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Numerical modelling of erosion rates, life span and maintenance volumes of mega nourishments.

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ABSTRACT

Mega-nourishments, aiming at providing long-term coastal safety, nature qualities and recreational space, have been applied recently at the Holland coast and are considered at various other places in the world. Methods to quickly evaluate the potential and lifetime of these coastal mega nourishments are therefore very much desired, which is the main objective of this research. Two types of mega nourishments can be distinguished: feeder-type mega nourishments may erode freely to feed adjacent coasts for a more natural, dynamic dune growth while permanent mega-nourishments are designed to preserve safety levels and need to maintain their size and shape and thus needs to be nourished themselves. The design and impact assessment studies for both types of mega nourishments require detailed morphological studies to determine the morphological evolution. In this paper 2DH (Delft3D) and 1D (UNIBEST-CL+ and LONGMOR) numerical models were calibrated using data of the Sand Motor mega-nourishment and were then applied to model a series of mega-nourishments with various width over length ratios and volumes in order to derive relations and design graphs for erosion rates, life span and maintenance volumes. These relations and design graphs can be used in project initiation phases and feasibility studies. The magnitude of the modelled wave-driven longshore sediment transport rates in 1D coastline models depend on the representation of wave refraction on the lower shoreface, since a distinction should be made between the non-rotating lower shoreface and active surfzone. It was shown that the life time of nourishments is mainly determined by the dimensions of the nourishment and incoming wave energy.

Keywords:
Coastal morphodynamics, Mega nourishment, Process-based modelling, Delft3D, UNIBEST, LONGMOR

1 Introduction

In the Netherlands, coastal dunes and beaches form a major part of the first line of defence against flooding by the sea. In 1990 the Dutch government decided on a policy of “Dynamic Preservation Policy” to stop structural erosion of the coast, using nourishments as the preferred intervention to maintain the 1990 coast line (Mulder et al, 2011). In 2000 it was decided to extend the policy and also maintain the sand volume in the so-called Coastal Foundation, defined as the area between the -20 m depth contour and the landward boundary of the dune area. The annual average nourishment volume since 1990 of about 6 million m^3 was raised to 12 million m^3 (see e.g. van Koningsveld and Mulder, 2004). Since 2000, the dominant nourishment methodology has changed from beach nourishments

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with a typical volume of several hundred thousand m^3 of sand to more cost-effective and less disturbing shoreface nourishments with a typical volume in the order of one to several million m^3 (van der Spek et al., 2007).

An update of the sediment balance of the coastal foundation taking into account sea level rise (de Ronde, 2008) concludes that in order to maintain the active sand volume of the coastal foundation - the yearly nourishment volumes require upscaling from 12 to 20 million m^3 per year. Moreover, considering worst-case sea level rise scenario's, the commission on delta safety in The Netherlands (Deltacommissie, 2008) advises to pro-actively raise nourishment volumes up to 85 million m^3 per year until the year 2050. The extra buffer this would create, might be beneficial to different societal functions.

Recently mega-nourishments have been carried out in the Netherlands near Ter Heijde (Mulder and Tonnon, 2010; Stive et al., 2013) and near Petten (Kroon et al, 2015). Near Ter Heijde, about 19 million m^3 of sand was dumped to protect the rather small beach-dune system at that location and for nature and recreational purposes. This mega-nourishment known as the Sand Motor, was constructed in the shape of a hook of approximately 2.5 kilometre in alongshore length and 1 kilometre in cross-shore width. The mega-nourishment near Petten consists of about 40 million m^3 of sand and is about 10 kilometres long and 350 to 550 m width in cross-shore.

Both mega-nourishments provide protection for a large stretch of coast over an estimated timescale of at least 20 years, reducing the required maintenance volumes and nourishment frequencies. This is not only cost effective, but also preserves local ecology. They also offer opportunities for nature and recreation. Both nourishments differ in the aspect that the Sand Motor near Ter Heijde is created as a temporary coastal feature that may freely evolve, while the mega-nourishment near Petten (being part of the Dutch primary coastal defence) needs to be nourished to maintain its size and shape. A distinction can therefore be made between two types of mega-nourishments:

1. Permanent mega-nourishments (or beach extensions) that are designed to preserve momentaneous safety levels and need to maintain their size and shape and thus need to be nourished (Petten)
2. Feeder-type mega-nourishments that may erode freely, thus feeding adjacent beaches and dunes with sand for a more natural, dynamic growth (Ter Heijde)

The design and impact assessment studies of both types of mega-nourishments generally require detailed morphological studies, either to determine the nourishment requirements to maintain their size and function (mega-nourishments for safety such as near Petten) or to determine the evolution and life span (mega nourishments such as near Ter Heijde). Previous work on parameterising the life time of nourishments (Dean and Yoo, 1992) focused on relatively small beach nourishments using a standard diffusion type coastline model. Dean and Yoo (1992) present the proportion of the nourishment volume remaining in the project area over a 20-year period taking into account the long-term effective wave height (H_{0eff} ; see Dean and Yoo, 1992) and alongshore nourishment length. Based on their design graph however, one finds that only about 30% of the original volume of the Sand Motor (H_{0eff} of 1.2m and alongshore length of about 2000m), would remain after 3 years, while in reality about 82.5% of the volume remained after 3 years (see Figure 3). It is envisaged that the cross-shore extent may be of relevance for mega-nourishments.

This paper therefore focusses on providing model-based estimates of erosion rates, life span and maintenance volumes of large mega-nourishments, taking into account the wave climate, length and width. The design graphs based on these estimates can be used in project initiation phases and feasibility studies. First 2DH process-based and 1D coast line model numerical models are calibrated on measurement data of the mega-nourishment near Ter Heijde, The Netherlands. Then design graphs for erosion rates and life span of mega-nourishments are derived based on a series of 1D and 2DH computations for mega-nourishments with various width over lenght ratios and volumes. Next, long-term effects and nourishment requirements to maintain the shape and size of mega-nourishments are investigated. Finally, a step by step description to apply the design graphs is given and then applied to estimate erosion volumes and maintenance volumes for the mega-nourishment near Petten, The Netherlands.

2 Methodology

Data on the morphodynamic evolution of mega-nourishments is scarce and only a few years of data are available for the mega-nourishment near Ter Heijde, The Netherlands. Therefore this paper applies numerical models to study the morphodynamic evolution, erosion rates and life span of mega nourishments. Typical model approaches that are used for the evaluation of nourishments are coastline models and coastal area models. Coastline models assume gradually varying flow conditions, more or less parallel depth contours and a constant cross-shore profile and originate from analytical solutions of the diffusion equation to small amplitude departures for a rectilinear coast (Pelnard-Considère, 1956). Coastal model such as Delft3D (Lesser et al., 2004) resolve variations in both horizontal dimensions (de Vriend et al., 1993, Nicholson et al, 1997).

Both type of models have their specific strong points and draw backs (see Table 1). In general, this comes down to a selection of either a fast model with limited detail (coastline models) or a more detailed description with large penalties on computational efficiency (coastal area models). In long-term applications, the latter model type often requires simplifications or input filtering techniques. Some relevant model characteristics of coastline models are discussed by (Capobianco et al., 2002) while the reduction of climate conditions is described by (Walstra et al., 2013).

Table 1 – Overview of advantages & disadvantages of coastline and coastal area models

Model type	Advantage	Disadvantage
Coastline	▪ Fast model allowing for the application of a full wave climate ▪ Time-series of wave conditions	▪ Less suitable for investigation of detailed morphology ▪ Includes the wave-driven current only
Coastal area	▪ Detailed sediment transport patterns and morphology ▪ Inclusion of tidal forcing and wind driven currents	▪ Computationally intensive and therefore requires reduction of the forcing conditions

Both model approaches have been applied for the evaluation of nourishments. Detailed process-based models (Delft3D) were, for example, applied at the Dutch coast by van Duin et al. (2004) at Egmond and Grunnet et al. (2005) at Terschelling. Ruggiero et al. (2010) uses the coastline model UNIBEST-CL+ to assess long-term coastline evolution at the West coast of the US, while other coastline models like GENESIS (Hanson, 1989) are also widely applied in the coastal engineering community. For example by Larson and Kraus (1991), for a theoretical analysis of the fate of beach fill material (for small nourishments) and by Thevenot and Kraus (1995) for the evolution of longshore sand waves on Southampton beach in New York state.

In this paper, we apply both models to study the morphodynamic evolution of mega-nourishments. A detailed Delft3D coastal area model is applied for the short-term evolution, while, the coastline models UNIBEST-CL+ (WL | Delft Hydraulics, 1994; Deltares, 2011) and LONGMOR (van Rijn, 2005) are used for the evaluation of mega-nourishments on longer time scales. Both the mega-nourishment near Ter Heijde and a range of idealised nourishment configurations have been modelled using these models. Design graphs and simple formulations for maximum erosion and half time (life span) of freely evolving nourishments and for initial erosion rates and long-term maintenance of permanent beach reclamations are derived based on these model results.

Delft3D

Delft3D is a coastal area model that solves the shallow water equations and the advection-diffusion equation for sediment. In this coastal morphodynamic application, a depth-averaged (2D) Delft3D hydrodynamic model is coupled to a SWAN spectral wave model. Delft3D applies the online morphology functionality to compute sediment transport and bed changes after each time step (Lesser et al., 2004). Non-cohesive sediment transport is modelled following Van Rijn (2007a,b). In order to speed up the simulations and archieve reasonable computational times (in the order of days), a morphological scale factor (Ranasinghe et al., 2011) was applied in combination with the so-called mormerge or parallel-online method (Roelvink, 2006). In this approach, all representative wave conditions are run in parallel and the bathymetry is updated every time step using a weighted average (based on the occurrence of the wave conditions) of the computed bed changes for each individual wave condition.

UNIBEST-CL+

The UNIBEST-CL+ (WL | Delft Hydraulics, 1994) is a 1D coastline model consisting of two modules. The longshore transport module calculates the tide- and wave induced longshore currents and resulting sediment transport rates. It uses a built-in wave propagation and decay model (Battjes and Stive, 1984) to model wave transformation over a constant cross-shore beach profile. Longshore transport rates are computed for a range of coastline angles and the transports as function of coast orientation is schematized in a so-called S-φ relation. The coastline module uses the S-φ relation obtained from the longshore transport module to calculate the alongshore transport on each stretch of coast. Based on the gradient of the alongshore transport, the coastline changes are being calculated after which the longshore transport rates are updated and the procedure is repeated. UNIBEST-CL+ includes a so-called dynamic boundary option to only rotate the depth contours over a pre-defined cross-shore distance. Wave angles in the model are limited to the angle of maximum transport (i.e. about 42 degrees) to prevent coastline instabilities for situations with high-wave angle incidence (Ashton et al., 2001; Arriaga et al., 2017) which can be present temporarily along the initial strong curvature of the coasts of a mega-nourishment. A uniform beach profile is assumed to be present in coastline models, which is also used for the computation of the wave transformation towards the shore. A constant active height has been applied in this study, which is in line with common practice. In UNIBEST, a so-called dynamic boundary can be specified that defines the part of the coast (i.e. most seaward cross-shore extent) that rotates over time with the coastline (due to transport gradients) while the lower shoreface orientation (MSL -6m to MSL -10m) remains static. This rotation of the cross-shore profile affects wave refraction and nearshore waves. This option is not available in traditional coast line models in which the entire profile is rotated along with a coastline reorientation.

LONGMOR

The 1D model LONGMOR is a coastline model which computes the mean position of the coastline at every time-step directly from the gradients of the longshore transport capacity (van Rijn, 2005; McCall, 2013). LONGMOR computes the longshore transport and the longshore transport gradient at each location based on the specified wave climate, rather than making use of the Qs-φ curve. This implies that the model is sensitive to wave chronology effect; wave directions are therefore ideally specified in alternating or random order. LONGMOR does not apply the dynamic boundary used in UNIBEST-CL+ and the rotation of the coastline is therefore assumed to affect the whole cross-shore profile (i.e. all depth contours up to the offshore boundary).

2.1 Model set-up and parameter settings

The model set up and parameter settings for the Delft3D, UNIBEST-CL+ and LONGMOR models applied to model both the Sand Motor and a range of mega-nourishments with various width over length ratios and volumes are summarized in Table 2. The model setup and parameters settings are based on the calibration of the models with measurement data as presented in Section 3. Sediment at the Dutch coast generally consists of 200 to 300 μm sand (Kohsiek, 1984; Van Straaten, 1965) which fines in the offshore direction. Medium size sand was also used for the construction of the Sand Motor (Huisman et al., 2016). Schematized tidal forcing, wave conditions and cross-shore profiles representative for the central Dutch coast are applied.

Table 2 Input parameters for all three models

Model aspect	Delft3D	UNIBEST-CL+	LONGMOR
Model type	Process-based. Two dimensional and depth averaged model (2DH)	Equilibrium based. 1D coastline model	
Model domain	Flow grid: 24 x 3.8 km Wave grid: 33 x 3.9 km dx= 20x20 m in area of interest.	180 km length with dx = 50m in area of interest.	35 km in length with dx = 50m.
Model Time	5 years	200 years	20 years
Time step	0.25 minutes	100 steps per year	3.6 minutes
Bathymetry	Equilibrium Dean profile with constant slope near waterline (Dean-Moore-Wiegel profile, Stive et al., 1993) Nourishment slope: 1:50		No profile. Using bulk transport formulation with wave height at breaker line
Boundary condition	Water level (harmonic) at 19mdepth [offshore] Lateral boundaries: Neumann(harmonic)	Wave conditions at 6.3m depth [nearshore]	Wave conditions at 19m depth [offshore]
Wave forcing	10 representative offshore wave conditions based on 23 years of observations at Noordwijk	269 (modelled) nearshore wave conditions near Noordwijk	10 representative offshore wave conditions based on 23 years of observations at Noordwijk
Tidal forcing	Tidal component: M2 = 0.80m and M4 = 0.22m	No tidal forcing	
Morphological Factor	372.07 for all wave conditions combined	1 on 1 timescale for hydrodynamics and morphology	
Active height	Implicitly by process formulations in Delft3D	8.5m for Sand Motor case, 7m for artificial cases	10m (between -7m and +3m MSL)
Seawater	Temperature: 15 °C; Density = 1025 kg/m^3; Salinity ≈ 34 ‰		
Sediment characteristics	D_{10}=150 μm, D_{50}=200 μm, D_{90}=300 μm, D_{SS}=200 μm, Porosity =40%, Density=2650 kg/m^3 Note that LONGMOR only uses the D_{50} of the grain size distribution		

Sediment transport	TRANSPOR2004 (van Rijn, 2007a and van Rijn, 2007b)	Parameterized bulk transport formulation (van Rijn, 2014)

2.2 Wave climates and net longshore transport rates

Representative wave and wind forcing derived from a 23-year data set from measuring station Noordwijk, in the central part of the Dutch coast were applied. For UNIBEST, a nearshore wave climate with 269 wave conditions was generated using a SWAN model for the central part of the Dutch coast. For Delft3D and LONGMOR, ten representative offshore wave conditions were derived by binning the measured, offshore wave times series into 5 wave directional classes of 30° and two wave height classes (0-1,5 and 1.5-4m). For each of the ten wave conditions the probability of occurrence and the representative wave period and mean wind speed and –direction were determined, see Table 3. In order to set the total probability of occurrence of 100%, the probability of occurrence of offshore directed waves was distributed over the 5 lower wave conditions (w01 to w05). The peak period T_p was calculated from the significant wave period T_s by using the relation $T_p = 1/0.95 * T_s$. Wave roses of the full and reduced wave climate are presented in Figure 1.

Table 3 – Wave & wind conditions derived from the dataset of 23 year wave & wind observations near Noordwijk.

# of wave cond.	**Sig. wave height H_s [m]**	**Peak wave period T_p [s]**	**Wave direction [°N]**	**Wind speed [m/s]**	**Wind direction [°N]**	**Occurrence [%]**
w01	1.08	5.24	240.0	8.87	217.1	19.544
w02	2.43	6.89	241.4	14.61	228.9	3.14
w03	0.89	5.24	267.7	6.61	243.4	16.174
w04	2.64	7.22	267.5	13.31	367.8	2.08
w05	0.84	5.67	299.5	5.29	278.8	17.174
w06	2.61	7.46	299.6	12.21	293.8	2.02
w07	0.82	5.94	328.3	4.90	358.0	23.604
w08	2.64	7.94	326.4	11.70	339.0	2.19
w09	0.72	5.16	354.3	6.22	56.1	13.954
w10	2.24	7.03	353.0	12.52	32.7	0.12
					SUM:	**100**

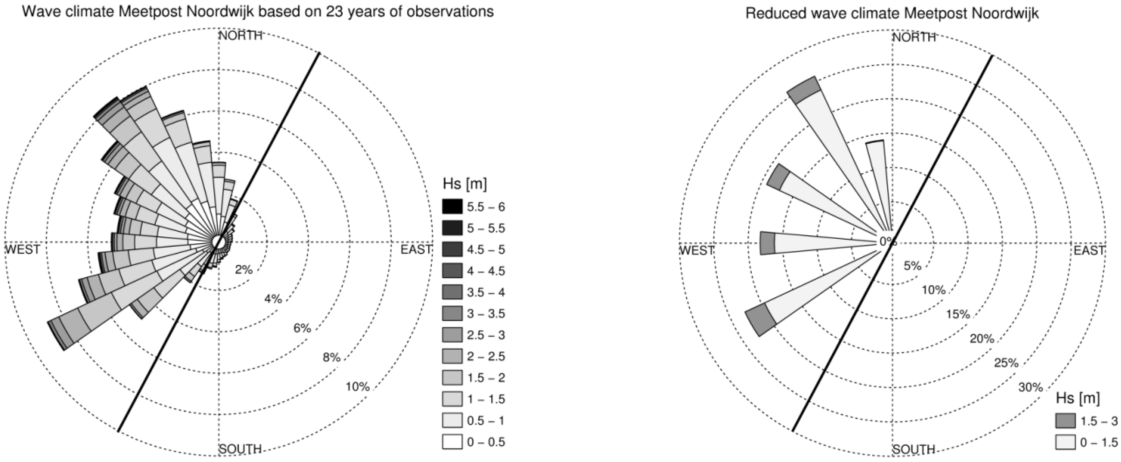


Figure 1 – Wave rose of the full wave climate (left) and reduced wave climate (right), solid black line represents coastline.

For a fair comparison between the models applied in this study, all models were calibrated on a net annual alongshore transport of 200.000 m^3/year, being the average alongshore transport in the surf zone for the central part of the Dutch coast (van Rijn, 1997).

3 Hindcast of Sand Motor mega nourishment

The Delft3D, UNIBEST and LONGMOR models are calibrated with field data for the Sand Motor mega nourishment as constructed at the Holland coast (Delfland section) a few kilometres south of The Hague from June until August 2011 (Stive et al., 2013; de Schipper et al., 2016). In total, a volume of 19 million cubic meters of sand has been nourished in order to create the large scale nourishment with approximate dimensions of 2.5 km alongshore length and 1 km cross-shore extent (see Figure 3a). The shore-normal of the undisturbed coastline before construction of the Sand Motor is about 310°N, but is shown rotated with the alongshore direction from left to right in the figures here for practical reasons.

3.1 Bathymetric data

Between the moment of completion of the Sand Motor (August 2011) and September 2014, 25 bathymetric surveys have been carried out using a real-time kinematic differential global positioning system (RTKDGPS) and (for subareal parts) a single beam echo sounder mounted on a waverunner jetski. Figure 3 shows the bathymetry of the Sand Motor after construction (survey 1 - August 2011: Figure 3a) and after 3 years (survey 25 – September 2014: Figure 3b).

For each survey, the volume change of the Sand Motor Peninsula (red polygon in Figure 3a) with respect to the first measurement has been computed. It was found that in the first 3 years a total volume of 2.8 million m^3 has disappeared from the initial area, which is approximately 17% of the initial volume of the Sand Motor Peninsula as measured (16.35 10^6 m^3). It is noted that during the first half year after construction a relatively large number of winter storms occurred. During this period the mean significant wave height at station “Europlatform” at approximately 30m MSL was 1.45 m and the exceedence probability of a significant wave height of 3m was 7.3%, while these values were 1.27m and 4.1% for the long-term averaged wave climate. It is assumed that the sediment is mainly redistributed towards the dune area and to the adjacent coast.

Figure 2 shows the volume decrease of the Sand Motor Peninsula, in which all surveys are displayed. Bathymetric surveys were carried out right before and after (rectangular marker in Figure 2) the severe storm of 5 December 2013. These measurements indicate that that nearly 280.000 m^3 of sand was eroded from the Sand Motor peninsula. It is assumed that a considerable amount of sand has been brought offshore by high undertow velocities and it is expected that under calm conditions a net cross shore sand transport towards the shore will transport some of this sediment back to shore.

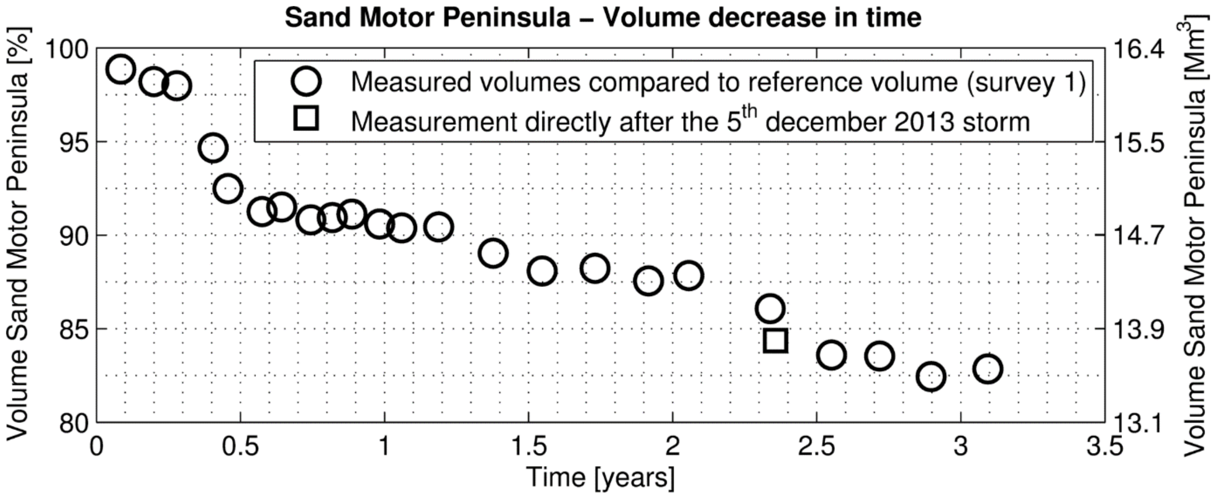
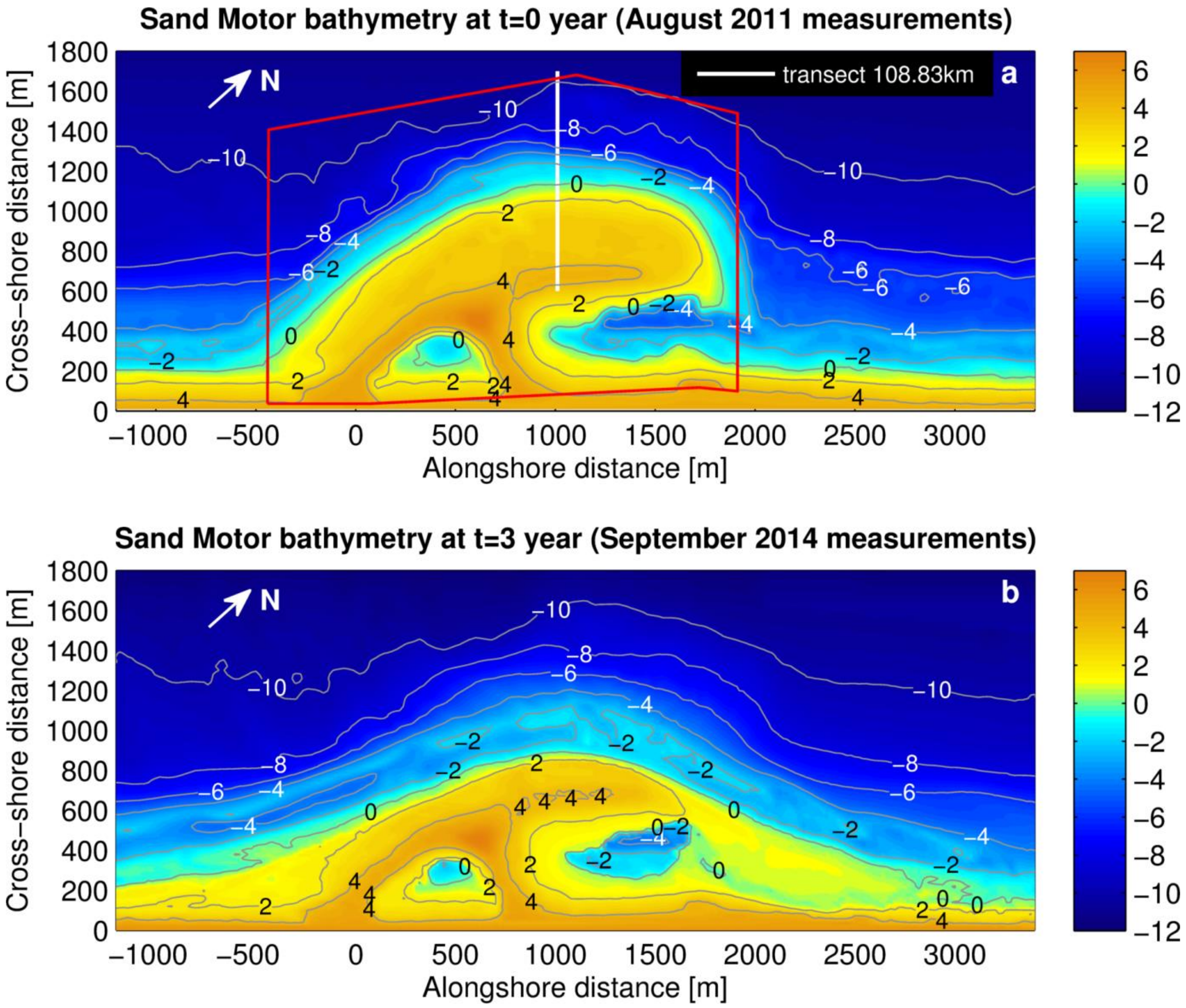


Figure 2 Volume decrease in time for the Sand Motor Peninsula (red polygon in Figure 3)



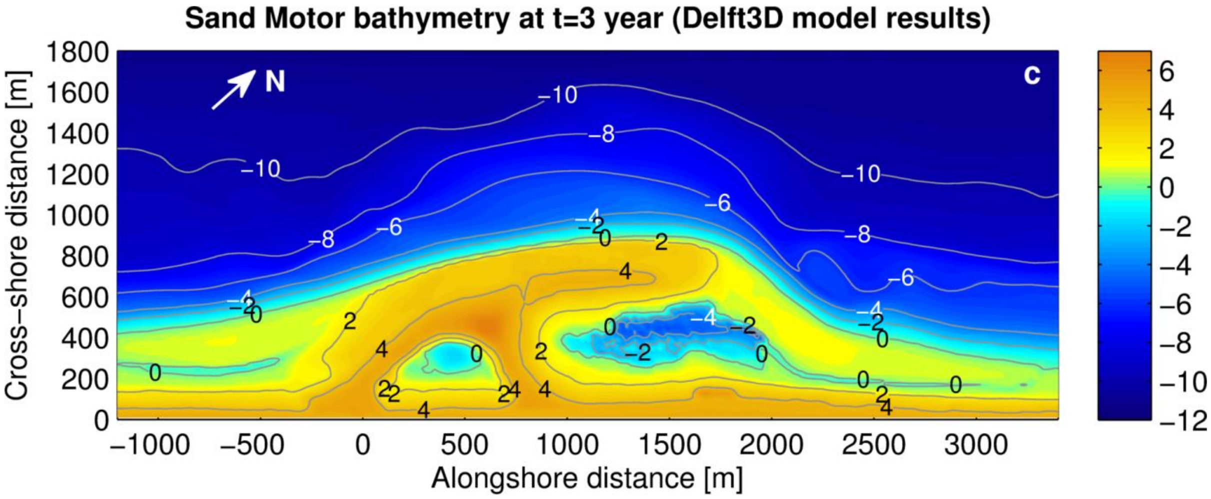


Figure 3 – Top view of Sand Motor nourishment. Bathymetry measurements (panel a: August 2011; panel b: September 2014) and Delft3D model results (panel c). Depth with respect to MSL. The white line in panel a depicts transect 108.83 for which the cross-shore profile is shown later. The red polygon shows area called 'Sand Motor Peninsula' for which volume calculations are carried out

3.2 Calibration Delft3D

The Delft3D model of the Sand Motor mega nourishment was run for 5 years. After 3 years, a good resemblance between modelled and measured bathymetry was observed (Figure 3b & c). At the eastern part, the spit growth is correctly predicted as well as the formation of the channel, although the shape of the channel is slightly different. Large erosion can be observed at the top of the Sand Motor as well as accretion of sediment on both adjacent sides, which is in good agreement with the measurements. However, the model predicts a steeper cross-shore profile which was not shown in the measurements and the overall shape of the nourishment is slightly different than measured. The measurements show a much more symmetrical shape than the model results, in which the latter is shifted to the right. The reduction in seaward extent of the Sand Motor model is in good agreement with the measurements.

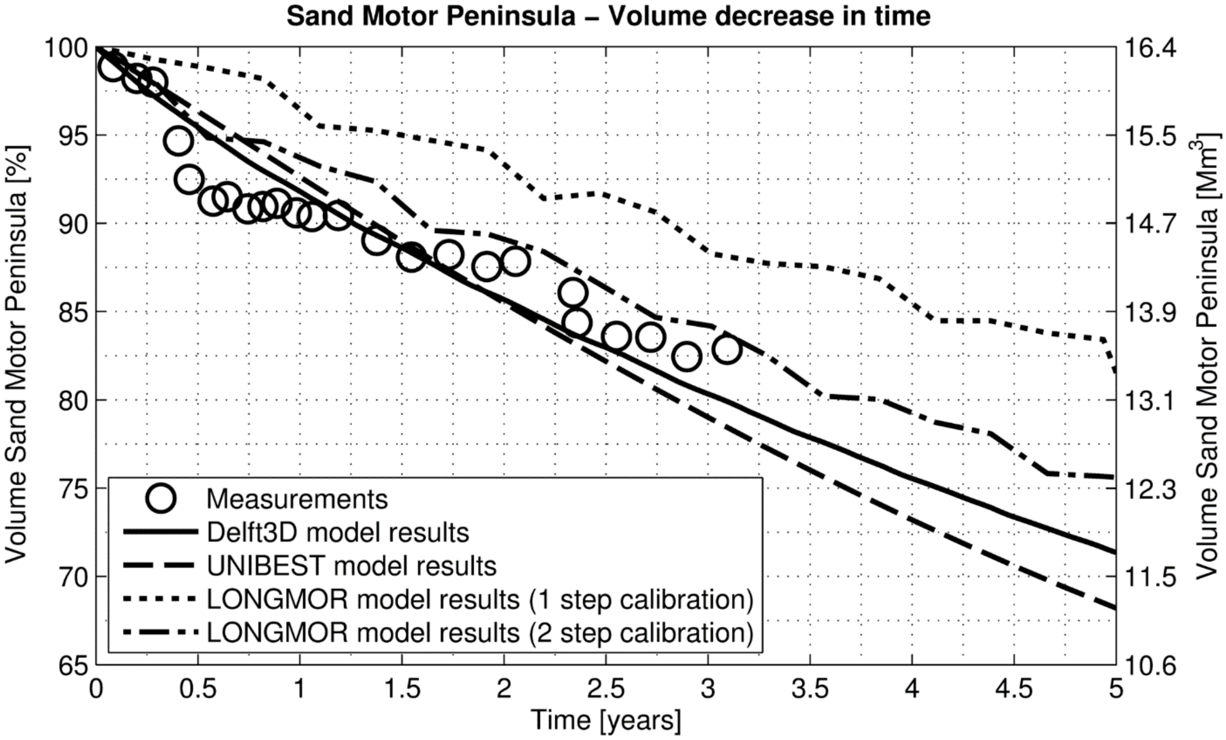


Figure 4 – Volume decrease in time for the Sand Motor Peninsula + model results

Figure 4 shows the measured volume decrease in time for the Sand Motor Peninsula, combined with computed results for Delft3D (solid black line), UNIBEST (dashed black line) and LONGMOR (dotted black line and dash-dotted black line). The UNIBEST and LONGMOR results are discussed in Section 3.3. Overall, the Delft3D result is in good agreement with the measurements and it is concluded that the Delft3D model is capable of predicting volume decrease in time for mega nourishments. The underestimation of the volume decrease in the first year is attributed to the application of a yearly averaged wave climate. Especially in the first half year after construction, a number of consecutive winter storms resulted in relatively largerosion rates of the Sand Motor. Over the course of a few years, results with the year-averaged wave climate are more in line with measurements. It is noted that due to the use of the mormerge approach, the results do not respond to the individual wave conditions of the wave climate used, but show a gradual, averaged response.

Figure 5 shows the cross-shore profiles at transect 108.83 km (see Figure 3a) for the first 3 years according to the Delft3D model results (upper plot) and measurements (lower plot). These measurements shown are carried out at August 2011, August 2012, August 2013 and September 2014. It can be seen from the model results that during a period of 3 years the mean water line moved approximately 250m towards the shore, which is in very good agreement with the measurements. Although the seaward extent reduction is calculated correctly, measurements show a considerable amount of sand being placed between a cross-shore distance of 1000 to 1200m, which is not present in the model results. The absence of this berm is due to the used computation type (2DH), the absence of infragravity waves and the mormerge approach, in which the latter causes a smoothed profile due to averaging over 10 wave conditions. However, in general, the model results are in good agreement with the measurements.

Based on the good agreement between modelled and measured erosion volumes and shoreline retreat, it is concluded that Delft3D can be applied to study the evolution of a series of mega-nourishments with various dimensions.

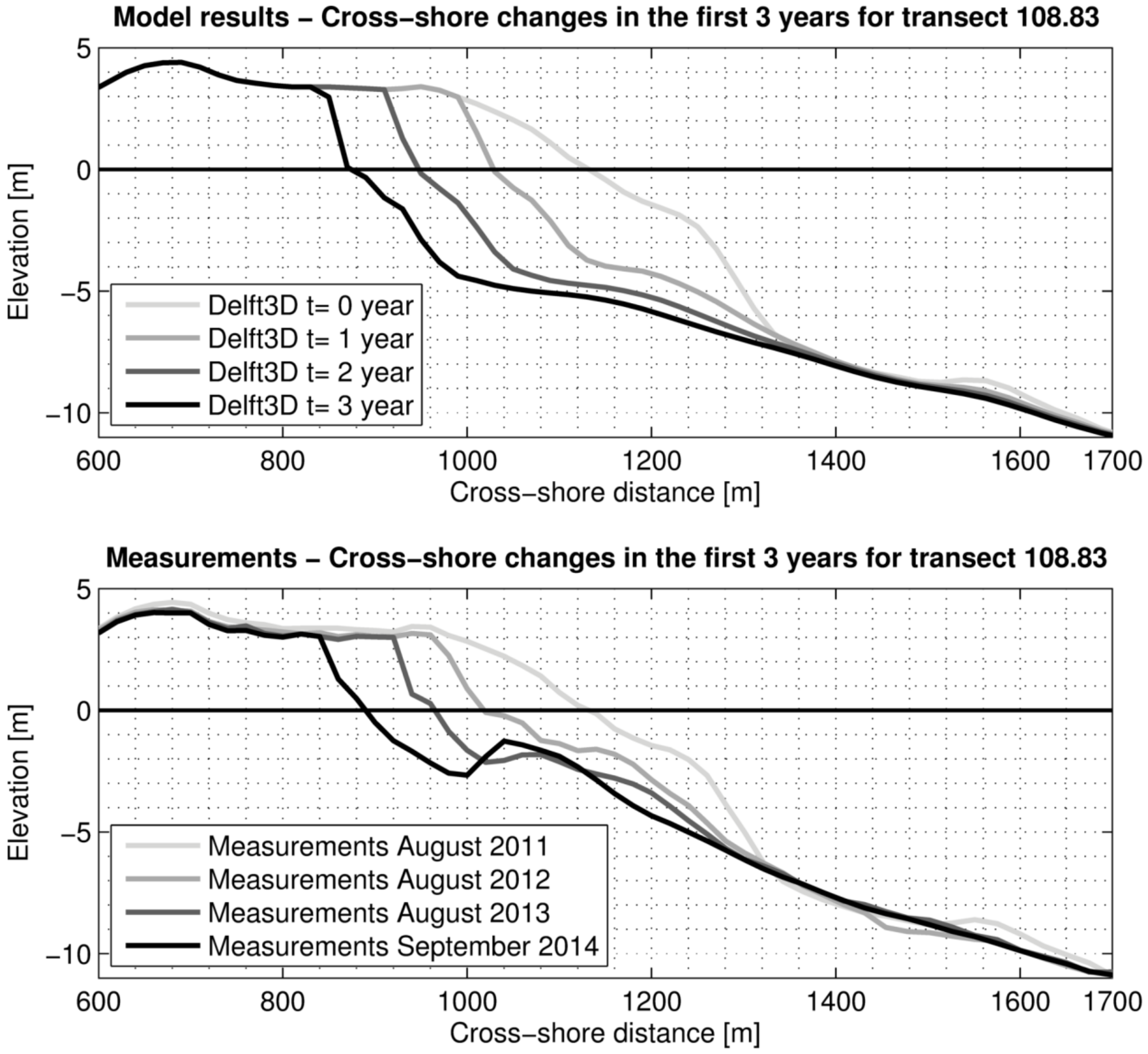


Figure 5 – Cross-shore profiles at transect 108.83km. Model results (upper) and measurements (lower)

3.3 Calibration 1D line models

UNIBEST

In order to compare model results and measurements, the initial Sand Motor shape is implemented in the UNIBEST model (see Figure 6b). It is noted that detailed characteristics such as ‘the hook’ at the East of the Sand Motor cannot be implemented because of the strong curvature in coastline. The initial volume of the Sand Motor Peninsula is accounted for by using an active height of 8.5m. The model input parameters are given in Table 2. The cross-shore profile extends to a water depth of 6.3m on which a detailed nearshore wave climate consisting of 269 wave conditions is imposed. This boundary is also used as the dynamic boundary, which means that the coast rotates with the shoreline over time (also see Section 3.5). In the first months of the simulation, wave angles may locally exceed 45 degrees due to the strongly curved coastline. In these cases, transports rates are limited to the maximum transport (at about 42 degrees) to prevent instabilities. The net alongshore sediment transport of the UNIBEST model was 200.000 m^3/year for a straight coastline. Calibration of the transport rates or wave angles was therefore not necessary with the UNIBEST model. The computed and measured volume decrease over time is very similar to the transport rates computed with the Delft3D model (see Figure 4; with UNIBEST results represented by the black dashed line). This is remarkable since cross-shore processes and tidal forcing are not taken into account within the UNIBEST model, but is also in line with findings by Luijendijk et al. (2017) who found that volume changes at the Sand Motor are predominantly the result of the alongshore wave-driven currents. The good UNIBEST results for the Sand Motor case illustrate that this model can be used to study erosion rates, life span and maintenance volumes of mega nourishments.

The effect of using different wave climates in the Delft3D and UNIBEST models and the effect of using a dynamic boundary in UNIBEST is discussed in Section 3.4.

LONGMOR

As is the case for UNIBEST, the rather steep alongshore coastline profile of the Sand Motor may lead to coastline instabilities due to the large relative wave angles (>45°) occurring at that part. The parameterized alongshore transport formulation (van Rijn, 2014) used in LONGMOR varies with $\sin(2\theta_{br})$ and the alongshore transport will therefore decrease for relative wave angles larger than 45°, which may lead to coastline instabilities. The coastline position is numerically computed from an explicit Lax-Wendroff scheme including a smoothing-parameter to suppress numerical oscillations of the computed coastlines. The value of the smoothing parameter α (in the range of 0.0001 to 0.001) can be determined by trial and error.

Figure 4 shows the calculated volume of the Sand Motor Peninsula according to the LONGMOR model (dotted black line) using the same wave climate with 10 offshore wave conditions as is used in Delft3D. The offshore wave heights are converted to wave heights at the breaker line by a refraction analysis assuming shore-parallel depth contours. Similar to the other models, LONGMOR is calibrated to a net annual alongshore transport of 200.000 m^3/year for a straight coastline. As can be seen from the figure, the LONGMOR model significantly underestimates the volume decrease in time with respect to the measurements (approximately 30%). This discrepancy between the Delft3D and LONGMOR result has the following causes:

- Different wave refraction seaward of the active surf zone. The depth contours outside the surf zone rotate with the coast in the LONGMOR model, while Delft3D uses a more realistic (almost stationary) lower shoreface orientation.
- Wave focusing resulting in enhanced wave heights at both seaward corners is neglected.
- Cross-shore transport gradients which may be relatively large during the initial years due to the presence of the relatively steep beach profiles are neglected in LONGMOR.

The results of the 1D LONGMOR-model can be significantly improved by calibration of the schematized wave climate (by slightly adjusting the wave angles and durations) using measured erosion volumes, which is only possible if substantial validation data are available. The resulting wave climate is slightly more asymmetric than the wave climate used in the Delft3D-model runs. The net annual alongshore transport is kept constant at 200.000 m^3/year to the north by slightly adjusting the sediment transport coefficients. Figure 4 shows the computed volume decrease as a function of time for this so called 2-step calibrated LONGMOR model (dash-dotted black line). The measured initial erosion volumes after 3 years are reasonably well simulated, but the measured erosion after 0.5 and 1 year are underestimated. This result shows that a 1D coastline model following a traditional approach without a dynamic boundary can be calibrated if measurement data are available, which is the case even for mega nourishments (such as the Sand Motor) with a relatively large seaward extent of about 1 km over a short alongshore distance.

3.4 Sensitivity for wave climate conditions

Very similar transport rates can be obtained using a full (269 conditions) and reduced wave climate (10 wave conditions) in Delft3D and UNIBEST (Figure 6, panel a). The modelled morphological development of the Sand Motor for each of these sets of boundary conditions is very similar and also in line with the observed development (Figure 6, panel c). It is noted that the cross-shore profile in the UNIBEST model was extended to a depth of 19 m in order to apply the representative offshore wave climate used in the Delft3D model in UNIBEST. For this case, wave refraction was computed for a lower shoreface with shore parallel contours (for the zone MSL -19m to MSL -6.3m) which is similar to using the SWAN model for the offshore wave transformation.

Transports rates from LONGMOR (using the reduced wave climate) are significantly smaller and as a consequence, the modelled morphological development of the Sand Motor lags behind the observed development. This under prediction of transport rates and morphological development is attributed to the traditional representation of wave refraction on the lower shoreface in LONGMOR (see next Section). As discussed in the previous section, the results of LONGMOR can significantly be improved by calibration using measured erosion volumes.

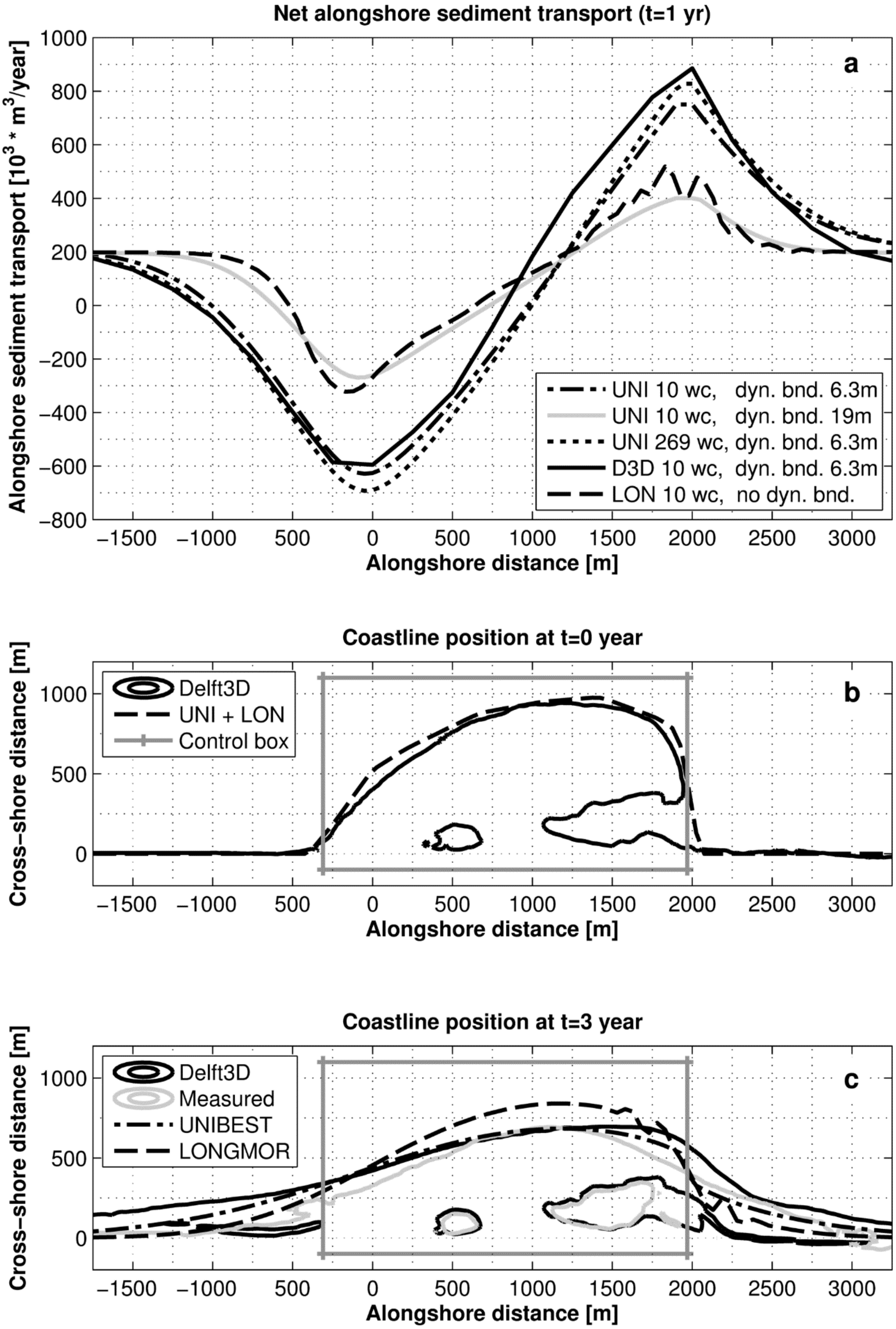


Figure 6 – Computed alongshore sediment transport at t=1 year with the Delft3D, UNIBEST and LONGMOR models (panel a), initial coastline position (panel b) and coastline position at t=3 year for the Sand Motor (panel c). wc = wave conditions

3.5 Impact of wave refraction on lower shoreface

The magnitude of the modelled wave-driven alongshore transport at the Sand Motor with a coastline model (e.g. UNIBEST or LONGMOR) depends on the assumptions made for the position of the 'dynamic boundary', which defines the part of the coast that rotates in the same way as the shoreline. A considerably lower transport is computed when it is assumed that the whole profile (till deep water at 19m; e.g. LONGMOR) rotates dynamically compared to the assumption of only re-orientation in the nearshore zone (i.e. till 6.3 m; Figure 6, panel a). Subsequently, it was also observed that modelled erosion volumes for the Sand Motor Peninsula (Figure 7) were underpredicted using an offshore position of the 'dynamic boundary'. The UNIBEST model with a nearshore position of the 'dynamic boundary' better represents the computed Delft3D and observed erosion volumes than models using an offshore position of the 'dynamic boundary' (such as LONGMOR; Figure 7).

This observed impact on the transport magnitude results from the difference in wave refraction over the deep water section of the cross-shore profile as a result of the different re-orientation of the profiles. Typically, a dynamic boundary definition in deep water (e.g. 19m water depth) will result in a re-orientation of the full profile towards the average wave incidence angle, which means that individual wave conditions will become more shore-normal due to refraction on the lower shoreface (MSL -6m to MSL -10m), which will not take place for a situation with a non-rotating lower shoreface (i.e. with 'dynamic boundary' in the nearshore). This will in turn reduce the sediment transport since the sediment transport is directly dependent on the incoming wave angle (Qs-φ relation). It is noted that the UNIBEST and LONGMOR models represent similar physics when the dynamic boundary of the UNIBEST model is placed in deep water.

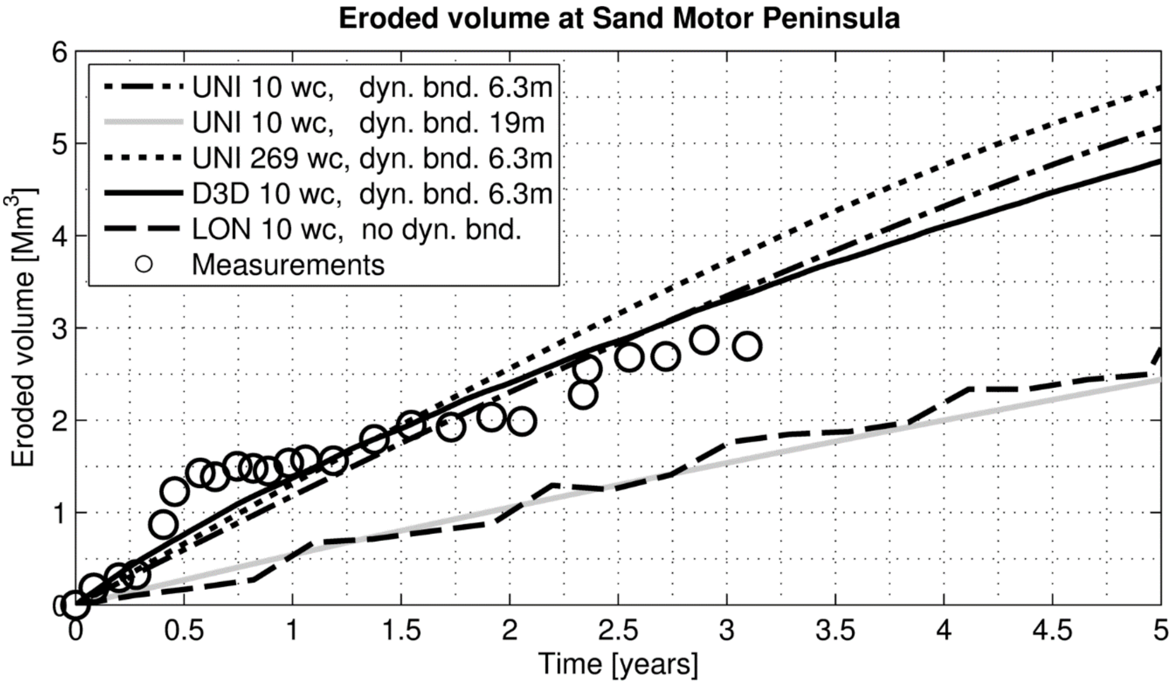


Figure 7 – Eroded volume Sand Motor Peninsula; Measurements and model results

It was observed that a similar representation of the transport rates could be achieved with either nearshore or offshore wave climate conditions when a realistic setting is applied for the location of the 'dynamic boundary'. There is no generic position setting for the dynamic boundary, which is valid for every coastal region, since this parameter setting depends on the active region and time scales that are investigated with the model. Typically, the position of the ‘dynamic boundary’ will coincide with the position of depth-of-closure of the considered cross-shore profile. The optimal setting for the dynamic boundary for the Sand Motor case was at a water depth of 6.3m.

It is noted that traditional 1D coastline models, such as LONGMOR, do not include a ‘dynamic boundary’ concept and will therefore consistently underestimate alongshore transport rates. Consequently, the morphological evolution of large scale nourishments is underestimated. In short it is recommended for coastal modelling studies to apply a ‘dynamic boundary’ concept to provide a realistic representation of the wave refraction on the lower shoreface.

4 Evolution of mega nourishments

4.1 Lifetime and maintenance

Information on the morphological evolution of mega nourishments is often not available in the initial phases of these projects, as models are applied only for the final design and/or impact assessment study. Details on erosion rates, lifetime and maintenance volumes of mega nourishments would, however, be very useful. For this reason relations and design graphs were derived based on a series of 1D and 2DH computations for two types of mega nourishments:

- Feeder-type mega nourishments that may erode freely thus feeding adjacent beaches (Section 4.4). A design graph and relation for the half-time is provided in order to estimate the life span of these type of nourishments
- Permanent mega nourishments (or beach extensions) that are designed to preserve momentaneous safety levels and which are kept in place by regular sand nourishments (Section 4.5). Design graphs and relations for erosion rates and maintenance volumes are provided.

The design graphs and relations are based on a series of mainly UNIBEST-CL+ computations for a wide range of idealised nourishment configurations (see Section 4.2). These configurations cover the most relevant physical properties of the nourishment such as nourishment shape, size and adopted maintenance strategy. The ability of the UNIBEST-CL+ model to assess the morphological development of the nourishments has been verified by means of an inter-comparison with the Delft3D model (Section 4.3).

4.2 Idealised mega nourishment configurations

The evaluated dimensions of the nourishments were chosen such that they span the range of potential nourishment configurations. Most relevant parameters are the seaward extent (*333m; 667m; 1000m*), the width over length ratio (*1:2.5; 1:5; 1:10*) and the net annual alongshore transport *Qs*, which can be considered a proxy for the wave climate intensity (100.000 m^3/year; 200.000 m^3/year; 400.000 m^3/year). This means that 9 different idealised nourishment configurations were tested (Figure 8). Note that the nourishment with a cross-shore width of 667m and a W/L ratio of 1:5 is referred to as the reference nourishment.

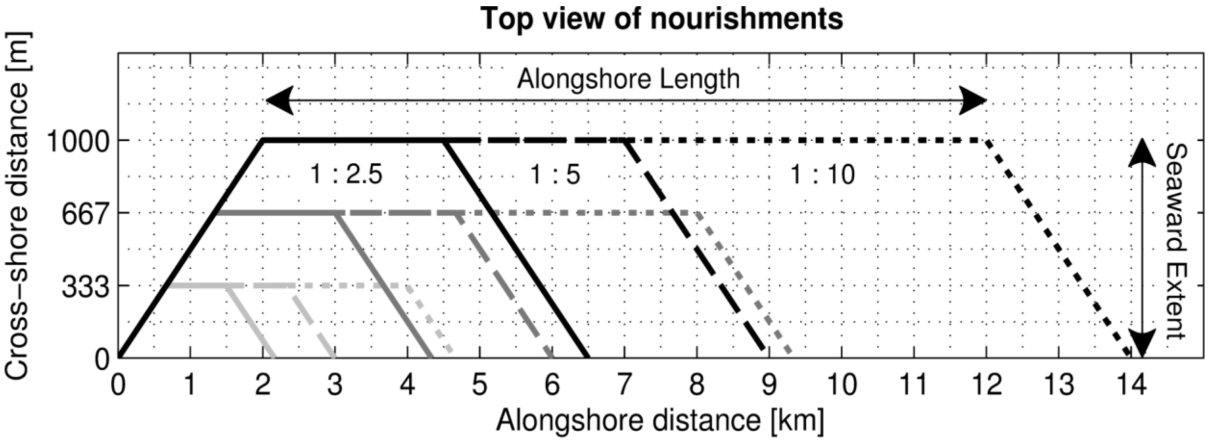


Figure 8 – Top view of nourishments (note that the x- and y-axis do not have the same scale)

The alongshore length is specified at the seaward side of the nourishment. From there, the nourishment will attach to the adjacent coast with a length over width ratio of 2:1. The alongshore length of the nourishment may also be computed from the alongshore distribution of the sand for more complex nourishment shapes. The mean cross-shore width within the nourishment area (i.e. ½ $L_{alongshore}$ to both sides) should then be computed.

$$L_{alongshore} = 2 \cdot \frac{\int Y_{cst} \cdot abs\left(x - x_{centre}\right) dy}{\int Y_{cst} dy} \qquad \text{(eq. 1)}$$

The mega nourishments have an elevation of MSL+2m and a cross-shore slope of 1:50, which attaches in deeper water to an equilibrium profile (Dean profile). Table 4 shows the nourishment dimensions and volumes for both UNIBEST and Delft3D. It is noted that the differences in sand volumes between Delft3D and UNIBEST are the result of a slightly different cross-shore distribution of the sediment. UNIBEST assumes a uniform cross-shore distribution, while Delft3D applies more volume in deeper water for larger nourishments.

Table 4 – Overview of nourishment dimensions and initial volumes

Nour nr. [#]	**Seaward extent [m]**	**Width / length ratio [-]**	**Alongshore length [m]**	**Volume in UNIBEST [10^6 m^3]**	**Volume in Delft3D [10^6 m^3]**
1	333	1:2.5	833	3.11	2.70
2	333	1:5	1665	5.01	4.31
3	333	1:10	3330	8.93	7.56
4	667	1:2.5	1668	12.45	13.44
5	667	1:5	3335	20.31	21.82
6	667	1:10	6670	35.80	38.49
7	1000	1:2.5	2500	28.00	35.17
8	1000	1:5	5000	45.50	57.28
9	1000	1:10	10000	80.50	101.51

Besides the nourishment dimensions, also the net annual alongshore transport *Qs* has been varied in the UNIBEST-CL+ coastline model by means of adjusting the magnitude of the *S*-*φ* curve, which effectively means that the sensitivity of the longshore transport for small changes in coastline orientation is varied. Wave climates with net alongshore transport rates of 100.000, 200.000 and 400.000 m^3/year were used, with a coastline orientation which deviated 6.6° from the coastline orientation of net zero sand transport.

A more generic parameter to describe the sensitivity of the longshore transport for small changes in coastline orientation is used herein, which is referred to as longshore transport intensity (*LTI*). The *LTI* is defined as the variation of the net longshore transport for a small change of the coastline orientation ($\partial Q_s/\partial\theta$). A change in the longshore transport intensity (*LTI*) effectively means that the intensity of the wave conditions is varied. The longshore transport intensity parameter can be approximated for a given wave climate and given coastline orientation by a simple relation which is defined as follows:

$$\frac{\partial Q_S}{\partial \theta} \approx \frac{Q_S}{\Theta} \cdot \mathrm{COS}(2 \cdot \Theta) \qquad \text{(eq. 2)}$$

with Qs net longshore sediment transport [m^3/yr], θ the coastline orientation [°] and Θ a relative difference between the coast orientation and the coastline orientation of net zero sand transport [°] which is larger than zero. Alternatively, $\partial Q_s/\partial\theta$ can be directly be derived from computed net longshore sediment transport ($Q_{s,net}$ [m^3/yr]) for a coastline orientation which was modified by +/-1^o ($Q_{s,net+1}$ and $Q_{s,net-1}$) from which *LTI* is computed as follows : $LTI=0.5[\,|Q_{s,net} - Q_{s,net+1}| + |Q_{s,net} - Q_{s,net-1}|\,]$. The average Holland coast is characterised by an *LTI* of 30.000 m^3/yr/degree (i.e. net transport of 200.000 m^3/yr and Θ-parameter of about 6.6 degrees. Besides the reference climate condition, the *LTI*-value was also varied in the range of 15.000 to 60.000 m^3/yr/degree (i.e. Q_s= 100.000 to 400.000 m^3/yr with Θ of about 6.6 degrees.

It is noted that the sensitivity of the longshore transport for small changes in coastline orientation can only be defined when both the net transport and coastline orientation of net zero sand transport are known, because the net transport alone is insufficient to describe the local wave climate. For example, a net longshore transport of zero for the undisturbed section of the coast does not mean that the coastal erosion of the land reclamation is zero.

4.3 Initial alongshore transport rates

For practical reasons the Delft3D model was applied only for the short term computations (i.e. up to 5 year) and acts as a reference for the applied coastline models. An inter-comparison of the computed alongshore transport rates in Delft3D and UNIBEST shows that the models provide very similar results (see Figure 9). The transport peaks at the edges of the nourishment are very similar. The only difference between the computed alongshore transport rates is present at the straight middle section of the nourishment (i.e. at x= 10 km), which has a substantially larger computed transport in the Delft3D simulations (about 300.000 m^3/year for the Delft3D simulation and 200.000 m^3/year for the UNIBEST simulation). These larger sediment transport rates at the middle section are solely the result of the steeper cross-shore nourishment profile (1:50), as was found from UNIBEST simulations with the nourishment profile shape which gave similar results as Delft3D. The locally larger transport rates are expected to erode relatively more sand from the updrift side than from the downdrift side of the nourishment in the first months until a more natural cross-shore profile has developed (see development of cross-shore profile in Figure 5). The total losses from the nourishment area are not expected to be influenced, which means that no effect on the lifetime of the nourishment is expected.

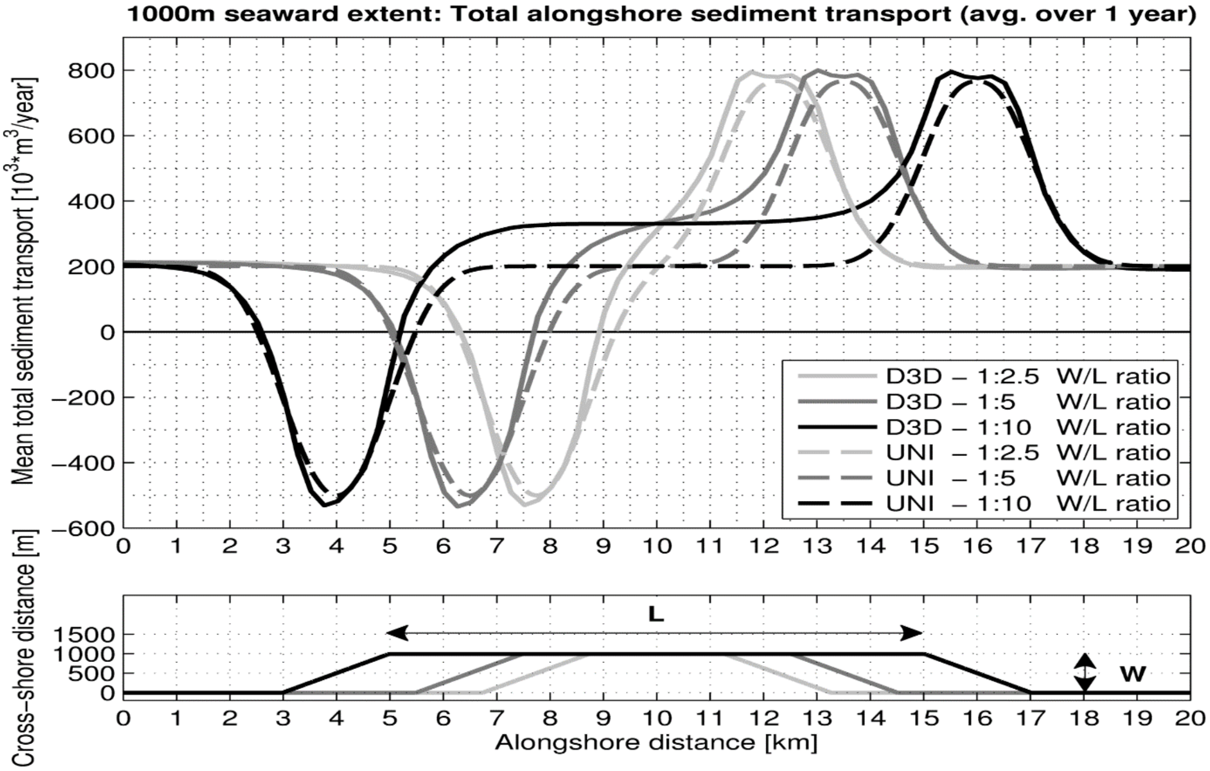


Figure 9 – Net alongshore sediment transport vs. alongshore distance for the 1000m seaward extent nourishments. W = seaward extent; L = alongshore length.

4.4 Feeder-type mega nourishments

The temporal evolution of a feeder-type mega nourishment is evaluated on the basis of the remaining sand volume in the nourishment area, which also includes half of the transition slope from the nourishment to the coast (see example in Figure 10). Note that nourishment volumes in the coastline models were obtained by multiplying the coastline position with the active height of the profile (7m for all nourishments). Additionally, also the transport rates are evaluated as they provide insight in the accretion and erosion zones (i.e. zones with gradients). For this purpose the time-averaged transport rates up to a depth of 10m were extracted from the Delft3D model.

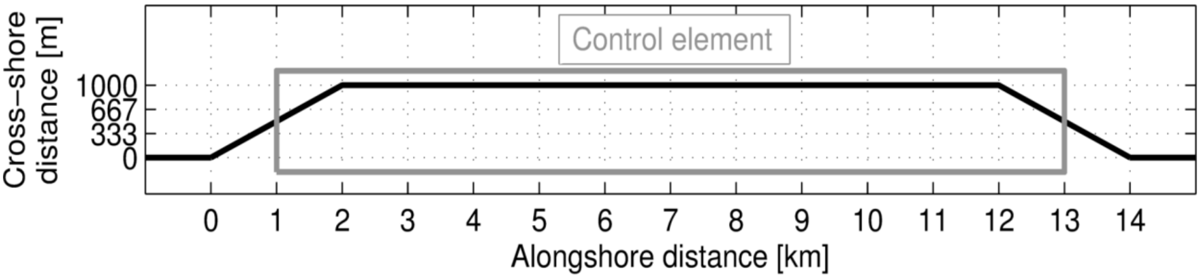


Figure 10 – Illustrative example of a control element as used for the volume calculations

4.4.1 Morphological reshaping

The morphology of feeder-type mega nourishments quickly changes into a ‘bell shape‘ (see Figure 11 for a UNIBEST-CL+ result), which is in-line with the aim of these nourishments to feed the adjacent coasts. As expected, the erosion starts at the edges of the nourishment and progresses inward over time. These edges coincide with the peaks and troughs in the alongshore transport rates (see Figure 9).

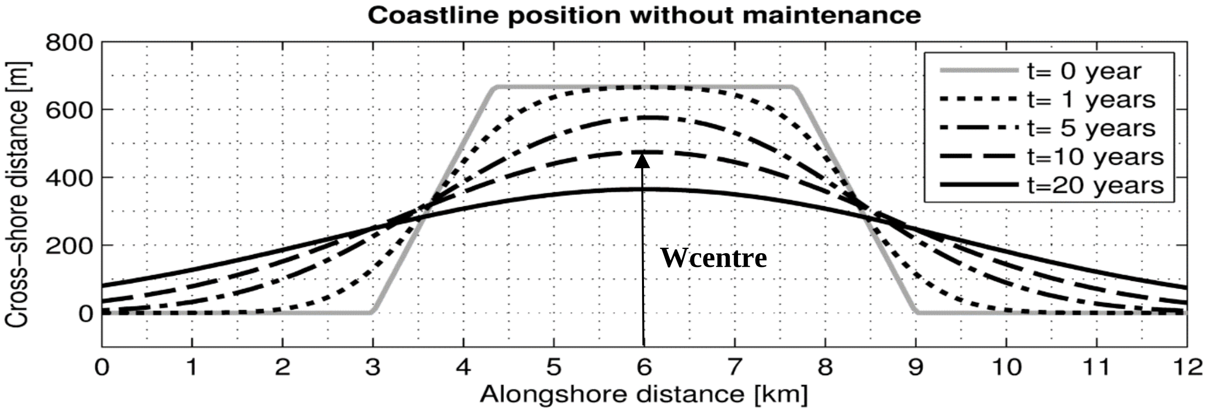


Figure 11 – Coastline position for the first 20 years without maintenance

The maximum erosion at the centre of the freely evolving nourishment is a relevant parameter for the design process. This holds especially for relatively short nourishment configurations for which the erosion is more likely to progress to the centre of the nourishment. Model simulations for the different nourishment configurations (Table 4) show that the length of the reclamation (L_{nour}) is the most governing parameter for the resistance against erosion, while also the longshore transport intensity ($\partial Q_s/\partial\theta$), active height and the time from construction (T) determine the magnitude of the erosion at the centreline. Noticeable is that cross-shore width was not important for the retreat at the centre of the nourishment (but very relevant for erosion at the sides). The maximum computed retreat at the centre of the beach reclamation could be captured by means of a simple formulation (equation 3), which had a good representation of the computed retreat with an R^2 of 0.97 (Figure 12).

$$W_{centre} = W_{ini}\left(1-\mathrm{e}^{-y}\right)$$

$$\Delta T > 0 \qquad y = Lnour \Big/ 4.28\cdot\left(\frac{\partial \mathrm{Q_S}}{\partial\theta}\cdot\frac{T}{h_{active}}\right)^{0.6} \qquad \text{(eq. 3)}$$

With:

W_{centre}	Minimum cross-shore width at centre of nourishment [m]
W_{ini}	Initial cross-shore width of the nourishment [yr]
L_{nour}	Initial length of the nourishment [m] (see eq. 1)
T	Time since construction of the nourishment [yr]
h_{active}	Active height of the nourishment [m] ($\approx V_{ini} / (L_{nour} * W_{ini})$)
$\frac{\partial \mathrm{Q_S}}{\partial\theta}$	Longshore transport intensity parameter [m^3/yr/degree]

The interpretation of the results of the formulation for coastline retreat at the centre of the nourishment (eq. 3) is considered a good estimate for the potential erosion over multiple years. Seasonal variability of the wave conditions is, however, not directly accounted for in the yearly averaged longshore transport intensity, which means that situations with considerable temporal variability in the wave climate conditions (e.g. due to storms on shorter time scales) may require the use of a conservative estimate of *LTI* which is representative for the shorter period of time. It is also noted that the coefficient in equation (with value of 4.28) contains various physical aspects which have not been accounted for explicitly, such as the profile shape and sediment properties. The formulation is applicable for land reclamations which cover the full cross-shore width of the active zone, which means that different (quicker) coastline retreat may take place for nourishments which are placed only at the waterline or on the sub-tidal bar. Situations which deviate considerably from the Dutch coastal situation (i.e. typical profile steepness and 250 µm sand) may need to be accounted for by upscaling this parameter (e.g. adjusting this parameter equivalent to the impact on net sediment transport rates that is expected from deviating the considered physical parameter). The sand diameter effect (say 0.2 to 0.5 mm sand) is assumed to be partly represented by the range of *LTI*-values used.

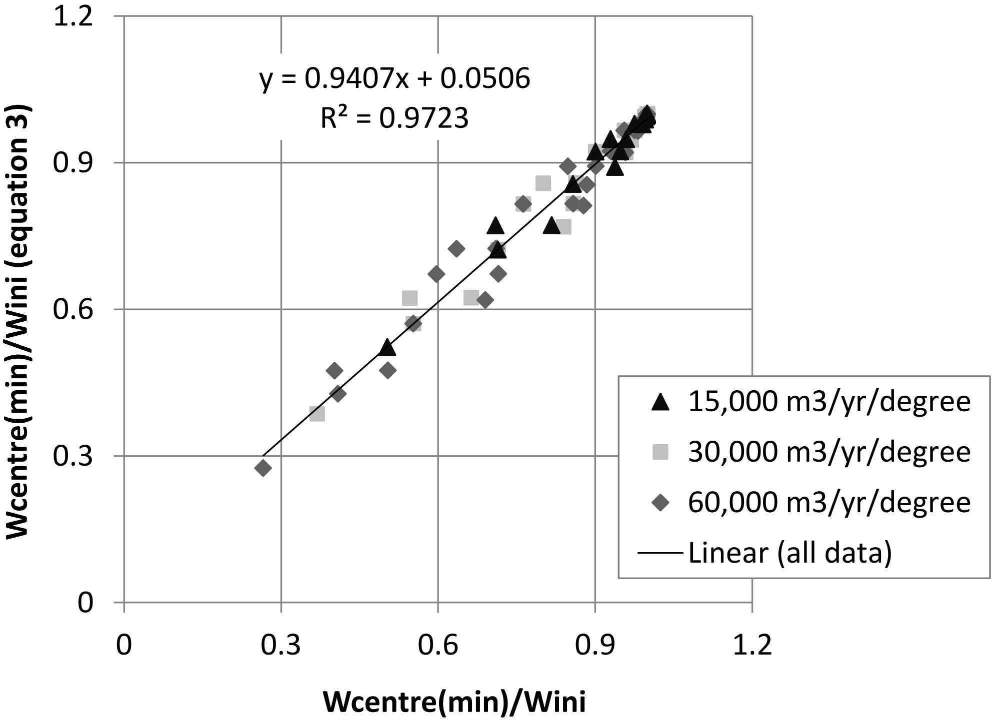


Figure 12 – Inter-comparison of computed Wcentre(min) / Wini ratio and equation 3

4.4.2 Life time

The lifespan of a nourishment can either be defined by a certain threshold value (for the cross-shore coastline position or volume) or by the half-life of the nourishment. The latter is preferred since the definition of a threshold can be arbitrary. The half-life is defined as the amount of time it takes for the nourishment to reduce to 50% of its initial volume. Results are shown for a representative climate for the Holland coast for the Holland coast ($\partial Q_s/\partial\theta$ = 30.000 m^3/yr/degree) and a more severe wave climate ($\partial Q_s/\partial\theta$ = 60.000 m^3/yr/degree) for width over length ratios of 1:2.5 to 1:10 (Figure 13). Note that the quiet wave climate conditions ($\partial Q_s/\partial\theta$ = 15.000 m^3/yr/degree) were not shown as they provided a similar but slower response.

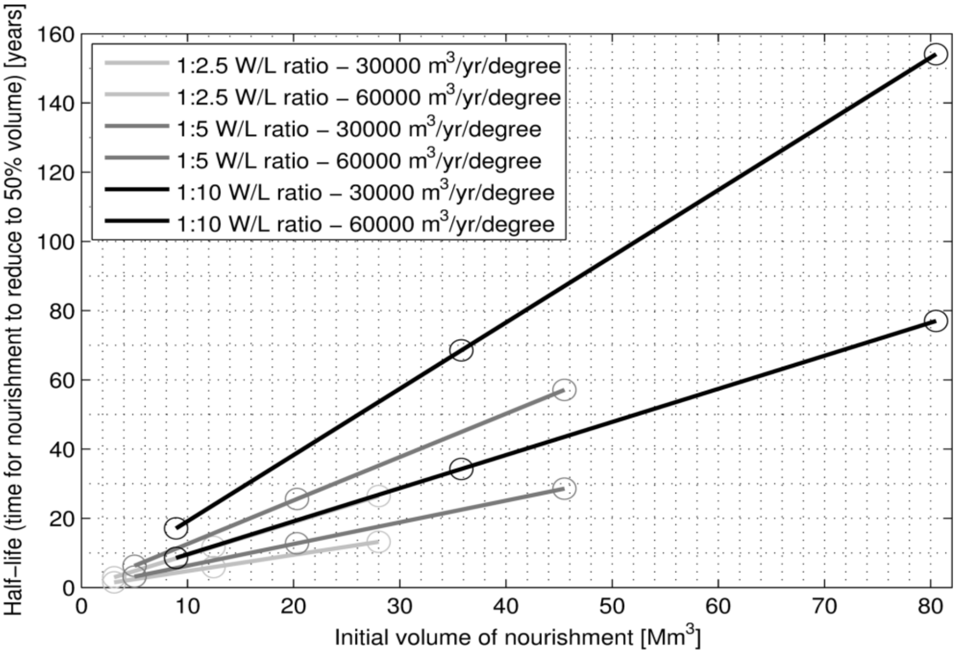


Figure 13 – Half-life of each nourishment plotted against its volume

A linear relation between the initial volume and the half-life of a nourishment was found (Figure 13) from the UNIBEST simulations. It appears that lifetime scales linearly with the nourishment volume (V_{ini}) and is inversely related to the geometry of the nourishment (W/L ratio). Note that a longer alongshore nourishment retains more sand in the initial nourishment area than a shorter nourishment with the same volume, since the coastline angles are closer to the natural orientation for longer nourishments. It is noted that simulations with a similar *LTI* (e.g. 30.000 m^3/yr/degree) gave the same half-time of the nourishment even when the net transport rate and coast angle combination was very different. For example 200.000 m^3/yr and 6.6° gave same result as 300.000 m^3/yr and 10° (i.e. 30.000 m^3/yr/degree line in Figure 13). Hence, longshore transport intensity parameter ($\partial Qs/\partial \theta$) is considered a very relevant parameter to the actual lifetime of the nourishment.

A formulation (eq. 4) that describes Figure 13 can be used to estimate the half time of nourishments at the Holland coast. The impact of the wave climate, cross-shore profile and sediment are confined in the constant ($1.91 \cdot 10^4$ per degree) and $\partial Q_S/\partial \theta$ term, which scales with the longshore transport intensity (*LTI*).

$$T_{1/2} = 1.91 \cdot 10^{-2} \cdot V_{ini} \cdot (0.2 \cdot L_{ini}/W_{ini} + 1) \left(\frac{\partial Q_S}{\partial \theta} \right)^{-1} \qquad \text{(eq. 4)}$$

With:

$T_{1/2}$	Half-time of the nourishment volume [yr]
V_{ini}	Initial volume of the nourishment [m^3]
L_{ini}	Initial length of the nourishment [m]
W_{ini}	Initial cross-shore width of the nourishment [m]
$\frac{\partial Q_S}{\partial \theta}$	Longshore transport intensity parameter (*LTI*) [m^3/yr/degree] (Sensitivity of net transport rate Qs for rotation of the coastline θ)

The half time of the nourishment ($T_{1/2}$) can also be used to compute the remaining volume (V_t) or losses at a moment in time after construction (T).

$$V_t = V_{ini} \cdot e^{-T/T_{1/2}} \qquad \text{(eq. 5)}$$

The formulation for the lifetime of freely evolving nourishments is applicable for coastlines with relatively low-angle wave impact. This means that the undisturbed coastline orientation is within 20° of the equilibrium orientation. Asymmetric reshaping of the nourishment is expected for cases with increasing angles of relative wave incidence (Arriaga et al, 2017), as the sensitivity of the transport for coastline reorientation may be significantly different at one side of the nourishment than for the other side. Instability may even occur for very high angles of wave incidence (Ashton et al, 2001).

It is noted that above half time assessment implicitly assumes that all sediment will be mobilised on the longer-term by the alongshore wave-driven current, which means that sediment should be placed equally over the active part of the cross-shore profile. In practice, however, a small part of the nourishment sand may remain at the location of the nourishment, as sand may have been nourished outside the active zone. The sediment in deeper water may even affect wave refraction in such a way that a permanent seaward protrusion remains as a result of focussing of the waves (i.e. wave directions towards centre of the nourishment). Consequently, slightly more sand is expected to remain in the nourishment area of large scale sand nourishments at the end of its lifetime than predicted by the formulation.

4.5 Permanent mega nourishments

Both the UNIBEST and LONGMOR models were used to explore the maintenance volumes of permanent mega nourishments, which need to be maintained on a regular basis. The required total maintenance volume over the lifetime depends on the 1) frequency of the maintenance nourishments, 2) seaward extent of the beach reclamation and 3) longshore transport intensity (*LTI*). It is also noted that initial rates of erosion are generally larger than the long-term average erosion for beach reclamations that are not maintained regularly.

Both the UNIBEST and LONGMOR models were used to explore the effects of various maintenance intervals (2 and 5 years) for one case (type 5) which has a seaward extent of 667m, a width over length ratio of 1:5 and an alongshore length of 3335m at the seaward side and 6000m at the landward side. A yearly-average wave climate with a longshore transport intensity of 30.000 m^3/yr/degree was also applied (similar as for the freely evolving nourishment. The required maintenance volumes of the permanent type are assessed for maintenance frequencies of 2 and 5 year. These were then generalised to other maintenance frequencies on the basis of available model simulations.

4.5.1 Influence of maintenance frequency

The required total maintenance volume (V_{20yr}) for the reference nourishment (B=667m) varies considerably depending on the frequency of the maintenance (see Table 5). In general, a reduction of the long-term average maintenance volumes will take place with an increase of the maintenance interval. A low maintenance volume requirement will be obtained if the beach reclamation is restored only after 20 years of free erosion, which requires a nourishment of 9.2 10^6 m^3 in the control area (see Figure 10). However, the coastline may have retreated in such a way that maintenance needed to be carried out more frequently. The total maintenance volume is largest for a continuous maintenance scheme, but does not differ much from a 1 year interval scheme. A more realistic 5 year interval scheme has significantly smaller maintenance volumes.

Table 5 – Maintenance scheme and corresponding maintenance volumes after t= 20 years

Maintenance scheme	Cumulative maintenance volume after 20 years [10^6 m^3]	Volume in first maintenance period [10^6 m^3]
Continuous	16.8	1.32 (avg. 1st year)
1 year interval	15.3	1.23
2 year interval	14.6	2.19
5 year interval	13.1	4.24
20 year interval	9.2	-

An advantage of frequently maintained mega nourishments is the relatively quick development of coastal arches on both flanks (Figure 14). It is noted that the approach for nourishing was slightly different in the LONGMOR which nourishes only the junctions of the beach reclamation while the UNIBEST model restores the original coastline.

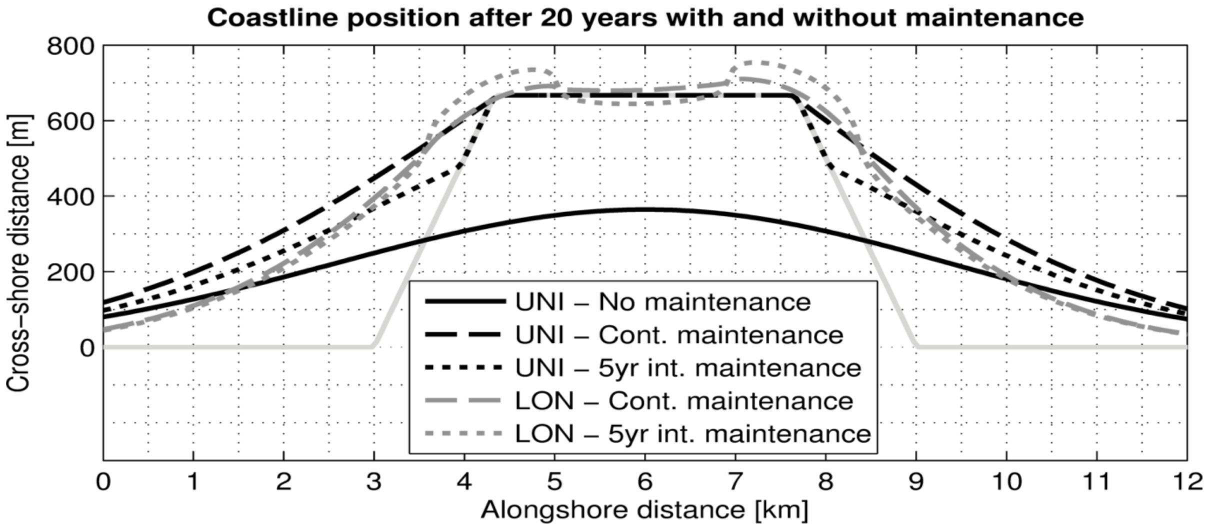


Figure 14 – Coastline position at t= 20 years with and without maintenance

Figure 15 shows the maintenance schemes in a more visual way, by plotting the supplied maintenance volumes in time. It can easily be seen that a shorter maintenance period requires a greater nourishment volume at t= 20 year.

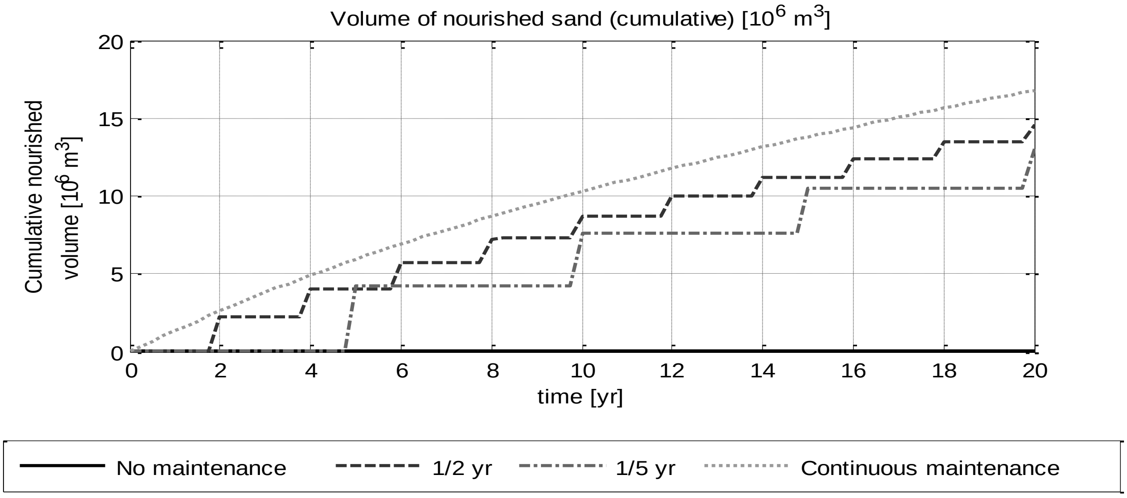


Figure 15 – Eroded volume & Supplied volume in time for continuous, 2yr and 5yr maintenance

4.5.2 Initial erosion rates

The initial erosion rates averaged over the first 2 and first 5 years at a permanent mega nourishment depend both on the cross-shore extent as well as on the longshore transport intensity (*LTI*). Figure 17 and Figure 18 show the erosion rates averaged over the first 2 years and erosion rates averaged over the first 5 years respectively. The erosion rate averaged over the first two years for a cross-shore width of 1000m is similar as found from Sand Motor data (i.e. black triangle, Figure 16).

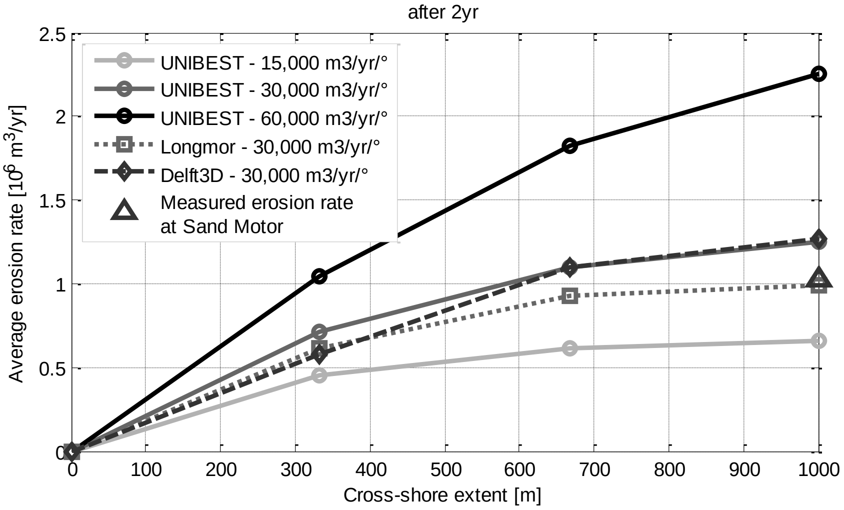


Figure 16 – Erosion rates (averaged over 2 years) plotted against the seaward extent

It is noted that Delft3D, UNIBEST and LONGMOR simulations provide very similar results again. This indicates that the wave driven alongshore current, which is present in all models, is dominant for nourishment redistribution. Processes such as tidal flow, flow contraction, wave focusing, cross-shore sediment transports are of smaller relevance. Small differences between the coastline models (LONGMOR and UNIBEST) are likely to be caused by small differences in the applied wave climates, differences in alongshore transport formulations and different numerical computation schemes.

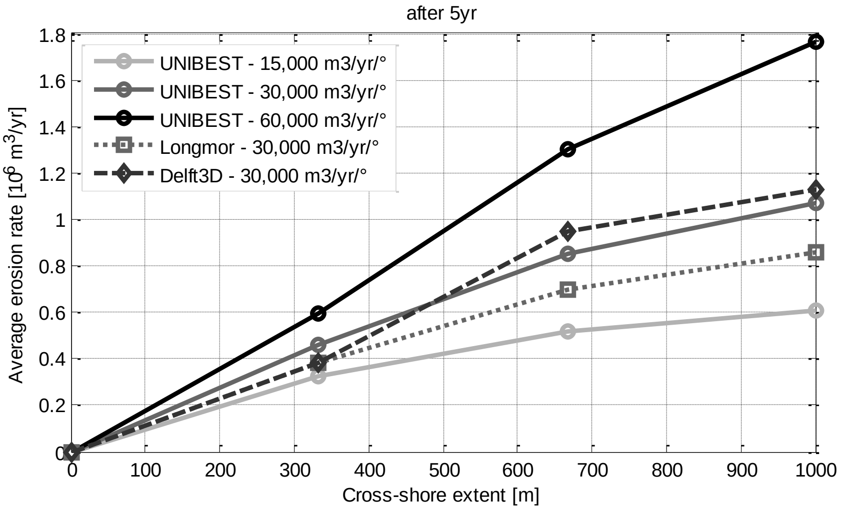


Figure 17 – Erosion rates (averaged over 5 years) plotted against the seaward extent

4.5.3 Long-term maintenance volumes

The actual long-term maintenance volumes are typically smaller than the initial losses, as the coastline develops a more gradual shape over time adjacent to the beach reclamation (see Table 5). This is related to the size of the nourishment (i.e. cross-shore width and length) and the average longshore transport intensity ($Q_s/\partial\theta$). Additionally also the maintenance interval affects the required nourishment volumes. An overview of the long-term average required maintenance volumes over a 20 year period is shown in Figure 18. A conservative estimate of the short-term longshore transport intensity parameter may be used to account for (temporary) more energetic wave conditions or deviations in the profile shape and sediment size.

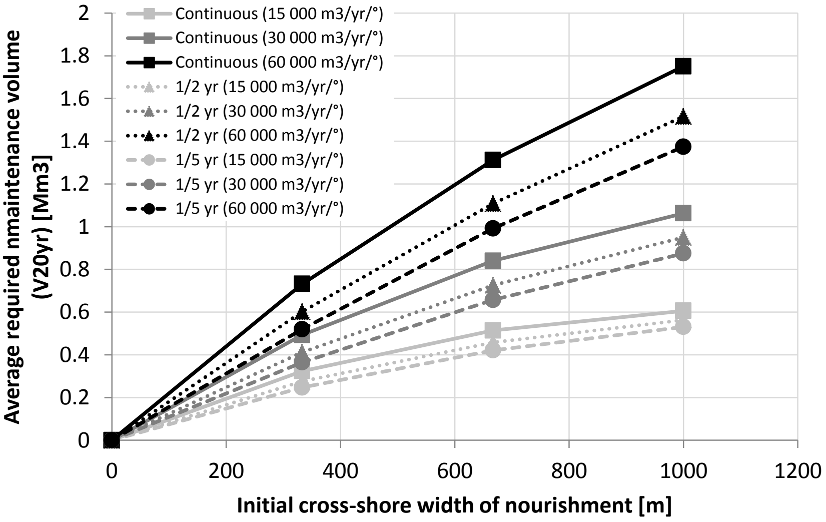


Figure 18 – Average maintenance volumes (over first 20 year) plotted against the seaward extent (UNIBEST results)

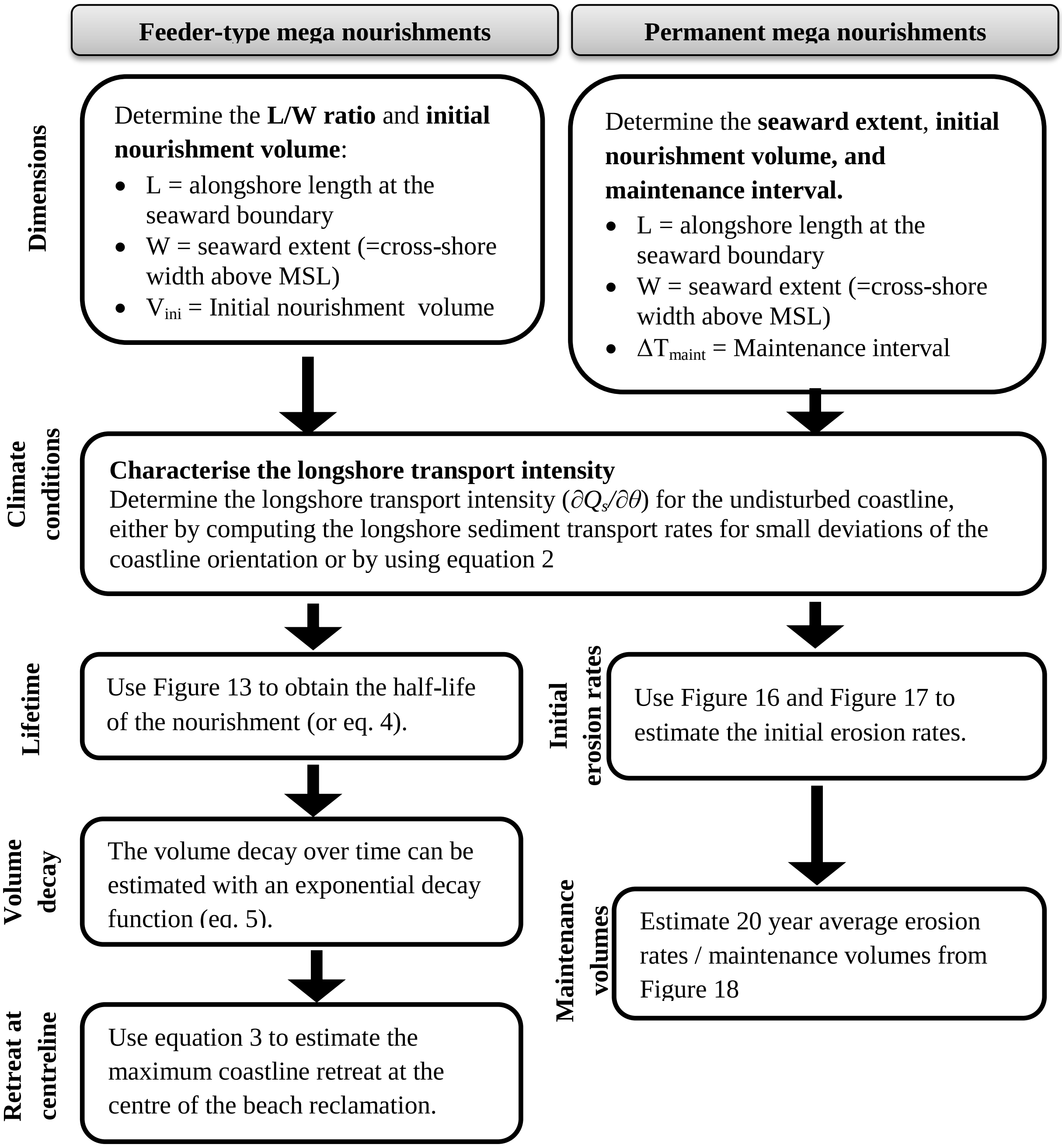
It is noted that cross-shore width of the nourishment had a considerable influence on the required long-term maintenance volumes, while the alongshore length was irrelevant for land reclamations since they are maintained before erosion is taking place at the centre of the nourishment. This is in contrast with the formulations for the lifetime ($T_{1/2}$) of the freely evolving nourishment and coastline retreat at the centre (W_{centre}/W_{ini}), which were determined predominantly by the length of the nourishment (see equation 3 and 4).

5 Application of design graphs

The relations and design graphs derived in this paper are applied to the permanent mega nourishment in front of the Hondsbossche en Pettemer seawall (HBPZ) near Petten. This mega nourishment is designed to maintain momentaneous safety levels and needs to be maintained. Hence, the focus will be on erosion rates and maintenance volumes. A general step-by-step approach will be presented, which subsequently will be applied on the HBZW nourishment.

5.1 Step-by-step approach

A step-by-step approach can be followed to assess the lifetime of a feeder-type mega nourishment or the maintenance volumes of a permanent mega nourishment. The design graphs in Section 4 are used for this purpose.



Determine the **L/W ratio** and **initial nourishment volume**:

- L = alongshore length at the seaward boundary
- W = seaward extent (=cross-shore width above MSL)
- V_{ini} = Initial nourishment volume

Determine the **seaward extent**, **initial nourishment volume, and maintenance interval.**

- L = alongshore length at the seaward boundary
- W = seaward extent (=cross-shore width above MSL)
- ΔT_{maint} = Maintenance interval

Characterise the longshore transport intensity
Determine the longshore transport intensity ($\partial Q_s/\partial\theta$) for the undisturbed coastline, either by computing the longshore sediment transport rates for small deviations of the coastline orientation or by using equation 2

Use Figure 13 to obtain the half-life of the nourishment (or eq. 4).

The volume decay over time can be estimated with an exponential decay function (eq. 5).

Use equation 3 to estimate the maximum coastline retreat at the centre of the beach reclamation.

Use Figure 16 and Figure 17 to estimate the initial erosion rates.

Estimate 20 year average erosion rates / maintenance volumes from Figure 18

Figure 19 – Step by step approach for deriving the maintenance volumes or half-time of nourishments

5.2 Permanent mega nourishment near Petten, The Netherlands

The permanent mega nourishment in front of the Hondsbossche en Pettemer seawall (HBPZ) near Petten is designed to maintain momentaneous safety levels and withstand storms with a return period of 1 in 10.000 years. The mega-nourishment consists of a beach nourishment of approximately 30 million m^3 and a shoreface nourishment of approximately 10 million m^3. According to the contractor (Hoogheemraadschap & Rijkswaterstaat, 2014; Van Oord - Boskalis, 2013), the dimensions of this nourishment are:

- Approximate length of 8,000m
- Width over length ratio of about 1:25Seaward extent of about 350m (part above MSL) with respect to original hard sea defence
- An initial wear layer of 1m (in the vertical) was applied to account for initial losses

It is noted that the actual seaward extent with respect to the surrounding coast is larger than the provided distance from the existing hard sea defence, since this structure is about 200 m seaward from the natural coast (at MSL; Figure 20). The design of the nourishment is represented as the dark grey area, while the existing hard sea defence is shown in light grey area seaward of the dashed line (Van Oord - Boskalis, 2013). For that reason a value of 350 + 200 = 550m will be used in this research.

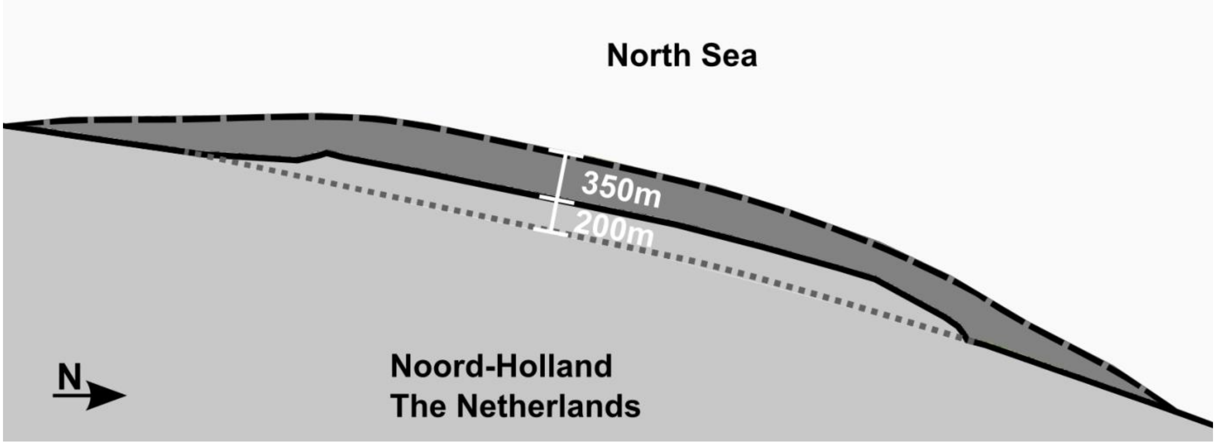


Figure 20 – Illustrative figure of HBZW nourishment design. In light grey the original hard sea defence is shown (part above dotted line), while the dark grey section represents the contour of the nourishment itself (part above MSL). Figure adapted and edited from Van Oord - Boskalis (2013).

The net alongshore transport near Petten is in the range of 200.000 to 300.000 m^3/year (van de Rest, 2004; van Rijn, 1995a, 1995b; van Thiel de Vries, 2009). Furthermore, the equilibrium relative wave angle is estimated to be similar to that along the Delfland coast (i.e. about -7° with respect to the coast normal). Following equation 3, the longshore transport intensity is about 30.000 to 40.000 m^3/yr/degree.

According to the design graphs (Figure 16 and Figure 17), the expected initial erosion is about 700.000 to 850.000 million m^3/year in the first five years of the lifetime of the mega nourishment (using a longshore transportintensity parameter 40.000 m^3/yr/degree). The long-term maintenance over 20 years is expected to be somewhat smaller at about 650.000 m^3/yr (Figure 18, 5-yearly maintenance), which means that a total maintenance volume of about 13 million m^3 is expected over the first 20 year period. It is expected that almost the full sand maintenance volume will need to be nourished at the corners of the land reclamation as the longshore transport is expected to be dominant on decadal time scales.

At this moment, no official maintenance estimates from the contractor are publicly available. Therefore, the estimates originating from the design graphs cannot be validated. It is expected that after a couple of years, monitoring data from surveys is made available on which the estimates in this research can be validated.

6 Discussion

Alongshore redistribution of sediment at the Sand Motor was modelled with the numerical models Delft3D, LONGMOR and UNIBEST, which provided a good representation of the observed morphological changes. The modelled erosion in the first 1,5 year after construction of the Sand Motor was similar to the observed 1.8 million cubic meter of erosion in this period (de Schipper et al., 2016). These models have been used to produce design graphs for the erosion rates, life span and maintenance volumes of mega nourishments. The present results are valid for wave-dominated open sandy coastlines with medium sand in the range of 0,2 to 0,4 mm and a regular lower shoreface with shore-parallel depth contours (i.e. beyond the 8m depth contour). The mega nourishment should be placed far away from structures. Furthermore, the shape of the nourishment should be approximately trapezoidal with a maximum seaward extent of 1 km, maximum alongshore length of 10 km and side slopes of 1 to 2. The current studies focuses on coasts with mesotidal conditions (tidal range < 2 m; nearshore currents < 0.3 m/s) which are dominated by waves with a small angle of wave incidence (i.e. <30 degrees with shore-normal at the point of wave breaking). Instabilities may occur at coasts with persistent high-angle waves (e.g. alongshore sandwaves or spit formation; Ashton et al., 2001; Falques and Calvete, 2005) which are not considered in this paper.

The ability of the coastline models to represent the coastal evolution of the Sand Motor suggests that transport gradients due to the alongshore wave-driven current are the governing morphological process. This is in-line with findings in other literature on the relevance of tide and waves (Van Duin et al., 2004; Luijendijk et al., 2017).

It is noted that other processes may also act during storm conditions, such as long (infra-gravity) waves (van Thiel de Vries et al., 2008) and transport to deeper water by the undertow current. These cross-shore components were not taken into account in the UNIBEST model and are only partly accounted for in Delft3D (due to the parallel online approach, 2DH calculation method). Effects of these cross-shore processes on the evolution of the Sand Motor and lifetime of other land reclamations is, however, considered small since eroded sediment by storm conditions typically remains within the active zone where the alongshore redistribution of sediment takes place. For example, flume tests of dune erosion have shown that deposition most often takes place at a few meters below the water-level at which the storm impact takes place. A restoration of the beach profile is also likely to take place after the storms, which brings the sediment back to the depth-zone with the alongshore wave-driven current (Ruessink et al., 2007; Walstra et al., 2012; Walstra, 2016). Moreover the validation of coastline evolution with the Sand Motor case shows a good prediction with only wave-driven transport component.

The representation of the wave climate conditions is of relevance for the temporal evolution of a land reclamation (or nourishment). The long-term climate in this study results in a gradual erosion over time, but short-term variations in transport as a result of varying wave conditions are not represented. Consequently, the computed lifetime and transport rates in the Delft3D and UNIBEST models in this study are less applicable on the short-term (i.e. seasonal or 1 year), but are considered valid for multi-year periods which is shown by the reasonable agreement of the erosion at the Sand Motor after 1.5 year. If a short period (seasons) is considered the user should account for the possible larger persistence of the extreme conditions in the climate schematization (*LTI*).

The input reduction of the wave climate for the Delft3D simulations (i.e. 10 conditions instead of 269 conditions) was also shown to have a much smaller impact than other aspects such as the refraction of waves on the lower shoreface. For practical applications it is, however, considered relevant to include the longshore transport intensity parameter (*LTI*) in the reduction method of the wave climate conditions (Walstra et al., 2013), since it is relevant for lifetime and reshaping of nourishments. In many cases this is implicitly done by including sufficient wave height and directional bins in the climate schematization.

The wave climate and associated *LTI*-parameter is considered the most dominant parameter for the lifetime of land reclamations on sandy coasts far away from structures (i.e. not affected by the wave sheltering of structures). Consequently, the wave direction was not included in the formulations for the lifetime of the land reclamation. This low relevance of the wave direction is the result of the accretion of sediment on the updrift side of a nourishment in case of situations with oblique wave incidence, which compensates for the additional losses at the downdrift side of the nourishment. Land reclamations near structures require detailed studies to include wave shielding effects.

It should, however, be noted that a land reclamation which is placed at the beginning of a beach section or close to a structure (instead of in the middle of a beach section) is affected both by 1) shielding of wave conditions by the structure which reduces the erosion and 2) a larger influence of the wave direction as it can result in enhanced erosion when the waves are directed away from the shielded area where the land reclamation is placed (or vice versa when waves are directed towards the structure). Furthermore, the spatial variation in the climate conditions (i.e. wave energy) in the region with the reclamation can result in enhanced or reduced erosion. In this case it is best to take a conservative (i.e. high) estimate of the wave energy as a proxy for the whole reclamation. Current studies furthermore consider a situation where similar sediment is applied for the nourishment as for the adjacent coast, since situations with a rocky lower shoreface or variations in sediment can induce either additional downdrift erosion as a result of blockage of the transport by a reclamation with coarse sediment (Dean and Yoo, 1992) or a quick mobilization of the sediment of the reclamation if it is finer than the natural sediment. Effects of spatial varying sediment on alongshore wave-driven transport is, however, expected to be small for mega nourishments at the Holland coast which consist of medium sand, such as the Sand Motor, since the behaviour of the size fractions is very similar in the nearshore region (Huisman et al., 2017).

Morphological changes as a result of alongshore redistribution of sand result in reorientation of the coastline and subsequently in an adjusted transformation of the waves. Especially the nearshore region is influenced on short and intermediate timescales (i.e. from MSL -5m to MSL +2m at the Sand Motor). This feedback from morphological changes to wave forcing conditions is implicitly accounted for by the bed updating of the Delft3D model, but should be explicitly defined in coastline models for accurate reproduction of the wave transformation. This means that nearshore re-orientation should be fed back to the wave transformation, while the offshore bathymetry (and coastline orientation) should remain stable. An implicit assumption of some coastline models (e.g. LONGMOR or Genesis, Hanson and Kraus, 1989) that the coastline re-orientation affects the full profile until deep water (e.g. until 25 m depth) is not considered realistic at engineering timescales and may lead to an over-estimation of wave refraction on the lower shoreface and subsequent under-estimation of the transport rates and erosion rates. It is noted that a small local overestimation is possible for specific situations where the waves approach obliquely at the updrift side of the perturbation or when gross transports from both directions are of similar magnitude. However in both situations, the transport away from the nourishment will be underestimated when a modelling concept with deep-water contour rotation is applied. An approach with a separately defined orientation of the static offshore and active nearshore part of the cross-shore profile in the UNIBEST model therefore provided much better prediction of the transport rates and lifetime of the Sand Motor. A division between the offshore and

nearshore part is typically made at the position of the depth-of-closure, since this is the ultimate position where sediment is redistributed to in cross-shore position on monthly to yearly timescales.

The applied active height of the profile should also be defined explicitly in coastline models. A single, alongshore averaged active height is considered adequate for this type of studies focusing on aggregated parameters such as total volume loss. Alongshore varying active heights may be considered to model detailed coastal shapes on shorter time-scales but leave relatively much room for tuning of the results. The active height can be derived from the depth-of closure and the active area of the dry beach. The depth of closure can either be computed from a relation with the waves (Hallermeijer 1978, 1981; Birkemeier 1985) or derived from observed morphological changes.The active height has a large impact on the computed coastline evolution and hence the diffusiveness of the nourishment. This active height is used for the translation of sediment budgets to coastline changes. In the considered cases the active height is set to a fixed value of 7 m. It is observed that a change of this active height by 1m typically has a linear effect on the modelled nourishment volume and therefore on the diffusiveness of nourishments. It is noted that the active height depends on the timeframe for which the model is used. For instance, in 20 years' time, sediment at larger depths can be mobilised compared to a timeframe of 1 year. However, this dependency is currently not incorporated in the rule of thumb.

The UNIBEST and LONGMOR coastline models used in this study apply an asymmetric shape of the Sand Motor for the model hindcasts, which was derived from volume computations of measured cross-shore profiles along the Sand Motor. Representation of the precise details of the spit development was not pursued in this study that focuses on aggregated parameters such as erosion rates and half-time of the mega nourishment. These aggregated parameters were hardly affected by the asymmetric shape which mainly affects the location of the erosion, but to a lesser extent the total aggregated erosion rates. Luijendijk et al. (2017), Kaergaard and Dronen (2015) and Arriaga et al (2017) describe model concepts focusing on a more precise representation of the development of the spit.

The parameterization of the lifetime of a land reclamation based on the longshore transport intensity parameter (*LTI*) relates to work by other researchers on 'diffusion' of coastal perturbations (Pelnard-Considére, 1956; Dean and Yoo, 1992; Huisman et al., 2013; Arriaga et al., 2017) which have also shown that the parameter for alongshore redistribution was influenced by parameters such as wave height, profile steepness and active height of the zone with alongshore transport. The current approach with the *LTI* adds to this a simple approach to quantify this parameter from the 'yearly net alongshore transport' and 'average wave incidence angle relative to the coast orientation', which are two key figures of the considered coast which are often known from literature and therefore applicable in initial assessments. The *LTI* parameter also shows that a coastline cannot be characterized from the net (or gross) alongshore transport rates alone (i.e. without the angle of wave incidence), which shows that the coastal morphological behaviour of sandy land reclamations is determined mainly from the wave energy. It is also very useful that a characterization with *LTI* is less dependent on the actual location along the coast than the net transport rates, since it is not affected directly by the orientation of the coastline. It is therefore also considered useful to classify coasts along the world with an *LTI* parameter, which can be used as a 'morphological boundary condition' for initial assessments, similar to hydraulic boundary conditions which were for example assessed (e.g. Van Rijn, 1997;Wijnberg and Kroon, 2002).

The formulations in this research provide a first estimate of the lifetime and losses of land reclamations on the basis of available information on typical wave angles and net yearly transport rates, which should aid the decision process and feasibility studies of coastal managers. Even for some situations with more complex climate conditions than considered in the current studies (e.g. with temporal variability in conditions or spatial varying wave energy) an estimate can be made by assuming conservative climate conditions. Complex situations with spatially varying sediment or coastal structures do, however, require a more detailed assessment of the behaviour of a land reclamation (e.g. with process based model) as is also the case in the design phase of a study. It is envisaged that the basic engineering formulations can provide input to other fields of research which would otherwise only use initial assumptions on the behaviour of the reclamation from previous experience (e.g. economic science or ecological studies).

7 Conclusion

In this paper relations and design graphs for erosion rates, life time and maintenance volumes of both feeder-type and permanent mega nourishments were derived using numerical models. Both 2D process-based (Delft3D) and 1D coast line (UNIBEST, LONGMOR) models were calibrated and validated on measurement data of the mega-nourishment near Ter Heijde, The Netherlands and were then applied to model a series mega-nourishments with various width over length ratios and volumes.

- The morphological evolution of the Sand Motor could be reproduced both with a process-based numerical area model (Delft3D) as well as with a 1D coastline model (UNIBEST). The Delft3D results showed detailed predictions with realistic spit growth, channel formation and sedimentation and erosion volumes, but predicted a steeper cross-shore profile and less symmetrical plan form shape in comparison with measurements.

- Modelled erosion rates in UNIBEST were in line with observations at the Sand Motor. LONGMOR underestimated measured erosion volumes (with approximately 30%) due to the traditional representation of wave refraction on the lower shoreface. The LONGMOR results can, however, be improved by calibration on measured erosion volumes, which is only possible if a substantial amount of measurement data are available.

- The magnitude of the modelled wave-driven longshore sediment transport rate in 1D coastline models depends on the representation of wave refraction on the foreshore. A much more precise representation of transport rates at the Sand Motor was obtained when a so-called ‘dynamic boundary’ was applied (i.e. in the UNIBEST model), which defines the extent of the nearshore part of the coast that rotates with the shoreline while the orientation of the foreshore remains static. Traditional 1D coastline models (e.g. LONGMOR) assume that the entire profile rotates and consequently underestimate alongshore sediment transport rates as incident waves refract over the entire profile and thus become more shore-normal (resulting in lower alongshore sediment transport rates). With a non-rotating foreshore (i.e. with a ‘dynamic boundary’ in the nearshore), waves will refract somewhat less, resulting in larger sediment transport rates away from the nourishment and larger erosion rates.

- A realistic prediction of volumetric change and transport rates can be obtained either with a full (269 conditions) and a well-defined reduced wave climate (10 wave conditions) with the Delft3D and UNIBEST models.

The relations and design graphs for erosion rates, life time and maintenance volumes can be used for initial estimates in project initiation phases and feasibility studies. However, design phases and impact assessment studies require more extensive modelling. To account for local variations in longshore sediment transport and wave climate, the relations and design graphs were derived for various values of longshore transport intensity (*LTI*) which describes the sensitivity of the longshore transport for small changes in coastline orientation. It is noted that the net transport alone is insufficient to describe the response of interventions. For example, a net longshore transport of zero for the undisturbed section of the coast does not mean that the coastal erosion of a mega nourishment is zero.

- A linear relation is found between the half time of freely evolving mega nourishments and the initial nourishment volume. Furthermore, the half time of the nourishment is negatively correlated with the width over length ratio and the wave climate intensity.

- Erosion rates of considered realistic size mega nourishments (with regular 1/1 year to 1/5 year maintenance and Holland coast wave climate) mainly depend on the seaward extent of the nourishment. Additionally, the erosion rates are also very sensitive to the wave climate intensity.

- Maintenance volumes at permanent mega nourishments are considerably lower if maintenance frequency is reduced. A lower maintenance frequency however, results in larger coastline retreat between the maintenance operations. Coastline retreat at the centre of the mega nourishment is related to the length of the nourishment, wave climate intensity, active height and maintenance interval.

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