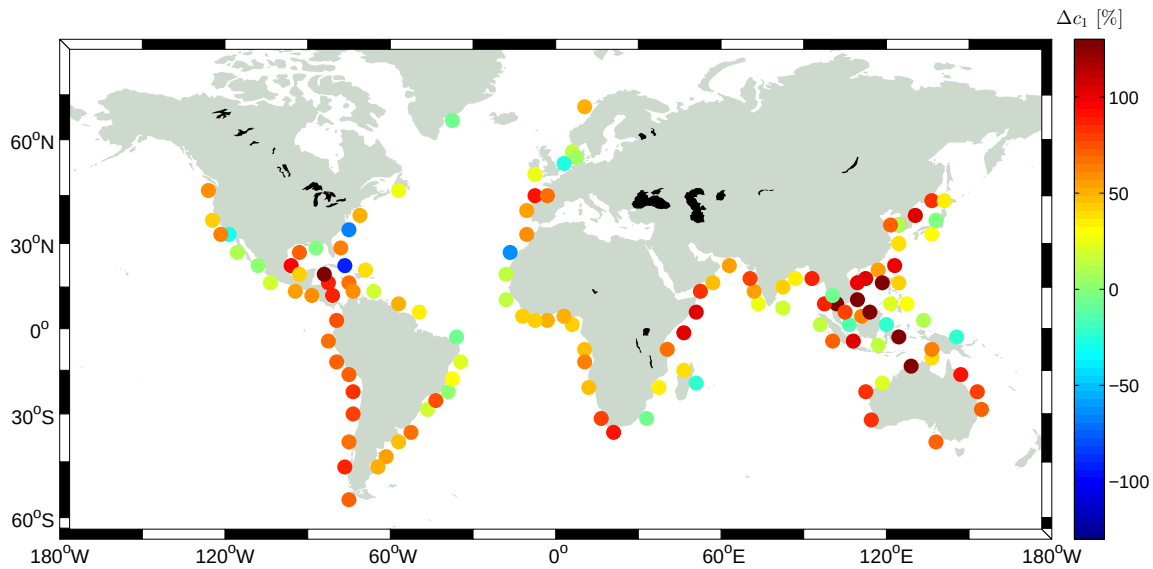


**Figure 6-10:** Comparison tool results for ECMWF and NOAA wave model data. For all runs the values for  $c_1$ ,  $\overline{H}_s$  and  $\overline{T}_p$  are vertically aligned in the sub-plots. The simulation are sorted on *ascending*  $c_1$  of the simulation using the ECMWF wave data

| Parameter        | Difference [%] |         |
|------------------|----------------|---------|
|                  | Mean           | Maximum |
| $c_1$            | 55             | 150     |
| $\overline{H}_s$ | 15             | 57      |
| $\overline{T}_p$ | 23             | 92      |

**Table 6-4:** Mean and maximum difference in percent for parameters of the model runs with NOAA and ECMWF wave model data relative to the values of ECMWF

Figure 6-11 presents the spatial variation in the difference of the diffusion coefficient. Some of the largest deviations seems to occur at locations where the wave height is relatively low (e.g. in the South Chinese Sea). Besides this no clear spatial sorting is found in the figure for the value of the diffusion coefficient.



**Figure 6-11:** Global variation of the difference in diffusion coefficient between the simulations using the ECMWF and NOAA wave model data.  $\Delta c_1 = (c_{1,NOAA} - c_{1,ECMWF}) / c_{1,ECMWF} \cdot 100$

## 6-7 Summary

The effect of several parameters on the diffusion coefficient has been analysed in a sensitivity analysis. The diffusion coefficient rapidly increases for sediment sizes smaller than  $250 \mu\text{m}$ . For larger sediments however the effect of an increased flow resistance of the grains is cancelled out by the increasing LST on a steeper cross shore profile. A large sensitivity is found for a different sediment transport formulation. Another formulation can predict a diffusion coefficient that deviates in the order of 100% from the default model. Also the bottom friction and roughness do influence the results of the diffusion coefficient. The tool simulations for the same geographical locations furthermore result in a large difference of the diffusion coefficient due to the use of different global wave data sources. The wave climate uncertainty together with the other tool sensitivities show that the estimate of the diffusion coefficient can only be used as a first estimate.

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## Chapter 7

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# Discussion

Several processes that have been excluded in this research will be discussed followed by a discussion regarding the consequence of the model assumptions and simplifications. This chapter ends with an elaboration on the relevance of this research for engineering practice and some of the problems that will arise when the tool and the empirical relations are used.

### Exclusion of physical processes

Several sediment transport processes are not considered for the simulation of the alongshore redistribution. One of these processes is the horizontal tide that causes an alongshore flow velocity which enhances the sediment transport rates. A noticeable effect is especially expected for a strong asymmetrical tide. Besides tidal asymmetry, local flow contraction can occur around the tip of a mega nourishment which enhances the redistribution of sediments. Kaji et al. (2014) analysed this process for the Sand Engine and concluded that the tidal flow increases the sediment transport rates around the head of the nourishment. The effect of local flow contraction is expected to be mainly relevant at the initial stage of the nourishment when the coastline gradients are large. It therefore mainly affects the coastline development in the first years and most probably has a limited effect on the lifetime. In addition vertical tides and storm surges could also affect the LST rates by changing the cross shore profile shape and the location of wave breaking.

Besides the tide, sediment transport by wind is also not included in this research. Measurement of the Sand Engine volume changes however suggest that this process could have a considerable effect: 740.000 m<sup>3</sup> of sediments were transported outside the measurement area to either deeper water, further away in alongshore direction or to the dunes and the hinterland (van Gelder-Maas, 2014). This is a significant part of the total amount of sediment that have been transported (about 2.5 Mm<sup>3</sup>). The exact contribution of wind driven sediment transport to this amount is however unknown.

The near bed velocities calculated in the Unibest LT-module are used in a sediment transport formulation to estimate the LST from which it is widely known that these formulations also have there inherent uncertainty. The use of different transport formulation already cause a difference in the model results in the order of  $\pm 100\%$  (see Section 6-2). All transport formulations also use uniform sediment characteristics while in reality sediment sorting takes place in longshore and cross shore direction. The uncertainties related to sediment transport make the results of this tool only applicable to obtain a first estimate for the redistribution rate of a mega nourishment.

The coastline model is furthermore unable to model spit development that takes place for beaches that are attacked by waves with a large angle of wave incidence (larger than 45°). For a high angle wave climate the transports are maximised in the Unibest model. In reality however the LST would decrease causing a coastline growth and spit development. The redistribution rate of a mega nourishment along a coast with high angle waves is therefore a topic for further research.

Finally, coastal erosion processes are also affected by features of the coastline which were not attributed in this research. Different coastline shapes that cause gradients in LST are not considered due to the assumption of an alongshore uniform shoreline. Also other causes of coastal erosion are not included such as sediment loss into offshore canyons, sand mining and river damming. The empirical relations for the lifetime and the Dol however include an erosion value that can be quantified by analysing site specific causes of coastal erosion.

## Tool assumptions

The grain size dependent exponential shape of the cross shore profile is an assumption that is expected to have a large effect on the modelling results. It does not take into account the large variation in cross shore profiles with different secondary features such as offshore bars. According to Mil-Homens et al. (2013) these profile variations have a large effect on the LST. His research showed that different cross shore profiles with the same averaged bed slope can result in LST differences in the order of 50%. In addition the profile shape does generally not only depend on the sediment size but also on other parameters such as the wave forcing, the tidal flow and the water level variations. The linear beach profile is furthermore often an incorrect schematisation of the backshore that can consist of dunes, berms and vegetation. The profile shape can strongly deviate from a real beach profile due to the strong schematisation which affects the estimation of the LST rates and the erosion due to overwash.

The Unibest model also assumes no time variation in cross shore profile shape. It does therefore not include the coupling between changing wave conditions and corresponding changes in cross shore profile shape. In this thesis it was already shown that this cross shore profile shape can have a significant effect on the alongshore sediment transport rates (see Figure 6-3). The inclusion of cross shore profile variability in alongshore sediment transport calculations could result in better estimates for the redistribution rate of a mega nourishment.

To estimate the erosion rate of the shore due to SLR a simple model has been used which was developed by Bruun (1962). This model has a limited predictive capability and is only suitable to obtain an indicative estimate of the coastal response (Ranasinghe and Stive, 2009). Besides this a global constant value for the rise in sea level was assumed for this thesis to estimate the coastal retreat. The choice for the model of Bruun and the assumption of a constant SLR make that the coastal response should be interpreted as an indication only.

Furthermore an estimation was made for landward erosion of the beach during a storm. It came out to be difficult to translate this event driven erosion to a yearly averaged estimate for the coastal retreat because multiple storms can pass by during the lifetime of a mega nourishment that differ in severity. Besides this it is questionable if the erosion rate due to overwash can be assumed to be the same along the entire coast because of the local character of this process. The MN-tool developed for this thesis can therefore only be used for an indication if erosion by overwash is relevant for a specific case. A more detailed model study in combination with the use of coastline measurements is advised for the cases where it has a considerable effect. and measurements of the coastline development to obtain a good estimate for the erosion rate.

Due to the assumption of an infinity long alongshore uniform coast the relations derived for the lifetime and the Dol do not apply to a closed coastal cell such as a bay. For these shores the equations give an underestimation of the lifetime because of the open model boundaries.

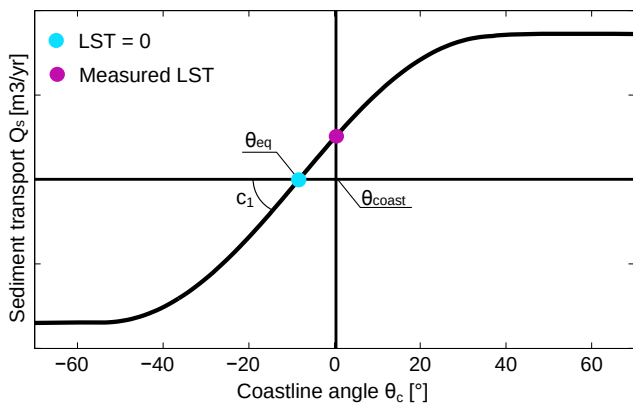
## Practical application

The diffusion coefficient is very sensitive to deviations in the wave energy. A representative nearshore wave climate is therefore of high importance for an accurate simulation of the coastline development. The global wave data sources in combination with a 1D wave transformation is in many cases not sufficient to obtain an accurate nearshore wave climate. This calculation neglects the coastal curvature (e.g. in bays) and the

offshore bathymetry which affect the refraction and the diffraction of waves. The coast can furthermore be sheltered for waves from specific directions. It is therefore preferred to use a 2D process based wave transformation model such as Swan to transform an offshore wave climate to nearshore. Besides the use of the global wave models it is even more preferred to use site specific wave observations (e.g. from a wave buoy). Unfortunately accurate (long term) wave observations are often not available.

Another difficulty for the practical application is to obtain an accurate value for the active height of the profile ( $h_p$ ) and the erosion rate of the shore ( $E$ ). The active height is an uncertain parameter that depends on the wave climate and the time scale that is considered. For a first estimate the sum of the DoC and the height of the profile above MSL could be used. Also the erosion rate of the shore is hard to estimate because of its variation in time, the lack of accurate coastline measurement and the difficulty to predict future changes in coastal erosion.

Another point that limits the practical application is the lack of tool calibration. Such a calibration is especially important to reduce the uncertainty in the LST gradient. Without calibration the results of the tool are only applicable for a first rough estimate of the nourishment behaviour. When however estimates are available of the net LST a calibration is possible for the diffusion coefficient by estimating the gradient of the  $S$ - $\theta$  curve. This verification method is illustrated in Figure 7-1. First the equilibrium coastline angle should be estimated (e.g. based on a weighted average of the wave directions). A second point of the  $S$ - $\theta$  curve is defined by the actual coastline orientation and the measured LST. Using these two point the steepness of the curve representing the diffusion coefficient can be computed. In many cases however accurate measurement of the LST are lacking and the estimation for the equilibrium angle also has an uncertainty.



**Figure 7-1:** Verification method to estimate the diffusion coefficient based on net LST measurements. If accurate measurements for the net LST are available, the  $S$ - $\theta$  curve can be estimated based on two points: The equilibrium shoreline orientation  $\theta_{eq}$  with a LST of zero (blue dot) and the actual shoreline orientation  $\theta_{coast}$  corresponding to the measured net LST (purple dot). The diffusion coefficient  $c_1$  is the gradient of the curve at  $\theta = \theta_{eq}$ .



# Conclusion

The objective is to determine the relative influence of wave climate parameters and nourishment dimensions on the *lifetime* of a mega nourishment for a straight sandy shore. A first estimate for the lifetime can be made with the self-developed Mega Nourishment tool. This tool includes longshore and cross shore sediment transport processes to estimate the speed of nourishment *redistribution* and the *erosion* of the autonomous shore. Wave climates from global models are used in the tool to make a quick first assessment of the nourishment lifetime at a certain location in the world.

Four evaluation criteria are used and defined to assess the relative influence:

- **Diffusion coefficient**,  $c_1$  [ $\text{m}^3/\text{yr}/^\circ$ ]: Gradient of S- $\theta$  curve which quantifies the redistribution rate
- **Half-time**,  $T_{50\%}$  [yr]: Time to reduce sand volume within the initial area of the nourishment by 50%
- **Lifetime**,  $T_L$  [yr]: Time for which the coastline position remains seaward of its initial position
- **Distance of Influence**,  $DoI$  [m]: The alongshore length for which the lifetime is larger than zero

Empirical relations are derived for the above evaluation criteria based on the results of a large number of tool simulations. Both the tool and the empirical relations can be used for an initial design of a mega nourishment.

### Sand Engine comparison

A mega nourishment was executed in a pilot project called "the Sand Engine". The tool predictions are compared with previous model results by Stam (2014) and volume measurements of the Sand Engine pilot. All model simulations show a fast redistribution of the nourishment in the first years which is decreasing in time. The rate at which these changes take place however differs considerably depending on the wave climate used in the simulation. A representative wave climate is therefore of high importance to obtain an accurate estimate of the coastline development. The results of Stam and the tool simulation that uses wave buoy data show the best correspondence with the observations. The measurement period is however too short to draw a quantitative conclusion regarding the future speed of redistribution of the Sand Engine.

The lifetime of the Sand Engine is less sensitive for different wave climate conditions. Under the assumption of an average erosion rate of 2 m/yr, the Sand Engine is expected to be sufficient to protect about 10 km of coast for a period of 50 years. A reduction in coastal maintenance is furthermore predicted for the entire Delfland coast. A different assumption for the average erosion rate however has a large impact on the predicted lifetime.

## Redistribution

The redistribution rate of the nourishment is quantified by the diffusion coefficient ( $c_1$ ) and the half-time ( $T_{50\%}$ ). Conclusions are drawn based on the model simulations for the redistribution:

**1. The half-time depends on the diffusion coefficient, the volume and the  $L/W$  ratio**

The half-time is inversely related to the diffusion coefficient and linearly depends on the volume. The half-time depends on the length over width ratio due to variations in the initial nourishment area. The half-time also show a slight increase for wave climates that approach the coast under an angle. This effect is small for angles less than  $10^\circ$ , less than 5% increase, and is therefore not taken into account. An equation is made for the half-time that reproduces the tool results:

$$T_{50\%} = 0.020 \frac{V}{c_1} \sqrt{L_{mn}/W_{mn}} \quad (8-1)$$

**2. The diffusion coefficients is predominantly influenced by the averaged wave climate energy**

Several averaged wave height parameters have been analysed from which the relation between the diffusion coefficient and the RMS significant wave height ( $\overline{H_s^2}^{1/2}$ ) resulted in the smallest scatter. This value is equivalent to the averaged wave energy and shows that the diffusion is more affected by the higher waves in the climate. When putting more emphasize on the higher waves in the climate, the relation with the diffusion coefficients becomes weaker. Equation 8-2 is empirically derived. There is a 95% probability that the model result deviate less than 35% from this equation.

$$c_1 = 0.026 \cdot \overline{H_s^2}^{1.35} \quad (8-2)$$

**3. The diffusion coefficient is slightly lower for a large directional spreading and wave steepness**

The reduction due to a large directional spreading is physically explained by a lower sediment transport gradient for larger angles of wave incidence. Waves with a larger steepness have a lower group velocity which reduces the wave energy transport. The model results can be reproduced with a self-developed empirical relation (8-3). There is a 95% probability that the tool result deviate less than 22% from this equation. The powers in the equations show the relative influence of the parameters.

$$c_{1,s} = 0.016 \cdot \overline{H_s^2}^{1.34} \cdot |\theta_{w,r}|^{-0.12} \cdot (\bar{s})^{-0.19} \quad (8-3)$$

**4. The diffusion coefficient is insensitive for grain sizes larger than  $250 \mu m$**

The transport formulation of Van Rijn et al. (2004) result in a slight reduction of the LST for grain sizes larger than  $250 \mu m$  due to a higher flow resistance of the grains. This effect is counteracted by the more intense wave breaking on a steeper cross shore profile that is associated with larger grains.

**5. The diffusion coefficient is sensitive for grain sizes smaller than  $250 \mu m$**

For grain sizes smaller than  $250 \mu m$  the increased diffusion due to a reduces flow resistance dominates over the decrease as a result of the milder cross shore profile shape. The diffusion coefficient therefore increases on average 40% for a  $D_{50}$  of  $175 \mu m$  and more than 100% for a  $D_{50}$  of  $150 \mu m$ .

**6. The wave data quality is important for an accurate estimate of the diffusion coefficient**

The waves from the ECMWF wave model are lower in height and period compared to the model of NOAA. This results in an on average 46% higher diffusion coefficient for the simulations with NOAA data. This large difference emphasises the importance of obtaining a representative wave climate.

**7. Different sediment transport formulations result in large variations in the diffusion coefficient**

By default the sediment transport formulation of Van Rijn et al. (2004) is used, which is the most recent and advanced formulation. Large differences in the order of  $\pm 100 \%$  are found for other transport formulations. It is impossible to conclude whether one of the formulations is correct for a specific case.

### 8. Diffusion coefficients are underestimated for a dynamic boundary chosen too far offshore

The location of the dynamic boundary affects the refraction pattern of the waves. The angle of wave incidence reduces for all coastline orientations if the dynamic boundary is taken far offshore resulting in a reduction of the LST gradient. Minor changes in the locations of the dynamic boundary (about 1-2 m) hardly influence the results.

### 9. The tool simplifications give rise to a large uncertainty between tool results and reality

Several processes such as wind driven sediment transport are not included, the cross shore profile is simplified, the wave climates from the global wave models are not representative and no model calibration is done. This in combination with the model sensitivity to several parameters emphasises that the tool can only make an initial rough estimate of the nourishment redistribution.

## Cross shore Erosion

An indicative estimate is provided for the coastal erosion due to SLR. For this estimate the Bruun rule was applied using an SLR prediction of 0.98 m in 95 years. Coastal retreat rates that were calculated were generally smaller than 1.5 m/yr. It should be noted that these retreat rates are indicative since the Bruun rule has a limited predictive capability. The exact properties of the considered coastline may have an effect on the actual retreat rates.

The landward erosion during storms was found to rapidly increase as soon as the crest level of the profile comes below a threshold value. The impact of storms depends on the occurrence of antecedent storms. Consequently, it is not possible to directly relate an event driven erosion to a yearly averaged coastal retreat. The results can therefore only be used to obtain an indication whether this process has a significant contribution to the coastal erosion. More detailed modelling is advised in case the tool indicates an erosion rate due to overwash.

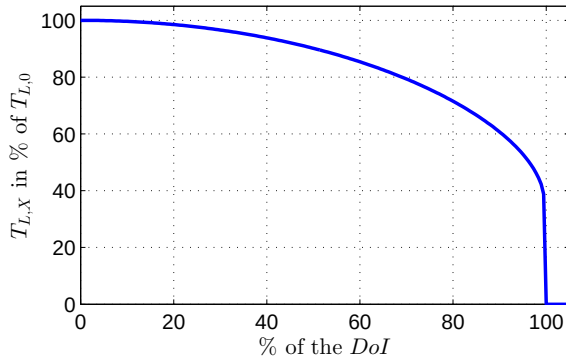
## Lifetime of a mega nourishment

The lifetime is a function of the nourishment *redistribution*, the coastal *erosion* and the alongshore *distance* from the nourishment. Two empirical relations are derived based on the tool results: one for the lifetime at the nourishment center (Equation 8-4) and one for the DoI (Equation 8-5). Both equations are exponentially related to the diffusion coefficient, the erosion rate and the nourishment size parameters. A change in the diffusion coefficient has a relatively minor effect on the lifetime at the center of the nourishment. At this center the lifetime does not depend on the shape of the nourishment surface but only on the nourishment volume. An accurate estimate of the erosion rate is furthermore of high importance to estimate the lifetime.

$$T_{L,0} = 0.11 \left( \frac{V_{mn}}{\sqrt{c_1 h_p E}} \right)^{\frac{2}{3}} \quad (8-4)$$

$$\frac{DoI}{L_{mn}} = 6.44 \left( \frac{c_1 W_{mn}}{E L_{mn}^2 h_p} \right)^{0.40} + 1 \quad (8-5)$$

The relation between lifetime and distance is given in a design graph which is developed based on the model results (see Figure 8-1). This graph shows how the lifetime reduces from the center of the nourishment (at  $x = 0$ ) till zero at the distance of influence. For a coastal stretch with a length of 0.8 times the DoI, the lifetime is equal to 70% of the lifetime at the nourishment center.



**Figure 8-1:** Design graph for the lifetime  $T_{L,X}$  in % of the lifetime at the nourishment center  $T_{L,0}$  (y-axis) as function of the percentage of the DoI

### Recommendations for further research

It is recommended to assess the influence of other parameters on the redistribution rate and lifetime of the mega nourishment. For example an analysis can be made regarding the effect of the coastal curvature on the speed of redistribution. Furthermore the lifetime can also be analysed for coasts with different boundary conditions, for example a beach bounded by headlands. The influence of more complicated profile shapes on the redistribution rate could also be assessed in further research. This could be combined by including cross shore profile variations in the calculation of the LST.

This thesis included a general analysis of the impact of different coastal parameters on the lifetime of a mega nourishment. Due to the large uncertainties in this approach, it is questionable if the results will become better by including other processes that are expected to have a minor contribution to the redistribution rate (such as the tidal flow and wind). To assess the effect of these kind of processes it is recommended to use a specific case rather than a general approach. For such a case it can be interesting to assess the impact of tidal asymmetry and tidal flow contraction around the tip of a mega nourishment.

A first estimate for the lifetime of a mega nourishment can be made with the relations presented in this thesis. For a detailed design of a mega nourishment it is however advised to perform a detailed site specific model study. This study would include wave modelling to obtain a representative near shore wave climate. Furthermore it is advised to take measurements on for example the cross shore profile, the erosion rate, the LST and the sediment characteristics. Part of these measurements can be used to calibrate a model to reduce the uncertainty of the output. In a more detailed analysis the three dimensional change in nourishment shape can be simulated which gives a better approximation on the active profile height and the flow velocities around the nourishment. To better estimate the lifetime it is recommended to focus mainly on an accurate estimation of the erosion rate of the shore.

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# Appendix A

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## The Sand Engine Pilot

A full scale pilot project has currently been executed called the Sand Engine to investigate this innovative concepts of dredging larger volumes of sand (Mulder and Tonnon, 2011). This innovative concept has only been implemented in one specific situation and the first official research results will be available in 2016. Most literature on this concept is therefore limited and focused on this one particular case. This appendix will focus on this pilot project and is aimed at defining distinctive features and relevant processes of the sand engine in order to understand the behaviour of a mega nourishment.

### A-1 Context

The Sand Engine has been build in the Netherlands, a low-lying country of which more than 50 % of the land lies below mean sea level. To prevent flooding from the sea, the land is primarily protected by beaches and dunes along the 350 km long North-sea coast. Due to a reduction in sediment supply from the rivers and a SLR over the past centuries the Dutch coast is eroding (Pranzini and Williams, 2013). After years in which coastal erosion was primarily mitigated by hard constructions the government decided In 1990 to implement a new nourishment policy, named 'dynamic preservation'. According to this policy the coastal foundation should be maintained and the coastline should be kept at its 1990 position mainly by means of soft solutions. Since then the Dutch have gained over 20 years of experience with beach and foreshore nourishments and executed around 300 nourishments at more than 60 different locations (Pranzini and Williams, 2013). A foreshore nourishment typically has a length of approximately 2 to 5 km, a total volume of 1-2 Mm<sup>3</sup> of sand (300-500 m<sup>3</sup>/m) and has a lifetime of 3-5 years (Stive et al., 2013; Bosboom and Stive, 2012).

Mulder and Tonnon (2011) stated that the current yearly nourishment volume of 12 Mm<sup>3</sup> per year should be increased to 85 Mm<sup>3</sup> per year by 2050 as a result of accelerated SLR in the 21<sup>st</sup> century which will result in wider, less accessible and unattractive beaches. In this context the concept of a local mega-nourishment was developed and eventually executed in a pilot project at the Delfland coast.

### A-2 Design, features and predictions

The Sand Engine was constructed in 2011 and consisted of 21 Mm<sup>3</sup> sand (approximately 10,000 m<sup>3</sup>/m). After construction it had an area of 128 ha, stretched 2.4 km of coastline and extended 1 km offshore. Several salient shapes were considered in the design and eventually a hook-shaped local nourishment was preferred. Figure A-1 shows the initial shape of the sand engine a few months after construction and Figure A-2 includes a picture of the shape after 2 years. It can clearly be seen that the sand engine has spread by the waves and the tide towards the north and the south during the two years after construction.

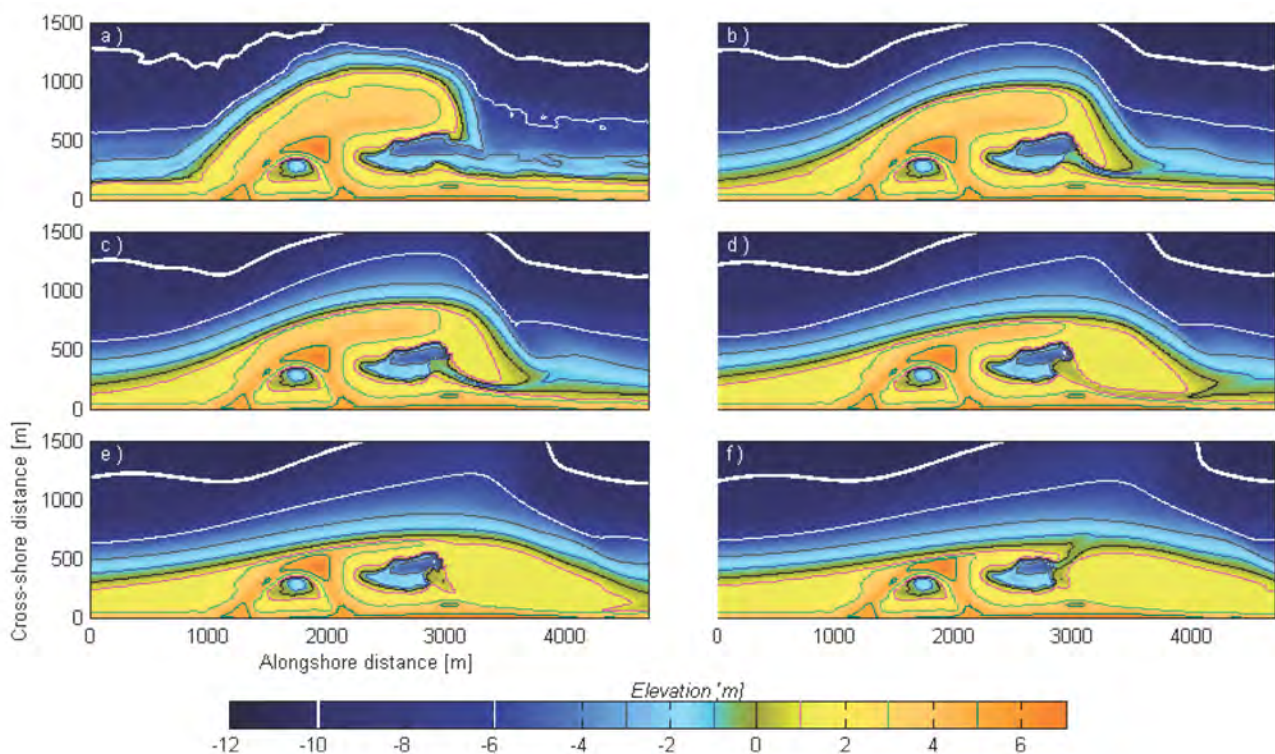
Model prediction of the morphological behaviour of the Sand Engine till 20 years after construction show a continuation of this symmetrical spreading process (see Figure A-3). Since the completion of the Sand Engine, field measurements of the bathymetry and aerial photographs have been made on a regular basis to follow the morphological behaviour. According to Stive et al. (2013) these measurements are in good correspondence to the model prediction. There is therefore a reasonable level of confidence that the longer term model predictions provide a reliable forecast for the morphological development of the peninsula in the coming years.



**Figure A-1:** The Sand Engine in September 2011 (Photo from: flickr.com/photos/zandmotor)



**Figure A-2:** The Sand Engine in September 2013 (Photo by Joop van Houdt flickr.com/photos/zandmotor)



**Figure A-3:** Predictions of the morphological behaviour of the Sand Engine. (a) is the initial bathymetry after construction and (b-f) are the predictions for 3, 5, 10, 15 and 20 years after construction. (Source: Stive et al., 2013)

According to Stive et al. (2013) this mega-nourishment has several advantages in comparison to the traditional beach and foreshore nourishments. First of all such a large nourishment has a lifetime of

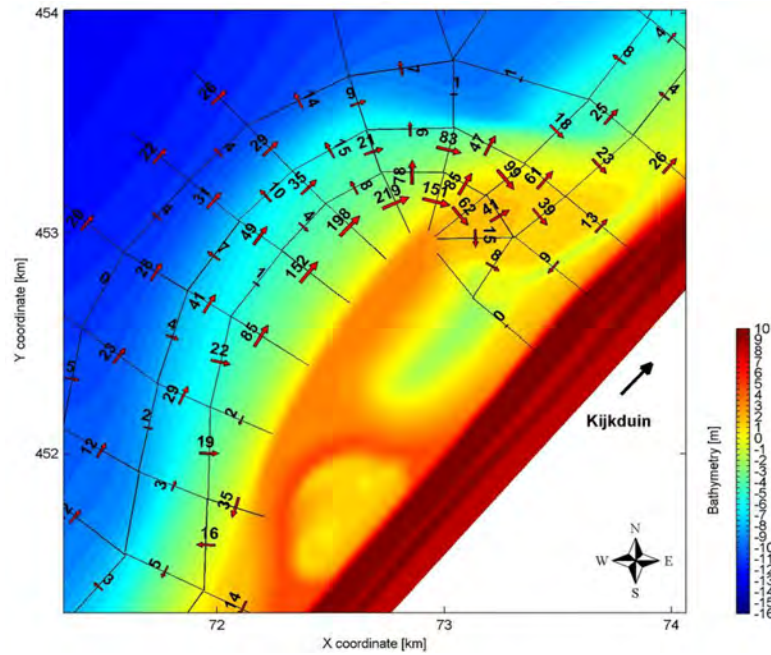
approximately 20 years instead of the 3 to 5 year of the current shoreface nourishments. Furthermore the nourishment only have to be executed on a small stretch of coasts. This local character in combination with the longer lifetime of the nourishments will reduce the ecological stress in the adjacent areas. Another advantage of this type of nourishment mentioned by Stive et al. (2013) is the more natural way sand diffuses in longshore direction to feed the shoreline over a stretch of 10 km. Finally the large perturbation provides space for recreation and nature development on the short and medium term. A mega nourishment can thus be seen as a multifunctional solution for a coastal erosion problem.

## A-3 Processes

A mega nourishment is a local perturbation of the natural system which brings the system further from its equilibrium situation. Because nature always strives to restore its equilibrium, this salient shaped bulge of sediment will be flattened by natural forces that transport the sediments in longshore and cross-shore direction. Especially these LST processes can deliver sediments to the adjacent beaches. As also discussed in the previous chapter, LST is therefore one essential underlying process of the mega nourishment concept. When applying this concept at another location on earth, the conditions should be such that this LST rate is sufficient to diffuse the mega nourishment longshore. This section will specifically focus on the available knowledge on the processes causing the sediment transport at the Sand Engine. For determining and quantifying these main processes some site specific information on the coastal characteristics and the hydrodynamic conditions is summarised in the enumeration below:

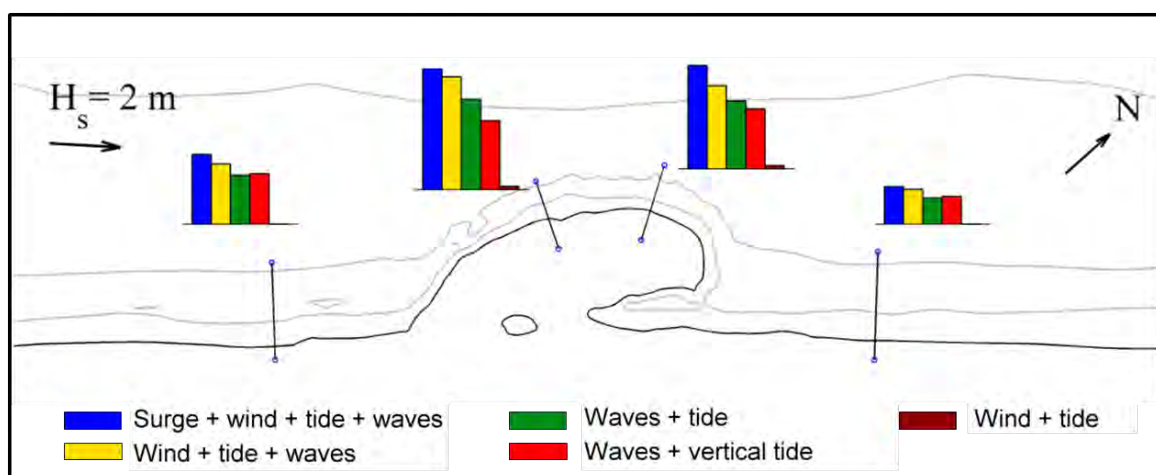
- Median grain diameter ( $D_{50}$ ) used in the morphological calculation = 215  $\mu\text{m}$  (Tonnon et al., 2009)
- Tidal amplitude is 1.5 m during neap tide and 2 m during spring tide
- Maximum tidal currents are 0.4 to 0.5 m/s in the situation without the Sand Engine and higher velocities up to 0.9 m/s in the situation with the Sand Engine due to flow contraction (Pekkeriet, 2011)
- Monthly average wave height of 1 to 1.7 m with dominant directions of south-west and north-north-west (Kaji, 2013) and a significant wave period ( $T_{1/3}$ ) of 5 to 8 seconds (Tonnon et al., 2009)
- Wave dominated ( $\text{RTR} < 3$ ), Dissipative beach ( $\Omega > 5$ ) with spilling breakers ( $\xi < 0.5$ )
- Storm wave climate with wave heights of about 5 m occurring with an average return period of 1 year (Pekkeriet, 2011)
- Storm surges of 2 to 4 m with average return period of 1 and 100 years respectively (Pekkeriet, 2011)
- Underwater slope of the Sand Engine is approximately 1:50, underwater slope of the original beach was approximately 1:80 (Pekkeriet, 2011)

Pekkeriet (2011) made a prediction of the annual averaged LST rates over a period of five years. These predictions show that sediment is transported in longshore direction to the north and the south (see Figure A-4). Recently a graduation research has been performed by Kaji (2013) which included an analysis of three parameters influencing this LST along the Sand Engine: the tide, the curvature of the coastline and the sediment size. According to this study, the horizontal tide does influence the net sediment transport in two ways: 1) by strengthening and weakening of the longshore wave-drive current and 2) by generating a suspended sediment transport further offshore where wave driven currents are negligible. Sediment size has significantly increased due to selective erosion and possible bed armouring after construction which resulted in lower transport rates. Kaji compared the longshore transport for two different sediment sizes in a model calculation with a significant wave height  $H_s = 3$  m, a peak period of  $T_p = 7$  s and a wave direction  $\theta = 311^\circ$ . According to the results the net longshore transport averaged over one tidal cycle reduced by 50 % when using a grain diameter of 300  $\mu\text{m}$  instead of 215  $\mu\text{m}$ . Coarsening of the sediments will however also result in steepening of the beach profile which increases the sediment transport.



**Figure A-4:** Calculated averaged annual LST volumes at the Sand Engine ( $\times 1000 \text{ m}^3$ ), over five years of simulation. The bathymetry corresponds to the predicted morphological situations after five years (Source: Pekkeriet, 2011)

Kaji et al. (2014) extended the research on different forcing processes that influence the longshore transport of the Sand Engine by considering the importance of storm surge, wind, tide and waves. In a model calculation with a significant wave height  $H_s$  of 2 m coming from the south-west, the relative magnitude of the LST is calculated at four cross-sections for different combinations of processes (see Figure A-5). These results show that the tidal flow and the wind hardly enforces any sediment transport. Tidal currents do however enhance the sediment transport in combination with waves of 2 meter. The enhancement is primarily visible at the tip of the sand engine where the tidal flow is enforced due to flow contraction. Another interesting aspect is the enhanced sediment transport by wind driven currents in the direction of the incoming waves. When wind is excluded from the simulation, the sediment transport reduces by 30%.



**Figure A-5:** Longshore sediment transport through 4 cross-sections for one wave condition at the Sand Engine including graphs that show the relative magnitude of the sediment transport for different combinations of processes (Source: Kaji et al., 2014)

# Model background

## B-1 Behavioural and process based models

There are two main types of models that can be used as a tool to model the morphodynamics of a coastal system: process based and behaviour oriented models. Process-based models are based on balance equations and are often used to produce detailed results. They do therefore require an accurate and large number of input parameters, are computationally expensive and are not preferred for the simulation of long time scales. This high level of detail is not immediately required to make a first assessment of the long term longshore diffusion of the mega nourishment. For such an assessment a behaviour oriented coastline model like Unibest-CL+ is better applicable. This type of model does require relatively few input parameters and is better able to quickly model the influence of a wide range of parameters on long time scales (decades to centuries). Coastline models are based on single-line theory and always assume an equilibrium profile of the coast. These models only include the calculation of LST, the process that drives the longshore spreading of a mega nourishment.

## B-2 Unibest-CL+

This section provides some background information regarding the Unibest-CL+ model.

### B-2-1 LT-module equations

In order to calculate the alongshore sediment transport for a given wave condition and a certain coastline orientation a system of three equation is numerically solved along the cross shore ray:

- The wave energy balance

$$\frac{d}{dx} \left( c_g \cos \theta_w \frac{E_w}{\omega_r} \right) + \frac{D_b}{\omega_r} + \frac{D_f}{\omega_r} = 0 \quad (\text{B-1})$$

- The equation for wave setup

$$\frac{d}{dx} S_{xx} + \rho g (h_0 + \eta) d \frac{d\eta}{dx} = 0 \quad (\text{B-2})$$

- The alongshore momentum equation

$$\frac{d}{dx} S_{xy} + \rho g d \frac{dh_0}{dy} + \rho \frac{g}{C^2} \mathbf{V} |V_{tot}| = 0 \quad (\text{B-3})$$

The three nonlinear spatial differential equation given above include three unknowns  $E, \eta$  and  $V$  and are solved for each of the cross shore grid points by linearising the equation and solving the system iteratively. The seaward limit of the cross shore grid serves as a boundary where the values of  $E, \eta$  and  $V$  are known.

In the equations the water depth  $d$  is defined as  $d = h_0 + \eta + z$ . The relative wave frequency  $\omega_r$  is a function of the peak frequency, the angle of wave incidence  $\theta$  and the alongshore flow velocity  $V$ :  $\omega_r = \omega - kV \sin \theta$ .

In Equation B-1 the wave energy, the dissipation due to wave breaking  $D_b$  and the dissipation due to bottom friction  $D_f$  are balanced. The wave energy  $E$  per square meter of water surface is derived from linear wave theory (see Equation B-4). The dissipation of wave energy is a function of a depth limited wave height and is calculated with Equation B-5. The dissipation of energy due to bottom friction is defined by Equation B-6 and is a function of the water density, the dimensionless friction factor  $f_w$  and the near bottom wave orbital velocity  $U_{rms}$ . The effect of the bottom friction in the wave energy balance is in general only noticeable for coasts with a significantly shallow foreshore and shoreface.

$$E_w = \frac{1}{8} \rho g H_{rms}^2 \quad [J/m^2] \quad (B-4)$$

$$D_b = \frac{1}{4} \rho g \alpha_c Q_b \left( \frac{\omega_r}{2\pi} \right) H_m^2 \quad \text{with} \quad \frac{1 - Q_b}{-\ln Q_b} = \left( \frac{H_{rms}}{H_m} \right)^2 \quad \text{and} \quad H_m = \frac{0.88}{k} \tanh \left( \frac{\gamma k d}{0.88} \right) \quad (B-5)$$

$$D_f = \rho f_w \pi^{-1/2} (U_{rms})^3 \quad \text{with} \quad U_{rms} = \frac{1}{2} \omega_r \frac{H_{rms}}{\sinh(kd)} \quad (B-6)$$

In the momentum balance (equation B-3) the alongshore flow velocity is balanced by a tidal water level gradient and a the flow resistance governed in a friction term. In this term the Chezy coefficient is a function of the water depth and the bottom roughness according to Equation B-7. In this thesis the effect of the tidal water level gradient is not considered.

$$C = 18 \log \left( \frac{12d}{k_0} \right) \quad (B-7)$$

### B-2-2 Sediment transport

The Unibest LT-module includes several transport formulation. The transport model of van Rijn 2004 (also denoted as TR2004) is the main formulation used throughout this thesis and is one of the most recent transport formulations. It is the most extensive formulation which includes several physical processes. compared to the previous equations of van Rijn the TR2004 model is improve by adding several modification such as a bed roughness predictor based on the median grain size  $D_{50}$  and a predictor for the suspended sediment size as function of the  $D_{10}$  and the  $D_{50}$ . For a more detailed description of the TR2004 model reference is made to Van Rijn et al. (2004).

### B-2-3 Coastline evolution

The coastline evolution is governed by the CL-module of the Unibest-CL+ model. It is based on single-line theory which was introduced by Pelnard-Considere (1956). This theory assumes a constant equilibrium cross shore profile which can move seaward or landward over its entire active height. Beyond the active height, the profile does not change. To simulate the coastal changes a continuity equation (B-8) together with an equation of motion (B-9) are solved by the CL-module for a set of initial and boundary conditions. When combining these two equations and performing a first order Taylor expansion of  $Q_s$  at  $\theta_c = \theta_{eq}$

the well known diffusion equation is obtained (B-10). In these equation  $s_1$  represents the gradient of the  $S$ - $\theta$  curve. Note that  $s_1$  is equal to the coefficient  $c_1$  if the coastline equals the equilibrium orientation ( $\theta = \theta_{eq}$ ).

$$h_p \frac{\partial y}{\partial t} + \frac{\partial Q_s}{\partial x} + q_b = 0 \quad (\text{B-8})$$

$$Q_s(\theta_c) = Q_{s0} - s_1 \frac{\partial y}{\partial x} \quad \text{with} \quad s_1 = -\frac{dQ_s}{d\theta_c} \quad (\text{B-9})$$

$$\frac{\partial y}{\partial t} = -\frac{s_1}{h_p} \frac{\partial^2 y}{\partial x^2} \quad (\text{B-10})$$



# Run specification MN-tool

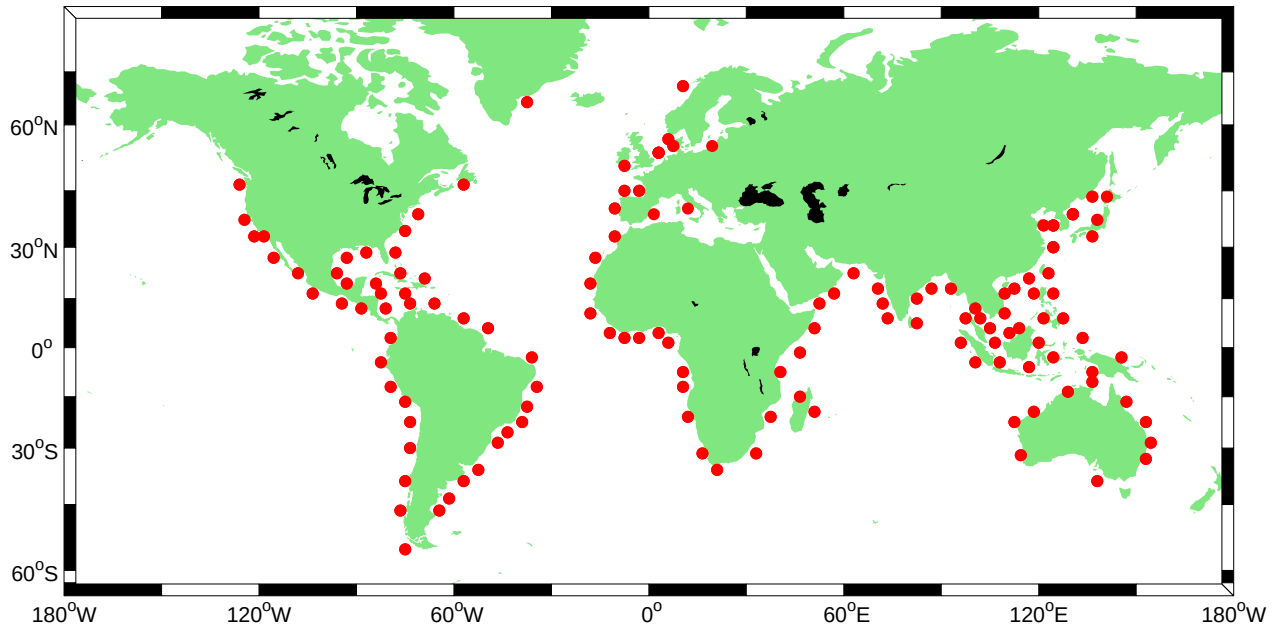
The MN-tool is used to assess the relative influence of the different coastal parameters on the diffusion coefficient  $c_1$ , the half-time, the lifetime and the Dol of a mega nourishment. For this assessment model runs were performed with different parameters. This appendix provides a detailed description of the chosen model values for the different runs.

## C-1 Model parameters Unibest LT-module

The redistribution rate of the mega nourishment can be described by a diffusion coefficient. analysed by altering the input parameters of the alongshore part of the tool. For this analysis several cases are defined with different wave climates and coastline orientations. For each of these cases a model run is executed for a set of default model parameters. Subsequently some of the default parameters are altered to assess their influence on the nourishment redistribution.

### C-1-1 Theoretical cases based on wave climate and coastline orientation

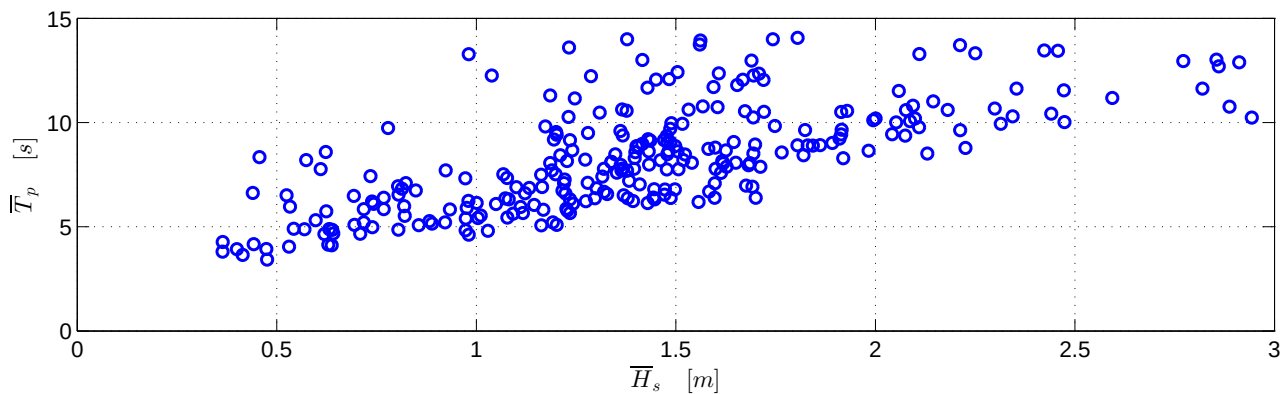
137 locations around the world were selected to obtain a set of theoretical cases for a mega nourishment. At these locations, visualised with red dots on the world map in Figure C-1, offshore wave data is taken from the global wave models (NOAA and ECMWF). For the case in front of the Dutch coasts also wave buoy data is used from three wave buoys on the North Sea. For each geographical location the coastline orientation is estimated by looking at the actual orientation of the shore. In total 272 theoretical cases are defined that are characterised by a different wave climate and coastline orientation. They cover a wide range of wave climates with different waves heights, lengths and directions.



**Figure C-1:** Selected locations for wave climates

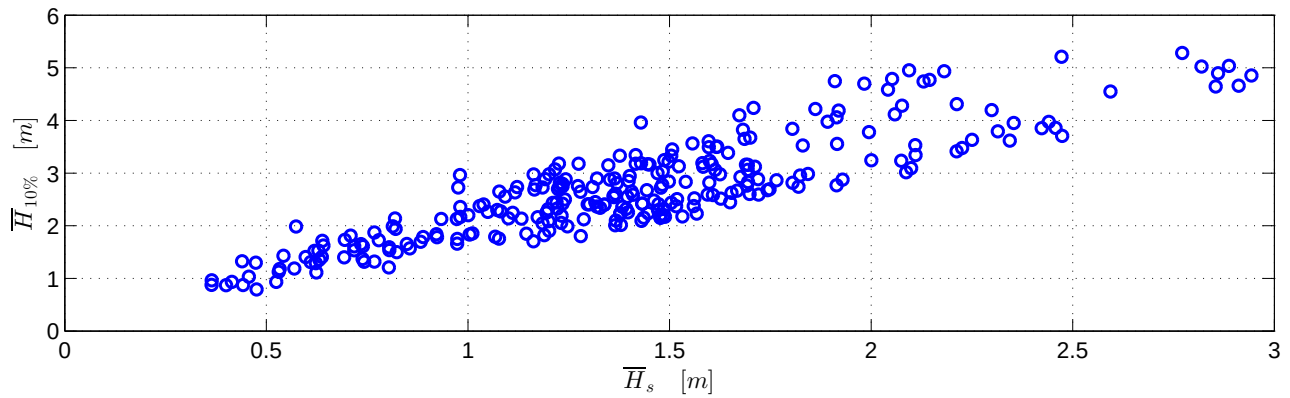
### C-1-2 Wave climate characteristics

The characteristics of the wave climates are evaluated at the DoC calculated with the equation of Hallermeier (1981). Figure C-2 shows the scatter plot between mean significant wave height  $\overline{H}_s$  and mean wave peak period  $\overline{T}_p$ . The waves with the larger periods generally include the climates that are dominated by ocean swell whereas the climates with low mean peak periods represent the wind driven wave climates.



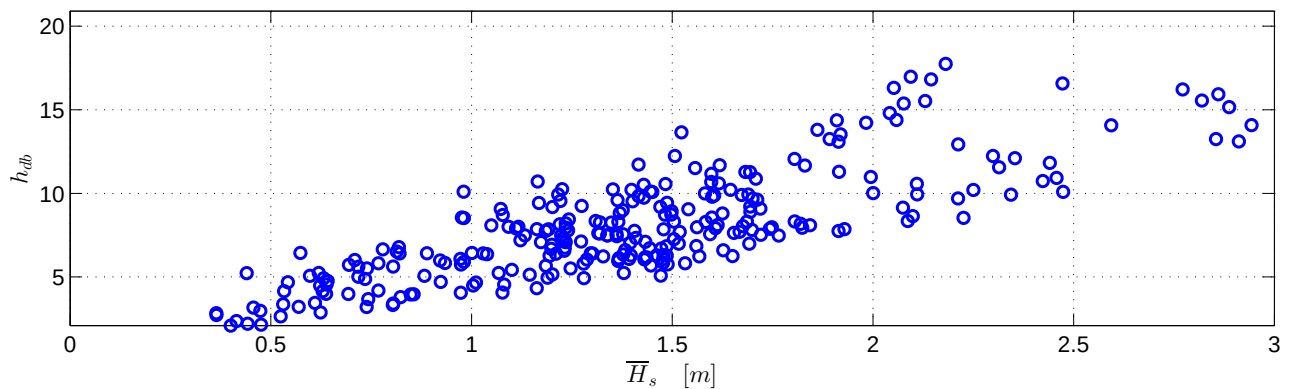
**Figure C-2:** Mean significant wave height as function of the mean peak period

Each of the wave climates also has a different distribution of the wave heights. This is visualised in Figure C-3 that shows the relation between the mean and the mean of the 10 % highest significant wave heights.



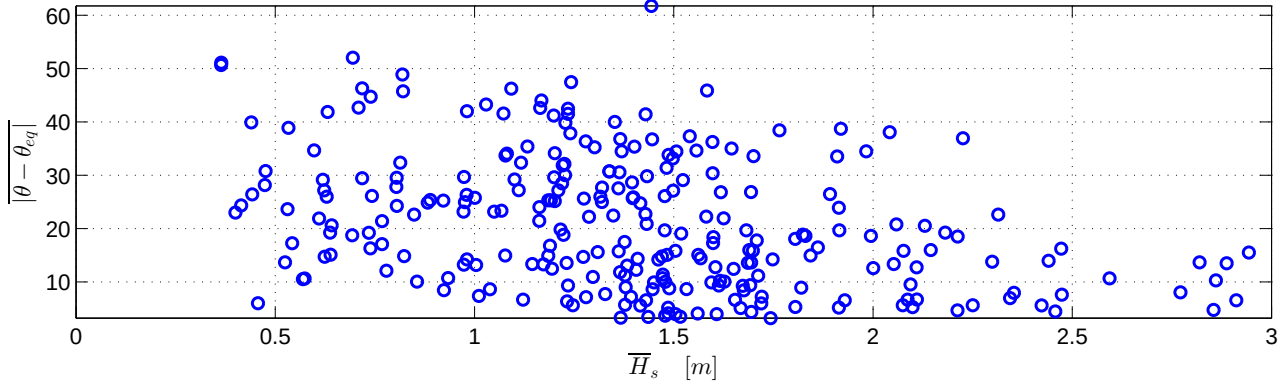
**Figure C-3:** Mean significant wave height as function of the 10% highest significant wave heights

In Figure C-4 the relation between the mean significant wave height and the location of the dynamic boundary is shown. This location is calculated with the DoC formulation at Hallermeier (1981). At this depth the transformed wave climates are compared. The location of the dynamic boundary is furthermore important for the refraction of the waves.



**Figure C-4:** Mean significant wave height as function of the water depth at the dynamic boundary which is located at the DoC

Finally a scatter diagram is presented in Figure C-5 between the mean significant wave height and the averaged absolute value of the deviation in angle of wave incidence from the coastal normal which is a representative value for the directional spreading of the wave climate. A small value of this deviation represents a climates with waves that travel mainly in one direction. A larger value is obtained when the wave directions show a large spreading.



**Figure C-5:** Mean significant wave height as function of the directional spreading of the wave climates

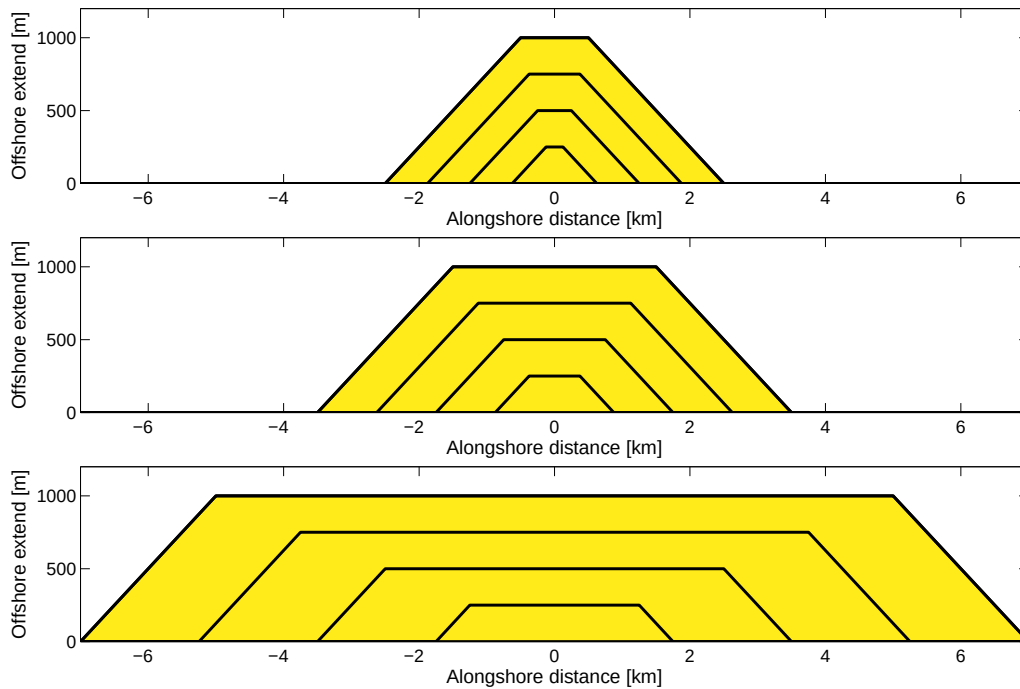
### C-1-3 Default model

For each of the cases defined above a default model run is done with the Unibest LT-module and the CL-module. In this run the following parameters were specified:

- Sediment size:  $D_{50} = 250 \mu\text{m}$ ,  $D_{10} = 0.6D_{50} = 150 \mu\text{m}$ ,  $D_{90} = 1.4D_{50} = 350 \mu\text{m}$
- Values for sediment transport formulation of Van Rijn et al. (2004):
  - Sediment density:  $2650 \text{ kg/m}^3$
  - Seawater density:  $1025 \text{ kg/m}^3$
  - Porosity: 0.4
  - Temperature:  $15^\circ\text{C}$
  - Salinity: 35 ppm
  - Factors for current-related and wave-related transport: 1
- No tidal flow
- Beach slope: 1:40
- Nourishment size:  $h_p = 7\text{m}$ ,  $W_{mn} = 700\text{m}$ ,  $L_{mn} = 1700\text{m}$ ,  $x = 2$
- Dynamic boundary:  $h_{db} = DoC$  according to Hallermeier (1981)
- Wave friction factor:  $f_w = 0.01$
- Bottom roughness:  $k_b = 0.01\text{m}$
- Coefficients for wave breaking:  $\gamma = 0.8$  and  $\alpha_c = 1$

## C-2 Model parameters for lifetime

Model runs were performed with the Unibest CL module with varying diffusion coefficients and nourishment dimensions to derive empirical relations for the lifetime and the DoI. For the diffusion coefficient twenty values are chosen with equal spacing on a logarithmic scale. These values range from 0.003 till 0.4. Besides this the nourishment dimensions are varied. Four different values for the offshore width ( $W_{mn} = 250, 500, 750$  and  $1000\text{m}$ ) were used in combination with 7 different ratios of length over width ( $L_{mn}/W_{mn} = 3, 4, 5, 6, 7, 9$  and  $12$ ). Figure C-6 includes the different nourishment dimensions for the  $L_{mn}/W_{mn}$  ratios 1, 3 and 10. Two values for the active height were defined:  $h_p = 7$  and  $10 \text{ m}$  for all runs. The orientation of the outer ends of the nourishments are for all model runs 1:2, meaning that the alongshore length of the nourishment equals:  $L_{mn} = L_{base} + 2 \cdot W_{mn}$ . See also Figure 3-12 for the definition of the nourishment dimensions.



**Figure C-6:** Part of the nourishment dimensions that were used for the tool with different ratios of length over width (1, 3 and 10)

### C-3 Xbeach model parameters

As mentioned in Section 2-2 the landward sediment loss during storms is expected to occur only in the overwash and inundation regime. This process is therefore expected to be very sensitive to the height of the profile relative to the storm surge level and the storm wave energy. These two parameters will therefore be varied in the tool. The amount of sediments that are lost can furthermore be dependent on the shape of the profile, the duration of the storm and the sediment properties. The following parameters are therefore used to analyse the landward erosion during storms:

- Wave conditions:  $H_s$  of 3, 5, and 7 m with corresponding  $T_p$  of 8, 10.5, and 12.5 s.
- Storm durations: 10, 20, 30 and 40 h
- Profile crest levels: varying between 1 and 5 m
- Sediment sizes:  $D_{50}$  of 150, 250 and 350  $\mu m$

For the cross shore profile the DMW profile is used with a beach slope of 1:40. All other values of the Xbeach models are kept at their default value.



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## Appendix D

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# Coastal classifications

Coastal systems has been classified based on different coastal characteristics and parameters. All of the classification schemes proposed in literature show the wide variability in coastal types around the world and none of them can provide an integrated scheme that can cover all coastal systems (Finkl, 2004). This section will describes four of these classification schemes and defines the .

### D-1 Tectonic classification

Inman and Nordstrom defined three major classes of coast based on the plate tectonic theory: leading-edge (or collision) coasts, trailing-edge coasts and marginal-sea coasts. Leading-edge coasts occur near two converging plate boundaries. Coastal areas which are far away from plate boundaries are of the trailing-edge type. Inman and Nordstrom divided the trailing-edge coasts into three sub-classes. Neo-trailing-edge coasts are located near plate boundaries that begin to separate (for example the coast of the Red Sea). Afro-trailing-edge-coasts have a trailing-edge coasts at the opposite side of the continent (e.g. the Atlantic and Indian Ocean coasts of Africa) and Amero-trailing-edge coasts have a leading-edge coasts on the opposite side of the continent (e.g. the east coast of America). The third main group of coastal shapes, defined as marginal-sea coasts, are sheltered from the open ocean by island arcs that are formed near two converging ocean plate boundaries(e.g. Vietnam, southern China and the Gulf of Mexico).

The plate tectonic setting of a coast shows a strong correlation with the width of the continental shelves (Bosboom and Stive, 2012) which strongly affects the hydrodynamic conditions. Inman and Nordstrom (1971) and Pilkey et al. (2011) also showed that the tectonic setting of the coast show a relation with the sediment input and the type of sedimentary features. Table D-1 presents a summary of the typical coastal characteristics for each of the coastal classes. According to this table long beaches and dune systems with relatively fine sediments mainly occur along trailing and marginal sea coasts where wave energy is lower but tides and storm surges are higher. Under the high wave energy conditions along leading edge coasts beaches are generally small and coarse. Figure D-1 and D-2 show two examples of the leading-edge and trailing-edge coast.

**Table D-1:** Summary of coastal characteristics for the different categories of the tectonic classification (Sources: Bosboom and Stive, 2012; Davis Jr and FitzGerald, 2009; Pilkey et al., 2011; Davis, 1997)

| Coastal class             | Leading-edge                               | Trailing-edge<br>Neo-         | Afro-                        | Amero-                                                 | Marginal sea                                 |
|---------------------------|--------------------------------------------|-------------------------------|------------------------------|--------------------------------------------------------|----------------------------------------------|
| Location                  | Near converging plates                     | Near young spreading centres  | Continent in middle of plate | Far away from plate boundaries                         |                                              |
| Look                      | Rugged cliffed coasts with mountain ranges | Steep coasts backed by cliffs | Lowlying or hilly            | Lowlying or hilly                                      | Lowlying or hilly                            |
| Shelf width               | Narrow, steep gradient                     | Narrow, steep gradient        | Narrow to wide, low gradient | Mainly wide, low gradient                              | Mainly wide, low gradient                    |
| Waves                     | Higher                                     | Lower                         | Lower                        | Lower                                                  | Lower                                        |
| Tides                     | Lower                                      | Lower                         | Higher                       | Higher                                                 | Higher                                       |
| Storm surge               | Lower                                      | Lower                         | Higher                       | Higher                                                 | Higher                                       |
| Main sediment source      | Rapidly flowing streams                    | -                             | Wind deposition              | Continental shelf                                      | Meandering rivers                            |
| Sediment size             | Coarse                                     | Coarse                        | Fine                         | Fine                                                   | Fine                                         |
| Sedimentary features      | Few                                        | Few                           | Few                          | Many                                                   | Many                                         |
| Type of sediment features | Small coarse eroding beaches               | Small coarse 'pocket' beaches | Beaches                      | Deltas, barriers, tidal flats, marshes, beaches, dunes | Deltas, tidal flats, marshes, beaches, dunes |



**Figure D-1:** Example of a leading edge coast: America west coast (photo by Franco Folini)



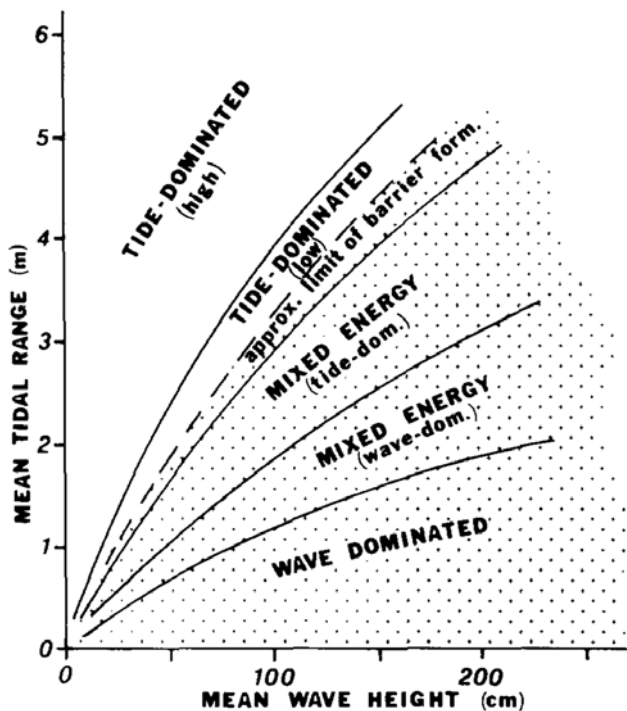
**Figure D-2:** Example of a trailing edge coast: Netherlands (photo by Bas Kers)

## D-2 Wave and tide dominance

Hayes (1979) recognised that the relative importance of wave height and tidal range has a major influence on the coastal morphology. He therefore distinguished 5 coastal classes varying from wave-dominated to tide-dominated (see Figure D-3). According to Davis Jr and Hayes (1984) it is this relative importance rather than the absolute size of tidal range and wave height that determines the coastal sedimentary features. Davis Jr and Hayes further emphasised the sensitive balance between wave height and tidal range especially when both parameters become smaller. This sensitivity allows for the existence of wave-dominated, mixed energy and tide-dominated morphologies along one stretch of coastline.

One of the parameters to distinguish between the different classes is the RTR, which is defined as the ratio between the MSTR and the wave height just before breaking  $H_b$ . Beaches show fully wave-dominated sediment features for  $RTR < 3$  and are fully tide-dominated for  $RTR > 15$ .

Shore parallel sediment bodies can typically be found along wave-dominated shores. Davis Jr and Hayes mentions several examples of these sediment bodies including longshore bars, beaches, barrier islands, beach ridges and fore dunes. All of these features are best developed on wide coastal plains that can accommodate large amounts of sediments. Typical coastal features that occur in tide-dominated areas are estuaries, salt marches and large tidal flats. The finest sediments along these coasts are often found on the upper intertidal zone whereas the coarsest sediments occur further offshore where tidal currents are stronger (Schwartz, 2006)).



**Figure D-3:** Relationship between tidal range and wave height (Source: Davis Jr and Hayes, 1984)



**Figure D-4:** Example of a tide dominant beach (photo by A.D. Short)

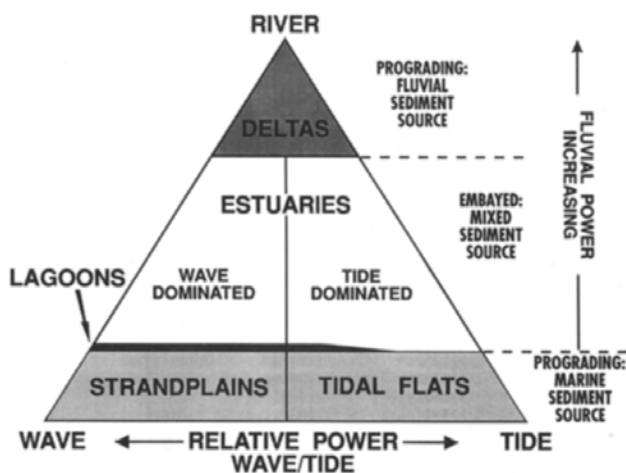


**Figure D-5:** Example of a wave dominant beach (photo by Rodrigo Sá Barreto)

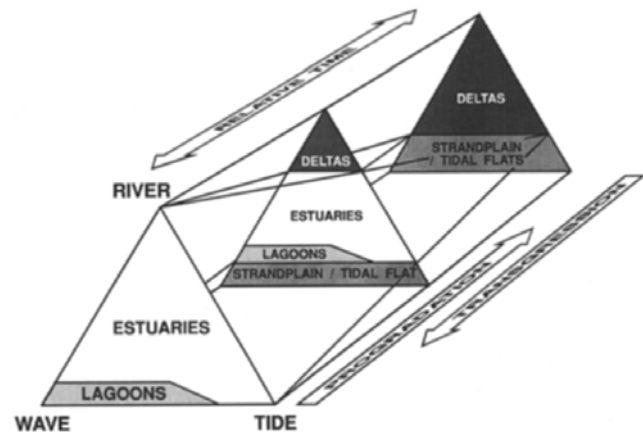
### D-3 Ternary process-based coastal classification

Besides wave and tide dominance, Boyd et al. (1992) also took the sediment import into account to make a process based classification of coastal systems. For this classification a ternary diagram was made which includes the main coastal environments: deltas, estuaries, lagoons, strand plains and tidal flats (see Figure D-6). The triangular diagram includes the relative power of wave and tidal processes on the horizontal axis and the fluvial power on the vertical axis. As found in the classification by Davis Jr and Hayes, Strandplains and tidal flats do develop along wave and tide-dominated coasts respectively. Often these coasts receive sediments from a marine source (often in the form of onshore or longshore sediment transport). With increasing river sediment import wave-dominated and tide-dominated estuaries start to develop. These estuaries have a mixed marine and fluvial sediment import and show sedimentary features shaped by wave and tide. Lagoons do form when there is only little river sediment import. Deltaic sedimentary features are common along coasts where the fluvial power dominates.

Boyd et al. (1992) also included relative time which refers to changes in relative sea level change river sediment supply. These changes can directly be related to transgression and progradation of the shoreline. By including relative time, an additional dimension is added to the triangular diagram creating a three-dimensional prism (see Figure D-7). If in time the shoreline is moving landward (transgression), the coastal environments starts to form estuary and lagoon systems (the front triangle of Figure D-7). If in contrast the coastline is extending in time (progradation) deltaic systems, strandplains and tidal flats become more common (the back triangle of Figure D-7).



**Figure D-6:** Ternary process based classification of coastal environments on the basis of the relative importance of waves and tide and the amount of river sediment import (fluvial power) (Source: Boyd et al., 1992)



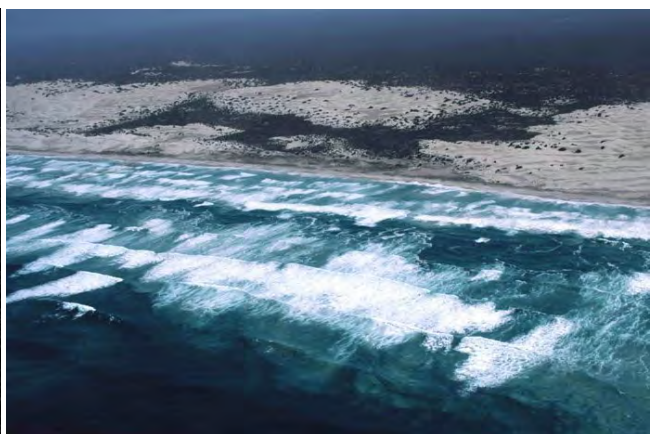
**Figure D-7:** Evolutionary coastal classification including the relative time as a third dimension. (Source: Boyd et al., 1992)

## D-4 Beach states

A more specific classification limited to wave dominated beaches with a micro-tidal range was developed by Wright and Short (1984), which includes six different beach states. The different beach states range from a reflective state to a dissipative state. Wright and Short (1984) and Bosboom and Stive (2012) have described some specific characteristics for the two extreme beach states. Reflective beaches are in general attacked by long and small amplitude waves and tend to have narrow and steep cross-shore profiles. Sediments are generally coarse and there is often a pronounced bed step at the base of the swash zone composed of the coarsest sediments. Wave tend to break as a collapsing or surging type and the mild wave climate often brings sediment onshore. This type of beach is mostly found along coasts with a swell wave climate. In contrast, dissipative beaches are attacked by a storm wave climate with steep, short and high energy waves. These waves are generally of the spilling type and do break far offshore. The cross-shore profile is highly dynamic, is wide and flat to dissipate the wave energy and consist of multiple linear bars with fine sediments. Figure D-8 and D-9 show an example of a reflective and a dissipative beach.



**Figure D-8:** Example of a reflective beach (Source: Short)

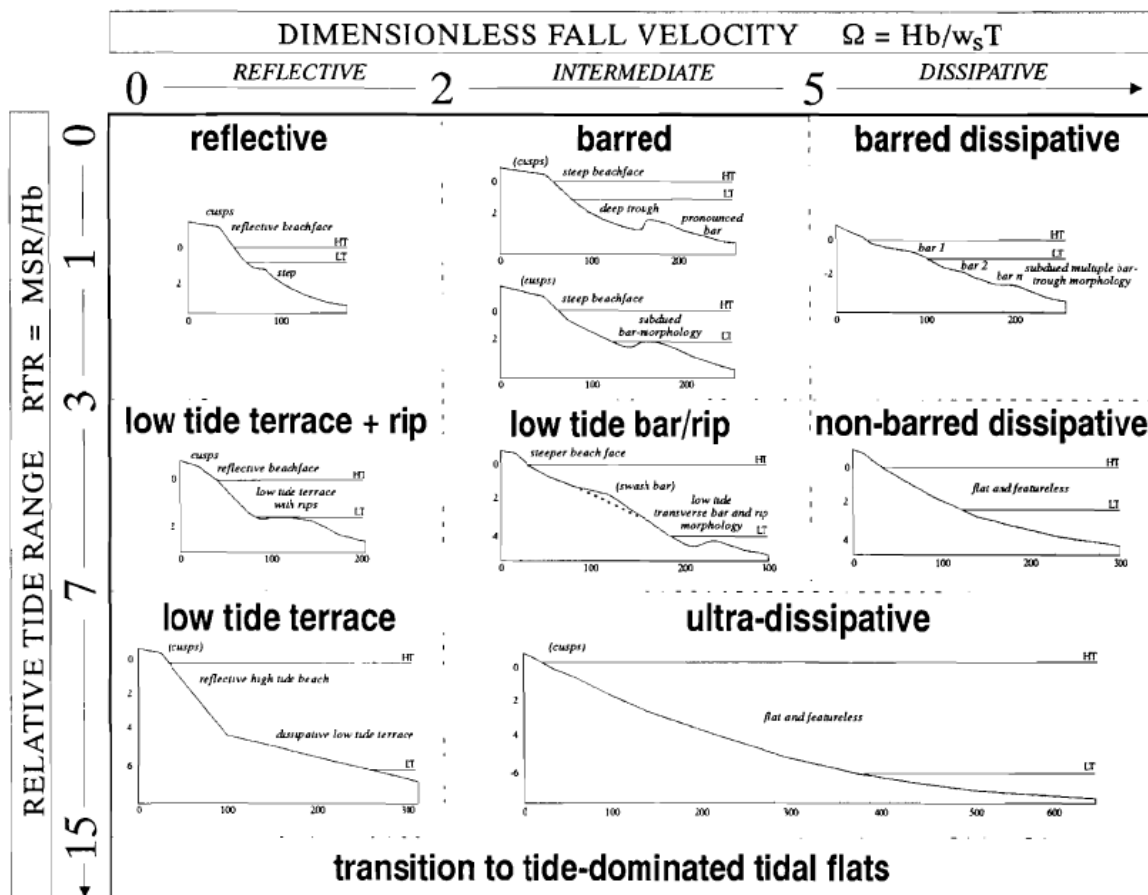


**Figure D-9:** Example of a dissipative beach. (Source: Short)

Wright and Short used the dimensional fall velocity ( $\Omega$ ) as a parameter to distinguish between these different states. This parameter is calculated by dividing the wave height at breaking  $H_b$  by the sediment fall velocity  $w_s$  and the wave period  $T$  (see Equation D-1)

$$\Omega = \frac{H_b}{w_s T} \quad (\text{D-1})$$

The beach model by Wright and Short was extended by Masselink and Short (1993) who included the influence of the tide. For their research they surveyed 15 transects across several beaches along the Queensland coast in Australia with a macro-tidal range. From this survey 9 different states were defined based on the RTR and the dimensionless fall velocity ( $\Omega$ ). Figure D-10 presents the conceptual beach model of Masselink and Short. The upper three states are comparable to the ones defined by Wright and Short. When the tidal range increases along a reflective beach, a flat terrace with possible rip currents forms at the low tide level. Intermediate beaches with a RTR of 3-7 have a mild sloping mid-intertidal zone with a possible swash bar and a low tide transverse bar and rip morphology. For dissipative beaches the profile becomes milder and bars are disappearing when the RTR increases. For a RTR of 7-15 ultra-dissipative beaches with a very wide intertidal zone form along intermediate and dissipative coasts..



**Figure D-10:** Conceptual model of beaches in which multiple beach states are distinguished on the basis of the dimensionless fall velocity ( $\omega$ ) and the RTR (Source: Masselink and Short, 1993)

## D-5 Wave climate

Davies and Clayton (1980) categorised the different coastal types by using the deep water wave climates as a parameter. Four main wave environments were defined:

- Storm wave environments
- West coast swell environments
- East coast swell environments
- Protected sea environments
- Trade and monsoon generated waves
- Tropical cyclone generated waves

Schwartz (2006) described the different wave environments in terms of seasonality, deep water wave height, wave period and direction (see Table D-2). Bosboom and Stive (2012) further elaborated on some typical characteristics for these wave environments. The storm wave climate is the most energetic one and mainly occurs on mid latitudes (40° and 60° N and S) Wave periods are generally about 5 s but in storms the period may go up to 14 s. Storm waves are in the order of 2 to 5 m in height. These waves are often characterised as irregular, multi directional and short-crested. In contrast swell waves are mainly dominant along low latitudes (0-40°) and consist of long, relatively low waves which are uniform in shape, direction and size. The global distribution of wave environments is visualised in Figure D-11.

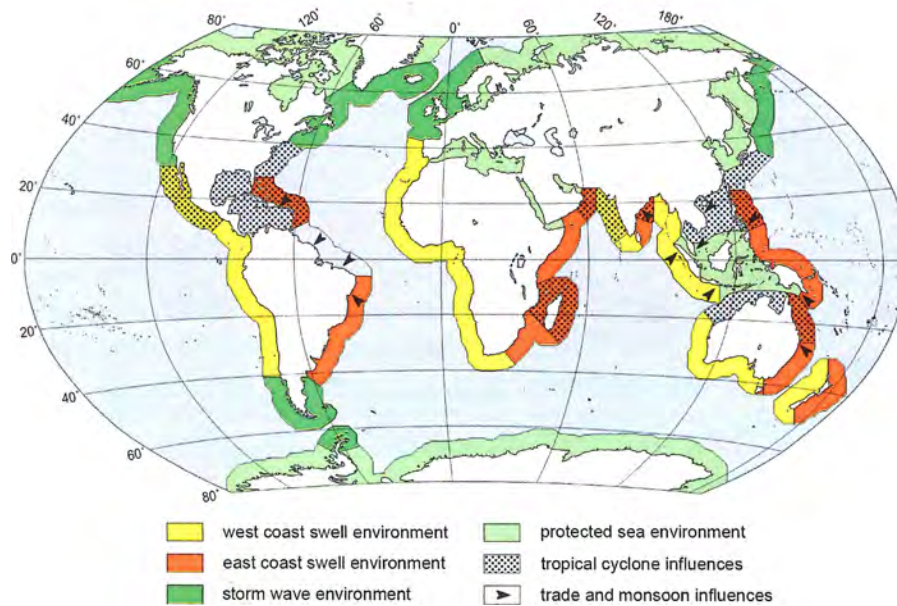
The waves on deep water are often strongly influenced by the local geometry of the coastal zone before reaching the shoreline. Therefore there is only a weak relation between the specific coastal features and the deep water wave environments. Nevertheless some generalizations were made by Bosboom and Stive. Sandy coasts attacked by storm waves are generally dynamic and continuously reshaped by the waves of the spilling type. They often have bars, wide beaches with dune systems and a wide littoral zone. Sediments tend to become finer in the offshore direction where wave energy reduces. In contrast a swell dominated coasts often has a narrow littoral zone with an abrupt transition from coarse sediments close to the shore to fine sediments offshore with waves of the collapsing type. Coastlines in a monsoon wave climate are similar to the shores in a swell climate. Shorelines that are located in a cyclonic environment are only temporarily (one or two times per year) attacked by high waves and storm surges. The coastal morphology is therefore mainly determined by the year round average wave climate.

**Table D-2:** Characteristics of deep water wave environments (Source: Schwartz, 2006)

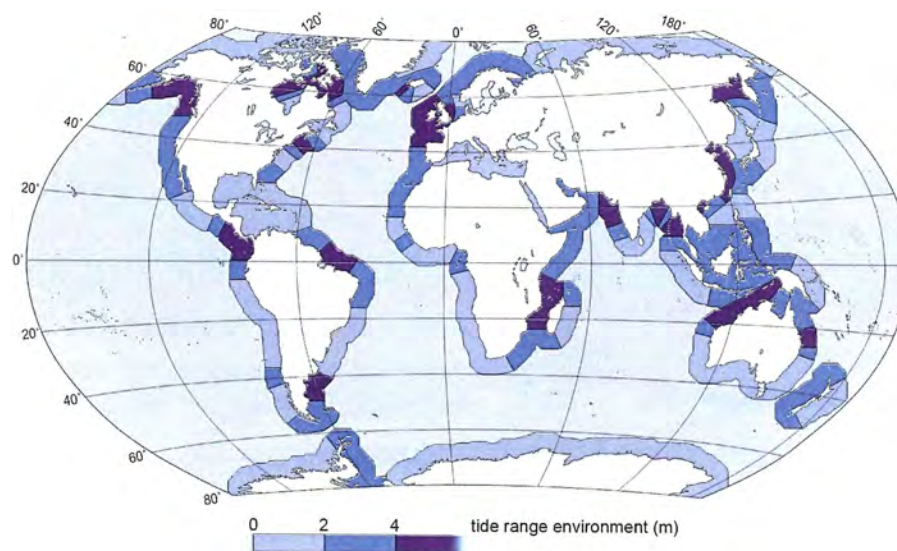
|                   | Seasonality                                                      | Deep water height | Period  | Direction                                          |
|-------------------|------------------------------------------------------------------|-------------------|---------|----------------------------------------------------|
| Storm wave        | Northern Hemisphere - winter<br>Southern Hemisphere - year round | 2-5 m             | 10-14 s | Predominantly W to SW                              |
| West coast swell  | Northern Hemisphere - winter<br>Southern Hemisphere - year round | 1.5-3 m           | 12-14 s | Northern Hemisphere - NW<br>Southern Hemisphere SW |
| East coast swell  | Northern Hemisphere - winter<br>Southern Hemisphere - year round | 1-2 m             | 8-12 s  | Northern Hemisphere - NE<br>Southern Hemisphere SE |
| Protected coasts  | Depending on location                                            | Max 0.5 m         | 3-5 s   | Variable                                           |
| Trade winds       | winter                                                           | 0.5-1.5 m         | 6-9 s   | Parallel winds                                     |
| Monsoons          | summer                                                           | 1.5-1             | 4-6 s   | NW & SW                                            |
| Tropical cyclones | summer                                                           | High              | Short   | Variable                                           |

## D-6 Tides

Davies and Clayton (1980) also classified the different coastal systems on the basis of the tidal type and tidal range. The tidal type can be characterised as diurnal (one tidal cycle per day), semi-diurnal (two tidal cycles per day) and mixed (two tidal cycles per day with different tidal ranges). The tidal range is subdivided into three classes: Macro-tidal (tidal range < 2m), meso-tidal (tidal range 2-4 m) and micro-tidal (tidal range > 4 m). Micro tidal ranges are most often found along open oceanic coasts with narrow continental shelves, whereas tidal ranges become larger in funnel shaped areas, in estuaries and on wide, shallow shelves. shows the global distribution of the mean spring tidal range.



**Figure D-11:** Global distribution of wave environments (Source: Bosboom and Stive, 2012, adjusted from Davies and Clayton, 1980)



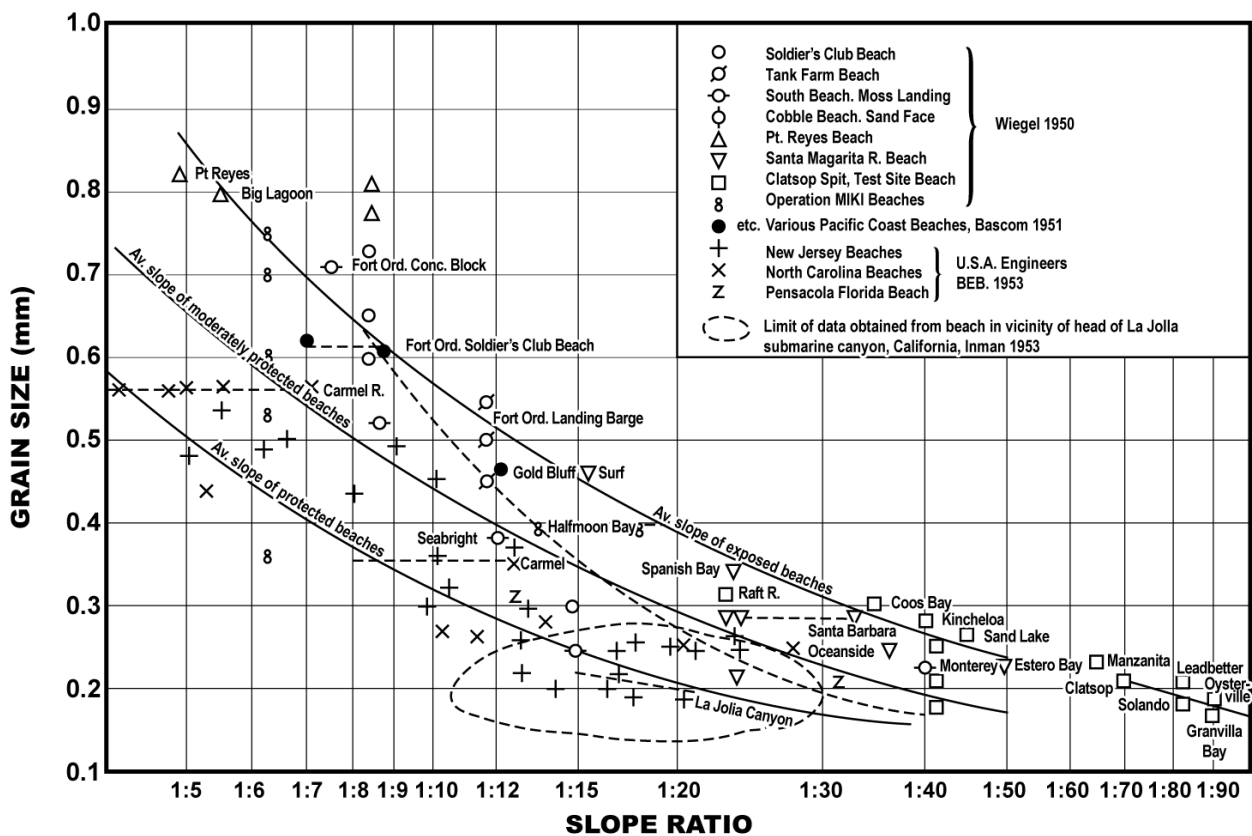
**Figure D-12:** Global distribution of MSTR (Source: Bosboom and Stive, 2012, adjusted from Davies and Clayton, 1980)

## D-7 Sediment size

The sediment size and grading are the most relevant parameters for most sediment transport formulations (Bosboom and Stive, 2012). One of the widely used sediment classification based on sediment size is called the Wentworth scale (Wentworth, 1922). This scale depends on powers of two to separate the different sediment classes and is presented in Table D-3. The sandy classes are the most relevant for the evaluation of sandy strategies. According to this classification the size of sand particles range from  $62 \mu\text{m}$  till  $2 \text{ mm}$ . Sediments become cohesive for sizes smaller than  $74 \mu\text{m}$  (Dalrymple, 2002). Sand is therefore considered as non-cohesive material. Bird (1996) described the relation between particle size and average slope of the beach face (see the third column of Table D-3). In general coarser sediments will result in a steeper beach profile.

**Table D-3:** Sediment classification based on particle size by Wentworth (1922) and mean slope of the beach face (Bird, 1996)

| Classification   | Particle diameter [mm] | Mean slope of beach face [°] |
|------------------|------------------------|------------------------------|
| Boulder          | > 256                  |                              |
| Cobble           | 64 - 256               | 24                           |
| Pebble           | 4 - 64                 | 17                           |
| Gravel           | 2 - 4                  | 11                           |
| Very coarse sand | 1 - 2                  | 9                            |
| Coarse sand      | 0.5 - 1                |                              |
| Medium sand      | 0.25 - 0.5             | 7                            |
| Fine sand        | 0.125 - 0.25           | 5                            |
| Very fine sand   | 0.062 - 0.125          | 1                            |
| Silt             | 0.004 - 0.062          |                              |
| Clay             | < 0.004                |                              |



**Figure D-13:** Grain size and slope ratio for different beaches (Source Komar, 2009)

## D-8 Conclusion

No single classification scheme has been found that can cover all different type of coasts. Still many different schemes have been proposed in literature that are focussed on specific features of and processes acting on the coastal system. This chapter has discussed several coastal classification based on the earth tectonic setting, the characteristics of the coast and the processes working on the coasts. In the tectonic classification coasts are defined into three main classes that each show their own specific characteristics: leading-edge, trailing-edge and marginal sea coasts. Coastal material can be classified on the basis of

sediment size and beach slope and the shape of the coasts is described by several beach planforms. Different coastal environments can also be classified based on the type of waves, the tidal range and the relative importance of both parameters. When the fluvial sediment transport is also included, a ternary process based classification scheme can be made that distinguishes different coastal forms. The combination of wave forcing, tidal forcing and sediment characteristics has furthermore an influence on the shape of the cross-shore profile which is reflected into several beach states ranging from reflective till dissipative.

