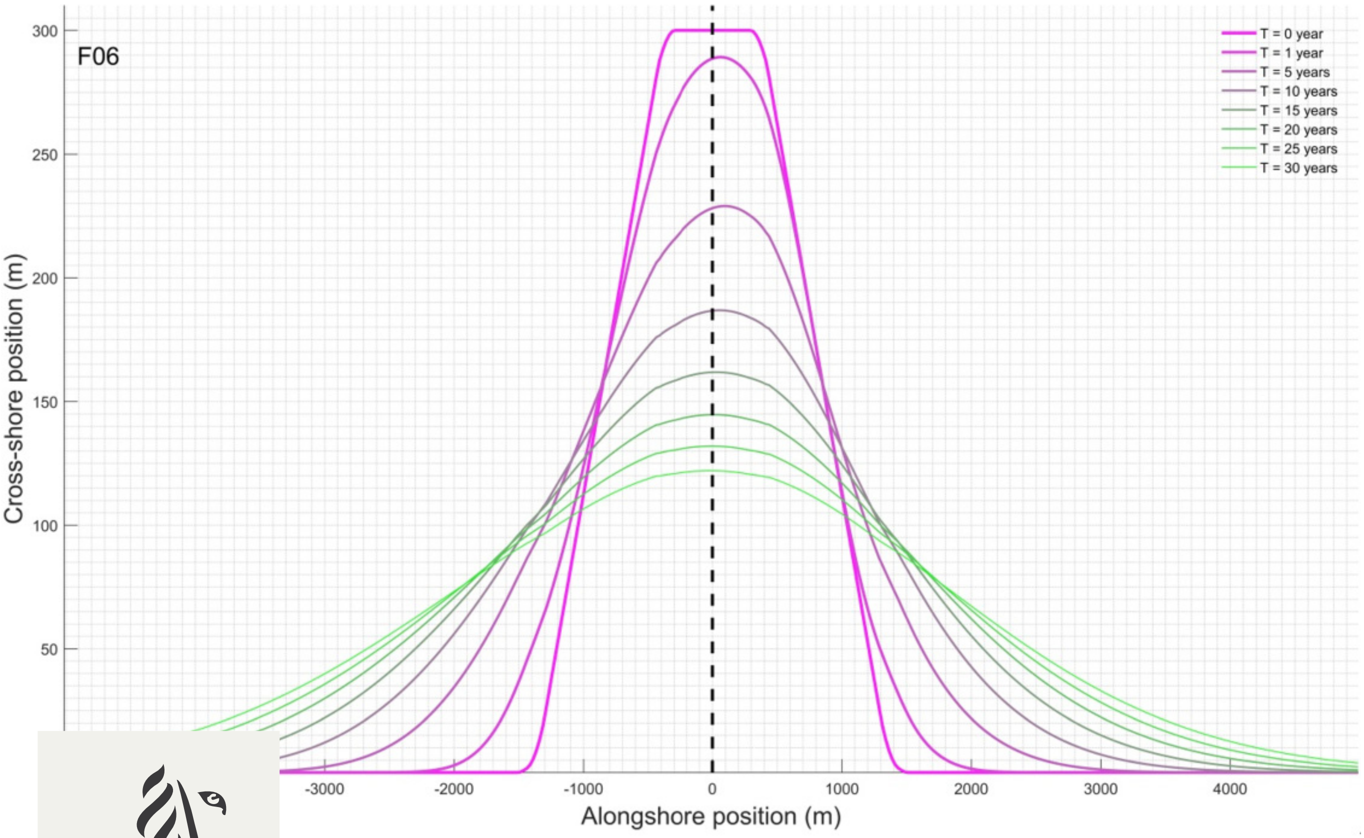

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Alternative nourishment methods for the Belgian coast

Exploring the possibilities for feeder-type mega nourishments along the Belgian coast

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Van de Lageweg, W.I.; Dan, S.; Verwaest, T.; Mostaert, F.

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Abstract

The natural dynamics of the Belgian sandy coast system are severely disturbed nowadays. The human activities have changed the natural patterns for the sediment transport, which has resulted in accretion and erosion issues along the Belgian coast. The anticipated acceleration of the sea level rise will increase the vulnerability of the Belgian coast to extreme events.

To strengthen the safety of the coast, the Flemish government has approved the Masterplan Kustveiligheid in 2011. This Masterplan consists of a suite of measures to prevent flooding related to a 1000-year flood event. Nourishment of beaches is considered one of the most important measures to maintain and enhance coastal safety. Nowadays, beach nourishments along the Belgian coast (~annual volume 0.5 million m^3) are constructed using a traditional method: by heightening the upper and intertidal beach.

A possible alternative for creating a safer and more resilient Belgian coast are feeder-type mega nourishments such as the so-called Sand Engine along the Dutch coast. This innovative soft engineering intervention makes use of natural processes (i.e. waves, currents, wind) to redistribute the nourished sand across the entire coastal profile (i.e. shoreface, subaqueous and sub-aerial beach, and dune area) and represents a paradigm shift in coastal management.

In this exploratory study, quantitative predictions of shoreline change across decadal timescales for a potential feeder type nourishments along the Belgian coast are made. Using the coastline model UNIBEST-CL+, the study aims to i) identify suitable locations for a feeder-type mega nourishment along the Belgian coast, ii) evaluate the alongshore sediment transport post-construction for a range of idealized mega nourishment with varying dimensions (alongshore and cross-shore extent, volume), iii) quantify the dispersion time of these mega nourishment designs, and iv) explore the sensitivity of the predicted shoreline changes and lifespan predictions to the hydrodynamic (i.e. waves and tidal currents) and sedimentary (i.e. grain size and sediment transport formulation) conditions.

An identification of the current functions and usage of the Belgian coast is firstly made. By mapping opportunities from the coastal protection perspectives, nature development and recreation, an overview of the preferred locations for a feeder-type mega nourishment is generated. To address the multi-functionality of a mega nourishment, a location in which as many functions as possible can be combined is preferred.

Then, thirteen idealized nourishments are listed. The nourishments have a seaward extent ranging between 150 m and 900 m with variable alongshore lengths to evaluate the effect of geometry on resultant shoreline changes. The smallest nourishment has a volume of 1 million cubic meter of sand and the largest one is 30 million cubic meter. Using UNIBEST-CL+, all nourishment designs show a morphological reshaping from the original trapezoidal shape to a smoother bell shape during the first years post construction. As a result of the reshaping, the seaward head of the nourishment retreats and sand is being fed to the adjacent beaches, leading here to coastal advance. A key finding is that the dispersion time scales approximately linear with the initial nourishment volume for the same width-to-length ratio. A cost-effectiveness analysis indicates that a feeder-type mega nourishment should be considered a tool of opportunity for Belgian coastal managers. The tool can be employed when sand is available at a low cost relative to the regular nourishment program, and when the interest rate is low relative to the decadal average. When sea-level rise is taken into account, the required sand volumes will increase and the cost-effectiveness improves.

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1 Introduction

1.1 Background to project

The Belgian coastal area faces two important challenges in the coming decades: i) vulnerability to extreme storms, and ii) the limited space for nature and socio-economic activities. To strengthen the safety of the Belgian coast and taking into account new opportunities for nature and socio-economic development, the Masterplan Kustveiligheid (2011) was developed. This Masterplan proposes important interventions in the coastal zone to protect the Belgian coast.

One of the primary tools to intervene in the coastal system is the artificial nourishment of beaches. At present, beach nourishments are however rather expensive whereas repeated nourishments are necessary at regular intervals. Therefore, it has been decided to explore the suitability and feasibility of alternative nourishment methods for the Belgian coast.

Currently, the beach is nourished locally when its sand volume is considered insufficient to cope with an exceptional (1 in 1000 years) storm. These so-called ‘weak links’ along the coast are well monitored and subject to periodic nourishments. However, maintenance nourishments are generally necessary, in particular at locations along the coast where strong erosion occurs. The requirement to nourish frequently is not only costly but also disturbs the local ecosystem regularly and results in regular closure of beaches with adverse effects for local businesses and beach visitors.

A possible alternative is to use natural processes such as waves, currents and wind to redistribute the nourished sand in a more natural way along the coast. In doing so, the wave and tidal induced alongshore currents can potentially feed the weak links gradually for a long time (decades). Using natural processes for coastal protection is an innovative approach with a range of potential advantages over traditional nourishment methods:

1. Lower unit cost per cubic m for nourishments. A large volume of sand is placed at a fixed location in one operation.
2. Less disturbance of the coastal ecosystem. The nourishments will take place less often and in fewer areas than at the present time.
3. The newly created space, although temporary, can be used for nature and recreation and it can provide new opportunities for the local ecosystems.
4. Strategic reserve of sand. In case of extreme events large volumes of sand can be displaced from the beach in a very short period. A large volume of sand available relatively close to the eroded beach can speed up the beach recovery, acting such a source of sand for the alongshore transport.

Possible disadvantages of the alternative nourishment method are:

1. Possibility that the excess of sand will impede access to harbours.
2. Disturbance of the local landscape (e.g. very large beach) and negative ecological impact on some species.
3. Significant financial effort over a short time.

A striking example of this innovative approach for coastal protection is provided by the so-called Sand Engine mega nourishment built on the Dutch coast in 2011 (de Schipper *et al.*, 2016; Luijendijk *et al.*, 2017; Stive *et al.*, 2013; Tonnon *et al.*, 2018). The concept appeared several years ago as a paradigm shift from the classical approach of “fighting against nature” to the new approach which implies working together with nature (de Vriend *et al.*, 2015; Mulder & Tonnon, 2011).

A sandy mega nourishment provides a sustainable and flexible coastal management tool and is therefore considered a ‘no regret’ solution that could be implemented relatively soon (i.e. coming decade). These mega nourishments are anticipated to constantly feed the beach areas that are more susceptible to erosion and, as such, provide a longer-term solution to coastal protection. In addition, it can help the coastal system to adapt naturally to an accelerated rising sea level and creates a more flexible and adaptable coastal management.

Yet, such a mega nourishment requires careful study and planning before construction. The main issues related to the construction of a mega nourishment are: i) suitability of locations and associated dimensions, ii) expected evolution post construction for different time scales, iii) the impact on the adjacent beaches, and iv) a comprehensive monitoring plan. Therefore, an exploratory study is performed here to investigate and recommend qualitative solutions for all these issues.

1.2 Aims of project

The general objective of the project is to explore the potential for one or more feeder-type mega nourishments to supply sand using natural processes to the coastal weak links to provide sufficient coastal protection while creating additional opportunities for nature and socio-economic development. These mega nourishments can be a potential long-term solution for beach erosion enhanced by the accelerated sea level rise. However, the particularities of the Belgian coastal zone with a complex bathymetry and a range of hydrodynamic processes will require a detailed investigation before implementation. For example, the presence of the tidal sand banks in the coastal zone complicates the local bathymetry and affects how waves and tidal currents propagate to the coastline.

The main research question of this study focusses on the potential for one or more feeder-type mega nourishments along the Belgian coast. Accordingly, a number of specific research questions are formulated:

What are suitable locations for a mega nourishment along the Belgian coast?

What are the adequate dimensions (volume, along- and cross-shore extension) of a mega nourishment along the Belgian coast?

How will the local sediment transport change after the construction of the mega nourishment?

What is the expected lifetime of the mega nourishment?

What is the expected economic benefit of a mega nourishment?

To address the above research questions, a number of objectives are defined here:

Investigation of the main processes controlling the evolution of a feeder-type mega nourishment.

The evolution of a mega nourishment is controlled by gradients in the sediment transport. Coastal sediment transport can be subdivided into two categories: cross-shore transport and alongshore transport. Although both are important, previous research has shown that the alongshore sediment transport is the most important in the evolution of feeder-type mega nourishments (Luijendijk *et al.*, 2017). To investigate and quantify the sediment transport, a model that is able to provide an estimate of the alongshore sediment transport is needed. This study is providing quantitative estimates of the alongshore sediment transport and how this may change under varying hydrodynamic conditions.

Preliminary design of feeder-type mega nourishments.

The design of the mega nourishment is closely related to the sediment transport capacity (Tonnon *et al.*, 2018). Gradients in the alongshore sediment transport control the long-term evolution whereas the cross-shore transport may play a significant role during storms. Correct estimation of the sediment transport is vital for the design of a mega nourishment because it determines how long the coastal protection function can be maintained and also how fast the feeding of sand to the adjacent beaches proceeds. An incorrect estimate of the sediment transport may lead to sediment excess on adjacent beaches and can potentially cause sedimentation in undesirable locations such as harbours. Recommendations on minimum and maximum volumes of sand of the nourishments as a function of the location are made in this study.

1. *Evolution of the feeder-type mega nourishments on short (0 – 10 years) and medium (10-30 years) timescales.*

Quantitative estimates of the evolution of mega nourishments will be made using one dimensional coastline numerical models and expert judgement. Coastline models are computationally efficient and therefore allow us to explore many scenarios in terms of design of the nourishment but also in terms of the hydrodynamic conditions. These quantitative estimates will employ historical hydrodynamic information but will also evaluate possible changes in wave climate due to climate change during a sensitivity analysis. The Masterplan Kustveiligheid (2011) has a planning horizon of 2050 and therefore simulations are performed with a total duration of 30 years. Estimates of the shoreline changes post construction of a range of mega nourishment designs and for a range of hydrodynamic conditions are provided in this study.

2. *Cost effectiveness analysis.*

A mega nourishment has the potential to be a more cost effective coastal management tool to maintain coastal safety than traditional nourishment methods. A cost-benefit analysis is performed to quantify the possible economic benefits of a large nourishment compared with the regular nourishment program for the Belgian coast.

1.3 Structure of report

This report explores the potential for one or more feeder-type mega nourishments along the Belgian coast. Firstly, a review of the literature on existing and planned mega nourishments is performed. The review focusses on mega nourishments located in the North Sea basin because similar hydrodynamic conditions are expected for the Belgian coast. The review also identifies one dimensional coastline models that can be used to simulate the evolution of mega nourishments post construction. Secondly, possible locations for a feeder-type mega nourishment along the Belgian coast are identified based on a systematic investigation of the present functions and values of the Belgian coastal system. Thirdly, idealised modelling of shoreline changes post construction of mega nourishments varying in dimensions and size is performed, using one dimensional coastline models. This exercise provides quantitative estimates of rates of shoreline retreat, shoreline advance, alongshore sand dispersal and lifetime of a range of mega nourishment designs. Fourthly, a cost-benefit analysis of a mega nourishment along the Belgian coast is performed. Fifthly and last, the results of the aforementioned sections are summarized and strengths and limitations of the study are discussed.

2 Literature review on mega nourishments

A rising sea level and the expansion of built-up areas around the coast are causing beaches to become narrower and more vulnerable to storms. These trends are recognized for the Belgian coast in the document *Masterplan Kustveiligheid* (2011). To strengthen the safety of the Belgian coast against flooding as well as creating opportunities, this *Masterplan* is written with a vision for the Belgian coast with a focus on safety, attractiveness, nature, sustainability and economic development.

The natural dynamics of the Belgian sandy coast system are highly disturbed nowadays. The remaining natural beaches and dunes are intersected by structures: 171 beach groynes, the harbours of Zeebrugge, Blankenberge, Oostende and Nieuwpoort, and 38 km of dikes can be found along the Belgian coast (Vlaamse Baaien, 2014). These structures have disturbed the natural cross-shore and alongshore sediment transport. Fixation and fragmentation of the remaining natural dunes and beaches by roads and dikes has caused a further decrease of the natural dynamics.

Definitions of terms for coastal features and processes are provided here (Figure 1) to set out the coastal zonations, which are below related to nourishment types. Three major coastal features are identified:

- **Dunes:** the zone between the coastline and the coastal hinterland representing the most landward coastal feature described here (Figure 1). Dunes are active coastal features acting as a flexible sand reservoir and act as natural protection against flooding. The type and coverage with vegetation of the coastal dunes determines their mobility. At eroding coasts, dunes are moving backwards in parallel with the coastal erosion.
- **Beach**: the zone of unconsolidated material that extends from the mean low water line (MLWL) to the coastline. The beach can be subdivided into a foreshore and a backshore.
- **Shoreface**: the active littoral zone off the MLWL. This zone extends seaward from the beach to some distance beyond the breaker zone. In this littoral zone, the alongshore and cross-shore sediment transport mainly take place.

Sediment budget assessments show an erosive trend along parts of the Belgian coast (Houthuys, 2012). Annually, a volume of about 500 000 m^3 of sand is nourished in Belgium to increase coastal safety, at the same time also compensating for coastal erosion (Vlaamse Baaien, 2014, p.33).

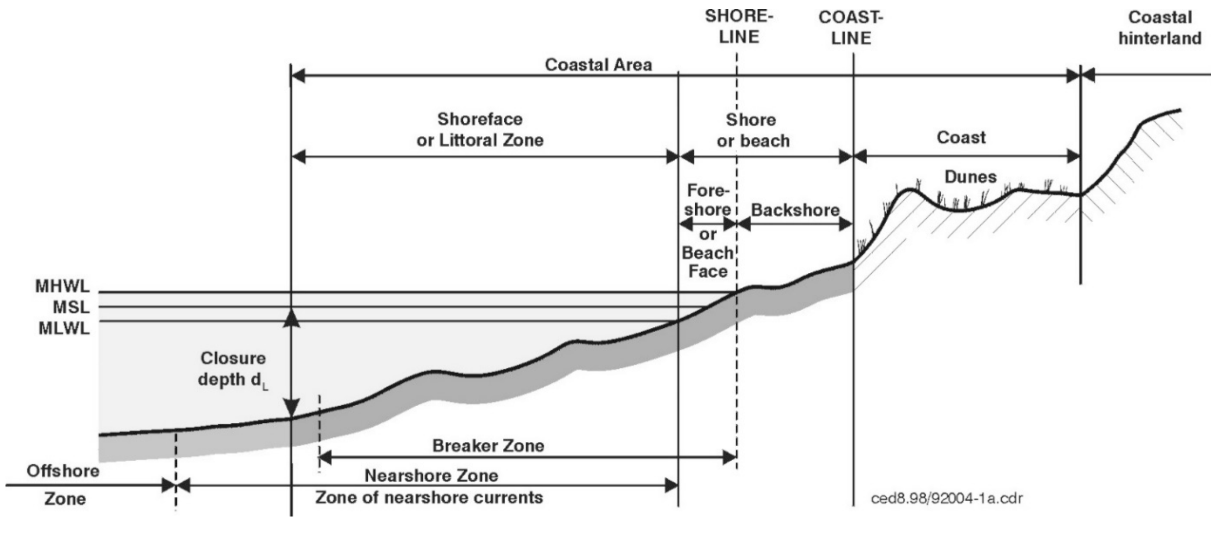

Figure 1 – Idealised coastal profile and definition of different zones and terms within the profile (http://bit.ly/2EIVnTX).

Four different sand nourishment types can be distinguished:

- **Dune nourishment**: a nourishment in the dune area. This type of nourishment is performed when a direct effect on coastal safety is required. Mostly, fairly small nourishments but with the highest costs (Table 1).
- **Beach nourishment**: a nourishment in the beach area, resulting in a higher and wider beach. As a result, the shoreline will move seaward for a couple of years.
- **Shoreface nourishment**: a nourishment in the shoreface or littoral zone. The costs of shoreface nourishments per unit volume are generally lower than dune and beach nourishments (Table 1).
- **Mega nourishments**: a nourishment with a large volume (>2000 m^3/m) and a low frequency of recurrence (25 years). Mega nourishments are generally multi-purpose and aimed at improving long-term coastal safety and stimulating nature development and recreation. Mega nourishments can be designed as shoreface nourishments, beach nourishments, dune nourishments or combinations thereof.

An important ‘building block’ in creating a more resilient and dynamic Belgian coast might be mega nourishments. These mega nourishments can provide the sand required to ‘hold the line’ as well as allowing natural processes to shape a more resilient coastal profile. Two types of mega nourishments exist (Tonnon *et al.*, 2018):

- **Permanent** mega nourishments (or beach extensions): designed to preserve momentaneous safety levels and need to maintain their size and shape, and thus need to be nourished themselves (e.g. Hondsbossche dunes, Petten, the Netherlands).
- **Feeder-type** mega nourishments: may erode freely, thus feeding adjacent beaches and dunes with sand for a more natural, dynamic growth (e.g. Sand Engine, Ter Heijde, the Netherlands, Figure 2).

Table 1 – Nourishment types and their characteristics. The information is based on (van der Spek, de Kruif, & Spanhoff, 2007; Stronkhorst, Bruens, van Vliet, & Schasfoort, 2012) and based on nourishments in the Netherlands.

	Dune nourishment	Beach nourishment	Shoreface nourishment	Mega nourishment
Amount (m^3 / m)	200	200	200 – 500	>2000
Recurrence time	Dependent on policies & storm occurrence	1 – 5 years	1 – 10 years	20 – 30 years
Effect on coastal profile	Narrower beach & steeper profile	Artificial & steeper profile	Natural profile with ability to grow with SLR	Natural profile with ability to grow with SLR
Visibility	High	High	Low	High
Costs*	€ 16 / m^3	€ 5 / m^3	€ 2.75 / m^3	€ 2.75 / m^3

*The provided numbers on costs are valid for the Netherlands in 2007 and merely listed here to provide indicative numbers for the different nourishment types. Prices of beach nourishments in Flanders can differ from those in the Netherlands.

Mega nourishments represent a paradigm shift in coastal management. The traditional management approach involved placing structures and using dune, beach and shoreface nourishments as interventions to obtain immediate protection effect. Mega nourishments, in contrast, are designed to *work with nature on a decadal time-scale* and, as such, represent a new and innovative approach to coastal management.

The *working with nature* concept of mega nourishments is most obvious in the feeder-type mega nourishments (e.g. Sand Engine, Ter Heijde, the Netherlands, Figure 2). This feeder-type nourishment involves placing a large volume of sand in a single location and designing it in such a way that natural processes such as waves and the wind move the sediment to areas along the coast to reduce coastal erosion and flood risk. The sand-scaping concept offers additional benefits in terms of habitat creation and environments that may provide a catalyst for economic development. Following Oost et al. (2016), the Sand Engine mega nourishment concept is defined here as: *'The addition of a surplus of sand to the coastal system, which is then redistributed by natural (drift) processes and usually leads to temporary coastal expansion and contributes to one or more coastal functions and values, like recreation, nature, protection against flooding and knowledge development'*. The concept of a Sand-Engine is considered a 'no-regret' solution, which could be realised on a short term and it is complementary to the concept of a more dynamic, natural coast as proposed in Masterplan Kustveiligheid (2011).

Figure 2 – Aerial view of the feeder-type mega nourishment called 'Sand Engine' near Ter Heijde along the Dutch coast in July 2017 (i.e. after six years of evolution since building completion in September 2011, see cover).

The design and impact assessment studies of mega nourishment generally requires detailed morphological investigations to understand their evolution, life span and effects on coastal safety. A number of mega nourishment projects have been carried out in recent years. Detailed monitoring programs were set-up for these nourishments involving morphological evolution, ecological trends, recreation opportunities and cost-effectiveness studies. Therefore, the next section will summarise the design of existing (i.e. Sand Engine near Ter Heijde, Hondsbossche dunes near Petten, Spanjaards dunes near Rotterdam harbour) and planned (i.e. Norfolk coast near Bacton, United Kingdom) mega nourishments, report on their evolution during the first couple of years after construction, and summarise the lessons learned from these projects. All projects are located in the North Sea basin to enable a translation of the findings to the Belgian coast due to the resemblances in coastal profiles and hydrodynamic conditions between the studied and Belgian cases. It is anticipated that this review of the literature on these other nourishment projects will be helpful in designing mega nourishment projects along the Belgian coast.

Numerical models can also be used to simulate how waves and currents move sand along the Belgian coast over decadal timescales. Therefore, in section 2.2 a summary of numerical models capable of simulating the evolution of mega nourishments is provided. One or more of these models was selected in a later phase of the project to:

1. Simulate the evolution of mega nourishments along the Belgian coast over decadal time scales.
2. Provide a sensitivity analysis on the potential locations, dimensions (volume, alongshore and cross-shore extent) and shapes (hook, bell, shoreface) of such a mega nourishment.

2.1 Synthesis of findings and learnings from existing and planned mega nourishments

2.1.1 Coastal protection perspective

The primary aim of all but the Spanjaards dune mega nourishment is coastal protection. The placement of a large volume of sand in front of the existing shoreline results in a seaward extension of the beach and hence creates an improved coastal protection. These seaward extensions of the mega nourishments differs substantially between the projects (Table 2). The artificial Sand Engine near Ter Heijde as well as the natural sand engine near Calais have the largest seaward extent of 1000 m. The Bacton nourishment has the smallest seaward extent of 50 m. Near critical infrastructure, however, the seaward extent is 100 m (Table 1).

Table 2 – Design volumes and dimensions of discussed mega nourishments.

Nourishment project	Volume of sand (million m^3)	Alongshore length (m)	Seaward extent (m)	Length-to-width ratio (m)
Sand Engine	18.7	2500	1000	2.5
Hondsbossche dunes	35.6	6750	300	22.5
Spanjaards dune	6.5	3000	150	20
Bacton	1.5	5000	50	100

All nourishments are designed to withstand a design storm to align with the coastal safety policies in the Netherlands and the United Kingdom. Generally, aeolian losses, hydraulic losses and sand settling are included in the design volume. Additionally, sea-level rise and soil subsidence are taken into account. For example, for the Hondsbossche dunes nourishment a soil subsidence of 0.1 m and a sea-level rise of 0.3 m across the 50-year design period were included. To compensate for the same sea-level rise (present day rate) along the Belgian coast across the next 50 years, a sand volume of 7.2 million m^3 is required (i.e. by assuming a coastal length of 60 km and a representative length of the coastal profile of 400 m). This volume of sand equates to about 14 years of the current annual nourishment volume of about 500.000 m^3 required for coastal maintenance (Vlaamse Baaien, 2014, p.33). Across 50 years, the compensational sand volume for sea-level rise of 7.2 million m^3 corresponds to 120.000 m^3 per km coastal stretch, or 120 m^3 per m coastal stretch.

The seaward extension and length-to-width ratios of mega nourishments are related to the types of mega nourishment (Table 2). Permanent mega nourishments are designed to preserve momentaneous safety levels and need to maintain their size and shape (Tonnon *et al.*, 2018). The maintenance of size and shape is easier accomplished with a smaller seaward extension and high length-to-width ratio as seen for the Hondsbossche dunes, Spanjaards dune and Bacton project. In contrast, feeder-type mega nourishments may erode freely to supply adjacent beaches and dunes with sand for a more natural and dynamic growth (Tonnon *et al.*, 2018). The Sand Engine near Ter Heijde and the one in Calais provide examples of feeder-type mega nourishments with a large seaward extension and lower length-to-width ratios. These differences in geometry between permanent and feeder-type nourishments has consequences for their evolution and lifetime, which are discussed in the next section.

2.1.2 Morphological evolution and lifespan perspective

The described projects provide the first data on the evolution of mega nourishments. The Sand Engine was constructed in 2011 and has evolved for approximately 7 years. Construction of the Hondsbossche dunes was finalised in 2015 and the nourishment has developed for almost 3 years now. Spanjaards dune was built in 2009 and has evolved for about 9 years now.

Valuable information on the initial development of mega nourishments can be obtained from these projects but it should be noticed that they have been in place for 3-9 years now, while their design lifetime is 25-50 years. The duration of the monitoring programs of these mega nourishment projects is currently insufficient to provide a detailed picture of the long-term evolution (>10 years).

The permanent mega nourishments Hondsbossche dunes and Spanjaards dune were dynamic during the first 3 years after construction. Both projects showed widespread erosion in the shoreface region and substantial accretion in the dune area. Typically, accretion of the dune area was 0.5 – 1.5 m during the first 3 years with higher accretion rates associated to the presence of marram grass (van der Meulen *et al.*, 2014). For the Hondsbossche dunes, a maximum coastline retreat of 120 m was measured between May 2015 and August 2017 (i.e. 53 m/year). For both mega nourishment projects, the wind and wave dynamics were largest immediately after construction but the morphological changes have decreased over time.

The feeder-type Sand Engine showed even larger initial morphological changes, partly due to its more extreme seaward design and partly due to a number of winter storms immediately after construction. During the first 4 years, the Sand Engine became 260 m narrower (i.e. 65 m/yr) and 2.2 km longer (i.e. 550 m/yr) (Oost *et al.*, 2016). Locally, up to 100 m retreat of the coastline was measured after the first winter period. The variety of geomorphological features making the Sand Engine up contributes to a complex morphodynamic behaviour. The spit, lagoon and channel on the northern side of the Sand Engine represent the most dynamic features with high flow velocities and substantial changes in channel planform and dynamics over time.

A key finding is that measurements and predictions from numerical models of the morphological development of the Sand Engine on the short-term (0-5 years) are in good agreement. This applies to 2D coastal area models as well as 1D coastline models. Such models are also used in the current planning and design phase of the Bacton nourishment project (Sutherland *et al.*, 2017) 1D coastline models cannot be used to replicate detailed morphology but they are capable of simulating the volume decrease over time, the lifetime and the maximum coastline retreat at the centre of the nourishment. Based on this good agreement between model predictions and measurements of the morphological development of the Sand Engine, Tonnon et al. (2018) derived relations and design graphs to assist in the planning and design phase of new mega nourishment projects. These relations and design graphs are applied in Section 3 to estimate the lifespan, volume decay and coastline retreat of a possible Sand Engine along the Belgian coast for a range of scenarios (i.e. location, volume of sand, design).

Ecological perspective

The coastal protection function of a mega nourishment is generally combined with realising added value for nature development and recreational opportunities. The diversity in coastal landscape types and dynamics can be increased due to the construction of a mega nourishment, particularly by a feeder-type such as the Sand Engine. The sand spit, the lagoon, dune lake and shoals are examples of coastal features hardly seen along the Dutch coast.

Ecological colonisation and development has, however, proven difficult on the mega nourishment projects in the Netherlands. For all three nourishment, the low-nutrient, dry and drifting sand combined with salt spray provide an extreme environment in which it is challenging for vegetation to establish itself.

The Sand Engine remains scarcely vegetated and also no birds have been seen breeding yet. The lagoon showed periods of poor water quality. Dune growth is lagging behind the expectations. No shift towards longer-living benthos species compared to traditional (i.e. smaller and more frequent) sand nourishments is observed. The Hondsbossche dunes shows an increase in the number of plant species, with a positive effect on richness and vitality of a smaller grain size and a higher calcium carbonate content of the substrate. Close to the active beach, a very vital growth of the marram grass is observed while in the tall dune area a very slow colonisation is observed. The dune valley is freshening and some rare plant species have appeared. Some embryonic dunes are observed on the beach. Last, Spanjaards dune showed a slower development of the anticipated habitats with limited colonisation of the target species taking place (van der Meulen *et al.*, 2017). Maps of potential habitat in 2016 showed that there was sufficient suitable area for grey dune (12.6 hectares available, 9.8 hectares needed) but not for dune marsh (2-5 hectares available, 6.1 hectares needed).

A number of explanations are provided to explain the observed slow ecological colonisation and development of mega nourishments:

- **Time consuming**: Ecosystems require time to develop from a constructed abiotic starting morphology. Consequently, mega nourishments with an ecological component also require time to allow for colonisation and succession. Therefore, it is advised to legally protect the area from the start of the project to safeguard the best possible boundary conditions.
- **Abiotic-biotic environments**: The construction of the abiotic environment should always be consistent with target biotic environment. More time (>5 years) is preferred to allow for biotic development. Plant species colonising an environment by themselves are expected to be more successful. Spontaneous colonisation of plant species demonstrates a match between the abiotic and biotic environments. This highlights that artificial introduction could be less successful because of a mismatch between the abiotic condition and the introduced species. Always use native species, which are available locally.
- **Expertise**: Knowledge about the morphological and ecological processes and associated habitat conditions should be the basis of all activities.
- **Management**: Focus is primarily on man and less on ecology. Removal of waste from the beach hinders dune formation. Also, a conscious management decision was made not to apply a zoning by allocating specific areas as resting, breeding and growing zones. Shared use of these zones with recreational functions has led to destruction of newly established vegetation and dunes, and disturbance of birds and mammals.

2.1.3 Recreational perspective

Mega nourishments offer additional area (Sand Engine, 128 hectares; Hondsbossche dunes, 200 hectares; Spanjaards dune, 40 hectares) and a variety of coastal environments resulting in an appealing area for leisure activities. Recreation is more important on the Sand Engine and Hondsbossche dunes compared with the Spandjaards dune nourishment, which has been designated as a Natura 2000 area with limited opportunities for recreation. A survey of visitors of the Sand Engine revealed that bathers, dog walkers, hikers and surfers (wind, wave, kite) are the dominant users from a recreational perspective.

The Sand Engine and Hondsbossche dunes offer additional recreational opportunities compared with the situation before the construction of these nourishments. However, some considerations are important to keep in mind when using a mega nourishment for recreational purposes, particularly for a design with a larger seaward extent:

- **Seaward extent**: A large seaward extent appears less suitable for locations with a strong bathing focus. The associated dynamic nature of a large seaward extensions are also unfavourable for a bathing location.
- **Drainage channel**: The construction of a drainage channel poses a potential risk to recreational users. The flow velocities can become high. Additionally, users can become closed in at high tide and then find themselves seaward of the channel. Due to channel lengthening, the lagoon can become disconnected from the North Sea and decay processes may occur, potentially resulting in unpleasant odours.

- **Currents**: The currents at the head of a mega nourishment are stronger, particularly for those with a larger seaward extent. These currents may pose a potential risk to recreational users.

2.1.4 Cost-effectiveness perspective

A cost assessment was performed for the Sand Engine to establish the cost effectiveness of the mega nourishment compared with regular coastal maintenance (Oost et al. 2016). The benefits for nature and recreation were not included in the analysis because there is insufficient statistical information on these functions. From the cost-effectiveness study for the Sand Engine the following conclusion can be drawn:

- Construction of the Sand Engine was cost effective based on the sand requirements and prices of sand at the time of decision making.
- Based on the current (i.e. much lower) price of sand for regular nourishments, the Sand Engine would not have been a cost efficient investment from the perspective of coastal protection. In this case, a Sand Engine can only be efficient when an even lower price of sand for such a mega nourishment can be obtained (i.e. due to volume discounts) or when the Sand Engine can function effectively for a longer period than the regular nourishment program using the same volume of sand.
- From the perspective of coastal maintenance, a Sand Engine is ‘an instrument of opportunity’ for coastal managers that can be employed cost effective if large volumes of sand are available at low cost.

For the Bacton project, it is expected that the costs per m^3 of sand will be about half the prices compared to a conventional beach nourishment (Engineer, 2017). These prices are not final yet and will depend on the final design because the design influences cost.

2.1.5 Other values and functions perspective

The design and realisation of a mega nourishment affects a number of other values and functions. First, water extraction should be taken into account. Initially, a salinity intrusion is to be expected and this process may need to be counteracted by installing pumps in the dune area as was done for the Sand Engine (Oost et al. 2016). Across longer timescales, a freshwater lens may be formed and this lens may create a barrier to salt water intrusion in the groundwater system. The freshwater lens is particularly efficient when it can connect to an impenetrable clay layer at shallow depth. However, longer monitoring periods are required to confirm this behaviour predicted from model studies for the existing mega nourishments.

Second, a mega nourishment leads to sediment dynamics in the nearshore zone, which may hinder harbour access and shipping routes. The presence of harbours should therefore be explicitly taken into account.

Third, the innovative aspect and knowledge generation of mega nourishments has attracted businesses, researchers and international interest. In particular, the large seaward extent and high degree of dynamics of the Sand Engine contribute to the interest. Mega nourishments provides a living laboratory in which coastal protection, ecology and economic development are combined and can be showcased to outsiders. It is anticipated that new mega nourishment projects will lead to new research questions and new innovations tailored to the local situation.

2.2 Identification of numerical models capable of simulating the morphodynamic development of feeder-type mega nourishments

2.2.1 Numerical simulation of shoreline changes

Numerical models can be used to simulate shoreline changes. Depending on the application, these models can simulate shoreline changes from small (10-100 m) to large (100 km) spatial scales and across short (hours-days) to long (decades) time scales. Three model approaches can be identified:

1. Profile evolution models, simulating cross-shore processes but ignoring longshore processes (e.g. XBeach)
2. Coastline models, simulating shoreline changes from gradients in longshore sediment transport but ignoring cross-shore processes
3. Coastal area models, simulating both cross-shore and longshore processes.

Volume changes at the mega nourishments are shown to be predominantly the result of longshore currents (Luijendijk *et al.*, 2017; Tonnon *et al.*, 2018). Profile evolution models are therefore not included in this review.

2.2.2 Coastline and coastal area models

Coastline models are based on the concept that the beach profile shape remains constant as it retreats or advances coast (Capobianco *et al.*, 2002; Pelnard-Considere, 1956; Thomas & Frey, 2013). This behaviour implies that volume changes are directly related to shoreline changes. Spatial and temporal gradients in longshore transport result in shoreline retreat or advance. Common assumptions made in coastline models are (Thomas & Frey, 2013):

- The beach profile remains constant
- The shoreward and seaward vertical limits of the coastal profile are constant
- Sand is transported alongshore due to breaking waves induced longshore currents
- Details of the nearshore circulation pattern are ignored
- A long-term trend in shoreline evolution exists
- An infinite supply of sand (at the lateral boundaries).

Coastal area models resolve variations in cross-shore as well as alongshore directions (de Vriend *et al.*, 1993; Nicholson *et al.*, 1997; Tonnon *et al.*, 2018; van Maanen *et al.*, 2016).

Both model types have their strengths and weaknesses (Table 3). Coastline models generally allow for fast and efficient computations. Application of a full wave climate or variable wave conditions are also possible. Coastline models are less suited for detailed morphological investigations and in most cases include wave-driven currents only (i.e. no tides). Coastal area models are capable of simulating detailed sediment transport patterns and morphological changes. These models have the ability to include a wide range of parameters but, as a result, they can be complex to set up and computationally expensive. Essentially, coastline models provide fast simulations with limited detail while coastal area models provide more detailed simulations with large penalties on computational efficiency (i.e. they are slower) and effort needed to analyse the model results.

Table 3 – Overview of advantages and disadvantages of coastline and coastal area models*.

Model type	Advantage	Disadvantage
Coastline	Fast model allowing for the application of a full wave climate	Less suited to investigate morphological details
(e.g. Unibest-CL+, BEACHPLAN)	Time series of wave conditions possible	Includes wave-driven currents only
Coastal area	Detailed sediment transport patterns and morphology	Computationally intensive and therefore requires reduction of the initial and boundary conditions
(e.g. Delft3D, TELEMAC3D)	Inclusion of tidal forcing and wind-driven currents	Requires rich datasets and can be complex to setup

*Adapted from (Tonnon *et al.*, 2018).

Coastal area models have been applied to evaluate the evolution of mega nourishments. For example, the coastal area model Delft3D was used to explore the initial evolution of the Sand Engine mega nourishment near Ter Heijde in the Netherlands (Mulder and Tonnon 2011; Luijendijk et al. 2017; Tonnon et al. 2009, 2018). Delft3D was also used to model the evolution of large shoreface nourishments near Egmond (van Duin *et al.*, 2004) and near Terschelling (Grunnet & Ruessink, 2005) in the Netherlands. The TELEMAC coastal area modelling suite was used to model the evolution of five beach nourishment option intended to defend the Bacton coast (Norfolk, United Kingdom) from erosion (Sutherland *et al.*, 2017).

Some projects also applied coastline models to simulate the morphological development of mega nourishments. The coastline model BEACHPLAN is used to assess the best size and shape of potential mega nourishments near Slaughden in the United Kingdom (Sutherland *et al.*, 2017). Ruggiero et al. (2010) used the coastline model UNIBEST-CL+ to simulate large decadal-scale shoreline changes for the Pacific northwest coast of the United States. Tonnon et al. (2018) used the coastline models UNIBEST-CL+ as well as LONGMOR to evaluate the morphological development of the Sand Engine near Ter Heijde on longer time scales.

The aforementioned projects highlight different uses of coastline and coastal area models in evaluating the evolution of mega nourishment. Coastline models are generally used as part of feasibility studies due to their fast computation enabling the investigation of multiple scenarios, sensitivity analyses and longer timescales (decades). Coastal area models are better suited to simulate detailed morphologies across short timescales (0-5 years) and can therefore inform decision making in the option selection and final design phase of mega nourishment projects.

In this study, we seek to make quantitative predictions of coastal change across decadal timescales as part of a feasibility study. This study requires the selection of a quantitative model with the appropriate complexity (French *et al.*, 2016). A feasibility study will be performed aimed at addressing questions on suitable locations, appropriate volumes of sand to last 30 years, and sensitivity to changes in climate and bathymetry of a possible mega nourishment along the Belgian coast. Such a study requires a fast model with limited morphological detail. This requirement is best achieved using a coastline model (Table 3). It is expected that coastline models with longshore transport formulations can be used to study volume decay, lifespan and shoreline retreat of mega nourishments.

2.2.3 Conclusion on the model capabilities

Four well-established and widely employed coastline models are:

i. GenCade (http://cirp.usace.army.mil/)
ii. UNIBEST-CL+ (https://www.deltares.nl/en/software/unibest-cl/#features)
iii. LITPACK (https://www.mikepoweredbydhi.com/products/litpack)
iv. BEACHPLAN (http://www.hrwallingford.com/software/pyxis).

Each model has advantages and disadvantages. Therefore, model selection needs to be done on a case-by-case base and tailored to local conditions and study questions.

UNIBEST-CL+ and BEACHPLAN have both been applied successfully in a study evaluating the evolution of a mega nourishment. BEACHPLAN was used in a feasibility study evaluating multiple hydrodynamic and nourishment design scenarios for a shingle beach in the United Kingdom (Sutherland *et al.*, 2017). UNIBEST-CL+ was used to simulate the evolution of the Sand Engine near Ter Heijde in the Netherlands (Tonnon *et al.*, 2018). The ability of these models to successfully simulate the evolution of a mega nourishment under similar climatic conditions and nourishment designs as foreseen along the Belgian coast is promising, therefore UNIBEST-CL+ is selected to be applied in this study.

3 Possible locations for a feeder-type mega nourishment along the Belgian coast

To identify scenarios for a possible feeder-type mega nourishment along the Belgian coast, an overview of the current and future functions and values is required. A similar analysis was performed for the Dutch coast in Oost et al. (2016) to examine suitable locations for a potential future Sand Engine type nourishment.

The Belgian coastal zone is one of the most intensively used seas in the world. Shipping, fisheries, recreation, sand exploitation, wind mills, and provision of important habitats and coastal safety against flooding. All these functions make use of what the coastal zone has to offer. However, this busyness causes a high pressure on the coastal zone and some functions may be conflicting. Any proposed changes to the Belgian coastal zone will therefore have to be examined critically for their impact on this region and the other functions.

Within the context of a designing a possible mega nourishment along the Belgian coast, the considered current values and functions are coastal management, nature, recreation in or near the shoreline and other functions and values such a groundwater extraction, salinization and access to harbours. An important aspect in designing scenarios for a possible mega nourishment is that existing functions and values are retained, and improved where possible.

The considered future functions and values are based on development plans with a legal status. They focus on extensions of habitat areas, the construction of new dune areas and the expansion of a tidal inlet. Future function development plans with a legal and approved status are relatively few and the overall picture of current functions and usage does therefore not change substantially when including these future developments.

Based on the overview of the current and future functions and values along the Belgian coast, opportunity maps are produced. These maps show the opportunities for a possible mega nourishment from the coastal management, nature, recreation and other functions and values perspectives. Specifically, the maps show coastal stretches with a:

- moderate opportunity for a mega nourishment
- good opportunity for a mega nourishment

If no opportunity is identified, the coastal stretch is left blank.

In Section 3.1, the current and future functions and values along the Belgian coast are described. In Section 3.2, opportunity maps are produced. In both Sections, individual maps are produced for the functions of coastal management, nature, recreation and other functions and values. In Section 3.2, the individual maps are also summarized in a synthesis map in which moderate and good opportunities for a possible mega nourishment along the Belgian coast are identified.

3.1 Identification of functions and values along the Belgian coast

As part of previous work, a system of beach "**sections**" (*secties* in Dutch) along the Belgian coast was already developed. In total, there are 277 sections, each approximately 250 meters in width. However, section 1 and sections 256-277 are located in France and the Netherlands, respectively. Therefore, this study will focus on sections 2 through 255 (Figure 3). Annual beach and shoreface monitoring surveys are conducted based on this system of sections. Previous studies on the Belgian coast have aggregated the sections into groups of 2 to 10 called "**stretches**" (*stroken* in Dutch), based on their similar morphological trends. There are 51 coastal stretches along the Belgian coast (Figure 3).

This project uses the aforementioned framework as a basis. In identifying the current and future functions and values along the Belgian coast, a spatial reference will be made to the relevant coastal stretches and sections.

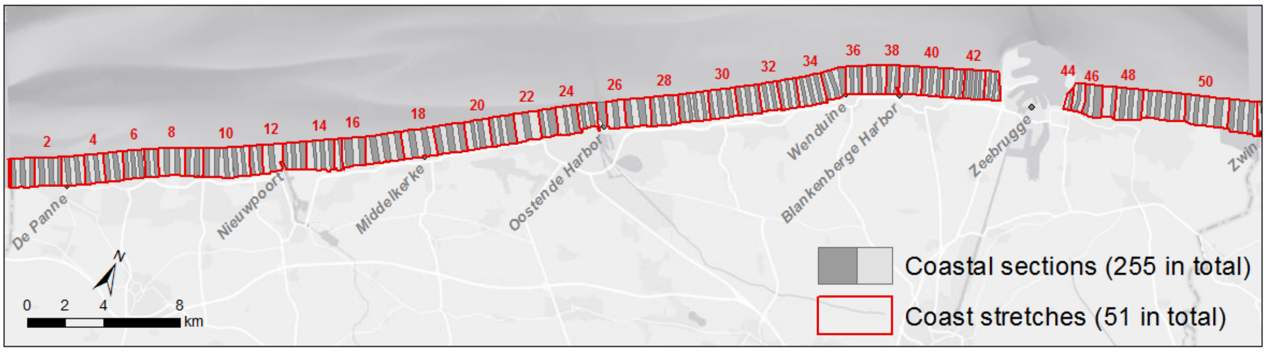

Figure 3 – Coastal sections and stretches along the Belgian coast*.

*From Vandebroek et al., 2017 – WL Project 12_155).

The coastal stretches were grouped into three analysis cells for this exploratory study on alternative nourishment methods based primarily on the presence of harbours (Figure 4). Table 4 presents the alongshore cells (groups of sections) selected for this study. Please note that coastal stretches 39 – 51 are considered out of scope for this project. This area has a particular sediment dynamics controlled by the presence of the Zeebrugge harbour and by the Appelzak tidal gully, yet not fully understood and quantified. Evolution of an eventual mega nourishment placed in this area is difficult to predict and quantify at this moment.

Table 4 – Alongshore divisions cells for this exploratory study on alternative nourishment methods.

Cell #	Stretches	Sections	Length (km)	Description
1	1-12	2-59	14.3	De Panne to Nieuwpoort harbour
2	13-25	60-117	16.6	Nieuwpoort harbour to Oostende harbour
3	26-38	118-184	15.5	Oostende harbour to Blankenberge harbour

The onshore limit of the cells for this study was taken as the maximum inland extent of survey data (i.e. the maximum inland extent which all surveys used for the volume calculations reached). This generally results in an inland limit somewhere in the dunes, in the case of a natural coastline, or just beyond the seawall, where development exists. The offshore limit of the cells is defined at an offshore distance of about 1500 m from the local coastline.

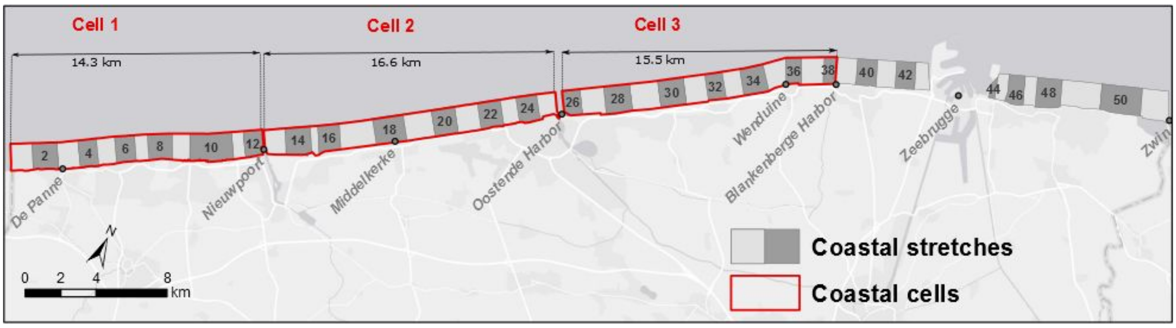

Figure 4 – Definition of coastal stretches and coastal cells as used in this project.

3.1.1 Coastal safety

Existing functions and values

The Masterplan Kustveiligheid was approved in 2011 by the Flemish government and describes existing and future coastal safety issues and how to mitigate them. All beach profiles along the Belgian coast are tested every six years to see ensure that they meet the safety standards. These tests showed that some sections are eroding, some remain constant while others are accreting. To increase coastal safety, also counteracting erosion, a yearly sand volume of ca. 500.000 m^3 of sand was nourished along the Belgian coast during the decades before 2011.

The Masterplan Kustveiligheid identifies a number of sections with an unacceptable low level of safety against coastal flooding (Figure 5, Figure 6, Table 5). As a consequence, these coastal zones do not provide the legally required safety levels to withstand a 1 in 1000 years storm.

Table 5 – Identification of weak links along the study zone.

Weak link	Coastal cell	Length (m)
De Panne – section 8	1	250
De Panne – centrum (section 13 to 18)	1	1500
St. Idesbald – Koksijde-centrum (section 21 to 31)	1	2395
Middelkerke – Westende (section 74 to 88)	2	5125
Raversijde – Oostende Wellington (section 97 tot 108)	2	3835
Oostende centre (s. 109 to 117) + Haven Oostende + Oostende Oost (s. 118 to 120)	2 & 3	2125 & 800
Oostende – Oost (section 121)	3	354
De Haan-Wenduine (section 172 to 176)	3	1092

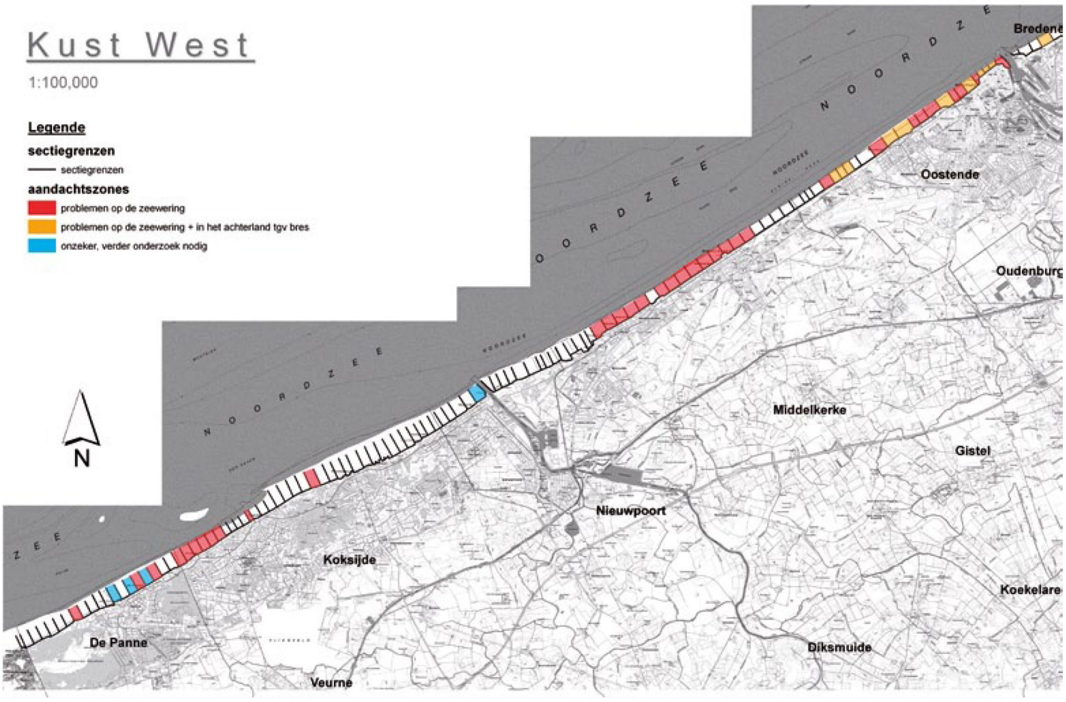

Figure 5 – Weak links in the coastal safety function along the Belgian coast, western region.

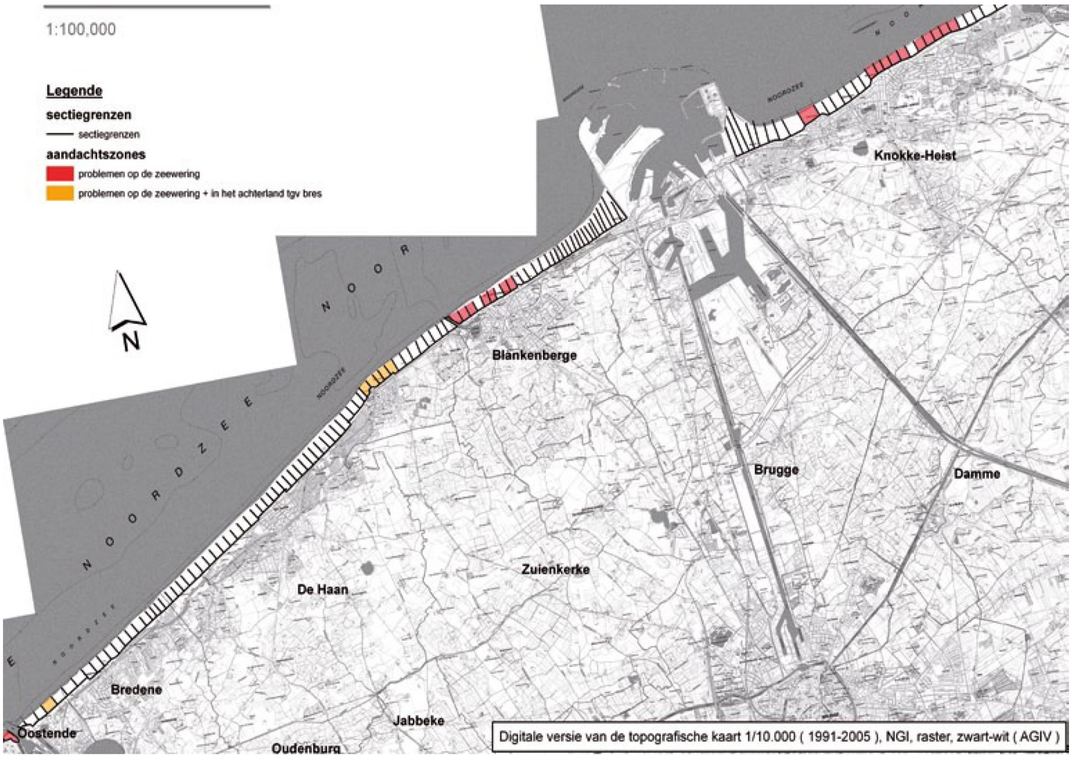

Figure 6 – Weak links in the coastal safety function along the Belgian coast, eastern region.

In cell 1, coastal sections 8 and 13 to 18 near De Panne as well as sections 21 to 31 and 39 near Koksijde are considered weak (Table 5). The total length of weak coastal sections is 4145 m in cell 1 (i.e. 29% of length of cell 1).

In cell 2, coastal sections 74 to 88 near Middelkerke as well as sections 97 to 108 near Raversijde are considered weak (Table 5). Additionally, sections 109 to 120 near Oostende are weak. The total length of weak coastal sections is 11885 m in cell 2 (i.e. 72% of length of cell 2).

In cell 3, coastal section 121 near Oostende as well as sections 172 to 176 near De Haan-Wenduine are considered weak (Table 5). The total length of weak coastal sections is 2246 m in cell 3 (i.e. 16% of length of cell 3).

With 72% of its length considered a weak link, coastal cell 2 between Nieuwpoort and Oostende provides the lowest level of safety against flooding along the Belgian coast. In coastal cell 1, between De Panne and Nieuwpoort, almost a third of the length is considered a weak link. Coastal cell 3, between Oostende and Wenduine, provides the highest level of safety against flooding because only 16% of the length of this cell is considered weak.

A number of weak 'hotspots' along the Belgian coast can be identified within each coastal cell. These hotspots are multi-kilometre weak coastal sections for which a mega nourishment may provide a sustainable solution to overcome the safety issues. In cell 1, sections 21 to 31 near Koksijde (length of 2395 m) provide the longest weak stretch. In cell 2, three hotspots are located: one near Middelkerke (sections 74 to 88; length of 5125 m), one near Raversijde (sections 97 to 108; length of 3835 m), and one near Oostende (sections 109 to 120; length 2951 m). The Middelkerke and Raversijde hotspots are separated by a short 2.5 km safe coastal stretch and could therefore be considered one extensive weak coastal stretch. In cell 3, sections 172 to 176 between De Haan and Wenduine (length of 1092 m) provide the longest weak stretch.

In addition to the identification of weak links, the flooding risk along the Belgian coast is also assessed in the Masterplan Kustveiligheid (2011). Flooding maps for a number of storm scenarios were created. The greatest flooding risk is present for the harbours of Nieuwpoort, Oostend, Blankenberge and Zeebrugge. A mega nourishment is not an option for harbours to lower the flooding risk. For the coastal towns, Middelkerke -Westende, Oostende - Raversijde, Oostende -Mariakerke, Middelkerke, Oostende-Wellington, Bredene and De Haan-Wenduine show the greatest flooding risk. For some of these coastal towns, the flooding risk may be lowered by constructing a mega nourishment along the coast.

Future wishes for coastal safety

In 2015, the coastal safety along the Belgian coast was improved due to works done in response to the 2011 assessment (Table 5). Some of the works are completed, some are in progress. However, some weak links remain (De Roo, 2018):

- Coastal section 8: wave overtopping for one test profile above the limit of 1 L/s/m, but below the limit for the second test profile.
- Coastal section 13: too much wave overtopping.
- Coastal sections 16 and 17: dune erosion beyond safety line and too much wave overtopping.
- Coastal section 22 and 23: too much wave overtopping.
- Coastal section 39: too much wave overtopping at dune crossing.
- Coastal sections: 85 and 86: coastal defence study is performed for the Casino Middelkerke.
- Coastal sections: 105-108: coastal defence project in progress near Raversijde.
- Coastal sections: 110-113: wave overtopping above the limit of 1 L/s/m.
- Coastal section 173: wave overtopping for one test profile above the limit of 1 L/s/m, other test profiles okay

Notably, an area to perform coastal protection experiments is identified near De Panne in the Marine Spatial Plan (2014) of the Belgian Federal Public Service Health , Food Chain Safety and Environment (Figure 7). Experiments may involve an investigation testing the effects of raising the sand banks on the safety of the coast. It is not specified in the Marine Spatial Plan (2014) if an investigation of the effects of a mega nourishment on the coastal safety is also considered. But the latter option would fit within the scope of a coastal protection experiment and would also have less consequences on the nearshore currents and sediment behaviour compared to the option of raising the sand banks. Although not explicitly specified in the Marine Spatial Plan (2014), the test zone for coastal protection is located within coastal cell 1 and closest to coastal stretches 2, 3 and 4 (Figure 4).

Figure 7 – Identification of test zone for innovative coastal protection schemes along the Belgian coast*.

*From Marine Spatial Plan (2014) of the Belgian Federal Public Service Health, Food Chain Safety and Environment.

3.1.2 Nature

Existing functions and values

Natura2000 areas and other nature areas (e.g. protected dune areas and forests) are identified in Figure 8. These areas may legally restrict the construction of a mega nourishment. Important Natura2000 areas along the Belgian coast are:

a. ‘Poldercomplex’ / VEN-gebied ‘Middenkust’
b. Vogelrichtlijn gebied ‘Westkust’ / VEN-gebied ‘Westkust’
c. Vogelrichtlijn gebied ‘Kustbroedvogels te Zeebrugge-Heist’ / VEN-gebied ‘De Zwinstreek’
d. Vogelrichtlijn gebied ‘Baai van Heist, Sashul, Vuurtorenweide en Kleiputten van Heist’
e. Vogelrichtlijn gebied ‘Het Zwin’
f. De mariene vogelrichtlijn gebieden SBZ1, SBZ2, SBZ3
g. De habitatrichtlijn gebieden ‘Polders’, ‘Duingebieden inclusief Ijzermonding en Zwin’
h. Het mariene habitatrichtlijn gebied ‘Trapegeer-Stroombank (H1)’

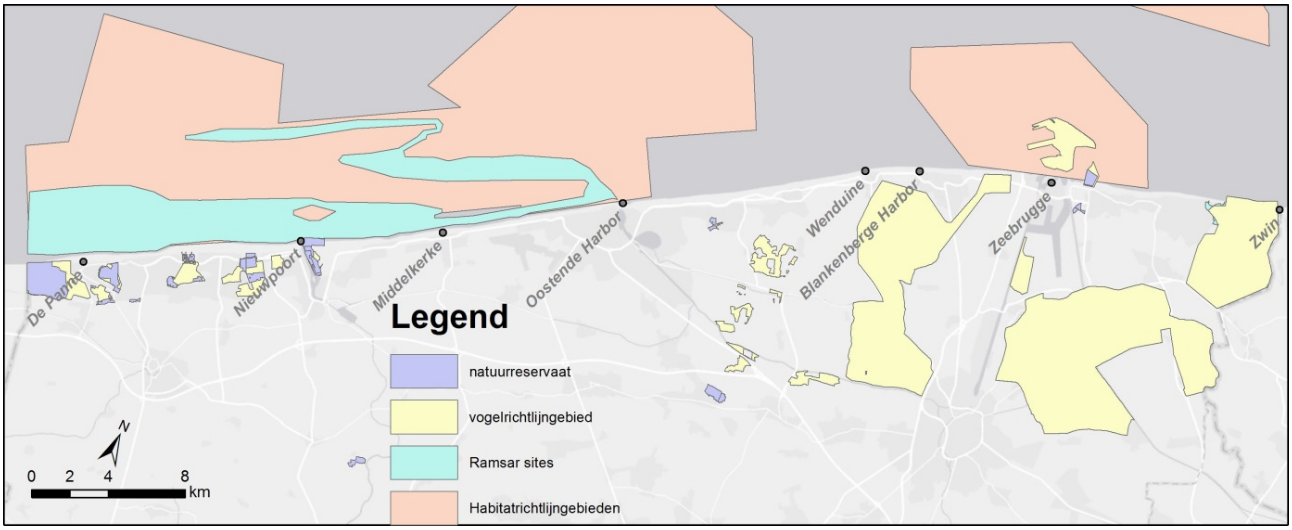

Figure 8 – Nature areas along the Belgian coast*.

*Data from Kustatlas.be.

All nature areas located east of the harbour of Blankenberge are out of scope for the current feasibility study on a possible mega nourishment (Figure 8).

Dune development can be part of a mega nourishment due to the potential increase in dry beach area. Therefore, we focus on and describe the locations of dunes (Figure 9) and their functioning (Figure 10 and Figure 11) along the Belgian coast.

Dunes provide important ecosystem services as well as offering a natural defence against coastal flooding and recreational opportunities along the Belgian coast (Provoost *et al.*, 2014). Dunes are present as a soft sea defence along the majority of the Belgian coastline. In coastal towns Middelkerke and Oostende (cell 2) dunes are scarce (Figure 9).

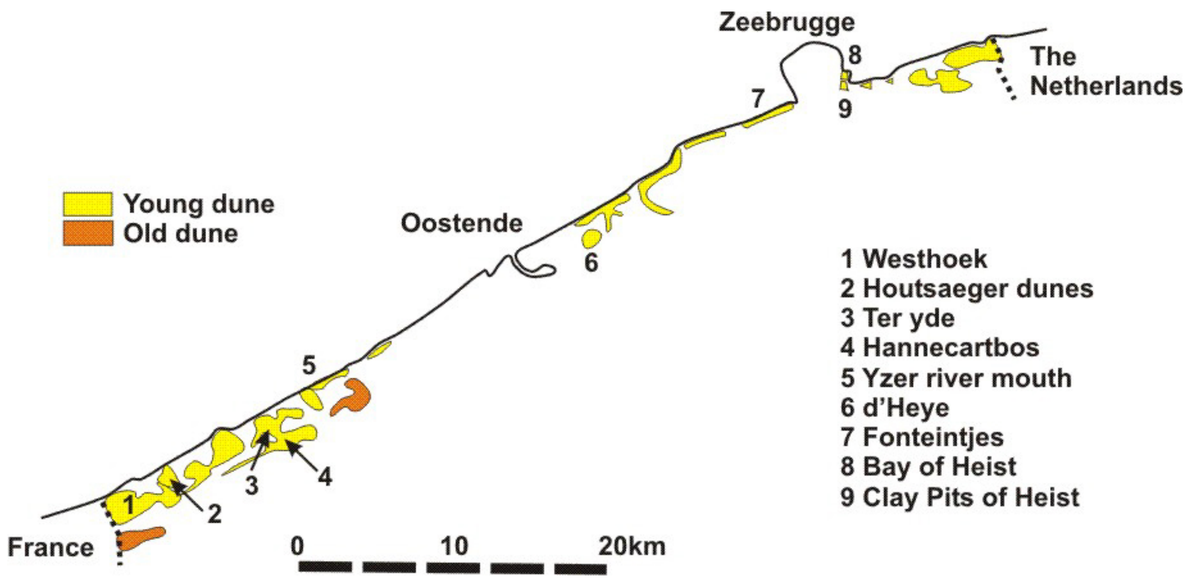

Figure 9 – Protected dune areas along the Belgian coast*.

*Data from www.coastalwiki.org

The size of the dune area determines the potential for ecosystem services in dunes. A less fragmented and therefore larger dune area as well as a wider dune are beneficial in the provision of ecosystem services (Figure 10). A minimum of tens of meters of dune width are required for natural geomorphological processes to occur and an optimal ecological functioning (Provoost *et al.*, 2014). Many geomorphological processes are cyclic, some on a seasonal basis and some on a longer-term multi-year basis. For example, beach and dune erosion occurs during (winter) months with intense storms. During the calmer summer months, the beach generally accretes naturally and also aeolian sediment transport processes can deposit sand in the dune area to re-build them. Longer-term erosional beach accretion and erosion trends also exist and these may dampen or amplify the seasonal dune processes.

The red zones in Figure 10 have a width of at least 80 m or, in case of a narrower width, connect with a wider dune area (e.g. dunes near mouth of Ijzer). Many of these wider dune areas show a high or intermediate level of ecosystem dynamics (Figure 11).

The narrower (i.e. green) zones in Figure 10 are not functioning optimally from an ecological perspective. The space required for dune dynamics such as erosion and aeolian sediment transport processes is simply unavailable.

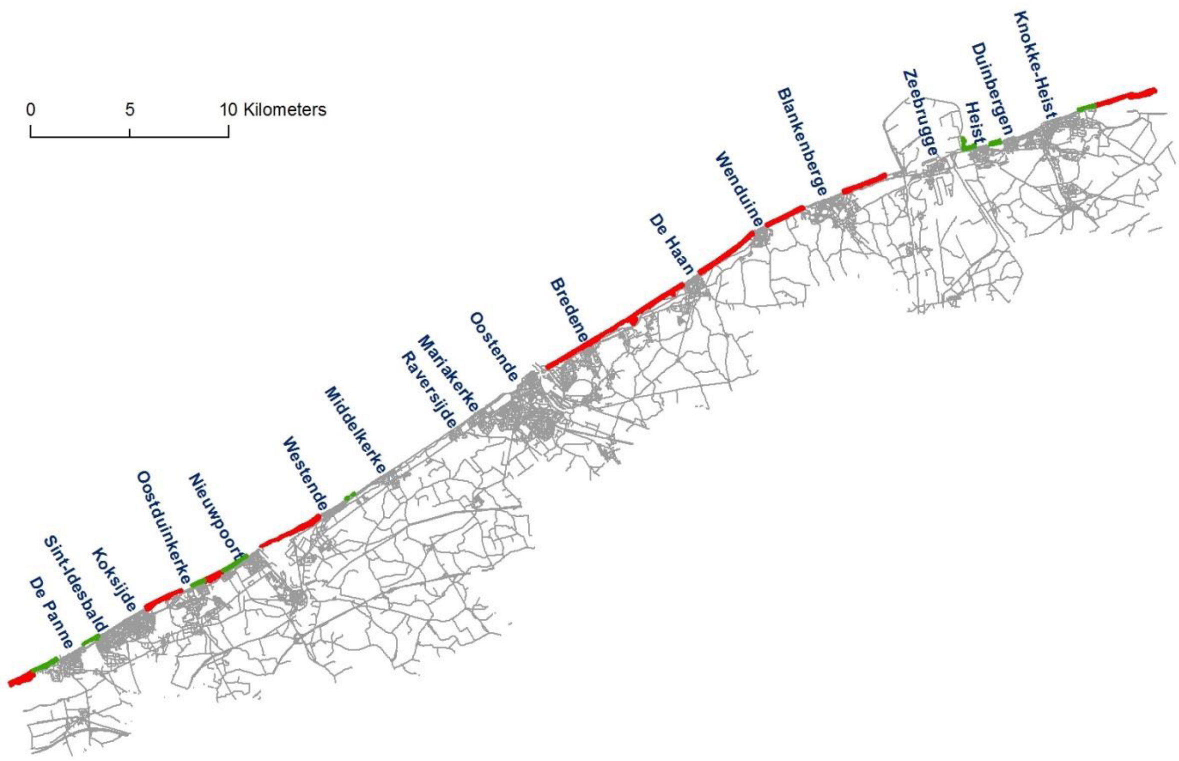

Figure 10 – Potential for ecosystem services (ES) in dune areas along Belgian coast:
wide (red) and narrow (green) dunes with a higher ES potential in wider dunes*.

*From Provoost, Dan, and Jacobs (2014).

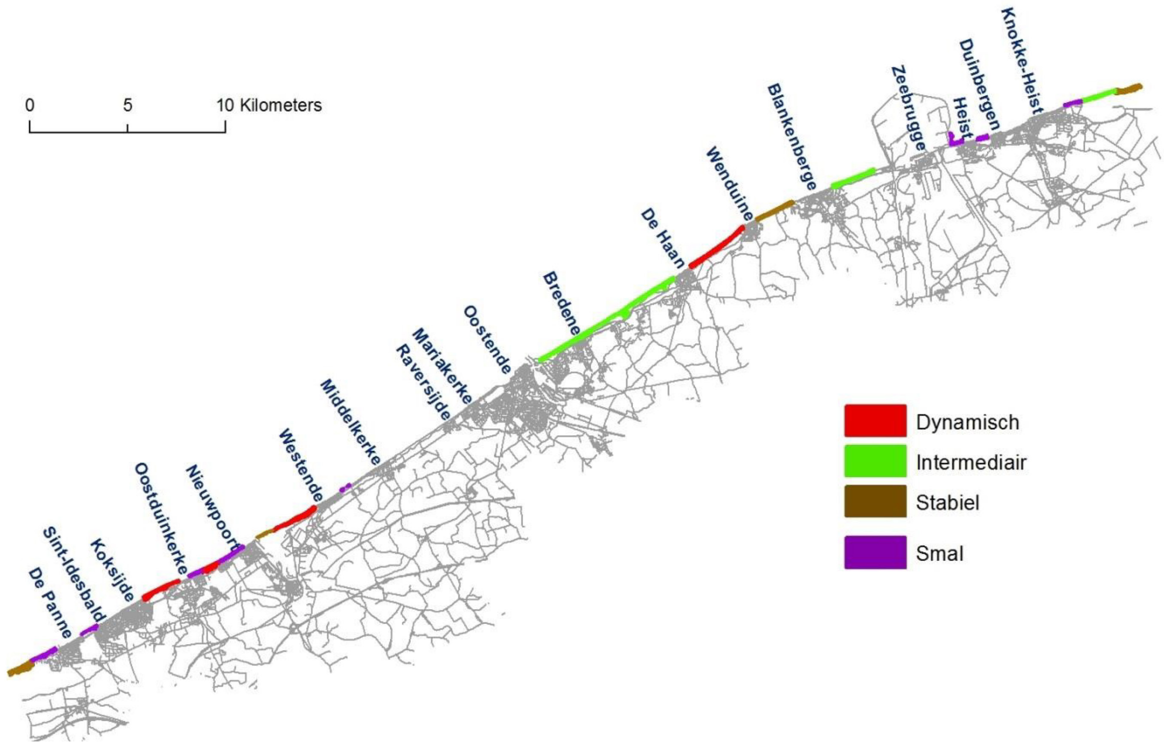

Figure 11 – Ecosystem dynamics of existing dune areas along Belgian coast*.

*From Provoost, Dan, and Jacobs (2014).

Future wishes for nature development

A map was made of nature development plans, which have been legally approved, to provide an overview of future wishes and developments from the nature perspective. These nature development plans include new protected habitat areas, dune areas or tidal inlets (Figure 12).

Figure 12 – Nature development plans along the Belgian coast.

Few plans have been approved for nature development within a distance of 10 km from the shoreline. Approved projects for nature development include (Figure 12):

- Zwin tidal inlet project: an increase of the tidal inlet area with 120 hectares. The old dike will be removed and a new, more landward, dike will be built (Masterplan Kustveiligheid, 2011).
- Dune development on beaches near Mariakerke and Raversijde is considered. A dune row is present on the landward side of the existing dike on both sides of Raversijde, i.e. Raversijde disconnects these two dune rows. These dune areas are ecologically valuable and are part of habitatrichtlijngebied Duingebieden incl. Ijzermonding en Zwin (deelgebied Warandeduinenen en duinen van Raversijde). Sections of these dunes are also part of GEN-gebied (Grote Eenheden Natuur) ‘Middenkust’. Furthermore, these dune areas provide a natural protection against coastal flooding and have a recreational value. In this project, new dunes will also be developed on the seaward side of the existing dike. The low recreational usage of this area (in comparison to beaches in front of coastal towns) enables the development of embryonic dunes and thus added ecological value.

A number of areas in the Belgian part of the North Sea have also been designated for future nature conservation purposes (Figure 13):

- A designation of four sensitive subzones within the Special Area for Conservation (SAC) ‘Flemish Banks’. In these subzones, fishing is only allowed using environmentally friendly techniques, or under specific conditions. Also, sand and gravel mining is limited within the Flemish Banks SAC.
- A designated area for a ‘plug at sea’: a high-voltage station at sea to which cables run from several wind parks. A resting place for seals may be created here.
- A designated area for wind farms and other forms of renewable energy: shipping and fishing are prohibited in these areas. The absence of shipping and fishing provides opportunities for species like cod, bib, whiting, craps and shrimp.
- Two artificial reefs are built in the wind farm zone to attract more fish and other marine animals.
- Two areas for future ‘energy atolls’ are designated. These are envisaged to be doughnut shaped islands where energy can be stored. The sandy beaches of these islands may provide breeding spots for coastal birds.

The majority of the identified nature conservation measures in Figure 13 is not relevant in exploring possibilities for a mega nourishment, simply because the locations of these future measures are offshore.

Figure 13 – Identification of nature conservation measures in the Belgian part of the North Sea*.

*From Marine Spatial Plan (2014) of the Belgian Federal Public Service Health, Food Chain Safety and Environment.

To improve nature and dune development as part of coastal management in the Netherlands, Lammerts and Van Haperen (2015) identified four strategies. These strategies may also be relevant for the future nature and dune development along the Belgian coast and are described below:

1. **Deploy natural processes at the landscape level**. At this first level, processes can spontaneously proceed on the scale of undisturbed gradients without noteworthy human influence. For the Dutch coast, this entails as complete as possible gradients of the coastal foundation up to and including the inner dune edges or high salt marshes. This only seems to be possible on uninhabited parts of the Wadden islands and is often already a given fact there. For the intensively used Belgian coast, allowing natural processes at the landscape level seems not possible.
2. **Deployment of natural dynamics within the limitations of the physical and social environments**. At this second level, undisturbed natural processes are no longer possible on complete coastal gradients, but are possible on components of the system where long sea to land gradients can be created. For the Dutch coast, this mainly concerns connections between the nearshore coastal zone and dunes and salt marshes. This is possible for the large dune complexes of Holland and on some parts of the Wadden islands and Schouwen-Duiveland. For the Belgian coast, this may be possible for the larger dune complexes as identified in Figure 10, the mouth of the Ijzer and the Zwin tidal inlet.
3. **Deployment of dynamics on the scale of individual dune and salt marsh habitats**. These are essentially technical and planned deployments of measures that are derived from natural processes.

An example is the reactivation of blowouts in dune areas to allow a better sand circulation towards the inland dunes.

4. **Active semi-natural management in fixed coastal areas**. Examples are mowing, cutting, chopping and regulated forms of grazing.

Possible use of a feeder-type mega nourishment within the four strategies

In strategy 1, the human influence is minimal. The possibilities for this strategy are mainly at the locations where nourishments only have a minor role. A mega nourishment would not be logical here.

In strategy 2, a feeder-type mega nourishments could play a role. The coastal management and the dune management could be brought into line with each other such that the surplus in sand can shift to the dunes, while coastal protection is safeguarded. This is not so easy everywhere, because infrastructure, like roads and pipelines, hinder the spraying of sand.

In strategies 3 and 4, the scale level for landscape processes is so low that feeder-type mega nourishments would not have any significant role.

3.1.3 Recreation and infrastructure

Recreational opportunities along the Belgian coast are identified in Figure 14. This figure provides an overview of the opportunities to use the Belgian beach and, by extension, an overview of the most visited coastal areas. This map confirms that most of the Belgian coast is intensively used for recreational purposes.

In coastal cell 1, recreational opportunities are centred around the cities of De Panne and Nieuwpoort. Multiple beach clubs, supervised swimming beaches and beach shower facilities are available. Fewer opportunities are available between Sint Idesbald and Oostduinkerke, as well as west of De Panne.

In coastal cell 2, recreational opportunities on the beach are plentiful west of Middelkerke and east of Mariakerke. Between these coastal cities, recreational opportunities are fewer.

In coastal cell 3, recreational opportunities are mostly located near Wenduine and near Blankenberge. The coastal stretch between Vosseslag and Wenduine has fewer recreational opportunities.

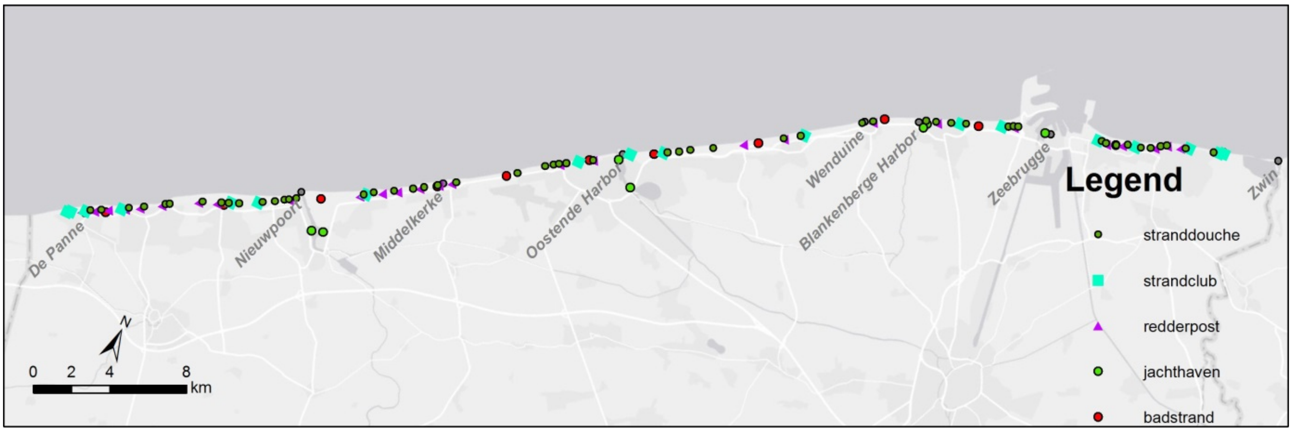

Figure 14 – Recreational opportunities along the Belgian coast*.

*Functions shown here are centred around the beach: swimming beach, supervised beach with lifesavers, beach club, beach shower, and recreational harbours.

The layout and main industrial infrastructure along the Belgian coast are identified in Figure 15. This map provides an overview of the main coastal towns, regional industrial estates and hiking, cycling and car routes in the coastal region. Combined with the information from Figure 14, this map provides an overview of the main activities in the coastal region, the degree of recreational and infrastructural pressure and the most heavily used areas along the coast.

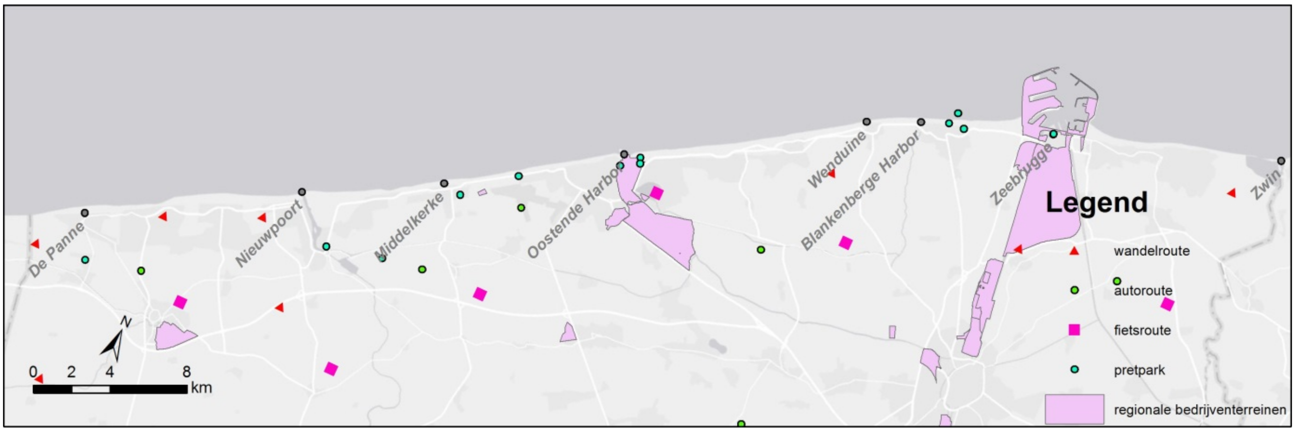

Figure 15 – Layout of the Belgian coast with infrastructural routes and larger industrial estates shown*.

*Functions shown here are within the larger coastal region: regional industrial estates, hiking, cycling and car routes, and entertainment parks.

Future wishes for recreation

Tourism is and will remain one of the most important activities in the coastal region. Local plans may exist to stimulate tourism and recreation in the future but no regional or larger-scale plans for the development of recreational opportunities along the Belgian coast are identified. It is therefore expected that the maps of recreational opportunities identified in Figure 14 and Figure 15 are representative into the (near) future.

3.1.4 Other functions and values

In addition to coastal safety, a number of other functions and uses can be identified for the Belgian part of the North Sea (Figure 16). These include:

i. Energy, cables and pipelines
ii. Shipping, ports and dredging
iii. Fisheries and aquaculture
iv. Sand and gravel exploitation
v. Military use
vi. Cultural heritage (e.g. wrecks)
vii. Scientific research, measuring poles, radars and masts

All of these functions will be briefly described below, with a focus on the nearshore zone and in the context of a possible mega nourishment.

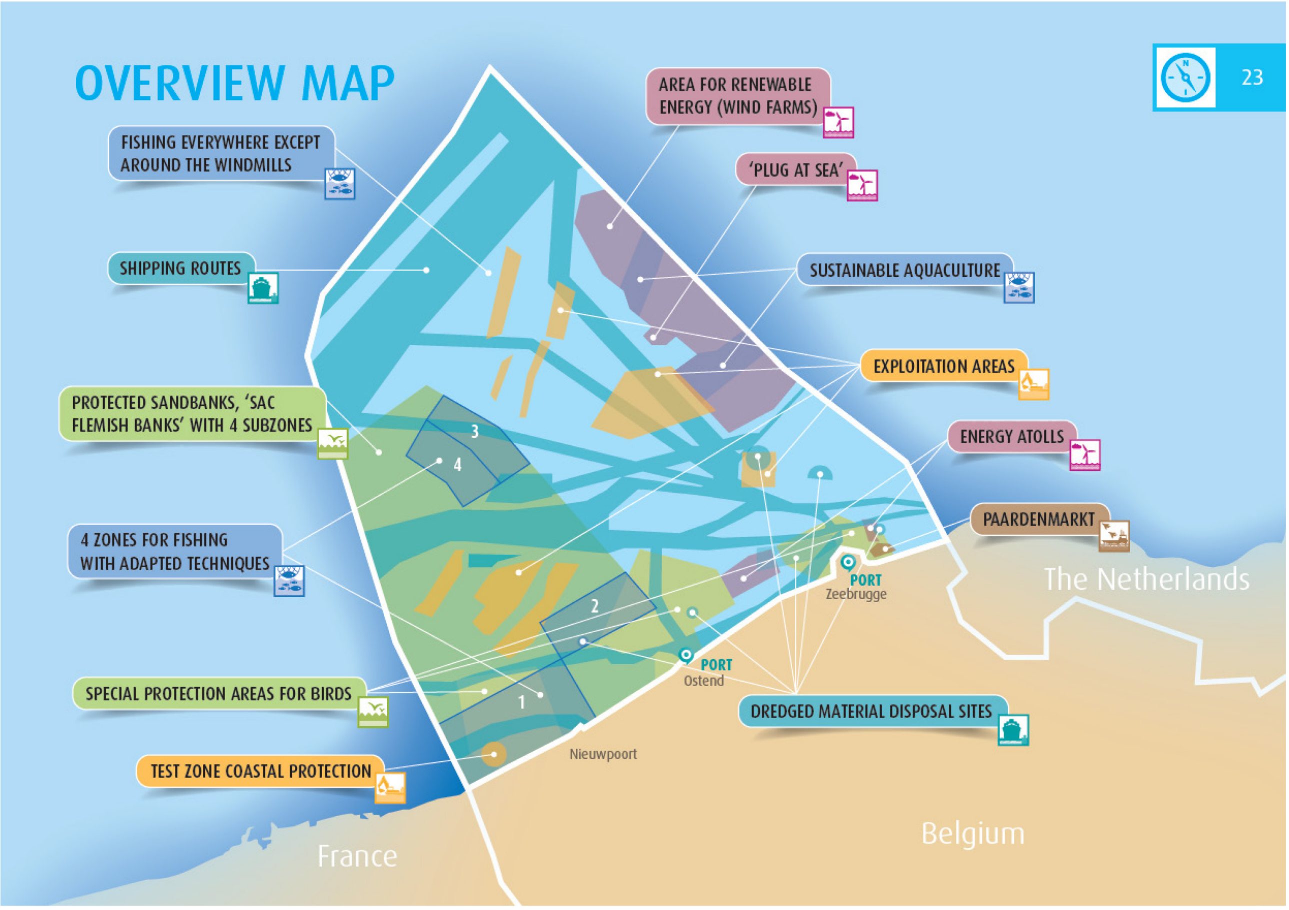

Figure 16 – Overview map of all functions in the Belgian part of the North Sea*.

*From Marine Spatial Plan (2014) of the Belgian Federal Public Service Health, Food Chain Safety and Environment.

Energy, cables and pipelines

There are no oil pipelines in the Belgian part of the North Sea (Figure 17). Two areas are designated for the establishment of 'energy atolls'. One of these proposed atolls is located in the eastern part of the study area, near Wenduine. The other atoll is located east of Zeebrugge and out of scope for the current feasibility study. Also, no pipelines are located in the study area. One gas pipeline is located east of Zeebrugge and out of scope for the current feasibility study. New cables for electricity and communication as well as pipelines for gas are clustered as much as possible into corridors (Figure 18). This clustering is done to hinder other activities such as sand and gravel mining, fishing and shipping as little as possible.

Figure 17 – Energy, cables and pipelines with identification of main corridors in the Belgian part of the North Sea.

*From Marine Spatial Plan (2014) of the Belgian Federal Public Service Health, Food Chain Safety and Environment.

Figure 18 – Energy, cables and pipelines in the nearshore zone (shoreline to approx. 10 km offshore) of the Belgian North Sea.

*From kustatlas.be.

Shipping, ports and dredging

The Belgian part of the North Sea is one of the busiest seas in the world for shipping. It gives access to all Belgian sea ports and it provides a passageway for all ships between the northern and southern parts of the North Sea. Therefore, specific shipping routes have been designated to indicate that shipping has priority over other activities in these areas (Figure 19). Shipping routes are connecting the ports of Nieuwpoort, Oostend and Zeebrugge with the North Sea. Importantly, a shipping route is present along the shoreline between Oostend and Zeebrugge. Additionally, the ports of Zeebrugge and Oostend may be extended on the seaward side in the future and a zone surrounding the these ports has therefore been reserved for that purpose.

Figure 19 – Shipping routes, ports and dredging in the Belgian part of the North Sea*.

*From Marine Spatial Plan (2014) of the Belgian Federal Public Service Health, Food Chain Safety and Environment.

Dredging is necessary to maintain navigation and to construct ports. The dredged material is dumped later at sites specifically designated for this purpose (Figure 20). Most of these dumping sites are located close to ports and also an area near Zeebrugge is reserved as an alternative disposal site, to minimize disturbance to fishing grounds.

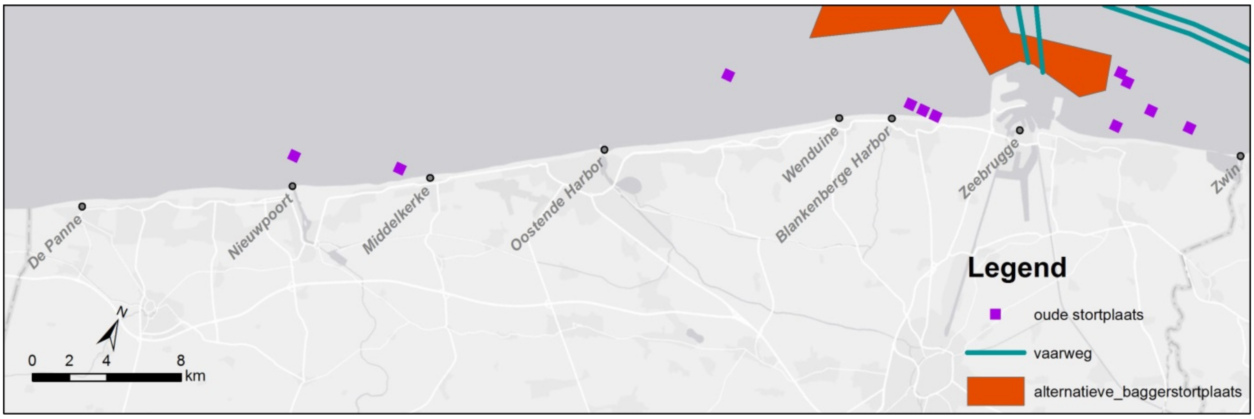

Figure 20 – Shipping routes and disposal sites for dredged material in the nearshore zone (shoreline to approx. 10 km offshore) of the Belgian North Sea*.

*From kustatlas.be.

Fisheries and aquaculture

To conserve and strengthen the ecological function of the Belgian part of the North Sea, sustainable forms of fishing are developed (Figure 21). Sustainable aquaculture is allowed at the site of two wind farms.

Figure 21 – Fisheries and aquaculture in the Belgian part of the North Sea*.

*From Marine Spatial Plan (2014) of the Belgian Federal Public Service Health, Food Chain Safety and Environment.

Within the Special Area for Conservation (SAC) 'The Flemish Banks', four zones for fishing with adapted techniques are defined (Figure 21, Figure 22):

1. In zone 1, fishing is only allowed using adapted gear such as nets which cause less disturbance to the sea floor.
2. In zones 2 and 4, new techniques can be tested in an effort to develop more environmentally friendly forms of fishing.
3. Zone 3 is the most stringent zone: here, a ban on all techniques disrupting the sea floor is in place.

Zone 1 is most relevant from the perspective of construction a mega nourishment since this zone is located close to the shoreline (Figure 22). Zone 1 extends approximately from the Belgian-French border to Westende and should therefore primarily be taken into account when designing a mega nourishment in coastal cell 1 (Figure 4).

Figure 22 – Fisheries and aquaculture in the nearshore zone (shoreline to approx. 10 km offshore) of the Belgian North Sea*.

*From kustatlas.be.

Sand and gravel exploitation

Two to three million cubic meters of sand is exploited annually from the Belgian part of North Sea. Four main exploitation sites are designated (Figure 23). A permit is required to exploit sand and gravel in addition to an environmental report on the impact of the exploitation on the local environment. The ecologically valuable gullies are not available for exploitation (Figure 23).

All sand and gravel exploitation areas are located more than 10 km offshore and will therefore not influence the construction of a mega nourishment along the shoreline.

Figure 23 – Sand and gravel exploitation in the Belgian part of the North Sea*.

*From Marine Spatial Plan (2014) of the Belgian Federal Public Service Health, Food Chain Safety and Environment.

Military use

The Belgian part of the North Sea is used for military activities and exercises. Several zones are designated for military activities (Figure 24, Figure 25). Specifically, zones are designated for military exercises and zones are designated for defusing mines. During military exercises, no shipping, fishing, dredging or exploitation is allowed in these zones. In a zone called 'Paardenmarkt' (Figure 25), war ammunition was dumped after World War One. The evolution of this storage site is monitored carefully and activities disturbing the sea floor are forbidden here.

One military zone extends to the shoreline between Nieuwpoort and Westende (Figure 25). The presence of this military zone along this coastal stretch in coastal cell 2 may influence the construction of a mega nourishment and should therefore be taken into account in the design process.

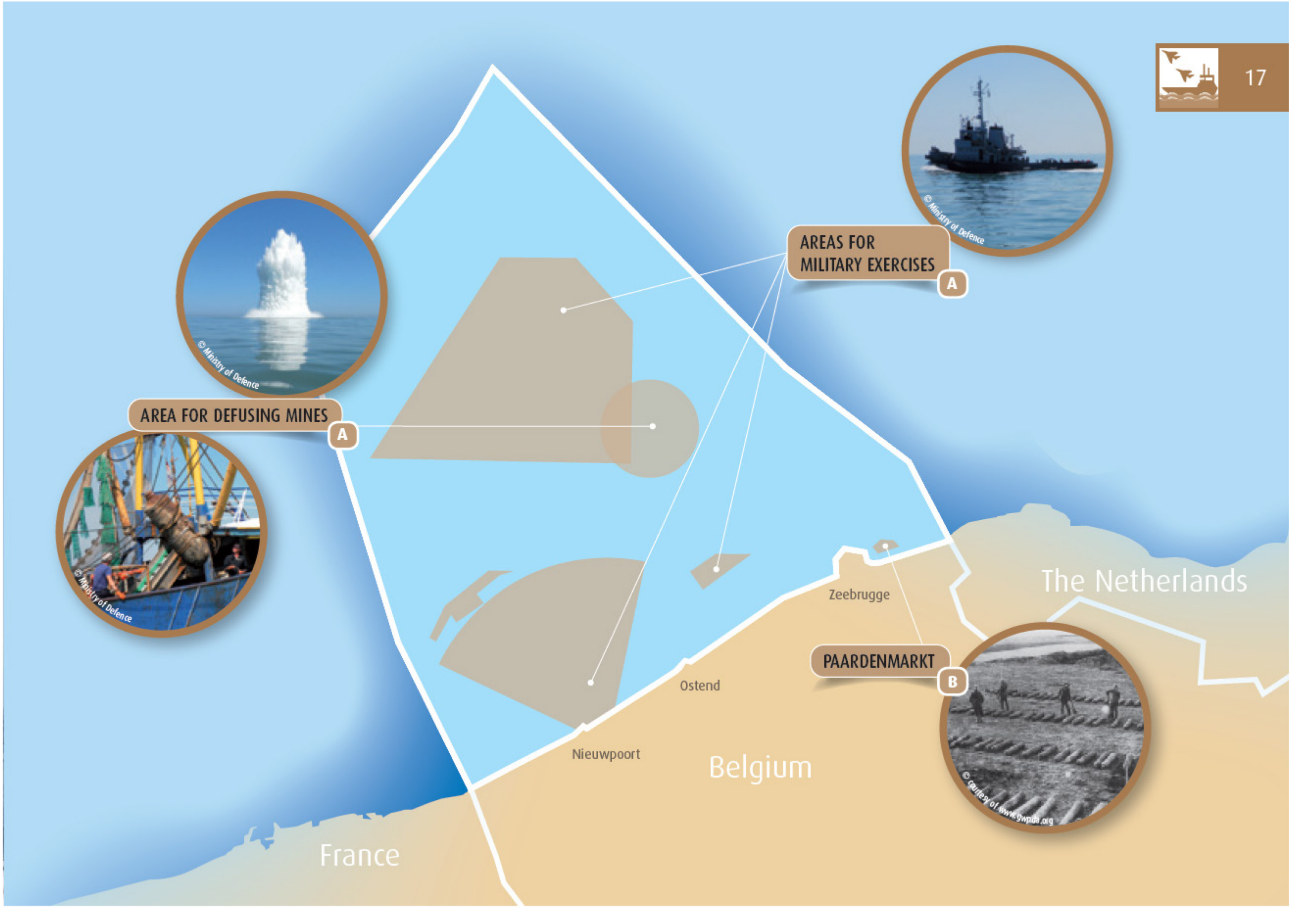

Figure 24 – Military use of the Belgian part of the North Sea*.

*From Marine Spatial Plan (2014) of the Belgian Federal Public Service Health, Food Chain Safety and Environment.

Figure 25 – Military uses in the nearshore zone (shoreline to approx. 10 km offshore) of the Belgian North Sea*.

*From kustatlas.be.

Cultural heritage

A number of 215 registered wrecks are present in the Belgian part of the North Sea (Figure 26) and they are considered cultural heritage. The wrecks are popular with divers and sport fishers. Zeebrugge and Oostend are hotspots for wrecks (Figure 26, Figure 27). Wrecks may provide some limitations for the construction of a mega nourishment because they can be protected as underwater cultural heritage. However, the presence of a nearby wreck can also be considered an opportunity from a tourism perspective in constructing a mega nourishment.

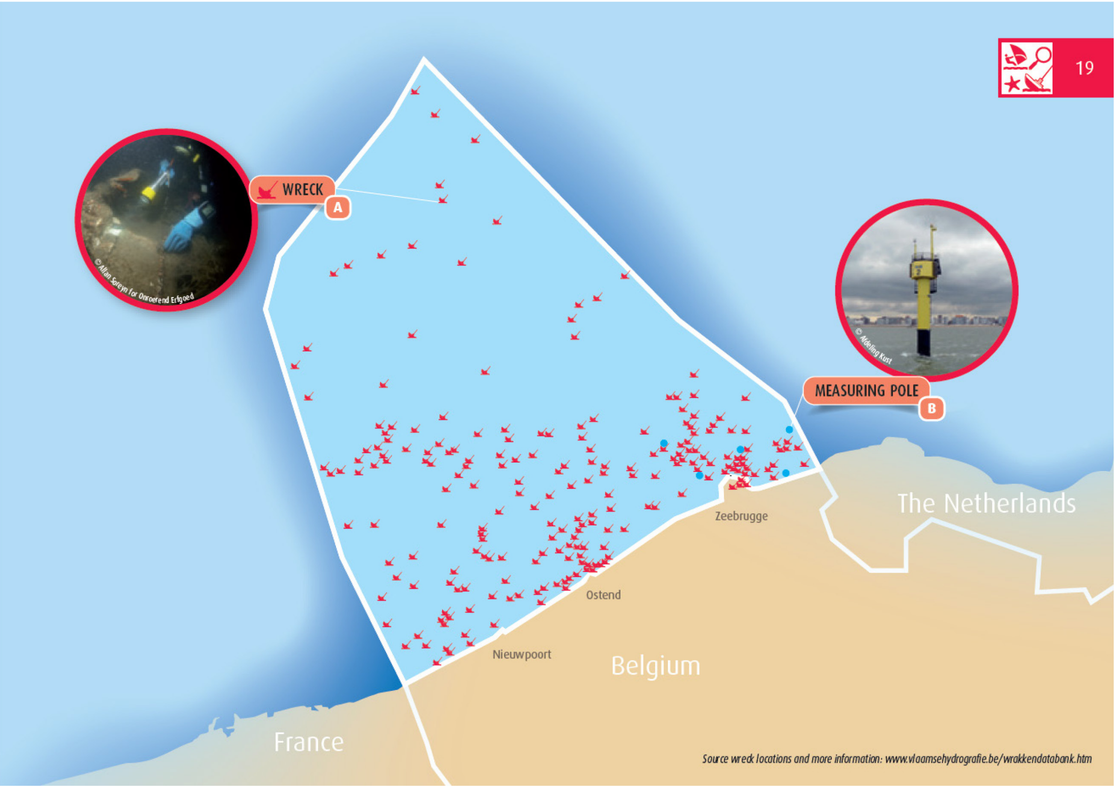

Figure 26 – Wrecks in the Belgian part of the North Sea*.

*From Marine Spatial Plan (2014) of the Belgian Federal Public Service Health, Food Chain Safety and Environment.

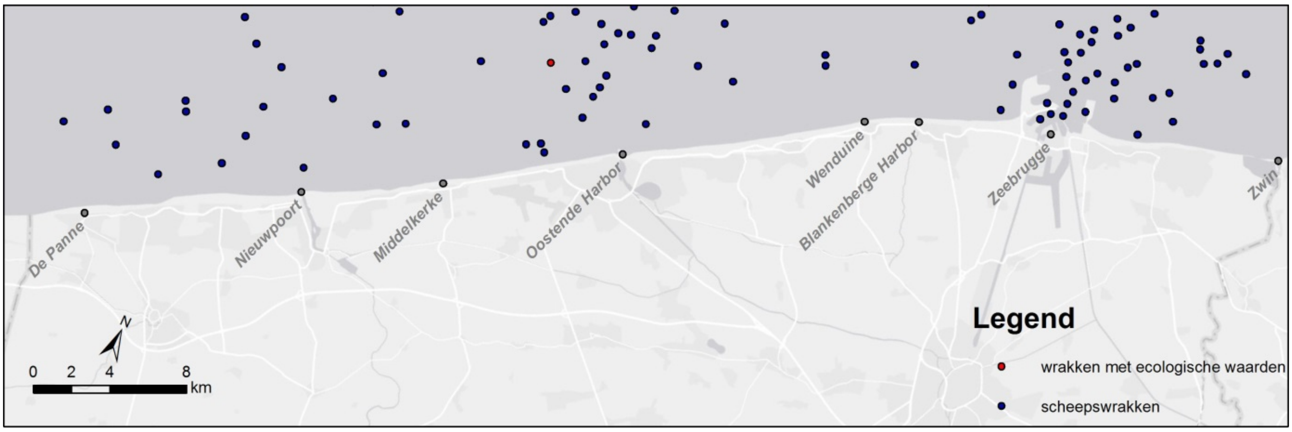

Figure 27 – Wrecks in the nearshore zone (shoreline to approx. 10 km offshore) of the Belgian North Sea*.

*From kustatlas.be.

Scientific research and measurement stations

Buoys, measuring poles and radars are present in the Belgian part of the North Sea (Figure 28) and collect data to support amongst others navigation, weather predictions and coastal safety. The majority of the measuring poles is located near Zeebrugge. The waverider Trapegeer near De Panne is closest to the shoreline with a distance of 3 km. This indicates that none of the measuring poles provide an obstruction to the construction of a mega nourishment along the Belgian coast.

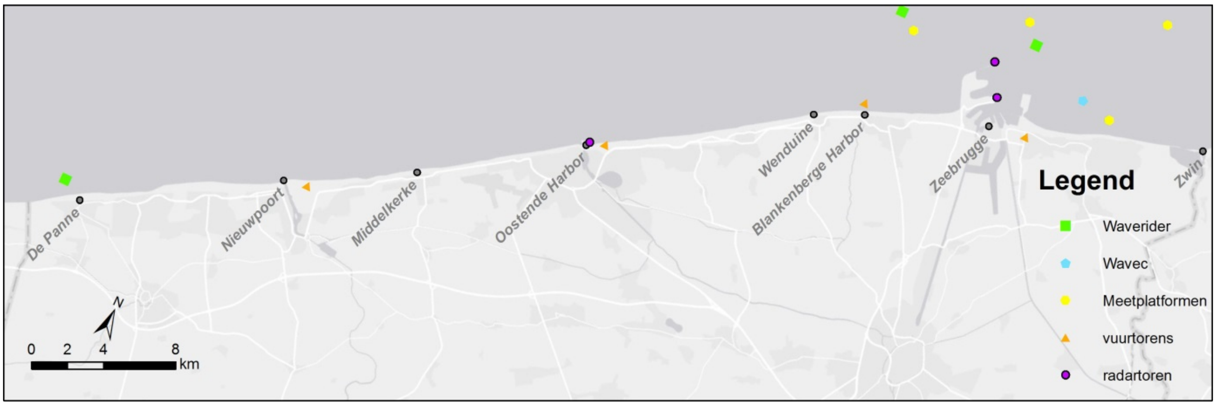

Figure 28 – Buoys, measuring poles and radars in the nearshore zone (shoreline to approx. 10 km offshore) of the Belgian North Sea*.

*From kustatlas.be.

3.2 Opportunities for a feeder-type mega nourishment along the Belgian coast

Maps illustrating the opportunities for a feeder-type mega nourishment along the Belgian coast from the coastal safety, nature development, recreation and other functions perspectives were produced based on the current functions as identified in Section 3.1. The opportunity maps show:

- Moderate opportunity for a feeder-type mega nourishment
- Good opportunity for a feeder-type mega nourishment

When no opportunity is identified, the coastal stretch is left blank. Firstly, the criteria for determining the opportunities for a feeder-type mega nourishment are described and shown in an opportunity map for each of the individual perspectives of coastal safety, nature development, recreation and other functions. Secondly, a map is synthesising the opportunities for a feeder-type mega nourishment from all three perspectives.

3.2.1 Coastal safety

The criteria to determine opportunities for a feeder-type mega nourishment from a coastal safety perspective are:

1. A good opportunity is identified when a weak link is present in the coastal stretch as shown in Figure 5 and Figure 6. A seaward extension of the sandy beach provides an opportunity to overcome the safety issues in these coastal stretches.
2. A good opportunity is identified in the coastal stretches for which a test zone for coastal protection has been designated (Figure 7). A mega nourishment provides an innovative method for coastal

safety and this area could serve as a testing zone for such a large man-made feature at the Belgian coastal system.

3. A moderate opportunity is identified for sections in the vicinity of but not directly next to harbours.
4. For all harbours and deep channels, a mega nourishment is not an opportunity.

Some of the weak links identified in Figure 5 and Figure 6 have been addressed by works to overcome the coastal safety issues. Yet, the identified weak links can be considered persistent vulnerable coastal sections. A mega nourishment may provide a long-term and flexible solution to overcome the coastal vulnerability by supplying a large volume of sand to the coastal profile.

The four criteria result in the opportunity map for a mega nourishment along the Belgian coast from a coastal safety perspective as shown in Figure 29.

In coastal cell 1 (Figure 4), good opportunities are identified in sections 8, 13-18 and 21-31 near De Panne (Figure 29). These coastal sections could be considered as a single weak link in the coastal defence system of about 4 km in length (Table 5). In addition, the test zone for innovative coastal protection measures is located here and provides an additional opportunity for a mega nourishment along these coastal sections.

In coastal cell 2 (Figure 4), good opportunities are identified in sections 74 to 88 near Middelkerke. These coastal sections provide a single weak link in the coastal defence system of about 5 km in length (Table 5). A moderate opportunity is identified for the sections 97 to 108 due to the vicinity of Oostende harbour. A mega nourishment may be feasible towards the western sections but the presence of Oostende harbour will need to be critically evaluated. The other weak links identified in Table 5 are deemed too close to Oostende harbour and therefore no opportunities for a mega nourishment are identified.

In coastal cell 3 (Figure 4), one moderate opportunity is identified (Figure 29). A smaller coastal stretch near De Haan – Wenduine consisting of the section 172 to 176. The length of the stretch is about 1100 m, which may be too short for a mega nourishment to be effective.

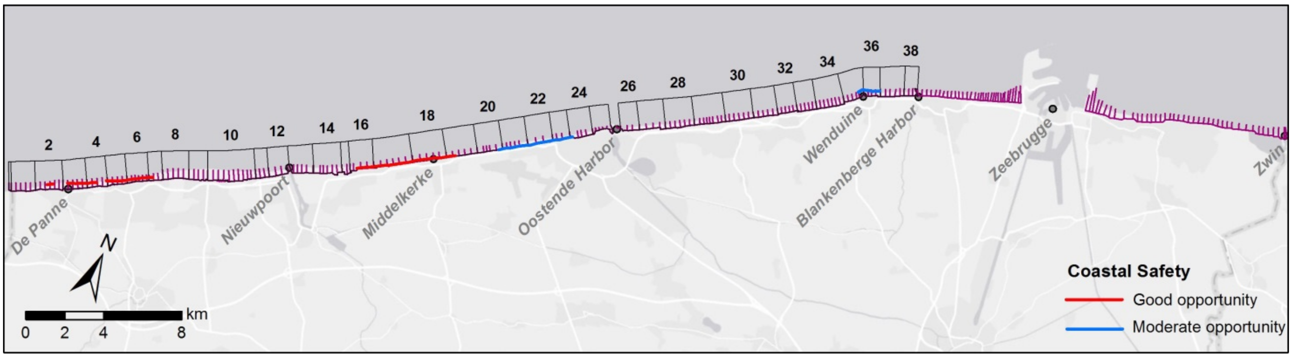

Figure 29 – Opportunity map for a feeder-type mega nourishment along the Belgian coast from the perspective of coastal safety (i.e. by addressing the weak links in the coastal defence).

3.2.2 Nature

A mega nourishment is expected to have a positive effect on nature and ecological development, primarily by providing space to develop ecological habitats that are not present currently. The criteria to determine opportunities for a mega nourishment from a nature perspective are:

1. A good opportunity is identified when intermediate ecosystem and dune dynamics are currently present in the coastal stretch as shown in Figure 11. A seaward extension of the existing but limited dune habitat and sandy beach provides an opportunity to develop a more dynamic ecosystem in these coastal stretches.

2. A moderate opportunity is identified in the coastal stretches with soft sea defences (Figure 9). The dunes present here are completely fixed by vegetation or too small to function optimally (Figure 11). A mega nourishment provides an innovative means to expand the dune with the option to create ecological habitats currently not seen along the Belgian coast
3. A moderate opportunity is identified for sections located in a Natura2000 area because these may hinder the construction of a mega nourishment.
4. For all harbours, deep channels and coastal towns, a mega nourishment is not an opportunity.

Figure 30 shows the opportunity map for a feeder-type mega nourishment along the Belgian coast from a nature perspective. A good opportunity is identified in coastal cell 3 (Figure 4) and some moderate opportunities are identified in coastal cells 1 and 2.

In coastal cell 1 (Figure 4), moderate opportunities are identified in sections 2-12, 18-21, 35-43 and 46-56 (Figure 30). About half of the dune area in coastal cell 1 is already classified as dynamic, particularly the stretches east of Koksijde (Figure 11). A mega nourishment can reinforce and strengthen these ecosystem dynamics but the mega nourishment tool is not fully effective here since safety against flooding is not a necessity, and therefore a moderate opportunity is identified. Similarly, the existing dune areas west of Sint-Idesbald are classified as stable or small (Figure 11).

In coastal cell 2 (Figure 4), two moderate opportunities are identified. These are located in sections 63-72 near Sint-Laureins and sections 88-105 between Middelkerke and Mariakerke (Figure 30). The sections near Sint-Laureins are already classified as dynamic (Figure 11). A mega nourishment can reinforce and strengthen these ecosystem dynamics but the mega nourishment tool is not fully effective here and therefore a moderate opportunity is identified. The moderate opportunity for sections 88-105 is identified based on plans to develop a second dune row in front of the existing dike. A mega nourishment can be used here to expand the dry beach and dune area but the limited dynamics of these planned dunes may render the mega nourishment not fully effective. It is important to note that for these sections an extensive and elongated dune area exists on the landward side of the sea dike while, in some sections, a dry beach is lacking on the seaward side of the dike. The road will provide a barrier to connect the existing dune area on the landward side to a possible mega nourishment on the seaward side.

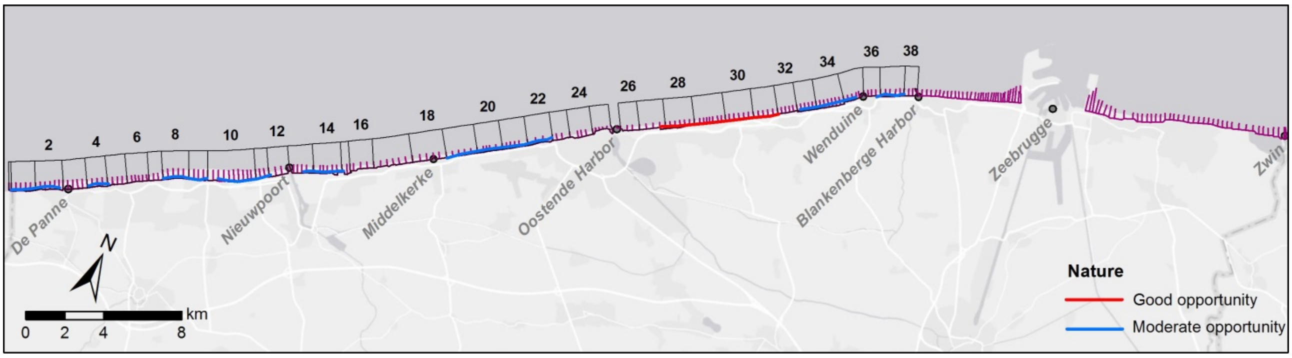

Figure 30 – Opportunity map for a feeder-type mega nourishment along the Belgian coast from the perspective of nature development (i.e. by fulfilling the ecosystem potential by expanding dune areas where possible).

In coastal cell 3 (Figure 4), one good opportunity and two moderate opportunities are identified. The good opportunity is located in sections 125-150 between Bredene and De Haan (Figure 30). This coastal stretch is classified as 'intermediate dynamic' in terms of ecology (Figure 11). Construction of a mega nourishment along this stretch will increase the area available for dynamics and may, as such, provide an effective means to reach and expand the potential of the existing dune areas. Also, the added space resulting from a mega nourishment provides an opportunity to create new ecological habitats complementing the existing ones. The moderate opportunities are located in sections 156-170 between De Haan and Wenduine, and sections 175-181 between Wenduine and Blankenberge (Figure 30). The sections between De Haan and Wenduine are already classified as dynamic (Figure 11). A mega nourishment can reinforce and strengthen these ecosystem dynamics and a moderate opportunity is identified. The moderate opportunity for sections 156-170 is identified based on the presence of a stable dune area (Figure 11). A mega nourishment can be used here to expand the dry beach and dune area but the limited dynamics of these existing dunes may render the mega nourishment not fully effective. Also, this latter stretch is located relatively close to Blankenberge harbour, which may limit the opportunities for a dynamic mega nourishment.

3.2.3 Recreation

A mega nourishment is expected to have a positive effect on recreation, primarily by providing space to develop recreational opportunities that are not present currently. The criteria to determine opportunities for a mega nourishment from a recreation perspective are:

1. A good opportunity is identified for coastal sections with limited recreational opportunities as shown in Figure 14. Here, a mega nourishment is able to offer a new area for recreation with new forms of recreation. This new area for recreation may lead to a better distribution of visitors along the Belgian coast and new coastal amenity services.
2. A moderate opportunity is identified in the coastal stretches with moderate recreational opportunities as shown in Figure 14. Here, a mega nourishment would complement existing recreation by contributing new forms of extensive recreation and associated coastal amenity services.
3. For all coastal towns, a mega nourishment is not an opportunity due to the wide beach and potential risk to bathers due to the strong dynamics involved.
4. For all harbours and deep channels, a mega nourishment is not an opportunity.

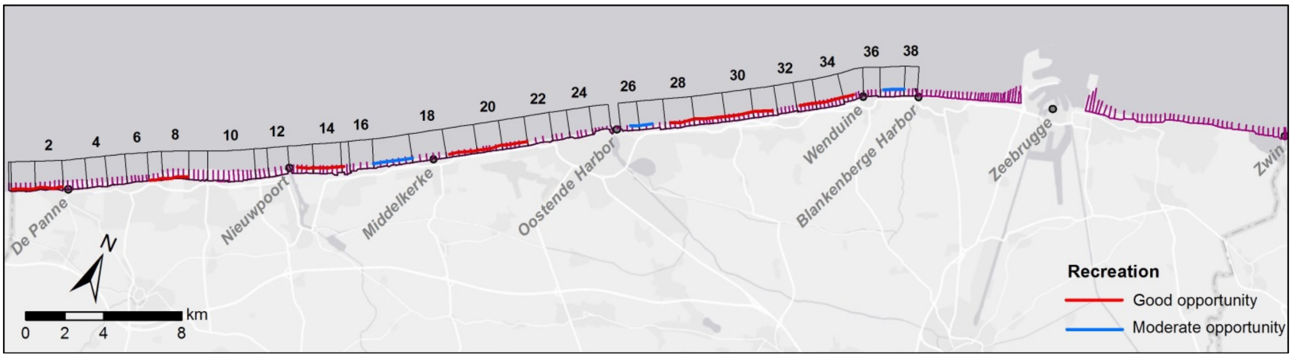

Figure 31 – Opportunity map for a feeder-type mega nourishment along the Belgian coast from the perspective of recreation (i.e. the provision of new recreational opportunities).

Figure 31 shows the opportunity map for a feeder-type mega nourishment along the Belgian coast from a recreation perspective. Good opportunities are identified in all three coastal cells (location in Figure 4 and Table 4). In *coastal cell 1* two good opportunities are identified in sections 2-12 near De Panne and in sections 32-39 between Koksijde-Bad and Oostduinkerke-Bad (Figure 30). Currently, few opportunities for recreation are available for these coastal stretches (Figure 14) and a mega nourishment provides an opportunity to develop new forms of recreation here.

In *coastal cell 2* two good opportunities are identified in addition to a moderate opportunity (Figure 30). The good opportunities are located in sections 63-72 near Sint-Laureins and sections 88-102 between Middelkerke and Mariakerke. Here, few opportunities for recreation exist in the current situation (Figure 14) and a mega nourishment provides an opportunity to develop new forms of recreation. A moderate opportunity is identified in sections 77-82 near Westende-bad en de Krokodille. Few recreational opportunities currently exist here but the alongshore extent of this stretch is limited with plenty of recreational opportunities in the adjacent stretches, and therefore the opportunity for a mega nourishment is moderate.

In coastal cell 3 two good opportunities and two moderate opportunities are identified (Figure 30). The good opportunities are located in sections 127-149 between Bredene-Bad and De Haan, and sections 156-172 between De Haan and Wenduine. Here, few opportunities for recreation exist in the current situation (Figure 14) and a mega nourishment provides an opportunity to develop new forms of recreation. Moderate opportunities are identified in sections 120-124 just west of Oostende harbour, and sections 177-181 between Wenduine and Blankenberge. For both stretches few recreational opportunities currently exist, but sufficient recreational opportunities are available in the adjacent stretches, therefore the opportunity for a mega nourishment along these stretches is moderate.

3.2.4 Other functions and values

The other current functions and values along the Belgian coast are of secondary importance in identifying opportunities for a mega nourishment along the Belgian coast. Most of the identified functions take place farther offshore and will therefore not interact with a mega nourishment.

i. Energy, cables and pipelines are not present in the study area (Figure 18).
ii. Harbours are excluded from the opportunity maps and the navigation routes are generally located more offshore (Figure 20). The presence of a navigational route close to the shoreline between Oostende and Zeebrugge harbour needs to be further investigated and may potentially limit the construction of a mega nourishment along this stretch in coastal cell 3.
iii. Restrictions related to fisheries and aquaculture are generally located more offshore (Figure 21). Zone 1 is located close to shoreline in coastal cell 1 and in the western part of coastal cell 2. The implications of this zone needs to be investigated further and may potentially limit the construction of a mega nourishment along this stretch in these coastal cells.
iv. All sand and gravel exploitation areas are located more than 10 km offshore and will therefore not influence the construction of a mega nourishment along the shoreline (Figure 23).
v. One military zone extends to the shoreline between Nieuwpoort and Westende (Figure 25). The presence of this military zone along this coastal stretch in coastal cell 2 may influence the construction of a mega nourishment and should be taken into account in the design process.
vi. Many wrecks are present in the Belgian coastal zone (Figure 27). Wrecks may provide some limitations for the construction of a mega nourishment because they can be protected as underwater cultural heritage. However, the presence of a nearby wreck can also be considered an opportunity from a tourism perspective in constructing a mega nourishment.
vii. None of the existing measuring stations and radars provide an obstruction to the construction of a mega nourishment along the Belgian coast (Figure 28).

3.2.5 Synthesis of location identification

Based on the current functioning and future requirements of the Belgian coast, an overview map of the possibilities for a mega nourishment can be made. Figure 32 shows the opportunity map for a mega nourishment from the individual perspectives of coastal safety, nature development and recreation. This overview map of the three individual perspectives may be useful when assigning different weighting factors to the perspectives in deciding on the opportunities for a mega nourishment.

Figure 33 presents a synthesis map of opportunities for a feeder-type mega nourishment along the Belgian coast from the integrated perspectives of coastal safety, nature development and recreation. Three coastal stretches are identified in which three functions can be combined. Two of these stretches combine two ‘good’ ratings with one ‘moderate’ rating. The third of these stretches combines one ‘good’ rating with two ‘moderate’ ratings. Substantial parts of the Belgian coast also combine two functions and hence also provide good opportunities for a mega nourishment.

Below, all the identified coastal stretches in Figure 33 are described in more detail including their alongshore length and relation to other coastal stretches.

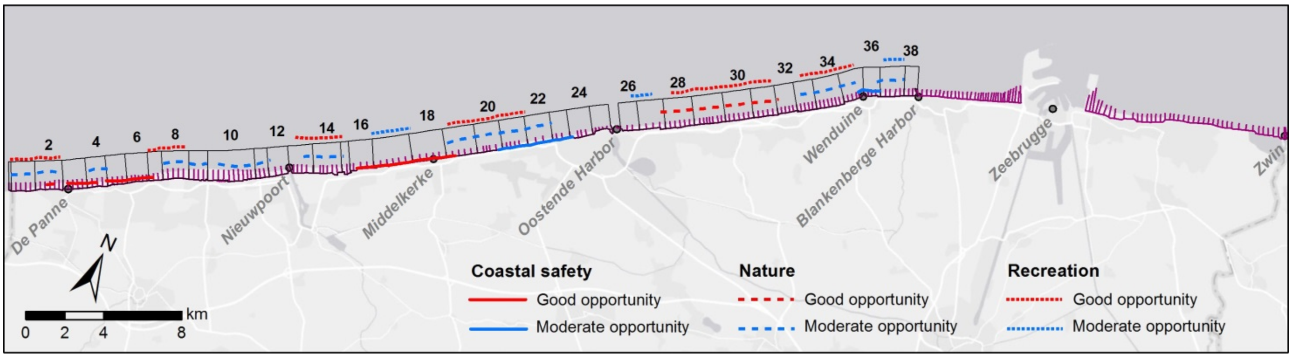

Figure 32 – Opportunity map for a feeder-type mega nourishment along the Belgian coast from the individual perspectives of coastal safety, nature development and recreation.

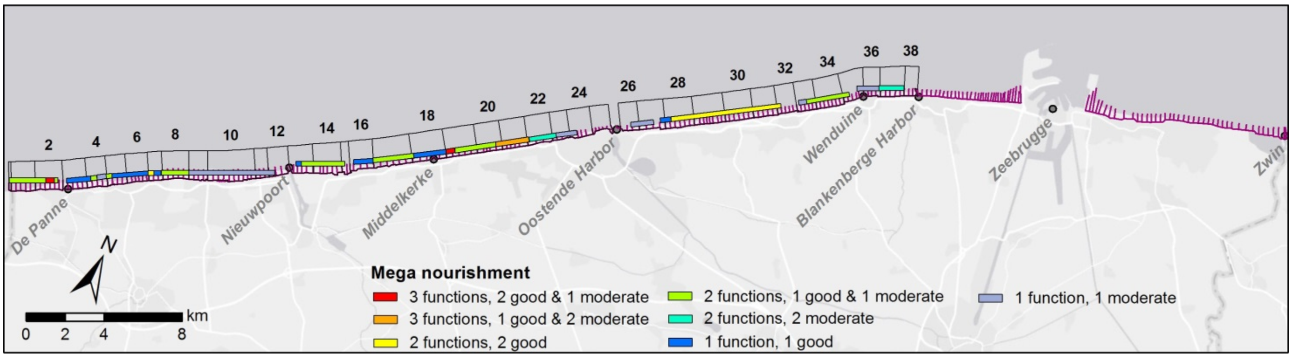

Figure 33 – Synthesis map of opportunities for a feeder-type mega nourishment along the Belgian coast from the integrated perspectives of coastal safety, nature development and recreation.

Table 6. Summary of opportunity rating for a feeder-type mega nourishment along the Belgian coast for **coastal cell 1** from the Belgian-French border to Nieuwpoort (Figure 4)*.

Coastal sections	Coastal Stretch Opportunity Rating	Alongshore length of stretch (m)
2-8	2 functions, 1 good & 1 moderate	1730
9-10	3 functions, 2 good & 1 moderate	500
11	2 functions, 1 good & 1 moderate	210
14-18	1 function, 1 good	1255
19	2 functions, 1 good & 1 moderate	265
20-21	1 function, 1 moderate	520
22	2 functions, 1 good & 1 moderate	260
23-31	1 function, 1 good	1875
32	2 functions, 2 good	240
33-34	1 function, 1 good	480
35-39	2 functions, 1 good & 1 moderate	1345

40-57	1 function, 1 moderate	4470
Total		13150

*Identification of coastal stretches with associated combined opportunities proceeds from west to east (see also Figure 33).

In *coastal cell 1*, a total length of 13.15 km of coastal stretches with some form of opportunity for a mega nourishment are identified (Table 6). Opportunities are greatest towards the west in coastal cell 1 and are generally smaller in the east. West of De Panne, three coastal stretches are identified with either opportunities for two functions or even three functions (Figure 33), representing an alongshore length of 2440 m. Between De Panne and Koksijde-Bad, opportunities are mostly limited to one function and for some coastal sections two functions. Opportunities are greater again between Koksijde-Bad and Oostduinkerke with mostly two functions identified. This coastal stretch of good opportunity represents an alongshore length of 2065 m. East of Oostduinkerke, opportunities for a mega nourishment are smaller because just one function can be satisfied.

Table 7 – Summary of opportunity rating for a feeder-type mega nourishment along the Belgian coast for **coastal cell 2** from Nieuwpoort to Oostend (Figure 4)*.

Coastal sections	Coastal Stretch Opportunity Rating	Alongshore length of stretch (m)
62	1 function, 1 good	225
63-71	2 functions, 1 good & 1 moderate	2310
74-76	1 function, 1 good	1045
77-82	2 functions, 1 good & 1 moderate	2000
83-87	1 function, 1 good	1745
88	3 functions, 2 good & 1 moderate	335
89-96	2 functions, 1 good & 1 moderate	2260
97-102	3 functions, 1 good & 2 moderate	1635
103-106	2 functions, 2 moderate	1515
107-109	1 function, 1 moderate	1095
Total		14165

*Identification of coastal stretches with associated combined opportunities proceeds from west to east (see also Figure 33).

In *coastal cell 2*, a total length of 14.165 km of coastal stretches with some form of opportunity for a mega nourishment is identified (Table 7). Generally, two functions are identified and for some stretches three functions can be combined (Figure 33). The opportunities in coastal cell 2 arise from the presence of weak links in the coastal defence as well as sufficient options to develop nature and recreation (Figure 32). West of Westende-Bad, two functions are identified over a length of 2310 m. Between Westende-Bad and Middelkerke, a stretch with two functions is also identified over a length of 2000 m. East of Middelkerke, opportunities for a mega nourishment are greater. For a coastal stretch spanning from Middelkerke-Oost along Raversijde to Mariakerke the opportunity exists to combine two or three functions across a length of 5745 m. East of Mariakerke, opportunities are limited in coastal cell 2.

In *coastal cell 3*, a total length of 12.132 km of coastal stretches with some form of opportunity for a mega nourishment are identified (Table 8). Along three stretches, two functions can be combined and along four stretches a single function is identified (Figure 33). There are no stretches identified in coastal cell 3 where three functions can be combined, primarily due to the absence of coastal safety opportunities in large parts of cell 3. West of Bredene, no or a single function is identified. East of Bredene up to De Haan, a coastal stretch of 5761 m is identified in which two functions can be combined. Between De Haan and Wenduine, a coastal stretch of 2065 m is identified in which also two functions can be combined. East of Wenduine, opportunities are generally smaller due to the proximity of Blankenberge harbour and Zeebrugge harbour. Yet, one coastal stretch is identified in which two functions can be combined: between Wenduine and Blankenberge harbour a stretch of 1217 m is present.

Table 8 – Summary of opportunity rating for a feeder-type mega nourishment along the Belgian coast for **coastal cell 3** from Oostende to Blankenberge (Figure 4)*.

Coastal sections	Coastal Stretch Opportunity Rating	Alongshore length of stretch (m)
121-123	1 function, 1 moderate	1066
125-126	1 function, 1 good	531
127-151	2 functions, 2 good	5761
157-158	1 function, 1 moderate	400
159-168	2 functions, 1 good & 1 moderate	2065
172-176	1 function, 1 moderate	1092
177-181	2 functions, 2 moderate	1217
Total		12132

*Identification of coastal stretches with associated combined opportunities proceeds from west to east (see also Figure 33).

A long list of preferable locations for a feeder-type mega nourishment

A number of preferable coastal stretches for the construction of a feeder-type mega nourishment can be identified based on the synthesis opportunity map (Figure 33). This first selection (i.e. a long list) of preferable locations for a mega nourishment incorporates coastal stretches where two or more functions can be combined in constructing a mega nourishment (Figure 34). The more functions can be combined in a coastal stretch, the more suitable it is considered for a mega nourishment. Additionally, the coastal stretch needs to be of sufficient length (i.e. > 1000m) to accommodate a mega nourishment. Coastal stretches with two or more functions but with a length shorter than 1000 m are therefore not included in the long list of preferred locations.

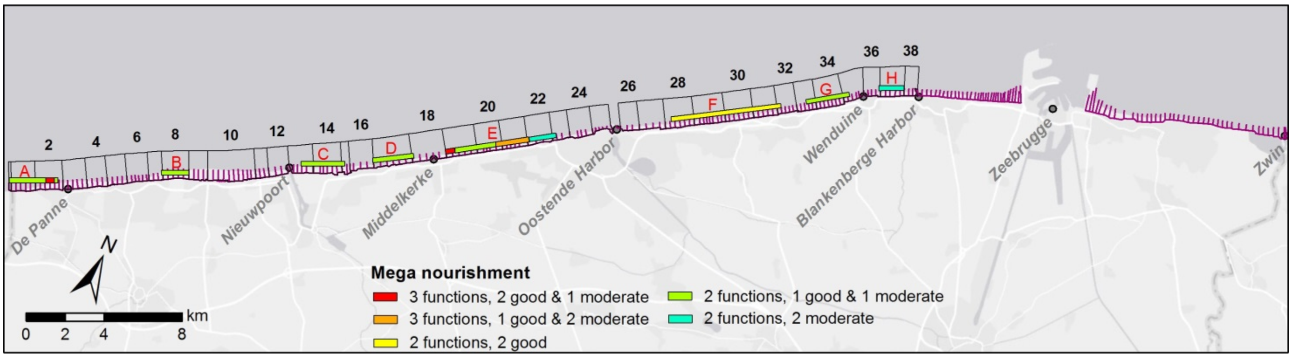

Figure 34 – Map of preferable coastal stretches for a feeder-type mega nourishment along the Belgian coast*.

*This first selection (i.e. a long list) of preferable locations for a mega nourishment (i.e. a long list) incorporates coastal stretches where two or more functions can be combined while attaining a length of at least 1 km.

In coastal cell 1, opportunities for a feeder-type mega nourishment are greatest west of De Panne (Figure 34 – location A) and between Koksijde-Bad and Oostduinkerke (Figure 34 – location B). The first identified stretch extends to the French border and may therefore be less suitable. The second identified stretch is relatively short (i.e. 1345 m) for a mega nourishment to be effective.

In coastal cell 2, three coastal stretches that seem promising for the construction of a feeder-type mega nourishment are identified (Figure 33). Firstly, a stretch west of Westende-Bad covering a length of 2310 m exists (Figure 34 – location C). Secondly, a stretch of 2000 m ranging from Westende-Bad to De Krokodille is promising (Figure 34 – location D). Thirdly, for a coastal stretch from Middelkerke-Oost to Mariakerke opportunities exists to combine two and in some places three functions across a total length of 5745 m (Figure 34 – location E). The first coastal stretch may be located too close to Nieuwpoort harbour. All three coastal stretches are of sufficient length to accommodate a mega nourishment, but particularly the third one offers an extensive area for the construction and development of a mega nourishment.

In coastal cell 3, three coastal stretches that seem promising for the construction of a feeder-type mega nourishment are identified. Firstly, a coastal stretch of 5761 m is identified from Bredene to De Haan (Figure 34 – location F). Secondly, a stretch of 2065 m exists between De Haan and Wenduine exists (location G). Thirdly, a coastal stretch of 1217 m is identified between Wenduine and Blankenberge harbour (location H). For this third option H, the proximity of Blankenberge harbour and Zeebrugge harbour may be problematic. This last option is also relatively short for a mega nourishment to be an effective coastal management tool.

A short list of preferable locations for a feeder-type mega nourishment

A short list of preferable locations for a feeder-type mega nourishment along the Belgian coast is made by ranking the locations identified in the long list (Figure 34). Ranking is done based on the following criteria:

i. Opportunities to combine multiple functions (i.e. coastal safety, nature, recreation). The ability to develop more functions is considered beneficial for coastal management. In rating, coastal safety has priority over nature development, which has priority over recreation.
ii. The length of the coastal stretch. Longer coastal stretches provide more space to fully develop the feeder-type mega nourishment concept.
iii. Proximity to a harbour. Close proximity to a harbour is rated negatively.

The ranking for the three different criteria is shown in Table 9. It can be seen that location E in coastal cell 2 and location F in coastal cell 3 (Figure 34) are clear front runners. They score 22 and 23 points, respectively, out of a maximum of 24 points. These high scores indicate that both locations score well on all three considered criteria. Location A is ranked third, but a serious concern for location A is the proximity of the French-Belgian border, since part of a mega nourishment could end up into French coast. Location B and location D both score 12 points when the points from the three criteria are summed. Location D is, however, deemed more suitable because the opportunities are greater, particularly from a coastal safety perspective. Each of the top-three ranked locations is positioned within a different coastal cell (Figure 4): location A is positioned in coastal cell 1, location E is positioned in coastal cell 2, and location F is positioned in coastal cell 3 (Figure 35).

Table 9 – Scoring of preferable coastal stretches for a feeder-type mega nourishment based on three criteria: i) opportunities to combine coastal functions, ii) length of the stretch, and iii) proximity to a harbour*.

Location	Coastal sections	Opportunities	Length of stretch	Proximity to harbour	Total
A	2-11	6	6	1*	13
B	32-39	3	3	6	12
C	63-71	3	5	3	11
D	77-82	5	2	5	12
E	88-106	8	7	7	22
F	127-151	7	8	8	23
G	159-168	3	3	4	10
H	177-181	1	1	2	4

*The maximum number of points for every criterion is 8 (i.e. the number of locations), leading to a maximum total score of 24 points across three criteria. Harbour is replaced with French-Belgian border for location A.

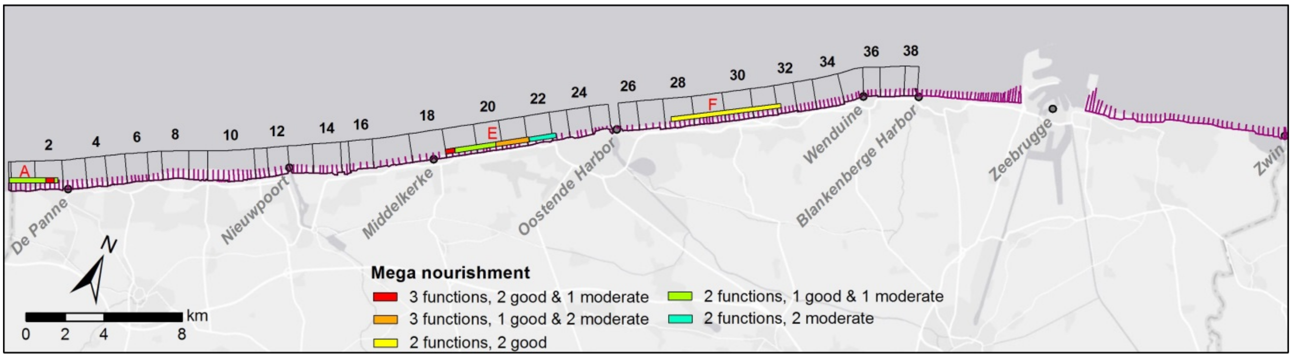

Figure 35 – Three preferable coastal stretches for a feeder-type mega nourishment along the Belgian coast.

*Ranking of the locations was based on the opportunities to combine coastal functions, length of the coastal stretch and proximity to a harbour (see also Table 9).

Below, all preferable locations on the long list (Figure 34 and Table 9) are described in more detail, including an assessment of their strengths and weaknesses. The locations are described in the order they are ranked (Table 10):

1. Location F. This coastal stretch is located in coastal cell 3 (Figure 4), has a length of 5761 m and involves coastal sections 127-151 (Table 8). The coastal stretch extends approximately from Bredene up to De Haan (Figure 35). The long coastal stretch allows to explore smaller as well as larger mega nourishment scenarios. The coastal stretch generally shows mild erosion and the beach near Bredene is sometimes nourished (Houthuys, 2012). Good opportunities for nature and recreation development exist (Figure 32). A potential strength is the absence of large infrastructure such as roads and coastal towns along this stretch. The absence of infrastructure also leads to wider dunes, in places up to 400 m, which could be connected to a mega nourishment. A potential weakness is that coastal safety is not an issue along this coastal stretch. Coastal safety east of Wenduine could be strengthened in the long term by a mega nourishment in location F. A mega nourishment near Bredene may also reduce the flood risk along this coastal stretch.

2. Location E. This coastal stretch is located in coastal cell 2 (Figure 4), has a length of 5745 m and involves coastal sections 88-106 (Table 7). The coastal stretch extends approximately from Middelkerke to Mariakerke (Figure 35). The long coastal stretch allows to explore smaller as well as larger mega nourishment scenarios. Nourishments take place frequently along this coastal stretch to overcome safety issues (Houthuys, 2012). A mild accretion is seen towards the east and a mild erosion towards the east. Almost no dry beach is present in the coastal sections 93-97 near Raversijde-west. Good opportunities for nature and recreation development exist towards the west, while coastal safety issues are also a concern towards the east (i.e. for sections 97-106) (Figure 32). A potential strength is the considerable coastal safety issue in coastal cell 2 (Figure 29), which may be addressed by a mega nourishment in Location E. Essentially, a mega nourishment in Location E may provide coastal cell 2 with sufficient sand to widen the beaches along a substantial part of the cell. In turn, the wider beaches will provide a greater safety barrier to storms and thus raise the overall safety level of coastal cell 2. Figure 29 shows that the greatest opportunities for a mega nourishment from the coastal safety perspective are located in coastal cell 2. A mega nourishment between Middelkerke and Mariakerke may also reduce the flood risk along this coastal stretch. A potential weakness is the proximity of Oostende harbour to the eastern part of locality E. This weakness may be addressed by constructing the mega nourishment towards the western part of the locality (i.e. closer to Middelkerke). However, the construction of a wave breaking infrastructure in Middelkerke should be taken into account. Another potential weakness is the presence of the sea dike and road close to the beach for large parts of locality E. The dike and road disconnect the beach from the dunes and will also provide limitations to the sand dynamics (i.e. sand transport driven by wind, dune dynamics).

3. Location A. This coastal stretch is located in coastal cell 1 (Figure 4), has a length of 2440 m and involves coastal sections 2-11 (Table 9). The coastal stretch extends approximately from the French-Belgian border to De Panne (Figure 35). The medium length of the coastal stretch allows to explore smaller and medium-sized mega nourishment scenarios, but dimensions similar to the ones used for the Dutch Sand Engine (i.e. alongshore length of about 4.5 km on landward side) are not feasible here. Nourishments are rare along this coastal stretch and the western part (i.e. sections 2-6) shows mild accretion while the eastern part (i.e. sections 7-11) shows mild erosion (Houthuys, 2012). A moderate opportunity for nature development exists and a good opportunity for recreation (Figure 32). Coastal safety is generally not an issue along this coastal stretch near De Panne. A potential strength is the western location of locality A. Given that the dominant net alongshore transport of sediment along the Belgian coast is directed eastward, the entire coastal system in coastal cell 1 will eventually benefit from a mega nourishment. And if sediment is able to by-pass Nieuwpoort harbour, also the coastal system in coastal cell 2 will benefit in the long term from a mega nourishment in locality A. At the same time, the western position of locality A near the French-Belgian border is also a weakness: by constructing a mega nourishment in locality A, it is almost a certainty that part of the sand volume will be transported into the French coastal waters. Another potential strength of locality A is the presence of a test zone for coastal protection in the nearshore zone (Figure 23), although the implications of such a test zone for the constructions of a mega nourishments are currently unclear and it will have to be further investigated if this locality is pursuit. The presence of two tidal inlets ('slufters') west of De Panne further complicates the construction of a mega nourishment in locality A. The slufters are already silting up and a mega nourishment would is likely to stimulate this development.

4. Location D. This coastal stretch is located in coastal cell 2 (Figure 4), has a length of 2000 m and involves coastal sections 77-82 (Table 9). The coastal stretch extends approximately from Westende-Bad to Middelkerke (Figure 34). An identical rating score is obtained for locality B (Table 9) but locality D is ranked higher due to the potential to solve some coastal safety issues near Middelkerke. The

medium length of the coastal stretch allows to explore smaller and medium-sized mega nourishment scenarios, but dimensions similar to the ones used for the Dutch Sand Engine (i.e. alongshore length of about 4.5 km on landward side) are not feasible here. This coastal stretch is nourished yearly and the nourishment volumes show an increasing trend (Houthuys, 2012). The annual nourishment are required to maintain a constant beach width. Consequently, a good opportunity for coastal safety is identified and a moderate opportunity for recreation (Figure 32). No nature development opportunities are identified for this coastal stretch. A potential strength of locality D is that it a mega nourishment will have a direct benefit for coastal safety. Also, locality D is located in coastal cell 2, which has the widest coastal safety issues. Construction of a mega nourishment in locality D will therefore contribute to a better coastal safety in coastal cell 2 in the long term. As such, locality D may provide an alternative to locality E to overcome the coastal safety issues in coastal cell 2 if locality E turns out to be unsuitable. Potential weaknesses of locality D include the relative short alongshore length, thus limiting the size of the mega nourishment, and the limited opportunities for nature development.

5. Location B. This coastal stretch is located in coastal cell 1 (Figure 4), has a length of 2065 m and involves coastal sections 32-39 (Table 9). The coastal stretch extends approximately from Koksijde-Bad to Oostduinkerke (Figure 34). The medium length of the coastal stretch allows to explore smaller and medium-sized mega nourishment scenarios, but dimensions similar to the ones used for the Dutch Sand Engine (i.e. alongshore length of about 4.5 km on landward side) are not feasible here. Nourishments take place yearly in the western sections (i.e. 32-34) and resulting in beach accretion (Houthuys, 2012). In the eastern sections, there are no nourishments and beach erosion is observed since 1988. A good opportunity for recreation and a moderate opportunity for nature development are identified). A potential strength of locality B is its potential to address the coastal safety issues near Koksijde-Bad in the longer term (Figure 32). Another potential strength of locality B is the presence of a test zone for coastal protection in the nearshore zone (Figure 23), although the implications of such a test zone for the constructions of a mega nourishments are currently unclear and will have to be further investigated if this locality is pursuit. Potential weaknesses of locality B include the relatively short alongshore length, thus limiting the size of the mega nourishment, and the lack of immediate coastal safety issues.

6. Location C. This coastal stretch is located in coastal cell 2 (Figure 4), has a length of 2310 m and involves coastal sections 63-71 (Table 9). The coastal stretch extends approximately from Nieuwpoort and Westende-Bad (Figure 34). The medium length of the coastal stretch allows to explore smaller and medium-sized mega nourishment scenarios, but dimensions similar to the ones used for the Dutch Sand Engine (i.e. alongshore length of about 4.5 km on landward side) are not feasible here. Nourishments take place yearly in the most western sections (i.e. 63-64) to overcome the beach erosional trend (Houthuys, 2012). In the eastern sections, smaller volumes are nourished and the beach shows an accretion trend. A good opportunity for recreation is identified and a moderate opportunity for nature development (Figure 32). A potential strength is the considerable coastal safety issue in coastal cell 2 (Figure 29), which may be addressed by a mega nourishment in Location C. Essentially, a mega nourishment in Location C may provide the weak links in coastal cell 2, particularly the coastal stretch between Westende-Bad and Middelkerke with sufficient sand to widen the beaches and, as such, improve the broader coastal safety in cell 2. Potential weaknesses of locality C include the relatively short alongshore length, thus limiting the size of the mega nourishment, the proximity of Nieuwpoort harbour, and the lack of addressing any coastal safety issues immediately.
7. Location G. This coastal stretch is located in coastal cell 3 (Figure 4), has a length of 2065 m and involves coastal sections 159-168 (Table 9). The coastal stretch extends approximately from De Haan to Wenduine (Figure 34). The medium length of the coastal stretch allows to explore smaller and

medium-sized mega nourishment scenarios, but dimensions similar to the ones used for the Dutch Sand Engine (i.e. alongshore length of about 4.5 km on landward side) are not feasible here. Nourishments are rare along this coastal stretch but the morphological trend may be influenced by nourishments near De Haan (Houthuys, 2012). The beaches show accretion since early 2000. A good opportunity for recreation is identified and a moderate opportunity for nature development (Figure 32). A potential strength of this coastal stretch is the lack of large infrastructure (i.e. a sea dike and a road) close to the beach, similar to locality F also located within coastal cell 3. Therefore, the relatively wide existing beach and dune area can be connected to a mega nourishment without disturbing any existing infrastructure. Another possible strength of locality G is its potential to address the coastal safety issues near Wenduine in the longer term. Morphological modelling of the evolution of a mega nourishment constructed at locality G provides indication of how long it will take for the sand to reach the weaker links near Wenduine. Larger is the potential mega nourishment sooner will take for the sand to reach this area. Potential weaknesses of locality G include the relatively short alongshore length, thus limiting the size of the mega nourishment, and the lack of addressing any coastal safety issues immediately.

8. Location H. This coastal stretch is located in coastal cell 3 (Figure 4), has a length of 1217 m and involves coastal sections 177-181 (Table 9). The coastal stretch is located between Wenduine and Blankenberge harbour (Figure 34). The short length of the coastal stretch allows to explore just smaller-sized mega nourishment scenarios. No nourishments take place along this coastal stretch (Houthuys, 2012). The beach shows an accretional trend, probably driven by nourishments performed westward. The fewest opportunities of the preferred coastal stretches are identified along this locality: a moderate opportunity for nature development and a moderate opportunity for recreation (Figure 32). A potential strength of locality H is the ability to address a coastal safety issue near Wenduine. However, Wenduine is located westward of locality H while the dominant net alongshore transport of sediment along the Belgian coast is directed eastward. This behaviour makes the effectiveness of locality H in addressing the coastal safety issue near Wenduine uncertain. Morphological modelling of the evolution of a mega nourishment constructed at locality H will provide some indication of the sand from locality H can reach the weaker links near Wenduine. Weaknesses of locality H include the limited number of functions that can be combined, the short alongshore length, thus limiting the size and effectiveness of the mega nourishment, the proximity of Blankenberge harbour, and the planned hard defence measures near Wenduine. A series of groynes is proposed along Wenduine beach to overcome erosion issues and also an extension of Blankenberge harbour is foreseen.

Table 10 – Ranking of preferable coastal stretches for a feeder-type mega nourishment along the Belgian coast based on three criteria: opportunities to combine coastal functions, length of stretch and proximity to harbour*.

Rank	Location	Coastal sections	Opportunities	Length of stretch	Proximity to harbour	Total
1	F	127-151	7	8 [5761]	8	23
2	E	88-106	8	7 [5745]	7	22
3	A	2-11	6	6 [2440]	1*	13
4	D	77-82	5	2 [2000]	5	12
5	B	32-39	3	3 [2065]	6	12
6	C	63-71	3	5 [2310]	3	11
7	G	159-168	3	3 [2065]	4	10
8	H	177-181	1	1 [1217]	2	4

*Harbour is replaced with French-Belgian border for location A.

4 Idealised modelling of shoreline changes post construction of a mega nourishment

Three preferable localities were identified in section 3. For all three localities, the behaviour and evolution of thirteen (13) idealized nourishment designs will be tested with UNIBEST-CL+. The coastal orientation and bathymetry differs between these localities and therefore different developments in time may be expected for the three different localities. Below, the study area, parameter settings and model choices are described for locality F. The simulations for locations E and A follow the same approach and are not explicitly reported here. A synthesis of the findings for the three locations is however included in Section 4.2.

Using UNIBEST-CL+, the aims of this chapter are to:

1. Study the alongshore sediment transport post-construction of idealized feeder-type mega nourishments of varying dimensions and volumes,
2. Quantify the shoreline changes resulting from the construction of these mega nourishments of varying sizes,
3. Quantify the dispersion rate of these mega nourishments of varying sizes.

4.1 Locality F – Bredene to De Haan

4.1.1 Study area

Locality F is located in coastal cell 3 between Oostende harbour and Blankenberge harbour. It has a length of 5761 m and it involves coastal sections 127-151. The coastal stretch extends approximately from Bredene up to De Haan it is mildly erosive and the beach near Bredene is typically nourished annually (Houthuys, 2012). Good opportunities for nature and recreation development exist. A potential strength is the absence of large infrastructure such as roads and coastal towns along this stretch. The absence of infrastructure also leads to wider dunes, in places up to 400 m, which could be connected to a mega nourishment.

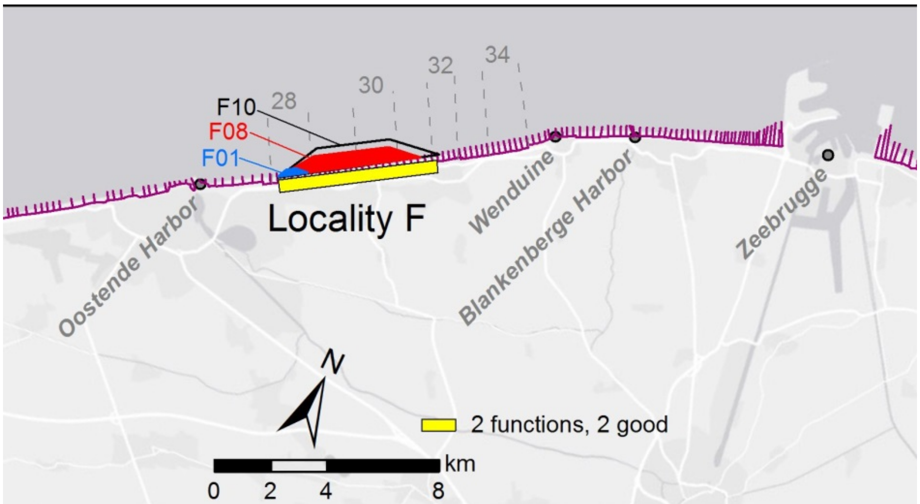

Figure 36 – Locality F between Bredene and De Haan.
The designs and dimensions of three idealized mega nourishments (F01, F08 and F10) are also shown (see Table 13 for all designs).

4.1.2 UNIBEST-CL+ Model setup

This section describes the model setup and validation for the UNIBEST-CL+ model. UNIBEST-CL+ consists of two modules: i) the alongshore transport (LT) module, and ii) the coastline (CL) module. Within the LT module, the relation between the alongshore sediment transport and the coastline angle is established for each locality. This relation is a function of the wave climate, tidal conditions, sediment characteristics and coastal bathymetry, and therefore information on these parameters is provided first. Then, the LT module is used to simulate changes in the shoreline position as defined in the CL module of UNIBEST-CL+. As part of the CL module description, the shoreline position, dimensions, grid sizes, dimensions and characteristics of coastal structures, and the applied timeframe and output settings will be introduced. The calibration of this model using data from Mariakerke is presented in Appendix I.

4.1.2.1 Alongshore Transport module

4.1.2.1.1 Coastline angle and active height

The first step in setting up the LT module is the definition of the coastline angle. The angle (degrees North) of the offshore directed coast normal of the coastline should be specified in nautical coordinates. In this coordinate system, North is 0° and coordinates rotate clockwise (i.e. East is 90°). The coastline orientation and coast normal for Locality F are shown in Figure 37. The coastline has an **angle of 59°** relative to the North. The **coast normal angle is 329°** relative to the North. Although fairly straight, small deviations in coastline angle along this coastal stretch can be observed. The majority of coastline angles is within 59° ± 2°.

Figure 37 – Identification of coastline angle and coast normal for Locality F.

To calculate a nourishment volume in UNIBEST-CL+, the active height, or closure depth, needs to be determined. The closure depth of a coastal profile is defined as the depth for which sediment can be mobilised and hence sediment can be transported in cross-shore and alongshore directions. The closure depth is challenging to establish exactly, depends on the temporal and spatial scales considered, and can be estimated in a number of ways. First, the Hallermeier (1981) equation, which is based on linear wave theory, can be used to estimate the "closure depth," or seaward limit of significant profile change. The Hallermeier equation is defined as:

$$D = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right) \quad (1)$$

Where *D* is the closure depth (m), H_e is the extreme significant wave height occurring 12 hours or 0.137% of the time (m), and T_e is the extreme significant wave height corresponding with H_e (s).

Wave characteristics were extracted at a location in the vicinity of Bredene at a depth of 5 m TAW

Wave data for this was obtained from a SWAN model developed by IMDC for Flanders Hydraulics Research between 2005 and 2009 (IMDC 2009a, IMDC 2009b). The model domain includes the entire Belgian coast between France and the Netherlands and has a spatial resolution of 250 x 250 meters. Nearshore time series (significant wave height, period, and direction) from 1996 to 2005 were readily available for 9 points (5 m water depth) along the coast. The location closest to Bredene was selected and the following parameters were used to calculate the closure depth: H_e of 2.71 m and a T_e of 7.41 s. The calculated closure depth *D* for Locality F is 5.25 m TAW. This value is in agreement with an earlier study looking at the alongshore sediment transport patterns for the Belgian coast (Dan & Vandebroek, 2017).

A second estimate of the closure depth can be made using the CUR (1990) as written in Kamphuis (2010):

$$D = 1.6H_e \quad (2)$$

Using Equation 2, a closure depth *D* of 4.34 m TAW is estimated for Locality F.

A third estimate of the closure depth can be made using a rule of thumb defined in the UNIBEST-CL+ 7.1. User Manual: the closure depth is about two to three times the yearly significant wave height. With a yearly significant wave height of 1.32 m, a maximum closure depth of 3.96 m TAW is estimated for Locality F using this third method.

The depth of closure is challenging to determine with estimates ranging from 3.96 m to 5.25 m TAW using three different methods. All three estimates are based on a 10-year wave climate, while predictions across a 20-year timeframe will be made with potentially larger wave events. It is therefore decided to use the largest estimate of the depth of closure of 5.25 m for this study.

4.1.2.1.2 Wave climate

A wave climate for the Belgian coastal zone was generated using SWAN (Simulating Waves Nearshore) in Verwaest et al. (2008). The wave climate is based on about ten years (1996-2005) of wind and wave observations at different locations distributed along the Belgian coastline and in the Belgian coastal waters. Ten nearshore wave climates are extracted from the SWAN simulation in Dan and Vandebroek (2017). Here, the wave climate extracted near Bredene is used as a representative wave climate (Figure 38).

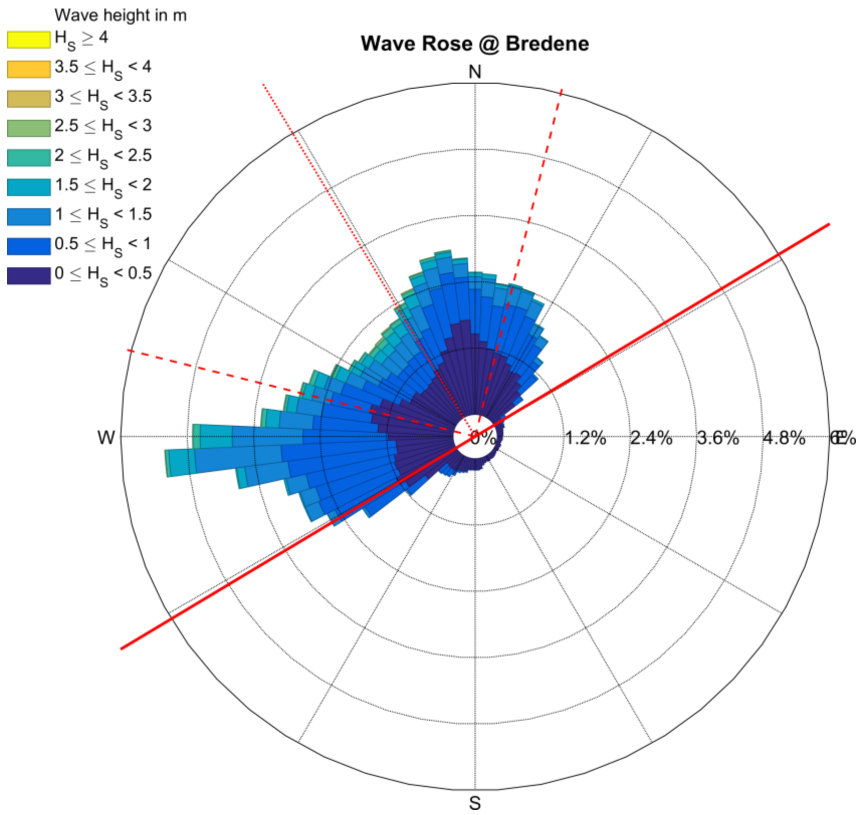

Figure 38 – Wave rose summarising wave height and direction information at Bredene*.

*Wave climate extracted at 5.28 m depth contour (1634 m from coastline) from a 10-year (1996-2005) SWAN wave hindcast for the Belgian coastal zone. The solid red line corresponds to the coastline, the dotted red line is the coast normal, and the dashed red lines correspond to the angle (~45°) with maximum alongshore sediment transport.

Table 11 – Nearshore wave statistics at Bredene. % oblique is calculated as waves with an angle >45° with the coast normal.

	1996-2005
$H_{s,\,mean}$	0.66 m
$T_{p,\,mean}$	4.76 s
θ_{mean}	319°
% Oblique	48.4
H_s > 0.5 m	46.0%
H_s > 1.0 m	20.4%
H_s > 2.0 m	1.7%

The mean wave climate at Bredene over a 10-years period is characterized by a waves coming from western and northern directions (Figure 38). The mean wave direction is 319° N (Table 11), which is in close agreement with the coast normal orientation of 329° (Figure 37). The percentage of oblique waves (i.e. waves with an angle greater than 45° with the coast normal) is 48.4%. Most of the oblique waves (70%) are coming from the west (Figure 38). The average significant wave height is 0.66 m, although a substantial inter-annual variation exists with a mean wave height up to 0.75 m in some stormier years and a lower mean wave height of 0.51 m in a calmer year. At this nearshore location, about 50% of the waves is smaller than 0.5 m and the other half is larger than 0.5 m. 20% of the waves is larger than 1 m and 1.7% of the waves is larger than 2 m. The mean peak period of the waves near Bredene is 4.76 s (Table 11).

4.1.2.1.3 Sediment characteristics

Regular sediment composition surveys are performed for the Belgian coast. The Belgian coast is a sandy coast with variations in grain size in both alongshore and cross-shore directions (Figure 39). Grain size is about 160 µm near De Panne and typically increases towards the east reaching sizes up to µm micron near het Zwin. A median grain size (**D_{50}**) of about **200-250 µm** is observed near Bredene. Also, a **D_{90}** of about **300 µm** is observed for this coastal stretch.

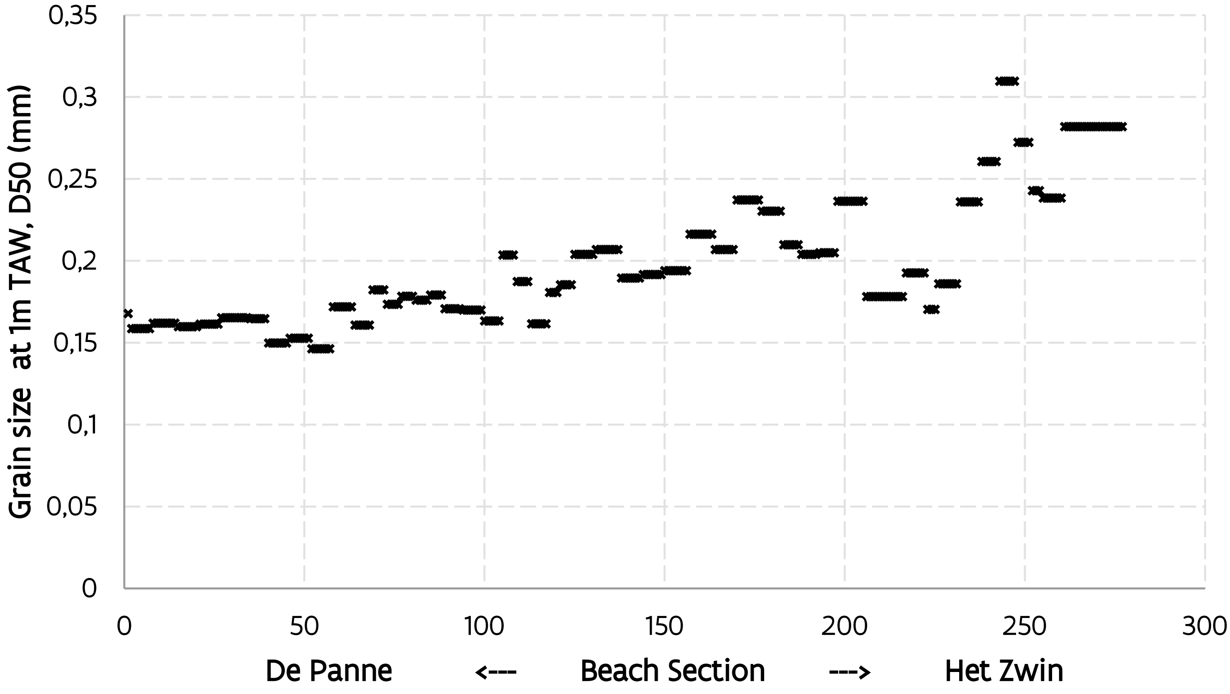

Figure 39 – Grain size trend along the Belgian coast from VITO survey (personal communication Koen Trouw).

4.1.2.1.4 Coastal bathymetry and profile extraction

Figure 40 shows the representative coastal profile for locality F. The profile is extracted from the bathymetric map shown in Figure 41. An almost constant elevation is observed between a cross-shore distance of 0 m and 250 m. Between 250 m and 750 m, the profiles show a relatively steep elevation decline. Beyond 750 m, a platform with an elevation of -5 m LAT extents to a cross-shore distance of about 1500. All the nourishment designs remain within a 1500 m cross-shore location.

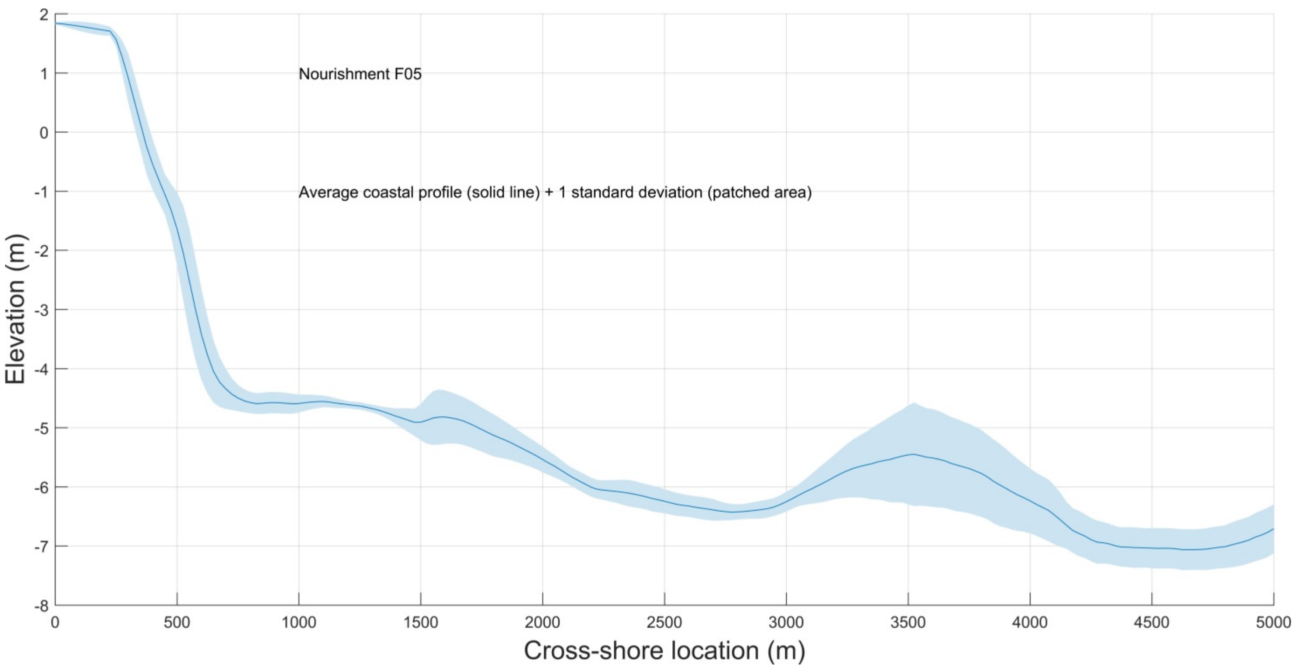

Figure 40 – Average coastal cross-shore profiles of the ten nourishment designs in locality F. LAT = Lowest Astronomical Tide.

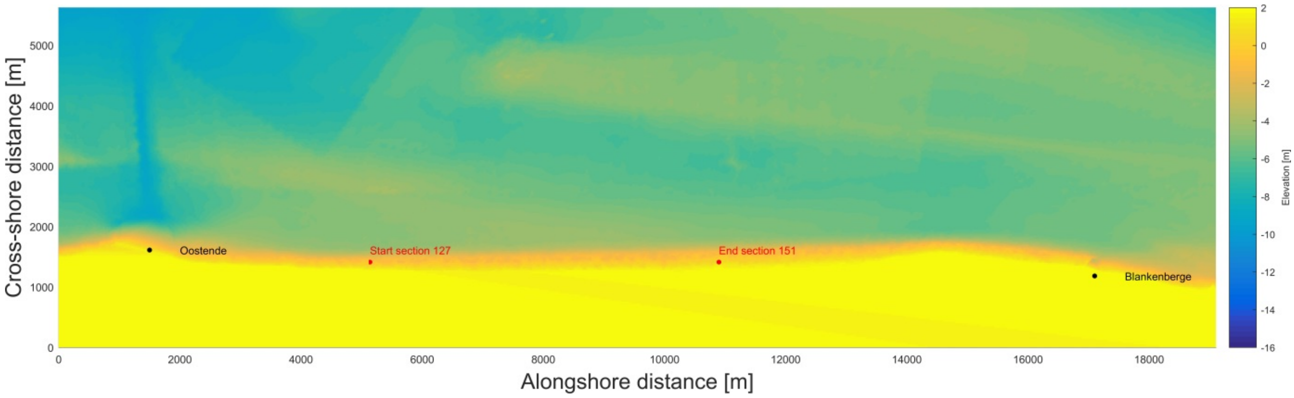

Figure 41. Bathymetry of Locality F region of interest from Oostende in the west to Blankenberge in the east*.

*The start of coastal section 127 and the end of coastal section 151 have been indicated and this coastal stretch covers a distance of 5761 m.

The coastal profiles are used to calculate the volume of sand required for each nourishment scenario in locality F (Table 13). The mega nourishments have an elevation of +1.8 m LAT (+ 2.3 m TAW) to enable a smooth transition at the dry beach with the existing profile. A higher elevation would create a steep slope favouring the cross-shore transport, while the main working principle for a feeder type nourishment is dissipation due to alongshore transport. To implement the nourishments, the existing profile is shifted seaward as a function of the nourishment seaward extent (i.e. 150 m, 300 m, 600 m and 900 m) and attached to the existing profile farther offshore.

The nourishment volumes required range between 0.75 million m^3 of sand for scenario F01 and 25.4 million m^3 of sand for scenario F12 (Table 13). For reference, the required sand volume in scenarios F12 and F13 is similar to the volume used for the Sand Engine in the Netherlands. All other scenarios have a smaller initial volume.

4.1.2.1.5 S-ϕ relation for Locality F

Reference run

The reference run of the alongshore transport module shows a net sediment transport rate of 213.000 m^3/year (Figure 42). The net transport is directed towards the northeast. The equilibrium coast angle is 24.3°, resulting in an equilibrium orientation of 305°. *In UNIBEST-CL+ the coast is allowed to rotate within the so-called active layer, which is usually defined as the cross shore extent within which a certain proportion (90–98%) of the longshore transport takes place. When the transport is constant the equilibrium orientation was reached.*

The angle of the coastal orientation upon which the cross-ray is defined. In UNIBEST the coastal orientation is expressed as the direction of the seaward directed coast-normal, measured clockwise relative to the North. A maximum net sand transport of about 300.000 m^3/year is generated at coastline orientations of 350° (i.e. southwest directed transport) and 260 ° (i.e. northeast directed transport).

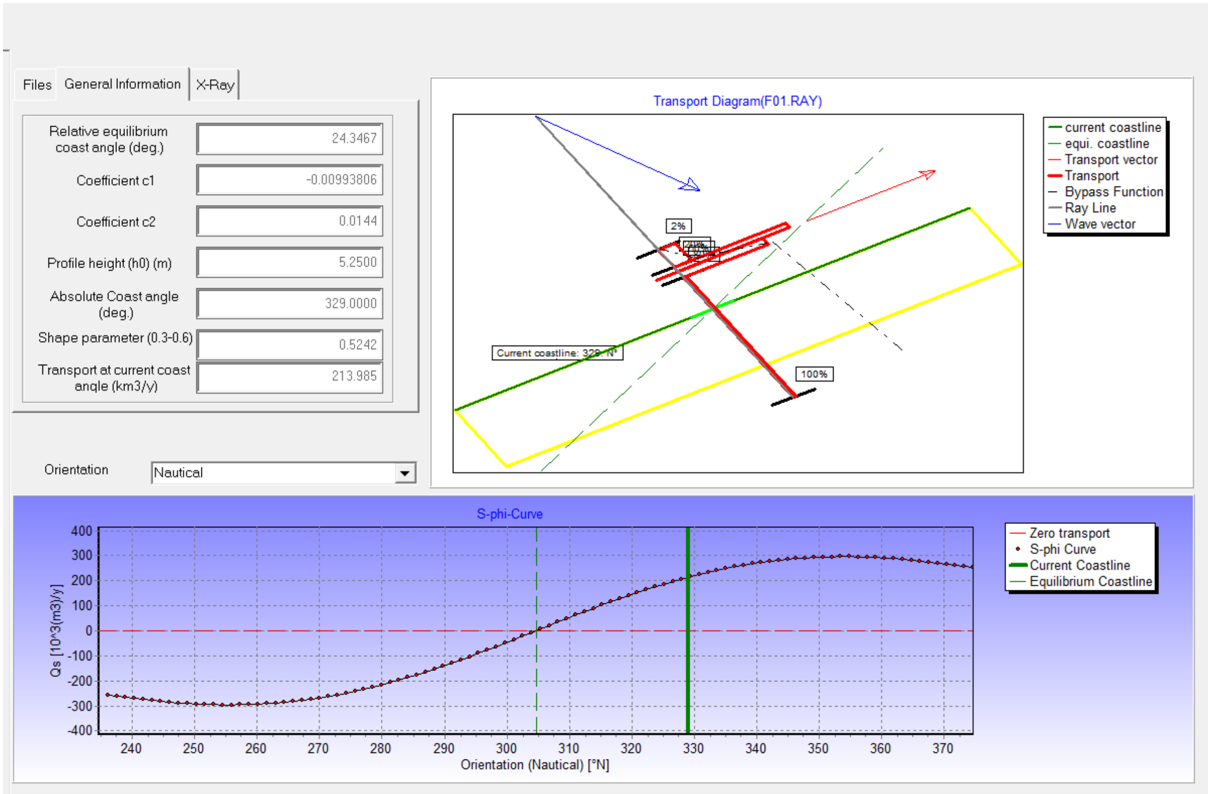

Figure 42 – Transport ray of UNIBEST-CL+ summarised into S-ϕ curve for reference run of Locality F.

In the study *Sediment Budget for the Belgian coast* by Vandebroek et al. (2016), a sediment budget is developed for the Belgian coast. This study provides the best opportunity to validate the UNIBEST-CL+ simulated alongshore sediment transport rates because it employs several methods to estimate the alongshore sediment transport rate. The findings from two observational studies (Verwaest et al., 2010; Trouw et al., 2015), three empirical formulations (CERC; Kamphuis, 1991, Svasek, 2012), and two numerical studies (Wang et al., 2012, 2015) are reported.

Figure 43 presents a synthesis of the alongshore sediment transport rates along the Belgian coast developed in Vandebroek et al. (2016). The net sediment transport rates are typically 150.000 m^3/year in north-eastern direction. The transport rates show an increase towards the east with a typical value of 250.000 m^3/year at locality F. The alongshore sediment transport rates are challenging to estimate and may fluctuate from year to year, which is reflected by the uncertainty bounds. For locality F, a lower bound estimate of the alongshore sediment transport rate is 200.000 m^3/year, and an upper bound estimate is 300.000 m^3/year. As can be seen in Figure 43, the alongshore sediment transport rate of 213.000 m^3/year observed in the reference run with UNIBEST-CL+ for locality F falls within the rates reported in Vandebroek et al. (2016).

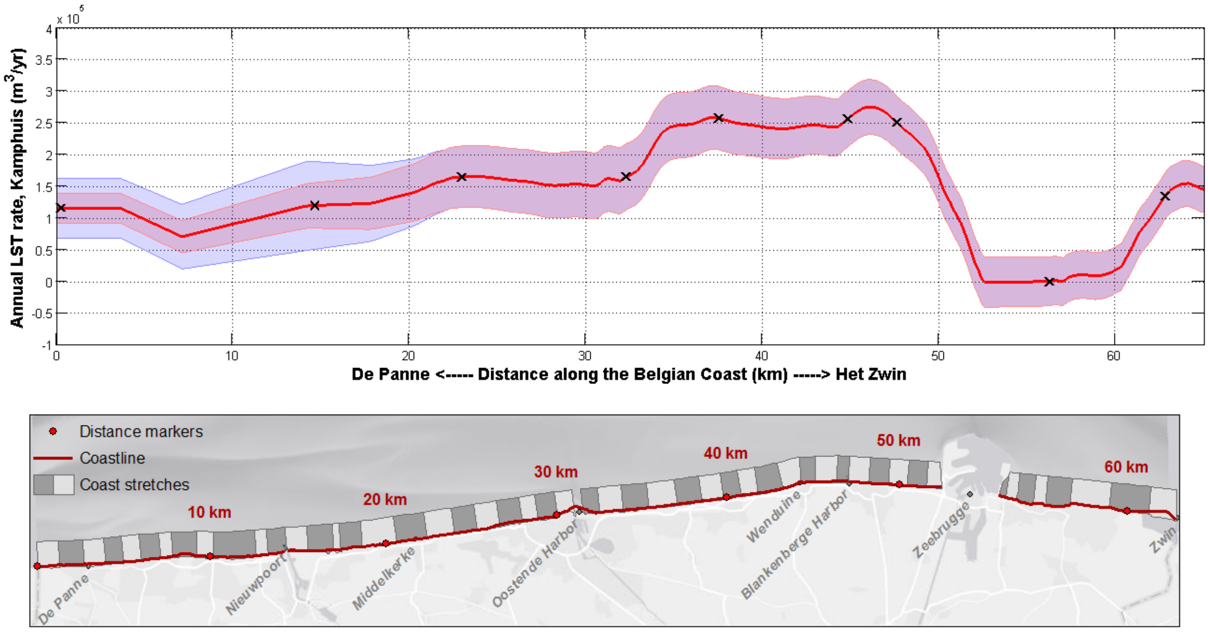

Figure 43 – Annual net alongshore transport rate along the Belgian coast as reported in (Vandebroek *et al.*, 2016)*****.

*The red line represents the estimated average transport rate and the shaded areas correspond to uncertainty estimates. Note the larger uncertainty towards the east where fewer observations were available.

Sensitivity analysis

The reference run F01 of the alongshore transport module showed a net sediment transport rate of 213.000 m3/year (Figure 42). In run F01A, a reduced wave climate with 53 instead of 91 wave conditions was employed. All waves with an orientation >90° with the coast normal were removed. In this way, 11% of the wave events were removed, which was compensated with the UNIBEST-CL+ normalization base to maintain the simulation duration of 365 days, by increasing the weight of the remaining wave events. The reduced wave climate in run F01A results in an increase in alongshore sediment transport to 238.000 m^3/year with a similar equilibrium coastline orientation (Table 12).

Table 12 – Observed and simulated net annual alongshore sediment transport rates for Locality F along the Belgian coast.

RUN ID	LST (m^3/year)	Equilibrium angle (°)
Vandebroek et al (2016)	250.000 *[200K – 300K]*	NA
F01 – Reference run	213.000	305
F01A – Reduced wave climate, removed >90°	238.000	305
F01B – Shortened cross-shore profile	244.000	299
F01C – CERC formulation	462.000	300
F01D – van Rijn (2004) formulation	157.000	302

In run F01B, the cross-shore profile is shortened to align the wave boundary conditions with the wave extraction location. The wave boundary condition is located about 1400 m closer to the coastline in F01B compared with F01. The shortened cross-shore profile in run F01B results in an increase in alongshore sediment transport to 244.000 m^3/year with a 299° equilibrium coastline orientation (Table 12).

In run F01C, the CERC sediment transport formulation is used instead of the Bijker (1967, 1971) formulation. CERC formula calculates the sediment transport mainly based on the wave height and agle of approach to the coast, while Bijker formula is more complex accounting for the bedload transport where bed shear stress, the local grain size, bottom roughness and water and sediment densities play a significant role.

All other settings in F01C are identical to F01B, and the outcome should therefore be compared to F01B rather than F01. For the CERC formulation, default parameters were used and included the parameter A (0.025), the gamma breaker coefficient (0.6), and the seawater density (1025 kg/m^3). The CERC formulation results in a significant increase in alongshore sediment transport to 462.000 m^3/year with a 300° equilibrium coastline orientation (Table 12).

In run F01D, the van Rijn (2004) sediment transport formulation is used instead of the CERC formulation. For the van Rijn (2004) formulation, default parameters were used and included a D_{10} (120 µm), a D_{90} (300 µm), and a porosity (0.4). The van Rijn (2004) formulation results in a reduction in alongshore sediment transport to 157.000 m^3/year with a 302° equilibrium coastline orientation (Table 12). The alongshore sediment transport rate simulated in F01D is smaller than the lower bound estimate of 200.000 m^3/year reported in Vandebroek et al. (2016).

4.1.2.2 Coastline module

4.1.2.2.1 Definition of coastline position and dimensions

The coastal stretch of 5761 m allows us to explore smaller as well as larger mega nourishment scenarios (Figure 44). Table 13 shows thirteen nourishment scenarios for locality F with a landward alongshore length ranging between 1500 m (F01) and 8900 (F12). Ten out of the thirteen scenarios fit within the available alongshore length at locality F. Scenarios F11, F12 and F13 do not fit within the available space.

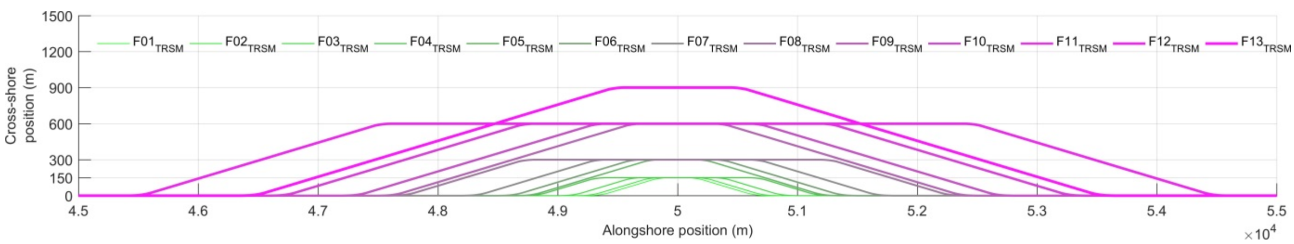

Figure 44 – Trapezoidal nourishment designs with smoothed transitions*.

*Details on the design parameters of all 13 scenarios can be seen in Table 13.

To better observe the difference for the evolution of the different scenarios the shape of the mega- nourishments was approximated as trapezoidal. However, it was observed that sharp angles at the smaller side of the trapeze can generate errors when modelled with UNIBEST, so a smooth trapezoidal shape for the nourishment designs are used in this study to systematically investigate the effect of varying cross-shore extent and alongshore length of a mega nourishment (Figure 44). The advantage of this design is the smaller alongshore length compared to the Gaussian designs, allowing to fit more of the scenarios within the study area. Also, the model instabilities seen for trapezoidal designs with sharp edges are overcome by the smoothing.

The nourishments will be constructed from the western boundary (i.e. coastal section 127) to the east (Figure 36). All nourishment designs have coastal section 127 as their most western boundary (Table 13).

Table 13 – Overview of trapezoidal nourishment designs with smoothed transitions for locality F*.

Nourishment ID	Seaward extent (m)	Alongshore length seaward (landward) (m)	Width-to-Length ratio (-)	Coastal sections involved	Nourishment volume in UNIBEST-CL+ (10^6 m^3)
F01	150	150 (1500)	1:1	127-132	0.75
F02	150	300 (1650)	1:2	127-133	0.88
F03	150	600 (1950)	1:4	127-135	1.16
F04	150	1200 (2550)	1:8	127-138	1.72
F05	300	300 (2600)	1:1	127-138	2.69
F06	300	600 (2900)	1:2	127-140	3.24
F07	300	1200 (3500)	1:4	127-142	4.35
F08	300	2400 (4700)	1:8	127-147	6.56
F09	600	600 (4900)	1:1	127-148	10.1
F10	600	1200 (5500)	1:2	127-150	12.3
F11	600	2400 (6700)	1:4	127-156*	16.7
F12	600	4800 (8900)	1:8	127-167*	25.4
F13	900	900 (7250)	1:1	127-159*	20.8

*It is larger than study area for locality F (see also Figure 36). The seaward extension is the distance between the present day shoreline position and maximum offshore extension of the nourishment.

Each nourishment is implemented in a 100-km wide model in which the middle sector of 25 km contains the region of interest (Table 14). Within the region of interest, the finest grid size of 25 m is specified. Four sectors with a total width of 37.5 km are specified on both adjacent sides of the region of interest to locate the model boundaries far away from the region of interest and to minimise boundary effects. Each of the four sectors consists of a different grid size, with a coarser grid towards the boundaries to minimise computational time.

Table 14 – Definition of model domain and grid size within UNIBEST-CL+.

	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	Sector 7	Sector 8	Sector 9
Length (km)	12	14	9	2.5	25	2.5	9	14	12
Grid size (m)	800	400	200	100	25	100	200	400	800

4.1.2.2.2 Coastal structures

No coastal structures were defined. This includes groynes, revetments and offshore breakwaters. Inclusion of such structures would have extend the duration of the numerical modelling exercise considerably, without a significant increase in the knowledge of the system. A limited number of structures can be included in the model, but when the number it is larger, such as the number of groynes contained by one of the coastal cells from the study, the instabilities strongly affect the accuracy of the results.

No sources and sinks were specified since there are none in the study zone.

4.1.2.2.3 Boundary conditions

The position of the coastline was assumed to be constant (Y constant) on the left and right boundaries of the model.

4.1.2.2.4 Timeframe and output settings

Run input:

Start time = 0 year, time steps/year = 52, number of cycles = 1

Run output:

First time step = 0, time step period = 4 (the moment when the results of the modelling are recorded), maximum number of steps = 1560

Period definition:

From year 0 to year 30.

Table 15 – UNIBEST-CL+ model settings of reference run for Locality F.

Parameter	Value
Cross-shore profile	
X-point dynamic boundary	-2625 m
X-point truncation transport	-2625 m
Reference level	-2.3 m
Sediment transport	
Transport formula	Bijker (1967,1971)
D_{50}	250 µm
D_{90}	300 µm
Waves & tides	
Breaking, bottom friction & roughness	Default parameters
Wave climate	91 conditions; H_{sig} = 0.66 m, T_p = 4.76 s
Tides	Not specified directly, but included as water level changes
S-φ curve	
Net alongshore transport	244.000 m^3/year; equilibrium angle 30.1°
Grid & boundary conditions	
Grid	100 km domain; 1241 cells; 25 m cells to 800 m cells
Boundaries	Coastline (Y) constant
Output	
Duration	30 years
Output frequency	4 weekly

The model settings for the reference run for Locality F are summarised in Table 15. A 30-year period is specified to match the planning horizon of the Masterplan Kustveiligheid (2011).

4.1.3 Results of UNIBEST-CL+ model simulations for locality F

4.1.3.1 Sediment transport behaviour of nourishments post-construction

The sediment transport behaviour of the idealized nourishment designs (Figure 44) results in morphological reshaping. The morphological reshaping takes place in cross-shore and alongshore directions and changes over time. To describe and quantify the coastline changes resulting from this morphological reshaping, time stacks of the coastline position (Figure 45), snapshots of the coastline position (Figure 46), time stacks of coastline retreat and advance rates (Figure 47), the alongshore dispersion of sand (Figure 48), and the volume decay of sand and half lifetime of the nourishment are presented (Figure 55).

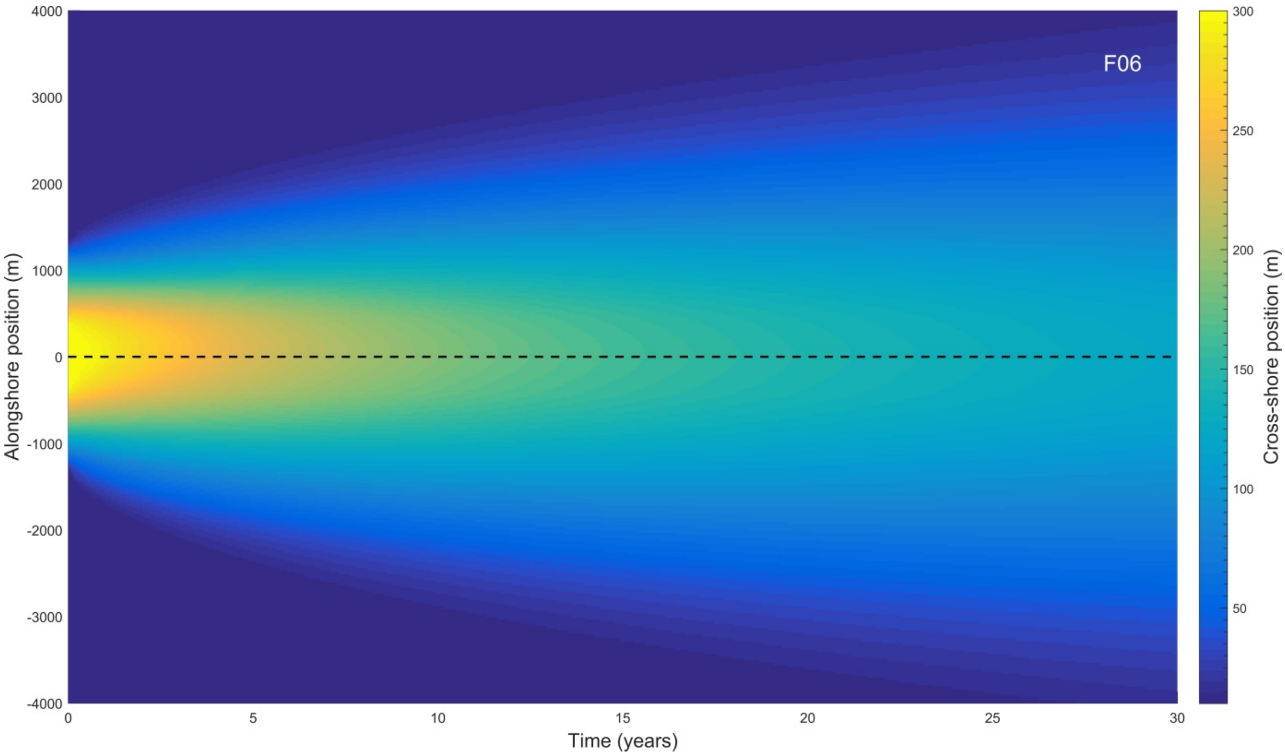

Figure 45 – Time stack coastline position over time as simulated with UNIBEST-CL+ for scenario F06.

The morphological reshaping for nourishment design F06 is described in detail first. Then, a comparison between scenarios F01, F06 and F10 is shown in the next section. F01 represents the smallest scenario with an initial volume of 0.75 million m^3 of sand and a seaward extent of 150 m. F06 will be referred to as the 'medium' scenario with an initial volume of 3.24 million m^3 of sand and a seaward extent of 300 m. F10 represents the largest scenario with an initial volume of 12.3 million m^3 of sand and a seaward extent of 600 m. F10 was selected as the largest volume scenario because it represents the largest design that fits into the study area (Table 13).

Figure 45 shows the coastline position of nourishment design F06 for a 30-year period following construction. The distance between the mega nourishment coastline and the present day coastline is decreasing with decreasing yearly rates. The alongshore variation is also expressed in this figure. It can be seen that the original trapezoidal design is quickly reshaped into a smoother bell shape, which is also clear from Figure 46 in which selected snapshots of the coastline position are presented. Erosion is initiated at the edges of the nourishment and progresses inward, resulting in a decrease in cross-shore distance from the original coastline. Similarly, sand is being redistributed to the adjacent beaches, resulting in beach advance and an increase in cross-shore distance. The coastal stretch receiving sand from the nourishment increases over time and results in beach advance farther from the nourishment as time progresses.

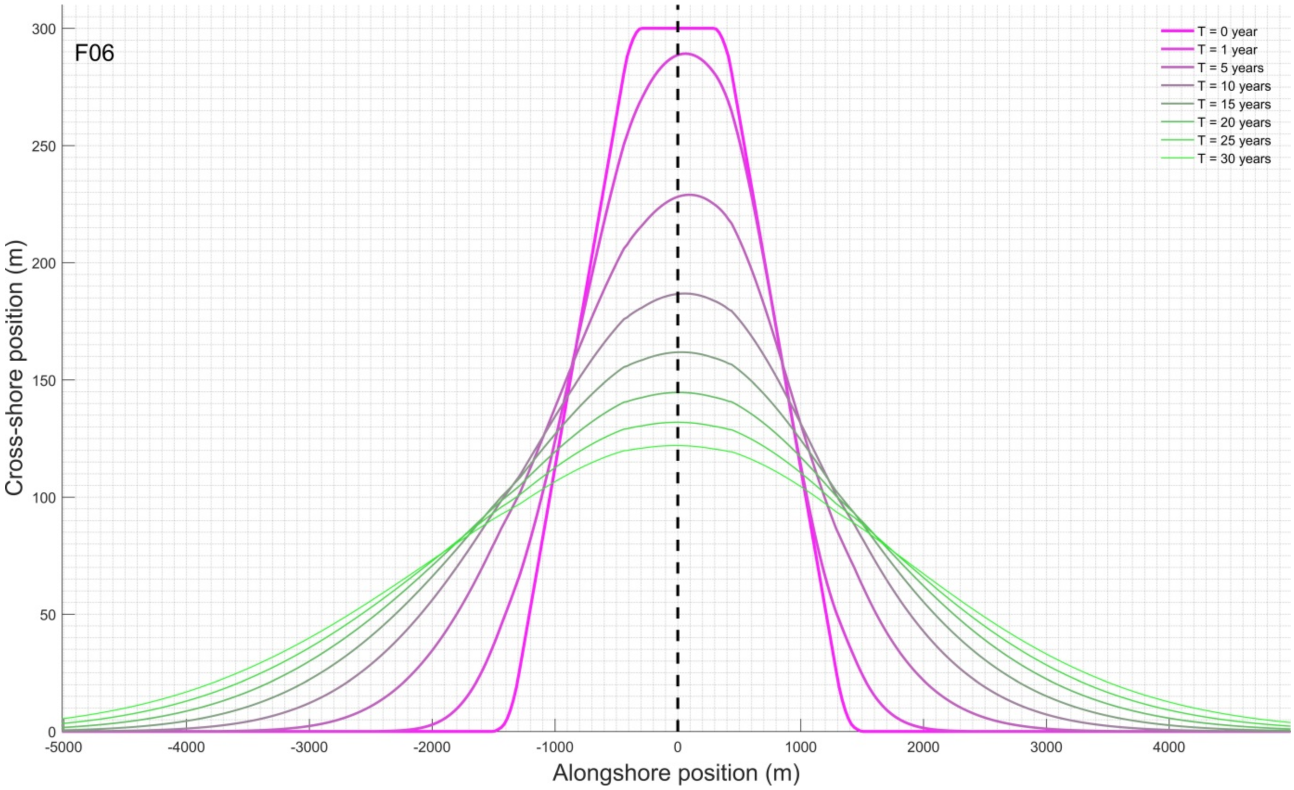

Figure 46 – Snapshots of coastline development (0 m TAW) in time as simulated with UNIBEST-CL+ for scenario F06.

Morphological reshaping of the constructed nourishment F06 results in coastline retreat and advance (Figure 47). Retreat occurs predominantly along the coastline where the nourishment was constructed. Retreat rates are initially high (15 m/yr) and decrease during the 30-year period. Retreat rates are generally greatest in the nourishment centre (i.e. alongshore position is 0 m) and decrease towards the edges of the nourishment. The eroded sand is redistributed to the adjacent beaches leading here to shoreline advance. The advance rates are highest initially (11 m/yr) and decrease during the 30-year period. Shoreline advance is greatest directly adjacent to the original nourishment and decreases with distance from the nourishment. However, the peak of the advance rates moves on the lateral sides of the nourishment as time progresses (Figure 47).

As a result of the re-distribution of sand from the nourishment to adjacent beaches, the alongshore length of the reshaped nourishment increases over time (Figure 48). From the constructed alongshore length of 2700 m, the alongshore length increases to 8700 m after 30 years. The increase in alongshore length is greatest during the first years, reaching the available coastal length of 5761 m for locality F after 10 years. Given that Oostende harbour is located about 4.5 km from the nourishment centre, the nourished sand for scenario F06 is not expected to affect this harbour in the first decade after construction, and only in a limited way in the decades after.

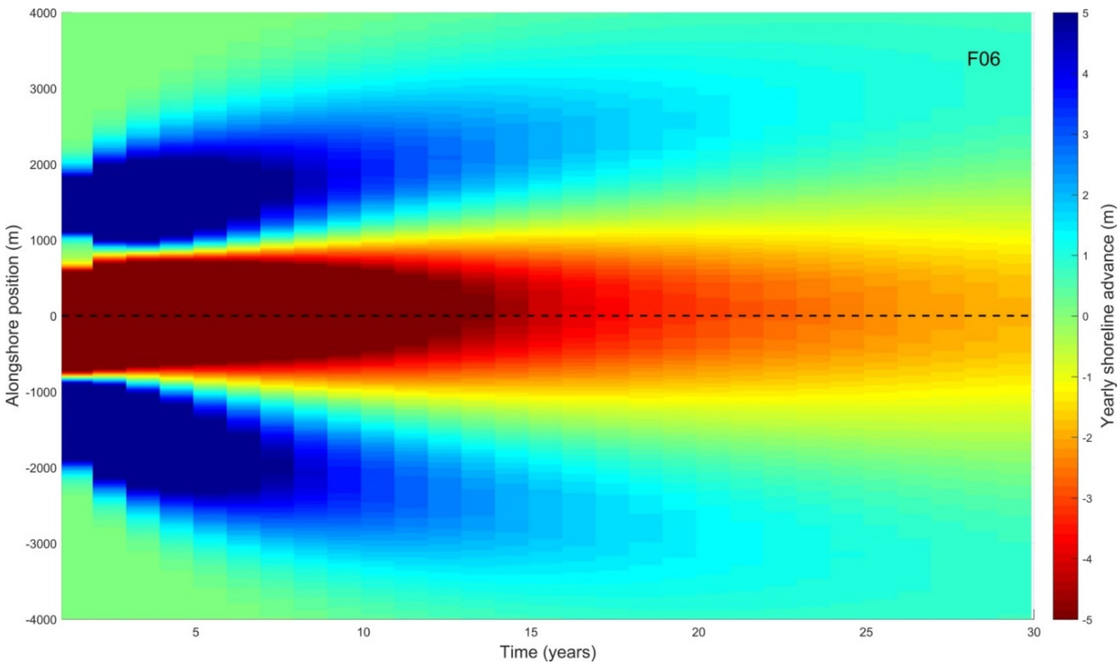

Figure 47 – Time stack of coastline advance and retreat over time as simulated with UNIBEST-CL+ for scenario F06*.

*The central part show intense retreat while the lateral sides of the nourishment show advance due to the alongshore dispersion of the sediments.

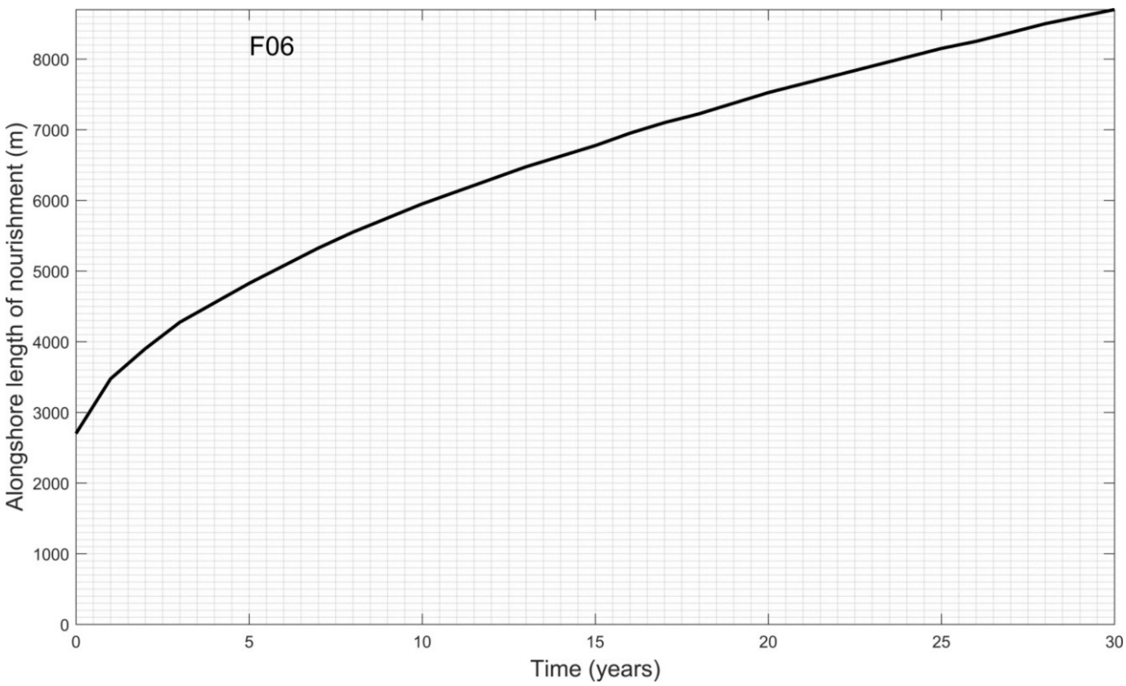

Figure 48 – Alongshore dispersion of sand over time as simulated with UNIBEST-CL+ for scenario F06*.

*The alongshore length of the nourishment is defined as the length over which a cross-shore distance of more than 10 m with the original coastline exists. This definition explains the discrepancy between the alongshore length reported here and in Table 13.

4.1.3.2 Coastal retreat of nourishments

Figure 49 shows the evolution of the maximum seaward extent of the small (F01), medium (F06) and large (F10) nourishment designs. As constructed, the initial seaward extents are 150 m, 300 m and 600 m for the small, medium and large designs respectively. The small design shows a retreat from 150 m to 40 m, a total of 110 m, during a 30-year period. The retreat is largest in the first years post construction and progressively declines. The medium design shows a retreat from 300 m to 120 m, a total of 180 m, during a 30-year period. The large design shows a retreat from 600 m to 375 m, a total of 225 m, during a 30-year period.

The above numbers indicate that the initial design has an effect on the total retreat and, by extension, on the retreat rates. The large design shows a total retreat twice as large as seen for the small design during the same 30-year period (Figure 49). The length-to-width ratios of the designs are also important in determining the retreat (Table 13). As erosion proceeds from the edges of the nourishments inward (Figure 47), the longer designs show an initially slower retreat of the maximum seaward extent. For example, the large design with a length-to-width ratio of 2 is able to maintain the maximum seaward extent of about 600 m for a couple of years post construction, while the small design with a length-to-width ratio of 1 shows retreat immediately post construction. For designs with length-to-width ratio of 3 and 4 (Table 13), the onset of the retreat is further delayed.

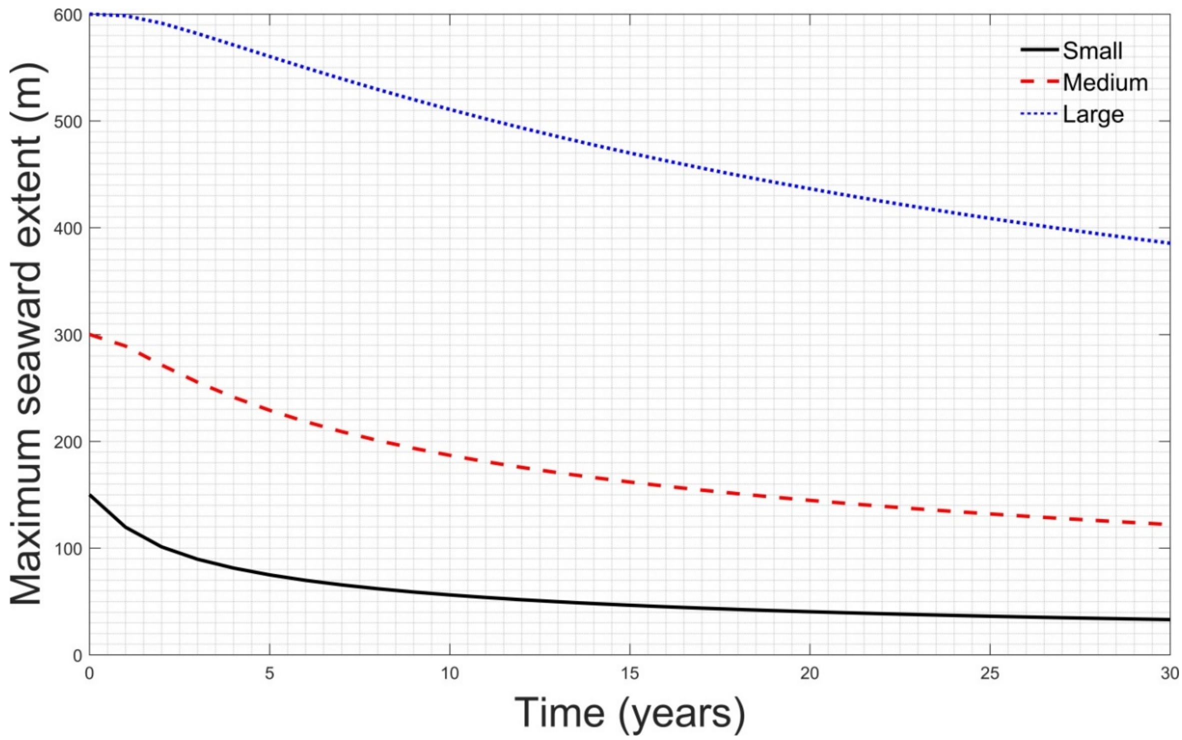

Figure 49 – Evolution of the maximum seaward extent for a small (F01), medium (F06) and large (F10) nourishment as simulated with UNIBEST-CL+ for locality F.

The average retreat rates are initially high and decrease over time for all designs (Figure 50). The smaller designs show the highest initial average retreat rates of about 20 m/yr. Medium designs typically show initial average retreat rates up to 15 m/yr. The large designs show the lowest initial average retreat rates of about 10 m/yr. As time progresses, the larger designs maintain higher retreat rates than the smaller designs. For example, the small design has a retreat rate of 0.9 m/yr after 15 years, while the large design still has a retreat rate of about 5.0 m/yr. Notably, the maximum retreat rates are 33 m/yr, independent of the nourishment design. These retreat rates are observed near the edges of the nourishment during the first year post construction.

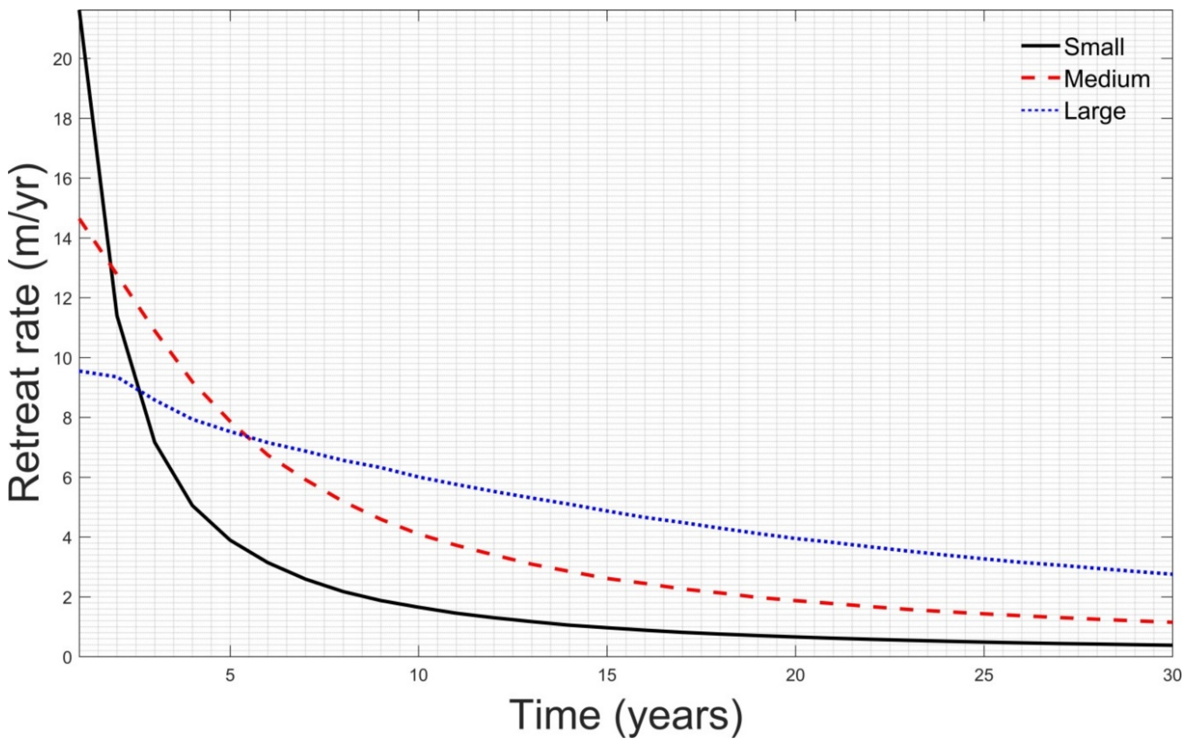

Figure 50 – Average coastline retreat rates over time for a small (F01), medium (F06) and large (F10) nourishment as simulated with UNIBEST-CL+ for locality F*.

The average retreat rate is calculated across the shoreline showing more than 0.1 m retreat.

The average advance rates are initially high and decrease over time for all designs (Figure 51). The initial average advance rates are about 11 m/yr for all designs. As time progresses, the larger designs develop higher advance rates than the smaller designs. For example, the small design has an advance rate of 0.4 m/yr after 15 years, while the large design then has an advance rate of about 2.1 m/yr. Notably, the average advance rates are lower than the average retreat rates. Additionally, the maximum advance rates can up to be 47 m/yr, increasing with nourishment size. The highest advance rates are observed on the beaches directly adjacent to the nourishment during the first year post construction.

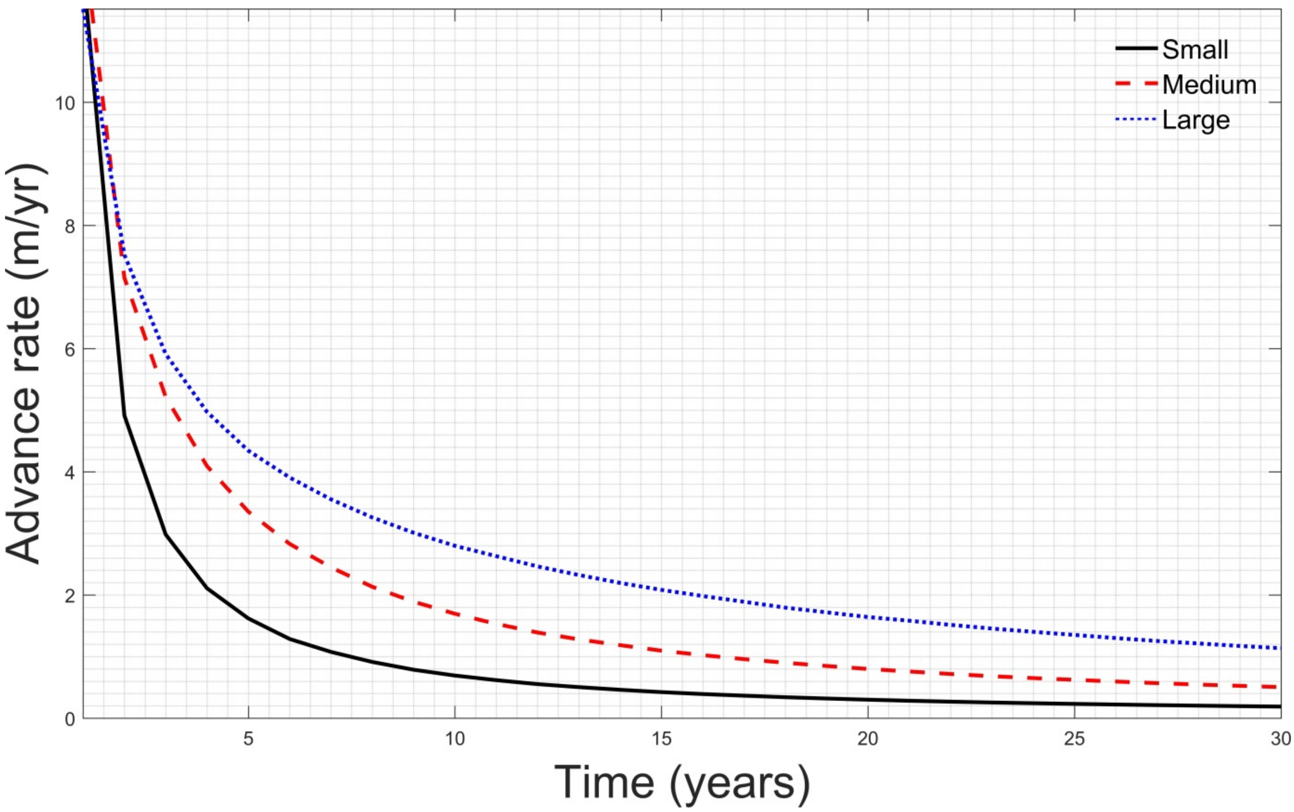

Figure 51 – Average coastline advance rates over time for a small (F01), medium (F06) and large (F10) nourishment as simulated with UNIBEST-CL+ for locality F*.

*The average advance rate is calculated across the shoreline showing more than 0.1 m advance.

4.1.3.3 Alongshore dispersion of nourishments

The alongshore dispersal of sand of a nourishment post construction is important to determine the positioning relative to towns and harbours. The alongshore dispersal is the redistribution of the sand on the lateral sides of a nourishment; at the end of a mega nourishment lifetime the sand was equally redistributed within a certain coastal cell. The alongshore length available for locality F is 5761 m, approximately equal to the constructed alongshore length of the large design in Figure 52. After 30 years, the alongshore length of the large design has increased to about 11.7 km. For the medium design, the alongshore length is about 8.7 km after 30 years; the available coastal length is reached 10 years post construction. The small design reaches a coastal length of 5800 m after 30 years, and thus mostly stays within the available study area during the simulation time frame.

Alongshore sand dispersal is also determined by the way that adjacent beaches are supplied with sand, which can be symmetrical or asymmetrical. A feeding asymmetry towards the southwest is predicted by UNIBEST-CL+ (Figure 53). The development of the average coastline position on the southwest side of the nourishment shows an advance of almost 50 m in 30 years. On the northeast side, a smaller advance of 43 m across 30 years is predicted. These values represents a 16% difference in coastline position between the SW located beaches and NE located beaches for the medium F06 design. UNIBEST-CL+ simulations indicate that the feeding asymmetry increases with nourishment size, which is illustrated by the 6% difference between SW and NE beaches for F01 and the 35% difference for nourishment design F10.

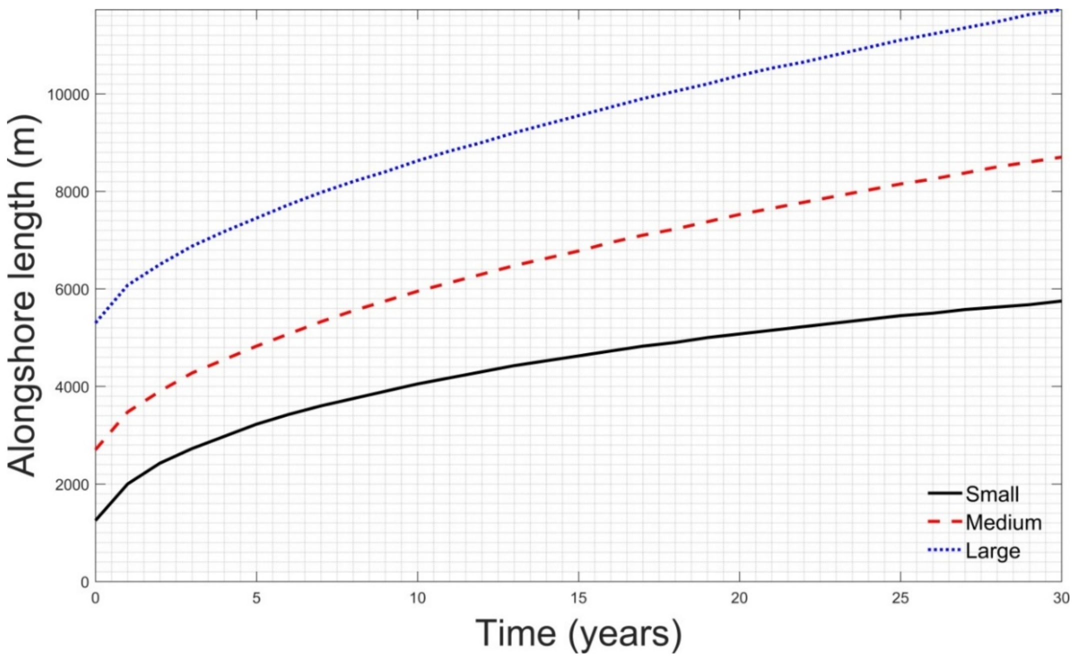

Figure 52 – Alongshore dispersion of sand over time for a small (F01), medium (F06) and large (F10) nourishment as simulated with UNIBEST-CL+ for locality F.

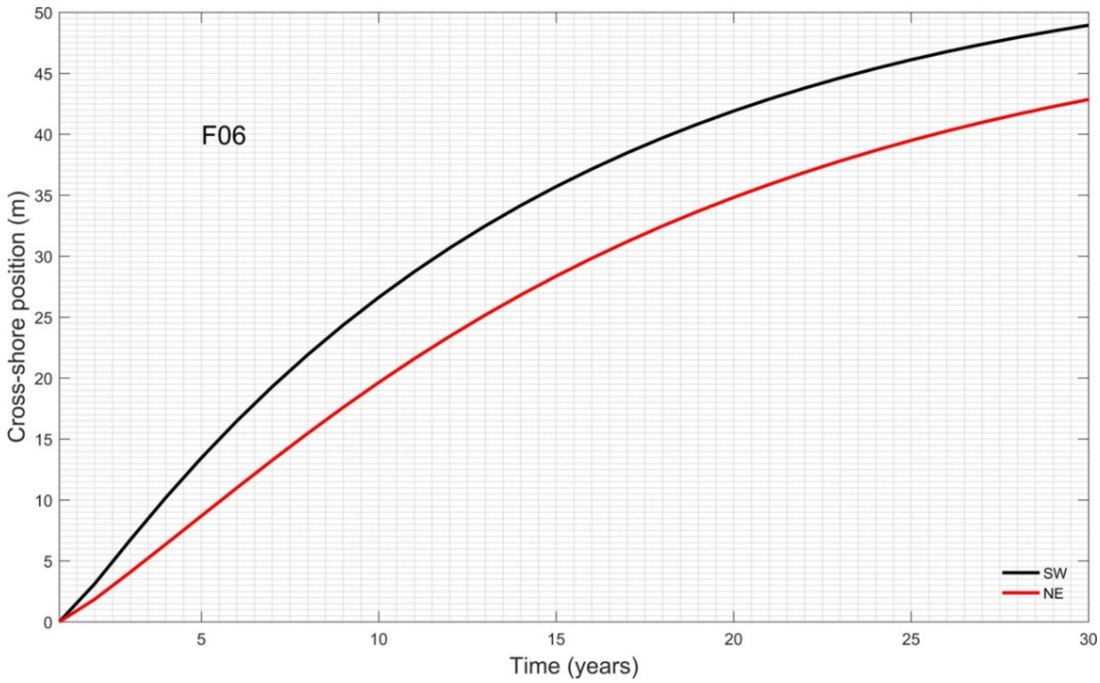

Figure 53 – Development of average coastline position predicted by UNIBEST-CL+ in 2.5 km control boxes located southwest (SW) and northeast (NE) of the constructed nourishment.

The asymmetry with larger advance rates on the SW part is contrary to the present net alongshore transport which is towards NE. This asymmetry is related to the fact that the orientation of the coastline is variable along the mega nourishment, while the wave climate remains the same. Therefore the angles that the waves approaching the coast are different than for a straight coast with large implications for the sediment transport, considering that a variation between 0° to 45° result in 0 transport to maximum transport, respectively. The migration of the nourishment centre line also quantifies the alongshore morphological reshaping of the nourishment designs. From Table 16 it can be seen that the migration rates of the centre line are limited across the 30-year period for all designs. The smallest designs show a small migration of maximum 25 m, i.e. one model grid cell, towards the southwest. The larger designs show a migration towards the northeast but alongshore migration rates are typically smaller than 10 m/yr.

Table 16 – Migration distance of nourishment centre line for all tested nourishment designs for locality F*.

Nourishment ID	Centre line migration distance (m)
F01_SM	-25
F02_SM	-25
F03_SM	-25
F04_SM	0
F05_SM	-25
F06_SM	0
F07_SM	25
F08_SM	150
F09_SM	75
F10_SM	150
F11_SM	200
F12_SM	275
F13_SM	225

*Migration distance is here defined as the distance from the original nourishment centre to the alongshore position with the maximum seaward extent after 30 years (m). A negative distance represents a migration towards the southwest and a positive distance a migration towards the northeast.

In short, the alongshore sand dispersal of the idealized nourishment designs post construction as simulated with UNIBEST-CL+ is complex. The simulations show a stagnant to northeast migration of the nourishment centre line. This migration direction is consistent with the direction of the net alongshore sediment transport direction predicted by UNIBEST-CL+ (Figure 42). Yet, a feeding asymmetry towards the SW is observed in which these beaches show a greater coastline advance than the beaches located NE of the constructed nourishment. This latter finding is somewhat counterintuitive and will be further investigated in the sensitivity analysis presented below.

4.1.3.4 Volume decay of nourishments

Morphological reshaping results in sand loss from the original nourishment location. Sand is being eroded from the nourishment head and fed to the adjacent beaches (Figure 46). The feeding of the adjacent beaches leads to a sand loss and volume decay from the nourishment area (Figure 55). Here, the sand volume decay is quantified on the basis of the remaining sand volume in the nourishment area. The control box includes the trapezoidal shape from the initial head position to the original coastline and it cuts in half the sides of the shape. This definition of the control box is consistent with the one used in Tonnon et al. (2018) (Figure 54).

The sand volume decays rapidly during the first years post construction for all nourishment designs (Figure 55). As time progresses, the volume decay decreases. Decay rates depend on the nourishment design and are higher for smaller designs and designs with a lower width-to-length ratio (Table 13).

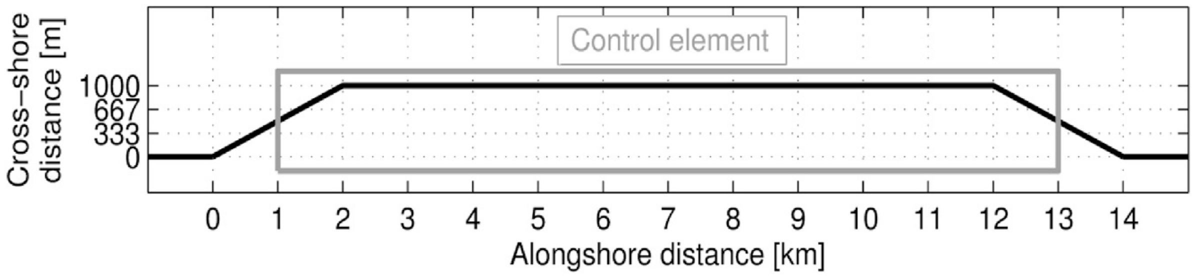

Figure 54 – The control box used in Tonnon et al. (2018).

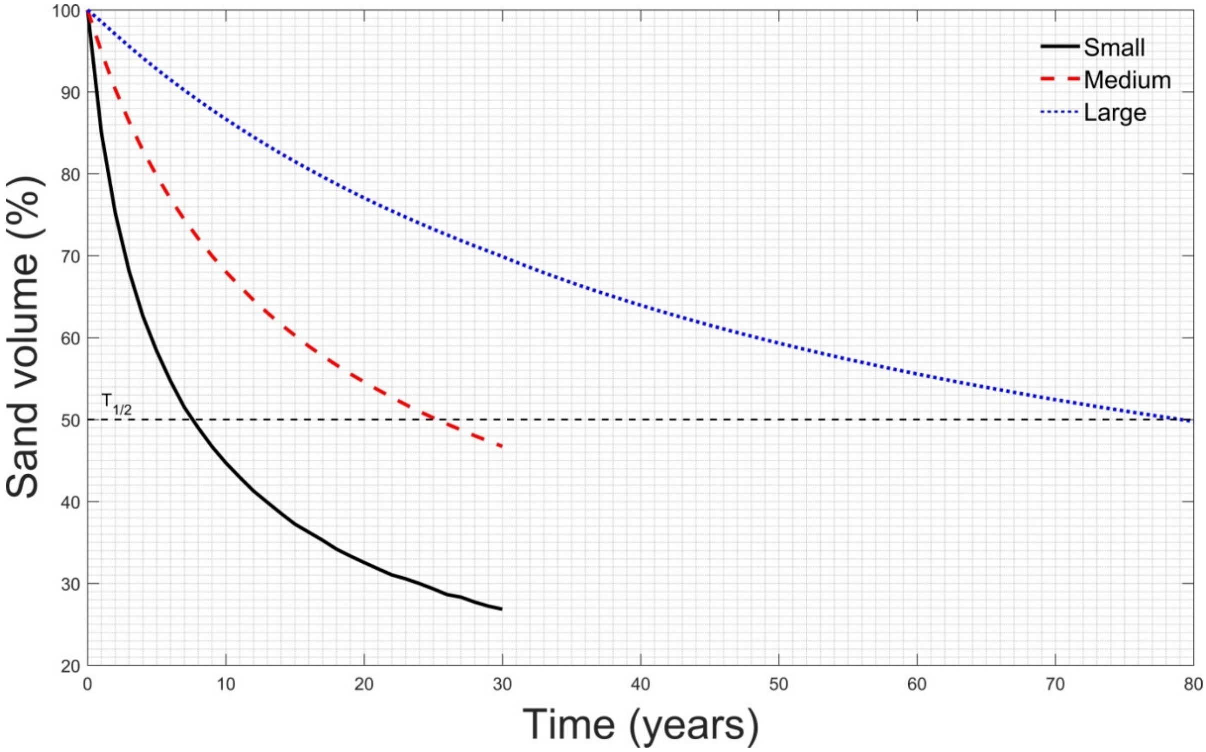

Figure 55 – Normalized sand volume decay over time for a small (F01), medium (F06) and large (F10) nourishment as simulated with UNIBEST-CL+ for locality F*.

*Half lifetime ($T_{1/2}$) is defined as the number of years required to reduce the sand volume to 50% of its initial volume.

The dispersion rate of a nourishment provides important information concerning the planning horizon and cost-effectiveness analyses. Half lifetime is defined as the number of years required to reduce the sand volume to 50% of its initial nourished volume (Figure 55). Table 17 shows the half lifetimes for all tested nourishment designs for locality F. The half lifetimes range from 7.6 years for the smallest F01 design to more than 250 years for nourishment design F12. For the designs with a seaward extent of 150 m (i.e. F01 – F04), the half lifetime ranges between 7.6 years and 22.3 years. For the designs with a seaward extent of 300 m (i.e. F05 – F08), the half lifetime ranges between 20.0 years and 72.5 years. For the designs with a seaward extent of 600 m (i.e. F09 – F12), the half lifetime ranges between 57.6 years and 257 years.

Table 17 – Half lifetimes ($T_{1/2}$) for all tested nourishment designs for locality F.

Run ID	F01	F02	F03	F04	F05	F06	F07	F08	F09	F10	F11	F12	F13
$T_{1/2}$ (years)	7.6	9.1	12.8	22.3	20	25.3	38.1	72.5	57.6	79.1	126	257	150

Half lifetime scales approximately linear with the initial nourishment volume for the same width-to-length ratio (Figure 56). This means that a double sand volume results in approximately a twice as long half lifetime. Furthermore, the geometry of the nourishment design has a large effect on half lifetime. A longer alongshore nourishment maintains more sand in the initial nourishment area than a shorter nourishment with the same volume. This geometry effect can be illustrated by comparing nourishment designs F08 and F09. Design F09 has 54% higher initial sand volume than design F08 (Table 13), yet the half lifetime of F08 is almost 15 years longer than that of F09 (Table 17). The geometry effect is also visualized in Figure 56 in which the 1:4 width-to-length designs result in the highest half lifetime for identical volumes compared to the other designs.

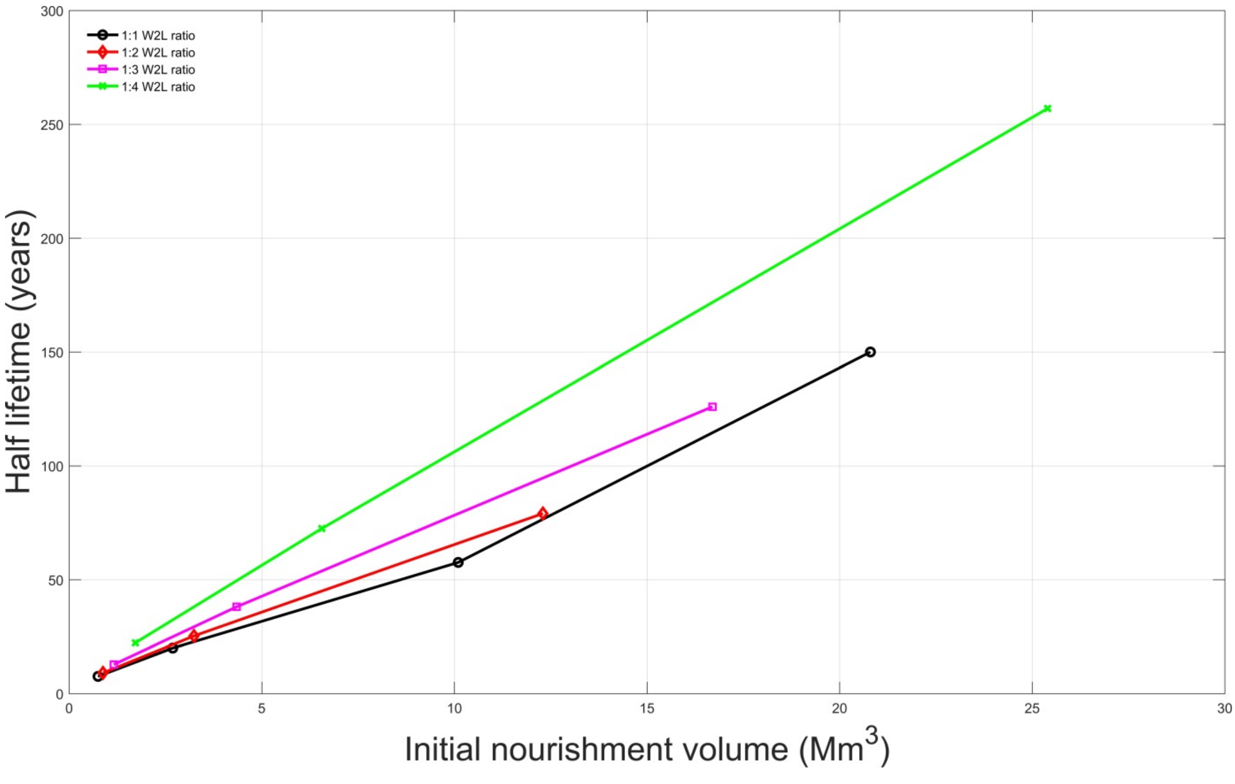

Figure 56 – Relationship between nourishment volume and half lifetime for four width-to-length designs.

A key observation is that the half lifetimes predicted by UNIBEST-CL+ for locality F along the Belgian coast are substantially higher than the half lifetimes predicted for the Dutch coast in Tonnon et al. (2018), despite similar net alongshore sediment transport rates of 200.000 to 300.000 m^3/year. For example, for a scenario with an initial volume of 20 million m^3 of sand they predict a half lifetime of about 19 years. For nourishment design F13 with a similar initial volume (Table 13), the predicted half lifetime is 150 years (Table 17). This difference is partly explained by the longer alongshore design of the nourishment design in the Belgian case slowing down the volume decay.

A more fundamental explanation for the difference in half lifetime for the Belgian and Dutch coasts is a lower Longshore Transport Intensity (LTI) for the Belgian coast. Tonnon et al. (2018) use a net alongshore sediment transport rates of 200.000 m^3/year and a coastline orientation that deviated 6.6° from the coastline orientation of net zero alongshore sediment transport for the Dutch coast. Combining these two values gives a LTI of about 30.000 m^3/year/degree. For the Belgian coast, the same net alongshore sediment transport rates of 200.000 m^3/year is used. However, the coastline orientation deviates 30.1° from the coastline orientation of net zero alongshore sediment transport (Table 12). Combining these two values gives a LTI of about 6.600 m^3/year/degree for the Belgian coast. Essentially, the lower LTI for the Belgian coast indicates a smaller sensitivity of the alongshore sediment transport for small changes in coastline orientation, i.e. a mega nourishment, along the Belgian coast than observed for the Dutch coast. In turn, gradients in alongshore sediment transport are smaller, resulting in smaller shoreline changes (i.e. erosion and advance), and a longer half lifetime of the nourished sand. In conclusion, sand will remain longer in place along the Belgian coast than the Dutch coast.

4.1.3.5 Sensitivity to annual net alongshore sediment transport, wave climate and active height

The sensitivity of the shoreline changes simulated with UNIBEST-CL+ to the annual net alongshore sediment transport and wave climate are evaluated below. The net alongshore sediment transport is varied across a range from 100.000 m^3/yr to 400.000 m^3/yr (i.e. a Longshore Transport Intensity (*LTI*) of 3333 – 13333 m^3/yr/degree with a ϑ of 30°). This range covers and extends beyond the calculated net alongshore sediment transport for the Belgian coast (Figure 43).

The wave climate has a large effect on the magnitude and direction of the net alongshore sediment transport along the Belgian coast. In the current wave climate, waves are dominantly coming from western and northern directions (Figure 38) with a mean H_{sig} of 0.66 m and a mean T_{peak} 4.76 s (Table 11). However, some recent studies have suggested that wave characteristics in the Northern Atlantic Ocean may be changing (Castelle *et al.*, 2018). Specifically, these authors find an increased winter-mean wave height, variability and periodicity in the Northeast Atlantic over the period 1949 to 2017. Therefore, the wave characteristics from 1985 to 2017 are evaluated to establish if a similar trend exists for the Belgian part of the North Sea and, lastly, the sensitivity of shoreline changes simulated with UNIBEST-CL+ to a change in wave climate characteristics (i.e H_{sig}, T_{peak}, θ) is explored.

Annual net alongshore sediment transport

In addition to the variability in net alongshore sediment transport along the Belgian coast (Figure 43), the Q_{annual} displays a large annual variability (Figure 57). During the 10-year period, there is a net quantity of sand transported in northeast direction of 2.3 million m^3, which corresponds to an annual mean of 234.000 m^3. The annual mean value agrees well with findings from Vandebroek et al. (2016) (Figure 43) but is about half of the largest Q_{annual} obtained for 1999 (466.154 m^3), and almost three time the volume of the smallest Q_{annual} obtained for 2003 (88.234 m^3) (Figure 57). These findings indicate that Q_{annual} in the year with largest waves is a factor of five larger than the Q_{annual} generated during the the year with lower waves. In addition, these results show that the Q_{annual} is consistently directed towards the northeast, which is consistent with other studies on the Belgian coast (Vandebroek et al. 2016) as well as with results for the Dutch coast reported by Van Rijn (1997). The variation of the Q_{annual} when the coastline orientation increase or decrease 5° is shown in Figure 57. The bathymetry used for the coastline orientation sensitivity analysis was the one presented in Figure 40.

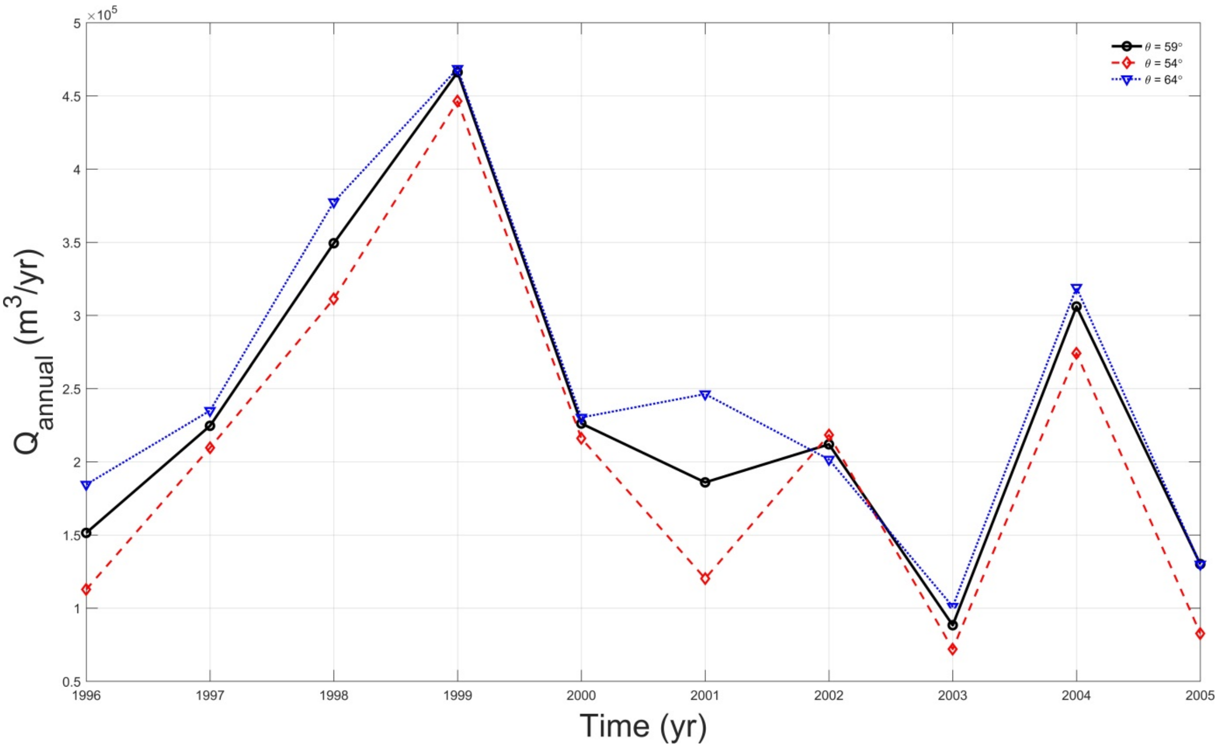

Figure 57 – Net annual alongshore sediment transport computed with UNIBEST-CL+ using the Bijkerk (1967,1971) formulation and a 10-year wave climate (see Figure 38)*.

*All transport is directed towards the northeast. The local coastline orientation of 59° (see Figure 37) and the sensitivity of the transport to a variation in coastline orientation of ±5° is also shown.

Figure 58 shows the coastline position simulated with UNIBEST-CL+ 30 years after the nourishment construction as a function of the annual net alongshore sediment transport. Substantial differences in coastline retreat at the nourishment and coastline advance of the adjacent beaches exist between the different scenarios. For example, the maximum seaward extent of the highest transport scenario of 400.000 m^3/yr is 97.3 m whereas the seaward extent of the lowest transport scenario of 100.000 m^3/yr is 173.3 m. These seaward locations represent a difference of 76 m in the prediction of the cross-shore position 30 years post-construction. Relative to the reference run, the largest transport scenario results in a 25 m shoreward position whereas the lowest transport scenario predicts a 50 m seaward position (Table 18).

In addition to the cross-shore position, the net alongshore sediment transport also has an effect on the alongshore dispersion of the sand from the nourishment (Figure 58). Essentially, a higher net alongshore sediment transport results in a larger alongshore dispersion of sand in which beaches located farther from the original nourishment location are also fed (Table 18). In the scenario with the highest transport scenario of 400.000 m^3/yr, beaches across a length of more than 10 km receive sand from the nourishment whereas this applies to a 6-km beach stretch in the lowest transport scenario of 100.000 m^3/yr.

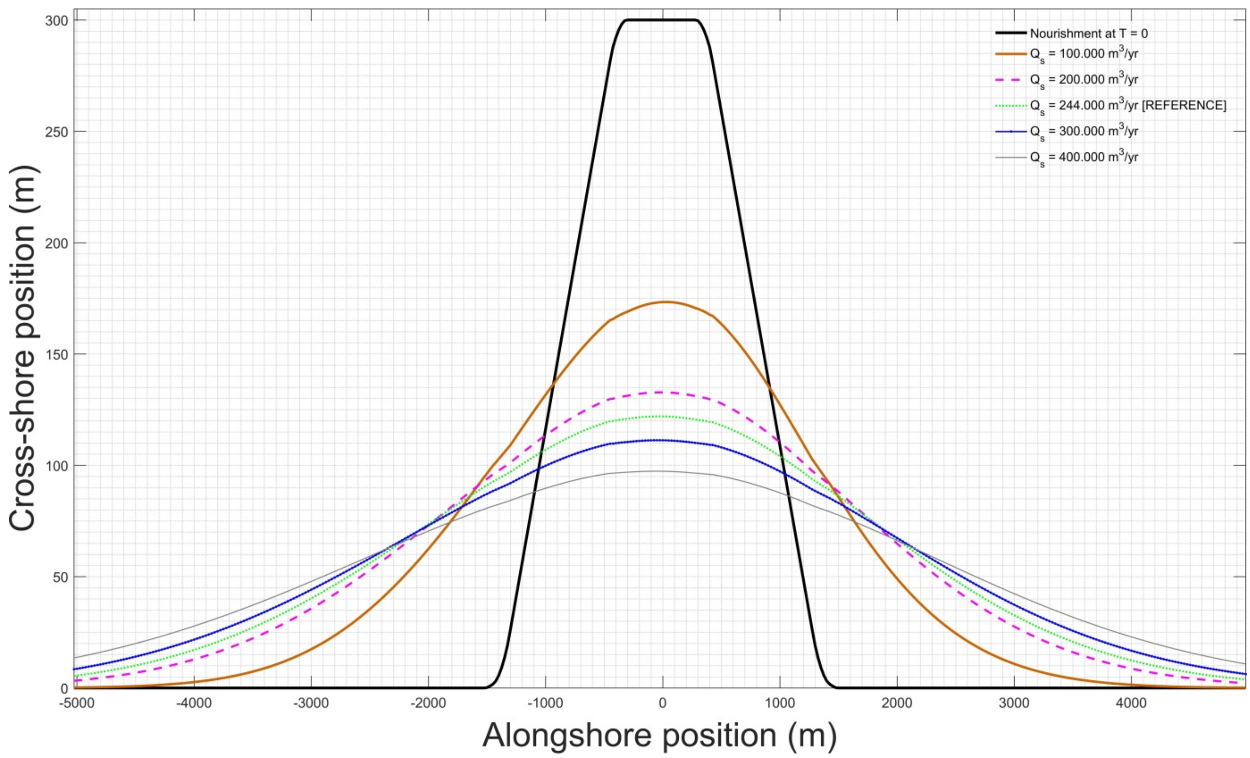

Figure 58 – Snapshots of final coastline position (i.e. 30 years) as a function of net alongshore sediment transport for scenario F06 (see Table 13) simulated with UNIBEST-CL+.

Table 18 – Descriptive statistics of coastline position and volume decay as a function of net alongshore sediment transport for scenario F06.

Run ID	Net alongshore sed. transport (m^3/yr)	Max. seaward extent (m)	Alongshore length (m)	Half lifetime (yr)
Sensi_100	100.000	173.3	6375	61.0
Sensi_200	200.000	132.8	8100	30.8
Sensi_244 [REF]	243.971	122.0	8700	25.3
Sensi_300	300.000	111.2	9400	20.5
Sensi_400	400.000	97.3	10450	15.4

The differences in shoreline changes as a function of the annual net alongshore sediment transport are also reflected in the volume decay and the half lifetime of the nourishment post construction (Figure 59). A higher annual net alongshore sediment transport results in a faster volume decay and a lower half lifetime (Table 18). For the highest net alongshore sediment transport of 400.000 m^3/yr, a half lifetime of 15.4 years is predicted whereas the lowest net alongshore sediment transport of 100.000 m^3/yr results in a half lifetime of 61.0 years. These half lifetimes indicate that 50% of the nourished sand can be transported from the original nourishment area about four times quicker during conditions generating the highest alongshore sediment transport rates compared to conditions resulting in the lowest alongshore sediment transport rates.

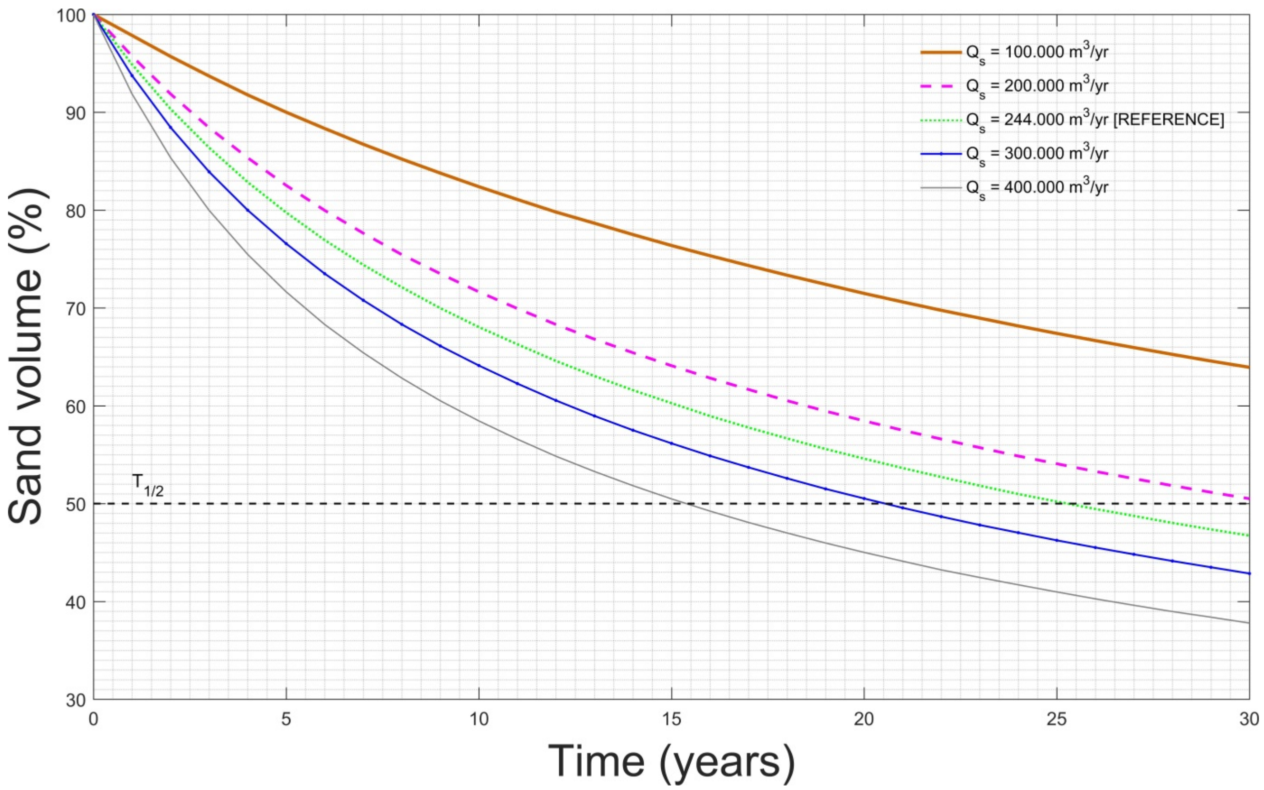

Figure 59 – Volume decay and half lifetime ($T_{1/2}$) as a function of net alongshore sediment transport.

Wave climate

Table 19 provides an overview of the sensitivity of the net alongshore sediment transport at locality F for the significant wave height (H_{sig}), the peak wave period (T_{peak}) and the wave direction (θ). A 10% increase (decrease) in H_{sig} results approximately in a 30% increase (decrease) in net alongshore sediment transport compared to the reference simulation. The equilibrium angle with the coastline orientation generating zero transport remains about constant at 30° independent of the H_{sig} scenario.

The sensitivity of the net alongshore sediment transport at locality F to the peak wave period (T_{peak}) is lower than sensitivity to the significant wave height (Table 19). A 10% increase (decrease) in T_{peak} results approximately in a 3% increase (decrease) in net alongshore sediment transport compared to the reference simulation. This finding suggests that the net alongshore sediment transport is relatively insensitive to the specification of the peak wave period.

The greatest sensitivity of the net alongshore sediment transport at locality F in terms of magnitude as well as direction is observed for the wave direction (θ) (Table 19). A 36° rotation North results in a net alongshore sediment transport with a magnitude equal to about ¼ of the reference run. Strikingly, the direction of the net alongshore sediment has reversed and it is directed southward in this scenario. When applying a 36° rotation North, the reversal in sediment transport direction is primarily the result of the occurrence of waves with a higher significant wave height from the direction generating maximum southward-directed sediment transport (Figure 60, 14°) combined with a smaller wave height for the direction generating maximum northward-directed sediment transport (Figure 60, 284°). The +36° increase of θ also has a large effect on the equilibrium angle which is reduced to -6.1°. As a result, the Longshore Transport Intensity (*LTI*) is 9500 m^3/yr/degree and higher than the reference scenario (8105 m^3/yr/degree), indicating a higher sensitivity to changes in coastline orientation in the +36° increase of θ scenario.

A southward rotation of the wave direction is challenging to simulate with the UNIBEST-CL+ model. For all southward rotations greater than 4°, the model is unstable and the simulation fails (Table 19). The model failure in these cases is caused by the large angles between the coastline and approaching waves generated for the northern edge of the nourishment. However, the sensitivity of the net alongshore sediment transport at locality F to a southward rotation is lower than a northward rotation. An 18° southward rotation results in a 19% increase in net alongshore sediment transport (Table 19). Yet, the equilibrium angle also increases for this scenario to 48° and, consequently, the *LTI* decreases with about 25% compared to the reference run. A lower *LTI* is indicative of a smaller sensitivity to changes in in coastline orientation, and therefore smaller shoreline changes post construction of a nourishment are expected for a southward rotation.

Figure 60 shows the coastline position simulated with UNIBEST-CL+ 30 years after the nourishment construction as a function of the wave climate. It can be seen that the changes in shoreline are relatively insensitive to the peak wave period and most sensitive to the wave direction. As a consequence, the difference in the maximum seaward extent of the shoreline between the two peak wave period scenarios is only 2 m while the two wave direction scenarios result in 37 m difference in the prediction of the maximum seaward position of the shoreline (Table 20). So despite generating the lowest alongshore sediment transport rate, the relative small difference with the equilibrium coastline orientation in the northward rotation scenario (Table 19) indeed results in the fastest shoreline changes, which is attributed to the higher *LTI* for this scenario.

Table 19 – Sensitivity of net alongshore sediment transport and equilibrium angle in UNIBEST-CL+ to changes in wave climate.

RUN ID		Q_s (m^3/year)	Eq. angle (°)
REF	Reference run (see Table 12)	243.971	30.1
H10_Plus	H_{sig} +10%	327.752	30.0
H10_Minus	H_{sig} -10%	177.481	30.1
T10_Plus	T_{peak} +10%	250.328	30.7
T10_Minus	T_{peak} -10%	233.662	29.4
D10_Plus	Wave direction θ +36° (rotate North)	-57.946	-6.1
D10_Minus	Wave direction θ -36°(rotate South)	270.227	65.8
D05_Minus	Wave direction θ -18° (rotate South)	290.949	48.0
D10D_Minus	Wave direction θ -10° (rotate South)	278.575	39.8
D05D_Minus	Wave direction θ -5° (rotate South)	258.441	34.7
D04D_Minus	Wave direction θ -4° (rotate South)	258.288	33.8

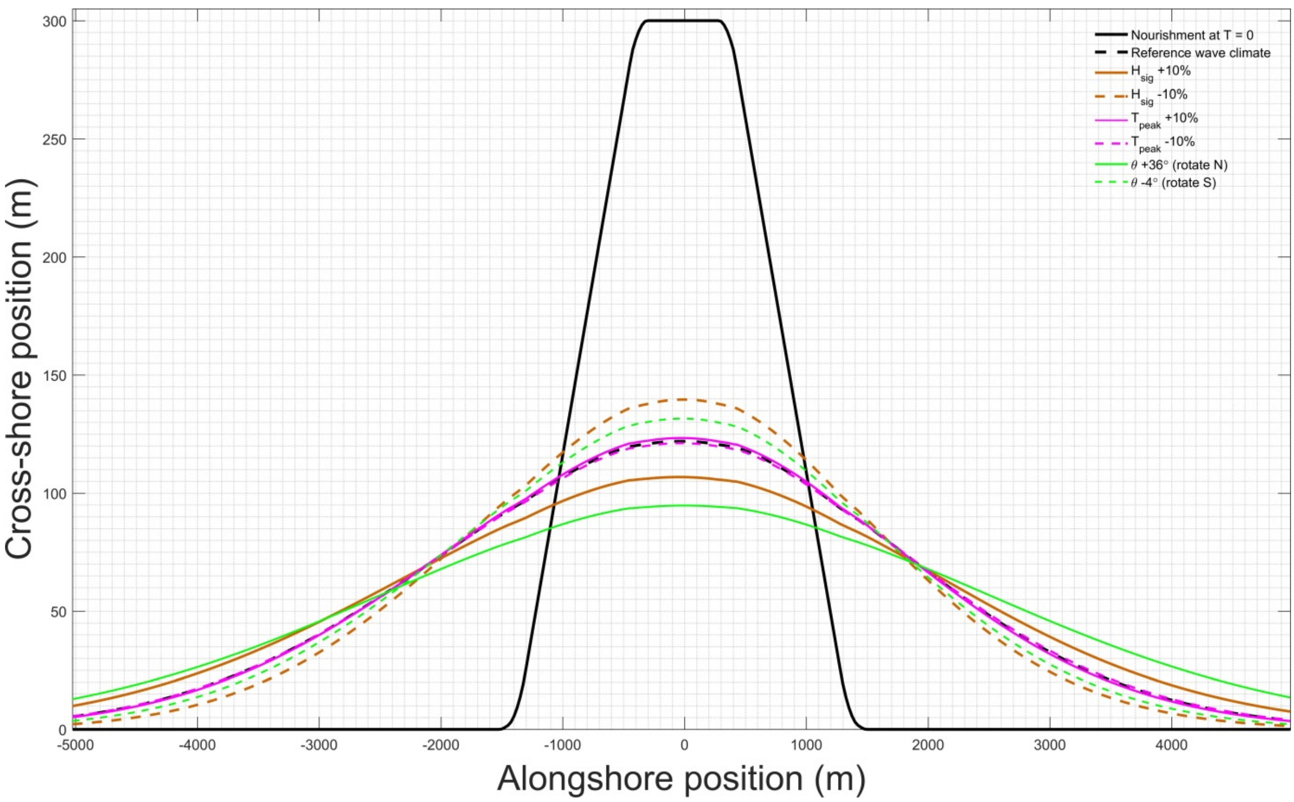

Figure 60 – Snapshots of final coastline position (i.e. 30 years) as a function of the wave climate for scenario F06 (see Table 13) simulated with UNIBEST-CL+.

The *LTI* also provides a proxy for alongshore dispersion of the sand from the nourishment (Figure 60). Essentially, a higher *LTI* results in a greater alongshore dispersion of sand in which beaches located farther from the original nourishment location are also fed (Table 20). In the scenario with the highest LTI of 9500 m^3/yr/degree, beaches across a length of more than 10 km receive sand from the nourishment whereas this applies to a 7.7-km beach stretch in the lowest *LTI* scenario of 5900 m^3/yr/degree.

Table 20 – Descriptive statistics of coastline position and volume decay as a function of the wave climate for scenario F06.

Run ID	Max. seaward extent (m)	Alongshore length (m)	Half lifetime (yr)
REF	122.0	8700	25.3
H10_Plus	106.8	9700	18.8
H10_Minus	139.7	7750	34.8
T10_Plus	123.3	8625	25.9
T10_Minus	121.1	8725	24.9
D10_Plus	94.8	10700	14.5
D04D_Minus	131.6	8150	30.1

The wave climate has the potential to affect the volume decay and the half lifetime of the nourishment post construction (Figure 61). In agreement with the observed shoreline changes, the volume decay and half lifetime is most sensitive to the wave direction. A 36° rotation North results in a quicker volume decay and a reduction of the half lifetime of about 11 years to a half lifetime of 14.5 years (Table 20). An increase in wave height and a decrease of the peak wave period also result in a reduction of the half lifetime. In contrast, a decrease in wave height, an increase in peak wave period and a southward rotation of the wave direction are predicted to result in a slower volume decay and, consequently, a larger half lifetime (Table 20).

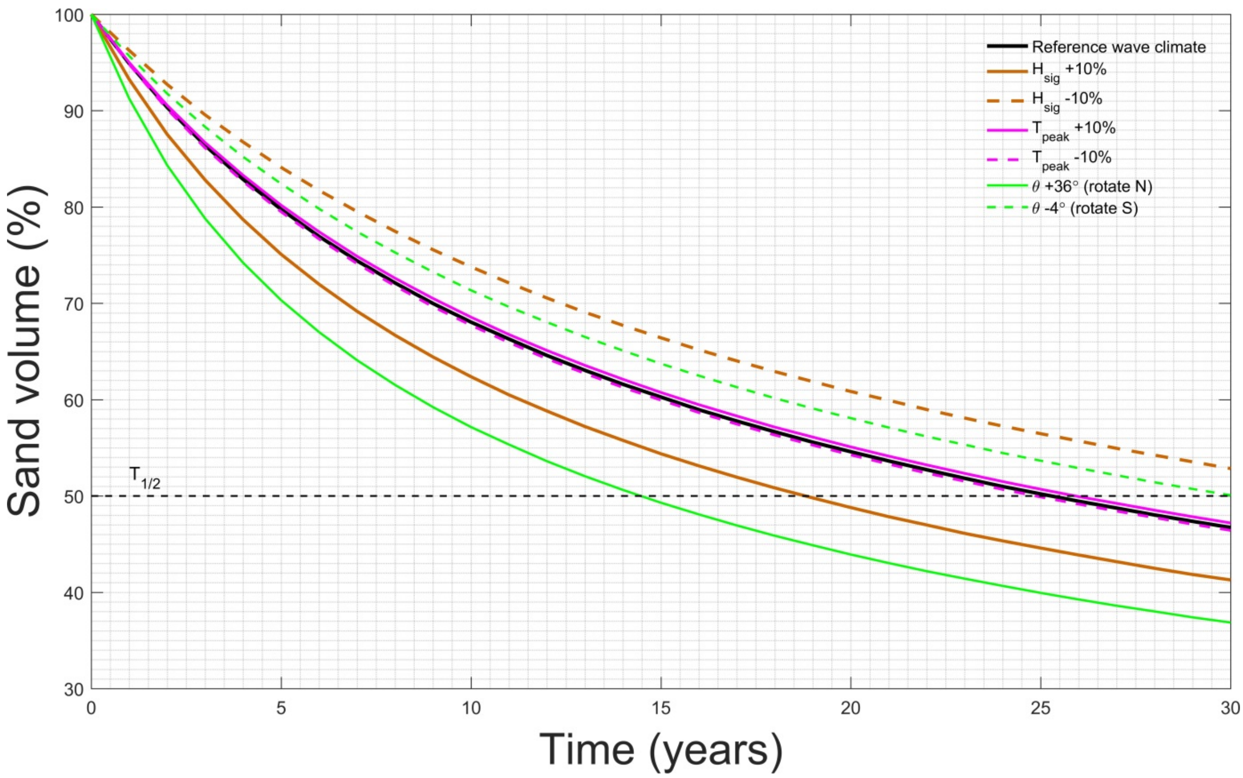

Figure 61 – Volume decay and half lifetime ($T_{1/2}$) as a function of the wave climate.

The above results demonstrate that the wave climate has a large effect on the magnitude and direction of the net alongshore sediment transport along the Belgian coast. Some recent studies have suggested that the wave characteristics in the Northern Atlantic Ocean may be changing (Castelle *et al.*, 2018). Therefore, it is important to evaluate wave trends in the Belgian part of the North Sea to quantify possible changes and to understand how these changes might affect the net alongshore sediment transport along the Belgian coast.

Figure 62 and Figure 63 present an overview of the winter wave characteristics measured in the Belgian North Sea between 1985 and 2017. Consistent with Castelle et al. (2018), the winter period is here defined as the months December, January, February and March. From Figure 62, it is noticed that the mean significant winter wave height generally varies between 0.8 m and 1.2 m during a 32-year period.

It can be concluded that an increase in wave energy as observed for the Northern Atlantic Ocean by Castelle et al. (2018) is not seen for the Belgian part of the North Sea. A weak upward trend in winter wave energy may exist but this trend is of millimetre-scale and much smaller than the inter-annual variation in winter wave energy (Figure 62). Therefore, a significant change in net alongshore sediment transport along the Belgian coast is not expected as a result of a change in winter wave height. Reliable observations on the peak wave period and, of particular interest in driving the net alongshore sediment transport (Table 19 and Figure 60), the wave propagation direction are only available for the Belgian part of the North Sea since 2006. No clear trends in the winter peak wave period and the wave propagation direction are observed across the period 2006 – 2017, in agreement with the observations on the significant wave height. Therefore, historical observations (Figure 62) suggest that the applied reference wave climate (Table 11) provides the best predictor for the future wave climate along the Belgian coast.

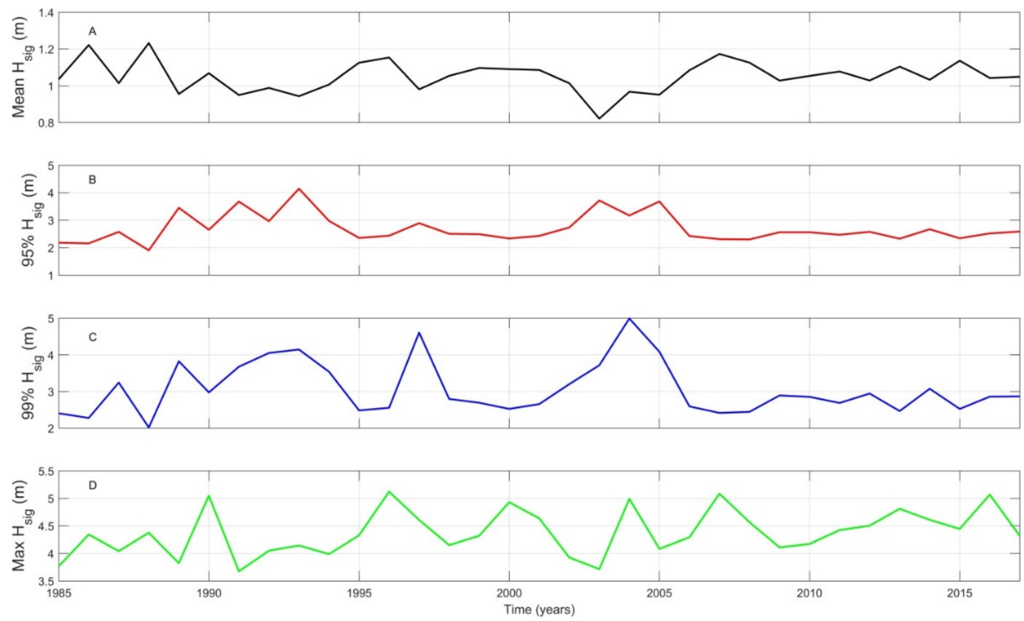

Figure 62 – Measured winter (DJFM) wave height characteristics for wave station Westhinder (2° 26' 21"E - 51° 22' 51"N) in the Belgian North Sea between 1985 and 2017*.

*Data from https://meetnetvlaamsebanken.be

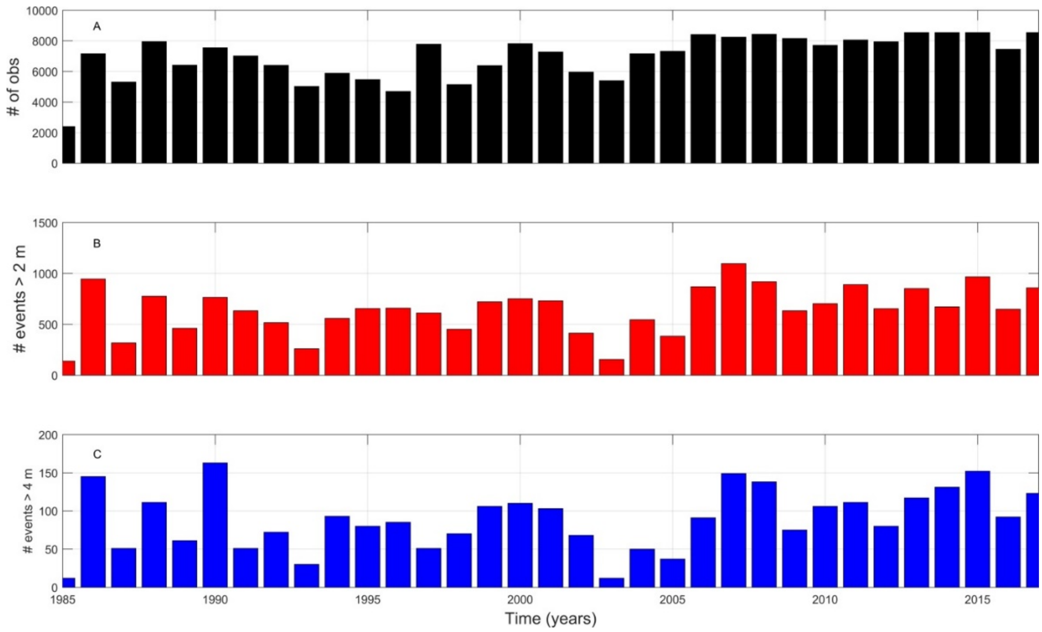

Figure 63 – Number of wave observations (A), wave events greater than 2 m (B), and wave events greater than 4 m (C) for the winter (DJFM) periods between 1985 and 2017 for wave station Westhinder (2° 26' 21"E - 51° 22' 51"N) in the Belgian North Sea.

*Data from https://meetnetvlaamsebanken.be

Active height

The active height is used in the coastline module of UNIBEST-CL+ to estimate the coastline retreat or advance from the balance of the incoming and outgoing sediment transport in a cross-shore ray. The active height summates the parts of the beach profile subject to change to the wave action during a certain period of time. The gradients in alongshore sediment transport result in accreted or eroded volumes, which in turn lead to advance or retreat in shore normal direction. The active height can be estimated based on the wave climate, the local bathymetry and the timeframe. It is important to realise that the active height is not known exactly and generally used as a calibration parameter. As a rule of thumb, the active height is about 2 to 3 times the annual significant wave height (Deltares, 2011). Also, the active height of eroding coasts is generally larger than the active height of accreting coast and the active height is expected to increase for a longer timeframe because a larger part of the coastal profile is potentially activated. Below, four active height scenarios are evaluated. The reference scenarios applies an active height of 5.25 m since is the calculated closure depth for the central part of the Belgian coast. The other three scenarios are used to explore the sensitivity of the shoreline changes to active heights ranging between 2.5 m (i.e. short time scales) and 11 m (longer time scales).

Figure 64 shows the coastline position simulated with UNIBEST-CL+ 30 years after construction of the nourishment as a function of the active height. A larger active height results in a slower dispersion of sand from the nourishment area with smaller shoreline changes. For example, the maximum seaward extent of the largest active height scenario of 11 m is 164.6 m whereas the seaward extent of the lowest active height scenario of 2.5 m is 86.7 m (Table 21). These seaward locations represent a difference of 78 m in the prediction of the cross-shore position 30 years post-construction. Relative to the reference run with an active height of 5.25 m, the smallest active height of 2.5 m scenario results in a 35 m shoreward position whereas the largest active height of 11 m scenario predicts a 43 m seaward position (Table 21).

In addition to the cross-shore position, the active height also has an effect on the alongshore dispersion of the sand from the nourishment (Figure 64). A smaller active height results in a greater alongshore dispersion of sand in which beaches located farther from the original nourishment location are also fed (Table 21). In the scenario with the lowest active height scenario of 2.5 m, beaches across a length of more than 11 km receive sand from the nourishment whereas this applies to a 6.7-km beach stretch in the largest active height of 11 m scenario.

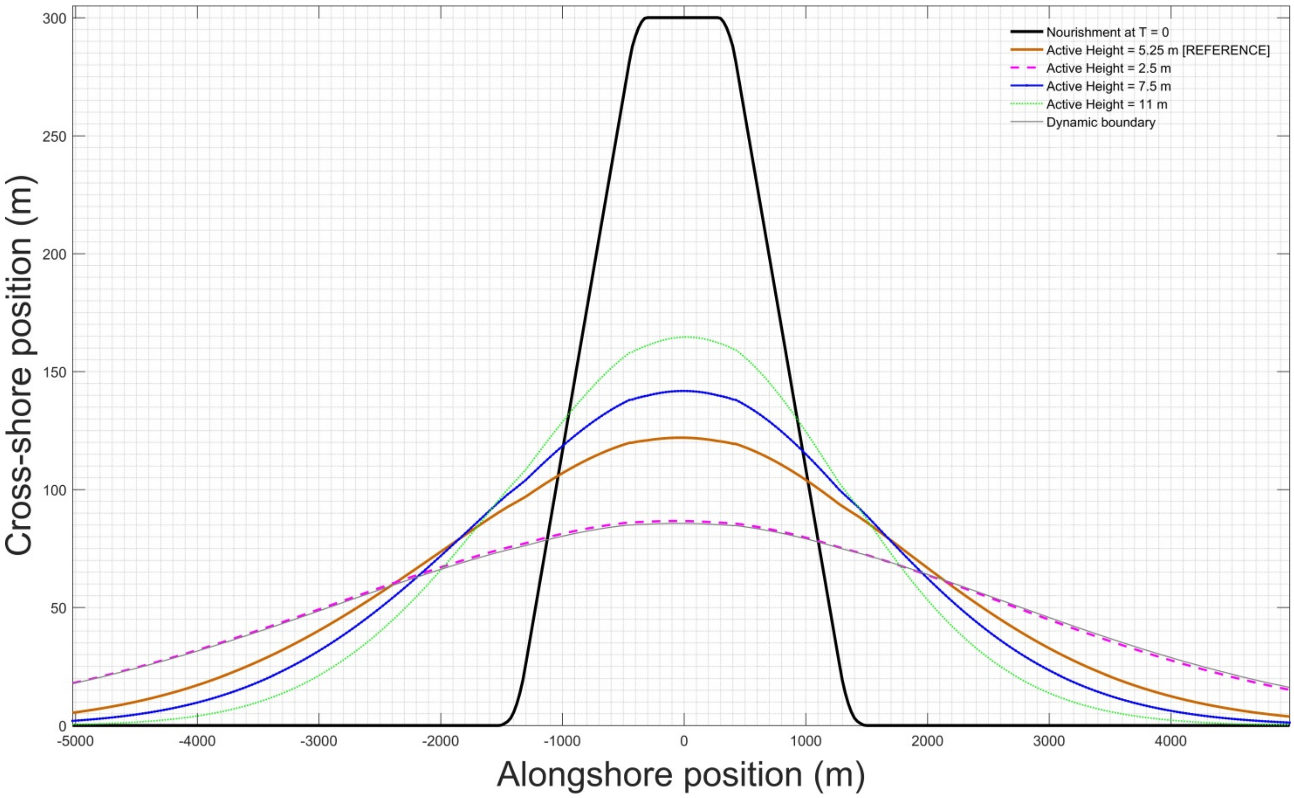

Figure 64 – Snapshots of final coastline position (i.e. 30 years) as a function of active height of the coastal profile for scenario F06 (see Table 8) simulated with UNIBEST-CL+.

Table 21 – Descriptive statistics of coastline position and volume decay as a function of the active height for scenario F06.

Active height (m)	Maximum seaward extent (m)	Alongshore length (m)	Half lifetime (yrs)
2.5	86.7	11450	12.0
5.25 [REFERENCE]	122.0	8700	25.3
7.5	141.8	7650	36.1
11	164.6	6675	52.9

The active height also affects the volume decay and the half lifetime of the nourishment post construction (Figure 65). In agreement with the observed shoreline changes, the volume decay is fastest and the half lifetime lowest for the smallest active height of 2.5 m (Table 21). The differences in half lifetime as a function of active height are considerable with about 25 years for the reference run up to almost 53 years for an active height of 11 m (Table 21). Notably, a linear relation is found between the active height of the coastal profile and the half lifetime of a mega nourishment (Figure 66). This observation implies that a twice as large active height results in a double half lifetime, which is convenient for predictive purposes.

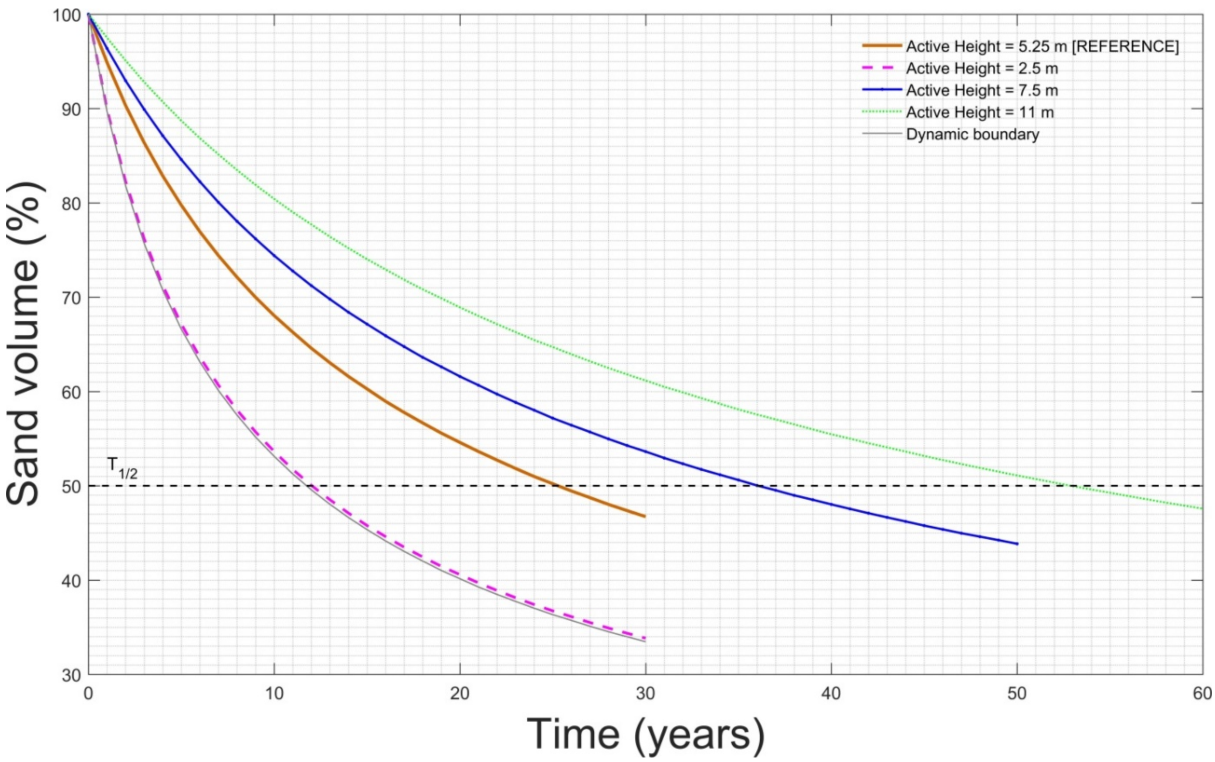

Figure 65 – Volume decay and half lifetime ($T_{1/2}$) as a function of the active height of the coastal profile for scenario F06 (see Table 8) simulated with UNIBEST-CL+.

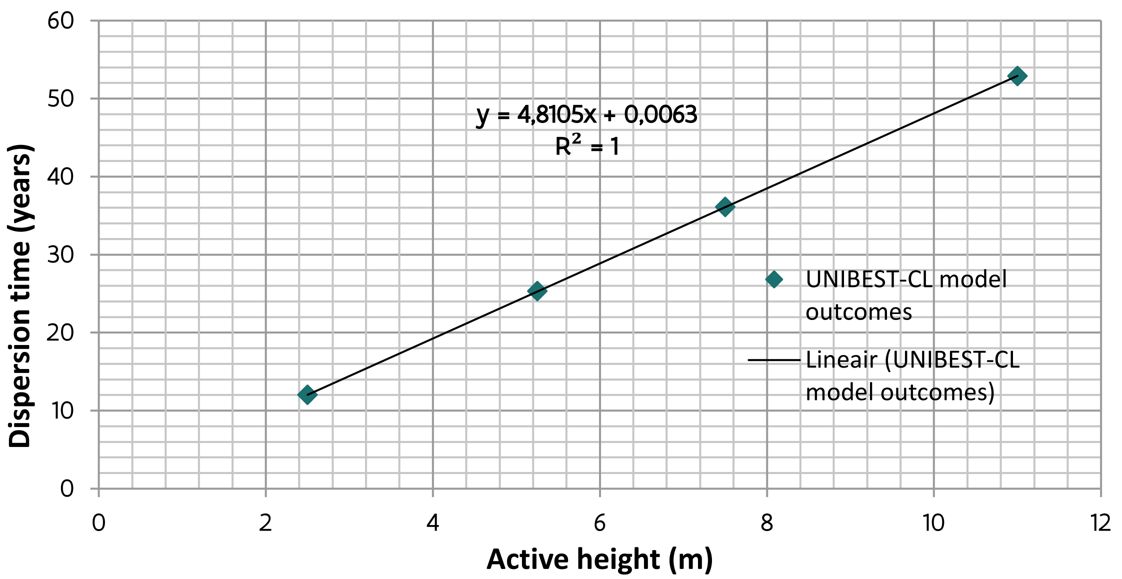

Figure 66 – Relationship between active height of the coastal profile and the dispersion time (i.e. the half lifetime, see Figure 66) for scenario F06 (see Table 13) simulated with UNIBEST-CL+.

4.2 Synthesis of model simulations

The behaviour and evolution of idealized mega nourishments for three locations along the Belgian coast is simulated with UNIBEST-CL+. UNIBEST-CL+ was used to simulate the evolution of the Sand Engine near Ter Heijde in the Netherlands (Tonnon *et al.*, 2018). The ability of UNIBEST-CL+ to successfully simulate the evolution of a sandy mega nourishment under similar climatic conditions and nourishment designs as foreseen along the Belgian coast is promising. Consequently, UNIBEST-CL+ is selected as the coastline model to be used in the current study with the aims to:

1. Study the alongshore sediment transport post-construction of a feeder-type mega nourishment
2. Quantify the dispersion rate of a feeder-type mega nourishment
3. Quantify the coastal retreat of a feeder-type mega nourishment

Three preferable locations for feeder-type mega nourishments are identified based coastal safety, nature development and recreational opportunities. Locations northeast of Blankenberge are considered out of the scope of this study due to the presence of Zeebrugge harbour, the Zwin tidal inlet and the proximity of the Scheldt estuary. From the three selected locations, location A stretches from the Belgian-French border to De Panne (sections 2-11, 2440 m), location E is between Middelkerke and Mariakerke (sections 88-106, 5745 m), and location F begins in Bredene and ends in De Haan (sections 127-151, 5761 m). The simulation horizon is 30 years to align with the planning horizon of 2050 (Masterplan Kustveiligheid, 2011).

A validation of the UNIBEST-CL+ model on data from the Mariakerke nourishment is performed. Data on large nourishments is scarce and hence the careful hydrodynamic and morphological monitoring for the Mariakerke nourishment provides a unique opportunity to calibrate the UNIBEST-CL+ model for the Belgian coast. The combined beach-shoreface nourishment has a total volume of about 1Mm^3 of sand and was constructed in early 2014. This means that approximately three years of data on cross-shore evolution and volume decay is available to validate the UNIBEST-CL+ model. The model simulations show a good agreement with the observations on cross-shore evolution and volume decay. This finding indicates that UNIBEST-CL+ is capable of simulating shoreline changes following the construction of a large nourishment along the Belgian coast. When detailed information on hydrodynamics, bathymetry and sediment characteristics is available, it is expected that robust and reliable predictions of future shoreline behaviour can be made with UNIBEST-CL+.

UNIBEST-CL+ is used to predict the net alongshore sediment transport rates for each of the three aforementioned locations along the Belgian coast (Table 22). Prediction of the net alongshore sediment transport rate requires information about the wave climate, coastline orientation, cross-shore profile and sediment characteristics. Since the wave climate has very low variation between the three location the 10-year wave hindcast generated using SWAN is extracted near Bredene was applied for all three locations. The Bijker (1967, 1971) formulation is used to predict sediment transport for all three locations, but the sensitivity of the net alongshore sediment transport to other formulations such as CERC (1984), Van Rijn (2004) and Kamphuis (1991) is also explored.

UNIBEST-CL+ predicts transport rates varying from 168.291 m^3/year for location E to 243.971 m^3/year for location F (Table 22), which are directed northeast for all three locations. The transport direction towards the northeast is consistent with earlier sediment budget studies for the Belgian coast (Vandebroek *et al.*, 2016) and also the magnitude of the transport is similar for two out of the three locations. As shown in Figure 43, the reported net alongshore sediment transport rate decreases towards the southwest with a rate of 250.000 ± 50.000 m^3/year for location F, a rate of 150.000 ± 50.000 m^3/year for location E, and a rate of 120.000 ± 50.000 m^3/year for location A. The UNIBEST-CL+ predicted transport rates of locations E and F agree with the reported rates shown in Figure 43 whereas the predicted transport rate of location A is higher than the reported rate. The application of the wave climate extracted near Bredene as well as the increased uncertainty in the reported transport rate for the most southwestern part of the Belgian coast may provide explanations for the disagreement in the UNIBEST-CL+ predicted and earlier reported net alongshore sediment transport rate for location A.

Table 22 – Net alongshore sediment transport for three locations along the Belgian coast as simulated with UNIBEST-CL+*.

Location	Net alongshore sediment transport (m^3/yr)
A – De Panne	214.004
E – Middelkerke	168.291
F – Bredene	243.971

*The transport is calculated using the Bijker (1967, 1971) sediment transport formulation and the wave climate extracted near Bredene for all three locations. De Panne is located most southwest, Bredene is located most northeast.

Thirteen nourishment designs are modelled for a period 30 years post construction. The nourishments have a trapezoidal shape with seaward extents ranging from 150 m to 900 m (Figure 44). The alongshore length is varied to test the effect of nourishment geometry on resultant shoreline changes. Although dependent on the exact cross-shore profile, the smallest nourishment designs typically have an initial volume of 1 million m^3 of sand and the largest ones are up to 30 million m^3 of sand. As a reference, the Sand Engine near Ter Heijde in the Netherlands had an initial volume of about 19 million m^3 of sand.

All nourishment designs show a morphological reshaping from the original trapezoidal shape to a smoother bell shape during the first years post construction. As a result of the reshaping, the head of the nourishment is retreating and sand is being fed to the adjacent beaches, leading here to coastal advance. After 30 years of simulation, the differences in predicted seaward extent and alongshore length for the three locations is limited (Table 23). The predicted retreat in locations A and F is similar, and is about 15 m more shoreward than predicted for location E. The predicted alongshore length differs 500 m with the greatest (smallest) alongshore dispersal for location F (location E).

Table 23 – Comparison of shoreline changes following the construction of a mega nourishment
for the three preferred locations along the Belgian coast*.

Location	Max. seaward extent (m)	Alongshore length (m)	Half lifetime (years)
A – De Panne	118	8300	27.9
E - Middelkerke	133	8200	31.6
F – Bredene	120	8700	25.3

*For each location, nourishment design 06 (seaward extent of 300 m, alongshore length of 2900 m) is used. The maximum seaward extent and alongshore length values apply to 30 years of UNIBEST-CL+ simulation.

For all nourishment designs, morphological changes are initially rapid but they decline as time progresses. For example, maximum retreat rates up to 35-40 m/year near the lateral edges of the nourishment are predicted during the first year post construction for the smallest nourishment designs. Average retreat rates are typically between 5 m/year and 10 m/year during the first five years post construction and lower than 5 m/year after that. Similarly, maximum advance rates up to 40-45 m/year on the beaches directly adjacent to the nourishment are predicted during the first year post construction for the largest nourishment designs. Average advance rates are typically between 3 m/year and 10 m/year during the first five years post construction and lower than 3 m/year after that.

The sand volume decays rapidly during the first years post construction for all nourishment designs. As time progresses, the volume decay decreases. Decay rates depend on the nourishment design and are higher for smaller designs and designs with a lower width-to-length ratio (i.e. greater seaward extent).

The dispersion rate of a nourishment provides important information concerning the planning horizon and cost-effectiveness analyses. Half lifetime is here defined as the number of years required to reduce the sand volume to 50% of its initial nourished volume. Half lifetime for the medium-sized 06 nourishment design is predicted to be between 25 years (location F) and 32 years (location E) (Table 23). A key finding is that half lifetime scales approximately linear with the initial nourishment volume for the same width-to-length ratio. This means that a double sand volume results in approximately a twice as long half lifetime, which allows for straightforward predictions beyond the presented cases in this study.

A striking difference in half lifetime is noted for mega nourishment of similar volume along the Belgian and Dutch coasts. For example, Tonnon et al. (2018) report a half lifetime of about 19 years for a scenario with an initial volume of 20 million m^3 of sand whereas a similar initial volume is predicted to have a half lifetime of about 100 years for the Belgian coast. The differences in half lifetime and rate of shoreline changes more generally between the Belgian and Dutch coasts can be explained by the longshore transport intensity (LTI). For the Dutch coast, Tonnon et al. (2018) use a net alongshore sediment transport rates of 200.000 m^3/year and a coastline orientation that deviates 6.6° from the coastline orientation of net zero alongshore sediment transport for the Dutch coast. Combining these two values gives a LTI of about 30.000 m^3/year/degree. For the Belgian coast, the same net alongshore sediment transport rates of 200.000 m^3/year is used. However, the coastline orientation deviates 30° from the coastline orientation of net zero alongshore sediment transport. Combining these two values gives a LTI of about 6.600 m^3/year/degree for the Belgian coast. Essentially, the lower LTI for the Belgian coast indicates a smaller sensitivity of the alongshore sediment transport for small changes in coastline orientation, i.e. a mega nourishment, along the Belgian coast than observed for the Dutch coast. In turn, gradients in alongshore sediment transport are smaller, resulting in smaller shoreline changes (i.e. erosion and advance), and a longer half lifetime of the nourished sand. In short, sand will remain longer in place along the Belgian coast than the Dutch coast.

The sensitivity of the predicted shoreline changes and dispersion rate to a range of parameters (i.e. wave climate, tides, grain size) is also explored. The outcome of these sensitivity analyses are used to provide upper and lower bound predictions of future shoreline changes. Given the reported net sediment transport ranges in Figure 43, a 10% higher (lower) maximum seaward extent and alongshore length, and a 20% higher (lower) in half lifetime provides a robust upper (lower) bound estimate (Table 23). This sensitivity shows that a half lifetime of about 20 years would be possible if the wave climate in the next 30 years is more energetic than the one used during this simulation. However, an analysis of the wave climate in the Belgian part of the North sea during the last 30 years as part of this study shows no trend in wave energy and the number of winter storms. As such, historical observations as used during this study provide the best predictor for the future wave climate along the Belgian coast.

UNIBEST-CL+ is well suited to address long-term (decadal) shoreline changes due to its computational efficiency, but it also has a number of limitations. The model assumes approximately parallel depth contours, gradually varying flow conditions and a constant cross-shore profile. However, the nearshore bathymetry of the Belgian coast is complex and shows a number of tidal sandbanks. Process based models for the coasts such as Delft3D and Telemac can resolve variations in cross-shore as well as alongshore directions and they are better suited to explore the effects of the non-uniform bathymetry on the evolution of a mega nourishment. Moreover, the effect of the tidal currents can be explored with this type numerical models. A schematised and simplified wave climate is used in this study with 91 conditions representing the 10-year climate, not varying along the coastline (extracted at Bredene location), so even the effect of individual storms can be better explored using more complex models.

In this study, the alongshore sediment transport post-construction of a mega nourishment along the Belgian coast is evaluated using the coastline model UNIBEST-CL+. This model is validated using measurements on cross-shore position and volume decay from a nourishment near Mariakerke. The model is used to predict shoreline changes (coastal retreat and advance, alongshore dispersion) and dispersion rate of a series of idealized mega nourishments with various width-to-length ratios and sand volumes. Quantitative estimates of shoreline retreat, feeding of sand to adjacent beaches and dispersion rate are provided. A linear relation is found between the half lifetime and the initial sand volume for nourishments with the same width-to-length ratio. Sensitivities to the wave climate, bathymetry and sediment characteristics are explored to provide quantitative input for feasibility studies on a possible mega nourishment along the Belgian coast.

5 Cost-benefit analysis of a feeder-type mega nourishment

A mega nourishment has the potential to be a more cost effective way to maintain coastal safety as well as the coastline position under accelerated sea level rise compared to traditional nourishment methods. The reasoning is that the larger volume of sand involved in a mega nourishment is expected to lower the price per cubic meter (i.e. economy of scale). So although the initial investment may be higher due to the larger sand volume, the costs may be lower across the lifecycle of a mega nourishment compared to traditional methods in which the beaches are nourished annually.

Another reason for a feeder-type mega nourishment to be more cost effective than the traditional methods is the different type of nourishment involved. In the traditional method, the beach is generally nourished, but this is relatively expensive because of the high costs involved in transporting the sand from the sea to the beach. Shoreface nourishments are generally cheaper and it is anticipated that the majority of a mega nourishment is constructed as a shoreface nourishment.

A cost-effectiveness analysis was also performed for the Sand Engine along the Dutch coast (Oost *et al.*, 2016). Prior to construction, in 2010, the insights on sand requirements and the prices of sand indicated that the construction of the Sand Engine was attractive, even if the added value from the creation of additional nature and recreation opportunities was not taken into consideration. In 2016, five years post-construction, the construction of the Sand Engine would not have been cost effective anymore due to substantially lower sand prices for regular nourishments as well as new insights into the volume of sand that is required annually. A key learning from a financial point of view is that a mega nourishment can be considered an effective coastal management tool if the economy of scale reduces the sand price significantly, and should therefore be timed accordingly (e.g. low prices due to availability of dredging material in close vicinity).

It is also noted in the evaluation of the Sand Engine project that the additional functions and values created in constructing a mega nourishment may provide alternative motivations to initiate such a project, even if it is not financially attractive from the coastal maintenance perspective alone. Also, a possible increase in the annual amount of sand required for coastal maintenance, in relation to accelerated sea level rise, might change the perspective, because it would become financially attractive to nourish on a larger scale.

A cost effectiveness assessment can be made transparent with a Life Cycle Costing (LCC) calculation (de Weerdt, 2015). In an LCC calculation, different scenarios of the price of sand, lifespan of the nourishment, maintenance needs and interest rate are used to make a systematic and quantitative comparison between “regular” coastal maintenance and an alternative including the construction of a mega nourishment.

Below, the assumptions on sand volume, cost, lifespan and interest rate for a number of feeder-type mega nourishment scenarios are introduced first. Then, these scenarios are compared to the regular coastal management for the same coastal stretch.

5.1 Assumptions on sand volumes, price of sand, lifespan and interest rates

The parameters needed to evaluate the cost effectiveness are the interest rate, the nourishment volume, the price of sand and the projected lifespan of the nourishment. Information on these parameters and the motivation for specific choices is provided below. Following specification of these parameters, a number of possible scenarios for the construction of a feeder-type mega nourishment are defined.

5.1.1 Interest rate

The interest rate quantifies the rate of growth of money per unit of time. It is used to determine the present and future value of money and annuities. The present value (*PV*) can be calculated with the future value (*FV*), the interest rate *(i*) and the number of years from present (*n*) according this formulation:

$$PV = \frac{FV}{(1+i)^n} \tag{1}$$

It is important to adjust the interest rate for inflation, such that a *real* interest rate is used in the calculations. Data from the World Bank shows that the *real* interest rates for Belgium varied between 7.2% and 8.8% between 2008 and 2016 (Table 24). Real interest rates of up to 12.5% have been recorded for Belgium during the eighties whereas interest rates were as low as 4% during the early 2000s. These values highlight that the real interest rate across decadal timescales is highly uncertain. Note that the real interest rate can be considered a discount rate when a delayed investment is made (i.e. annual nourishment vs. a one-off mega nourishment).

Table 24 – Real interest rate for Belgium across the period 2008 to 2016*.

Year	2008	2009	2010	2011	2012	2013	2014	2015	2015	2016
Interest rate (%)	7.2	8.7	7.5	7.4	7.4	8.4	8.8	8.3	7.8	7.2

*From data.worldbank.org.

For government purposes, a lower real interest rate is generally assumed because the delayed investment is used for other societal purposes (de Nocker & Broekx, 2011). In the report '*MKBA Kustveiligheid – beoordeling alternatieven per zone*' a real interest rate of 4% is used up to 2050 and a 2.6% rate between 2050 and 2100. To align with this report on the Belgian coastal safety, real interest rates up to 4% will be evaluated in this study and the sensitivity to real interest rate between 0% and 4% is evaluated.

5.1.2 Price of sand

The average price per cubic meter of nourishment sand for the Belgian nourishment program is estimated at €5 for foreshore nourishments and €10 for beach nourishments (Table 25). For the regular nourishment program, it can be assumed an average ratio of shoreface and beach nourishments is 50/50. Given the aforementioned prices, this would result in an average nourishment price of €7.5 per m^3 of sand. The annual nourishment volume along the Belgian coast is 500.000 m^3 of sand, which results in an annual investment of €3.75 million.

The Sand Engine in the Netherlands had a total cost of about €50 million. Given the total nourishment volume of 19.5 million m^3 of sand, the nourishment price was €2.6 per m^3 of sand. Based on the pricing of sand for a foreshore nourishment (€4.5/m^3) and beach nourishment (€8.5/m^3) in the Netherlands at that time (i.e. period 2007-2011), a cost reduction of 40% (relative to regular foreshore price) to 70% (relative to regular beach price) was obtained due to economy of scale. Translating this cost reduction to the Belgian case suggests that a nourishment price of €3 per m^3 of sand may be expected for a Belgian mega nourishment of similar size (Table 25). It is likely that the economy of scale effect is smaller for smaller nourishment designs, which would lead to a higher price per m^3 of sand than the aforementioned €3.

Table 25 – Nourishment prices for the Belgian coast*.

Nourishment type	Sand price (€/m^3)
Beach	10
Shoreface	5
Mega	3

*Price level of 2010-2017. The prices of the beach and shoreface nourishments are based on the regular nourishment program. The price of the mega nourishment is unknown and estimated here based on the cost reduction obtained for a mega nourishment (i.e. the Sand Engine) relative to a regular shoreface or beach nourishment in the Netherlands.

5.1.3 Nourishment volume and assumed lifespan

Different mega nourishment scenarios can be distinguished on size (a small, medium and large mega nourishment (Table 26)). As a first approximation lifespan is assumed equal to the half lifetime, which is defined as the number of years required to reduce the sand volume to 50% of its initial nourished volume (cfr. work package 4 with results from UNIBEST-CL+ simulations). In follow-up studies a location-dependant lifespan has to be determined, considering the boundaries around a feeder-type mega nourishment location, e.g. the presence of harbours and the cross-shore transport between coastline and nearby sea bottom. The medium size mega nourishment will be considered, because it is assumed lifespan matches with the time horizon until 2050 (30 years).

Table 26 – Initial volume and assumed lifespan of a small, medium and large mega nourishment as calculated with UNIBEST-CL+. The total costs are calculated using a sand price of €3 per m^3.

Nourishment	Volume (million m^3)	Assumed lifespan (years)	Cost (million €)
Small	0.75	7.6	2.25
Medium	3.25	25.3	9.75
Large	12.5	79.1	37.5

5.1.4 Definition of scenarios

This cost assessment examines to what extent a feeder-type mega nourishment along the Belgian coast is cost effective. More specifically, how will the comparison between the regular coastal maintenance and a mega nourishment work for different scenarios of the price of sand, the volume of sand, the lifespan and interest rates. It is assumed that regular maintenance and a mega nourishment are equally effective in terms of coastal safety and no nourished cubic meters are lost. Therefore, this study is limited to a comparison of the alternatives based on an analysis of the costs, which are made transparent with a Life Cycle Costing (LCC) calculation.

Three alternatives of "regular" coastal maintenance are defined:

i) Regular maintenance of Belgian coastline with an annual volume of sand of 0.5 million m^3. This volume applies to the entire coastline of Belgium with a total length of 67 km. Independent of the exact location of a mega nourishment, the Belgian coastline can be subdivided into smaller coastal cells of about 15 km alongshore length bounded by harbours (i.e. Nieuwpoort, Oostende, Blankenberge, Zeebrugge). It is assumed that the majority of the sand from a mega nourishment will remain within a coastal cell. For a fair comparison, the volume of sand for the regular maintenance program along a 15-km coastal stretch is included. Therefore, we assume an annual volume of sand of 125.000 m^3 for the regular nourishment program. Given a price of €7.5 per m^3 of sand, this amounts to €937.500 for a 15-km coastal stretch in the regular nourishment program on an annual basis.

ii) It is likely that sand volume required for regular maintenance will increase into the future due to accelerated sea-level rise. For the Belgian coast, sea level is projected to rise about 15 cm to 35 cm by 2050 (Church *et al.*, 2013). Simplified geometrical calculations indicate that an additional sand volume of 2.6 million m^3 will be required to compensate this volume (i.e. assuming an elevation of 0.35 m and a coastal profile of 500 m across a coastal stretch of 15 km). On a yearly basis, this will require an additional sand volume of about 80.000 m^3 during 32 years (2018-2050). Adding this sand volume needed to compensate for accelerated sea-level rise to the on-going annual sand volume for regular maintenance results in an annual volume of about 200.000 m^3. Given a price of €7.5 per m^3 of sand, this amounts to €1.5 million for a 15-km coastal stretch in the regular nourishment program on an annual basis.

iii) Furthermore, a scenario in which regular nourishments are further intensified is evaluated. For this scenario, an annual nourishment volume of about 500.000 m^3 (i.e. four times the current volume) for a 15 km coastal stretch is evaluated. Given a price of €7.5 per m^3 of sand, this scenario amounts to €3.75 million for a 15 km coastal stretch in the regular nourishment program on an annual basis. Note that this latter scenario corresponds to an annual nourishment volume of 2 million m^3 for the entire Belgian coast with an annual cost of €15 million.

One alternative feeder-type mega nourishment scenario is defined:

- Nourishment volume of 3.25 million m^3 (in situ)
- Construction price is €9.75 million (using 3 euro/m^3)
- Considering the half lifetime calculation result of 25.3 years, a lifespan of 30 years is assumed
- No maintenance costs

5.2 Results

All prices are compared after a period of 30 years. This period is consistent with the planning horizon 2050 outlined in Masterplan Kustveiligheid (2011). Two parameters determine the cost effectiveness of a mega nourishment along the Belgian coast. Firstly, the economy of scale is expected to reduce the price per cubic meter of sand. In agreement with the price reduction observed for the Sand Engine in the Netherlands, a 40% reduction relative to the regular foreshore nourishment price is assumed here for the Belgian coast. Consequently, the large investment is expected to result in a lower price.

Secondly, making a single, large, early investment is generally more expensive than spreading smaller investments over time, which can partly be done at a later time. Whether this effect is significant or negligible is dependent on the interest rate in the following years. Figure 67 shows that the interest rate has a large effect on the costs of the regular nourishment program. Without interest, the costs increase linearly with the time horizon. For a more realistic interest rate of 4%, the present value of the costs increases slower with the time horizon.

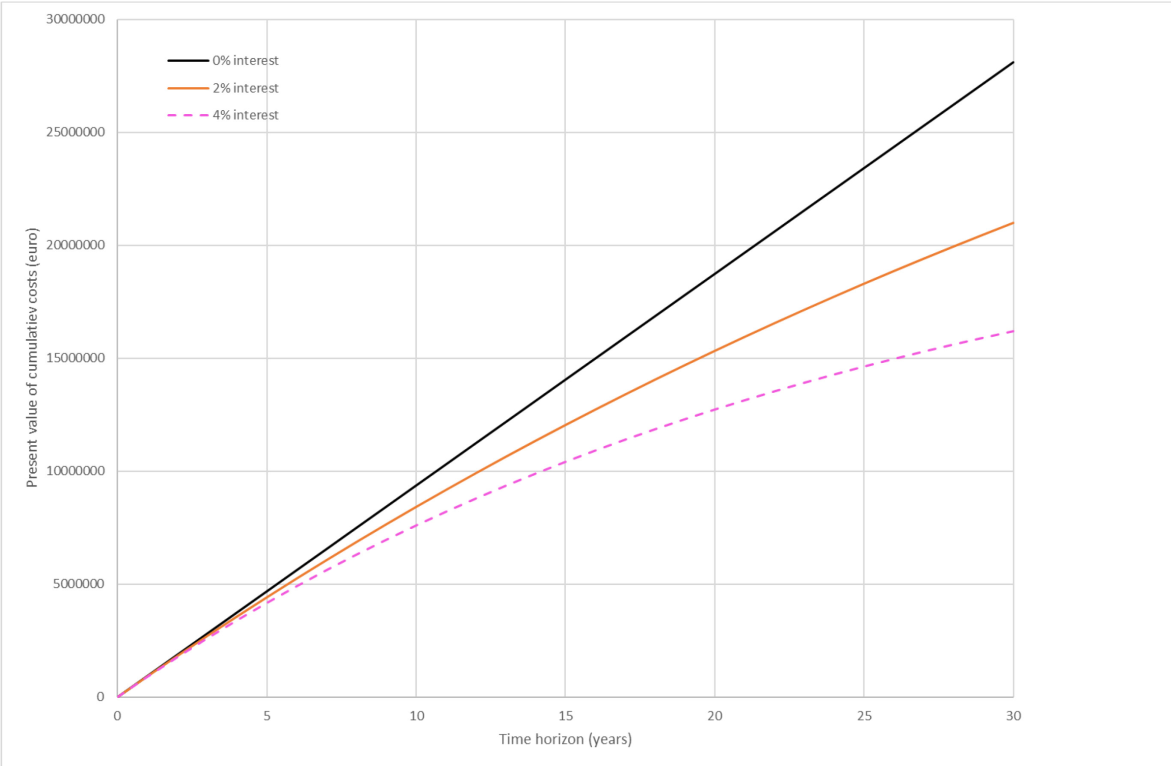

Figure 67 – Effect of interest rate on present value of cumulative costs of regular nourishment program, assuming 125.000 m^3 annual nourishment volume, for different time horizons.

An increase in the annual nourished sand volume results in an increase in the cumulative costs (Table 27). When taking into account the nourishment requirement to grow with sea-level rise (200.000 m^3/year for a 15 km stretch of coast), the costs range between €26 million and €45 million depending on the interest rate after a period of 30 years. When significantly expanding the current nourishment practice to an annual volume of 500.000 m^3 per year (for a 15 km stretch of coast), the costs increase to €65 million for a 4% interest rate and more than €112 million for a 0% interest rate after a period of 30 years.

Table 27 – Cumulative costs (**in million €)** after a 30-year period of three scenarios of regular nourishment program intensities as a function of the interest rate.

	125.000 m^3/yr	**200.000 m^3/yr**	**500.000 m^3/yr**
0% interest	28.1	45.0	112.5
2% interest	21.0	33.6	84.0
4% interest	16.2	25.9	64.8

The total amount of nourished sand for the 125.000 m^3/year regular nourishment program is equal to 3.75 million m^3. This is a similar amount as the 3.25 million m^3 for the feeder-type mega nourishment scenario. The cost of this mega nourishment scenario of €9.75 million is less than the cost of the regular nourishment program (between 16 and 28 million € depending on the interest rate). When accelerated sea-level rise is taken into account, the required sand volumes will increase and medium sized mega nourishments can be expected to become even more cost effective.

This cost-effectiveness analysis indicates that a mega nourishment should be considered a tool of opportunity for Belgian coastal managers. The tool can be employed when sand is available at a low cost relative to the regular nourishment program, and when the interest rate is low relative to the decadal average.

Note that this calculation of cost effectiveness only considers an analysis of the coastal maintenance. To obtain an overall cost effectiveness, one should also include decadal sand balance evaluations considering all boundaries (e.g. potential losses of sand cross-shore), as well as the potential advantages and disadvantages of other functions associated with a mega nourishment such as opportunities for recreation and nature development. These aspects are, however, difficult to quantify and will also depend on the chosen location as well as the specific design of the mega nourishment.

6 Conclusions

Feeder-type mega nourishments represent a new and innovative approach to coastal management. The traditional management approach involved placing structures and using dune, beach and shoreface nourishments as interventions to obtain immediate effect. In contrast, mega nourishments are designed to *work with nature on a decadal time-scale* and, as such, represent a new and innovative approach to coastal management. Mega nourishments represent a paradigm shift in coastal management. Advantages of feeder-type mega nourishments compared to the traditional nourishment methods include:

- Lower unit cost per cubic m for nourishments. A large volume of sand is placed at a fixed location in one operation.
- Less disturbance of the coastal ecosystem. The nourishments will take place less often and in fewer areas than at the present time.
- The newly created space, although temporary, can be used for nature and recreation and it can provide new opportunities for the local ecosystems.
- Strategic reserve of sand. A large volume of sand available in the nearshore system for long-term adaptation to climatic changes (e.g. increased storminess, accelerated sea-level rise).

Potential disadvantages of a feeder-type mega nourishments are:

- Access of harbours may be impeded due to sand from the nourishment entering.
- Disturbance of local coastal system and a negative impact on ecology initially.
- Significant financial effort over a short time.

A feeder-type mega nourishment provides a multifunctional solution to address some of the longer-term (i.e. decadal) challenges of the Belgian coast. Firstly, the multi-functionality of a feeder-type mega nourishment allows to create opportunities for nature development and new types of recreation in addition to the offered coastal protection. In doing so, new and attractive coastal landscapes can be created along the Belgian coast. Secondly, the availability of more sand in the coastal profile can be part of a flexible and no-regret solution for long-term adaptation to accelerated sea level rise and possible changes in storminess resulting from climate change.

This study has explored possible locations for feeder-type mega nourishments along the Belgian coast. Initially, the current usage and functions of the Belgian coast were mapped. Then, locations with excellent opportunities for a feeder-type mega nourishment were identified based on the ability to provide coastal protection and the potential to develop new types of recreation/tourism and nature. Eight locations along the Belgian coast between the Belgian-French border and Blankenberge (east of Blankenberge is out of scope for this study) were shortlisted as opportune for a feeder-type mega nourishment with two locations as clear front runners: i) Bredene to De Haan, and ii) Middelkerke to Mariakerke.

For the Bredene to De Haan location, good opportunities for nature and recreation development exist. A potential strength is also the absence of large infrastructure such as roads and coastal towns along this coastal stretch. The absence of infrastructure leads to wider dunes, in places up to 400 m, which could be connected to a mega nourishment. This connection is essential for keeping the sand in the active beach area for longer time and improve the beach capacity to respond extreme events. A potential weakness is that coastal safety is not a major issue along this coastal stretch.

For the Middelkerke to Mariakerke location, good opportunities for nature and recreation development exist towards the west, while coastal safety issues are also a concern towards the east (i.e. for sections 97-106). A potential strength is the overall considerable coastal safety issue in coastal cell 2 from Nieuwpoort to Oostende, which may partly be addressed by a mega nourishment. Essentially, a mega nourishment in this location may provide coastal cell 2 with sufficient sand to widen the beaches along a substantial part of the cell. In turn, the wider beaches will provide a greater safety barrier to storms and thus raise the overall safety level of this coastal stretch. It is clear from the analysis in Chapter 3 that the greatest opportunities for a mega nourishment from the coastal safety perspective are located in coastal cell 2 from Nieuwpoort to Oostende. A potential weakness is the proximity of Oostende harbour towards the east. This weakness may be addressed by constructing the mega nourishment towards the western part of the locality. Another potential weakness is the presence of the sea dike and road close to the beach for large parts of this coastal cell. The dike and road disconnect the beach from the dunes and will also provide limitations to the accepted sand dynamics (i.e. sand transport driven by wind, dune dynamics). This weakness may be addressed by the creation of a new dune in front of the dike.

For these two preferred locations, thirteen idealized feeder-type mega nourishments with various width-to-length ratios and sand volumes are evaluated in Chapter 4. At construction, these mega nourishments have a seaward extent ranging from 150 m to 900 m, an alongshore length of 1500 m to 8900 m, and sand volumes ranging from about 1 million cubic meter of sand to 25 million cubic meter of sand. For reference, the sand volume of the Sand Engine mega nourishment in the Netherlands was about 20 million cubic meter of sand.

Using the coastline model UNIBEST-CL+, quantitative estimates of shoreline retreat, feeding of sand to adjacent beaches and lifespan of all thirteen mega nourishments are provided. Qualitatively, these mega nourishments can be subdivided into ‘small’, ‘medium’ and ‘large’ designs. For this purpose, the small designs refer to mega nourishments between 1 and 5 million cubic meter of sand. The medium designs refer to mega nourishments between 5 and 10 million cubic meter of sand. The large designs refer to mega nourishments larger than 10 million cubic meter of sand. The small designs are consistent with the ongoing larger nourishment projects along the Belgian coast such as the Mariakerke combined beach and shoreface nourishment as well as the planned Knokke-Heist nourishment. The large designs are disproportionately large compared with the annual nourishment volume of about 500.000 cubic meter of sand for the entire Belgian coast. The medium designs provide the most appropriate solution because they build most logically on current nourishment practices.

The cost-effectiveness analysis in Chapter 5 also indicates that medium sized mega nourishments can be considered a tool of opportunity. The tool can be employed when sand is available at a low cost relative to the regular nourishment program, and when the interest rate is low relative to the decadal average. In these cases, a mega nourishment can be a cost-effective coastal management tool. Note that this calculation of cost effectiveness only considers coastal maintenance. To obtain an overall cost effectiveness, one should also include the potential advantages and disadvantages of other functions associated with a mega nourishment such as opportunities for recreation and nature development. When accelerated sea-level rise is taken into account, the required sand volumes will increase and medium sized mega nourishments can be expected to become even more cost effective.

UNIBEST-CL+ predicts a half lifetime of 20 to 75 years for these medium mega nourishment designs, depending on the design. As a rule of thumb, a greater seaward extent results in faster dispersion of the nourished sand from the nourishment location. The model simulations show a nearly symmetrical dispersion of the sand to the southern and northern beaches, despite the presence of a net alongshore sediment transport directed towards the north east. The symmetrical dispersion of the nourishment is consistent with observed behaviour for other large nourishments such as the Dutch Sand Engine. Furthermore, model simulations indicate that twice the volume of sand will result in a twice as large lifetime for the same nourishment design. This implies that predictions beyond the tested cases in this study can robustly be made.

A key observation is that the half lifetimes predicted by UNIBEST-CL+ for the Belgian coast are substantially higher than the half lifetimes predicted for the Dutch coast in Tonnon et al. (2018), despite similar net alongshore sediment transport rates of 150.000 to 300.000 m^3/year. For example, for a scenario with an initial volume of 20 million m^3 of sand Tonnon et al. (2018) predicted a half lifetime of about 19 years. For a nourishment with a similar initial volume along the Belgian coast, the predicted half lifetime is about 125 years. This difference is partly explained by the greater alongshore length of the nourishment design in the Belgian case slowing down the volume decay.

However, a more fundamental explanation for the difference in half lifetime for the Belgian and Dutch coasts is a lower Longshore Transport Intensity (LTI) for the Belgian coast. The LTI quantifies the sensitivity of the alongshore sediment transport to changes in coastline orientation. For the Dutch coast, Tonnon et al. (2018) use a net alongshore sediment transport rates of 200.000 m^3/year and a coastline orientation that deviated 6.6° from the coastline orientation of net zero alongshore sediment transport. Combining these two values gives a LTI of about 30.000 m^3/year/degree. For the Belgian coast, the same net alongshore sediment transport rates of 200.000 m^3/year can be used. However, UNIBEST-CL+ indicates that the coastline orientation deviates 30.1° from the coastline orientation of net zero alongshore sediment transport. Combining these two values gives a LTI of about 6.600 m^3/year/degree for the Belgian coast. Essentially, the lower LTI for the Belgian coast indicates a smaller sensitivity of the alongshore sediment transport for small changes in coastline orientation, i.e. a mega nourishment, along the Belgian coast than observed for the Dutch coast. Consequently, gradients in alongshore sediment transport are smaller, resulting in smaller shoreline changes (i.e. retreat and advance), and a longer half lifetime of the nourished sand. In short, sand will remain longer in place along the Belgian coast than the Dutch coast. On the one hand, this slower dispersion behaviour is beneficial because the coastal protection function is maintained longer for the nourishment location. On the other hand, feeding of sand to the adjacent beaches is slower and therefore the coastal protection function is also lower in the adjacent areas.

Sensitivities of the model simulations to a range of hydrodynamic, bathymetric and sediment characteristics are explored. This analysis indicates that the results are primarily sensitive to the applied sediment transport formulation and the wave propagation direction. The applied alongshore sediment transport rates based on a 10-year wave climate are shown to vary annually by a factor of 4 and are consistent with earlier sediment budget studies for the Belgian coast. Furthermore, an analysis of 30 year of wave observations from Westhinder wave station suggests that the applied reference wave climate provides the best predictor for the future wave climate along the Belgian coast because no evidence was found for changes in wave characteristics during this period.

It is important to note that the applied coastline model UNIBEST-CL+ has limitations in terms of predictive ability of shoreline changes. The coastline model is computationally efficient but many processes are not included. For example, UNIBEST-CL+ assumes a uniform cross-shore profile and a constant depth of closure neglecting alongshore and most cross-shore bathymetric variations. Given the significant cross-shore bathymetric differences along the Belgian coast due to the presence of tidal sand banks, the presented results are only representative for the location they were derived for. Process based models for coastal areas such as Delft3D or TELEMAC may be used to provide additional insights on the morphological evolution of a feeder-type mega nourishment, including e.g. the effect of a non-uniform bathymetry and the effect of tidal currents on the alongshore sand transport.

Feeder-type mega nourishments provide a living laboratory in which coastal protection, ecology and economic development are combined and can be showcased to outsiders. It is therefore recommended to set up a pilot feeder-type mega nourishment project along the Belgian coast. Such a pilot will provide the answers to many of the uncertainties and open questions still remaining after the modelling exercises. A detailed monitoring plan would have to be made to measure and observe the morphological, ecological and socio-economic evolution post construction of such a pilot. A similar monitoring plan is currently undertaken for the Sand Engine pilot mega nourishment in the Netherlands, but the results from this project cannot be 1:1 translated to the Belgian coast due to the differences between the Dutch and Belgian coasts. The two preferred locations for a feeder-type mega nourishment along the Belgian coast (i.e. Middelkerke - Mariakerke, Bredene – De Haan) would be suitable locations for such a pilot project.

When adhering to the *work with nature* philosophy, further project development of the potential feeder-type mega nourishment pilots will require co-creation between experts from different disciplines and stakeholders including community members and field practitioners to reach the best possible solution to prepare the Belgian coastal zone for future challenges.

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Appendix

Data on the morphodynamic evolution of mega nourishments is scarce. Mega nourishments are a relatively new tool in coastal management and many uncertainties still exist about their evolution post construction. Detailed monitoring of existing and planned mega nourishment projects is therefore crucial to gain a better understanding on their morphodynamic evolution. In turn, morphodynamic models such as Delft3D and UNIBEST-CL+ rely on high-quality observations to be able to make robust predictions of future shoreline changes.

In the Netherlands, about seven years of data is now available for the Sand Engine mega nourishment project (de Schipper et al. 2016; Luijendijk et al. 2017). A hindcast shows that both complex coastal area models such as Delft3D and simpler coastline models such as UNIBEST-CL+ are capable of simulating the observed shoreline changes following the construction of the Sand Engine on the short term (i.e. first five years post construction) (Tonnon et al. 2018). Longer observational time series are required to ensure that also the long term (> five years) shoreline changes are captured by these models.

In Belgium, a mega nourishment has not been constructed. Yet, a large nourishment was done in Mariakerke in 2014. The beach-shoreface nourishment has a total volume of about 1Mm^3 of sand and is carefully monitored in terms of hydrodynamic forcing and morphological changes. Therefore, the data from the Mariakerke nourishment provides a good opportunity to calibrate the UNIBEST-CL+ model for the hydrodynamic forcing and coastline morphological response along the Belgian coast. The Mariakerke nourishment provides a unique case to test how well the UNIBEST-CL+ model can replicate the observations on shoreline change resulting from one of the largest nourishments to date along the Belgian coast.

First, some background information on the Mariakerke nourishment is provided, including the motivation for the project, location and dimensions of the nourishment. Second, the morphological changes post construction are described with a focus on cross-shore profiles because these will be compared to the UNIBEST-CL+ simulations. Then, the UNIBEST-CL+ model settings are described and motivated. Last, the observations of the Mariakerke nourishment are compared to the UNIBEST-CL+ hindcast simulations and sensitivity analyses on the hydrodynamic forcing, sediment transport formulation, inclusion of structures and sediment sources are performed.

Mariakerke nourishment

The Flemish Government aims to reinforce all weak coastal sections to meet the required safety levels to respond to a storm-event with a return-period of 1000 years till the year 2050, expressed in a vision for the Flemish Bays (2014). The vision includes sustainable engineering and the creative use of soft coastal protection measures, as an alternative to the traditional hard structure solutions. Many uncertainties still exist around these soft protection measures. The Mariakerke coastal area, one of the weakest links along the Belgian coast in terms of protection against storms (Kust 2011; De Roo 2018), was selected to serve as a pilot project. The pilot included a combined beach and shoreface nourishment, and a detailed monitoring scheme to track the hydrodynamic conditions and resultant shoreline changes.

Mariakerke is located in the coastal cell between Nieuwpoort harbour and Oostende harbour. The study area involves coastal sections 80-117 (Figure 68), with special interest in sections 102-110 because here the combined beach and shoreface nourishment was constructed. This coastal stretch generally shows erosion (~8 m^3/m/yr) and the beach near Mariakerke is typically nourished annually (Houthuys 2012). Infrastructure such as buildings and roads are build up to the beach and dunes are therefore absent. Groynes are present and spaced about 400 m in alongshore direction.

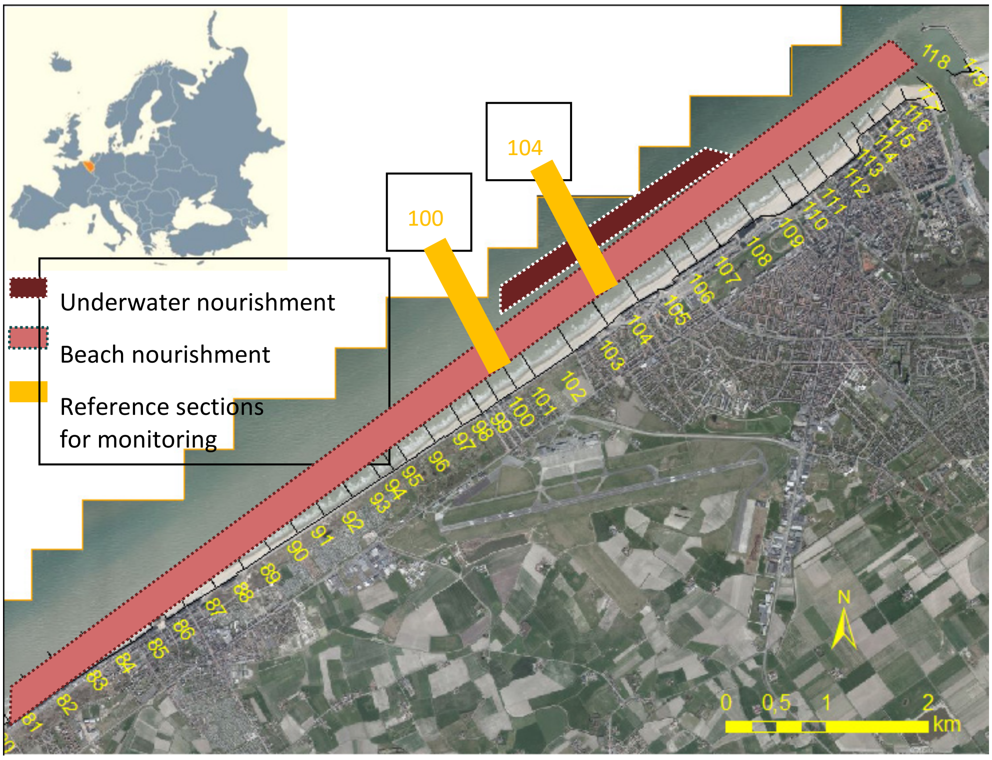

Figure 68 – Mariakerke shoreface nourishment location and reference sections*.

*Figure from Dan et al. (2016).

The Mariakerke pilot involved the execution and monitoring of a combined beach and shoreface nourishment and the comparison to an adjacent coastal stretch where only a beach nourishment was constructed (Figure 68, section 100 is beach nourishment only, section 104 is a combined beach and shoreface nourishment). Here, we will focus on the combined beach and shoreface nourishment (i.e. section 104) because a shoreface nourishment is governed by hydrodynamic processes that can be simulated with the UNIBEST-CL+ model, in contrast to a beach nourishment for which other processes such as wind transport and human disturbances may also play a role.

A large beach nourishment (872.100 m^3) was constructed in coastal sections 97 to 106 during the October 2013 to February 2014 period (Figure 68). This beach nourishment was complemented by a shoreface nourishment of 303.800 m^3 of sand in April-May 2014. The total sand volume of the combined beach and shoreface nourishment is 1.175.900 m^3. The combined nourishment affects the position of the local shoreline over an alongshore length of 2500 m with a maximum seaward extent of 50 m. The length-to-width ratio of the combined nourishment is 50.

It is important to note that the Mariakerke coastal area is heavily managed and nourished. In addition to the aforementioned nourishments as part of the pilot project, a number of additional beach nourishments were done on nearby beaches during the study period. For example, beach nourishments took place for sections 74-89 (968.800 m^3) between April and June 2014, for sections 97-102 (190.900 m^3) in June 2014, and for sections 82-87 (118.900 m^3) in 2015 (Dan et al. 2016). Since these nourishments were done relatively close to the study area, it is likely that sand from these nourishments has entered the study area and has affected the morphological response, although it is unknown to what extent. This nourishment history illustrates that the Mariakerke pilot is not an ideal case to calibrate the UNIBEST-CL+ model for the Belgian coast, but it is the best one available in terms of observations and type of nourishment (i.e. shoreface). Some of the uncertainties (e.g. the role of sediment sources due to additional nearby nourishing) will be explored in the sensitivity analysis.

The Lidar and single beam surveys provide insights into the morphological changes post construction of the combined shoreface and beach nourishment (Figure 69 to Figure 74). Figure 69 shows accretion in the Mariakerke area (section 104) due to the construction of the beach nourishment. Accretion is also visible for the adjacent northern beaches as a result of an earlier beach nourishment here. Figure 70 shows a positive sediment budget for the emerged beach in the Mariakerke area in 2017, about three years post construction. Some morphological reshaping has taken place in 2017 with some erosion relative to 2014 closer to the edges of the Mariakerke area but the majority of the beach nourishment is still in place.

Figure 71 shows accretion in the Mariakerke area (section 104) due to the construction of the shoreface nourishment. The sand thickness is generally about two to three meters and the shoreface nourishment continues north of the Mariakerke area. Figure 72 shows a positive sediment budget for the shoreface in the Mariakerke area in 2017, about three years post construction. Morphological reshaping has smoothed the constructed nourishment design. The reshaping has resulted in limited coastline retreat and an overall migration of sand towards the northeast, which is consistent with earlier observations on the net alongshore sediment transport along the Belgian coast (Vandebroek et al. 2016). Also, an accretion of sand has taken place on the shoreface of the adjacent northern beaches in 2017 (Figure 72). The northern shoreface accretion is likely the result of the beach nourishment along this coastal stretch in 2013 as well as sediment transport from the nourished sand in the Mariakerke study area. The accreted shoreface in the Mariakerke study area (Figure 71) has connected with the accreted shoreface of the northern beaches in 2017 (Figure 72).

The evolution of the cross-shore profiles provides additional insight into the morphological reshaping following a combined beach and shoreface nourishment (Figure 73) and a beach nourishment only (Figure 74). The beach as well as the shoreface nourishment result in a seaward displacement of the coastal profile of about 50 meters (Figure 73). In the first year post construction, some morphological reshaping of the profile takes place while the profile changes are minimal after 2015 . Between 2014 and 2015, some sand of the shoreface nourishment is transported landward while sand of the beach nourishment is moved seaward, essentially smoothing the profile. Minimal changes occur on the seaward side of the profile, suggesting that most of the sand remains within the profile and the -6 m TAW level provides a good estimate of the depth of closure across the 2013-2017 period.

The profile evolution following a beach nourishment show limited changes (Figure 74), in agreement with profile evolution for the combined beach and shoreface nourishment (Figure 73). The 2015, 2016, and 2017 profiles show some transport of sand from the upper parts of the nourished beach to lower parts. But overall, changes are limited and retreat and advance rates are in the order of meters rather than tens of meters.

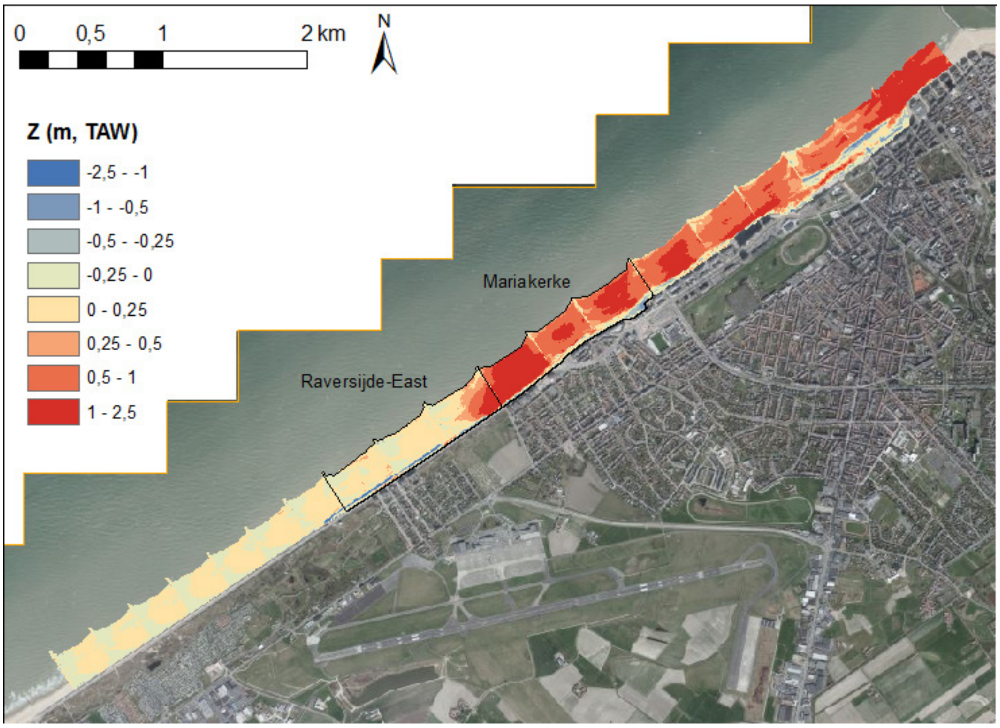

Figure 69 – Elevation changes for the emerged beach between April 2014 (immediately post construction) and April 2013 (pre nourishment)*.

*Figure from Dan et al. (2016).

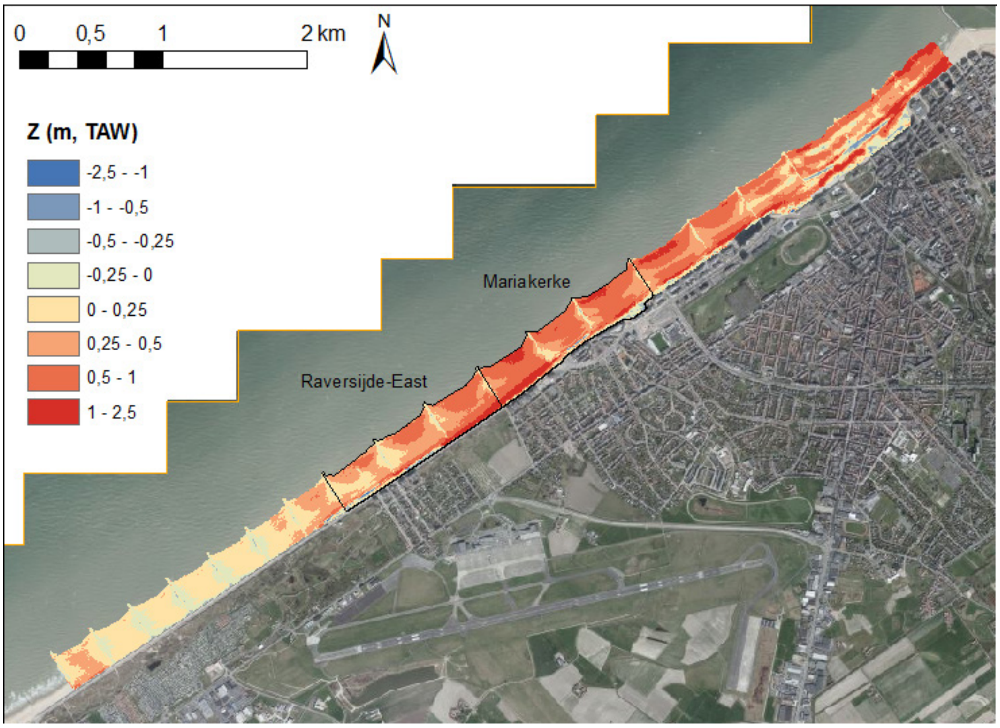

Figure 70 – Elevation changes for the emerged beach between January 2017 and April 2013 (pre nourishment)*.

*Figure from Dan et al. (2016).

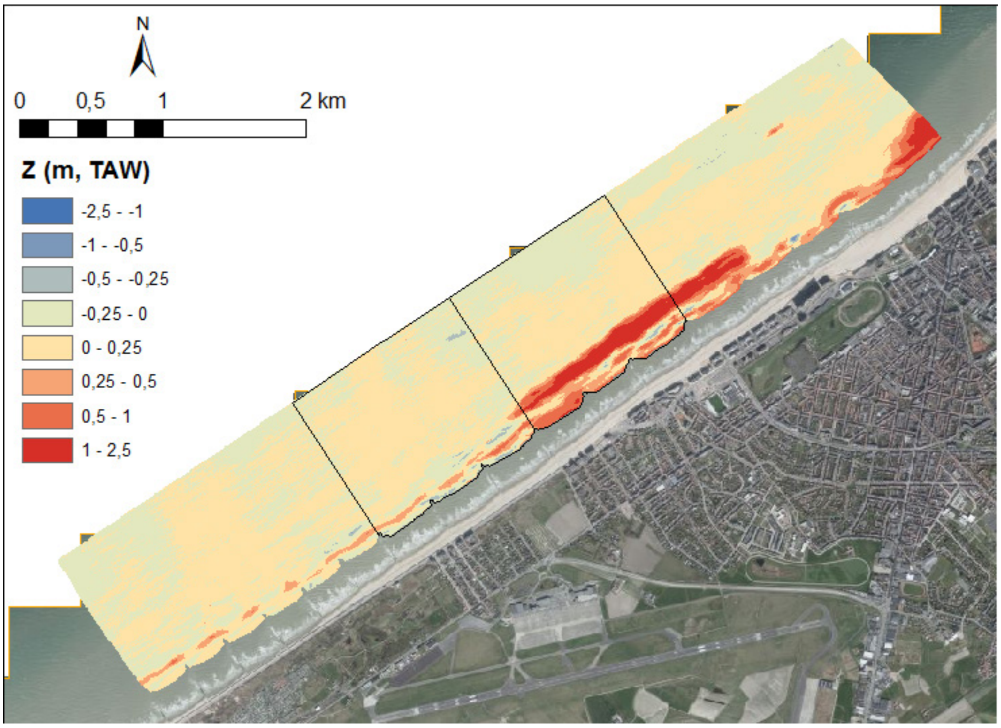

Figure 71 – Elevation changes for the shoreface between May 2014 (immediately post nourishment) and April 2013 (pre nourishment).

Figure from Dan et al. (2016).

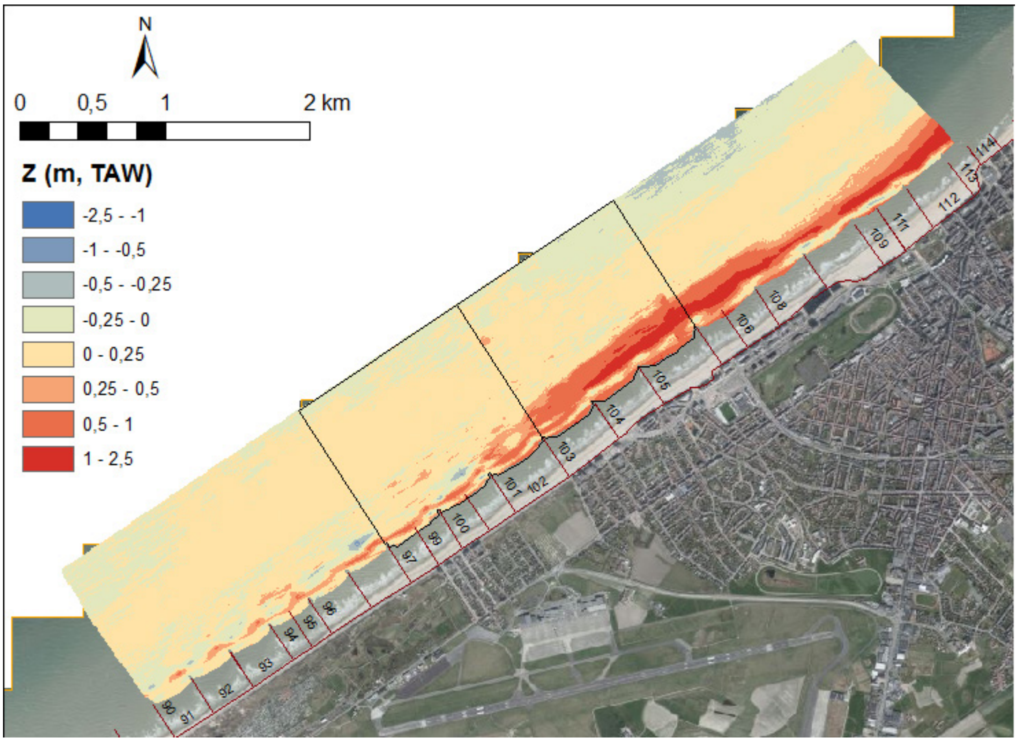

Figure 72 – Elevation changes for the shoreface between January 2017 and April 2013 (pre nourishment).

Figure from Dan et al. (2016).

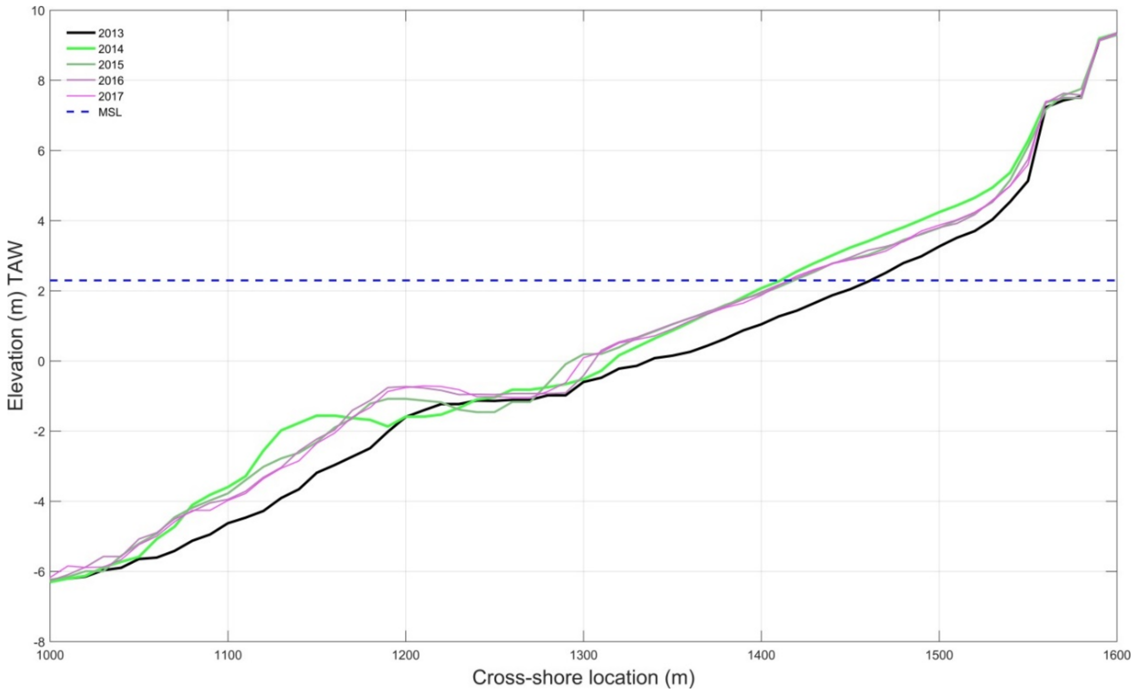

Figure 73 – Profile evolution between 2013 (pre nourishment) and 2017 for section 104
in which a combined shoreface and beach nourishment was constructed in early 2014.

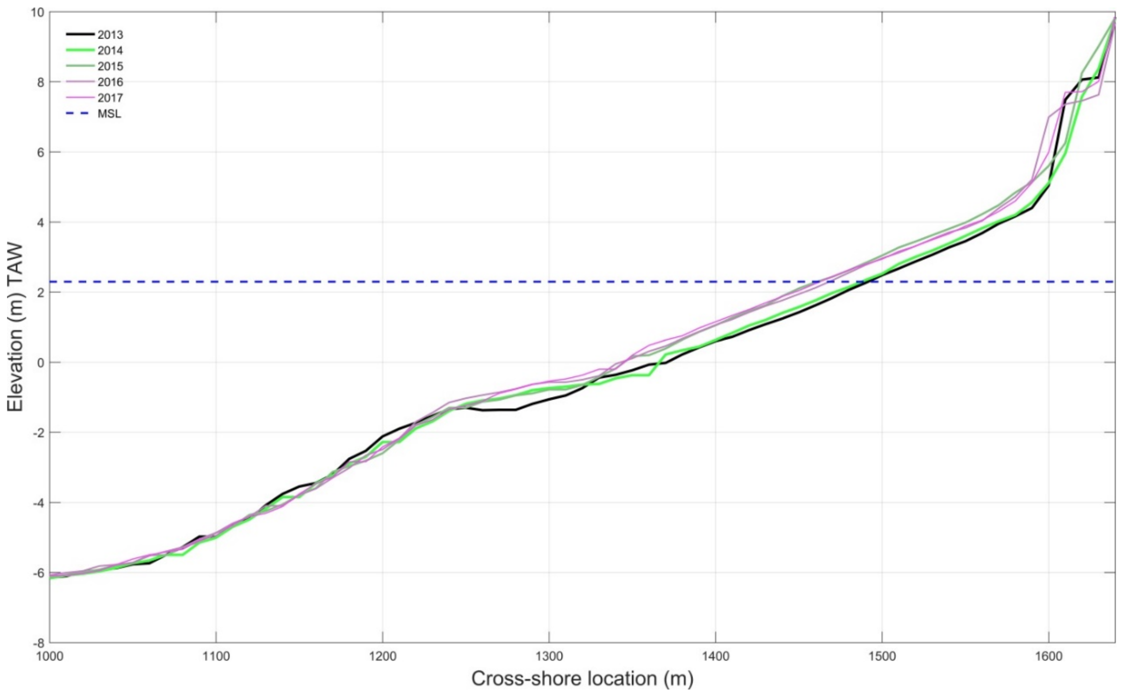

Figure 74 – Profile evolution between 2013 (pre nourishment) and 2017 for section 100 (see Figure 68)
in which a beach nourishment was constructed in June 2014.

UNIBEST-CL+ Model setup

This section describes the UNIBEST-CL+ model setup for the calibration on the Mariakerke nourishment. UNIBEST-CL+ consists of two modules: i) the alongshore transport (LT) module, and ii) the coastline (CL) module. Within the LT module, the relation between the alongshore sediment transport and the coastline angle is established for each locality. This relation is a function of the wave climate, tidal conditions, sediment characteristics and coastal bathymetry, and therefore information on these parameters is provided first. Then, the LT module is used to simulate changes in the shoreline position as defined in the CL module of UNIBEST-CL+. As part of the CL module description, the shoreline position, dimensions, grid sizes, dimensions and characteristics of coastal structures, and the applied timeframe and output settings will be introduced.

Alongshore Transport module

The first step in setting up the LT module is the definition of the coastline angle. The angle (degrees North) of the offshore directed coast normal of the coastline should be specified in nautical coordinates. In this coordinate system, North is 0° and coordinates rotate clockwise (i.e. East is 90°). The coastline orientation and coast normal for Mariakerke are shown in Figure 75. The coastline has an angle of 57° relative to the North. The coast normal angle is 327° relative to the North. Although fairly straight, small deviations in coastline angle along this coastal stretch can be observed. The majority of coastline angles is within 57° ± 2°.

Figure 75 – Identification of coastline angle and coast normal for Mariakerke.

The active height, or closure depth, of a coastal profile is defined as the depth for which sediment can be mobilized, and sediment can be transported in cross-shore and alongshore directions. The closure depth is challenging to establish exactly, depends on the temporal and spatial scales considered, and can be estimated in a number of ways. First, the Hallermeier (1981) equation, which is based on linear wave theory, can be used to estimate the "closure depth," or seaward limit of significant profile change. The Hallermeier equation is defined as:

$$D = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right) \qquad (1)$$

Where D is the closure depth (m), H_e is the extreme significant wave height occurring 12 hours or 0.137% of the time (m), and T_e is the extreme significant wave height corresponding with H_e (s).

Using a H_e of 3.21 m and a T_e of 8.33 s, a closure depth D of 6.28 m TAW is estimated for Mariakerke. This estimate of the closure depth is about 1 m higher than obtained in an earlier study looking at the alongshore sediment transport patterns for the Belgian coast (Dan and Vandebroek 2017).

A second estimate of the closure depth can be made using the CUR (1990) as written in Kamphuis (2010):

$$D = 1.6H_e \qquad (2)$$

Using Equation 2, a closure depth D of 5.14 m TAW is estimated for Mariakerke, which is in agreement with the aforementioned earlier sediment budget study for the Belgian coast (Dan and Vandebroek 2017).

A third estimate of the closure depth can be made using observations from the Mariakerke nourishment. From Figure 73 it can be seen that almost no sand has been mobilized around -6 m TAW for section 104 during the survey period. This observation suggests that a depth of closure of 6 m TAW is appropriate for the Mariakerke nourishment.

The depth of closure is challenging to determine with estimates ranging from 5.14 m to 6.28 m TAW using three different methods. Wave data are available at the 6 m depth of closure level. For practical reasons, it is therefore decided to use the medium estimate of the depth of closure of 6 m for this calibration exercise.

Wave climate

The wave climate measured with a directional wave rider at Raversijde is used to identify the wave forcing for the calibration (Figure 77). The directional wave rider was specifically installed for pilot nourishment project and is located 380 m from the shoreline at coordinates 2° 52' 32"E - 51° 13' 13"N. Data can be freely obtained from https://meetnetvlaamsebanken.be/ and are available at 30-min intervals. Daily observations on significant wave height H_{sig}, peak wave period T_{peak}, and the direction of wave propagation ϑ are extracted from 1/1/2013 to 31/12/2017 (Figure 76). During this 4-year period, waves are predominantly coming from western and northern directions (Figure 77). The mean wave direction is 249° (Table 28). The average significant wave height is 0.65 m. At this nearshore location, 53.1% of the waves is smaller than 0.5 m. 17.6% of the waves is larger than 1 m and 1.6% of the waves is larger than 2 m. The mean peak period of the waves near Raversijde is 5.35 s (Table 28).

To match the wave observations as closely as possible with the morphological information from the surveys, a shorter period ranging from 1/7/2014 to 30/06/2017 was selected for the calibration (Table 28). However, the descriptive statistics of this shorter period are similar to the longer observational period shown in Figure 76.

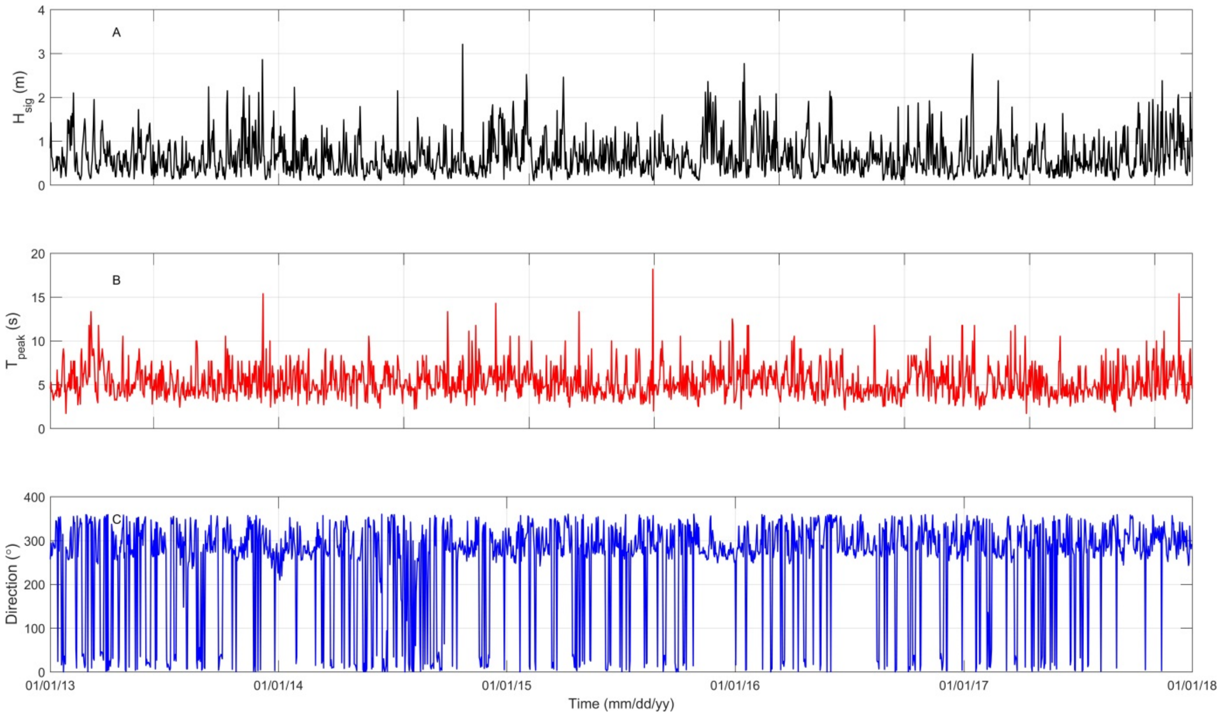

Figure 76 – Daily wave observations*.

*H_{sig} is significant wave height; T_{peak} is peak wave period; Direction is wave propagation direction relative to the North) measured at Raversijde directional wave rider (2° 52' 32"E - 51° 13' 13"N, ~380 m from the shoreline) between 1/1/2013 and 31/12/2017. Data from https://meetnetvlaamsebanken.be/.

Table 28 – Wave statistics measured at Raversijde directional wave rider for two periods (2° 52' 32"E - 51° 13' 13"N, ~380 m from the shoreline).

Parameter	1/1/2013-31/12/2017	1/7/2014-30/06/2017
$H_{s, mean}$	0.65 m	0.65 m
$T_{p, mean}$	5.35 s	5.31 s
θ_{mean}	249°	251°
H_s > 0.5 m	53.1%	52.6%
H_s > 1.0 m	17.6%	16.7%
H_s > 2.0 m	1.6%	1.6%

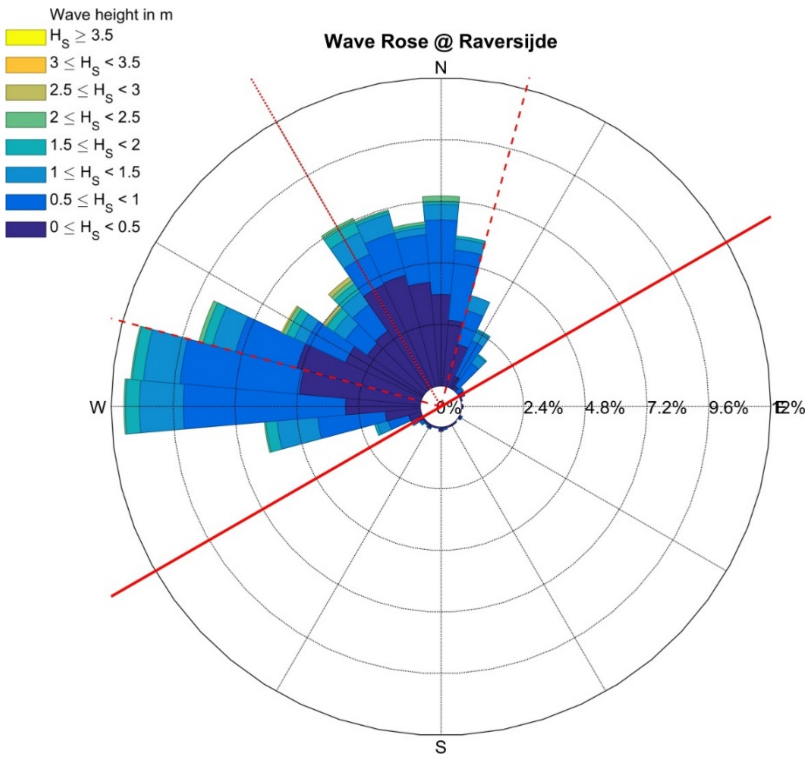

Figure 77 – Wave rose summarising wave height and direction information at Raversijde.
Wave data extracted from a directional wave rider (2° 52' 32"E - 51° 13' 13"N, ~380 m from the shoreline between 1/1/2013 and 31/12/2017*.

*The solid red line corresponds to the coastline, the dotted red line is the coast normal, and the dashed red lines correspond to the angle (~45°) with maximum alongshore sediment transport.

Sediment characteristics

Regular sediment composition surveys are performed for the Belgian coast. The Belgian coast is a sandy coast with variations in grain size in both alongshore and cross-shore directions. Grain size is about 160 µm near De Panne and typically increases towards the east reaching sizes up to 300 µm micron near het Zwin. A median grain size (D_{50}) of about 210 µm is observed near Mariakerke (i.e. section 104). Also, a D_{90} of about 300 µm is observed for this coastal stretch.

Coastal bathymetry and profile extraction

The cross-shore profile of section 104 as measured in 2013 is used as the representative profile for the Mariakerke coastal zone (Figure 73). The upper dry beach part of the profile is highly managed. It shows an almost constant decline from the +5 m TAW to 0 m TAW level. A platform or berm with an elevation from 0 m TAW to -1 m TAW, i.e. just below the lowest astronomical tide level, is visible between cross-shore positions 1225 m and 1300 m. Beyond this berm, the profile continues to decline in elevation to the -6 m TAW level at cross-shore position 1000 m, which corresponds to the depth of closure in this study.

S-ϕ relation

The reference run of the alongshore transport (LTR) module shows a net sediment transport rate of 156.000 m^3/year (Figure 78). The net transport is directed towards the northeast. The equilibrium coast angle is 27.5°. When referenced back to the unrotated coastline, an equilibrium orientation of 299.5°. A maximum net sand transport of about 200.000 m^3/year is generated at coastline orientations of 345° (i.e. southwest directed transport) and 255° (i.e. northeast directed transport).

The sediment budget is developed for the Belgian coast (Vandebroek et al., 2016) provides the best opportunity to validate the UNIBEST-CL+ simulated alongshore sediment transport rates because it employs several methods to estimate the alongshore sediment transport rate. The findings from two observational studies (Verwaest et al., 2010; Trouw et al., 2015), three empirical formulations (CERC; Kamphuis, 1991, Svasek, 2012), and two numerical studies (Wang et al., 2012, 2015) are reported.

Figure 43 presents a synthesis of the alongshore sediment transport rates along the Belgian coast developed in Vandebroek et al. (2016). The net sediment transport rates are typically 150.000 m^3/year in northeastern direction. The transport rates show an increase towards the east with a typical value of 150.000 m^3/year at Mariakerke. The alongshore sediment transport rates are challenging to estimate and may fluctuate from year to year, which is reflected by the uncertainty bounds. For Mariakerke, a lower bound estimate of the net alongshore sediment transport rate is 100.00 m^3/year, and an upper bound estimate is 200.00 m^3/year.

As can be seen in Figure 43, the alongshore sediment transport rate of 156.000 m^3/year observed in the reference run with UNIBEST-CL+ for Mariakerke is in good agreement with the rates reported in Vandebroek et al. (2016).

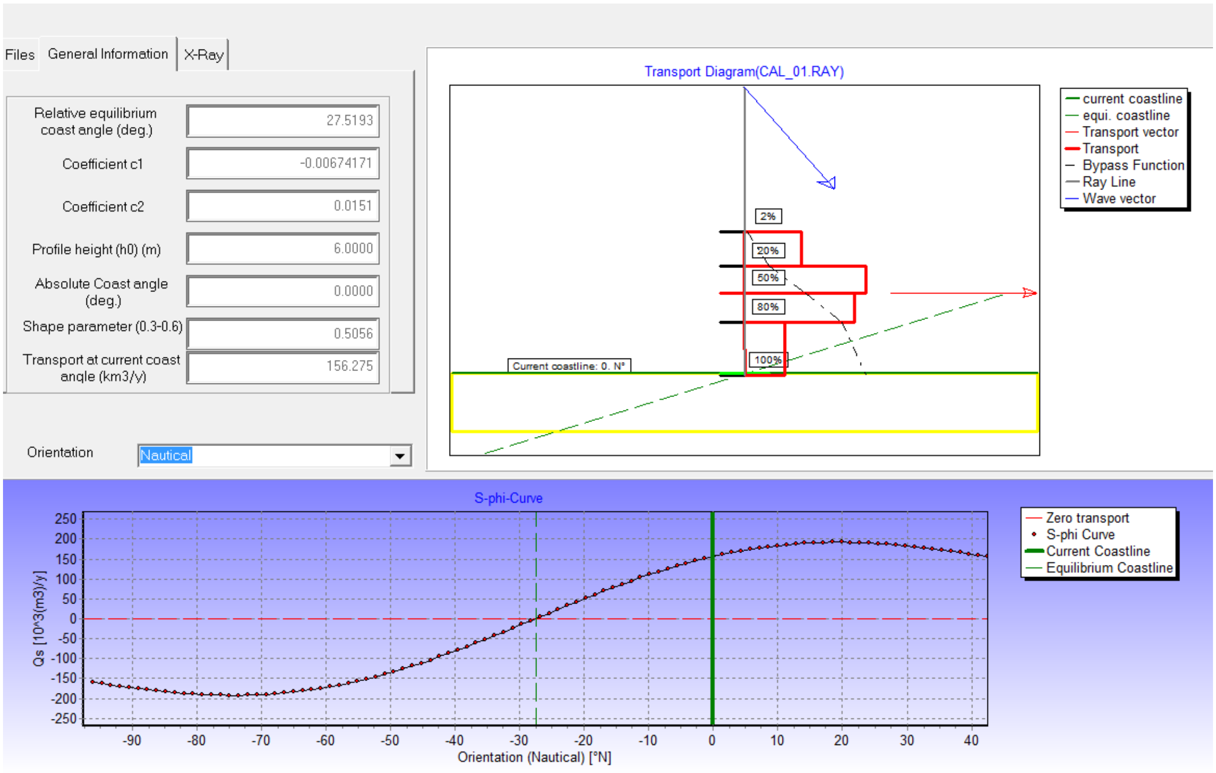

Figure 78 – Transport ray of UNIBEST-CL+ summarised into an S-ϕ curve for the reference run of Mariakerke using the 2013 cross-shore profile of section 104 (Figure 73).

Coastline module

Definition of coastline position and dimensions

The Mariakerke nourishment is designed as a trapezoidal shape in UNIBEST-CL+ matching the constructed shape as accurately as possible (Figure 36 and Figure 71). A seaward extent of 50 m is chosen with an alongshore length of 2000 m and 2500 m on the seaward and landward sides, respectively (Table 29). These nourishment dimensions result in a width-to-length ratio of 1:50 and the involvement of coastal sections 102-110. The sand volume for the Mariakerke nourishment as calculated with UNIBEST-CL+ is 1.1 Mm^3, which is in close agreement with the applied sand volume of 1.175.900 m^3 for the combined beach and shoreface nourishment at Mariakerke. However, it is important to note that a homogeneous sand thickness is assumed in UNIBEST-CL+ as a result of the applied shift in cross-shore profile, while the sediment thickness varies heterogeneously along the cross-shore profile in the real-world case (Figure 73).

Table 29 – Overview of UNIBEST-CL+ nourishment trapezoidal design for Mariakerke*.

Nourishment ID	Seaward extent (m)	Width-to-Length ratio (-)	Alongshore length seaward (landward) (m)	Coastal sections involved	Nourishment volume in UNIBEST-CL+ (10^6 m^3)
CAL_01	50	1:50	1800 (2500)	102-110	1.1

*These design parameters are selected to best match the constructed nourishment (see Figure 68 and Figure 71).

The nourishment is implemented in a 100 km long model in which the middle sector of 25 km contains the region of interest (Table 30). Within the region of interest, the finest grid size of 25 m is specified. Four sectors with a total width of 37.5 km are specified on both adjacent sides of the region of interest to locate the model boundaries far away from the region of interest and to minimise boundary effects. Each of the four sectors consists of a different grid size, with a coarser grid towards the boundaries to minimise computational time. In total, the model consists of 1241 cells.

Table 30 – Characteristics of the UNIBEST-CL+ grid used in the calibration on the Mariakerke nourishment.

	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	Sector 7	Sector 8	Sector 9
Length (km)	12	14	9	2.5	25	2.5	9	14	12
Grid size (m)	800	400	200	100	25	100	200	400	800

Coastal structures

No coastal structures were defined. This includes groynes, revetments and offshore breakwaters. Also, no sources and sinks were specified. The addition of coastal structures is explored in the sensitivity analysis and described in more detail below.

Boundary conditions

The position of the coastline was assumed to be constant (Y constant) on the left and right boundaries of the model.

Table 31 – UNIBEST-CL+ model settings for the LTR and CLR modules as used in the reference run for the calibration on the Mariakerke pilot nourishment.

Parameter	Value
Cross-shore profile	
X-point dynamic boundary	0 m
X-point truncation transport	0 m
Reference level	-2.33 m
Sediment transport	
Transport formula	Bijker (1967,1971)
D_{50}	210 µm
D_{90}	300 µm
Waves & tides	
Breaking, bottom friction & roughness	Default parameters
Wave climate	1096 conditions; H_{sig} = 0.65 m, T_p = 5.31 s
Tides	Not specified
S-φ curve	
Net alongshore transport	156.000 m^3/year; equilibrium angle 27.5°
Grid & boundary conditions	
Grid	100 km domain; 1241 cells; 25 m cells to 800 m cells
Boundaries	Coastline (Y) constant
Output	
Duration	June 2014 to July 2017
Output frequency	Monthly

Timeframe and output settings

Run input:

Start time = 0 year, time steps/year = 12, number of cycli = 1

Run output:

First time step = 0, time step period = 1 (i.e. output for every month), maximum number of steps = 36

Period definition:

From year 2014 to year 2017 (i.e. a period of 3 years).

Runtime is about 30 seconds.

A summary of the UNIBEST-CL+ model settings as used in the reference run for the calibration on the Mariakerke pilot nourishment is provided in **Table 31**.

Results of UNIBEST-CL+ model calibration

Sediment transport behaviour of nourishment post-construction

The sediment transport behaviour of the idealized nourishment designs results in morphological reshaping. The morphological reshaping takes place in cross-shore and alongshore directions and changes over time. To describe and quantify the coastline changes resulting from this morphological reshaping, snapshots of the coastline position (Figure 79), time stacks of coastline retreat and advance rates (Figure 81), the alongshore dispersion of sand (Figure 81), and the volume decay of sand are presented (Figure 85).

It can be seen that the original trapezoidal design is quickly reshaped into a smoother bell shape (Figure 79). Erosion is initiated at the edges of the nourishment and progresses inward, resulting in a decrease in cross-shore distance from the original coastline. Similarly, sand is being redistributed to the adjacent beaches, resulting here in beach advance and an increase in cross-shore distance. The coastal stretch receiving sand from the nourishment increases over time and results in beach advance farther from the nourishment as time progresses.

Morphological reshaping of the Mariakerke nourishment results in coastline retreat and advance (Figure 80). Retreat occurs predominantly along the coastline where the nourishment was constructed. Retreat rates are initially high (up to 3 m/month) and decrease during the 3-year period. Retreat rates are generally greatest near the edges of the nourishment and decrease towards the nourishment centre (i.e. alongshore position is 0 m). The eroded sand is redistributed to the adjacent beaches leading here to shoreline advance. The advance rates are highest initially (up to 5 m/month) and decrease during the 3-year period.

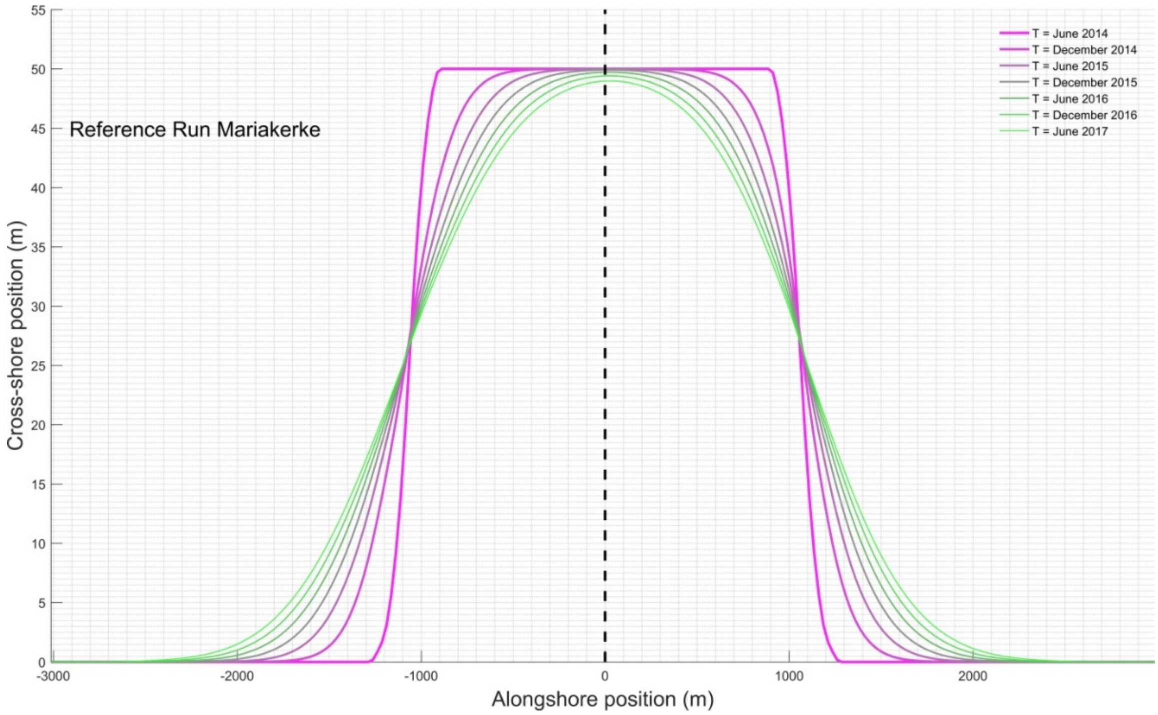

Figure 79 – Snapshots of coastline development in time as simulated with UNIBEST-CL+ for the Mariakerke nourishment reference run with parameters as shown in Table 31.

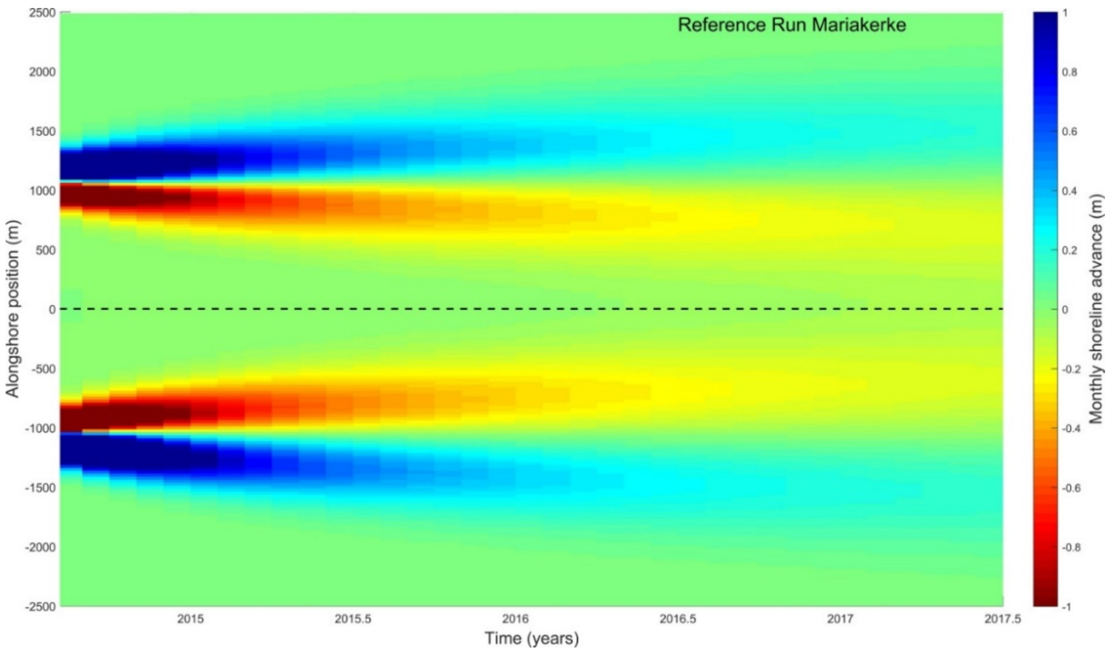

Figure 80 – Time stack of coastline advance and retreat over time as simulated with UNIBEST-CL+ for the Mariakerke nourishment reference run.

*Note that monthly advance and retreat are shown.

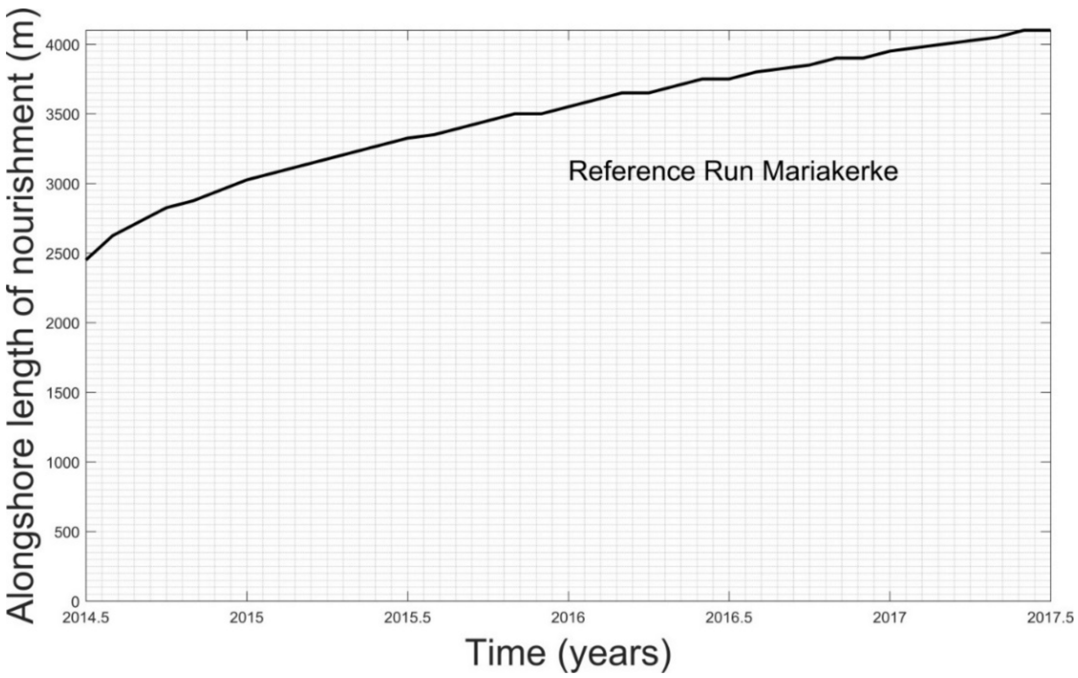

Figure 81 – Alongshore dispersion of sand over time as simulated with UNIBEST-CL+ for the Mariakerke nourishment reference run*.

*The alongshore length of the nourishment is defined as the length over which a cross-shore distance of more than 1 m with the original coastline exists. This definition explains the discrepancy between the alongshore length of the constructed nourishment reported here and in Table 29.

Shoreline advance is greatest directly adjacent to the original nourishment and decreases with distance from the nourishment. However, the peak of the advance rates moves away from the nourishment centre as time progresses. As a result of the re-distribution of sand from the nourishment to adjacent beaches, the alongshore length of the reshaped nourishment increases over time (Figure 81). From the constructed alongshore length of 2450 m, the alongshore length increases to 4100 m after 3 years.

Coastal retreat of nourishment

Figure 82 shows a comparison of the evolution of the observed and simulated seaward extent of the Mariakerke nourishments. The observations show a retreat to 43 m during the first year post construction and then a small advance to 45 m and 46 m in 2016 and 2017. The simulation show a gradual retreat to 46 m in 2017, which is consistent with the observations. Yet, the coastline retreat observed in 2015 and 2016 for section 104 of the Mariakerke nourishment is underestimated by the UNIBEST-CL+ model.

The average shoreline retreat rates are initially high and decrease over time (Figure 83). The modelled Mariakerke nourishment shows initial average retreat rates of approximately 1.25 m/month. As time progresses, the retreat rates decrease to less than 0.25 m/month. The maximum retreat rates are initially up to 3 m/month (Figure 83), or up to 8 m during the first year post construction (Figure 79). These modelled retreat rates are found near the edges of the nourishment.

The average shoreline advance rates are initially high and decrease over time (Figure 84). The modelled Mariakerke nourishment shows initial average advance rates of approximately 1.75 m/month. As time progresses, the retreat rates decrease to less than 0.25 m/month, in agreement with the retreat rates. The maximum retreat rates are initially up to 4.5 m/month (Figure 83), or up to 10 m during the first year post construction (Figure 79). The highest advance rates are observed on the beaches directly adjacent to the nourishment during the first year post construction.

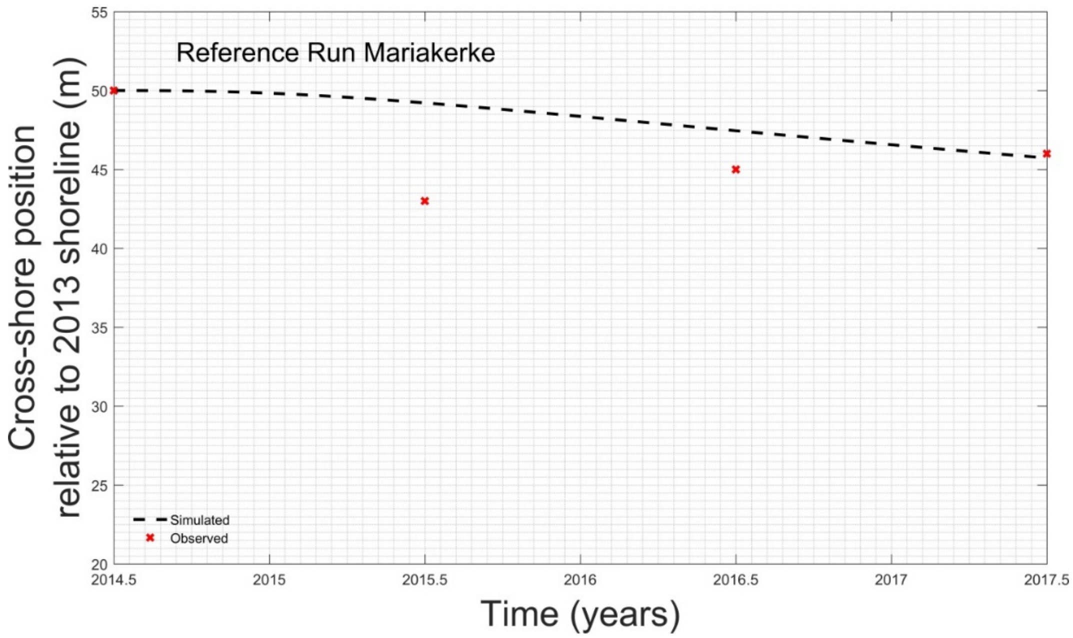

Figure 82 – Evolution of the observed and simulated seaward extent of the Mariakerke nourishment for section 104 (see Figure 68).

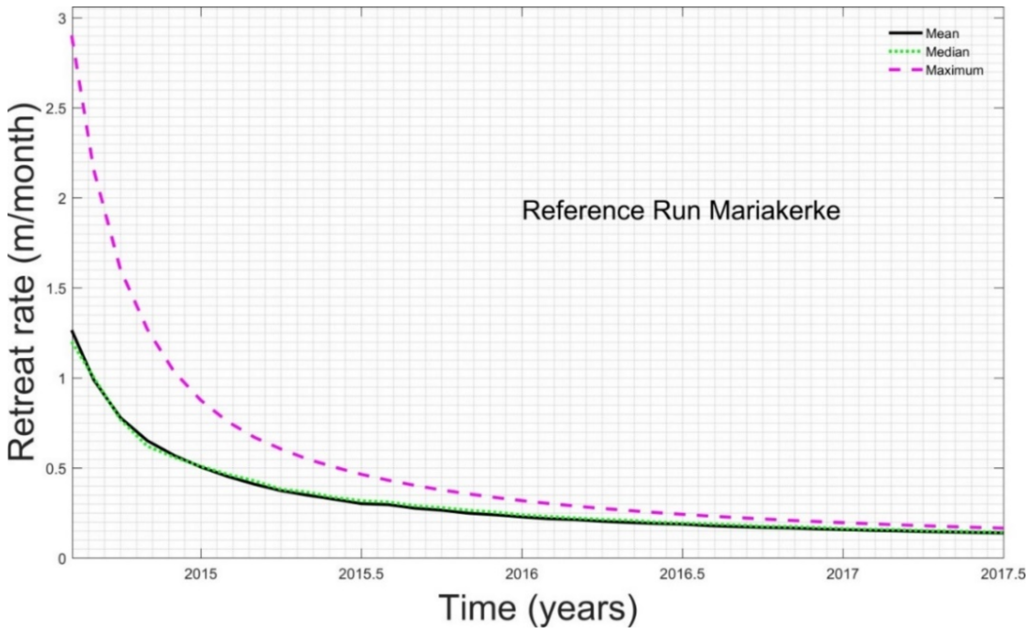

Figure 83 – Coastline retreat rates over time for the Mariakerke nourishment as simulated with UNIBEST-CL+*.

*Note that monthly retreat rates are shown.

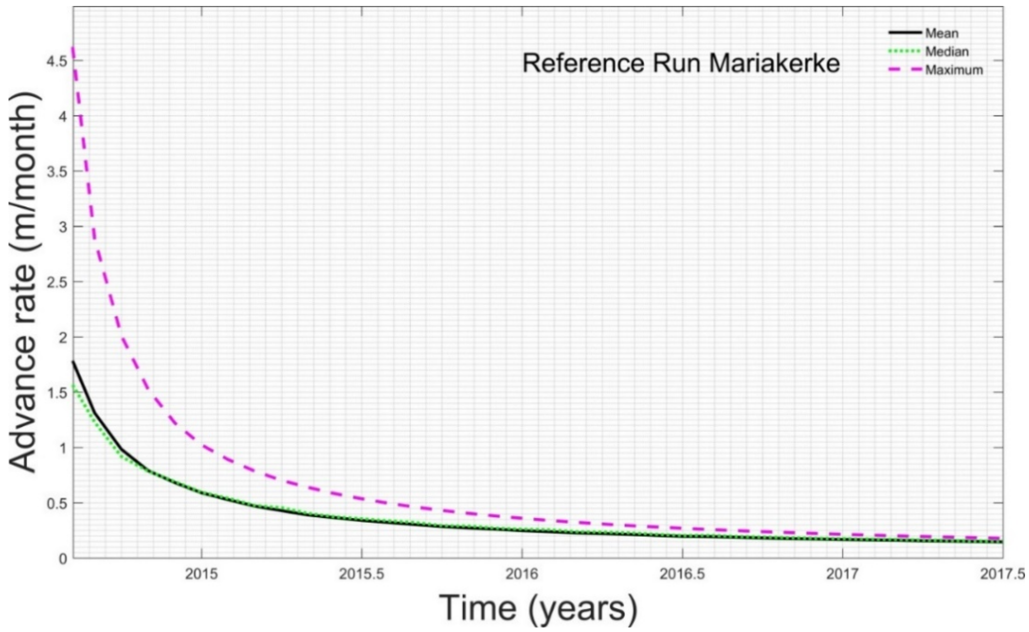

Figure 84 – Coastline advance rates over time for the Mariakerke nourishment as simulated with UNIBEST-CL+*.

*Note that monthly advance rates are shown.

Volume decay

Morphological reshaping results in sand loss from the original nourishment location (Figure 85). Sand is being eroded from the nourishment head and fed to the adjacent beaches (Figure 79). The feeding of the adjacent beaches leads to a sand loss and volume decay from the nourishment area (Figure 85). Here, the sand volume decay is quantified on the basis of the remaining sand volume in the nourishment area including half of the trapezoidal edge from the nourishment head to the original coastline. This definition of the control box is consistent with the one used in Tonnon et al. (2018).

The sand volume decays from 1.07 million m^3 to about 0.94 million m^3 during the first three years post construction as simulated with UNIBEST-CL+ (Figure 85). Volume decay decreases in an almost linear fashion during the three years post construction. Using UNIBEST-CL+, a sand loss of approximately 12% is predicted during the first three years post construction. Observations of the volume decay of the Mariakerke nourishment show a smaller sand loss than simulated with UNIBEST-CL+ (Figure 86). A 2.8% loss is seen in the first year, a 3.3% gain in the second year, and a 7.4% loss relative to the constructed sand volume in the third year post construction. These observations suggest an overestimation of the sand loss from the nourishment area by the UNIBEST-CL+ model. However, interpretation of the observed volume decay results is not trivial because many processes play a role in the sediment transport post construction of the nourishment. For example, a closer inspection of the observed volume decay shows erosion of the beach nourishment and accretion of the shoreface nourishment. Such distinction cannot be made for the modeled nourishment, in which the shoreline migrates homogeneously. Furthermore, some additional nourishments were done in the vicinity of the Mariakerke nourishments during the simulated period. These nourishment may have affected the volume decay of the Mariakerke nourishment, but were not included in the reference run presented here. The effects of these additional nourishments on the simulated volume decay will be evaluated in the sensitivity analysis.

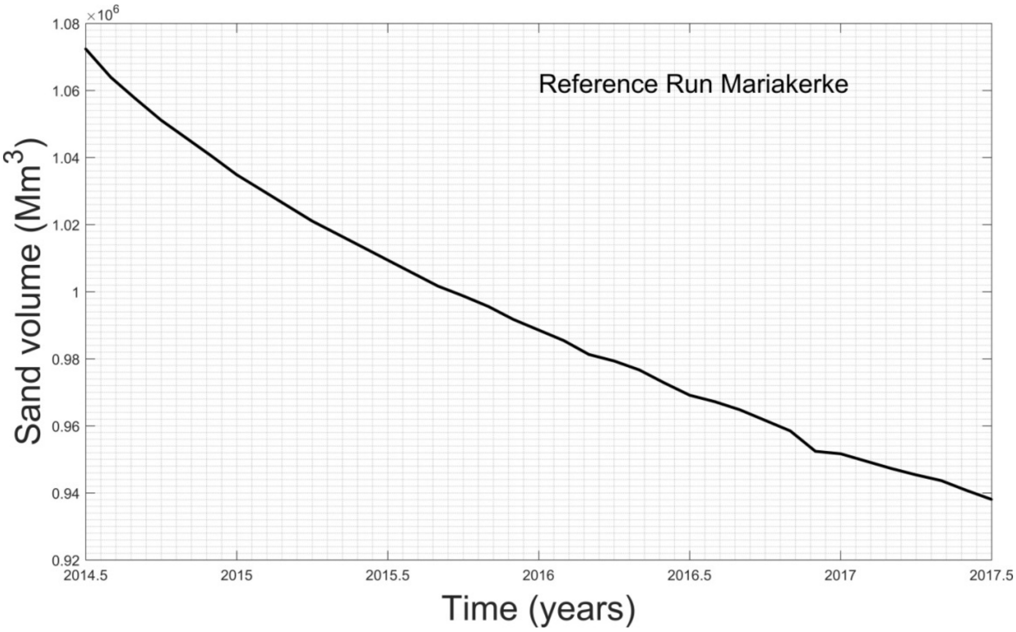

Figure 85 – Sand volume decay over time for the Mariakerke nourishment
as simulated with UNIBEST-CL+.

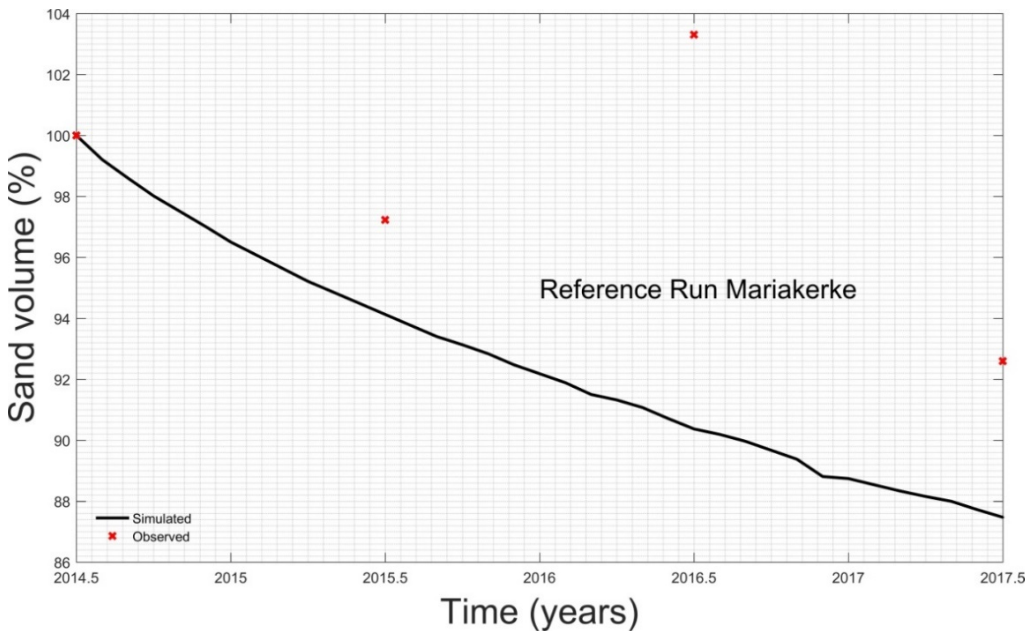

Figure 86 – Normalized sand volume decay over time for the Mariakerke nourishment
as observed and as simulated with UNIBEST-CL+.

Sensitivity analysis

A sensitivity analysis of the UNIBEST-CL+ results is performed for a range of parameter settings (Table 32). This analysis focusses on the sediment transport formulation, grain size, tidal conditions, and the effects of additional sediment sources and groynes on the alongshore sediment transport and resultant shoreline changes. The sediment transport formulation, grain size and tidal conditions are specified in the longshore transport (LTR) module and therefore result in updated net alongshore sediment transport rates (Table 32). In contrast, the effects of additional sediment sources and groynes is investigated in the coastline (CLR) module and hence these scenarios employ the net alongshore sediment transport rates of the reference run (Table 32).

A study by Vandebroek et al. (2016) indicates that the net alongshore sediment transport rate is typically 150.000 m^3/year in northeastern direction at Mariakerke (Figure 43). A lower bound estimate of the net alongshore sediment transport rate is 100.00 m^3/year, and an upper bound estimate is 200.00 m^3/year. The net alongshore sediment transport rate of 156.000 m^3/year simulated in the reference run using the Bijker (1967, 1971) sediment transport formulation (Table 32) is in good agreement with the typical rate reported in Vandebroek et al. (2016) for Mariakerke. The sensitivity analysis shows that other sediment transport formulations such as CERC (1984), Kamphuis (2000) and Van Rijn (2004) result in a poorer agreement the rate reported in Vandebroek et al. (2016).

Table 32 – Settings explored in UNIBEST-CL+ sensitivity analysis of Mariakerke nourishment and resultant annual net alongshore sediment transport and equilibrium angle.

RUN ID		Q_s (m^3/year)	Eq. angle (°)
CAL01	Reference run (see Table 31)	156.275	27.5
CAL02	CERC transport formulation	505.922	25.8
CAL03	Kamphuis transport formulation	66.245	19.9
CAL04	Van Rijn (2004) transport formulation	208.500	24.6
CAL05	D_{50} = 150 micron	274.940	27.8
CAL06	D_{50} = 300 micron	94.640	27.6
CAL07*	Water level variation: -2 m to +2 m	187.783	24.3
CAL08*	Water level & symmetrical tides of 0.25 m/s	187.503	24.3
CAL09*	Water level & asymmetrical tides of 0.25 m/s (F) & 0.2 m/s (E)	198.041	25.9
CAL10	Additional sediment sources (in CLR module)	156.275	27.5
CAL11	Groynes implemented as structures (in CLR module)	156.275	27.5

* Note that a simplified wave climate using 4-day wave observations rather than daily wave observations was used in CAL07*, CAL08* and CAL09* to satisfy the UNIBEST-CL+ condition of a maximum of 3000 wave-tide conditions. Although the wave statistics H_s, T_p and ϑ are similar to the Reference run CAL01, the simplified wave climate results in a Q_s of 189.185 m^3/yr and an equilibrium angle of 24.3°.

The reference run employs a median grain size D_{50} of 210 µm, in agreement with observations made during a beach survey in 2003 (Figure 39). Applying a finer grain size with a D_{50} of 150 µm results in a higher net alongshore sediment transport of almost 275.000 m^3/year (Table 32). A coarser grain size with a D_{50} of 300 µm results in a lower net alongshore sediment transport of almost 95.000 m^3/year. The net alongshore sediment transport generated with both a finer and a coarser grain size are outside the lower and upper bounds of 100.000 m^3/year and 200.000 m^3/year provided in Vandebroek et al. (2016). It is noted that the net alongshore sediment transport generated in UNIBEST-CL+ is sensitive to the specification of the fall velocity, in addition to the specification of the median grain size D_{50}.

The addition of tides has limited effect on the net alongshore sediment transport generated in UNIBEST-CL+ (Table 32). A simplified wave climate is used in the tidal scenarios to stay within the maximum number of wave-tidal conditions (i.e. 3000) simulated. Without tides, this simplified wave climate (4-day observations; H_s = 0.63 m; T_p = 5.22 s; ϑ = 199°) results in net alongshore sediment transport of 189.000 m^3/year. The addition of a water level variation from -2 m to +2 m (CAL07) as well as symmetrical tidal velocities of 0.25 m/s (CAL08) result in a similar annual net alongshore sediment transport. Asymmetrical tides with a 20% higher maximum flood velocity result in a 5% increase annual net alongshore sediment transport. These findings suggest that not the magnitudes of the tidal amplitude and the tidal velocities but the asymmetry in the ebb and flood determines the effect tides have on the annual net alongshore sediment transport.

However, observations on the asymmetry of the tides along the Belgian coast are scarce, in particular close to the shoreline. The measurements made in the nearshore zone of Blankenberge during Flanders Hydraulics project 00_067 show a flood dominance with flood velocities 10%-20% higher than ebb velocities. The flow magnitudes vary as a function of the wave intensity but typical values are in the order of 0.2 m/s to 0.5 m/s. CAL09 with a flood velocity of 0.25 m/s and an ebb velocity of 0.2 m/s results in a net alongshore sediment transport within the bounds provided by Vandebroek et al. (2016) for Mariakerke (Figure 43). A higher flood velocity of 0.5 m/s with an ebb velocity of 0.4 m/s results in a higher net alongshore sediment transport of 226.000 m^3/year.

Changes in shoreline position are a result of gradients in the net alongshore sediment transport (Figure 87 - Figure 90). Figure 87 shows that the sediment transport formulation has a substantial effect on the simulated shoreline position with UNIBEST-CL+. The results show a faster shoreline retreat for the nourishment as well as faster shoreline advance for adjacent beaches with sediment transport formulations generating a higher annual net alongshore sediment transport rate (Table 32) such as CERC (1984) and Van Rijn (1984) compared to the Bijker (1967, 1971) formulation. Similarly, the Kamphuis (2000) formulation results in smaller shoreline changes than the Bijker (1967, 1971) formulation due to a lower annual net alongshore sediment transport rate (Table 32). The difference in shoreline retreat at the nourishment head (i.e. alongshore position 0 m) between the slower Kamphuis and faster CERC formulations is more than 10 metres (Figure 87), which corresponds to a 20% difference in the prediction of the shoreline position. Similarly, feeding of sand to the adjacent beaches depends strongly on the applied sediment transport formulation. With the CERC formulation, beaches located 1000 m farther from the nourishment than predicted with the Kamphuis formulation receive sand (Figure 87).

Application of a smaller median grain size of 150 µm results in greater shoreline changes than employing a median grain size of 210 µm (Figure 88). Similarly, a larger median grain size of 300 µm results in smaller shoreline changes compared to the reference run with a median grain size of 210 µm (Figure 88). The difference in shoreline retreat at the nourishment head (i.e. alongshore position 0 m) between the finer and coarser grain sizes is about 5 metres (Figure 88). This finding indicates that the sensitivity to the grain size is smaller than the sensitivity to the sediment transport formulation.

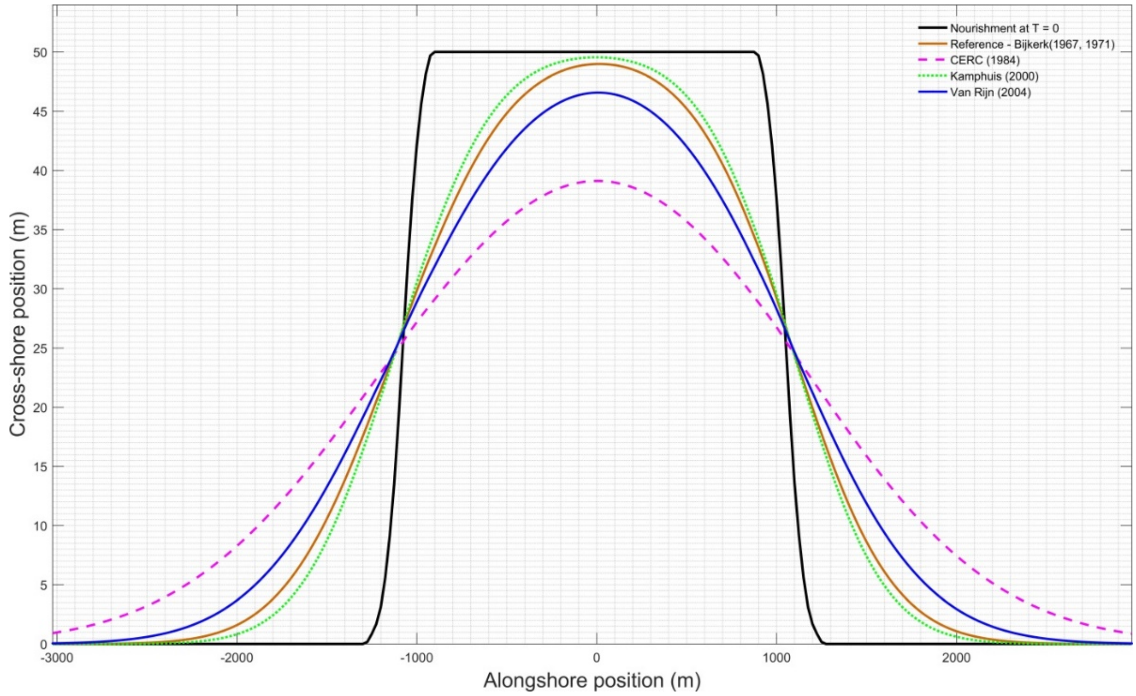

Figure 87 – Final coastline position of four UNIBEST-CL+ scenarios
in which the sensitivity to the sediment transport formulations is evaluated.

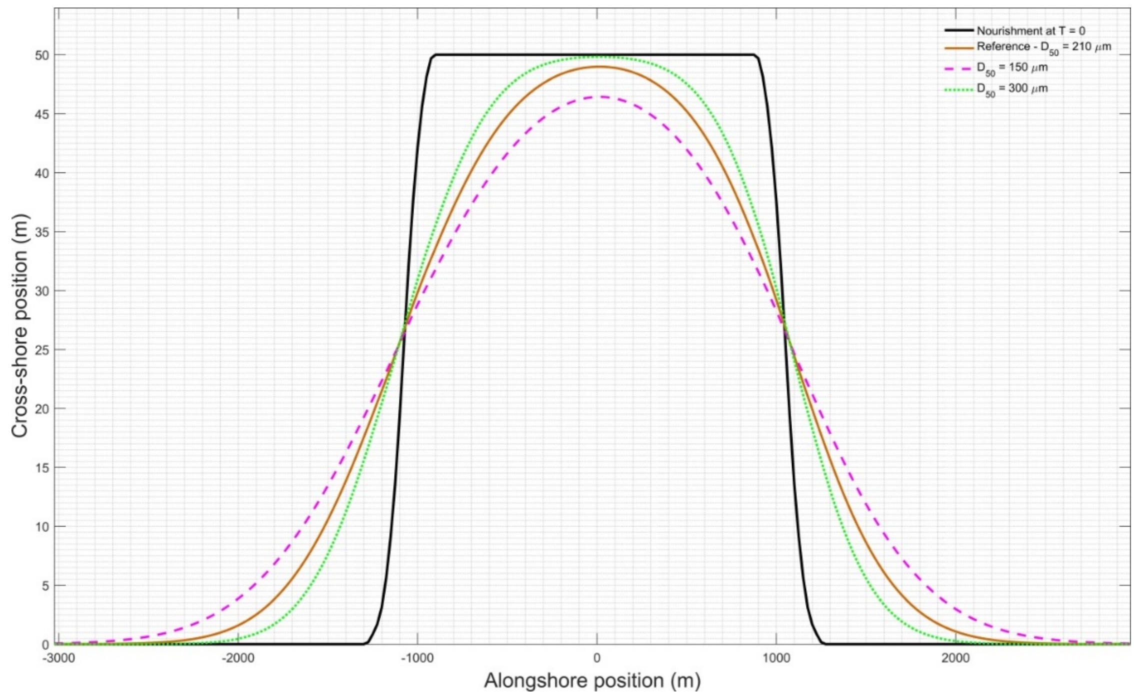

Figure 88 – Final coastline position of three UNIBEST-CL+ scenarios
in which the sensitivity to grain size (D_{50}) is evaluated.

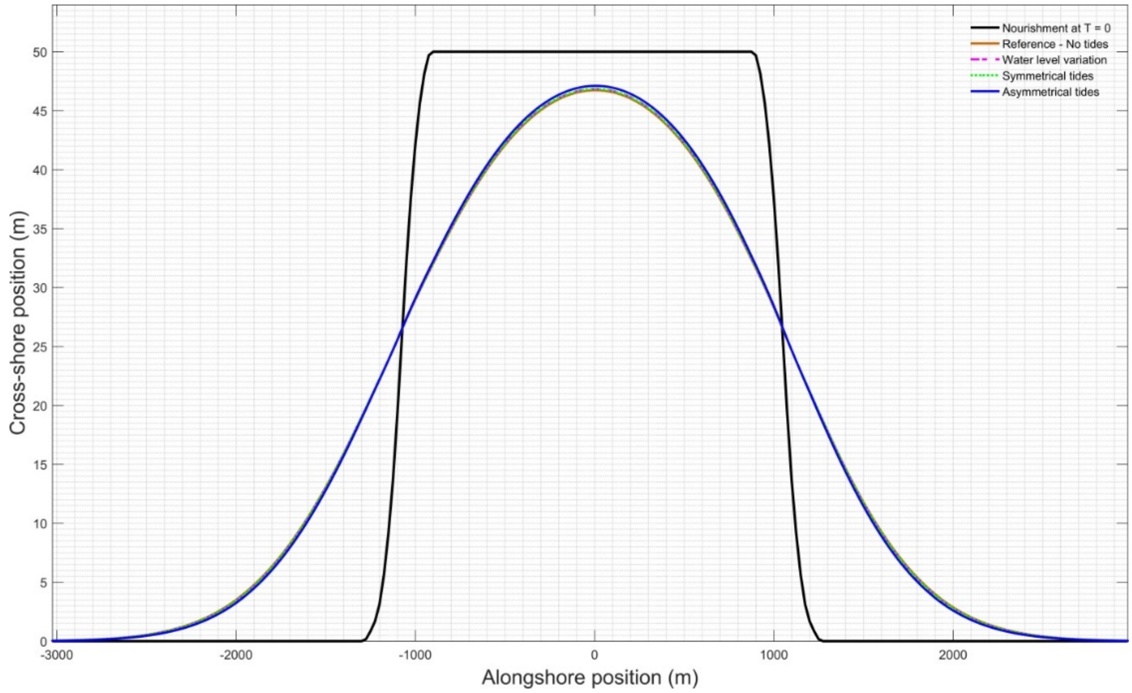

Figure 89 – Final coastline position of four UNIBEST-CL+ scenarios in which the sensitivity to tides is evaluated*.

*A tidal amplitude of 2 m is used, in agreement with water level observations at Oostende. In the symmetrical tides scenario, a maximum flood and ebb velocity of 0.25 m/s is used. In the asymmetrical scenario, maximum ebb velocities are reduced to 0.2 m/s.

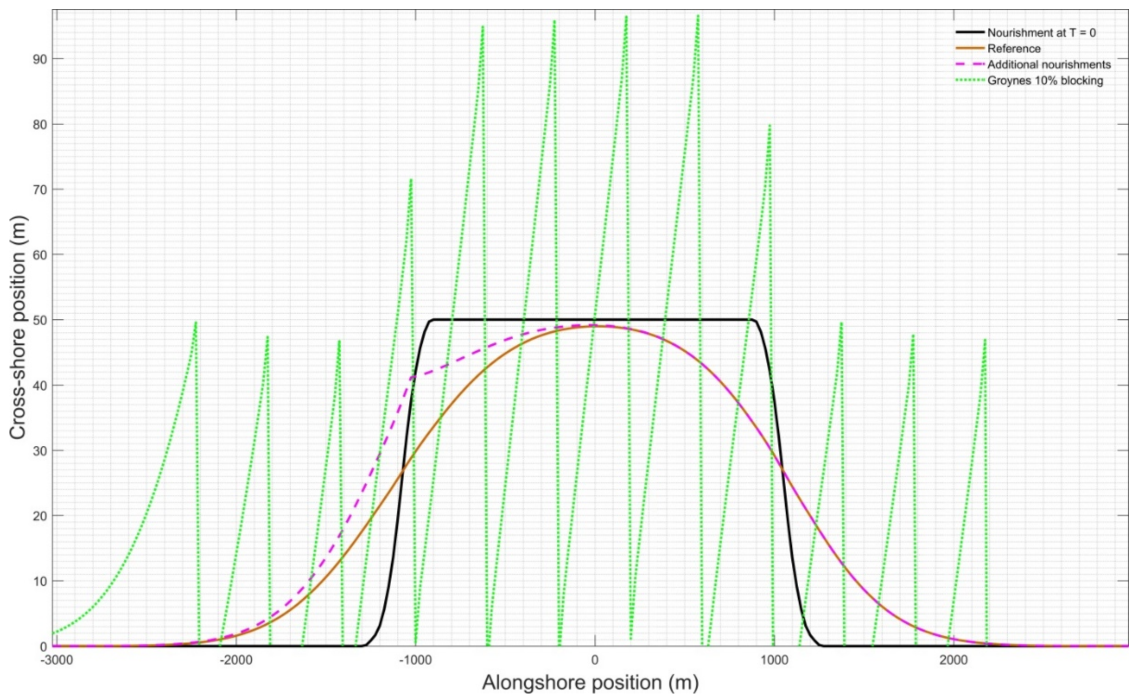

Figure 90 – Final coastline position of three UNIBEST-CL+ scenarios in which the sensitivity to three additional nourishments acting as sediment sources, and to groynes spaced 400 m apart is evaluated.

Application of a tidal signal has limited effects on the resultant shoreline (Figure 89). A variation in water level, symmetrical tides and asymmetrical tides do not significantly alter the position of the shoreline compared with the reference run without tidal signal.

Inclusion of nourishments on adjacent beaches and groynes results in a different shoreline position (Figure 90). In the scenario with additional nourishments, the shoreline is shifted more seaward on the updrift side of the nourishment. The additional nourishments act as a sand source and feed the Mariakerke nourishment. Given the limited time period of three years, the sand from the additional nourishments has reached the updrift side of the Mariakerke nourishment but not the downdrift side yet. The inclusion of groynes result in a saw-tooth shoreline with retreat up to the original shoreline in places and advance up to almost 100 m in other places. The results for groynes with a blocking factor of 10% are shown with similar but more extreme saw-tooth patterning seen for higher blocking factors of 25%, 50%, 75% and 100%. The shoreline position simulated with groynes does not agree with observations of the Mariakerke nourishment (Figure 68).

Shoreline retreat at section 104

The observed shoreline retreat at section 104 of the Mariakerke nourishment (Figure 68) provides an opportunity to test the model performance for the different scenarios (Figure 91 - Figure 94). The observations show a retreat to 43 m one year post construction and then an advance to 46 m three years post construction. None of the scenarios with different sediment transport formulations is able to mimic the observed retreat followed by a shoreline advance (Figure 91). Rather, all scenarios show a gradual retreat in which the retreat rate is correlated with net alongshore sediment transport rate, i.e. a higher net alongshore sediment transport rate results in a higher shoreline retreat rate. The reference run employing the Bijkerk (1967, 1971) sediment transport formulation shows the best agreement with the June 2017 observation.

Also, the reference run employing a median grain size D_{50} shows the best agreement with the June 2017 observation (Figure 92). A finer grain size results in an overestimation of the cross-shore position at section 104 whereas a coarser grain size results in an underestimation.

Furthermore, the addition of tides does not alter the prediction of the cross-shore position at section 104 (Figure 93). Therefore, it could be argued that the same model result can be obtained without including a tidal forcing.

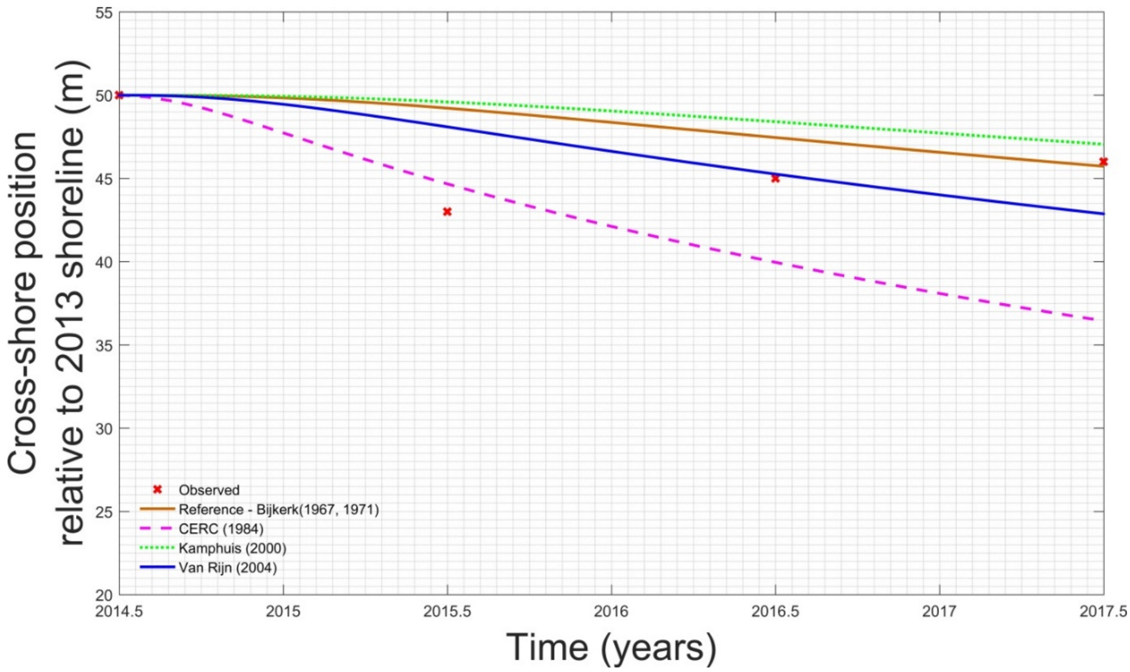

Figure 91 – Comparison of cross-position at section 104 (see Figure 36) over time as observed at the Mariakerke nourishment and as simulated with UNIBEST-CL+ with four sediment transport formulations.

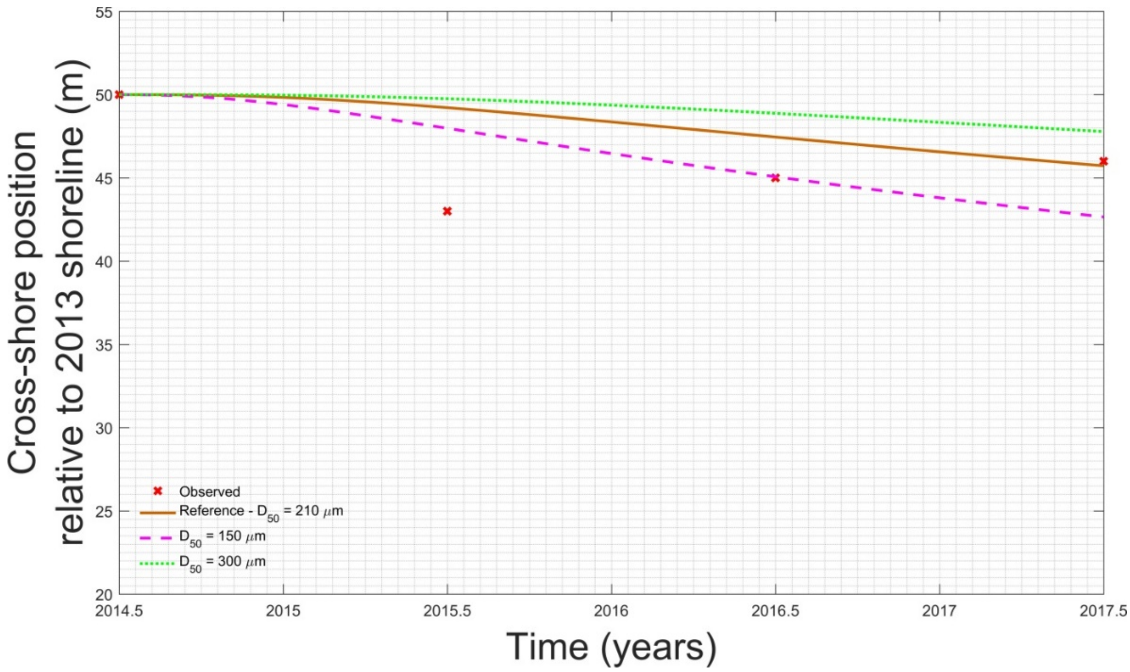

Figure 92 – Comparison of cross-position at section 104 (see Figure 1) over time as observed at the Mariakerke nourishment and as simulated with UNIBEST-CL+ with three different grain sizes.

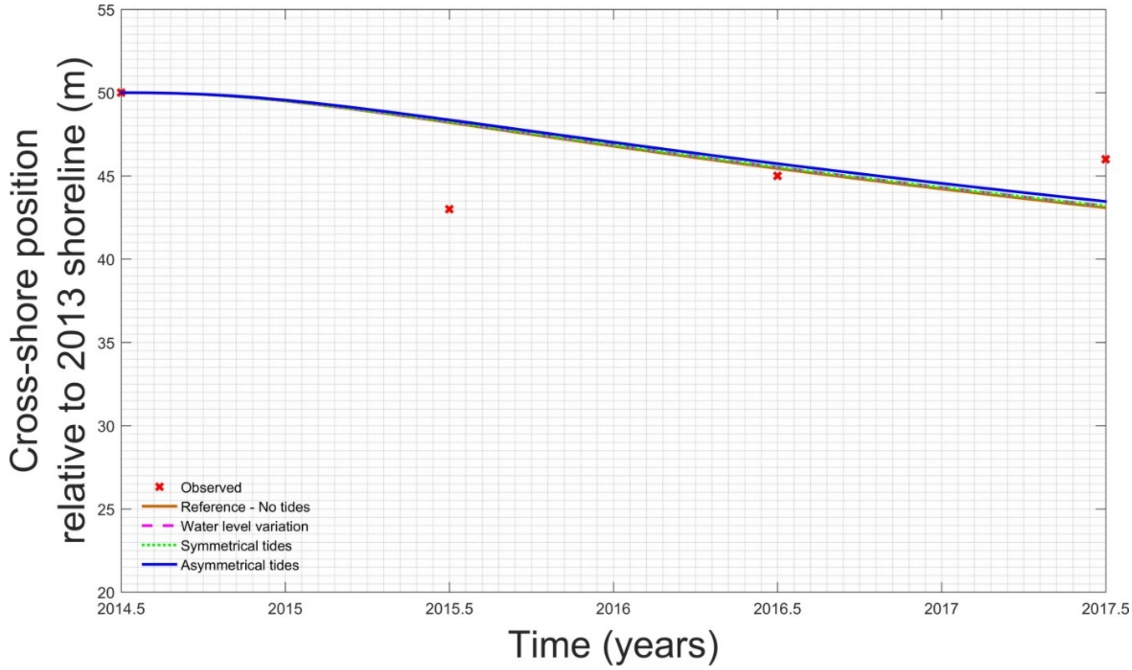

Figure 93 – Comparison of cross-position at section 104 (see Figure 1) over time as observed at the Mariakerke nourishment and as simulated with UNIBEST-CL+ for different tidal conditions.

*A tidal amplitude of 2 m is used, in agreement with water level observations at Oostende. In the symmetrical tides scenario, a maximum flood and ebb velocity of 0.25 m/s is used. In the asymmetrical scenario, maximum ebb velocities are reduced to 0.2 m/s.

The reference run without additional nourishments or groynes shows the best agreement with the June 2017 observation (Figure 94). The additional nourishments act as a sand source and result in a slower shoreline retreat with a poorer agreement for section 104. Yet, if the advancing trend seen in the observed cross-shore position continues into 2018, then it may be better predicted by the scenario with additional nourishments.

Lastly, the run with groynes shows a shoreline retreat during the first 1.5 years and an advance during the final 1.5 years, which is qualitatively similar to the observed cross-shore evolution (Figure 94). However, the simulated retreat rates underestimate the observed rates for a relatively low blocking factor of 10%. Higher blocking factors (not shown here) result in advance rather than retreat, and thus a poorer agreement with the observed cross-shore evolution.

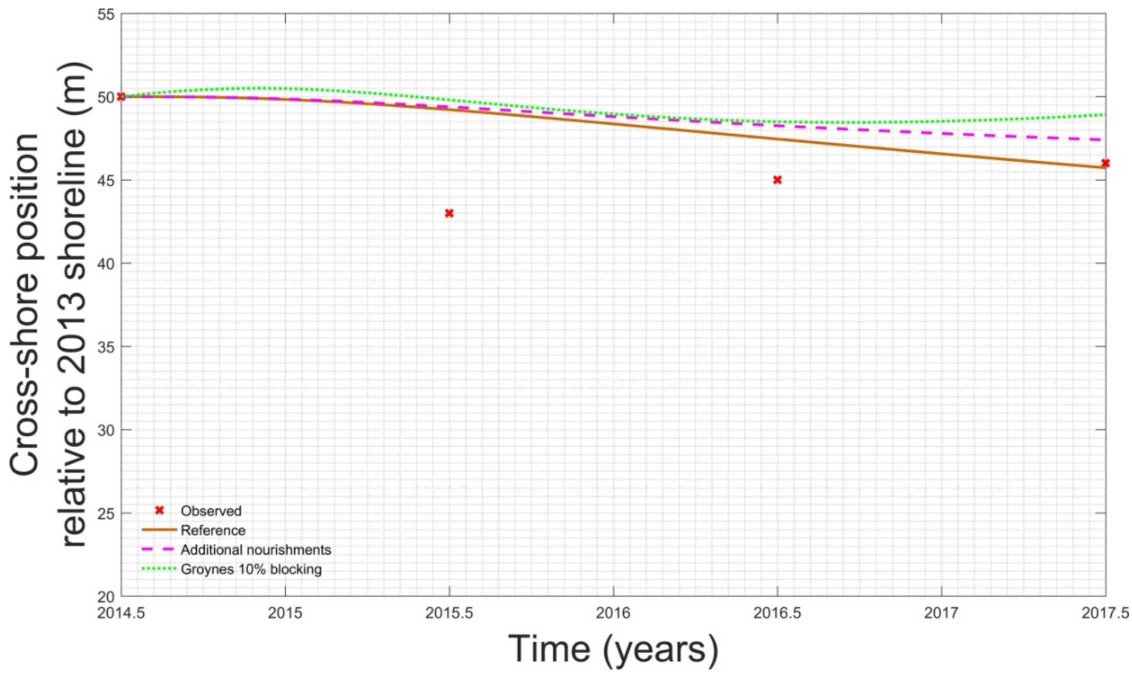

Figure 94 – Comparison of cross-position at section 104 (see Figure 1) over time as observed at the Mariakerke nourishment and as simulated with UNIBEST-CL+ applying three additional nourishments acting as sediment sources, and applying groynes spaced 400 m apart.

7.1.1 Volume decay of Mariakerke nourishment

In addition to the one-dimension cross-shore view at section 104, the observed volume decay of the Mariakerke combined beach and shoreface nourishment (Figure 69, Figure 70 and Figure 72) can be used to evaluate UNIBEST-CL+ model performance in three dimensions (Figure 95 - Figure 98). The observations show a volume decay of 7.5% in June 2017, with a striking volume increase to 103.5% of the original volume in June 2016.

All tested scenarios in UNIBEST-CL+ overestimate the volume decay of the Mariakerke nourishment. This applies to all sediment transport formulations for which the Kamphuis (2000) formulation shows the best agreement (Figure 95) due to the generation of the lowest net alongshore sediment transport (Table 32). Similarly, a coarser median grain size of 300 µm than the median grain size of 210 µm in the reference run results in a better agreement with the observations (Figure 96). As also noted in the comparison with the cross-shore position, the addition of tides does not affect the agreement with the observations (Figure 97). Lastly, the addition of groynes results in a poorer agreement with the observations compared with the reference run (Figure 98).

The best match with the observed volume decay is obtained in the run with additional nourishments acting as sediment sources (Figure 98). The observed and predicted volume decay differs only 1.3% in June 2017, which can be considered an excellent agreement given the many processes that are neglected in the UNIBEST-CL+ model.

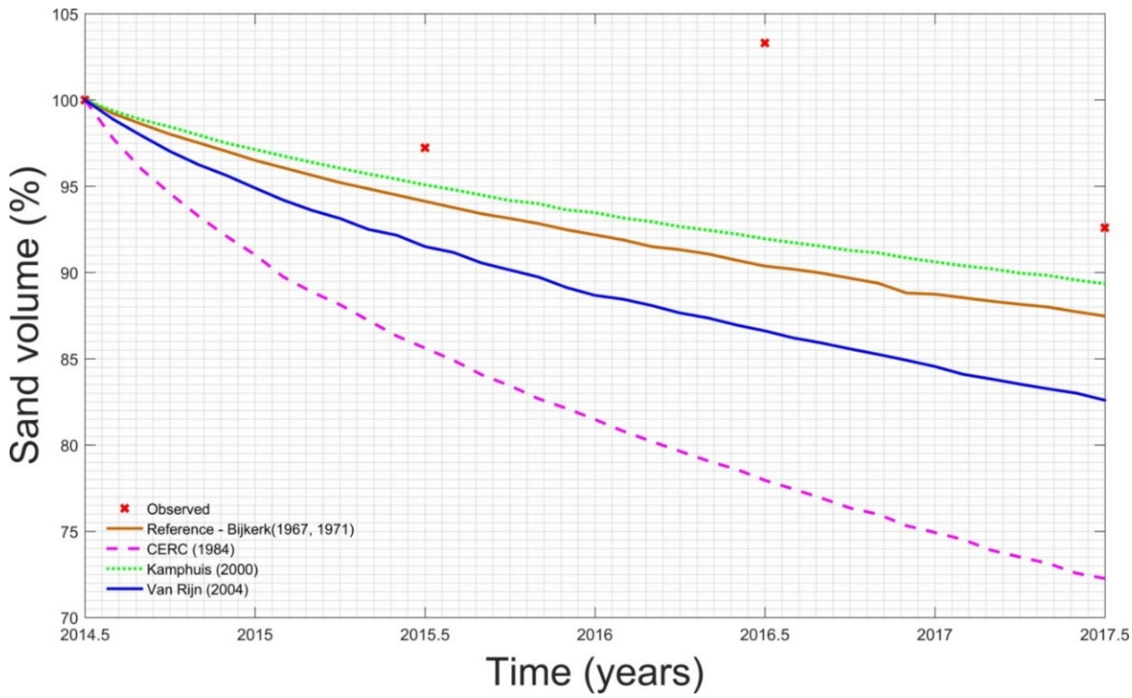

Figure 95 – Normalized sand volume decay as observed at the Mariakerke nourishment and as simulated with UNIBEST-CL+ with four sediment transport formulations.

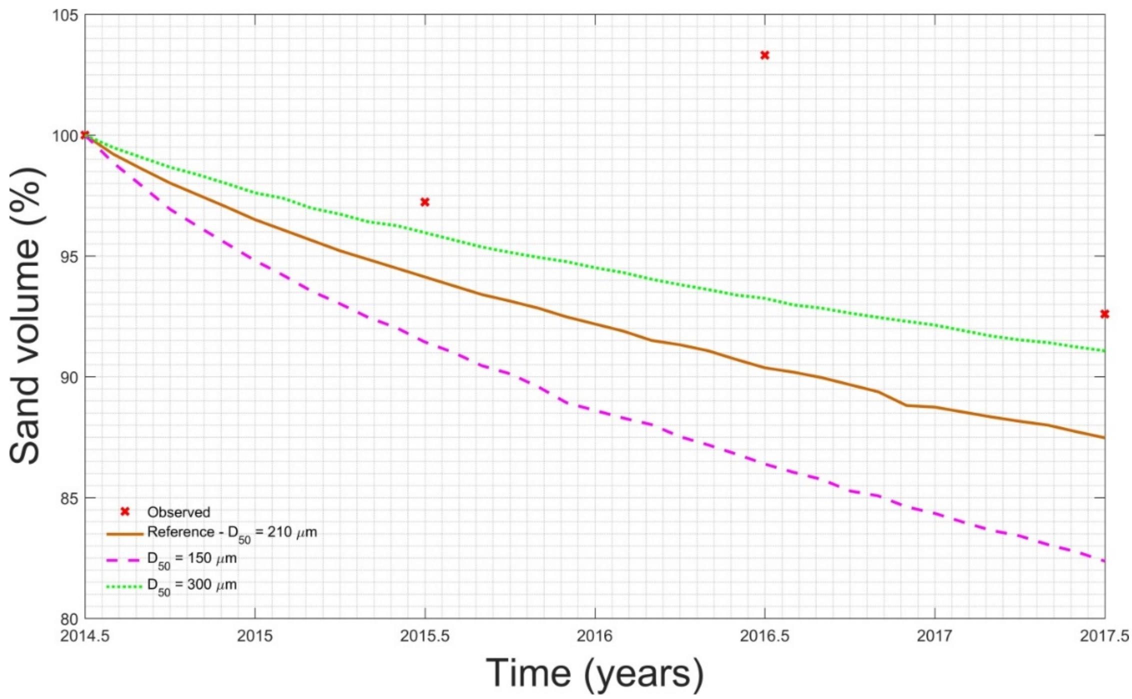

Figure 96 – Normalized sand volume decay as observed at the Mariakerke nourishment and as simulated with UNIBEST-CL+ with three grain sizes.

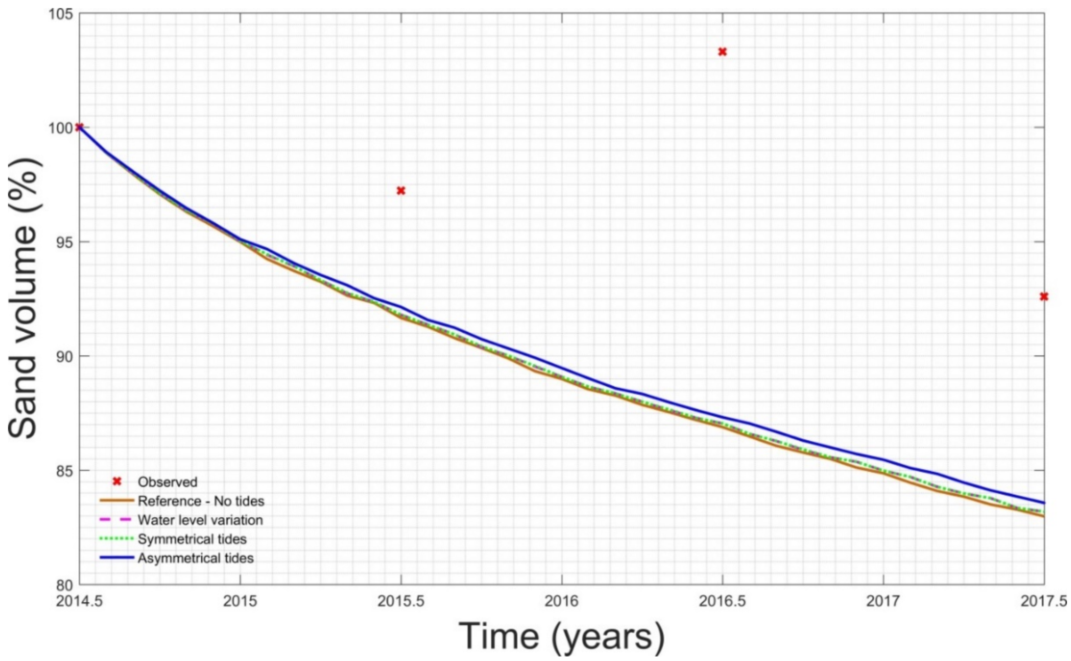

Figure 97 – Normalized sand volume decay as observed at the Mariakerke nourishment
and as simulated with UNIBEST-CL+ applying different tidal conditions*.

*A tidal amplitude of 2 m is used, in agreement with water level observations at Oostende. In the symmetrical tides scenario, a maximum flood and ebb velocity of 0.25 m/s is used. In the asymmetrical scenario, maximum ebb velocities are reduced to 0.2 m/s.

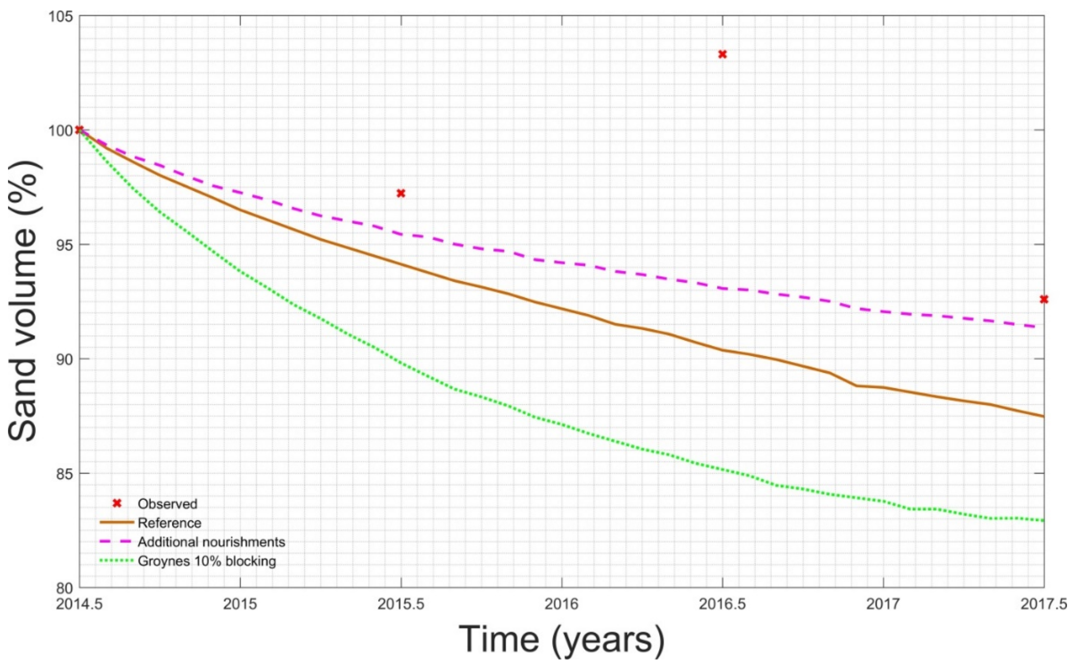

Figure 98 – Normalized sand volume decay as observed at the Mariakerke nourishment and as simulated with UNIBEST-CL+ applying three additional nourishments acting as sediment sources, and applying groynes spaced 400 m apart.

Synthesis

A calibration of the UNIBEST-CL+ model on data from the Mariakerke nourishment is performed. Data on large nourishments is scarce and hence the careful hydrodynamic and morphological monitoring for the Mariakerke nourishment provides a unique opportunity to calibrate the UNIBEST-CL+ model for the Belgian coast. The combined beach-shoreface nourishment has a total volume of about $1Mm^3$ of sand and was constructed in early 2014. This means that about three years of data on cross-shore evolution and volume decay is available to calibrate the UNIBEST-CL+ model.

The generated annual net alongshore sediment transport rate provides a first comparison between model simulation and observations (Table 32). The reference run shows the best agreement with observations on annual net alongshore sediment transport provided in Vandebroek et al. (2016) (Figure 43). This finding indicates that application of daily wave observations, the Bijker (1967, 1971) sediment transport formulation, and detailed measurements of grain size and the representative cross-shore profile are sufficient to simulate the observed annual net alongshore sediment transport for the Mariakerke coastal zone.

The reference run also shows a good agreement with the observations on cross-shore evolution and volume decay (Figure 91 - Figure 95). The cross-shore position as measured at section 104 shows a retreat of 4 m three years post-construction in June 2017, which is well replicated by the UNIBEST-CL+ model. The observed volume decay of 7.5% in June 2017 is overestimated by the UNIBEST-CL+ model by about 5%. The overestimation is attributed to additional nourishments acting as sand sources for the Mariakerke nourishments. Indeed, a scenario accounting for these additional nourishments shows a better agreement with the observed volume decay (Figure 98).

It is important to note that the beach and shoreface nourishments at Mariakerke show different behaviour, which, by definition, cannot be replicated by the UNIBEST-CL+ model. At Mariakerke, the beach nourishment is eroding whereas the shoreface nourishment is generally accreting. Combining these two trends results in an overall erosional state and, importantly, a change (i.e. a flattening) of the coastal profile at Mariakerke. However, UNIBEST-CL+ is merely able to shift the cross-position of the entire profile and therefore, by definition, unable to fully replicate the observed trends in cross-shore position and volume decay because this would require a change in profile shape.

The calibration of UNIBEST-CL+ on the observations of the Mariakerke nourishment shows that the model is well capable of simulating shoreline changes following the construction of a large nourishment along the Belgian coast. When detailed information on hydrodynamics, bathymetry and sediment characteristics is available, it is expected that robust and reliable predictions of future shoreline behaviour can be made with UNIBEST-CL+.

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