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Coastline modelling - Phase III

Investigation of the influence of model schematisation on a hindcast for the coast of Domburg

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Summary
This report describes the modelling of coastline evolution at Domburg with the coastline models UNIBEST-CL+ and PONTOS. The main aim is to distinguish the relevance of modelling choices for the performance of a coastline model in this area. An important aspect concerned the modelling of the protrusion at Domburg. This is the third phase of a series of studies that investigate coastline modelling. The following conclusions were drawn on the relevance of specific model aspects:

- Longshore sediment transport dominates the coastline evolution at Domburg.
- The effect of cross-shore sediment exchange could not be shown to provide a significant contribution to the coastline evolution at Domburg.
- Longshore-varying nearshore wave climates are required to resolve the observed local coastline development at Domburg. It is expected that situations with a complex shoreface require accurate nearshore wave conditions.
- Other modelled processes provided a small but less significant improvement to the model results. This holds for (1) the horizontal and vertical tide which can increase the rate of longshore transport by approximately 10%, (2) for imposing a sediment influx at the model boundary which improved the predictions for the sea-dike north-east of West-Kapelle and (3) the application of spatially varying cross-shore profiles which were only relevant in combination with offshore wave conditions since the profiles affect the wave propagation towards the coast.

With respect to the ability of the models it was found that the uncalibrated UNIBEST-CL+ model with nearshore wave conditions performed well for the considered case study at Domburg. The PONTOS model requires a robust implementation of nearshore wave conditions to resolve detailed coastline features such as at Domburg. In the present version, calibration of the alongshore transport is needed to obtain a good alongshore redistribution of sediment within PONTOS.

A synthesis of the results of the Phase I to III studies is provided, which gives an overview of the relevance of model components of coastline models. The relevance of specific processes is also explained in relation to the considered typical coastal situation. It is recommended to investigate the ability of the coastline models for these situations.

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Contents

1 Introduction

1.1 Background

One-line and multi-line process-based coastal evolution models are commonly used in coastal engineering projects to predict the effect of natural or anthropogenic changes on coastlines over periods of many decades. As such, several coastal evolution models were used to assess the nourishment volumes required to maintain the Dutch coastline during and after the reinforcement of the so-called Zwakke Schakels (Weak Links) coastal zones. Although applied in apparently similar manners, the various coastal evolution models predicted substantially different nourishment volumes.

In order to be able to effectively develop and manage long-term coastal management plans, it is essential to understand how coastal evolution models work, and why they can lead to different model predictions. This information can help to better inform decision-makers and can be used to more accurately assess predictions of future nourishments.

The reasons that the various coastal evolution models predicted different nourishment volumes for the Zwakke Schakels coastal zones are unknown. However, possible sources for these inconsistencies can be identified: differences in the data of the individual sites available to the modellers; differences in the interpretation of these data and the translation of these data into a model; differences in the numerical calculation within the coastal evolution models themselves; and differences in the interpretation of the model results by the modellers and by the clients.

A study has been performed within the framework of the KPP B&O kust project in 2012 to investigate these issues for three coastline models. This concerned UNIBEST-CL+ (WL|Delft Hydraulics, 1994), PONTOS (Steetzel, et al., 1998) and Longmor (Van Rijn, 2005). Phase 1 of this study made a comparison between the model computations of alongshore sediment transport for a set of artificial conditions/profiles and simplified coastline situations. This revealed that the computated transports may differ considerably between the models which has an impact on computed coastline evolution. This was mainly due to (1) different implementations of the effect of wave refraction on the lower shoreface and (2) different transport formulations. Furthermore, there was some influence from aspect like the order of the conditions and interpolation along the coast. In Phase 2 of this study the models were applied with similar settings to a specific case at Domburg. This showed that results were reasonably comparable if the rates of sediment transport are calibrated on the basis of field data. The nourishment volumes for larger areas were also comparable and provide a reasonable to good prediction on larger scales. However, at smaller spatial scales the more detailed local coastline shape at Domburg was not represented well. This may have to do with the fact that the models were not optimized as similar settings needed to be applied to make the models comparable.

It is therefore suggested that adding model specific processes and settings may improve the model forecasts. One can think of aspects like alongshore varying wave conditions, non-uniform coastal profiles, inclusion of cross-shore sediment transport and the influence of tide.

1.2 Approach

Phase III will build on the knowledge gained in Phase I and Phase II of this project, in which differences in the cross shore and longshore processes included in PONTOS and UNIBEST-CL+ were identified as possible sources of differences in model predictions of coastline evolution and nourishment requirements. Phase III will focus on the coastline at Domburg, also studied in Phase II.

Phase III is aimed at improving the prediction of the coastline development at Domburg by incrementally adding processes to the UNIBEST-CL+ and PONTOS coastline evolution models. In particular, Phase III will focus on the effect of the variations in the cross shore profile shape on longshore and cross shore sediment transport, and the effect of computing nearshore wave conditions using a detailed external numerical wave model compared to the use of simple internal cross-sectional wave propagation routines of the coastline models themselves. Due to the complexity of the coast, and conclusions found in Phase II, the LONGMOR model will not be evaluated in this phase. In a similar fashion to the way models were set up in Phase I and Phase II, the model complexity in Phase III will be increased incrementally, thereby giving insight in the relevance of various model components.

1.3 Contents

This report first describes the data used in this study (Chapter 2). Two chapters with model simulations for UNIBEST and PONTOS are then provided (Chapter 3 and 4). These chapters describe the considered scenarios, model setup, results and the model performance for various model components. An analysis of the findings of the models is then given in Chapter 5. This includes the interpretation of the relevance of model components of coastline models, as well as a discussion on the application of the PONTOS and UNIBEST-CL+ models for other coastal studies.

The project is part of the KPP-B&O Kust 2013 programme carried out by Deltares for Rijkswaterstaat Waterdienst. The work carried out in this project was done by Deltares in cooperation with Arcadis.

2 Site description and Environmental data

2.1 Introduction

The area selected for study in this project is the northwest-facing coast of Walcheren, Zeeland, The Netherlands, see Figure 2.1. This coast corresponds with the case study area in the investigation preceding this report on differences between coastline evolution models (Deltares, 2013). The coastline is characterised by the sea-dike at Westkapelle, sandy beaches and dunes between Westkapelle and Oostkapelle, and a seaward protrusion of the coast at Domburg, see Figure 2.1 (right panel).

The coastline at Domburg is actively maintained to compensate for the coastline retreat at Domburg. The so-called Momentary Coast Line (MCL), which is an approximate, but robust measure for the position of the active coastal zone, at Domburg has been shown to retreat by 2–5m per year (Deltares, 2010). Approximately 6.5 million m^3 was nourished in the coastal zone around Domburg between 1990 and 2010 (Deltares, 2013; source : Rijkswaterstaat).

Figure 2.1 Arial photograph of the northwest-facing coast of Walcheren, including the locations of Westkapelle, Domburg and Oostkapelle. Images courtesy of Google Earth.

2.2 Bathymetric and topographic data

The basic information required for each study in the coastal zone is a combined dataset with bathymetric and topographic data of the area. In this project such a dataset is needed for a preliminary assessment of characteristic features in the study area, and for setting-up the UNIBEST and PONTOS models. The UNIBEST model defines the initial coastline position with a single coastline that was defined on the basis of the computed volume of sediment between two vertical levels of cross-shore profiles (as used for the MCL line). The multi-layer approach, as used in PONTOS, requires bathymetric data for the definition of initial positions for each of the vertical layers in the model.

In this project two datasets with measured bathymetry/topography are used as input for the models. Both the JARKUS-dataset and the 'Vaklodingen'-dataset of the Dutch Coast (source: Rijkswaterstaat) are considered for the area near Domburg. The JARKUS-dataset consists of yearly measured cross-shore profile information for prescribed locations along the coastal stretch (RSP-locations; "RijksStrandPalen"). Since the length of the measured JARKUS profiles is limited to the nearshore area, the 'Vaklodingen'-dataset is used as additional information for the locations further offshore. The dataset with 'Vaklodingen' covers a much larger area compared to the JARKUS-dataset, but the measurements are not performed each year. For each year that no offshore data are available the last data prior to that year are used. The combined dataset with JARKUS- and 'Vaklodingen'-data used for this study covers the period between 1970 and 2012.

Figure 2.2 shows, as an example, the measured bathymetry and topography for the year 1990. Above water level the coastal stretch near Domburg is relatively straight, with elongated sandy beaches and dunes between Oostkapelle and the sea-dike near Westkapelle. On the other hand, the underwater bed levels show relatively large variations across the study domain. Both southwest and northeast of the coastline-of-interest deep tidal channels are present, and in-between (in front of Domburg) a relatively flat, shallow area exists.

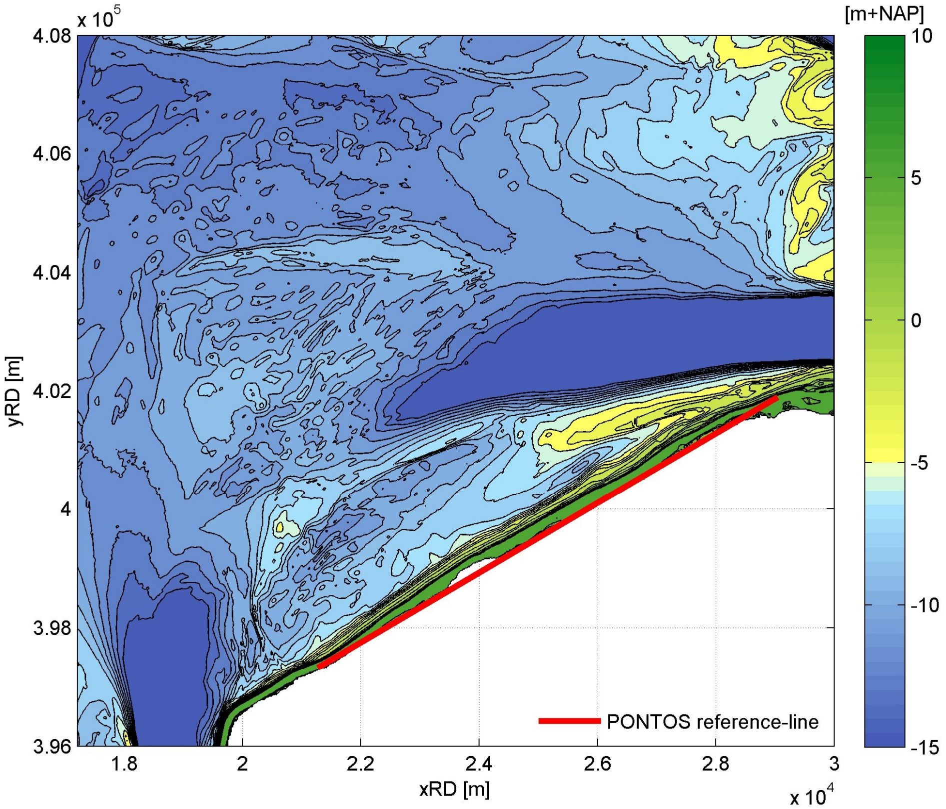


Figure 2.2 Bathymetric data for the study area near Domburg (Vaklodingen, 1989).

A more detailed view on the coastline near Domburg (Figure 2.3) shows the relevance of changes in the coastal zone for Domburg, as it is located on a coastline protrusion into the sea. This protrusion is the result of coastline retreat on both sides of the city. In order to maintain the protruded position of the coastline, nourishments are required on a regular basis in this area.

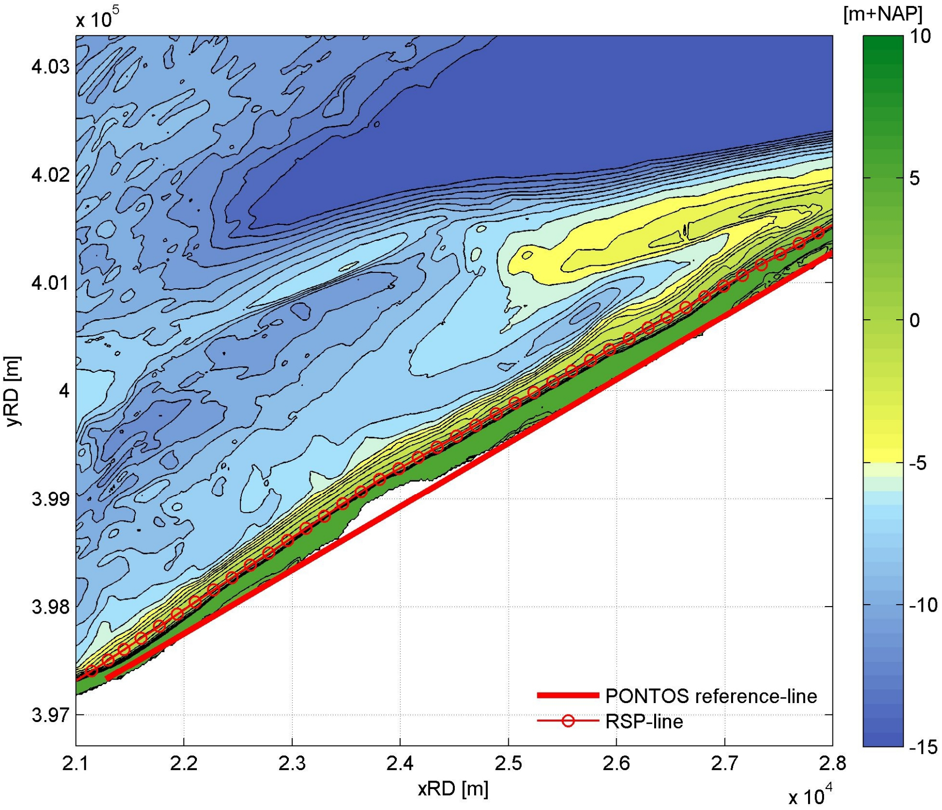


Figure 2.3 Detailed view on bathymetric data for the coastline area near Domburg (Vaklodingen, 1989).

2.2.1 Alongshore coastline positions

The most important input for all coastline models is obviously the (initial) position of the coastline in the area of interest. For Phase III of the Domburg-case it is decided to use the so-called 'Momentane KustLijn' (MKL or MCL) as definition for the coastline position. The MCL-position is a robust indicator for the position of the low-tide waterline, based on sediment-volumes in the active coastal zone. The use of a volume-based coastline definition (MCL) is preferable because coastline models (UNIBEST and PONTOS) are using the sediment volumes at profiles along the coast as a proxy for the coastline development. The initial coastline positions for the model setups in the previous project phase were based on the Mean Sea Level (MSL)-line. In comparison to the MCL-line, the MSL-line is more sensitive to (small-scale) temporal and spatial fluctuations in the coastal profiles, and is therefore less robust.

In Figure 2.4 the MCL-positions for the coastal area near Domburg are presented as function of the so-called RSP-locations (= 'RijksStrandPalen'). The figure specifically shows the indicative coastline positions for three different years: 1976, 1990 and 2012. And in addition, also an envelope of all registered coastline positions for the period between 1970 and 2012 is visualized in the figure.

The figure shows an alongshore varying coastline that is characterized by protruding coastline positions near Domburg (RSP km 15.00) and near the north-eastern boundary of the considered area (between RSP km 10.25 and km 11.45). The coastline protrusion near the city of Domburg has the tendency to erode, but this is not directly clear from the figure because the MCL-position is maintained by performing (beach) nourishments on a regular basis. The coastline protrusion in the north-east is migrating seaward despite its tendency to erode, which is expected to be the result of nourishments. The coastal zone is morphologically active, since a large sand ridge is connected to the coastline. The total amount of sediment in the area seems quite stable, but the sediment distribution within the area varies substantially. The coastline at Domburg can be labelled as a 'complex' coastline, because of the large variation in bathymetry of the coastline and foreshore.

Figure 2.4 indicates that relatively large variations in coastline position are found for almost the entire coastal stretch. The largest variations are found near the shore-connected sand mass (km 10.25 – km 11.45). But closer to Domburg also substantial variations are recorded. The large coastline shift southwest of Domburg (RSP km 16 to 18) can be explained by the fact that a series of large nourishments has been carried out in order to strengthen the primary sea defenses at that location.

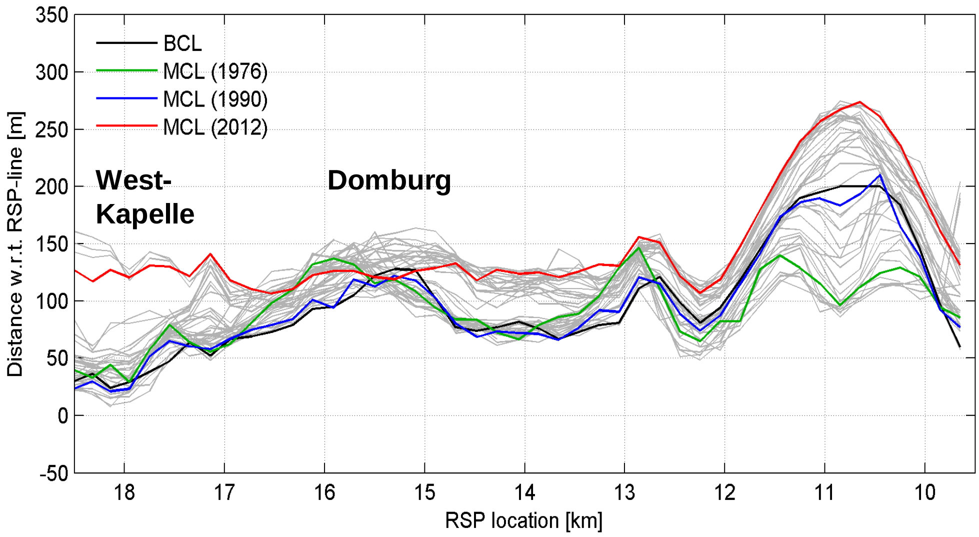


Figure 2.4 Overview of determined MCL-positions in the coastal area near Domburg, for all years in the period 1970 – 2012. The MCL-positions for the years 1976, 1990 en 2012 are highlighted to show the tendency of coastline evolution. The BCL line shows the Basis Kustlijn, which is a theoretical "minimal" coastline position to be maintained.

2.2.2 Cross-shore profiles

Cross shore profiles near Domburg (JARKUS transects 16001428–16001632) are generally quite longshore uniform (see dark grey points in Figure 2.5). An exception is the coast north of Domburg at Oostkapelle, which is characterised by a shallow foreshore and an offshore bar, see e.g. Figure 2.6. The light grey points in Figure 2.5 at approximately 800m from the dune foot in show this bar.

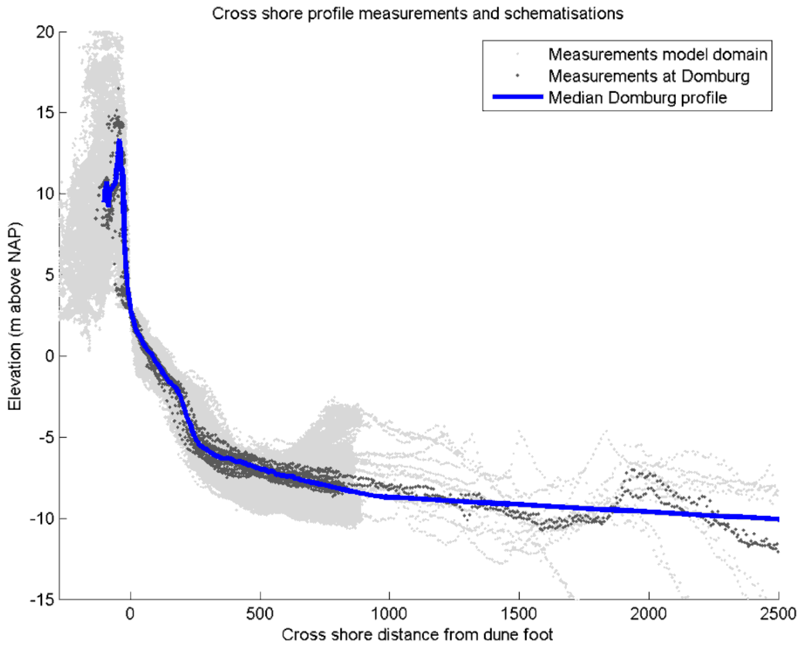


Figure 2.5 All measured cross shore transects along the entire model domain (light grey), transects at Domburg (dark grey), and representative cross shore profile (blue).

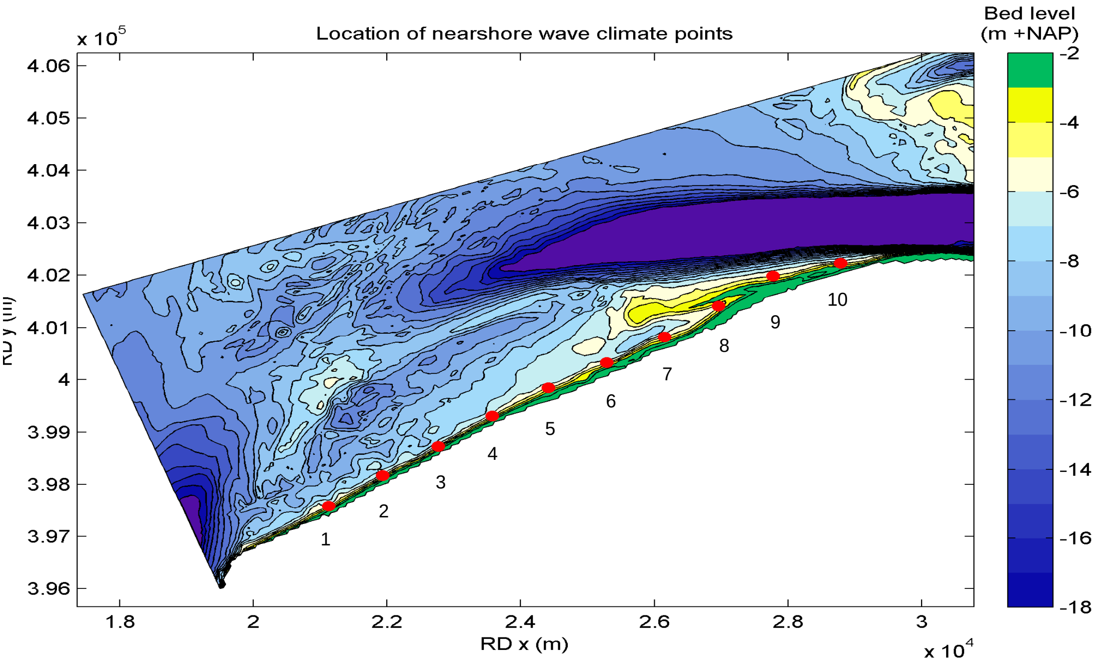


Figure 2.6 Position of ten equidistant nearshore wave, tide and cross shore profile locations along the coast of Walcheren.

An overview of ten cross shore profiles representative for the ten locations along the coast of Walcheren shown in Figure 2.6, is provided in Figure 2.7. The profiles shown in red in Figure 2.7 are representative for each of the ten coastal sections shown in Figure 2.6, and will be used in Chapter 3 and Chapter 4 to represent longshore variations in the cross shore profile in the coastline models.

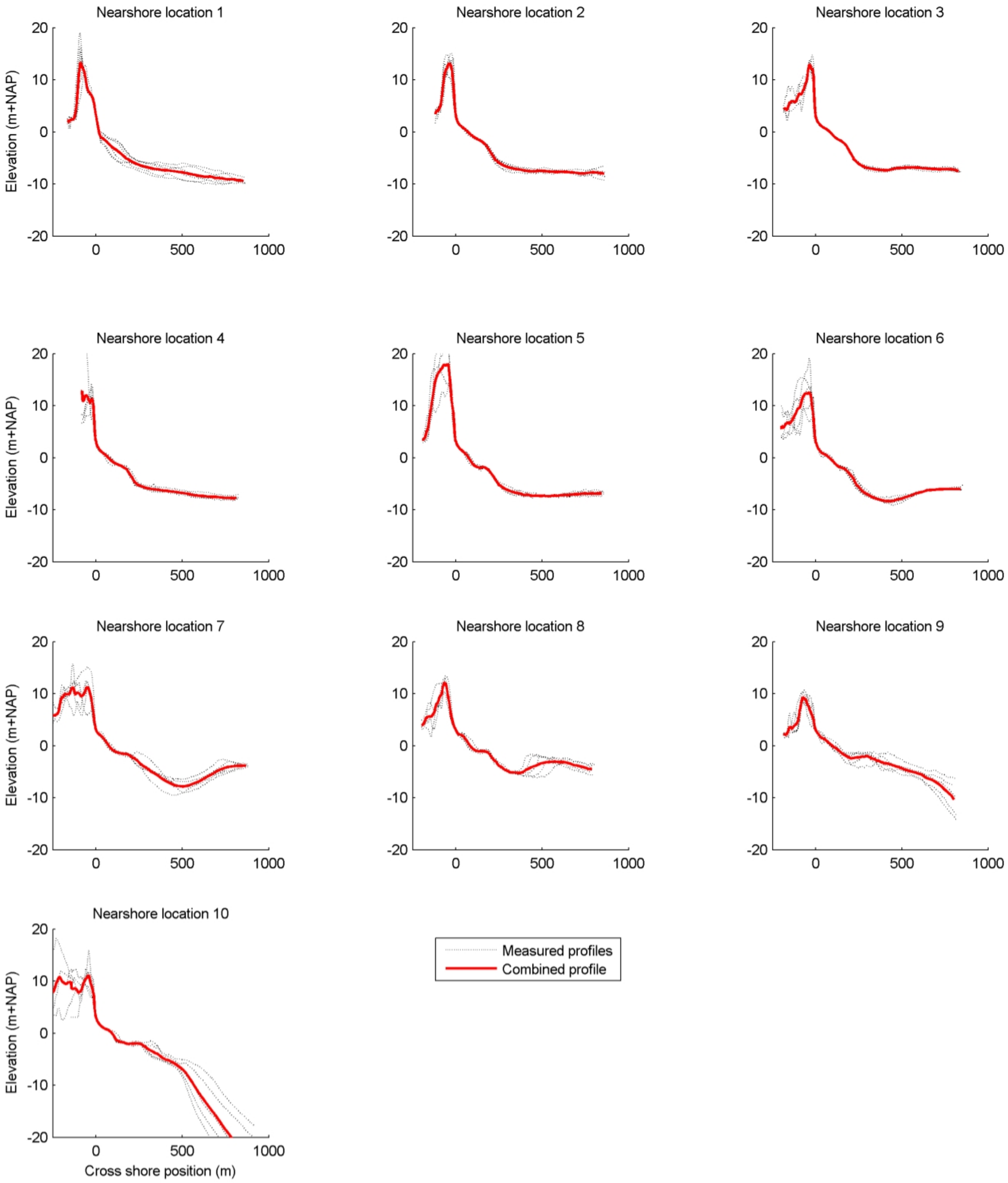


Figure 2.7 Representative cross shore profiles at ten locations, based on average JARKUS data for each nearshore location measured in 1989.

2.3 Sediment

The sediment at the coast of Walcheren is predominantly medium grained sand. For this study the sand is assumed to have a median grain diameter (D50) of 315µm, which corresponds to the value used in Phase II of this project.

2.4 Waves and Tide

As input for the coastline models (schematized) wave climates and flow conditions are needed for the calculation of (alongshore) sediment transport rates and resulting coastline changes. The Phase III simulations are performed both with offshore and nearshore wave conditions as input. This differs from the Phase II modelling which only applied offshore wave conditions in the modelling. Furthermore, the Phase III studies also investigate the impact of tide on the coastline evolution of the Domburg area.

2.4.1 Offshore wave data

The offshore wave data used in this study are based on an earlier analysis of directional wave data measured at the 'Europlatform' wave buoy (Deltares, 2009), discussed in Appendix A. This analysis categorised 21 years of wave measurement data into 117 representative offshore wave conditions, detailed in Table A.2 and shown in wave-rose form in Figure 2.8. The data show a dominance of wave conditions coming from the South West and North, as well as substantial, but less frequent, wave conditions from the West to North-West.

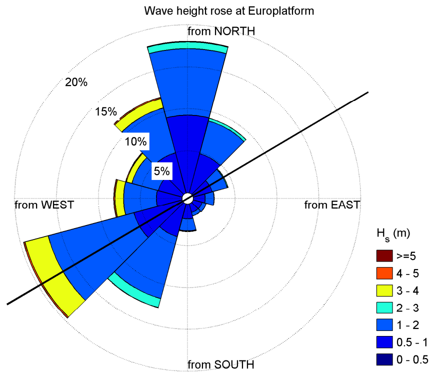


Figure 2.8 Wave rose of representative offshore wave conditions, derived from wave data measured at the Europlatform wave buoy. The thick black line indicates the approximate coastline orientation at Domburg.

2.4.2 Nearshore wave data

In addition to the offshore wave climate data, representative wave climates are extracted at the ten nearshore locations along the coast of Walcheren (shown in Figure 2.6) from the results of an earlier wave propagation study (Deltares, 2009). In this study, the offshore wave climate at Europlatform described in Section 2.4.1 was transformed to 5m water depth off the coast of Walcheren using the SWAN numerical wave model, see Appendix A for details. The depth of 5 meter was chosen because almost all wave-driven alongshore sediment transport takes place between NAP-5m and the shoreline.

The resulting nearshore wave climate at ten nearshore locations along the coast of Walcheren discussed in Section 2.2.2 are shown in Figure 2.9. The figure shows in particularly a substantial variation of the dominant nearshore wave direction along the coast caused by the presence of offshore bathymetric features.

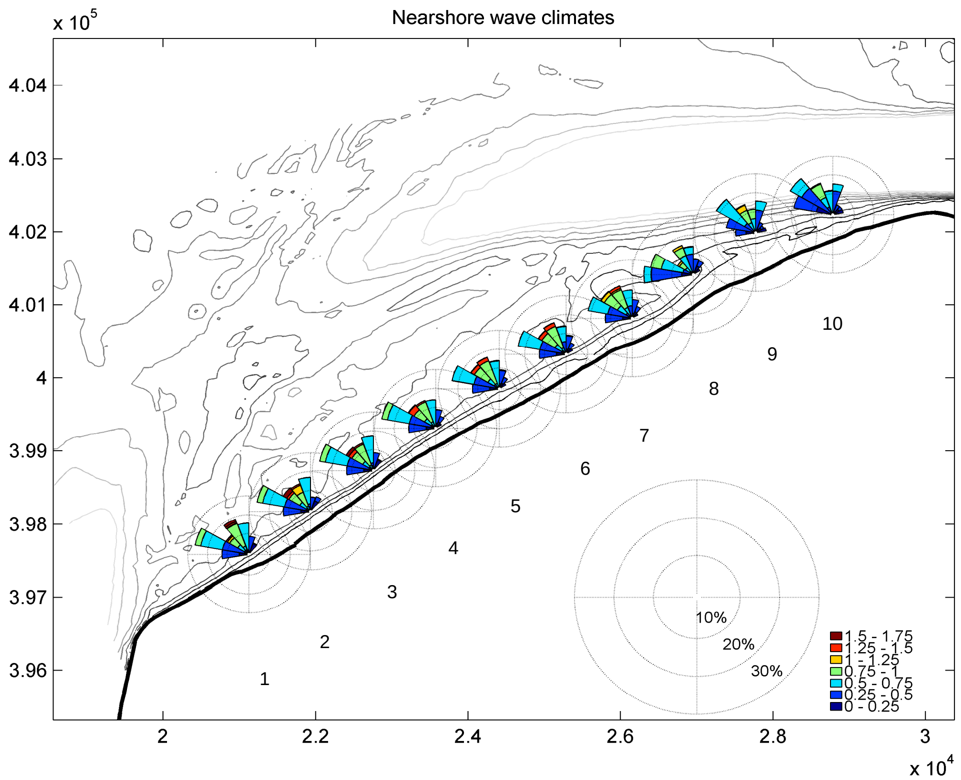


Figure 2.9 Wave roses of nearshore wave climates at ten nearshore locations

The set of nearshore climates has two advantages with respect to the single offshore wave climate: (1) the offshore-to-nearshore transformation of wave conditions has been modelled by a sophisticated wave model, instead of by an inbuilt parameterized wave transformation formulation in the coastline models; (2) assessment of the effect of alongshore variations in local wave conditions is possible because multiple nearshore locations are considered.

2.4.3 Tide information

Information on the horizontal and vertical tide was derived from the operational models within the MATROOS database (i.e. Kuststrook fijn Waqua model). As an example, Figure 2.10 shows computed tidal flow velocities for some phases of a spring tide at the coast of Walcheren.

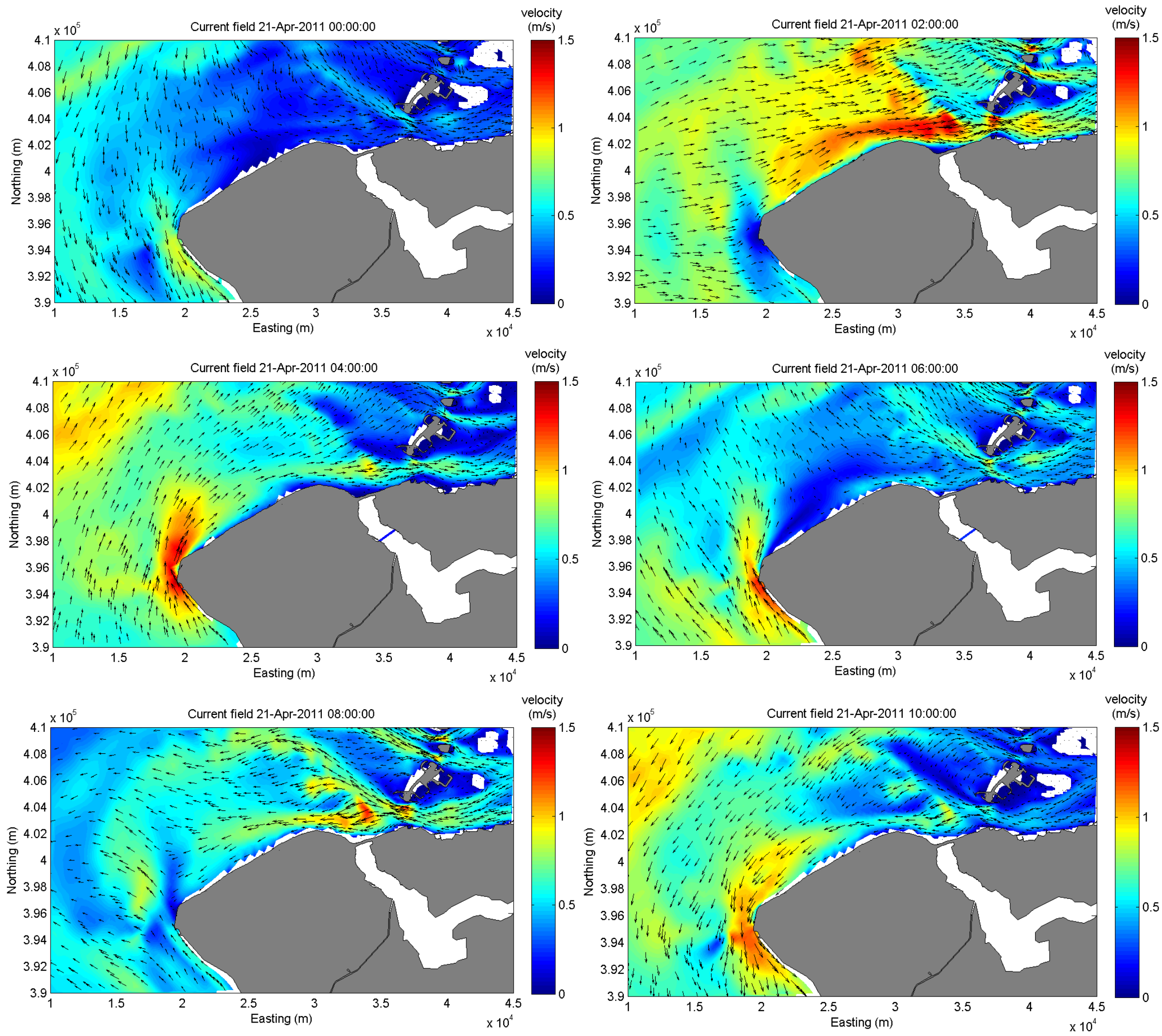


Figure 2.10 Typical spring tide current fields and magnitudes computed by the MATROOS "Kuststrook Fijn" flow model around the Walcheren coast.

The tidal flow velocities and water level elevations at the ten nearshore locations (see Figure 2.6) were derived from the numerical models for some months. Figure 2.11 shows the ellipses of the tidal water levels and flow velocities at each of the output locations. Note that the tidal wave changes from a progressive wave (i.e. line shaped) to a standing wave (i.e. more rounded shape) from Westkapelle to Domburg. Furthermore, a slight net residual current can be seen at the North-Western side (i.e. side of Domburg).

It is assumed (but not confirmed) that in this case wave conditions are more dominant than flow conditions in determining the magintude of net sediment transport, in the upper parts of the coastal profiles. Therefore the influence of tide has been investigated only with the UNIBEST-CL+ model, which should give insight into the relative contribution of the horizontal tide. Furthermore, no horizontal tide was included in the PONTOS model setup for this project phase, as the effects are expected to be similar as in the UNIBEST-CL+ model.

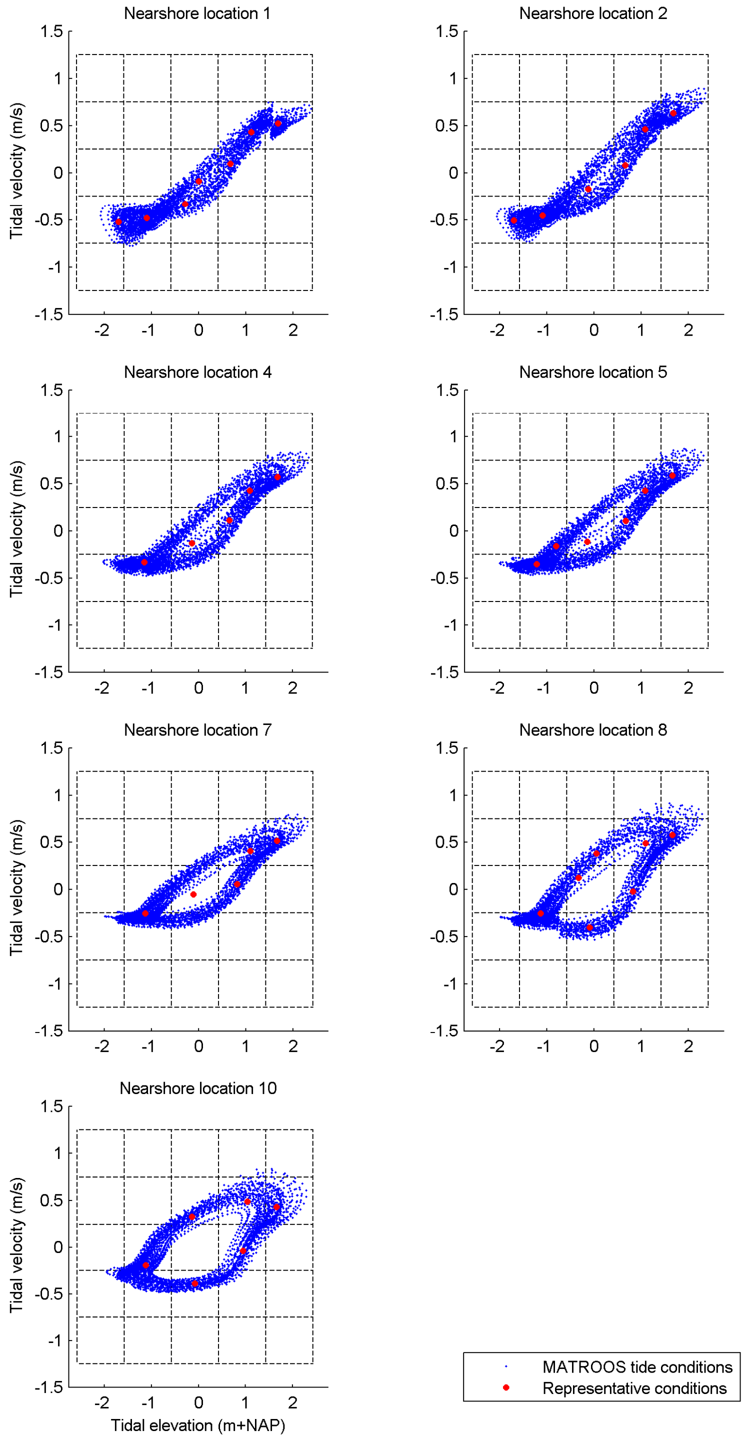


Figure 2.11 Representative tide conditions at ten nearshore locations

2.5 Nourishment information

In order to maintain the protruded coastline position near Domburg nourishments are required on a regular basis in this area. In the period 1990–2008 the coastal area was nourished on twelve occasions (see Figure 2.12 and Table 2.1).

Figure 2.12 Locations of the twelve nourishments carried out in and around the model area (indicated by red box) in the period 1990–2008.

The majority of the nourishments in the area have been beach nourishments, with only one foreshore nourishment carried out in 2008. The total nourishment volume introduced to the northwest-facing coast of Walcheren during this period is approximately 6.5Mm^3. Of this volume, approximately 5.5Mm^3 was nourished within the model area with a length of approximately 6 km. It should be noted that a substantial part of this total volume (~2 Mm3) was nourished in 2008 in the southwestern part of the domain for the purpose of reinforcing the primary sea defenses (sea-dike) at that location. Latter volume contributed thus only indirectly to the evolution of the coastline protrusion at Domburg.

Table 2.1 shows the nourishment-events that took place in the study area in the period 1990–2008. Between 2008 and 2012 no additional nourishments are performed in this area. The nourishment locations are defined in terms of the position within the local coordinate system of the coastline model (see next section for the definition). The nourishment scheme in Table 2.1 equals the scheme that was used for the model setup in Phase II of the project.

Table 2.1 Overview of nourishment-events in (a 6 km long) coastal stretch around Domburg, for the period 1990 – 2012.

X_{min} [m]	X_{max} [m]	Z_{min} [m+NAP]	Z_{max} [m+NAP]	T_{start} [yr]	T_{end} [yr]	Type	Volume [m^3]
1073	2300	-2.0	3.0	1990.4	1990.5	beach	8 000
2505	3529	-2.0	3.0	1990.4	1990.5	beach	9 600
4139	5645	-2.0	3.0	1992.4	1992.5	beach	637 000
2505	4139	-2.0	3.0	1993.4	1993.5	beach	318 000
2300	4139	-2.0	3.0	1994.4	1994.5	beach	453 000
0.00	1566	-2.0	3.0	1995.4	1995.5	beach	530 600
0.00	4358	-2.0	3.0	2000.4	2000.5	beach	885 200
0.00	3728	-2.0	3.0	2004.4	2004.5	beach	767 900
0.00	873	-7.0	-3.0	2008.4	2008.5	foreshore	825 500
0.00	873	-2.0	3.0	2008.4	2008.5	beach	606 100
1073	1891	-2.0	3.0	2008.4	2008.5	beach	110 400
2096	4358	-2.0	3.0	2008.4	2008.5	beach	369 600
							5 520 900

It should be noted that in the period 1990–2008 some (minor) nourishments were also carried out in the coastal area further northeast of Domburg, near Oostkapelle. These nourishments are not taken into account in this study, since the area around Domburg is the target area for the model simulations.

2.6 Sediment fluxes from data

Information on the sediment fluxes is needed for the purpose of calibrating the coastline models. This requires estimates for the incoming and outgoing sediment fluxes in the study area. However, making decent estimates of sediment fluxes in a relatively large domain is rather difficult. In literature only a limited amount of estimates are provided, and in most cases these estimates are based on similar modelling experiences as this project (thus: estimate = model result, without proper calibration).

In Phase II a rough estimate is made for the rate of sediment loss from the active zone between NAP -6.1 m and NAP +3 m (= “BCL/MCL-layer”). Based on the difference between sediment volume changes and nourishment volumes, it is concluded that the yearly-averaged net sediment outflow from the active layer approximates 100,000 m3/yr.

Other than the above mentioned estimate of sediment losses from the active layer around the waterline, no other information about sediment fluxes in the study area is considered for calibration purposes. As discussed later on, the calibration efforts for the PONTOS model are (in this study) limited to the calibration of cross-shore sediment exchange between vertical layers, based on measured profile/coastline changes.

3 UNIBEST modelling

3.1 Introduction

This chapter describes the performance of the UNIBEST-CL+ model for the coast of North Walcheren for the period from 1990 to 2012. The model has been setup with the aim of distinguishing the relevant aspects that need to be included in a typical UNIBEST-CL+ model to hindcast the coastline evolution at a complex coast (like at Domburg) reasonably well. For this purpose, a number of model simulations is set up which activate or deactivate specific processes.

3.2 Model setup

This study will investigate what physical processes are required to be included in an UNIBEST-CL+ model in order to improve the skill of the model in hindcasting the coastline development around Domburg, relative to the skill of the model in Phase II. In order to achieve this, a simple UNIBEST-CL+ model of the coast of Walcheren is set up that is similar to that of the UNIBEST-CL+ model of Phase II. The model is subsequently made more complex by the addition of more realistic initial and boundary conditions.

All UNIBEST-CL+ models described in this section are set up using sediment transport rates and S-Φ curves computed by UNIBEST-LT at the 10 model input locations along the coast of Walcheren shown in Figure 2.6. These transport rates are computed using either offshore wave conditions and cross shore profiles that extend to deep water (MSL-32m), or nearshore wave climates and cross shore profiles that only extend to shallow water (MSL-5m), as will be discussed in the following sections. Longshore transport rates at all model input locations are computed in UNIBEST-LT using an estimate of the median sediment grain size of 315 µm, the default Van Rijn 2004 transport formulation parameters and the default model parameters for wave transformation. The sensitivity of the model results to variations of these model parameters has not been investigated in this study. As discussed in Phase II, UNIBEST-CL+ interpolates the coefficients of the S-Φ curves that are computed by UNIBEST-LT at the ten model input locations, at all other locations along the coast. In contrast to Phase II, the simulated longshore transport rate is not calibrated in the UNIBEST-CL+ simulations of Phase III.

In accordance with the UNIBEST-CL+ model setup of Phase II, the active profile height used to compute the erosion and accretion of the coastline is set to 14m for all cross shore transects. It should be noted that nourished sediment is redistributed instantaneously over this active height in the UNIBEST-CL+ model. The dynamic zone within which the coastline is allowed to rotate in the UNIBEST models is set to the area above MSL-5m.

All model simulations are run with a longshore grid resolution of 50m and are set to run from 01-01-1990 until 31-12-2012. It is noted that the 2012 nourishment is not implemented in the model since it is not included in the Jarkus measurements for 2012. The lateral boundary at the North-East (Oostkapelle) end of the model (x = 9000 m) is set to a condition of zero-coastline angle change. The lateral boundary at the South-West (Sea-dike) end of the model (x = 0m) is set to a fixed sediment transport rate, as described in the following sections. Note that although the UNIBEST-CL+ models have been set up to model 9km of the coast of Walcheren, all analysis presented in this section will refer only to the 6km of coast surrounding Domburg (locations 1–7).

3.2.1 Data needed to setup the model

In order to simulate coastline development using the UNIBEST-CL+ model, the model must be provided with initial and boundary conditions. In this study, the coastline in all simulations run with UNIBEST-CL+ are initialised using the measured MCL-position of 1989, which is derived from the JARKUS-transect data described in Section 2.2.2. Since the shape of the cross shore profile changes along the coast, see e.g. Figure 2.7, the MSL-position is computed relative to the MCL-position at the ten 10 locations along the coast of Walcheren shown in Figure 2.6. This computed offset between the MCL-position and the MSL-position is subsequently interpolated at all other locations along the coast to initialise the MSL position in the whole model domain, shown in Figure 3.1.

The UNIBEST-CL+ models are forced using either the offshore, or nearshore wave climates, and where appropriate, the tidal schematisation data described in Section 2.4.3. The nourishment scheme described in Section 2.5 and Table 2.1 is applied in all model simulations, where all nourishments are programmed to be carried out in 1/10th of a year (i.e. from 25th of May to the 30th of June). The nourishment is included in the model as a local coastline accretion, which is computed by dividing the nourished volume by its length and the applied active height in the UNIBEST-CL+ model.

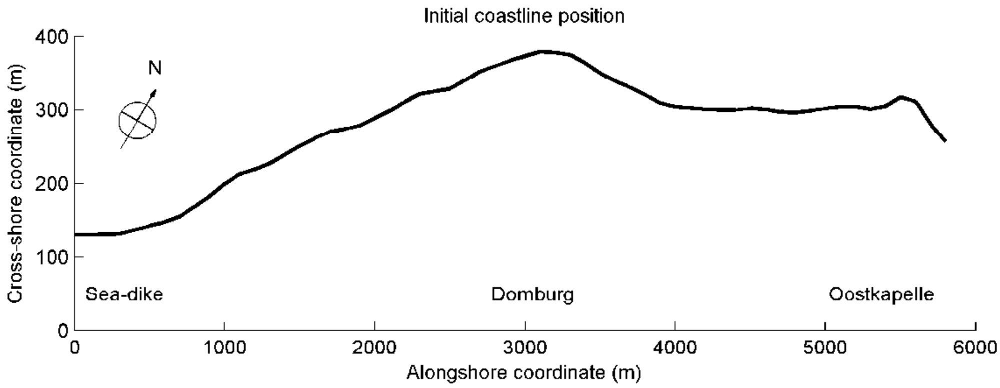


Figure 3.1 Initial coastline position in model coordinates.

3.2.2 Basic model setup

In order to investigate the effect of the inclusion of detailed initial and boundary conditions on the simulated coastline development in UNIBEST-CL+, a simple reference model is set up. In the reference model, the cross shore profile and wave climate are assumed to be uniform in the entire longshore domain of the model. The median cross shore profile for Domburg, used as the representative cross shore profile in Phase II and shown in blue in Figure 2.5, and the offshore wave climate described in Section 2.4.1 are input in UNIBEST-LT at each of the ten longshore locations to compute longshore transport rates and S-Φ curves. As in Phase II, this implies that sediment transport gradients are generated only by variations in the coastline angle.

3.2.3 Model setup comparison with Phase II model

Five modifications of the UNIBEST-CL+ Reference model in Phase III have been made with respect to the UNIBEST-CL+ model used in Phase II. These changes have been summarised in Table 3.2. The modification of the simulation period has been carried out in order to better simulate the evolution of the large-scale nourishments carried out in 2008. The initial shoreline position has been changed from the MSL-position in 1990, to a cross shore position based on the MCL measured in 1989, in order to make direct comparison to MCL-positions during the simulation period possible. The offshore wave climate has been modified from the wave climate at Europlatform in the PONTOS Dutch Coast model, to the wave climate at Europlatform described in Appendix A. This has been done in order to allow the use of nearshore wave climates computed by the SWAN model (discussed in Appendix A) in the sensitivity simulations of Phase III, without reanalysis of the offshore wave climate. All three modifications described above are consistent with the modification of the PONTOS Basic model in Phase III, described in Section 4.2.3. In Phase II, longshore sediment transport rates were calibrated in order to enable simple comparisons between the coastline evolution models. In Phase III UNIBEST-CL+, as PONTOS, has not been calibrated towards a set longshore sediment transport rate, thereby allowing larger differences to occur between the coastline evolution models. Finally, the cross shore resolution in the UNIBEST-LT models at the ten model input locations has been increased to better describe the wave transformation and longshore sediment transport in the surf zone.

Table 3.1 Overview of difference between the original UNIBEST-CL+ Phase II model, and the UNIBEST-CL+ reference Phase III model.

Original Phase II model	**Reference model Phase III**
Simulation period: 1990–2008.	Simulation period: 1990–2012.
Initial coastline position based on 1990 cross shore MSL-position.	Initial coastline position based on 1989 cross shore MCL-position, transformed to MSL-position.
Offshore wave climate derived for Europlatform in the PONTOS Dutch Coast model.	Offshore wave climate derived from Europlatform data and described in Appendix A (Table A.2).
Mean longshore transport rate calibrated to 100,000 m^3/year	Longshore transport rate not calibrated.
Coarse cross shore resolution in UNIBEST-LT model.	Fine cross shore resolution in UNIBEST-LT model.

3.2.4 Overview of model simulations

In Phase III, the effect of the addition of more realistic physical boundary conditions on the predicted shoreline development in UNIBEST-CL+ is investigated through a series of sensitivity studies, summarised in Table 3.2:

- In the first sensitivity simulation (U1; Deep), the effect of imposing longshore-varying cross shore profiles is investigated by imposing varying cross shore profiles (shown in red in Figure 2.7) at each of the ten model input locations for longshore transport computations in UNIBEST-LT. Each profile is extended to an offshore depth of MSL-32m in UNIBEST-LT using a constant planar slope, which is a synthetic way of extending the profile to deep water. The offshore wave climate described in Section 2.4.1 is imposed at the offshore boundary of all ten profiles, implying longshore uniformity in the offshore wave boundary conditions. All wave transformation from a depth of MSL-32m to the shoreline is accounted for by the UNIBEST-LT model, under the assumption of longshore uniformity of the bathymetric contours.
- The second sensitivity simulation (U2; Shallow), is set up to investigate the effect of imposing longshore-varying nearshore wave climates and longshore-varying cross shore profiles on the predicted shoreline development in UNIBEST-CL+. In this simulation, the longshore-varying cross shore profiles applied in sensitivity simulation U1 are truncated to a depth of MSL-5m. The nearshore wave climates computed at a depth of MSL-5m by the SWAN wave model (described in Appendix A) and shown in

Figure 2.9, are imposed at the offshore boundary of the ten cross shore profiles in UNIBEST-LT in order to compute longshore transport S-Φ curves. In this simulation, wave transformation up to a depth of MSL-5m is accounted for by the SWAN wave model, which allows for a correct representation of wave refraction and breaking on offshore bathymetric features. Wave transformation and sediment transport from a depth of MSL-5m until the shoreline is accounted for by the UNIBEST-LT model.

- The third sensitivity simulation (U3; Shallow representative), investigates the effect of only longshore-varying wave climates. In this simulation, the representative cross shore profile used in the Reference simulation (U0) is truncated to a depth of MSL-5m. This truncated representative profile and the longshore-varying nearshore wave climates used in sensitivity simulation U2 are applied in the UNBEST-LT computation at all ten model input locations. In this simulation, wave transformation up to a depth of MSL-5m is accounted for by the SWAN wave model, including complex wave transformation across the complex offshore bathymetry. Wave transformation and sediment transport from a depth of MSL-5m until the shoreline is accounted for by the UNIBEST-LT model, where the profile above MSL-5m is considered constant in the longshore domain of the model.
- The effect of including tidal water level variations and longshore tidal currents on the shoreline development computed by UNIBEST-CL+ is investigated in the fourth sensitivity simulation (U4; Shallow with tide). In this simulation, the cross shore profiles and nearshore wave climates of sensitivity study U2 (Shallow) are applied in combination with the longshore-varying nearshore vertical and horizontal tide schematisations described in Section 2.4.3 and indicated by red circles in Figure 2.11 in the UNIBSET-LT computations of wave transformation and sediment transport S-Φ curves at the ten model input locations.
- In the fifth sensitivity study (U5; Shallow with flux), the sensitivity of the coastline evolution computed in UNIBEST-CL+ to the lateral boundary condition imposed at the south-western (sea-dike) end of the model is investigated. This sensitivity simulation is identical to sensitivity simulation U2, with the exception that the lateral boundary condition at the sea-dike end of the model is modified from zero flux, to an import of 30,000 m^3/year.

Table 3.2 Comparison of UNIBEST-CL+ Phase III model sensitivity variations.

Code	**Name**	**Cross shore profile**	**Offshore depth**	**Wave climate**	**Tide climate**	**Lateral boundary condition**
U0	Reference	Longshore-uniform	MSL-32m	Offshore	None	0 m^3/year
U1	Deep	Longshore-varying	MSL-32m	Offshore	None	0 m^3/year
U2	Shallow	Longshore-varying	MSL-5m	Nearshore	None	0 m^3/year
U3	Shallow Representative	Longshore-uniform	MSL-5m	Nearshore	None	0 m^3/year
U4	Shallow with Tide	Longshore-varying	MSL-5m	Nearshore	Horizontal and vertical tide	0 m^3/year
U5	Shallow with Flux	Longshore-varying	MSL-5m	Nearshore	None	30,000 m^3/year

3.3 Results

3.3.1 Reference simulation (U0)

Simulated longshore transport rates across the model domain in the Reference simulation are shown for six points in time in Figure 3.2. The figure shows that computed transport rates are in the order of 0–300,000 m^3/year towards the north-east. Sediment transport rates near the south-western (sea-dike) boundary are consistently zero (due to the imposed lateral boundary condition), and generally increase with distance from the sea-dike boundary. Longshore transport rates in the model domain tend to increase over time; near Oostkappelle (x = 6000 m) the sediment transport rate changes from approximately 100,000 m^3/year in 1992 to approximately 250,000 m^3/year in 2012. Since the imposed wave climate does not change over time, this increase in the sediment transport rate can only be explained by a change in the coastline orientation. Furthermore, because no addition sediment can enter the model at the sea-dike lateral boundary, the increased sediment transport rates imply greater longshore sediment transport gradients and hence greater coastline erosion.

The effect of the longshore sediment transport gradients on the simulated development of the coastline is shown in Figure 3.3. The figure shows a gradual accretion of the coast at the sea-dike end of the model (x = 0–1000m), which takes place in the model prior to the large-scale nourishments in that area in 2008. The figure furthermore shows that the protrusion in the coastline at Domburg (x = 2500–3500 m) is not maintained in the model simulation, and that the coast at Oostkapelle end of the domain (x = 4000–6000 m) gradually retreats over the simulation period. The result of these changes in the shoreline is a general smoothing of the entire coast surrounding Domburg. The results show that the simulated coastline development in the Reference simulation of Phase III shows no substantial improvement over the simulated coastline development in Phase II.

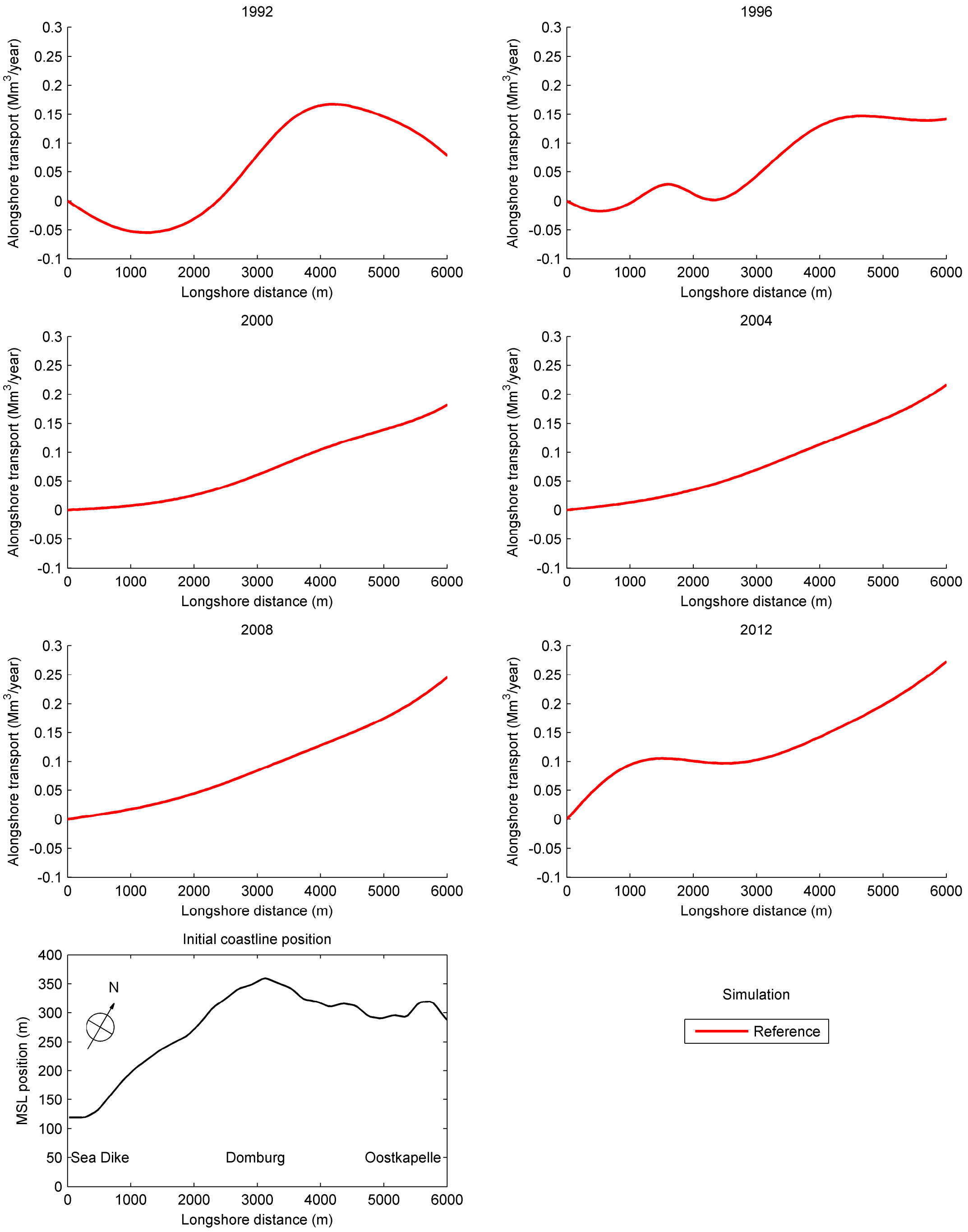


Figure 3.2 Longshore transport computed in the 'Reference' scenario

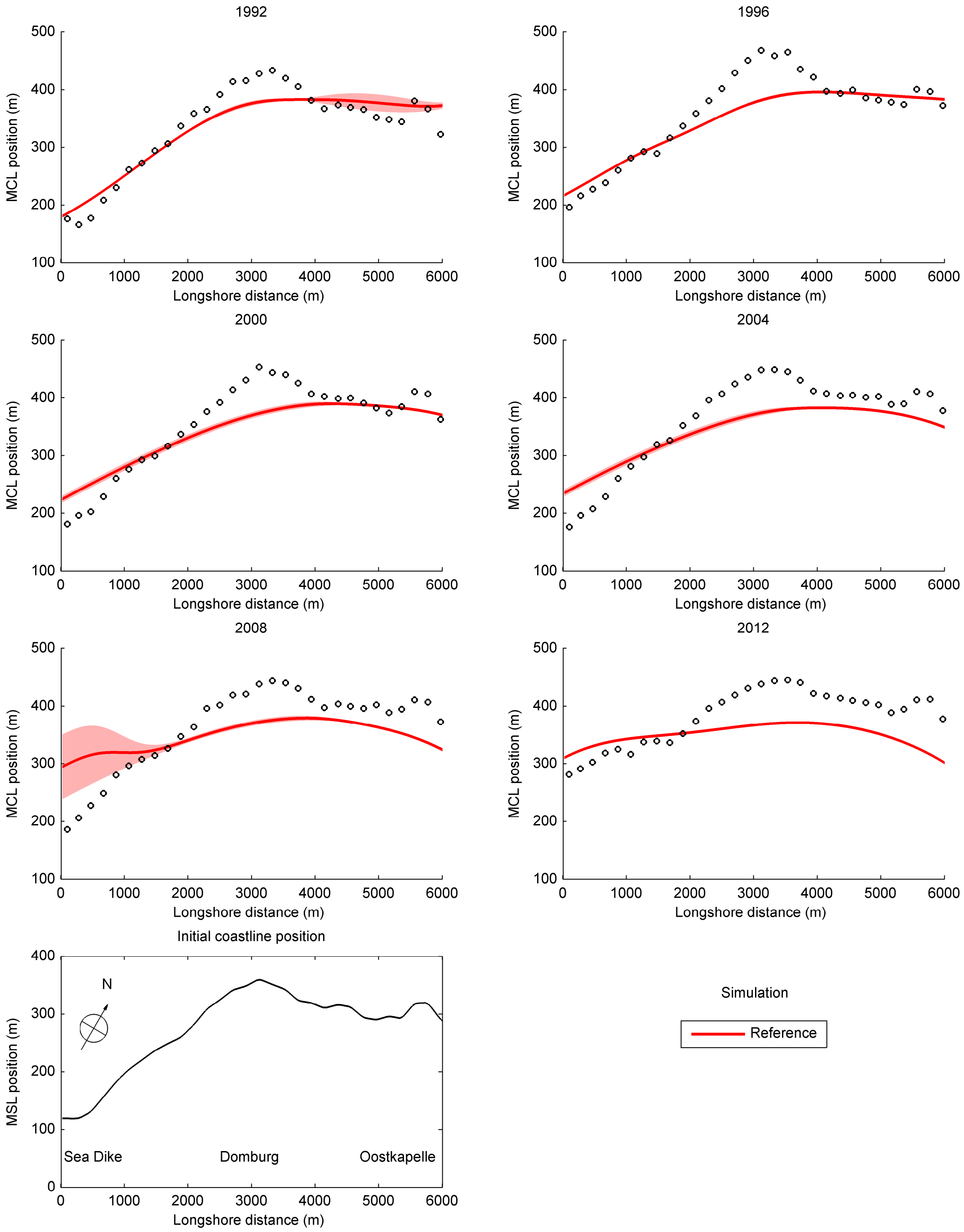


Figure 3.3 Measured MCL-position (circles) and MCL-position computed in the 'Reference' scenario (solid line). Shaded areas indicate the spread in the computed shoreline position from the start to the end of the year (mainly due to nourishments).

3.3.2 Deep sensitivity simulation (U1)

Figure 3.4 shows simulated longshore sediment transport rates in the Reference simulation (U0) and the Deep sensitivity simulation (U1) for six points in time. The figure shows comparable transport rates in both simulations for the coast to the south-west of Domburg (x = 0–3000 m). Transport rates computed in the Deep sensitivity simulation at the coast near Oostkapelle (x = 4000–6000 m) are smaller than those computed by the Reference simulation. This indicates that UNIBEST-CL+ is sensitive to changes in the shape of the profile imposed in this area in the Deep sensitivity simulation, compared to the Representative profile imposed in the Reference simulation. In the remaining computational domain, the difference between the shape of the profile in the Deep sensitivity simulation and the Reference simulation are less substantial, leading to lesser differences in the computed longshore transport rates.

The simulated coastline development in the Reference simulation and the Deep sensitivity simulation are shown together in Figure 3.5. The figure shows similar coastal accretion in at the sea-dike end of the model (x = 0–1000 m) and coastal retreat around Domburg (x = 1000–3500 m) between both simulations. However, the coastline near Oostkappele (x = 4000–6000 m) accretes slightly in the Deep sensitivity simulation, rather than retreats as in the Reference simulation.

The results of this sensitivity simulation show that including longshore variation in the cross shore profile shape do improve the prediction of the coastline development in the north-eastern section of the model domain (x = 4000–6000 m), but that this modification is not sufficient to reproduce the coastline development at Domburg (x = 2500–3500 m), or the coastline development at the sea-dike section of the model (x = 0–1000 m).

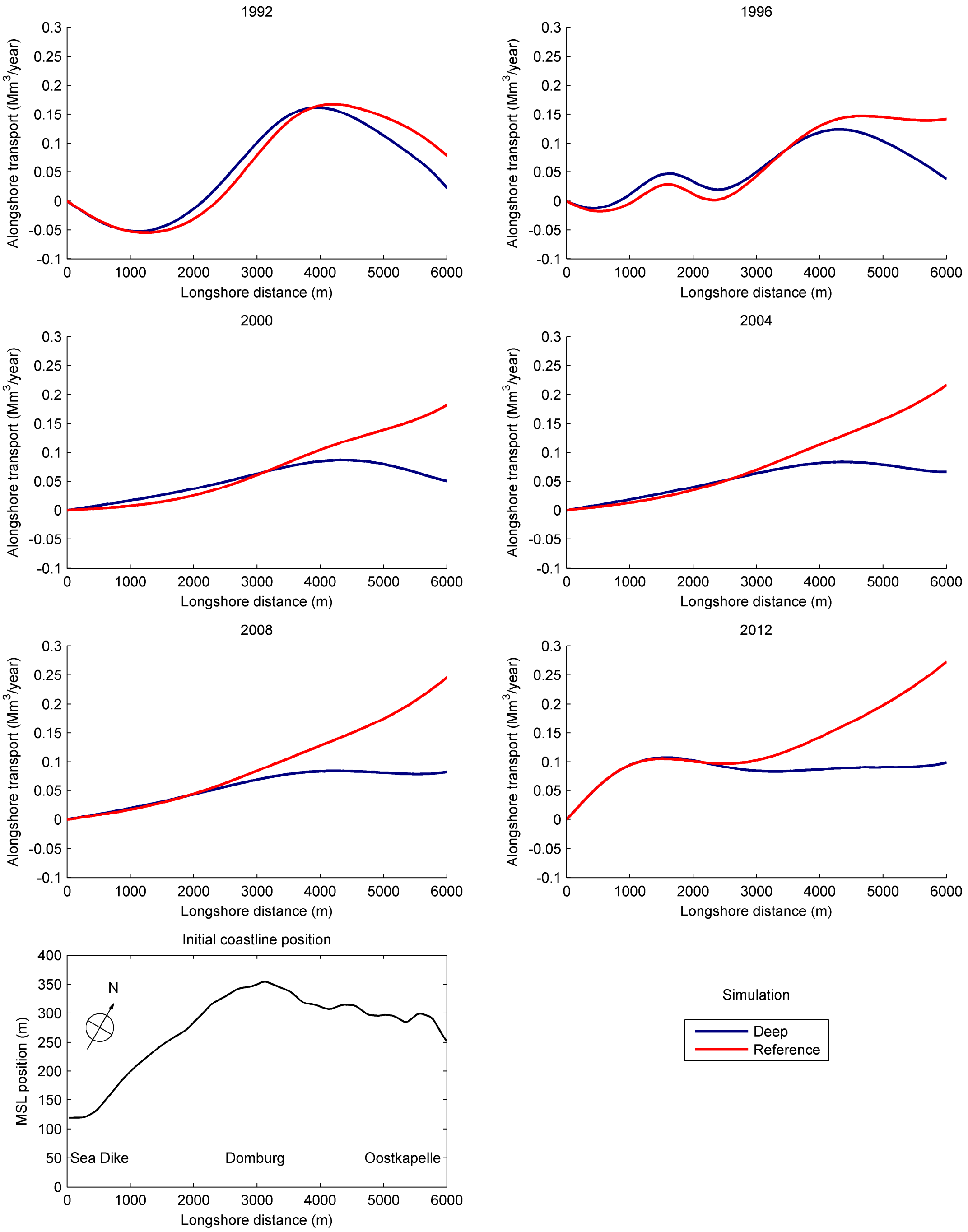


Figure 3.4 Longshore transport computed in the reference 'Deep' scenario (blue) and the 'Reference' simulation (red).

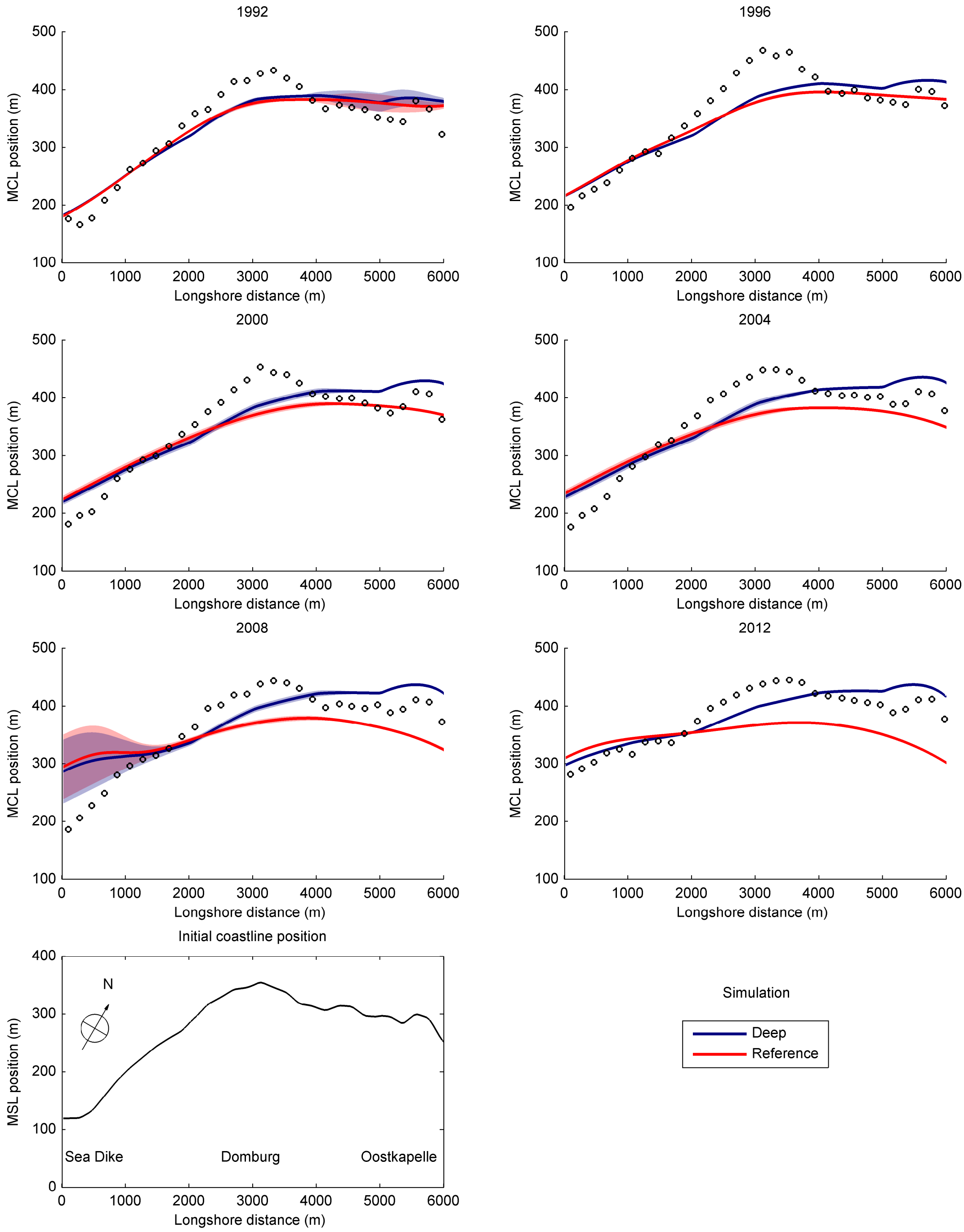


Figure 3.5 MCL-position computed in the reference 'Deep' scenario (blue) and the 'Reference' simulation (red). Shaded areas indicate the spread in shoreline position from the start to the end of the year (mainly due to nourishments).

3.3.3 Shallow sensitivity simulation (U2)

The simulated longshore sediment transport rates of the Shallow sensitivity simulation (U2) and the Deep sensitivity simulation (U1) are shown together for six points in time in Figure 3.6. The figure shows a considerable difference in computed transport rates between the two sensitivity simulations. Firstly, all computed transport rates in the Shallow sensitivity simulation are positive (directed towards the north-east), whereas the transport rates in the Deep sensitivity simulation vary between positive and negative values. Secondly, sediment transport rates in the Shallow sensitivity simulation are relatively uniform in longshore direction in the initial stages of the model simulation (i.e. 1992), thereby leading to lower initial longshore sediment transport gradients than in the Deep sensitivity simulation. This is particularly relevant in the area around Domburg (x = 2500–3500 m), where in the Shallow sensitivity simulation the initial longshore transport gradient is relatively small, whereas that in the Deep sensitivity simulation is relatively large.

The simulated coastline development in the Shallow sensitivity simulation and Deep sensitivity simulation are shown together in Figure 3.7. The figure shows that the lesser transport gradients around the coastal protrusion at Domburg identified above in the Shallow sensitivity simulation lead to substantially less coastal retreat, and in some years to coastal accretion, than in the Deep sensitivity simulation. The predicted coastal evolution at Domburg in the Shallow sensitivity simulation is significantly more accurate than that predicted by the Deep sensitivity simulation. The figure also shows that the coastline at the sea-dike end of the model domain (x = 0–1000 m) erodes in the Shallow sensitivity simulation, rather than accretes as in the Deep sensitivity simulation. Finally, the simulated development of the coast near Oostkapelle (x = 4000–6000 m) is better reproduced by the Shallow sensitivity simulation, than the Deep sensitivity simulation.

The results of this sensitivity simulation show that in the case of UNIBEST-CL+, more superior predictions of the coastline development are achieved by applying longshore-varying nearshore wave climates. In particular, the results show that the coastal protrusion at Domburg (x = 2500–3500 m) is maintained, rather than eroded, and the coast at Oostkapelle (x = 4000–6000 m) is maintained, rather than accreted, if nearshore wave climates are used.

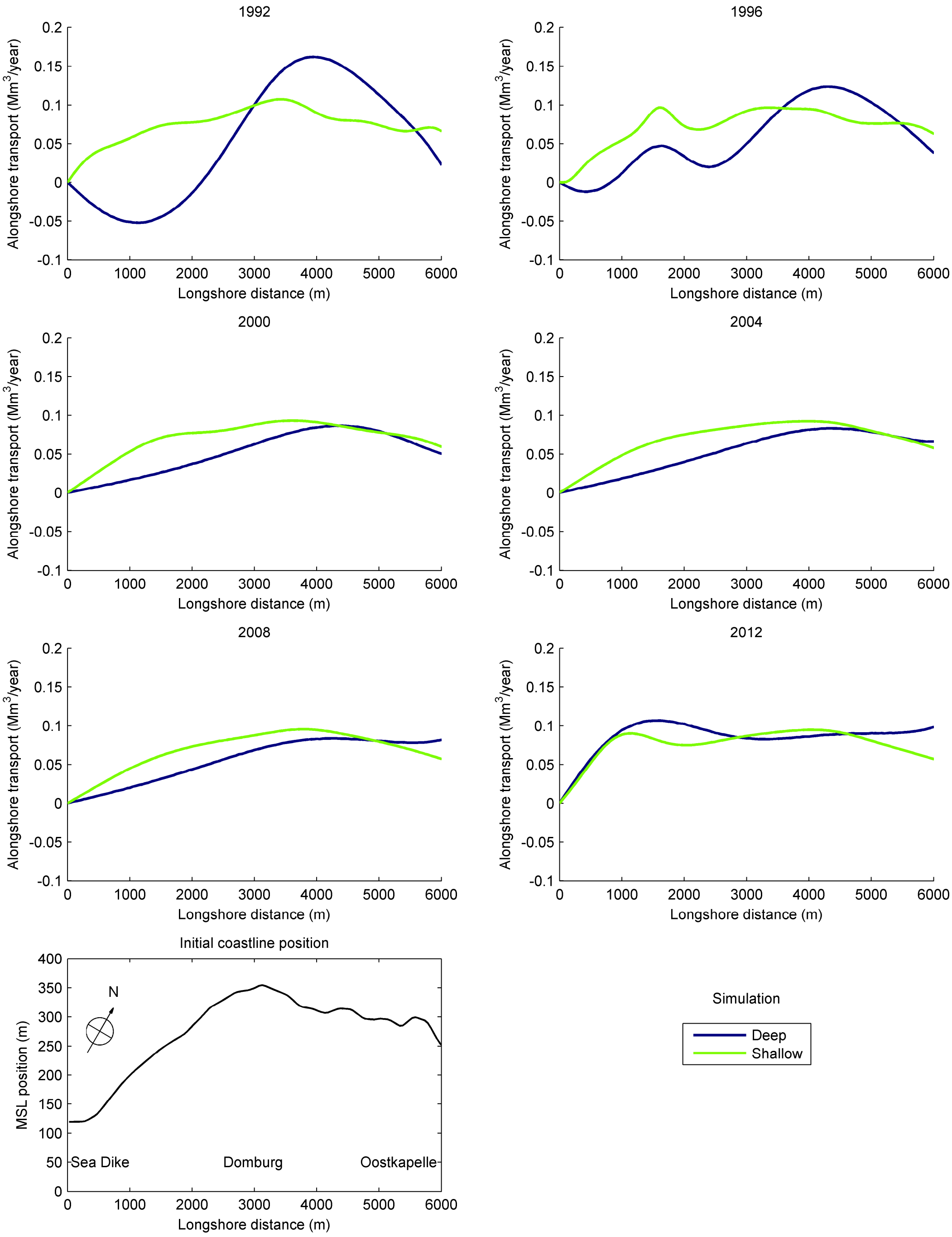


Figure 3.6 Longshore transport computed in the reference 'Deep' sensitivity simulation (blue) and the 'Shallow' sensitivity simulation (green).

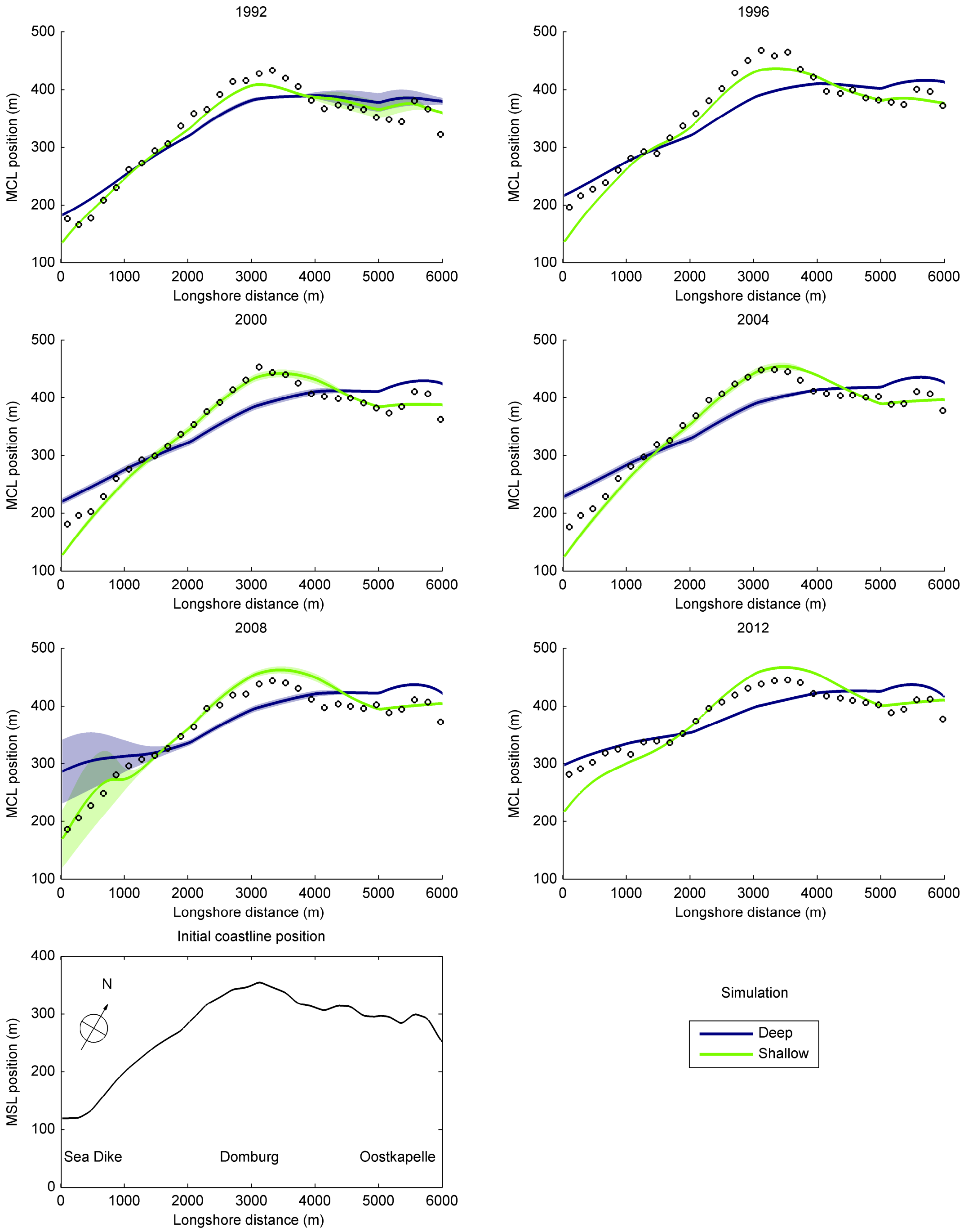


Figure 3.7 MCL-position computed in the reference 'Deep' sensitivity simulation (blue) and the 'Shallow' sensitivity simulation (green). Shaded areas indicate the spread in shoreline position from the start to the end of the year (mainly due to nourishments).

3.3.4 Shallow Representative sensitivity simulation (U3)

Figure 3.8 shows longshore sediment transport rates computed in the Deep sensitivity simulation (U1), the Shallow sensitivity simulation (U2) and the Shallow Representative sensitivity simulation (U3) for six points in time. The figure shows only minor differences between the results of the Shallow sensitivity simulation and the Shallow Representative sensitivity simulation compared to those of the Deep sensitivity simulation. This implies that although the shape of the cross shore profile above a depth of MSL-5m does affect the predicted longshore transport rates, these differences are substantially smaller than those caused by the application of longshore-varying nearshore wave climates.

The conclusion given above is supported by the predicted coastline development in the three sensitivity simulations shown in Figure 3.9. This figure shows little difference in the coastline development predicted by the Shallow sensitivity simulation and the Shallow Representative sensitivity simulation. The figure does not show any considerable improvement in the predicted coastline development in the Shallow sensitivity simulation (with longshore-varying cross shore profiles) compared to the Shallow Representative sensitivity simulation (without longshore-varying cross shore profiles).

The results of this sensitivity simulation show that the UNIBEST-CL+ model is relatively insensitive to the shape of the cross shore profile above a depth of MSL-5m, as long as the wave climate at a depth of MSL-5m is correctly computed using the SWAN wave model.

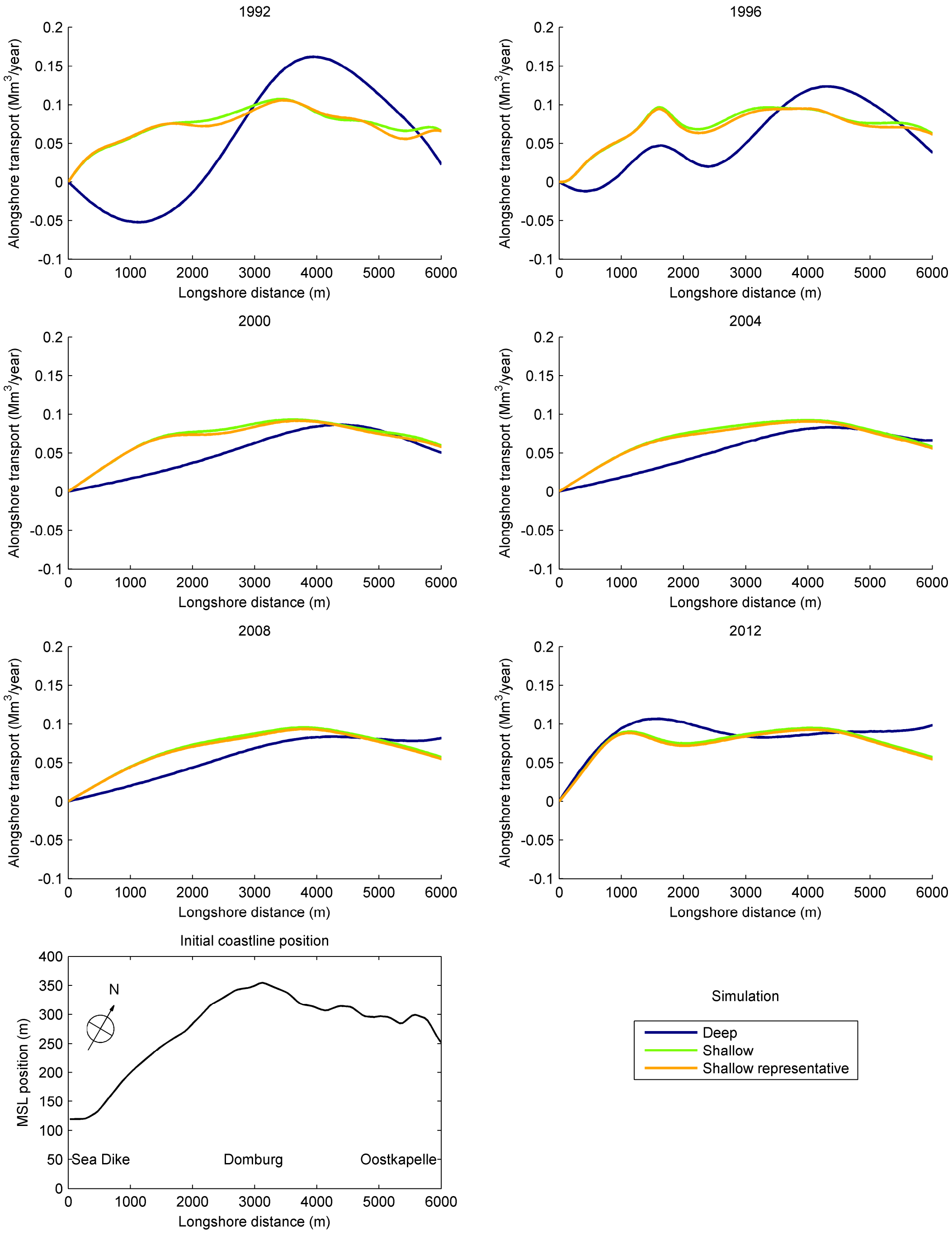


Figure 3.8 Longshore transport computed in the reference 'Deep' sensitivity simulation (blue), the 'Shallow' sensitivity simulation (green) and the 'Shallow representative' sensitivity simulation (orange).

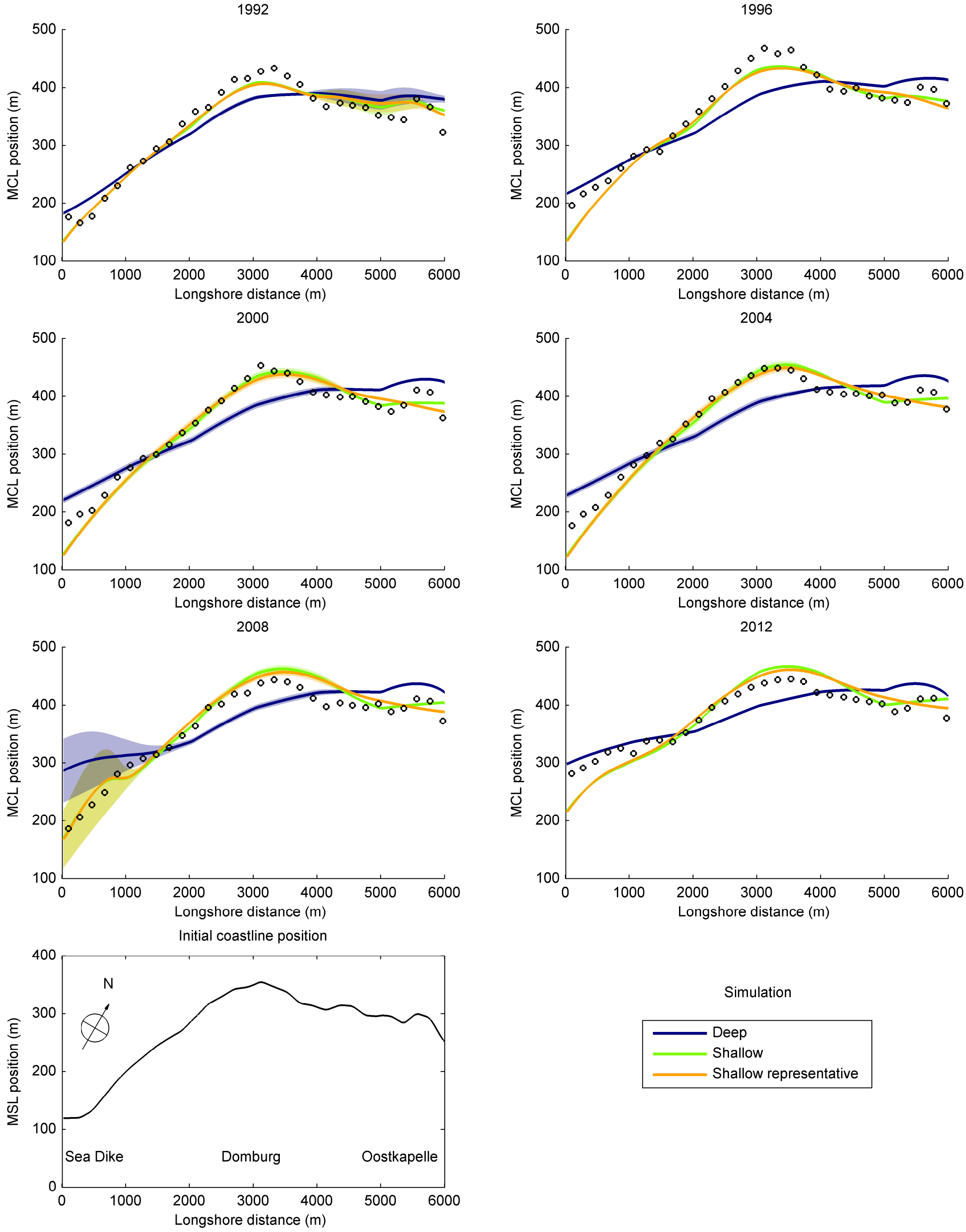


Figure 3.9 MCL-position computed in the reference 'Deep' sensitivity simulation (blue), the 'Shallow' sensitivity simulation (green) and the 'Shallow representative' sensitivity simulation (orange). Shaded areas indicate the spread in shoreline position from the start to the end of the year (mainly due to nourishments).

3.3.5 Shallow with Tide sensitivity simulation (U4)

Sediment transport rates computed in the Shallow sensitivity simulation (U2) and the Shallow with Tide sensitivity simulation (U4) are shown for six moments in time in Figure 3.10. The figure shows that the inclusion of vertical and horizontal tide in the Shallow with Tide sensitivity simulation increases the longshore sediment transport rate by approximately 10% in north-easterly direction, except at the sea-dike end of the model (x = 0–1000 m).

Although the longshore sediment transport rate is increased by the inclusion of tidal forcing, the computed longshore transport gradients are not altered to a great degree, as shown by the similarity in the computed coastline evolution between the two sensitivity simulations shown in Figure 3.11.

The results of this sensitivity simulation show that the inclusion of tidal forcing in the UNIBEST-CL+ simulation increased the computed longshore sediment transport rate by approximately 10%, but that this does not significantly improve the predictions of the development of the coast of Walcheren.

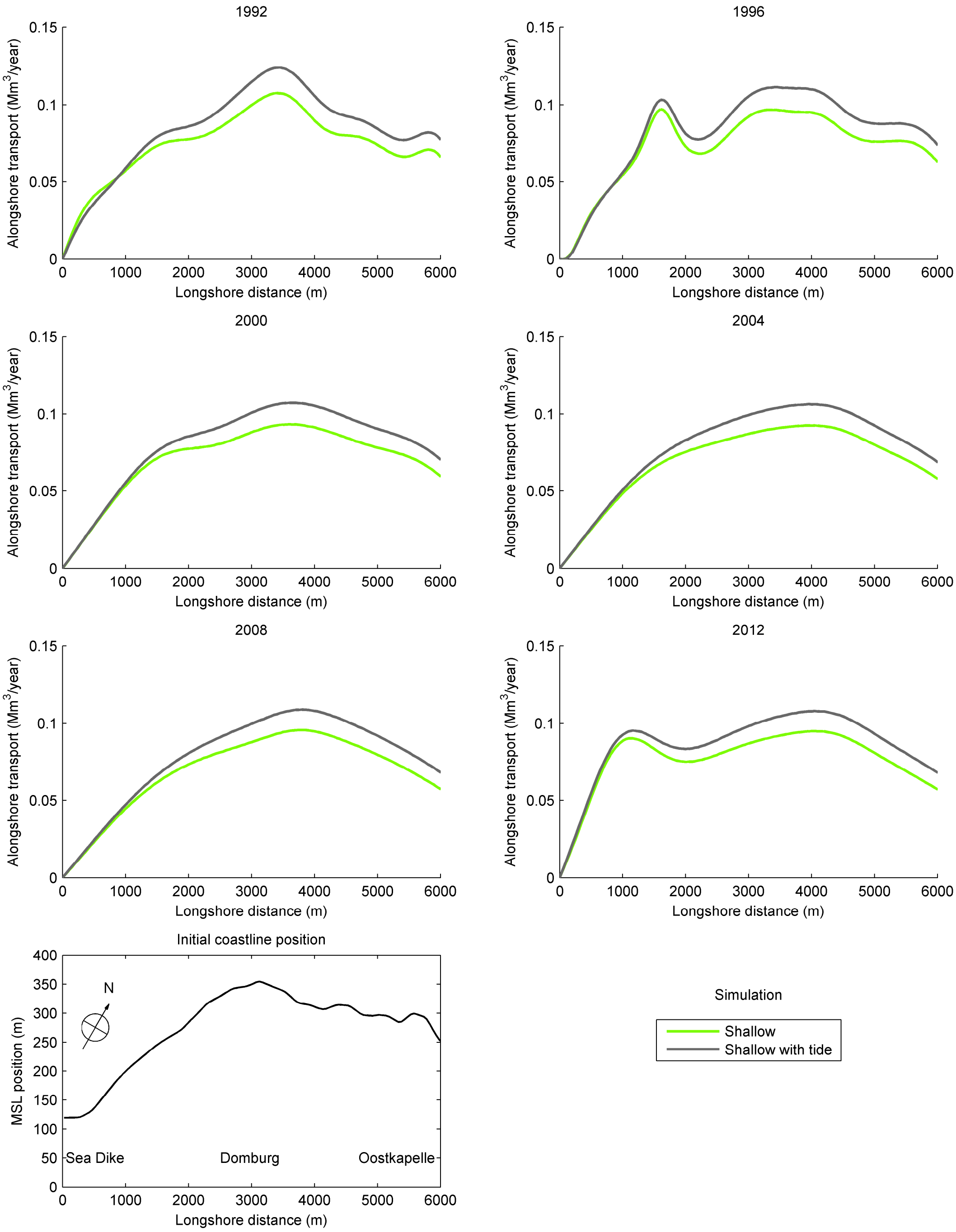


Figure 3.10 Longshore transport computed in the reference 'Shallow sensitivity simulation (green) and the 'Shallow with tide' sensitivity simulation (grey).

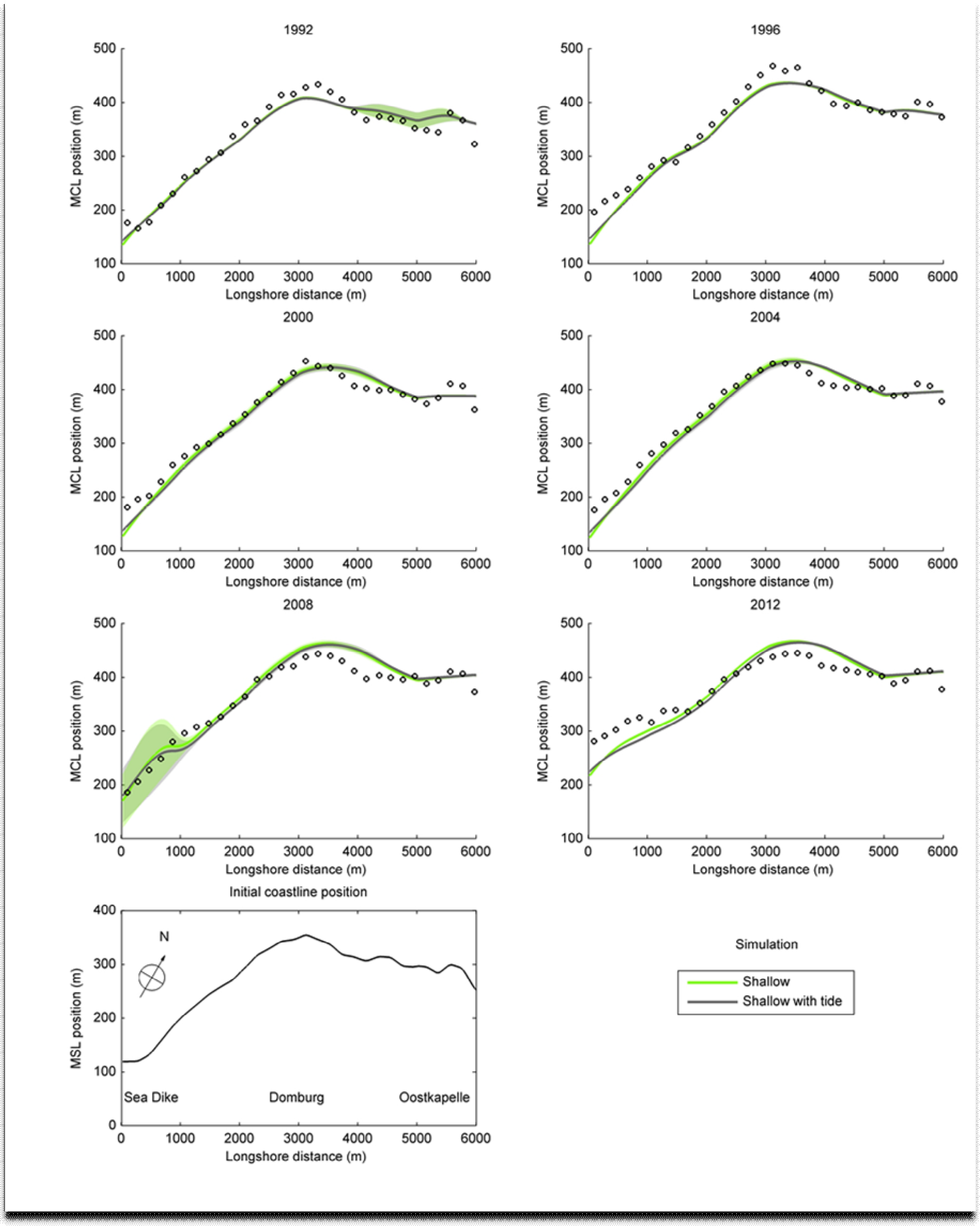


Figure 3.11 MCL-position computed in the reference 'Shallow sensitivity simulation (green) and the 'Shallow with tide' sensitivity simulation (grey). Shaded areas indicate the spread in shoreline position from the start to the end of the year (mainly due to nourishments).

3.3.6 Shallow with Flux sensitivity simulation (U5)

Figure 3.12 shows the longshore sediment transport rate computed in the Shallow sensitivity simulation (U2) and the Shallow with Flux sensitivity simulation (U5) for six points in time. The figure shows a significant increase in the computed longshore transport rate at the sea-dike end of the model in the Shallow with Flux sensitivity simulation, compared to the Shallow sensitivity simulation. This difference ranges from the imposed boundary condition flux of 30,000m^3/year at the model boundary to zero difference between the simulations at approximately x = 1000–2000 m. There are no appreciable differences in the computed longshore sediment transport rates for the coast to the north-east of Domburg (x = 2500–6000 m).

The coastline development computed by the two sensitivity simulations is shown in Figure 3.13. The figure shows that the effect of imposing 30,000m^3/year sediment influx at the sea-dike boundary (x = 0 m) leads to less erosion of the coastline near the sea-dike boundary in the Shallow with Flux sensitivity simulation than in the Shallow sensitivity simulation, thereby producing a more accurate representation of the measured coastline development in that area. The coastline development at Domburg (x = 2500–3500 m) and at Oostkapelle (x = 3500–6000 m) is not affected by the change in the lateral boundary condition between the two sensitivity simulations.

The results of this sensitivity simulation show that the imposition of an estimate of the sediment flux at the sea-dike boundary (x = 0 m) of the UNIBEST-CL+ of 30,000m^3/year leads to better predictions of the coastline development between the sea dike and Domburg (x = 0–2500 m), without affecting the remaining model domain.

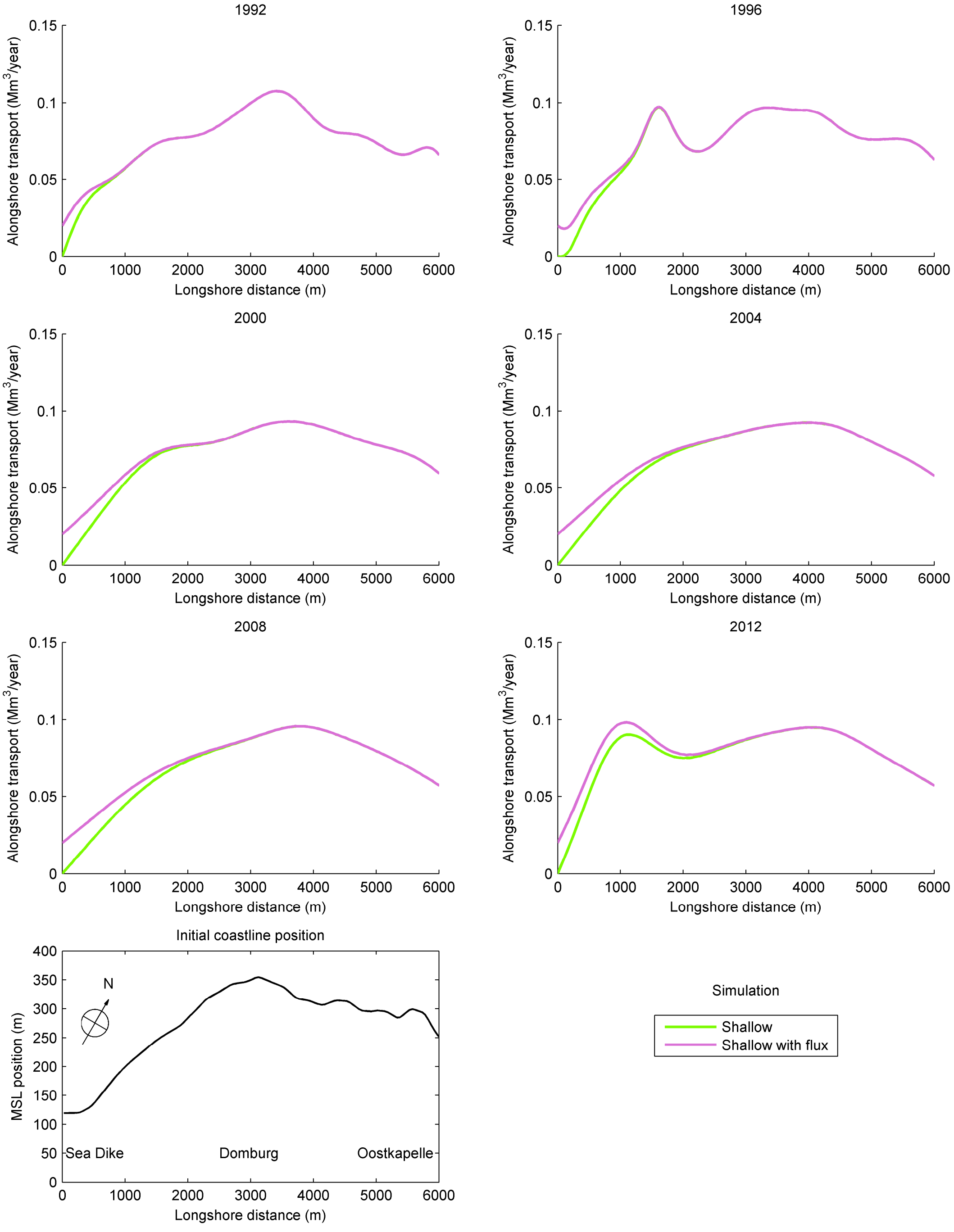


Figure 3.12 Longshore transport computed in the reference 'Shallow sensitivity simulation (green) and the 'Shallow with flux' sensitivity simulation (magenta).

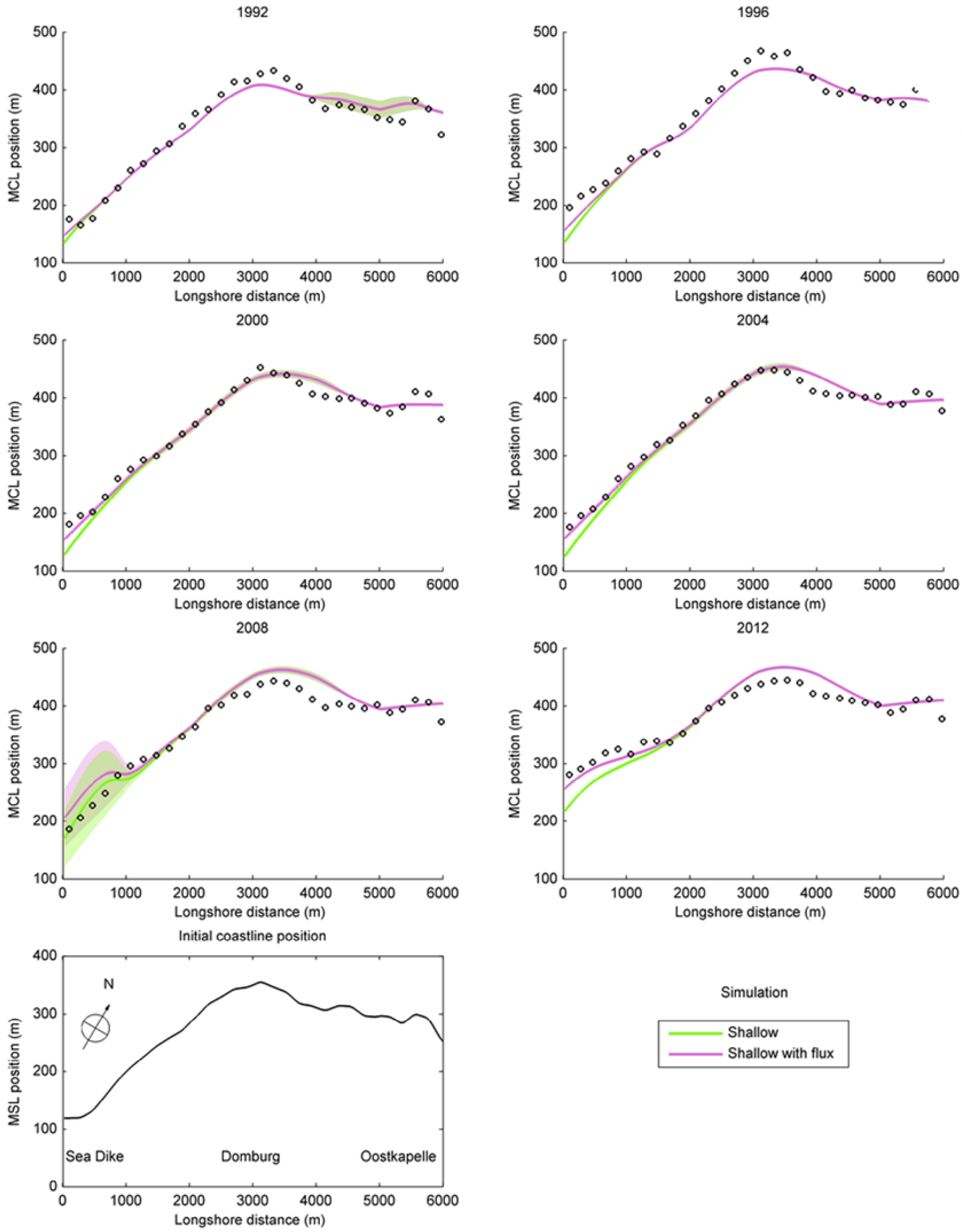


Figure 3.13 MCL-position computed in the reference 'Shallow sensitivity simulation (green) and the 'Shallow with flux' sensitivity simulation (magenta). Shaded areas indicate the spread in shoreline position from the start to the end of the year (mainly due to nourishments).

3.4 Analysis

The results of all the sensitivity simulations discussed in this chapter have shown that the greatest improvement to the simulated coastline development of the coast of Walcheren in UNIBEST-CL+ is achieved by the application of longshore-varying nearshore wave climates, instead of applying the offshore wave climates. This improvement is thought to be due to the fact that the SWAN model used to compute the nearshore wave climates allows for the correct transformation of offshore wave conditions to the shore, taking in to account the complex bathymetry of the foreshore of Walcheren. On the other hand, if the offshore wave climate is imposed directly in the UNIBEST-CL+ model, the wave transformation from offshore to nearshore is carried out using a more simple, cross-shore wave model that cannot account for the spatial complexity of the foreshore bathymetry.

In the case of the coast of Walcheren, wave refraction and focussing across the foreshore is sufficiently large to affect the nearshore wave climate and longshore transport gradients. The effect of the complex bathymetry of the foreshore may be lesser in areas where the foreshore is more longshore uniform, for instance for stretches of the Holland coast. In these cases, smaller differences are expected to occur between UNIBEST-CL+ models forced by offshore wave climate data and those forced by nearshore wave climate data.

3.5 Conclusions

This chapter has focussed on identifying the effect of the inclusion of detailed physical processes and boundary conditions in UNIBEST-CL+ on the simulated coastline development at Domburg. This analysis has been carried out in an exploratory manner, with sensitivity simulations of increasing complexity. The main conclusions of this analysis are summarised below:

- The application of longshore-varying nearshore wave climates in the UNIBEST-CL+ model greatly increases the accuracy of the simulated coastline development. (Sensitivity simulation U2).
- The application of longshore-varying profiles in the UNIBEST-CL+ models, without applying longshore-varying wave climates does not improve model predictions of the coastline development at Domburg and improves the prediction of the coastline development at Oostkapelle a little. (Sensitivity simulation U1).
- The effect of including longshore-varying cross shore profiles is small compared to the use of longshore uniform profiles in the UNIBEST-CL+ model if nearshore wave climates are applied. (Sensitivity simulation U3).
- The effect of including horizontal and vertical tidal motions in the UNIBEST-CL+ model is to increase the longshore transport rate by approximately 10%. This does not substantially alter the predicted coastline development. (Sensitivity simulation U4).
- Model predictions of the coastline development between the sea-dike of Westkapelle and Domburg can be improved by imposing a sediment influx at the model boundary. This condition does not affect the coastline development to the north-east of Domburg. (Sensitivity simulation U5).

It should finally be noted that although some of the sensitivity simulations carried out with the UNIBEST-CL+ model have led to reasonably accurate representations of the measured coastline development at Domburg, no calibration of the model has been carried out to improve the model results further.

4 PONTOS modelling

4.1 Introduction

This chapter describes the model setup and results of the PONTOS model for the coast of North Walcheren for the period from 1990 to 2012.

Background

In many coastal engineering projects process-based coastline models are used to predict the (long-term) effect of natural and anthropogenic changes on coastlines. In the past decade several coastal evolution models were used to assess the effects of coastal reinforcements and (large) nourishments along the Dutch Coast. For example, in the context of so-called ‘Zwakke Schakel’-projects in the Netherlands, coastline models were used to predict the nourishment volumes required to maintain ‘strengthened’ parts of coastal sections. In these projects it became evident that relatively large differences exist between the predictions made by different coastline models.

In order to understand why (and when) the observed differences occur between some of these coastline models, it is essential to understand how each of the models work. By gaining more insight in the capabilities of the various models, it is possible to identify (and subsequently deal with) the fundamental differences. The information about the models can also be used to improve them, and to extend their applicability in different types of projects regarding coastal zone management.

In 2012 a project has been initiated by Rijkswaterstaat Waterdienst that aims at gaining more insight in the observed differences between three commonly used models (UNIBEST-LT/CL, PONTOS, and LONGMOR). In close collaboration Deltares and ARCADIS already studied the fundamental differences between the coastline models. In two previous project phases model comparisons are made, based on both schematic test cases (Phase I) and a more specific case study for the coastal area near Domburg (Phase II). The results of both project phases are presented in the report “Modelling coastline maintenance; a review of three coastline models” [Deltares/ARCADIS, 2013].

In 2013 a third project phase has been started, in which the case study ‘Domburg’ is considered in more detail. The schematic model approach in Phase II was useful to enable one-to-one comparisons between the three considered coastline models, but the approach is insufficient to make use of the full potential of all models. In Phase III of the project the case study ‘Domburg’ is considered again, but in contrast to the previous two phases this phase focusses on individual improvements of the model setups. For both UNIBEST-LT/CL and PONTOS specific functionalities are studied in more detail. The main goal of these elaborations is to obtain well-supported results from the modelling of coastline evolution near Domburg, using the specific strengths of both models.

This chapter describes the analyses and results of the modelling work that is performed with the coastline evolution model PONTOS.

Main objectives

The main objective of Phase III of this project is to gain more insight in the essential aspects of coastline modelling that are required to obtain decent estimates of (the rate of) coastline changes and coastal maintenance requirements. In this case the coastal area near Domburg is considered, for which simulations are performed with two commonly used coastline models: UNIBEST-LT/CL and PONTOS.

The objective of this specific chapter is to provide an overview of all steps that are taken in order to improve the original PONTOS model setup that was used for case study ‘Domburg’ in Phase II, and to give a best-possible estimate of the coastline evolution near Domburg.

Approach
In this study the original Phase II model setup (previous project phase) is used as a starting point for further enhancement of the coastline model for Domburg. First, some minor modifications are made to the original model setup in order to study the influence of some model aspects that already were included in the original model setup. Subsequently, a renewed Phase III model is built that differs more significantly from the original setup. For the Phase III model alongshore varying (relative) layer positions are considered that are determined on the basis of analyses of detailed bathymetric data of the study area. Later on, the Phase III model is further enhanced by imposing multiple nearshore wave climates, and by calibration of some of the essential model parameters. Afterward, a comparison is made between the enhanced Phase III model and the original Phase II model.

Phase II model - Original slightly updated model
Phase III models - Alongshore varying layer positions - Multiple nearshore climates / calibration of model paramters

Figure 4.1 Overview of PONTOS model runs

Finally, all relevant information that is gathered during the process of model building is combined in order to draw conclusions about the essential aspects of the PONTOS model that enable decent modelling of the coastline evolution near Domburg.

4.2 Model setup

This section describes the most important aspects of the model setup for the PONTOS model that was used in the Phase III modelling of coastline evolution near Domburg. Firstly, the datasets are presented that were used to setup and calibrate the model (Section 4.2.1). Secondly, the basic settings of the (enhanced) model setup are described (Section 4.2.2). And finally, a brief summary is provided of differences and similarities between the Phase II and Phase III model setups (Section 4.2.3).

4.2.1 Data needed to setup and calibrate the model

The data required to set-up a PONTOS-model for the Domburg concerns:

- bathymetric and topographic data,
- coastline positions,
- nourishment information,
- wave and flow conditions,
- estimates of transport fluxes at the model boundaries.

These data are described in Chapter 2.

4.2.2 Basic model setup

This section describes the basic model settings that are used for simulations of coastline evolution near Domburg. The primary objective for this aspect of the study is to set-up a PONTOS model that is able to simulate coastline development such that the results closely resemble observed coastline changes. The basic model setup thus consists of a realistic schematization of measured profiles in coastal area, a nourishment scheme with ‘real’ nourishments, and representative estimates for the hydraulic conditions.

In the following the most important aspects of the basic model setup are described in more detail. For some specific model settings that (may) change during the process of model building only brief description are provided, since these settings are discussed in more detail in the next chapter (“simulations / results”).

Time definition

The model simulations in Phase III are performed for two different periods. The basic model setup focusses on the most recent period, 1990 – 2012, during which several nourishments took place. The year 1990 is chosen as starting point for the simulations for the reason that in 1990 a so-called Basis KustLijn (BKL or BCL) is set for the Dutch Coast, which is a theoretical “minimal” coastline position that should at least be maintained. Since 1990 nourishments take place on a regular basis along the coast, to ensure that the MCL position does not exceed the minimal BCL position.
In contrast to the runs in Phase II of the project, the end time of the simulations is set at the end of 2012, instead of 2009. The main reason for changing the end time is the fact that some large nourishments are carried out in 2008, just before the end of the original end time. By extending the simulation time, the end results of the simulations are less affected by recently added nourishment volumes. It is noted that the 2012 nourishment is not implemented in the model since it is not included in the Jarkus measurements for 2012.

In addition to the period-of-interest (1990 – 2012), also the period from 1976 up to 1988 is considered, for a series of simulations that is used for calibrating the PONTOS model. The additional period is selected for the fact that no nourishments took place in the study area during that period (except for dune reinforcements at one specific location, southwest of Domburg). The model settings regarding the time definition (simulation periods) are summarized in Table 4.1.

Table 4.1 Summary of the considered simulation periods.

Type of simulation	Start of simulation	End of simulation
Phase II	1990	2009
Phase III (incl. nourishments)	1990	2012
Phase III (excl. nourishments)	1976	1988

Grid definition

For PONTOS the grid definition for the model setup is divided in two parts: a horizontal grid and a vertical grid. The latter is typical for multi-layer coastline models, since in this type of models the vertical layer distribution determines the thickness of the vertical layers that can develop individually.

<u>Horizontal grid</u>

The horizontal grid definition that is used to setup the coastline model is identical to the grid that is used in Phase II. A so called “reference line” is set along the coastal stretch to define the basis of the models local coordinate system. The origin of the local grid is located at RD-coordinate: Xrd = 21278 m, Yrd = 397328 m. The reference line has a length of 9000 m, and the (constant) coastline orientation equals 59.56° w.r.t. North directed along coast (see Table 4.2). The coastline normal is thus defined in the direction 329.56°. Note that the PONTOS reference line is also shown in Figure 2.3.

Table 4.2 Definition of the so-called “reference line” in the PONTOS model.

X_{RD} -coordinate	Y_{RD} -coordinate	Coastline orientation	Alongshore length
21278.0	397328.0	59.56° N	9000 m

<u>Vertical grid (layer distribution)</u>
The coastline model PONTOS is a multi-layer model that consists of five vertical layers (Y0 – Y4). Layer Y0 is referred to as the “dune-layer”, Y1 is the “beach-layer”, Y2 is the “foreshore-layer”, and Y3 + Y4 are considered as the “lower layers” or offshore layers. By default, the vertical grid extends from the (representative) dunetop level towards a minimum level at NAP -20 m. In this specific case study a more complex bathymetry is found, such that it is decided to redefine the original layer levels. The adjusted layer definition is such that the minimum level is set at NAP -15 m, and that the combination of layers Y1 and Y2 is similar to the layer definition of the BCL (Basis KustLijn).

In Table 4.3 the original and adjusted layer levels are presented that are used in this project. The original levels were used for the model setup in Phase II, while the adjusted levels are introduced for the renewed model setup in the current project phase (Phase III).

Table 4.3 Overview of the upper- and lower- bounds of the five vertical layers in the PONTOS model (Y0 – Y4). Both the original *definition and an* adjusted *definition are considered in this study.*

Layer ID	Layer name	Original layer levels		Adjusted layer levels	
		Upper level	**Lower level**	**Upper level**	**Lower level**
Y0	***Dune layer***	**var.**	**3**	**var.**	**3**
Y1	***Beach layer***	**3**	**-2**	**3**	**-1.5**
Y2	***Foreshore layer***	**-2**	**-7**	**-1.5**	**-6**
Y3	***Lower layer 1***	**-7**	**-13**	**-6**	**-10.5**
Y4	***Lower layer 2***	**-13**	**-20**	**-10.5**	**-15**

Layer positions
The definition of layer positions is one of the most essential aspects for setting up a coastline model. For a one-line model, such as UNIBEST-CL, only the initial coastline-position (1 line/layer) is required as input, while for a multi-layer approach initial layer positions are needed for each of the vertical layers. Specifically for PONTOS, five layer positions (Y0 – Y4) are defined per cross-shore profile at each alongshore location.

In Figure 4.2 an example is presented for the definition of layer positions, based on the adjusted layer levels and the “reference profile” that was used during Phase II of the project. As shown in the figure, the layer positions are determined by a volumetric approach that is similar to the one used for the determination of a MCL-position (see: “Leidraad Zandige Kust”). It should be noted that, in this project phase, the MCL-position can be approximated by averaging the layer positions for Y1 and Y2.

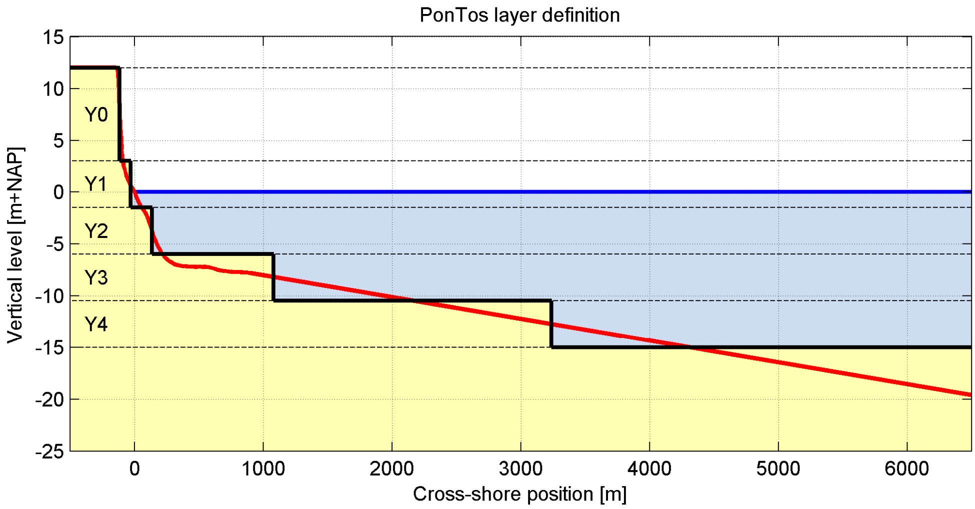


Figure 4.2 Example of the definition of layer positions for the PONTOS model, based on a prescribed cross-shore profile.

In contrast to Phase II, the definition of layer positions for this third project phase is based on alongshore variations in measured cross-shore profiles, rather than a fixed profile-shape. In Phase II an alongshore variation of layer positions was imposed by relating the relative layer positions of the “reference profile” to an alongshore varying coastline position (Mean Sea Level-line). The basic idea for Phase III is that not the actual coastline position is prescribed, but that for a large series of locations along the coastline individual layer positions are determined from measured coastal profiles.

<u>Definition of layer positions (Y0, Y1, Y2)</u>
Figure 4.3 presents the ‘raw’ output of analyses of layer positions for the coastal area near Domburg. The figure shows the calculated positions for layers Y0, Y1 and Y2 along the model’s reference line, for each year in the period 1970 – 2012 (grey lines). Three specific years (1975, 1989 and 2012) are shown in color to emphasize the development of each of the layers in time. Similar to Figure 2.4 (that showed MCL-positions w.r.t. RSP-line), also in Figure 4.3 the two distinct coastline protrusions near Domburg (x = 3000 m) and the ‘shore-connected sand ridge’ (x = 6500 – 7500 m) are visible.

The presented layer positions for 1989 are used as input for the basic model setup for PONTOS. The 1975-positions are additionally used as input for the model setup for the ‘no-nourishment’ period 1976 – 1988. Figure 4.3 also shows the (observed) layer positions for the year 2012; this information is not directly used as input for a model setup, but it is used to assess the output of model simulations instead.

Above it is mentioned that this figure shows the ‘raw’ data for the layer position. ‘Raw’ here means that the information is a direct result from the profile analyses. The actual model input is a slightly smoothed version of this ‘raw’ data in order to prevent initial small-scale disturbances in the simulation. For example, the sudden transition in layer position between x = 6000 and x= 6500m is smoothed in the dataset that is included in the model setups.

While the (initial) layer positions are used as direct input for the model simulations, the MCL-positions are determined by the model on the basis of these layer positions, since no “real” cross-shore profile information is processed in the model. For convenience, the ‘real’ MCL information is presented as well (in Figure 4.4), in order to make the dependency between both the layer positions and the MCL-position visible. Comparison between Figure 4.3 and Figure 4.4 shows that the MCL-position is (approximately) equal to the averaged positions of layers Y1 and Y2.

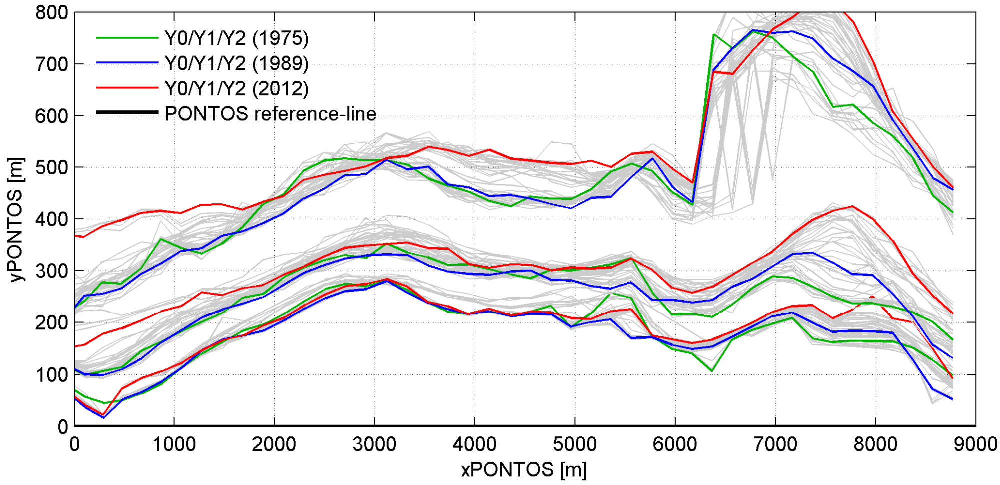


Figure 4.3 Overview of determined layer positions (Y0, Y1, Y2) in the coastal area near Domburg, for all years in the period 1970 – 2012. The layer positions for the years 1975 and 1989 are highlighted because they are used as input for model setups in this study, and 2012 is shown because it is the last year in the considered dataset.

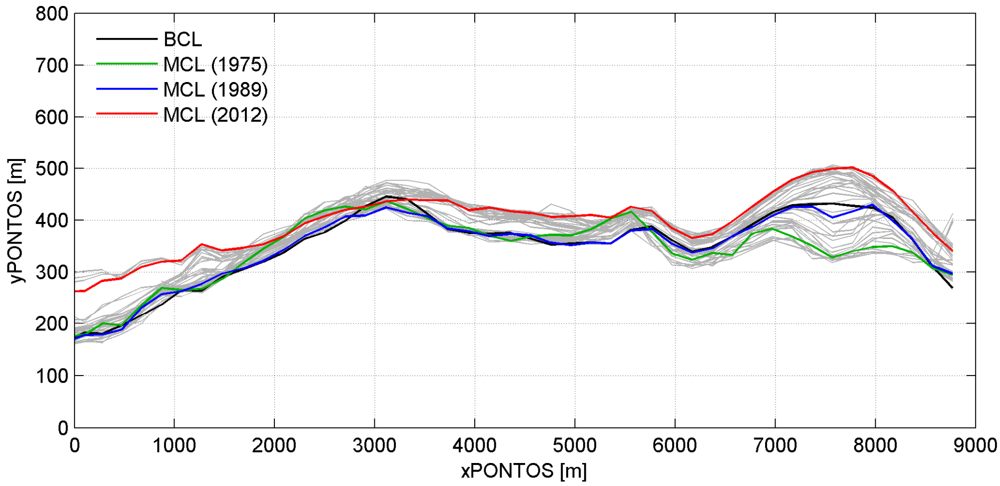


Figure 4.4 Overview of determined MCL-positions in the coastal area near Domburg, for all years in the period 1970 – 2012. The MCL-positions for the years 1975 and 1989 are highlighted because they correspond to the input for model setups in this study, and 2012 is shown because it is the last year in the considered dataset.

<u>Definition of layer positions (Y3, Y4)</u>

Due to the complex bathymetry off the coast near Domburg (see), caused by tidal channels and shoals, it was decided to schematize the position of the deeper offshore layers Y3 and Y4. The main reason for the schematization is the fact that large bed level variations cause problems when determining layer positions based on a volumetric approach. Several methods can be used to define the position of deeper layers, and therefore it is more convenient to apply a basic schematization (under the assumption that these deeper layers do not play a substantial role in the coastline's evolution).

The cross-shore position of layer Y3 is set at a distance of 2500 m from the reference line; without alongshore variations. The position of layer Y4 is set at a "y = 9000 m". These layer positions are both based on analyses of volumes and contour lines for the offshore bathymetry ().

Dune height schematization
In addition to the alongshore varying layer positions in the PONTOS model, also a varying upper level of layer Y0 is implemented in the Phase III model setup. Y0 represents the "dunes" in the model, and unlike all other vertical layers, the thickness of this layer is varied, based on the measured variations in dune height along the coastline.

Figure 4.5 shows the dune height variation along the coastline for each of the years in the period 1970 – 2012. From the dataset one representative dune height variation is selected.

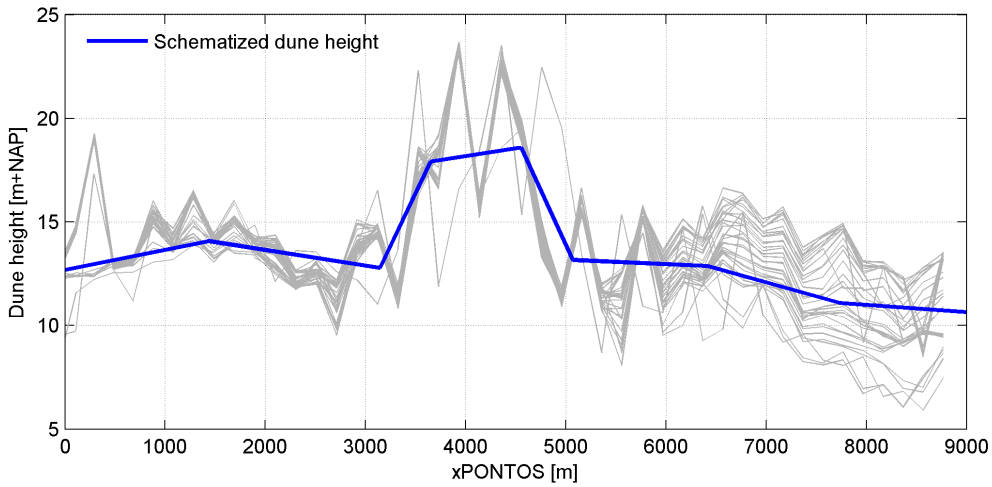


Figure 4.5 Schematization of dune height variations along coastline.

Sediment characteristics
For the model setup of both the Phase II as for the Phase III model, the same sediment characteristics are used. The used sediment grain size is chosen to be constant within the model domain, both in alongshore direction and in cross-shore direction. The imposed grain size (D50) is set at 315 μm.

Wave conditions
For the model simulations in Phase III either offshore wave conditions or nearshore wave conditions are used. The basic model setup consists of one offshore wave climate (which is presented in Figure 2.8). The use of one wave climate implies that alongshore uniform conditions are applied.
For further enhancement of the basic model setup also nearshore wave climates are considered. As a first step, the offshore wave climate is exchanged for one nearshore climate. And as a second step the single nearshore wave climate is exchanged for a series of nine local wave climates along the coastal stretch.

Tidal conditions
In this study no tidal conditions are implemented in the model setups, under the assumption that wave-driven sediment is dominant in the coastal area near Domburg. Some quick test-simulations do confirm that the influence of (schematized) tidal conditions on the coastline evolution near Domburg is indeed limited.

Alongshore transport calibration
In contrast to the previous project phase, the alongshore transport rates are not calibrated in this study. In general, calibration of the alongshore transport rates does affect the speed at which coastline changes take places, but due to the lack of additional information (other than the rough estimates used in the previous study) it is decided to focus on calibration of cross-shore processes instead of calibration of alongshore processes.

Cross-shore transport calibration
One of the primary objectives for the setup of a renewed PONTOS model for Domburg is to determine profound calibration coefficients for the cross-shore processes in the model. In the previous phase of the project the cross-shore transport calibration was underexposed and limited to the basic settings that prescribe that the applied initial (relative) layer positions are in equilibrium state. In the Phase III model alongshore varying (relative) layer positions are considered, such that calibration of the cross-shore processes requires more attention.

In practice cross-shore transport rates are calibrated indirectly, by scaling the calculated “equilibrium layer width” for each of the vertical layers. During simulations cross-shore exchange of sediment between layers is primarily driven by the calculated difference between the “actual layer width” and the “equilibrium layer width”. Cross-shore transport is then used to add or remove sediment from a layer, in order to reduce the difference between the actual layer width and the equilibrium state. In Section 4.3.2 the calibration of “equilibrium layer width” is discussed in more detail.

Lateral boundary conditions
In the Phase III model so-called “open” lateral boundaries are considered, such that sediment transport can take place freely through these boundaries. In the previous study it was decided to “close” the left boundary to force a certain net alongshore transport gradient. Earlier model simulations with PONTOS already showed that the direction of the net alongshore transport might differ per individual vertical layer, and that the net transport is directed towards the left boundary in layer Y1. In order not to “trap” sediment near the lateral boundaries it is decided to “open” them in this study.

Nourishment scheme
In the basic model setup for Phase III a “real” nourishment scheme is imposed for the coastal area near Domburg (see Table 2.1). In addition to the basic model setup, also a similar model is built for the period 1976 – 1988, in which no nourishments took place. Obviously, no nourishment scheme is imposed in that model setup.

4.2.3 Model setup comparison with Phase II model
In an attempt to improve the model setup of the PONTOS model for Domburg several changes are made to the original Phase II model setup. Table 5 summarizes the most important differences between both models. It should be noted that most of the modified model features are discussed stepwise in the next section of this chapter, such that the individual contributions are clear.

Table 4.4 Overview of differences between the original Phase II model, and the basic Phase III model.

Original Phase II model	**Basic Phase III model**
Simulation period: 1990 – 2009	Simulation period: 1990 – 2012
Initial layer position based on MSL 1990	Initial layer position based on MCL 1989
Relative layer positions based on one representative coastal profile	Individual layer positions based on analyses of a large series of coastal profiles
Original definition of vertical layer levels	Adjusted definition of vertical layer levels
Alongshore constant upper level of dune layer	Alongshore varying upper level of dune layer
Closed 'left' boundary (no transport)	Open 'left' boundary
Old offshore wave climate	New offshore wave climate
	Additional [1a]: nearshore wave climate (1 location)
	Additional [1b]: nearshore wave climates (9 locations)

4.3 Results

The basic model setup for Phase III of the project differs at several points from the setup that is used in the previous project phase. This chapter describes the steps taken to extent the existing "Phase II model setup" towards a more enhanced model. In the following sections the effects of some essential differences in model setup are discussed. First the model results of the original Phase II setup are presented, followed by results due to some minor adjustments to the original setup. Then, the results of different enhanced model setups for Phase III are discussed in more detail. The chapter concludes with the results of the final (calibrated) "Phase III PONTOS model" for Domburg.

4.3.1 Basic model setup Phase II

As a starting point for the simulations of coastline evolution near Domburg, the final model setup from the previous project phase is used. This setup is enhanced by adding additional components and/or improving calibration settings. In this section the results of simulations with the Phase II model setup are presented and the effect of several adjustments to the Phase II setup is discussed.

Original Phase II model setup

In Figure 4.6 to Figure 4.8 the main results are presented of a simulation with the original Phase II model setup for Domburg, for the period 1990 - 2009. Figure 4.6 shows the initial alongshore transport rates (per layer and in total); Figure 4.7 presents the evolution of the individual layers (Y0, Y1, Y2) and in Figure 4.8 the evolution of the MCL-position is shown. In the latter two a comparison is made between simulated results and results that are based on measurements (JARKUS).

In all figures the model output is presented for the coastal area between "x = 0 m" and "x = 6000 m", where Domburg is located near "x = 3000 m". The entire model domain extends up to "x= 9000 m", but since this study focuses on the area near Domburg, the results for the last 3 km are not shown in the figures.

Figure 4.6 shows the net alongshore transport that is determined on the basis of the imposed (old) offshore wave climate. PONTOS calculates alongshore transport rates for each individual vertical layer, and the contributions of each layer also presented in the figure. The results show that the alongshore variation of the (initial) transport rates is identical for each individual layer. The reason is that the initial layer positions in the original Phase II model setup are directly coupled to the position of Mean Sea Level, by a predefined (alongshore constant) reference profile. As a consequence, the initial coastline orientation (and thus the calculated transport) is equal for each vertical layer.
From Figure 4.6 it is concluded that the net alongshore transport rate varies between -20,000 m^3/year (southwestward) and +100,000 m^3/year (northeastward). Transport in the layers Y2 and Y3 (foreshore) is generally directed in northeastward direction, while the sediment transport in layer Y1 is directed southwestward. The result that the direction of alongshore transport varies per layer is a typical example of a feature in which a multi-layer model differs from a one-line model. Whether this specific difference significantly influences the model's output (with respect to a one-line model result) is part of the further analyses.

In Figure 4.7 the simulated (and measured) evolution of the layer positions is presented. The initial layer positions (solid lines) confirm that (initially) no alongshore variation exists in the relative distances between the layer positions. At the end of the simulation (after 19 years) the spacing between the different layers has clearly been changed, due to alongshore and cross-shore processes and several nourishment events. Both the positions of Y1 and Y2 have moved substantially in seaward direction. In the final result (= end 2008) also clearly the influence of the in 2008 imposed nourishments are recognized (in left side of domain).

A similar conclusion can be drawn when considering the simulated MCL-position (Figure 4.8). In the entire domain the final MCL-position is located (relatively far) seaward of the initial position. There is a net gain of sediment volume in (at least: the upper part of) the coastal zone. The 'measured' MCL-position for 2008 suggests that the sediment gain is overestimated by the model.

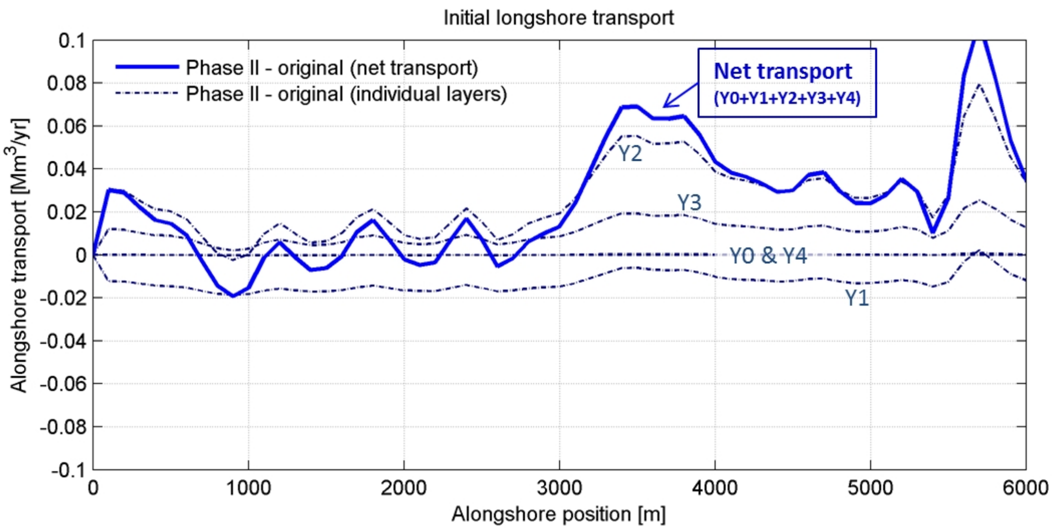


Figure 4.6 Initial alongshore transport rates along the coastline for original Phase II model setup. Both the individual layer contributions (dashed lines) and the net transport (solid line) are presented.

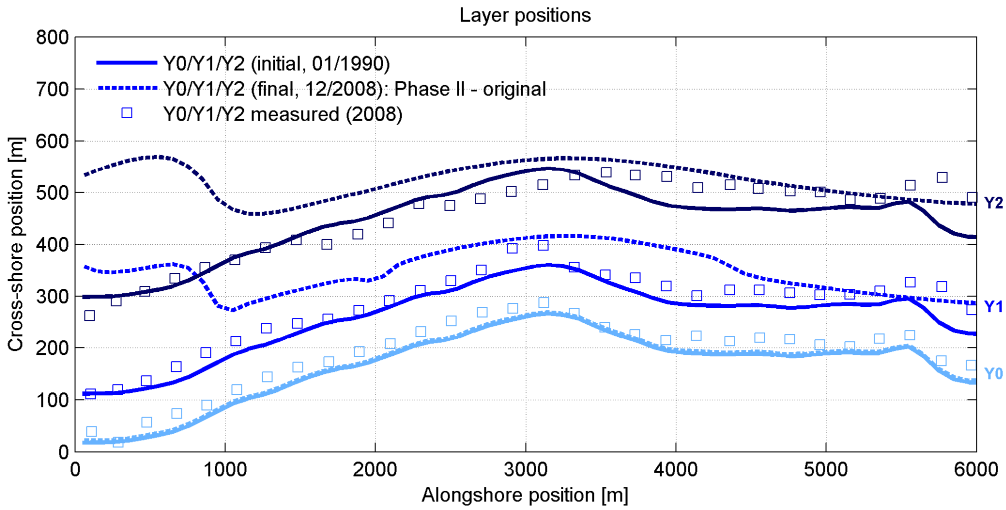


Figure 4.7 The cross-shore positions of layers Y0, Y1 and Y2 for original Phase II model setup. The figure shows initial positions (solid), simulated positions after 2008 (dashed), and layer positions based on 2008 profile-measurements (squares).

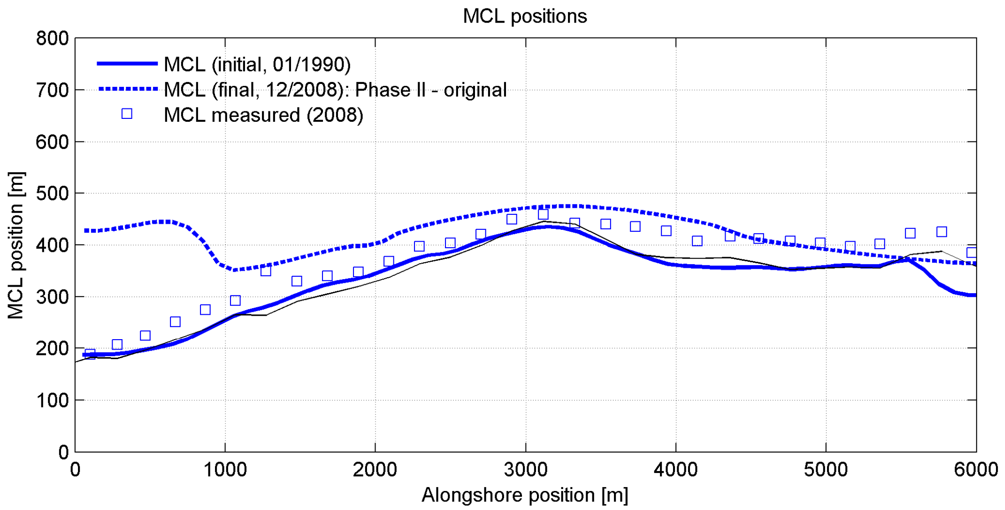


Figure 4.8 MCL-position along the coastline for original Phase II model setup. The figure shows the initial position (solid), the simulated position after 2008 (dashed), and the MCL-position based on 2008 profile-measurements (squares).

The difference between simulated and measured layer/MCL positions is substantial in both Figure 4.7 and Figure 4.8. Both figures suggest that the model is not fully capable to reproduce all relevant processes/dynamics that drive the morphological system at this location. It should be noted that not all nourished volumes for the year 2008 are captured in the 2008 measurements (since these were performed in the middle of 2008), but still the difference between simulation and observation are too large. This 'gain' of sediment is related to the applied sediment transport rate and transport gradients in the model (alongshore and cross-shore), because the transport has not been calibrated.

In order to understand the mechanisms that are essential to simulate a realistic coastline evolution near Domburg, the original Phase II model setup is further enhanced in the following of this chapter. Step-by-step additions and/or changes are made to improve the model setup, or at least to understand the important aspects of the model setup.

Adjusted Phase II model setup
The results of the original Phase II setup show quite a large difference w.r.t. measured data regarding the coastline evolution. Before shifting to a more comprehensive model setup with alongshore varying (relative) layer positions (as foreseen for the Phase III setup), first some (minor) adjustments are made to the original Phase II model in order to enable decent comparisons later on. The four adjustments that are made to the original setup are presented in Table 4.5.

First, the length of the simulation has been changed, such that a larger time difference exists between the last nourishment-event and the end-time of the simulation. In addition, the initial coastline position is based on the MCL-position of 1989 instead of the MSL-position of 1990. The change from 1990 to 1989 is done for the reason that profile measurements are mostly recorded mid-year.
Second, the ‘closed’ left boundary in the original setup is opened again, such that outgoing sediment is not trapped within the model.
Third, the offshore wave climate has changed slightly (based on same dataset, but other classification of climate). The ‘new’ offshore climate is also used to determine nearshore conditions at several locations along the coast (see Phase III model setup).
Fourth, the definition of the vertical layer levels has been changed. The default settings are adjusted, such that the minimum level of the vertical grid is set at NAP -15 m, instead of NAP -20 m; which better suits the bathymetry in the study area.

Table 4.5 Overview of adjustments made to original Phase II model setup.

	Original model setting	**Adjusted model setting**
Adjustment 1	- Simulation period: 1990 – 2009 - Initial layer position based on MSL 1990	- Simulation period: 1990 – 2012 - Initial layer position based on MCL 1989
Adjustment 2	- Closed ‘left’ boundary (no transport)	- Open ‘left’ boundary
Adjustment 3	- Old offshore wave climate	- New offshore wave climate
Adjustment 4	- Original definition of vertical layer levels	- Adjusted definition of vertical layer levels

<u>Adjustment 1: Extended simulation period and initial layer positions</u>
The first adjustment to the original Phase II model setup does not change the processes during the simulations, because only small changes are made to the initial layer positions and the length of the simulation. The effect of the first adjustment is visualized in Figure 4.9. The figure shows that (1) the initial MCL-position slightly differs, and (2) the effect of the 2008-nourishments is less pronounced. Overall, the level of improvement is limited, but the extended simulation length allows for better comparisons between simulation and measurement (the result is not disturbed by the 2008-nourishments).

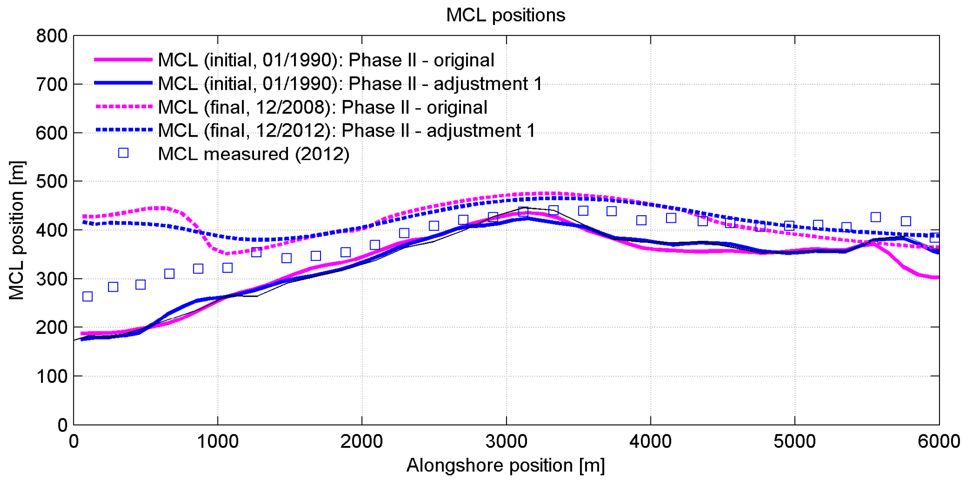


Figure 4.9 Comparison of MCL-positions along the coastline. The figure shows initial positions (solid), simulated positions after a full simulation (dashed), and the MCL-position based on 2012 profile-measurements (squares).

<u>Adjustment 2 + 3: 'Open' lateral boundaries + renewed offshore wave climate</u>

The effects of the second and third adjustments are discussed together in this subsection. Both adjustments do affect the calculated alongshore transport rates. The second adjustment enables sediment transport through the left-side model boundary, such that the leftward directed transport in Y1 is not blocked. The third adjustment could result in small differences in alongshore transport due to reclassification of the wave climate; but no substantial changes are expected, since the underlying data for both wave climates is similar.

Figure 4.10 shows the combined effect of adjustments 2 & 3 on the initially calculated alongshore transport rates. The result is compared to the initial transport that is determined for the model setup "Phase II – adjustment 1". The figure shows two differences between the presented results. First, the net transport at the left boundary is not forced to 0.0 Mm^3/year, as expected because the boundary is 'open'. And second, the entire transport pattern is shifted due to the adjustments (while the pattern remains constant). The shift can be explained by the reclassification of the wave climate. The transport gradients do not change due to the adjustments.

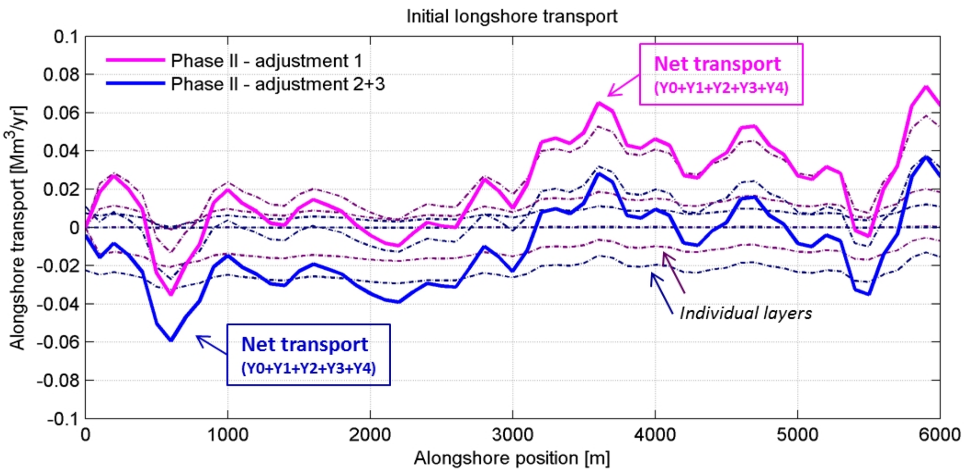


Figure 4.10 Comparison of initial alongshore transport rates along the coastline. Both the individual layer contributions (dashed lines) and the net transport (solid line) are presented.

Adjustment 4: Renewed definition of vertical layer levels

The fourth and last adjustment is the adjustment of the vertical layer levels (as defined in Table 4). The model adjustment affects the initial layer positions. Figure 4.11 shows the changes in layer positions due to this redefinition.

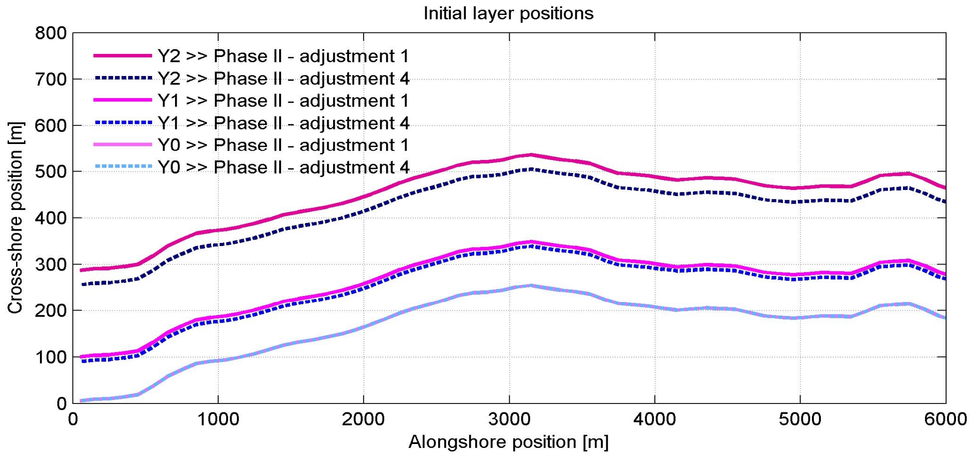


Figure 4.11 The initial cross-shore positions of layers Y0, Y1 and Y2 along the coastline. The figure shows the effect of an adjusted definition of the vertical layer levels: original definition (magenta) versus adjusted definition (blue).

A consequence of the redefined layers is that the vertical distribution of sediment transport changes. For example, the net alongshore transport rate remains constant, while the distribution over the individual layers differs. The overall effect of this adjustment on the coastline evolution is however limited.

Combination of Phase II model setup adjustments

The combined effect of all four adjustments to the original Phase II model setup is shown in Figure 4.12. The figure shows the difference between MCL-positions (initial and final) for the original and the adjusted model setup. From the figure it is concluded that the adjustments do not improve the model results. However, these adjustments were primarily intended to ‘connect’ the Phase II setup to a renewed Phase III setup, and to study the relative importance of several model aspects.

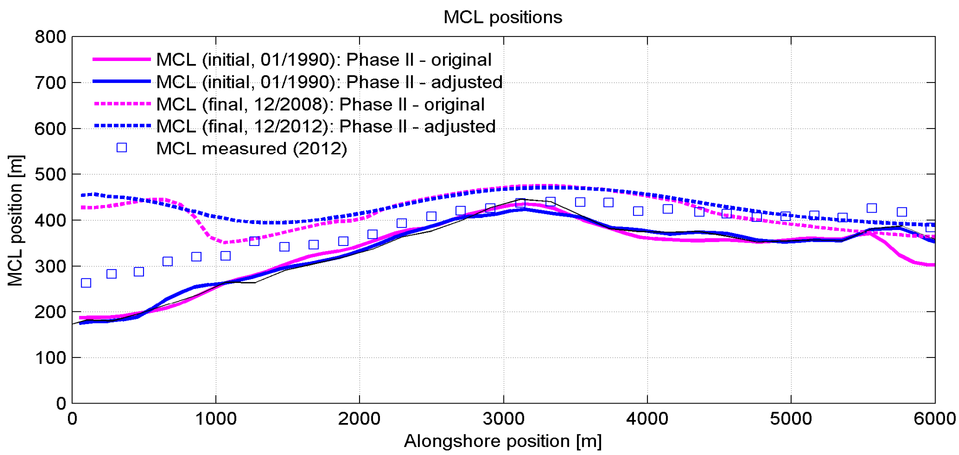


Figure 4.12 Comparison of MCL-positions along the coastline. The figure shows initial positions (solid), simulated positions after a full simulation (dashed), and the MCL-position based on 2012 profile-measurements (squares).

In general, the model results for each of the simulations with the Phase II setup show that PONTOS tends to overestimate the sediment volumes in the upper part of the coastal zone (layers Y0 – Y2). The sediment gain is primarily caused by the nourishments that took place during the simulation. It seems that the model is not sufficiently able to re-distribute the sediment throughout the coastal zone. An effort will be made to improve the model performance by means of the inclusion of sediment losses over the model boundary and towards deeper water.

4.3.2 Basic model setup Phase III

In the previous section it is shown that the Phase II model did not yet satisfactory reproduce the coastline evolution at Domburg. It is concluded that nourished sediment volumes stay in the active morphological zone for a relatively long time, while the observations show a faster decay of sediment volumes. In this section an attempt is made to enhance the model setup by considering alongshore variations in the (relative) layer positions, and by calibrating some aspects of the basic model.

In the following subsections the renewed basic setup of the Phase III model is studied. First, the results of the non-calibrated version are discussed, followed by an attempt to improve the calibration of the model on the basis of a simulation for a period without nourishments. At the end, the calibrated basic model is tested for the default simulation period (1990 – 2012).

Basic model setup (non-calibrated)

This section describes the results of a simulation with the non-calibrated version of the basic Phase III model. As discussed in Section 4.2.3, the model setup differs at various points from the original Phase II model. In the previous section already some (minor) adjustments are made to the Phase II model in order to reduce the differences between both models. The largest remaining difference between the models “Phase II – adjustment 4” and “Phase III – basic” is the definition of the layer positions; which is now directly based on analyses of measured cross-shore profiles, for each individual vertical layer. In addition also a schematized dune height variation is added to the model setup.

In Figure 4.13, Figure 4.14 and Figure 4.15 the main results of a simulation with the non-calibrated Phase III model are presented. The figures contain the same information as previously discussed for the original Phase II model.

Figure 4.13 shows the initial alongshore transport rates (net effect and individual layer contributions). From the figure it is concluded that the largest alongshore variation in transport rates is found for layer Y2 (foreshore), while the transport rate in layer Y1 is relatively constant and southwest-directed. The net alongshore transport in layer Y2, southwest of Domburg ($x < 3000$ m), is primarily directed southwestward; resulting in a negative transport gradient, which means that the coastal protrusion near Domburg is losing sediment. Just northeast of Domburg the transport gradient for layer Y2 is positive (with a northeastward direction of transport), also resulting in sediment loss near Domburg (as expected).

Figure 4.14 and Figure 4.15 show the coastline evolution for the upper part of the coastal zone (either layers Y0 – Y2 or the MCL). From both figures it can be concluded that the model simulates a coastline evolution that results a final coastline position that is positioned relatively far seaward of the initial position. Obviously, the performed nourishments do have a large influence on the amount of sediment that is present in the upper part of the coastal zone, but the model seems to overestimates the volumes. The measured coastline position and layer positions do confirm that the coastline has moved seaward along the entire coastal stretch, but the degree of change is much smaller.

As mentioned before, the coastline model seems to have some problems in removing sediment from the active upper layer of the coastal area. Either sediment losses over the lateral boundaries or losses towards deeper water are required to produce results that match the observed coastline changes. The results in Figure 4.14 and Figure 4.15 suggest that the implementation of alongshore varying cross-shore profile information (in terms of alongshore varying relative layer positions), without further calibration, does not directly 'solve' the problem that was found in Phase II of the project.

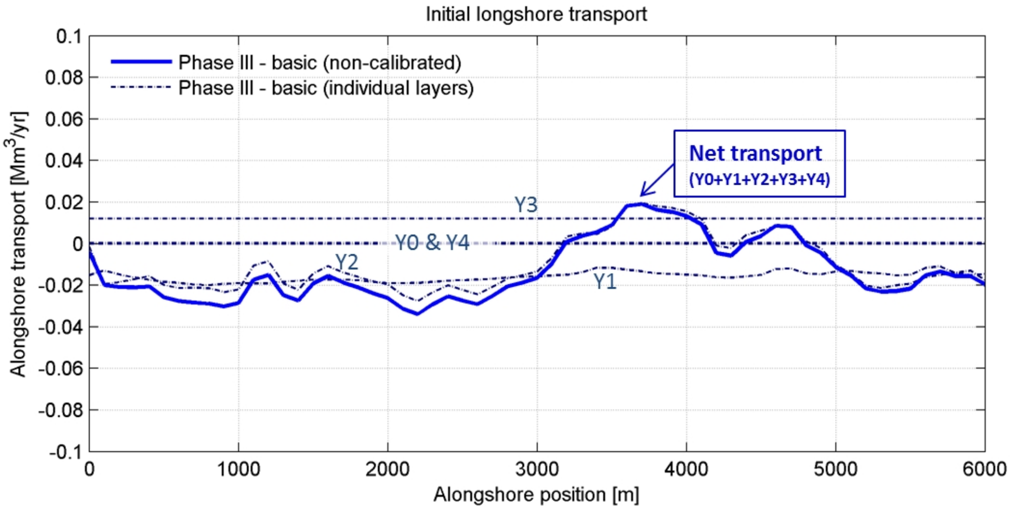


Figure 4.13 Initial alongshore transport rates along the coastline for non-calibrated Phase III model setup. Both the individual layer contributions (dashed lines) and the net transport (solid line) are presented.

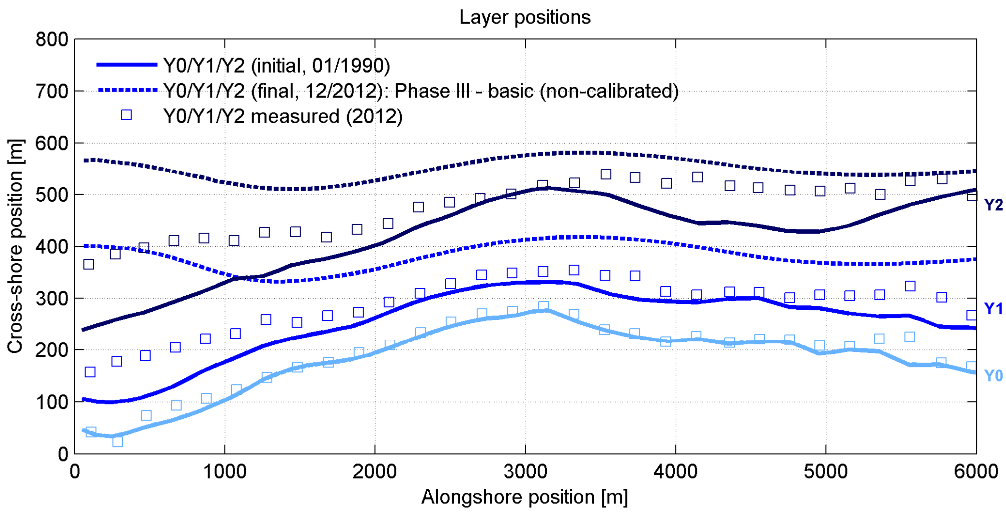


Figure 4.14 The cross-shore positions of layers Y0, Y1 and Y2 for non-calibrated Phase III model setup. The figure shows initial positions (solid), simulated positions after 2012 (dashed), and layer positions based on 2012 profile-measurements (squares).

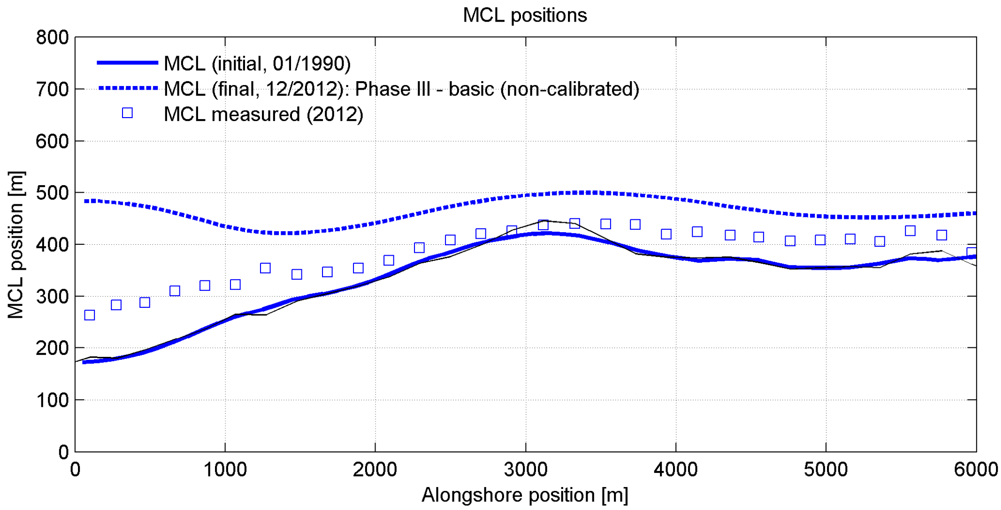


Figure 4.15 MCL-position along the coastline for non-calibrated Phase III model setup. The figure shows the initial position (solid), the simulated position after 2012 (dashed), and the MCL-position based on 2012 profile-measurements (squares).

Calibration of basic model setup, based on period 1976 – 1988 (no nourishments)

The previous section showed that the model results for the basic non-calibrated Phase III model differ quite a bit from the observed coastline changes. However, no specific calibration of the model settings has been performed so far. In the following the coastline model is calibrated on the basis of simulations with the same model setup, but for another simulation period. For the purpose of calibration a period is selected in which no nourishments are performed in the coastal area. By considering such a period, the model's performance for an undisturbed coastline evolution is tested (and possibly improved).

<u>Simulation with non-calibrated model for period 1976 - 1988</u>

Figure 4.16 shows the result of a simulation with the basic Phase III model, for the period 1976 – 1988. The figure shows that the PONTOS result approximates the observed undisturbed coastline evolution for the considered period of 13 years. However, too much flattening out of the coast is seen in the Domburg area. Some fine-tuning is preferred, but the result of the "undisturbed" period is better than the basic simulation for the period with nourishments. The result in Figure 4.16 shows that the simulated position of layer Y1 resembles the retreat of the Y1 position at Domburg (x = 3000m) quite well, but the model overpredicts the position of the Y1 layer at the sea-dike (x = 0m) and Oostkapelle (x = 6000m) ends of the model. The differences between the measured and modelled positions of the Y2-layer are somewhat larger.

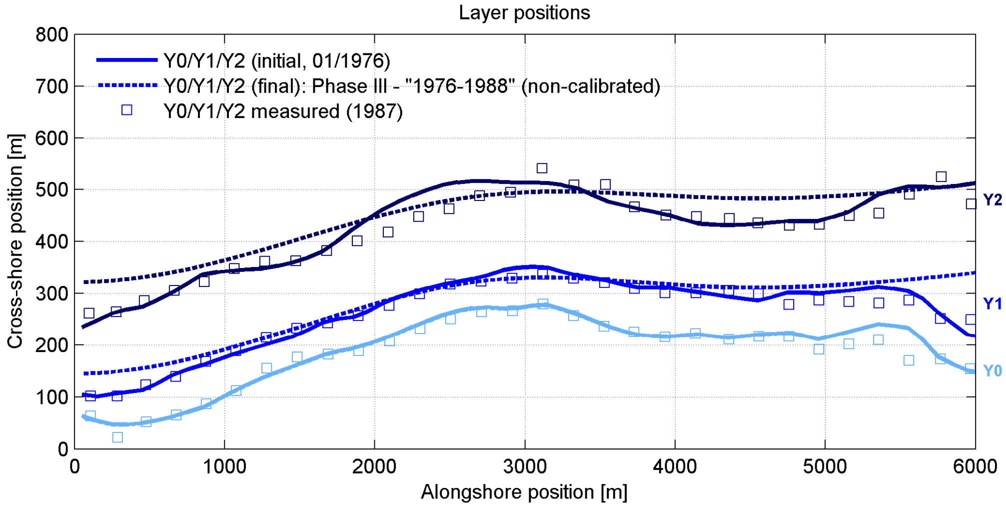


Figure 4.16 The cross-shore positions of layers Y0, Y1 and Y2 for non-calibrated Phase III model setup (period 1976 – 1988). The figure shows initial positions (solid), simulated positions after 1987 (dashed), and layer positions based on 1987 profile-measurements (squares).

<u>Calibration of “equilibrium layer width” (CWI-settings)</u>

A common method to calibrate the multi-layer PONTOS model is to tune the so-called CWI-settings, which are used to define the “equilibrium layer width” between each of the individual layers (i.e. defining the schematized cross-shore equilibrium profile).
By default, the model calculates a “theoretical” equilibrium width on the basis of the imposed hydraulic conditions. Tuning of the equilibrium width is done by adjusting the CWI-settings and sediment characteristics. In practical applications, however, it is possible that the calculated theoretical equilibrium profile differs from the ‘actual’ equilibrium profile that is found from measurements. In that case the initially calculated equilibrium profile can be modified by scaling factors: the CWI-settings.
The tuning of CWI-settings comprises the definition of a quotient between “preferred equilibrium layer width” and “theoretical equilibrium layer width” (default = 1). For example, a CWI setting of 0.5 can be used if the calculated theoretical equilibrium distance between two layers is two times as large as the distance (between these layers) that is observed from measurements. This can be done separately for each vertical layer. It is common practice to use alongshore constant CWI-settings, especially for relatively small model domains with a limited amount of wave- /tidal- stations (here: 1).

Alongshore varying CWI-settings are only applied in cases/models where it is evident that alongshore variations exist in (the shape of) the equilibrium profiles due to factors other than the prescribed hydraulic conditions or sediment characteristics. An example for this is a morphological feature that originates from other physical mechanisms than modelled in this type of coastline model (e.g. a shore-connected sand ridge). In that case alongshore varying CWI-settings can be used for local adjustments of the equilibrium profiles.

Figure 4.17, Figure 4.18 and Figure 4.19 show how the “equilibrium width” on the basis of the original CWI-settings is adjusted for each vertical layer, for the purpose of model calibration. The “equilibrium width” is modified in such a way that the equilibrium distances between the layers relate to the distances between the initially imposed layer positions.

From Figure 4.17 it is concluded that the ‘original’ equilibrium width (magenta solid line) is substantially larger than the initial layer width (blue crosses), which means that the model will try to enlarge the initial distance between Y1 and Y0 by cross-shore sediment exchange. By reducing the CWI-setting a renewed equilibrium layer width (blue solid line) is obtained that matches the initial layer information. All this, obviously, under the assumption that the input layer width is close to an equilibrium situation.

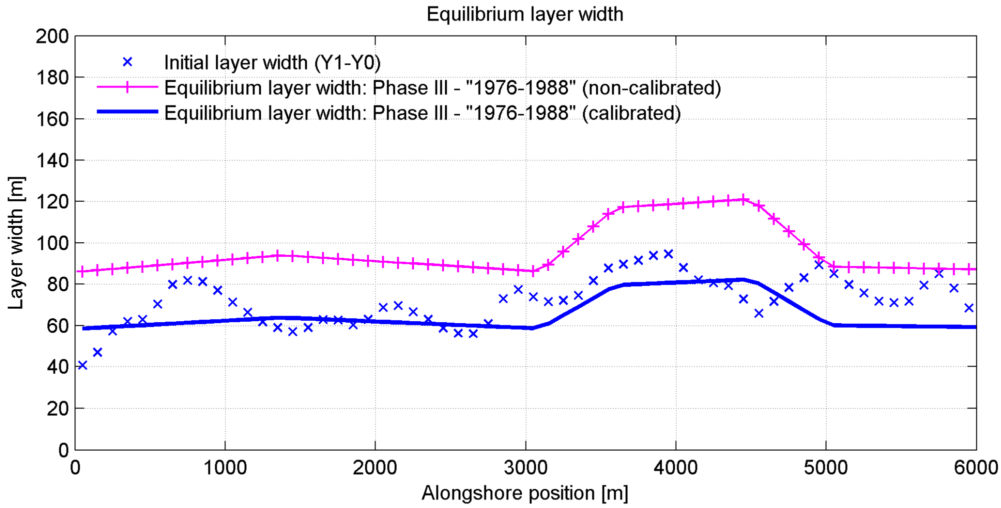


Figure 4.17 Calibration of equilibrium layer width (Y1 – Y0), based on Phase III model for period 1976 – 1988. The figure shows the initial layer width of the model setup, and both the non-calibrated and calibrated equilibrium layer distances. Note that the equilibrium changes because of variation in the dune height while the CWI setting is constant.

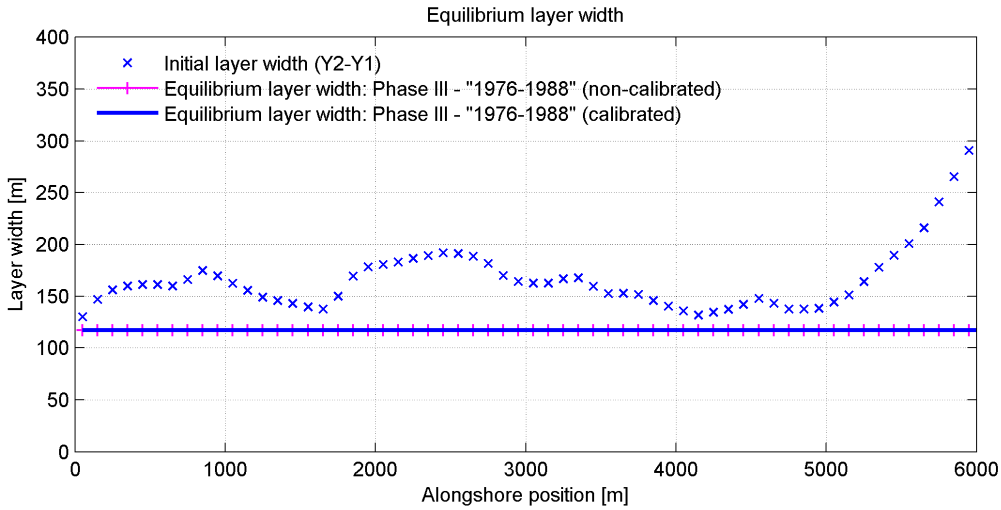


Figure 4.18 Calibration of equilibrium layer width (Y2 – Y1), based on Phase III model for period 1976 – 1988. The figure shows the initial layer width of the model setup, and both the non-calibrated and calibrated equilibrium layer distances.

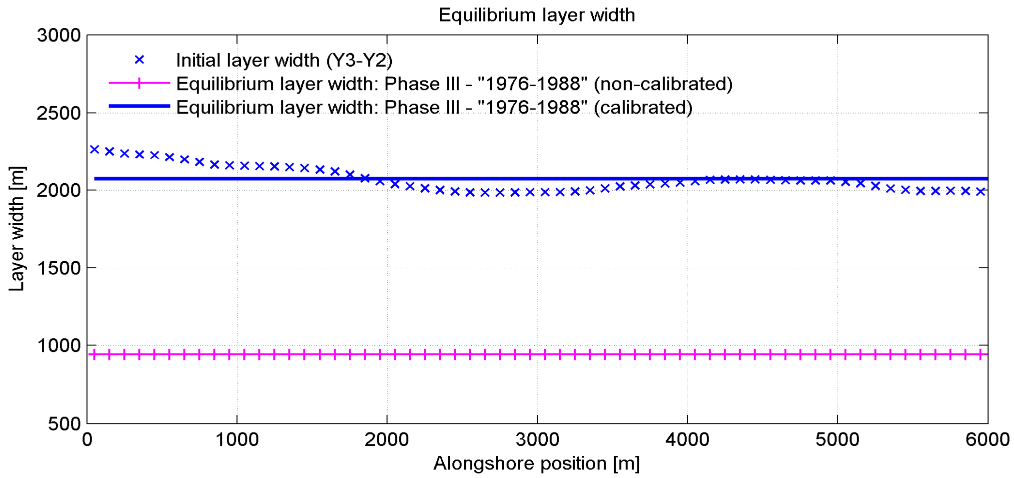


Figure 4.19 Calibration of equilibrium layer width (Y3 – Y2), based on Phase III model for period 1976 – 1988. The figure shows the initial layer width of the model setup, and both the non-calibrated and calibrated equilibrium layer distances.

Similar to the adjustment of the equilibrium layer width between layers Y1 and Y0, also the equilibrium width between Y3 and Y2 is adjusted (see Figure 4.19). The equilibrium width is changed from <1000 m to >2000 m. Due to this adjustment, a larger distance between Y3 and Y2 is maintained during the simulations. The model settings for the equilibrium width between Y2 and Y1 (Figure 4.18) have not been changed, because the original setting were sufficient.

<u>Simulation with calibrated model for period 1976 – 1988</u>
In Figure 4.20 the results of the non-calibrated and the calibrated version of the Phase III model (for the period 1976 – 1988) are presented. The figure shows that the calibrated model simulation resulted in final layer positions for Y1 and Y2 that are shifted a bit landward with respect to the results of the non-calibrated model. It is concluded that the calibrated model therefore results in a slightly improved position of layer Y2 (and a similar result for Y1), but that the longshore variation in the predicted coastline development is not substantially improved. The predicted coastline development remains more diffuse than shown in the measurements.

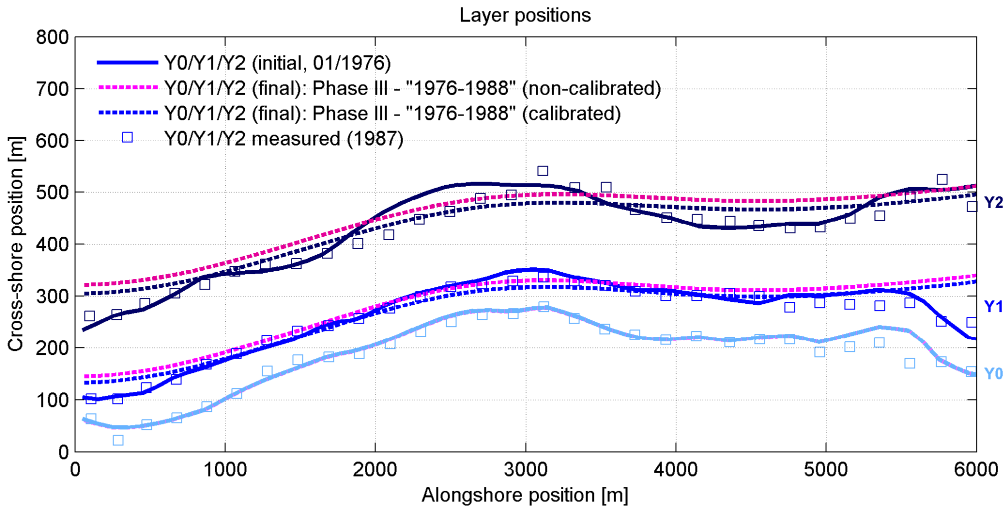


Figure 4.20 Comparison of cross-shore positions of layers Y0, Y1 and Y2. The figure shows initial positions (solid), simulated positions after 1987 (dashed), and layer positions based on 1987 profile-measurements (squares).

Calibration of basic model setup, based on period 1990–2012
On the basis of model simulations for the period 1990–2012, a calibrated version of the basic Phase III model is created. The calibrated version of the model is considered as "the" basic model setup. In this section the Phase III model is compared to the Phase II model.

Figure 4.21 shows the results of both model setups: "Phase II – original" versus "Phase III – basic (calibrated)". From the figure it is clear that the differences between both models are limited. The final MCL-position near Domburg is almost identical for both simulations, but both models predict a MCL-position that is located further seaward than observed. The MCL-position in the area northeast (right) of Domburg is better simulated with the renewed Phase III model setup, while the results are (again) quite similar in the area southwest (left) of Domburg. In this area the MCL-line is more "smoothed" for the Phase III model, but this is primarily caused by the fact that the simulation length is extended by four years, such that the dominant effect of the 2008-nourishment is attenuated. In both cases the amount of sediment in that area is largely overestimated by PONTOS.

Overall, it can be concluded that the Phase III model does not produce significantly 'better' results than the Phase II model, when comparing simulated coastline positions with observed coastline positions. The results of the Phase III model are similar with previous runs which show that the PONTOS model gives consistent results. Calibration of cross-shore transport parameters lead to slight improvements in the shoreline prediction for a period without nourishments. Simulations for a period without nourishments result in less bias in the prediction of the shoreline position than in the period with nourishments. The processing of nourishments in the PONTOS model therefore requires more attention before the overall model results can be judged as satisfactory.

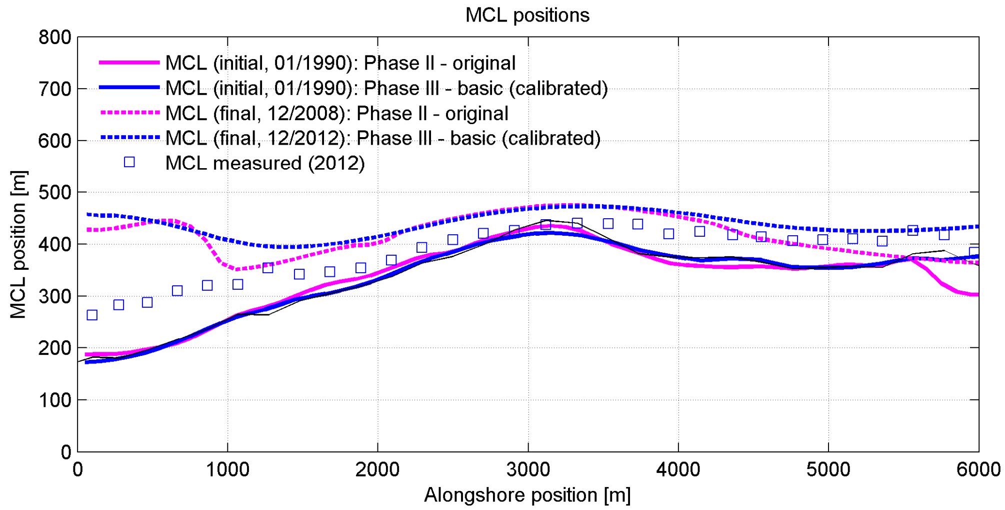


Figure 4.21 Comparison of MCL-positions along the coastline. The figure shows initial positions (solid), simulated positions after 2012 (dashed), and the MCL-position based on 2012 profile-measurements (squares).

4.3.3 Additional: Sensitivity to alongshore variation of calibration settings

In this study it was found that the application of (shallow) nearshore wave conditions in the PONTOS model setup leads to problems when trying to simulate coastline evolution in the relatively complex coastal area near Domburg. In order to compensate for the fact that the present model cannot account for local variations in hydraulic forcing in the coastal zone by using the regular model input-options, two (advanced) calibration methods are tested in this section. These calibration methods are not typically applied, since they only are intended to 'mimic' effects that cannot be accounted for by regular (physical) input and basic calibration efforts.

In the following two sections the parameter settings are varied in the alongshore, in order to illustrate the sensitivity of the model results to changes in their values. It is emphasized that these 'advanced' methods would not normally used in practice without a thorough substantiation and corresponding analysis based on calibration and validation.

Additional Sensitivity 1: Alongshore variation in settings for equilibrium width of layers

In the first additional sensitivity simulation, the CWI-settings are varied in the alongshore, instead of the alongshore constant settings that are used for the calibration of the basic model. Using alongshore varying CWI-settings implies that an alongshore varying "equilibrium layer width" is imposed for certain layers, without varying the hydraulic boundary conditions. By default, the equilibrium layer width is directly related to the hydraulic forcing and sediment characteristics, but in 'complex' situations these aspects can be decoupled by imposing alongshore varying CWI-settings. Figure 4.22 to Figure 4.24 show examples of the effect of varying CWI-settings on the equilibrium width of different layers.

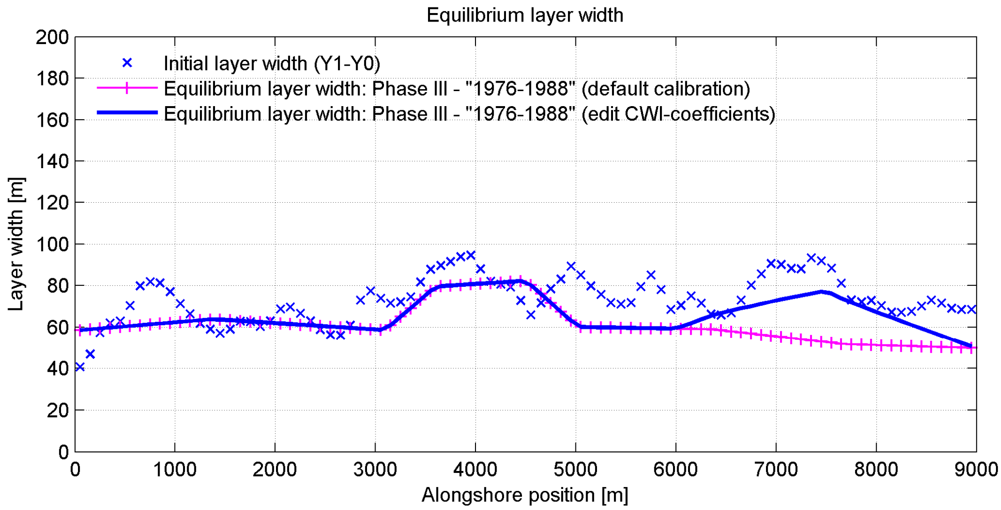


Figure 4.22 Adjusted calibration of equilibrium layer width (Y1 – Y0), based on Phase III model for period 1976 – 1988. The figure shows the initial layer width of the model setup, and both the non-calibrated and calibrated equilibrium layer distances.

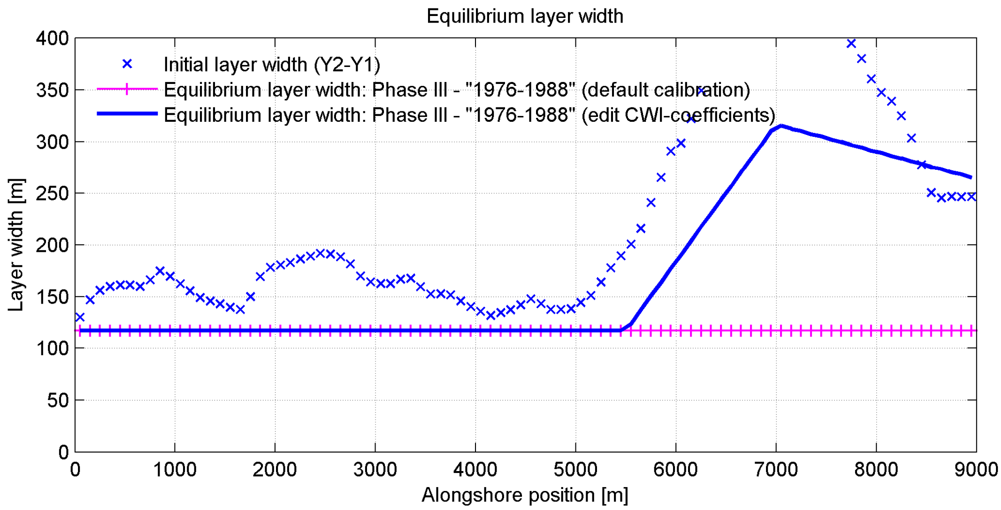


Figure 4.23 Adjusted calibration of equilibrium layer width (Y2 – Y1), based on Phase III model for period 1976 – 1988. The figure shows the initial layer width of the model setup, and both the non-calibrated and calibrated equilibrium layer distances.

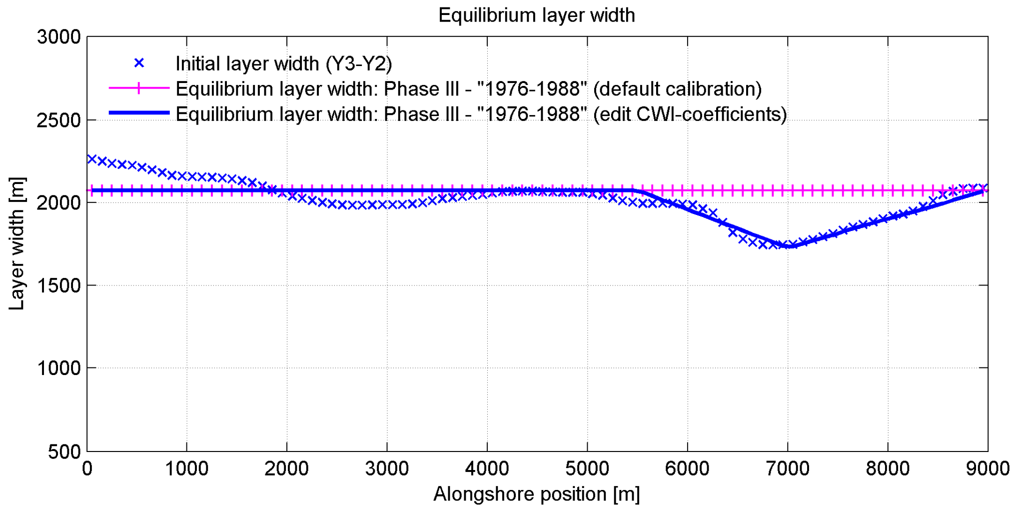


Figure 4.24 Adjusted calibration of equilibrium layer width (Y3– Y2), based on Phase III model for period 1976 – 1988. The figure shows the initial layer width of the model setup, and both the non-calibrated and calibrated equilibrium layer distances.

A test-simulation with a model that is based on the basic Phase III setup for the period 1976–1988, with additional settings for the “equilibrium layer width” as shown in Figure 4.22 to Figure 4.24, shows that simulated layer development can strongly be affected by local adjustments of the CWI-settings. The results of the test-simulation, in which CWI-settings are varied in the area northeast of Domburg, are presented in Figure 4.25. The figure covers the entire model domain (up to x = 9000 m), such that the area with locally adjusted CWI-settings is shown entirely. The model results show that the coastline protrusion near x = 7000 m is less impacted than for the basic model setup.

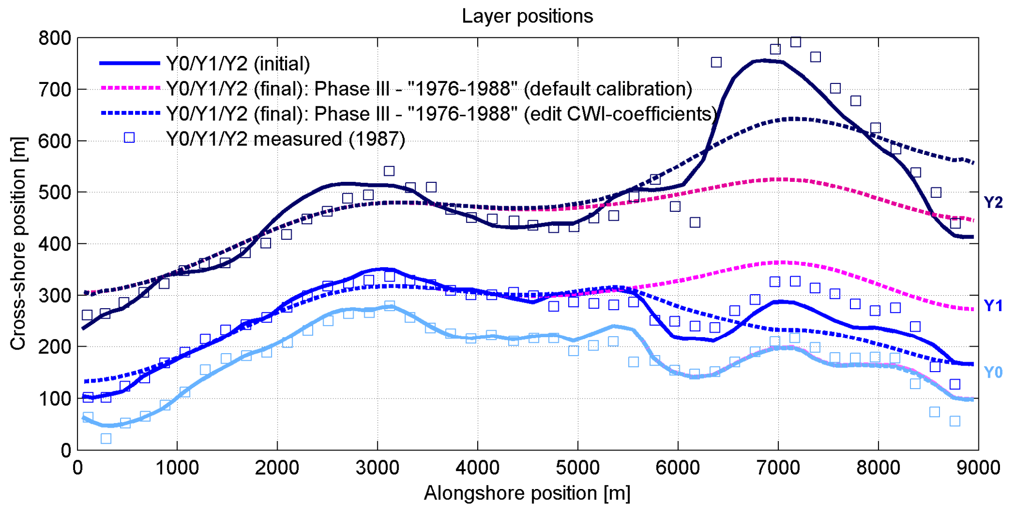


Figure 4.25 Comparison of cross-shore positions of layers Y0, Y1 and Y2. The figure shows initial positions (solid), simulated positions after 1987 (dashed), and layer positions based on 1987 profile-measurements (squares).

In conclusion, this additional sensitivity simulation emphasizes that the use of locally varied CWI-settings cannot be used without a proper analysis of the coastal system. Wrong usage of this these settings could result in unrealistic model behaviour. In this specific case, the use of local adjustments near the shore-connected sand ridge seems plausible since this area is characterized by a feature that cannot be solved properly with regular coastline models. A local 'fix' is thus one of the possibilities to overcome that problem.

Additional Sensitivity 2: Alongshore varying relative wave angle
In the second additional sensitivity simulation, an alongshore varying correction factor is applied on the "dominant wave angle". This is an in-model procedure to modify the imposed hydraulic boundary conditions locally. Since the application of nearshore wave conditions does not work out for this complex study area, advanced calibration of the "dominant wave angle" is one of the options to bypass this problem. However, as stated earlier, usage without decent substantiation is not recommended.

As an example, the dominant wave angle is modified around the coastline protrusion near Domburg. Left of the protrusion the wave angle is rotated anti-clockwise (by an arbitrary 5 degrees), and right of the protrusion the angle is rotated clockwise (5 degrees). This modification, which is visualized in Figure 4.26, crudely mimics the effect of wave refraction around the coastline protrusion.

The result of a test-simulation with additional local modification of "dominant wave angle" (based on the basic Phase III model for the period of 1976 – 1988) is presented in Figure 4.27. The figure shows clearly that the distinct shape/orientation of the coastline near Domburg is maintained much better when using a locally adjusted wave angle.

Three important conclusions can be drawn on the basis of this result:

1. Modification of the relative dominant wave angle has a substantial effect on the simulated coastline development in PONTOS, which is in line with the expected effect for most coastline evolution models.
2. The use of local wave conditions seem to be essential to simulate the coastline evolution near Domburg in PONTIS
3. The use of a local modification factor for the dominant wave angle appears to approximate the effect of multiple nearshore wave climates, when used properly.

Figure 4.26 Manual setting of an alongshore varying correction factor for the "dominant wave angle".

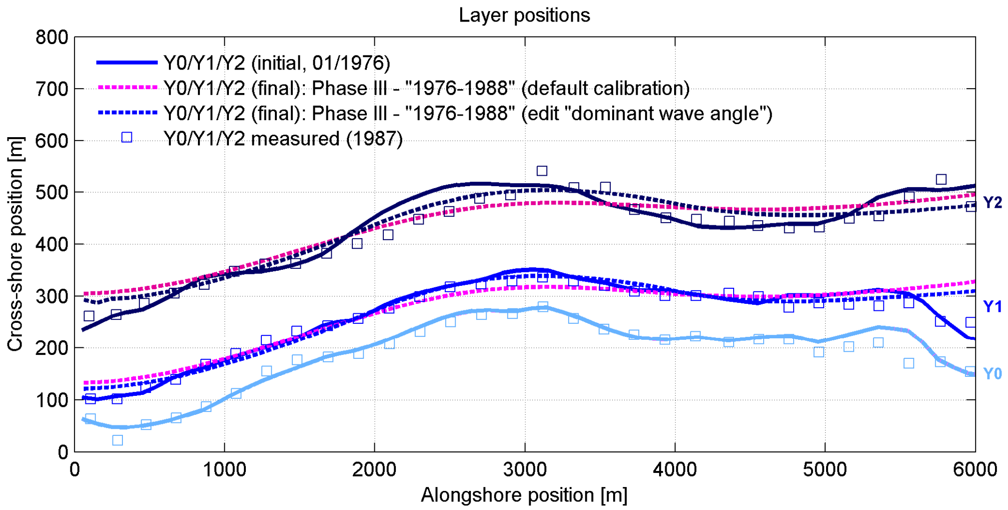


Figure 4.27 Comparison of cross-shore positions of layers Y0, Y1 and Y2. The figure shows initial positions (solid), simulated positions after 1987 (dashed), and layer positions based on 1987 profile-measurements (squares).

To conclude this example, it is emphasized (again) that the use of a local modification factor for the dominant wave direction cannot be used without a proper analysis of the coastal system. Wrong usage of this model modification could result in unrealistic model behaviour. In this specific case, the use of local modifications seems to work out well, but it should be clear that this is a calibration which is not preferable. It would be better to improve the feature in PONTOS which allows for the application of nearshore wave climates for complex study areas.

4.3.4 Final model

To conclude this chapter more results of the “final Phase III model” are presented in sequence. The final model setup is defined as being the “*calibrated, basic Phase III model setup*” (thus: without nearshore wave conditions and without alongshore varying calibration factors).

In the following figures the model results of four different output-parameters are presented for multiple moments in time during the simulation. Figure 4.28 shows the simulated (and measured) MCL-positions, Figure 4.29 shows the alongshore sediment transport rates. Figure 4.30 and Figure 4.31 both show the simulated cross-shore transport rates at the level NAP -1.5 m and NAP -6 m respectively.

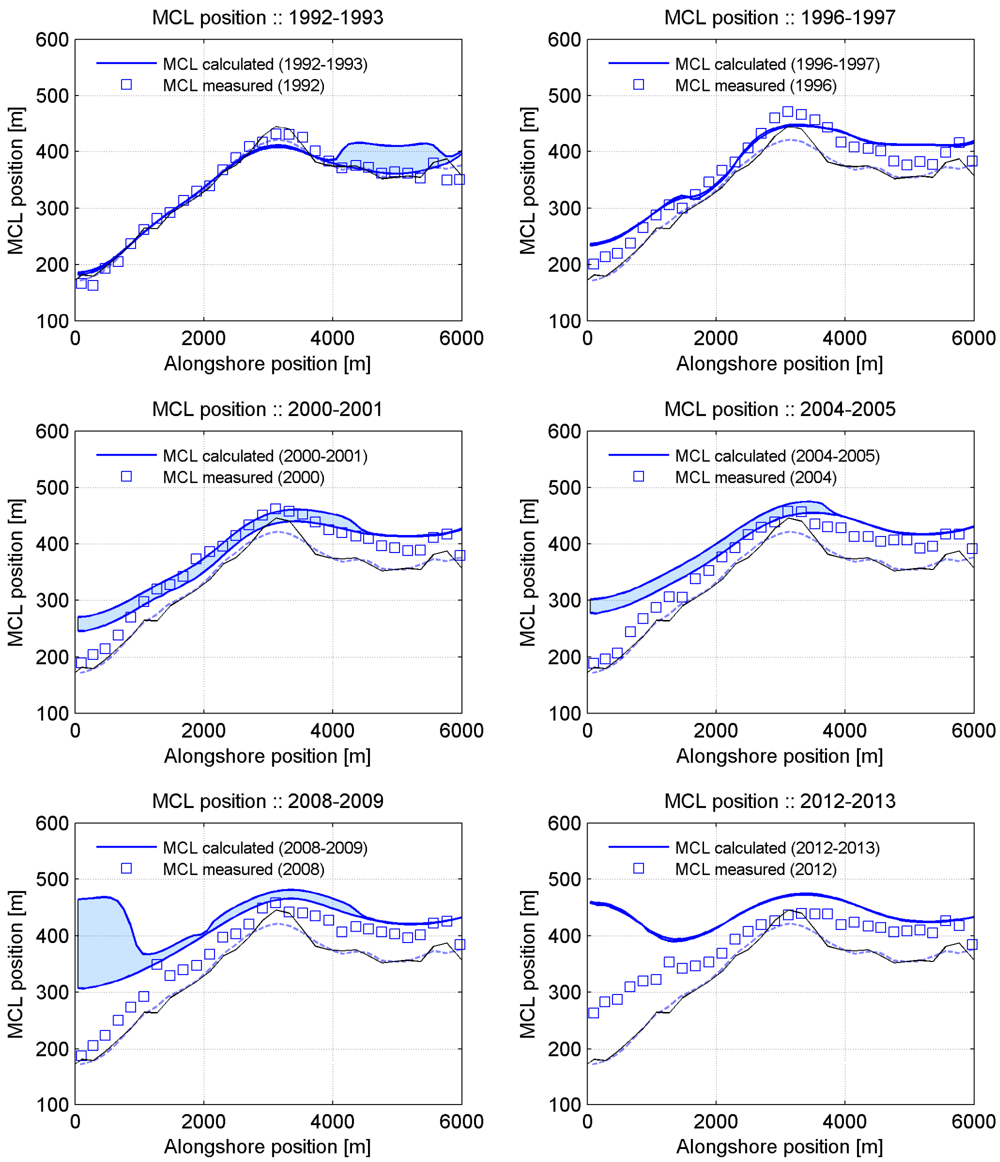


Figure 4.28 Final Phase III model setup: evolution of MCL-position near Domburg in the period 1990 – 2012. The figure shows initial positions (dashed), simulated positions (solid/patches), and MCL-positions based on profile-measurements (squares).

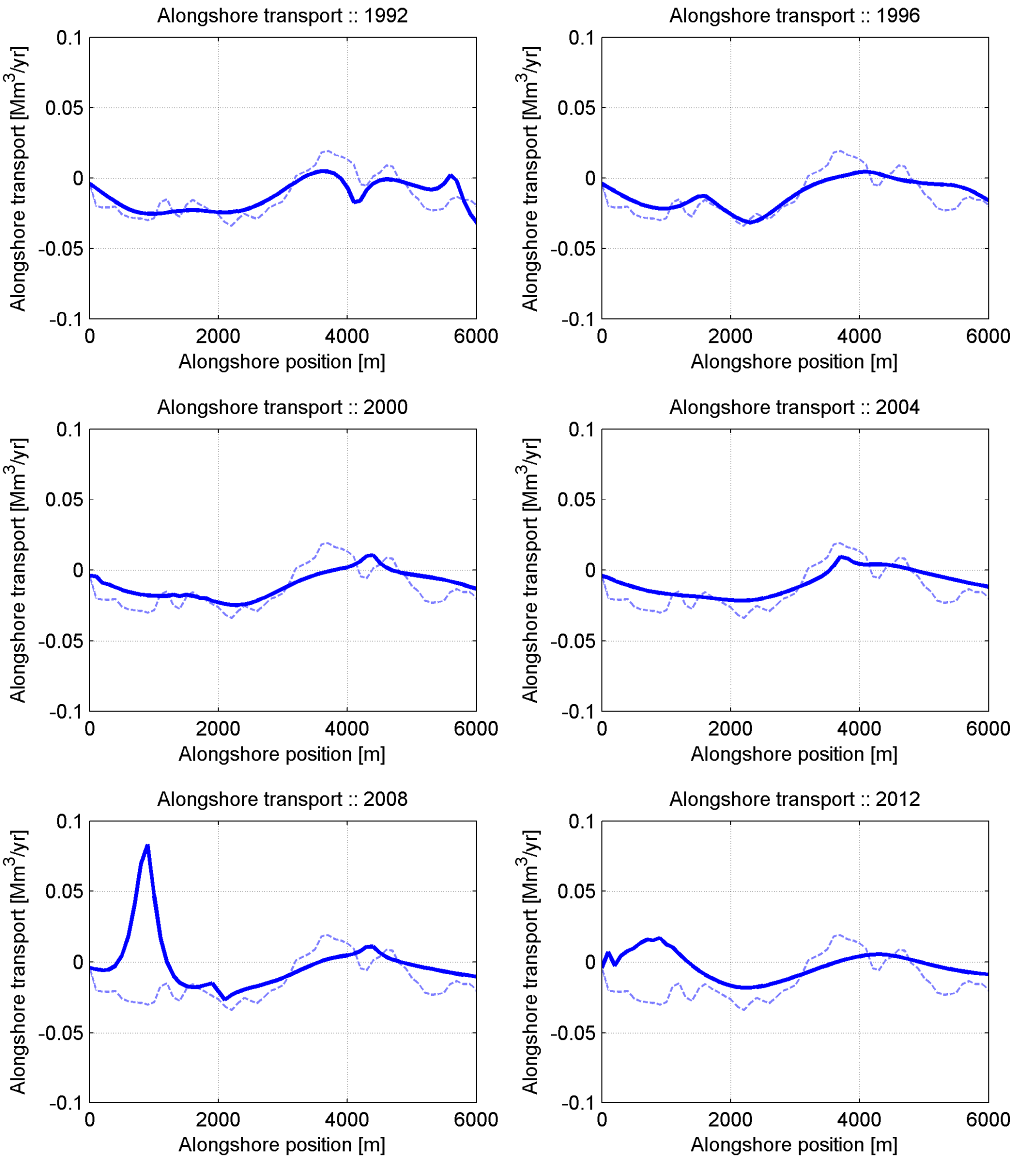


Figure 4.29 Final Phase III model setup: alongshore transport rates, in the period 1990 – 2012. The figure shows the initial transport rates (dashed) and the development during the simulation (solid).

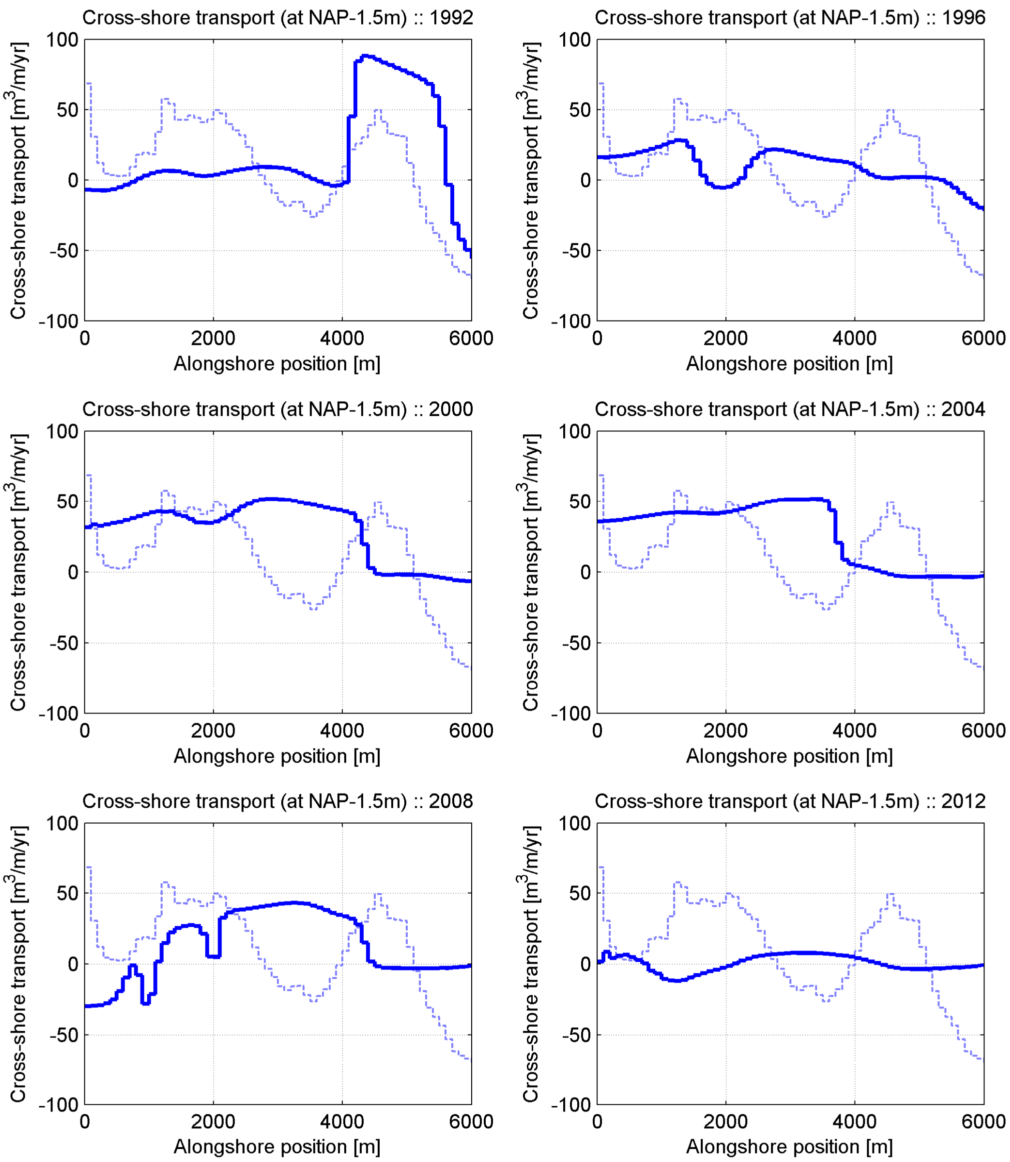


Figure 4.30 Final Phase III model setup: cross-shore transport rates over the NAP -1.5 m depth contour, in the period 1990 – 2012. The figure shows the initial transport rates (dashed) and the development during the simulation (solid).

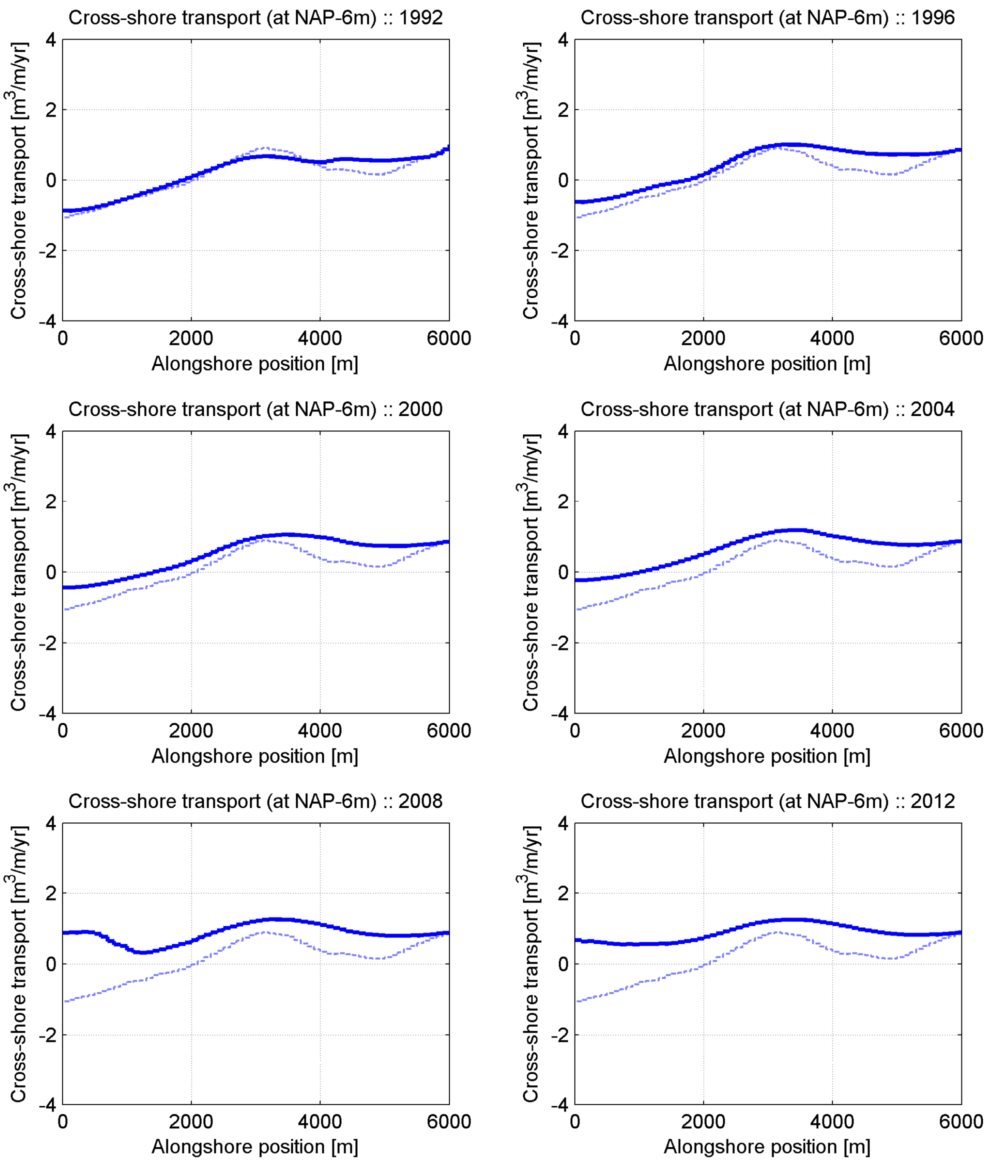


Figure 4.31 Final Phase III model setup: cross-shore transport rates over the NAP -6 m depth contour, in the period 1990 – 2012. The figure shows the initial transport rates (dashed) and the development during the simulation (solid).

4.4 Analysis

Based on all work that is done in order to improve the setup of the PONTOS model for Domburg, and to gain more insight in the essential aspects needed for proper coastline modelling, two topics were selected that are discussed in more detail in this section:

- Nearshore wave conditions
- Nourishments

Both topics need more attention in future studies, since improvement of model formulations related to these aspects seems to be essential for decent modelling of coastline evolution. In this section a descriptive analysis is provided on both topics.

4.4.1 Nearshore wave conditions

PONTOS is not (yet) fully capable of dealing with the application of nearshore wave conditions in complex coastal areas such as the case near Domburg and therefore no simulations have been presented in this report with the application of nearshore wave climates. However, Additional Sensitivity Simulation 2 showed that model predictions of the shoreline development may improve if the wave climate is allowed to vary in the longshore direction. In order to introduce this effect in a physical manner, more effort is needed to develop the model to allow for input for both offshore and nearshore conditions. By enabling a combined input for the wave conditions it should be possible to enhance the schematization of cross-shore variations in the wave conditions (between ‘nearshore’ and ‘offshore’ locations). All this, however would have (substantial) consequences for the current description of the model formulations.

4.4.2 Nourishments

One of the conclusions from the results in this study is that the application of nourishments in the PONTOS model leads to more seaward predictions of the shoreline than found in the measurements: the predicted MCL-position is approximately 20–60m more seaward in the area surrounding Domburg than in the measurements. While the correct nourishment volumes are added to the coastal area, it is shown that these volumes stay present in the upper layers of the coastal zone for a relatively long time in the model, compared to observational data. This section shortly describes the two basic mechanisms that ‘should’ result in a decay of the nourishment volumes at the nourishment locations.

When considering nourishments it is expected that the added sediment volumes are redistributed throughout the model domain, in time, by both alongshore processes and cross-shore processes. Alongshore sediment ‘losses’ are expected as a result of gradients in the alongshore transports as a result of changes in the coastline angle and wave forcing at nourishments. Cross-shore ‘losses’ are expected due to the fact the nourishments result in a (relatively) steepened coastal profile that deviated from an equilibrium state.

Figure 4.31 shows that the calculated cross-shore transport rates are relatively low, such that losses of sediment towards deeper water are restricted. This may be in contrast to the measured positions of the Y1 and Y2 layer shown in Figure 4.14, that seem to indicate a flattening of the coastal profile over time to the north and south of Domburg. However, at this stage it appears that PONTOS will not predict the correct distribution of nourished sediment using the current cross shore “equilibrium layer width” mechanism. To increase the model skill in predicting shoreline development around nourishments it is therefore suggested to:

- Improve cross shore transport gradients by to attempting to calibrate the actual cross-shore transport rates rather than use an “equilibrium layer width”
- Improve cross shore transport rates by investigating the cross-shore transport processes during ‘extreme’ wave conditions
- Validate the longshore transport rates and gradients predicted by PONTOS.

4.5 Conclusions

The objective of this chapter was to provide an overview of all steps that are taken in order to improve the original PONTOS model setup that was used for case study ‘Domburg’ in Phase

II, and to give a best-possible estimate of the coastline evolution near Domburg. The original Phase II setup of the PONTOS model for Domburg is modified in this study by adding new features, by reconsidering earlier choices, and by (re-)calibrating some of the essential model settings.

The most important conclusions that can be drawn from the presented work in this chapter are:

- For the current runs without calibration of alongshore transport it was found that nourished sediment in PONTOS was not redistributed throughout the model domain as quickly as observed in reality, leading to more seaward development of the coast in the model than in reality.
- Sediment transport gradients in the alongshore and cross-shore direction (i.e. towards deeper water) seemed to be underestimated by the PONTOS model for the Domburg case. Calibration of the alongshore sediment transport is considered necessary to improve results, since the calibrated phase II PONTOS model provided reasonable predictions for the sediment budgets of the North-Walcheren coast.
- The modelling of the coastline protrusion at Domburg could not appreciably be improved in the Phase III PONTOS models, relative to the Phase II models, as the coastline still diffuses substantially over time.
- Further calibration of the equilibrium width of the layers (with respect to the Phase II model) and adjustment of the transport at the model boundary did not improve the model predictions substantially.
- Sensitivity tests with the relative wave angle around Domburg have a greater impact on the model predictions of the coastline change than modification of the cross shore transport parameters. In particular, the diffusion of the coastline position at Domburg is reduced substantially by the application of longshore-varying dominant wave angles.

The following recommendations for further development and validation of the PONTOS model are provided by Arcadis:

- Calibration of cross-shore transport parameters in the PONTOS model led to less improvement in the model results than modification of the relative wave direction and subsequent longshore transport rates. For improvement of both the alongshore and cross-shore transport gradients for ‘complex’ coastal areas it is therefore required to develop an option to impose near-shore wave conditions (rather than offshore conditions).
- With respect to cross-shore sediment losses it is recommended to investigate the role of storm events on the net cross-shore transport pattern.
- In order to better distinguish the effects of alongshore and cross-shore processes in relation to (large) nourishments, it is recommended to put more effort on validating the model’s performance on the basis of ‘real’ cases with large nourishment events (i.e. ‘Zwakke Schakel’ projects or the ‘Zandmotor’).

5 Analysis of model components

5.1 Introduction

This chapter provides the synthesis of the modelling effort in Chapters 3 and 4. This concerns a summary of the various model components and their relevance for coastline modelling (Section 5.2) and guidelines for the effective use of the models (Section 5.3). The synthesis tries to account for the fact that different model components can have different impacts at other coastal stretches than the coast of North-West Walcheren.

5.2 Relevance of model components

A number of model components were investigated in the Phase I, II and II coastline modelling studies. A description of these model components and their relevance for cross-shore sediment transport are summarised and described in Table 5.1.

Table 5.1 Overview of model components and their relevance

Model component	Summary of relevance
PHASE I	
Transport formulations	Different sediment transport formulations are available in the models. Resulting in large differences in computed net-transport rates and sensitivity to environmental conditions. Of the three models, UNIBEST-CL+ and PONTOS are most similar for computed longshore transport, where the average relative difference in computed longshore transport per wave condition is 13% (standard deviation 48%). Differences in computed sediment transport between UNIBEST/PONTOS and LONGMOR were for the considered range of conditions on average about 50%.
Method of computing transport rates (climate vs. time series) (net vs. gross transport)	The three models differ in the way in which wave climate transports are computed. UNIBEST-CL+ computes net sediment transport for varying angles of coastline rotation before the main morphological simulation with a dedicated process-based model. The PONTOS and LONGMOR models compute longshore transports every numerical time step, using simplified transport formulations. PONTOS uses net-transports to update the coastline, whereas in LONGMOR gross transports are computed for every wave condition and imposed as a user-defined time series. The actual choice for a wave climate (UNIBEST), net longshore transport (PONTOS) or wave time series (LONGMOR) should be well thought off as it typically dominates the model results.
Re-orientation of the coastline / foreshore	The way in which the coastline model accounts for re-orientation of the coastline during the simulations significantly affects the net transports for situations where considerable re-orientation of the coastline is expected throughout simulations. This works as follows: (1) net-gradients in alongshore transport enforce a coastline re-orientation more normal to the incoming waves, (2) the waves do then experience less refraction towards the shore and (3) the effective net alongshore transport is smaller. Typically, PONTOS and LONGMOR assume that the full profile up till deep water will experience re-orientation. UNIBEST assumes that only the nearshore part of the profile will re-orientate while the deeper foreshore will keep its orientation.

Alongshore interpolation of wave conditions	The interpolation of longshore transport rates along the coast is of relevance for situations with wave climates with a considerable proportion of oblique waves (relative to the coast). UNIBEST interpolates the computed sediment transport and equilibrium coastline angle, which gives stable results. PONTOS interpolates the wave conditions along the coast, which can lead to opposing zones of sediment transport convergence and divergence between the two models. LONGMOR is unable to compute transport under spatially varying wave conditions. In practice this aspect is, however, not considered to have a large impact on the results.
Numerical scheme	The numerical scheme used in PONTOS and LONGMOR may become instable under specific conditions and affect the numerical diffusion. It is advised to test the influence of the alpha parameter and set it to a minimum value for which the model is still numerically stable.
Alongshore schematisation method of the coastline	The schematisation of the coastline differs for each of the models. The UNIBEST and PONTOS model use an approach with a reference coastline which is located landward of the actual coast, while the shoreline is directly included as input in the LONGMOR model. Results should be similar for most models, but the approach with the reference coastline allows for the inclusion of abrupt changes in the coastline (e.g. different coastline position at both sides of a structure). This issue was, however, not verified in detail in the studies.
PHASE II	
Active height of the profile (i.e. time scale)	The active height of the profile influences the time scale at which coastline changes (e.g. retreat, accretion or re-orientation) take place. Within PONTOS the active height is accounted for by the different layers, while it should be specified in UNIBEST and LONGMOR on the basis of estimates of the depth of closure. The rate of coastline changes also differed, as the models respectively compute changes for a quickly reacting layer (PONTOS) or aggregate changes over the whole active height (UNIBEST / LONGMOR) which gives a slower response. Both approaches are valid, but should be used with care.
Calibration of net-alongshore transport	Differences in net longshore sediment transport rate were responsible for the majority of the variability in the nourishment predictions. The calibration of the net longshore transport rate reduces nourishment volume differences between models from a 300% to just 10%. For the considered case at Domburg it was found that PONTOS and LONGMOR required considerable calibration as the computed transports were smaller than expected on the basis of global estimates of the sediment budgets. The UNIBEST model can be applied with some confidence without calibration as the process based transport formulations give it some more robustness. Results show that that correct calibration of longshore sediment transport is crucial to maintaining inter-model and model-data similarity.
Inclusion of nourishments	The inclusion of nourishments works quite well in the coastline models (i.e. about 10% difference for calibrated models). It was found that simulations with pro-active nourishments (i.e. supplying sediment such that the coastline remains in place) yielded similar results as pre-defined nourishments. Some attention should be paid to the distribution over the vertical layers in PONTOS.

PHASE III	
Cross-shore sediment transport & schematisation method of the coastline	Cross-shore sediment transport generally has a small influence on coastline evolution of sandy coasts, since the magnitude of cross-shore transport is often small compared to the alongshore transport. However, for specific parts of the coast the cross-shore transports may affect the model predictions significantly. One can think of coastal sections with active tidal channels very near to the coast (e,g. near to tidal basins). Furthermore, an initial effect of cross-shore redistribution may take place for nourishments. For the coast around Domburg the effect of the multiple layers was small, because the cross-shore sediment transport magnitude in this area is relatively small compared to the alongshore transport rates. The UNIBEST and LONGMOR models can include cross-shore sediment transport as losses or sources in the model. They assume that the sediment is taken from the whole of the active part of the surfzone. PONTOS uses an approach with multiple layers which allows for cross-shore flux of sediment between the nearshore layers and the offshore layers.
Offshore versus nearshore wave conditions	Coastline models need nearshore wave conditions (from 2D wave transformation models) for coasts which are not alongshore uniform or which have a complex geometry of the foreshore with shoals and tidal channels. The reasoning behind this is that most of the alongshore sediment transport takes place in the upper part of the coastal profile (e.g. above NAP-6m). Consequently, the nearshore conditions that drive these changes should be well represented. Simulations with UNIBEST model showed that a better representation of detailed coastline features (such as the protrusion at Domburg) can be obtained for areas with a complex foreshore. In the case of Domburg the nearshore conditions are significantly impacted by the shoals of the Eastern Scheldt ebb-tidal delta. PONTOS simulations with slightly adjusted wave angles also showed the relevance of small changes in incoming wave angle (as a result of refraction) on detailed morphology of the coast.
Cross-shore profile shape in the zone with alongshore transport	Variation of the cross-shore profile shape on alongshore sediment transport is smaller than the influence of many other parameters such as the use of nearshore wave climate conditions or the selection of a transport formulation. It is, however, noted that large changes in cross-shore profile shape along the shore may have an influence on wave refraction towards the shore and therefore indirectly affect the alongshore sediment transport gradients significantly.
The effect of vertical and horizontal tide	Horizontal and vertical tide have some influence on the resulting net sediment transport, but this influence was shown to be smaller than other considered aspects like transport formulations for the Domburg case. However, it cannot be excluded that other areas of the coast (e.g. in tidal basin inlets) may experience a significant impact of the tidal flow. Furthermore, it should be checked whether the considered study area experiences smaller or larger wave impacts during the high or low water phase of the tide.

5.3 Guidelines for model setup

Typically, the most important aspects to account for when applying a coastline model are:

- Aims of the modelling effort
- Spatial and temporal scale
- Characteristics of the study area
- Model specific settings

When starting off with setting up a coastline model, it is relevant to clarify the aims of the study. Some studies require detailed information for a specific location (e.g. a specific town or an area with structures) while others aim at obtaining inside in the total aggregated volume of nourishment sand that is needed for a specific section of the coast (e.g. the budget for the Rijnland coast). Or even the aggregated volume required for the full coast during a decade (e.g. rapid assessment tools for policy making). The first type requires insight in the smaller scale variations in the coastline position (and needs nearshore wave conditions or cross-shore profile information) whilst some of the aggregated studies can be performed without considering the small alongshore variations in the wave climate (see Figure 5.1).

In fact the aim of the study also influences the relevant spatial and temporal scale at which the study should be resolved. Typically, coastline models are employed at a scale of 5 to 100 kilometres. Studies which aim at smaller spatial scales (e.g. size of the nourishment itself) can better be resolved by detailed models like Delft3D, which resolves detailed sediment transports and wave transformation.

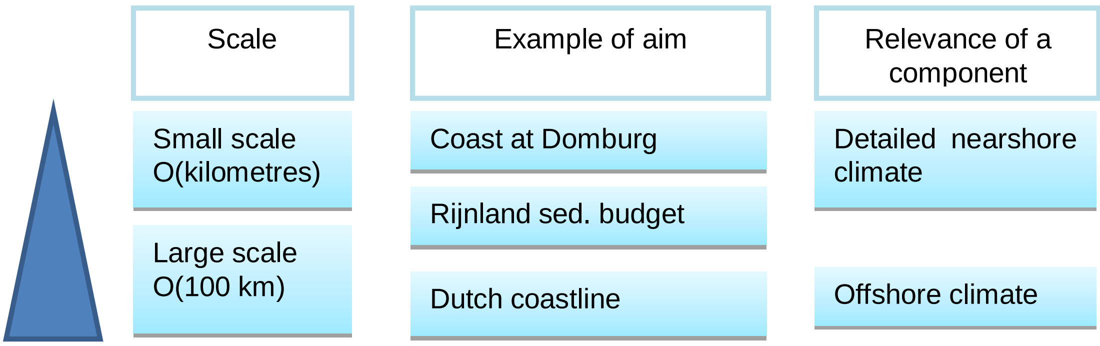
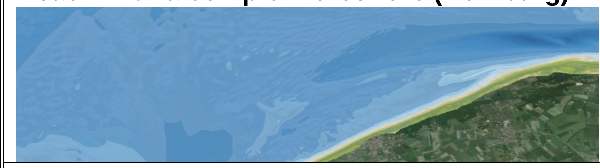
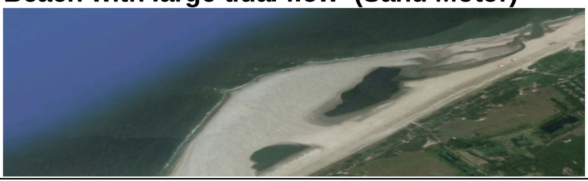
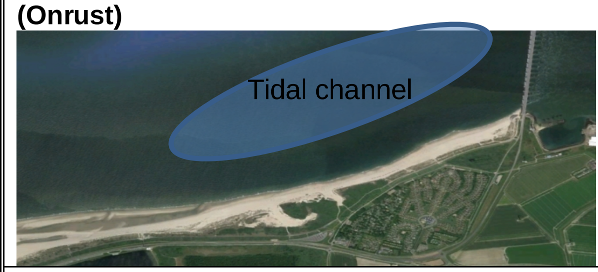


Figure 5.1 Small scale and large scale studies and some typical aims

Besides the aims of the study, the physical characteristics also play a role (see Figure 5.2). The relevant processes that drive sediment transport should in any case be resolved in the model. This means that different approaches should be chosen for different parts of the coast. The simplest case concerns a uniform sandy coast with small tidal influence and waves from relatively 'low angles' (i.e. dominate by waves that come in at angles less than 45º from the shore-normal). Such a coast can be studied with a model that computes just the wave-driven alongshore current. For some areas also the tide is of importance. Additional to this some processes can be important. First of all, some coasts have complex foreshores which require the use of detailed wave computations and alongshore varying nearshore wave conditions. Secondly, there are beaches with large differences in water levels. Thirdly, beaches can experience considerable tidal flow velocities (e.g. close to tidal basins or at a protrusion of the coast) which should be modelled with the inclusion of the effect of sediment transport due to the tide. Very specific situations along a coast may also require the estimation of cross-shore sediment transport. This holds especially, if a tidal channel is present very near to the shoreline. A particular, rather complex, situation concerns the detailed processes near to harbour moles or breakwaters. The hydrodynamics and transport processes are affected by wave diffraction and setup driven flows. Similarly complex is the modelling of small groynes along the coast, which requires an assessment of the partial blockage of the transport.

Figure 5.2 Overview of typical study areas with some relevant processes

Type	Relevant processes
Uniform beach with moderate to small tide 	• Wave-driven alongshore transport. • Tidal flow impacting transport (gradients) depending on the modelling aims
Beach with a complex foreshore (Domburg) 	• Wave-driven alongshore transport with alongshore varying wave conditions • Tidal flow impacting transport (gradients) depending on the modelling aims
Beach with large tidal flow (Sand Motor) 	• Wave-driven alongshore transport with alongshore varying nearshore wave conditions. Wave focussing on the head of a coastline feature can be of relevance. • Tidal flow generating alongshore transport (gradients) and horizontal circulation patterns.
Beach with large tidal range (Wales) 	• Wave-driven alongshore transport (possibly with alongshore variability due to the shallow foreshore) • Tidal water levels impacting the duration of sediment transport at the beach, as it impacts the nearshore wave condtions. • Tidal flow driving transport on the beach
Beach with nearby tidal channel (Onrust) 	• Wave-driven alongshore transport with alongshore varying wave conditions to account for the effect of the tidal channel on wave propagation. • Tidal flow at the beach • Cross-shore transport towards the channel (either in the model or by application of known transports as sinks.
Coastline near to structures (IJmuiden) 	• Wave-driven alongshore transport • Wave diffraction and sheltering behind the breakwaters • Water level setup driven currents (e.g. rip currents)
Coast with small groynes (Noord-Holland) 	• Wave driven alongshore transport • Tidal flow constriction • Water level setup driven currents • Impact of partial blockage of transport

Finally, the model specific features are also of relevance. This concerns aspects like the diffusion coefficient (alpha) in the PONTOS and LONGMOR models. This diffusion coefficient should be set at a value for which the model is stable, but also a value that minimises the artificial diffusion. Other aspects include the time and spatial discretisation which should be sufficient to resolve the considered processes sufficiently. Furthermore, each of the considered processes requires a number of input settings which may be related to the modelling approach.

5.4 Conclusions

This chapter provides an overview of model components of coastline models and their relevance for the specific situations that were investigated in the Phase I to III coastline modelling studies. In general it can be stated that transport formulations, calibration of alongshore sediment transport, the active height of the profile and (nearshore) wave conditions are the most essential aspects of a coastline model. Additionally, the cross-shore sediment transport, tidal flow and method of re-orientation of the shoreline can be relevant for specific situations along the coast. The actual selection of processes depends strongly on the considered area of interest and the aims with model.

6 Conclusions

6.1 Conclusions

The main aim of this report is to distinguish the causes for differences in predictions of coastline models for the 'Zwakke Schakels' studies. For this purpose a case study focussing on coastline evolution at Domburg is investigated, which should show the relevance of modelling aspects and modelled processes. This is the third phase of a series of studies that investigate coastline modelling. The commonly applied coastline models UNIBEST-CL+ and PONTOS are used. An important distinction between these models is that the UNIBEST-CL+ model uses a straightforward approach with a single line to schematise the coastline, whereas the PONTOS model uses a more complex approach which schematises the coast with five layers (at different vertical levels).

The study with UNIBEST investigated the influence of (1) Offshore conditions versus alongshore varying nearshore wave conditions, (2) alongshore variation in the cross-shore profile, (3) horizontal and vertical tide and (4) transport boundary conditions. The PONTOS study focussed mainly on the influence on the coastline evolution of cross-shore sediment transport. The following conclusions were drawn with respect to the relevance of specific processes for the case study at Domburg.

- Longshore sediment transport dominates the coastline evolution at Domburg. The computed gradients in the alongshore transport alone provided good predictions for the coastline evolution at Domburg.
- Because of the successful hindcast for Domburg solely based on longshore transport gradients and the fact that calibration on parameters related to cross-shore transport did not improve the Pontos model predictions substantially, it is concluded that the relevance of the cross-shore sediment exchange to the coastline evolution was very small (i.e. compared to the effect of alongshore varying nearshore wave conditions). Hence the added value of a multi-line model is minimal for this case study. A multi-layer approach may, however, be useful for cases where the initial (first year) cross-shore redistribution is of importance.
- Longshore-varying nearshore wave climates are required to resolve the observed local coastline development at Domburg.
- It is expected that situations with a complex shoreface always will require accurate nearshore wave conditions to determine the longshore transports.
- Other modelled processes provided a small but less significant improvement to the model results. This holds for (1) the horizontal and vertical tide which can increase the rate of longshore transport by approximately 10%, (2) for imposing a sediment flux (i.e. calibration) at the model boundary which improved the predictions for the sea-dike north-east of West-Kapelle and (3) the application of spatially varying cross-shore profiles which were only relevant in combination with offshore wave conditions since the profiles affected the wave propagation towards the coast.

The main conclusions with respect to the model related choices and ability to resolve the coastline development at Domburg are:

- It was found that the modelled coastline development at Domburg was substantially different for the UNIBEST-CL+ and PONTOS model. The UNIBEST-CL+ results matched better with the observations since it uses nearshore wave conditions. This

indicates that a straightforward one-line model can resolve coastline evolution for a complex coast such as at Domburg.
- The applied state-of-the-art process based transport formulation Van Rijn (2004) in UNIBEST-CL+ provided reliable and robust predictions of the alongshore transport (gradients) at the Domburg coast without the need for a detailed calibration.
- Alongshore sediment transport (gradients) were underestimated with the current PONTOS model, which results in modelled nourishments that are not as mobile as observed in the field at Domburg. The current standard procedure for PONTOS to use uncalibrated alongshore transport from the build-in transport formulation therefore needs to be improved. Without this improvement the longshore transport in the PONTOS model will require a calibration when considering coastal areas with a complex bathymetry.
- Application of nearshore wave conditions resulted in significantly improved model predications for the local coastline feature at Domburg with the UNIBEST-CL+ model.
- Nearshore wave conditions could not be applied in the Phase III PONTOS model. It is, however, considered necessary to add nearshore wave conditions to the PONTOS model to resolve coastline features such as at Domburg. Sensitivity simulations with altered wave angles along the coast did show that the model performance of PONTOS can improve significantly as a result of alongshore variation in wave forcing.

The discrepancies in the predicted maintenance nourishment volumes for the ‘Zwakke Schakels’ described in the introduction of this report, which initiated this comparative study, can partly be explained by the obtained results. For the Domburg case it was found that the use of uncalibrated longshore transports in the PONTOS model results in a smaller mobility of nourishments than observed in the field, which may also be a cause for the differences in the predicted diffusion of the large scale nourishments which are part of the ‘Zwakke Schakel’ designs. Although not proven on the basis of the current case at Domburg, it is expected that PONTOS will predict lower nourishment volumes to maintain the coast compared to predictions based on models with state-of-the-art transport formulations (such as in UNIBEST-CL+). Additionally, the use of nearshore conditions may also be relevant for some parts of the Holland coasts. Overall, it is fair to conclude that the coastline development near more complicated coasts such as at Domburg can be modelled with sufficient accuracy using a one-line model provided that the nearshore wave climate is represented correctly.

The synthesis of the results of the models provided an overview of the relevance of model components for the different phases of the model studies. Besides the findings of this Phase III study it is stressed that some modelling aspects that were investigated in the previous phases of the coastline modelling studies are also of relevance. This concerns the selection of the transport formulation, calibration of alongshore sediment transport, selection of the active height of the profile and correct handling of the re-orientation of the shoreline. It is also stressed that a good application of coastline models depends on (1) the aims of the studies, (2) temporal and spatial scales involved, (3) characteristics of the study area and (4) model specific settings and capabilities.

6.2 Recommendations

The following recommendations are put forward:

- Investigate the relevance of coastline models at other typical coastal sections (see Figure 5.2). In particular the redistribution of recent nourishments like the ones at Katwijk-Noordwijk or at the Pettemer zeewering can be studied. Furthermore, little knowledge is available on the application of coastline models in areas near to structures where wave sheltering, diffraction and setup driven currents are expected to be of relevance.

- Investigate the relevance of time-series of wave conditions versus the use of a static wave climate since it is becoming more common to use time domain computations
- Setting up a reference database with computed sediment transports (and transport gradients) which can be used to assess the consistency with other studies.
- Investigate the orders of magnitude of alongshore and cross-shore transport processes for different parts of the coast. Maps can be made which show what processes should be accounted for at different parts of the Dutch coast.
- Performing or repeating sediment budget studies for the Holland Coast, Wadden and South-Western delta.

Literature

Deltares, 2009. Sand demand of the Eastern Scheldt, morphology around the barrier. Technical Report Z4581. Delft, The Netherlands.

Deltares, 2010. Herziening Basis Kustlijn, Technical Report 1200104. Delft, The Netherlands.

Deltares, 2013. Modelling coastline maintenance: a review of three coastline models. Technical Report 1206171-005. Delft, The Netherlands.

A Nearshore Wave Transformation

A.1 Introduction

This Appendix describes the wave model that was used for his study. This concerns a model that was set up during a study of the Sand Demand of the Eastern Scheldt (Deltares, 2009). For completeness, the information from the wave model in that report is provided in this appendix.

A.2 Model setup

The following steps were performed to derive representative nearshore (normal) wave conditions:

- Selection of offshore data point with wave measuremernts
- Schematisation of measured offshore wave data to a limited number of representative conditions;
- Transformation (i.e. wave propagation towards the coast) of waves from offshore to the area of interest near to the Eastern Scheldt Barrier and along the coasts of Walcheren and Schouwen.

A.2.1 Selection of offshore data point

For the derivation of representative normal wave conditions, a data point with a long series of wave measurements is required. At some locations on the North Sea such wave measurements over a long period (tens of years) are available. In this study offshore wave and wind data from the ‘Europlatform’ were used, as this is the ‘nearest data point where also measurements of the wave directions are available. For the analyses, 21 years (1979 to 2002) of wave height measurements and 22 years of wind data (1983 to 2005) at the ‘Europlatform’ were used. However, as it is too time consuming to simulate the wave propagation towards the coast over a long period of time, these data had to be schematised. For this purpose the time series of wave conditions is schematised to a limited number of typical wave conditions, which are representative for the total time series of wave conditions.

A.2.2 Schematisation of wave measurements

First of all, a distinction was made between sea (local wind generated) and swell (propagating from elsewhere) waves. To make this distinction a typical relation between Hs and Tp was used to split the sea and swell waves (eq. 1).

$$H_s = \left(\frac{1}{4.5} T_p \right)^B + C \qquad (1)$$

Above relation has been established on the basis of a relationship for the maximum steepness of wind-sea waves, as found in the Joint North Sea Wave Project (JONSWAP). For the maximum steepness of the waves in wind-sea, a coefficient for ‘B’ of 2 and a coefficient for ‘C’ of 0 were found in the JONSWAP project. For the ‘Europlatform’ a line with a more or less similar shape was used to divide sea and swell waves (B = 1.8, and C = -0.45) with an additional constraint for the minimal peak wave period (Tp) for swell (should be >5s). In Figure A.1 a plot of the wave measurements at the 'Europlatform' and the applied splitting line between sea and swell are presented.

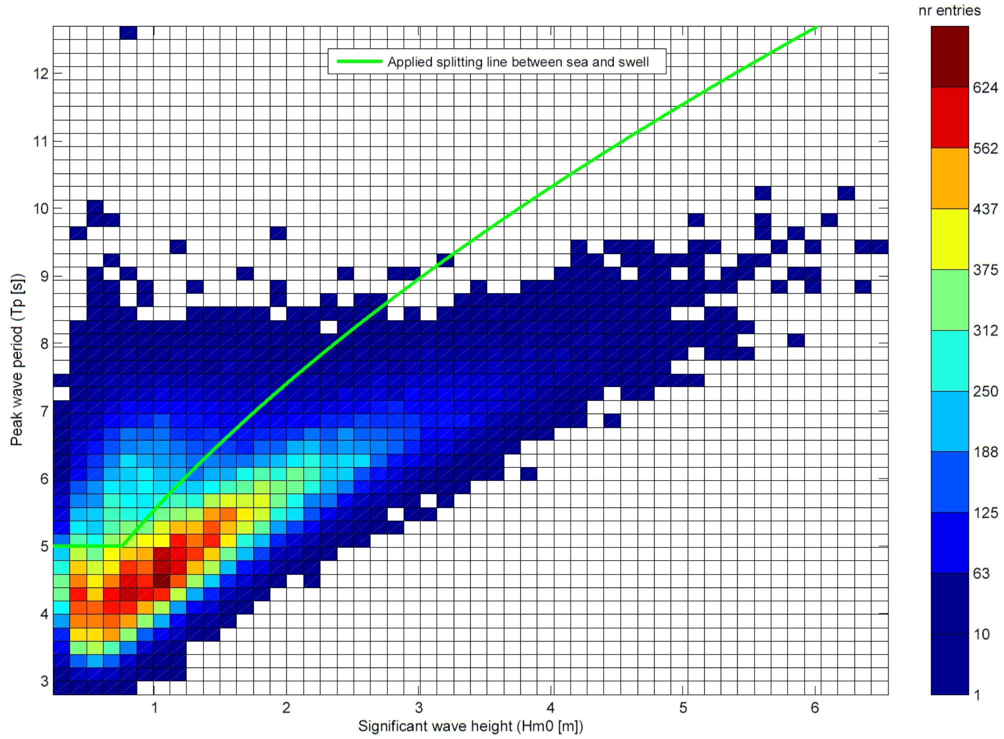


Figure A.1 Scatter plot of wave conditions (on wave height and period) showing the applied differentiation between sea and swell

Secondly, a schematisation was made for the wind-sea and for the swell data separately. This was done by bunching measurements in bins with more or less similar wave conditions. For each of these 'wave bins' the corresponding wind measurements were also bunched. More elaborately, the procedure can be described as follows:

4 the wave measurements are bunched in bins with a characteristic range of wave height, wave period and wave direction. In this study, the measured waves smaller than 0.35m were ignored.
5 For each bin typical wind conditions (wind speed and wind direction) were computed from the wind measurements that correspond with (were measured at the same time as) the wave measurements in that bin.
6 The number of measurements in each bin is a measure for the duration of a condition.

The bin sizes for the wave height, wave period, wave direction, wind speed and wind direction are presented in Table A.1. The bin size of the wave height bins was 1.5m, with an exception for the first class which ranged from 0.35 to 1m. Wave directions were divided in 30° sectors. For the wave period three bins were used, ranging respectively from 1-5 s, 5-10s and larger than 10s.

Class		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Significant wave height	(H_s) [m]	0.35-1	1-2.5	2.5-4	4-5.5	5.5-7	>7						
Peak wave period	(T_p) [s]	1-5	5-10	>10									
Wave direction	(dir) [°N]	15 - 45	45 - 75	75 - 105	105 - 135	135 - 165	165 - 195	195 - 225	225 - 255	255 - 285	285 - 315	315 - 345	345 - 15

Table A.1 Classification of normal wave conditions at offshore location (Europlatform)

The schematised normal wave climate is presented in Table A.2.

Cond.	Hs [m]	Tp [s]	Peak wave direction [°N]	Duration [Days]
1	0.6	4.4	1	11.04
2	0.7	4.3	29	11.93
3	0.6	4.1	59	6.71
4	0.7	4.0	90	4.33
5	0.7	3.8	120	3.51
6	0.6	3.8	151	3.53
7	0.7	3.9	183	5.68
8	0.7	4.0	213	13.34
9	0.7	4.2	239	18.59
10	0.7	4.2	269	8.61
11	0.6	4.3	300	6.65
12	0.6	4.4	331	6.95
13	1.2	4.7	1	2.84
14	1.2	4.7	30	3.67
15	1.2	4.7	60	2.25
16	1.3	4.6	91	2.4
17	1.2	4.4	120	1.46
18	1.3	4.4	152	1.18
19	1.3	4.4	184	3.4
20	1.3	4.6	214	12.31
21	1.3	4.6	237	12.92
22	1.3	4.6	268	4.52
23	1.2	4.7	300	2.53
24	1.2	4.7	331	2.19
25	0.9	5.2	2	0.92
26	0.9	5.2	27	0.64
27	0.9	5.2	59	0.22
28	0.9	5.2	84	0.031
29	0.9	5.2	123	0.016
30	0.9	5.1	149	0.036
31	0.9	5.2	185	0.042
32	0.9	5.2	215	0.13
33	0.9	5.2	239	0.53
34	0.9	5.2	270	0.29
35	0.9	5.2	301	0.34
36	0.9	5.2	331	0.5
37	1.7	6.0	359	16.18
38	1.6	5.8	29	9.37
39	1.7	5.7	58	3.9
40	1.7	5.5	87	1.14
41	1.6	5.4	118	0.26
42	1.9	5.5	154	0.26
43	1.8	5.5	186	1.51
44	1.8	5.6	217	14.29
45	1.8	5.7	237	23.92
46	1.8	5.7	269	8.82
47	1.7	5.8	301	8.03
48	1.8	6.1	332	12.6
49	3.0	7.3	357	2.78
50	3.0	7.0	29	1.13
51	2.8	6.7	56	0.36
52	2.7	6.1	87	0.073
53	2.8	6.2	123	0.042
54	3.2	6.4	150	0.036
55	3.0	6.3	185	0.29
56	2.9	6.4	217	3.88
57	3.0	6.7	236	9.99
58	3.1	6.7	270	3.58
59	3.0	6.8	300	2.4
60	3.0	7.3	332	4.15
61	4.5	8.6	356	0.2
62	4.2	8.3	28	0.036
63	4.7	8.0	71	0.0052
64	4.6	8.0	146	0.01
65	4.2	7.8	179	0.01
66	4.3	7.5	219	0.089
67	4.4	7.7	239	0.59
68	4.5	7.7	270	0.49
69	4.4	7.8	300	0.34
70	4.4	8.5	331	0.5
71	5.6	9.2	350	0.0052
72	5.8	7.9	210	0.0052
73	6.0	8.9	240	0.026
74	5.8	8.0	284	0.0052
75	5.9	8.9	289	0.0052
76	5.9	9.4	332	0.042
77	5.6	10.2	346	0.0052
78	6.2	10.2	339	0.0052
79	0.5	5.0	0	0.78
80	0.5	5.0	28	0.31
81	0.6	5.0	63	0.1
82	0.6	5.0	92	0.01
83	0.5	5.0	122	0.026
84	0.5	5.0	154	0.0052
85	0.5	5.0	186	0.031
86	0.6	5.0	211	0.073
87	0.6	5.0	243	0.14
88	0.6	5.0	270	0.14
89	0.6	5.0	301	0.29
90	0.6	5.0	331	0.49
91	0.7	6.0	358	19.44
92	0.7	5.7	26	3.98
93	0.7	5.9	60	1.2
94	0.7	5.9	87	0.6
95	0.7	5.8	120	0.31
96	0.6	5.9	152	0.24
97	0.7	5.8	182	0.51
98	0.7	5.7	211	0.73
99	0.7	5.7	242	1.61
100	0.7	5.8	271	1.68
101	0.7	5.8	302	3.05
102	0.7	6.0	334	9.27
103	1.3	6.7	357	8.72
104	1.2	6.5	27	1.07
105	1.2	6.5	60	0.37
106	1.2	6.6	90	0.2
107	1.3	6.8	123	0.057
108	1.4	6.6	148	0.042
109	1.4	7.2	182	0.1
110	1.1	6.2	212	0.068
111	1.1	6.1	240	0.23
112	1.2	6.4	273	0.35
113	1.2	6.5	302	0.85
114	1.3	6.8	335	4.52
115	2.8	8.7	350	0.016
116	2.7	8.7	335	0.031
117	0.7	12.6	344	0.0052

Table A.2 Schematised normal wave climate (all year)

A.2.3 Transformation of waves from offshore to nearshore

The schematised wave climate is representative only for the offshore location. Therefore the propagation of waves towards the coast should be modelled to attain normal wave conditions at relevant nearshore locations. For this purpose SWAN model simulations were carried out for all five climate scenarios (all year, winter, spring, summer, autumn). The SWAN model is a model that computes the transformation of waves due to a number of physical processes, like wave breaking, whitecapping, shoaling and refraction.

In the wave computations a constant waterlevel at mean sea level (excluding surge, tide and sea level rise) was applied. Note that these water levels are not expected to have a significant impact on the SWAN results for most of the selected locations (which have considerable water depth). The structures (e.g. the Eastern Scheldt storm surge barrier) were schematised as a closed boundary with zero reflection.

Model computations were performed for two typical bathymetries, namely:

- Bathymetry data of the Dutch coast for 2004 (supplemented with 2003 data) were used. Figure A.2 presents an overview of the applied wave grids and 2004 bathymetry.

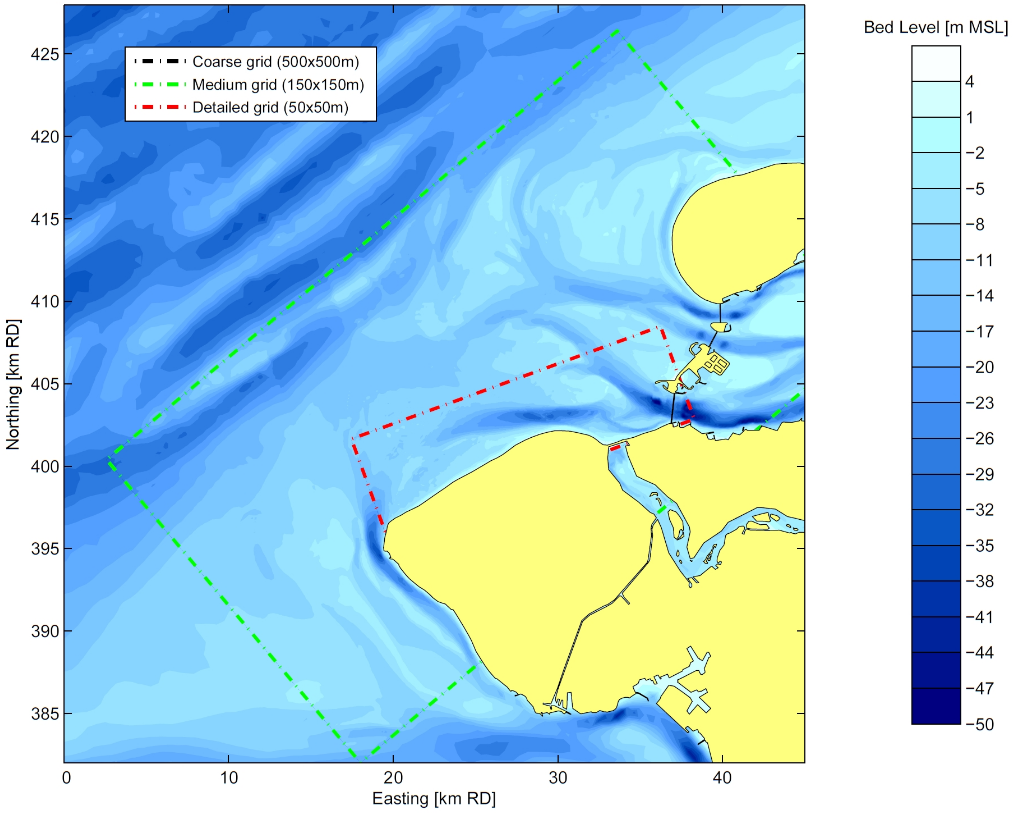


Figure A.2 Large scale bathymetry of the wave model