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# Evolution of beach extensions

**Numerical modelling of large scale nourishments using UNIBEST & Delft3D**

**MSc Thesis**

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Gerwin Stam

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**Executive summary**
Recently, nourishments have been carried out on a large scale to counteract the on-going erosion along the Dutch Coast. The main advantage of these large beach extensions is that large stretches of coastline are protected for a long time scale (e.g. 20 years), which decreases the frequency of nourishing significantly. This is not only cost effective, but also positive for preserving local ecology. In this research two types of large scale nourishments can be distinguished: The *'permanent type'* which is applied locally and has the form of a land reclamation which needs to be maintained in time (Hondsbossche Sea Defence). The other one being the *'temporary type'*, which is expected to diffuse along the coast in order to strengthen a larger stretch of coastline (Sand Motor).
One of the most challenging issues in the design of large scale nourishments is estimating the erosion rates in time and consequently the lifespan of such nourishments. This is relevant because it can lead to a more efficient design or provides more control over maintenance. The problem definition reads: *"Currently it is not known how the erosion rates of large scale nourishments are related to their size, shape and sediment characteristics"*. The final research goal is *to develop design graphs for the erosion rates and lifespans of beach extensions at the Dutch coast*.

For this research use has been made of two numerical models; the equilibrium based UNIBEST model and the process based Delft3D model. Various nourishments are implemented in both models in which variations are made in the *seaward extent* (=width of nourishment), *L/W ratio* and the *net annual alongshore transport* (indicates the wave climate' intensity in this research). Both models are validated by using measurements at the Sand Motor.

The main conclusion of this research is that the wave-induced alongshore transport is considered the most important driving force for the diffusion of nourishments. Tidal forcing does also play a role but the effect on the alongshore transport is a factor 10 less compared to the sediment transports for waves and tide combined. This conclusion is reinforced by the large resemblance between the model results of Delft3D (wave + tidal forcing) and UNIBEST (tide only). From using UNIBEST in combination with a time series wave climate (2 years) applied at the Sand Motor, it can be concluded that the sediment loss at large scale nourishments is event driven (i.e. storm events) just as can be observed in reality. The time series wave climate provides a near perfect fit of model results on measurement with respect to volume decrease in time.
This research shows that the dynamic boundary within UNIBEST has a very large effect on the alongshore sediment transports. The dynamic boundary defines which part of the coast rotates in the same way as the coastline and can therefore have a significant effect of refraction. By using the Delft3D offshore wave climate while keeping the dynamic boundary close to shore, similar results can be obtained with UNIBEST as with Delft3D. Because of the presence of a dynamic boundary UNIBEST can be considered a more advanced coastline model.
Furthermore, it can be concluded that when the alongshore length is increased, the erosion rates in the first years remain approximately the same. Extending a nourishment in alongshore direction simply protects an additional stretch of coast equal to the length of the additional nourishment length itself. The amount of seaward extent appears to have much more influence. The erosion rates rapidly increase when the nourishment is extended further into sea. With the UNIBEST results the half-life (amount of time it takes for the nourishment to reduce to 50% of its initial volume) is compared to the initial volume of each nourishment. The relation seems to be very linear in which each L/W ratio shows a different slope. Figure 4.6 shows the design graph for the temporary nourishments (focus on lifespan). Figure 4.7 & Figure 4.8 (UNIBEST) and Figure 5.9 & Figure 5.10 (Delft3D) show the design graphs for the permanent nourishments (focus on maintenance).

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# Evolution of beach extensions

*Numerical modelling of large scale nourishments using UNIBEST & Delft3D*

By Gerwin Stam

This thesis is submitted in partial fulfilment of the requirements for the degree of

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in the field of

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**Graduation committee:**

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Cover picture: Aerial photo of the Sand Motor taken on 20 March 2012, roughly 8 months after construction (Rijkswaterstaat & Joop van Houdt, 2012)

# Preface

This master thesis can be considered the conclusion of my education at the Faculty of Civil Engineering & Geosciences at the Delft University of Technology. Within this study I followed the Hydraulic Engineering masters in which I chose the track Coastal Engineering because of my great interest in the highly dynamic coastal zone with all its processes involved such as the sheer force of breaking waves during storms.

With this thesis I hope to add some valuable knowledge to the field of coastal engineering and to obtain a better understanding of the many processes involved regarding large scale nourishments. In my opinion, the latter is a truly unique solution for strengthening the coast and maintaining safety levels in man's constant battle with sea. It is the perfect example of building *with* nature; realising hydraulic infrastructure in cooperation with nature & ecology rather than destroying part of nature to replace it with an artificial structure.

I completed this thesis at Deltares, an independent research & knowledge institute in the field of water, subsurface terrain and infrastructure. At Deltares I was provided with all the tools and necessities to fulfil this thesis, for which I am very grateful.

First of all, I would like to thank my supervisors at Deltares, Pieter Koen Tonnon and Bas Huisman, with whom I had many meetings and discussions about this thesis. They were the ones who helped me set up the numerical models and the ones who were always available for questions. Without their help and expertise this thesis would not have been fulfilled. I would also like to thank the other members of my graduation committee, chairman Marcel Stive, Arjen Luijendijk and Gerben de Boer, who were present at the progress meetings in which we had valuable discussions which in turn lead to a better understanding of the problem and new input to continue this research. I would also like to thank Leo van Rijn, who was involved during the early stages of this research and took the time to give valuable new input during the meetings we had. His expertise on the field of sediment transport was of tremendous help. Furthermore, I owe my gratitude to Jan Kramer who took the time for helping me out with the UNIBEST time series feature.

Second, many thanks go out to my fellow students at Deltares, who were of great help when struggling on various kinds of problems (mostly Matlab related) and with whom I had many lunch- and coffee breaks during my time at Deltares.

Finally I would like to thank my parents and family for believing in me and supporting me throughout my entire study. Without their help and (financial) support I would not have been able to complete this study. A special thanks goes out to Lisa for all the happy moments we share, for always being there for me and for her love throughout my entire study.

Gerbert Nico (Gerwin) Stam

Delft, August 2014

## Summary

Because of the on-going erosion along the Dutch coast, sand is nourished regularly to maintain the coastline position and safety levels. Since the year 2000, a volume of 12 million $m^3$ of sand is supplied artificially every year. In the past, these nourishments have been carried out with relatively small volumes only, which automatically implies that multiple nourishments on various locations along the Dutch coast are needed to counteract this on-going erosion. Recently, nourishments have been carried out on a larger scale (Sand Motor, Hondsbossche Sea Defence) that beside safety also serve natural and recreational functions. The main advantage of these large beach extensions is that large stretches of coastline are protected for a long timescale (e.g. 20 years), which decreases the frequency of nourishing significantly. This is not only cost effective, but it is also positive for preserving local ecology. Besides, this method is considered future-proof; additional sand can always be added to maintain safety levels, while this is much more difficult for a hard sea defence. Within this research a distinction is made between two types of large scale nourishments:

1. Permanent type: This nourishment is applied locally and has the form of a land reclamation which needs to be maintained in time (Hondsbossche Sea Defence).
2. Temporary type: This nourishment is expected to diffuse along the coast in order to strengthen a larger stretch of coast (Sand Motor).

It is expected that these two types of large scale nourishments will be applied more often in the near future. However, one of the most challenging issues in the design of large scale beach extensions is estimating the erosion rates in time and consequently the lifespan of a beach extension. A more exact prediction of the erosion rates and lifespan is relevant because it can lead to a more efficient design of beach extensions or can give more control over maintenance. Considering the above, the problem definition can be formulated as:

*Currently, it is not known how the erosion rates of large scale nourishment are related to their size, shape and sediment characteristics.*

The final research goal of this study is *to develop design graphs for the erosion rates and lifespans of beach extensions at the Dutch coast*. With these design graphs it should be relatively easy to make first approximations of lifespans and maintenance volumes when designing a nourishment.

In order to fulfil the research goal and to give an answer to the problem definition, various nourishments are implemented in two numerical models: the process based Delft3D model and the equilibrium based UNIBEST model. Variations are made in the seaward extent (= width of nourishment, *333m, 667m, 1000m*), L/W ratio (in which the alongshore length varies, *1:2.5, 1:5, 1:10*) and the net annual alongshore transport (in this research an indicator for the intensity of the wave climate, *100 000 – 400 000 $m^3$/year*). Both coastline models are set up to represent a large stretch of the Dutch coastline in order to provide a wide applicability of the desired design graphs. Both models are using the 'TRANSPOR 2004' sediment transport formulations and are calibrated on a net annual alongshore transport of 200 000 $m^3$/year (*grain size D50* = 200 μm) after which the transports are manually scaled to lower & higher values. To check the validity of both models, the Sand Motor nourishment is implemented and the model outcome is subsequently compared to measurements. It turns out that both models perform well on predicting morphological changes on a long timescale which provides enough confidence for using both models for simulating the artificial nourishments.

The main conclusion of this research is that waves are considered the most important factor for the redistribution of sand. Breaking waves stir up the sediment, which is then transported by the wave-induced alongshore current. Tidal forcing does also play a role but the effect on the alongshore sediment transport is a factor 10 smaller compared to the forcing of waves and tide combined. This conclusion is reinforced by the very large resemblance between the model results for Delft3D (waves + tidal forcing) and UNIBEST (wave forcing only). These similar results are a bit unexpected due to the fact that both models are based on a different concept; Delft3D is process based in which the sediment transports follow from all underlying processes involved in the coastal zone (e.g. current velocities and sediment concentrations) while UNIBEST is based on an equilibrium approach for calculating the sediment transports and coastline position. The resemblance between both models enhances the idea that the alongshore sediment transport is by far the most important driving force for the diffusion of nourishments along the Dutch coast. From using UNIBEST in combination with a time series wave climate it can be concluded that the sediment loss at large scale nourishments is event driven (i.e. storms with high waves) just as can be observed in reality. When applying a 3-hour interval time series for 2 years at the Sand Motor, a near perfect fit of model results can be found on measurements with respect to volume decay in time.
However, this research shows that the location of the dynamic boundary (located at a certain depth and corresponding cross-distance from the coastline) has a very large effect on alongshore transports. The dynamic boundary is incorporated in UNIBEST only and defines which part of the coast rotates in the same way as the coastline. This parameter can have a significant effect on refraction. Locating the dynamic boundary close to shore (at an approximate depth of 6m) shows equivalent results compared to Delft3D. However, locating the dynamic boundary further offshore results in an underestimation of transports and therefore an underestimation of the diffusiveness of nourishments. This approach is used in the more traditional 1D line models, for instance LONGMOR. Therefore UNIBEST can be considered a more advanced 1D line model because of the presence of a dynamic boundary.

Although the alongshore sediment transports are very equivalent for Delft3D and UNIBEST, an anomaly can be found at the straight middle section of the nourishment for which substantial higher alongshore sediment transports are being calculated by Delft3D (≈ 50% more). It turns out that these higher transports are caused by the steeper cross-shore nourishment profile solely (1:50 vs. 1:110) and that this effect can also be observed in UNIBEST when implementing a steeper cross-shore nourishment profile. It was expected that tidal contraction (increase of flow velocity around the nourishment) also increases the sediment transports, but this is not observed in the model results. In fact, the velocities due to the tide only are slightly higher, but the effect is only noticed near the edges of the nourishment. At the straight middle section of a nourishment the same current velocities are observed as at the adjacent stretch of coast.

Initially it was intended to vary the grain size D50 in this research instead of the net annual alongshore transport. However, it appears that the grain size D50 has a small effect on the alongshore transports and therefore has minor influence on the diffusivity of large scale nourishments. When the grain size is doubled from 200 μm to 400 μm, the alongshore sediment transport reduces with 19% only (from 200 780 $m^3$/year to 163 630 $m^3$/year respectively). The effect on nourishment performance is even less; diffusivity of nourishments is only 3 – 6 % slower with a grain size of 400 μm. It can therefore be concluded that within the range D50 = 200 – 400 μm, the grain size has little to no effect on the diffusivity of nourishments.

This research uses different width-to-length ratios to vary the shape of nourishments. It can be concluded that when the alongshore length is increased, the erosion rates in the first years remain approximately the same. Extending a nourishment in alongshore direction simply protects an additional stretch of coast equal to the length of the additional nourishment length itself. Only at longer timescales the extra volume of the extended nourishment can make a substantial difference due to the fact that the gradients in coastline sustain longer in time.
The amount of seaward extent appears to be much more important. The erosion rates rapidly increase when the nourishment is extended further into sea. The effect is strongly dependent on the magnitude of the alongshore transport; for larger alongshore transports the effect is much more noticeable than for smaller alongshore transports.
With the UNIBEST results the half-life (amount of time it takes for the nourishment to reduce to 50% of its initial volume) is compared to the initial volume of each nourishment. The relation seems to be very linear in which each L/W ratio shows a different slope. Figure 4.6 shows the design graph for the temporary nourishments (lifespan). Figure 4.7 & Figure 4.8 (UNIBEST) and Figure 5.9 & Figure 5.10 (Delft3D) show the design graphs for the permanent nourishments (maintenance).

Various recommendations follow from this research, the most important ones being:

- The outcome of this research is only valid for the Dutch coast because of the wave climate which has been used. It is recommend to apply other (foreign) wave climates, for instance with larger equilibrium wave angles.
- All nourishments in this research are using nourishment edges with a width/length ratio of 1:2. During this research it is thought that these initial edges are very important for the rate of diffusion, especially in the first years when the coastline orientation has not changed much. It is recommended to do a sensitivity analysis with various ratios which can be applied on one nourishment in order to quantify this effect on the erosion rates.
- Although alongshore sediment transport seems to be the dominant factor for nourishment performance, cross-shore process might be important during storm events (e.g. infragravity waves). It is therefore recommend to quantify the effect of the cross-shore processes during storms on the performance of nourishments.
- The active height parameter in UNIBEST turns out to be a sensitive parameter for the calculation of nourishment volumes. Currently a rule of thumb is used which does not incorporate the timescale for which one is interested.

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# 1 Introduction

Because of the on-going erosion along the Dutch coast, sand is nourished regularly to maintain the coastline position and safety levels (Mulder, Hommes, & Horstman, 2011). Since the year 2000, a volume of 12 million $m^3$ of sand is supplied artificially every year (Stronkhorst, Mulder, De Ronde, Huisman, & Sprengers, 2012). Current plans are to increase this depositing volume in relation with the amount of sea level rise (de Ronde, 2008). In the past, these nourishments have been carried out with relatively small volumes and as a consequence of this, the effects are mainly local. This automatically implies that multiple nourishments on different locations along the Dutch coast are needed to counteract this on-going erosion.

However, recently large beach extensions have been carried out near Ter Heijde (Sand Motor), Noordwijk and Petten that besides safety also serve natural and recreational functions. The main advantage of these large beach extensions is that large stretches of coastline are protected for a long timescale (e.g. 20 years). In this way, the frequency of nourishing decreases significantly. This is not only cost effective, but it is also positive for preserving local ecology. Besides, this method is considered future-proof; additional sand can always be added to maintain safety levels, while this is much more difficult for a hard sea defence. These large scale nourishments are also proposed by the 'Deltacommissie 2008' because of their 'great social benefit' for the Netherlands (Staatscommissie voor Duurzame Kustontwikkeling, 2008).

A distinction can be made between two different purposes for large scale nourishments:

1. Large scale nourishments can be applied to maintain safety levels on a local scale. In this case the nourishment must be preserved as long as possible, so in fact the nourishment can be seen as a permanent land reclamation. An example of this kind of nourishment is the one near Petten, which will be constructed during the year 2014.
2. Large scale nourishments can also be applied for maintaining safety on a larger stretch of coastline. In this case, it is expected for the nourishment to diffuse along the coast in order to strengthen a large stretch of coastline in a natural way while preserving local ecology. The Sand Motor is the most suited example for this case. During the lifespan of these types of nourishments, the sand will gradually spread along the Dutch coast to fulfil the coastal demand for sediment.

In the first case, the focus will be on making better estimations for the erosion rates in relation to the nourishment characteristics (e.g. shape, size). This will result in better predictions regarding maintenance. In the second case, the focus will be on making better estimations for the lifespan of such nourishments in order to give more control over safety levels in time.
Although erosion rates and volumes are coupled to each other, it is very important to keep in mind which purpose the nourishment serves.

It is expected that these two types of large scale nourishments will be applied more often in the near future, both in the Netherlands and worldwide. However, one of the most challenging issues in the design of large scale beach extensions is estimating the erosion rates in time and consequently the lifespan of a beach extension. A more exact prediction of the erosion rates and lifespan is relevant because it can lead to a more efficient design of beach extensions or can give more control over maintenance. It can also lead to a more reliable long term planning with respect to safety, nature and recreation.

## 1.1 Problem definition

Considering the introduction, the problem definition can be formulated as:

*"Currently, it is not known how the erosion rates of large scale nourishments are related to their size, shape and sediment characteristics."*

## 1.2 Research goal & research questions

The focus of this research will be on the relation between the erosion rate and the characteristics of large scale nourishments. These characteristics are for instance size, shape and grain size. The primary research goal of this study is to develop design graphs for the erosion rates and lifespans of beach extensions at the Dutch coast.
Furthermore, it is expected that there will be a critical seaward extent for which the nourishment itself starts to influence the external forcing. This external forcing is in turn responsible for the morphological changes of the nourishment. If the nourishment becomes big enough, then:

- Contraction of tidal forcing is likely to occur which results in increased flow velocities and hence larger sediment transport capacities.
- The depth contours of the nourishment will influence the propagating waves from offshore to nearshore. Due to this refraction, different incoming wave angles are to be found in close proximity of the nourishment.

It is likely that the effects described above have an influence on the erosion rates of nourishments. Secondary goal of this research is to investigate if the erosion rates are influenced by the dimensions of the nourishment itself. If this appears to be the case, the effects will tried to be quantified.

The research questions of this study are:

- How does the erosion rate of nourishments depend on their size, shape and grain size?
- At what seaward extent are the erosion rates of large scale nourishments influenced by the dimensions of the nourishment itself?

Typical sub questions for this research question are:

- What are typical shapes of large scale nourishments?
- What parameters influence the redistribution of sand?
- How is the diffusion of sediment influenced by the volume?
- How is the diffusion of sediment influenced by the shape?
- How is the diffusion of sediment influenced by the grain size?

## 1.3 Approach

The approach for answering the research questions is formulated in the MSc Thesis Proposal, which is preceding this document. For convenience it is presented again. Slight adaptations have been made to some parts based on new opinions and understanding. The overall research can be divided in four major parts.

### 1.3.1 Part 1: Literature study + data analysis of existing beach extension

In order to get a better understanding of the important processes that occur near large scale nourishments, a literature study will be performed. Appendix A of this research provides some global background information on subjects as coastal hydrodynamics, sediment transport, cross-shore transports and alongshore transports, which is originating from the MSc Thesis Proposal. The first part of this research will be a continuation of this background information where data and findings of an existing large scale nourishment will be investigated. For this research the Sand Motor is chosen, because of the large amount of high quality data available, such as measured volumes in time and the morphological development. The data analysis might also concern other nourishments, depending on the amount of available data.

### 1.3.2 Part 2: Model set-up

To answer the research question and to systematically analyse the different nourishments, use will be made of numerical models. For this research, both the UNIBEST (CL+ & LT modules) and Delft3D modelling suites will be used. First, a simple model will be created with UNIBEST. For more information about this model, see chapter 3.1 and appendix B.1. This model is easy to set-up and will give quick results about the diffusivity of nourishment, which is valuable for the more detailed process-based Delft3D model. The UNIBEST model will incorporate wave forcing only to examine the effects on morphological behaviour of waves only. Second, the Delft3D modelling suite will be used to get more detailed results.

Because this study will focus on long term events (timescale of decades), computation time plays an important role in modelling such events with Delft3D. Therefore an idealized morphological model will be created, which still has a strong resemblance with the Dutch coast. In this idealized model, a rectangular grid and alongshore uniform equilibrium beach profile will be used to restrict computation time. Furthermore, a simple but representative wave and tidal climate will be applied. For instance 10 wave conditions can be applied together with the most important tidal constituents for the Dutch coast: M2 and M4 (and possibly O2). In this way, representative gross and net longshore sediment transports can be found. The next step is implementing a reference nourishment, for instance the Sand Motor, into the model and track the morphology and behaviour in time. In this way the model can be validated after which the artificial nourishment can be implemented.

### 1.3.3 Part 3: Simulating large scale nourishments

The third part of this study consists of implementing nourishments with different sizes, volumes and shapes into the model and carrying out long term simulations (approximately 5 – 10 years for Delft3D and substantial longer periods for UNIBEST). By implementing each nourishment into the same model, a solid comparison can be made between different nourishments. Erosion rates at specific points of the nourishment will be extracted from the model and presented in graphs. Table 1.1 shows the main parameters which will be varied in this research; the *seaward extent* (= width of nourishment), the *L/W ratio* and the *net annual alongshore transport Qs*. The length and volume are indirectly varied by this approach.

*Table 1.1 – Parameters and corresponding values which will be varied in the model*

| Seaward extent = width |
|---|
| 333 m |
| 667 m |
| 1000 m |

| L/W ratio |
|---|
| 2.5 : 1 |
| 5 : 1 |
| 10 : 1 |

| Alongshore transport Qs |
|---|
| 100 000 $m^3$/year |
| 200 000 $m^3$/year |
| 400 000 $m^3$/year |

Combining these parameters will result in 27 different nourishments and hence 27 simulations (3 * 3 * 3 = 27), which are all listed in Table 1.2. Figure 1.1 shows the top view for the 9 different nourishment dimensions. Note that the length and width do not have the same scale.

The alongshore length is specified at the seaward side of the nourishment. From there, the nourishment will attach to the adjacent coast in a L/W ratio of 2:1.

Initially it was intended to vary the *grain size D50* with values of 200 µm and 400 µm. However, early UNIBEST results showed that there is little difference in the resulting net annual alongshore transport: 200 780 $m^3$/year for 200 µm D50 and 163 630 $m^3$/year for 400 µm D50 (see section 3.1.1 for the wave climate, location close to Noordwijk).
This small difference resulted in very similar nourishment behaviour. Because the proposed design graphs should have a wide applicability, the focus is shifted towards *net annual alongshore transport Qs* instead of *grain size D50*. As stated before, UNIBEST calculates an undisturbed net annual alongshore sediment transport of approximately 200 000 $m^3$/year for the 200 µm grain size. From this result, the alongshore transport is manually scaled by a factor ½ and 2 to obtain values of 100 000 and 400 000 $m^3$/year in order to create more bandwidth for the applicability of the results. Chapter 3 will provide more information on the shift to alongshore sediment transports.

*Table 1.2 – List of different nourishments to be modelled (27 in total)*

| **Alongshore transport Qs(6.5°) = 100k $m^3$/year** | **Alongshore transport Qs(6.5°) = 200k $m^3$/year** | **Alongshore transport Qs(6.5°) = 400k $m^3$/year** | **Seaward extent [m]** | **W/L ratio [-]** | **Along-shore length [m]** |
|---|---|---|---|---|---|
| SIM01 | SIM10 | SIM19 | 333 | 1:2.5 | 833 |
| SIM02 | SIM11 | SIM20 | 333 | 1:5 | 1 665 |
| SIM03 | SIM12 | SIM21 | 333 | 1:10 | 3 330 |
| SIM04 | SIM13 | SIM22 | 667 | 1:2.5 | 1 668 |
| SIM05 | SIM14 | SIM23 | 667 | 1:5 | 3 335 |
| SIM06 | SIM15 | SIM24 | 667 | 1:10 | 6 670 |
| SIM07 | SIM16 | SIM25 | 1000 | 1:2.5 | 2 500 |
| SIM08 | SIM17 | SIM26 | 1000 | 1:5 | 5 000 |
| SIM09 | SIM18 | SIM27 | 1000 | 1:10 | 10 000 |

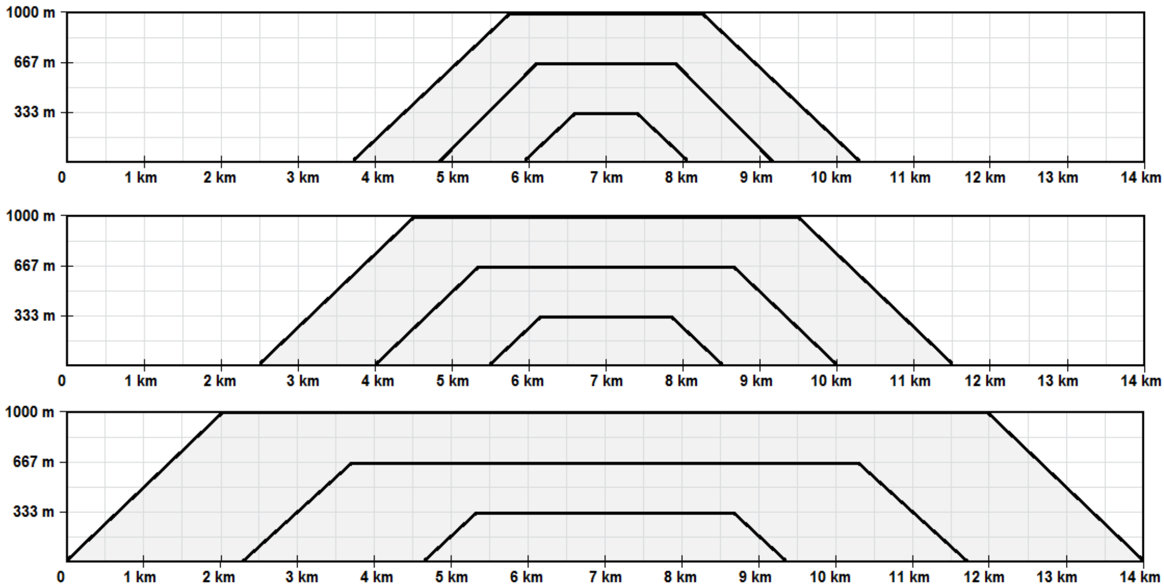



*Figure 1.1 – Top view of nourishment dimensions. Upper plot: 1:2.5; Middle plot: 1:5; Lower plot: 1:10 (note that the x- and y-axis do not have the same scale!)*

Figure 1.2 shows the approximated nourishment volumes for each combination of L/W ratio and seaward extent. These volumes are derived from the Sand Motor case, which has a volume of approximately 20 million $m^3$ of sand and has a seaward extent of 1000 m with a L/W ratio of 2.5:1 (the upper right block). Note that these volumes are an approximation only. The 'real' nourishment volume depends on the cross-shore beach profile and the construction height above the water.

| | 333 m | 667 m | 1000 m |
|---|---|---|---|
| **2.5 : 1** | ≈ 2 million $m^3$ | ≈ 8 million $m^3$ | ≈ 20 million $m^3$ |
| **5 : 1** | ≈ 4 million $m^3$ | ≈ 16 million $m^3$ | ≈ 40 million $m^3$ |
| **10 : 1** | ≈ 8 million $m^3$ | ≈ 32 million $m^3$ | ≈ 80 million $m^3$ |

*Figure 1.2 – Approximated volumes for each combination of L/W ratio and seaward extent*

### 1.3.4 Part 4: Post processing

Delft3D can give various types of data as output, for instance water levels, water depths, depth averaged velocities, settling velocities, bed levels, bed shear stresses and sediment transports. Because the focus of this research is on morphological changes, bed levels and sediment transports are considered of high importance. For instance, the development of bed levels in time will give a good representation of the evolution of a large scale nourishment. This does not mean that the hydrodynamics are of low importance, because these processes are responsible for the morphological changes.

Permanent nourishments: Erosion rates

The first step in processing the data is obtaining the erosion volumes in time for each simulation. This can be done by considering a rectangular box around the nourishment and comparing the volumes at each time step with the initial volume. From this, the eroded volume can be plotted in time. This results in 27 plots, 1 for each simulation (or the results can be grouped together). An example is given in Figure 1.3 and Figure 1.4.

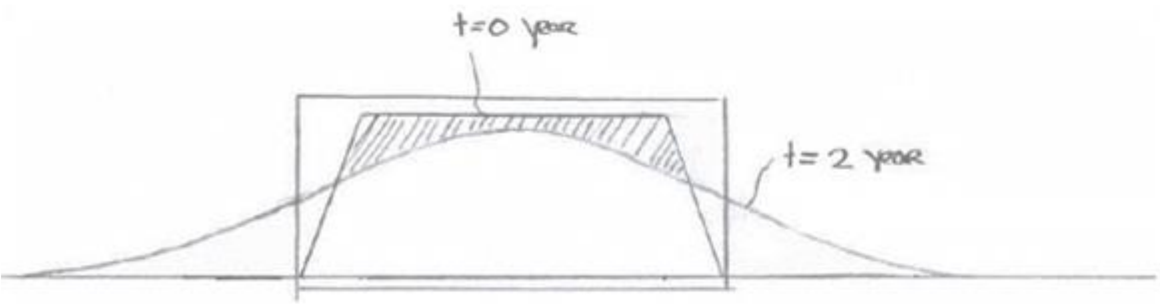



*Figure 1.3 – Rectangular 'control element' for which the eroded volumes can be calculated in each year*

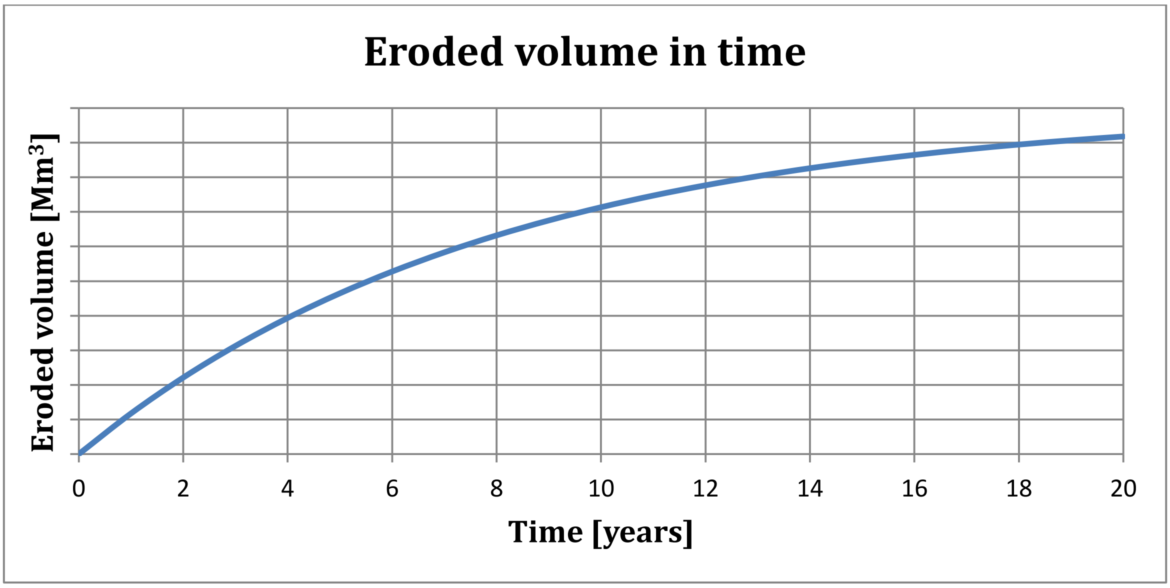



*Figure 1.4 – Conceptual figure of eroded volume in time*

The final goal for this type of nourishments is obtaining graphs such as erosion rates plotted against the seaward extent. In such a graph, sets of lines appear for each alongshore transport. A conceptual figure can be seen Figure 1.5.
This approach is most suited for ‘permanent type’ nourishments, for which the erosion rate is the most important parameter.

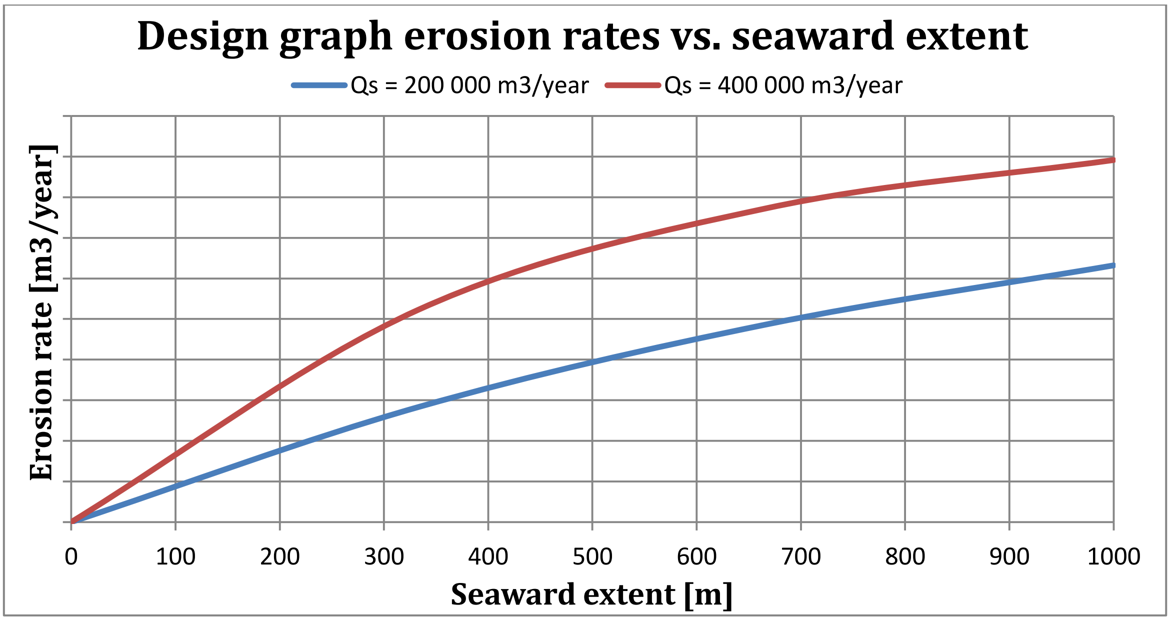



*Figure 1.5 – Conceptual figure of erosion rates plotted against the seaward extent*

Temporary nourishments: Lifespan
In order to link the morphological changes to the lifespan of a nourishment, first a definition of the lifespan must be formulated. This can be done in several ways. For instance, one can consider a rectangular shape around the nourishment and monitor the amount of sand inside this 'control element'. Then, a certain threshold value can arbitrarily be defined, for instance 5% of the total volume. When the volume inside the control element drops below this threshold value (because of the sand redistribution along the coast), it can be assumed that the nourishment has fulfilled its function. In this way, the lifespan is defined as the amount of time it takes for the control element to get from 100% volume to 5% volume. Figure 1.6 shows an illustrative example, in which the lifespan is approximately 17 years.
Another way of defining the lifespan is by making use of the notion half-life. The half-life is defined as the amount of time it takes to reach 50% of the initial nourishment volume. This might be a better way for defining lifespan when large amounts of sediment remain in the lower shoreface and therefore difficulties arise when defining a threshold value.

The sand volume of the nourishment can be obtained by integrating all the longitudinal cross sections on each transect and multiplying these by the width of each grid cell. In this way the volume of the entire profile is known for every output time step. By subtracting the developing profiles in time from the initial profile, the volume of the nourishment at each time step can be found.

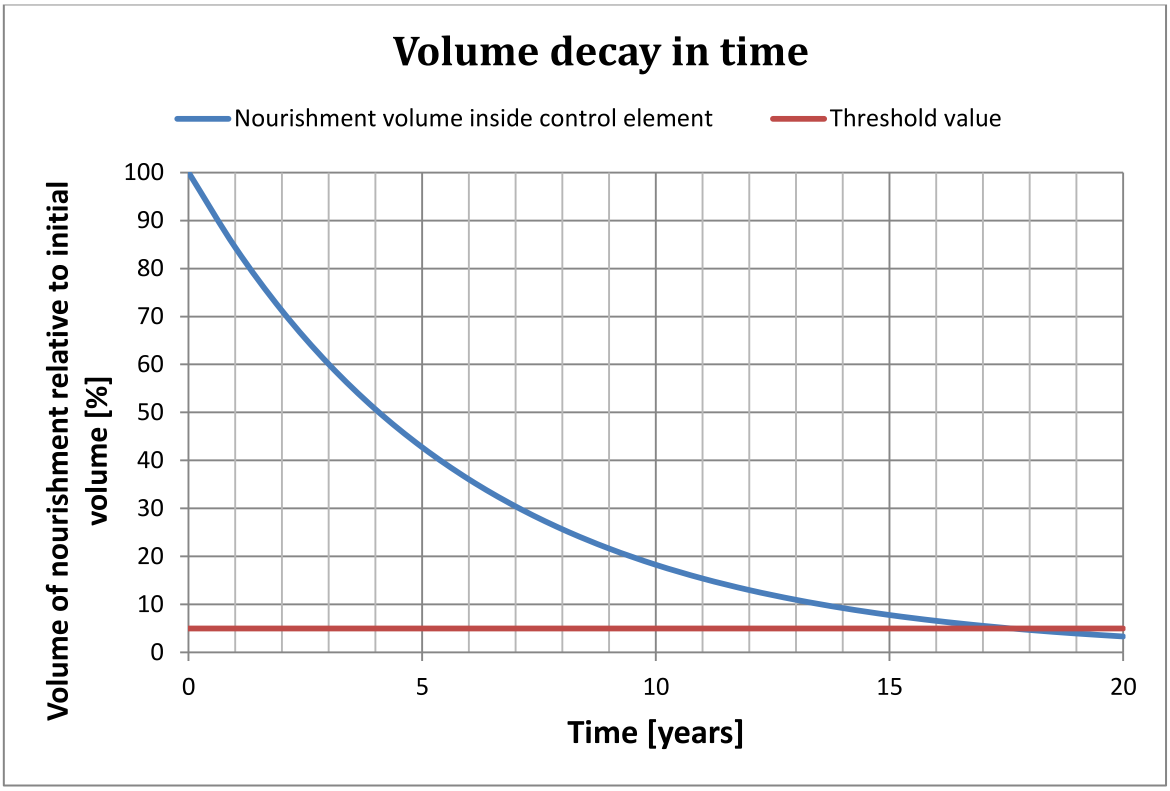



*Figure 1.6 – The lifespan is defined as the time it takes for the volume to drop below a certain threshold value*

## 1.4 Outline of this document

This document will proceed with a literature study in which relevant information originating from various scientific articles, lecture slides and/or course material is presented (chapter 2). In the same chapter a data analysis is carried out for an existing large scale nourishment, the Sand Motor.

Chapter 3 explains the model-set up for both UNIBEST & Delft3D, in which detailed information can be found on various aspects like boundary conditions, implementation of the tide, grid sizes, wave conditions etc. This chapter also treats the calibration and validation of both models.

In chapter 4 and 5, the UNIBEST and Delft3D model results are presented respectively, in which graphs of nourishment volumes in time & eroded volumes in time are presented. These chapters also treat the comparison of nourishments in which the desired design graphs are presented. Chapter 5 will also go into more detail on the subject of alongshore sediment transport.

Chapter 6 provides a comparison between Delft3D & UNIBEST with respect to the Sand Motor and the artificial nourishments of this research. In chapter 7 the design graphs are used for a prediction of the eroded volumes in the first couple of years at a large scale nourishment which is currently under construction, the 'Hondsbossche & Pettemer Sea Defence'.

In chapter 8 a discussion is triggered in which various subjects and choices in this research will be explained and discussed. After the discussion, conclusions will be drawn in chapter 9, in which a distinction will be made between the 'permanent' nourishments (land reclamations) and the 'temporary nourishments'. Chapter 10 deals with the recommendations, which are necessary because this research is not comprehensive and further research is needed on many subjects.

The various appendices are situated at the end of this document.

# 2 Literature study & data analysis

This chapter will give an overview of existing literature related to the subject of this thesis (paragraph 2.1). In paragraph 2.2 an existing nourishment, the Sand Motor, will be analysed.

## 2.1 Review of relevant literature

This paragraph reviews several scientific articles and reports which are relevant for this particular research. First, relevant articles will be given for numerical coastline models and model performance in general. Second, articles related to coastal behaviour and nourishment design are presented.

<u>Numerical coastline models and model performance</u>

- Campbell, Dean, Mehta, and Wang (1989) reviewed available methods for predicting beach-nourishment performance and showed that the time $t_{50\%}$, required for a project to lose 50% of material is approximately:

$$t_{50\%} = K \frac{l^2}{H_b^{5/2}} \qquad (1)$$

  in which $t_{50\%}$ is in years, $K$ is a proportionality factor of 0.172, $l$ is the project length in kilometres and $H_b$ is the height of the breaking waves that mobilize the sediment. It is stressed that the material lost from the project is transported alongshore to adjacent areas and continue to provide benefits there.
  Various nourishments have been modelled in a continued research by Dean and Yoo (1992) using both a simple and a more sophisticated one line model. In the simple model, refraction and shoaling is represented by a one-step procedure whereas the more sophisticated one uses a grid-based solution. Results show that indeed, the longevity of a nourishment is strongly depending on the project length and wave height. It is also stressed that the simple and detailed methods yield very similar results. Limitations to this research are that background erosion, as is present for the Dutch coast, is not taken into account. This can be of considerable magnitude, especially over long time periods.

- Roelvink and Walstra (2004) state that by imposing an alongshore water level gradient on the lateral boundaries of process based coastline models (the so-called Neumann boundary conditions), much of the complexity of setting up such a model is taken away. Most of the time these lateral boundary conditions can be assumed to be zero; only in tidal cases or cases with travelling storm surges along a coast, the alongshore gradient varies in time. But even then, it can be easily calculated. In this way, nesting the model in a regional tidal model is not needed, which is a step in reducing the complexity of applying morphodynamic models in coastal engineering problems.
  The paper also states that applying a 2DH model provides much added value over the use of a (single) line model (e.g. UNIBEST-CL+), because it gives a much better representation of the non-uniform processes around coastal structures.

- Ranasinghe et al. (2011) states that so far no attempts have been made to develop a method for the a priori determination of the highest morphological acceleration factor (MORFAC or simply MF) that is suitable for a given simulation (so called ‘critical MORFAC’ or $MF_{crit}$). At present, the determination of the latter is done by trial and error. This paper presents some initial insights which demonstrate some of the main

dependencies and sensitivities of the MF approach. Their research was undertaken via a strategically designed numerical modelling exercise using the morphodynamic model Delft3D where a 'hump' and 'trench' are simulated with various MF.
Their research indicates that $MF_{crit}$ for a given application will be governed by morphodynamics of bed protrusions (hump) in the domain rather than those of bed depressions (trench). This is intuitively correct because velocities (and therefore sediment transports) will increase over a bed protrusion while they will decrease over a bed depression. The higher velocities and sediment transports will eventually lead to hydrodynamic instabilities in the model. Furthermore, it can be stated that:

- $MF_{crit}$ is strongly dependent on the Froude number *Fr* and the grid size *dx*; $MF_{crit}$ decreases exponentially as *Fr* increases, while it shows linear increase with dx.
- It seems that $MF_{crit}$ is not directly governed by the Courant number (*Cr*)
- $MF_{crit}$ has a dependency on time step *dt* of a second order to that of *Fr* and *dx*.
- A safe first estimate for the $MF_{crit}$ is given by: $\mathrm{CFL_{MF}} = \frac{C_{bed}\mathrm{MF}dt}{dx} < 0.05$

The criterion above is based on few strategic model simulations of a simple case. Therefore, the results and conclusions presented may not be directly applicable to complex real-life situations which incorporate non-uniform forcing and morphology. It is very likely that $MF_{crit}$ in such situations should be considerably smaller.
Furthermore, the paper states that the highest reported MF values used in simulations including wave forcing are limited to about 50. In medium to long term simulations that include extreme wave events, it is wanted to have a time varying MF. Then it is possible to set low MF values for wave conditions during storms, where even the smallest multiplication factors can lead to erroneous results. During calm conditions a considerably higher MF can be chosen because the morphological changes will be minimal in comparison.

- The scientific paper of Walstra, Hoekstra, Tonnon, and Ruessink (2013) introduces a framework for input reduction for long-term morphodynamic simulations in wave-dominated coastal settings, which is particular relevant for this research. The aim of input reduction is to make accurate reproductions of the morphology with a limited number of forcing conditions. This is mainly done to avoid excessive computation time, which occurs when simulating a full set of conditions. The framework consists of four steps:
  1. Selection of the input reduction period
  2. Selection of the representative wave conditions
  3. Sequencing of the selected conditions
  4. Determine the wave climate duration

  This framework is then applied on two sites; Noordwijk, located in the Netherlands, and Hasaki Oceanographic Research Station in Japan. At these two locations, the influence of input reduction techniques on the wave-driven morphological evolution of nearshore sandbars on the time scale of their quasi-cyclic offshore directed behaviour has been investigated by utilizing the process-based cross-shore model UNIBEST-TC. The performance of this model with reduced wave climate is referenced to a simulation with the actual (full) wave forcing. Because this master thesis research comprises various simulations of nourishments along the Dutch coast, the focus will only be on the Noordwijk case. At Noordwijk, the offshore migration of the sandbars is gradual and not coupled to individual storms.
  The main conclusion is that input reduction can have a major impact on model simulations to such extent that major characteristics of cyclic behaviour of for instance tidal sandbars are no longer reproduced. For the Noordwijk case, synthetic series (individual conditions combined randomly in a time series) can yield realistic behaviour, provided that the time span after which the sequence is repeated is not too

large. Furthermore, it can be stated that although episodic events (i.e. storms) result in the largest morphological change, conditions with low wave forcing must be retained to obtain realistic long-term behaviour. It is stressed that because of the potentially huge impact on the actual simulation, it is necessary to consider input reduction as an essential part of model set-up, calibration and validation.

- In the article of Stive et al. (2013), numerical model predictions of the long term evolution of the Sand Motor are described. Furthermore, first conclusions are taken about the effectivity of large scale nourishments like the Sand Motor with respect to coastal protection. Also, light is shed on the effects of the Sand Motor on possible climate change leading to accelerated relative sea level rise (SLR) and increasing river discharges. The conclusion is:

  […] *"Preliminary numerical model results indicate that this nourishment will result in the widening of the beach along an 8 km stretch of the coastline and a beach area gain of 200 ha over a 20-year period. Initial observations show indeed a redistribution of the sand feeding the adjacent coasts, roughly 40% toward the south and 60% toward the north. While the jury is still out on this globally unique intervention, if proven successful, it may well become a global generic solution for combating SLR-driven coastal recession on open coasts." (page 1008).*

- Stive, de Vriend, Nicholls, and Capobianco (1993) describe the first results towards the development of a predictive method for cross-shore spreading of beach and shore nourishments. The cross-shore profile used as the initial profile in their calculations is termed the Dean-Moore-Wiegel profile (DMW-profile). It consists of a Dean profile (equilibrium profile with a grain diameter dependence in the proportionality constant), but near the waterline, a constant slope related to the grain diameter and the exposure of the coast is used, which is first proposed by Wiegel (1964).

$$D = Ax^{2/3} \quad \text{for} \quad \frac{dD}{dx} \leq \tan\beta \tag{2}$$

$$D = D^* - \tan\beta(x^* - x) \quad \text{for} \quad \frac{dD}{dx} > \tan\beta \tag{3}$$

where *D* is the mean still water depth, *x* the cross-shore distance belonging to the Dean profile, tan *β* the beach slope and *A* the proportionality constant. The parameters denoted with an asterisk ($x^*$ and $D^*$) are evaluated at dD/dx = tan *β*. The method described above can be easily applied for the numerical model in this research.

Coastal behaviour and nourishment design

- In his paper about coastal erosion and control, van Rijn (2011) states that coastal erosion is strongly dependent on the type of coast and depends among others on the exposure, wave climate, surge levels, sediment composition and beach slope. When there is substantial erosion over a period of 5 years, it can be argued to nourish the area with a sediment volume equal to the volume loss in this period. This method is considered relatively cheap if the borrow area is not too far away (<10 km). In the article it is also stated that large-scale erosion can be stopped by massive beach and shoreface nourishment over long periods of time (20 years), but this approach is only (economically) feasible if sufficient amounts of sand are available. On the other hand, hard structures like groynes and detached breakwaters require a high capital investment plus continuous costs for maintenance and additional costs of supplementary beach nourishments to counteract local erosion problems. The paper concludes with the statement that the real solution for on-going erosion is either nourishing or building a detached breakwater. The latter is a rather complicated process.

- The paper of van Rijn, Tonnon, and Walstra (2011) focusses on the numerical simulation of erosion of plane sloping beaches by irregular wave attack in three wave flumes of different scales (beach slopes of 1:10, 1:15 and 1:20). Amongst others, Delft3D has been used to simulate the flume experimental results focusing on wave height distribution and morphological development. Beach erosion can be simulated reasonably well using default values for the sand transport parameters. The Delft3D model shows a systematic over-prediction of the erosion of the upper beach which is related to the inaccurate dry-bed procedure applied. Model performance for accretive tests is rather poor, which is mainly caused by the over prediction of the upper beach erosion. The paper states that a practical field application is the erosion of the plane sloping beaches which are formed after the construction of a nourishment. Immediately after the nourishment is in place, the beach profile usually consists of two plane sloping sections: a mild sloping upper beach (slopes between 1:50 and 1:150) and a steep sloping lower beach (slopes between 1:10 and 1:30). The lifetime of these nourished beaches is relatively short at exposed locations.
  Furthermore the paper states that for the Dutch coast a beach nourishment containing fine sand (200 µm) with a volume of the order of 250 $m^3$/m may be easily eroded away in one or two winter seasons. The lifetime will be significantly larger (50%) when relatively coarse material is used (300 or 400 µm). The nourishment is most effective when it is made landward of the inner bar crest. The bar crest can act as a terrace and thereby reducing the incoming wave height.

- Ashton and Murray (2006) showed that for waves approaching under an angle of more than 45° with respect to the coastline, instabilities occur in perturbations of the coastline (e.g. nourishments). Figure 2.1b, derived from the lecture notes of Coastal Dynamics I (Bosboom & Stive, 2012), shows the sediment transport as a function of the relative wave angle (deep water wave angle relative to the shore). For low angles, the transport increases with larger relative angles. The opposite occurs for high-angle waves; the transport decreases for increasing angle.
  Figure 2.1c shows the response of the coastline to low-angle waves. At location 1, 3 and 5 the transport rates are equal. However, going along the coast from 1 to 2 and from 4 to 5, the transport decreases due to the decreasing relative wave angle. This causes erosion at point 3 and hence a flattening of the perturbation (negative feedback).
  For high-angle waves, angles greater than 45° with respect to the shoreline, the opposite effect is found (Figure 2.1d). The decrease in relative wave angle results in

an increase of sediment transport. The bump is slowly being filled up with sediment leading to growth of the initial perturbation (positive feedback).

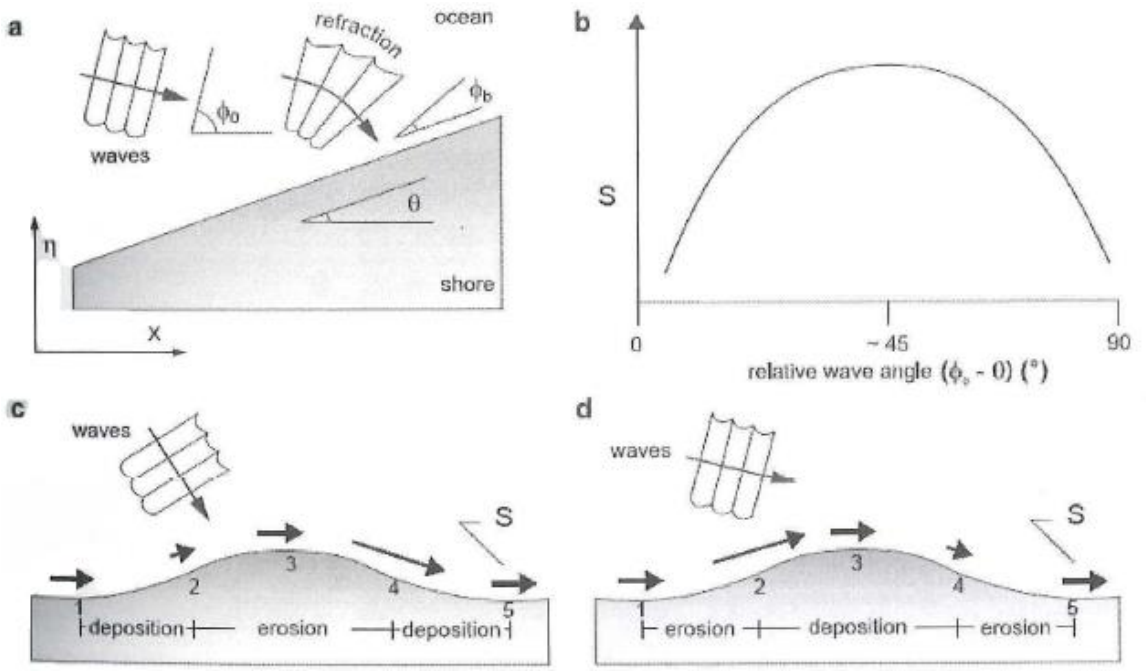



*Figure 2.1 – Response of a perturbation in the shoreline to low-angle waves and high-angle waves*

- In the article 'Modelling shore-normal large-scale coastal evolution' (Niedoroda, Reed, Swift, Arato, & Hoyanagi, 1995), the concepts of a coastal shelf-slope profile in dynamical equilibrium are combined with the sediment supply, hydrodynamic climate and sea level change. A numerical model is presented to predict the evolution of the shelf surface in response to marine sedimentary processes. In order to do so, the profile is seen as an equilibrium response to the variables of sedimentation. The profile will translate landward or seaward when sea level rises or falls respectively. This will occur with the shape of the profile varying according to changes in: the rate of sea level change, the time averaged wave and bottom current conditions, the average sediment supply rate and the sediment grain size distribution.
  Main conclusions are that profile adjustments affect mainly the coefficient of curvature of the profile:
  1. When the rate of sea level rise increases, the profile becomes more straight; it decreases the slope of shoreface but increases the shelf slope.
  2. When the sediment input is increased, the profile curvature is also increased; the shoreface steepens while the shelf floor flattens
  3. A more intense hydraulic climate straightens the profile in a manner similar to an increase in sea level rise rate
  4. An increase in grain size increases the profile curvature in the same way it does when the sediment input is increased.

- In the paper of Grunnet, Ruessink, and Walstra (2005), the influence of tides, wind and waves on the redistribution of nourished sediment is investigated at Terschelling, The Netherlands. A calibrated morphodynamic model of the barrier island of Terschelling is applied to investigate the relative contribution of tides, wind and waves with respect to the cross-shore and alongshore distribution of a 2 $Mm^3$ nourishment.

To do so, several simulations have been carried out to investigate the effect of each individual forcing. The main conclusions are presented below:
Model results show that wave forcing can be considered as the most significant forcing; the stirring and transport by waves and wave-induced currents are by far the dominant contributor to the net sediment transport along the coast. Furthermore, alongshore wind-driven currents increase sediment transport rates. Model results show that tidal forcing is of the least significance. This negligible tidal influence is related to the small tidal currents in front of the island (≈ 0.5 m/s). The paper states that this should not lead to neglecting the tidal forcing in the model; for instance, ignoring the vertical tide will lead to incorrect predictions of the cross-shore evolution of the shoreline. In this research, also the horizontal tide has been included in the simulations in order to enforce a correct direction of the tidal wave propagation, although the transport capacity of the horizontal tide was practically zero. Interestingly, it appears to be unnecessary to include the horizontal tide when tidal currents in the area of interest are too small to mobilise the sediment by themselves. By omitting the horizontal tide, practically identical net bed level changes can be found. As a consequence of this, a simplified approach in model set-up can be achieved by only prescribing vertical tides at the model boundaries.

- In the scientific article about variability of shore and shoreline evolution, Stive et al. (2002) state that if we understand the reasons behind centennial and decadal variability, shore nourishments can be designed in such way that the human interventions are cooperating with the natural processes rather than in conflict with one another. In the end, this could minimise the long-term cost of such human interventions in the coastal system. An example of this argument can be a structural erosion problem along a certain stretch of coastline. If it is able to attribute a significant part of this erosion to an adjacent tidal basin, it may be a better option to consider the sediment sharing system and nourish at a more effective location (in this example at the ebb-tidal delta to feed the sink more directly). Also, seasonal and annual variability should be taken into account when designing nourishments. The paper states that if the source material of the nourishment does not differ too much from the native material, it is expected that the natural variability remains approximately constant.

## 2.2 Data analysis of reference nourishment

This paragraph will review existing reports of a large scale nourishment, which can be used as reference. For this research, the Sand Motor nourishment has been chosen. There are two reasons for this choice. Within this research a very similar nourishment as the Sand Motor is simulated, so this data analysis will yield valuable insight and validation for these simulations. Furthermore, the Sand Motor is studied and monitored by Deltares. Therefore much information about various aspects of the Sand Motor is at hand. Below, various data and findings are discussed regarding the Sand Motor nourishment.

### 2.2.1 Wave data

Within the report ‘T0-rapportage Monitoring en Evaluatie pilot Zandmotor’, the wave climate is studied close to the Sand Motor. This wave climate is considered representative for the ‘Delflandse Kust’. Quantifying the wave climate is of high importance because waves are considered the dominant process for sediment transport. A distinction has been made between a long term wave climate (1990 – 2010) and a short term wave climate (2010). The long term climate is considered as a mean wave climate and the short term climate is considered for constructing the nourishment. The wave data is originating from the IJmuiden monitoring station and the Europlatform monitoring station in the period from 1979 to 2010. Then, these offshore wave parameters ($H_{m0}$, $T_{m02}$) are transformed to a location close to the Sand Motor using a wave transformation matrix and by using SWAN simulations. For more information see Tonnon and Baptist (2011). Table 2.1 shows the near shore wave statistics for both the long term and short term.

*Table 2.1 – Near shore wave statistics for the short and long term (Tonnon & Baptist, 2011)*

| Near shore wave statistics | Short term (2010) | Long term (1990 – 2010) |
|---|---|---|
| Mean $H_{m0}$ | 0.95m | 0.97m |
| Mean $T_{m02}$ | 5.6sec | 5.6sec |
| Mean wave direction | 305° | 297° |
| $H_{m0}$ > 1m | 37.1% | 38.8% |
| $H_{m0}$ > 2m | 6.0% | 6.1% |
| $H_{m0}$ > 3m | 0.3% | 0.9% |
| $H_{m0}$ > 4m | 0.0% | 0.1% |

The mean wave climate over a period of 20 years is characterized by a dominant SW direction. For the short term period, the directions are scattered in the directions SW and NW.

### 2.2.2 Sediment composition

In the T0-report, research has been carried out on the sediment composition near the Sand Motor. The Dutch coastal system is characterized by a non-uniform sandy coast and shows variability on the beaches and the shallow foreshore. This variability is due to the wave climate, the wind climate, the tide, the coastal profile and the origin of the sand. The sand near the Delflandse Kust is mainly originating from the river Rijn. However, the sediment composition is since 1990 influenced by nourishing, in which sand is used from offshore regions. This section will present the conclusions of different studies on sediment analysis at the location of the Sand Motor and neighbouring areas, for more information see Wijsman and Verduin (2011) and Medusa (2010). A distinction can be made between sediment on the beach and sediment in the surfzone/shallow foreshore.

<u>Beach sediment characteristics</u>

According to sediment sampling in late 2010 by Wijsman and Verduin, the sediment on the beach near the location of the Sand Motor can be characterised as medium to fine sand. For the entire area, the mean D50 is found to be **344 µm**. According to the Medusa survey carried out in November 2010, lower D50 values are expected. In their research, the D50 is calculated using the correlation between measured 40-Potassium values. The mean D50 on the beach near the Sand Motor is found to be in the range of **260 – 285 µm**.

<u>Surfzone and shallow foreshore</u>

Also in the shallow foreshore, the sediment can be characterised as medium to fine sand. For the entire area, the mean D50 is found to be **253 µm**. According to the Medusa survey, values of **300 µm** are to be found.

The results above clearly illustrate that there is a lot of variation between the two surveys. This is probably due to the different measuring techniques that have been used. The medusa survey uses the correlation between measured values of heavy metals to calculate the D50. It is possible that this method is not suitable for a disturbed sediment system which is the case for nourishments.

Furthermore, in the paper of Huisman, Sirks, van der Valk, and Walstra (2014), research has been carried out on the time and spatial variability of sediment grading near the Sand Motor. They present the results of four field surveys (Table 2.2), in which sediment samples are taken along various transects near the Sand Motor and are subsequently analysed by using the dry or wet sieve method. The T1 survey is carried out during the final stages of construction. The main conclusion is that significant coarsening of sediment (20 to 30 %) took place at the exposed part of the Sand Motor.

*Table 2.2 – Overview of average sediment properties for the considered measurement surveys*

| | D10 [µm] | D30 [µm] | D50 [µm] | D60 [µm] | D90 [µm] | Std [-] | Skew [-] |
|---|---|---|---|---|---|---|---|
| T0 (oct 2010) | 125 | 185 | 232 | 275 | 469 | 0.73 | -0.07 |
| **T1 (jun 2011)** | **151** | **204** | **278** | **309** | **482** | **0.64** | **0.06** |
| T2 (aug 2012) | 166 | 240 | 301 | 360 | 591 | 0.70 | 0.01 |
| T3 (feb 2013) | 157 | 218 | 268 | 295 | 459 | 0.61 | -0.03 |

### 2.2.3 Morphological developments

Between the moment of completion of the Sand Motor (August 2011) and July 2013, 18 surveys have been carried out by the company Shore Monitoring & Research. Each survey consists of detailed bathymetry measurements on fixed lines along the coast (in Dutch: jarkusraaien). In between those lines of measurements, data has been interpolated to acquire bathymetry maps with full coverage. The surveys are carried out by using jet skis, 4WD quads and manual GPS measurements. Twelve surveys have been carried out in the first year and six surveys have been carried out in the second year.

By using these detailed bathymetry maps of the Sand Motor, the morphological changes (both shape and volume) have been analysed in these first two years. The results and findings are mainly retrieved from the report ‘Morfologische ontwikkeling van de Zandmotor pilot in de eerste 2 jaar na aanleg’ (Shore Monitoring & Research, 2013). Figure 2.3 shows the bathymetries right after completion of the Sand Motor and after 2 years (survey 1 vs. 18).

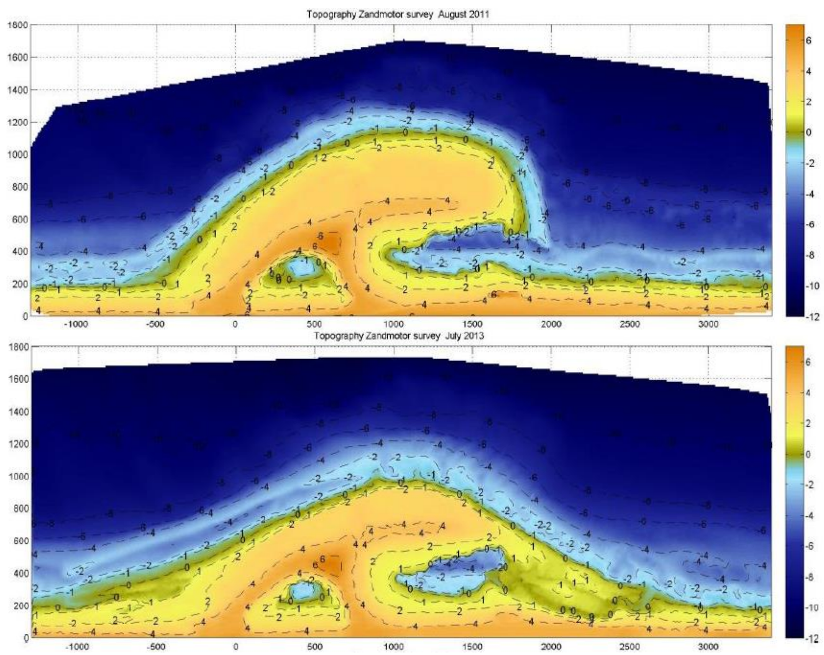



*Figure 2.2 – Survey 1: Bathymetry Sand Motor August 2011 (upper) & Survey 18: Bathymetry Sand Motor July 2013 (lower). (Shore Monitoring & Research, 2013)*

Changes in volume

An extensive analysis of both bathymetries shows that in the first two years a total volume of 2.04 $Mm^3$ has disappeared from the initial area, which is defined by the red polygon in Figure 2.3. This is approximately 12.5% of the initial volume in this area (16.35 $Mm^3$). More than half of this loss (1.23 $Mm^3$) is occurring in the first six months after completion of the nourishment. In total, 1.65 $Mm^3$ is redistributed towards the South and the North, indicated by the magenta and blue polygon in Figure 2.3. Approximately 60% of the total sedimentation is found in area North and 40% is found in area South. In the entire area, the overall sediment loss is 0.39 $Mm^3$ over a period of 2 year. It is assumed that this sediment is mainly redistributed towards the dune area and adjacent to the measured areas.

Table 2.3 shows the measured volumes in all three areas after 1, 6, 12 and 24 months after completion. Table 2.4 shows the volume *changes* compared to the initial survey.

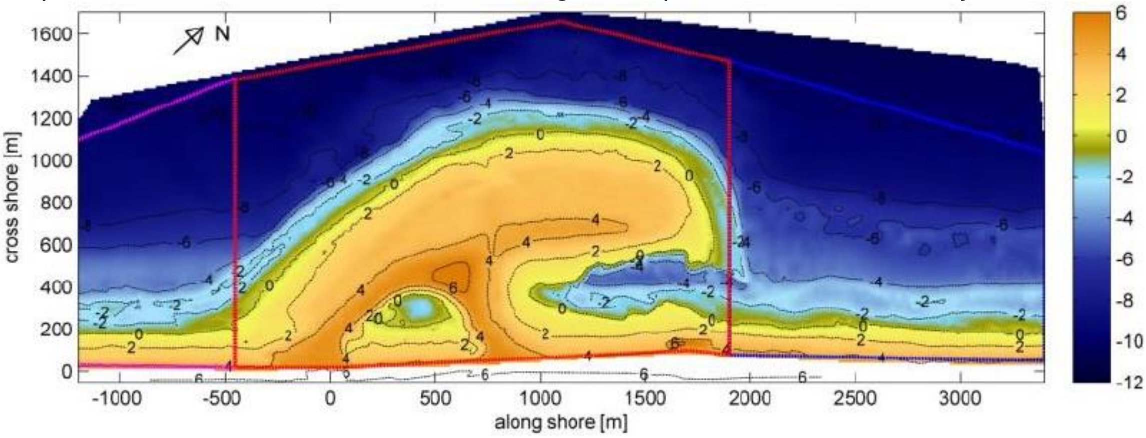



*Figure 2.3 – Areas for which the volume calculations are carried out (red, blue and magenta polygons). (Shore Monitoring & Research, 2013)*

*Table 2.3 – Measured volumes for all three areas. The right column shows the sum of the previous three*

| **Survey** | **Sand Motor peninsula (red polygon) [$Mm^3$]** | **Area South (magenta polygon) [$Mm^3$]** | **Area North (blue polygon) [$Mm^3$]** | **Total survey area [$Mm^3$]** |
|---|---|---|---|---|
| #1: August 2011 After 1 month | 16.35 | 0.01 | 0.73 | 17.09 |
| #6: January 2012 After 6 months | 15.12 | 0.34 | 1.21 | 16.67 |
| #12: July 2012 After 1 year | 14.81 | 0.45 | 1.41 | 16.67 |
| #18: July 2013 After 2 year | 14.31 | 0.63 | 1.79 | 16.74 |

*Table 2.4 – Changes in volume compared to survey 1*

| **Survey** | **Sand Motor peninsula (red polygon) [$Mm^3$]** | **Area South (magenta polygon) [$Mm^3$]** | **Area North (blue polygon) [$Mm^3$]** | **Total survey area [$Mm^3$]** |
|---|---|---|---|---|
| #6: January 2012 After 6 months | -1.23 ≈ 7.5% | +0.33 | +0.43 | -0.46 |
| #12: July 2012 After 1 year | -1.54 ≈ 9.4% | +0.45 | +0.62 | -0.47 |
| #18: July 2013 After 2 year | -2.04 ≈ 12.5% | +0.64 | +1.01 | -0.39 |

<u>Changes in shape</u>

Figure 2.4 shows the changes in shape between the post construction survey and the July 2013 survey (2 years in between). A redistribution of sand can be observed, in which the alongshore length scale is increased and the cross-shore length scale is reduced. The shape in each survey is acquired by following the location of the 0 m NAP contour.

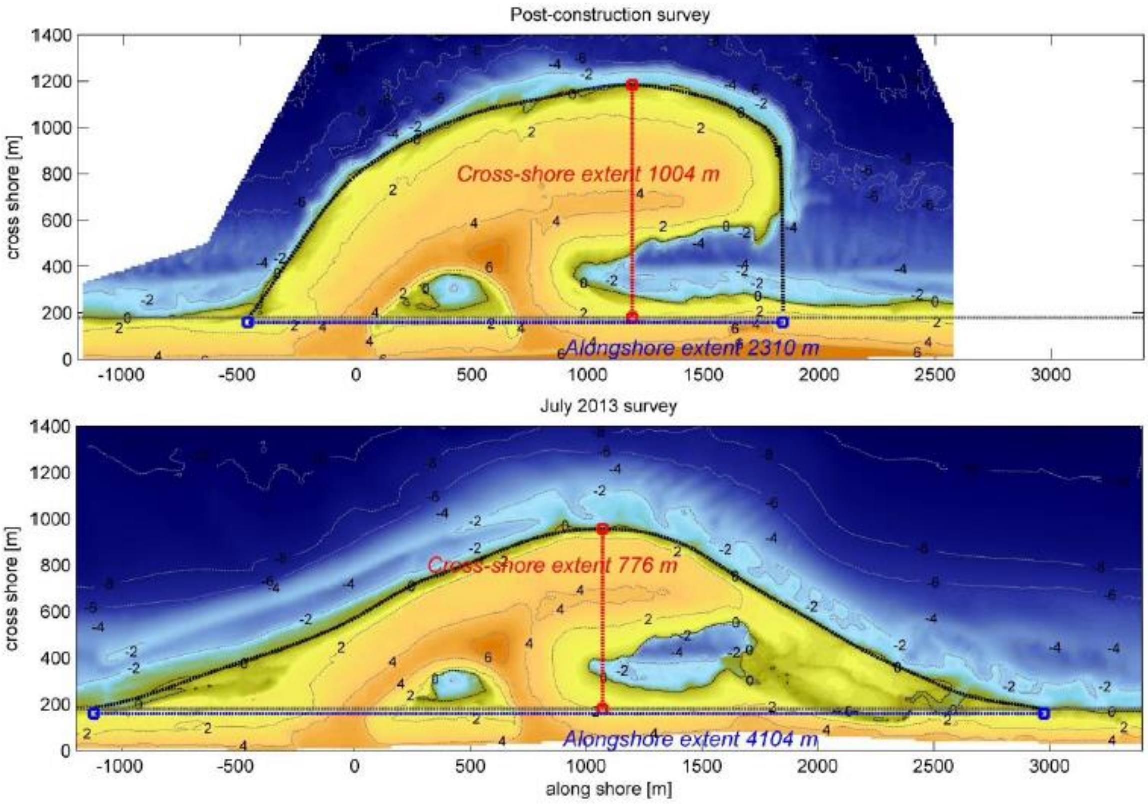



*Figure 2.4 – Contour lines of the Sand Motor: post-construction (upper figure) and after two years (lower figure). (Shore Monitoring & Research, 2013)*

Table 2.5 shows the values for the cross-shore extent and alongshore extent along with their ratio. Note that the first and last rows represent the situations presented in Figure 2.4. Moreover, a clear difference can be observed between the post construction survey carried out by the building contractor and the first survey carried out by Shore Monitoring & Research, even though there is just one month in between.

*Table 2.5 – Cross-shore extent and alongshore extent for different surveys*

| **Survey** | **Cross-shore extent [m]** | **Alongshore extent [m]** | **Cross-shore / Alongshore ratio [-]** |
|---|---|---|---|
| Post construction survey | 1004 | 2310 | 1 : 2.30 |
| #1: August 2011 After 1 month | 957 | 2365 | 1 : 2.47 |
| #12: July 2012 After 1 year | 836 | 3823 | 1 : 4.57 |
| #18: July 2013 After 2 year | 776 | 4104 | 1 : 5.29 |

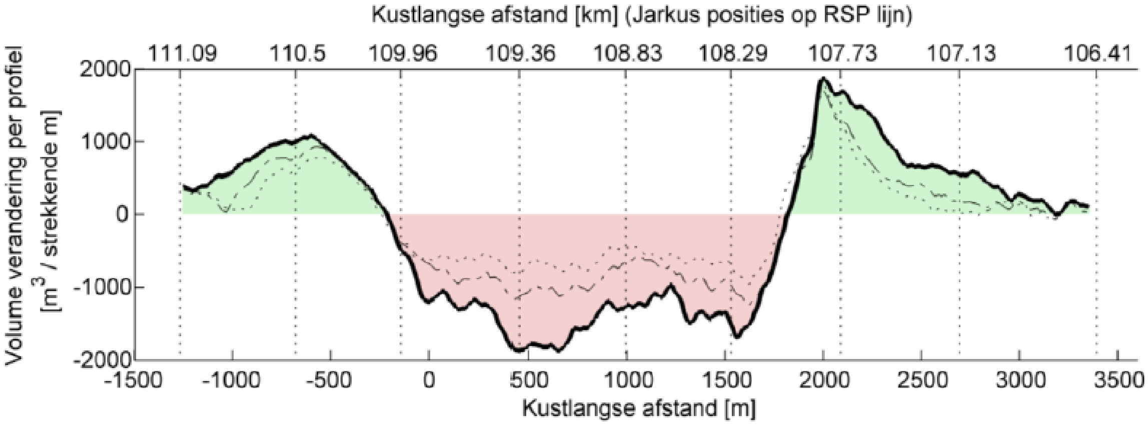



*Figure 2.5 – Changes in volume plotted against the alongshore stretch of coastline: the dotted line represent the situation after 6 months, the dash-dot line the situation after 1 year and the solid line after 2 years. Red = erosion; green = accretion. (Shore Monitoring & Research, 2013)*

Figure 2.5 displays the redistribution of sand by showing the changes in volume per running meter. In order to do so, the volumes of sand have been determined between the +4 m NAP profile and the -10 m NAP profile. The figure shows that in the first six months the accretion reaches an area of 800 meter towards the North (right part of Figure 2.5). Toward the South, the accretion stretches out a part of 600 meters in the first half year. The next six months (January – July 2012) show a pattern which is hardly changing, possibly due to the mild weather conditions in this period. The next 12 months (July 2012 – July 2013) show a similar pattern as observed in the first six months of the Sand Motors existence.

Table 2.6 shows the dates of every survey combined with the average wave conditions in the preceding period. High waves are defined as a daily average wave height of $H_s$ > 2.5 m.

*Table 2.6 – Survey dates and corresponding wave climate in the intermediate periods (Shore Monitoring & Research, 2013)*

| **Survey** | **Survey dates** | **Average wave conditions in the previous period at the offshore location Europlatform** |
|---|---|---|
| #1 | 2011: August 1,2 and 3 | $H_S$= 1.35 m, 2 days of high waves (with respect to July fifth) |
| #2 | 2011: September 1, 2 and 3 | $H_S$= 1.04 m, 0 days of high waves |
| #3 | 2011: October 13,14 and 16 | $H_S$= 1.38 m, 6 days of high waves, 1 storm day |
| #4 | 2011: November 10, 11 and 12 | $H_S$= 1.15 m, 0 days of high waves |
| #5 | 2011: Dec. 26, 27, 28 and 31 | $H_S$= 1.79 m, 11 days of high waves |
| #6 | 2012: January 15, 16 and 17 | $H_S$= 2.19 m, 7 days of high waves, 2 storm days |
| #7 | 2012: Feb. 26, 28, 29, March 1 | $H_S$= 1.34 m, 3 days of high waves |
| #8 | 2012: March 22, 23 and 24 | $H_S$= 0.69 m, 0 days of high waves |
| #9 | 2012: April 30, May 1, 2 and 3 | $H_S$= 1.10 m, 0 days of high waves |
| #10 | 2012: May 26, 27, 28 and 30 | $H_S$= 1.07 m, 0 days of high waves |
| #11 | 2012: June 19, 20 and 21 | $H_S$= 1.09 m, 2 days of high waves |
| #12 | 2012: July 24, 25, 26 and 27 | $H_S$= 1.11 m, 1 days of high waves |
| #13 | 2012: August 20, 21, 22 and 24 | $H_S$= 0.70 m, 0 days of high waves |
| #14 | 2012: October 9, 10 and 11 | $H_S$= 1.31 m, 1 days of high waves |
| #15 | 2012: December 17, 18 and 19 | $H_S$= 1.52 m, 4 days of high waves |
| #16 | 2013: Feb. 26, 27, 28, March 1 | $H_S$= 1.47 m, 7 days of high waves, 1 storm day |
| #17 | 2013: April 25, 26 and 28 | $H_S$= 1.24 m, 1 days of high waves |
| #18 | 2013: July 1, 2 and 4 | $H_S$= 1.11 m, 0 days of high waves |

### 2.2.4 Extrapolation of volume decay in time

At the moment of writing, measured data is available for the period July 2011 – December 2013, approximately 2.5 years. For the extrapolation of volume decay in time, measured volumes of the Sand Motor Peninsula (red polygon in Figure 2.3) are used. This red polygon is placed tightly around both sides of the Sand Motor, so any redistribution of sand will result in sediment loss for this area. Through the scattered data, two exponential curves have been fitted, both with the following characteristics:

$$y = ae^{bx} + ce^{dx} \quad (4)$$

The 'exponential 2' curve fit consists of the sum of two single exponential functions. This provides a substantial better fit in the first two years when compared to a single exponential fit. In the first years the morphological changes are quite large due to initial adaptations and spit formation. It is however expected that on the long term the 'exponential 2' fit underestimates the volume decay in time. It might be that a single exponential fit provides better results on the long term.

At the start of December 2013, a complete survey has been carried out by Shore Monitoring & Research. Days after this, on December 5th, a severe storm swept over the Netherlands. Right after this storm, another survey has been carried out to see the results of one single storm. Nearly <u>280 000 m$^3$</u> of sand was 'lost' from the Sand Motor peninsula. A considerable amount of this Sand has been brought offshore by high undertow velocities and it is expected that under calm conditions a net cross shore sand transport towards the shore will result in slight sediment gain. Therefore, two fits have been carried out on the data; one with and one without the December storm. Fairly good results can be found for both fits (Figure 2.6).

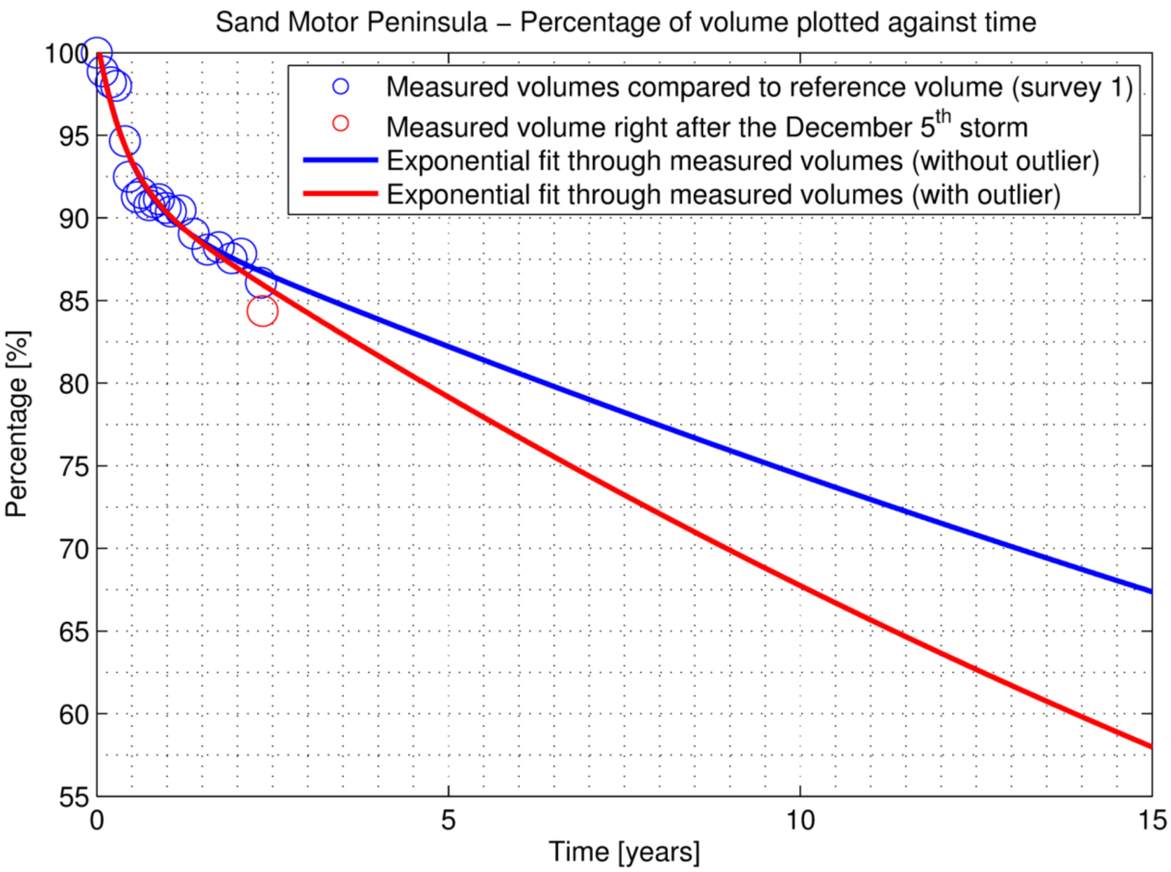



*Figure 2.6 – Extrapolated volume decay in time of Sand Motor Peninsula*

### 2.2.5 Sand Motor development in time

Figure 2.7 shows the different areas of the Sand Motor. In this section, the development of the most important areas will be described (mainly retrieved from Shore Monitoring & Research (2013)).

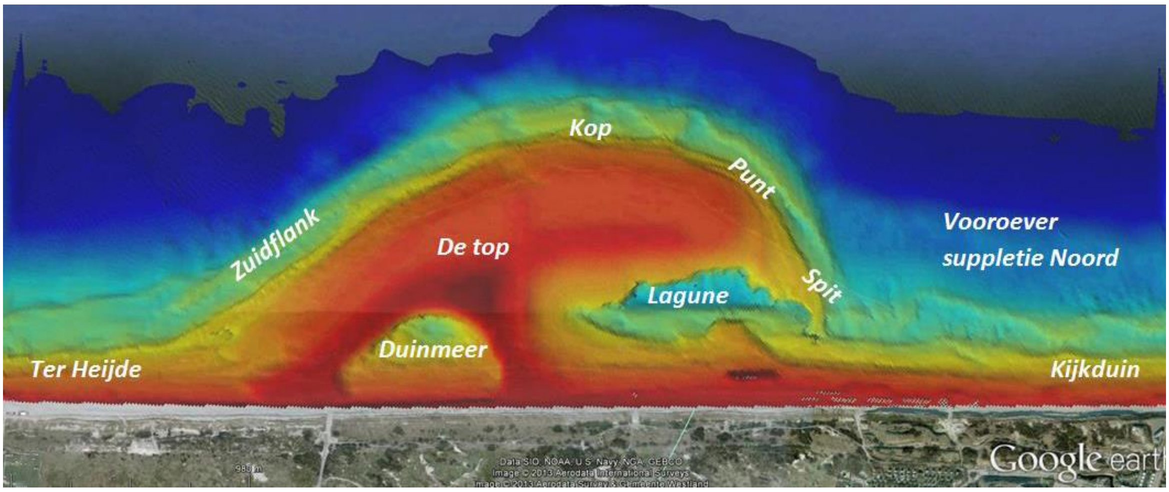



*Figure 2.7 – Names of the different areas at the Sand Motor (Shore Monitoring & Research, 2013)*

*De Spit*

This part of the Sand Motor has not been constructed and the development in time is purely initiated by sediment transport. The development of *de Spit* already started during construction, but the biggest morphological change occurred during winter, in both the first and second year. Every storm in this period resulted in a ‘forward jump’ of *de Spit*. In the last year, de Spit evolved in a sandy intertidal flat with even some vegetation on high ground.

*De Geul*

Simultaneously with the development of *de Spit*, a trench (*de Geul*) was developed. This trench connects the lagoon to the open sea and is initially located parallel to the beach. At first, the trench is narrow, deep and short (600m in December 2011). But when the De Spit is evolving, the trench is becoming longer (1200m in April 2012) and is migrating towards the shore. Besides, during this period the trench is gradually becoming wider and shallower. In April 2012 and December 2012, small trenches originated perpendicular to *de Geul*. They provide an extra connection between the lagoon and the sea. These little trenches are very dynamic and are all migrating in north-eastern direction. A human intervention took place in May 2012, in which a trench was dug between the lagoon and the sea. This has been done in order to close the main trench, in which large currents occurred. These currents were close to the beach and were considered unsafe with respect to swimmer safety. Within two months, the human excavated trench was completely closed off.

*Zuidflank*

Since completion of the Sand motor, the *Zuidflank* has seen much sedimentation; especially in the first year after construction. Also, the local morphology is characterized by sand ridges and trenches, for which some of them are permanently above water level.

*Lagune*

The lagoon is characterized by overall sedimentation. Gradually the entire lagoon will be filled up with sediment. Also at the seaward side sedimentation occurs due to aeolian influences.

## 2.3 Sensitivity of grain size & bed slope on alongshore sediment transport VR04

### Introduction

Previous results in this research show that doubling the sediment grain diameter from 200 µm to 400 µm results in only a slight decrease in alongshore sediment transport (≈ 19%) when using UNIBEST. This appendix will elaborate on the TRANSPOR2004 sand transport formulations (van Rijn, 2007a, 2007b, 2007c) and check whether this small difference can be explained.

As Appendix B section B.2 explains, TRANSPOR2004 takes the following aspects into account: For each wave class, the sand transport rate is determined, based on the computed wave height, depth-averaged cross-shore and longshore velocities, orbital velocities, friction factors and sediment parameters. The net total sediment transport is calculated by the summation of the net bed load ($q_b$) and net suspended load ($q_s$) transport rates, which are both averaged over the wave period. The net suspended load transport consists of two components ($q_s = q_{s,c} + q_{s,w}$); the current-related ($q_{s,c}$) and the wave-related ($q_{s,w}$) transports.

### Grain size effect

In the paper ‘a simple general expression for longshore transport of sand, gravel and shingle’ (van Rijn, 2014b), the CROSMOR model has been used to study the effect of the grain size on the longshore sediment transport by using the TRANSPOR2004 formulations. In this study, the grain diameter (D50) has been varied between 0.2 and 100 mm for one offshore wave condition ($H_{s,o}$ = 3m, $T_p$ = 8s, θ = 30°). The cross-shore profile is made of a plane bed without breaker bars. The CROSMOR-model computes both the bed load and suspended load transport. It can be concluded that suspended load transport is dominant for grain sizes smaller than 1 mm for these given conditions. Van Rijn found that the grain size effect can be represented by a trend line, which shows the following relation:

$$Q_s \propto \left(\frac{1}{d_{50}}\right)^{0.6} \tag{5}$$

According to this formula the alongshore transport **reduces with a factor $(200/400)^{0.6}$ = 0.66** when doubling the grain size, which yields an alongshore transport of 0.66 * 200 780 $m^3$/year = 132 500 $m^3$/year when applied to this research. This is still an underestimation of 19% compared to the calculated value by UNIBEST, which was 163 630 $m^3$/year. Van Rijn states that this effect of grain size is mainly caused by the strong decrease of the suspended load transport for increasing grain sizes in the range of 0.2 – 20 mm. For a 20 mm grain size the suspended load has reduced to almost zero.
However, the decrease in grain size is more noticeable for larger grain sizes since the volume and hence the weight of a grain is proportional with the power 3 to the grain size. Because in this research, only the lower limits of 0.2 mm and 0.4 mm are examined, it is expected that the decrease of suspended load transport is less strong than for instance a grain diameter of 1 to 2 mm. This is also in agreement with the alongshore transport formula of Kamphuis (1991), which found a smaller grain size effect of $Qs \propto (1/D50)^{0.25}$ which yields a factor of $(200/400)^{0.25}$ = 0.84 and a sediment transport of 168 650 $m^3$/year for this research. Kamphuis specifically states that his formula is not valid for grain sizes > 10 mm.

Simulations carried out with Delft3D show that a grain size of 0.4 mm results in alongshore transports of 145 000 $m^3$/year compared to 200 000 $m^3$/year for a grain diameter of 0.2 mm, which is in good agreement with the proportionality factor of 0.66 found by van Rijn. It should be noted that the difference in net annual alongshore transport for Delft3D and UNIBEST might be caused due to a different formulation for the bottom roughness. Delft3D uses a roughness predictor while UNIBEST uses a constant roughness. Because the bottom roughness has an influence on the flow, it can therefore have an effect on the sediment transports.

Overall it can be concluded that in the range from 0.2 mm to 0.4 mm, the **suspended sediment transport is not largely affected by the bigger (and heavier) grain diameter,** which causes a slight reduction in alongshore sediment transports only.

**Bed slope effect**
Van Rijn also analysed the effect of the bed slope on the alongshore sediment transport. In general, a steeper slope yields a smaller surf zone, which would suggest lower sediment transport rates. However, a steeper slope yields also larger wave heights and larger longshore current velocities due to more intense wave breaking. The overall effect is an increase in longshore current velocities and hence an increase in sediment transports.
Again the CROSMOR model has been used to examine three different slopes, representing the following locations:

- Egmond (The Netherlands) with a bed slope of tan β = 0.01 between the water line and the -8 m depth contour and a D50 of 0.2 mm.
- Noordwijk (The Netherlands) with a bed slope of tan β = 0.007 and a D50 of 0.2 mm.
- Duck (Atlantic coast, USA) with a relatively steep slope of tan β = 0.015 and a D50 of 0.2 mm.

Based on all model runs, the bed slope effect can be represented by the following relation:

$$Q_s \propto \left(\tan\beta\right)^{0.4} \qquad (6)$$

Hence, a twice as steep profile leads to an **increase in sediment transport of about 32%.** Note that in this particular research the bed slope is not varied and kept constant for all runs (UNIBEST & Delft3D).

# 3 Model set-up and model calibration/validation

This chapter explains the model set-up and model calibration/validation for both UNIBEST and Delft3D. In here, important input parameters and their corresponding values will be discussed. For a more detailed description of the underlying processes for both models, reference is made to appendix B.

## 3.1 UNIBEST-CL+

### 3.1.1 Model set-up

To implement various kinds of nourishments within the UNIBEST-CL+ model, first a slight adaptation has to be made to the model itself. Generally, the sediment transport will increase with increasing relative wave angle until its maximum is reached for approximately 40 to 45 degrees. For wave angles above these values the transport reduces again. This will give rise to problems near the edges of nourishments, because of the strong local gradient in coastline orientation. Simulating this with the standard UNIBEST-CL+ model will lead to increased transport towards the nourishment and will cause the nourishment to grow instead of to diffuse along the coast (see Ashton and Murray (2006) and chapter 2.1).
The adjustment which has been made in UNIBEST-CL+ can be explained as stated below:

First, for the standard S-φ curve the angle is computed for which maximum sediment transports occurs. This is computed by:

$$\theta_{Qs,\max} = 1 \big/ \sqrt{2C_2} \qquad (7)$$

The sediment transport for situations with relative wave angles larger than the angle of maximum transport is then forced to equal the maximum transport, instead of a decrease. This is illustrated in Figure 3.1. This method will yield more stable calculations for situations where the coastline has a large gradient locally, for instance at nourishment edges.

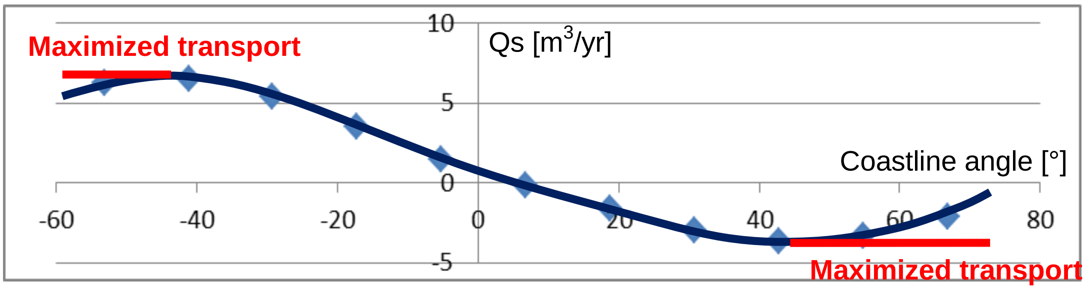



*Figure 3.1 – S-φ curve with forced maximum transports for relative wave angles larger than about 45 degrees*

Each nourishment is implemented in a 180 000 m wide model in which the middle section of 25 000 m contains the area of interest. An example of the biggest nourishment (10 000 m x 1 000 m) can be seen in Figure 3.2. In the area of interest the grid size is set to 50 m.

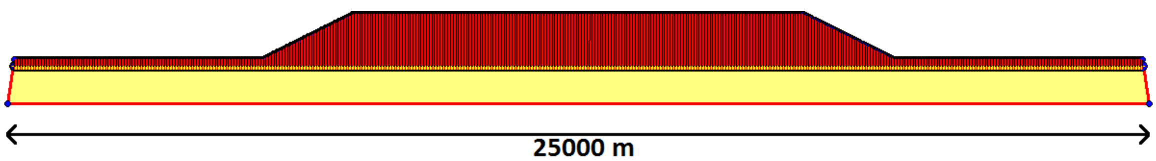



*Figure 3.2 – Top view of the biggest nourishment implemented in the UNIBEST-CL+ model*

Outside this area of interest, the model is extended by four sections on both sides. This is done in order to locate the boundaries as far as possible from the area of interest. Each section consists of a different grid size, in which the largest grid size is set to 800 m near the edges of the model. In this way excessive computation time in areas of little interest are avoided. The schematic layout of the entire model can be seen in Figure 3.3.

| | Sector 1 | Sector 2 | Sector 3 | Sector 4 | Sector 5 | Sector 6 | Sector 7 | Sector 8 | Sector 9 |
|---|---|---|---|---|---|---|---|---|---|
| Length: | 24 km | 28 km | 20 km | 5.5 km | 25 km | 5.5 km | 20 km | 28 km | 24 km |
| Grid size: | 800 m | 400 m | 200 m | 100 m | 50 m | 100 m | 200 m | 400 m | 800 m |


*Figure 3.3 – Model overview which shows the grid sizes in every sector*

Two boundary conditions have been applied; one at each side of the model. The type of boundary condition is for both sides a constant coastline position. In reality the coastline position is not constant at the position of the boundaries, but because of the location far away from the nourishments there is hardly any chance of unwanted boundary effects. Furthermore, if gradients occur near the boundaries, sediment is able to 'leave' the model area which is necessary for the diffusion of nourishments. Near the boundaries, very locally, large gradients can occur which can overestimate the sediment loss. For this reason, the boundaries are located at least 90 km from the area of interest.

The model uses one ray file in the entire model domain. This means that in the entire model one S-φ curve is imposed. The ray file, which contains the S-φ curve, has been computed using the UNIBEST-LT module and is originating from an existing UNIBEST model of the Dutch Coast. The location is chosen close to Noordwijk (Figure 3.4) for which nearshore transformed wave data is available. For comparison between UNIBEST and Delft3D, the cross shore profile is slightly adapted to match the DMW-profile which will also be used for the Delft3D simulations (see chapter 2.1). The cross shore profile can be seen in Figure 3.5.


*Figure 3.4 – Location of wave data (latitude: 52.238°, longitude: 4.411°)*

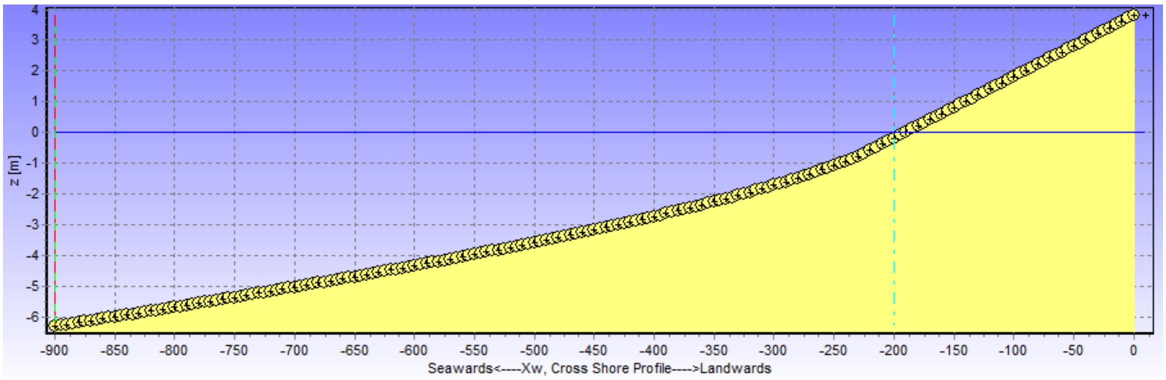



*Figure 3.5 – Cross-shore profile which is used for computing the ray file*

Because there is a difference in coastline orientation for the existing model of the Dutch coast and the schematic model used in this research, the coastline orientation parameter in the ray file has been adapted accordingly, which basically means that the wave climate and corresponding S-φ curve have been rotated.

The applied sediment transport formula is “TRANSPOR2004”. For a comprehensive description and validation of this formula reference is made to the articles “Unified View of Sediment Transport by Currents and Waves” (van Rijn, 2007a, 2007b, 2007c).
The forcing consists of waves only in which one year is schematised in 269 wave conditions with varying significant wave height, wave period, wave angle and duration. The average significant wave height is 1.76m, the minimum 0.25m and the maximum 2.95m. The wave direction ranges from 246.3° – 346.9° and the original shore normal is 298.8°. With the UNIBEST-LT module the mean equilibrium angle has been calculated, which is 6.5°.

The dynamic boundary, which is positioned at a certain depth and corresponding cross-shore distance from the coast, defines which part of the coast rotates in the same way as the coastline. This parameter can have a significant effect on refraction and therefore on the alongshore sediment transport. There is no optimal choice for the dynamic boundary but most of the time it is located at shallow water because refraction is then calculated in a realistic way. For all simulations in this research, the dynamic boundary is located at a depth of 6.3m. This is the same depth at which the wave conditions are imposed.

***Alongshore transports***
As mentioned before, simulations with 200 µm D50 and 400 µm D50 proved to have a small effect on alongshore sediment transport, which yields very similar results regarding nourishment performance. To increase the bandwidth of the model results and hence enlarge the applicability of the results on a variety of coasts, the focus will be shifted from *grain size D50* to *alongshore sediment transport Qs*. Therefore, the net annual alongshore transports are manually scaled to values of 100 000, 200 000 and 400 000 $m^3$/year. The D50 of 200 µm already provides a net alongshore transport of 200 000 $m^3$/year, so to obtain the other transports, the parameter c1 in the ray file has been multiplied with a factor and ½ and 2 respectively (Table 3.1).

*Table 3.1 – Gross and net annual alongshore sediment transports used in the UNIBEST-CL+ model*

| **Gross northward sediment transport [$m^3$/year] ↑** | **Gross southward sediment transport [$m^3$/year] ↓** | **Net sediment transport *Qs* [$m^3$/year] ↑** |
|---|---|---|
| 198 602 | 98 212 | **100 390** |
| 397 204 | 196 424 | **200 780** |
| 794 408 | 392 848 | **401 560** |

The S-φ curves (Figure 3.6) used in the simulations can be constructed with the parameters in the ray file by making use of the formula stated below:

$$Q_s = c_1 \theta_r * \mathrm{e}^{-(c_2 \theta_r)^2} \quad (8)$$

in which:

$Q_s$ = Alongshore sediment transport [$m^3$/year]

$c_1$ = Parameter describing the magnitude of the S-φ curve

$c_2$ = Parameter describing the curviness of the S-φ curve

$\theta_r$ = Absolute equilibrium angle (in °N)

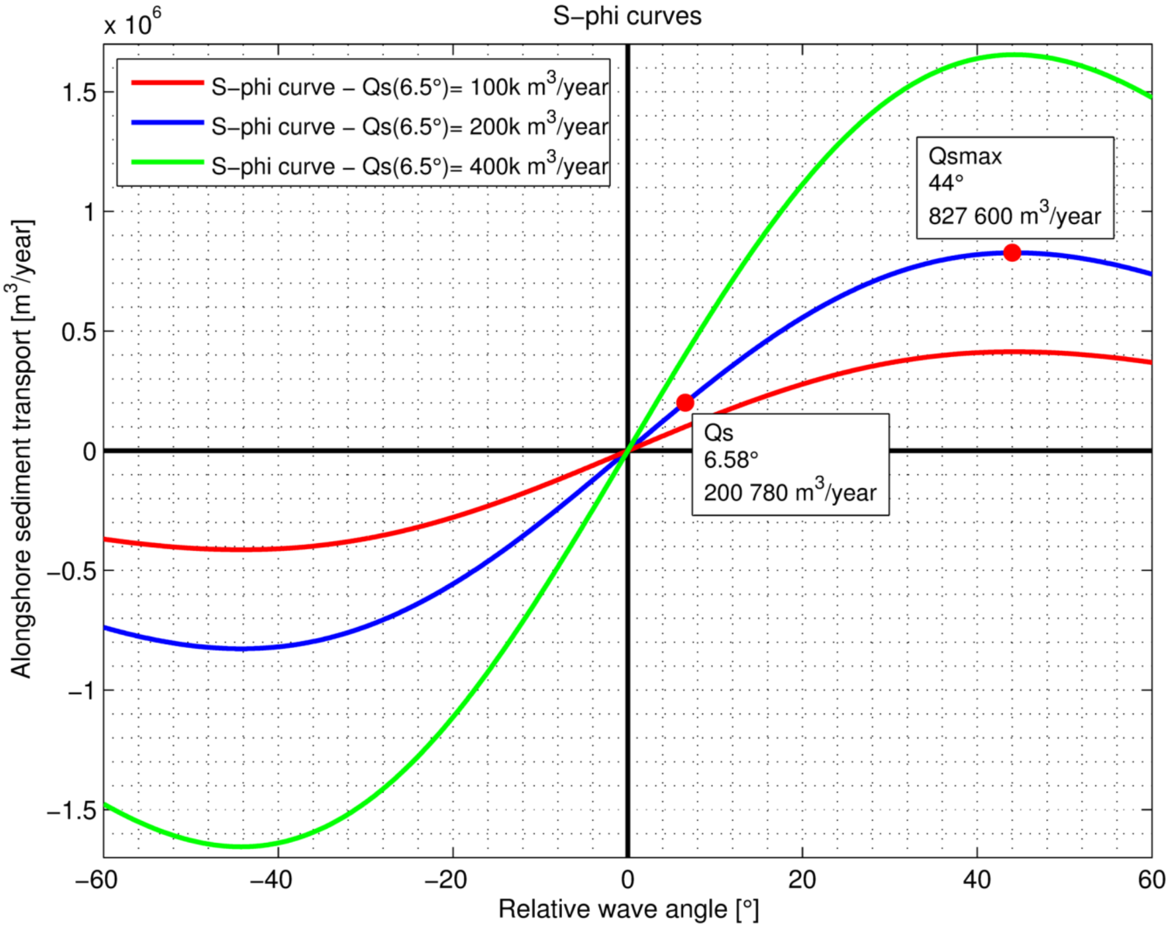



*Figure 3.6 – Three different S-φ curves used in the UNIBEST-CL+ calculations*

***Nourishment volumes***

To acquire nourishment volumes within UNIBEST, the active height needs to be determined. The active height of a coastal profile is defined as the height for which sediment can be mobilized and consequently can be transported in cross-shore and/or alongshore direction. This height is dependent on the coastal profile, the location, the wave climate and the considered timescale. For the Dutch coast with its particular wave climate and when a timescale of around 20 years is considered, a value of **7 meters** is a good estimate for the active height. This value is slightly based on the following rule of thumb: the active height is approximately 2 to 3 times the 1/1 year significant wave height (Deltares, 2011b). For this particular location, the 1/1 year significant wave height equals approximately 2.9m.

It is important to state that the active height needs to be kept constant for all simulations in order to compare the coastline positions in time. Furthermore, this approach implies that sediment below this height is not moving and is therefore not taking part in the diffusion of nourishments.

Then, each nourishment (9 dimensions * 3 different alongshore sediment transports = 27) is implemented in the model and simulated during a period of 200 years. Since the active height is determined, nourishment volumes can be calculated by multiplying the coastline position (in x and y direction) with the active height.

Table 3.2 shows the initial volumes for every nourishment in UNIBEST-CL+. Because the coastline position is calculated in time, the nourishment volumes can also be acquired in time. Results are discussed in chapter 4.

*Table 3.2 – Initial nourishment volumes for the nourishment implementation in UNIBEST-CL+*

| Simulation number [-] | Seaward extent [m] | Alongshore length [m] | Nourishment volume in UNIBEST-CL+ [million m$^3$] |
|---|---|---|---|
| 01, 10, 19 | 333 | 833 | 3.11 |
| 02, 11, 20 | 333 | 1665 | 5.01 |
| 03, 12, 21 | 333 | 3330 | 8.93 |
| 04, 13, 22 | 667 | 1668 | 12.45 |
| 05, 14, 23 | 667 | 3335 | 20.31 |
| 06, 15, 24 | 667 | 6670 | 35.80 |
| 07, 16, 25 | 1000 | 2500 | 28.00 |
| 08, 17, 26 | 1000 | 5000 | 45.50 |
| 09, 18, 27 | 1000 | 10000 | 80.50 |

### 3.1.2 Model calibration & model validation

***Model calibration***

Calibrating the model is not an essential aspect because the ray file is originating from an existing calibrated model of the Dutch coastal system. Only the cross-shore profile has been adapted to match the D3D model, but wave forcing and other parameters remain the same.

***Model validation***

The model can be validated in two different ways. The first one is by comparing the calculated net sediment transports with the observed or measured transport along the Dutch Coast. The model calculates an undisturbed alongshore sediment transport of 200 780 m$^3$/year for the 200 µm grain size. For the 400 µm grain size, a net sediment transport of 163 630 m$^3$/year is calculated. In appendix A.4 it was found that in the central part of the Dutch coast (from Wassenaar to Zandvoort) a net yearly sediment transport of 200 000 m$^3$/year in northward direction is observed. In the paper of van Rijn (1997) about the sediment budget of the central coastal zone of Holland, a similar value of 210 000 m$^3$/year has been observed near Noordwijk. Regarding the alongshore sediment calculations, it t is therefore assumed that the UNIBEST-CL+ results are considered reliable.

A second way to validate the model is by implementing a reference nourishment into the UNIBEST-CL+ model and subsequently compare the model results with measured data. In section 2.2, measurements have been analysed for the Sand Motor nourishment by looking at volume decay in time. For a comparison between the model and these measurements, the initial Sand Motor shape is implemented in the UNIBEST model in the best way possible. However, detailed characteristics such as 'the hook' at the East of the Sand Motor cannot be implemented because of the strong curvature in coastline.
Because the strength of the model should be the wide applicability for the Dutch coast, the model is altered as little as possible. Use has been made of the UNIBEST-CL+ model which calculates a net sediment transport of 200 000 m$^3$/year (200 µm D50), which can be considered a representative value for the central part of the Dutch coast. Only the active height has been changed from 7m to 8.5m in order to match the initial Sand Motor volume and to account for the increased height at which the Sand Motor is constructed.

Results can be seen in Figure 3.7 and Figure 3.8 in which the solid green line represents a *yearly averaged wave climate* and the dotted green line represents a *time series wave climate*. The time series consists of wave observations at a location close to the Sand Motor (lat: 52.06, lon: 4.18) in the period august 2011 – august 2013. Every 3 hours, a measurement is carried out. The time series is then repeated in time. For this case the cross-shore profile is extended to match the water depth of the model boundary with the wave observations (10.3m). The dynamic boundary is kept at a water depth of 6.3m.

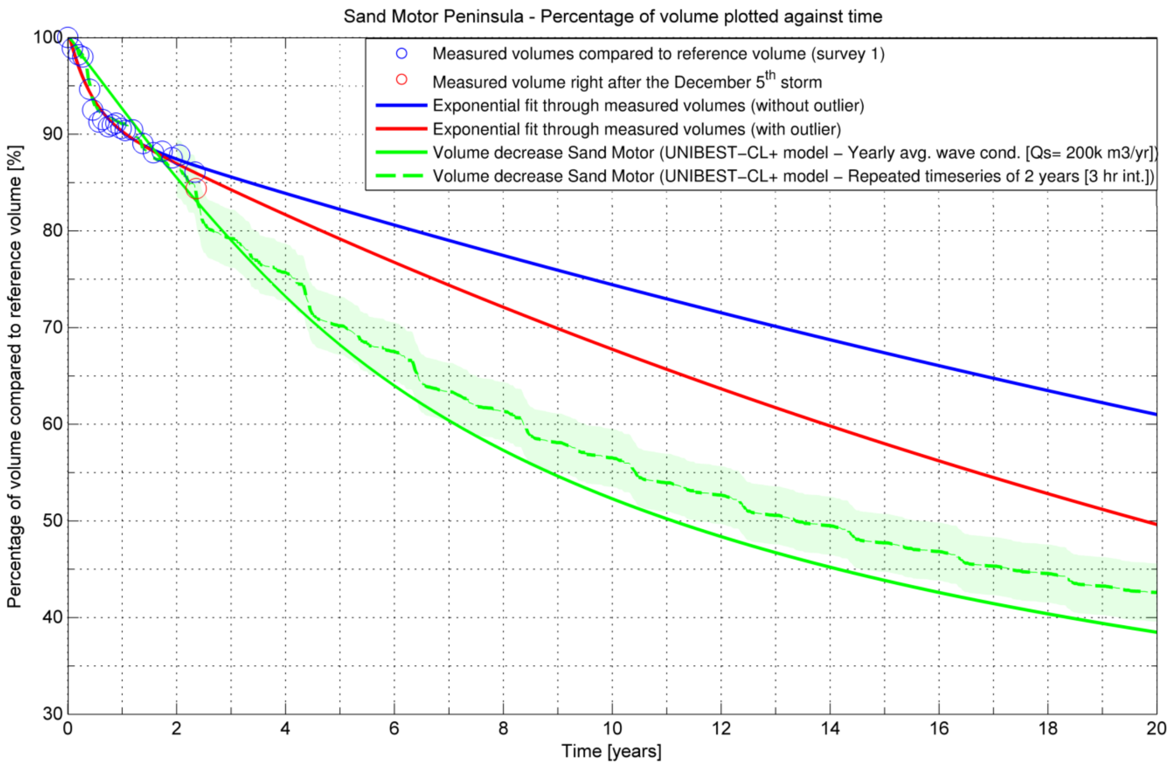



*Figure 3.7 – Volume decay of Sand Motor (green lines are according to UNIBEST-CL+ model)*

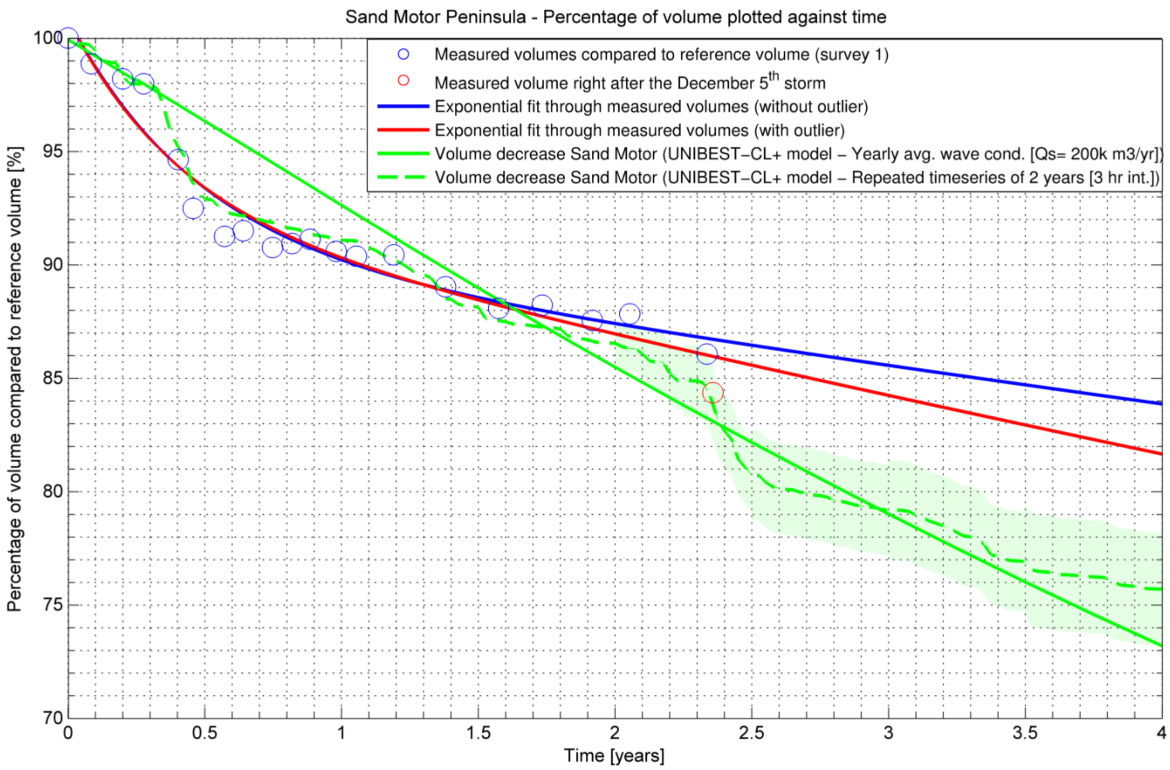



*Figure 3.8 – Close-up of volume decay of Sand Motor (green lines are according to UNIBEST-CL+ model)*

The green coloured band shows the uncertainty of the prediction in a qualitative way. Only the first two years are valid results because they are based on actual measurements. After this time, the time series has been repeated and the uncertainty increases.

When taking into account a timeframe of 20 years, the resemblance between the time series and yearly averaged wave climate is remarkable. Overall it can be concluded that:

- Using a time series results in an exceptional good fit to the measured volumes (blue dots) in the first 2.5 years.
- Volume decrease for the Sand Motor seems to be very dependent on storm events, because all steps in the graph correspond to fairly high wave heights ($H_s$>2m).
- When validating the model, the dynamic boundary turns out to be a very sensitive parameter. The dynamic boundary can be defined as the location (with a certain depth) to which the alongshore transport is being computed. This part is supposed to rotate in the same way as the coastline and hence can have a large effect on refraction. For both the time series wave climate and the yearly averaged wave climate the dynamic boundary is located at a depth of 6.3m. Placing the dynamic boundary further offshore results in a dramatic drop in sediment transport peaks due to the incorrectly calculated effect of refraction.
- Calm wave conditions result in less pronounced behaviour and therefore long periods of calm waves have little influence on the volume of the Sand Motor.
- Both the time series wave climate and the yearly averaged wave climate are assumed to make a solid prediction of the volume decrease in time, while the time series wave climate shows a more detailed representation of events and the yearly averaged wave climate shows the general trend.
- The simulation with a yearly averaged wave climate shows a slight under prediction of volumes in the first 1.5 years, and possibly a slight over prediction for the period after.
- The UNIBEST-CL+ model performs well on the Sand Motor case, therefore the model is considered reliable for use in this research with other large scale nourishments.

Figure 3.9 shows the coastline position after 2 years (green lines) and 20 years (red lines) for both the time series wave climate (dotted lines) and yearly averaged wave climate (solid lines). There is hardly any difference in coastline position which is expected because of the high resemblance in the volume decay graph.

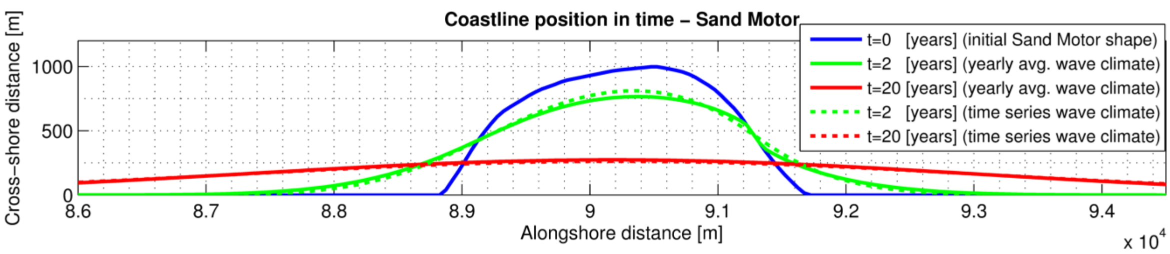



*Figure 3.9 – Coastline position of the Sand Motor implemented in UNIBEST-CL+*

## 3.2 Delft3D

This section will provide an overview of various aspects of the Delft3D model, for instance the grid, bathymetry, boundary conditions, forcing, simulation times and morphological aspects. Furthermore, calibration and validation will be discussed.

### 3.2.1 Model set-up

***Grid & bathymetry***

The Delft3D model makes use of two different grids; a wave grid and a flow grid. The wave grid is slightly bigger in alongshore and cross-shore direction with respect to the flow grid in order to avoid unwanted boundary effects near the edges of the flow grid. Table 3.3 and Figure 3.10 show the grid properties of both grids.

*Table 3.3 – Grid properties for both flow and wave grid*

| Grid type | Alongshore direction [m] | Cross-shore direction [m] | Grid spacing [m] | Number of grid cells [#] |
|---|---|---|---|---|
| *Flow grid* | 24 000 | 3 800 | 20x20 in area of interest. | 152 224 |
| *Wave grid* | 33 000 | 3 900 | 50x50 near the boundaries | 180 288 |


*Figure 3.10 – Top view and dimensions of flow grid (blue) and wave grid (grey)*

The bathymetry consists of an alongshore uniform DMW-profile, which is basically a combination of a Dean profile with a constant slope above the waterline (for this case 1:30, see also section 2.1). Both the initial cross-shore profile and the cross-shore profiles with nourishment implementation can be seen in Figure 3.11. Furthermore, the top view of the bed level for the smallest and biggest nourishment can be seen in Figure 3.12. The seaward extent is measured from the intersection of the DMW-profile and the -2 m contour line. The top level of each nourishment is located at a level of -2 m.

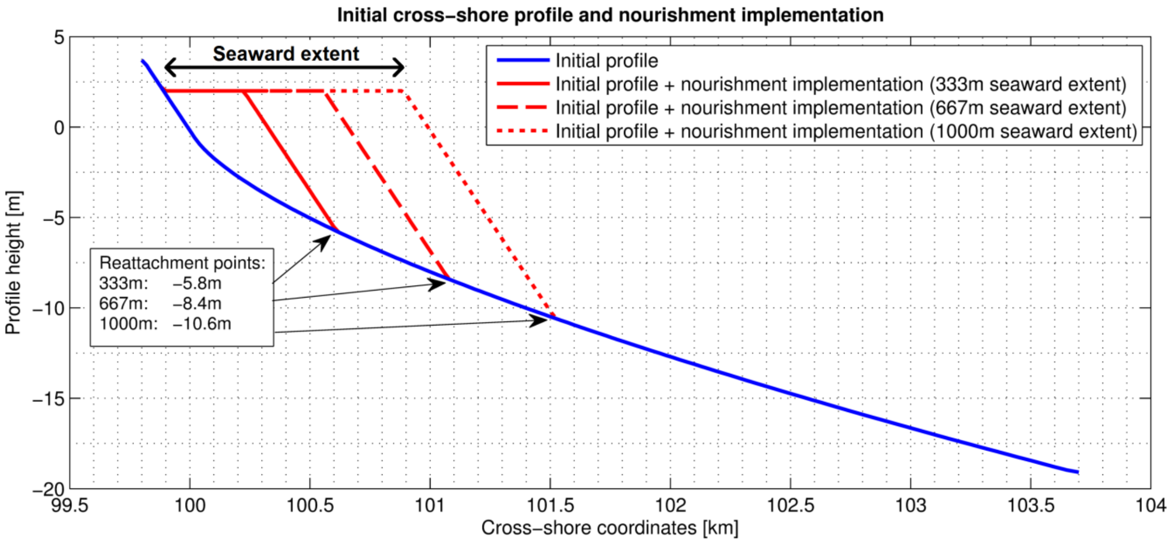



*Figure 3.11 – Initial cross-shore profile and cross-shore profiles for the 333m, 667 and 1000m nourishments*

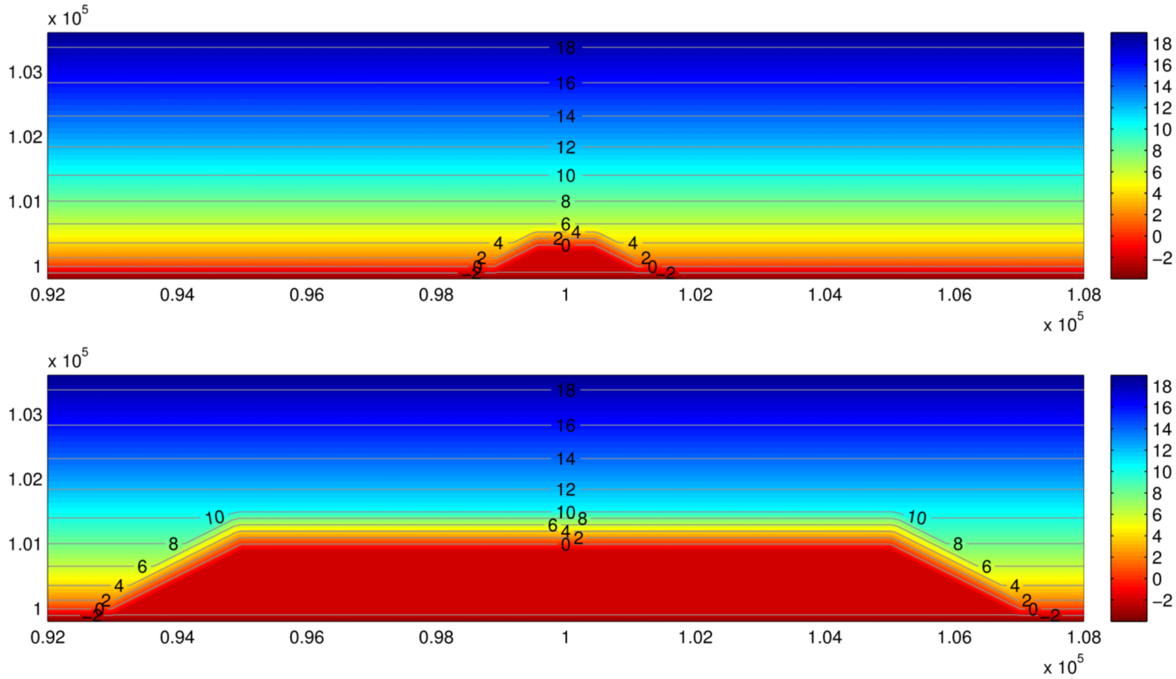



*Figure 3.12 – Top view of bathymetry for smallest (333m x 833m) and largest (1 000m x 10 000m) nourishment*

***Model boundaries & external forcing***

Boundary conditions have to be applied to the three open boundaries that can be found in the model domain, i.e. the western, northern and eastern boundary. At the northern boundary a harmonic water level boundary is applied which imposes the M2 and M4 tidal constituents. Their values are calculated by interpolating water level data from tidal stations of Scheveningen and IJmuiden. Furthermore a phase angle is introduced to account for the delay in water level when the tide propagates along the Dutch Coast in Northern direction. For both the eastern and western boundaries, Neumann boundaries of the harmonic type are used. A Neumann boundary can be described as a water level gradient and has proved to be very useful for lateral boundaries (see section 2.1 and Roelvink and Walstra (2004)). The components and corresponding input can be seen in Table 3.4. It should be stated that the morphological tide is obtained by multiplying the amplitudes of both tidal components with a factor 1.1. This is done in order to account for the spring-neap cycle, which is missing in the hydrodynamic simulation.

*Table 3.4 – Tidal components for the northern boundary (harmonic water level)*

| Tidal component | Frequency [deg/hour] | Tidal period [hour] | Amplitude [m] | Phase Begin [deg] | Phase End [deg] |
|---|---|---|---|---|---|
| M2 | 29.0323 | 12.4 | 0.8 | 0 | 16.84 |
| M4 | 58.0645 | 6.2 | 0.22 | 316.43 | 327.27 |

Besides water level input, wave and wind forcing is imposed on the western, northern and eastern boundaries. The wave and wind conditions are retrieved by analysing a data set of 23 years from a measuring station near Noordwijk consisting of wave/wind observations with a 3 hour interval. The actual coastline near Noordwijk has a shore normal of 298° and it is assumed that the incoming waves for this particular stretch of coastline will originate between angles of 223° and 13° which equals a range of 150°. This value is subsequently divided in 5 equal classes of 30° each. Furthermore, the wave heights are divided in 2 classes. This results in 5*2 = 10 wave conditions in total. Therefore, the reduction technique which is used is binning of the wave direction and wave height for which the corresponding occurrence is retrieved from the 23 years dataset of wave observations. The 10 conditions cover a combined occurrence of 85.3% compared to the entire dataset of 23 years. Finally, both the wave conditions and the wind conditions are rotated by an angle of 62° to match the shore normal of 0° in the Delft3D model. The (rotated) wave and wind conditions are listed in Table 3.5. The peak period $T_p$ is calculated by using the relation $T_{peak}$ = 1/0.95 * $T_s$, in which $T_s$ represents the significant wave period. Wave and wind roses of the full and reduced climates can be seen in Figure 3.13 and Figure 3.14.

*Table 3.5 – Wave conditions derived from the dataset of 23 year wave observations near Noordwijk*

| # of wave cond. | Sig. wave height $H_s$ [m] | Peak period $T_p$ [s] | Rotated wave direction [°] | Wind speed [m/s] | Rotated Wind direction [°] | Occurrence [%] | Corrected occurrence [%] |
|---|---|---|---|---|---|---|---|
| w01 | 1.08 | 5.24 | 302.0 | 8.87 | 279.1 | 16.60 | 19.544 |
| w02 | 2.43 | 6.89 | 303.4 | 14.61 | 290.9 | 3.14 | 3.14 |
| w03 | 0.89 | 5.24 | 329.7 | 6.61 | 305.4 | 13.23 | 16.174 |
| w04 | 2.64 | 7.22 | 329.6 | 13.31 | 329.8 | 2.08 | 2.08 |
| w05 | 0.84 | 5.67 | 1.5 | 5.29 | 340.8 | 14.23 | 17.174 |
| w06 | 2.61 | 7.46 | 1.6 | 12.21 | 355.8 | 2.02 | 2.02 |
| w07 | 0.82 | 5.94 | 30.3 | 4.90 | 60.0 | 20.66 | 23.604 |
| w08 | 2.64 | 7.94 | 25.4 | 11.70 | 38.0 | 2.19 | 2.19 |
| w09 | 0.72 | 5.16 | 58.3 | 6.22 | 120.1 | 11.01 | 13.954 |
| w10 | 2.24 | 7.03 | 55.0 | 12.52 | 94.7 | 0.12 | 0.12 |
| | | | | | **SUM:** | **85.28** | **100** |

The last column depicts the corrected occurrence. The occurrence is manually corrected because it is wanted to increase the occurrence of the ‘low’ wave conditions only. If this correction is not applied beforehand, the mormerge approach (explained in the next section) will automatically scale the occurrences to 100% for all conditions. In this way, the ‘high’ wave conditions are overrated which leads to an overestimation of the sediment transports and therefore the morphology.

***Hydrodynamic time & morphological time***

Within Delft3D, two timescales can be distinguished; the hydrodynamic timescale and the morphological timescale. Because changes in morphology occur on a substantial larger timescale than changes in hydrodynamics, it is allowed to use a certain ‘upscaling’ factor for the morphology, the so called MorFac (morphological acceleration factor).

Because of this large difference in timescale, the various hydrodynamic conditions can be considered to occur simultaneously, which allows them to be simulated in parallel. Then, the simulation can be split up into a number of parallel processes, which all represent different wave conditions. Every time step, the bathymetry changes are merged in one model which is then returned to the individual processes. This approach is called the ‘parallel online’ or ‘mormerge’ approach. More information on this subject can be found in Appendix B. The hydrodynamic time is preferably a multiple of one tidal cycle, which is previously defined as 12.4 hours = 744 minutes. The reason behind this is that the wave calculations are then carried out for a complete tidal cycle and hence for all occurring water levels. The spin-up time is defined as the amount of time required by the model to adjust itself to match the prescribed boundary and initial conditions (see Table 3.6). The time step for the hydrodynamic calculations is set to 0.25 minutes which results in Courant numbers smaller than 22.

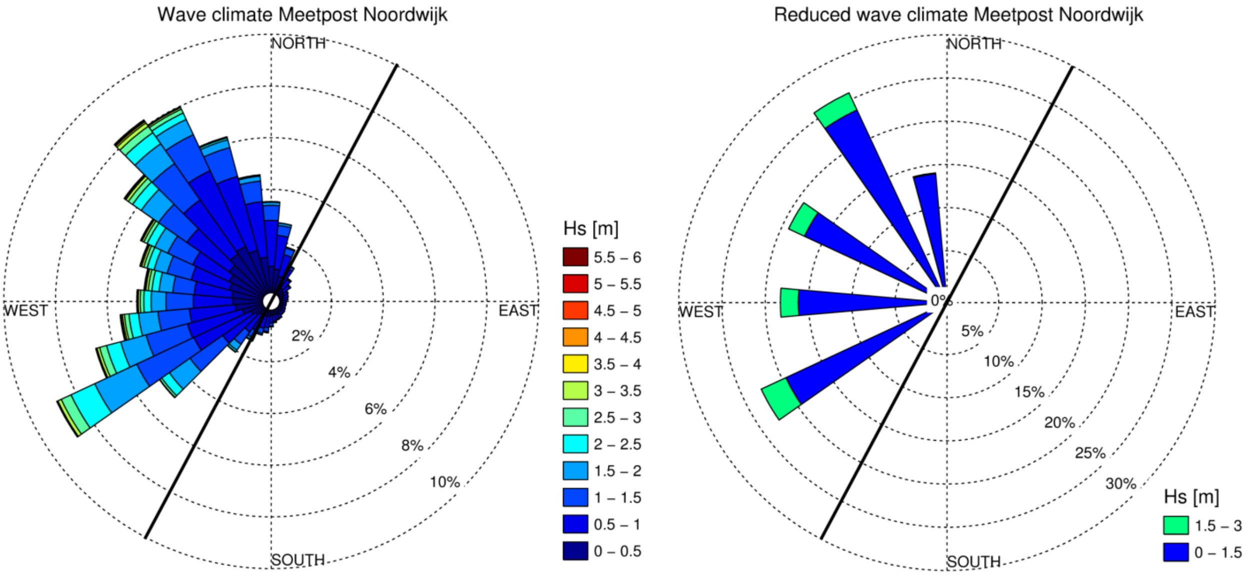



*Figure 3.13 – Wave rose of the full wave climate (left) and reduced wave climate (right) at Meetpost Noordwijk*

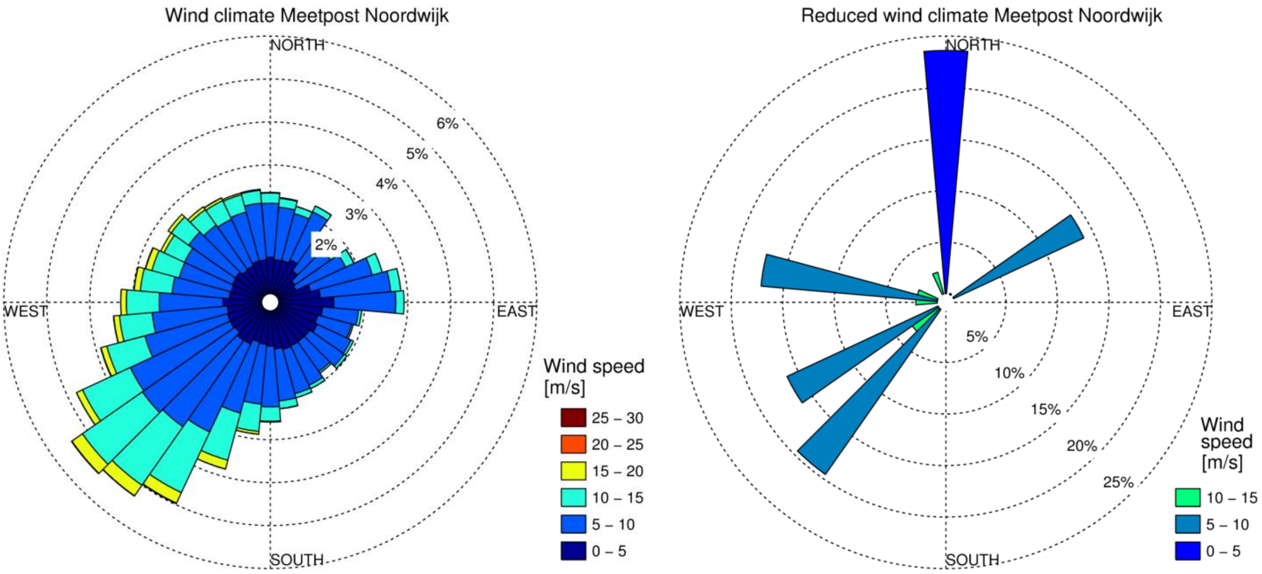



*Figure 3.14 – Wind rose of the full wind climate (left) and reduced wind climate (right) at Meetpost Noordwijk*

The MorFac is calculated by:

$$\text{MorFac} = \frac{\text{Morphological time}}{\text{Hydrodynamic time} - \text{spin-up time}} \qquad (9)$$

*Table 3.6 – Hydrodynamic time & morphological time with resulting MorFac*

| Spin-up time [min] | # of tidal cycles | Hydrodynamic time [min] | Morphological time [years] | Morphological time [minutes] | MorFac |
|---|---|---|---|---|---|
| 372 | 10 | 10*744 = 744 | 5 | 2 629 800 | 372.07 |

The choice for the number of tidal cycles is based on the maximum tolerable MorFac. Increasing the hydrodynamic time, while keeping the morphological time as a constant, will result in a lower MorFac and hence a more reliable result. When simulating 3 years of morphological time a substantial lower MorFac (223.24) is found according to equation (9).

Comparison of both MorFac's in two identical simulations showed excellent similarity with respect to morphological results. Furthermore, the higher MorFac showed no numerical instabilities and is considered reliable for this model.
The total MorFac is the sum of each individual (or effective) MorFac. This individual or effective MorFac can be calculated for each wave condition by multiplying the occurrence (weight factor) with the total MorFac. The highest MorFac is approximately 88 and corresponds to a calm wave condition. Stormy conditions should have relatively low MorFac's because high waves already induce large sediment transports by themselves and therefore have large impacts on morphology.

*Table 3.7 – Occurrences (weight factors) for each wave condition & the effective MorFac*

| # of wave conditions | $H_s$ [m] | $T_p$ [s] | Wave direction [°] | Occurrence or weight factor | Effective MorFac |
|---|---|---|---|---|---|
| w01 | 1.08 | 5.24 | 302.0 | 0.19544 | 72.72 |
| w02 | 2.43 | 6.89 | 303.4 | 0.0314 | 11.68 |
| w03 | 0.89 | 5.24 | 329.7 | 0.16174 | 60.18 |
| w04 | 2.64 | 7.22 | 329.6 | 0.0208 | 7.74 |
| w05 | 0.84 | 5.67 | 1.5 | 0.17174 | 63.90 |
| w06 | 2.61 | 7.46 | 1.6 | 0.0202 | 7.51 |
| w07 | 0.82 | 5.94 | 30.3 | 0.23604 | 87.82 |
| w08 | 2.64 | 7.94 | 25.4 | 0.0219 | 8.15 |
| w09 | 0.72 | 5.16 | 58.3 | 0.13954 | 51.92 |
| w10 | 2.24 | 7.03 | 55.0 | 0.0012 | 0.45 |
| | | | **SUM:** | **1** | **372.07** |

***Model parameters & calculation methods***
As mentioned before the Delft3D model uses the 'parallel online' approach, which makes it possible to split up the simulation in parallel processes. Next to this approach, other non-default formulations and parameters are being used, as will be discussed in this section.

- The simulations make use of the roller model for calculating wave heights and wave breaking. The wave breaking index ($\gamma_w$) is not set as a constant, but is being calculated by the expression of Ruessink, Walstra, and Southgate (2003), in which $\gamma_w$ increases linearly with the product of the local wave-number and water depth *kh*. It is expected that this approach will result in sediment transports closer to shore and in a more narrow range compared to the SWAN calculations. SWAN is still used for calculating the wave directions. The roller slope parameter $\beta_{rol}$ and breaker delay parameter $F_{lam}$ are set to default values (Giardino, Brière, & Van der Werf, 2011).

- The sediment transport formula which is used for the model is TRANSPOR2004, which is further discussed in Appendix B, section B.2. Instead of a constant roughness in the model domain, the roughness predictor of van Rijn, Walstra, and van Ormondt (2004) is used. The horizontal eddy viscosity is set to a value of 0.25 $m^2$/s which limits lateral mixing of sediment in the model domain.

- In the entire model domain one sediment fraction is imposed, which is sand with a specific density of 2650 kg/$m^3$, a dry bed density of 1600 kg/$m^3$ and a D50 of 200 μm.

***Nourishment volumes***
Table 3.8 shows the initial nourishment volumes as they are implemented in the Delft3D model. For comparison the volumes for the UNIBEST-CL+ simulations are also enclosed. The

observed differences between Delft3D and UNIBEST-CL+ are due to the differences in nourishment height. For UNIBEST, this active height is set to a fixed value of 7m, whereas in Delft3D this value varies with the amount of seaward extent (see also Figure 3.11).

*Table 3.8 – Occurrences (weight factors) for each wave condition & the effective MorFac*

| Sim. nr. [-] | Seaward extent [m] | Alongshore length [m] | Volume in UNIBEST-CL+ [Mm$^3$] | Volume in Delft3D [Mm$^3$] | Difference D3D compared to UNIBEST [Mm$^3$] |
|---|---|---|---|---|---|
| 10 | 333 | 833 | 3.11 | 2.70 | -0.41 [-13 %] |
| 11 | 333 | 1665 | 5.01 | 4.31 | -0.70 [-14 %] |
| 12 | 333 | 3330 | 8.93 | 7.56 | -1.37 [-15 %] |
| 13 | 667 | 1668 | 12.45 | 13.44 | +0.99 [+ 8 %] |
| 14 | 667 | 3335 | 20.31 | 21.82 | +1.51 [+ 7 %] |
| 15 | 667 | 6670 | 35.80 | 38.49 | +2.69 [+ 8 %] |
| 16 | 1000 | 2500 | 28.00 | 35.17 | +7.17 [+26 %] |
| 17 | 1000 | 5000 | 45.50 | 57.28 | +11.78 [+26 %] |
| 18 | 1000 | 10000 | 80.50 | 101.51 | +21.01 [+26 %] |

### 3.2.2 Model calibration & model validation

***Model calibration – alongshore transports***

Alongshore transports are induced by waves and currents and can be considered a driving force for the diffusion of nourishments. Each wave condition induces a certain amount of sediment transport in an eastbound and/or westbound direction. The summation of sediment transports for every individual wave condition adjusted with its corresponding weight factor will provide the net and gross transport rates. The transport rates are retrieved by using DETRAN and are carried out for a transect which covers the entire cross-sectional area of the model (see Figure 3.15). Furthermore, the transport calculations are performed on an alongshore uniform depth profile. The observed net transport is approximately 247k m$^3$/year. This value is then manually scaled to a transport of **200k m$^3$/year** for comparison with UNIBEST results and this value is used for all model runs. Results can be found in Table 3.9.

*Table 3.9 – Alongshore gross and net transports for each wave condition (minus = westbound)*

| # of wave cond. | $H_s$ [m] | $T_p$ [s] | Wave dir. [°] | Alongshore transport [m$^3$/day] | | |
|---|---|---|---|---|---|---|
| | | | | Gross transport (westbound) | Net transport | Gross transport (eastbound) |
| w01 | 1.08 | 5.24 | 302.0 | 0 | 296 | 296 |
| w02 | 2.43 | 6.89 | 303.4 | 0 | 517 | 517 |
| w03 | 0.89 | 5.24 | 329.7 | 0 | 162 | 162 |
| w04 | 2.64 | 7.22 | 329.6 | 0 | 396 | 396 |
| w05 | 0.84 | 5.67 | 1.5 | -13 | -5 | 8 |
| w06 | 2.61 | 7.46 | 1.6 | -35 | -33 | 2 |
| w07 | 0.82 | 5.94 | 30.3 | -180 | -170 | 10 |
| w08 | 2.64 | 7.94 | 25.4 | -434 | -434 | 0 |
| w09 | 0.72 | 5.16 | 58.3 | -44 | -38 | 6 |
| w10 | 2.24 | 7.03 | 55.0 | -13 | -13 | 0 |
| Alongshore transport / **day** [m$^3$/day] | | | | **-719** | **678** | **1397** |
| Alongshore transport / **year** [m$^3$/year] | | | | **-262 700** | **246 700** | **509 400** |
| Alongshore transport scaled by a factor **0.8107** to get 200k transport [m$^3$/year] | | | | **-213 000** | **200 000** | **413 000** |

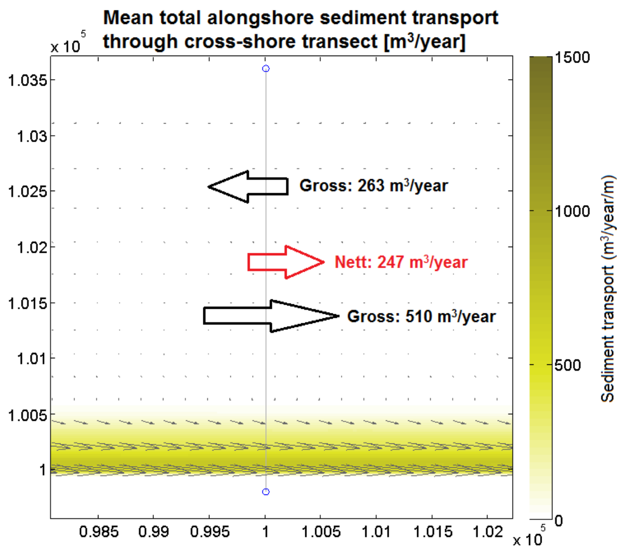



*Figure 3.15 – Mean total alongshore transports*

The occurring net and gross alongshore transports are found to be in good agreement with observed values along the Dutch coast.

***Model validation – Implementation of the Sand Motor***

The model has been validated by implementing the Sand Motor as a reference nourishment (Figure 3.16) and comparing the model results with observations.

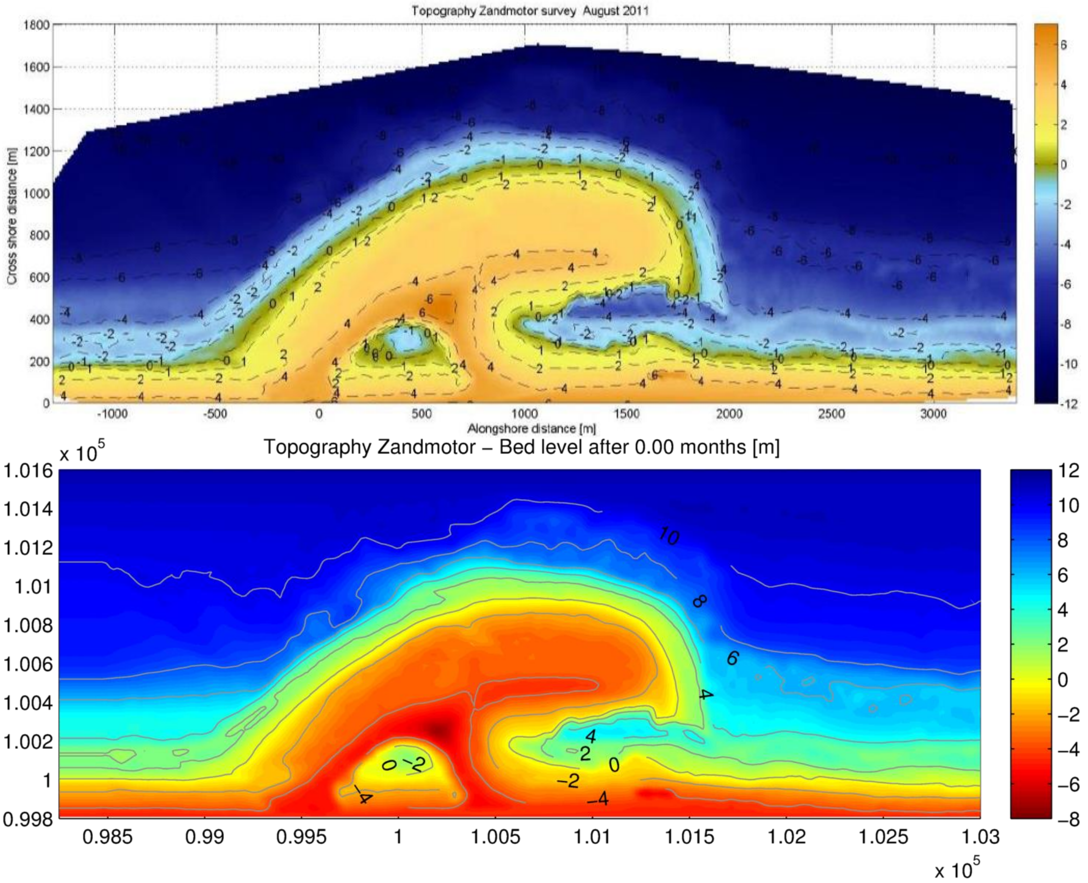



*Figure 3.16 – Measured topography Sand Motor August 2011 (upper) and initial bathymetry Delft3D (lower). Upper figure from Shore Monitoring & Research (2013)*

Topography August 2012 (12 months)

When the measured bathymetry is compared to the model prediction after a period of 12 months, a fairly large resemblance can be observed (Figure 3.17). At the eastern part the spit growth is correctly predicted as well as the formation of the channel, although the shape of the channel is slightly different. Large erosion can be observed at the top of the Sand Motor as well as accretion of sediment on both adjacent sides, which is in good agreement with the measurements.

However, the model predicts a steeper cross-shore profile which is not occurring in the measurements and also the overall shape of the nourishment is slightly different than the measured shape. The measurements show a much more symmetrical shape than the modelled nourishment, in which the latter is shifted to the right.

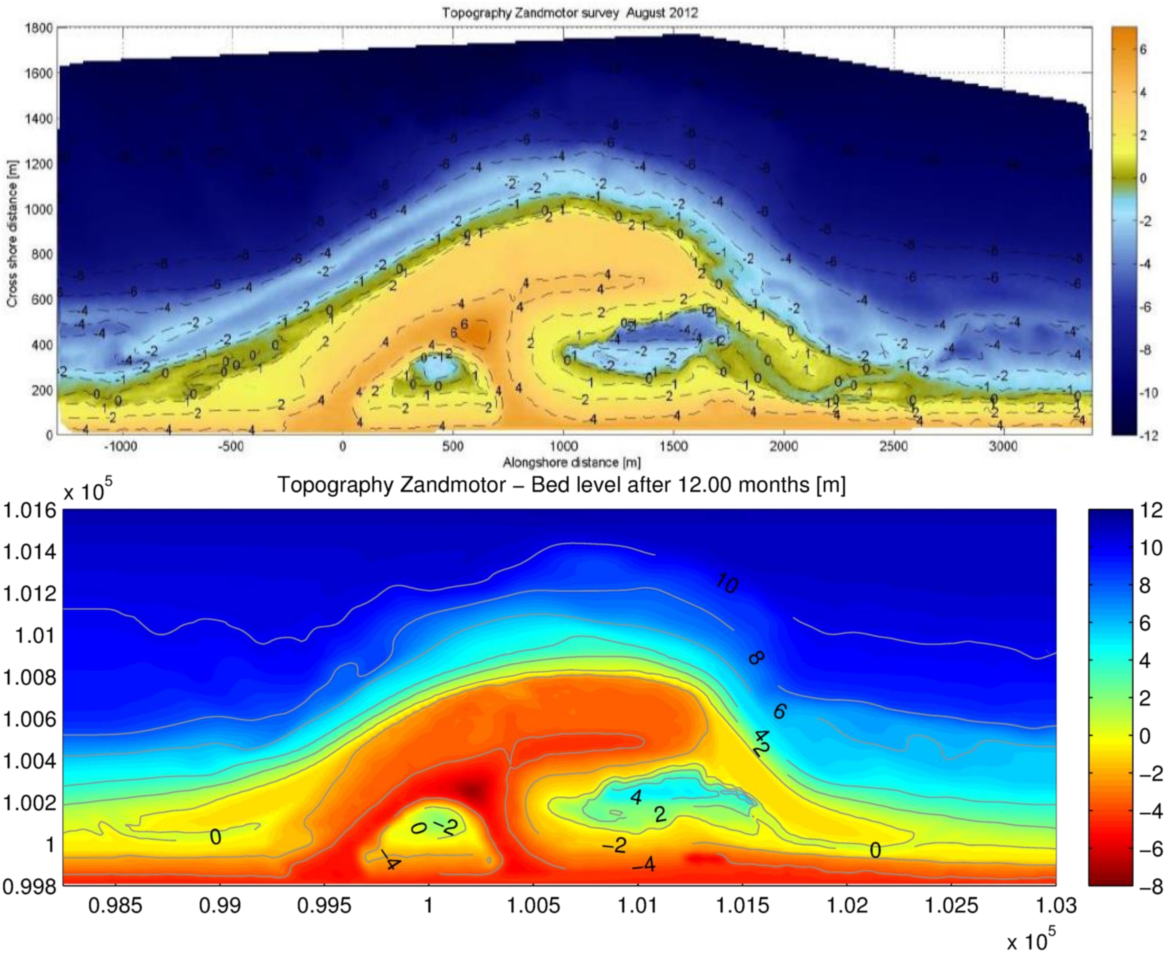



*Figure 3.17 – Measured topography Sand Motor August 2012 (upper) and simulated topography Delft3D (lower). Upper figure from Shore Monitoring & Research (2013)*

Topography July 2013 (23 months)

Figure 3.18 shows again the measured bathymetry (upper figure) and the simulated bathymetry (lower figure), in this case after a period of 23 months (July 2013). Same conclusions can be drawn as before. The overall shape is shifted to the right in the simulated model and the prediction of the channel on the left is wrong. However, the overall eroding pattern at the top and the overall sedimentation on either side is correctly predicted as well as the lengthening of the channel on the right, which is confirmed by the cumulative erosion/sedimentation plot shown in Figure 3.19. They are to be found in good agreement with measurements.

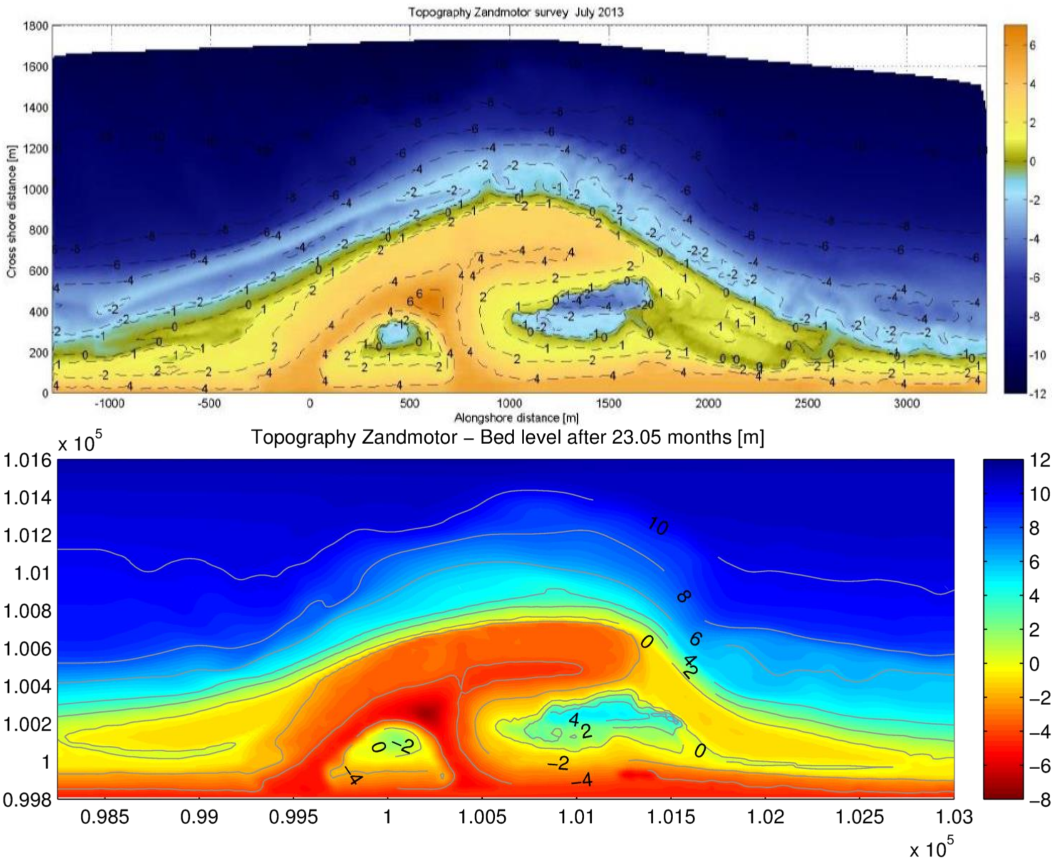



Figure 3.18 – Measured topography Sand Motor July 2013 (upper) and simulated topography Delft3D (lower). Upper figure from Shore Monitoring & Research (2013)

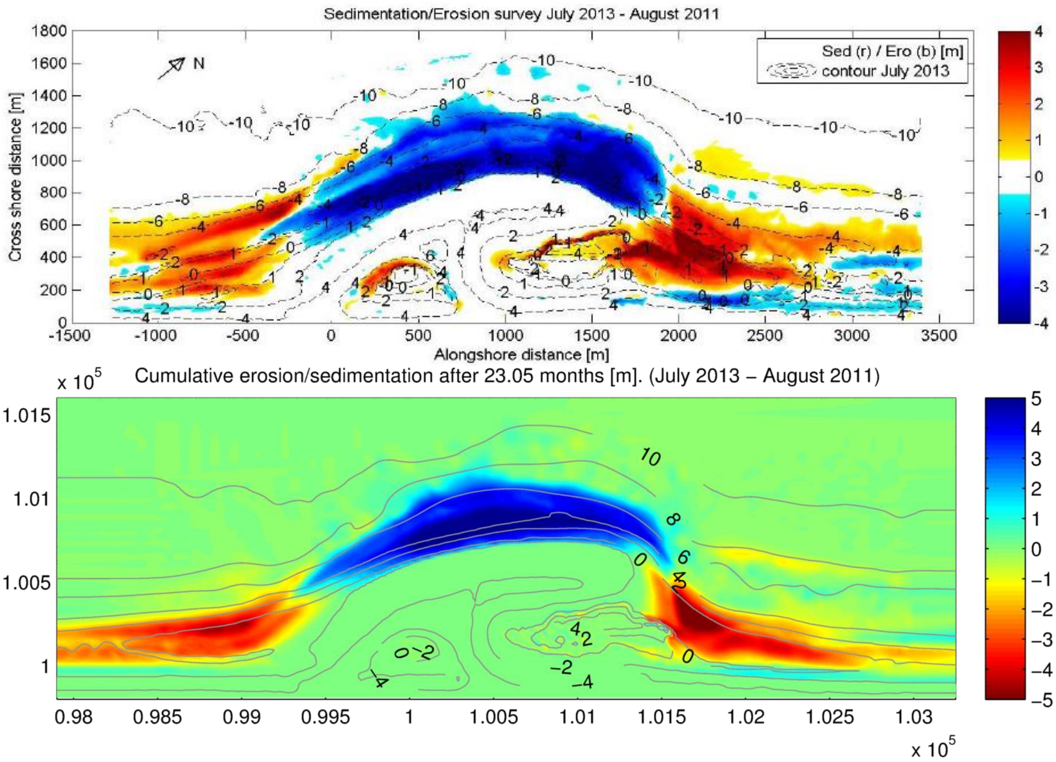



Figure 3.19 – Cumulative erosion/sedimentation: measured (upper) and modelled (lower) after 23 months. Upper figure from Shore Monitoring & Research (2013)

Volume decrease Sand Motor Peninsula

Figure 3.20 shows the volume decrease in time for the Sand Motor Peninsula. The magenta dots represent the calculated volumes of the Delft3D model for the first 3 years. After this period, an exponential fit has been used to extrapolate the results (magenta line). Overall, the result is found to be in good agreement with the measurements and it is expected that the model is capable of predicting volume decrease in time. Although underestimating the first year, the long term trend is clearly visible. The underestimation at the beginning is probably due to the fact that a mormerge approach has been used in combination with a yearly averaged wave climate. As mentioned before, the behaviour of large scale nourishments is highly considered event driven, but in the model no single events are present, just averaged wave conditions to cover an entire year. The mormerge approach is therefore smoothing the volume decay in time to a regular smooth line.

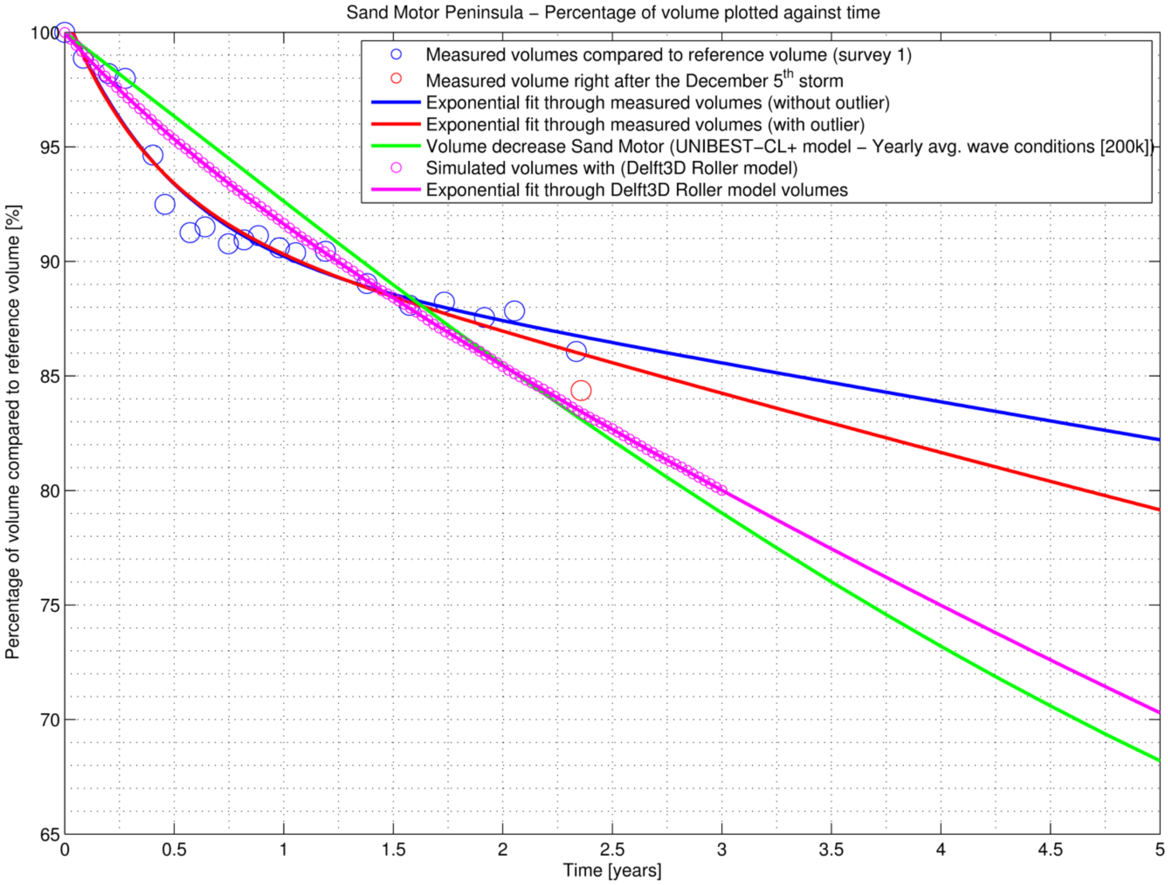



*Figure 3.20 – Volume decay of Sand Motor (magenta coloured dots and line represent the Delft3D results)*

Both the analysis of the Sand Motor topography and the volume decrease in time show that the model is capable of reproducing the diffusion of large scale nourishments along the Dutch coast. The model is therefore considered to be reliable regarding nourishment performance in time, and provides sufficient confidence for use within this research.
Additionally, a cross-shore analysis of the Sand Motor can be found in Appendix D, in which measurements are compared to a CROSMOR model and in which the cross-shore changes in the first years are examined for the Delft3D model.
It is striking to see the large resemblance between Delft3D and UNIBEST. This might be because of the well placed of a dynamic boundary in UNIBEST, which is not incorporated in traditional 1D coastline models.

# 4 UNIBEST-CL+ model results

The question which will be tried to answer by using the UNIBEST-CL+ modelling suite is:

- How does the erosion rate of nourishments depend on their size, shape and grain size?

The results which will be presented here can be considered as a lower value for diffusion, because only wave driven sediment transport is considered within the UNIBEST-CL+ modelling suite. Tidal forcing is not taken into account.
Because this approach is much less computational extensive compared to Delft3D, it will give first impressions on the decrease of volume in time, erosion rates and lifespans.

## 4.1 Nourishment volumes in time & eroded volumes in time

For each nourishment, a fictional box (called 'control element') is placed halfway around the edges of the nourishment so that the nourishment is enclosed by this 'control element'. The amount of volume inside this box is then considered in time. The results can be seen in Table 4.1.

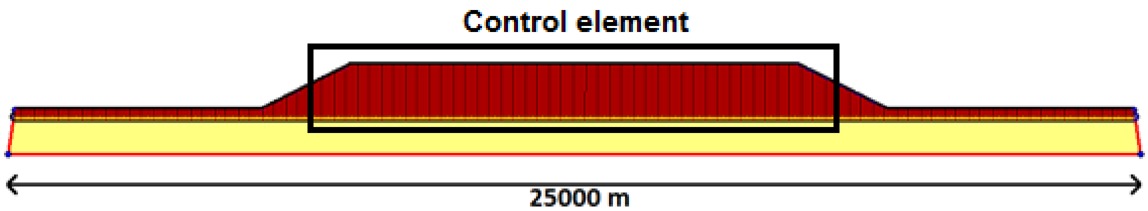



*Figure 4.1 – Illustrative example of a control element as used for the volume calculations*

*Table 4.1 – Nourishment volumes in time according to the UNIBEST-CL+ model*

| SIM | Initial volume [Mm³] | Alongshore transport [k*m³/year] | Volume at t= 2 year | | Volume at t= 5 year | | Volume at t= 10 year | | Volume at t= 30 year | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mm³ | % | Mm³ | % | Mm³ | % | Mm³ | % |
| 333m 1:2.5 | 3.11 | 100 | 2.21 | 71.3 | 1.65 | 53.2 | 1.25 | 40.1 | 0.75 | 24.3 |
| | | 200 | 1.79 | 57.7 | 1.25 | 40.2 | 0.91 | 29.4 | 0.54 | 17.4 |
| | | 400 | 1.37 | 44.2 | 0.91 | 29.4 | 0.66 | 21.2 | 0.38 | 12.4 |
| 333m 1:5 | 5.01 | 100 | 4.10 | 81.8 | 3.38 | 67.6 | 2.72 | 54.3 | 1.74 | 34.8 |
| | | 200 | 3.58 | 71.6 | 2.72 | 54.3 | 2.07 | 41.4 | 1.27 | 25.3 |
| | | 400 | 2.94 | 58.7 | 2.07 | 41.4 | 1.53 | 30.5 | 0.91 | 18.1 |
| 333m 1:10 | 8.93 | 100 | 8.02 | 89.8 | 7.28 | 81.5 | 6.44 | 72.1 | 4.68 | 52.5 |
| | | 200 | 7.49 | 83.9 | 6.44 | 72.1 | 5.36 | 60.1 | 3.57 | 40.0 |
| | | 400 | 6.74 | 75.5 | 5.36 | 60.1 | 4.21 | 47.1 | 2.63 | 29.5 |
| 667m 1:2.5 | 12.45 | 100 | 11.22 | 90.1 | 9.86 | 79.2 | 8.35 | 67.1 | 5.64 | 45.3 |
| | | 200 | 10.26 | 82.4 | 8.35 | 67.1 | 6.62 | 53.2 | 4.18 | 33.5 |
| | | 400 | 8.88 | 71.3 | 6.62 | 53.2 | 5.00 | 40.2 | 3.03 | 24.3 |
| 667m 1:5 | 20.31 | 100 | 19.08 | 93.9 | 17.71 | 87.2 | 16.07 | 79.1 | 12.25 | 60.3 |
| | | 200 | 18.12 | 89.2 | 16.07 | 79.1 | 13.80 | 67.9 | 9.54 | 47.0 |
| | | 400 | 16.67 | 82.1 | 13.80 | 68.0 | 11.12 | 54.7 | 7.12 | 35.1 |
| 667m 1:10 | 35.80 | 100 | 34.57 | 96.6 | 33.20 | 92.7 | 31.55 | 88.1 | 27.34 | 76.4 |
| | | 200 | 33.61 | 93.9 | 31.56 | 88.1 | 29.17 | 81.5 | 23.39 | 65.3 |
| | | 400 | 32.16 | 89.8 | 29.17 | 81.5 | 25.82 | 72.1 | 18.79 | 52.5 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1000 m 1:2.5 | 28.00 | 100 | 26.69 | 95.3 | 24.95 | 89.1 | 22.66 | 80.9 | 17.17 | 61.3 |
| | | 200 | 25.50 | 91.1 | 22.66 | 80.9 | 19.40 | 69.3 | 13.31 | 47.5 |
| | | 400 | 23.51 | 84.0 | 19.40 | 69.3 | 15.55 | 55.5 | 9.90 | 35.4 |
| 1000 m 1:5 | 45.50 | 100 | 44.19 | 97.1 | 42.45 | 93.3 | 40.15 | 88.2 | 34.01 | 74.7 |
| | | 200 | 43.00 | 94.5 | 40.15 | 88.2 | 36.68 | 80.6 | 28.42 | 62.5 |
| | | 400 | 41.01 | 90.1 | 36.68 | 80.6 | 31.82 | 69.9 | 22.32 | 49.1 |
| 1000 m 1:10 | 80.50 | 100 | 79.19 | 98.4 | 77.45 | 96.2 | 75.15 | 93.4 | 68.95 | 85.7 |
| | | 200 | 78.00 | 96.9 | 75.15 | 93.4 | 71.68 | 89.0 | 62.75 | 77.9 |
| | | 400 | 76.01 | 94.4 | 71.68 | 89.0 | 66.64 | 82.8 | 54.24 | 67.4 |

The results are grouped with respect to the amount of seaward extent. Only the 333m seaward extent graphs will be presented and explained in this chapter. In Appendix F, all results can be found. Figure 4.2 shows the nourishment volumes for the first ten years.

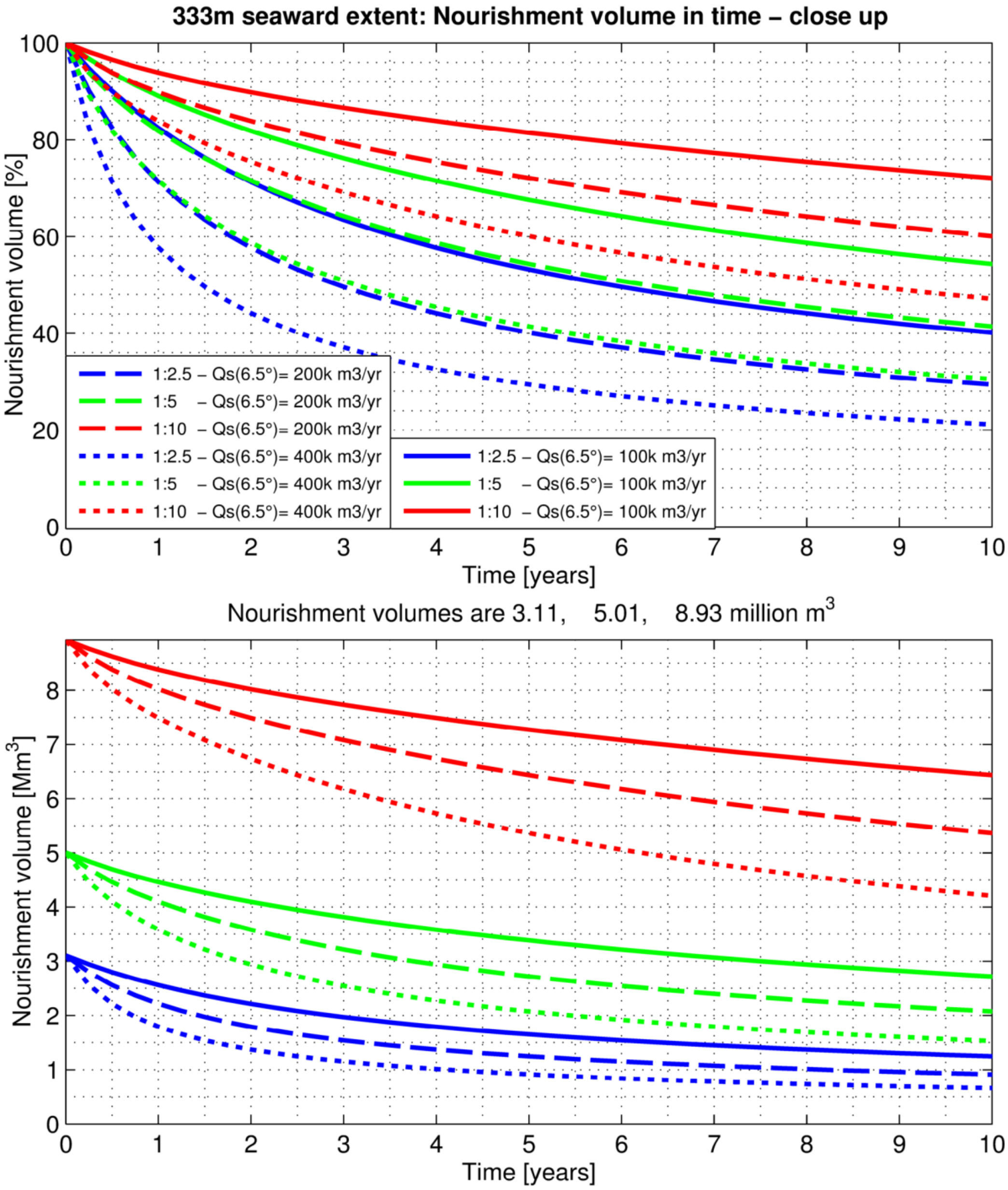



*Figure 4.2 – Nourishment volumes in time for 333m seaward extent – close-up*

Figure 4.3 shows nourishment volumes and erosion volumes over a period of 200 years.

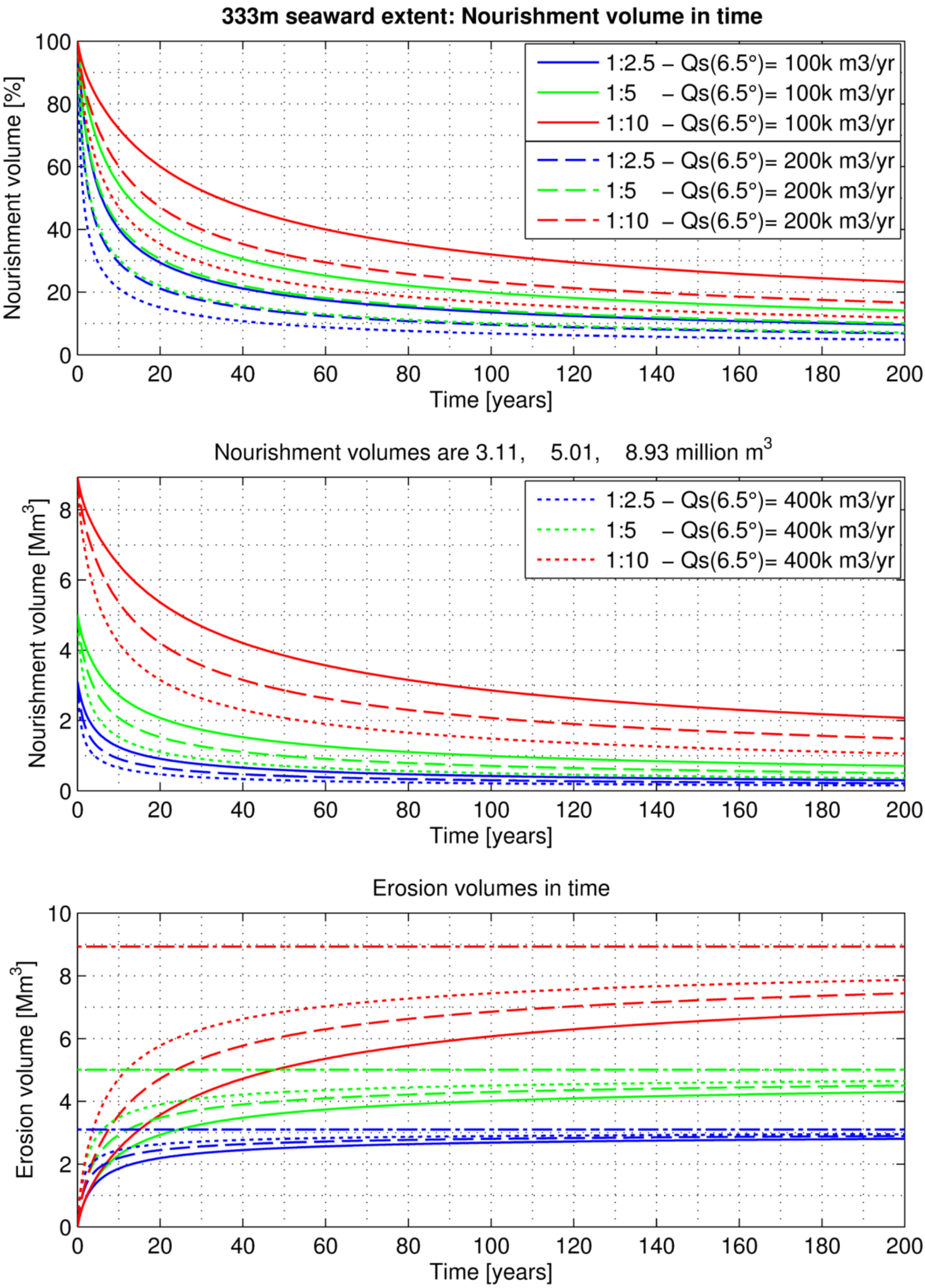



*Figure 4.3 – Nourishment volumes / erosion volumes in time for 333m seaward extent*

## 4.2 Alongshore sediment transport

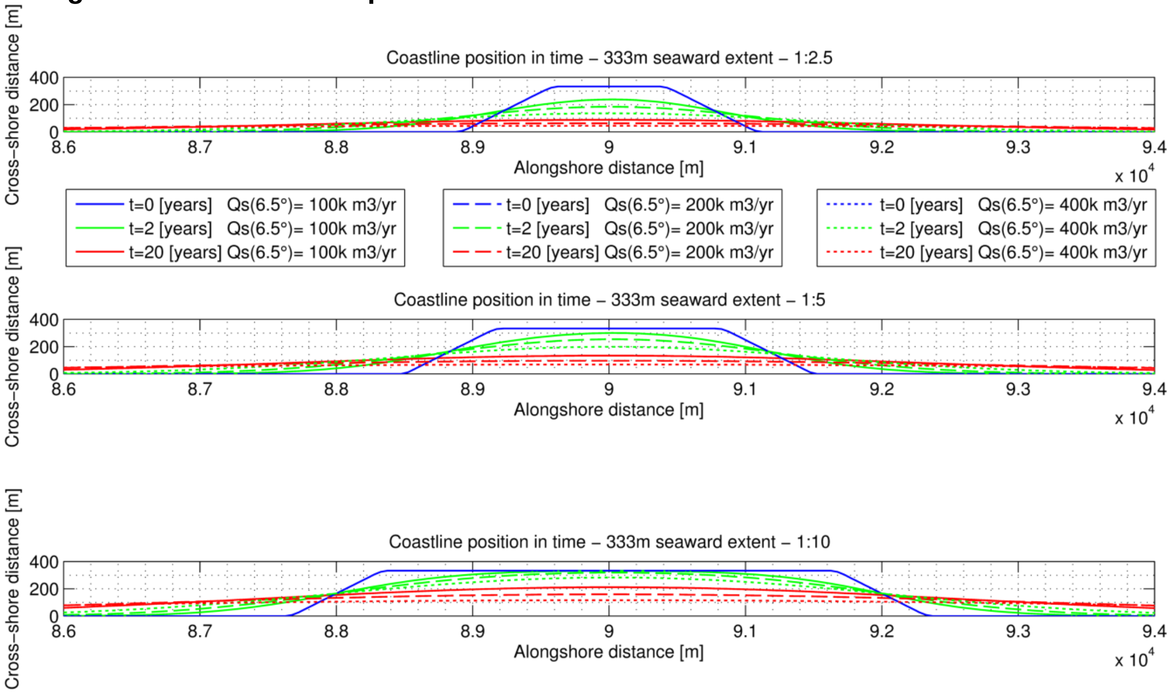



*Figure 4.4 – Coastline position in time for the 333m seaward extent nourishments*

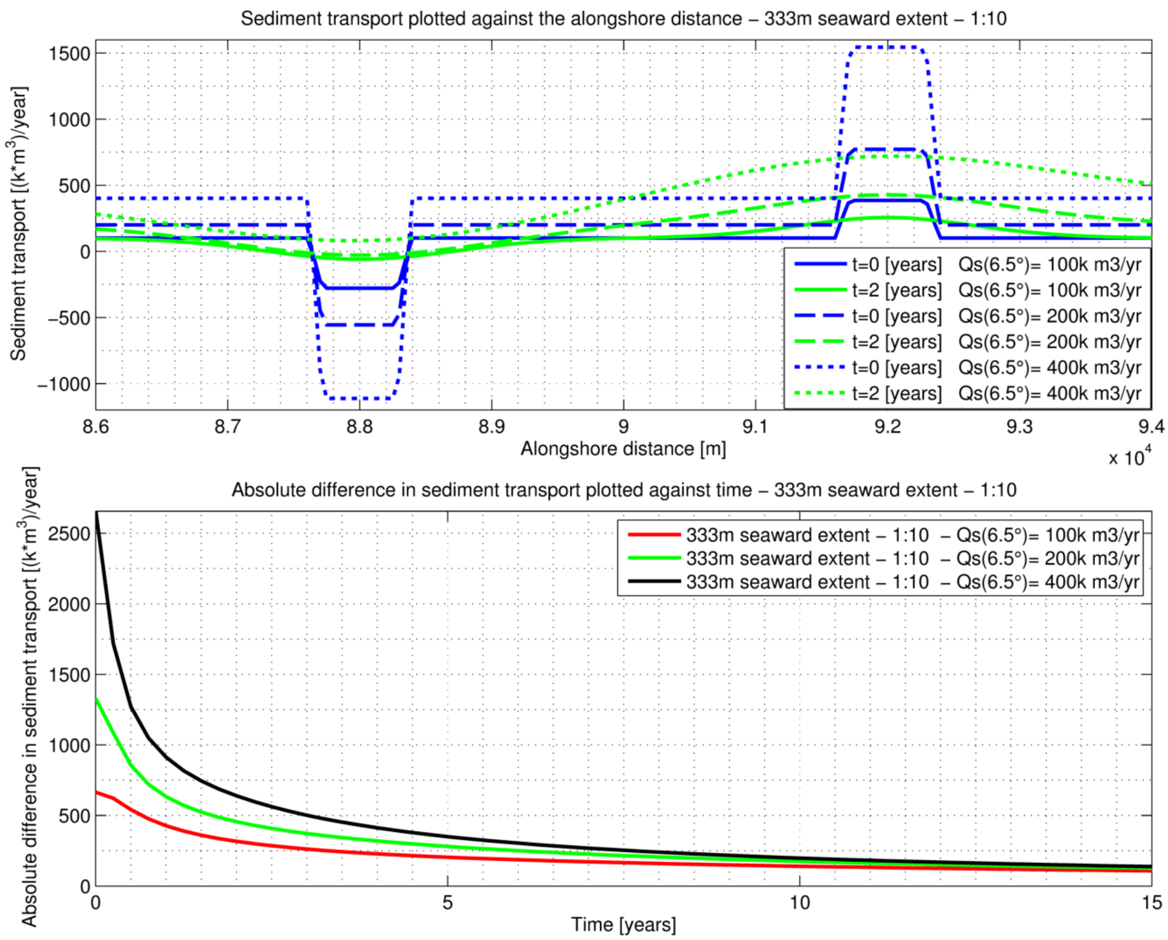



*Figure 4.5 – Sediment transport in alongshore direction (upper) and in time (lower) for the 333m 1:10 nourishment*

Figure 4.4 and Figure 4.5 show the coastline positions and alongshore sediment transports respectively. The coastline position is shown after 2 years (green lines) and after 20 years (red lines). Figure 4.5 also shows the absolute difference in sediment transport plotted. These differences are responsible for the diffusion of nourishments.

### 4.3 Design graphs

This section will provide figures in which all the data is combined to provide a comparison between the nourishments. First, the half-life of each nourishment is plotted against its volume (Figure 4.6). The half-life is defined as the amount of time it takes for the nourishment to reduce to 50% of its initial volume. It can clearly be seen that the relation between half-life and volume is linear according to Unibest. This is expected because in UNIBEST the transports are calculated with the S-φ curve and local coastline angle. The sediment transports are therefore not dependent on the amount of volume or the size of the nourishment. In reality it is expected that this is the case, for example wave sheltering due to the nourishment size. Simulations with Delft3D will hopefully provide an answer to this.

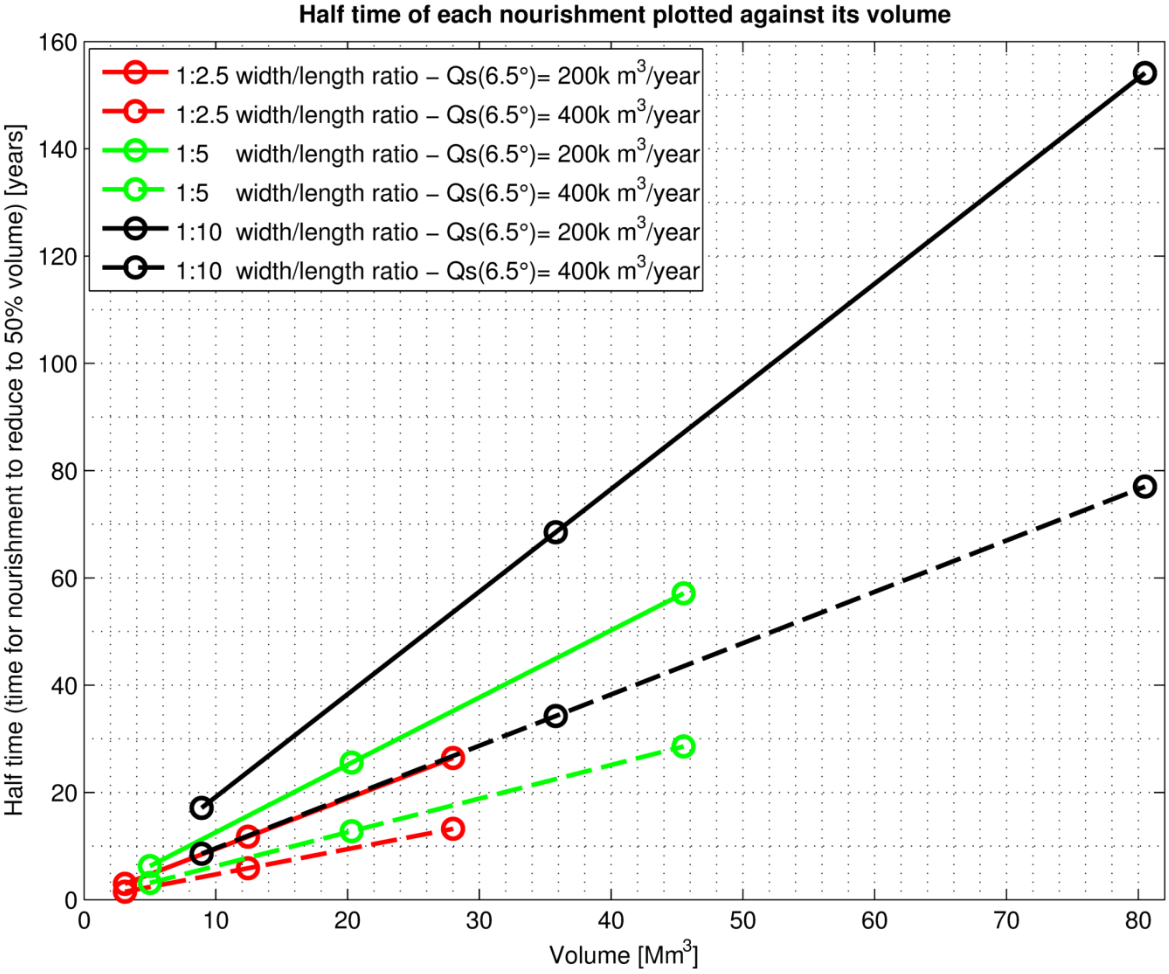



*Figure 4.6 – Half-life of each nourishment plotted against its volume*

Furthermore, the eroded volumes are compared to the amount of seaward extent. In order to do so, the average eroded volume is calculated for the simulations with the same seaward extent. Then, the cumulative eroded volume is divided by the timeframe in which it occurred to scale the volumes to $m^3$/year. This is done for two cases, the average over 2 years and the average over 5 years. The results can be seen in Figure 4.7 and Figure 4.8.

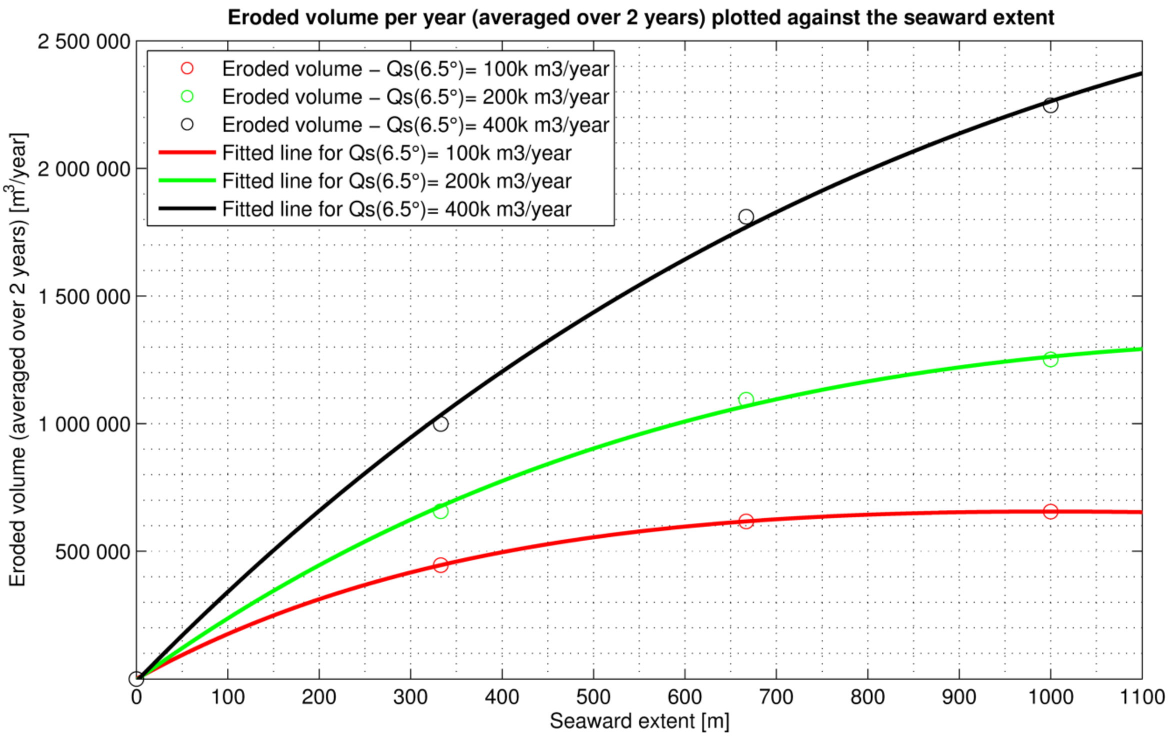



*Figure 4.7 – Eroded volume per year (averaged over 2 years) plotted against the seaward extent*

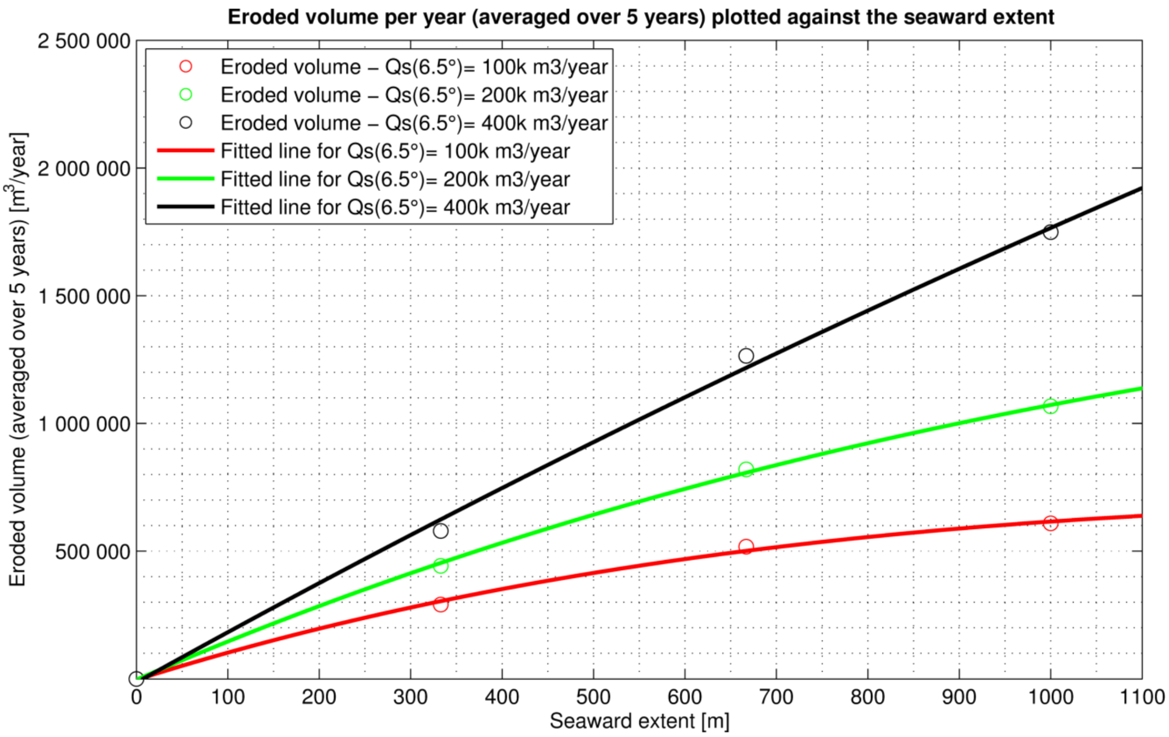



*Figure 4.8 – Eroded volume per year (averaged over 5 years) plotted against the seaward extent*

Both figures are considered important since they can be used to get to a first approximation of maintenance volumes. This will be further explained in chapter 7.

## 4.4 UNIBEST sensitivity analysis

Within this research use has been made of a UNIBEST model with a certain set of fixed parameters. Because the conclusions are based on the outcome of the model, it would be very interesting to see how sensitive the model is to changes in these parameters. In this appendix, the sensitivity of the dynamic boundary, the wave climate, the active height and the cross-shore profile are examined. The sensitivity analysis has been carried out for one specific nourishment only: Simulation 13 with a seaward extent of 667m and an alongshore length of 1668m.

### Wave climate & dynamic boundary

The UNIBEST simulations in this research are all using a cross-shore DMW-profile (see 3.1), which has a cross-shore extent of **700m** at a depth of **6.3m**. The dynamic boundary is also located at this position and can be defined as the location to which the alongshore transport is being computed. The dynamic part of the profile is supposed to rotate in the same way as the coastline. For a coast that rotates significantly, for instance at the nourishment edges, this can have a significant effect on refraction (Deltares, 2011b).
Because the wave climate which is used in UNIBEST is already transformed to nearshore conditions, it would be unrealistic to extend the cross-shore profile and relocate the dynamic boundary at a larger depth. For that reason the same wave climate as used in Delft3D is imposed on the UNIBEST model. The (offshore) wave climate consists of 10 wave conditions (see section 3.2) and to match the Delft3D model, the DMW-profile is extended to **19m** depth at a cross-shore extent of **3600m** (Figure 4.9).

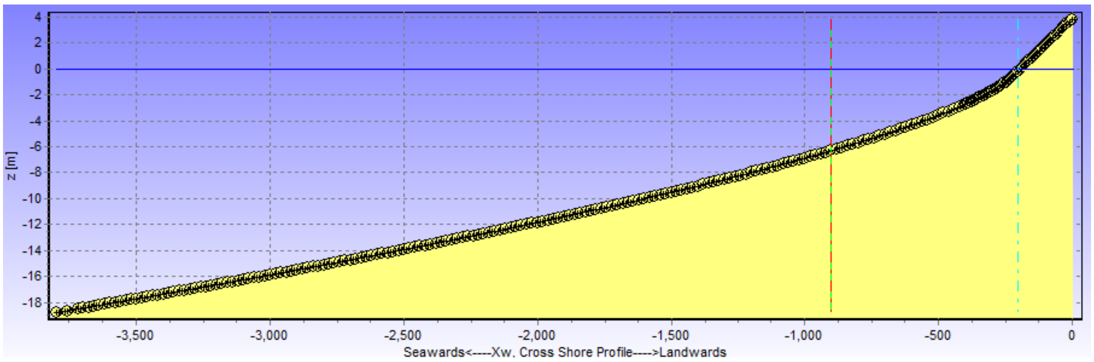



*Figure 4.9 – Extended cross-shore DMW-profile implemented in UNIBEST*

As can be seen in Figure 4.10, the (offshore) Delft3D wave climate performs almost similar to the nearshore UNIBEST wave climate when considering the same dynamic boundary located at a depth of 6.3m (solid blue vs. solid red line). The difference in sediment transport after 1 year is approximately 5%, which is considered very low since both wave climates are very different. Nourishment performance (e.g. eroded volume in time) is also performing really well with a slight difference of 7% after a period of 5 years.

When comparing different dynamic boundaries (6m, 8m, 10m and 19m) with the same D3D wave climate (red lines), large differences can be observed. Placing the dynamic boundary further offshore results in substantial lower peaks in alongshore sediment transports. Increasing the dynamic boundary from 6m water depth to 8m water depth shows a decrease in peak sediment transport of 19%. In the unrealistic case of a located dynamic boundary at 19m water depth, a decrease of 43% can be observed.

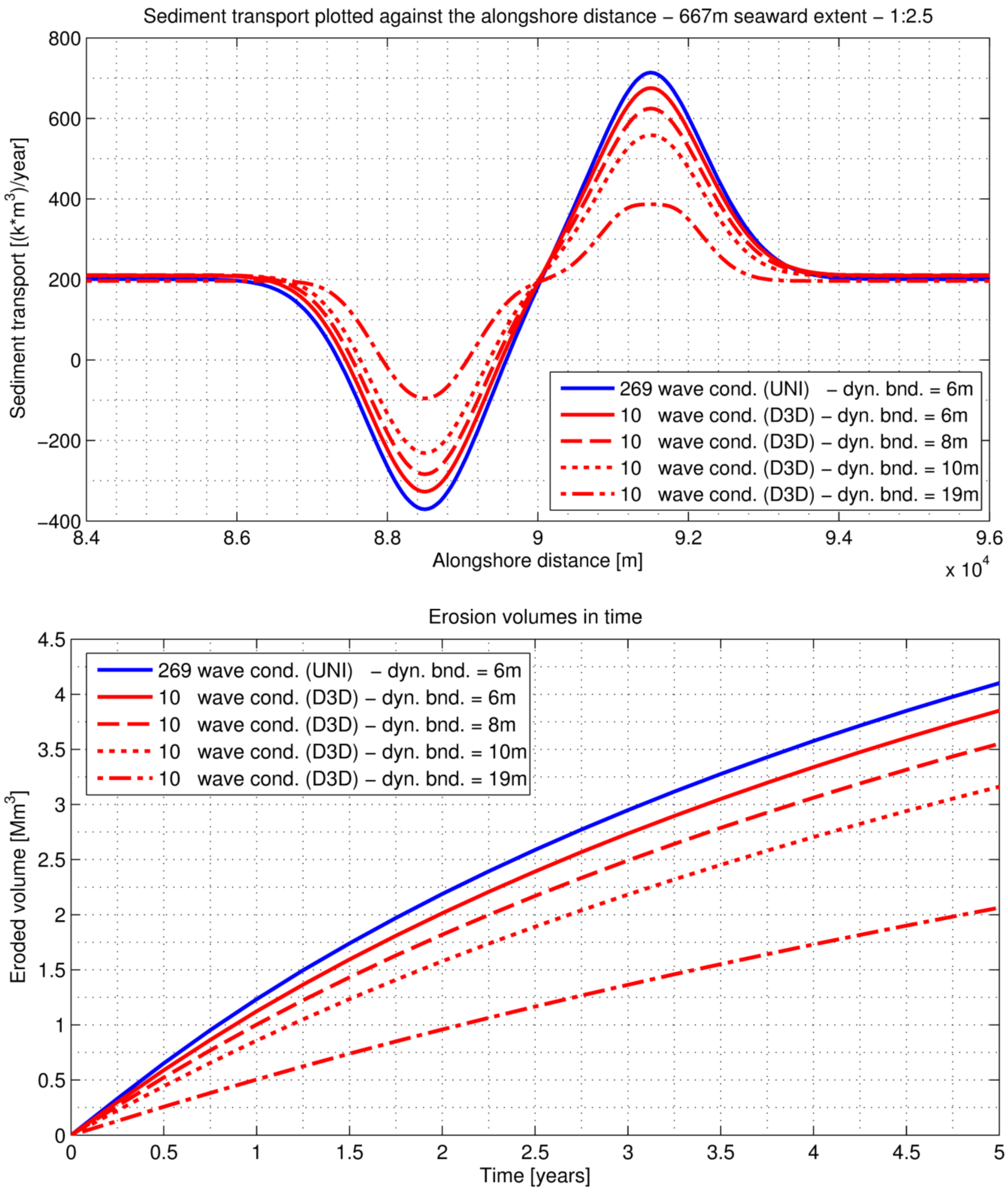



*Figure 4.10 – Alongshore sediment transport at t=1 year (upper figure) and eroded volume in time (lower figure)*

As it turns out, the dynamic boundary is a very sensitive parameter when setting up a coastline model. It can be concluded that a nearshore wave climate and an offshore wave climate perform almost exactly the same when the dynamic boundary is kept constant.
Traditional 1D coastline models do not include such a dynamic boundary and will therefore consistently underestimate nourishment performance since most of the time nearshore wave conditions are not available and the entire cross-shore profile rotates in the same way as the coastline. Refraction is then wrongfully calculated which reduces the peaks in alongshore sediment transport. UNIBEST shows that a 1D line model can also be used in a more sophisticated way by means of the dynamic boundary.

## Comparison of three wave climates

Figure 4.11 shows the alongshore sediment transports at t= 1 year for three different wave climates, which have all been simulated using UNIBEST. As is concluded above, the UNIBEST wave climate and the D3D wave climate near Noordwijk are very similar. However, the D3D Egmond wave climate, consisting of 9 wave conditions, shows slightly larger net transports on the straight coastline and substantial larger transport peaks at the surroundings of the nourishment. This can be explained by also taking the gross sediment transport rates into account (Table 4.2). The higher gross transport rates represent a more energetic wave climate, which induces a larger sediment transport for the same relative wave angle.

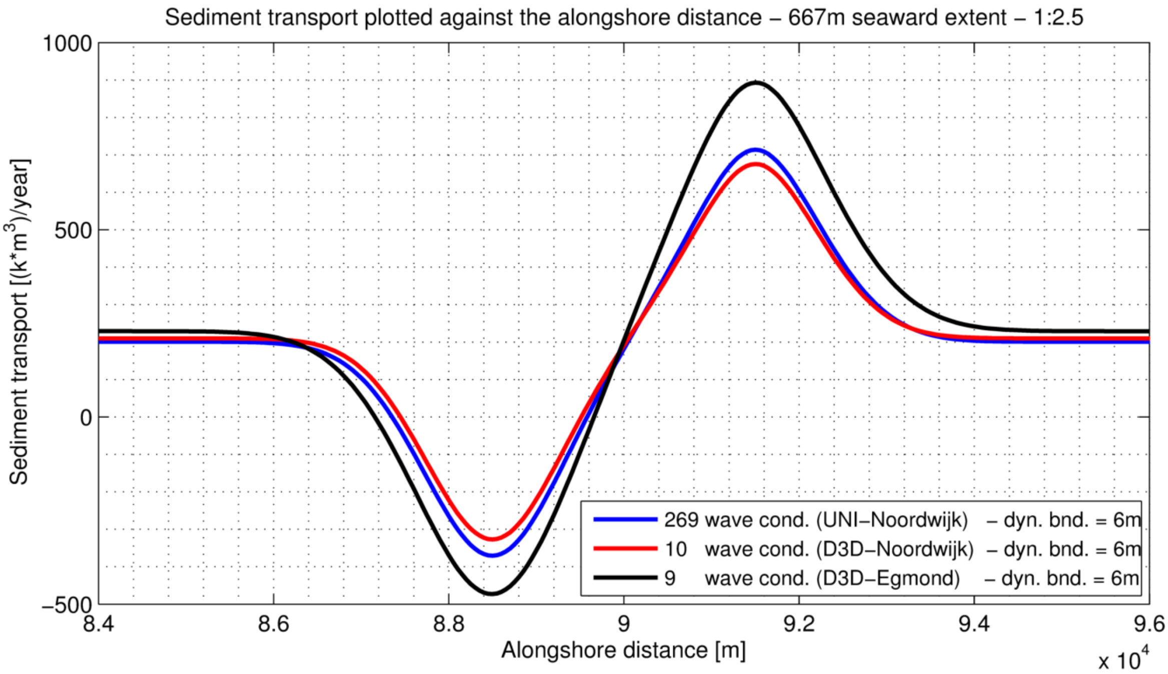



*Figure 4.11 – Alongshore sediment transport at t=1 year for three different wave climates within UNIBEST*

*Table 4.2 – Gross and net sediment transport rates for three different wave climates in UNIBEST*

| **Wave climate** | **Gross northward sediment transport [$m^3$/year] ↑** | **Gross southward sediment transport [$m^3$/year] ↓** | **Net sediment transport *Qs* [$m^3$/year] ↑** |
|---|---|---|---|
| UNI Noordwijk (269 cond.) | 397 204 | 196 424 | **200 780** |
| D3D Noordwijk (10 cond.) | 404 900 | 194 880 | **210 020** |
| D3D Egmond (9 cond.) | 496 984 | 267 784 | **229 200** |

### Actual cross-shore profile vs. fictional DMW-profile

Every simulation in this research uses the DMW-profile, so it is interesting to see what effect a different cross-shore profile has on the alongshore transports. In order to find out, the actual profile belonging to the existing UNIBEST-LT model is implemented (Figure 4.12). With the actual profile no noticeable difference in alongshore sediment transport and nourishment performance has been found. It can be concluded that the alongshore sediment transport and nourishment performance is insensitive to *small* changes in bathymetry.

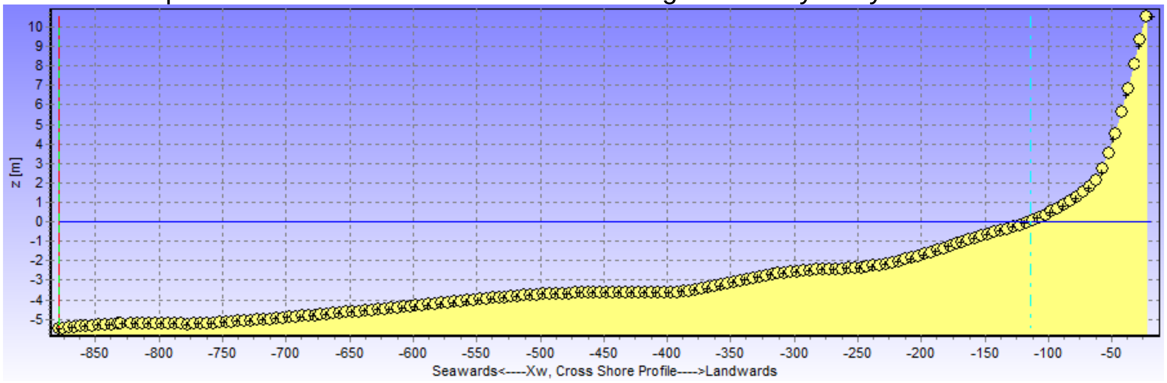



*Figure 4.12 – Original profile of the UNIBEST model (location close to Noordwijk)*

### Active height

For all simulations the active height is set to 7 meters, which was determined in section 3.1 by a rule of thumb which holds: the active height is approximately 2 to 3 times the 1/1 year significant wave height (2.9 m in this case). It would be interesting to see what happens to nourishment performance in time when this active height is increased, for instance by 1 m.

In order to make a fair comparison, the nourishment volume needs to be preserved, which means that the initial seaward extent has to be reduced respectively. The initial nourishment volume is 12.45 $Mm^3$ with a seaward extent of 667m and a length of 1668m. When the active height is set to 8 meters, the initial seaward extent reduces to 605m. As it turns out, increasing the active height while preserving the initial nourishment volume leads to no noticeable difference in nourishment performance.

<u>However, increasing the active height *only* will increase the initial nourishment volume and will result in slower diffusion along the coast.</u> For that reason, the active height is still considered an important parameter in this research!

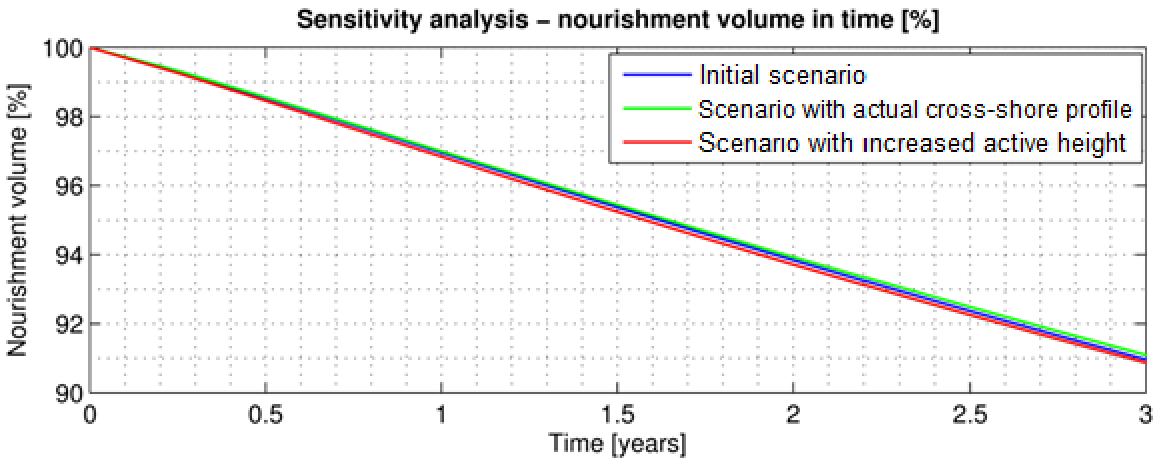



*Figure 4.13 – Nourishment volume in time for adapted profile and increased active height*

## 4.5 Effect of nourishing on the adjacent coastline

This research contains various nourishment dimensions and volumes. For safety aspects and strengthening the Dutch coastline, it would be interesting to see how each nourishment performs considering the advancement in coastline position on adjacent stretches of coast. To do so, two timeframes are chosen (20 and 40 years) at which the coastline position is examined. The length of the stretch is then defined as the length of the coast where there is progression in coastline position of at least 15m. For comparison, the calculated values are corrected for the nourishment length itself. This process is also carried out for a value of 30m. Results are shown in Table 4.3.

Results show that for the 333m seaward extent case, considerable gain can be achieved by increasing the alongshore length of the nourishment. After a period of 40 year, a substantial larger stretch of coastline has progressed. This is probably due to the fact that the gradients in coastline will sustain longer in time and therefore induce larger sediment transports.

For the 667m and 1000m seaward extent cases, it can be concluded that when the alongshore length of the nourishment increases, the stretch of coastline which is protected will only be lengthened by the additional alongshore length of the nourishment itself. This is at least true for the considered timescale of 20 and 40 years. It is expected that substantial larger differences will be found when taking a larger timescale in consideration.

*Table 4.3 – Effect of nourishment on adjacent coastline.* ***Values are corrected for nourishment length itself***

| Sea-ward extent [m] | Along-shore length [m] | Init. Vol. [$Mm^3$] | T = 20 yr. Stretch of coastline (accret. > 15m) | T = 40 yr. Stretch of coastline (accret. > 15m) | T = 20 yr. Stretch of coastline (accret. > 30m) | T = 40 yr. Stretch of coastline (accret. > 30m) |
|---|---|---|---|---|---|---|
| 333 | 833 | 3.49 | 8 485 m | 10 936 m | 5 485 m | 5 736 m |
| 333 | 1665 | 5.43 | 9 303 m | 12 603 m | 6 753 m | 8 503 m |
| 333 | 3330 | 9.31 | 9 788 m | 13 788 m | 7 488 m | 10 338 m |
| 667 | 1668 | 14.02 | 10 965 m | 15 665 m | 8 915 m | 12 565 m |
| 667 | 3335 | 21.80 | 11 097 m | 16 097 m | 9 147 m | 13 297 m |
| 667 | 6670 | 37.37 | 11 162 m | 16 262 m | 9 162 m | 13 562 m |
| 1000 | 2500 | 31.50 | 11 550 m | 16 950 m | 9 700 m | 14 300 m |
| 1000 | 5000 | 49.00 | 11 550 m | 17 100 m | 9 700 m | 14 500 m |
| 1000 | 10000 | 84.00 | 11 550 m | 17 100 m | 9 700 m | 14 500 m |

# 5 Delft3D model results

The results are grouped with respect to the amount of seaward extent, the same way as was done for the UNIBEST results. The exact same control element is used to consider the amount of nourishment volume in time (chapter 4). In this chapter, only the 333m seaward extent graphs will be presented and explained. In Appendix G, all results can be found.

## 5.1 Nourishment volumes in time & eroded volumes in time

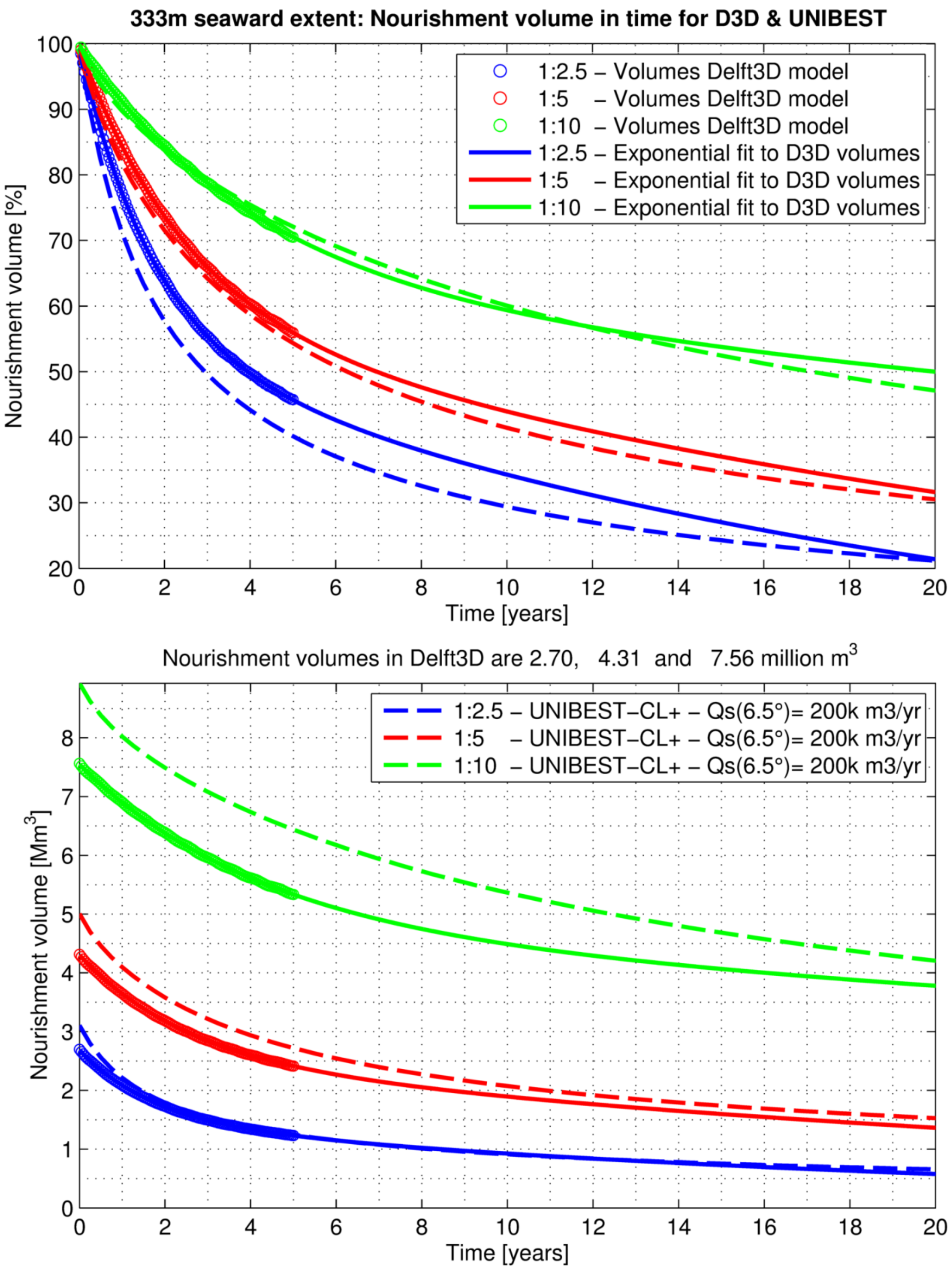



*Figure 5.1 – Nourishment volumes in time for 333m seaward extent – D3D & UNIBEST*

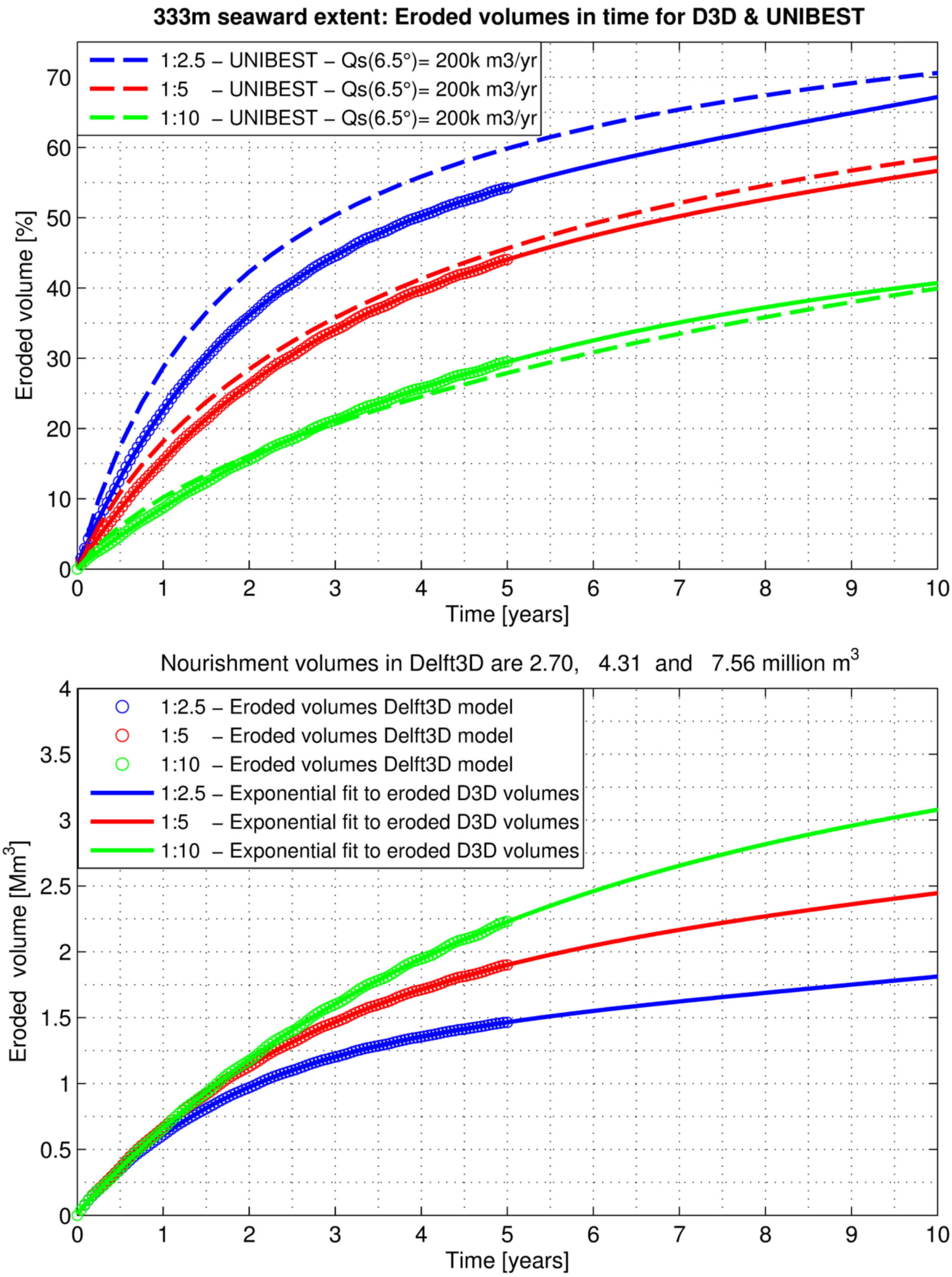



*Figure 5.2 – Eroded volumes in time for 333m seaward extent – D3D & UNIBEST*

Figure 5.1 shows calculated volumes in time for the 333m seaward extent nourishments, both for Delft3D and UNIBEST. The upper plot shows percentages and the lower plot absolute volumes. Figure 5.2 shows eroded volumes for the 333m seaward extent nourishments. Once again the upper plot shows percentages, while the lower plot shows absolute volumes.

## 5.2 Alongshore sediment transport

Figure 5.4 shows the alongshore sediment transport plotted against the alongshore distance of the nourishment. Figure 5.3 shows how these values are obtained; transects are taken until a depth contour of 10m for which the sediment transport through each transect is calculated. Sediment transports (suspended load + bed load) are averaged over full tidal cycles only.

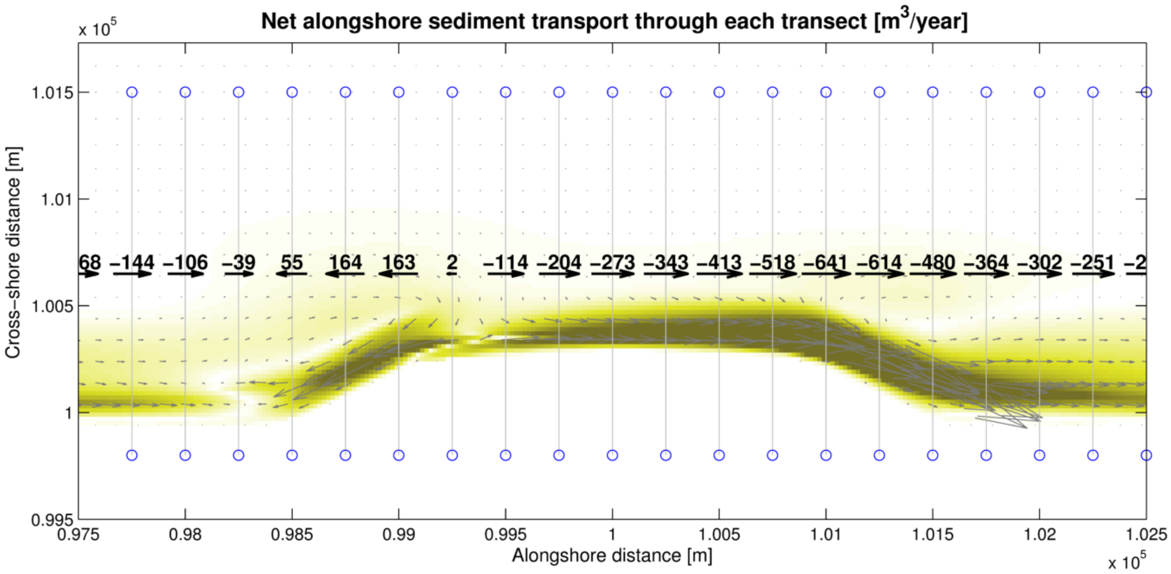



*Figure 5.3 – Top view of 333m x 1665m nourishment with alongshore sediment transports through each transect*

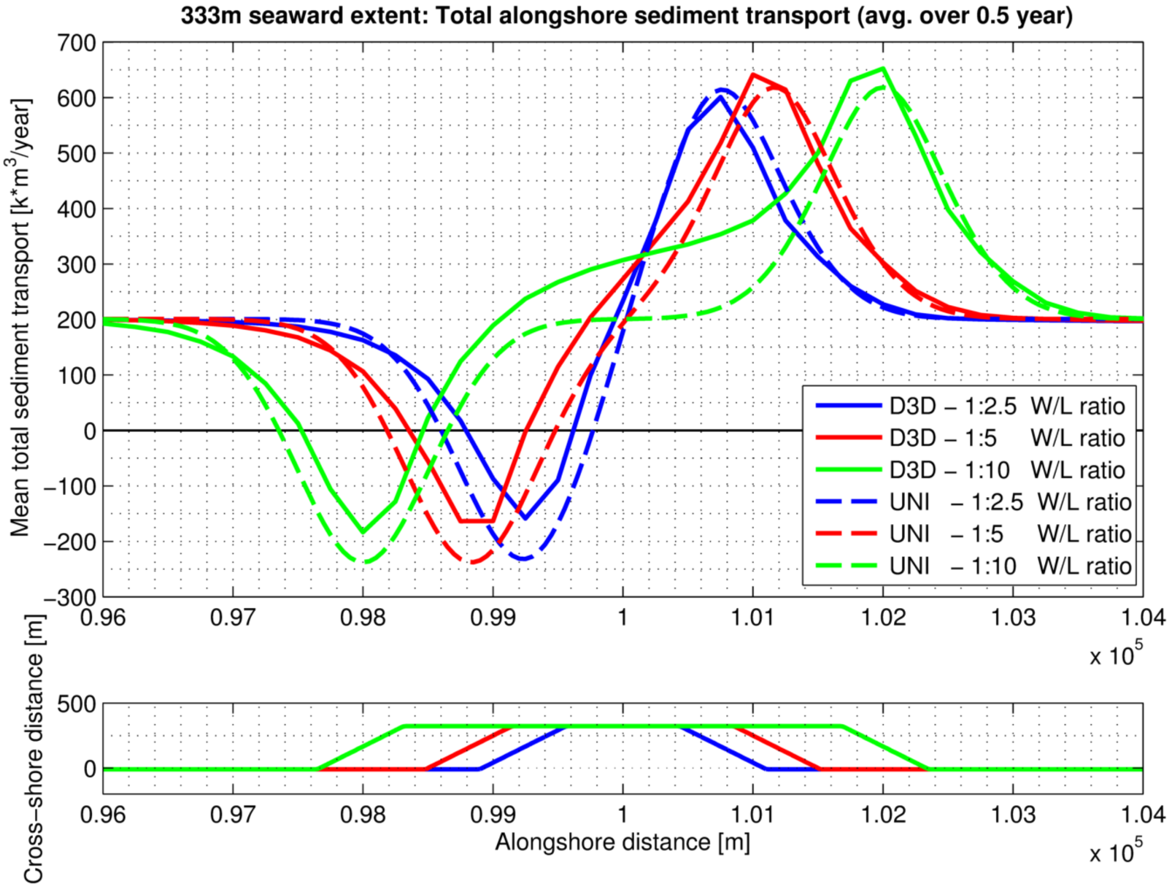



*Figure 5.4 – Net alongshore sediment transport vs. alongshore distance for the 333m seaward extent nourishments*

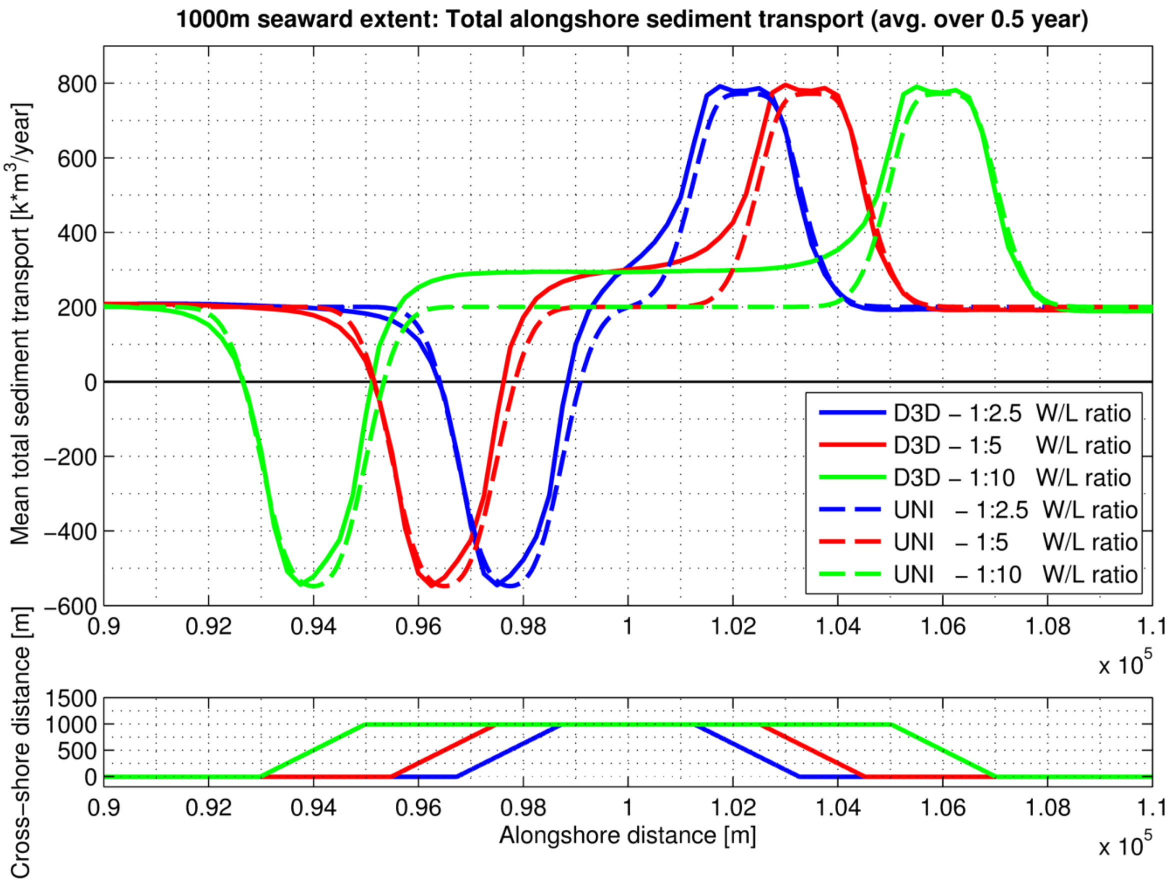



*Figure 5.5 – Net alongshore sediment transport vs. alongshore distance for the 1000m seaward extent nourishments*

Both Figure 5.4 and Figure 5.5 show a remarkable resemblance between the sediment transports calculated by UNIBEST and the sediment transports calculated by Delft3D. This is especially true for the large nourishments (1000m seaward extent).

However, at the straight middle section of the nourishments an anomaly can be observed between both models. At this section Delft3D calculates a substantial higher sediment transport (approximately 300 000 $m^3$/year) with respect to the adjacent coast on either side and with respect to the UNIBEST results in general (approximately 200 000 $m^3$/year). The effect is most noticeable for large nourishments in which a long straight middle section is present (Figure 5.5). The explanation for this effect will be further discussed in the next section.

### 5.2.1 Effect of increased cross-shore steepness on sediment transport

Recapitulating the above, Delft3D and UNIBEST show large resemblance regarding alongshore sediment transports, except at the middle section of the nourishment for which the Delft3D transports are approximately 1.5 times larger than for UNIBEST. This effect is most noticeable for nourishments with large alongshore lengths. The question which arises is:

*"Are these higher alongshore transports induced by the steeper (1:50) cross-shore nourishment profile or can they be the effect of tidal contraction?"*

In order to answer this question, the cross shore nourishment profile originating from the Delft3D model (Figure 5.6) has been implemented within the UNIBEST model. This cross-shore profile is applied at the straight middle section of the nourishment only. All other sections use the standard DMW-profile. Then, both the initial sediment transports (t=0) of the standard UNIBEST run (1 cross-shore profile) and the initial transports of the adapted UNIBEST run (2 cross-shore profiles) are compared to the initial transport from Delft3D.

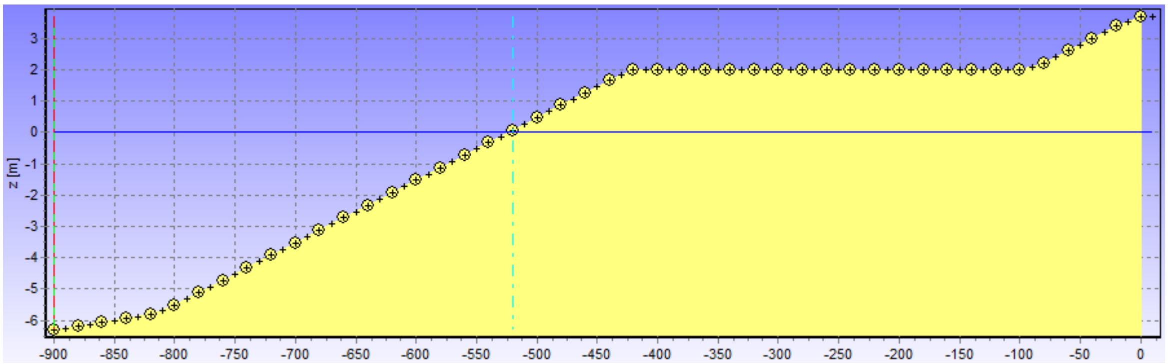



*Figure 5.6 – Cross-shore profile for the nourishment section within UNIBEST*

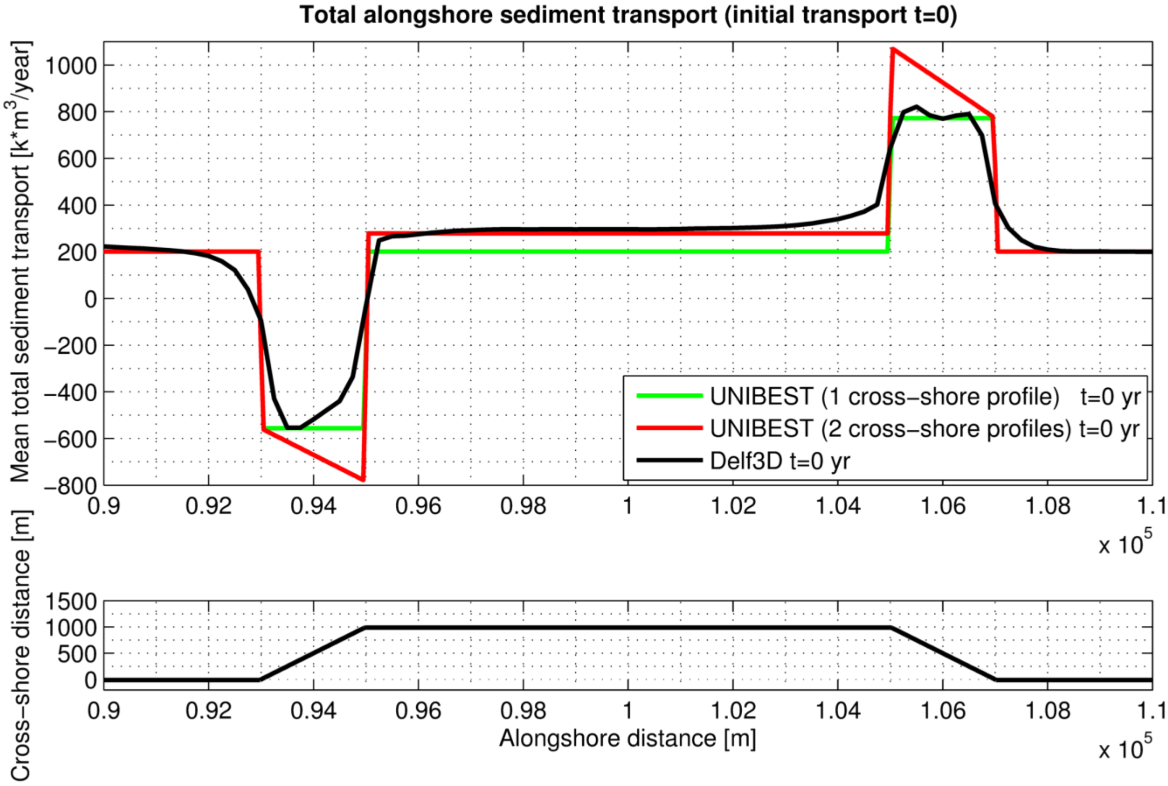



*Figure 5.7 – Comparison of alongshore sediment transport for UNIBEST with 1 & 2 cross-shore profiles*

The analysis has been carried out for the largest nourishment only (1 000m by 10 000m) because for this simulation the effect is most noticeable. The result can be seen in Figure 5.7.

It appears that UNIBEST with the adapted cross-shore profile in the middle section also calculates higher sediment transports, approximately the same values as Delft3D (Table 5.1). Because in UNIBEST no tidal components are present, the effect of the higher transports is solely due to the increased steepness of the cross-shore profile.

*Table 5.1 – Sediment transport at unaltered stretch of coastline & (straight) middle section of nourishment*

| **Simulation** | **Sediment transport at unaltered stretch of coastline [m$^3$/year]** | **Sediment transport at straight middle section of nourishment [m$^3$/year]** |
|---|---|---|
| UNIBEST (1 cross shore profile) | 200 780 | 200 780 (+ 0%) |
| UNIBEST (2 cross shore profiles) | 200 780 | 278 640 (+ 39%) |
| Delft3D (spatial varying cross-shore profile) | ≈ 200 000 | ≈ 296 000 (+ 48%) |

According to an analysis of the bed slope effect on alongshore sediment transport carried out by van Rijn (2014b), a twice as steep cross-shore profile leads to **an increase in sediment transport of about 32%** (see also section 2.3). The average steepness of the standard DMW-profile is about 1:110 between the waterline and the 6m depth contour. For the cross-shore profile near the nourishment a steepness of 1:50 has been used.

Concluding the above, the observed increase in sediment transport of 39% between the two UNIBEST runs is in good agreement with the analysis of van Rijn (section 2.3). When comparing the Delft3D runs with UNIBEST while using the same cross-shore profile, roughly the same sediment transports are being calculated. Therefore it is assumed that the higher sediment transports along the straight sections of the nourishment are caused solely due to the increased steepness of the cross-shore profile.
Furthermore, it is assumed that tidal contraction does not play a significant role and hence does not lead to increased sediment transports at large scale nourishments.

5.2.2 Adaptation-length of alongshore transports near nourishments.
When looking at the initial alongshore transports calculated by Delft3D and UNIBEST, it can clearly be seen that the transports differ (Figure 5.7); in UNIBEST they are block shaped and act instantaneously on each stretch of coastline depending on the local coastline orientation. In Delft3D a certain *adaptation-length* is observed which can be defined as the length that is needed for the sediment transport to adapt to the new equilibrium transport which applies at that particular stretch of coastline. In Figure 5.7, adaptation-lengths are visible at alongshore distance x= 0.91-0.93, 0.95-0.97, 1.02-1.05 and 1.07-1.08 x10$^5$ meter.

When looking at the alongshore transport graphs for each nourishment, it can be concluded that the adaptation length for the initial transports can be considered constant with a magnitude of 1500 meters. This conclusion is also valid for the middle section. A straight middle section of at least 3000m is therefore necessary to achieve the equilibrium situation. Nourishments with less alongshore length are continuously adapting to the new cross-shore profile.

### 5.2.3 Tidal contraction

At the beginning of this research it was expected that the effect of tidal contraction near a nourishment would cause a noticeable increase in sediment transport which would lead to larger gradients and therefore would cause more erosion. Tidal contraction occurs due to the large size of the nourishment, in which the tidal velocities are being concentrated in a narrow space right in front of the nourishment which leads to larger current velocities.

This paragraph will try to quantify this effect on the alongshore sediment transport. In order to do so, the largest nourishment has been simulated in a model where only a tidal forcing is applied. The same is done for a straight bottom and the resulting sediment transports are then compared.

It appears that the alongshore sediment transport on a straight coast due to tidal forcing only has a magnitude of approximately **24 000 m$^3$/year** (eastward direction). Note that this value is much smaller than the results of the model in which tide and waves were combined (≈ 247 000 m$^3$/year). The sediment transports on the straight middle section of the largest nourishment (1 000m by 10 000m) are surprisingly equivalent: approximately **22 000 m$^3$/year**.

This can be explained by looking at Figure 5.8, in which the maximum depth averaged velocities in a tidal cycle are examined. It can clearly be seen that only at the edges of the nourishment substantial higher velocities can be found compared to the surrounding area. At the straight middle section of the nourishment the current velocities are equivalent to the velocities at the straight coast.

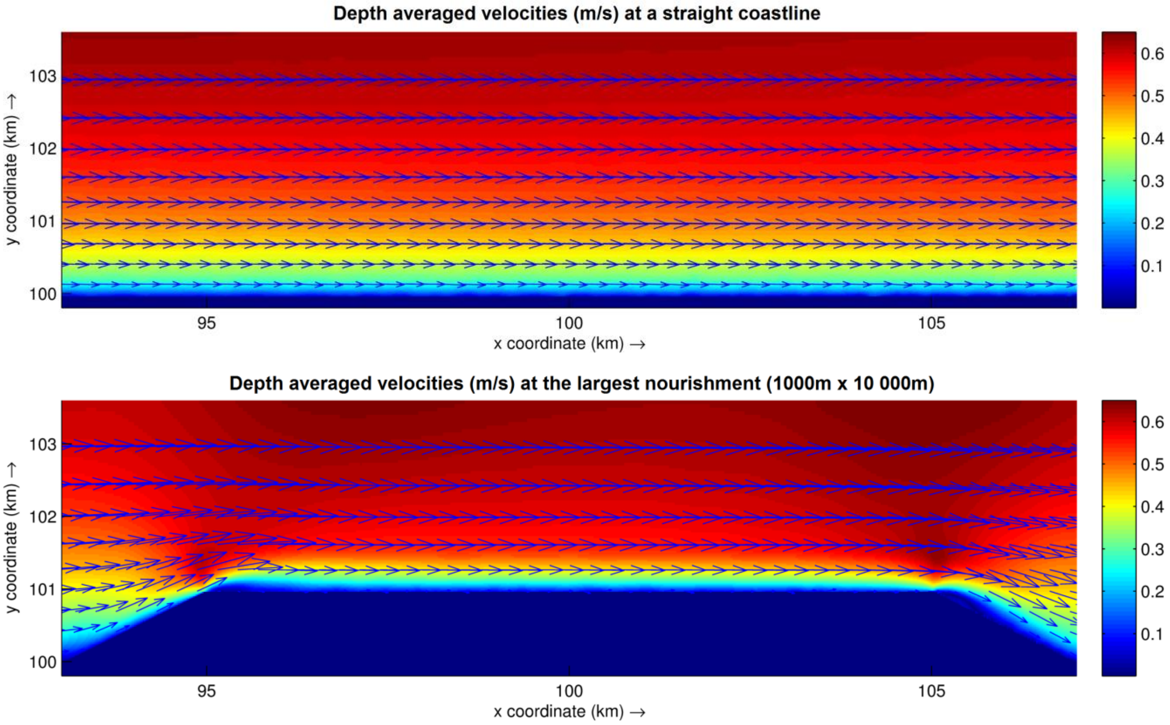



*Figure 5.8 – Maximum depth averaged velocities (m/s) at a straight coastline and at the largest nourishment*

It can be concluded that tidal contraction does not have a big impact on the amount of sediment transport and hence on the diffusivity of large scale nourishments. It plays a marginal role at the edges of the nourishment only. The effect is not noticeable at the straight sections of a nourishment. However, this brief analysis has only examined one point in time in the entire tidal cycle. It might be possible that at another moment in time the effect is much more noticeable.

## 5.3 Design graphs

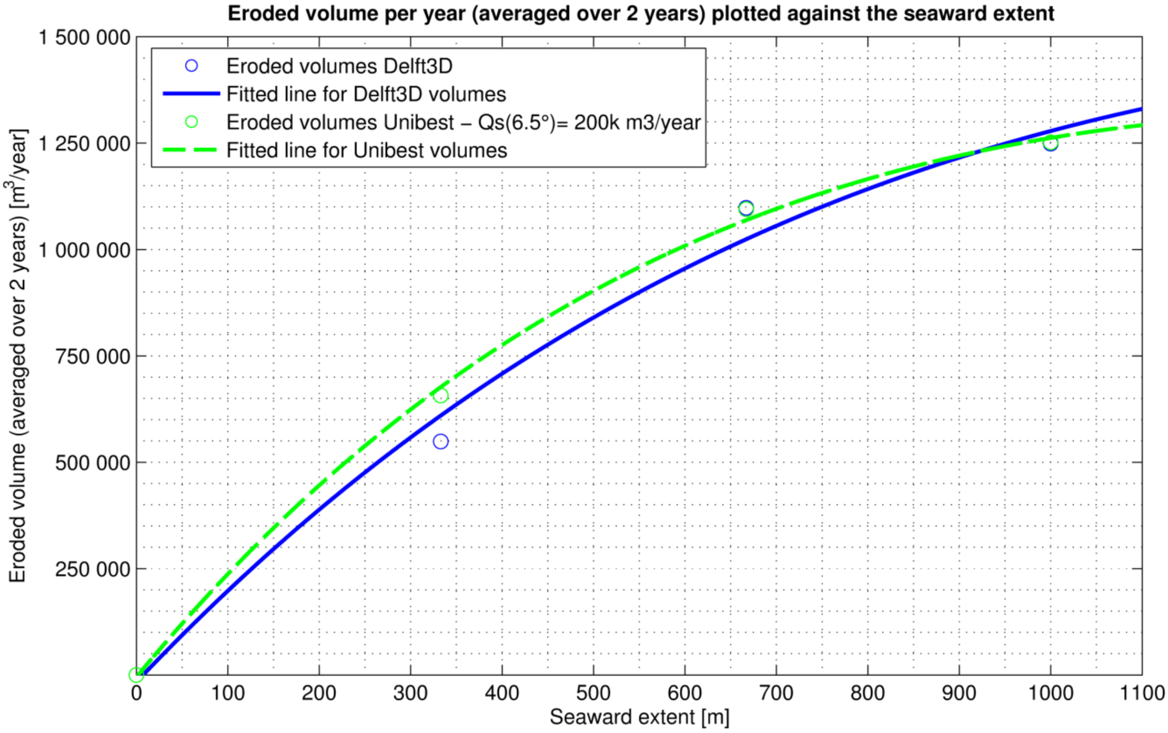



*Figure 5.9 – Eroded volume per year (averaged over 2 years) plotted against the seaward extent – D3D & Unibest*

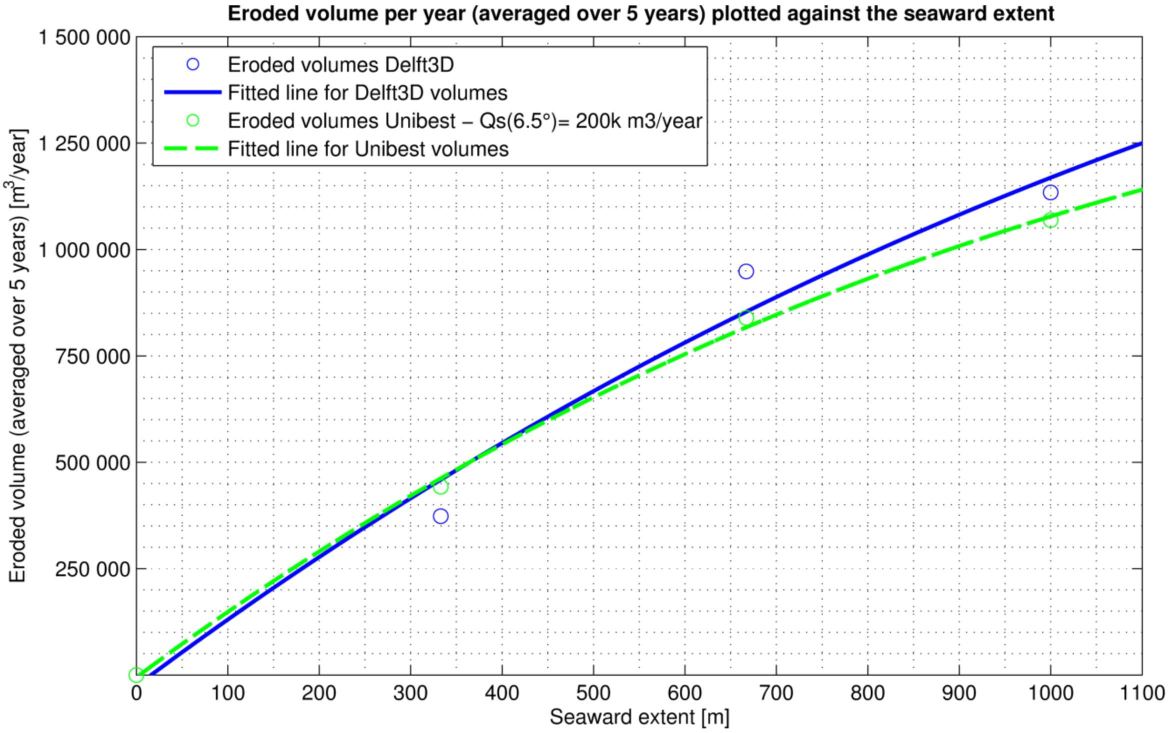



*Figure 5.10 – Eroded volume per year (averaged over 5 years) plotted against the seaward extent – D3D & Unibest*

Figure 5.9 and Figure 5.10 show the eroded volumes per year against the seaward extent averaged over a 2 & 5 year period respectively. Once again Delft3D and UNIBEST show equivalent results. These graphs can be used for estimating maintenance volumes.

# 6 Comparison of Delft3D & UNIBEST results

This chapter will present the findings and conclusions of a comparison between the UNIBEST and Delft3D results. The graphs with the results from both models are already presented in this document and will therefore not be presented again.

## 6.1 Sand Motor case

Both models are validated by implementing the Sand Motor nourishment (see section 3.1.2 for UNIBEST and section 3.2.2 for Delft3D). When taking into account a timeframe of 20 years, the resemblance between the results of the time series wave acclimate and the yearly averaged wave climate within UNIBEST is very large. Another striking similarity can be noticed between UNIBEST and Delft3D results (see Figure 3.20).
However, it turns out that the dynamic boundary in UNIBEST is a very sensitive parameter. When placing the dynamic boundary close to shore, similar results can be found as with Delft3D. But placing the dynamic boundary further offshore results in a dramatic drop in sediment transport peaks (up to 43%) due to the wrongfully calculated refraction effect, which has a large effect on the diffusivity of nourishments. From the Sand Motor case it can be concluded that alongshore sediment transport is probably the most important driving force for the diffusion of nourishments and that UNIBEST in combination with a well-placed dynamic boundary provides similar results to Delft3D.

## 6.2 Schematized nourishments

Also for schematized nourishments it turns out that UNIBEST and Delft3D perform very similar. This can best be observed when looking at the alongshore transports (Figure 5.4, Figure G.6 and Figure G.9), which show an exceptional resemblance especially for the 667m and 1000m seaward extent cases. Only at the straight middle section of the nourishments significant differences can be observed. This could be due to the effect of tidal contraction in which the tidal current is concentrated in front of the nourishment or it could be the effect of the steeper cross-shore nourishment profile. According to section 5.2.1, in which the steeper nourishment profile has been implemented in UNIBEST, the latter proves to be the case.

## 6.3 Conclusion

Surprisingly and a bit unexpected is the fact that the UNIBEST & Delft3D results are very similar. This is counter intuitive since both models are based on a completely different concept (see Appendix B – Model description and comparison). Since these models perform so equal and both models have been validated by using the Sand Motor case (see chapter 3), it can be concluded that UNIBEST can be used for simulating large scale nourishments, even when strong curvature in coastline exists.
Furthermore, the UNIBEST time series provide a near perfect fit on the measured data at the Sand Motor within the first two years. This enhances the conclusion that the alongshore sediment transport is the most important driving force for the diffusion of nourishments along the Dutch coast.
Another important conclusion is about using UNIBEST in combination with a nearshore located dynamic boundary. Traditional 1D coastline models do not include such a dynamic boundary and will therefore consistently underestimate alongshore sediment transports and therefore nourishment performance since most of the time nearshore wave conditions are not available and the entire cross-shore profile rotates in the same way as the coastline. Refraction is then wrongfully calculated which reduces the peaks in alongshore sediment transport. UNIBEST shows that a 1D line model can also be used in a more sophisticated way by means of a well-placed dynamic boundary.

# 7 Application of the design graphs

In this chapter the design graphs will be applied on an existing large scale nourishment, but first a short recap will follow for the location and use of the design graphs within this research.

- Temporary nourishments: Focus on lifespan
  - **Figure 4.6** in section 4.3 shows the half-life compared to the initial volume for which relatively easy the half-life can be read when the initial volume, L/W ratio and net annual alongshore transport are known. When the half-life is known, an exponential decay can be assumed to get to arbitrary chosen threshold values. This design graph is based on UNIBEST results only.
- Permanent nourishments: Focus on erosion rates
  - **Figure 4.7** and **Figure 4.8** in section 4.3 show the erosion rates plotted against the seaward extent averaged over 2 and 5 years respectively for which initial eroded volumes can be calculated. These graphs are based on UNIBEST and are presented for net annual alongshore transports of 100k, 200k and 400k $m^3$/year.
    **Figure 5.9** and **Figure 5.10** in section 5.3 also show the erosion rates plotted against the seaward extent averaged over 2 and 5 years respectively. These graphs are based on Delft3D and are carried out for a net annual alongshore transport of 200k $m^3$/year only. For convenience, the UNIBEST line is also plotted.

## 7.1 Hondsbossche & Pettemer Sea Defence

This section will apply the design graphs of this research on a mega nourishment at the ‘Hondsbossche & Pettemer Sea Defence’ (HPSD) which is currently under construction near Petten (see section E.2 in Appendix E). Because this nourishment has the function of a land reclamation, it can be considered a permanent nourishment and therefore needs to be maintained in time. Hence, the focus will be on erosion rates and maintenance volumes for the first years.

In order to apply the design graphs, first the alongshore transports on the unaltered stretch of coast has to be known. This is not easy to determine, but for the Dutch coast various studies are carried out (van de Rest, 2004; van Thiel de Vries, 2009). These studies suggest an alongshore transport near Petten in the range of 150 000 – 200 000 $m^3$/year. However, the alongshore transports in this region show a very large gradient in the form of a rapid increase in northward direction which makes obtaining a representative value a sensitive task. For instance, just south of the HPSD the transport is nearly zero, while just north of the HPSD values of 400 000 $m^3$/year can be found. In here a value of 200 000 $m^3$/year will be used.

The nourishment consists of a beach extension of approximately 30 million $m^3$ and a foreshore nourishment of approximately 10 million $m^3$. Because the focus of this research is on beach extensions, only the 30 million $m^3$ nourishment will be analysed. As of the latest figures (Hoogheemraadschap & Rijkswaterstaat, 2014), the dimensions of this nourishment are:

- Approximately 8 000m length of newly developed beaches
- Seaward extent of 350 – 550 m (part above MSL)
- Length to width ratio of approximately 25:1 to 30:1

The seaward extent proves to be a tricky parameter in this case, since the currently existing hard sea defence is already shifted towards sea with respect to the adjacent coast. This can be visualized by looking at Figure 7.1 in which the design of the nourishment can be seen and for which a fictional coastline is drawn in between the adjacent coastlines (Van Oord - Boskalis, 2013). It is questionable whether to take this extra seaward extent into account and for that reason the range 350 – 550 is considered.

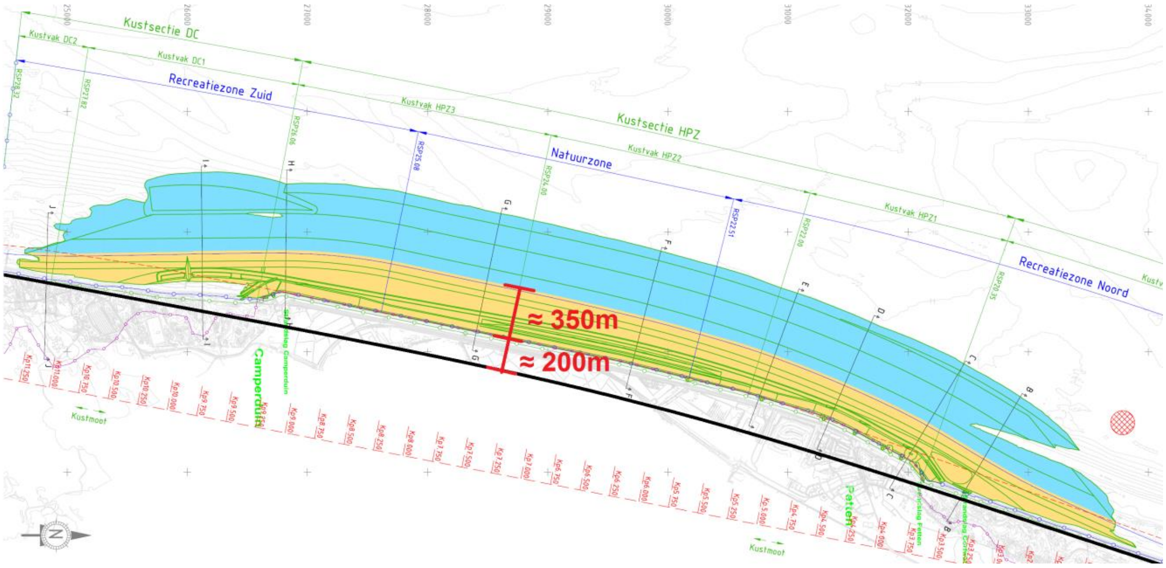



*Figure 7.1 – HPSD nourishment design. The black line represents fictional coastline when adjacent coastline is extended (Van Oord - Boskalis, 2013)*

According to the design graphs the expected erosion is:

*Table 7.1 – Eroded volume per year averaged over 2 year and 5 years*

| **Considered timeframe** | **Expected erosion rates [$m^3$/year]** | **Expected maintenance volume [$Mm^3$]** |
|---|---|---|
| 2 years | 600 000 – 900 000 | Every 2 years: 1.2 – 1.8 |
| 5 years | 475 000 – 700 000 | Every 5 years: 2.4 – 3.5 |

If the nourishment is **maintained every 2 years**, this means that **1.2 – 1.8 $Mm^3$** needs to be nourished. If the nourishment is maintained **every 5 years**, **2.4 – 3.5 $Mm^3$** needs to be nourished to account for the sediment loss.

According to the contractor Van Oord – Boskalis, the erosion rates are (Van Oord - Boskalis, 2013):

- 580 000 $m^3$/year for the 1st year
- 320 000 $m^3$/year for the 2nd, 3rd and 4th year
- 370 000 $m^3$/year for the 5th year

If maintenance is carried out **every 2 years**, **0.9 $Mm^3$** needs to be nourished. For the situation when **every 5 years** maintenance is carried out, **1.9 $Mm^3$** needs to be nourished. These numbers are quite close to the lower limit of the design graph predictions, but are still 20 – 25% smaller.

Furthermore, it can be stated that in the design of the nourishment the contractor takes initial sand losses into account by adding a ‘wear layer’ of 1m on top of the nourishment.

## 7.2 Step-by-step approach

This section provides a step-by-step approach for applying the design graphs on nourishments along the Dutch coast.

<u>Temporary nourishments: Focus on lifespan</u>

1. Retrieve the **L/W ratio** for the nourishment by looking at the seaward extent (cross-shore width of nourishment above MSL) and the alongshore length (taken at the seaward boundary without nourishment edges). Furthermore, determine or estimate the **volume** of the total nourishment.
2. Determine the **net annual alongshore transport** at the considered stretch of coast.
3. Use Figure 4.6 to obtain the half-life of the nourishment. This is the time which is needed for the nourishment to reduce to half its initial volume.
4. Further volume decay in time can be obtained by assuming an exponential decay function:

$$V(t) = V_{\text{initial}} * 2^{-t/t_{1/2}} \quad (10)$$

in which $t_{1/2}$ is the half-life and $t$ an arbitrarily chosen moment in time.

<u>Permanent nourishment: Focus on erosion rates</u>

1. Determine the **seaward extent** as accurate as possible from the nourishment design, since this is a sensitive parameter for erosion rates.
2. Determine the **net annual alongshore transport** at the considered stretch of coast.
3. For a net alongshore transport close to 200k $m^3$/year, use Figure 5.9 and Figure 5.10 to obtain erosion rates in $m^3$/year averaged over 2 years and 5 years respectively. For lower or higher transports (range 100k – 400k $m^3$/year) use Figure 4.7 and Figure 4.8.
4. When the erosion rates per year are known it is possible to calculate maintenance volumes. This can be done by multiplying the erosion rates by the timeframe for which the erosion rates are averaged. For instance the erosion rates averaged over 2 years multiplied by 2 gives the volume which is needed after 2 years.

# 8 Discussion

A number of different aspects may have an influence on the applicability of the methods and design graphs in this research. These aspects are:

- Inclusion of physical processes
- UNIBEST and Delft3D model concepts
- General approach

**Inclusion of physical processes**

- This research has its limitations because it assumes that only the alongshore processes are of importance when considering the diffusion of nourishments. Most of the time this is a valid assumption, but during storms the cross-shore processes can have a significant effect on sediment transport. These cross-shore processes are not taken into account in UNIBEST and are partly accounted for in Delft3D. However due to the mormerge approach and the depth averaged calculation method (2DH), these cross-shore processes are not modelled correctly. For instance, during storms a strong undertow can occur which can cause severe erosion of sediment in offshore direction.

- Infragravity waves are also not taken into account. Generally, these waves have periods in the range of 20 – 200 seconds, where they are often standing in the cross-shore direction, resulting in a stationary drift velocity field in the bottom boundary layer (Aagaard & Masselink, 1999). They are considered important for nearshore bar formation and the generation of three-dimensional features such as rip currents, but can also have a significant role in changing the cross-shore profile, for instance due to heavy storm impact (dune erosion). This change in cross-shore profile might lead to different alongshore transports.

**UNIBEST and Delft3D model concepts**

This research shows that UNIBEST is quite capable of simulating the diffusivity of large scale nourishments along the Dutch coast. However, a UNIBEST sensitivity analysis (section 4.4) shows that some parameters can have a large influence on the model results:

- The applied active height of the profile has a large impact on the computed coastline evolution and hence the diffusiveness of the nourishment. This active height is used for the translation of sediment budgets to coastline changes. In the considered cases the active height is set to a fixed value of 7m. It is observed that a change of this active height by 1 m has a very large effect on the resulting volumes and therefore on the diffusiveness of nourishments. It is noted that the active height depends on the timeframe for which the model is used. For instance, in 20 years of time, sediment at larger depths can be mobilised compared to a timeframe of 1 year. However, this dependency is currently not incorporated in the rule of thumb.

- The dynamic boundary, which is positioned at a certain depth and corresponding cross-shore distance from the coast, defines which part of the cross-shore profile rotates in the same way as the coastline. This parameter can have a significant effect on refraction. Sensitivity tests show that the location of the dynamic boundary has a very large effect on sediment transport and therefore on the evolution of a nourishment. There is no optimal choice for the dynamic boundary, but it is most of the time located at shallow water (for instance at a depth of 6m) since the foreshore is not expected to change orientation if it is located outside the littoral zone. However, if the dynamic boundary is specified too close to shore, the alongshore sediment transports are cut off which causes an underestimation of the alongshore transports.

- In order to obtain stable results within UNIBEST, the model has been adapted to cope with relative wave angles larger than ≈ 44° (see section 3.1). For larger values, the transport would normally decrease, but the model adaptation ensures a maximization of transports for these large angles. This is necessary to obtain stable results and the adaptation is mainly used at locations where the coast has a strong curvature, for instance at the edges of nourishments. However, this adaptation may cause an overestimation of alongshore transports when strong curvature of the coast is present, for instance directly after construction at the edges of the Sand Motor. Appendix B.3.4 shows that the adaptation was not necessary for the artificial nourishments used in this research. The edges of the nourishments with a L/W ratio of 2:1 together with the equilibrium coast angle of 6.5° never caused relative wave angles of 44° or more. For yearly averaged wave climates at the Dutch coast, the equilibrium angle is close to the shore normal and the adaptation is not used that often and limited to strong curvature coasts only. However, when using a time series of wave conditions, the waves can originate from almost every direction, so the UNIBEST adaptation for maximizing sediment transports is required much more often. Further research is needed in order to quantify the overestimation.

- Another interesting point of discussion is the comparison between the roller model (expression of Ruessink) and the van der Westhuysen expression (see Appendix C). Both expressions are using a variable wave breaking index $\gamma_w$, which increases linearly with the product of the local wave-number and water depth, *kh*. It turns out that the 'background horizontal eddy diffusivity coefficient $D_h$' has a very large effect on morphology. This research uses the roller model with a low value of 0.25 $m^2/s$ for all model runs. However, it seems that the van der Westhuysen expression performs substantial better when the parameter $D_h$ is increased to a value of $D_h$ = 1.00 $m^2/s$, supposedly even better than the roller model when looking at bathymetry changes after 3 years. This is an interesting observation since the parameter $D_h$ is normally chosen very low to prevent lateral mixing of sediment. Further research is however necessary to give a decisive answer about the use of the van der Westhuysen expression in combination with larger values for the diffusivity parameter.

- For the Delft3D model it was necessary to perform a wave input reduction. A dataset of 23 years wave observations has been reduced to 10 individual wave conditions each with a specific occurrence. This should provide a representative wave climate for the Dutch coast. Although this is an ordinary procedure, errors are always introduced while doing this. It is possible to verify the input reduction by implementing a large part of the wave observations into UNIBEST and check the corresponding net and gross transport rates. These can then be compared to the transport rates for the set of 10 wave conditions.

- Due to the 2DH approach of the model, 3-dimensional features cannot be modelled such as density currents and undertow. These processes can have a large effect on the velocity distribution over depth. For instance, undertow causes a current close to the bottom which is opposite to the direction of the regular current. In the 2DH model the current velocities are completely uniform over depth.

**General approach**

- All nourishments in this research are trapezoidal shaped with nourishment edges which are triangular in a ratio of 1:2 (cross-shore width/alongshore length). Since the sediment transports in UNIBEST are driven by the relative coastline angle, it might be possible that this ratio, basically the alongshore steepness, plays an important role in nourishment performance. It is expected that this is true for at least the first year after construction, since the coastline angles have not changed much in such a short timeframe. This could be of high importance for the 'permanent type' of nourishment where erosion is not wanted since the nourishment needs to be maintained.
  Furthermore, the cross-shore steepness is kept constant for all nourishments (1:50). It might be possible that this steepness also plays an important role in sediment transport, for which further research is recommended.

- As mentioned in the introduction, the alongshore sediment transport Qs = 200 000 $m^3$/year corresponding to a grain size of 200 μm has been manually scaled by a factor ½ and 2 in order to get lower and respectively higher transport. This results in respectively faster or slower diffusion of the nourishment and therefore provides more bandwidth in the results. In fact, this scaling mainly enlarges / decreases the peaks of the S-φ curve (on the y-axis). The physical meaning of this is that the intensity of the wave climate is changed. However, the influence of the equilibrium coast angle (the x-axis) is not represented well in this approach. For instance, a twice as large alongshore transport can also be achieved by an increased equilibrium coast angle. The idea behind this is that if the alongshore sediment transport on a stretch of coast is known, one can easily find the corresponding design graph. For this purpose it is necessary to compute the ratio of sediment transport divided by the current coastline angle. This can be compared to the ratios of the design graphs (e.g. 200 000 $m^3$/year divided by 6.5°). The approach used in this research is thus only applicable if data on the alongshore transport is available together with the equilibrium coast angle.

- Due to the small equilibrium angle of 6.5° for the wave climate which has been used, the outcomes of this research are valid for the Dutch coast only. The Dutch coast can be classified as exposed with a nearly perpendicular wave approach with an angle of incidence of 1° - 10° (Mangor, 2004). It would be interesting to see whether the design graphs still can be used with different wave climates, for instance with a larger angle of incidence.

# 9 Conclusions

This chapter provides the answers to the research questions and determines whether the research goals which are stated in the introduction are achieved (section 9.1). Furthermore, some general conclusions are published based on the findings of this research (section 9.3).

## 9.1 Research questions and research goals

The primary research question '*How does the erosion rate of nourishments depend on their size, shape and sediment characteristics'* will be answered by answering all sub questions:

- *What are typical shapes of large scale nourishments?*
  Every nourishment in this research uses a trapezoidal shape for its alongshore profile. The shape is specifically chosen after analysing various reference nourishments. For most places where nourishments are applied, not just safety is considered an important factor, but also factors like recreation and ecology. For recreational purposes it is wanted to have a wide and sandy beach, so most large scale nourishments which have been applied at the Dutch coast are of the type 'beach nourishments' or 'beach extensions', in contrast to for instance backshore nourishments or shoreface nourishments, which are respectively located in the dune area or beneath the water surface.
  If protecting the coast has the highest priority while keeping recreational purposes in mind, a straight pushed forward stretch of coastline is a clear option. At both sides the advanced stretch of coastline returns to the unaltered coast under a certain angle. These 'corners' are most likely outside the area which needs to be protected and generally have a mild alongshore slope. A milder slope results in less pronounced gradients in sediment transport and therefore slower erosion in time. This particular solution has been applied at the 'Hondsbossche Zeewering', 'Noordwijk' and 'Katwijk'. An exception to the above is the Sand Motor, which uses a specific and highly spatial varying shape with inner lakes and lagoons. This is done because the Sand Motor is considered a first experiment for large scale nourishments in which many aspects are investigated, for instance ecology, swimming safety and recreation, so a large variability is preferred.

- *What parameters influence the redistribution of sand?*
  The main finding of this research is that waves are considered the most important factor for the redistribution of sand. Breaking waves stir up the sediment, which is then transported by the wave-induced alongshore current. The resulting sediment transport is considered a measure for the diffusivity of nourishments along the coast. Tidal forcing does also play role, but the effect on the alongshore sediment transport is a factor 10 smaller compared to the forcing of waves and tide combined:
  - Tidal forcing only generates an alongshore sediment transport of approximately 22 000 $m^3$/year (200 μm D50)
  - Waves and tidal forcing combined generate an alongshore sediment transport of approximately 247 000 $m^3$/year (200 μm D50).

  Also other parameters have influence, for instance the grain diameter (discussed hereafter) and the cross-shore slope of the nourishment.
  In general, the larger the grain size, the smaller the alongshore sediment transport. And a steeper cross-shore slope generally results in a larger alongshore sediment transports.

- *How is the diffusion of sediment influenced by the volume?*
  For every run carried out with UNIBEST the half-life has been calculated, which can be defined as the amount of time it takes for the nourishment to reduce to 50% of its initial volume. This half-life is then plotted against the initial volume of each nourishment (see Figure 4.6). According to the UNIBEST results, the relation between volume and half-life is very linear. This was as expected since the sediment transports in UNIBEST are calculated with the S-φ curve and the position of the coastline angle relative to the wave angle. The transports are therefore not directly dependent on the size (= volume) of the nourishment. It was expected that simulations with Delft3D would find a different relation between volume and diffusion (i.e. half-life) of the nourishment, but this could not be verified since it was not possible to perform very long runs with Delft3D. Limitations in computation time resulted in runs with a maximum of 5 years in morphological development. However, since the Delft3D results even after extrapolating are more or less comparable to the UNIBEST results, it is not expected that the Delft3D results will differ much.

- *How is the diffusion of sediment influenced by the shape?*
  This research uses different width-to-length ratios (1:2.5, 1:5 and 1:10) to vary the shape of nourishments. The main conclusion when comparing these different ratios is that increasing the alongshore length of the nourishment does not increase the *erosion rates* when considering a timeframe of for instance 20 years. This effect is also observed in section 4.4, where the effect of nourishing on the adjacent coastline has been examined. The main conclusion in this section is that extending a nourishment simply protects an additional stretch of coast equal to the length of the additional nourishment length itself. Only at longer timescales the extra volume of the extended nourishment can make a substantial difference. This is due to the fact that the gradients in the coastline, for extra-long nourishments, will remain larger for a longer period of time, simply because more sediment is available.

  The amount of seaward extent, for which three values are examined (333m, 667m and 1000m), seems to be much more important. According to Figure 4.7, the erosion rates rapidly increase when the nourishment is extended further into sea. The effect is strongly dependent on the magnitude of the alongshore transport (= severity of the wave climate). A climate with a large transport capacity quickly fades the seaward protruding nourishment away.

- *How is the diffusion of sediment influenced by the grain size?*
  This research uses the TRANSPOR2004 sediment transport formulations developed by van Rijn (2007a, 2007b, 2007c), which are implemented in both UNIBEST and Delft3D. It appears that the grain size D50 has a small effect on the alongshore sediment transports and therefore a secondary influence on the diffusivity of large scale nourishments:
  - When the grain size is **doubled from 200 μm to 400 μm**, the alongshore sediment transport reduces with **19%** (from 200 780 $m^3$/year to 163 630 $m^3$/year).
  - When looking at nourishment performance in time, the diffusivity of large scale nourishments is only **3 - 6 %** slower with a grain size of 400 μm and is largest for nourishments with 1000m seaward extent.

  For the current simulations with a median grain diameter ranging from 200 μm to 400 μm, the grain size has little to no effect on the diffusivity of a nourishment, which is a bit unexpected and counter intuitive. Note that in this research only the D50 has been altered. It is possible that for instance sediment grading and armouring also has an effect on the magnitude of sediment transport.

The secondary research question *'At what seaward extent are the erosion rates of large scale nourishments influenced by the dimensions of the nourishment itself'* is much harder to answer since no hard evidence has been found within the Delft3D results. This may be related to the mormerge approach used in all Delft3D runs which results in smoothed morphological behaviour. For these results it is very hard to find the effect of each individual wave condition on aspects like morphology and sediment transport.

## 9.2 Engineering guidelines

For engineering applications it can be very valuable to have an overview of the typical life span of nourishments at the Dutch coast. First, a nourishment type is discussed which is allowed to spread along the coast. And after that a nourishment type which is maintained.

### Diffusive nourishments

This part will present some specific conclusions on the 'temporary type' of nourishments which are allowed to spread along the coast and in which the lifespan is of high importance:

- Nourishments designs with a large seaward extent may place a considerable amount of sand at larger depths where it is inactive. This is often undesirable since the sediment should not remain at large depths where it cannot be picked up by waves and currents. This is the case for nourishments which extend very far into sea because their reattachment point to the original cross-shore profile is located at a large depth.
- It is expected that for nourishments with a large seaward extent a substantial loss of sediment in offshore direction can occur. The optimal seaward extent is therefore in the range of 400m – 700m for which the erosion rates are high and at the same time the sediment can be mobilised.
- When the lifespan of a nourishment is defined as the period of time it takes until the nourishment achieves 20% of its initial volume, even the smallest nourishment (333m x 833m) is still not diffused out after 20 years.
- Table 9.1 shows the performance of nourishments expressed in the eroded volumes after a period of 20 years.
- The half-lives for a nourishment of 20 $Mm^3$ are in the range of 18 to 38 years depending on the L/W ratio. For a nourishment with an initial volume of 30 $Mm^3$, half-lives are ranging from 29 to 57 years depending on the L/W ratio.

*Table 9.1 – Nourishment volumes and eroded volumes after 20 years for Qs(6.5°) = 200 000 $m^3$/yr (Delft3D)*

| Dimension of nourishment | Initial volume [$Mm^3$] | Nourishment volume at t=20 years [$Mm^3$] | Eroded volume at t=20 years [$Mm^3$] |
|---|---|---|---|
| 333m x 833m | 2.70 | 0.66 | 2.04 |
| 333m x 1665m | 4.31 | 1.36 | 2.95 |
| 333m x 3330m | 7.56 | 3.78 | 3.78 |
| 667m x 1668m | 13.44 | 5.36 | 8.08 |
| 667m x 3335m | 21.82 | 10.72 | 11.01 |
| 667m x 6670m | 38.49 | 25.65 | 12.84 |
| 1000m x 2500m | 35.17 | 21.77 | 13.40 |
| 1000m x 5000m | 57.28 | 42.07 | 15.21 |
| 1000m x 10000m | 101.51 | 86.12 | 15.39 |

**Maintaining nourishments**
This part will present some specific conclusions on the 'permanent type' of nourishments in which maintenance and therefore erosion rates are of high importance:

- Table 9.2 shows the eroded volumes per year averaged over 1 year and over 5 years. It seems that the decrease in eroded volume per year is largest for the smallest seaward extent. In a timeframe of 4 years, the erosion rates will decrease 50%. When maintenance is of highest priority, one should limit the amount of seaward extent (e.g. 200m – 500m) as much as possible and carry out maintenance as late as possible.

*Table 9.2 – Eroded volume per year averaged over 1 year and 5 years*

| Seaward extent [m] | Eroded volume per year averaged over 1 year [$m^3$/year] | Eroded volume per year averaged over 5 years [$m^3$/year] |
|---|---|---|
| 333 | 800 000 | 400 000 |
| 667 | 1 200 000 | 900 000 |
| 1000 | 1 300 000 | 1 100 000 |

## 9.3 Other conclusions
This section provides other conclusions which were not intentionally aimed at, but were found during this research.

- Capability of modelling large scale nourishments with UNIBEST
  Surprisingly and a bit unexpected is the fact that the UNIBEST & Delft3D results are very similar. This is counter intuitive since both models are based on a completely different concept (see Appendix B – Model description and comparison). Since these models perform so equal and both models have been validated by using the Sand Motor case (see chapter 3), it can be concluded that UNIBEST can be used for simulating large scale nourishments, even when a strong curvature in coastline exists. This is not usual, since UNIBEST is commonly used on a large spatial scale to simulate the long term behaviour of coastlines, for instance to see the long term effect of groynes on a stretch of coast. This research proves that UNIBEST can also be used on a smaller scale.
  Furthermore, the UNIBEST time-series approach resulted in a near perfect fit of the model output on the measurements with respect to volume decrease in time at the Sand Motor nourishment. This approach is carried out by using a 2-year time series consisting of wave observations with an interval of 3 hours. This is quite remarkable since UNIBEST only takes wave driven longshore currents into account, so this result enhances the idea that the alongshore sediment transport is the most important driving force for the diffusion of nourishments along the Dutch coast.

- Impact of profile steepness on alongshore transport at middle section of nourishments
  Although the computed alongshore sediment transports are very similar in the first half year for the Delft3D and UNIBEST model, substantial higher sediment transports are being calculated by Delft3D at the straight middle section of the nourishment. The effect is most noticeable for nourishments with large alongshore lengths and hence a long straight middle section. In general the sediment transports are 50% larger compared to the adjacent straight coastline (300 000 $m^3$/year vs. 200 000 $m^3$/year). This can be the effect of tidal contraction or just the effect of the steeper nourishment profile (1:50 vs. 1:110). To find out, a steeper cross-shore profile was implemented in UNIBEST which matches the cross-shore profile in Delft3D (both models use the TRANSPOR2004 transport formulations). It turned out that also in UNIBEST the sediment transports are much higher at the straight middle sections of the

nourishment. Therefore, these increased transports are solely the result of the steeper cross-shore profile since the tide is not implemented in UNIBEST. The potential increase of the transport for steeper slopes was also confirmed by a sensitivity analysis of the TRANSPOR2004 transport formulation (see section 2.3). It is noted that these increased transport rates may cause larger gradients and hence increased erosion rates.

- Effect of tidal contraction
  The impact of tidal contraction on the flow patterns and subsequent sediment transports are expected to be small since the model results for Delft3D and UNIBEST are so similar. In Delft3D a tidal forcing (M2 + M4) has been implemented in the model, while this is not the case for UNIBEST. A brief analysis of a Delft3D simulation where only tidal forcing is applied proved that the sediment transports on a straight unaltered stretch of coast are almost equivalent to a straight middle section of a nourishment. When looking at the depth-averaged velocities it turns out that only at the edges of the nourishment substantial higher velocities occur. Typically the spatial scale of the impact of flow velocity by tidal constriction was in the order of 500m to 1km for a nourishment with a large cross-shore extent (i.e. 1000m). Consequently, it is concluded that tidal contraction is of minor importance.

- Cross-shore changes at the Sand Motor
  Appendix D shows a brief analysis of the cross-shore changes at the Sand Motor. The main conclusion is that cross-shore processes may indeed play an important role, but that the alongshore current is strong enough to transport the sediment to adjacent areas and that bar formation is not of major importance. This is also observed by an analysis of van Rijn, in which the CROSMOR model has been used in order to see the morphological changes solely due to cross-shore processes. A very clear bar is formed just in front of the Sand Motor, which is far less visible in measurements. This enhances the idea that the gradients of the longshore current, which is not incorporated in the CROSMOR model, are large enough to flush the sediment away in longshore direction.

- Adaptation length of alongshore transports
  When looking at the **initial** alongshore transports calculated by Delft3D and UNIBEST, it can easily be observed that the transports differ; in UNIBEST they are block shaped and act instantaneously on each stretch of coastline depending on the local coastline orientation. In Delft3D a certain *adaptation-length* is observed which can be defined as the length that is needed for the sediment transport to adapt to the new equilibrium transport which applies at that particular stretch of coastline.
  It can be concluded that the adaptation length for the initial transports can be considered constant with a magnitude in the range of 1500 - 2000 meters. This conclusion is also valid for the middle section. A straight middle section of at least 3000m is therefore necessary to achieve the equilibrium situation. Nourishments with less alongshore length are continuously adapting to the new cross-shore profile and/or coastline orientation.

- Maximum steepness of nourishment junctions for use with UNIBEST
  For the Dutch coast it holds that the angle of incidence for a yearly averaged wave climate is in the range of 1° – 10° with respect to the shore normal (see Appendix B.3.4). Subsequently, a situation is considered with a yearly averaged wave climate of 10° from a northwest direction in combination with a regular trapezoidal shaped

nourishment. The junction at the right side of the nourishment is the most unfavourable, since the relative wave angle (incoming wave angle compared to shore normal) is largest here and therefore instabilities will occur first at this position. The analysis shows that a ratio of **1:1.5** (cross-shore width / alongshore length) results in relative wave angles just below 44°, so that the normal unaltered UNIBEST model can be used. Steeper junctions will results in larger values than 44° and hence require the adaptation of maximum sediment transports in UNIBEST. It is however still unclear what the real effect of the model adaptation is since these high angles only act on the initial coastline orientation and re-orientate quickly.

- Relevance of the dynamic boundary in UNIBEST
  The ability to define a dynamic boundary in the UNIBEST model was found to be essential for a good hindcast of the Sand Motor case because sensitivity tests show that the location of the dynamic boundary has a very large effect on sediment transport and therefore on the evolution of a nourishment. Because of this dynamic boundary offshore wave climates can be used in UNIBEST because a limit can be imposed on the amount of cross-shore profile which rotates in the same way as the coastline. Traditional 1D coastline models do not include such a dynamic boundary and will therefore consistently underestimate alongshore sediment transports and therefore nourishment performance since most of the time nearshore wave conditions are not available and the entire cross-shore profile rotates in the same way as the coastline. Refraction is then wrongfully calculated which reduces the peaks in alongshore sediment transport. *UNIBEST shows that a 1D line model can also be used in a more sophisticated way by means of a well-placed dynamic boundary.*

- D3D roller model (Ruessink' expression) vs. D3D Van der Westhuysen expression
  The application of a wave breaking formulation is very relevant for a good hindcast of sediment transport processes at the Sand Motor with Delft3D. Appendix C provides a brief analysis of two different wave breaking formulations within Delft3D: 'the roller model with the expression of Ruessink' and the 'van der Westhuysen expression', which are both applied on the Sand Motor model. Both expressions are using a variable wave breaking index $\gamma_w$, which increases linearly with the product of the local wave-number and water depth, *kh*. In this research, all simulations use the roller model with a diffusivity parameter $D_h$ of 0.25 $m^2/s$. It turns out that this diffusivity parameter has a large effect on morphology. In general, lower values are desired because this limits the lateral mixing of sediment, which in turn will result in less sediment loss to offshore locations.
  It can be concluded that the van der Westhuysen expression with a $D_h$ of 0.25 $m^2/s$ performs poorly due to an unnatural steep alongshore and cross-shore profile which is not observed in reality. Furthermore, the tidal channel at the east of the Sand Motor is not modelled correctly. However, increasing the parameter $D_h$ to 1.00 $m^2/s$ shows the opposite. The cross-profile is far less steep and the tidal channel is correctly predicted as can also be observed in reality.
  Furthermore, the roller model with the expression of Ruessink predicts a tidal channel at the west of the Sand Motor, which is not observed in reality. In general, when only looking at bathymetries, it can be concluded that the van der Westhuysen model with increased diffusivity performs slightly better than the roller model with the expression of Ruessink.

# 10 Recommendations

This chapter gives an overview of the recommendations resulting from this research. They are divided in general recommendations and specific recommendations (UNIBEST & D3D).

**General recommendations**

- The applicability of this research is limited to the Dutch coast only because of the wave climate which has been used. It would be very interesting to see how a nourishment performs for a different wave climate. This might expand the applicability of the design graphs to foreign coasts. One can for instance carry out a sensitivity analysis for which the mean wave angle is varied and the performance of nourishments in time is examined. Another interesting case is a wave climate with a much larger equilibrium coast angle (e.g. 20°). For such wave climates, the ratio between the peaks in alongshore sediment transport compared to the transport on a straight coast would be much smaller than for the Dutch coast. And these peaks are considered a driving force for erosion/sedimentation.
- All nourishments in this research are using nourishment edges with a width/length ratio of 1:2. During this research it is thought that these initial edges are very important for the rate of diffusion, especially in the first years when the coastline orientation has not changed much. It is recommended to do a sensitivity analysis with various ratios which can be applied on one nourishment in order to quantify this effect on the erosion rates.
- The effect of tidal contraction is not clearly visible in this research because the effect of waves on the alongshore transport is very dominant, but this does not mean tidal contraction does not occur. To further distinguish the effect of tidal contraction, it is recommended to perform extended testing of simulations with a tide only and focus on current velocities and sediment transports.

**UNIBEST recommendations**

- The active height parameter turns out to be a sensitive and important parameter for the calculation of nourishment volumes. It's currently calculated with a rule of thumb depending on the yearly maximum significant wave height. However, the active height is linked to the timeframe which is taken into consideration and therefore it would be better to incorporate this dependency in a rule of thumb.
- Within this research, the conclusion is drawn that tidal forcing has minor influence only on the alongshore sediment transport. To further confirm and validate this conclusion, it is recommended to implement the tide within the UNIBEST model and subsequently compare the results of the model run with wave forcing only.
- The UNIBEST time series looks very promising, but more research is needed to verify this and exclude coincidence. For instance, one can impose a time series on other large scale nourishments and/or experiment with extended time series.
- As follows from the discussion, the model adaptation for maximizing transport may result in an overestimation of sediment transports for strongly curved coasts, but this cannot yet be quantified for which further research is recommended.

**Delft3D recommendations**

- During this research it was not possible to do morphological simulations longer than 5 years due to the many nourishments involved and the extensive computation time of the model. The results are however extrapolated by means of exponential fitting, but this approach gives less accuracy on longer timescales. To obtain half-lives for each nourishment, it is recommended to extend the simulation period to 10 – 15 years (e.g. by using a restart file). The extrapolation will then be much more reliable and approximations can be made for the half-lives of each nourishment.

- Cross-shore processes are not being modelled correctly because of the mormerge approach, the 2DH approach and the absence of infragravity waves. Although it is not expected that the results differ very much, it is recommend to quantify the effect of cross-shore transports during storms on the diffusiveness of nourishments.
- Due to the mormerge approach, the morphological changes are being smoothed heavily and therefore the effect of each individual wave condition is not visible anymore. It would therefore be interesting to carry out a simulation with sequential wave conditions in which the effect of each wave condition on the morphology is clearly visible.
- The Delf3D simulations using the van der Westhuysen expression with variable wave breaking index (similar to the roller model with the expression of Ruessink) show a reasonably well resemblance of the morphological behaviour at the Sand Motor nourishment when the diffusivity parameter is increased. It might even be considered a better result than achieved by the Ruessink expression in the roller model. However, further research is required to check if this approach provides truly better results.
- The effect of the tide on the alongshore sediment transport might be underestimated due to the simple schematisation of the tide. In this research, only a M2 and M4 tide have been incorporated into the Delft3D model and the morphological tide has been simply calculated by multiplying the hydrodynamic tide with a constant factor (1.1). It would be better to incorporate more tidal constituents, for instance O2. However, this approach requires a much longer hydrodynamic time scale for which the computations need to be carried out and will therefore increase calculation time severely.

# Appendices

# A Background information

In this chapter some global background information will be given on topics such as coastal hydrodynamics, sediment transport and cross- and longshore transports. These topics are considered important because they can explain sedimentation and erosion, which is occurring at the Dutch coast. The processes involved are the driving forces for the redistribution of sand along the Dutch coast and are therefore responsible for the erosion rates at large scale nourishments. Sections A.1 to A.4 originate from the lecture notes of ‘Coastal Dynamics I’ (Bosboom & Stive, 2012).

## A.1 Coastal hydrodynamics

Coastal hydrodynamics deals with the near-shore hydrodynamics that are important for sediment transport.

Wave transformation

When waves are propagating from deep into shallow water depths, the waves will transform. The wave height, wavelength and direction change until the waves break and lose their energy. Wave transformation takes place because the waves are affected by the seabed, in other words, when the waves can ‘feel’ the ground beneath them. This happens when the water depth becomes less than about half the wavelength. The wave propagation speed $c$ decreases and the wavelength $L$ decreases correspondingly. As the waves move into more shallow water, the waves in deeper water tends to catch up with the waves in front. This results in a concentration of wave energy and an increase in wave height. This is called *shoaling*. Changes in water depth and thus propagation speed also occur along a wave crest. This forces a wave to bend towards the coast. This phenomenon is called *refraction*. Wave transformation due to sheltering by obstructions like islands or breakwaters is called *diffraction*. These characteristics can all be described by linear wave theory.

In reality, waves propagating towards the shore become more and more asymmetric (= non-linear). This is characterized by:

- Gradual peaking of the wave crest and flattening of the wave trough, which is called *skewness*.
- Steepening of the wave front, resulting in a pitched forward-wave shape, which is often called *asymmetry*.

These non-linearities give rise to a net flux of mass between wave trough and wave crest associated with wave propagation. And this automatically implies that there must be a net velocity below the wave through level as compensation: a return current (called undertow).
According to Bosboom & Stive, this undertow is important for seaward sediment transport because of the high offshore-directed velocity. The undertow is thought to be responsible for the severe beach erosion during heavy storms (see also section A.3).

Radiation stresses

“Radiation stress is the name that has been given to the depth-integrated and wave-averaged flow (or flux) of momentum due to waves.” (Bosboom & Stive, 2012)
If there is a change in these radiation stresses from one location to another, wave forces act on the fluid, impacting mean water motion and levels. These wave forces are responsible for:

- Lowering and raising the mean water level, respectively set-down and set-up
- Driving a longshore current in case of obliquely incident waves.

## A.2 Sediment transport

*"Sediment transport can be defined as the movement of sediment particles through a well-defined plane over a certain period of time. The movement of sediment particles depends on the characteristics of the transported material, for instance grain size, shape and fall velocity"* (Bosboom & Stive, 2012). Sediment particles will start moving after a certain threshold value is exceeded. This value is called the critical velocity or critical shear stress.

In general, two transport modes can be distinguished:

- *Bed load transport:* the transport of sediment particles in a thin layer close to the bed. There is a more or less continuous contact between the particles and the bed.
- *Suspended load transport:* the transport of particles that are suspended in the water without any contact with the bed.

The sum of the bed load and suspended load is called the total load.

<u>Sediment transport rates</u>

It is customary to express the sediment transport rates *S* in terms of *volumes* of accretion and erosion. The corresponding unit is $m^3$/s/m (*volumes* of sand per second per meter width). Changes in morphology of a system depend on the spatial and temporal fluctuations in the sediment transport rates. The continuity equation or mass balance reads:

$$\frac{\partial z_b}{\partial t} + \frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y} = 0 \qquad (11)$$

in which:

| | |
|---|---|
| $z_b(x, y, t)$ | bed level above a certain horizontal datum (m) |
| $S_x(x, y, t), S_y(x, y, t)$ | sediment transport rates per m width of flow in horizontal x- and y- direction ($m^3$/m/s including the effect of porosity) |

Equation 4.1 states that erosion occurs when the net sediment flux is negative. Consequently, sedimentation occurs when the net sediment flux is positive. However, waves and tides will respond different to the adjusted bed level. This gives rise to a change in sediment transport rates and consequently a change in the development of morphology. Evidently, a feedback exists between hydrodynamic processes and morphology; the coupling between the two is provided by sediment transport.

<u>Net sediment transport due to waves</u>

An oscillatory velocity signal, which is purely symmetric about the horizontal axis has a symmetric velocity profile and from this it follows that $\langle S \rangle = 0$. The symmetrical orbital motion simply moves the sediment back and forth without a net wave-averaged transport. When considering a positively skewed wave (characteristic for shoaling waves), larger peak velocities in the wave propagation direction than in de opposite direction will be found. Then it holds that $\langle S \rangle \neq 0$, even though $\langle u \rangle = 0$. This is due to the fact that the sediment load responds non-linearly to the velocity, such that more sediment is stirred up during the part of the wave cycle with velocities in the propagation direction. As a result of this, a net sediment transport in propagation direction occurs.

This wave orbital motion is very important in transporting material in the cross-shore direction but not in the alongshore direction (see also section A.3 and A.4).

## A.3 Cross-shore transport

Cross-shore transport is defined as the sediment transport transverse to the shoreline (see Figure A.1). In general cross-shore transport is responsible for short-term variations only, for instance changes in position and size of breaker bars and dune erosion during storms.

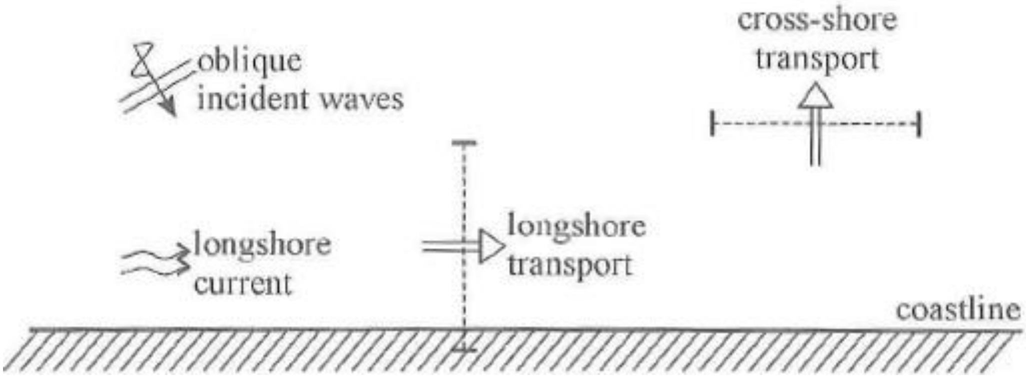



*Figure A.1 – Distinction between longshore transport and cross shore transport* (Bosboom & Stive, 2012).

<u>Equilibrium shoreface profile</u>

When evaluating shoreface profiles, a dynamic variation is observed in time. The profile variations remain in an envelope that seems stable over the years.

When a beach profile is exposed to a *constant* wave forcing at a fixed water level, a *stable* equilibrium profile (cross-shore profile of constant shape) will be reached after a sufficiently long time. However, in nature the forcing is far from constant and varies so rapid that a stable equilibrium is never reached. This is the reason why the shoreface profile continuously oscillates in response to the varying forcing. As a consequence, a different cross-shore profile will be found in winter than in summer, because of the differences in forcing. A winter profile is often called a storm profile. During storms, high and long waves cause erosion of the beach. This sediment is deposited in the surf zone. During summer, this sediment is returned to the beach by lower and shorter waves.

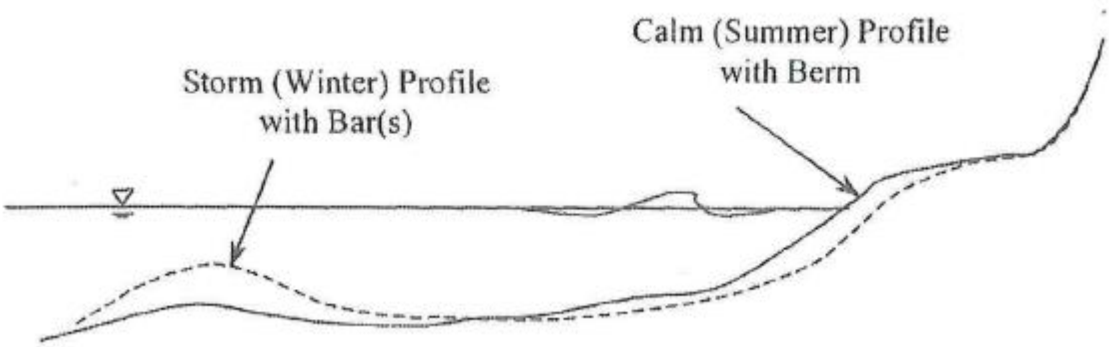



*Figure A.2 – Summer and winter profile showing the annual changes in beach profile (Roelvink & Stive, 1989)*

Roelvink and Stive (1989) made an analysis of the decomposition of the velocity moments using laboratory measurements. During extreme events, the transport contribution due to undertow is dominant. This explains that under higher and longer waves (during storms), a net offshore transport is observed, leading to the winter profile. In contrast to this, low and short waves build up the summer profile due to short wave skewness (see section A.2). Roelvink and Stive (1989) made also clear that the gross cross-shore transports are much higher than the net cross-shore transports, which is the reason why accurate net cross-shore transports predictions are very difficult.

## A.4 Longshore transport

Longshore transport is the net movement of sediment particles through a fixed vertical plane perpendicular to the shoreline (see Figure A.1). Long-term changes of the coastline are often the result of *gradients* in the longshore transport. The cross-shore transport has no direct influence on the longer term changes in beach position.
The presence of sediment transport itself does not lead to either erosion or deposition. If a small part of the beach is considered, the coastline will remain stable as long as $S_{in}$ is equal to $S_{out}$. Erosion occurs when $S_{out} > S_{in.}$ This is a logical consequence because a sediment balance holds in the considered part. Respectively, sedimentation occurs when $S_{in} > S_{out}$.

Longshore current

The longshore current velocity is driven predominantly by breaking waves which approach the coast at an angle. The longshore current is concentrated more or less in the surf zone and occurs regardless of sediment transport.
*"…Since the wave motion in the breaker zone is nearly perpendicular to the resulting current, the major influence of waves is to stir more material loose from the beach and keep it in suspension, thereby increasing the sediment concentration. It is the (wave-induced) longshore current (and not the oscillatory wave motion) that is mainly responsible for the net movement of material along the coast"* (Bosboom & Stive, 2012).

It turns out that the longshore transport is approximately proportional to $\langle S_y \rangle \propto \hat{u}^2 V$ , in which $\hat{u}$ is the magnitude of the cross-shore time-varying orbital motion and $V$ is the longshore current responsible for transport. From this, it can also be concluded that the effect of short waves is to mobilise the material which is consequently transported by the longshore current. The driving force which is responsible for the longshore current is known to be the cross-shore gradient in radiation stress. The radiation shear stress at the point of breaking can therefore be seen as this driving force integrated over the surf zone.

The (S-φ)-curve and yearly-averaged sediment transport

A common concept in longshore sediment transport is the (S-φ)-curve. This curve gives the transport as a function of the wave angle (relative towards the coast) for a given set of wave conditions. It follows that a wave angle of 42° gives the highest transports. In real life, wave heights, periods, and angles are weather dependent. Changes in wave height and wave period lead to different transport magnitudes. Changes in wave angle may lead to transports that not only have different magnitudes but opposite directions as well. To take this variability into account, the wave climate can be schematized in several classes; for instance a division into sectors of 30 degrees, 0.5 s $T_p$ and 0.5 m $H_s$. For morphological computations often such a full wave climate is then reduced to a limited number of wave conditions, which can still be used to obtain representative net longshore transport rates. "*The net longshore transport rate is defined as the residual transport rate as a result of all wave conditions and is much smaller than the gross longshore transport rates up and down the coast"* (Bosboom & Stive, 2012).

For the central part of the Dutch coast (from Wassenaar to Zandvoort) it holds that a net yearly transport of approximately 200 000 $m^3$/year can be found in northward direction. This can for instance be the result of a northward transport of 500.000 $m^3$/year and a southward transport of 300.000 $m^3$/year.

# B Model description and comparison

In this chapter an explanation will be given of the numerical models that have been used in this research. In section B.1 a short description of the UNIBEST-CL+ model will be given. Section B.2 will provide a description of the Delft3D model. This chapter concludes with the necessity for numerical modelling, a comparison between both models and a description of Delft3D in combination with large timescales (section B.3).

## B.1 UNIBEST-CL+

The UNIBEST software suit is an acronym of UNIform BEach Sediment Transport. It has been developed by WL-Delft Hydraulics (nowadays in development by Deltares) in order to create an integrated package with diagnostic capabilities in the study and simulation of longshore and cross-shore processes and related morphodynamics of beach profiles and coastline evolution (Deltares, 2011a). In this research the UNIBEST-CL+ model will be used, which consists of two integrated sub-modules:

- The Longshore Transport module (LT-module)
- The CoastLine module (CL-module)

The UNIBEST-CL+ module is specifically designed for the simulation of coastline changes due to longshore sediment transport gradients. These longshore transports are induced by tide and wave driven longshore currents.

<u>Longshore Transport (LT) module</u>

The LT-module calculates the tide and wave induced longshore currents and the resulting sediment transport for specific cross-shore beach profiles assuming that the beach is uniform in alongshore direction. Hydrodynamic aspects such as wave propagation and wave transformation are carried out by a built-in random wave propagation and decay model, which transforms offshore waves to nearshore waves, while taking into account refraction, non-linear dissipation by wave breaking and bottom friction. The longshore sediment transports and cross-shore distribution can be calculated by choosing one of the various transport formulas incorporated in the module.

<u>CoastLine (CL) module</u>

The CL-module is designed to simulate coastline changes due to longshore sediment transport gradients of an alongshore uniform coast. The module is based on the single line theory. In the single line theory, the behaviour of the coast is mapped onto a single line, which represents the coastline. This line can move seaward (accretion) or landward (erosion) depending on the sediment balance. Basically UNIBEST-CL+ solves a parabolic partial differential equation for the coastline position Y and angle of wave incidence φ:

$$\frac{\partial Y}{\partial t} - \frac{1}{d}\frac{\partial S_x}{\partial \varphi}\frac{\partial^2 Y}{\partial x^2} = 0 \qquad (12)$$

Several initial and boundary conditions can be imposed to represent a variety of coastal situations. Also, sediment sources and/or sinks can be implemented to incorporate effects as river sediment input, land subsidence, offshore sediment loss, etc. The model is capable of modelling the morphological impacts of various coastal engineering measures, such as headlands, groynes, revetments, breakwaters, sand by-pass systems and beach nourishments. The model can be used for conceptual design of coastal measures and the impact of those on adjacent coastal stretches.

## B.2 Delft3D

In this research the Delft3D modelling suite will be used. It has been developed by Deltares in close cooperation with the Delft University of Technology and it is able to make both 2D and 3D computations for coastal, river and estuarine areas. The software suite is composed of several modules, for instance the FLOW-module, WAVE-module and water quality module, which are all able to interact with each other. The heart of the Delft3D suite is the FLOW module that performs the hydrodynamic computations, sediment transport computations and resulting morphological changes. Figure B.1 shows the most basic form of the Delft3D package in a flow diagram. The bathymetry is fixed on a computational grid, which can be curvilinear or rectangular. Together with the boundary conditions and the initial conditions the model is able to run. External forcing, such as tides, wind and waves can be applied in the FLOW and WAVE modules. From this point, the sediment transports can be calculated which will lead to certain bed changes. Then, the initial bathymetry is updated with these bed changes and the process starts again. Several methods have been developed to accelerate this process (see section B.3.3 and Roelvink and Walstra (2004)).

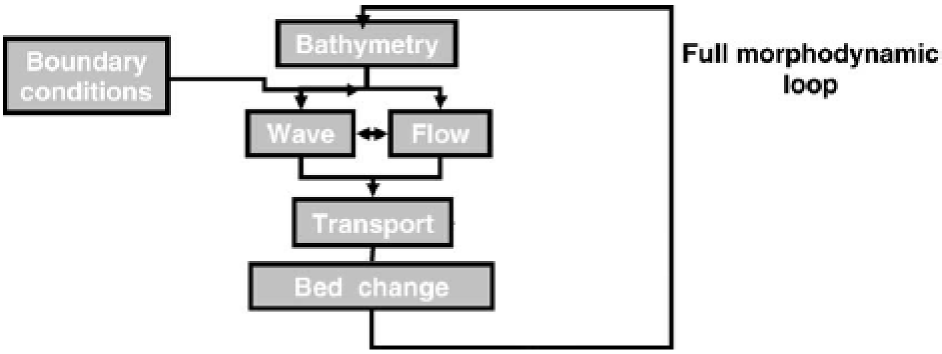



*Figure B.1 – Flow diagram of Delft3D (Roelvink, 2006)*

This chapter will present a short summary of the different modules that will be used in this research together with the governing equations and parameters of Delft3D. The information is mainly derived from Lesser, Roelvink, van Kester, and Stelling (2004), Roelvink (2006) and Deltares (2013a, 2013b).

### B.2.1 Delft3D-FLOW module

The Delft3D-FLOW module solves the unsteady shallow-water equations in two (depth averaged) or three dimensions. The total system of equations consists of the continuity equation, the horizontal momentum equation, a transport equation and the turbulence closure model. Because of the assumption that the vertical accelerations are small compared to the gravitational acceleration, the vertical momentum equation can be reduced to the hydrostatic pressure relation. This allows the module to be used for predicting the flow in shallow seas, coastal areas, estuaries, lagoons, rivers and lakes; i.e. systems in which the horizontal length and time scales are significantly larger than the vertical scales. The governing equations are summarized below. For the sake of clarity, the equations are presented in their Cartesian rectangular form only. They are largely taken from Lesser et al. (2004).

- <u>The continuity equation</u>
  The depth-averaged continuity equation reads:

$$\frac{\partial \zeta}{dt} + \frac{\partial \left[ h\bar{U} \right]}{\partial x} + \frac{\partial \left[ h\bar{V} \right]}{\partial x} = S \tag{13}$$

in which S represents the discharge or withdrawal of water, evaporation and/or precipitation.

- <u>The horizontal momentum equations</u>
  The horizontal momentum equations are given by:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + \frac{\omega}{h}\frac{\partial U}{\partial \sigma} - fV = -\frac{1}{\rho_0}P_x + F_x + M_x + \frac{1}{h^2}\frac{\partial}{\partial \sigma}\left( v_V \frac{\partial u}{\partial \sigma} \right) \tag{14}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + \frac{\omega}{h}\frac{\partial V}{\partial \sigma} - fU = -\frac{1}{\rho_0}P_y + F_y + M_y + \frac{1}{h^2}\frac{\partial}{\partial \sigma}\left( v_V \frac{\partial v}{\partial \sigma} \right) \tag{15}$$

in which the horizontal pressure terms, $P_x$ and $P_y$, are given by (Boussinesq approximations):

$$\frac{1}{\rho_0}P_x = g\frac{\partial \zeta}{\partial x} + g\frac{h}{\rho_0}\int_{\sigma}^{0}\left( \frac{\partial \rho}{\partial x} + \frac{\partial \sigma'}{\partial x}\frac{\partial \rho}{\partial \sigma'} \right) d\sigma' \tag{16}$$

$$\frac{1}{\rho_0}P_y = g\frac{\partial \zeta}{\partial y} + g\frac{h}{\rho_0}\int_{\sigma}^{0}\left( \frac{\partial \rho}{\partial y} + \frac{\partial \sigma'}{\partial y}\frac{\partial \rho}{\partial \sigma'} \right) d\sigma' \tag{17}$$

The terms $F_x$ and $F_y$ in equation (14) and (15) are the horizontal Reynold's stresses. They can be determined using the eddy viscosity concept. However, for large-scale simulations the shear stresses along closed boundaries can be neglected and the simplified formulations can be used as stated below:

$$F_x = v_H \left( \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right) \tag{18}$$

$$F_y = v_H \left( \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right) \tag{19}$$

In equation (14) and (15), $M_x$ and $M_y$ represent the contributions due to external sources or sinks of momentum.

- <u>The transport equation</u>
  The advection-diffusion equation to account for transport reads:

$$\frac{\partial[hc]}{\partial t}+\frac{\partial[hUc]}{\partial x}+\frac{\partial[hVc]}{\partial y}+\frac{\partial[\omega c]}{\partial \sigma}=h\left[\frac{\partial}{\partial x}\left(D_H\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_H\frac{\partial c}{\partial y}\right)\right]$$
$$+\frac{1}{h}\frac{\partial}{\partial \sigma}\left[\left(D_V\frac{\partial c}{\partial \sigma}\right)\right]+hS \tag{20}$$

in which S represents source and sink terms per unit area. To solve these equations, the horizontal and vertical viscosity ($v_H$ and $v_V$) and diffusivity ($D_H$ and $D_V$) need to be prescribed. Delft3D-FLOW assumes that the horizontal viscosity and diffusivity is a superposition of three parts: (1) molecular viscosity, (2) 3D turbulence and (3) 2D turbulence. These parameters have to be either prescribed by the user or to be computed by Delft3D-FLOW. Extensive documentation can be found in the Delft3D-FLOW user manual (Deltares, 2013a).

- <u>The turbulence closure model</u>
  Several turbulence closure models based on the eddy viscosity have been implemented in Delft3D-FLOW. They are needed because the scales of turbulent motion are usually much smaller than the spatial and temporal scale of the model itself. More information can be found in the user manual (Deltares, 2013a).

In order to solve this set of equations, several boundary and initial conditions are required. Two types of boundary conditions can be prescribed; open boundaries and closed boundaries. Closed boundaries allow no flow exchange, whereas open boundaries imitate a truly open water-water boundary. Because both boundaries can severely influence the model results, they should be located as far away as possible from the area of interest. Several boundary conditions can be specified, such as water levels, velocities, discharges, Neumann boundaries or Riemann boundaries.
In Delft3D-FLOW, the continuity and momentum equation are solved using an alternating direction implicit (ADI) method on a staggered grid, which can be rectangular, curvilinear or spherical. The water levels are defined in the middle of a grid cell, while the velocities are calculated perpendicular to every edge of the grid cell.

**Sediment transport in Delft3D**
Besides heat and salinity, also sediment can be described by the transport equation (20) in Delft3D-FLOW. Each sediment fraction must be classified as “sand” or “mud”, because different formulations are used for the bed-exchange and settling velocity of these different types of sediment. To fully describe the behaviour of sediment, additional formulations have to be added to the transport equation. In this research the most up to date formula will be used, the van Rijn (2004) formula. This formula makes a distinction between suspended transport and bed transport; a short description for both transports is given below. For further information and the implementation of this formula in Delft3D, reference is made to van Rijn et al. (2004).

- <u>Wave-related suspended transport</u>
  The wave-related suspended transport is an estimation of the suspended sediment transport due to wave velocity asymmetry effects. This type of sediment transport can be modelled using an approximation method proposed by Van Rijn (2002):

$$S_{s,w}=f_{SUSW}\gamma U_A L_T \tag{21}$$

in which:

| | | |
|---|---|---|
| $S_{s,w}$ | = | wave-related suspended transport (kg/m/s) |
| $f_{SUSW}$ | = | user specified tuning parameter |
| $\gamma$ | = | phase lag coefficient which is set to 0.1 |
| $U_A$ | = | velocity asymmetry value (m/s) |
| $L_T$ | = | the approximated suspended sediment load (kg/m$^2$): |

$$L_T = 0.007 \rho_s d_{50} M_e \tag{22}$$

in which $M_e$ is the excess sediment mobility number due to waves and currents (-):

$$M_e = \frac{\left(v_{eff} - v_{cr}\right)^2}{\left(s-1\right) g d_{50}} \tag{23}$$

in which $v_{cr}$ is the critical depth averaged velocity for initiation of motion based on a parameterisation of the Shields curve (m/s). For a more detailed overview of the parameters involved in these formulations, see van Rijn et al. (2004).

- Bed load transport
  For every “sand” sediment fractions the bed-load transport is calculated by applying the TR2004 approach. This approach first computes the magnitude and direction of the bed load transport. The computed sediment transport vectors are then relocated from water-level points to velocity points using an “upwind” scheme to ensure numerical stability. After this, the transport components are adjusted for bed-slope effects. The bed load is calculated using a quasi-steady approach; the net bed-load transport rate is obtained by time-averaging the instantaneous transport rate over the wave period *T*:

$$S_b = \left(\frac{1}{T}\right) \int S_{b,t} dt \tag{24}$$

$$S_{b,t} = 0.5 \rho_s d_{50} D_*^{-0.3} \left(\frac{\tau'_{b,cw,t}}{\rho}\right)^{0.5} \left(\frac{\max(0, \tau'_{b,cw,t} - \tau_{b,cr})}{\tau_{b,cr}}\right) \tag{25}$$

in which:

| | | |
|---|---|---|
| $\tau'_{b,cw,t}$ | = | instantaneous grain-related bed-shear stress due to both current and wave motion = $0.5 \rho f'_{cw} (U_{\delta,\mathrm{cw,t}})^2$ |
| $U_{\delta,\mathrm{cw,t}}$ | = | instantaneous velocity due to current and wave motion at reference height *a* |
| $f'_c$ | = | current-related grain friction coefficient = $0.24(\log(12h / \mathrm{k}_{s,grain}))^{-2}$ |
| $f'_w$ | = | wave-related grain friction coefficient = $\exp\left[-6 + 5.2(A_\delta / k_{s,grain})^{-0.19}\right]$ |
| $\alpha$ | = | coefficient related to relative strength of wave and current motion |
| $\beta_f$ | = | coefficient related to vertical structure of velocity profile |

| | | |
|---|---|---|
| $A_\delta$ | = | peak orbital excursion |
| $\tau_{b,cr}$ | = | critical bed-shear stress according to Shields |
| $\rho_s$ | = | sediment density |
| $\rho$ | = | fluid density |
| $d_{50}$ | = | particle size |
| $D_*$ | = | dimensionless particle size |

According to various field data sets, the most influential parameters of equation (25) are $f'_{cw}$ and $\mathrm{k}_{s,grain}$. Based on the findings from field data sets, the following expressions have been implemented in TR2004:

$$f'_{cw} = \alpha^{0.5}\beta_f\, f'_c + (1-\alpha^{0.5})\, f'_w \quad \text{and} \quad \mathrm{k}_{s,grain} = d_{90}$$

The bed load transport components in x- and y- direction are determined by also including the wave-related suspended transports in wave propagation direction:

$$S_{b,x} = f_{BED}\left(\frac{1}{T}\right)\int_{t=0}^{t=T}\frac{u_b}{\left(u_b{}^2+v_b{}^2\right)^{0.5}}S_{b,t}\,dt + S_{s,w}\cos\phi \tag{26}$$

$$S_{b,\mathrm{y}} = f_{BED}\left(\frac{1}{T}\right)\int_{t=0}^{t=T}\frac{v_b}{\left(u_b{}^2+v_b{}^2\right)^{0.5}}S_{b,t}\,dt + S_{s,w}\sin\phi \tag{27}$$

Where $f_{BED}$ is a user-specified scaling factor and $u_b$ and $v_b$ are near-bed velocities due to the combined action of currents and waves in x- and y-directions.

Once again, this section about sediment transport in Delft3D is a very brief summary which is adapted from the report “Description of TRANSPOR2004 and Implementation in Delft3D-ONLINE” by van Rijn et al. (2004).

### B.2.2 Delft3D-WAVE module

The Delft3D-WAVE module can run as a standalone module or can be coupled to the FLOW-module. Wave simulations may be performed using the second-generation wave model HISWA or the third-generation SWAN model. The use of the latter one is convenient because it can use the same curvilinear grid as used in the FLOW-module. SWAN can account for the following physics:

- Wave propagation in time and space, shoaling, refraction, diffraction and frequency shifting
- Wave generation by wind
- Triad and quadruplet wave-wave interactions
- White capping, bottom friction, depth induced breaking
- Wave-induced set-up.

For a more detailed description of the SWAN implementation in Delft3D-WAVE, reference is made to the user manual (Deltares, 2013b).

## B.3 Modelling diffusion of large scale nourishments

This section will explain why numerical modelling is an appropriate tool for solving the problem, which is outlined in chapter 1. Also, the differences between process-based models in comparison with behaviour based models will be explained together with a discussion on which type is most suited regarding this research.

### B.3.1 The necessity of numerical modelling

Because of the complexity of the problem and the many processes involved, analytical models or simple empirical relations are out of the question for solving the problem definition. The hydrodynamics (waves, tides, currents) of the Dutch coast are changing constantly and therefore the sediment transport along the coast is also subject to a great variability. This is especially true because of the nonlinear relation between hydrodynamics and sediment transport. The combination of these rapidly changing processes and the time scale of the problem (approximately 20 years) require a lot of small time steps to be taken to get accurate results. For these problems particularly, numerical models are very suitable. In general, the complexity of a diffusing sediment body along the coast is so high that the switch to numerical models is easily made.

### B.3.2 Process-based models versus behaviour models

Table B.1 shows a comparison between a process based model (for instance Delft3D) and a behaviour based model (for instance UNIBEST-CL+) on various aspects. Which model is best suited depends on the spatial and temporal scales of the problem, the relevant processes involved and the purpose of the research. At first glance, a behaviour based model seems best suited because of the long timescale involved in this research (≈ 20 – 25 years). However, in this research the effects of tide, flow contraction and sediment losses at the heads of the nourishment are considered important. These processes can only be incorporated by using a process-based model, such as Delft3D. This modelling package can also incorporate a good representation of the strong curvature in a coastline where nourishments are present. Moreover, a process-based model is commonly used for problems with similar spatial scales as in this research and together with the availability and in-house knowledge at Deltares, Delft3D is considered the most suited numerical model for this research. However, UNIBEST-CL+ will be used to obtain quick results for this problem.

*Table B.1 – Comparison between process-based models and behaviour based models*

| Process based model (Delft3D) | Behaviour based model (UNIBEST-CL+) |
|---|---|
| Describe elementary processes of flow and sediment response | Utilise empirical and semi empirical relationships |
| Equilibrium follows from balance of forces and transport contributions | The system is forced into an equilibrium |
| Sediment transports are calculated from local flow velocities | Sediment transport are calculated in relation to the coast angle and the forced equilibrium |
| Waves, tides, currents all attribute to coastline response | Waves dominant factor in coastline response |
| Used for medium-term time scales (months, years, on occasion decades) | Used for very long timescales (decades, centuries) |
| Medium spatial scale (up to 50 km) | Large spatial scale (up to 1000 km) |

Grunnet, Walstra, and Ruessink (2004) state that 3D morphodynamic computations with Delft3D are found to be potentially feasible for the simulation of nourishment behaviour. For large scale nourishments, the predictive capability of the model gives a reasonable representation of the profile development.

### B.3.3 Using Delft3D on large timescales

Table B.1 states that it is not common to use Delft3D on large temporal scales such as decades. The two limiting factors for a process-based model in combination with large temporal scales are computation capacity and numerical accuracy. Roelvink (2006) discusses four customary techniques to solve these problems and presents a new, fifth technique:

1. Tide-averaging approach. This approach is based on the fact that morphological changes take place on much longer time-scales than changes in the hydrodynamics. For this reason, it is acceptable to consider the bottom fixed during the computation of hydrodynamics and sediment transport over one tidal cycle. The rate of change of the bed level is computed from the gradients in the averaged transport from one tidal cycle.

2. Continuity correction. Because of limitations on the morphological time step (CFL criterion), it is necessary to update the sediment transport regularly. For instance, when the bathymetry has changed, the flow field and orbital velocity have also changed and will have to be recomputed. This can be calculated by using the ‘continuity correction’, under the assumption that only the flow *rates* are changing and not the flow *patterns*. The new flow field and orbital velocities are used to recompute the sediment transport rates.

3. Rapid Assessment of morphology (RAM) approach. This approach is an extension to the continuity correction by assuming that the transport at a given location is only a function of the water depth. Because of this simplification, the RAM approach is computationally very efficient. Another advantage of this method is that the computations to update wave, flow and transport fields can be carried out in parallel, using separate processors.

4. Online approach with morphological factor. This approach is totally different than the ones above, because here the flow, sediment transport and bottom are all updated on the same small time steps. However, this method does not take into consideration the difference in time scales between the flow and morphology. Therefore, the ‘morphological factor’ is introduced. This factor $n$ simply multiplies the depth change rates by a constant factor. For instance, by simulating 12 tidal cycles and using a value $n = 60$, approximately one year of morphological change will be simulated.

5. The ‘parallel online’ approach. This approach is based on the assumption that the morphology is not able to follow the rapid variations in hydrodynamic conditions and that these hydrodynamic conditions occur all on a much smaller timescale relative to the morphological changes. Because of the difference in time scale, the various hydrodynamic conditions can be considered to occur simultaneously, which allows them to be simulated in parallel. Then, the simulation can be split up into a number of parallel processes, which all represent different conditions. At a certain time step, the bottom changes are merged in one model which is then returned to the individual processes. The parallel execution of the different processes lends itself to an efficient implementation on a series of computers, called a cluster.

### B.3.4 Maximum relative coastline orientation for using Unibest

As already has been stated in the UNIBEST model set-up (section 3.1.1), there is a maximum relative wave angle (angle between *wave incidence* and *shore normal*) of about 44° for which UNIBEST can be used. Larger relative coastline angles will result in smaller alongshore transports and will cause instabilities when modelling large scale nourishments (see also Ashton and Murray (2006) and section 2.1). To by-pass this problem, the alongshore transports can be maximized for relative wave angles larger than 44°. This approach solves the instability problem, but might give rise to less accurate results regarding nourishment performance due to the unrealistic large sediment transports which are induced by these large gradients in coastline.

When modelling large scale nourishments in UNIBEST, the critical places for large relative wave angles are the junctions at both edges of the nourishment. This section will find out for which junction angles UNIBEST can still be used without the 'maximum sediment transport' adjustment. Because this is not only dependent on the coastline position but also on the wave angle, first a wave schematisation will be made for the Dutch coast:

Three datasets have been analysed for the Dutch coast:

1. A yearly averaged nearshore wave climate at Noordwijk containing 269 wave conditions. The average angle of incidence is **6.5°** with respect to the shore normal.
2. A yearly averaged nearshore wave climate at the Sand Motor, also containing 269 wave conditions. For this set, the average angle of wave incidence is **7.6°**.
3. A time series of wave observations at an offshore location near Noordwijk. When filtering out wave conditions which cannot occur at the coast itself, an average angle of incidence of **3.0°** is found. Note that the remaining wave conditions are offshore conditions only. Refraction will change the wave direction severely nearshore conditions.

According to Mangor (2004), coasts can be defined by the angle of incidence of the prevailing waves. According to the analysis above, the Dutch coast can be classified as a 'type 2' coast, which holds: Nearly perpendicular wave approach, angle of incidence 1° – 10°, net transport small to moderate. The classification has further been subdivided according to the wave exposure. The Dutch coast can be classified as 'Exposed', since the once per year event satisfies $H_{s,12h/y}$ > 3m. According to this, the main coastal characteristic is a wide stable sand beach, which is found to be in good agreement with reality. It should be noted that the classification given above is a simplification. Other parameters such as sediment supply from adjacent areas as well as seasonal variations in wave climate and storm surges can also play a significant role.

A situation will be considered with a yearly averaged wave climate of 10° from a northwest direction. If a regular trapezoidal shaped nourishment is considered, the junction at the right side of the nourishment is most unfavourable, since the relative wave angle is always largest here. Table B.2 shows 5 different angles for the junctions of a nourishment expressed in a 'cross-shore width / alongshore length' parameter. It shows that a value of **1:1.5** (W/L) results in the limiting relative wave angle for using the standard UNIBEST model at the Dutch coast.

*Table B.2 – Relative wave angle for different junction angles.*

| **Cross-shore width / alongshore length junction [-]** | **Shore normal at junction [°]** | **Relative wave angle [°]** |
|---|---|---|
| 1:0.5 | 63.4 | 73.4 |
| 1:1 | 45 | 55 |
| 1:1.5 | 33.7 | 43.7 |
| 1:2 | 26.6 | 36.6 |
| 1:5 | 11.3 | 21.3 |

# C D3D roller model Ruessink vs. D3D van der Westhuysen

## C.1 Introduction

This appendix provides a general comparison between different Delft3D runs which are applied for the Sand Motor case. One is carried out with the Delft3D roller model (Ruessink expression) which has also been used in this particular research. The other runs are carried out using the van der Westhuysen expression, which is implemented in the SWAN model.

As already has been explained in section 3.2.1, the roller model in this research uses a variable wave breaking index $\gamma_w$ according to the expression of Ruessink et al. (2003), in which $\gamma_w$ increases linearly with the product of the local wave-number and water depth, *kh*.
A similar approach is used by van der Westhuysen (2010); he states in his paper about '*depth-induced wave breaking under finite depth wave growth conditions*' that SWAN underestimates wave heights and wave periods in situations of finite depth wave growth. In his paper, this inaccuracy is addressed through a rescaling of the Battjes and Janssen (1978) bore-based model for depth induced breaking. He states that, "…optimal calibration settings of $\gamma_w$ were found to correlate with the dimensionless depth $k_pd$ (where $k_p$ is the spectral peak wave number and *d* is the water depth) and the local mean wave steepness". Furthermore, a new breaker index, based on the local shallow water nonlinearity is proposed.
From the above it can be concluded that the roller model with the expression of Ruessink and the van der Westhuysen expression both use a somewhat similar expression for wave breaking. It is therefore interesting to see how both models perform on the Sand Motor case.
However, recent findings on morphological behaviour of the Sand Motor show that the Westhuysen model with low values for the 'background horizontal eddy diffusivity coefficient $D_h$', shows an unnatural steep alongshore shape of the Sand Motor, which is not occurring in the model runs carried out with the roller model or as can be observed in reality. For that particular research, increasing the diffusivity parameter of the model improved the results drastically.

## C.2 Comparison

The Sand Motor case and the other D3D cases in this research are using the roller model with $D_h$ = 0.25 m$^2$/s. This paragraph will test two runs for the Sand Motor case using the van der Westhuysen expression in SWAN, both with different values for $D_h$ (0.25 m$^2$/s and 1.00 m$^2$/s) in order to check the sensitivity of this parameter. The diffusivity parameter is dependent on the magnitude of the model, the resolution of the grid and the time step. In general, lower values are desired because this limits the lateral mixing of sediment, which in turn will result in less sediment loss to offshore locations.
When comparing the D3D roller model (Ruessink expression) with the D3D van der Westhuysen expression (both with $D_h$ = 0.25 m$^2$/s), the difference in flattening of the Sand Motor shape can be immediately noticed, as well as the difference in depth contours. The van der Westhuysen simulation shows both a steep cross-shore profile (due to the close depth contours) and alongshore profile, which is not observed in reality. Also, no tidal channel can be seen at the east of the Sand Motor. The van der Westhuysen model with $D_h$ = 1.00 shows the opposite. The cross-profile is far less steep and the tidal channel is correctly predicted as is present also in reality. Furthermore, the Ruessink expression predicts a channel at the west of the Sand Motor, which is not predicted by the van der Westhuysen model and which is not observed in reality. In general, when only looking at bathymetries, it can be concluded that the van der Westhuysen model with increased diffusivity performs better than the roller model with the expression of Ruessink.

- Roller model: $D_h$ = 0.25 m$^2$/s

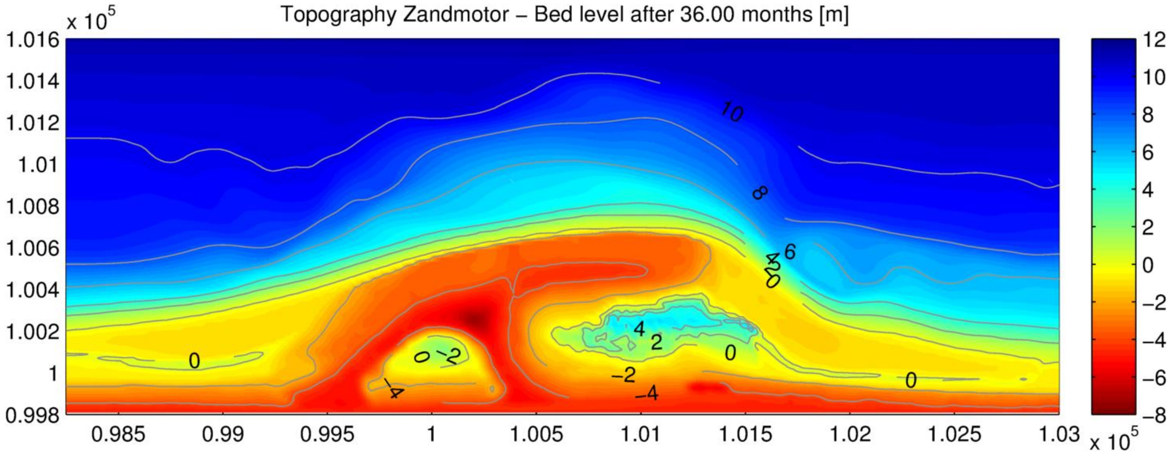



*Figure C.1 – Roller model – $D_h$ = 0.25 m$^2$/s: Topography Sand Motor after 36 months*

- Van der Westhuysen expression: $D_h$ = 0.25 m$^2$/s

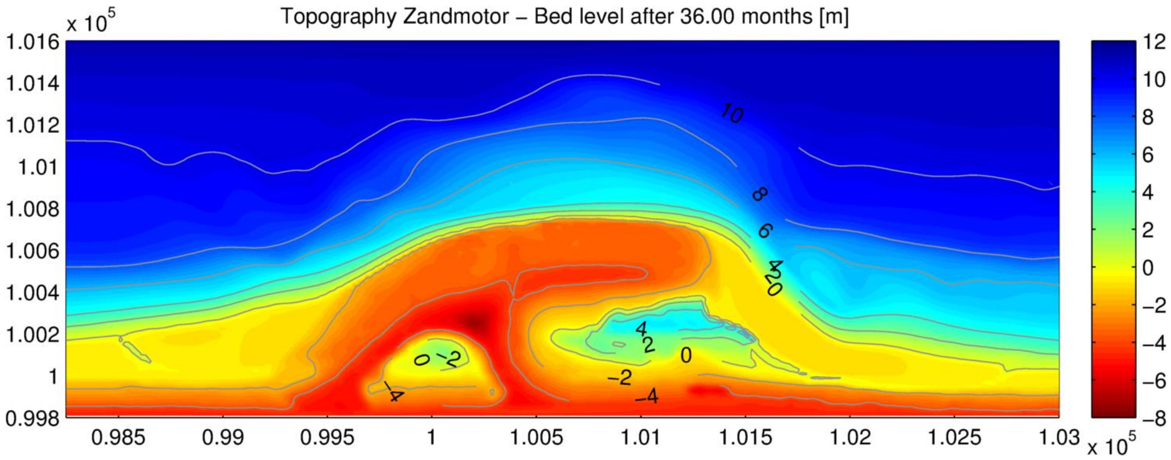



*Figure C.2 – Van der Westhuysen expression – $D_h$ = 0.25 m$^2$/s: Topography Sand Motor after 36 months*

- Van der Westhuysen expression: $D_h$ = 1.00 m$^2$/s

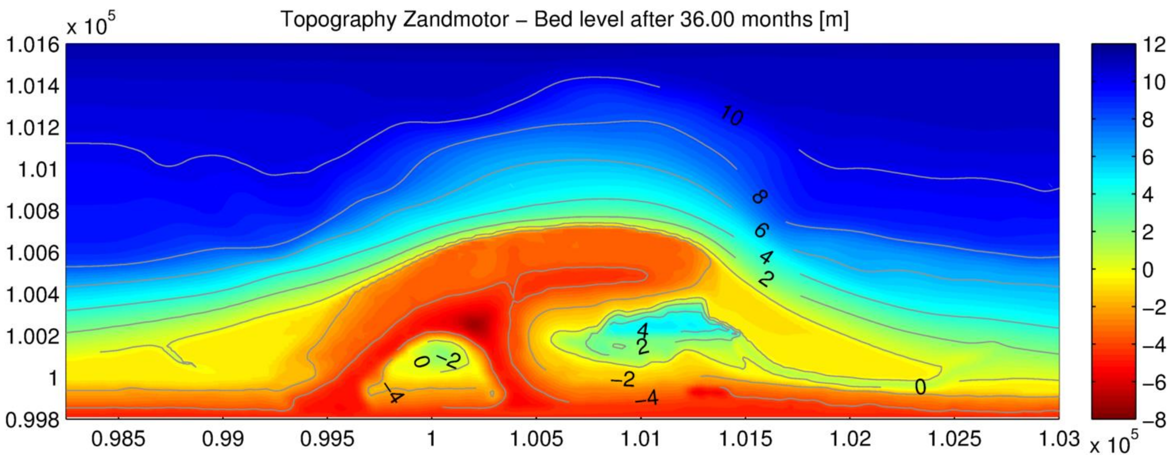



*Figure C.3 – Van der Westhuysen expression – $D_h$ = 1.00 m$^2$/s: Topography Sand Motor after 36 months*

# D Cross-shore changes for large scale nourishments

The redistribution of sand at large scale nourishments is not only the result of alongshore sediment transports. Cross-shore transports can also play a major role, especially during storms in which large waves can cause severe cross-shore erosion which leads to a net offshore directed sediment transport (see appendix A). Under these circumstances it is possible that sediment is eroded from the steep nourishment profile and deposited in front of the nourishment, where it forms a sand bar. This bar affects the point of wave breaking and hence the sediment transports. Because the focus of this research is mainly on alongshore transports and the Delft3D & UNIBEST model is not capable of reproducing bar formation, it is interesting to see if bar formation due to cross-shore processes takes place at the Sand Motor. In order to do so, measurements from Shore Monitoring & Research will be analysed as well as cross-shore model results using the model CROSMOR by van Rijn (2014a).

## D.1 Measurements of Jarkus transects

Figure D.1 shows the measured cross-shore profiles for 'Jarkusraai 108.83', for which measurements are carried out every 2 months. The location of this transect is at the centre of the Sand Motor, at the place where the seaward extent is maximum.

The dotted black line represents the cross-shore profile before construction of the Sand Motor, while the solid black line represents the situation just after construction. It is remarkable to see that the profile in a timespan of two years has become very steep near the waterline. No large sandbars can be observed, however a small migrating sandbar can be seen at -2m NAP. Furthermore, erosion can be observed below -8m NAP and -12m NAP.

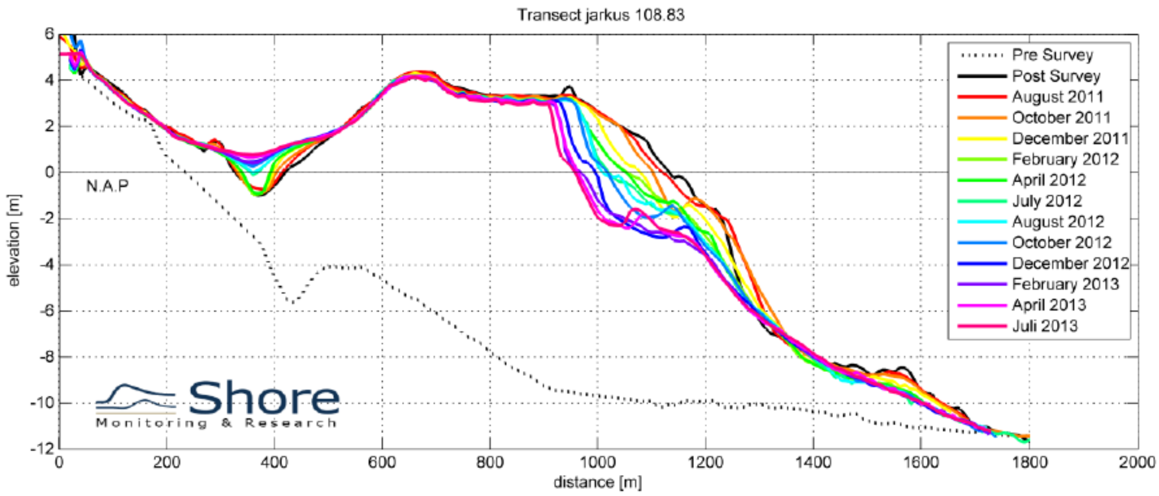



*Figure D.1 – Cross-shore profiles for 'Jarkusraai' 108.83 located at the centre of the Sand Motor (Shore Monitoring & Research)*

Figure D.2 shows the same as Figure D.1, but this time for 'Jarkusraai 109.36', which is located 500 m to the left of 'Jarkusraai 108.83' and crosses the dune lake. Similar behaviour as explained above can be observed here. However, for this transect a more pronounced bar is present, which is slowly migrating towards land, at roughly the same speed of the eroding land. Furthermore it can be stated that no erosion or sedimentation occurs below a level of -8m NAP.

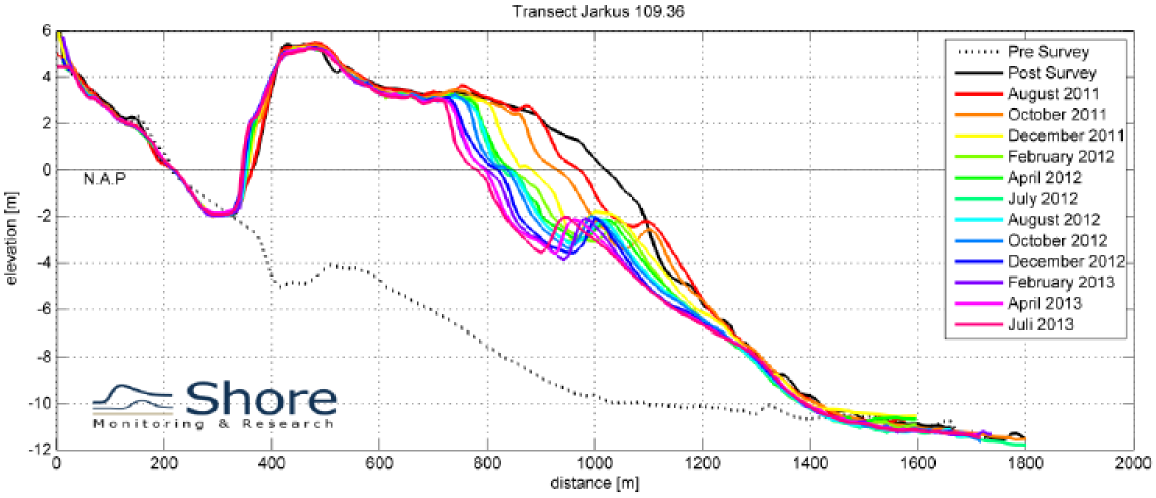



*Figure D.2 – Cross-shore profiles for 'Jarkusraai' 109.36 located just left at the centre of the Sand Motor (Shore Monitoring & Research)*

## D.2 Cross-shore changes CROSMOR

Figure D.3 has been adopted from a report by van Rijn, about the initial sand losses from mega nourishments and land reclamations. The figure shows the same transect as Figure D.1 with schematized profiles. The black and red lines are measured profiles, while the green and orange lines are computed by CROSMOR (a 2 dimensional cross-shore model based on a probabilistic approach). In the simulations, a mean annual wave climate has been used, on which a storm with an offshore $H_s$ of 5m and a duration of 5 hours is superimposed to simulate a 'once in 5 year storm event'. To simulate the flow contraction effect around the nourishment, the maximum tidal velocities during flood and ebb are assumed to be relatively large and therefore multiplied by a factor 2, which yields a 10% increase in erosion at the beach. As can be seen from the figure, the CROSMOR model predicts the formation of a sand bar in the deeper part of the profile, while this is not observed in reality. The formation of such a bar would be very likely if only cross-shore processes would take place. In reality however, the alongshore current is of high importance; it is expected that the formation of a bar is suppressed in the first years due to the presence of large alongshore transport gradients. This longshore current cannot be simulated by CROSMOR (van Rijn, 2014a).

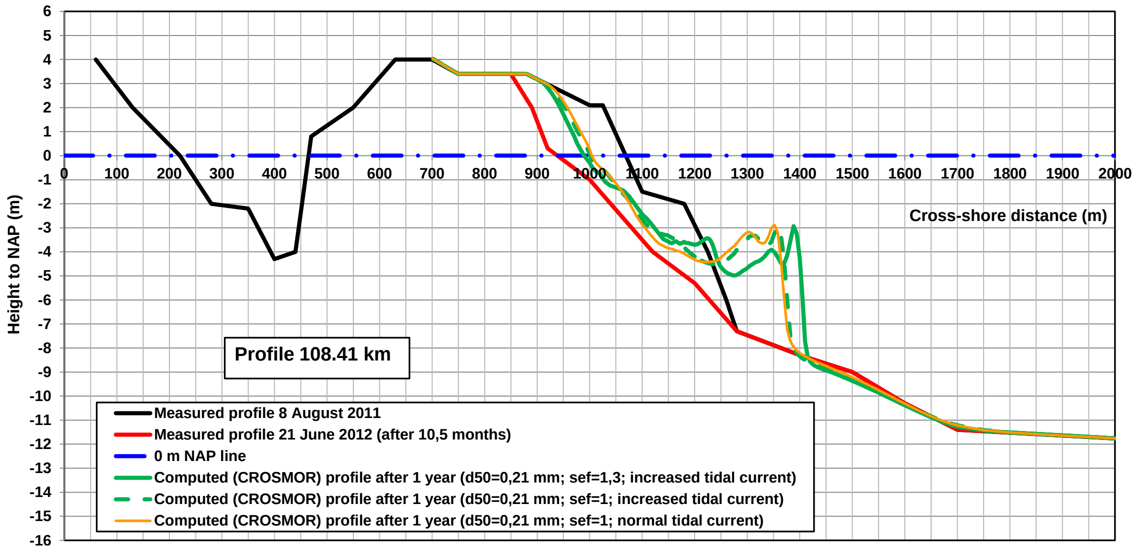



*Figure D.3 – Measured and computed cross-shore profiles for 'Jarkusraai 108.41' (van Rijn, 2014a)*

## D.3 Cross-shore changes Delft3D

Although the Delft3D model which has been used cannot predict bar formation due to the mormerge approach, the absence of infragravity waves and the absence of storm events, it is still interesting to observe changes in the cross-shore profile. Figure D.4 shows these cross-shore changes at the Sand Motor for the first 3 years. The location is chosen close to 'Jarkusraai 108.83', so a comparison can be made with measurements, Figure D.1.
Overall, the two show a remarkable resemblance, albeit that the profile is too steep in between a depth of -2m and -4m. Furthermore, small bar formation at -3m is not modelled at all, which was expected. Another similarity with measurements is that little to no changes take place below a depth of -8m, which is quite a good result for the Delft3D model.

The left part of the lagoon which is visible at a cross-shore distance of 400m shows no changes at all over a period of 3 years according to Delft3D. Measurements show gradual sedimentation and this is probably due to aeolian transport, which is not modelled by Delft3D.

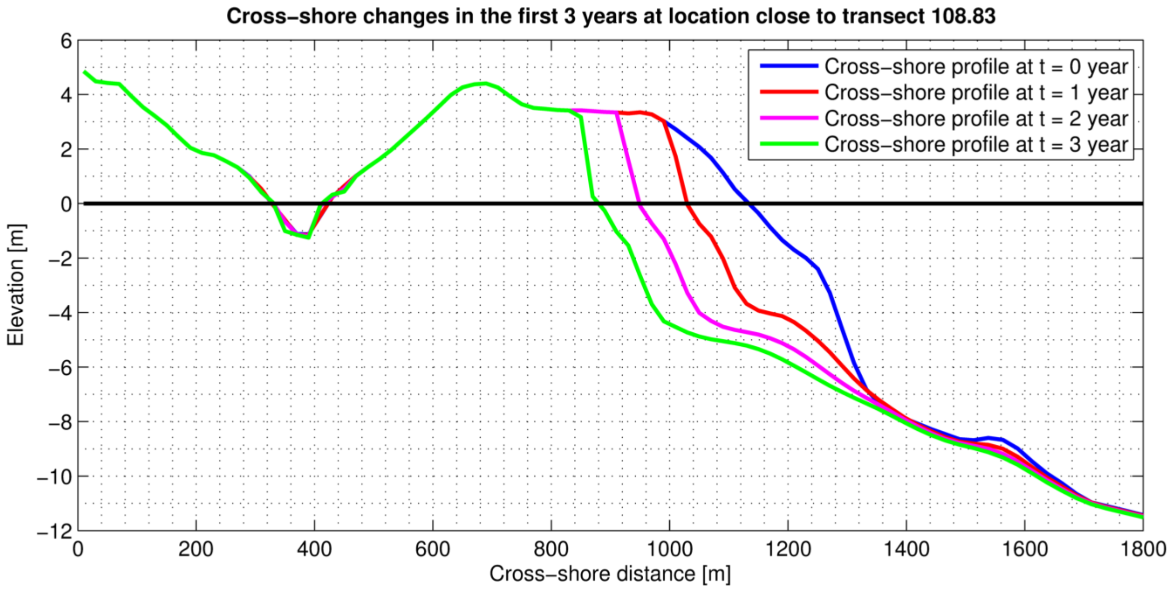



*Figure D.4 – Cross-shore profiles for the Sand Motor model in Delft3D for the first three years*

# E Summary of reference beach extensions

In the sections below, short summaries will be given of large beach extensions which are carried out along the Dutch coast. This will give insight into the different dimensions and volumes of these nourishments.

## E.1 Sand Motor

The first and probably the most familiar example of a large nourishment is the 'Sand Motor'. It is located in between Ter Heijde and Kijkduin and covers an area of about 128 hectare (Rijkswaterstaat, 2013). It has been constructed in the period March 2011 until October 2011 by using offshore sand from the North Sea, which is retrieved by dredgers. These trailer suction hopper dredgers transport the sand to the shore and nourish the sand on the desired location. Figure E.1 and Figure E.2 show the change in shape of the Sand Motor over the period July 2011 – July 2013. The changes in shape are entirely attributed to the local wind, wave and currents near the Sand Motor. These processes will spread the sand along the Dutch coast and will protect the coast for approximately twenty years.

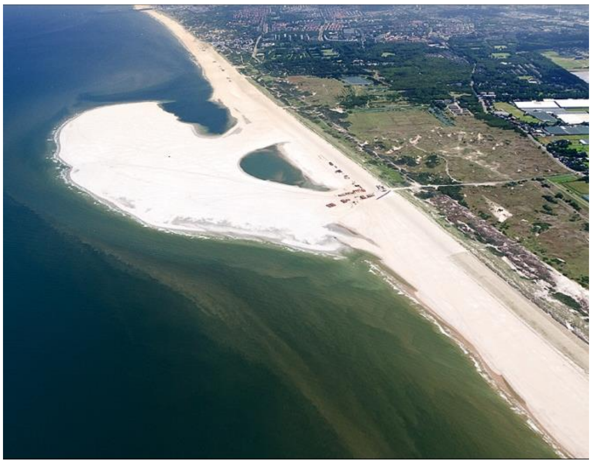


*Figure E.1 – Sand Motor – 11 July 2011 (©Rijkswaterstaat/Joop van Houdt)*

*Figure E.2 – Sand Motor – 1 July 2013 (©Rijkswaterstaat/Joop van Houdt)*

Table E.1 shows the main properties of the Sand Motor.

*Table E.1 – Properties of the Sand Motor*

| | |
|---|---|
| Volume of sand (hopper volume) | 21.5 million $m^3$ |
| Surface area | 128 hectare |
| Length along the coast | Approximately 2 500 m |
| Width perpendicular to the coast | Approximately 1 000 m |
| Total costs | € 70 million |
| Length/width ratio | 2.5 : 1 |
| Sand volume per m' (= volume density) | 10 750 $m^3$ / m' |

## E.2 Hondsbossche & Pettemer Sea Defence

A project very similar to the Sand Motor is carried out near Petten, Noord Holland. Instead of raising the current dykes to improve safety levels, a large scale nourishment of 20 million $m^3$ of sand has been chosen. This solution has been chosen because of its natural and recreational advantages. Besides, the solution is future-proof; more sand can always be added to maintain safety levels, while this is much more difficult for hard sea defences. Work will start at the end of 2013 and it is expected that it will be finished late 2015 (Rijksoverheid, 2012). It is also expected that this measure will protect the coast for the next 50 years. In Figure E.3 the Hondsbossche Sea Defence can be seen in present state. Figure E.4 shows an artist impression of the desired future.

*Figure E.3 – Transition of beach with the Hondsbossche hard sea defence (©Rijkswaterstaat, 18 October 2005)*

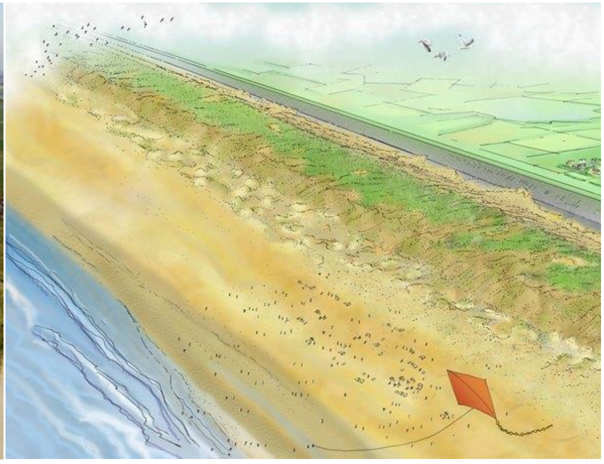


*Figure E.4 – Artist impression of future situation (dune area + beach) (©Kustopkracht)*

Table E.2 shows the (approximated) properties of the nourishment. In the beginning of December 2013 it was revealed that a joint venture of Boskalis & van Oord will construct the nourishment. They are also responsible for maintaining the nourishment for a period of 20 years (Hoogheemraadschap & Rijkswaterstaat, 2013; Koninklijke Boskalis Westminster N.V., 2013). Dredging companies would like to know the sediment losses in this maintenance period, because unexpected sediment losses will lead to extra costs.

*Table E.2 – Nourishment properties at the Hondsbossche & Pettemer Sea Defence*

| | |
|---|---|
| Volume of sand (hopper volume) | Approximately 30 million $m^3$ beach extension<br>Approximately 10 million $m^3$ foreshore nourishment |
| Length along the coast | Approximately 8 000 m of beaches |
| Width perpendicular to the coast | Approximately 250 – 350m |
| Total costs | Approximately € 250 million |
| Length/width ratio | ≈ 25:1 |
| Sand volume per m’ (= volume density) | ≈ 3 750 $m^3$ / m’ (beach extension only)<br>≈ 5 000 $m^3$ / m’ (beach extension + foreshore) |

In the period September 2007 – March 2008 the project ‘Dijk in Duin’ has been carried out. This project consists of the construction of a new dike, parallel to the boulevard. On top of this dike, a natural dune area is located which covers the dike completely. In this way, the dune area has been widened with 42 meter of sand, while maintaining the original dune height. Figure E.5 shows an artist impression of the project and in Table E.3 some properties of the project are displayed (van der Grinten & Ruessink, 2012). While this beach extension is not as large as the Sand Motor or Hondsbossche sea defence, its magnitude is considerably greater than ‘normal’ nourishments carried out every five years.

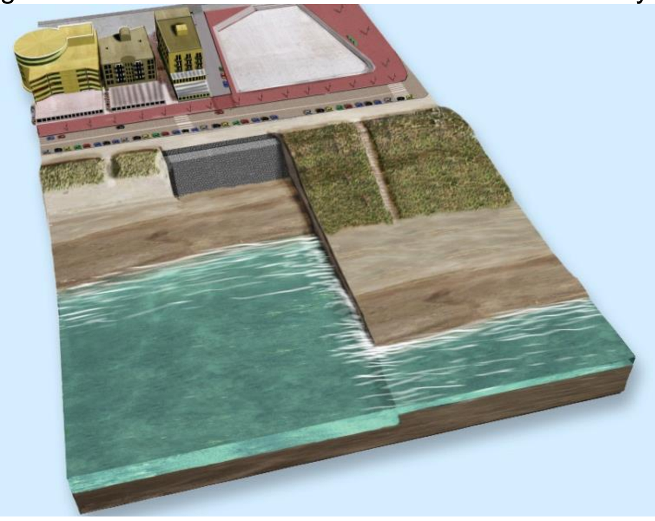


*Figure E.5 – Impression of old situation (left) and new situation (right) (©Provincie Zuid-Holland)*

*Table E.3 – Properties of project ‘Dijk in Duin’*

| | |
|---|---|
| Volume of sand (hopper volume) | 3 million $m^3$ |
| Length along the coast | Approximately 1500 m |
| Width perpendicular to the coast | Approximately 42 m |
| Length/width ratio | 36:1 |
| Sand volume per m’ (= volume density) | ≈ 2 000 $m^3$ / m’ |

## E.3 Katwijk

Present-day, the hard sea defence in Katwijk is not located at the coast itself, but crosses the inner city. Because of this, approximately 3000 people are not protected against flooding. Also, the present sea defence does not meet safety requirements which are prescribed by law. A part of the solution to solve these two problems is a seaward extent of the beach by means of nourishments. Underneath these artificial dunes a dike is constructed, which is completely covered by sand, very similar to the ‘Dijk in Duin’ construction at Noordwijk. Some properties of the nourishment can be seen in Table E.4 (Koopal, 2013).

*Table E.4 – Nourishment properties at Katwijk*

| | |
|---|---|
| Volume of sand (hopper volume) | 2.78 million $m^3$ |
| Length along the coast | Approximately 1500 m |
| Width perpendicular to the coast | Approximately 90 m |
| Length/width ratio | 17:1 |
| Sand volume per m’ (= volume density) | ≈ 1 850 $m^3$ / m’ |

# F UNIBEST-CL+ results

This appendix provides the figures on which the conclusions in chapter 0 are based on. The results are grouped with respect to the seaward extent. First, the volume decrease in time is given for the first 10 years. Second, the volume decrease & erosion volumes for the total simulated period (200 years) are given. Then, top views of the coastline positions are presented. Last, sediment transport is plotted against both the alongshore distance and time.

## F.1 Seaward extent: 333m

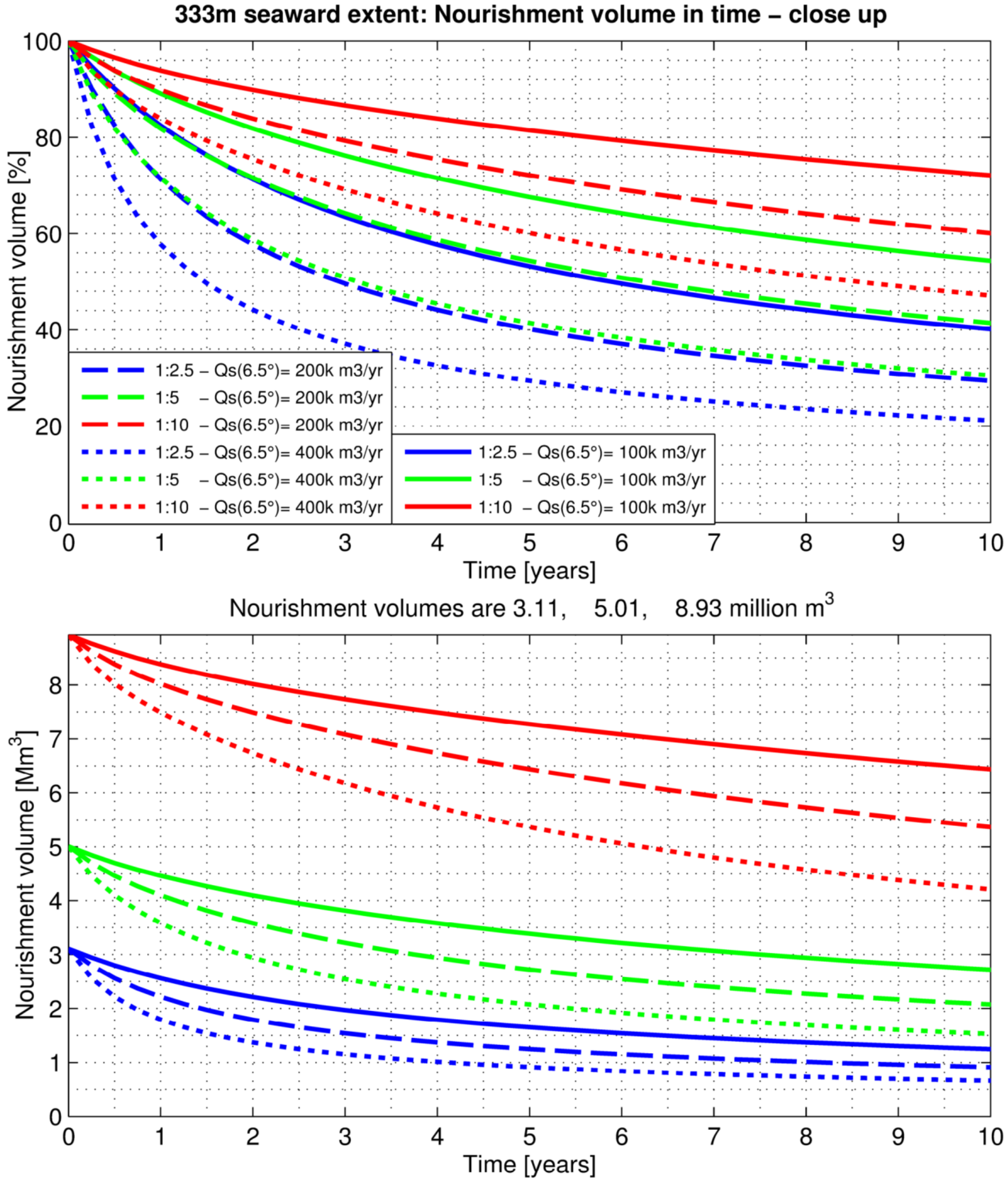



*Figure F.1 – Nourishment volumes in time for 333m seaward extent – close-up*

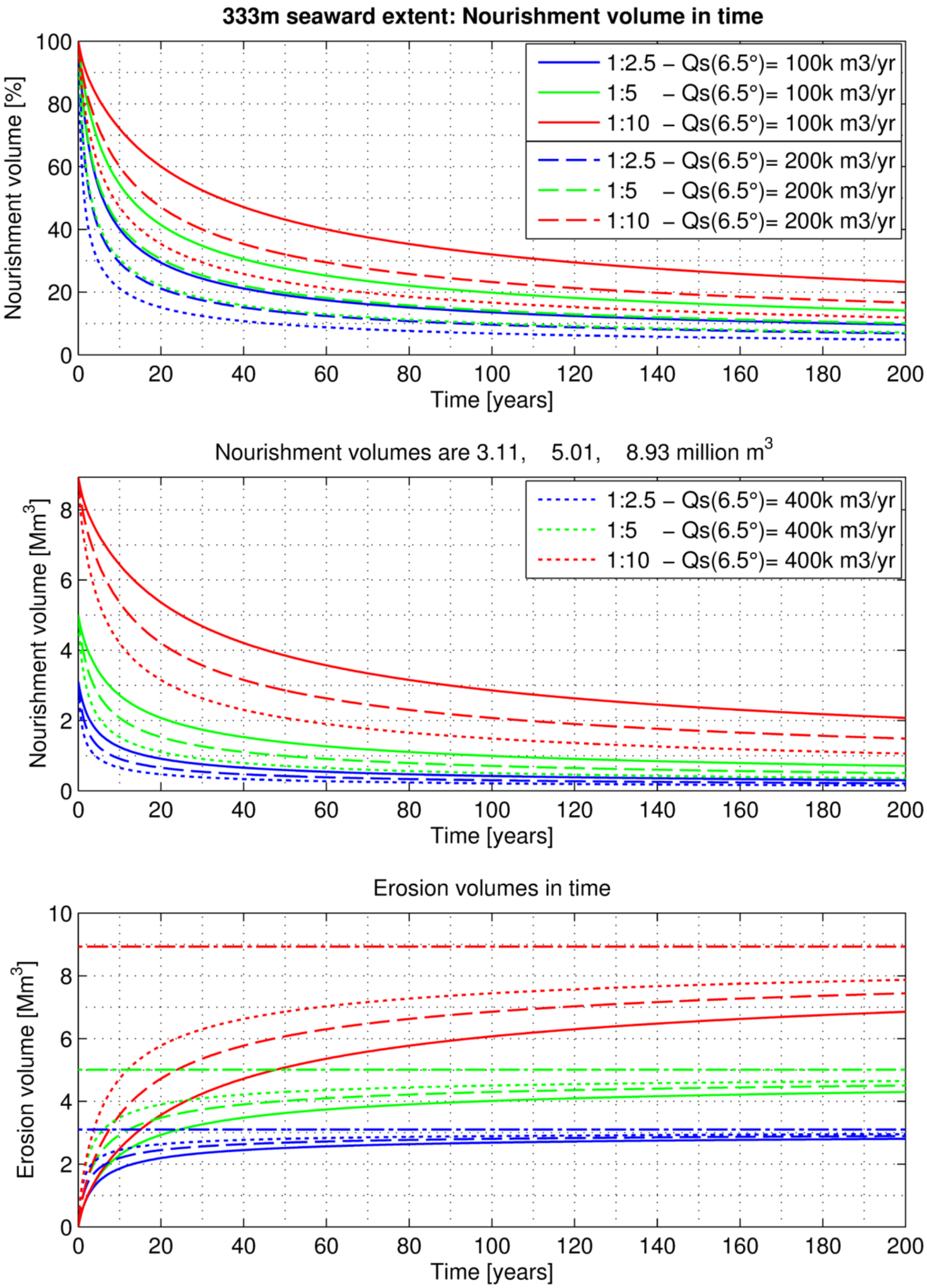



*Figure F.2 – Nourishment volumes / erosion volumes in time for 333m seaward extent*

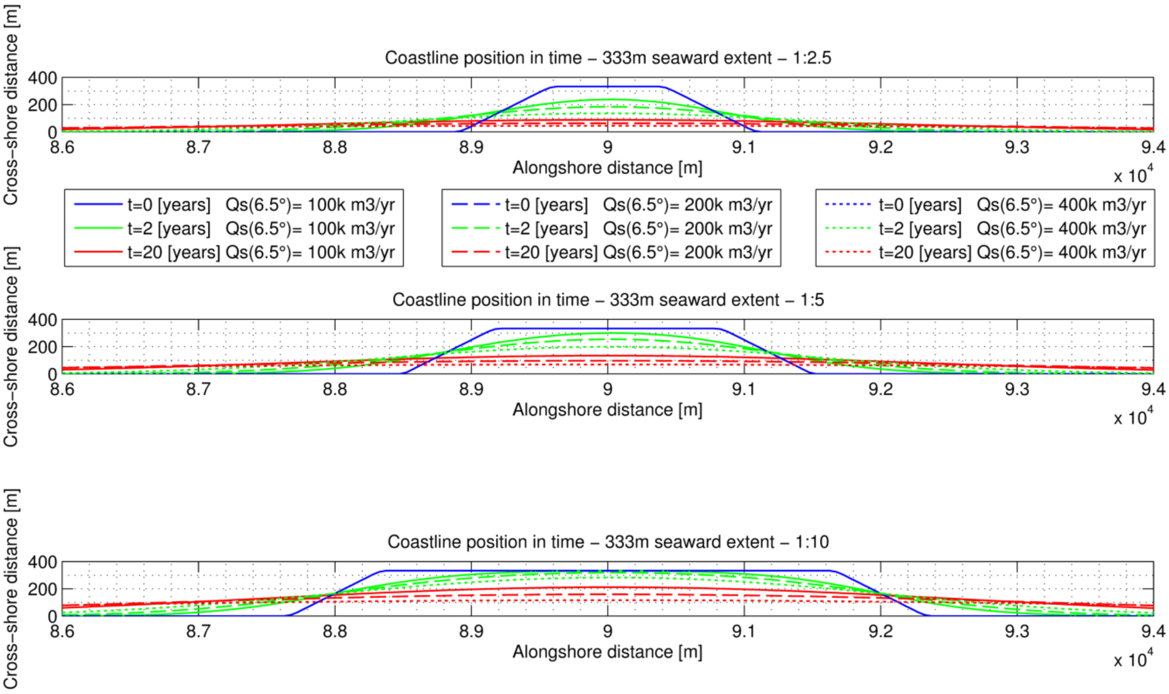



*Figure F.3 – Coastline position in time for the 333m seaward extent nourishments*

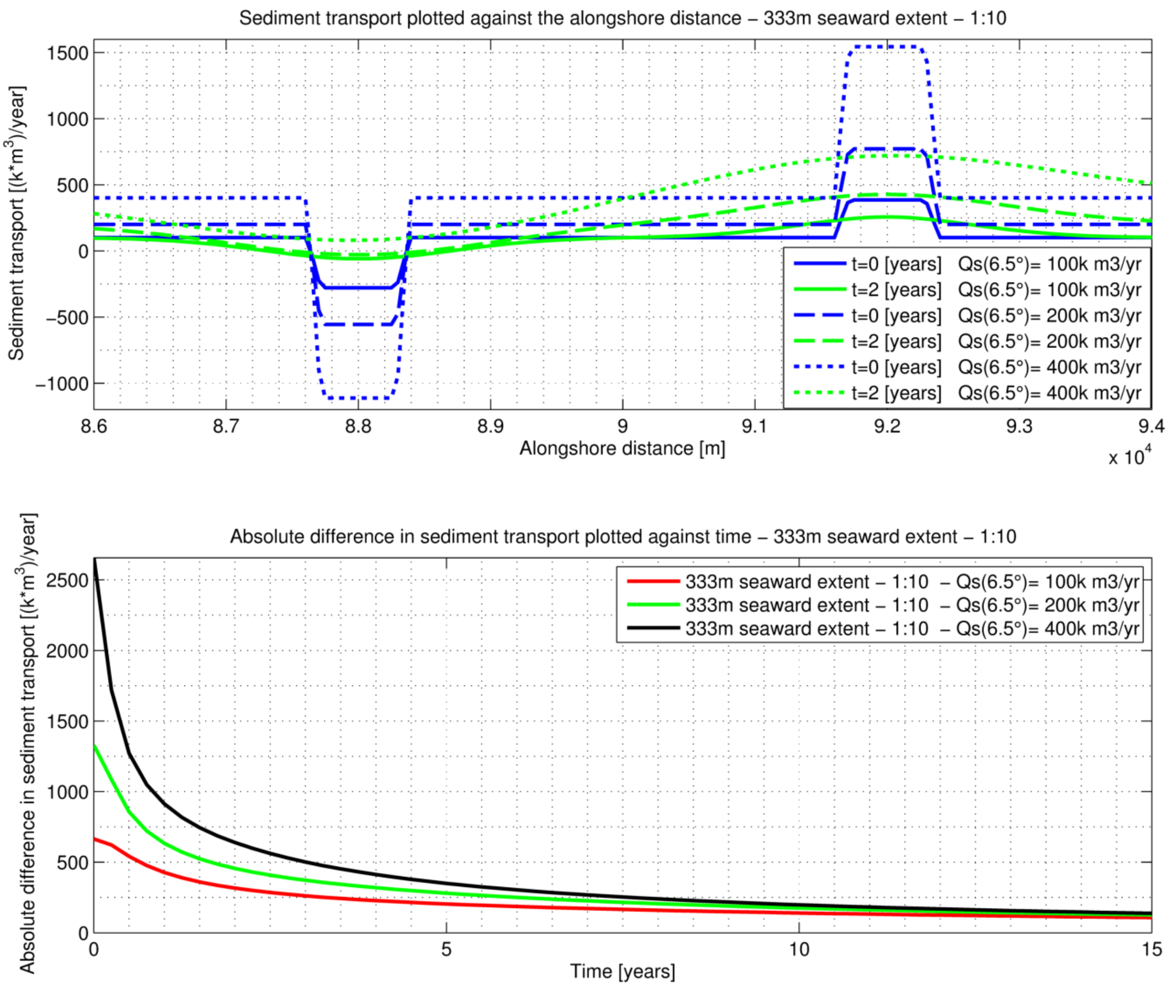
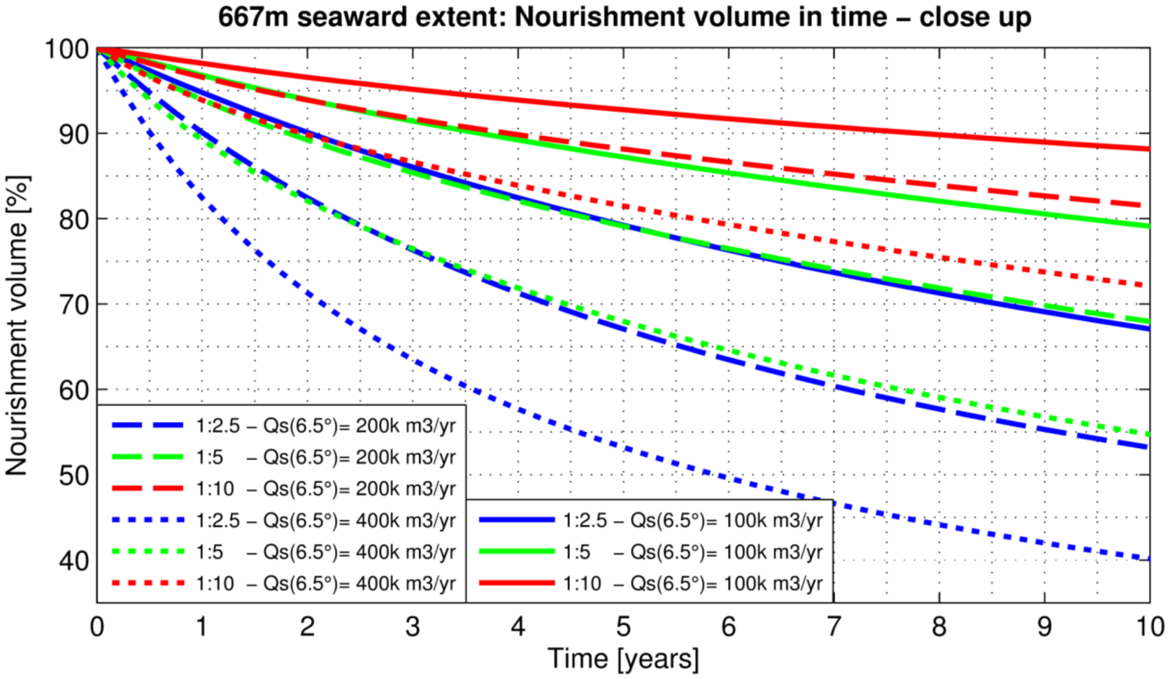



*Figure F.4 – Sediment transport in alongshore direction (upper) and in time (lower) for the 333m 1:10 nourishment*

## F.2 Seaward extent: 667m



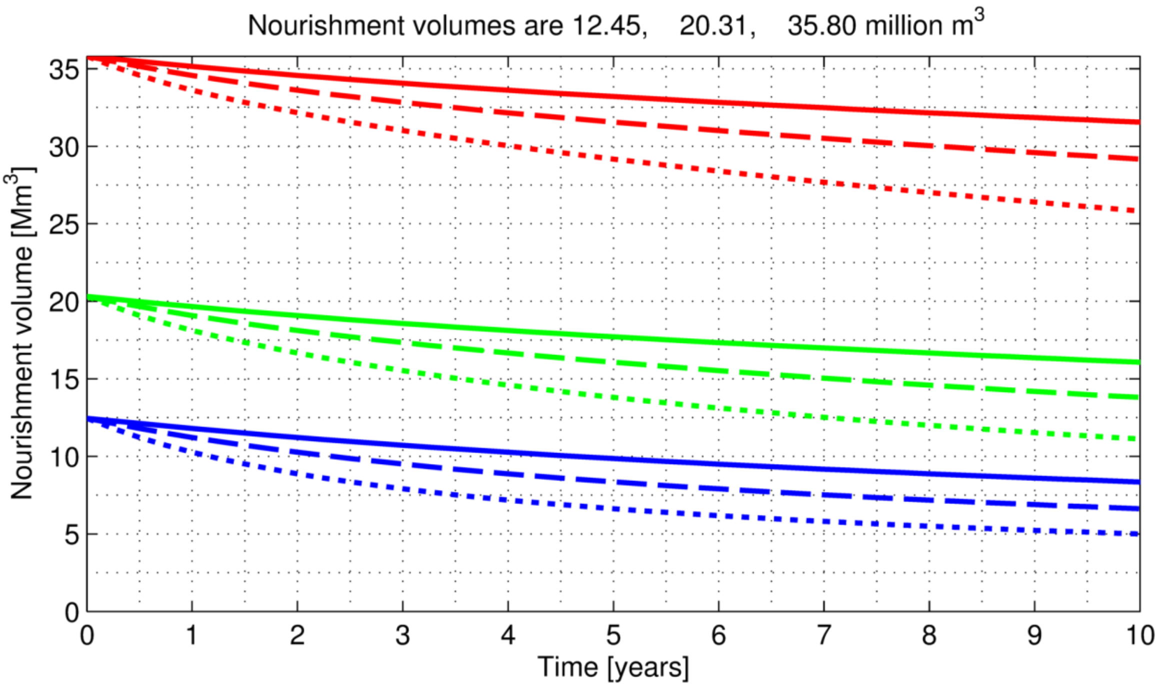




*Figure F.5 – Nourishment volumes in time for 667m seaward extent – close-up*

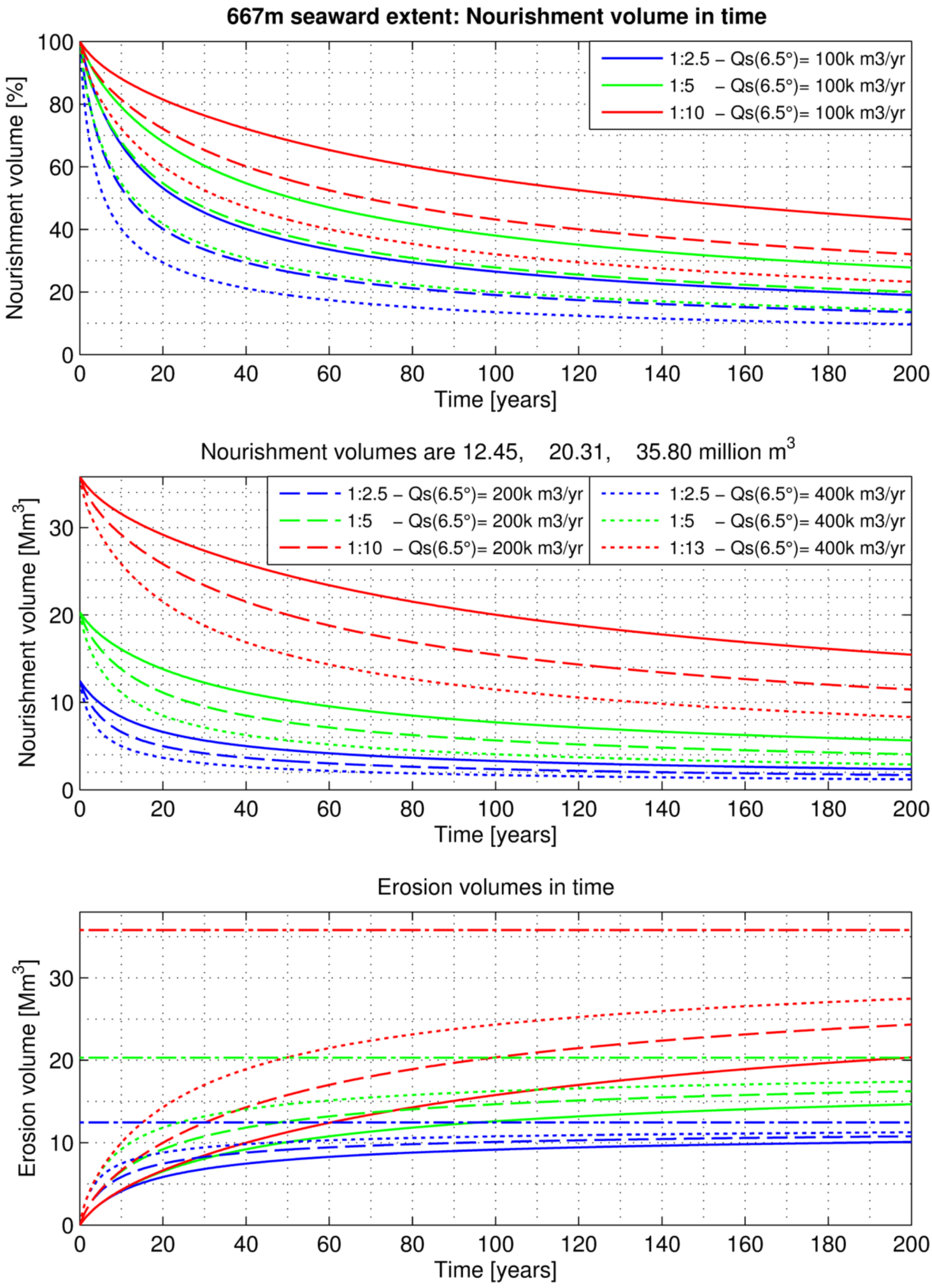



*Figure F.6 – Nourishment volumes / erosion volumes in time for 667m seaward extent*

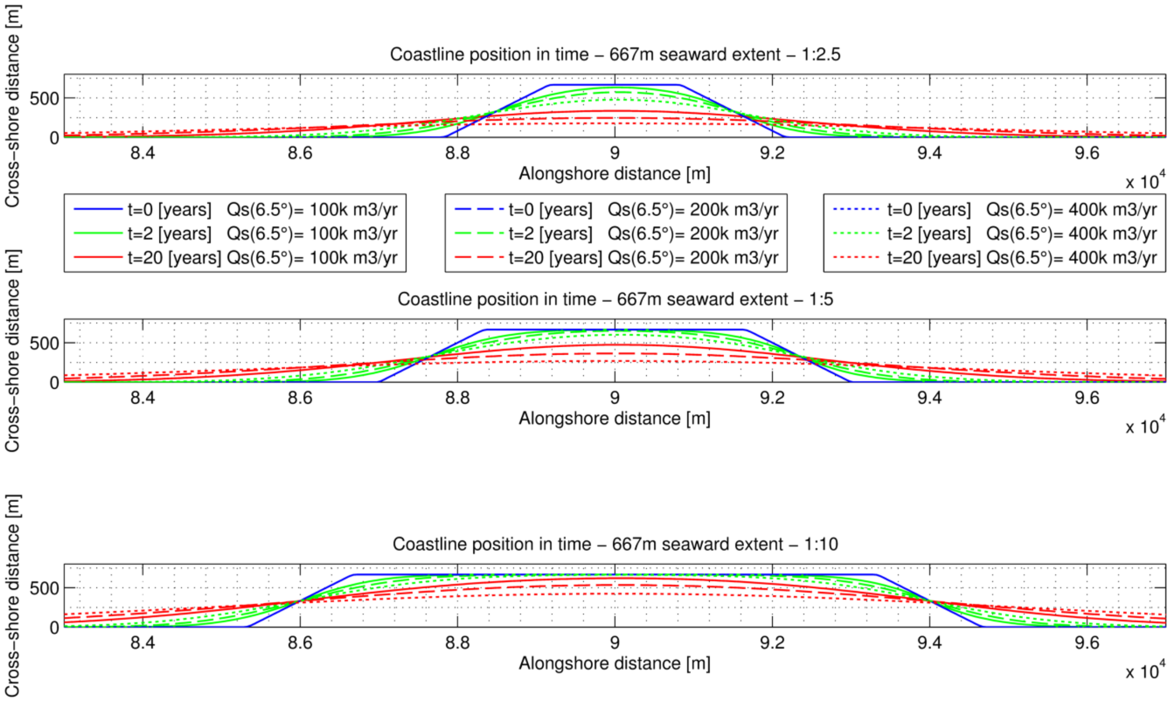



*Figure F.7 – Coastline position in time for the 667m seaward extent nourishments*

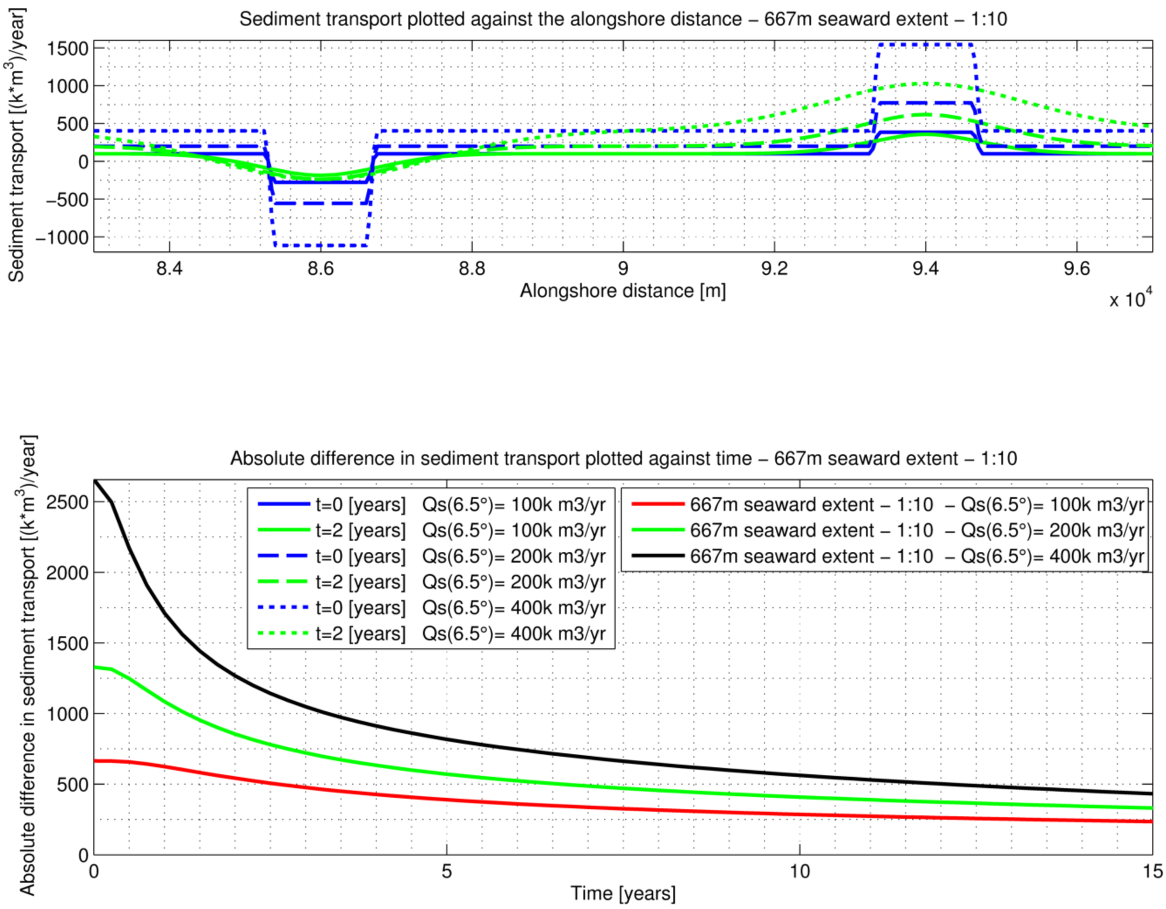
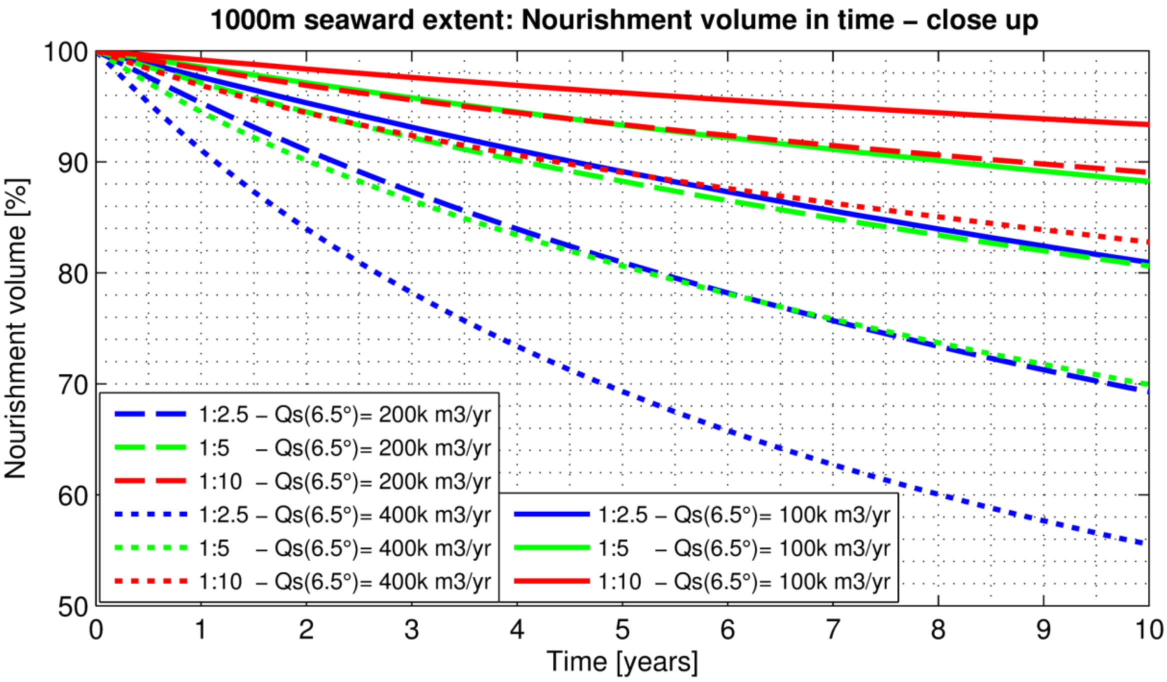



*Figure F.8 – Sediment transport in alongshore direction (upper) and in time (lower) for the 667m 1:10 nourishment*

## F.3 Seaward extent: 1000m



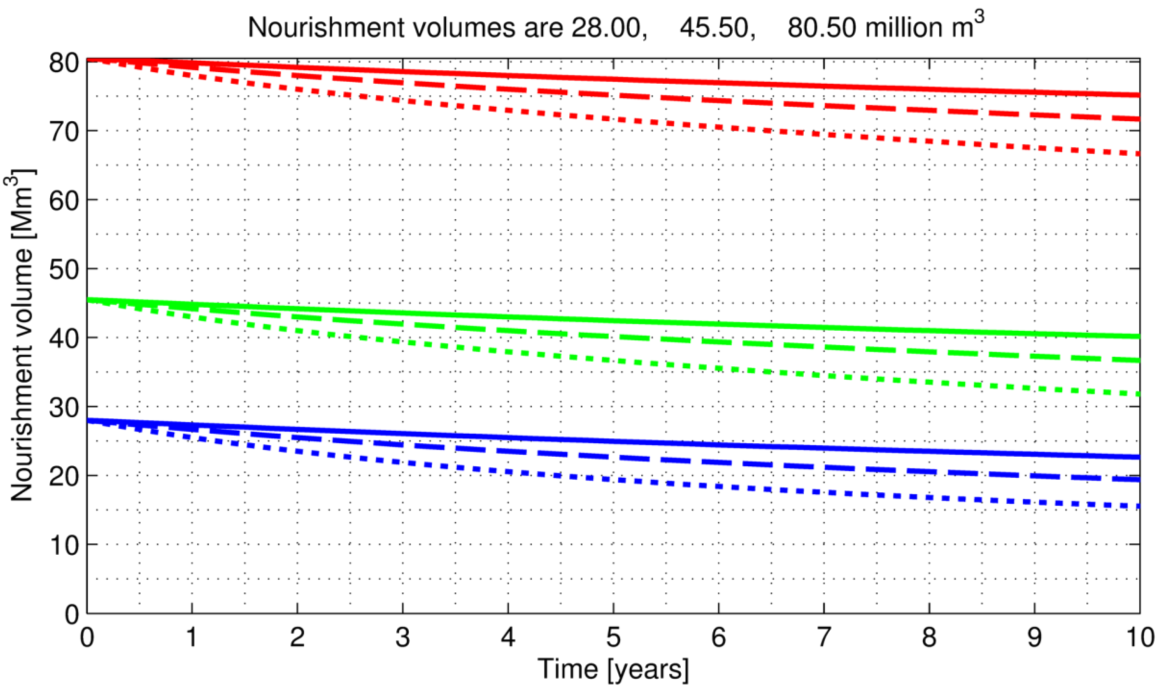




*Figure F.9 – Nourishment volumes in time for 1000m seaward extent – close-up*

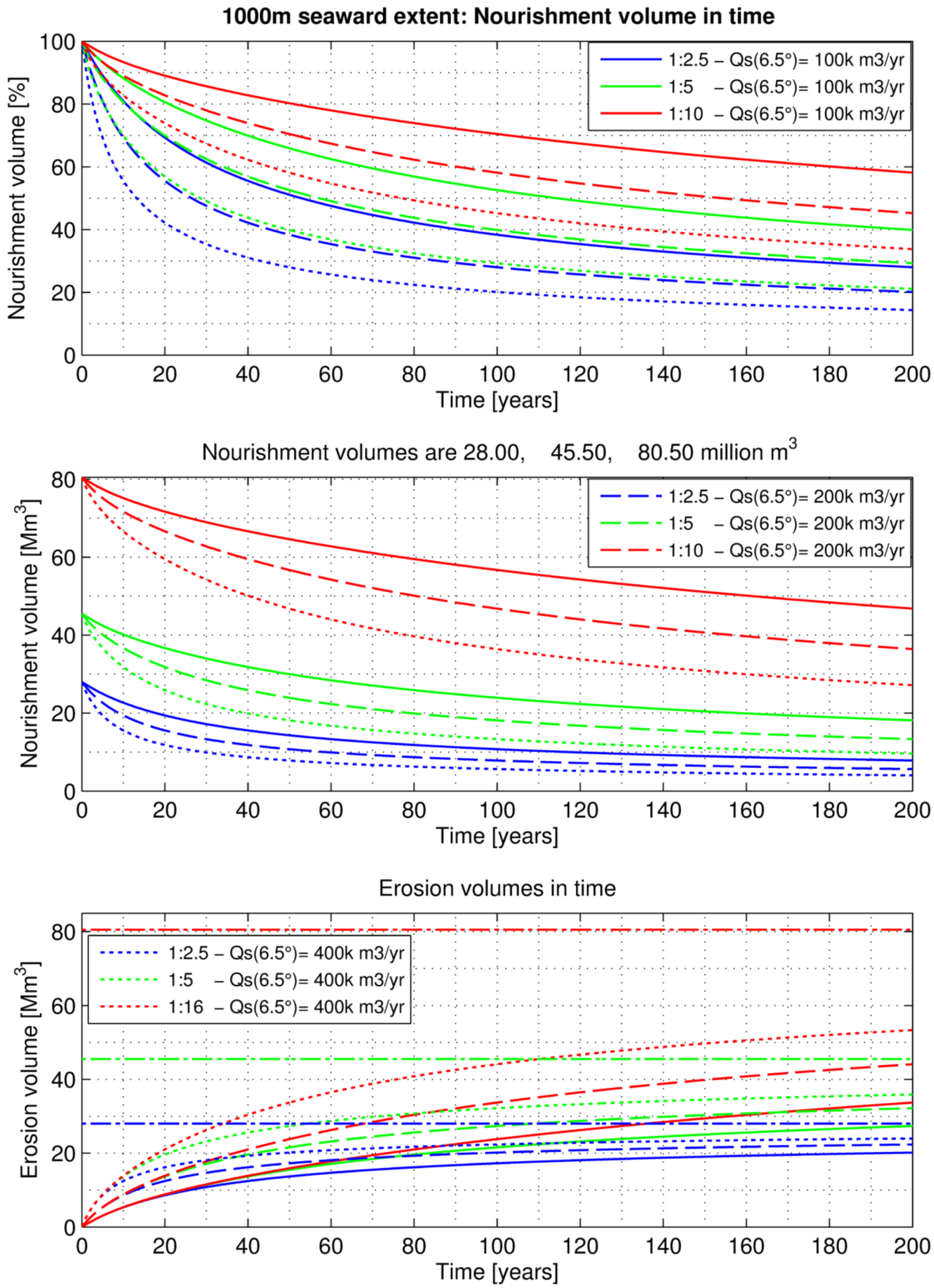



*Figure F.10 – Nourishment volumes / erosion volumes in time for 1000m seaward extent*

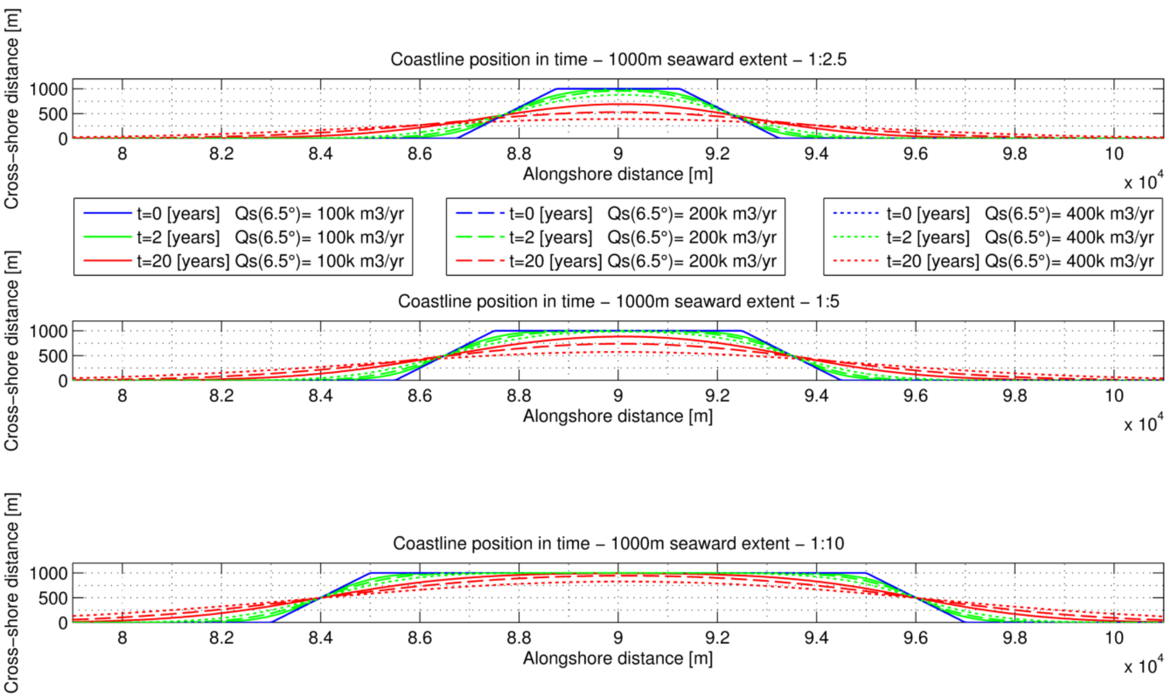



*Figure F.11 – Coastline position in time for the 1000m seaward extent nourishments*

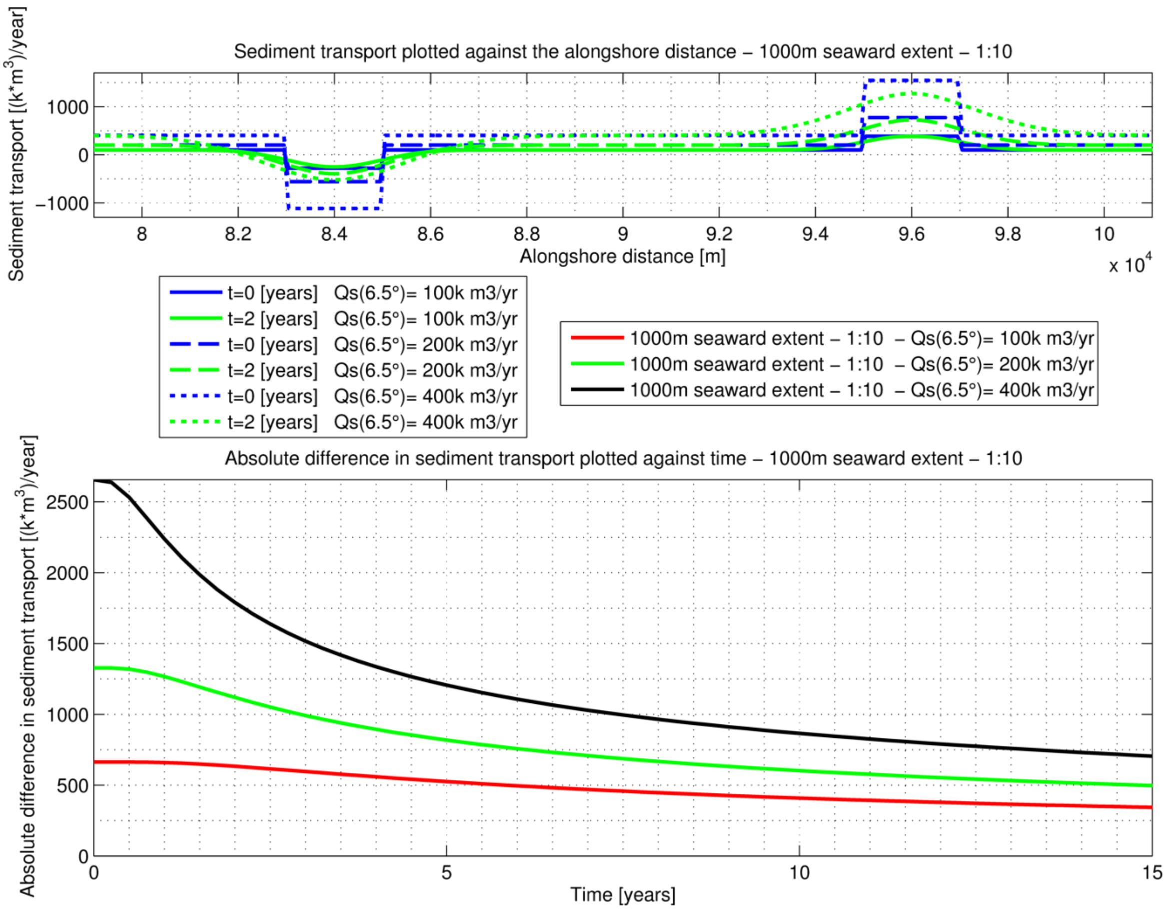



*Figure F.12 – Sediment transport in alongshore direction (upper) and in time (lower) for the 1000m 1:10 nourishment*

## F.4 Eroded volumes – 200 years

Figure F.13 shows the eroded volumes of each nourishment in this research which has been modelled with UNIBEST for a timeframe of 200 years. The stripe-dotted line shows the initial volumes of each nourishment.

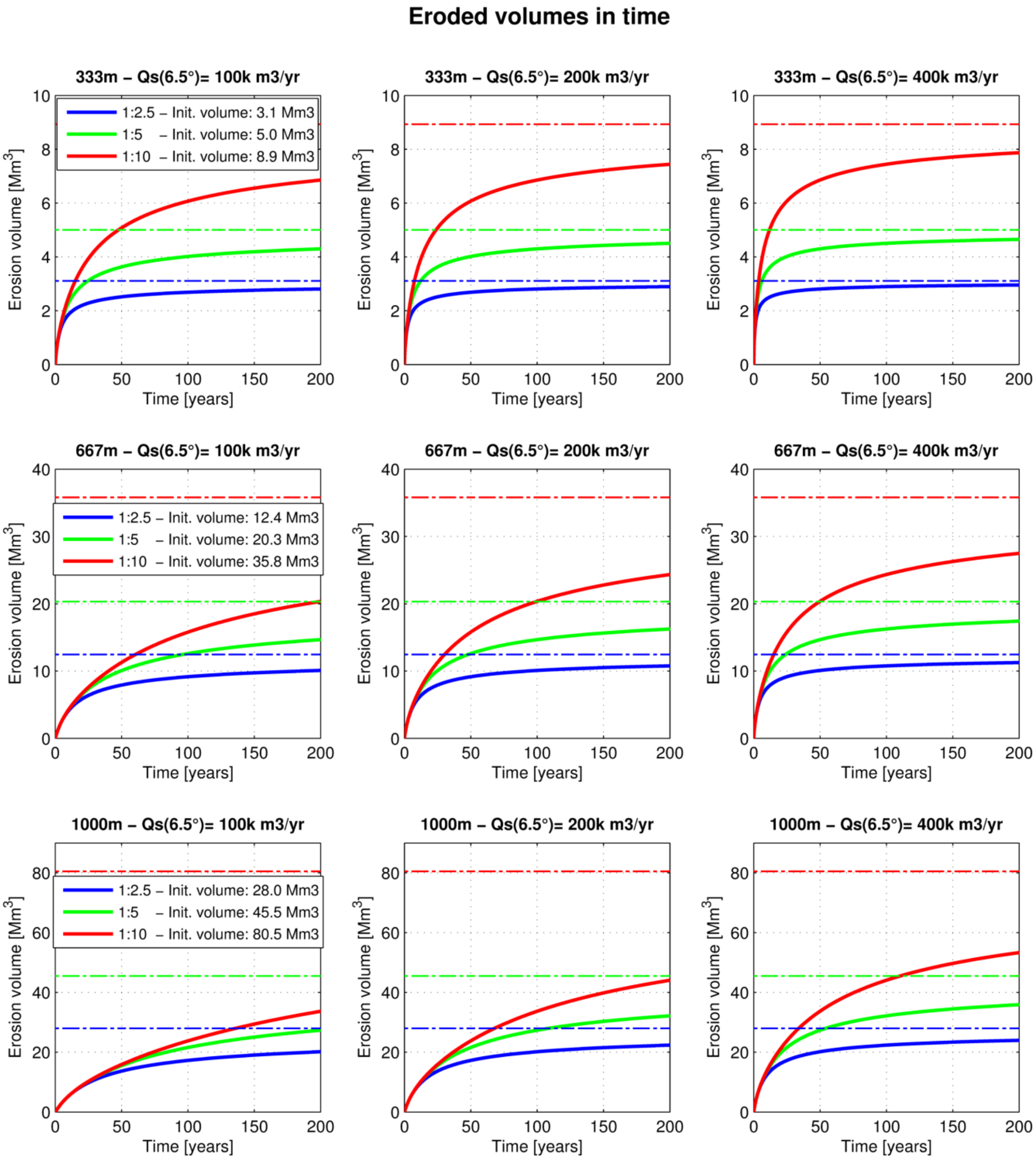



*Figure F.13 – Eroded volumes in time – 200 years*

## F.5 Eroded volumes – 20 years

Figure F.14 shows the eroded volumes of each nourishment in this research which has been modelled with UNIBEST for a timeframe of 20 years.

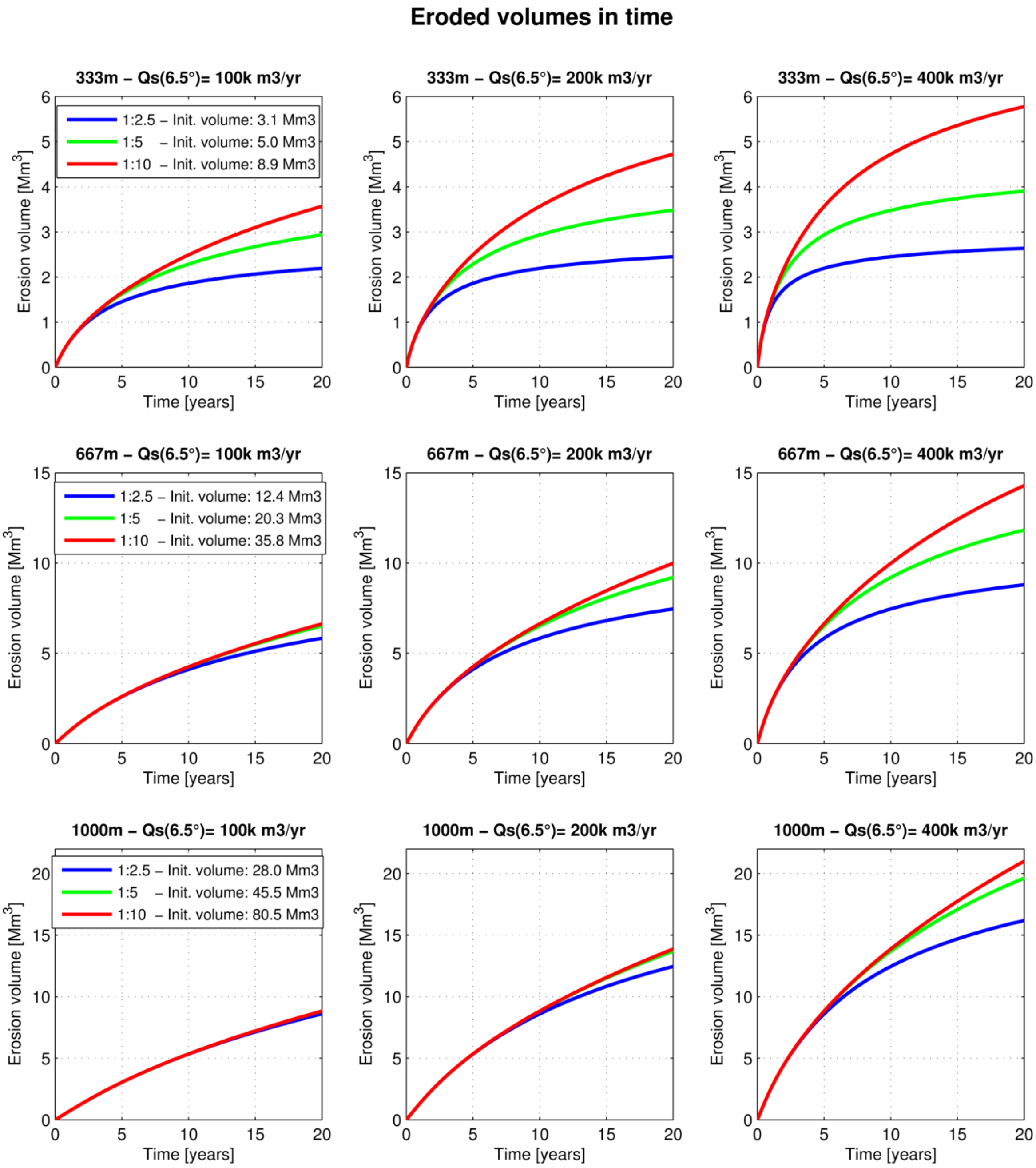



*Figure F.14 – Eroded volumes in time – 20 years*

# G Delft3D model results

This appendix shows all graphs and figures on which the conclusions in chapter 0 are based on. The results are grouped with respect to the seaward extent. First, the volume decrease in time is given for the first 20 years, both in percentages as in absolute volumes. Second, the eroded volumes for a period of 10 year are given. The last figure shows the alongshore sediment transport.

## G.1 Seaward extent: 333m

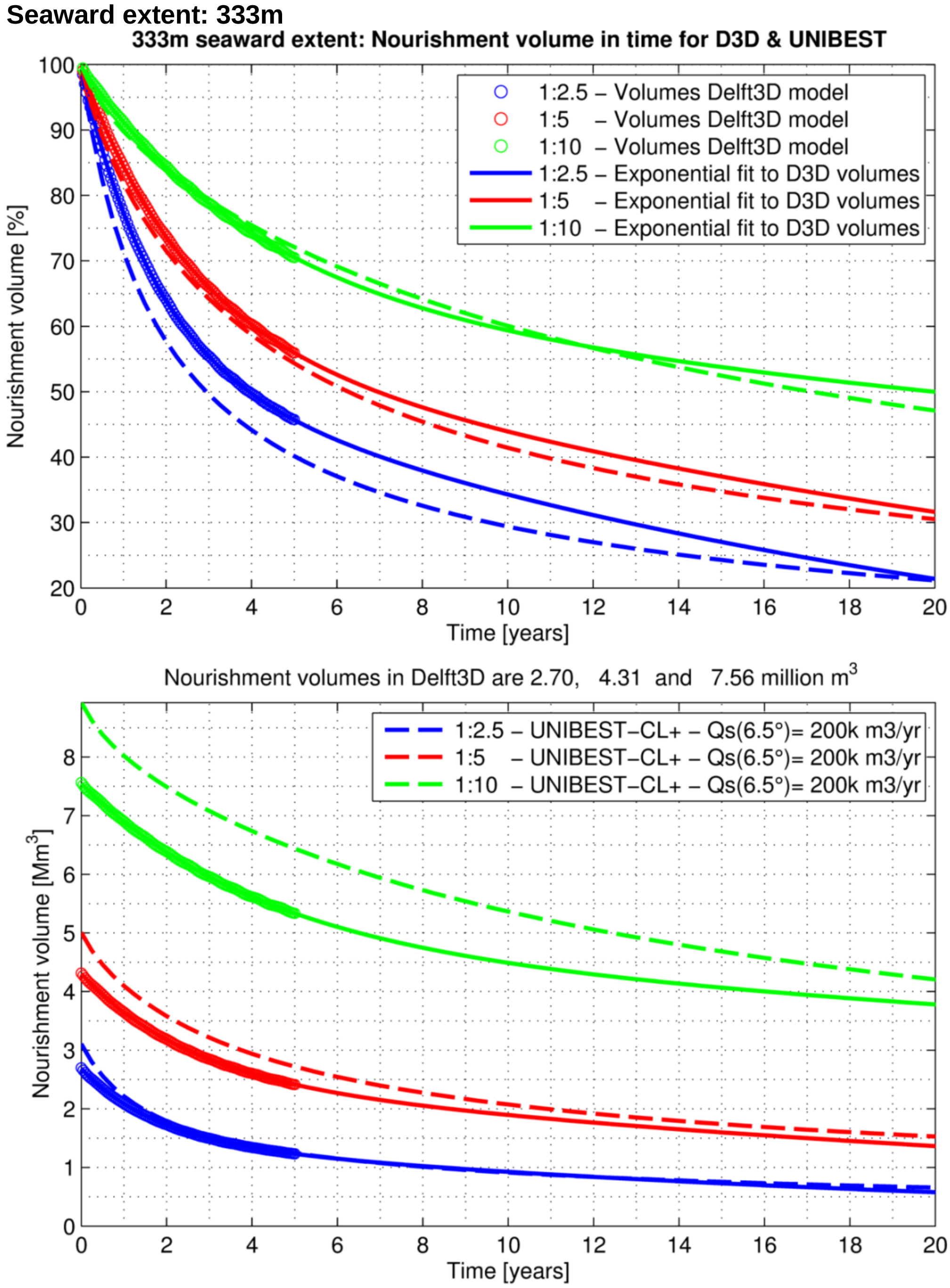



*Figure G.1 – Nourishment volumes in time for 333m seaward extent – D3D & UNIBEST*

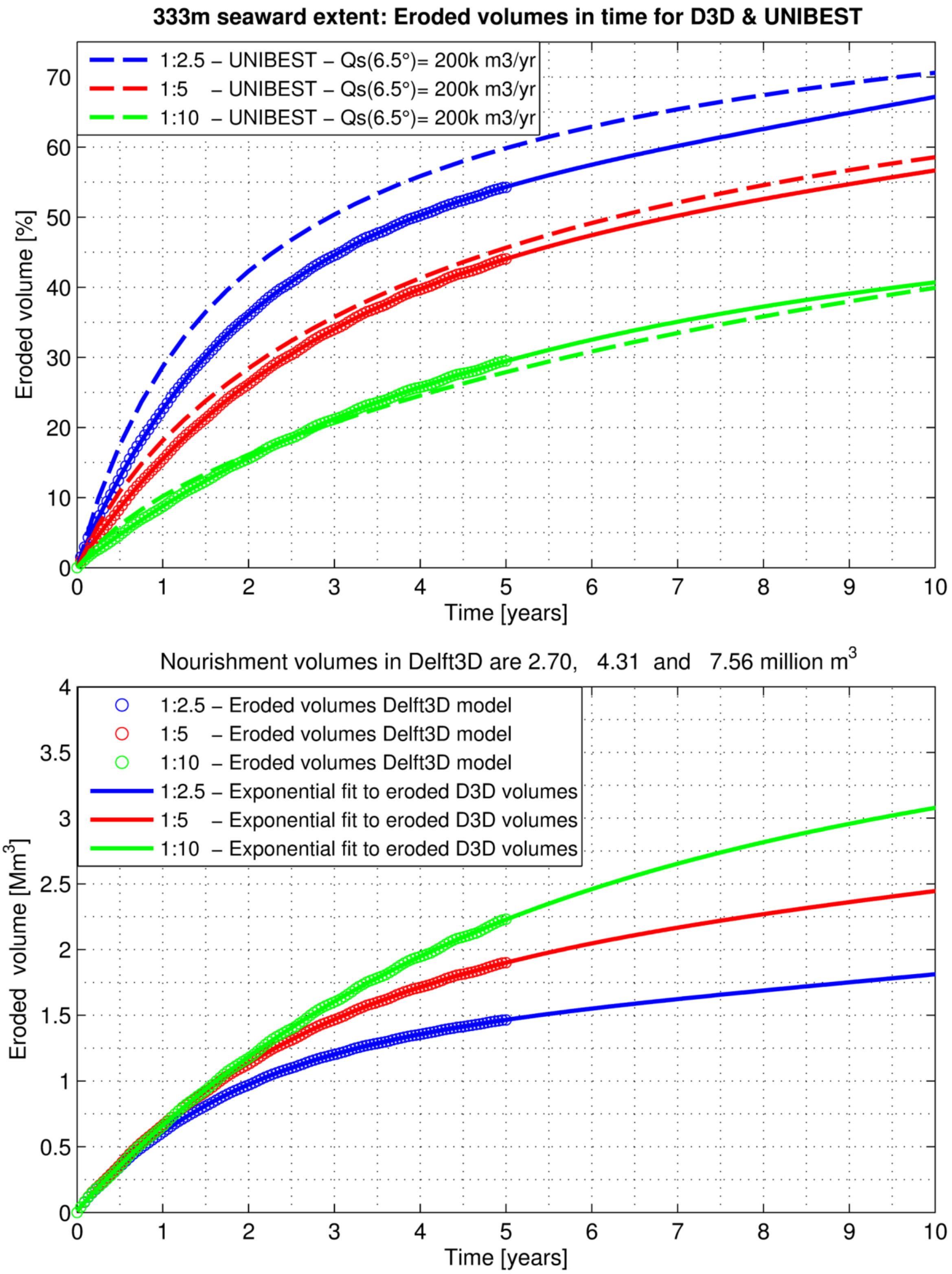



*Figure G.2 – Eroded volumes in time for 333m seaward extent – D3D & UNIBEST*

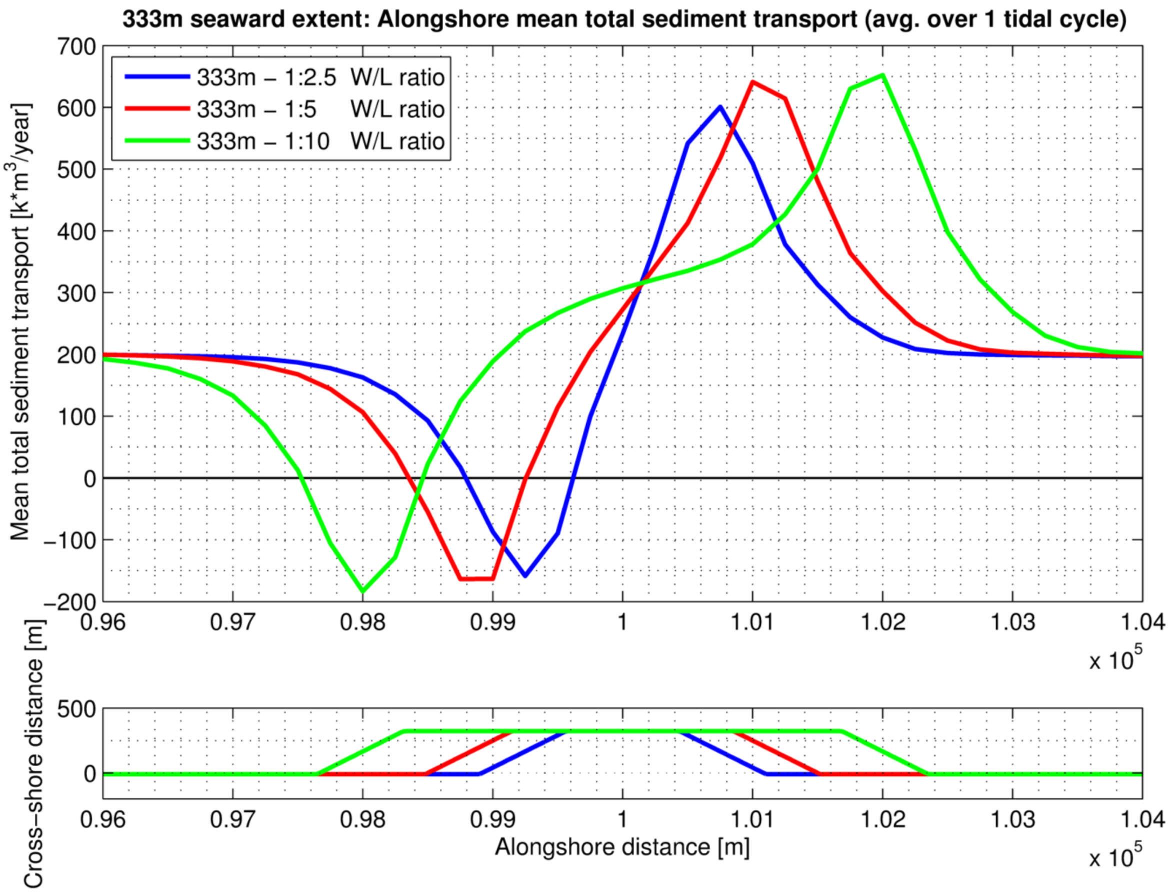



*Figure G.3 – Net alongshore sediment transport plotted against the alongshore distance for the 333m seaward extent nourishments*

## G.2 Seaward extent: 667m

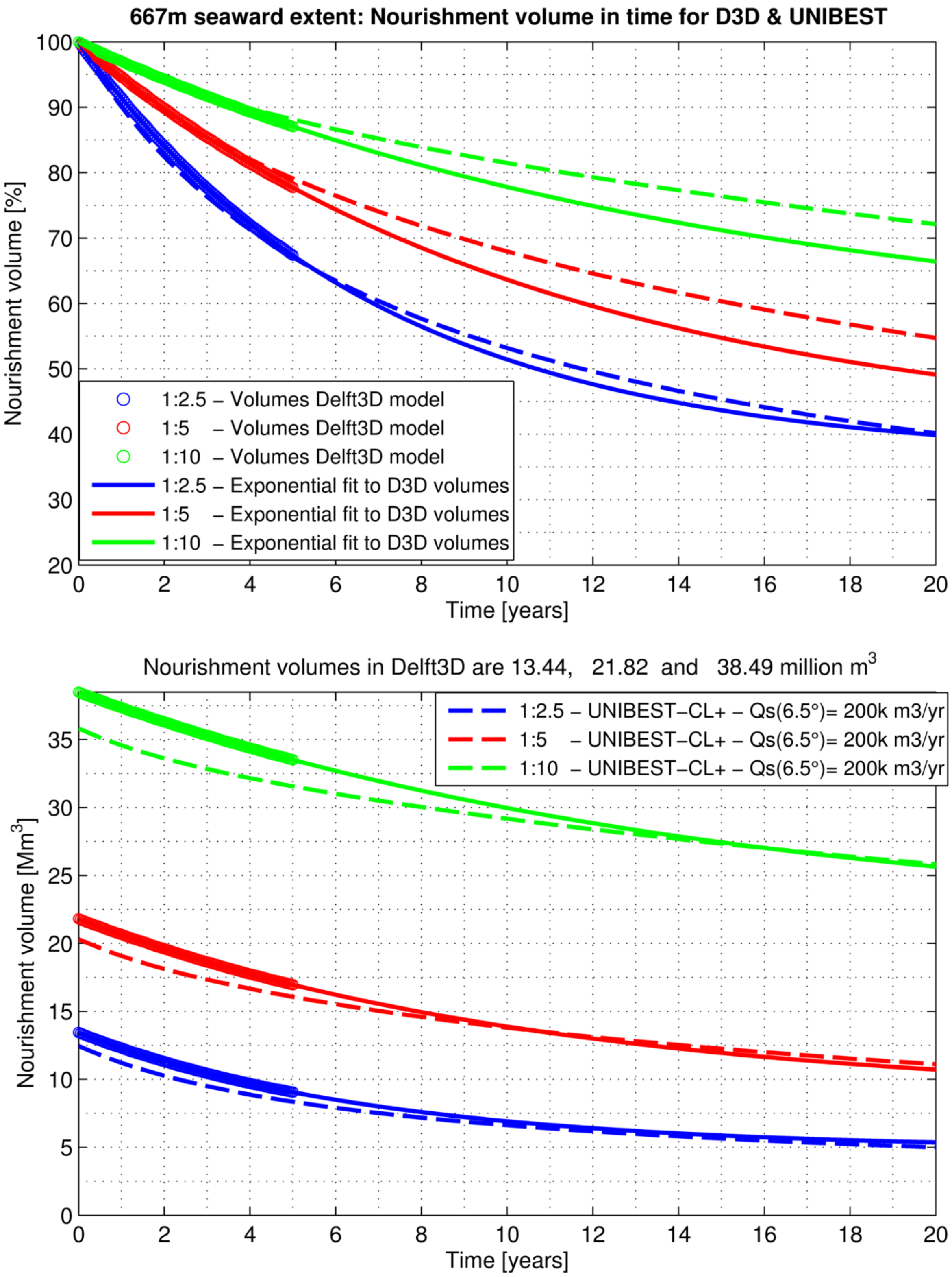



*Figure G.4 – Nourishment volumes in time for 667m seaward extent – D3D & UNIBEST*

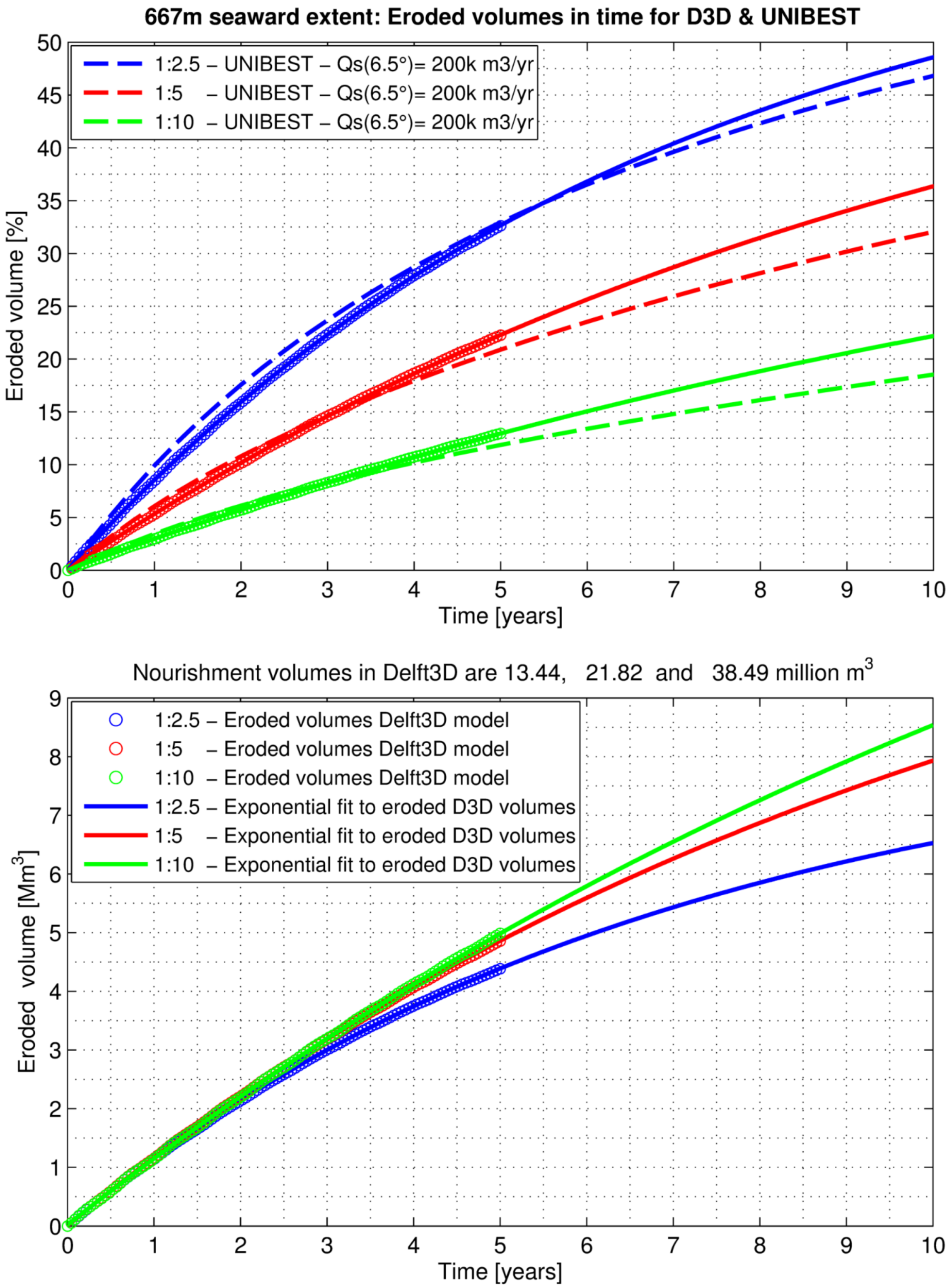



*Figure G.5 – Eroded volumes in time for 667m seaward extent – D3D & UNIBEST*

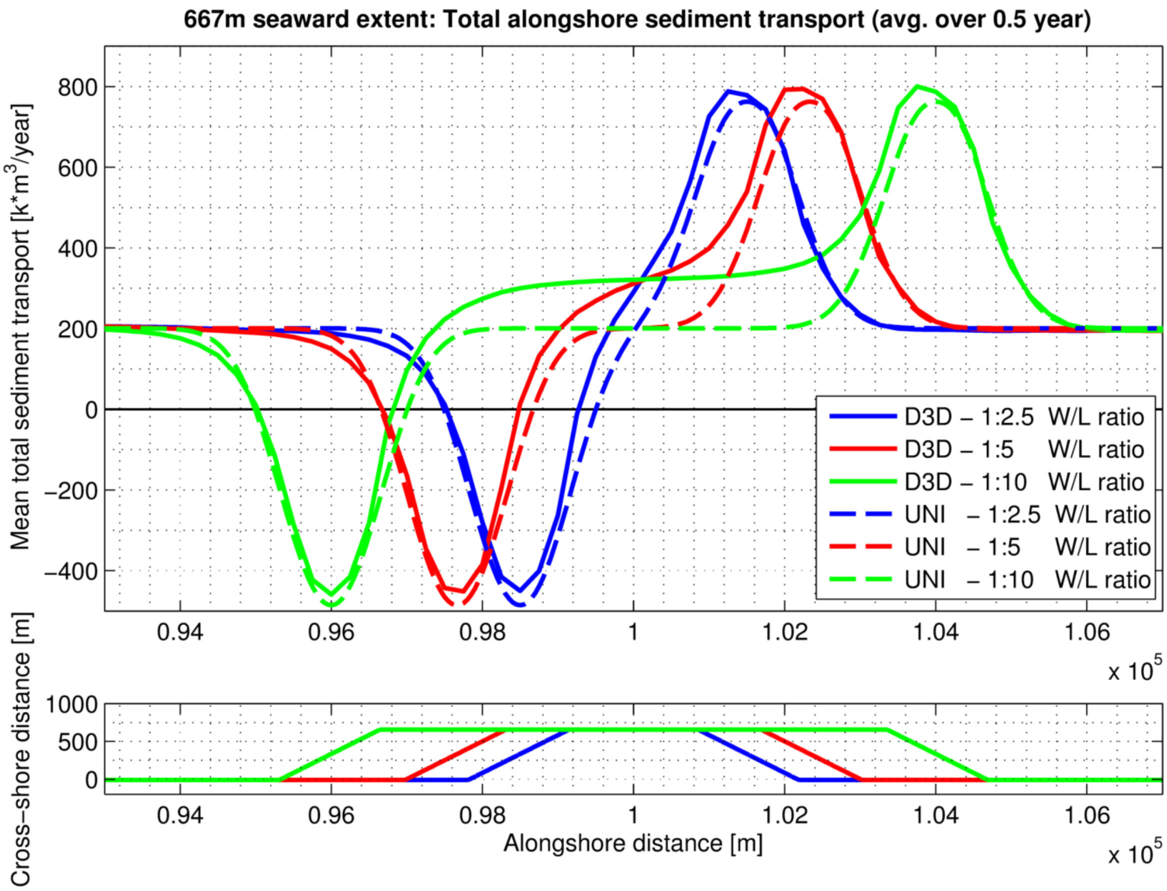



*Figure G.6 – Net alongshore sediment transport plotted against the alongshore distance for the 667m seaward extent nourishments*

## G.3 Seaward extent: 1000m

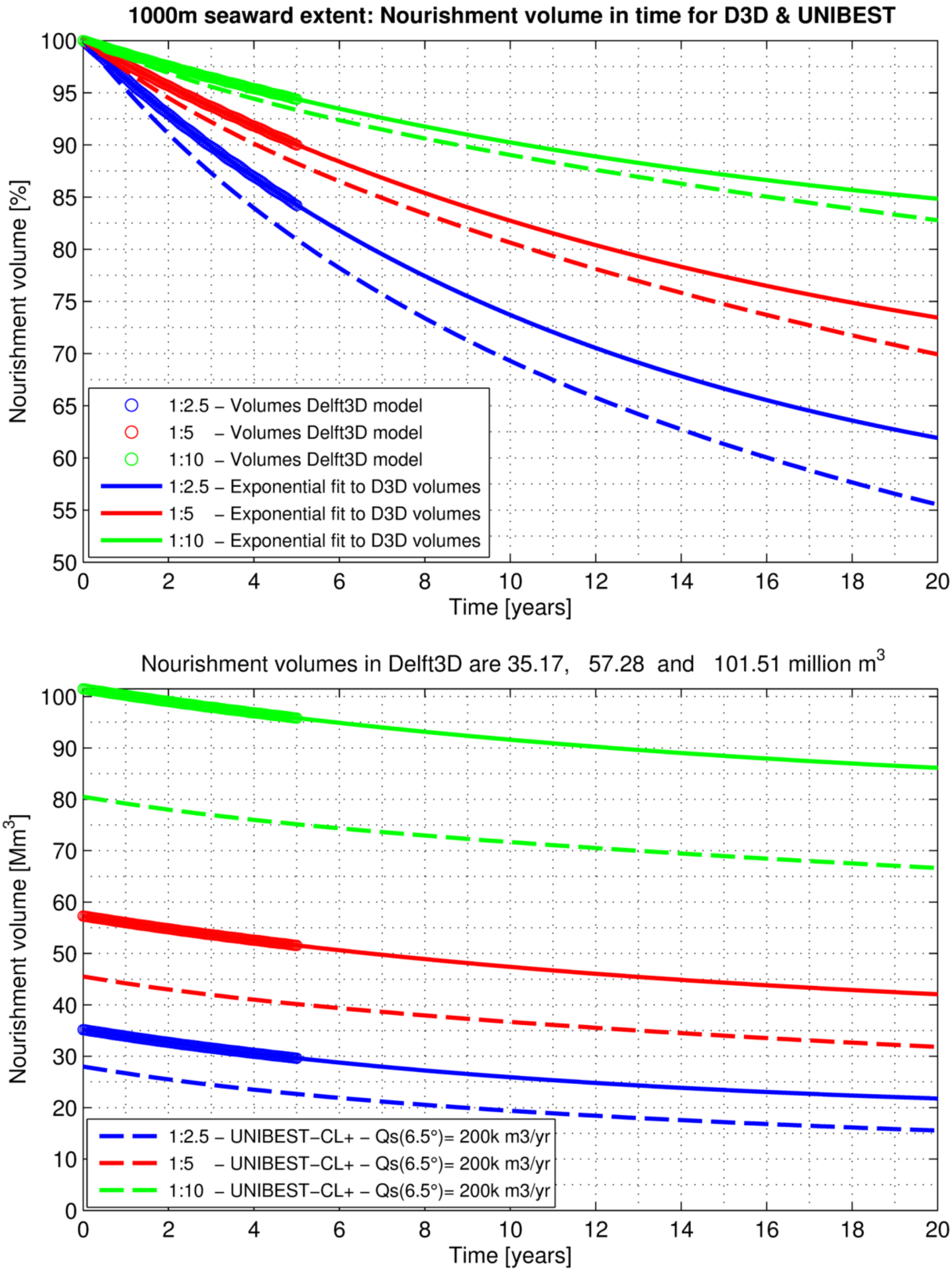



*Figure G.7 – Nourishment volumes in time for 1000m seaward extent – D3D & UNIBEST*

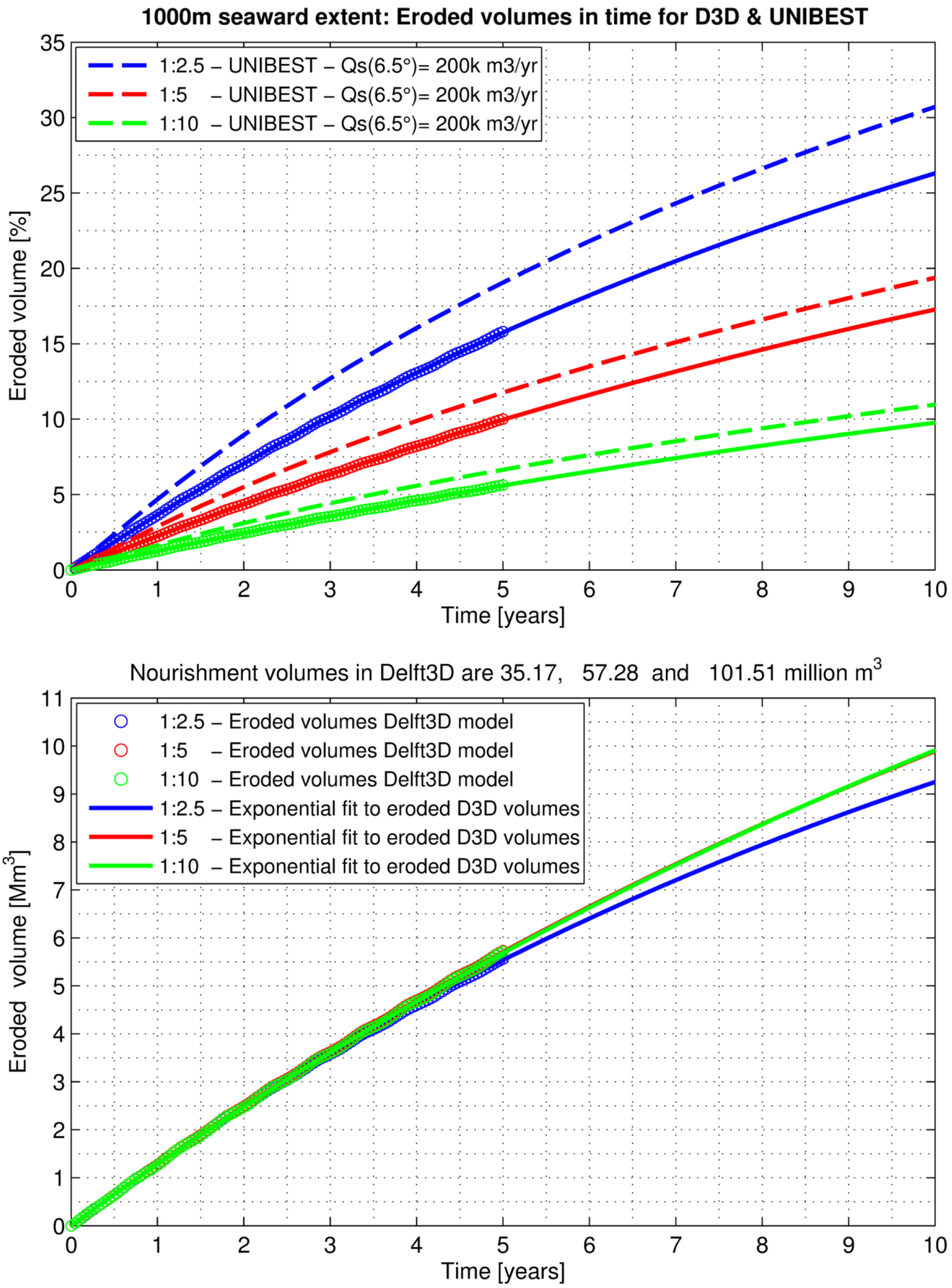



*Figure G.8 – Eroded volumes in time for 1000m seaward extent – D3D & UNIBEST*

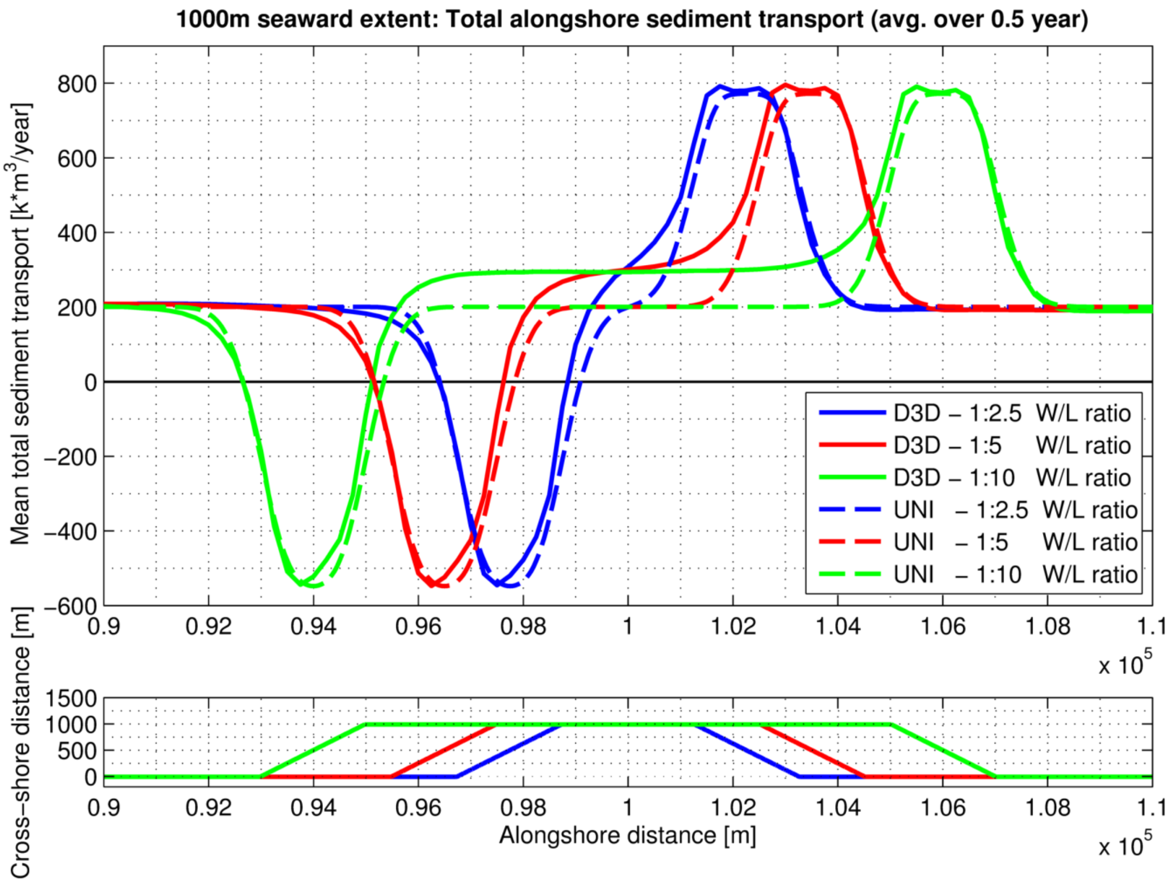



*Figure G.9 – Net alongshore sediment transport plotted against the alongshore distance for the 1000m seaward extent nourishments*

# H Bibliography

Aagaard, T., & Masselink, G. (1999). The surf zone. *Handbook of Beach and Shoreface Morphodynamics. Wiley, New York*, 72-118.

Ashton, A. D., & Murray, A. B. (2006). High-angle wave instability and emergent shoreline shapes: Wave climate analysis and comparisons to nature. *Journal of Geophysical Research: Earth Surface, 111*(F4). doi: 10.1029/2005JF000423

Bosboom, J., & Stive, M. J. F. (2012). *Coastal Dynamics I: Lectures Notes CIE4305*: VSSD.

Campbell, T., Dean, R. G., Mehta, A. J., & Wang, H. (1989). Short course on principles and applications of beach nourishment.

de Ronde, J. (2008). Toekomstige langjarige suppletiebehoefte. Delft: Deltares.

Dean, R., & Yoo, C. (1992). Beach-Nourishment Performance Predictions. *Journal of Waterway, Port, Coastal, and Ocean Engineering, 118*(6), 567-586. doi: doi:10.1061/(ASCE)0733-950X(1992)118:6(567)

Deltares. (2011a). UNIBEST-CL+ 7 *Readme*. Delft: Deltares.

Deltares. (2011b). UNIBEST-CL+ manual *Manual for version 7.1 of the shoreline model UNIBEST-CL+*. Delft: Deltares.

Deltares. (2013a). Delft3D-FLOW *User Manual*. Delft: Deltares.

Deltares. (2013b). Delft3D-WAVE *User Manual*. Delft: Deltares.

Giardino, A., Brière, C. B., & Van der Werf, J. J. (2011). Morphological modelling of bar dynamics with Delft3D. The quest for optimal parameter settings.: Deltares.

Grunnet, N. M., Ruessink, B. G., & Walstra, D.-J. R. (2005). The influence of tides, wind and waves on the redistribution of nourished sediment at Terschelling, The Netherlands. *Coastal Engineering, 52*(7), 617-631. doi: http://dx.doi.org/10.1016/j.coastaleng.2005.04.001

Grunnet, N. M., Walstra, D.-J. R., & Ruessink, B. G. (2004). Process-based modelling of a shoreface nourishment. *Coastal Engineering, 51*(7), 581-607. doi: http://dx.doi.org/10.1016/j.coastaleng.2004.07.016

Hoogheemraadschap & Rijkswaterstaat. (2013). Kust op Kracht: Voornemen tot gunning kustversterking verstuurd. from http://www.kustopkracht.nl/actueel/voornemen-tot-gunning-kustversterking-verstuurd.html

Hoogheemraadschap & Rijkswaterstaat. (2014). Kust op Kracht: Nieuwsbrief 09 - Maart 2014.

Huisman, B. J. A., Sirks, E. E., van der Valk, L., & Walstra, D. J. R. (2014). *Time and spatial variability of sediment gradings in the surfzone of a large scale nourishment*. Paper presented at the Proceedings 13th International Coastal Symposium, Durban (South Africa).

Kamphuis, J. (1991). Alongshore Sediment Transport Rate. *Journal of Waterway, Port, Coastal, and Ocean Engineering, 117*(6), 624-640. doi: doi:10.1061/(ASCE)0733-950X(1991)117:6(624)

Koninklijke Boskalis Westminster N.V. (2013). Persbericht - Boskalis en Van Oord versterken laatste Zwakke Schakel Hollandse kust. Papendrecht.

Koopal, A. (2013). Projectplan Kustversterking Katwijk. Amersfoort: Arcadis.

Lesser, G. R., Roelvink, J. A., van Kester, J. A. T. M., & Stelling, G. S. (2004). Development and validation of a three-dimensional morphological model. *Coastal Engineering, 51*(8–9), 883-915. doi: http://dx.doi.org/10.1016/j.coastaleng.2004.07.014

Mangor, K. (2004). *Shoreline Management Guidelines*: DHI Water & Environment.

Medusa. (2010). Tussentijdse rapportage Project Zandmotor Delfland, t0 meting. Groningen: Medusa Explorations BV.

Mulder, J. P. M., Hommes, S., & Horstman, E. M. (2011). Implementation of coastal erosion management in the Netherlands. *Ocean & Coastal Management, 54*(12), 888-897. doi: http://dx.doi.org/10.1016/j.ocecoaman.2011.06.009

Niedoroda, A. W., Reed, C. W., Swift, D. J. P., Arato, H., & Hoyanagi, K. (1995). Modeling shore-normal large-scale coastal evolution. *Marine Geology, 126*(1–4), 181-199. doi: http://dx.doi.org/10.1016/0025-3227(95)98961-7

Ranasinghe, R., Swinkels, C., Luijendijk, A., Roelvink, D., Bosboom, J., Stive, M., & Walstra, D. (2011). Morphodynamic upscaling with the MORFAC approach: Dependencies and sensitivities. *Coastal Engineering, 58*(8), 806-811. doi: http://dx.doi.org/10.1016/j.coastaleng.2011.03.010

Rijksoverheid. (2012). Laatste Zwakke Schakels langs de kust krijgen versterking. from http://www.rijksoverheid.nl/nieuws/2012/06/13/laatste-zwakke-schakels-langs-de-kust-krijgen-versterking.html

Rijkswaterstaat. (2013). De Zandmotor. from http://www.dezandmotor.nl/

Rijkswaterstaat & Joop van Houdt. (2012). 20 maart 2012 Zandmotor 04502. from https://www.flickr.com/photos/zandmotor/7024444817/

Roelvink, J. A. (2006). Coastal morphodynamic evolution techniques. *Coastal Engineering, 53*(2–3), 277-287. doi: http://dx.doi.org/10.1016/j.coastaleng.2005.10.015

Roelvink, J. A., & Stive, M. J. F. (1989). Bar-generating cross-shore flow mechanisms on a beach. *Journal of Geophysical Research: Oceans, 94*(C4), 4785-4800. doi: 10.1029/JC094iC04p04785

Roelvink, J. A., & Walstra, D.-J. (2004). Keeping it simple by using complex models. *Advances in Hydro-Science and Engineering, 6*, 1-11.

Ruessink, B. G., Walstra, D. J. R., & Southgate, H. N. (2003). Calibration and verification of a parametric wave model on barred beaches. *Coastal Engineering, 48*(3), 139-149. doi: http://dx.doi.org/10.1016/S0378-3839(03)00023-1

Shore Monitoring & Research. (2013). Morfologische ontwikkeling van de Zandmotor pilot in de eerste 2 jaar na aanleg (pp. 141). Delft.

Staatscommissie voor Duurzame Kustontwikkeling. (2008). Samen werken met water.

Stive, M. J. F., Aarninkhof, S. G. J., Hamm, L., Hanson, H., Larson, M., Wijnberg, K. M., . . . Capobianco, M. (2002). Variability of shore and shoreline evolution. *Coastal Engineering, 47*(2), 211-235. doi: http://dx.doi.org/10.1016/S0378-3839(02)00126-6

Stive, M. J. F., de Schipper, M. A., Luijendijk, A. P., Aarninkhof, S. G. J., van Gelder-Maas, C., van Thiel de Vries, J. S. M., . . . Ranasinghe, R. (2013). A New Alternative to Saving Our Beaches from Sea-Level Rise: The Sand Engine. *Journal of Coastal Research*, 1001-1008. doi: 10.2112/JCOASTRES-D-13-00070.1

Stive, M. J. F., de Vriend, H. J., Nicholls, R. J., & Capobianco, M. (1993). *Shore nourishment and the active zone: a time scale dependent view*. http://resolver.tudelft.nl/uuid:3cf1453e-4e19-468e-b94e-1d9422e1e70b

Stronkhorst, J., Mulder, J. P. M., De Ronde, J., Huisman, B. J. A., & Sprengers, C. (2012). Large-scale sand nourishment strategy of the Dutch coast; A systems approach *Book of Abstracts. International Conference Littoral 2012: Coasts of Tomorrow. Kursaal, Oostende, 27-29 November 2012* (Vol. 61, pp. 101-102): Coordination Centre for Integrated Coastal Zone Management.

Tonnon, P. K., & Baptist, M. J. (2011). T0-rapportage Monitoring en Evaluatie Pilot Zandmotor (pp. 187). Delft: Rijkswaterstaat Waterdienst; Deltares; IMARES.

van de Rest, P. (2004). *Morfodynamica en hydrodynamica van de Hollandse kust.* (MSc), TU Delft, Delft.

van der Grinten, R. M., & Ruessink, B. G. (2012). Evaluatie van de kustversterking bij Noordwijk aan Zee - De invloed van de versterking op de zandbanken. Utrecht.

van der Westhuysen, A. J. (2010). Modeling of depth-induced wave breaking under finite depth wave growth conditions. *Journal of Geophysical Research: Oceans, 115*(C1), C01008. doi: 10.1029/2009JC005433

Van Oord - Boskalis. (2013). Initieel Aanlegprofiel, Prognose van meerjarig hydraulisch zandverlies *Zwakke Schakels Noord-Holland, Versterking en Onderhoud, Kustdeel RSP17.00 - RSP28.32* (pp. 22).

van Rijn, L. C. (1997). Sediment transport and budget of the central coastal zone of Holland. *Coastal Engineering, 32*(1), 61-90. doi: http://dx.doi.org/10.1016/S0378-3839(97)00021-5

van Rijn, L. C. (2007a). Unified View of Sediment Transport by Currents and Waves. I: Initiation of Motion, Bed Roughness, and Bed-Load Transport. *Journal of Hydraulic Engineering, 133*(6), 649-667. doi: doi:10.1061/(ASCE)0733-9429(2007)133:6(649)

van Rijn, L. C. (2007b). Unified View of Sediment Transport by Currents and Waves. II: Suspended Transport. *Journal of Hydraulic Engineering, 133*(6), 668-689. doi: doi:10.1061/(ASCE)0733-9429(2007)133:6(668)

van Rijn, L. C. (2007c). Unified View of Sediment Transport by Currents and Waves. III: Graded Beds. *Journal of Hydraulic Engineering, 133*(7), 761-775. doi: doi:10.1061/(ASCE)0733-9429(2007)133:7(761) van Rijn, L. C. (2011). Coastal erosion and control. *Ocean & Coastal Management, 54*(12), 867-887. doi: http://dx.doi.org/10.1016/j.ocecoaman.2011.05.004

van Rijn, L. C. (2014a). Erosion of land reclamations protected by natural sand dunes and beaches.

van Rijn, L. C. (2014b). A simple general expression for longshore transport of sand, gravel and shingle. *Coastal Engineering, 90*, 23-39. doi: http://dx.doi.org/10.1016/j.coastaleng.2014.04.008

van Rijn, L. C., Tonnon, P. K., & Walstra, D. J. R. (2011). Numerical modelling of erosion and accretion of plane sloping beaches at different scales. *Coastal Engineering, 58*(7), 637-655. doi: http://dx.doi.org/10.1016/j.coastaleng.2011.01.009

van Rijn, L. C., Walstra, D. J. R., & van Ormondt, M. (2004). Description of TRANSPOR2004 and implementation in Delft3D-ONLINE: final report. Delft: WL| Delft Hydraulics.

van Thiel de Vries, J. S. M. (2009). Quickscan zwakke schakel Petten: aanvullend modelonderzoek (pp. 39). Delft: Deltares.

Walstra, D. J. R., Hoekstra, R., Tonnon, P. K., & Ruessink, B. G. (2013). Input reduction for long-term morphodynamic simulations in wave-dominated coastal settings. *Coastal Engineering, 77*(0), 57-70. doi: http://dx.doi.org/10.1016/j.coastaleng.2013.02.001

Wijsman, J. W. M., & Verduin, E. (2011). T0 monitoring Zandmotor Delflandse kust: benthos ondiepe kustzone en natte strand. Yerseke: IMARES Yerseke.