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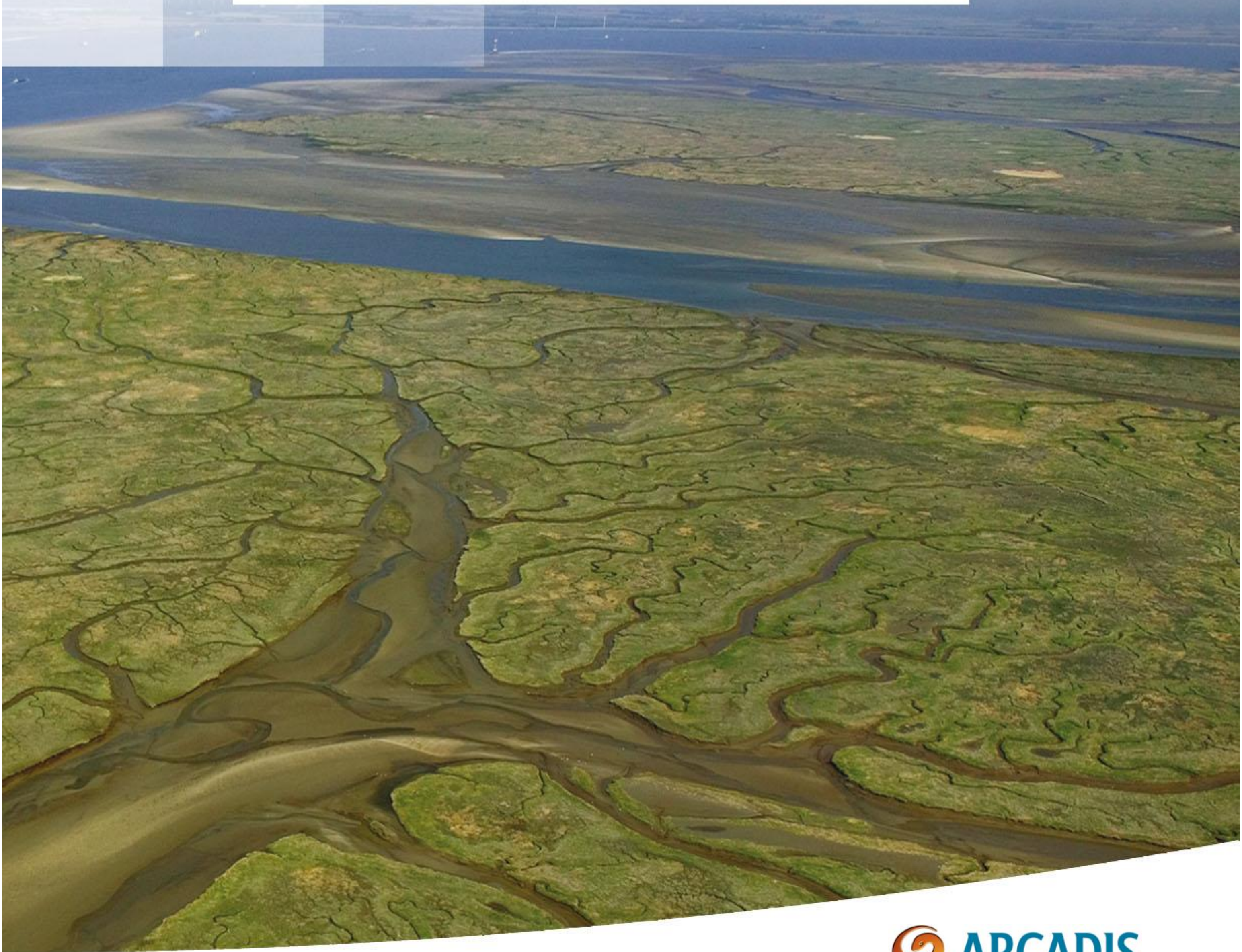
Modelling coastline maintenance

A review of three coastline models



ARCADIS

Modelling coastline maintenance

A review of three coastline models

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Summary
Coastal evolution models have been used in the past to assess nourishment volumes for the Zwakke Schakels projects on the Dutch coast. The results of these simulations showed substantial differences in required nourishment volumes for the affected coasts. This report focusses on identifying differences between three coastal evolution models (UNIBEST-CL+, PONTOS and LONGMOR) and the effect these differences have on model predictions of coastal evolution and nourishment volumes. In Part I of this report, a series of simple, schematic simulations is carried out in which clear differences between the models are identified. The results of Part I are used to set up and analyse a more complex, real-world simulation of the coast of Walcheren in Part II.

The results of Part I show clear differences in morphological evolution and predicted nourishment volumes between the three coastal evolution models. The greatest differences are due to differences in the computed sediment transport rate. Additional differences occur due to the manner in which waves are refracted from deep water, the coastline is allowed to rotate, the manner in which wave conditions are interpolated in the alongshore direction and the manner and timescales with which cross shore profiles respond to longshore transport gradients.

Part II of this study shows that the net longshore sediment transport rate is responsible for the majority of nourishment prediction differences between models. The calibration of the net longshore transport rate reduces nourishment volume differences between models from a 300% to just 10%. The most important recommendation of this study is to ensure all coastal evolution models are calibrated to the same longshore transport rate before comparative studies are carried out. Other recommendation include the incorporation of wave refraction models in PONTOS and LONGMOR and further investigation of the strengths of the cross shore transport model in PONTOS and the process-based longshore transport model in UNIBEST-CL+.

The study has only investigated the effect of differences between models, not differences between schematisation choices, model input methods and model analysis techniques. This study recommends investigating the relative contribution of these differences to the observed differences in model results.

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Contents

1 Introduction

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 Z*wakke 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.

This report will focus solely on identifying differences in coastal evolution model results due to differences in the numerical processing in the models themselves. The effect of differences in the way data, model input and model output are handled are removed by imposing identical boundary conditions on all models and by using the same metrics to analyse model results. This report will focus specifically on three coastal evolution models used commonly for the Dutch coast: UNIBEST-CL+ (WL|Delft Hydraulics, 1994), PONTOS (Steetzel, *et al*., 1998) and LONGMOR (Van Rijn, 1998; Van Rijn, 2002; Van Rijn, 2005).

This report is divided into two modelling parts. Part I describes a set of schematic simulations that are run to gain insight into the differences between the three coastal evolution models for relatively simple forcing conditions. Part I is discussed in Dutch, but an English summary is provided at the start of the chapter. The conclusions of Part I are used to study a more complex model setup in Part II. In this part, the evolution of the North-West coast of Walcheren, Zeeland, around Domburg is studied in all three coastline evolution models. In order to maintain similarity between the models, some simplifications are applied with respect to the highly complex processes in the area. The effect of model differences on the coastline evolution at Domburg and predicted nourishment volumes for that area of coast are examined. This report ends with a series of conclusions and recommendations based on the results of Part I and Part II.

The project is part of the KPP-B&O Kust 2012 programme carried out by Deltares for Rijkswaterstaat Waterdienst. The work carried out in this project was done by Deltares in cooperation with Arcadis.

2 Part I: Schematic cases

2.1 English summary

In Part I of this project, all three coastal evolution models are analysed by means of a number of simple, schematic simulations. These simulations highlight several key differences between the models that may lead to varying model predictions. These differences are summarised below. The full results of these schematic simulations are discussed in this section in Dutch.

- Computed longshore sediment transport rates can vary between the three models for given wave conditions by as much as a factor 2–4. 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%).
- The three models differ in the way in which wave climate transports are computed. In UNIBEST-CL+ the net sediment transport for varying angles of coastline rotation are computed before the main morphological simulation using a dedicated process-based model to simulate wave transformation (ENDEC; Battjes and Janssen, 1978) and wave driven sediment transport. The computed net transport is subsequently parameterised using an inverse exponential function of the coastline angle with three free parameters (see Part I), which is used in subsequent coastline morphology computations. The difference between the computed and parameterised transport rate is approximately less than 1% for regular wave climates.
  The PONTOS and LONGMOR models compute longshore transports every numerical time step, using simplified transport formulations. In PONTOS the coastline is updated using the net transport for the entire wave climate, whereas in LONGMOR gross transports are computed for every wave condition in the climate and these are imposed in a user-defined time series to update the coastline morphology. The definition of the wave time series in LONGMOR does affect the final model results.
- A significant contribution to the differences in modelled longshore transports and coastline change between the models can be explained by the assumptions made with regard to the rotation of the coast. For certain wave climates, these differences in model assumptions can significantly impact the predicted net sediment transport.
  In UNIBEST-CL+ the coast is allowed to rotate within the so-called active layer, which is usually defined as the cross shore extent within which a certain proportion (90–98%) of the longshore transport takes place. Depth contours beyond the active region are assumed not to change when the coastline rotates. This assumption means that waves approaching the coast at an angle will initially refract on the unchanging deep water depth contours and reach the active portion of the coast at an angle less than the deep water wave direction. In UNIBEST-CL+, the resulting equilibrium coastline angle for this wave condition is consequently less than the deep water wave direction.
  In LONGMOR, the active layer is assumed to extend to deep water and therefore the offshore offshore wave angle equals the wave angle at the seaward boundary of the active layer. In consequence, the equilibrium coastline angle for a given wave condition is always perpendicular to the deep water wave direction in LONGMOR.
  This principle applies in a similar manner in the PONTOS model. In PONTOS, equilibrium angles are computed for every vertical layer in the model, which theoretically all equal the offshore wave angle. However in certain limited situations, the equilibrium angle of a layer may differ from that of the offshore wave angle, due to cross shore

sediment transport gradients. Due to the cross shore sediment exchange between the vertical layers in PONTOS, the time scale required to reach the equilibrium coastline angle is greater in PONTOS than in LONGMOR and UNIBEST-CL+.

- Differences in the way longshore-varying wave conditions are interpolated in UNIBEST-CL+ and PONTOS can lead to very different longshore transport rates in the case of wave climates in which there is considerable wave energy in very oblique angles relative to the coast. In UNIBEST-CL+, sediment transports are interpolated between locations where wave climates are imposed. In PONTOS, wave conditions are interpolated in the longshore between imposed wave climates, after which the local sediment transport is computed. For certain wave climates, this 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.
- The LONGMOR and PONTOS models use an inherently unstable numerical scheme to compute coastline morphology. In order to prevent coastline instabilities growing in size, the LONGMOR model includes a numerical diffusion term. The user of this model is obliged to select the minimal magnitude of numerical diffusion for which the model remains stable. However, in some cases the contribution of numerical diffusion to the total coastline morphology may not be negligible. Although the PONTOS model uses a similar numerical scheme to update coastline morphology, this model does not appear to be sensitive to user-imposed stability criteria. When required to impose numerical stability, the user may reduce the maximum allowed coastline change per time step, which forces the model to use reduce the numerical time step. Although this reduction in the time step does ensure stability, varying values of the maximum tolerated coastline change per time step within the range of stability does not appear to affect the model results.
- Due to the differences in the models described above, the coastline evolution predicted by UNIBEST-CL+, PONTOS and LONGMOR differed in three simple test cases. Calibration of the sediment transport at one location in each of the models lead to a reduction in de differences between the computed the coastline development, but some variance remained largely due to the way refraction and cross shore sediment redistribution is computed in the models.

2.2 Inleiding

In het project worden drie kustlijn modellen geanalyseerd: UNIBEST-CL+, PONTOS en LONGMOR. Hoewel deze modellen verschillend zijn, maken zij alle drie gebruik van een relatie tussen de ruimtelijke gradiënten in het kustlangssedimenttransport en de uitbouw, of teruggang, van de kust:

$$h_p \frac{\partial y}{\partial t} + \frac{\partial Q_x}{\partial x} + q_s = 0 \qquad \text{(Vgl. 1)}$$

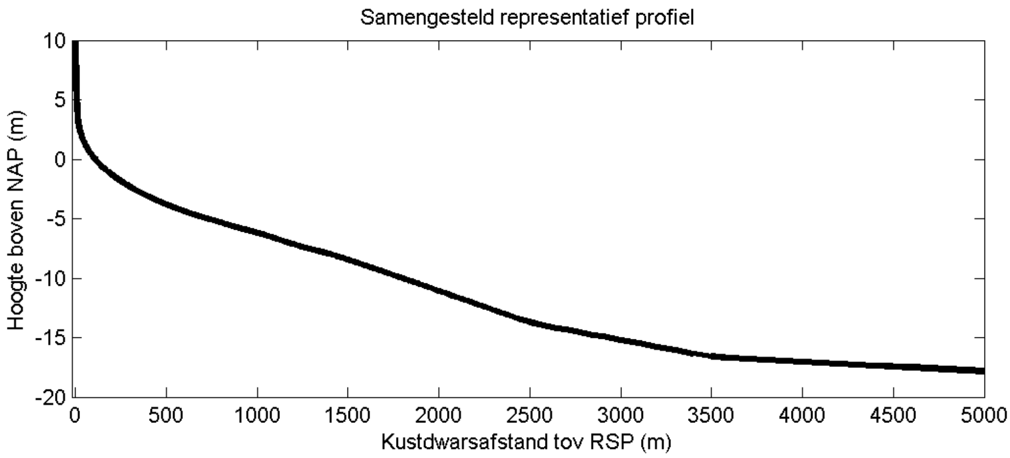
Waarbij y de positie van de kust in kustdwarsrichting, x de positie in kustlangsrichting, t de tijd, h_p de hoogte waarover de kust verandert, Q_x het kustlangssedimenttransport, en q_s additionele brontermen voor sediment zijn.

2.3 Doel Deel 1

Het doel van Deel 1 van dit project is om op overzichtelijke wijze verschillen tussen de drie kustlijnmodellen in kaart te brengen die kunnen leiden tot verschillen in voorspelde onderhoudsvolumen.

2.4 Aanpak Deel 1

In Deel 1 van dit project worden verschillen tussen de drie kustlijnmodellen onderzocht aan de hand van schematische, synthetische testgevallen. In alle testgevallen wordt gebruik gemaakt van een schematisch profiel dat gebaseerd is op Jarkus data van de kust voor Noordwijk en een Dean-profiel, zie Figuur 2.1, in het vervolg het representatief profiel genoemd. In het geval van het PONTOS model, wordt het dwarstransport zodoende afgeregeld dat het representatieve profiel in evenwicht is.



Figuur 2.1 Referentieprofiel dat gebruikt wordt in de vergelijking van kustlijnmodellen

In de testgevallen van Deel 1 worden stapsgewijs onderdelen van Vgl. (1) geanalyseerd en wordt de complexiteit van de testgevallen verhoogd. In oplopende mate van complexiteit zijn de volgende testgevallen gedefinieerd:

- Fase 1.1: analyse golf-gedreven langstransport voor individuele golfcondities (Q_x)
- Fase 1.2: analyse golf-gedreven langstransport voor golfklimaat (Q_x)
- Fase 1.3: analyse golf-gedreven langstransport-gradiënt (dQ_x/dx)
- Fase 1.4: analyse kustlijnverandering ($h_p dy/dt+dQ_x/dx$)

In Deel 1 worden verschillen als gevolg van getij-gedreven langstransport en de implementatie van de sedimentbronterm (q_s) niet geanalyseerd.

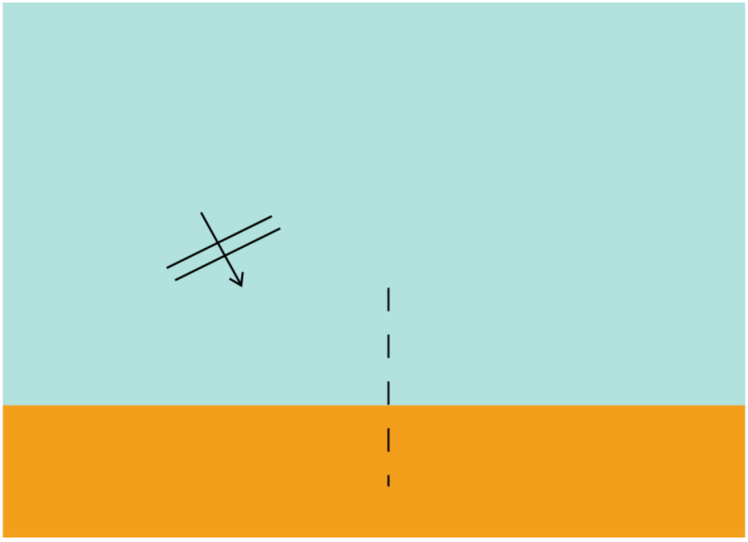
2.5 Analyse Deel 1

2.5.1 Fase 1.1: Golf-gedreven langstransport voor individuele golfcondities

In Fase 1.1 zijn verschillen in het berekende kustlangs sedimenttransport per golfconditie (Q_s) tussen de kustlijnmodellen onderzocht. Hiertoe zijn per model 1944 tot 5832 simulaties opgezet met variërende instellingen voor de golfforcering, sedimenttransport en dwarsprofiel eigenschappen, zie Tabel 2.1. Alle andere model parameters zijn op hun aanbevolen (default) waarde gezet en zijn niet veranderd. Voor alle model simulaties is het langstransport berekend door een enkel raaimodel met één golfconditie, zie Figuur 2.2. De resultaten van alle modelsimulaties van Fase 1.1 zijn bijeengebracht in een database waarin per golfconditie is vastgelegd hoe het berekende langstransport is gerelateerd aan de kustlijnoriëntatie. Voor elke willekeurige combinatie van modelparameters levert dit een zogenaamde S-Φ-kromme op.

Tabel 2.1 Variatie van golfforcering, sedimenttransport parameters en profieleigenschappen in Fase 1.1. Vetgedrukte waarden komen overeen met de referentie parameterinstellingen.

Parameter	**Variatie**
Golfhoogte op diep water	0.5m, **1m**, 2m, 3m, 4m, 5m
Diepwater golfsteilheid	2%, 3%, **4%**, 5%
Golfrichting t.o.v. kustnormaal	**-48°, -36°, -24°, -12°, 0°, 12°, 24°, 36°, 48°**
Sedimenttransportrelatie	**Van Rijn 2004**, Kamphuis, CERC. In geval van PONTOS wordt altijd eigen transportvergelijking gebruikt. In het geval van UNIBEST is ook Van Rijn 1993 onderzocht.
Korrelgrootte (D_{50})	100µm, **200µm**, 300µm
Profielsteilheid	0.5, **1,** 2 keer steilheid referentieprofiel



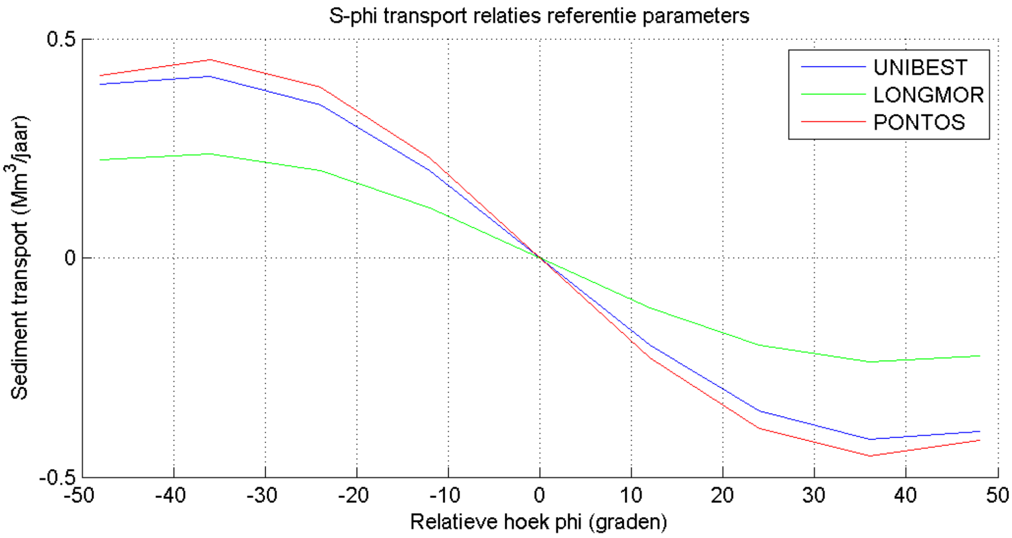
Figuur 2.2 Schematische langsuniforme kust met één golfconditie en één rekenraai.

In Figuur 2.3 zijn voor alle drie kustlijnmodellen de S-Φ krommen weergegeven voor de referentie parameterinstellingen (zie Tabel 2.1). Het figuur laat zien dat alle drie modellen sinus-vormige S-Φ krommen produceren, met maxima tussen 30° – 40°. De absolute waarden van het transport verschillen tussen de drie modellen, waarbij in dit referentiegeval de resultaten van UNIBEST en PONTOS sterk overeenkomen, en LONGMOR ongeveer 50% minder transport voorspelt voor alle relatieve kusthoeken dan de andere twee modellen.

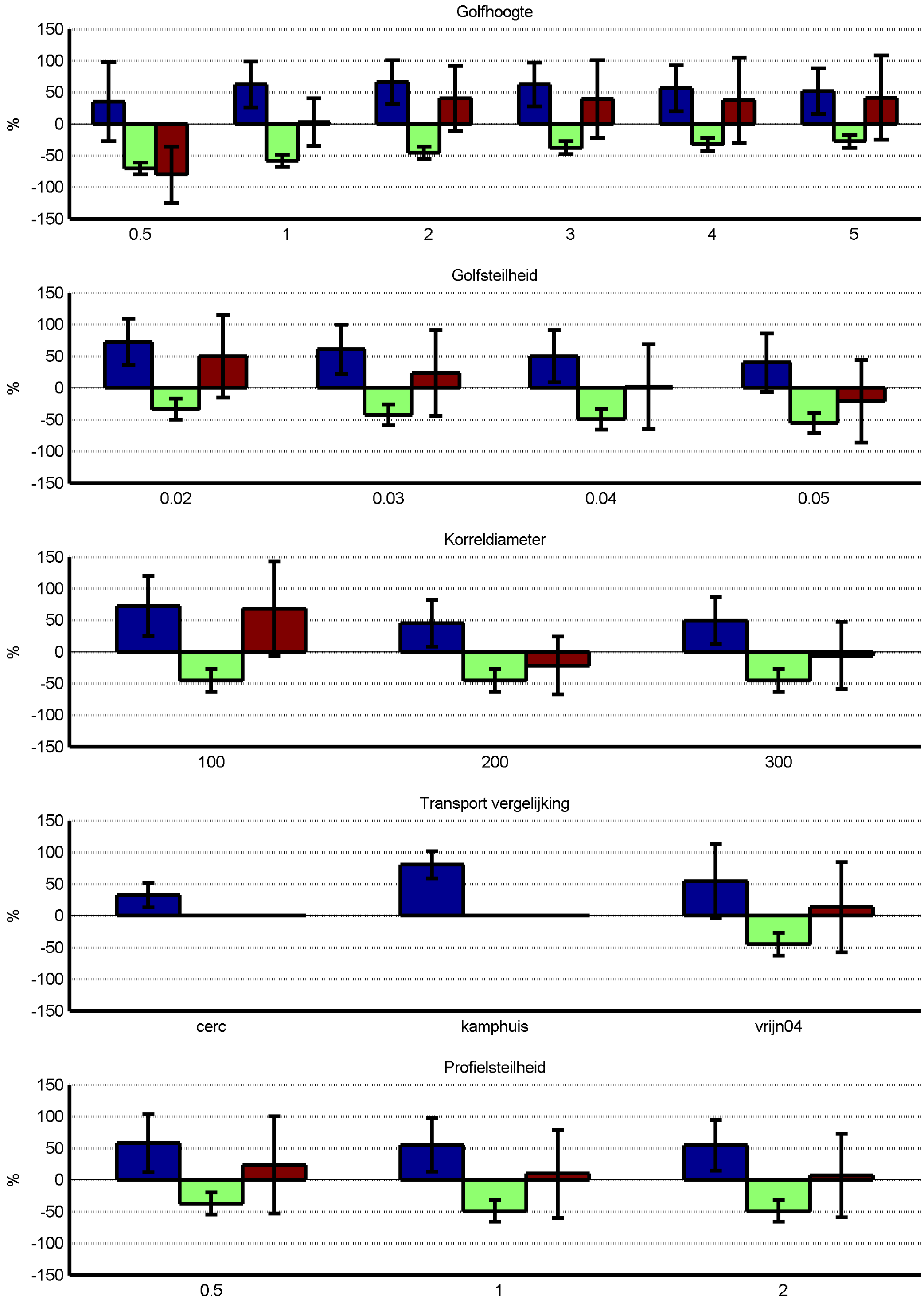
In Figuur 2.4 is het gemiddeld relatief verschil tussen de berekende transporten van elk model per parameter keuze weergegeven bij een relatieve kusthoek van -12°. Voor de parameter instelling van bijvoorbeeld een golfhoogte van 5m wordt dit berekend door het verschil tussen de twee modellen afzonderlijk voor alle parametercombinaties te vergelijken waarvan de golfhoogte 5m is, en het verschil te delen door het gemiddeld transport van de twee modellen. Het gemiddelde van de relatieve verschillen is in Figuur 2.4 weergegeven met gekleurde balken, de standarddeviatie van de verschillen is met een zwart balk weergegeven.

De overeenkomstigheid tussen UNIBEST en PONTOS die geldt bij de referentie parameterinstellingen is niet geldig voor andere parameter instelling, zoals blijkt in Figuur 2.4. Dit figuur laat zien dat de relatieve verschillen tussen UNIBEST en PONTOS groot (~50%) zijn bij kleine en grote golfhoogten, kleine golfsteilheden en kleine sedimentgrootten. Tussen UNIBEST en LONGMOR zijn de relatieve verschillen groot bij middelhoge golven, kleine golfsteilheden en alle korreldiameters. Tussen LONGMOR en PONTOS zijn de relatieve verschillen groot bij kleine golven, grote golfsteilheden en alle korreldiameters. Opmerkelijk hierbij is dat de standaarddeviatie van de verschillen tussen LONGMOR en PONTOS in alle gevallen kleiner is dan de standard deviatie tussen UNIBEST en de andere twee modellen. UNIBEST voorspelt voor alle parameter classificaties gemiddeld meer transport dan LONGMOR (alle blauwe balken zijn positief), en LONGMOR voorspelt voor alle parameter classificaties gemiddeld minder transport dan PONTOS (alle groene balken zijn negatief). UNIBEST voorspelt voor hoge golven, kleine golfsteilheid en kleine korreldiameters meer transport dan PONTOS (positieve rode balken). De onderlinge verschillen tussen alle modellen zijn niet sterk afhankelijk van de profielsteilheid.

In de analyse van sediment transport vergelijkingen is de PONTOS transport vergelijking ingedeeld met de Van Rijn 2004 vergelijking voor UNIBEST en LONGMOR. Hieruit blijkt dat het gemiddelde verschil voor alle simulaties met deze transportvergelijkingen groter is tussen UNIBEST en LONGOR (54%), en tussen LONGMOR en PONTOS (45%), dan tussen UNIBEST en PONTOS (13%). De relatieve verschillen tussen UNIBEST en LONGMOR zijn het grootst wanneer het Kamphuis sedimenttransport vergelijking gebruikt wordt.

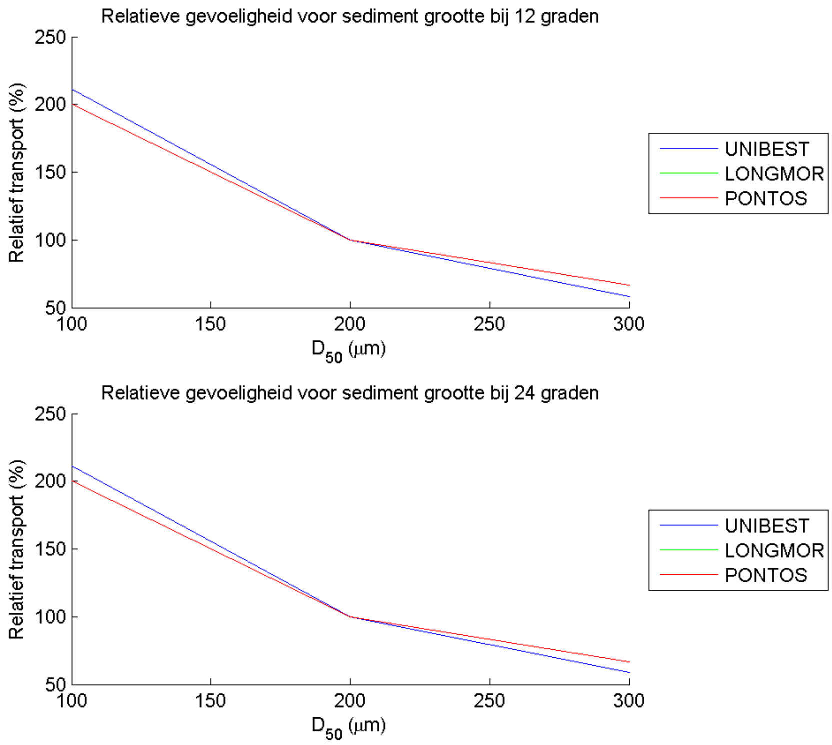


Figuur 2.3 S-Φ kromme voor de referentie parameter instellingen.

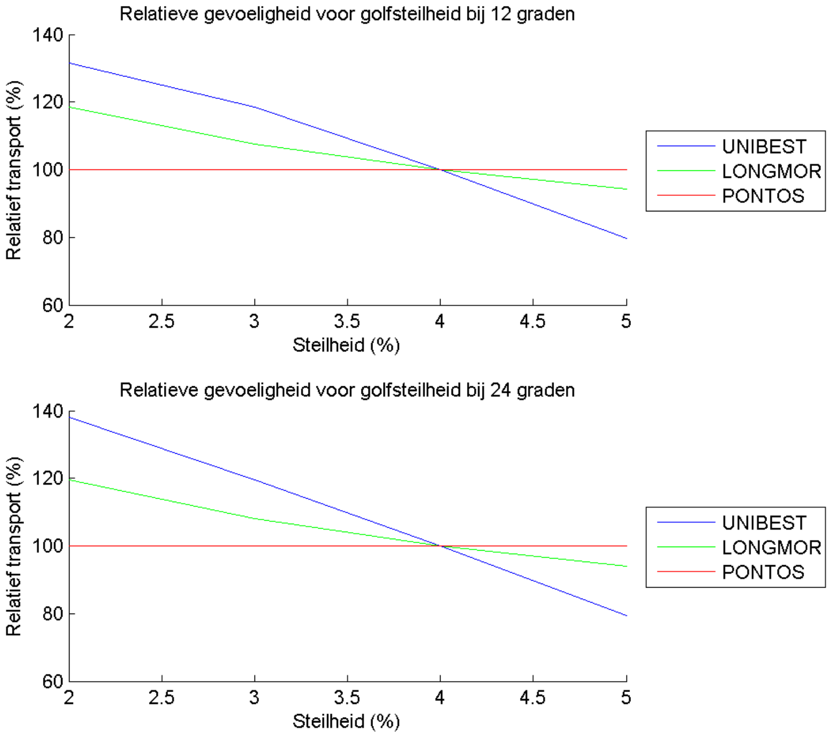


Figuur 2.4 Gemiddelde relatieve verschillen tussen UNIBEST en LONGMOR (blauw), LONGMOR en PONTOS (groen) en UNIBEST en PONTOS (rood) berekende transporten bij een relatieve kusthoek van 12°. Resultaten zijn per parameter classificatie, ten opzichte van het gemiddeld transport van beide modellen gedefinieerd. Positieve waarden geven aan dat het eerstgenoemde model meer transport voorspelt dat het laatstgenoemde model. De standarddeviatie van het verschil is aangegeven met een zwarte balk. In alle vergelijkingen wordt de PONTOS transportvergelijking ingedeeld met de Van Rijn 2004 resultaten van de andere modellen.

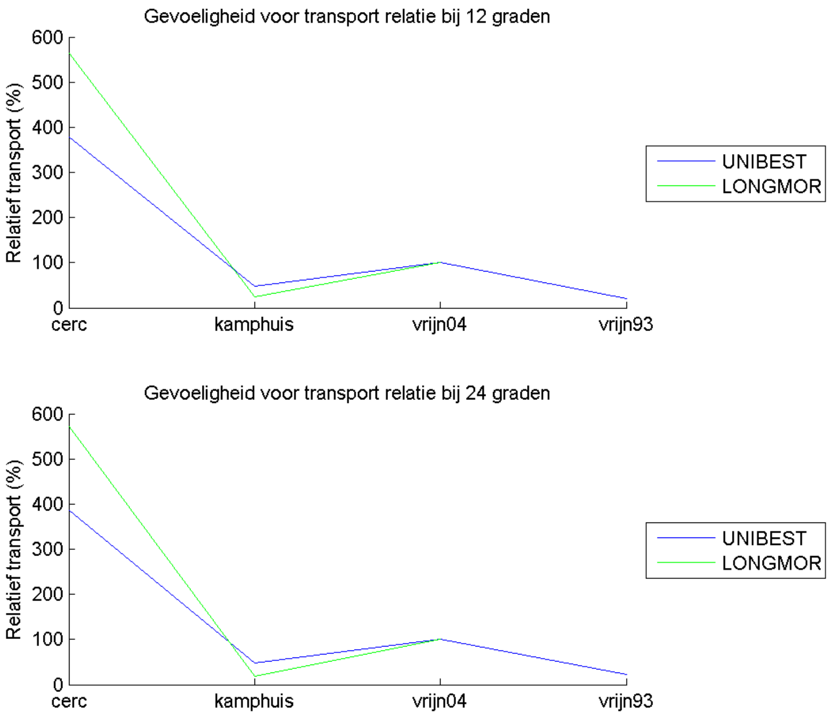
In Figuur 2.5–Figuur 2.7 zijn enkele gevoeligheden voor parameter instellingen inzichtelijk gemaakt voor de drie kustlijnmodellen. Achtereenvolgens zijn de gevoeligheden voor de sedimentgrootte (D_{50}), de golfsteilheid, en de transportformuleringen gepresenteerd. De gevoeligheden worden relatief uitgedrukt ten opzichte van het berekende transport met de referentie instellingen per model. Uit het eerste figuur blijkt dat alle modellen eenzelfde afhankelijkheid laten zien tussen de grootte van het langstransport en de sedimentgrootte (fijner sediment leidt tot groter transport). Opmerkelijk is dat de relatieve afhankelijkheid voor PONTOS en LONGMOR exact hetzelfde is. Uit Figuur 2.6 blijkt dat UNIBEST gevoeliger is voor golfsteilheid dan LONGMOR, en dat PONTOS geen gevoeligheid toont voor golfsteilheid. Dit laatste is te verklaren door het feit dat de achterliggende formuleringen van PONTOS niet afhankelijk zijn van de golfperiode. Tot slot laat Figuur 2.7 zien dat de keuze voor de te gebruiken langstransportformulering in LONGMOR en UNIBEST veel invloed heeft op de grootte van het berekende langstransport. Beide modellen laten hierin eenzelfde patroon zien, waarbij met CERC veruit de grootste transporten worden berekend. Hierbij moet worden opgemerkt dat de standaard coëfficiënten gebruikt zijn in de CERC-formulering die niet afhankelijk zijn van de korrelgrootte.



Figuur 2.5 Relatief langstransport als functie van sedimentgrootte (D50).



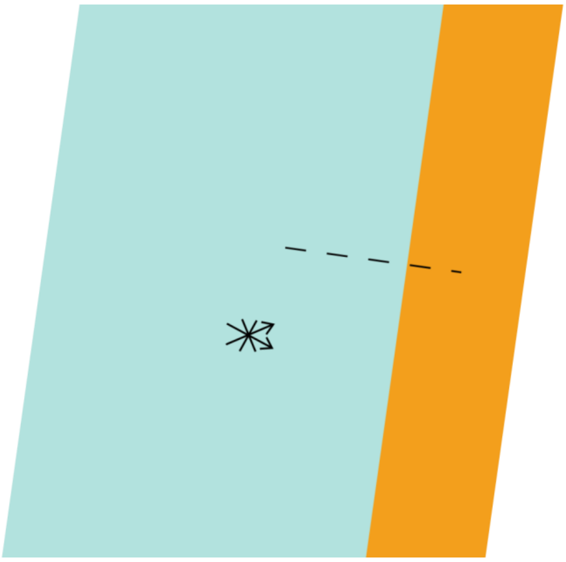
Figuur 2.6 Relatief langstransport als functie van de golfsteilheid.



Figuur 2.7 Relatief langstransport voor verschillende transportformuleringen.

2.5.2 Fase 1.2: Golf-gedreven langstransport voor golfklimaat

Tussen de drie kustlijnmodellen bestaan verschillen in de manier waarop uit een golfklimaat een gemiddeld netto kustlangssedimenttransport berekend wordt. Het effect van deze verschillen is in Fase 1.2 onderzocht. In elk model is het jaarlijks netto langstransport berekend in een enkele raai als gevolg van één representatief golfklimaat, zie Figuur 2.8. Het representatieve golfklimaat dat hiervoor gebruikt is, is gebaseerd op een analyse van het langstransport bij Egmond (Van Duin, 2002; Van Duin *et al.*, 2004) en staat beschreven in Tabel 2.2. Om vergelijkbare resultaten te verkrijgen met eerdere studies is in alle kustlijnmodellen de hoek van het kustnormaal 278° (Van Duin *et al.*, 2004).



Figuur 2.8 Schematische langsuniforme kust met één golfklimaat en één rekenraai.

Tabel 2.2 Representatief golfklimaat

	Golfrichting (nautische graden)	Significante golfhoogte (m)	Significante golfperiode (s)	Duur (dagen)
Golfconditie 1	205	0,75	5,0	96
Golfconditie 2	205	1,65	7,0	6
Golfconditie 3	225	1,25	6,3	46
Golfconditie 4	225	2,75	8,3	4
Golfconditie 5	245	1,25	6,3	11
Golfconditie 6	245	2,25	7,8	6
Golfconditie 7	295	1,25	6,5	19
Golfconditie 8	295	2,75	8,5	4
Golfconditie 9	325	1,25	7,5	31
Golfconditie 10	325	2,75	9,5	3
Golfconditie 11	345	0,75	5,6	35
Golfconditie 12	345	2,25	8,7	3

De bepaling van een jaarlijks gemiddeld netto langstransport in UNIBEST vindt plaats door voor elk raai en voor een aantal relatieve kusthoeken, het gemiddeld transport als gevolg van het golfklimaat te berekenen het UNIBEST-LT model. In het UNIBEST-LT model wordt golftransformatie over de bathymetrie van het profiel berekend met het ENDEC-1D model (Battjes en Janssen, 1978), en wordt sediment transport als gevolg van golven en stroming over het dwarsprofiel berekend, zie rode stippen in Figuur 2.9 (bovenste subfiguur). Het totale netto transport per relatieve kusthoek wordt opgeslagen, en door middel van de kleinste-kwadraten methode worden de berekende transporten benaderd door een analytische functie:

$$Q = c_1 \theta_r e^{-(c_2 \theta_r)^2} \qquad \text{(Vgl. 2)}$$

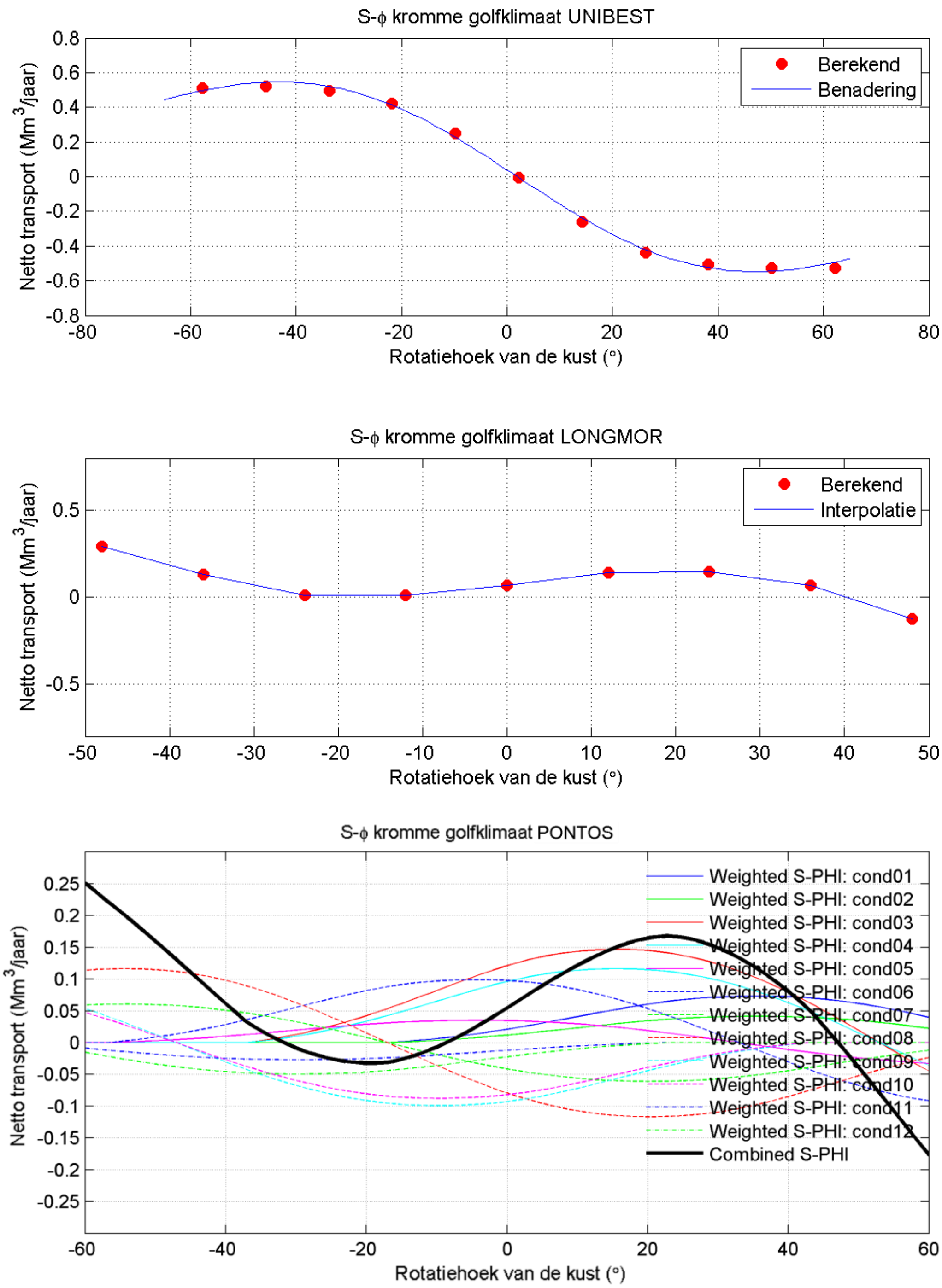
Waarbij θ_r de hoek is tussen de actuele kusthoek en de evenwichtskusthoek, en c_1 en c_2 calibratie coëfficiënten zijn. De analytische benadering wordt in vervolgberekeningen gebruikt en kan enige procenten afwijken van het berekende langstransport, zie blauwe lijn in Figuur 2.9 (boven).

In LONGMOR wordt niet gerekend met een netto transport als gevolg van een golfklimaat. Daarvoor in de plaats wordt het transport per golfconditie in het klimaat afzonderlijk in de tijd doorgerekend. De gebruiker van het model moet naar eigen inzicht de volgorde en duur van golfcondities kiezen om te komen tot een representatief netto transport die niet afhankelijk is van de chronologie van de golfcondities. In deze studie is dat bereikt door de morfologie van de kustlijn uit te schakelen, waardoor er geen afhankelijkheid bestaat tussen de volgorde van de golfcondities en het berekende netto transport. Door handmatig de relatieve kusthoek aan te passen is het mogelijk een S-Φ kromme voor LONGMOR te produceren ter vergelijking met de andere modellen, zie Figuur 2.9 (midden). Deze S-Φ kromme is echter alleen een nabewerking van LONGMOR uitvoer, en wordt niet als zodanig gebruikt in het LONGMOR model zelf.

Het bepalen van langstransport in PONTOS als gevolg van een golfklimaat vindt plaats door per raai voor het hele golfklimaat het netto langstransport te berekenen voor de actuele relatieve kusthoek. Dit netto transport wordt berekend door per laag en per golfconditie het gewogen langstransport te bepalen aan de hand van een parametrisch transportformule:

$$Q = c_0 \left(H_s^{2.8} / D_S \right) \theta_{rw} e^{-(c_2 \theta_{rw})^2} \qquad \text{(Vgl. 3)}$$

Waarbij θ_{rw} de relatieve kusthoek is ten opzichte van de golfrichting, c_0 en c_2 calibratie coëfficiënten, H_s de significante golfhoogte op diep water en D_s de korrelgrootte zijn. De waarden van de coëfficiënten c_0 en c_2 zijn in het model vastgelegd, en zijn bepaald door middel van calibratie aan de hand van UNIBEST-LT berekeningen. Hierdoor zijn onder bepaalde condities de verschillen tussen het transport in UNIBEST als gevolg van de analytische benadering en het transport in PONTOS gering, zie Figuur 2.4 (golfhoogte 1m, golfsteilheid 4%). Evenals LONGMOR maakt PONTOS geen expliciet gebruik van S-Φ krommen, maar kunnen S-Φ krommen bij wijze van nabewerking worden geproduceerd. In dit geval wordt door PONTOS per golfconditie in het klimaat een gewogen S-Φ kromme gemaakt, en worden deze krommen gesommeerd, zie Figuur 2.9 (onder).



Figuur 2.9 Bepaling van S-Φ krommen voor het representatief golfklimaat in UNIBEST.(boven), LONGMOR (midden), en PONTOS (onder).

Figuur 2.10 laat voor elk van de kustlijnmodellen de samengestelde S-Φ kromme zien voor het representatief golfklimaat. Het figuur laat zien dat de netto transporten voor een ongewijzigde kustlijnoriëntatie (0°) voor alle modellen positief zijn, waarbij de netto transporten nagenoeg gelijk zijn (0.04 – 0.07 Mm^3/jaar). Echter, de vorm van de UNIBEST kromme verschilt zeer van die van LONGMOR en PONTOS. In het bijzonder valt op dat de kromme voor UNIBEST een tegengestelde hellingshoek bij de nul-doorsnijding, en dat UNIBEST een hele andere evenwichtshoek voorspelt dan de andere twee modellen.

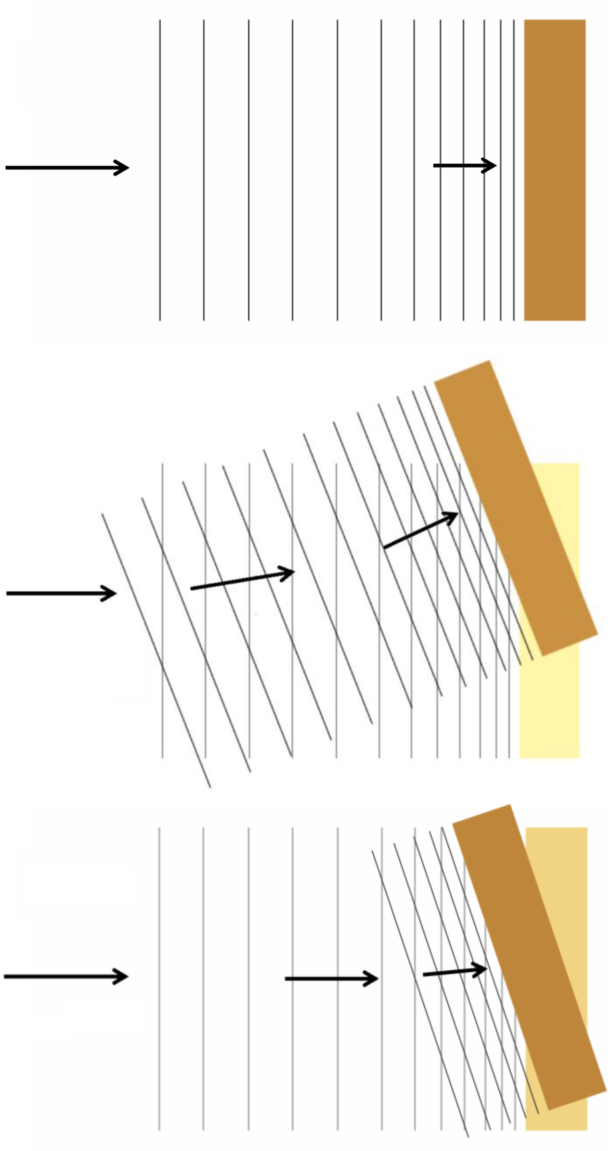
Het verschil in de vorm van de S-Φ krommen kan verklaard worden door verschillen in uitgangspunten over golfrefractie en kustrotatie in de drie kustlijnmodellen. Deze verschillen kunnen aan de hand van een voorbeeld met één golfconditie inzichtelijk gemaakt worden. In alle modellen geldt dat als een golf normaal op de contourlijnen en kustlijn invalt, er geen golfrefractie plaats vindt tussen diep water en de kust, zie Figuur 2.11 (bovenste subfiguur). Als de kustnormaal in LONGMOR en PONTOS roteert, draaien alle contourlijnen met de kust mee, zie Figuur 2.11 (midden). Golfrefractie vindt hierdoor plaats vanaf diep water tot aan de kust, en golven bereiken uiteindelijk de kust met een kleine hoek van inval. Wanneer de kustnormaal in UNIBEST roteert, draaien alleen de contourlijnen binnen de actieve zone de kust mee, zie Figuur 2.11 (onder). Hierdoor vindt golfrefractie alleen plaats binnen de actieve zone, en bereiken de golven de kust met een grote hoek van inval.

Als in UNIBEST een kleine actieve diepte wordt gekozen waarin de contourlijnen roteren en golven refracteren, is het langstransport ten gevolge van een willekeurige kustrotatie relatief groter dan wanneer een grote actieve diepte wordt gekozen, zie Figuur 2.12. Voor bepaalde combinaties golven en korrelgroottes, is het verschil tussen UNIBEST berekeningen met een kleine en grote actieve diepte, 50% van het berekende transport in het ‘normale’ UNIBEST model. Met een grote actieve diepte komen de kustrotatie uitgangspunten in UNIBEST en LONGMOR met elkaar overeen, en komt het berekende langstransport in UNIBEST meer overeen met LONGMOR dan met PONTOS. Het verschil tussen het berekende langstransport in UNIBEST met een grote actieve diepte en PONTOS duidt erop dat tijdens de calibratie van de coëfficiënten c_0 en c_2 in PONTOS de resultaten van UNIBEST-LT met een kleine actieve diepte zijn gebruikt.

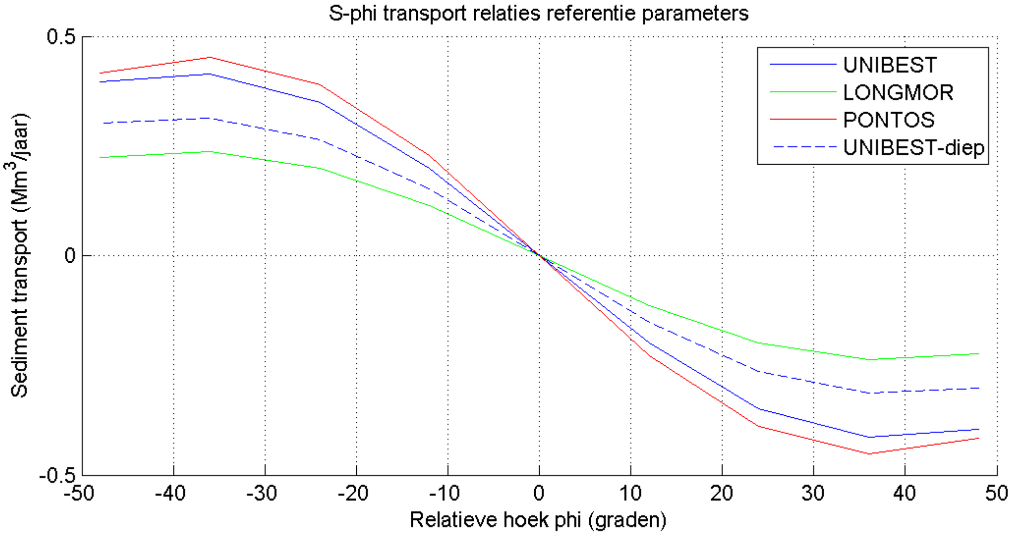
De evenwichtshoek van een kustlijn wordt op een vergelijkbare manier beïnvloed door de keuze van de actieve diepte als het langstransport. Figuur 2.13 (boven) laat zien dat in LONGMOR en PONTOS de evenwichtshoek van de kust gelijk is aan de hoek van inval van golven op diep water. In UNIBEST (Figuur 2.13 onder) zal de evenwichtshoek afhankelijk zijn van de initiële bodemcontouren buiten de actieve zone, en zal vaak kleiner zijn dan de hoek van inval van golven op diep water. Het is hierbij van uiterst belang om correcte initiële bodemcontouren buiten de actieve zone in UNIBEST op te geven.

Hoewel eerder is aangetoond dat het langstransport in UNIBEST met een kleine actieve diepte en PONTOS goed overeenkomen in het geval van één golfconditie, laat Figuur 2.10 laat zien dat dit niet het geval is als het referentie golfklimaat gebruikt wordt. In Figuur 2.14 worden de S-Φ krommen van LONGMOR, PONTOS en UNIBEST met een grote actieve diepte getoond. Dit figuur laat zien dat hoewel er verschillen zijn tussen het berekende transport in UNIBEST en de ander twee modellen, deze verschillen kleiner zijn dan als een kleine actieve diepte wordt gebruikt (Figuur 2.10). Met name is opvallend dat de hellingshoek van de S-Φ kromme bij de nul-doorsnijding in UNIBEST met een grote actieve diepte gelijk is aan die van de andere twee kustlijnmodellen. Door de beperkingen van de analytische vormfunctie, is de analytische benadering (blauwe lijn in Figuur 2.14) niet goed in staat om de berekende transporten (cirkels) in UNIBEST te reproduceren.

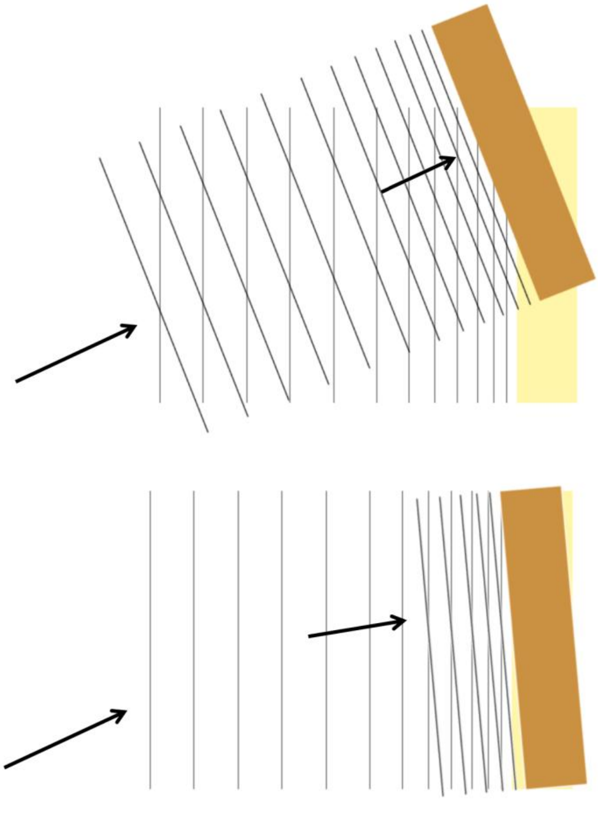
Figuur 2.10 S-Φ kromme op basis van het representatief golfklimaat.



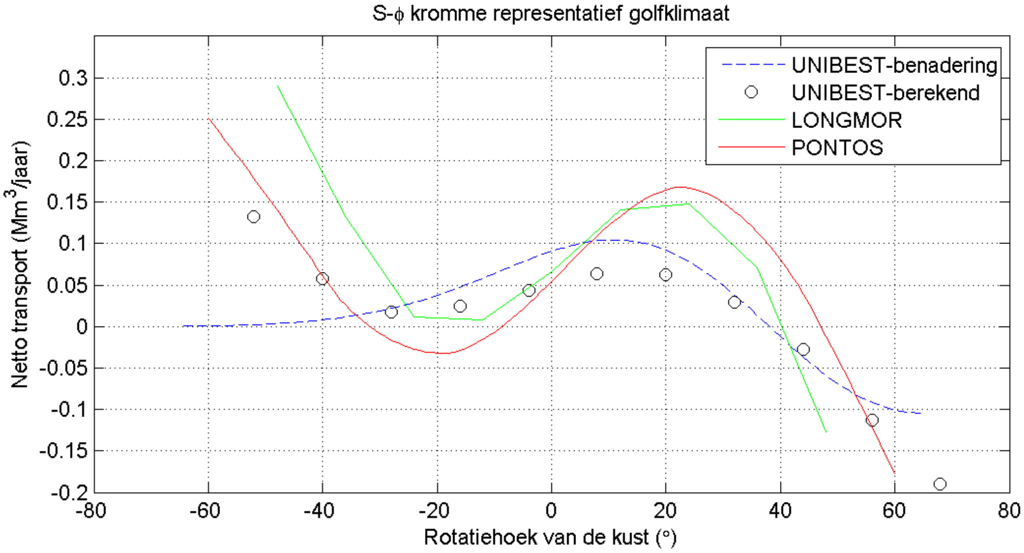
Figuur 2.11 Het effect van actieve diepte op golfrefractie en langstransport. Boven: golfrichting (zwarte pijlen) is normaal op contourlijnen (grijze lijnen) en kustlijn (bruin), golven vallen loodrecht in op kustlijn. Midden: in PONTOS en LONGMOR draaien alle contourlijnen met de kust mee, golven refracteren over grote afstand en bereiken de kust met een kleine hoek van inval. Onder: in UNIBEST draaien alleen de contourlijnen binnen de actieve zone met de kust mee, de golven staan normaal op de initiële contourlijnen (licht grijs), golfrefractie vindt allen plaats binnen de actieve zone en golven bereiken de kust met een grote hoek van inval.



Figuur 2.122.1 S-Φ kromme voor de referentie parameter instellingen (1 golfconditie), inclusief UNIBEST berekening waarbij de actieve zone het hele dwarsprofiel beslaat (UNIBEST-diep).



Figuur 2.13 Het effect van actieve diepte op evenwichtshoek. Boven: in PONTOS en LONGMOR draaien alle contourlijnen met de kust mee, langstransport wordt pas nul als het kustnormaal gelijk is aan de diepwater golfrichting. Onder: in UNIBEST draaien alleen de contourlijnen binnen de actieve zone met de kust mee, schuin invallende golven refracteren op diep water, langstransport wordt nul als het kustnormaal gelijk is aan de golfrichting bij het begin van de actieve zone.



Figuur 2.14 S-Φ kromme op basis van het representatief golfklimaat, waarbij in de UNIBEST berekening de actieve zone het hele dwarsprofiel beslaat.

2.5.3 Fase 1.3: Golf-gedreven langstransport-gradiënt

In Fase 1.3 zijn de verschillen onderzocht in de manier waarop langsvariërende golfcondities en relatieve kusthoeken in de drie kustlijnmodellen behandeld worden. Verschillen in de interpretatie van langsvariërende condities leiden tot verschillen in de langstransportgradiënt $\left(\frac{\partial Q_x}{\partial x}\right)$ en kunnen daarmee de kustlijnontwikkeling beïnvloeden. Om deze effecten te onderzoeken zijn drie schematische kustlijnmodel simulaties opgezet, zie Figuur 2.15.

In Test 1.3.1 wordt een rechte kustlijn gesimuleerd waarop op een afstand van 8000m van elkaar, twee schuin invallende golfcondities worden opgelegd met eenzelfde richting en periode, maar ander golfhoogte, zie Tabel 2.3. Op een vergelijkbare manier wordt in Test 1.3.2 een rechte kustlijn gesimuleerd met twee opgelegde golfcondities met gelijke golfhoogte en periode, maar verschillende golfrichting. Aangezien LONGMOR de mogelijkheid niet biedt om langsvariërende golfcondities op te leggen, zijn tests 1.3.1 en 1.3.2 alleen met UNIBEST en PONTOS uitgevoerd.

In Test 1.3.3 wordt een grotendeels rechte kustlijn met een centraal gelegen bolvormige kustuitbouw, met een breedte van 1000m in kustlangsrichting en 100m in kustdwarsrichting, gesimuleerd waarlangs schuin-invallende golven zijn opgelegd met een constante invalshoek. De kustlijnpositie in Test 1.3.3 inclusief bolvormige uitbouw ten opzichte van een rechte referentielijn wordt beschreven door:

$$y(x) = \max\left(0, -1200 + \sqrt{\max\left(0, 1300^2 - x^2\right)}\right) \qquad \text{(Vgl. 4)}$$

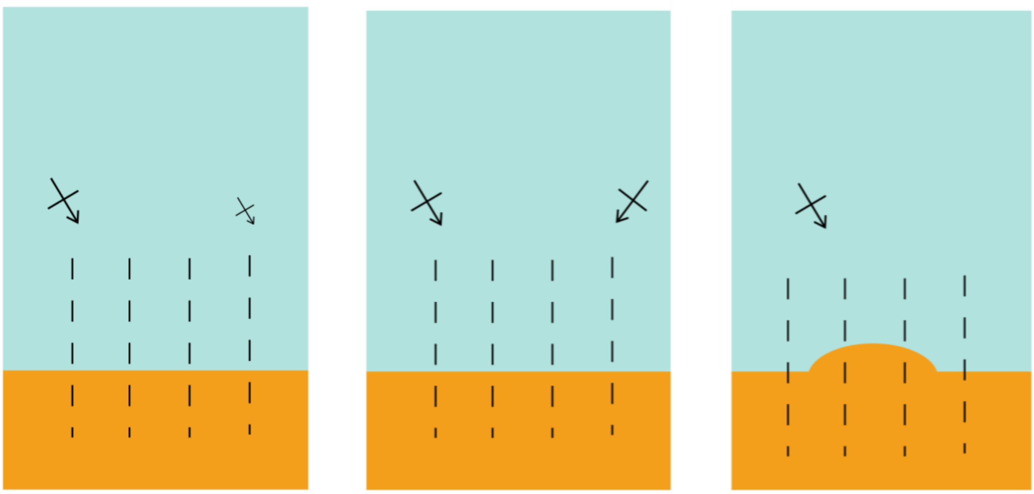
Test 1.3.3 is uitgevoerd met alle drie kustlijnmodellen.

Alle drie tests zijn uitgevoerd met een mediaan korreldiameter van 200μm. In simulaties met UNIBEST en LONGMOR is het Van Rijn 2004 sedimenttransportvergelijking gebruikt. In UNIBEST is de actieve diepte waarover contourlijnen met de kust meedraaien gesteld op de diepte waarbinnen 98% van het langstransport plaatsvindt. De numerieke roosterafstand in kustlangsrichting is in UNIBEST en LONGMOR gesteld op 100m. Omwille van de numerieke stabiliteit is in PONTOS de numerieke roosterafstand in kustlangsrichting op 200m gesteld.

In alle tests is het effect van veranderingen van de kustlijnpositie uitgesloten door, waar mogelijk, alleen de berekende initiële transporten te analyseren, of door de profielhoogte (h_p) dusdanig groot te maken dat er geen significante kustlijnverandering plaatsvindt tijdens de simulatie.

Tabel 2.3 Golf parameters in tests 1.3.1 – 1.3.3

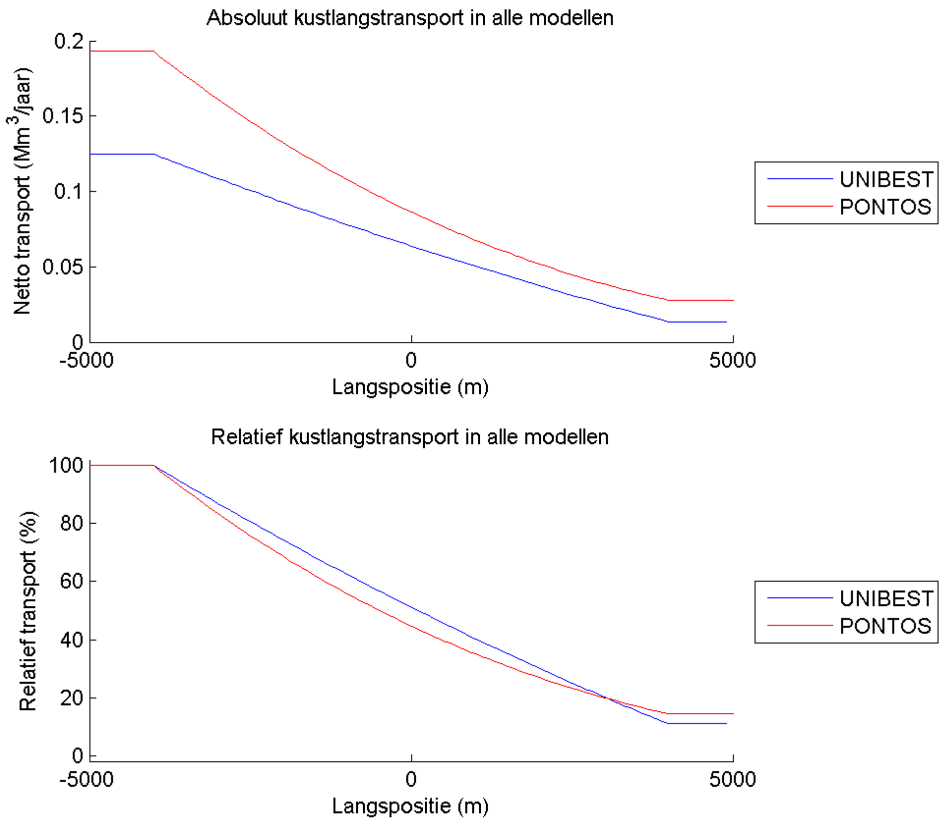
	Test 1.3.1	**Test 1.3.2**	**Test 1.3.3**
Golfhoogte op diep water	1m en 0,5m	1m	1m
Golfrichting t.o.v. kustnormaal	-10°	-10° en +10°	-10°
Golfperiode of diep water	5.66s	5.66s	5.66s
Kustlangspositie opgelegde golven	-4000m en +4000m	-4000m en +4000m	-4000m



Figuur 2.15 Langsuniforme kust met een langsvariërende golfhoogte (Test 1.3.1, links), langsuniforme kust met een langsvariërende golfrichting (Test 1.3.2, midden), en een bolvormige kust met languniforme golven (Test 1.3.3, rechts).

2.5.3.1 *Test 1.3.1*

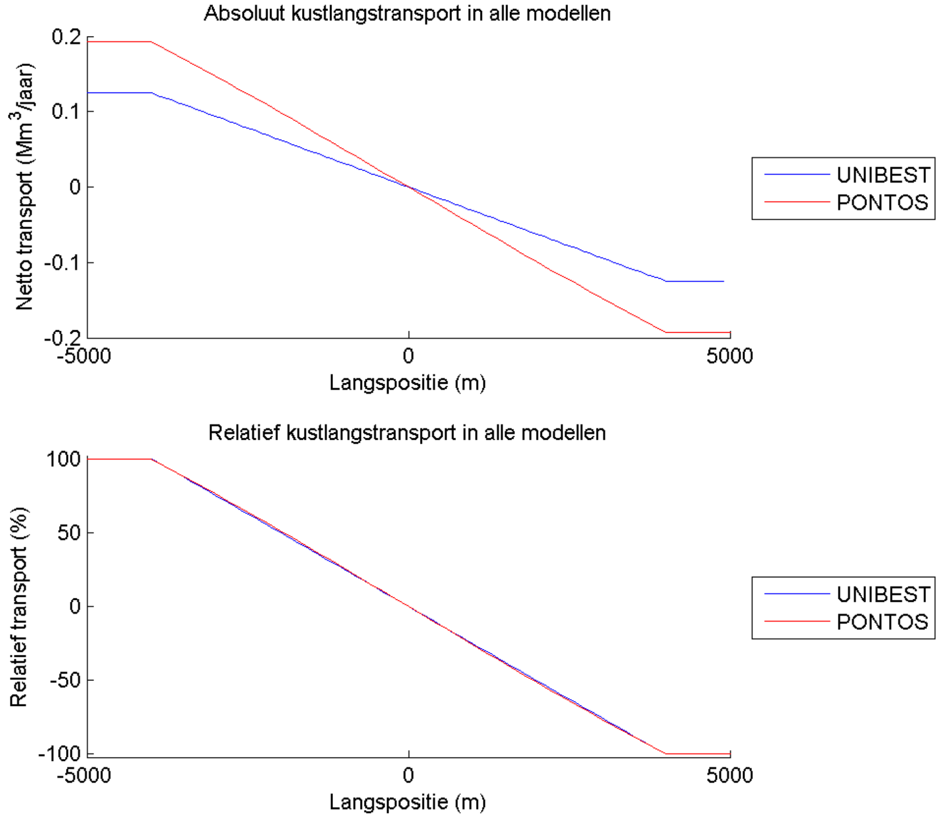
Het berekende initieel langstransport voor Test 1.3.1 is in Figuur 2.16 getoond. Het figuur laat zowel de absolute langstransporten die berekend zijn met UNIBEST en PONTOS (boven), als de relatieve transporten ten opzichte van de door elk model berekende transporten op kustlangscoördinaat -5000m (linker modelrand). Figuur 2.16 laat zien dat langsvariërende golfhoogten in UNIBEST en PONTOS tot andere transporten en transportgradiënten leiden. De verschillen in de absolute transporten zijn al in Fase 1.1 behandeld. De verschillen in de relatieve transporten kunnen verklaard worden door het feit dat in UNIBEST een lineaire interpolatie plaatsvindt in de kustlangsrichting van de berekende langstransport coëfficiënten van Vgl. 2. op de locaties waar de golven opgelegd zijn (-4000m en +4000m). In PONTOS vindt echter een lineaire interpolatie in de kustlangsrichting plaats van de golfhoogte op de locaties waar de golven opgelegd zijn. De geïnterpoleerde golfhoogte wordt vervolgens gebruikt om het langstransport in de tussenliggende gebieden te berekenen. Daar het langstransport geen lineaire functie van de golfhoogte is, leiden de uitgangspunten van UNIBEST en PONTOS tot verschillenden langstransportgradiënten.



Figuur 2.16 Absoluut en relatief langstransport in Test 1.3.1 als functie van de kustlangspositie.

2.5.3.2 *Test 1.3.2*

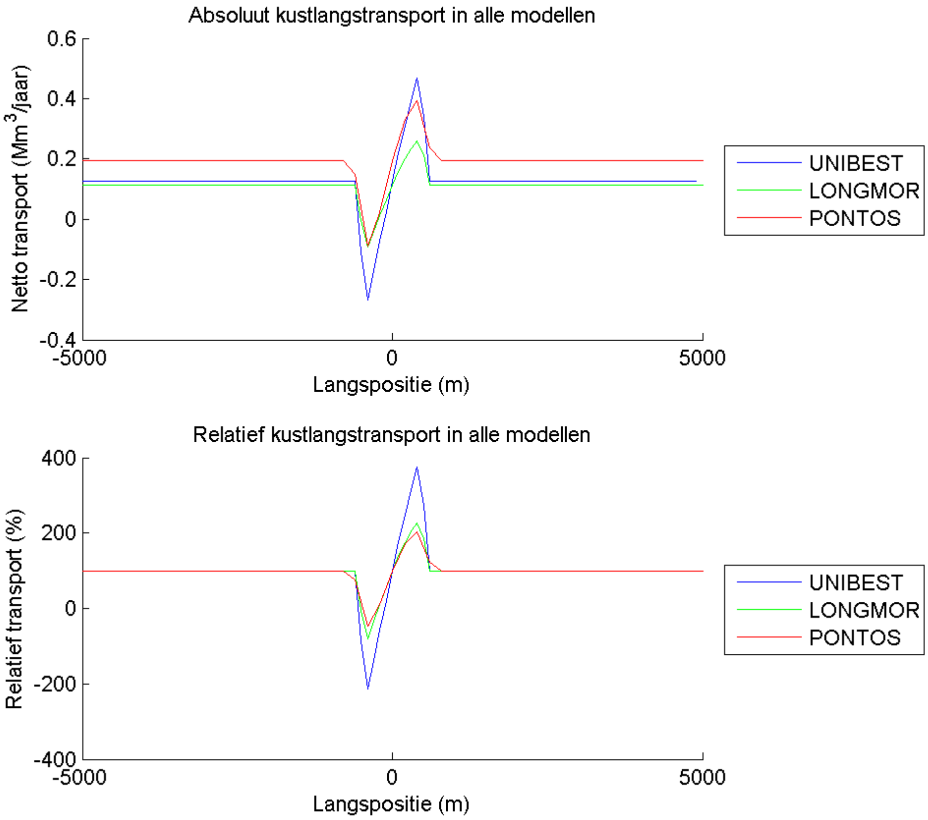
In Test 1.3.2 is voor UNIBEST en PONTOS een vergelijkbare verdeling van het langstransport in de kustlangsrichting berekend, zie Figuur 2.17. In dit geval zijn de verschillen in het relatief transport kleiner dan in Test 1.3.1, omdat de transportfuncties in beide modellen tussen de opgegeven golfhoeken bijna lineair met de relatieve kusthoek schalen. Bij grotere veranderingen van de hoek van inval van de golven, wordt verwacht dat de verschillen in de relatieve transporten groter worden tussen de twee modellen.



Figuur 2.17 Absoluut en relatief langstransport in Test 1.3.2 als functie van de kustlangspositie.

2.5.3.3 Test 1.3.3

In Test 1.3.3 worden voor alle drie modellen vergelijkbare transport patronen gevonden, met maximale negatieve transporten op de linkerzijde van de bol, en maximale positieve transporten op de rechterzijde van de bol, zie Figuur 2.18. Opvallend is de grote overeenkomst tussen de relatieve transporten in LONGMOR en PONTOS, en de grotere maximale relatieve transporten in UNIBEST dan in de andere twee modellen. Het feit dat de maximale relatieve transporten in UNIBEST groter zijn dan in de andere twee modellen is te verklaren aan de hand van de conclusies in Fase 1.2 en in Figuur 2.13 over het effect van de actieve diepte. Doordat de diepwater contourlijnen buiten de actieve zone in het UNIBEST model parallel lopen aan de referentielijn en niet aan de kustlijn, zijn de golven in UNIBEST aanzienlijk gerefracteerd waardoor de transporten lager zijn in vergelijking tot LONGMOR en PONTOS. Omdat de S-phi krommen zijn gedefinieerd als kustlijnrotatie (en niet als dieptelijnrotatie) leidt deze definitie, zoals beschreven in Fase 1.2, tot grotere gevoeligheid van het transport voor de kusthoekrotatie in UNIBEST dan in de andere twee modellen. In feite worden dus verschillende kustlijnrotatie definities gebruikt voor de kustrotatie in de drie modellen.



Figuur 2.18 Absoluut en relatief langstransport in Test 1.3.3 als functie van de kustlangspositie.

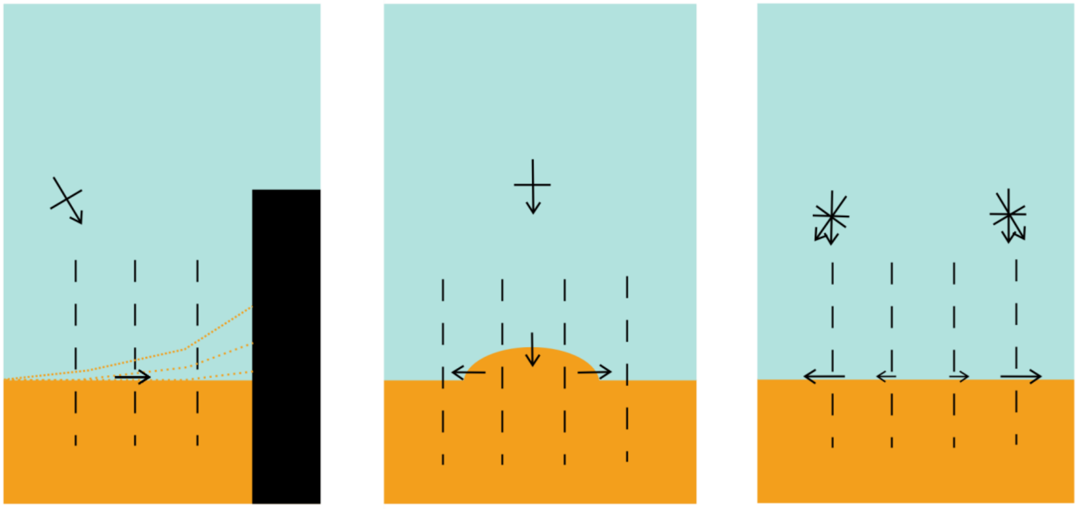
2.5.4 Fase 1.4: Kustlijnverandering

In Fase 1.4 zijn de verschillen onderzocht in de manier waarop langsvariërende transportgradiënten kunnen leiden tot andere aangroei of teruggang van de kust $\left(h_p \frac{\partial y}{\partial t}\right)$. Om deze verschillen te onderzoeken zijn drie simulaties uitgevoerd waarin de kustlijn zich gedurende een periode van 25 jaar mag ontwikkelen, zie Figuur 2.19.

In Test 1.4.1 is een initieel langsuniforme kust gesimuleerd met één schuin-invallande golfconditie (zie Tabel 2.4) die een langstransport genereert naar een gesloten modelrand toe. De transportgradiënt bij de gesloten rand zorgt voor een uitbouw van de kust. De snelheid van deze uitbouw en het uiteindelijke evenwichtshoek van de kust bij de gesloten rand wordt tussen de modellen vergeleken. In Test 1.4.2 is een initieel bolvormige verstoring in een rechte kust met één recht invallende golfconditie gesimuleerd. Door de vorm van de verstoring treden langsverschillen op in de relatieve kusthoek welke leiden tot langstransportgradiënten. De snelheid van de herdistributie van het suppletiemateriaal wordt tussen de modellen vergeleken. In Test 1.4.3 wordt een initieel langsuniforme kust gesimuleerd met twee golfklimaten die door hun netto langstransportrichting een divergerend langstransport creëren. De golfklimaten die hiervoor gebruikt zijn, zijn gebaseerd op het golfklimaat van Fase 1.2, en staan beschreven in Tabel 2.5. Omdat LONGMOR geen langsvariërende golfcondities kan simuleren, is Test 1.4.3 niet met LONGMOR uitgevoerd.

Evenals in Fase 1.3 zijn alle tests uitgevoerd met een mediaan korreldiameter van 200µm. In simulaties met UNIBEST en LONGMOR is het Van Rijn 2004 sedimenttransportvergelijking gebruikt. In UNIBEST is de actieve diepte waarover dieptecontouren met de kust meedraaien gesteld op de diepte waarbinnen 98% van het langstransport plaatsvindt. De initiële dieptecontouren buiten de actieve diepte zijn in UNIBEST langsuniform (parallel aan de kustlangs-as). De actieve hoogte waarover de kust zich uitbouwt of terugtrekt in LONGMOR en UNIBEST is gesteld op 10m. In PONTOS wordt deze hoogte niet gebruikt, en kan de kust zich theoretisch uitbouwen of terugtrekken over alle verticale lagen in het model. De numerieke roosterafstand in kustlangsrichting is in UNIBEST en LONGMOR gesteld op 100m. In PONTOS de numerieke roosterafstand in kustlangsrichting op 200m gesteld. Om de stabiliteit in het PONTOS model voor Test 1.4.2 te garanderen, is met een kleiner dan gebruikelijke tijdstap gerekend.

Om de morfologie van de kustlijn in alle kustlijnmodellen te vergelijken wordt naast de absolute kustpositie na 25 jaar simulatie, ook de relatieve, of geschaalde, kustpositie berekend. De relatieve kustpositie wordt berekend door het langstransport in de kustlijnmodellen lineair te schalen zodat het initieel langstransport op één referentielocatie in alle drie kustlijnmodellen gelijk is. Als uitgangspunt zijn de transporten in PONTOS en LONGMOR zo geschaald dat het initiële transport in de referentielocatie gelijk aan het door UNIBEST berekend transport. In Test 1.4.1 en 1.4.3 is de referentielocatie gesteld op x=-5000m (linker modelrand) en in Test 1.4.2 is de referentielocatie gesteld op x=400m (locatie maximum transport). Omdat in UNIBEST en LONGMOR de actieve hoogte waarover de kustlijn zich uitbouwt of terugtrekt gelijk gesteld wordt, kunnen de relatieve kustposities in deze twee modellen rechtstreeks met elkaar vergeleken worden. In het geval van PONTOS is een rechtstreekse vergelijking niet mogelijk omdat de hoogte waarover de kust zich uitbouwt niet bepaald wordt door één waarde, maar is afhankelijk van de berekende dwarstransporten.



Figuur 2.19 Schematisch initieel langsuniforme kust met een gesloten rand en uniform golfconditie (Test 1.4.1, links), een schematisch initieel bolvormige kust met een languniform golfconditie (Test 1.4.2, midden), en een schematisch initieel langsuniforme kust met divergerende golfcondities (Test 1.4.3, rechts).

Tabel 2.4 Golf parameters in tests 1.4.1 – 1.4.3

	Test 1.4.1	**Test 1.4.2**	**Test 1.4.3**
Golfhoogte op diep water	1m	1m	Klimaat 1 en 2
Golfrichting t.o.v. kustnormaal	-10°	0°	Klimaat 1 en 2
Golfperiode of diep water	5.66s	5.66s	Klimaat 1 en 2
Kustlangspositie opgelegde golven	-4000m	0m	-4000m en +4000m

Tabel 2.5 Golf parameters van golfklimaten 1 en 2. Beide golfklimaten hebben gelijke golfhoogten, golfperioden en duur van condities, maar tegengestelde golfrichtingen t.o.v. de kustnormaal.

Duur (dagen/jaar)	**Significante golfhoogte (m)**	**Significante golfperiode (s)**	**Golfrichting klimaat 1 (°)**	**Golfrichting klimaat 2 (°)**
132.7273	0.75	5.0	73	-73
8.2955	1.65	7.0	73	-73
63.5985	1.25	6.3	53	-53
5.5303	2.75	8.3	53	-53
15.2083	1.25	6.3	33	-33
8.2955	2.25	7.8	33	-33
26.2689	1.25	6.5	-17	17
5.5303	2.75	8.5	-17	17
42.8598	1.25	7.5	-47	47
4.1477	2.75	9.5	-47	47
48.3902	0.75	5.6	-67	67
4.1477	2.25	8.7	-67	67

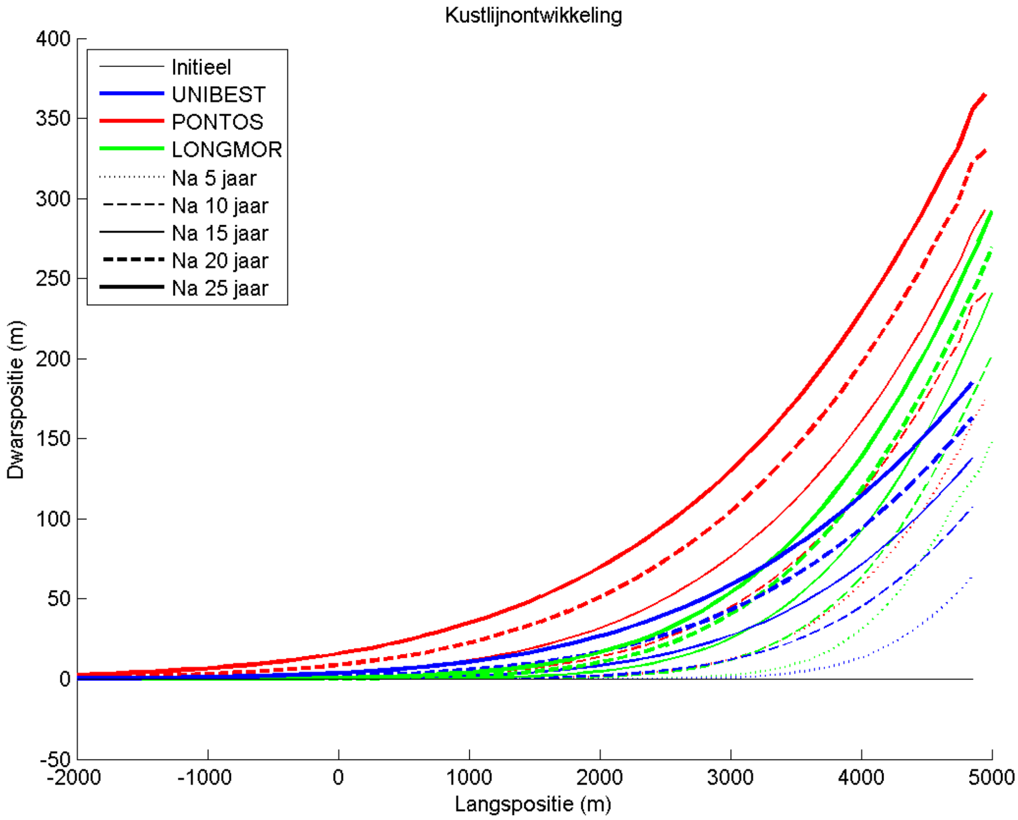
2.5.4.1 Test 1.4.1

De ontwikkeling van de kustlijn in Test 1.4.1 wordt voor alle drie kustlijnmodellen in Figuur 2.20 weergegeven. Het figuur laat zien dat in alle modellen de kustlijn bij de gesloten rechterrand begint uit te bouwen. De snelheid waarmee de kust zich uitbouwt in de richting van het initiële kustnormaal is in alle modellen in de eerste 5 jaar het grootst en neemt geleidelijk af in de tijd. Alle modellen bereiken een evenwichtskusthoek aan de gesloten rand, waar het transport nul is. Deze hoek blijft voor ieder model in de tijd gelijk, maar de hoek verschilt wel tussen de modellen onderling. De evenwichtshoek in LONGMOR is het grootst van alle modellen en is gelijk aan de hoek van inval van de golven. In LONGMOR is deze kusthoek de enige mogelijke hoek waarbij het langstransport bij de gesloten rand nul kan zijn. In PONTOS is de evenwichtshoek kleiner dan die in LONGMOR. Dit verschil komt doordat de kustlijnpositie in PONTOS gelijk gesteld wordt aan de positie van laag 2 in het model. Net als in LONGMOR kan het netto langstransport in laag 2 alleen nul kan zijn als de kustlijn normaal op de golfrichting staat. Echter, omdat er in PONTOS ook dwarstransport plaatsvindt, verliest laag 2 sediment naar hogere en diepere lagen, waardoor de kustlijnpositie terugtrekt. Dit dwarstransport eindigt op het moment dat alle lagen in het model dwars op de golfrichting staan. In werkelijkheid is dus de evenwichtshoek in het PONTOS model na 25 jaar nog niet bereikt. In UNIBEST is de evenwichtshoek bij de gesloten rand duidelijk minder groot dan in LONGMOR en PONTOS. Dit verschil wordt veroorzaakt door de manier waarop in UNIBEST de kust roteert. Omdat in UNIBEST de bodemcontouren op diep water niet veranderen, worden de golven in het model gerefracteerd voordat zij langstransport opwekken. Hierdoor is de hoek waarop nul transport plaatsvindt in UNIBEST kleiner dan die in PONTOS en LONGMOR, zie ook Figuur 2.13 voor schematische uitleg.

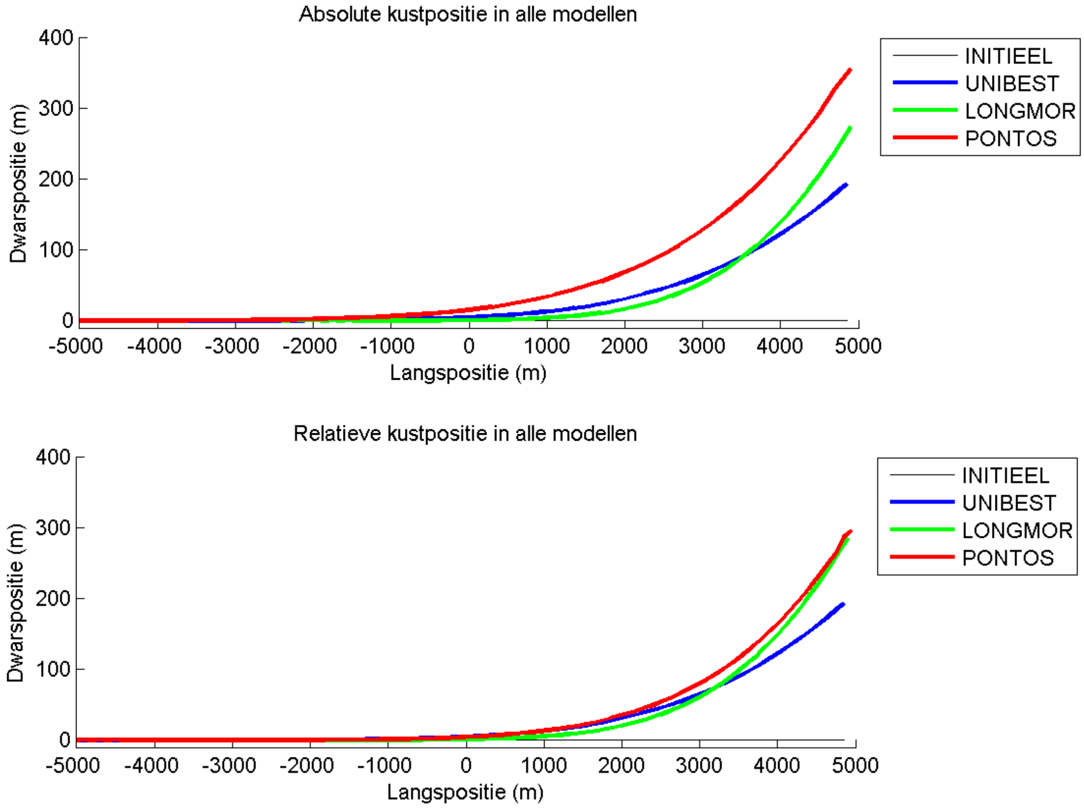
De uiteindelijke absolute en relatieve kustlijnposities van alle modellen na 25 jaar zijn in Figuur 2.21 weergegeven, waarbij de relatieve posities genormaliseerd zijn aan de hand van het inkomend langstransport. Het figuur laat zien dat de relatieve kustuitbouw bij de gesloten rand in LONGMOR en PONTOS groter is dan in UNIBEST, welke overeenkomt met de analyse van Figuur 2.20. Het figuur laat ook zien dat bij gelijk inkomend langstransport, de kusthoek bij de gelsloten rand in PONTOS en LONGMOR sterk met elkaar overeenkomen, en dat deze hoek groter is dan de kusthoek in UNIBEST.

Het effect van de actieve diepte waarover de kust kan roteren op de uiteindelijke kustpositie wordt in Figuur 2.22 benadrukt. In dit figuur is naast de uiteindelijke kustlijnpositie van de drie normale kustlijnmodellen, ook de uiteindelijke kustlijnpositie getoond van een UNIBEST simulatie waarbij de dieptecontouren over het gehele profiel met de kustlijn meedraaien (UNIBEST-diep; blauw gestippeld). De uiteindelijke kustpositie in de UNIBEST-diep simulatie komt in dit geval in grote mate overeen met het door LONGMOR berekende kustpositie, welke aantoont dat de verschillen tussen PONTOS en LONGMOR, en UNIBEST voornamelijk het gevolg zijn van de manier waarop golfrefractie op diep water in de verschillende modellen wordt verwerkt.

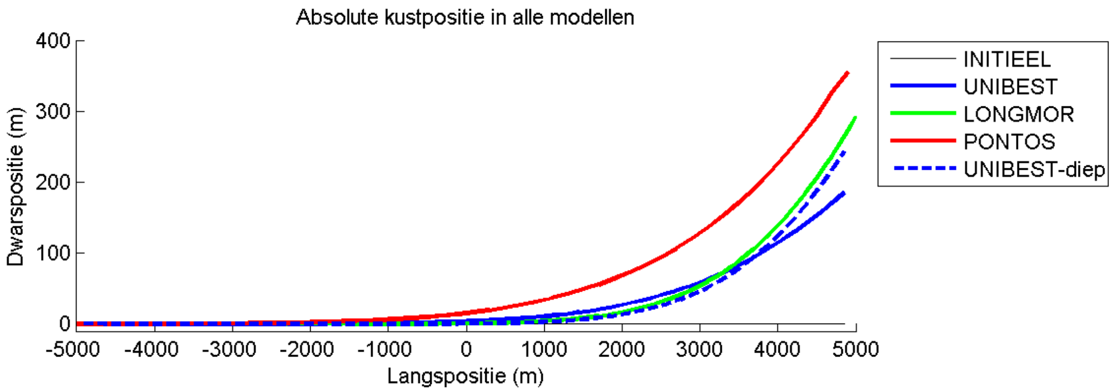
Het numerieke schema dat in LONGMOR gebruikt wordt om de morfologische ontwikkeling te simuleren is inherent instabiel. Om te voorkomen dat kleine instabiliteiten leiden tot grootschalige veranderingen in de modelresultaten, wordt een kunstmatige diffusieterm toegevoegd om instabiliteiten uit te smeren. De keuze van deze diffusieterm wordt aan de modelleur overgelaten, en dient zo klein mogelijk gekozen te worden dat de resultaten net geen instabiliteiten vertonen. In het geval dat de diffusieterm zeer klein gekozen kan worden, is het effect van deze diffusie op de uiteindelijke kustlijnpositie gering. Als er echter vanwege grote kustlijn- of transportgradiënten een groter diffusieterm gekozen moet worden, wordt de invloed van de kunstmatige diffusie belangrijker. In Figuur 2.23 is het effect van de kunstmatige diffusieterm weergegeven voor Test 1.4.1. Omdat PONTOS een vergelijkbaar numeriek schema gebruikt als LONGMOR om de morfologische ontwikkeling te simuleren, wordt een limiet geplaatst op de maximale uitwijking die plaats kan vinden in één tijdstap, waarop de rekentijdstap intern wordt aangepast. Aanpassing van deze limiet leidt niet tot significante verschillen in de modelresultaten.



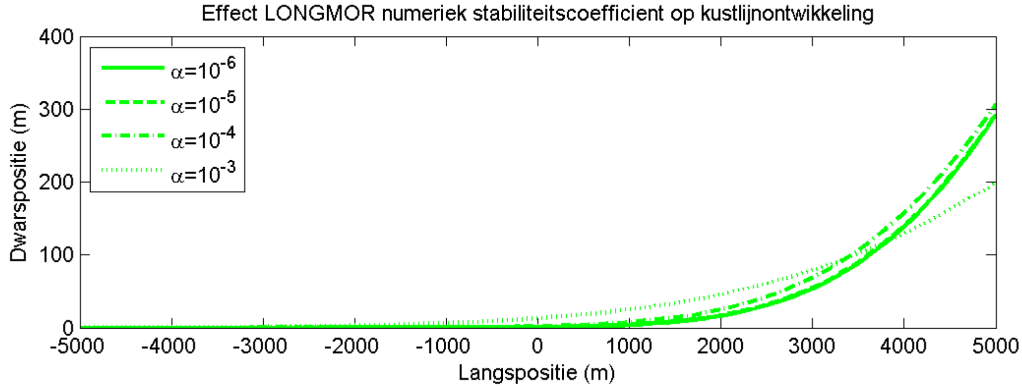
Figuur 2.20 Ontwikkeling van de kustlijn van Test 1.4.1 in de tijd in alle drie kustlijnmodellen.



Figuur 2.21 Absolute en relatieve kustlijnpositie van Test 1.4.1 na 25 jaar simulatie voor alle drie kustlijnmodellen.



Figuur 2.22 Absolute kustlijnpositie van Test 1.4.1 na 25 jaar simulatie voor alle drie kustlijnmodellen, inclusief UNIBEST berekening waarbij de actieve zone het hele dwarsprofiel beslaat (UNIBEST-diep).

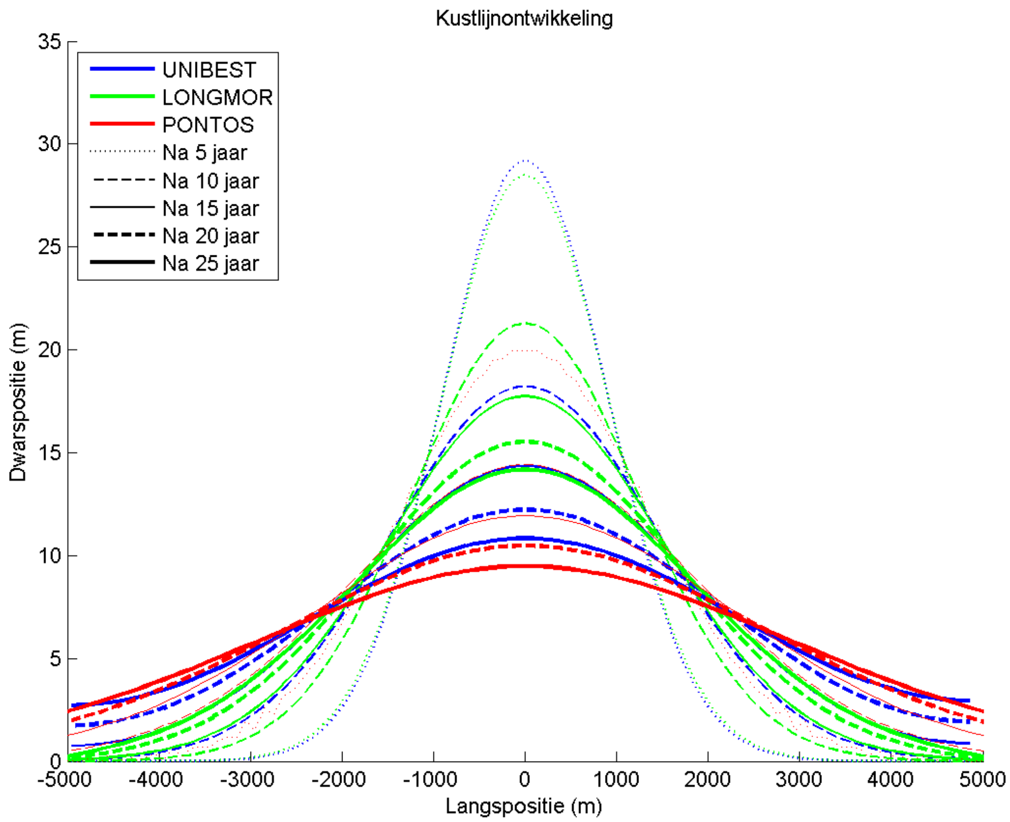


Figuur 2.23 Het effect van het numeriek stabiliteitscoefficient α op de ontwikkeling van de kustlijn van Test 1.4.1 in LONGMOR.

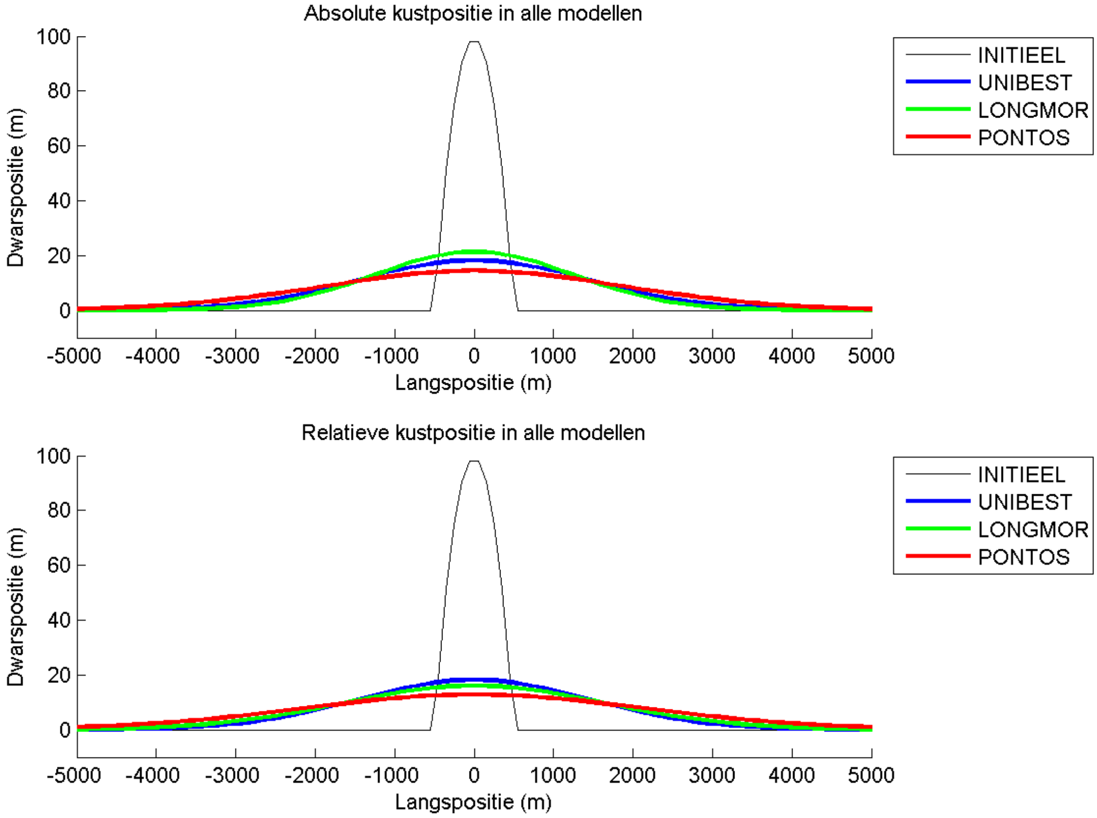
2.5.4.2 Test 1.4.2

De ontwikkeling van de kustlijn in de tijd in de UNIBEST, LONGMOR en PONTOS modellen is in Figuur 2.24 weergegeven. Het figuur laat zien dat de kustlijn in het PONTOS model sneller achteruit gaat dan in de LONGMOR en UNIBEST modellen; de kustlijn in de UNIBEST en LONGMOR modellen is na 10 jaar simulatie op een vergelijkbare locatie als de kustlijn in het PONTOS model na 5 jaar simulatie. Het initieel langstransport in het PONTOS model ligt qua grootte tussen het initieel transport in de LONGMOR en UNIBEST modellen (niet getoond), waaruit blijkt dat het verschil in de kustlijnpositie niet veroorzaakt wordt door een groot langstransport in het PONTOS model. Het verschil kan evenals bij Test 1.4.1 wel worden verklaard aan de hand van het feit dat de kustlijnpositie in PONTOS bepaald wordt door de positie van laag 2 in het model, en niet een gemiddelde positie van alle lagen. Omdat de actieve hoogte van laag 2 (5m) kleiner is dan de actieve hoogte in de LONGMOR en UNIBEST (10m), reageert de positie van deze laag sneller op langstransport gradiënten dan de kustlijnlijnpositie in LONGMOR en UNIBEST. Daarnaast vindt de her-distributie van sediment in de dwarsrichting in PONTOS op een langzamere tijdschaal (~jaren) plaats dan wat in UNIBEST en LONGMOR aangenomen wordt (instantaan). Deze combinatie maakt het mogelijk dat de kustlijnpositie in PONTOS sneller terugtrekt dan in UNIBEST en LONGMOR. Het is mogelijk dat andere indicatoren voor de kust, bijvoorbeeld de MKL-positie, minder verschillen tonen tussen de modellen. De gevoeligheid hiervoor wordt in Deel 2 van dit project verder onderzocht.

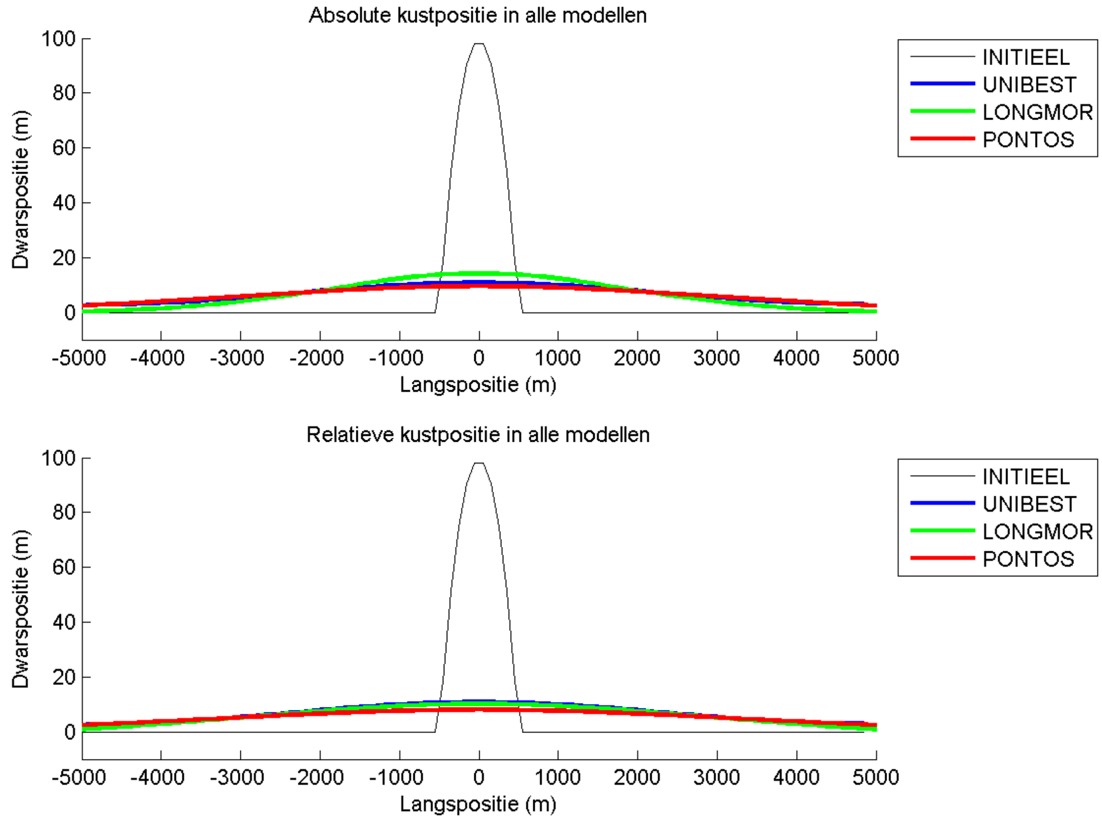
De absolute en relatieve kustlijnpositie in alle modellen na 10 jaar simulatie wordt in Figuur 2.25 getoond. Het figuur laat net als Figuur 2.24 zien dat er verschillen zijn in de absolute kustlijn ontwikkeling tussen de modellen, en daarnaast dat deze verschillen ook bestaan in de relatieve kustlijnontwikkeling. Het grootste verschil in de absolute kustlijnpositie van top van de bol is tussen LONGMOR en PONTOS (6.9m) en bedraagt ongeveer 8% van de gemiddelde terugtrekking van de bol. Voor de relatieve kustlijnpositie is het verschil het grootst tussen UNIBEST en PONTOS (5.4m) en bedraagt 6% van de gemiddelde terugtrekking van de bol. Voor zowel de absolute en relatieve kustlijnpositie is het verschil tussen UNIBEST en LONGMOR ongeveer de helft van de bovengenoemde maximale verschillen. De absolute en relatieve kustlijnpositie in alle modellen na 25 jaar simulatie is in Figuur 2.26 weergegeven. Het figuur laat zijn dat op deze tijdschaal de verschillen tussen de modellen kleiner zijn dan op de tijdschaal van 10 jaar. De verschillen in de absolute ligging van de maximale uitwijking van de bolling tussen de modellen bedraagt 4,6m, ongeveer 5% van de gemiddelde terugtrekking van de bolling. Als de langstransporten worden gecalibreerd, wordt het maximale verschil in de relatieve kustlijnpositie 2,8m (3%).



Figuur 2.24 Ontwikkeling van de kustlijn van Test 1.4.2 in de tijd in UNIBEST, LONGMOR en PONTOS. In dit overzicht is de initiële kustlijn wegelaten, die een maximale uitwijking heeft van 100m in dwarsrichting, om verschillen tussen de modellen inzichtelijk te maken.



Figuur 2.25 Absolute en relatieve kustlijnpositie van Test 1.4.2 na 10 jaar simulatie voor alle drie kustlijnmodellen.

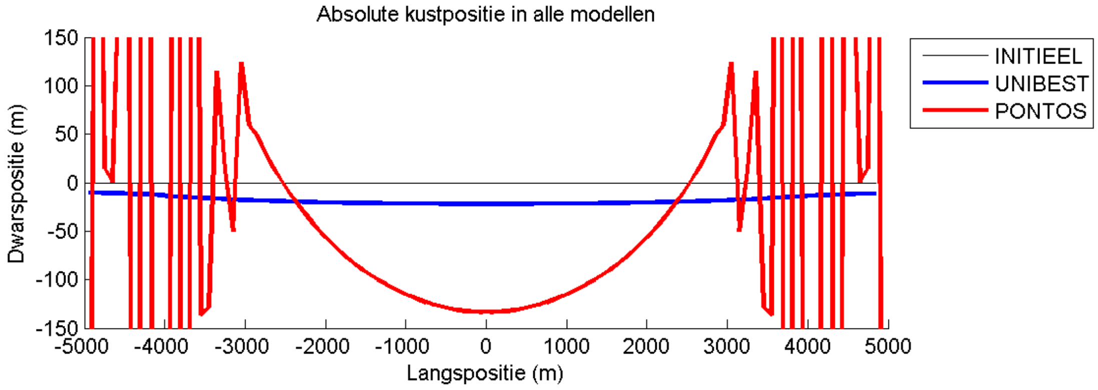


Figuur 2.26 Absolute en relatieve kustlijnpositie van Test 1.4.2 na 25 jaar simulatie voor alle drie kustlijnmodellen.

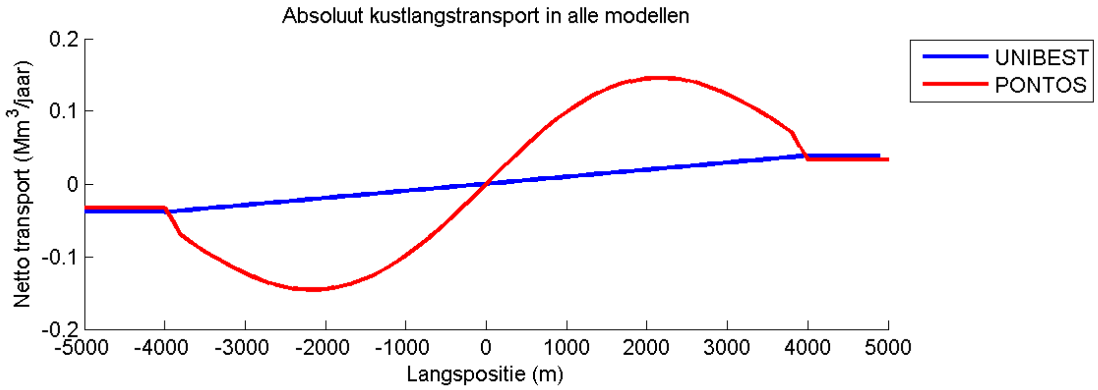
2.5.4.3 Test 1.4.3

In Test 1.4.3 wordt een initieel rechte kustlijn gesimuleerd met twee golfklimaten die leiden tot divergerend langstransport. Omdat LONGMOR niet beschikt over de mogelijkheid van langsvariërende golfrandvoorwaarden, is deze vergelijking alleen tussen UNIBEST en PONTOS opgezet.

De kustlijnposities in UNIBEST en PONTOS na 25 jaar simulatie zijn in Figuur 2.27 weergegeven. De resultaten tonen dat de kustlijnpositie in PONTOS instabiel wordt. Deze instabiliteiten zijn in tegenstelling tot Test 1.4.2 niet verholpen door het kiezen van een kleiner rekentijdstap. De verschillen tussen UNIBEST en PONTOS zijn mogelijk te verklaren door het in beide modellen berekend initieel langstransport, zie Figuur 2.28. Daarin is te zien dat de langstransportgradiënten in beide modellen zeer verschillen. Dit verschil wordt veroorzaakt door het feit dat in UNIBEST de coëfficiënten voor het langstransport in de langsrichting worden geïnterpoleerd, en in PONTOS alle golfcondities in de langsrichting worden geïnterpoleerd. In Test 1.3.1 en 1.3.2 zijn hieruit geen grote verschillen gekomen in het langstransport. Echter bij gebruik van golfklimaten, blijkt dit interpolatiemethode verschil tot veel groter verschillen in het langstransport te leiden. De berekende langstransporten in PONTOS (Figuur 2.28) leiden tot twee locaties waar het langstransport gradiënt nul is (~−2000m en ~+2000m). Op deze locaties wordt daarmee de kustlijnpositieverandering ook nul. Naar buiten toe van deze locaties vindt vervolgens onverwacht convergerend transport plaats. Deze transportgradiënten leiden vervolgens tot instabiliteiten die in de tijd blijven uitgroeien.



Figuur 2.27 Absolute kustlijnpositie van Test 1.4.3 na 25 jaar simulatie in de UNIBEST en PONTOS modellen. Resultaten voor LONGMOR zijn niet beschikbaar.



Figuur 2.28 Absoluut initieel langstransport in Test 1.4.3 in de UNIBEST en PONTOS modellen. Resultaten voor LONGMOR zijn niet beschikbaar.

2.6 Conclusies

Aan de hand van een aantal simpele en schematische simulaties is inzicht verkregen in de verschillen tussen de kustlijnmodellen UNIBEST, LONGMOR en PONTOS. De belangrijkste verschillen worden hieronder samengevat:

- Berekende langstransporten kunnen per golfconditie tussen de modellen verschillen met een factor 2–4. De grootste overeenstemming tussen transporten in UNIBEST en PONTOS is gevonden voor golven met een hoogte van 1m, steilheid van 4%, korreldiameter van 300µm en gebruik van de Van Rijn 2004 transport vergelijking in UNIBEST. Het verschil tussen UNIBEST en PONTOS neemt toe met groter en kleiner wordende golven, minder steile golven en kleiner sediment diameter. Ondanks deze verschillen is bij gebruik van de Van Rijn 2004 transport vergelijking in UNIBEST en LONGMOR het gemiddeld relatief transport verschil tussen UNIBEST en PONTOS (13%), kleiner dan het gemiddeld relatief transport verschil tussen UNIBEST en LONGMOR (54%) en tussen LONGMOR en PONTOS (45%), zie ook Figuur 2.4.
- In alle drie modellen wordt op een ander manier een S-θ kromme samengesteld uit een golfklimaat. In UNIBEST wordt aan het begin van de simulatie per profiel met een proces-gebaseerd UNIBEST-LT model voor een aantal discrete kustrotatiehoeken het netto langstransport berekend als gevolg van alle golfcondities in het golfklimaat. Om dit te bereiken wordt met het 1D-ENDEC model golfrefractie en golfbreking op het

dwarsprofiel berekend en wordt het sedimenttransport in het hele dwarsprofiel berekend. Het netto langstransport als functie van de kusthoekrotatie wordt vervolgens gereduceerd tot een parametrische beschrijving met drie vrije parameters (zie Vgl. 2). Het verschil tussen de parametrische beschrijving en de berekende transporten is in veel gevallen kleiner dan 1%. Deze geparametriseerde S-θ kromme wordt vervolgens gedurende de hele simulatie gebruikt om transporten op dat profiel te berekenen.
In PONTOS en LONGMOR wordt in het rekenhart niet gerekend met S-θ krommen, maar worden de langstransporten voor elke rekentijdstap opnieuw berekend. In PONTOS gebeurt dit door voor alle golfcondities in het golfklimaat het langstransport te berekenen met een parametrische transportvergelijking (Vgl. 3). Vervolgens wordt het op dat moment geldende netto-transport berekend door de transporten per golfconditie gewogen te sommeren. In LONGMOR wordt in plaats van het netto transport, het bruto transport als gevolg van het op dat moment geldende golfconditie berekend. Dit verschil tussen PONTOS/UNIBEST en LONGMOR maakt het zonder veranderingen in modelopzet mogelijk om met LONGMOR het effect van brutotransporten te onderzoeken. Echter heeft het ook tot gevolg dat de volgorde van opgelegde golfcondities tot verschillen in het eindantwoord kan leiden bij LONGMOR.

- De manier waarop de kust roteert, verschilt aanzienlijk tussen de drie kustlijnmodellen. In LONGMOR wordt verondersteld dat als de kustlijn roteert, alle dieptecontouren tot aan diep water met de kust mee roteren. In PONTOS kunnen alle lagen in het model afzonderlijk van elkaar roteren. Echter voor het bepalen van het transport in elke laag wordt voor de golfrefractie verondersteld dat alle diepte contouren tot op diep water evenwijdig staan aan de hoek van die laag (zie Vgl. 3). In LONGMOR en PONTOS zal bij één golfconditie en zonder verstoringen van constructies, de kust (uiteindelijk) altijd volledig naar de diep water golfrichting toe roteren. In UNIBEST wordt verondersteld dat de kust alleen roteert binnen een bepaalde actieve zone, bijvoorbeeld de zone waarbinnen 98% van alle langstransport plaatsvindt. De dieptecontouren buiten deze zone veranderen niet. Dit heeft tot gevolg dat de golfhoek bij binnenkomst in de actieve zone significant anders kan zijn in UNIBEST dan in PONTOS en LONGMOR, zie Figuur 2.11 en Figuur 2.13. In UNIBEST zal de kust daarom in het algemeen niet naar de diep water golfrichting maar na de golfhoek ter plaatse van de start van de actieve zone toe roteren. Als in UNIBEST alle dieptelijn geforceerd worden mee te draaien met de kust, wordt het berekende transport in geval van het referentiegolfconditie 24% kleiner bij hoekverdraaiing van 12° dan als alleen het actieve zone met de kust mee roteert, en komen de S-phi krommen tussen UNIBEST, LONGMOR en PONTOS goed overeen.
- De manier waarop golfcondities in UNIBEST en PONTOS in de langsrichting worden geïnterpoleerd verschilt; in PONTOS worden de afzonderlijke golfcondities (golfhoogte, –periode en –richting) in de langsrichting geïnterpoleerd, terwijl in UNIBEST de coëfficiënten voor het langstransport geïnterpoleerd worden. Hoewel dit verschil bij één golfconditie niet tot grote verschillen leidt (Test 1.3.1 en 1.3.2), kan het wel tot grote verschillen leiden bij het gebruik van een golfklimaat (Test 1.4.3). Bij extreem schuin invallende golfklimaten kan PONTOS instabiele transportgradiënten berekenen, en daardoor de kustlijnontwikkeling niet voorspellen. Hoewel de interpolatie in UNIBEST wel tot stabiele gradiënten leidt, is de waarde van het geïnterpoleerde transport niet per definitie correct in zulke situaties. In LONGMOR kan geen ruimtelijk variërende golfcondities worden opgegeven.
- De keuze voor de instelling van de kunstmatige diffusiecoëfficiënt in LONGMOR wordt aan de gebruiker overgelaten. De keuze van de coëfficiëntwaarde heeft veel invloed op de uiteindelijke ontwikkeling van de kustlijn. In sommige complexe situaties zal het niet mogelijk zijn om een hele kleine waarde voor de diffusiecoëfficiënt te gebruiken, waardoor mogelijk teveel kunstmatige diffusie in het model moet worden geïntroduceerd

om tot stabiele resultaten te komen. Door herhaaldelijk kleine, willekeurig periodes te kiezen waarvoor afzonderlijke golfcondities gelden, wordt de fysische diffusie verhoogd, en kan de kunstmatige numerieke diffusiecoëfficiënt kleiner worden gekozen. Hoewel PONTOS een vergelijkbaar numeriek schema gebruikt als LONGMOR om de morfologie van de kustlijn te simuleren, lijkt het model niet, of minder, gevoelig te zijn voor de invoerparameters met betrekking tot de numerieke stabiliteit. Dit verschil is niet verder onderzocht, maar wordt geacht het gevolg te zijn van de automatische tijdstapreductie in het PONTOS model, in combinatie met ingebouwde criteria voor de maximale toegestane kustlijnlijn uitwijking per rekentijdstap in het model.

- Als in alle kustlijnmodellen op één referentiepunt het initieel langstransport gelijk gesteld wordt, kan de uiteindelijke kustlijnligging tussen de modellen alsnog verschillen. De voornaamste redenen hiervoor zijn de manier waarop de kustrotatie invloed heeft op de golfrefractie (Test 1.4.1) en het verschil in de tijdschaal waarop sediment in de dwarsrichting over het profiel verspreidt wordt (Test 1.4.1 en 1.4.2).

3 Part II: Domburg case

3.1 Introduction

The results of Part I of this study have shown considerable differences between the way sediment transport is computed in the three coastal evolution models and the result this has on the computed coastline development. In Part II the effect of these differences is investigated for a more complex, real-world application. In order to carry out this analysis, a real-world case is simulated using the three coastal evolution models. In order to ensure that the differences between model results are due to the model differences identified in Part I, certain simplifications are made with regard to the local wave and tide forcing conditions, the longshore variation of the cross shore profile and the longshore sediment transport rate. These simplifications make it possible to isolate the effect of model differences on the predicted coastline morphology, without contamination from other sources such as model schematisation choices. However, these simplifications also imply that none of the model results are optimal predictions for the true coastline evolution. As such, the results of the coastline evolution models will be chiefly compared relative to each other, rather than to the observed morphology.

3.2 Objective

Several differences between the three coastal evolution models have been identified in Part I through the analysis of simple, schematic test cases. The objective of this research is to identify the effect of these differences in a real-world case on, in particular, the computed coastline morphology and predicted nourishment requirements.

3.3 Study area

The area selected for study in this project is the northwest-facing coast of Walcheren, Zeeland, The Netherlands, see Figure 3.1. The coastline in this area 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. Cross shore profiles near Domburg (JARKUS transects 16001428–16001632) are relatively longshore uniform, see dark grey points in Figure 3.2. However, the coast north of Domburg at Oostkapelle is characterised by a shallow foreshore and offshore bar, see light grey points at approximately 800m from the dune foot in Figure 3.2. Simulation results from previous research in the area using the Delft3D KustZuid model (e.g., Deltares, 2010b; see Figure 3.3) show that the depth-average tidal longshore current at an average of 8m water depth ranges from maxima of approximately 0.8m/s to the North-East and 0.6m/s to the South-West, with an RMS value of 0.4m/s.

The coastline at Domburg is actively maintained to compensate for the tendency of the protrusion to erode. 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 in previous studies (Deltares, 2010a). This stretch of coast was nourished on twelve occasions in the period 1990–2008; see Figure 3.4 and Table 3.1. 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, see Figure 3.4 and described in Section 3.4.

Figure 3.1 Arial photograph of the northwest-facing coast of Walcheren, including the locations of Westkapelle, Domburg and Oostkapelle. Images courtesy of Google Earth.

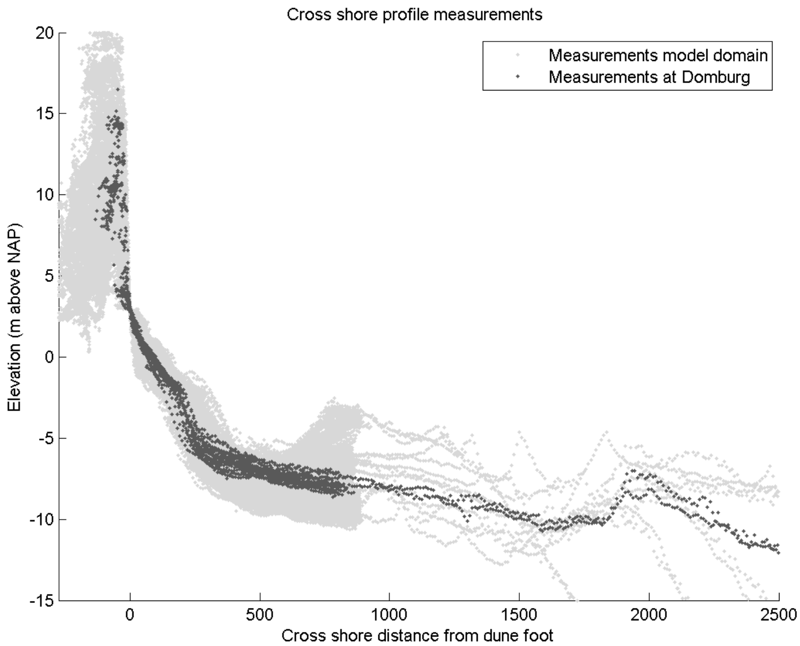


Figure 3.2 All measured cross shore transects along the entire model domain (light grey) and transects at Domburg (dark grey) between 1990–2008.

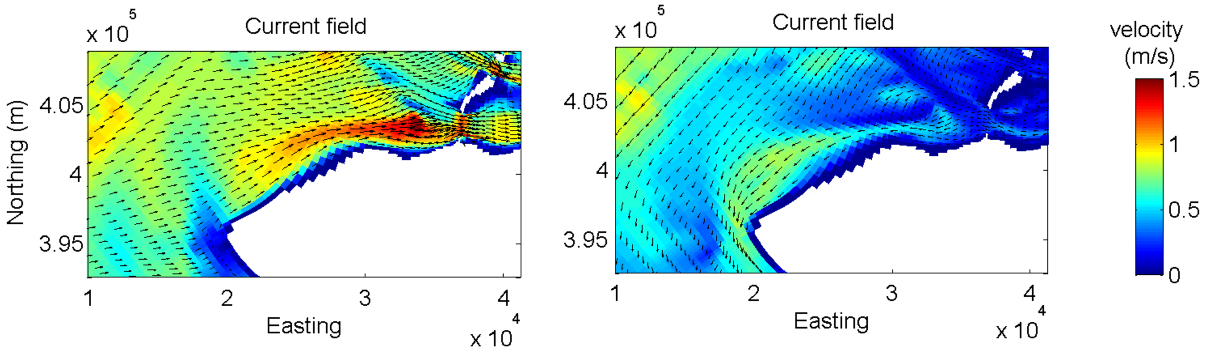


Figure 3.3 Typical spring tide current fields and magnitudes computed by the KustZuid flow model around the Walcheren coast during flood (left) and ebb (right). .

Figure 3.4 Locations of the twelve nourishments carried out in and around the model area (indicated by red box) in the period 1990–2008.

Table 3.1 Details of the twelve nourishments carried out in the study area in the period 1990–2008.

Year	Nourishment volume(m^3)	JARKUS coordinates of nourishment (m)	Nourishment type
2008	369,565	14060–16330	Beach
2008	110,435	16530–17350	Beach
2008	1,392,722	17550–19700	Foreshore
2008	1,022,609	17550–19700	Beach
2004	777,565	14650–18850	Beach
2000	886,127	14060–18830	Beach
1995	550,000	16860–18890	Beach
1994	453,000	14330–16050	Beach
1993	318,000	14300–15850	Beach
1992	637,000	12800–14300	Beach
1990	9,647	16120–17350	Beach
1990	8,000	14810–15830	Beach
Total	6,534,670		

3.4 Model setup

3.4.1 Model domain

The particular area of interest in this study is the behaviour of the coastal evolution models with respect to the bulge of the coast at Domburg. The foreshore in this location is relatively longshore uniform, with no obvious tidal channels near the coast, see Figure 3.5. The model domain is chosen such that it starts at the sea-dike at Westkapelle in the southwest (JARKUS-transect 16001814) and extends approximately six kilometres until JARKUS-transect 16001205, near Oostkapelle. This model extent is chosen specifically with the assumption that there is no incident longshore transport of sediment at the southern boundary at the edge of the sea-dike, and the tidal channel at the northern tip of Walcheren is sufficiently distant from the northern boundary of the model not to affect the coastal morphology. All model simulations are all set up to simulate the coastline evolution from 01/01/1990 until 31/12/2008.

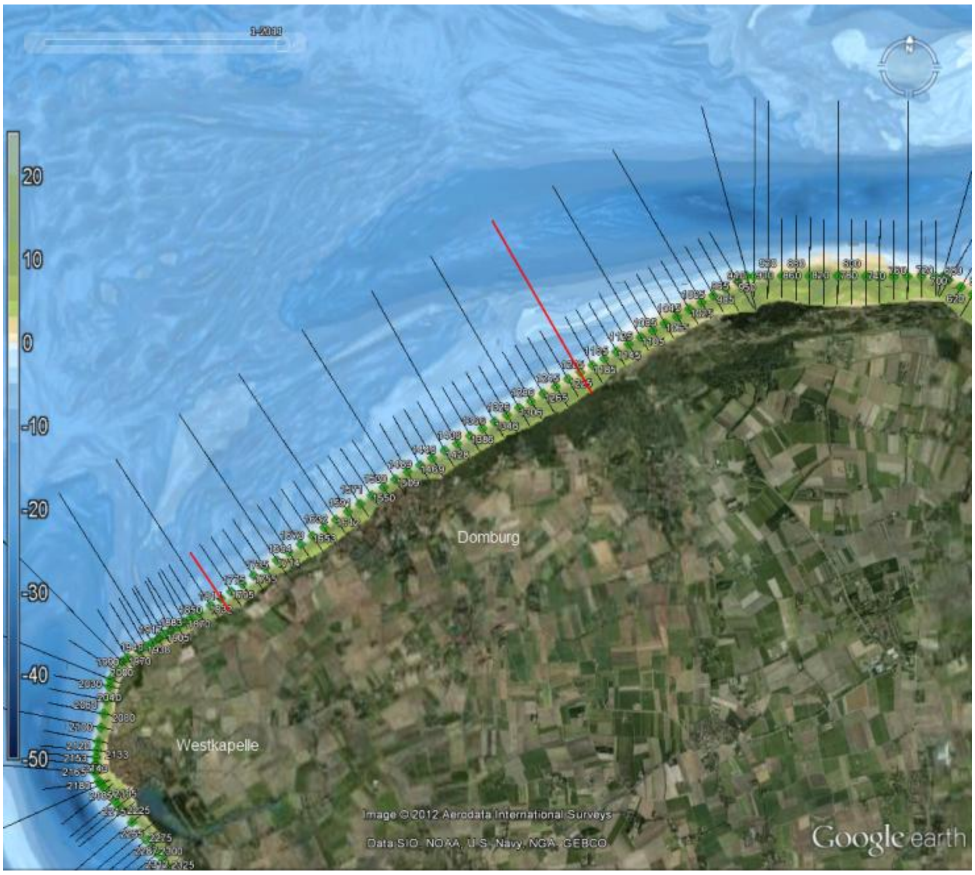


Figure 3.5 Measured bathymetry and JARKUS cross shore transect positions. Two transects in red (transect 16001205 and 16001814) represent the boundaries of the model domain.

3.4.2 Model grid

The model domain is schematised by a model grid with a longshore uniform grid spacing of 100m, see Figure 3.6. The initial position of the coastline in the UNIBEST-CL+ and LONGMOR models is set at the position of the mean sea level coastline position according to the 1990 JARKUS transect data, see Figure 3.7. In the PONTOS models, the position of layer 2 (which covers MSL-2m to MSL+3m) is related to the mean sea level coastline position in the JARKUS data. The reference line for all coastline models is determined by linear regression of the 1990 mean sea level coastline position and a landward translation of 200m. It should be noted that the reference line is not the same as the Dutch RSP base line.

3.4.3 Cross shore profile

In order to maintain compatibility between all three coastal evolution models, one representative cross shore profile is applied at all model grid points in the longshore direction. This representative profile is derived from the median cross shore profile in the area surrounding Domburg (JARKUS transects 16001428–16001632) for the period 1990–2008, see Figure 3.8. It should be noted that the measurements show some scatter around the representative median profile, which is primarily due to the slightly shallow foreshore to the north of Domburg, cf. Figure 3.5. The result of this schematisation is a deviation from reality that is expected to affect the ability of the coastline evolution models to accurately reproduce the observed coastal development. However, this limitation is deemed necessary in order to isolate the effect of model differences on the predicted coastline morphology.

Figure 3.6 Definition of the coastline model grids: coast reference line (black), initial mean sea level beach position (red) and numerical cross shore transects (green lines).

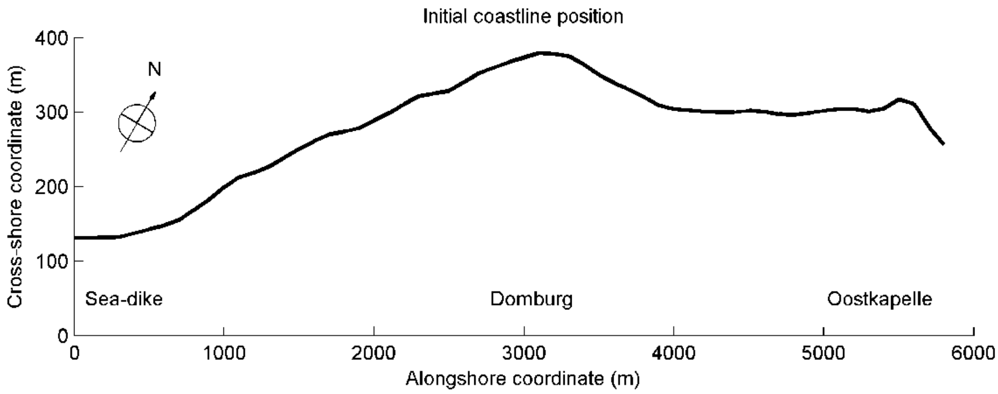


Figure 3.7 Initial coastline position in model coordinates.

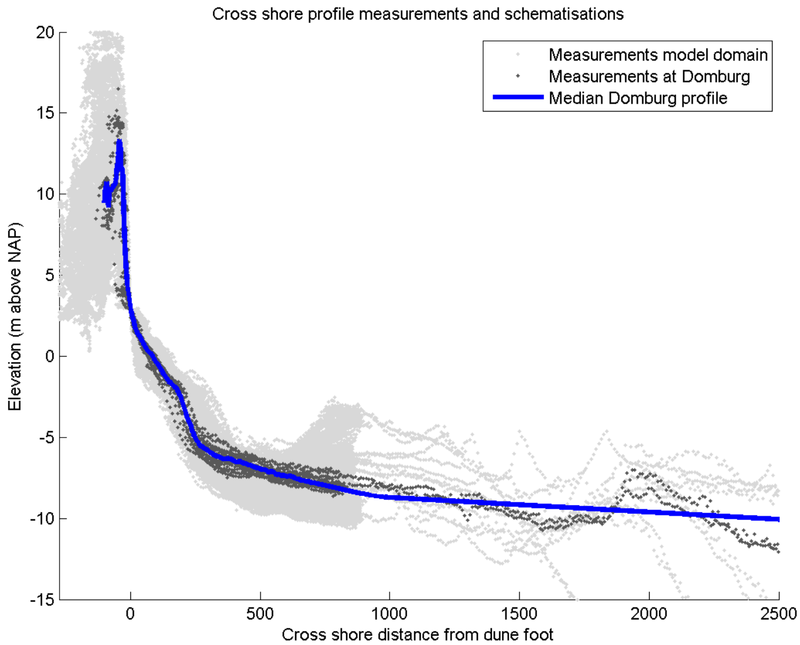


Figure 3.8 All measured cross shore transects along the entire model domain (light grey), transects at Domburg (dark grey), and representative cross shore profile (blue).

3.4.4 Wave boundary conditions

A longshore uniform wave climate is applied on the offshore boundary in all three coastline models. The wave climate used in this study is the climate taken from the PONTOS Dutch coast model at Europlatform, which is the nearest wave climate station in the model, see Appendix A. The climate is modified to remove all wave components from 60–240°N, which are not considered to contribute the longshore sediment transport at Domburg. The combined probability of occurrence of the wave components that are removed from the wave climate (40%) is applied to a fictitious wave condition with zero wave height, which is used to maintain the correct probability of occurrence of the true waves from 270–30°N, see Appendix A. Although the dominant wave direction of the true waves from 270–30°N is from the North, see Figure 3.9, the net sediment transport direction is towards the North-East due to the large contribution of high energy waves from 270°N and 300°N. In contrast to PONTOS and UNIBEST-CL+, the LONGMOR model requires a time series of wave conditions instead of a climate of wave conditions. In order to minimize model instabilities identified in previous research due to persistent transport from one direction, see Part I, physical diffusion in the LONGMOR model is maximised by generating a time series of random wave conditions selected from the impose wave climate. The probability of occurrence of each wave condition is ensured by dividing the expected duration of the condition into multiple three-day events, with the remainder imposed as one shorter event.

3.4.5 Sedimentological and morphodynamic parameters

All simulations are carried out using a median sediment size of 315µm. The default sediment transport relation is selected in each model (Van Rijn, 2005 in UNIBEST-CL+; Van Rijn, 2002 in LONGMOR; Steetzel, *et al*., 1998 in PONTOS) and default values are used in the sediment transport and wave transformation relations. In UNIBEST-CL+ and LONGMOR the active height of the profile, which represents the vertical extent across which the coastal profile erodes and accretes, is set at 14m. This value is based on twice the 1/1 year wave height (4.75m) plus the spring tidal range at Westkapelle. The active depth in UNIBEST-CL+, which represents the depth below MSL until which the coast is allowed to rotate, is set to the depth above which 98% of the longshore sediment transport takes place. In this schematic simulation of the Domburg the active depth is approximately 12.4m. In separate sensitivity simulations, the active depth is set to the entire profile depth (32m) in order to better mimic the assumptions made in the LONGMOR and PONTOS models.

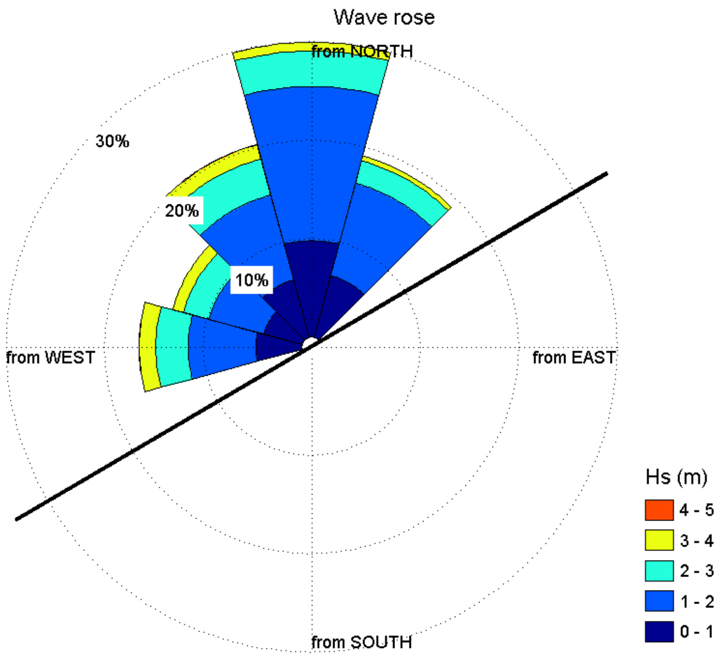


Figure 3.9 Wave rose of the deep water wave climate imposed on the coastline models and coastline orientation (solid black line) and shore normal (dashed black line).

3.4.6 Longshore sediment transport calibration

An estimate of the occurring longshore transport in the model area was made in order to equate the sediment transport in all three coastal evolution models. This estimate of the longshore transport was computed by assuming no flux of sediment across the model's southern boundary at the sea-dike. The total influx of sediment into the model domain due to nourishments over the period 1990–2008 was approximately 5.5Mm^3, see Figure 3.10 (second panel). Note that this is less than the value presented in Table 3.1 due to the fact that some nourishments took place partly outside the model domain. In that same period the total volume in the active coastal zone, as determined by the Momentary Coast Line position for all JARKUS transects in the model domain, increased by 3.6Mm^3, see Figure 3.10 (top panel). The total loss out of the model domain is therefore estimated at 1.9Mm^3 over the 19-year period from 1990–2008, or 100·10^{3}m^3/year, see Figure 3.10 (third panel). A first-order estimate of the transport gradient across the model domain is therefore 100·10^{3}m^3/year. Assuming that no transport takes place due to tides, the flux into the model domain at the sea-dike is zero and the increase in the MCL-position represents the entire increase in the volume of sediment along the coast, the wave-driven transport out of the model at the northern boundary should be set at 100·10^{3}m^3/year to ensure the correct gradient across the model. Similar wave-driven transport rates have been found in previous model studies

(Deltares, 2009). However, since the exact longshore transport at the northern boundary of the model may be highly sensitive to small numerical differences between the models, the average transport across the entire longshore domain is used instead of the transport at the northern boundary. This simplification is only strictly valid if the longshore sediment transport is uniform in the longshore direction. However, for the purposes of this study, the benefit of having comparable transport rates between the models is thought to outweigh the error in the estimation of the true net longshore transport. It should be noted that all the assumptions made in this computation will affect the overall ability of the coastline evolution models to predict the true coastline development.

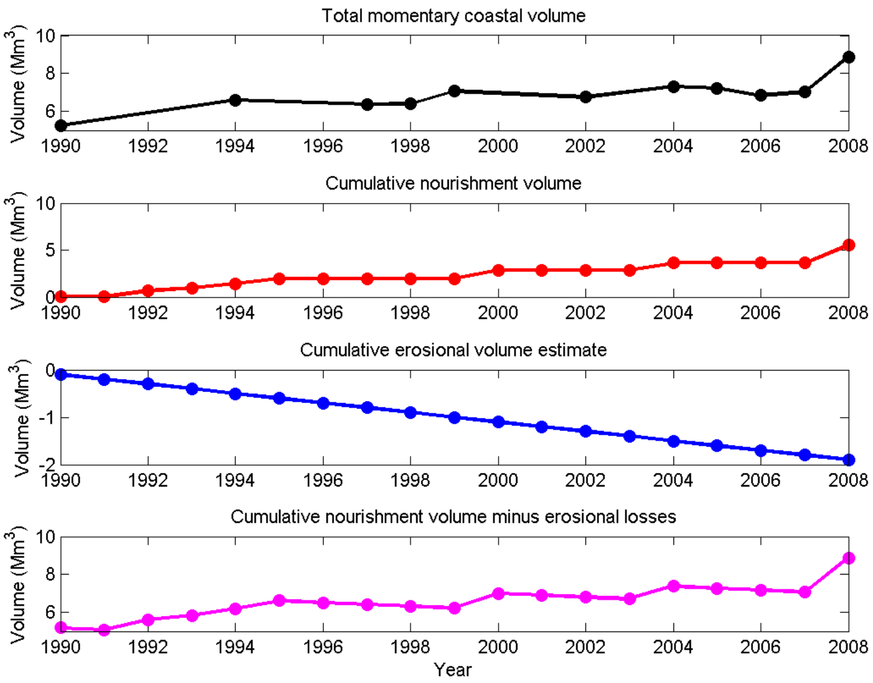


Figure 3.10 Total volume in the active coastal zone, as computed from the Momentary Coast Line for all JARKUS transects in the model domain (top panel); total cumulative nourishment volume in the model area (second panel); cumulative erosional losses estimate based on loss of 100·10^{3}m^3/year (third panel); cumulative difference between nourishment gains and erosional losses, relative to initial MCL-volume (bottom panel).

3.5 Model simulations

In order to identify the effect of the model differences discussed in the introduction, a series of simulations with increasing levels of complexity are carried out with the three coastline evolution models. The initial longshore sediment transport computed by the three models is addressed in the first model simulation (Case 1). In the subsequent simulations the morphology of the coastline is computed for a hypothetical situation in which the coastline is not managed with nourishments and no intervention take place (Case 2), and the current situation in which the locations, periods and volumes of the nourishments of the coast are derived from historical data (Case 3). In cases 4 and 5, intermediate results of the coastline models are used to predict the nourishment volume required to maintain the coastline.

As discussed in the objective of this report, the simplifications applied to the coastline models are such to allow a precise comparison between the models, rather than a comparison with reality. It is assumed that with further calibration, all three coastline evolution models are able to hindcast measured coastline changes correctly. However, such calibration would not allow the main objective of this study to be answered, and is therefore not discussed in this report.

3.5.1 Case 1: Initial longshore sediment transport

The initial longshore sediment transport, without any coastline development and without calibration, computed by all three coastline evolution models is presented in Figure 3.11 (top panel). In addition to the regular UNIBEST-CL+ simulation, the figure also shows the results of a UNIBEST-CL+ model in which the active depth is set to the entire profile depth rather than the depth at which more than 2% of the transport takes place (UNIBEST deep). The figure shows significant similarity between the results of the uncalibrated PONTOS and LONGMOR models, where both models have mean transports of approximately 20–50·$10^3 m^3$/year and respond similarly to changes in the coastline angle. The magnitude of the mean uncalibrated longshore transports in the UNIBEST-CL+ models (140–150·$10^3 m^3$/year) are substantially greater than those in the LONGMOR and PONTOS models. The standard UNIBEST-CL+ models shows large absolute changes in the longshore transport due to variations in the coastline orientation, whereas in the case of the UNIBEST deep model, the change in longshore transport due to changes in the coastline orientation is similar to that of the LONGMOR and PONTOS models.

The gross longshore transport per wave direction in the model wave climate in the UNIBEST-CL+, LONGMOR and PONTOS models is shown in Figure 3.12. The figure shows that the main difference between the models, and consequently the reason for the larger net transport in UNIBEST-CL+, is that UNIBEST-CL+ computes greater longshore transport than the other two models for waves coming from the West (270°N). This difference is not due to the difference in the active depth in UNIBEST-CL+, as demonstrated by the greater transport computed by the UNIBEST deep model. Instead, the difference in longshore transport may be due to the difference in model approaches and assumptions in the wave transformation routines in all three models, in particular for waves with large angles of incidence. Although it is not clear which model can more accurately predict the true longshore sediment transport for waves with large angles of incidence, this difference must be taken into consideration for large parts of the Dutch coastline.

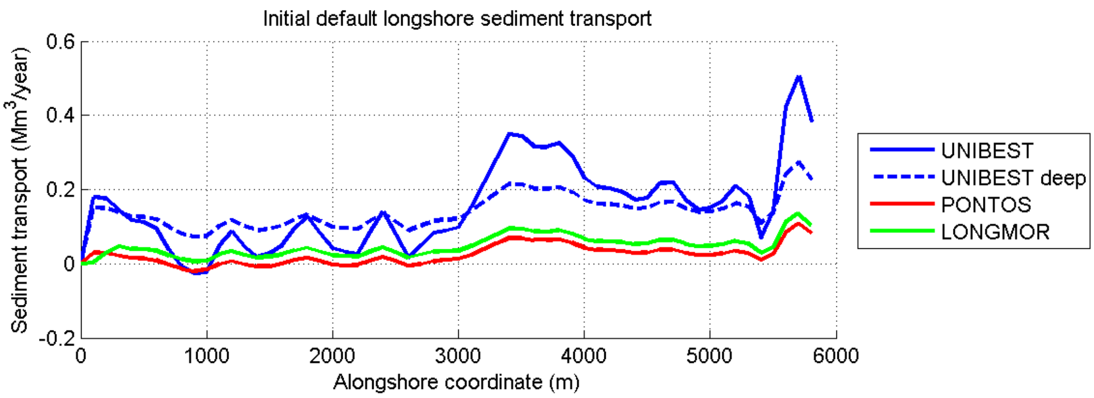


Figure 3.11 Longshore variation of the uncalibrated initial longshore sediment transport, for all three coastline evolution models, and in addition a UNIBEST-CL+ model in which the active depth is set to the entire profile depth (UNIBEST deep). Domburg located at approximately alongshore coordinate 3100m.

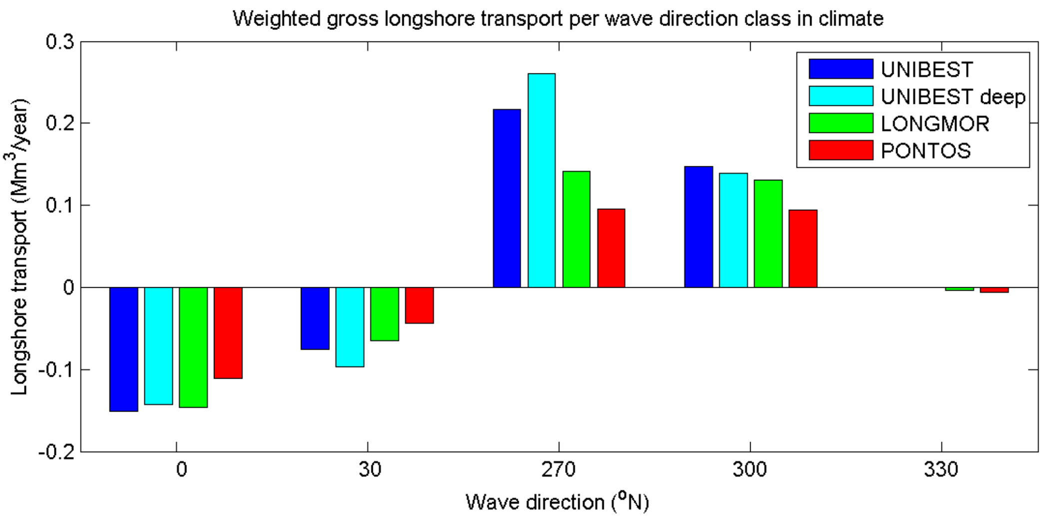


Figure 3.12 Gross longshore sediment transport in the UNIBEST-CL+, LONGMOR and PONTOS models per wave direction class in the imposed wave climate, weighted by the probability of occurrence of the wave conditions. Transports are valid for a coastline cross shore angle of 329.6°N (parallel to the model reference line).

Figure 3.13 shows the longshore sediment transport for all coastline evolution models, in which the transport has been calibrated to have a mean value of $100{\cdot}10^3 m^3$/year. This calibration was carried out by modifying one linear transport coefficient per model that is constant in space and time. The figure shows that the longshore transports in all models are similar, but that the PONTOS model has become relatively more sensitive to the orientation of the coast than the other models. This sensitivity is due to the fact that the PONTOS model is scaled using the greatest calibration factor and the unscaled transport originally fluctuated around the zero-transport line. This sensitivity implies that in this case the initial coastline change in the PONTOS model will be greater than in the UNIBEST-CL+ and LONGMOR models.

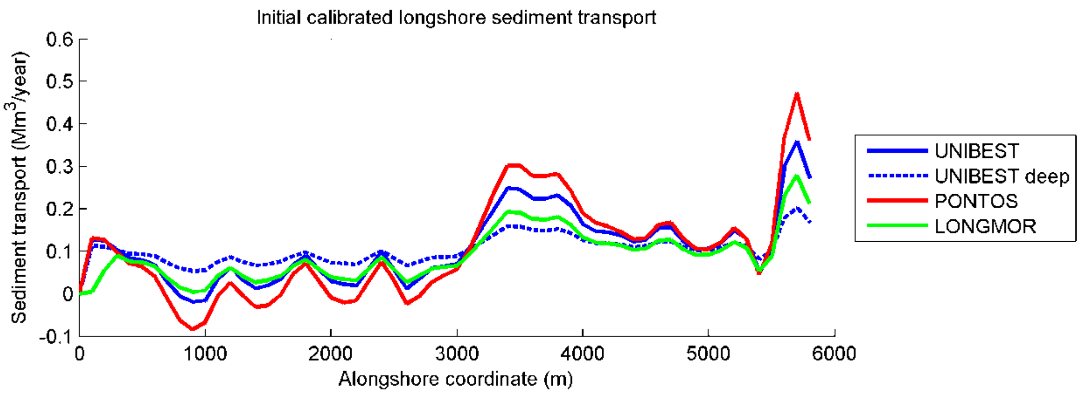


Figure 3.13 Longshore variation of the calibrated longshore sediment transport, for all three coastline evolution models, and in addition a UNIBEST-CL+ model in which the active depth is set to the entire profile depth (UNIBEST deep). Domburg located at approximately alongshore coordinate 3100m.

3.5.2 Case 2: Coastline change without intervention

Case 2 simulates the natural evolution of the coastline at Domburg without any nourishment interventions. All coastline evolution models are set-up to simulate the 19-year period from the start of 1990 until the end of 2008 using the calibrated longshore sediment transport coefficient found in Case 1, so that all models have a mean initial longshore transport of $100 \cdot 10^3 m^3$/year.

The development of the coastline in all models is shown in Figure 3.14. The figure shows that the calibrated PONTOS and UNIBEST-CL+ models predict similar rates of coastline retreat away from the model boundary at Domburg (86–90m over 19 years at alongshore coordinate 3100m), whereas the calibrated UNIBEST deep model predicts significantly smaller rates of retreat (56m over 19 years). Although this is similar to the predictions made based on the initial sediment transport, it is interesting to note that the coastal retreat in the UNIBEST-CL+ model almost matches that of the PONTOS model, despite lesser calibrated sediment transport gradients around Domburg, cf. Figure 3.13, and an initially greater active height of the coastal profile. This suggests that the initially large coastline change in the PONTOS model is compensated by rapidly diminishing longshore transport gradients as the coastline retreats, as well as increasing cross shore transport resulting in a greater distribution of the sediment loss across the vertical layers, thereby reducing the retreat of layer 2 in the model. The LONGMOR model appears to predict less coastline retreat at Domburg than the UNIBEST-CL+ model, but more than the UNIBEST deep model, which corresponds well with the initial longshore sediment transport gradients around Domburg.

All models except the PONTOS model predict coastline retreat at the sea-dike (alongshore coordinate 0m). This difference is due to the fact that in UNIBEST-CL+ and LONGMOR, the net sediment transport direction is towards the North-East. Although the depth-integrated net sediment transport direction in PONTOS is also towards the North-East, the net transport direction in Layer 2 (MSL-2m to MSL+3m) is towards the South-West because of the dominance of small waves from the North. These small northerly waves do not affect sediment transport in the deeper layers in the model. Since a zero-transport boundary is applied at the sea-dike end of all three coastline models, this net south-westerly transport in the PONTOS model leads to a slight progradation of the coastline.

As described in Section 3.4, a random time series of wave conditions is applied in the LONGMOR model. The effect of imposing an entirely random time series of three-day wave conditions in the model rather than a structured time series of wave conditions based on increasing wave height and wave direction is shown in Figure 3.15. In this figure the ‘standard’ simulation is computed using an entirely random time series of wave conditions. In the ‘fixed wave sequence’ simulation, the time series of wave conditions is ordered according to the reduced wave climate description in Appendix A, ranked by increasing wave direction and wave height. The figure shows that for equal numerical diffusion coefficients to the ‘standard’ simulation, the simulation with a structured wave condition time series develops coastline instabilities. These instabilities are removed by increasing the numerical diffusion coefficient, see ‘fixed wave sequence, large alfa’ simulation in Figure 3.15. The effect of this increased numerical diffusion coefficient on the coastline development can be significant, as shown by the ‘large alfa, no transport’ simulation, in which the computed coastline change is wholly due to numerical diffusion. The figure shows that for areas of the coast with large curvature (e.g., alongshore coordinates 3000m and 5500m) the coastline change due to numerical diffusion can be as much as 25m over the 19-year simulation period. Figure 3.15 also shows that the coastline development in both the ‘fixed wave sequence’ and ‘fixed wave sequence, large alfa’ simulations is significantly different to that in the ‘standard’ simulation for the entire coastline to the South-West of Domburg (alongshore coordinates 0m–3000m). These differences highlight the effect of gross transport versus net transport in predicting the final coastline evolution, and the importance of selecting realistic wave condition time series in the LONGMOR model.

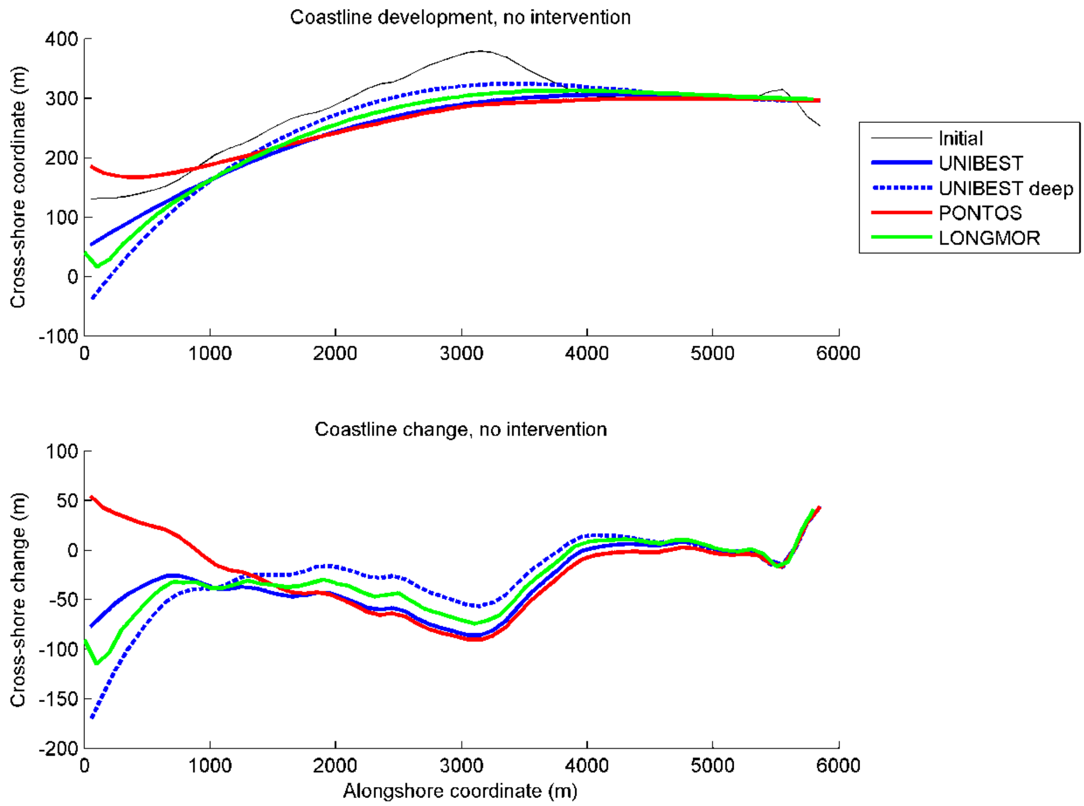


Figure 3.14 Coastline development (top panel) and coastline position change (bottom panel) after 19 years' simulation for Case 2, in all three coastline evolution models and one UNIBEST-CL+ model in which the active depth is set to the entire profile depth (UNIBEST deep). Note that the vertical axis in the top panel represents the cross shore coordinate in the model, not the Dutch RSP-coordinate. Domburg located at approximately alongshore coordinate 3100m.

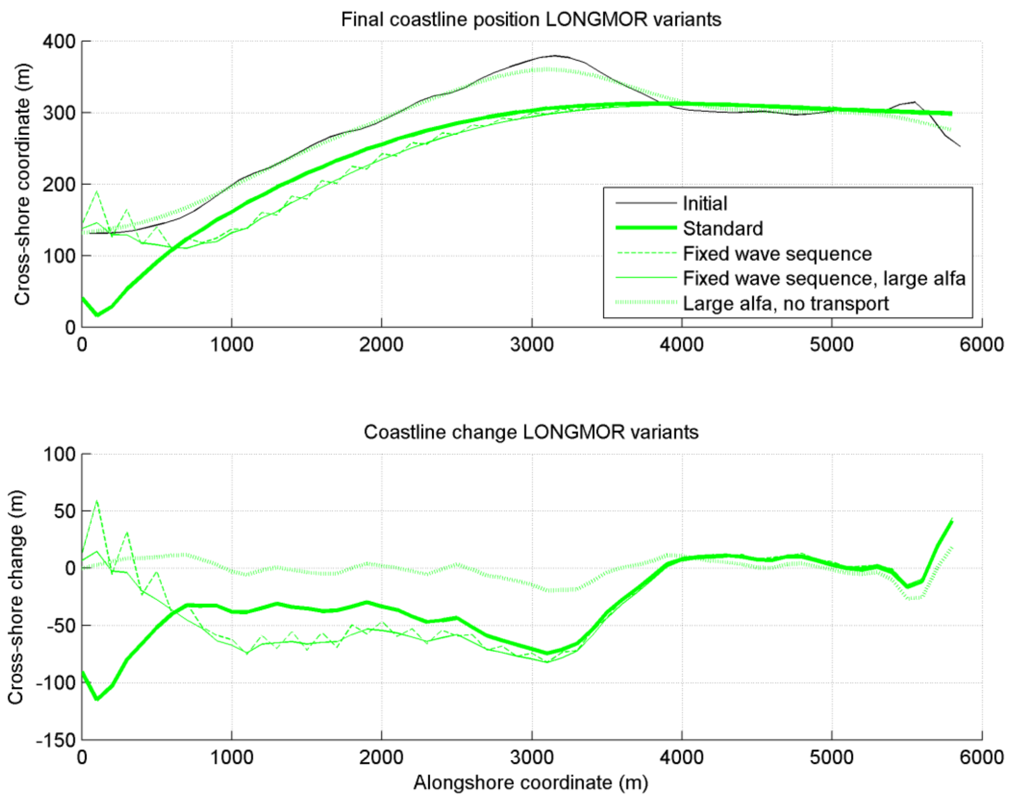


Figure 3.15 Coastline development (top panel) and coastline position change (bottom panel) after 19 years' simulation for LONGMOR model variants in Case 2. Domburg located at approximately alongshore coordinate 3100m.

3.5.3 Case 3: Coastline change with historical nourishments

Case 3 simulates the coastline development of the north-west coast of Walcheren over the 19-year period from the start of 1992 until the end of 2008, including the effect of the nourishments carried out in this area in that same period. The volumes, times and locations of these nourishments are based on the data presented in Section 3.3 and Table 3.1, which are converted to model coordinates and corrected for nourishments that partly took place outside the model domain, see Table 3.2 and Figure 3.16 for a graphical representation of the alongshore distribution of nourishments. Note that the total volume of the nourishments applied in the models in Case 3 is the same as the volume used to estimate the longshore transport gradient and mean longshore transport in Section 3.4. All nourishments in the model are set to start on day 146 and end on day 182 of the year in which they occur. All models are set to use the calibrated longshore transport coefficient found in Case 1. A random time series of wave conditions is applied in the LONGMOR model as discussed in Case 2.

The coastline development predicted by the three models for Case 3, including one UNIBEST simulation in which the active depth is set to the entire profile depth is shown in Figure 3.17. The figure shows that in comparison to Case 2, all models predict far lesser retreat of the coast at Domburg. The standard calibrated UNIBEST-CL+ models predicts the greatest retreat at Domburg (23m at alongshore coordinate 3100m), followed by the LONGMOR model (10m), the PONTOS model (1m). It should be noted however that the coastline position near Domburg in the PONTOS model may be affected by the imposition of zero transport at the sea-dike boundary, as described in Case 2. The UNIBEST model with the extended active depth (UNIBEST deep) predicts 12m coastal progradation instead of retreat at Domburg. All coastline models predict approximately equal coastline progradation to the north-east of Domburg (alongshore coordinates 4000m–6000m). Due to the large nourishments imposed on the model at the south-west boundary in 2008, all coastline models predict coastline progradation near the sea-dike boundary (alongshore coordinates 0m–1000m), but for reasons stated in Case 2, the coastline development in PONTOS is greater than in the other models at this location.

The difference between the coastline development at Domburg in the PONTOS model and the standard UNIBEST-CL+ model is less pronounced if a comparison is made between the predicted Momentary CoastLine (MCL) positions in each model, see Figure 3.18. The MCL-position is commonly used to assess the state of the Dutch coast, and at Domburg comprises a weighted average position of the entire coastal profile between MSL+3.0m and MLS-6.1m. Since the UNIBEST-CL+ and LONGMOR models assume a constant profile shape, the relation between the MSL-position and MCL-position is a constant (57.3m). In the PONTOS model the difference between the MSL-position and MCL-position is computed from the weighted positions of Layer 2 (between MSL-2m and MSL+3m) and Layer 3 (between MSL-7m and MSL-2m). Figure 3.18 shows that although the coastline (MSL-position) in the PONTOS model remains more or less in place after 19 years' simulation, the MCL-position in the model resembles that of the standard UNIBEST-CL+ model, indicating coastal retreat.

The results of Case 3 show that all three standard coastline evolution models predict similar amounts of coastal retreat if the MCL-position is chosen as the coastal state indicator. PONTOS indicates a change in the shape of the coastal profile at Domburg; the initial position of both MSL and MCL are set equal in the UNIBEST-CL+, LONGMOR and PONTOS models. However, the development of the MCL position in PONTOS differs to that of the MSL-position, indicating that the horizontal offset between the two coastline indicators does not remain constant as assumed in the LONGMOR and UNIBEST-CL+ models, which can only be explained by a change in the profile shape. The UNIBEST-CL+ model with extended active depth (UNIBEST deep) has lesser longshore sediment transport gradients than the other models, resulting in predicted coastal progradation rather than retreat at Domburg. All coastal evolution models predict large-scale coastal progradation to the north-east of Domburg, which has not been shown to occur in reality (cf. Deltares, 2010). Thus it can be concluded that the current model setup does not contain all relevant coastal processes in the model area, and other physical processes such as tidal currents, longshore varying wave conditions and longshore varying profile shapes may be required to accurately predict coastline change in the area.

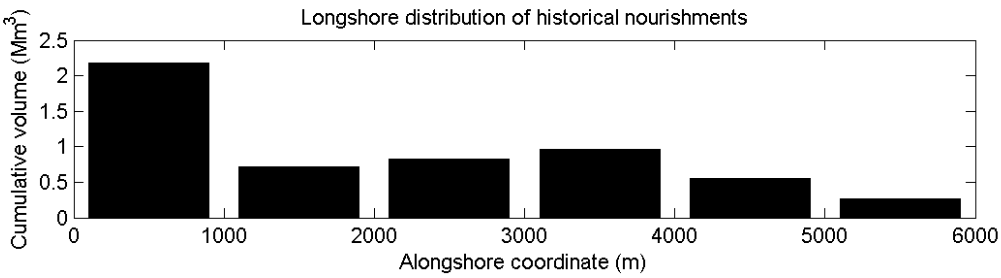


Figure 3.16 Alongshore distribution of the cumulative nourishment volume between 1990–2008. Note the large nourishment volume at the sea-dike end of the model (alongshore coordinate 0–1000m). Domburg located at approximately alongshore coordinate 3100m.

Table 3.2 Details of the twelve model nourishments imposed in Case 3. Note that some volumes differ relative to Table 3.1 due to these nourishments being partly carried out outside the model domain.

Year	**Nourishment volume(m^3)**	**Alongshore model coordinates of nourishment (m)**
1990	9,600	1100–2300
1990	8,000	2500–3500
1992	670,000	4100–5600
1993	318,000	2500–4100
1994	453,000	2300–4100
1995	530,600	0-1600
2000	885,200	0–4400
2004	767,900	0–3700
2008	369,600	2100–4400
2008	110,400	1100–1900
2008	825,500	0–900
2008	606,100	0–900

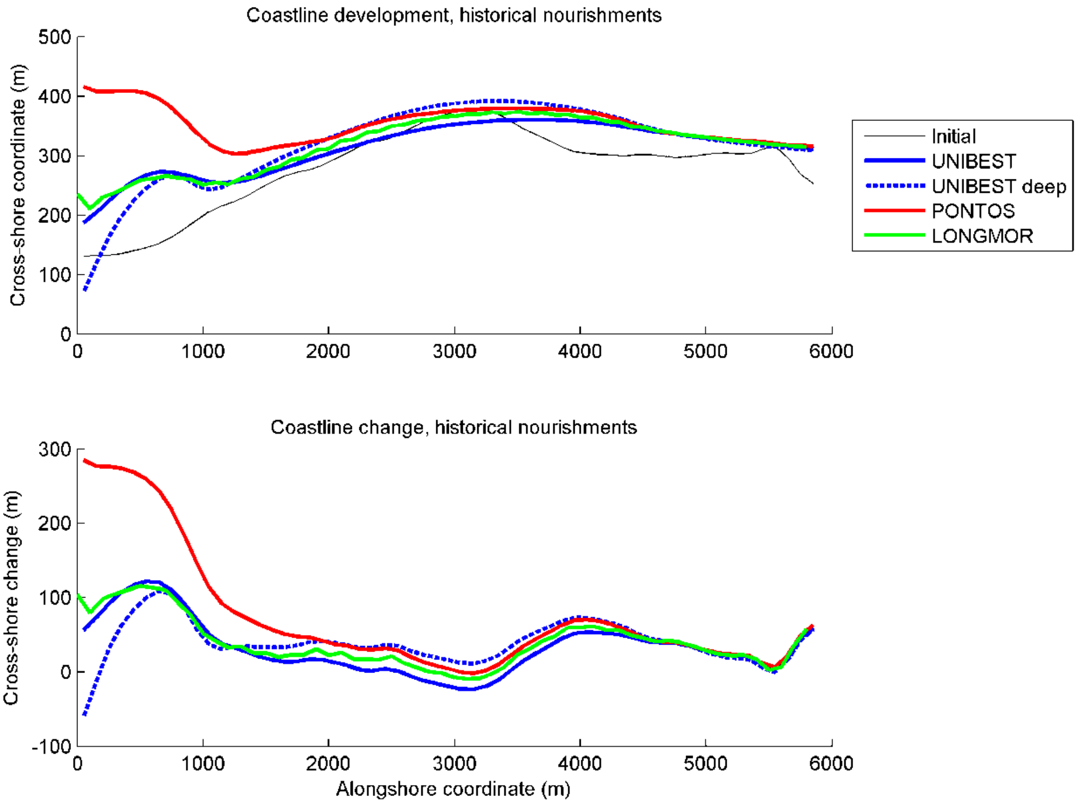


Figure 3.17 Coastline development (top panel) and coastline position change (bottom panel) after 19 years' simulation for Case 3, in all three coastline evolution models and one UNIBEST-CL+ model in which the active depth is set to the entire profile depth (UNIBEST deep). Domburg located at approximately alongshore coordinate 3100m.

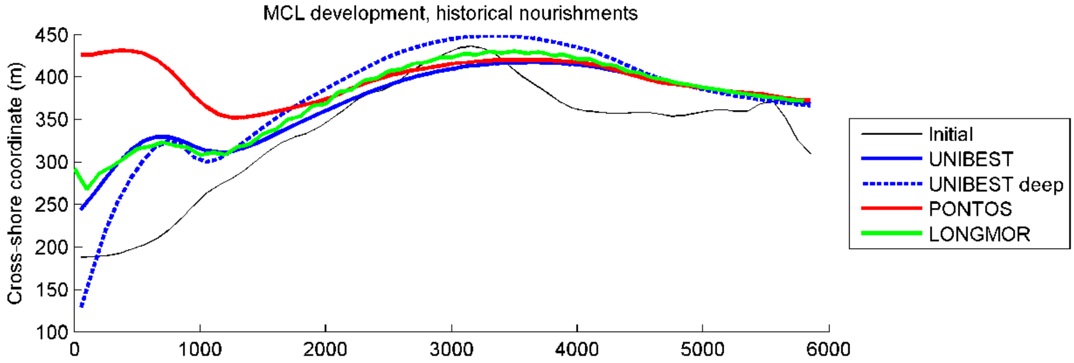


Figure 3.18 Momentary CoastLine (MCL) development after 19 years' simulation for Case 3, in all three coastline evolution models and one UNIBEST-CL+ model in which the active depth is set to the entire profile depth (UNIBEST deep). Domburg located at approximately alongshore coordinate 3100m.

3.5.4 Case 4: Coastline change with predicted nourishments

Case 3 has shown that given equal nourishment schemes and calibrated longshore transport, all three coastline models predict similar coastline evolution. In Case 4, the three models are used to hindcast coastline morphology in the period from the start of 1990 until the end of 2008, and to determine the amount of nourishments required to maintain the coastline. As in Cases 2 and 3, all models are run using the calibrated longshore transport found in Case 1. A random time series of wave conditions is applied in the LONGMOR model as discussed in Case 2.

A set of rules are imposed in order to determine where and when nourishments should be carried out in the model. First, the coastline in each model is split into six equal one-kilometre segments. The initial MSL-position in 1990 at every cross shore transect is defined as the coastline to be maintained. Each coastal segment may be nourished only once every four years; in years 1992, 1996, 2000, 2004 and 2008. If a nourishment is carried out in a coastal segment, the volume in each section must be at least $100{\cdot}10^3 m^3$. This minimum value represents the fact that mobilisation costs for small scale nourishments are too large to justify smaller nourishments. At the start of each four-year nourishment period (1992, 1996, etc.) a prediction is made of the future MSL-position of every cross shore transect in each coastal segment at the end of that four-year period (1996, 2000, etc.), by extrapolating the coastal retreat or progradation in the past four years and taking into account any nourishments carried out in that coastal segment in the past four years. A nourishment is carried out in every coastal segment in which the predicted future MSL-position of one or more cross shore transects extends 5m or more landward of the initial 1990 coastline, or three or more cross shore transects extend more than 0m landward of the initial coastline. In the case of the PONTOS model, the MCL-position is used instead of the MSL-position in all the computations above. The volume of the nourishment to be carried out in each period is determined by the sum of all predicted future landward exceedence distances in the coastal segment, multiplied by the transect width (100m) and the height of the active coastline according to the MCL-guidelines (9.1m at Domburg). The size of the nourishment is always set to a minimum volume of $100{\cdot}10^3 m^3$. In the UNIBEST-CL+ and LONGMOR models, the nourishment volume is distributed across the entire active height of the profile, whereas in the PONTOS model the nourishments are carried out in Layer 2 (MSL-2m to MSL+3m). The nourishment is spread equally in longshore direction across the entire coastal segment. The criteria set up in this study to predict nourishment volumes are an attempt to mimic the proactive decision-making processes involved in the real-life nourishment schemes. However, in reality many factors other than coastline position play a role in the determination of nourishment plans, which cannot be simulated in this model set-up.

Figure 3.19 shows the development of the MSL-position of all three coastal evolution models for Case 4. The figure shows that all three models are able to maintain the coastline position at Domburg to within approximately 10m of the original coastline position. The slight exceedence of the original coastline position may be due to the fact that all nourishments are spread across one-kilometre sections, rather than focussed on specific problem sites, such as the tip of Domburg. In a similar manner to Case 3, the coastline position in PONTOS appears to prograde farther at Domburg than in the UNIBEST model. A comparison of the MCL-position in all models in Figure 3.20 confirms that this is related to the difference in the cross shore distribution of sediment in the PONTOS model relative to the UNIBEST-CL+ and LONGMOR models. In general Figure 3.19 and Figure 3.20 highlight the similarities between the development of the coastline at Domburg in all three models, although some differences do occur between the 'UNIBEST deep' simulation and the other simulations to the North-East and South-West of Domburg.

Figure 3.21 shows the predicted proactive nourishment volumes applied in the three coastline evolution models in Case 4. The figure shows decreasing nourishment volumes in all models over time as the coastlines develop towards an equilibrium shape. The first predicted nourishment volume in 1992 is similar in magnitude in the standard UNIBEST-CL+, LONGMOR and PONTOS models. However, nourishment volumes decrease quickly over time in the PONTOS model, meaning that 1996–2004, the UNIBEST-CL+ and LONGMOR models predict larger nourishment volumes than PONTOS. The difference in nourishment volumes between the three coastline evolution models in 2008 is very limited and nourishment volumes appear to be reaching equilibrium in all three models.

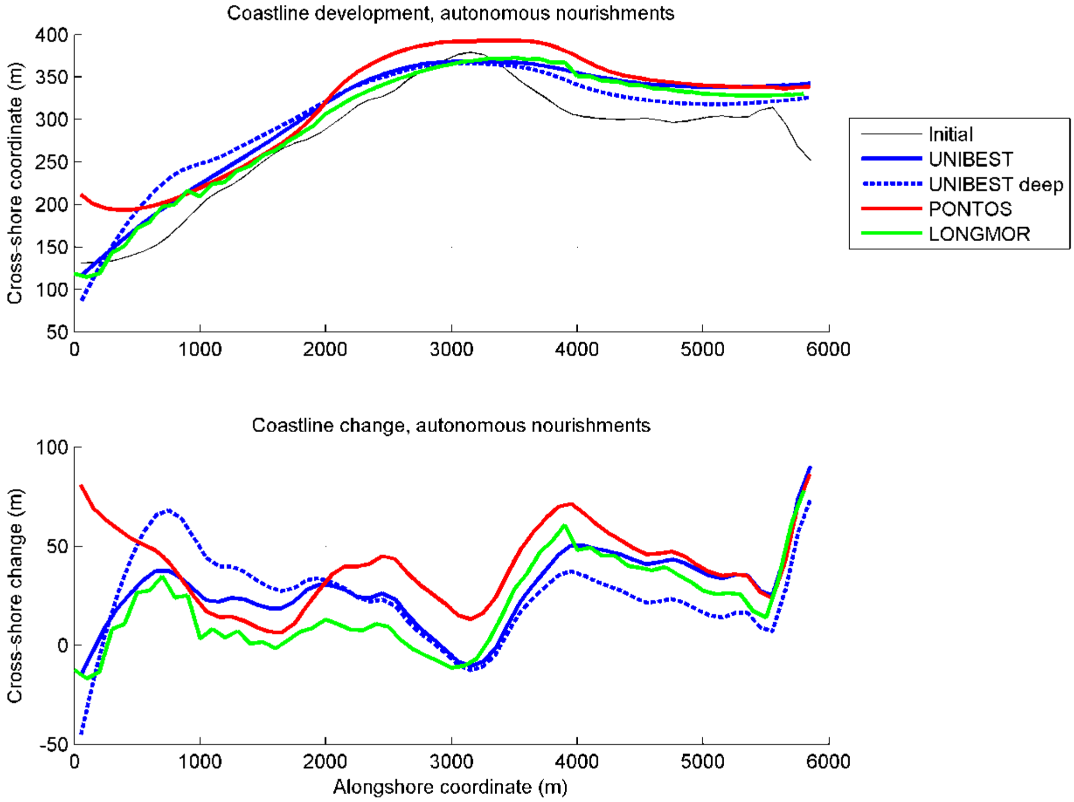


Figure 3.19 Coastline development (top panel) and coastline position change (bottom panel) after 19 years' simulation for Case 4, in all three coastline evolution models and one UNIBEST-CL+ model in which the active depth is set to the entire profile depth (UNIBEST deep). Domburg located at approximately alongshore coordinate 3100m.

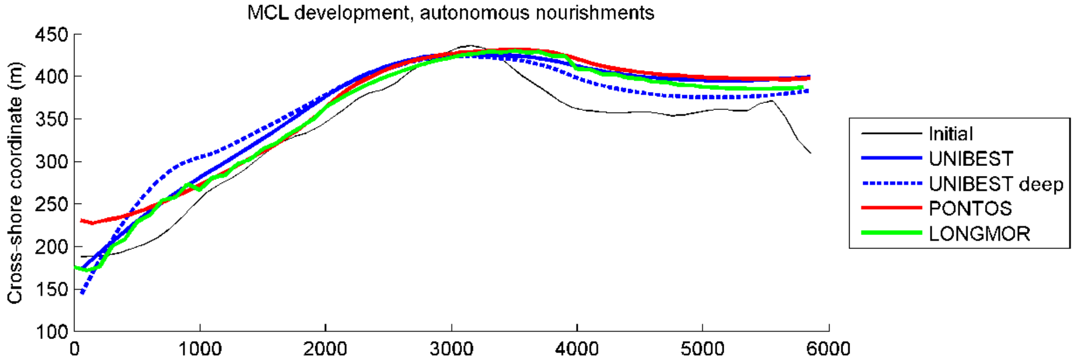


Figure 3.20 Momentary CoastLine (MCL) development after 19 years' simulation for Case 4, in all three coastline evolution models and one UNIBEST-CL+ model in which the active depth is set to the entire profile depth (UNIBEST deep). Domburg located at approximately alongshore coordinate 3100m.

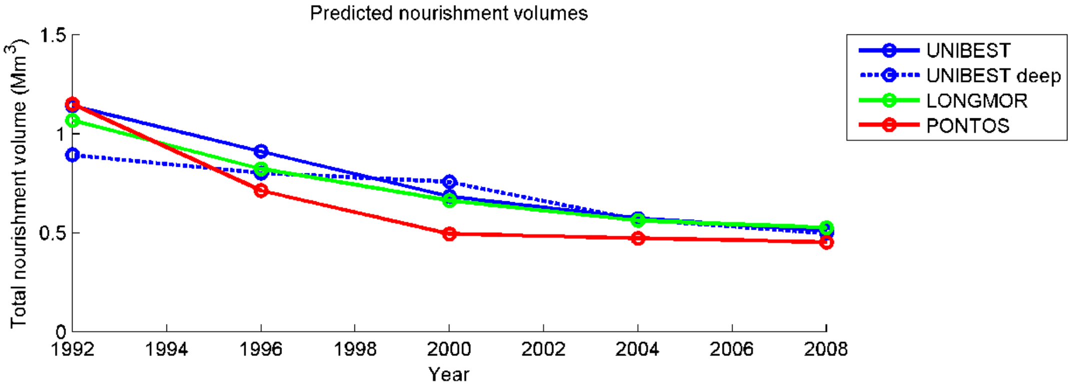


Figure 3.21 Predicted nourishment volumes for every four-year nourishment period in Case 4.

In addition to the nourishment scheme described above, the PONTOS model has the ability to compute losses relative to the initial coastline position in every cross shore transect at every computational time step, and to compensate these losses through automatic localised and instantaneous nourishments. In order to confirm that this reactive method of nourishment of the coast provides similar estimates of the total nourishment volume as the earlier simulations in Case 4, three sensitivity simulations are set up using the PONTOS automatic nourishment routine. In the first sensitivity simulation, the entire coastal profile in the PONTOS model (layers 1–5) is continuously maintained. In the second and third sensitivity simulations, the MCL-position of the coast is continuously maintained through nourishments in Layer 2 (MSL-2m to MSL+3m; sensitivity 2) or Layer 3 (MSL-7m to MSL-2m; sensitivity 3). The results of the coastline evolution of all three sensitivity simulations are shown in Figure 3.22. The results presented in the figure show similar coastline development in sensitivity simulation 2 (maintain MCL in Layer 2) to the earlier Case 4 PONTOS model for the coastline at Domburg.

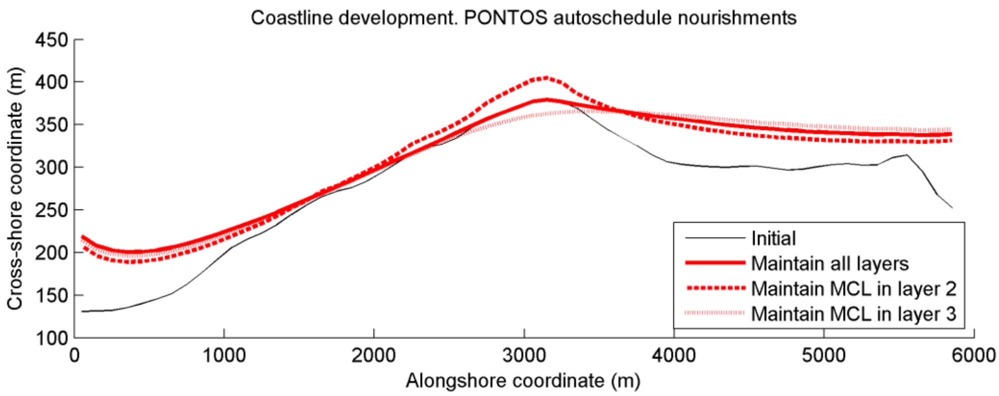


Figure 3.22 Coastline development after 19 years for PONTOS model automatic nourishment sensitivity simulations in Case 4. Domburg located at approximately alongshore coordinate 3100m.

The total nourishment volume over 19 years for all coastline models and sensitivity simulations is summarised in Figure 3.23. The figure shows remarkably little difference between the predicted nourishment volumes in all models and nourishment strategies. The largest nourishment volume is predicted by the standard UNIBEST-CL+ model (3.82Mm^3). The smallest prediction using the nourishment schedule described at the start of Case 4 is predicted by the PONTOS model (3.28Mm^3). This difference is just 14% of the nourishment volume predicted by UNIBEST-CL+, or just 10% of the nourishment volume carried out in reality. The sensitivity of the predicted nourishment volume in the UNBEST-CL+ model to the extent of the active depth, the difference between the ‘standard’ and ‘deep’ simulations, is 8% of the nourishment volume predicted by the standard UNIBEST-CL+ model. The effect of the automatic nourishment routine in PONTOS is a 12% decrease to 7% increase in the nourishment volume predicted by the standard PONTOS nourishment routine. Similarly, the effect of the larger numerical diffusion coefficient in LONGMOR used in the sensitivity simulations in Case 2 is an 8% increase in the nourishment volume predicted by the standard LONGMOR model (not shown in Figure 3.23). It should be noted that the inclusion of the measured nourishment volume is merely to indicate the relative effect of model differences compared to typical nourishment volumes. Due to the timing of the large-scale nourishments (1.9Mm^3 imposed in the models) towards the end of the simulation period in 2008, the models have little time to adjust their final results. In this respect, the reactive, automatic, nourishment schemes in PONTOS are expected to under predict the nourishment volume required for the coast. These simulations should instead be run another 3–4 years to compute the losses of the new nourishment in 2008. The proactive nourishment schemes used in all other simulations are not expected to under predict the nourishment volume, as the volume they introduce in the model in 2008 is designed to maintain the coast until 2012. In addition to this consideration, the total nourishment volume carried out in 2008 in reality includes additional sediment to increase the safety level of the coast. This additional sediment will of course not be predicted by the coastline evolution models. However, as stated in Sections 0 and 3.4, the purpose of this study is not to most accurately reproduce nourishment requirements at Domburg, and these limitations are accepted within the bounds of this study.

The alongshore distribution of predicted nourishment volumes computed by the proactive nourishment strategies in UNIBEST-CL+, PONTOS and LONGMOR are shown in Figure 3.24. The figure shows a clear difference between the predicted nourishment volume in PONTOS at the sea-dike end of the model (alongshore coordinate 0–1000m), compared to those predicted by the UNIBEST-CL+ and LONGMOR models. The reason for this difference is the effect of the closed boundary and southerly directed net transport in the top layers of the PONTOS model, as also described in Case 2. Although this difference does affect the total predicted nourishment volume in PONTOS, the figure also shows that the predicted nourishment volume around Domburg (alongshore coordinates 2000–4000m) is similar for the PONTOS and standard UNIBEST-CL+ models (2.8Mm^3 and 2.7Mm^3 respectively). Nourishment volumes predicted by the UNIBEST deep (1.3Mm^3) and LONGMOR (1.9Mm^3) models around Domburg (alongshore coordinates 2000–4000m) are significantly lower than whose predicted by the standard UNIBEST and PONTOS models.

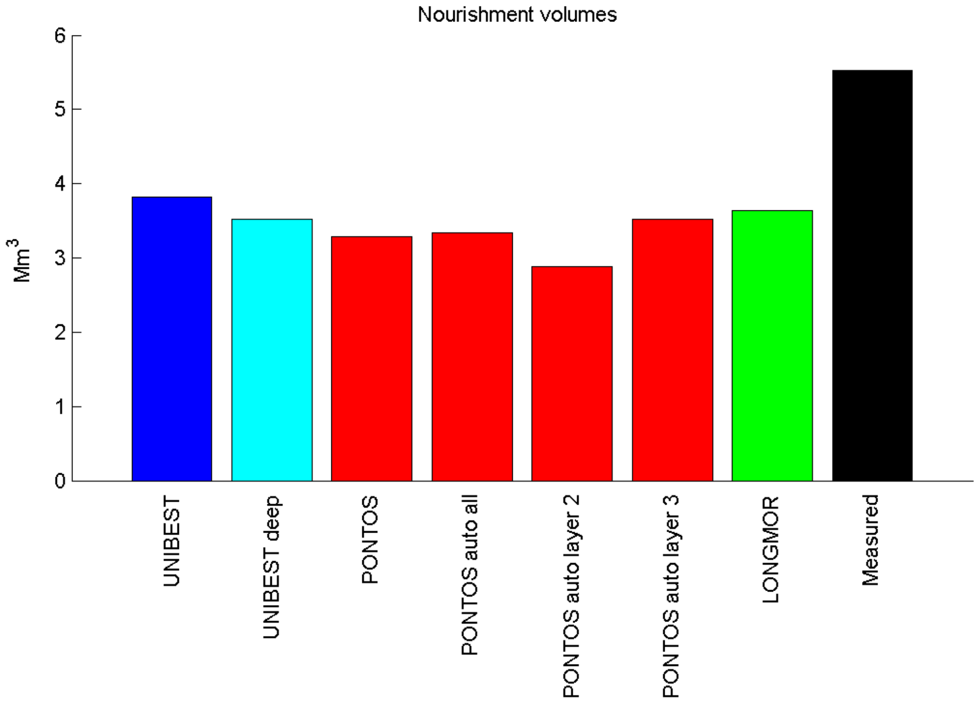


Figure 3.23 Total predicted nourishment volumes for all coastline models and their variants.

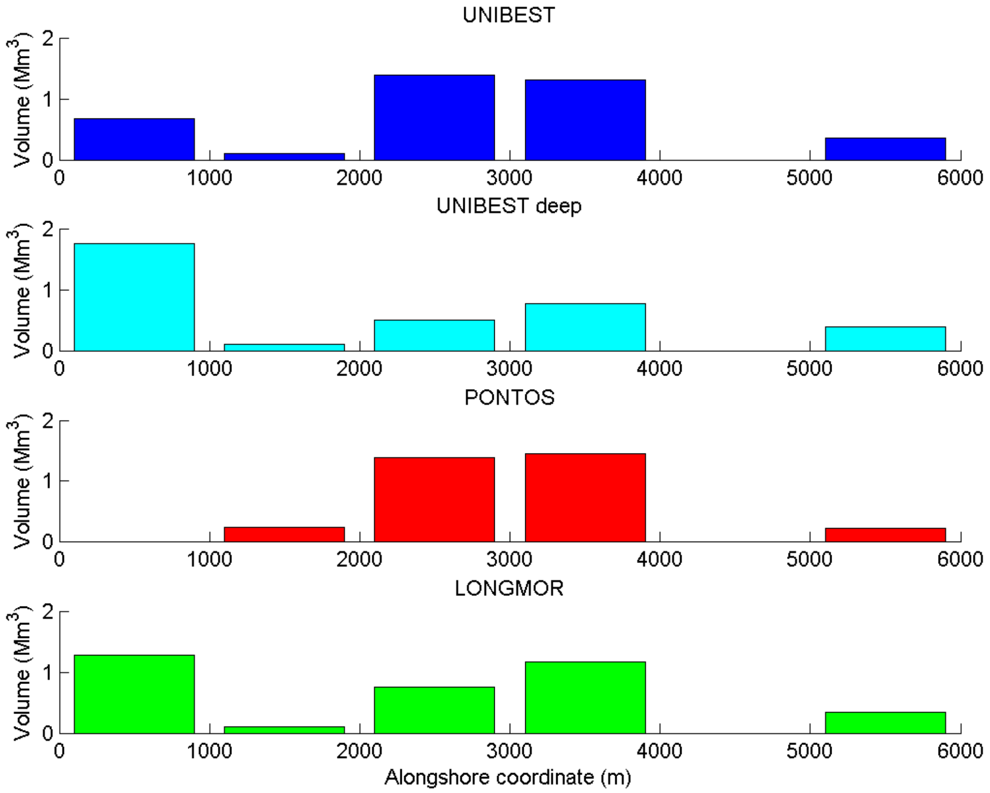


Figure 3.24 Alongshore distribution of predicted cumulative nourishment volumes for all proactive nourishment schemes. Domburg located at approximately alongshore coordinate 3100m.

3.5.5 Case 5: Predicted nourishments without calibrated longshore transport

In Case 5, the effect of the calibration of the longshore transport in the three coastline evolution models is examined by determining new nourishment schemes based on the same principles presented in Case 4, but using the uncalibrated longshore transport coefficient. In these uncalibrated simulations, the longshore transport is computed using default values for wave transformation and sediment transport, as described in the first section of Case 1.

The coastline development in all three uncalibrated models is shown in Figure 3.25. Despite net sediment transport differences of a factor 3–5 (see Case 1), the coastline development with nourishments is similar to that of Case 4. However, the effect of the longshore transport calibration on the total nourishment volumes is significantly greater than on the coastline evolution, see Figure 3.26. The total predicted nourishment volume over 19 years' simulation is just 1.65Mm^3 in the PONTOS model, which is partly due to the effect of the closed boundary condition at the sea-dike end of the model, as described previously in Case 2. In the PONTOS model this model assumption leads to steady accretion in the upper layers of the model at the sea-dike end, therefore removing the need for nourishments in that area and reducing the total nourishment volume. In future simulations a similar close boundary is not advisable. The nourishment volume predicted by the LONGMOR model is 2.40Mm^3, whereas the standard UNIBEST-CL+ model predicts 4.98Mm^3. This results in a factor 3 difference between the UNIBEST-CL+ and PONTOS models, or 47% of the total volume of nourishments carried out in reality. As stated in the previous section, the comparison to the measured volume should only be used to judge the relative effect of model differences, rather than the absolute accuracy of the models. All three coastline evolution models are expected to produce more accurate results if the constraints set by this comparative study are removed.

Similarly to Case 4, the alongshore distribution of the cumulative nourishment volume predicted for Case 5 by the proactive nourishment schemes is shown in Figure 3.27. Again, there is a clear difference between nourishment volumes at the sea-dike end of the model predicted by PONTOS and the other models. However, in Case 5 the difference between nourishment volumes around Domburg (alongshore coordinates 2000–4000m) predicted by PONTOS (1.1Mm^3) and the standard UNIBEST-CL+ (3.6Mm^3) are also striking. This indicates that contrary to Case 4, a substantial part of the total nourishment volume difference between the UNIBEST-CL+ and PONTOS models is due to the erosional process at Domburg. The figure shows that the overall similarity between nourishment volumes predicted by the LONGMOR and PONTOS models remains similar for the nourishment volume predicted around Domburg (1.2Mm^3 and 1.1Mm^3 respectively). In addition, the nourishment volume around Domburg predicted by the UNIBEST deep model (1.4Mm^3) is more similar to those predicted by the PONTOS and LONGMOR models, than that predicted by the standard UNIBEST-CL+ model. This indicates that the assumptions relating to the refraction of waves in deep water and depth to which the coast is able to rotate appear to substantially affect local nourishment volumes.

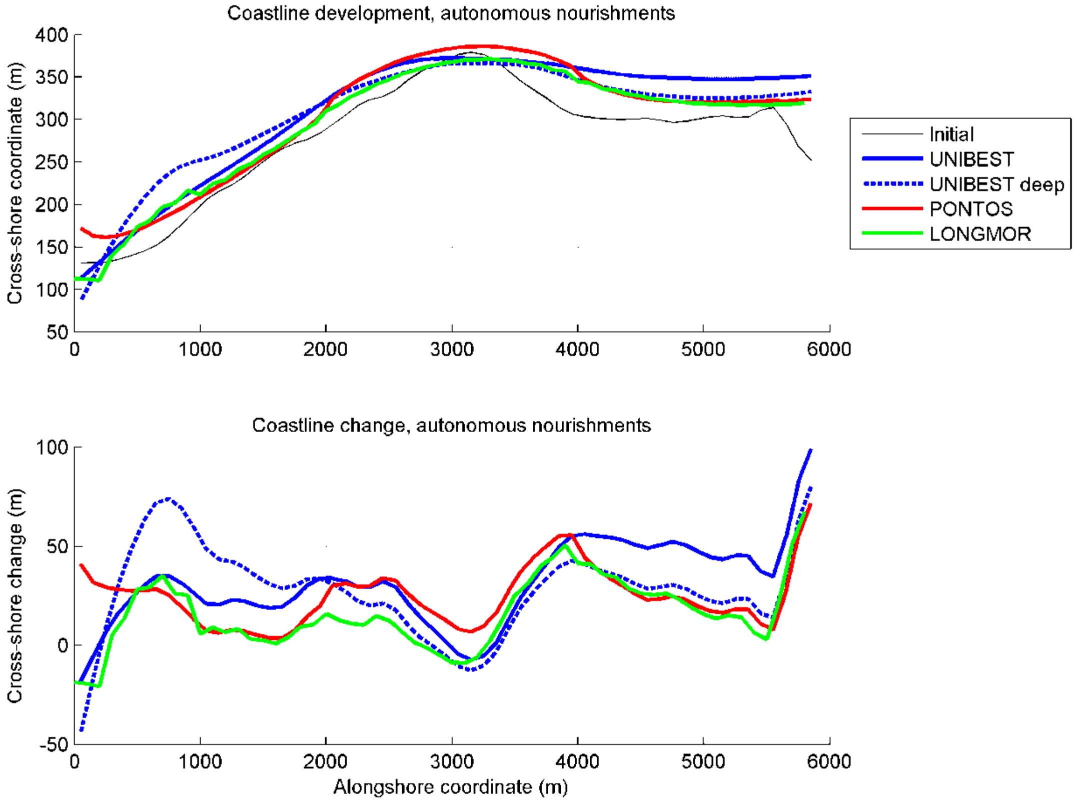


Figure 3.25 Coastline development (top panel) and coastline position change (bottom panel) after 19 years for uncalibrated longshore transport simulations, in all three coastline evolution models and one UNIBEST-CL+ model in which the active depth is set to the entire profile depth (UNIBEST deep). Domburg located at approximately alongshore coordinate 3100m.

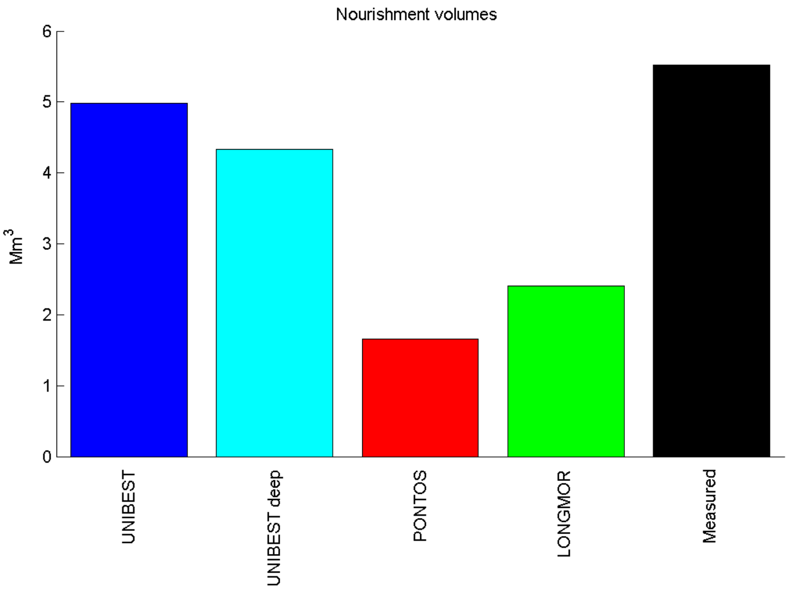


Figure 3.26 Total predicted nourishment volumes for all coastline models using uncalibrated longshore sediment transport rates.

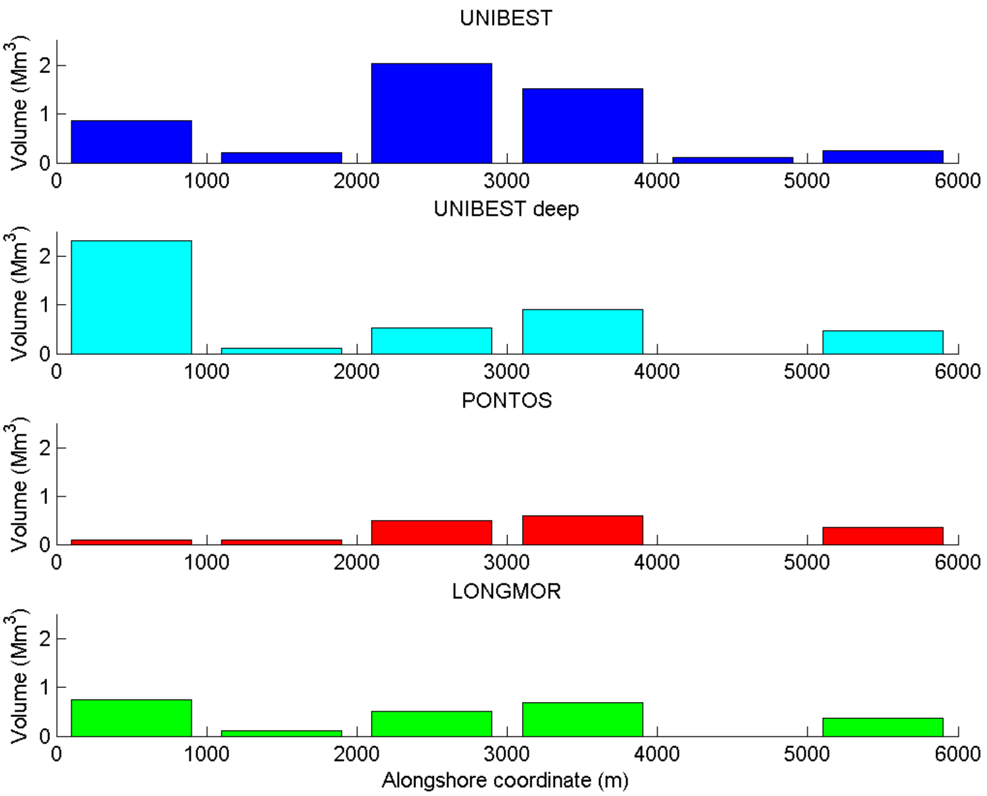


Figure 3.27 Alongshore distribution of predicted cumulative nourishment volumes for all proactive nourishment schemes, using uncalibrated longshore sediment transport rates. Domburg located at approximately alongshore coordinate 3100m.

3.6 Conclusions

This study has investigated the effect of differences between three coastal evolution models on the simulated coastline development and predicted nourishment volumes of a schematised stretch of the Dutch coast. The main conclusions of this research are listed below.

- The net longshore transport computed by UNIBEST-CL+ is significantly greater for the coast of Walcheren than that computed by either LONGMOR or PONTOS for the given wave climate (Case 1). This disparity in the longshore transport appears to be generated by waves of very steep angles of incidence, in this case waves coming from the West. In contrast to examples in earlier research (see Part I), the difference in longshore transport cannot be explained by the active depth used in UNIBEST-CL+ to rotate the coast. Further research into this difference may be of use in determining the applicability of all three models on coasts where waves may arrive at large angles of incidence.
- Once calibration of the mean longshore transport has taken place, the morphological development of the coastline in all three coastline models is similar (Cases 2–4). Small differences in the MSL-position of the coast occur between the three coastline evolution models. This is due in part to the way PONTOS computes the cross shore distribution of sediment, while UNIBEST-CL+ and LONGMOR assume a constant profile shape. These differences become less obvious once the more robust MCL-position is used

instead of the MSL-position as a coastal state indicator, indicating a similarity between the models for cross-shore averaged coastal development.

- Differences in the predicted nourishment volumes required to maintain the entire coastline in all three models with calibrated longshore transports are in the order of 10%. Differences in nourishment volumes due to the choice of the active depth in UNIBEST-CL+, the manner of applying nourishments in PONTOS, and the choice of numerical diffusion coefficient in LONGMOR are also of the order of 10% of the nourishment volumes in the standard simulations.
- Predicted nourishment volumes required to maintain the coast around Domburg (alongshore coordinates 2000–4000m) differ to a greater extent between models than those required to maintain the entire coastline. Although this can partly be explained by boundary effects in the PONTOS model, Case 5 shows that the depth to which the coast is allowed to rotate, and the subsequent effect on wave refraction in deep water, greatly affects localised nourishment volumes.
- The differences between nourishment volumes in the three coastal evolution models without calibration of the longshore transport (Case 5) are an order greater than those described in the previous conclusion: the difference in predicted nourishment volumes between the uncalibrated PONTOS model and uncalibrated UNIBEST-CL+ model was 300%. The difference between the uncalibrated LONGMOR model and uncalibrated UNIBEST-CL+ model is greater than 200%. Although part of the differences seen between the models are due to boundary condition effects, the results do show that the correct calibration of longshore sediment transport is crucial to maintaining inter-model and model-data similarity.

The results of this study highlight the similarities that are present between the models for the Domburg case, as long as all models are set-up, calibrated, run and analysed using the same method. Differences in overall nourishment volumes in the order of 10% may be expected as a result of the dissimilarities between the calibrated models, although differences in nourishment volumes in specific areas of the model are greater (e.g. 32% difference in predicted nourishment volumes at Domburg in the LONGMOR and PONTOS models; 53% difference in predicted nourishment volumes at Domburg in the UNIBEST deep and standard UNIBEST-CL+ models). Cases 4 and 5 have shown that large differences in the predicted nourishment volumes (up to a factor of 3) do occur when the longshore transport is not calibrated to a predefined value. Case 5 shows that a substantial part of this difference is related to the manner in which the coastline is allowed to rotate, and the subsequent effect on deep water wave refraction. It is worthwhile taking into account that Part I of this study has shown that even larger differences than those observed in the Domburg simulations in Part II do occur when single wave conditions, or simple wave climates, are used to force the coastline evolution models.

It should be noted that all simulations described in this report do not accurately reproduce the true coastal development at Domburg. This does not point to a fundamental deficiency in the models, but rather to the fact that the true coastal situation is too complex to be described by the relatively schematic initial conditions and boundary conditions applied in the models in this study. In particular the following assumptions and limitations are thought to affect the accuracy of the model results:

- The entire model domain has been schematised to have one cross shore profile that is representative for the entire area. In reality there is a considerable difference in profile shape between the northern and southern boundaries of the model. This change in profile shape is expected to affect wave transformation to the coast and affect the cross shore sediment distribution in PONTOS.

- None of the coastline evolution models in this study are set up to include the effect of sediment transport by tides. Instead, transport by tides has been implicitly accounted for by a modification of the wave-driven transport. This simplification skews the distribution of sediment transport by waves, and may be leading to incorrect development of the coastline.
- The entire model domain is simulated using one wave climate, based on data from the Europlatform climate station in the PONTOS model for the Dutch coast. Not only is this wave climate not completely representative for the area around Domburg, but the local wave climate is likely to vary in alongshore direction within the study area due to the presence of offshore sand banks and tidal channels. These gradients in wave forcing are likely to generate different sediment transport patterns and coastline evolution than those seen in the simulations in this study.
- The longshore sediment transport in the three coastline evolution models has been calibrated in Cases 2–4 using an estimate of the true sediment transport gradient in the region. As mentioned in Section 3.4.6, this estimate is subject to many simplifications that may be incorrect. In particular, the assumption of zero transport influx at the sea-dike boundary, the assumption that the change in the MCL-volume over time describes the entire coastal development and the assumption that the alongshore-mean sediment transport is a proxy for the transport gradient, may greatly affect the computation of the 'true' sediment transport rate. Any change in the calibrated sediment transport rate is likely to greatly affect the final model results, as demonstrated by Case 5.
- The large-scale nourishments carried out in 2008 in Cases 3 are likely to strongly affect the final model results. Similarly, the automatic nourishment schemes in PONTOS in Cases 4 and 5 are unable to reproduce the nourishment volumes applied in 2008 because they apply reactive, rather than proactive criteria to nourish the coast. In addition to these considerations, the total measured nourishment volumes may include additional sediment to increase the safety of the coast that will not be accounted for in the coastline evolution models.
- The choice of criteria in the proactive nourishment schemes in Cases 4 and 5 determine the total nourishment volume computed by each model. Although these criteria are set equal between the models and can therefore be used for comparative purposes, their values do affect the accuracy with which each model is able to reproduce the true nourishment volumes. In future studies attention should be paid to the definition and location of coastal segments upon which the decision to nourish is based.

This study therefore concludes that in order to accurately simulate the coastline at Domburg, all three coastline evolution models must be set up in a more complex manner, including longshore variability in wave conditions and profile shape, tides and better longshore transport rate estimates. In addition, increasing the simulation period until 2012 will help to reduce the effect of the large-scale nourishments in 2008 on the final model results. It is reiterated here however that greater calibration and complexity in the models would not be conducive to the premise of this study to maintain similarity between the models.

4 Conclusions and recommendations

The results of this study show that accurate estimates of the net longshore transport are essential to coastline modelling and nourishment predictions. Well-documented and publically available measurements of longshore sediment transport rates for locations along the Dutch coast would greatly assist the calibration of coastline evolution models and the unification of their results. In addition to improvements in data with which to calibrate coastline evolution models, this study recommends further research into the causes of differences in longshore sediment transport rates between the three models in this study:

- The research in Part I suggests that all three coastline evolution models predict significantly varying longshore sediment transport rates for any given wave condition. These differences reach as much as a factor of 2–4 for certain wave and sediment combinations. These differences cannot be solely explained by the choice of longshore sediment transport relation, since large differences between UNIBEST-CL+ and LONGMOR exist even in the cases where the exact same transport relation is used (i.e. CERC USACE, 1984; and Kamphuis, 1991). It is suggested that the implementation of the sediment transport relations, and in particular the definition and computation of wave characteristics within these relations, is compared between the coastline evolution models in order to determine possible sources of transport rate differences.
- The definition of the coastline rotation has been shown to greatly affect longshore transport rates, both in idealised simulations (Part I) and in the Domburg simulations (Part II). It is reasonable to state that the approach taken in the UNIBEST-CL+ model of limiting coastal rotation to a certain active coastal zone is more realistic than the approach taken in LONGMOR and PONTOS. Under oblique wave forcing, this difference of approach accounts for differences of up to 50% in the computed longshore sediment transport in UNIBEST-CL+. More importantly, this difference in model approaches has shown to drastically change the equilibrium coastline angle and shape of the S-θ curve for wave climates with dominant oblique wave components, and affect nourishment predictions. It is highly recommended to investigate the feasibility of including an inactive deep water zone in LONGMOR and PONTOS, or an additional deep water wave refraction module to aforementioned models to more accurately predict longshore transport rates and equilibrium coastline angles under high angles of wave incidence. Note that although the longshore transport rate in PONTOS is computed separately per vertical layer using the orientation of that layer, this does not address the issue of wave refraction over deeper part of the profile; the sediment transport rate in each layer in PONTOS still assumes that the whole profile below that layer has the same orientation as the layer itself for the purpose of wave refraction. In addition to these considerations, it should be noted that the definition of an active coastal zone requires an understanding of the physical processes involved over the duration of the model simulation. This study recommends the development of guidelines for setting the active coastal zone in UNIBEST-CL+, and other models, for varying coastal situations and simulation periods.
- Much of the difference between the longshore sediment transport under high angles of wave incidence computed by the three coastline evolution models can be attributed to the difference in the definition of the coastline rotation. However, Case 1 in this study has shown that significant differences between UNIBEST-CL+ and LONGMOR/ PONTOS still exist for waves with large angles of incidence even when the active coastal zone in UNIBEST-CL+ is set to deep water. This difference may be due to the

method in which wave refraction is computed, which is done using the ENDEC wave transformation model in UNIBEST-CL+, using Snell's law in LONGMOR, and is not explicitly computed in PONTOS (although wave refraction is included implicitly in the empirical best-fit of the database of process-based model data used to derive the sediment transport relation in PONTOS). Due to lack of measurement data, this study was unable to determine which coastline evolution model correctly predicts longshore transport under high angles of wave incidence. Since large angles of wave incidence occur along a significant stretch of the Dutch coast (Zeeland, Wadden Islands) this study highly recommends further research into the applicability of each of the coastline evolution models under such wave forcing and the cause of the differences shown in this study. In addition, this study recommends investigating the importance of applying a detailed process-based sediment transport model, such as UNIBEST-CL+, under such conditions, in comparison to the bulk-type sediment transport formulations used by the LONGMOR and PONTOS models.

- The accuracy of the modelled wave conditions at the start of the active coastal zone may be considered to be an essential part of making correct predictions of longshore sediment transport rates. For some stretches of the Dutch coast, the wave transformation routines used in the three coastline evolution models, and described above, may not be capable of accurately describing the wave transformation from deep water to the active coastal zone. In such cases, longshore non-uniform bathymetry, tidal currents and human structures may invalidate the assumptions behind the wave transformation routines. In such cases, the application of a more accurate wave transformation model, such as the SWAN wave model (Booij *et al*., 1999; Ris *et al*., 1999), to predict wave conditions at the edge of the active coastal zone would likely lead to more accurate predictions of longshore sediment transport. This study recommends investigating the possibility of applying such wave boundary conditions in LONGMOR and PONTOS, and the sensitivity of all three coastline evolution models to the enhanced wave boundary conditions.
- Although longshore sediment transport rates are initially computed with great accuracy in UNIBEST-CL+ to generate an S-θ curve, this information is subsequently parameterised by a simple exponential function when computing coastline change. This study recommends investigating whether a more accurate description of the computed S-θ curve would improve the model accuracy, and under what conditions this effect becomes important.

The recommendations given above will help to improve the consistency of the coastline evolution models with respect to the computed longshore sediment transport under given wave conditions. Although this factor contributes greatest to the differences in predicted nourishment volumes, other differences between the models exist that should be addressed:

- In UNIBEST-CL+ wave conditions are not interpolated between wave climate input locations, instead, the coefficients to describe the parameterisation of the S-θ net sediment transport curve are interpolated between these locations. This method therefore linearly interpolates the net sediment transport and thus has the advantage of typically generating sediment transport gradients that are numerically stable. The disadvantage to this method is that the gross sediment transport rates due to certain wave components in the wave climate may not be correctly accounted for in the interpolation of the net transport. However, since in most practical applications the UNIBEST-CL+ model is forced using very many separate (nearshore) wave input locations, typically derived from a local SWAN wave model, the precise method of interpolation will generally not significantly affect the longshore transport rate. In

PONTOS, wave conditions are interpolated between wave input locations that are typically, but not necessarily, spaced farther apart than UNIBEST-CL+ wave input locations. Although this appears more physically reasonable than interpolating the derived net sediment transport rate, Part I (fase 1.4) has shown that this method of interpolating wave conditions may lead to numerically unstable longshore transport gradients. Although both interpolation methods have their merits and weaknesses, this study has not investigated further under what conditions these weaknesses become important. This study therefore recommends the investigation of the limitations of reducing complex wave climates to a parameterised S-θ curve in UNIBEST-CL+, the limitations of interpolating net transport rates in UNIBEST-CL+, and the limitations of spatially interpolating very different wave conditions in PONTOS. In addition to the discussion as to whether longshore transports, or wave conditions should be interpolated, this study recommends that the possibility of interpolating wave *energy* instead of wave *height* in PONTOS is investigated, in order to bring the PONTOS model in line with other models such as SWAN and the concept that wave energy rather than wave height grows approximately linearly with wind fetch. Similar considerations may be noted for the interpolation of the wave period. In addition, this study advises against the spatial interpolation of the probability of occurrence of wave conditions in a wave climate in PONTOS on grounds of physical consistency. It is noted that this interpolation is not generally used in PONTOS models of the Dutch coast however. This study also strongly recommends that the possibility of including longshore-varying wave conditions in LONGMOR is investigated, in order to significantly increase the range of applications for which the model can be used.

- This study has shown that the numerical instability of the LONGMOR model is such that the model is limited in its applicability. For all future studies using the LONGMOR model, it is recommended that the modeller apply as much physical diffusion as possible through random time series of wave conditions, in order to reduce the need for numerical diffusion. Unfortunately this recommendation limits the applicability of LONGMOR to study gross and net transport effects (discussed later). This study recommends that alternative numerical schemes for LONGMOR are investigated that may remove the need for artificial numerical diffusion of the coastline. Although numerical stability constraints exist in the PONTOS model, this study has not found significant variation in PONTOS model results due to the application and modification of stabilisation parameters.

This study has shown that the coastline development in the Domburg simulations is similar in all three models, if the longshore sediment transport is calibrated to a predefined value. However, in these simulations, several model choices were made that limited the possible differences between the models. In typical coastal engineering applications these choices may be different and their effect should therefore be examined:

- The PONTOS model is the only of the three coastline evolution models to explicitly include a cross-shore distribution mechanism for sediment and cross-shore variation in the coastal profile development. In order to effectively investigate the effect of model differences, rather than the effects of model choices, this component of PONTOS has largely been minimalized in this study. For this reason, this report has not been able to show any significant importance of the multiple-layer approach in PONTOS relative to UNIBEST-CL+ and LONGMOR. In order to investigate the effect of the multiple-layer approach in PONTOS, and in what coastal regions this effect is greatest, this study highly recommends extending the complexity of subsequent model investigations to include a focus on cross-shore dynamics, whilst maintaining model consistency with other coastline evolution models.

- This study has not focussed on comparing the relative merits of the complex computation of longshore sediment transport in UNIBEST-CL+, compared to the bulk-type computations in LONGMOR and PONTOS, or on the merits of the cross-shore behaviour model in PONTOS, relative to the static cross-shore profile in UNIBEST-CL+ and LONGMOR. Important issues that are related to this include the data quality and quantity required to calibrate the cross-shore dynamics in PONTOS, the relative importance of cross-shore processes on coastal state indicators, the adaptability of the static cross-shore profile approximation, the relationship between the cross-shore behavioural model and the definition of the active depth and height, and the relative accuracy of detailed and bulk sediment transport formulae in uncalibrated situations. Future studies should aim to improve all three coastline evolution models by indicating under what conditions their assumptions become limiting, and improving upon those weaknesses using the strengths of the other models.
- This study has focussed on computing coastal evolution due to net sediment transport rates. This was approximated in LONGMOR through the use of a random time series of wave conditions, with each condition lasting a maximum of three days. In certain situations gross longshore transport can play a significant role in the coastline development and lead to changes along the coast that cannot be computed using net sediment transport rates. Since relatively few practical applications have been carried out on the Dutch coast focussing on gross longshore transports, this study recommends investigating where gross transports may be expect to affect model results, and to study several of such locations using either LONGMOR, or the research-version of UNIBEST-CL+, which can be driven by wave condition time series. Such research should lead to recommendations on the use of net sediment transport models in sensitive locations.
- In Case 4, this research has shown that the nourishment volumes computed by the PONTOS automatic nourishment feature closely mimic the nourishment volumes predicted for the Domburg coast by the other models in Case 4. This study recommends that similar automatic nourishment methods are considered for development in UNIBEST-CL+ and LONGMOR, and that these features are run alongside regular nourishment schemes in future model studies in order to validate their applicability. In addition, this study recommends investigating the development of proactive automatic nourishment schemes based on simple rules (such as those developed and applied in Case 4 and Case 5) in all three coastline evolution models, to better mimic current coastal management practices.

This study has shown the need for strict guidelines on wave climate data and net sediment transport rates required to maintain similarity between the results of difference coastline evolution models. However, many other factors may contribute to variations in nourishment predictions between models, including the analysis and interpretation of data used to set up the models, and of the output data of the models themselves. This study highly recommends researching the effect of the assumptions, analysis and interpretations of *modellers* on predicted nourishment volumes as a method of better understanding the causes of disparities in predictions, and as a first step in generating guidelines for future coastal evolution studies.

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A Wave climate

The wave climate used in this study for the Domburg case is based on the wave climate in the Dutch Coast PONTOS model, for the location of Euro Platform. All wave directions from 60°N–240°N were removed, as these are not thought to influence sediment transport at Walcheren, and replaced by a single wave condition perpendicular to the coast with minimum wave height, so as to cause no longshore transport. The original and modified wave climates are both presented in this appendix.

Table A.1: Original wave climate in Dutch Coast PONTOS model

Significant wave height (m)	Peak wave period (s)	Wave direction (°N)	Probability of occurrence (-)
0.01	0.01	0	0.0828
0.50	4.00	0	0.0503
1.00	5.66	0	0.0521
1.50	6.20	0	0.0284
2.00	7.16	0	0.0127
2.50	7.70	0	0.0057
3.00	8.44	0	0.0025
3.75	8.95	0	0.0021
4.75	10.07	0	0.0003
5.75	10.73	0	0.0000
6.75	11.62	0	0.0000
0.50	4.00	30	0.0333
1.00	5.66	30	0.0329
1.50	6.20	30	0.0170
2.00	7.16	30	0.0082
2.50	7.70	30	0.0039
3.00	8.44	30	0.0016
3.75	8.95	30	0.0009
4.75	10.07	30	0.0001
5.75	10.73	30	0.0000
6.75	11.62	30	0.0000
0.50	4.00	60	0.0209
1.00	5.66	60	0.0168
1.50	6.20	60	0.0099
2.00	7.16	60	0.0045
2.50	7.70	60	0.0016
3.00	8.44	60	0.0007
3.75	8.95	60	0.0005
4.75	10.07	60	0.0000
5.75	10.73	60	0.0000
6.75	11.62	60	0.0000
0.50	4.00	90	0.0118
1.00	5.66	90	0.0093
1.50	6.20	90	0.0050
2.00	7.16	90	0.0011
2.50	7.70	90	0.0003
3.00	8.44	90	0.0001
3.75	8.95	90	0.0000
4.75	10.07	90	0.0000
5.75	10.73	90	0.0000

6.75	11.62	90	0.0000
0.50	4.00	210	0.0261
1.00	5.66	210	0.0352
1.50	6.20	210	0.0295
2.00	7.16	210	0.0189
2.50	7.70	210	0.0104
3.00	8.44	210	0.0051
3.75	8.95	210	0.0020
4.75	10.07	210	0.0001
5.75	10.73	210	0.0001
6.75	11.62	210	0.0000
0.50	4.00	240	0.0398
1.00	5.66	240	0.0479
1.50	6.20	240	0.0387
2.00	7.16	240	0.0288
2.50	7.70	240	0.0193
3.00	8.44	240	0.0113
3.75	8.95	240	0.0073
4.75	10.07	240	0.0010
5.75	10.73	240	0.0001
6.75	11.62	240	0.0000
0.50	4.00	270	0.0240
1.00	5.66	270	0.0202
1.50	6.20	270	0.0150
2.00	7.16	270	0.0107
2.50	7.70	270	0.0061
3.00	8.44	270	0.0042
3.75	8.95	270	0.0044
4.75	10.07	270	0.0008
5.75	10.73	270	0.0001
6.75	11.62	270	0.0000
0.50	4.00	300	0.0208
1.00	5.66	300	0.0172
1.50	6.20	300	0.0123
2.00	7.16	300	0.0082
2.50	7.70	300	0.0056
3.00	8.44	300	0.0031
3.75	8.95	300	0.0028
4.75	10.07	300	0.0006
5.75	10.73	300	0.0000
6.75	11.62	300	0.0000
0.50	4.00	330	0.0311

1.00	5.66	330	0.0272
1.50	6.20	330	0.0187
2.00	7.16	330	0.0119
2.50	7.70	330	0.0075
3.00	8.44	330	0.0038
3.75	8.95	330	0.0038
4.75	10.07	330	0.0008
5.75	10.73	330	0.0002
6.75	11.62	330	0.0000

Table A.2: Reduced wave climate applied in coastal evolution models

Significant wave height (m)	Peak wave period (s)	Wave direction (°N)	Probability of occurrence (-)
0.01	0.01	0	0.0828
0.50	4.00	0	0.0503
1.00	5.66	0	0.0521
1.50	6.20	0	0.0284
2.00	7.16	0	0.0127
2.50	7.70	0	0.0057
3.00	8.44	0	0.0025
3.75	8.95	0	0.0021
4.75	10.07	0	0.0003
5.75	10.73	0	0.0000
6.75	11.62	0	0.0000
0.50	4.00	30	0.0333
1.00	5.66	30	0.0329
1.50	6.20	30	0.0170
2.00	7.16	30	0.0082
2.50	7.70	30	0.0039
3.00	8.44	30	0.0016
3.75	8.95	30	0.0009
4.75	10.07	30	0.0001
5.75	10.73	30	0.0000
6.75	11.62	30	0.0000
0.50	4.00	270	0.0240
1.00	5.66	270	0.0202
1.50	6.20	270	0.0150
2.00	7.16	270	0.0107
2.50	7.70	270	0.0061
3.00	8.44	270	0.0042
3.75	8.95	270	0.0044
4.75	10.07	270	0.0008
5.75	10.73	270	0.0001
6.75	11.62	270	0.0000
0.50	4.00	300	0.0208
1.00	5.66	300	0.0172
1.50	6.20	300	0.0123
2.00	7.16	300	0.0082
2.50	7.70	300	0.0056
3.00	8.44	300	0.0031
3.75	8.95	300	0.0028
4.75	10.07	300	0.0006
5.75	10.73	300	0.0000

6.75	11.62	300	0.0000
0.50	4.00	330	0.0311
1.00	5.66	330	0.0272
1.50	6.20	330	0.0187
2.00	7.16	330	0.0119
2.50	7.70	330	0.0075
3.00	8.44	330	0.0038
3.75	8.95	330	0.0038
4.75	10.07	330	0.0008
5.75	10.73	330	0.0002
6.75	11.62	330	0.0000
0.00	7.0	330	0.4041