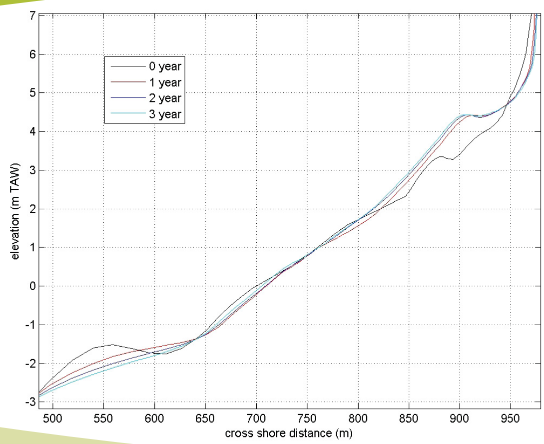
department
Mobility and
Public Works

Scientific support regarding hydrodynamics and sand transport in the coastal zone

EVALUATION OF XBEACH FOR LONG TERM CROSS-SHORE MODELLING



00_072 WL Rapporten

flanders HYDRAULICS RESEARCH

IMDC International Marine & Dredging Consultants

Vlaamse overheid

Scientific support regarding hydrodynamics and sand transport in the coastal zone

Evaluation of XBeach for long term cross-shore modelling

Zimmermann, N.; Trouw, K.; De Maerschalck, B.; Toro, F.; Delgado, R.; Verwaest, T.; Mostaert, F.

July 2015

WL2015R00_072_13

This publication must be cited as follows:

Zimmermann, N.; Trouw, K.; De Maerschalck, B.; Toro, F.; Delgado, R.; Verwaest, T.; Mostaert, F. (2015). Scientific support regarding hydrodynamics and sand transport in the coastal zone: Evaluation of XBeach for long term cross-shore modelling. Version 3.0. WL Rapporten, 00_072. Flanders Hydraulics Research & IMDC: Antwerp, Belgium

I/RA/11355/12.050/MIM/NZI. IMDC, Antwerp, Belgium

Waterbouwkundig Laboratorium

Flanders Hydraulics Research

Berchemlei 115
B-2140 Antwerp
Tel. +32 (0)3 224 60 35
Fax +32 (0)3 224 60 36
E-mail: waterbouwkundiglabo@vlaanderen.be
www.watlab.be

International Marine and Dredging Consultants

Coveliersstraat 15
B-2600 Antwerp
Tel. +32 (0)3 270 92 95
Tel. +32 (0)3 235 67 11
info@imdc.be
www.imdc.be

Document identification

Title:	Evaluation of XBeach for long term cross-shore modelling		
Customer:	Flanders Hydraulics Research	Ref.:	WL2015R00_072_13
Keywords (3-5):	XBeach; Cross shore modelling; Morphodynamics		
Text (p.):	58	Appendices (p.):	/
Confidentiality:	☐ Yes	Exceptions:	☐ Customer
			☐ Internal
			☐ Flemish government
		Released as from: September 2015	
	x No	x Available online	

Approval

Author	Reviser	Project Leader	Research & Consulting Manager	Head of Division
Zimmermann, N.	Trouw, K.	De Maerschalck, B.	Verwaest, T.	Mostaert, F.

Revisions

Nr.	Date	Definition	Author(s)
1.0	01/06/2015	Concept version	Zimmermann, N.;
2.0	15/07/2015	Substantive revision	Trouw, K.; Bolle, A.
3.0	17/07/2015	Final version	De Maerschalck, B.

Abstract

This report investigates the capabilities of XBeach for long term profile development. Typically cross-shore profile models are just applied to model storm impacts. Within the study an attempt is made to go beyond these common applications by focusing on medium (1 year) to long term applications (10 years). Potential applications include the evaluation of long term profile stability, such as in Knokke, the evolution of a beach or shoreface nourishment, and ultimately the evaluation of coastal retreat due to sea level rise. To this end, firstly the physical processes controlling the profile evolution are identified, secondly the implementation of these processes in XBeach and in Delft3D is reviewed, and finally the capabilities of XBeach are evaluated based on modelling exercises. The study shows promising results and highlights the current bottlenecks to be addressed.

Contents

List of tables

List of figures

1 Introduction

1.1 The assignment

In the frame of the project "Scientific support for hydrodynamics and sand dynamics in the coastal zone" executed by IMDC for Flanders Hydraulics Research (specification WL/09/23), tools are being developed in order to help answering morphology-related questions for Flanders Hydraulics Research itself and the relevant governmental services. The evaluation of cross-shore modelling capabilities of XBeach and Delft3D is one of these tools.

1.2 Aim of the study

The objective of the evaluation of cross-shore modelling capabilities is to evaluate whether models can be used to predict not only storm impacts, but also the longer term evolution of a profile. Potential applications include :

- Evaluation of the long term stability of the cross-shore profile (erosion in Knokke, accretion in De Panne)
- Evolution of a coarse-sized nourishment
- Evaluation of coastal retreat due to sea level rise

1.3 Overview of the study

Table 1-1 lists the reports written in the frame of this project.

Table 1-1 : Overview of reports

Reference WL / IMDC	Title
Literature review	
WL2010R744_30_2 / I/RA/11355/10.144/MIM	Literature review of physical processes
WL2011R744_30_3 / I/RA/11355/10.156/NZI	Literature review of models
WL2011R744_30_4 / I/RA/11355/10.157/JDW	Literature review of data
Blankenberge case	
WL2011R744_30_7 / I/RA/11355/11.055/NZI	Simplified Blankenberge case : Comparison of Delft3D and XBeach results
WL2012R744_30_18	Update of the sediment budget for the nearshore of Blankenberge-Zeebrugge
WL2012R744_30_17 / I/RA/11355/12.098/NZI/	Calibration of the Oostende-Knokke hydrodynamic and sediment transport model (OKNO)
WL2012A744_30_12 / I/RA/11355/12.048/NZI	Effect of a beach nourishment on the sedimentation of the entrance channel of the port of Blankenberge : Application of a simplified model for the Blankenberge area
WL2012R744_30_11 / I/RA/11355/12.049/lwa/NZI	Longshore modelling : realistic Blankenberge case
WL2013R00_063 / I/RA/11355/13.221/NZI	Toegankelijkheid haven Blankenberge: Optimalisatie van de haveningang

WL2013R13_105 / I/RA/11355/13.222/LWA/NZI	Energy atolls along the Belgian coast: Effects on currents, coastal morphology and coastal protection
Knokke case	
WL2013R12_107_1 / I/RA/11355/13.219/NZI	Inschatting van de morfologische impact van strandsuppleties te Knokke op het Zwin en de Baai van Heist
WL2015R12_107_2 / I/RA/11355/15.143/NZI/	Literature review coastal zone Zeebrugge - Zwin
WL2015R12_107_3 / I/RA/11355/14.175/LWA/NZI	Long term morphological model of the Belgian shelf: Calibration
WL2015R12_107_5 / I/RA/11355/15.145/NZI/	Advies suppletie Knokke – Effect op de morfologie van het Zwin en van de Baai van Heist: XBeach - modellering
Cross-shore modelling	
WL2015R00_072_13 / I/RA/11355/12.050/MIM/NZI	Evaluation of XBeach for long term cross-shore modelling
WL2015R12_107_6 / I/RA/11355/15.144/NZI/	Inventarisatie randvoorwaarden en morfologische impact van de Sinterklaasstorm op 6 december 2013
WL2015R12_107_4 / I/RA/11355/15.134/THL	Hindcast of the morphological impact of the 5-6 December 2013 storm using XBeach
Lessons learnt	
WL2015R00_072_19 / I/RA/11355/12.051/NZI/	Modelling tools and methodologies

1.4 Structure of the report

This report is structured in the following way:

- Chapter 1 is an introduction.
- Chapter 2 presents a literature review on cross-shore transport, and on the implementation of the physical processes in Delft3D and in XBeach.
- Chapter 3 presents the findings of the modelling exercises in XBeach.
- Chapter 4 concludes on the modelling capabilities.

2 Literature review on cross-shore transport

2.1 Objective

Contrary to longshore transport which is relatively well understood, cross-shore transport is still an area of intense research due to the delicate balance between onshore and offshore transport processes. The literature review aims to :

- identify dominant cross-shore transport processes in order to choose appropriate modelling tools,
- and identify their implementation in the morphological models Delft3D and XBeach.

Delft3D (Deltares, 2010a; 2010b) is a 3D morphological model based on the shallow water equations. It has been originally developed to study coastal areas and continental shelves and can be coupled to the wave model SWAN. XBeach (Unesco-IHE, 2009) focuses on nearshore processes and the profile response to time-varying storms, including dune erosion, overwash and breaching. It shares many similarities with Delft3D but it includes other processes such as instationary long waves and avalanching.

2.2 Processes

The main physical processes involved in cross-shore transport are summarized below.

Stokes drift, return flow and streaming

The Stokes drift, return flow and streaming are linked processes forming a vertical wave averaged velocity profile for linear waves. This profile is described by the theory of Longuet-Higgins (1953) and presented in Figure 2-1.

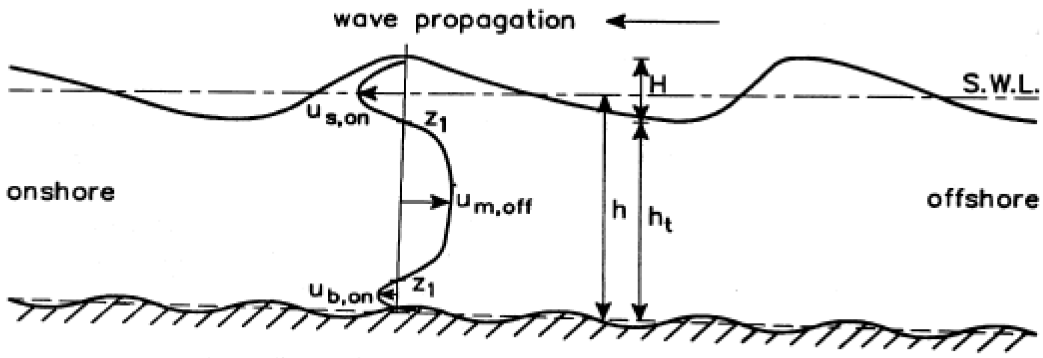


Figure 2-1: Time-averaged vertical velocity profile under waves according to Longuet-Higgins (1953), showing from top to bottom: Stokes drift, return flow and streaming.

Stokes drift

The Stokes drift contributes to onshore sediment transport.

For sinusoidal irrotational waves, water particles do not describe a perfectly closed circle due to the increase of the horizontal orbital velocity with the distance to bed (Stokes, 1847 ; cited by van Rijn and Walstra, 2003, p.79). The shore-directed velocity under the crest is higher than the sea-directed velocity under the trough. Water particles hence have a second order mean shore-directed velocity. This process becomes more pronounced in shallow water, where drift velocities are in the order of 0.1 m/s.

Return flow

The return flow contributes to offshore sediment transport.

The Stokes drift implies a net movement of water towards the shore in the upper part of the water column. This net mass flux has to be balanced by a return flow in the lower part of the water column. This return flow, also called undertow, has a mean offshore-directed velocity. In the case of overtopping during storms, the mass balance is modified by the loss of water on land and this effect may be negated.

Most sources identify the return flow as the dominant offshore transport process.

Streaming

Streaming contributes to onshore sediment transport.

According to Longuet-Higgins (1953), two additional effects play a role in the near-bed wave boundary layer. Firstly, the viscosity of the fluid is responsible for a downward transport of momentum into the boundary layer. Secondly, due to the vertical component of the orbital velocity and the principle of continuity, vertical velocities also exist within the boundary layer. Both effects result in a mean shear stress in the wave propagation direction.

Ruessink et al (2007) find the contribution of streaming to net transport small relative to the contribution of wave skewness. USACE (2008; Chap. III-3-2-a) identifies streaming as the dominant contribution to onshore shear stress, but it is unclear which non-linear wave processes are included in the comparison.

Wave non-linearity

Both wave asymmetry and wave skewness contribute to onshore sediment transport.

For classic non-linear wave theories, waves are not perfectly sinusoidal but present both a crest-trough asymmetry and skewness (Figure 2-2). Wave skewness means that crests are higher and of shorter duration than the troughs. Wave asymmetry means that the steepness – hence the acceleration – of the wave front is larger than that of the wave tail. In literature, the distinction between asymmetry and skewness is not always as clear.

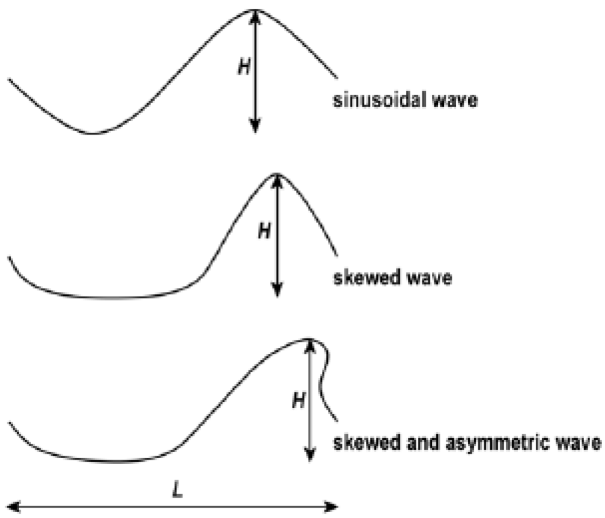


Figure 2-2: Sinusoïdal, skewed and skewed-asymmetric waves propagating to the right (reproduced from Grasmeijer, 2002).

Wave non-linearity may cause onshore transport through several near-bed effects:

- The shore-directed orbital velocity under the crest is higher than the sea-directed orbital velocity under the trough (skewness). Although the mean orbital velocity is zero, the mean bed shear stress is not and is directed onshore.
- The time between maximum velocity and flow reversal during each wave half-cycle is different and creates phase lag effects (asymmetry). Sediment stirred up during the negative half-cycle (wave tail) does not always have the time to settle before the positive half-cycle (wave front)

and is transported onshore, while sediment stirred up during the positive half-cycle has more time to settle before flow reversal occurs (Van der A et al, 2009).

- Large horizontal pressure gradients near the bed can loosen small blocks of sediment of several grain diameters high, creating a so-called “plug flow”. For asymmetric waves, these gradients are strongest during the rapid acceleration of the positive wave half-cycle and sediment is transported onshore (Foster et al, 2006). These pressure gradients are also referred to as “acceleration skewness” in literature.

Wave skewness is often cited as the dominant process for onshore transport in the shoaling zone while wave asymmetry becomes important in the inner surf zone and in the swash zone (Ruessink et al, 2007, 2011 ; ENCORA, 2011). The relative importance of their sub-causes is however still heavily discussed. Phase lag effects are observed but only become important for finer sand (Van der A et al, 2009 ; Ruessink et al, 2011). Horizontal pressure gradients are a dominant process but plug flow is not always observed (Berni, 2011 ; Ruessink et al, 2011).

Infiltration and exfiltration

Infiltration and exfiltration (vertical pressure gradients) indirectly contribute to on- and offshore transport.

Vertical pressure gradients have two opposing effects on sediment infiltration or exfiltration through the bed (Figure 2-3):

- During exfiltration, the vertical pressure gradients destabilize the sediment, which increases the near-bed concentration.
- During exfiltration, turbulent eddies in the boundary layer are pushed further from the bed and its thickness increases. This reduces the near-bed velocity.
- The opposite occurs during infiltration.

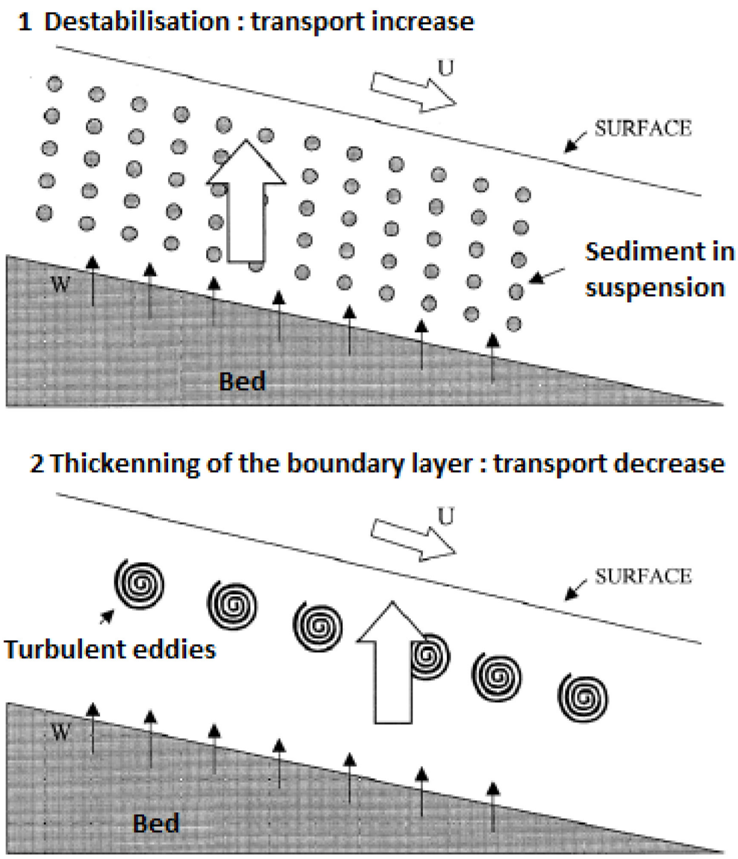


Figure 2-3: Two conflicting effects of exfiltration on sediment transport (adapted from Berni, 2011).

In practice it is difficult to isolate or to quantify these processes, except if the vertical pressure gradient is very large and positive upwards, in which case liquefaction can occur (Berni, 2011). For sand with a porosity of 0.5, liquefaction necessitates a pressure gradient of $1.8*10^4$ Pa/m.

Gravity

Gravity contributes to offshore sediment transport.

Gravity acts as a stabilizing force on the sediment (threshold of motion) and has a smoothening effect on outstanding morphological features such as bars. In average, due to the foreshore slope, gravity tends to transport sediment offshore.

Turbulence

Turbulence indirectly contribute both to on- and offshore sediment transport.

Turbulence is of major importance to explain the different transport behaviour in the shoaling zone and in the surf zone. In the shoaling zone, low turbulence implies a high sediment concentation near bed and a low sediment concentration in the water column, and the near-bed onshore transport processes are dominant. In the surf zone, the turbulence induced by wave breaking increases the sediment concentration in the entire water column and the return flow becomes dominant. Ruessink et al (2007) modelled successfully onshore and offshore bar migration with wave skewness, the return flow and a 3D model for turbulence.

Fall velocity

The fall velocity indirectly contributes both to on- and to offshore transport.

While breaking, waves dissipate energy through turbulence, which mobilizes sediments in the water column. This mobilization happens under the wave crest and can be intermittent depending on the fall velocity of the particle. The suspended transport direction then depends on the current direction at the particular moment of mobilization and on the time it remains in suspension (USACE, 2008 ; Chap. III-3-2-a).

Dean (1973) uses the fall time parameter H/wT, where H and T are the wave height and period and w the settling velocity, to describe whether the particle will be moving on- or offshore. If the fall velocity is high it will settle before experiencing the wave trough and will be transported onshore, while if the fall velocity is low it will still be in suspension and be transported offshore. This may result in the observed sediment sorting with the coarser sediment towards the beach, mentioned by Cornish (1898) and refined by Ippen and Eagleson (1955).

Several studies tried to determine under which wave conditions a shift between on- and offshore transport occurs, usually based on a dimensionless parameter. Seymour and Castel (1989) review the performance of six predictors from literature and conclude that the best one is only correct in two thirds of the cases.

Bed forms

Bed forms indirectly contribute both to on- and to offshore transport.

Bed forms may influence the sediment transport in different ways:

- Bed forms determine the flow resistance through the bed roughness, which may in turn strongly influence the suspended sediment concentration. Rougher beds create more turbulence than plane beds and more sediment can be stirred up.
- Similar to the fall velocity, the turbulent eddies created by the bed forms under the wave crest can prevent the sediment from settling within a wave cycle and sediment may be transported offshore (Figure 2-4).
- Bed forms exist only during one of three flow stages (Figure 2-5). For mild local wave conditions bed forms develop and reach an equilibrium. For moderate conditions the bed forms leave their equilibrium range but are still present. For strong wave conditions, as in the surf zone, bed forms are washed out and the flow is also called “sheet flow”. This, and the short time scale associated with their development, imply that often a great spatial variability of bed forms is encountered on a cross-shore profile (Soulsby, 2003).

During the COAST3D project, field measurements at Egmond in the Netherlands showed that small-scale bed-form activity is most pronounced on the seaward flanks of bars (Soulsby, 2003). Grasmeijer (2002) found it necessary to vary spatially the wave-related bed roughness to reproduce correctly the suspended sediment concentration and the morphological behaviour of a flume experiment.

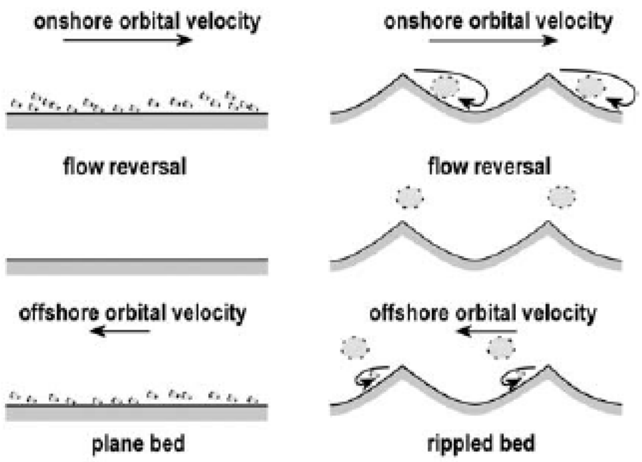


Figure 2-4: Effect of bed forms on the net sediment transport under a wave (reproduced from Grasmeijer, 2002).

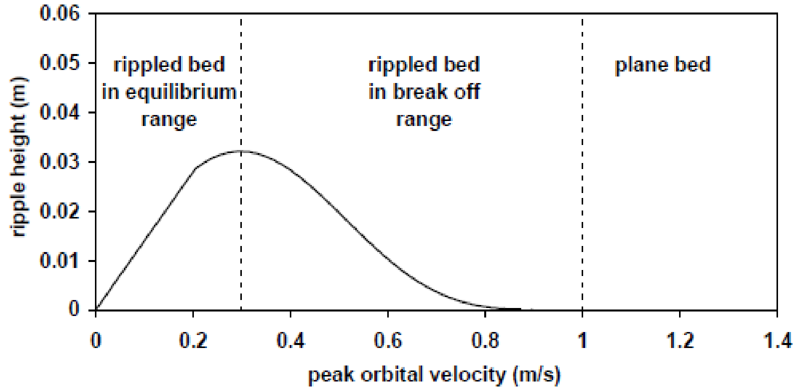


Figure 2-5: Example of ripple height versus peak orbital velocity for sand with a d50 diameter of 240 µm and a wave period of 4s, calculated with the bed form model of Van Rijn (1993) ; figure reproduced from Grasmeijer (2002).

Wind stress

The wind stress can contribute both to on- and offshore sediment transport.

The wind, especially during storm events, imposes a shear stress on the surface, creating a surface flow in its direction. Near-shore it is compensated by a bottom flow in the opposite direction. If the wind blows from sea it will result in an offshore-directed bottom flow. A wind from land results in an onshore-directed bottom flow.

On a somewhat larger scale, the combination of wind and the Coriolis force can generate upwelling and downwelling events which are based on a similar principle (Figure 2-6). Upwelling results in a net onshore transport and downwelling in a net offshore transport.

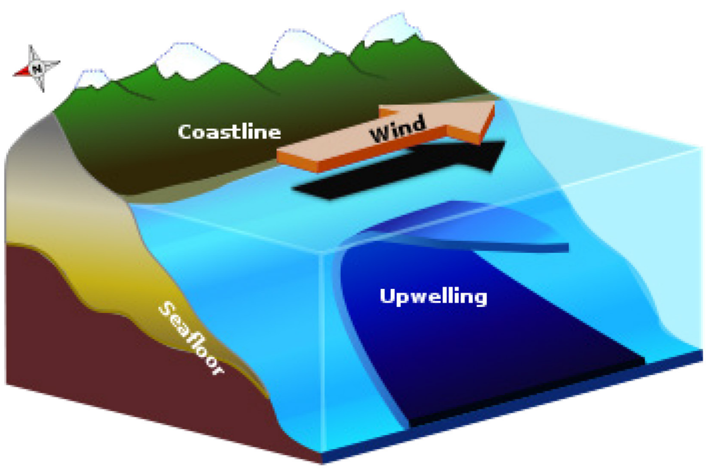


Figure 2-6: Example of upwelling circulation generated by the wind, here in combination with the Coriolis force which drives the current to the right in the Northern hemisphere.

Long waves

Long waves indirectly contribute to offshore transport during dune erosion events.

Although the contribution of long waves to sediment transport is small compared to wave skewness and the return flow (Ruessink, 2007), long waves indirectly play an important role as a sediment source.

Dune erosion is mainly the result of long waves – or swash motions / surf beat – reaching the dune foot combined to a critical wet slope of sand which is lower than its critical dry slope. This sudden avalanching and supply of sediment to the cross-shore profile is in return evacuated further by the return flow. During dune erosion events, the combination of long waves and return flow is reported to be much more important than that of wave asymmetry and skewness (Van Thiel de Vries, 2008).

Wave roller

The wave roller affects the consequences of on- and offshore transport.

The location of maximum sediment concentration relative to the location of zero net transport on the cross-shore profile is critical in explaining bar growth or decay. Once waves start breaking, the energy is not dissipated instantly, it needs some time. This energy dissipation occurs in the wave roller. Because of this delay, the location of maximum wave breaking and sediment concentration is shifted towards the coast, which can help offshore transport by the return flow to build the bar instead of diffusing it.

3D effects

3D effects affect the consequences of on- and offshore transport.

Although longshore and cross-shore currents are generally separated for simplicity, their combination is sometimes needed to explain a particular cross-shore behaviour.

Walstra et al (2011) show that the observed bar growth and offshore migration in Noordwijk aan Zee in the Netherlands can only occur because of the coupling with the local longshore transport. The model suggests that the bars would disappear for waves more perpendicular to the coast. Price et al. (2012) confirm the critical role of the wave direction / longshore transport in bar evolution based on more than ten years of Argus data.

Reniers and Battjes (1997) cite alongshore variations in pressure gradients, wind, and the wave roller as factors other than wave breaking affecting the location of maximum longshore current. In particular, alongshore variations in pressure gradients may create rip currents cutting through sand bars.

Souslby (2003) reports that 3D effects are vital to explain the morphological behaviour of the bar system at Egmond in the Netherlands on a time scale of 6 weeks, but that the system could be considered alongshore uniform on a time scale of years. Such 3D effects included observed shear waves, edge waves and rip currents.

2.3 Relative importance of the physical processes

The relative importance of each process determines whether the sediment is transported onshore or offshore. It depends on the hydrodynamic conditions, which explains the seasonal variability of cross-shore profiles, which tend to be mild in the summer and steep in the winter.

Advances in bar growth modelling also pinpoint how easily a system can shift its morphological configuration (Walstra et al, 2011). This illustrates the delicate balance of large quantities.

Nevertheless, some processes appear more important than others. Table 2-1 judges the importance of each process for onshore transport, offshore transport and bar behaviour, as compiled from literature.

Table 2-1: Relative importance of processes for onshore transport, offshore transport and bar behaviour, as compiled from literature

Process	Onshore transport	Offshore transport	Bar behaviour
Stokes' drift	-		-
Return flow		++	++
Streaming	-		-
Wave asymmetry	+		+
Wave skewness	++		++
In- and Exfiltration	--	--*	--
Gravity		=	+

Turbulence	=	=	+
Wind stress	- ?	- ?	-
Fall velocity	-- ?	- ?	--
Bed forms	-	-	=
Long waves	-	++**	++
Wave roller			+
3D effects			- to ++

* except liquefaction

** indirectly via dune erosion

Several processes mentioned in chapter 2 are related to intrawave phase lag effects. Their measurement in the field is tedious if not impossible, and none of these processes has been consistently reported as being critical to the modelling of a bar. They are hence not judged important here.

2.4 Implementation of processes in models

The 2DH implementation of the processes listed in chapters 2.2 and 2.3 in the morphodynamic models Delft3D and XBeach is reviewed here.

Required processes

In models, it is always convenient to try reducing the problem to a minimum number of dominant processes:

- Table 2-1 and literature attempts at bar growth modelling suggest that the dominant processes for onshore and offshore transport are respectively wave non-linearity (skewness and asymmetry) and the return flow (combined to turbulent mixing).
- Dune erosion by long waves is critical to supply the underwater profile with sediment during storm and to create a bar. This in turn may require a robust drying and wetting scheme.
- The growth and migration of a bar is probably the most sensitive point since it requires sediment transport to converge on or around the top of the bar, directed onshore from the sea and offshore from the beach. The location of this convergence point in return strongly depends on the wave roller and on the concentration profile via turbulence, and possibly via bed forms and 3D effects.

Stokes drift

In both models, Stokes drift is included in the hydrodynamics (see Generalized Lagrangian Mean method below), but its effect on sediment transport is not.

Return flow

In both models the return flow is accounted for with the popular Generalized Lagrangian Mean method (GLM). In this method the depth-averaged velocity, or Lagrangian velocity, is the sum of Stokes drift and the Eulerian velocity which is the return flow.

In Delft3D the advection-diffusion equation for suspended transport uses the Lagrangian velocity, which equals zero in cross-shore direction since there is no mean current from and to the coast. Sediment can therefore not be carried offshore by this process in a 2D model.

XBeach overcomes this issue by considering two velocity components for sediment transport. The velocity used in the advection-diffusion equation is the sum of the Eulerian velocity or return flow and an artificial onshore velocity to account for wave non-linearity, both skewness and asymmetry. In this way, although the model is depth-averaged, it still captures the two most important effects of the wave-averaged vertical flow structure.

Streaming

In Delft3D, streaming is modelled in a 3D model as a time-averaged wave shear stress. In 2D it is unclear however if streaming affects the sediment transport. The bed shear stress used to compute the reference concentration near-bed does not seem to include an explicit streaming component. One calibration parameter related to wave non-linearity might in fact rather be streaming. It is detailed in paragraph 2.4.

Wave non-linearity

Wave non-linearity refers here to wave skewness and wave asymmetry.

In Delft3D, the bed load transport magnitude under waves and currents is calculated from a combined wave and current shear stress according to the method of Van Rijn et al (2003). The transport direction is then split between the wave component in the direction of wave propagation and the current component in the direction of the current. This wave effect possibly refers to streaming. The effect of wave asymmetry on *suspended transport* is then added in the bed load component. However, since it is a function of onshore and offshore intrawave velocities, it is rather related to skewness than to asymmetry. Finally a correction of transport magnitude and direction for bed slope effects is added to the total bed load vector.

Two user-defined parameters then control this bed load transport: the wave-related bed load factor and the wave-related suspended load factor. These are scaling factors comprised between 0 and 1, with a realistic value more in the range 0-0.1 (Zimmermann et al, 2011). The bed load factor scales the streaming component and the suspended load factor scales the skewness component (Deltares, 2011, p.86, p.353-358).

In XBeach, wave non-linearity effects are included in suspended sediment transport as described in paragraph 2.4. Bed load transport per se is not included, however the bed load and suspended load fractions are determined from coefficients in the equilibrium concentration which are a function of the grain size, the local water depth and the relative sediment density. Bed load and suspended load therefore seem to have the same direction. Wave skewness and asymmetry do not influence the equilibrium sediment concentration, which depends on a combined wave and current shear stress according to the method of Souslby-Van Rijn (Soulsby, 1997).

In- and exfiltration

Delft3D does not include an in- and exfiltration module.

XBeach includes a groundwater module with in- and exfiltration of water according to Darcy’s law. It only influences sediment transport via the lower water volumes, and therefore currents in the swash zone.

Gravity

In Delft3D, gravity effects are taken into account with a bed slope correction on the direction and magnitude of the bed load transport. It does not play a role if the bedload transport is equal to zero, as is the case when the wave-related bed load and suspended load factors are set to zero (see discussion in paragraphs 0 and 0).

In XBeach, gravity effects are taken into account with a correction of the equilibrium concentration.

Turbulence

None of the two models includes the effect of wave breaking turbulence on the relative importance of bed load and suspended load. A 3D model with a turbulence closure scheme would be required to capture the mixing effect.

Wind stress

In both models, a wind field can be added to influence the hydrodynamics, however a 3D model would be required to capture the upwelling or downwelling circulation. The wind could still drive the flow alongshore.

Fall velocity

None of the two models includes intrawave lag effects as described in paragraph2.4. The fall velocity only appears through the settling time lag added to the advection-diffusion equation for suspended transport to model underloading and overloading of the flow (Galappatti and Vreugdenhil, 1985).

Bed forms

In Delft3D, the bed roughness can vary in space in two ways. The user can specify a file defining the space-varying roughness, which is however constant for the duration of the simulation, or a bed roughness predictor can be used. This second option is more realistic since it allows the bed forms and roughness to be computed at every time step from the local hydrodynamic conditions. Relaxation times are used to determine the time needed for the bed forms to adapt to new hydrodynamic conditions.

In XBeach the space-varying bed roughness can only be specified in a user-defined file. Since it is static, this option can only be used when time scales of bed form evolution are large compared to the simulation time (too long for ripples), or for stationary hydrodynamic forcing.

Long waves

Delft3D does not model long waves. A model extension for surf beat and wave roller can calculate the long wave field, but it seems to be time-averaged and in any case does not influence beach and dune erosion. The model also includes an artifice to model dune erosion by transferring the erosion from the last wet cell into the first dry cell (dry cell erosion), but it is physically incorrect. The Zandmotor project in the Netherlands seems to use a different system with a Dune Module, but it is not available here and has not been investigated yet.

XBeach on the other hand has been designed to model time-varying long waves. This surf beat is combined to an avalanching law and a robust drying-wetting scheme to produce realistic dune erosion. The avalanching simply results from the fact that the critical slope of wet sediment is lower than the critical slope of dry sediment. Hence when surf beat occasionally reaches the dune foot, the sediment becomes unstable and is redistributed instantly downward until the critical wet slope is reached. This new sediment can then be transported under water by other mechanisms such as the return flow.

Wave roller

Delft3D includes a model extension for surf beat and wave roller. The wave roller implementation follows a simple parameterisation instead of a roller energy balance. Its use may however possibly be inconvenient for real applications due to special requirements. Stationary conditions require a dummy FLOW and a dummy WAVE run before the real run and a set of boundary conditions of the form Neumann / water level / Neumann is recommended, which might complicate the use of nesting. Instationary conditions require the use of Riemann conditions at all boundaries and to create a specific file for wave conditions.

XBeach models the wave roller with a more complex roller energy balance. The energy dissipated by breaking waves is the source term of the roller energy, which dissipates again at a rate which depends on the slope of the wave front.

3D effects

3D effects may include longshore currents, wind circulations, circulation cells and rip channels formed by long waves, such as shear waves and edge waves.

Delft3D can model longshore currents and horizontal wind circulations, but not processes related to long waves except if these are explicitly applied at the boundaries (Reniers, 2013).

XBeach can model all of the above-mentioned processes.

Implementation summary

Table 2-2 summarizes which processes can be modelled with a 2DH model in Delft3D and XBeach.

Delft3D has two major drawbacks for cross-shore profile modelling: its 2D implementation of the return flow is insufficient and beach erosion is not possible (no long waves and avalanching, alternative “dry cell erosion” option unphysical). It might perform better with a 3D model, but would still be limited by the absence of beach erosion. A 3D model is not available in XBeach.

In Delft3D, due to the implementation of bed load and suspended transport discussed in the paragraphs above, it should be noted that wave-related transport is always onshore and that the only possible offshore-directed components are bed slope effects or suspended sediment diffusion. Since the bed slope effect scales on the bed load transport, if the wave-related scaling factors are set to zero, it is also zero. The diffusion component on the other hand is one to two orders of magnitude lower than the advection component, which explains why its effect is not visible (Zimmermann et al, 2011). The popular alternative approach of Bailard (1981) implemented in the transport formulae of Bijker (1971) may allow to get a tuneable balance between onshore transport by wave asymmetry and offshore transport by bed slope effects, however without return flow the physics of the model are still likely flawed.

Table 2-2: Implementation of processes in a 2DH model in Delft3D and XBeach from the point of view of sediment transport, and their importance for bar behaviour (see also Table 2-1).

Process	Delft3D	XBeach	Bar behaviour
Stokes' drift	No	No	-
Return flow	No (hydrodynamics only)	Yes	++
Streaming	Yes (in bed load)	No	-
Wave asymmetry	No	Yes (in suspended load)	+
Wave skewness	Yes (in bed load)	Yes (in suspended load)	++
In- and Exfiltration	No	No (hydrodynamics only)	--
Gravity	Yes (correction of bed load transport)	Yes (correction of equil. concentration)	+
Turbulence	No	No	+
Wind stress	No*	No*	-
Fall velocity	No**	No**	--
Bed forms	Yes (predictor)	Limited (initial conditions only)	=
Long waves	No	Yes	++
Wave roller	Limited (not convenient)	Yes	+
3D effects	Limited (longshore current and wind only)	Yes	- to ++

* A wind field can be added but a 3D model would be required to model the cross-shore recirculation; longshore flow forcing possible

** No intrawave lag effects, only underloading / overloading of suspended sediment

Other modelling remarks

Morphological simulations can also be artificially accelerated by the use of a morphological acceleration factor, also called MORFAC. The applicability domain of such a factor is however still debatable. A MORFAC induces an amplitude and phase error in the propagation of a bed form (Ranasinghe et al, in prep). Although this error is generally an order of magnitude smaller than errors induced by the numerical scheme, it may be more critical to model bar growth and migration, because the exact location of the convergence of sediment transport is so important. It is hence advised to begin modelling without MORFAC whenever possible.

A small note is also needed for the interpretation of model results. Care should be taken when estimating the net effect of a process in terms of mean values, as is done in literature, for several reasons:

- The mean shear stress may be different than zero, it will still have no effect if below the threshold of motion, while the maximum shear stress during a wave cycle may well be much above.
- The mean flow velocity is counter-intuitive in the case of several processes including wave asymmetry, i.e. always in reality, because the net sediment transport may well be directed in the opposite direction. The reason for this is the dependence of most sediment transport formulae on a power of the flow velocity, usually 3 to 5.
- The residual sediment transport still does not indicate where sedimentation or erosion will occur, since this is the result of its divergence (and not its gradient). A residual transport eddy for instance does on a first order not lead to sedimentation because it is a closed line of constant transport. This is especially relevant in 3D problems. A good workaround to this issue is to think in terms of accommodation space, which is the locations in which sediment would naturally like to settle, such as lower-energy environments like the centre of a flow eddy or an abandoned secondary channel.

2.5 Conclusion

The main processes governing cross-shore sediment transport have been described based on literature. The most important driving processes of cross-shore transport include onshore transport by wave non-linearity (skewness in the shoaling zone, asymmetry in the surf zone), offshore transport by the return flow and beach and dune erosion by long waves to supply the underwater profile with sediment.

The implementation of these processes in the hydro-morphological models Delft3D and XBeach has also been reviewed. Results suggest that Delft3D may not be suitable to model bar behaviour with a 2D model, primarily because dune erosion by long waves and offshore sediment transport by the return flow are not included. A 3D model performs better (Brière et al., 2010) but would still miss dune erosion. XBeach on the other hand includes all main processes necessary to model bar behaviour, with the exception of the effect of vertical mixing by wave breaking turbulence on the relative importance of onshore-directed transport by wave non-linearity and offshore-directed transport by the undertow.

3 Modelling exercise

3.1 Objective and methodology

Modelling of cross-shore transport and erosion during individual storm events is already commonly applied. As the needs evolve a few more delicate and longer term applications can be foreseen, such as the evolution of a nourishment over time (possibly of different grain size than the native sediment) and quantifying the long term coastal erosion trend.

The latter in particular is not well understood yet. Long term cross-shore erosion is typically believed to be due to rising sea level and its effect computed with the Bruun rule (Figure 3-1). This rule assumes that in average, the cross-shore profile shape is conserved over time and that the future profile after sea-level rise (SLR) can be simply shifted landwards in a mass-conserving way. This method assumes that the profile undergoes little morphological change seaward of the closure depth, which is consequently also the controlling parameter for the calculation. Other causes for long term erosion may be related to soft geology such as in deltaic environments, or to human impacts such as sand, gravel or rock mining which can alter the composition and equilibrium of the profile.

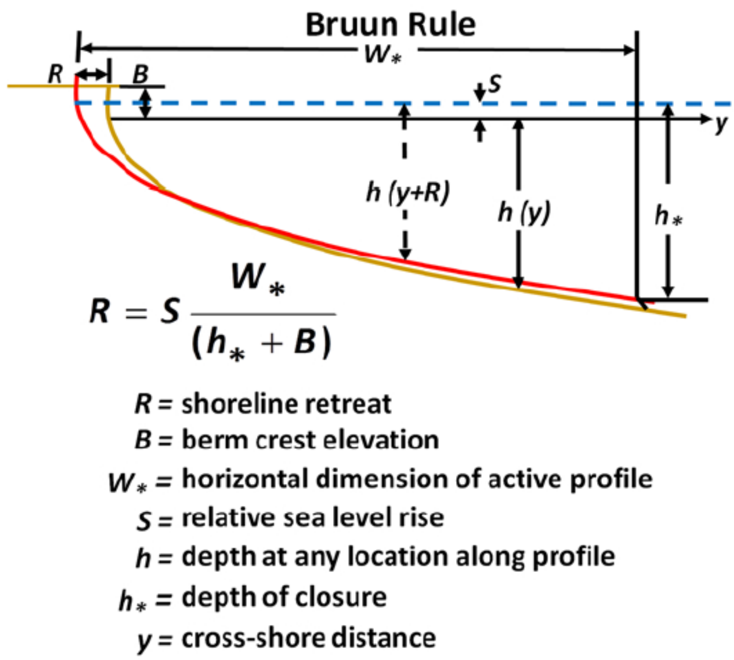


Figure 3-1 : Original Bruun rule, figure from Dean et al. (2014).

The objective of this modelling exercise is to investigate the potential of XBeach to model long term cross-shore erosion. Foreseen applications on the Flemish coast include the evolution of coarse-sized nourishments and potentially the evaluation of cross-shore erosion due to climate change.

Difficulties associated with long term cross-shore modelling are expected to be related to beach recovery during mild wave conditions, to long term profile stability and to computation time. Additionally certain processes and their implementation in models are not well-known and tested: swash zone dynamics, groundwater, multiple fractions, non-hydrostatic modelling.

The objective of this exercise is therefore to answer the following questions :

- Can the profile be stable in medium (1 year) to long term applications (>10 years) ?
- Can XBeach be used to evaluate the medium to long term evolution of a nourishment ?
- Does XBeach handle multiple sediment fractions properly ?

This exercise is done in two steps:

- Firstly a theoretical test case is set up which presents modelling difficulties. This test case is used to identify and address issues in long term cross-shore modelling.
- Secondly the modelling methods derived from the first step are applied on a profile on the Belgian coast to verify their applicability.

3.2 Settings

Theoretical test

The theoretical exercise consists of a steep profile in a swell-dominated environment (Figure 3-2). Waves typically have a significant wave height of 1 to 2m and a period of 10 to 20s. The tidal range is about 1m. In accordance with the beach steepness of up to 1:10, sediment has a grain size of about 600 µm on the beach. Further offshore the steepness decreases and the grain size decreases accordingly down to silt size on the shelf. A time period of one year is simulated.

The test case is inspired from an existing calibrated model (personal communication IMDC). Additional hypotheses are however made which have not been calibrated or validated against data. The exact background of the project is not relevant to the exercise. This test case is deemed particularly interesting for the stated objective because it is situated in a very energetic environment, and because a large variation in sediment size is present. This implies that the model applicability is more likely to be pushed to its limits compared to a profile on the relatively quiet Belgian coast.

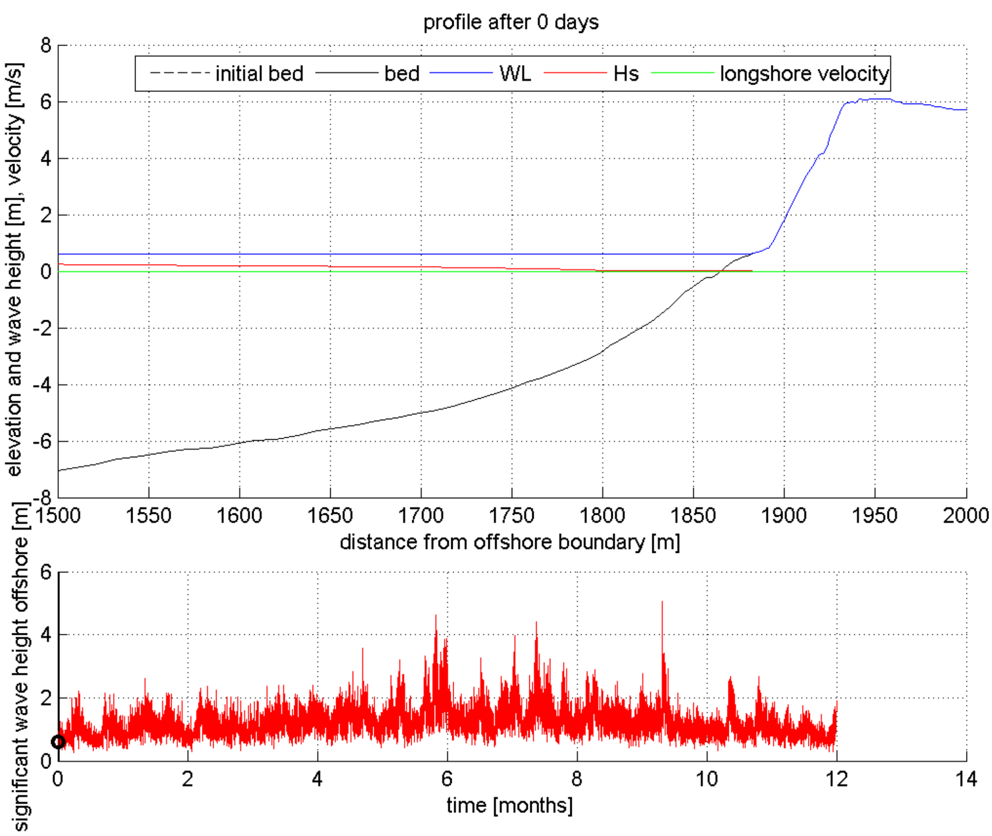


Figure 3-2 : Profile and wave climate used in the theoretical test.

In order to simulate one year of morphological changes, the following setup has been used:

- A truly 1D profile model is used (superfast option) with Snellius' law for wave refraction, instead of a 2D or a pseudo 1D model.

- The tide is simulated with only the water level variation. For tidal currents a 2D or a pseudo 1D model is necessary. In this particular case tidal currents are much smaller than longshore current (which is included).
- A morphological acceleration factor of 30 is used (with morfacopt = 1). Every hydrodynamic hour only two minutes of morphological changes are computed. With a long wave period in the order of 100s, this corresponds to about one full long wave. This is very short but given the simulation period of one year the associated errors are assumed to cancel out over time.
- Only one processor is used. This is because in the Easter 2012 release of XBeach used here, a bug prevents avalanching across domain boundaries in the case of multiple processors. An additional speed up is therefore expected in the future (about a factor 4).

Sensitivity tests are done with groundwater and with multiple sediment fractions. Groundwater is straightforward to use. With multiple fractions, three fractions of 540 µm, 100 µm and 60 µm are used and the bed composition is computed on 10 layers of 0.5m thickness each.

Belgian profile

A similar model has then been set up on the Belgian coast, see paragraph 3.4.

3.3 Results of theoretical test

Overview of simulations

Due to the large number of tests done, only the most relevant simulations are described. Table 3-1 presents an overview of relevant simulations:

- The reference case lt000 is the starting point of the exercise. It has been optimised for speed to estimate the maximum time period that can reasonably be simulated. The most important calibration parameter, the factor for onshore transport due to wave asymmetry, is equal to 0.5 instead of the default value of 0.1.
- The simulation lt002b includes groundwater. Its objective is to evaluate the stabilising effect of this new process. It is expected to become important for coarse sand and especially for gravel beaches. The permeability of sand lies in the range 10^{-5} to 10^{-2} m/s (West, 1995), with the latter values rather for well-sorted coarse sand. For sands the permeability can also be estimated from the grain size with Hazen's equation :

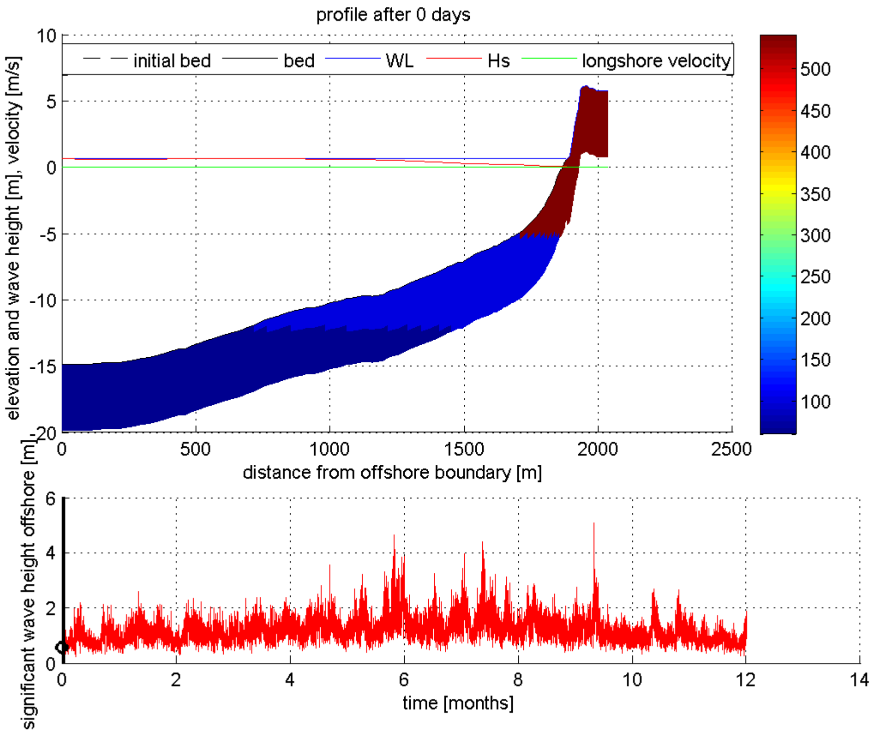
$$k = 10^{-2} d_{10}^2$$

  which would yield about $3.6*10^{-3}$ m/s for perfectly sorted 600µm sand. For testing purposes the maximum value of 10^{-2} m/s is used instead. The factor for onshore transport due to wave asymmetry has been slightly decreased, to 0.4 instead of 0.5 in the reference case (better calibration with groundwater).
- The simulation lt003a includes multiple sediment fractions. Its objective is to evaluate the importance of natural sediment sorting on profile development. The initial sediment distribution is specified according to horizontal geological layers chosen arbitrarily as follows: 540 µm above -5m LAT, 100 µm between -5 and -12m LAT and 60 µm below -12m LAT.
- Simulations lt003d to lt003f include multiple fractions and the groundwater settings of simulation lt002b. Three different initial distributions are compared: horizontal layers such as in lt003a, a uniform distribution (33% of each fraction) and vertical layers at the same depths of -5 and -12m LAT.
- Simulations lt005e, lt005f, lt006c and lt009c investigate the potential of XBeach to simulate coastal retreat due to sea level rise over a period of 10 years, based on simulation with multiple fractions lt003d. Lt005e and lt005f are respectively without and with a sea level rise of 1 cm/year. Lt006c shows the impact of a lower morfac (10 instead of 30) and lt009c shows the impact of a grain size dependent onshore transport factor (facas = 0 for 60 µm, 0.1 for 100 µm and 0.4 for 540 µm ; facsk = 0.1 for all fractions).

Table 3-1 : Overview of simulations for the theoretical test

Run	Description
Lt000	Reference case : calibrated model with single grain size (540µm), optimised for speed
Lt002b	Reference case + groundwater (permeability 10^{-2}m/s instead of 10^{-4}m/s)
Lt003a	Reference case + multiple sediment fractions (horizontal distribution)
Lt003d	Reference case + groundwater + multiple sediment fractions (horizontal distribution)
Lt003e	Reference case + groundwater + multiple sediment fractions (uniform distribution)
Lt003f	Reference case + groundwater + multiple sediment fractions (vertical distribution)
Lt005e	Same as lt003d with 10 years
Lt005f	Same as lt003d with 10 years + sea level rise 1 cm/year
Lt006c	Same as lt003d with 10 years + sea level rise 1 cm/year + morfac 10 instead of 30
Lt009c	Same as lt003d with 10 years + sea level rise 1 cm/year + morfac 10 instead of 30 + modified code with onshore transport dependent on grain size

Figure 3-3 presents the initial horizontal and vertical distributions of multiple sediment fractions. To visualise the sediment characteristics with multiple fractions, the arithmetic average grain size is computed (since d50 has little meaning with three fractions). A uniform distribution is equivalent to an average grain size of 233 µm.



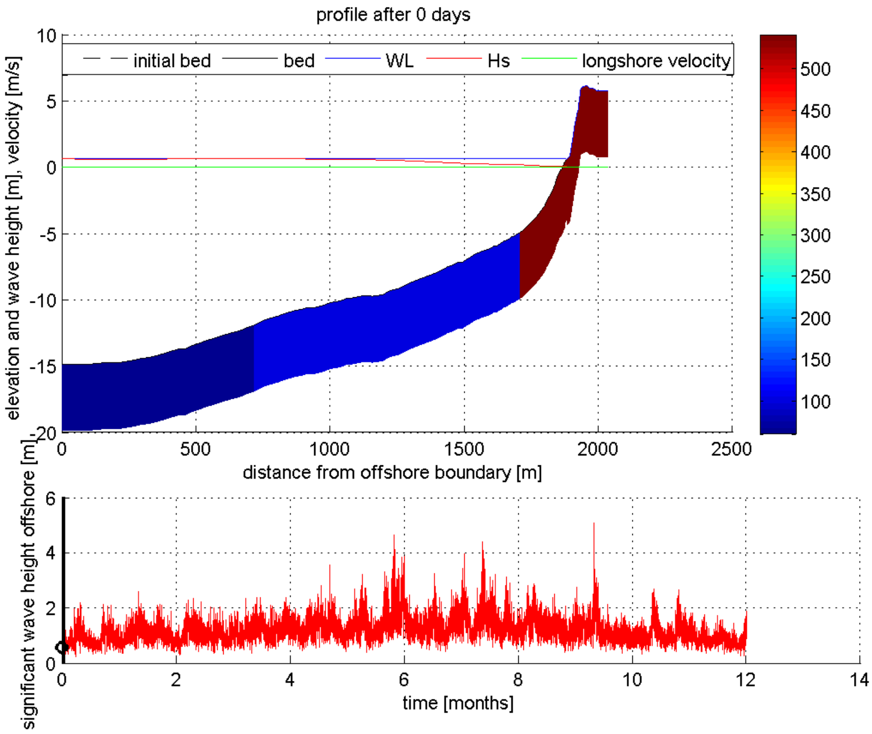


Figure 3-3 : Horizontal (top) and vertical distribution of multiple sediment fractions (bottom). Mean sediment size in color scale (µm).

The computation time of the reference run varies between 3 hours and 1 day depending on the computing machine and on its current workload. Comparable computation times have been achieved when adding groundwater or multiple fractions. It is hence possible to increase the simulation period further.

Discussion

Reference run (lt000):

The reference run consists of a model already calibrated over a short period (days to weeks). This calibration consists in adjusting the value for onshore transport by wave skewness (*facsk*) and for wave asymmetry (*facas*) until the profile is stabilised. Figure 3-4 shows that despite the calibration, the final profile looks rather unrealistic. Yet it is also promising that there is still a profile at all after one year of morphological changes under such energetic conditions. With the default values of XBeach the computed profile is totally unrealistic (not shown).

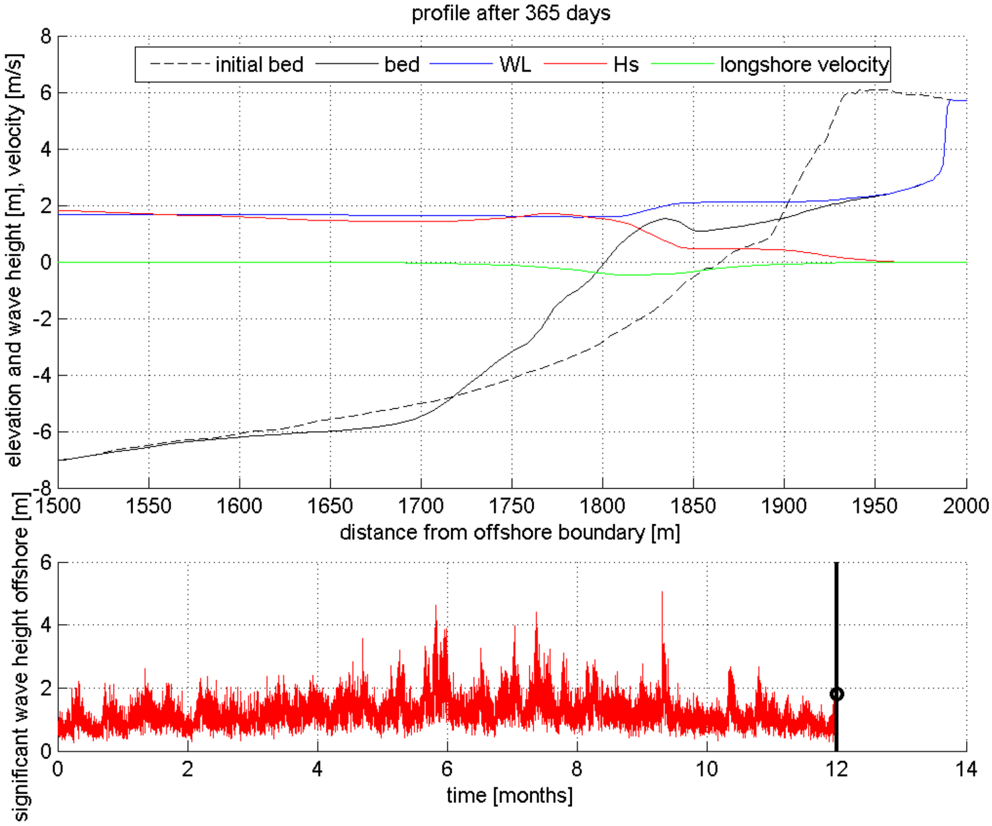


Figure 3-4 : Resulting profile development after one year of morphological changes for reference run (lt000).

This exercise shows that for long term applications the profile can be stabilised by carefully controlling onshore transport. It also shows that wave skewness and asymmetry alone are (in this case) insufficient to yield realistic long term results. Erosion is reasonably well modelled, beach recovery occurs, but the sediment is never pushed fully onto the dry beach. This is believed to be due to limitations in swash zone transport. The Nielsen transport formula incorporating horizontal pressure gradients has been shown to perform better than the transport formula used in XBeach for beach recovery (Van Rooijen et al., 2012). Also the sediment is coarse, it is possible that groundwater may play a non-negligible role in beach stabilisation.

Effect of groundwater (run lt002b) :

Adding groundwater with a permeability of 10^{-2} m/s results in a strong stabilisation of the profile (Figure

3-5). The profile shape after one year still looks realistic. However it is questionable whether this stabilisation is realistic or whether the selected groundwater settings cause artificial damping of morphological variability. The same succession of erosive and accretive events occur as in the reference case, but always with a reduced amplitude.

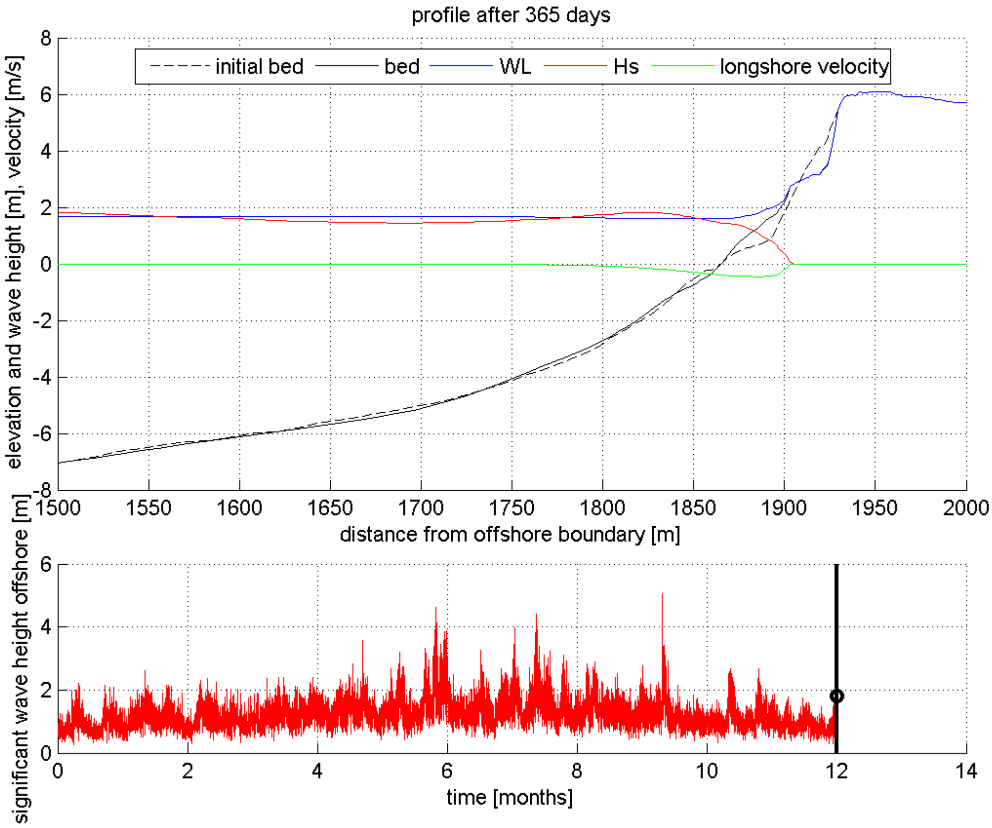


Figure 3-5 : Resulting profile development after one year of morphological changes with groundwater (lt002b).

This simulation shows that groundwater can be very important in stabilising the beach profile in the model. It is not known whether the results are physically acceptable. Groundwater can hence be used as a calibration parameter for long term cross-shore modelling.

Effect of multiple sediment fractions (lt003a, lt003d, lt003e, lt003f) :

Figure 3-6 shows the resulting profile and the average grain size after one year in run lt003a (reference case with multiple fractions and horizontal distribution). The general profile shape is comparable to the one with a single sediment size (540µm). Some additional observations can be made:

- There is accumulation of fine sediment near the water line. In view of the initial sediment distribution, this sediment can only come from offshore by onshore transport. Physically a natural segregation of grain sizes is expected, with coarser material nearshore in the zones of higher energy (surf zone, beach), and finer material deeper where wave action is lower. The cause of this unrealistic behaviour has not been found. The mathematical formulation used for onshore and offshore sediment transport only involves wave characteristics, no sediment characteristics.

- The upper layer exhibits a smooth transition from coarse material in the surf zone to fine material offshore. This reflects the expected segregation of material along the profile.
- Near the beach, deeper layers exhibit finer material than at the surface. This stratigraphy is

caused by the succession of storm events and calmer periods. New sediment brought by onshore transport can cover older sediment layers. On the contrary storms can expose older layers again by eroding the surface layers.

- The transition between fine and coarse material at -5m LAT is vertical although the initial distribution had horizontal layers. This seems to be due to the limited number of layers modelled. When sedimentation occurs a new layer is created at the top and the deepest layer is deleted. When erosion subsequently occurs the top layer eventually disappears and a new layer is created at the bottom. This layer is set equal to the layer just above it. If before this sedimentation-erosion cycle these two deepest layers had different composition, this information is now lost. In addition the formulations described in the technical manual also seem to promote exchange of information between layers. The technical manual is not detailed enough to identify the issue with certainty.

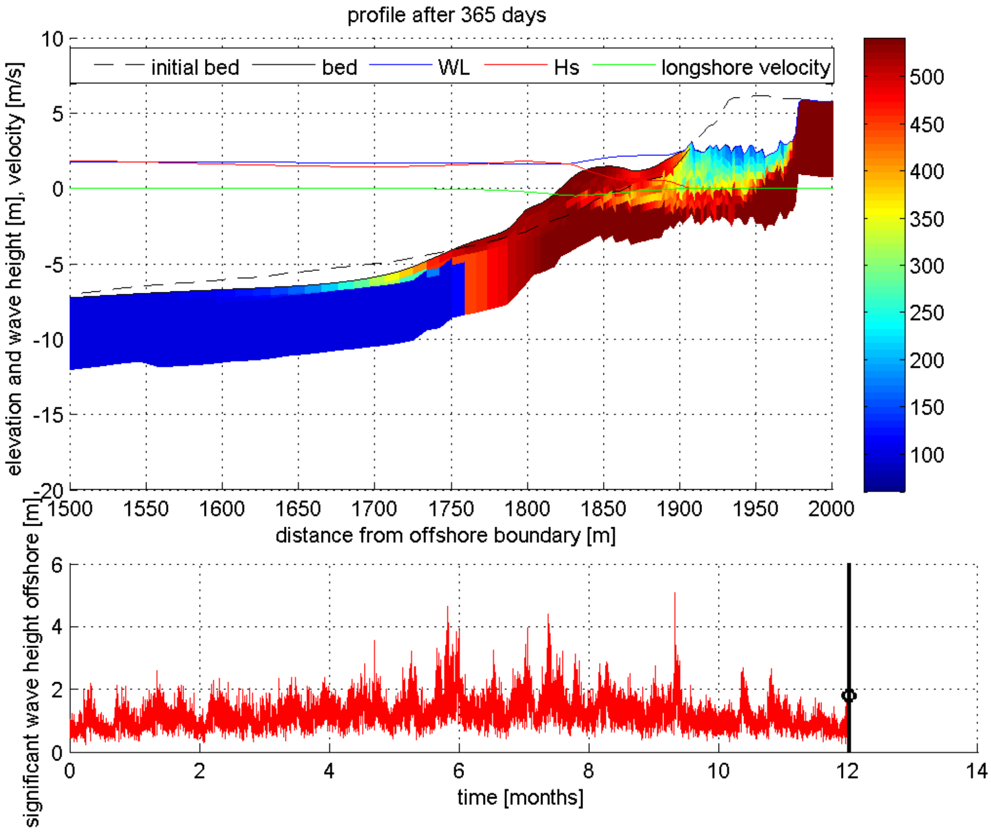


Figure 3-6 : Resulting profile development after one year of morphological changes with multiple fractions and a horizontal distribution (lt003a). Mean sediment size in color scale.

Figure 3-7 shows the resulting profile and the average grain size after one year in run lt003d (as lt003a with groundwater; horizontal distribution). The same remarks can be made as for run lt003a except that the profile stability is maintained. Due to the finer sediment used, the profile displays morphological evolution (erosion) deeper than in the single fraction case (still visible at -7m instead of -1m). This confirms that the grain size can strongly influence the closure depth, the main controlling parameter in the computation of coastal retreat due to sea level rise according to Bruun.

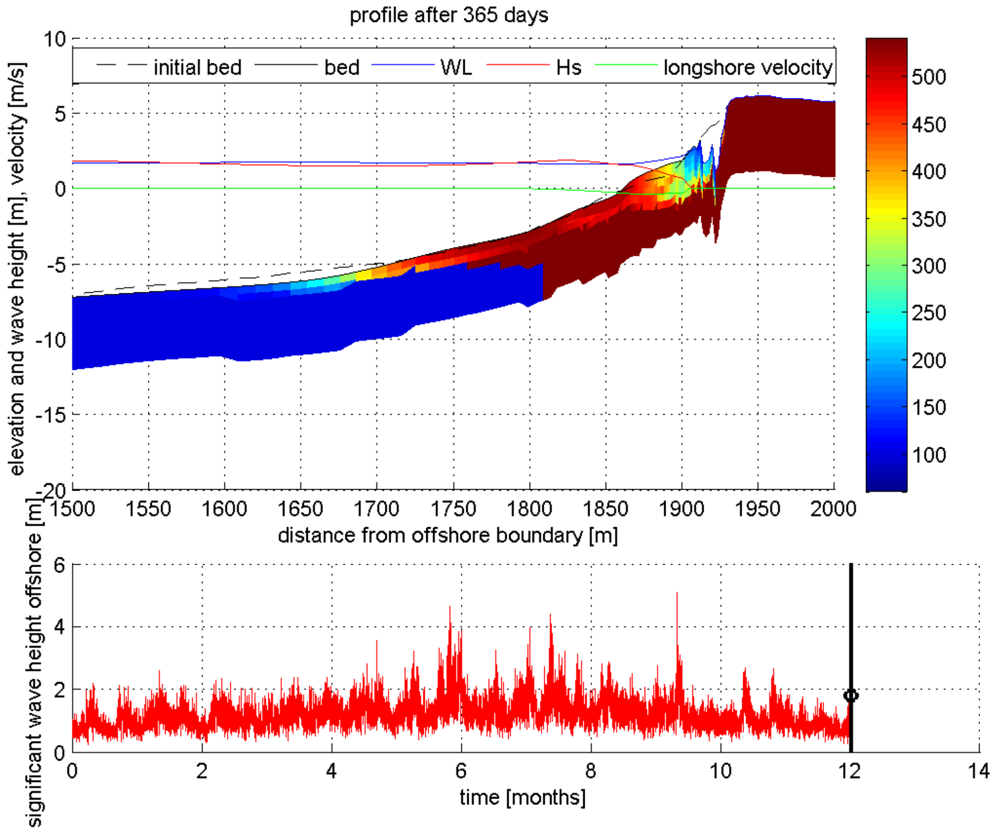


Figure 3-7 : Resulting profile development after one year of morphological changes with multiple fractions and a horizontal distribution (lt003d), with groundwater. Mean sediment size in color scale.

Figure 3-8 and Figure 3-9 respectively show the resulting profile and the average grain size after one year in run lt003e (as lt003d with uniform distribution) and in run lt003f (as lt003d with vertical distribution). A uniform distribution leads after one year to an obvious mass balance issue : the profile is eroded until about -7m LAT but the corresponding sediment is not present deeper offshore, nor is the yearly cross-shore transport capacity at the boundary sufficient to explain the loss. Given that this is a truly 1D model no longshore transport gradients should be present either. A vertical distribution yields a very similar result to that of the horizontal distribution because the deeper layers are not active until they reach the surface.

Finally some output variables related to sediment transport seem to be incomplete when using multiple fractions.

Limitations in the formulations used therefore currently limit the practical application of XBeach for long term modelling with multiple sediment fractions.

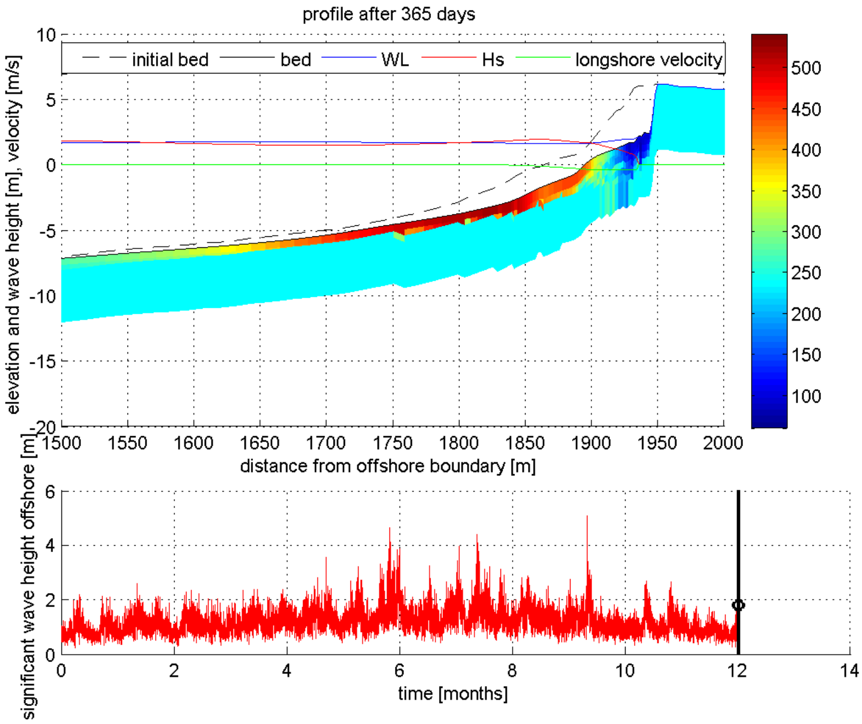


Figure 3-8 : Resulting profile development after one year of morphological changes with multiple fractions and a uniform distribution (lt003e), with groundwater. Mean sediment size in color scale.

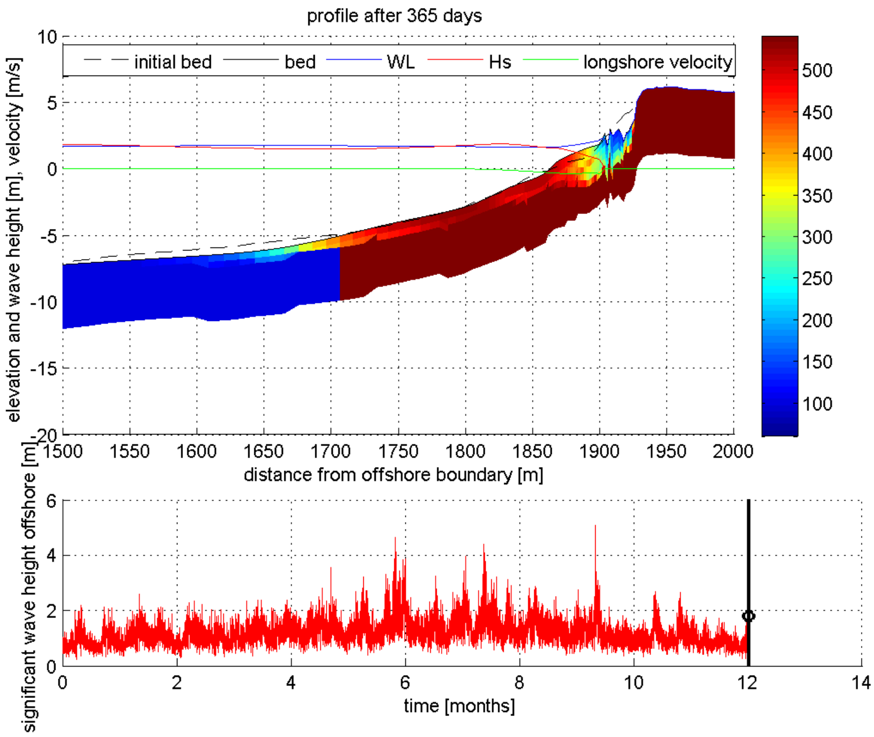


Figure 3-9 : Resulting profile development after one year of morphological changes with multiple fractions and a vertical distribution (lt003f), with groundwater. Mean sediment size in color scale.

Long term profile development and sea level rise (lt005e, lt005f, lt006c, lt009c):

The effect of sea level rise on coastal retreat is currently not modelled. It is usually estimated based on long term trends and on the Bruun rule. The Bruun rule relates the coastal retreat to sea level rise by assuming conservation of the profile shape and of mass up to the closure depth. There is however considerable debate about the applicability of this rule. As an example the background of the steep profile used in the previous paragraph is discussed.

The steep profile is thought to continuously loose sediment due to a variety of reasons, one of which being that fines present in and eroded from the coast deposit on the shelf and never come back. This small grain size combined to long swell waves imply a closure depth much larger than commonly computed from empirical formulas (30m instead of 8m), therefore large accommodation space for coastal retreat due to sea level rise (SLR).

The need for a modelling tool to assess the effect of sea level rise on coastal retreat therefore exists, but the capabilities are not there yet. Since the modelled cross-shore profile can be kept stable over a year, the exercise of the previous paragraph has been extended to a time horizon of 10 years to evaluate the capabilities and limitations of XBeach for such a task.

The objective of this exercise is to answer the following additional question:

- Can XBeach be used to estimate long term sediment losses and the relative impact of sea-level rise ?

Figure 3-10 shows that scaling up the time horizon to 10 years exacerbates the mass balance issue which was previously only visible with the uniform distribution of the sediment fractions (Figure 3-8). Further investigation shows that the mass balance is not closed in XBeach, and that small errors get compounded by the morfac, probably at each change in wave condition. A smaller morfac yields smaller mass losses and more fines on the beach (Figure 3-11)[1]. The issue is not solved with the more recent Groundhog Day 2014 release of XBeach. The inclusion of grain size dependent onshore transport factors facua, facas and facsk (lt009c) does form a workaround by giving more calibration parameters. Results are however not presented, because this change has been implemented in a more recent version of XBeach, which has different default parameters and would require a recalibration for full comparability.

The same simulation can nevertheless be run with sea level rise, and the results analysed to quantify its relative impact. Figure 3-12 shows the coastline movement in two simulations without and with sea level rise, corresponding to the profile shown in Figure 3-10. The continuous retreat is due to the mass balance issue. At first sight sea level rise does not seem to have an impact. This is confirmed by Figure 3-13, showing the relative coastline movement betwene the two simulations, hence the relative impact of sea level rise. The long term trend is hidden behind short term noise, but is stable to slightly accretive. The model does not predict erosion from sea level rise, but a profile shape change leading to a slight accretion (erosion of shelf, accretion of surf zone). This diagnostic is confirmed by additional non-reported tests eliminating possible sources of errors (such as a test without multiple fraction to remove the unrealistic mass loss of the fines). These results are not judged realistic.

[1] The height of the berm formed by the fines is surprisingly good, giving some credence to the calibration with groundwater.

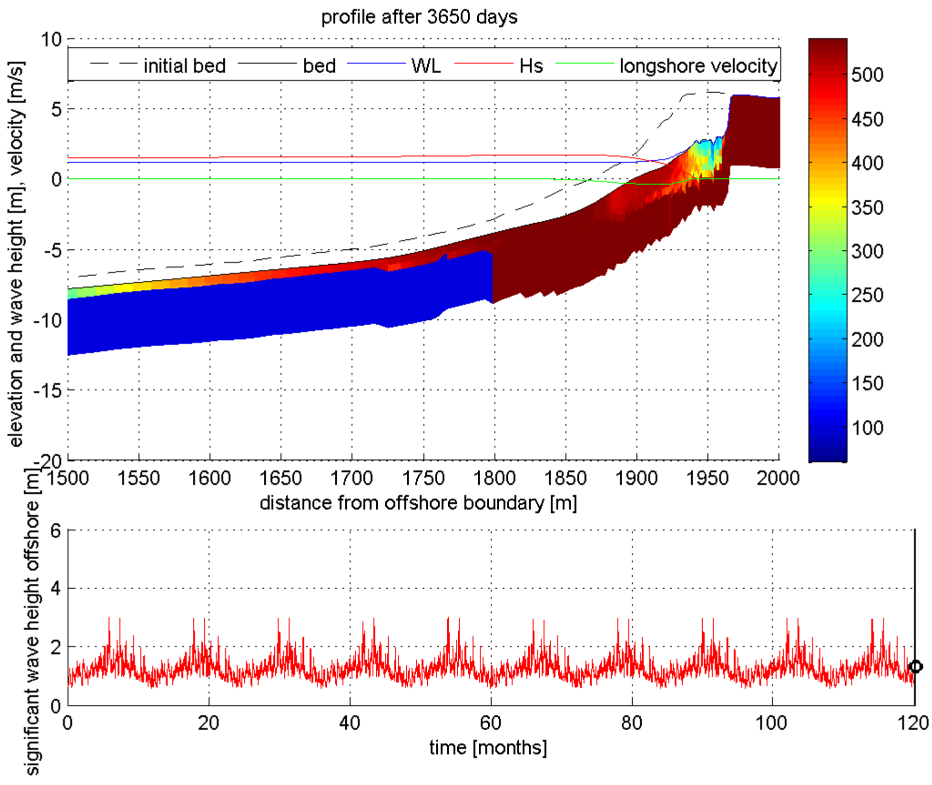


Figure 3-10 : Steep profile with groundwater and multiple sediment fractions horizontally distributed, as in Figure 3-7 but after 10 years (lt005e). Mean sediment size in color scale.

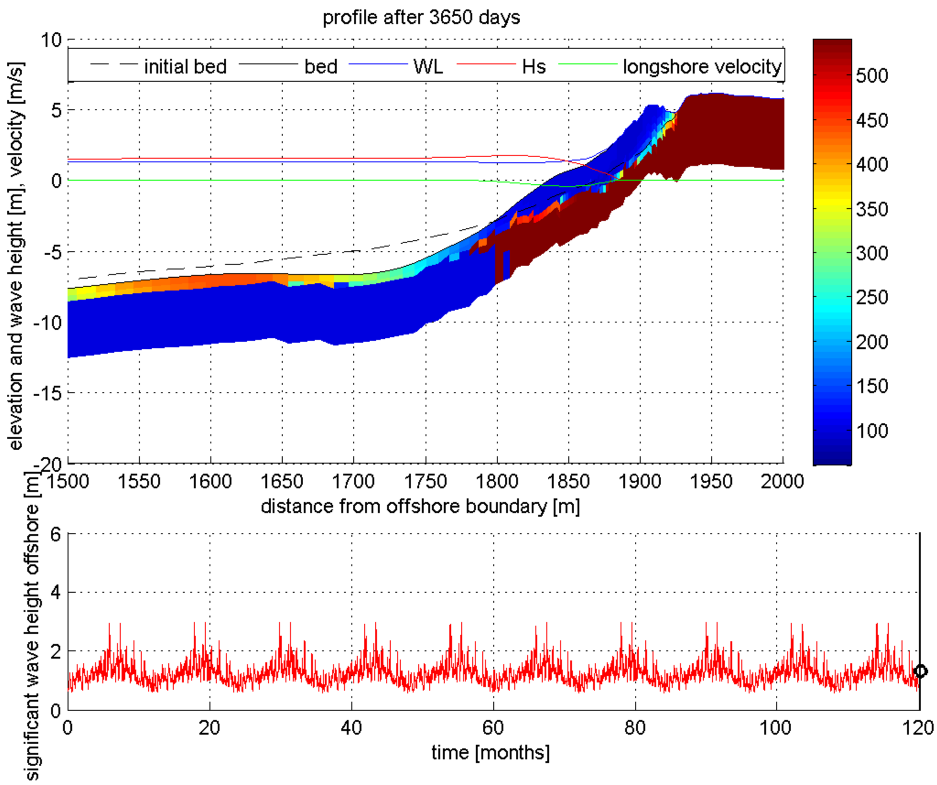


Figure 3-11 : Steep profile as in Figure 3-10 but with morfac 10 instead of 30 (lt006c). Mean sediment size in color scale.

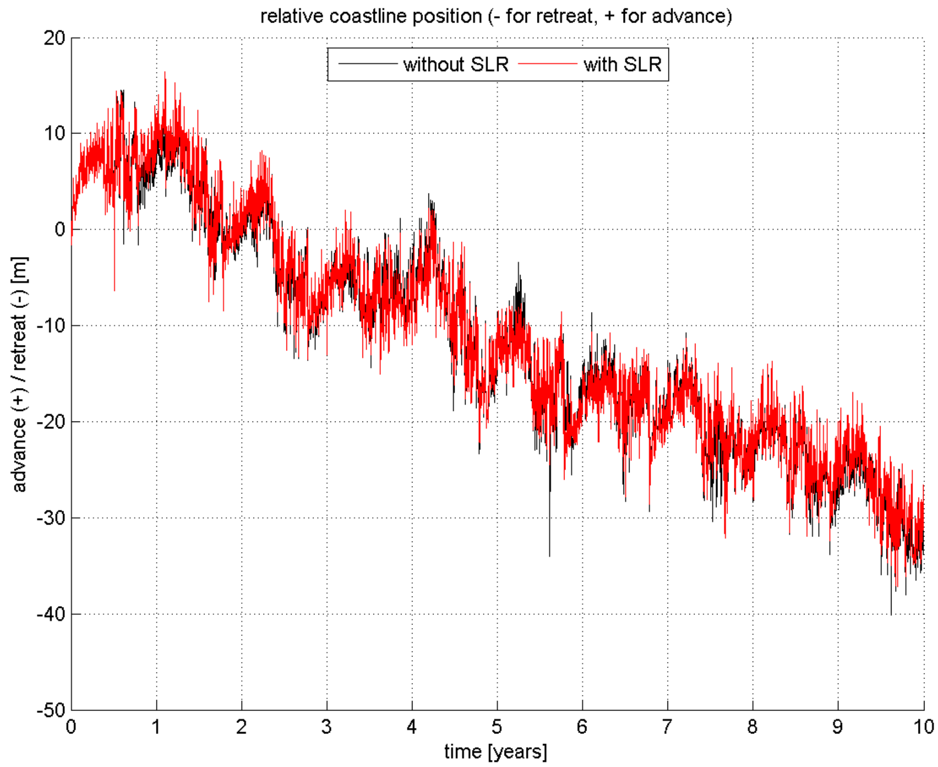


Figure 3-12 : Coastline movement in simulations without and with sea level rise of 1 cm/year (lt005e without SLR, lt005f with SLR)

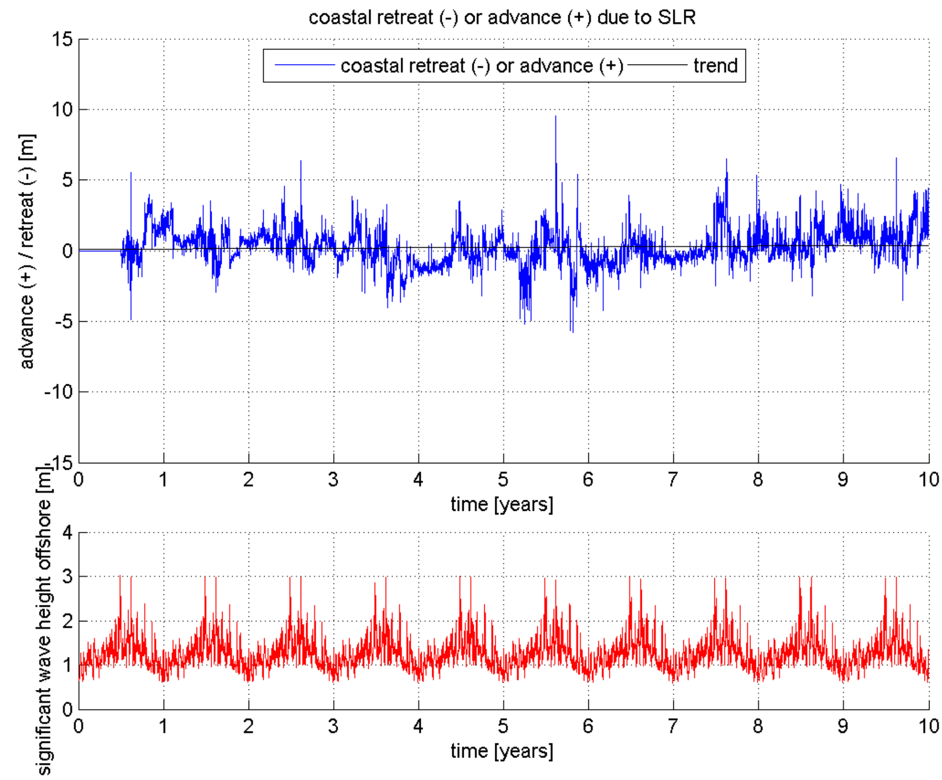


Figure 3-13 : Relative coastline movement with sea level of 1 cm/year compared to a reference simulation without sea level rise (lt005f – lt005e), showing a stable to accretive trend hidden behind short-term noise. The wave time series is identical in the two simulations.

3.4 Results of Belgian profile

Overview of simulations

Simulations are done for 4 different profiles (Figure 3-14):

- A real cross-shore profile of Mariakerke
- A real cross-shore profile of Bredene
- A real cross-shore profile of Knokke-Heist
- Straight profile: a profile with constant slope of 1:50 between +8m TAW and -10m TAW

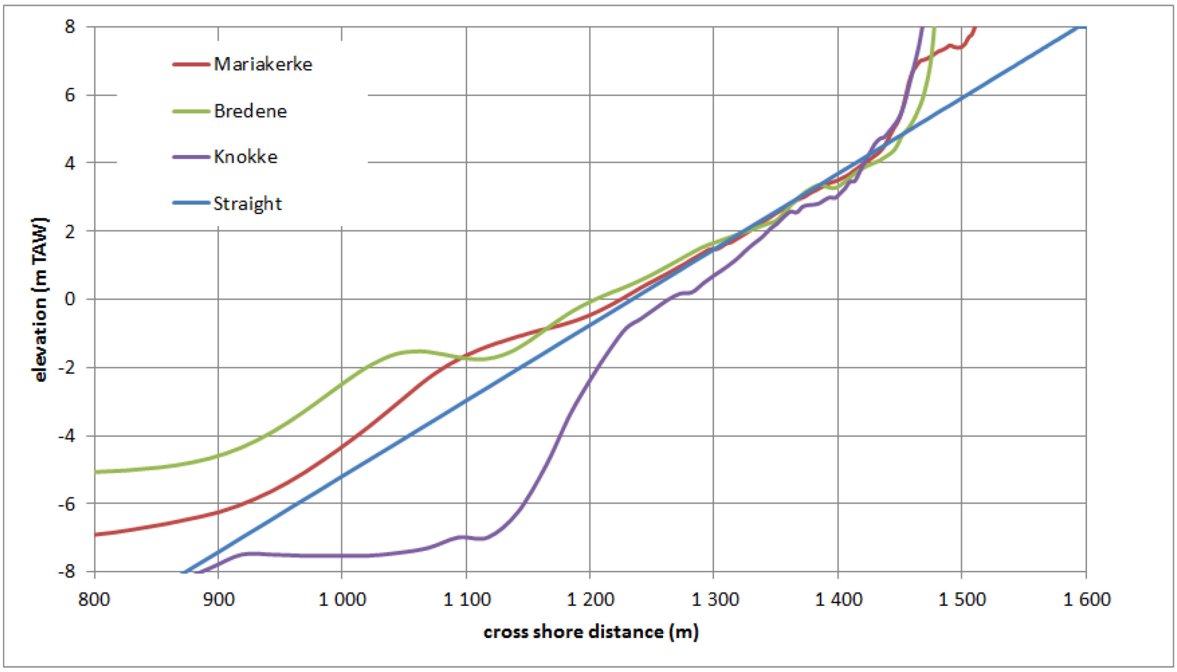


Figure 3-14 Cross-shore profiles used for the cross-shore modelling

The profile of Mariakerke is the cross-shore profile as measured in 2009 in section 105. The profile contains a steep berm with a toe at +4m TAW. The grain size (d50) is 0.2mm. Because of the steep berm and the yearly maintenance no real profile evolution can be compared. For this reason a comparable profile (with the same grain size) is selected at Bredene (2009, profile 130) where no yearly significant nourishments are done.

Another profile is selected in Knokke-Heist (section 240) for which human interference is limited (no regular nourishments). The grain size is coarse (0.3mm).

Also a profile with a constant slope of 1:50 between +8m TAW and -10m TAW is modelled for different grain sizes, in order to see the evolution towards a new equilibrium, independent of the occurrence of initial banks or berms.

The wave conditions are obtained from measurements in 2009 by the wave buoy in front of Ostend (OST) and the water levels as measured at the same time in the harbour of Ostend. For the modelling of the Knokke-profile the wave height is increased with 20% (based on the comparison of the wave climate for both locations) and the wave directions (based on the difference in modelled wave climate) are shifted with 15 degrees in order to take the changed direction of the coastline into account.

Simulations are done with the Easter 2012 version of XBeach. The superfast option (ny=0) is used. As a consequence, no tidal currents are incorporated.

Table 3-2 gives a list of relevant simulations, including the settings of the parameters that are varied during the execution of the project.

Table 3-2 List of simulations

run nr	*profile*	*WTI/default*	*morfac*	*Cmax(-)*	*d50 (mm)*	*remark*
kt001	Mariakerke	default	30	0.1	0.2	
kt002	Mariakerke	default	3	0.1	0.2	
kt003	Mariakerke	default	10	0.1	0.2	
kt004	Mariakerke	default	10	0.1	0.2	kt003 with coarser grid
kt010	Bredene	WTI	10	0.1	0.2	
kt011	Bredene	default	10	0.1	0.2	
kt012	Bredene	WTI	3	0.1	0.2	
kt012b	Bredene	WTI	1	0.1	0.2	
kt013	Bredene	default	1	0.1	0.2	
kt014	Knokke	WTI	5	0.1	0.3	
kt015	Knokke	WTI	5	0.1	0.2	
kt016	Knokke	default	5	0.1	0.2	
kt017	Knokke	WTI	5	0.1	0.1	
kt021	Knokke	WTI	5	0.1	0.3	
kt022	Knokke	WTI	5	0.1	0.3	with tide
kt023	Knokke	WTI	5	0.1	0.3	3 year extra after kt014
kt024	Knokke	WTI	5	0.1	0.2	3 year extra after kt015
kt025	Bredene	WTI	3	0.1	0.2	+ shoreface nourishment
kt026a	straight	WTI	3	0.1	0.15	
kt026b	straight	WTI	3	10	0.15	
kt026c	straight	WTI	1	10	0.15	
kt027a	straight	WTI	3	0.1	0.3	
kt027b	straight	WTI	3	10	0.3	
kt027c	straight	WTI	1	10	0.3	
kt028	straight	default	3	10	0.15	
kt029	straight	default	3	10	0.3	
kt030	straight	default	3	10	0.3	with facSk and facAs as in WTI
kt031	straight	default	3	10	0.3	with facSk and facAs and cf as in WTI
kt032	straight	default	3	10	0.3	WTI settings except for wetslp
kt033	straight	WTI	3	10	0.15	facSk and facAs = 0
kt034	straight	WTI	3	10	0.3	facSk and facAs = 0

Small differences with the Groundhog Day version can be observed where dune (berm) erosion occurs (cf. Figure 3-15 for the Knokke-profile). The figure shows the result above HW-level (around 4.5m TAW), where the differences are the largest. However, the Groundhog Day version was not able to simulate a full yearly wave and water level climate (limited number of different wave conditions possible).

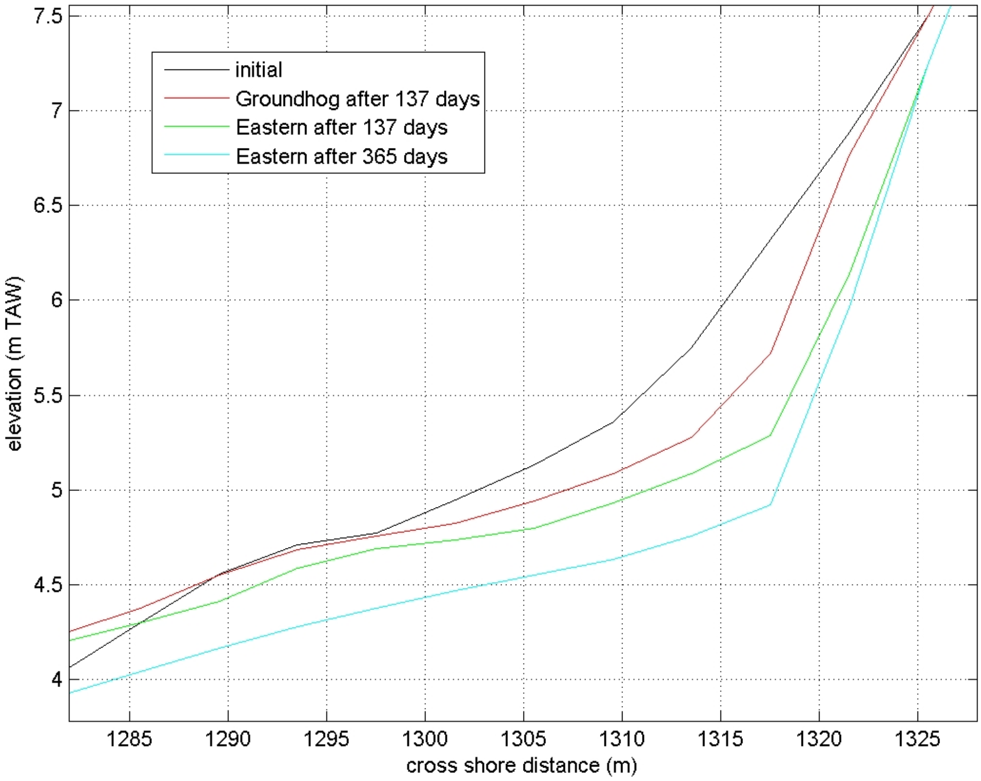


Figure 3-15 Comparison between Groundhog and Eastern Xbeach version at the dune foot for the Knokke-profile.

Sensitivity study

Influence of morfac

Since a complete time series is used, and thus with each time a different water level, the only way morfac can be used is morfacopt=1 to limit computation time: calculations are done for a reduced period (factor morfac) and the morphological result is multiplied with morfac.

This method has consequences for the hydrodynamics. If e.g. the water level increases by 0.5m over 1 hour and morfac 10 is used, this increase of water level occurs in the model in 6 minutes. Thus, the discharge of water at the offshore boundary is 10 times higher. This increase in cross-shore velocities causes also considerable cross-shore sediment transport over the profile. This is visible in Figure 3-16 (simulations kt001, kt002 and kt003), where for morfac 10 a lot of net influx of sediment is visible. This issue is less visible in the theoretical test case because no tide is applied. Nonetheless the sediment influx related to long waves can also be flawed.

For morfac 3 the extra cross-shore velocity due to the morphological acceleration is very small. For the intended duration of the simulations, using morfac 1 was not an option.

The effect of morfac 1 is also illustrated for the Bredene-profile (kt010 – kt012 and kt012b, Figure 3-17). It should be noted that for this profile, morfac 10 even causes a change in direction of cross-shore transport (offshore directed for morfac10, onshore for morfac 1 and 3). For this reason, morfac 3 was selected as optimal choice, only for Knokke morfac 5 is used (for timing reasons).

Also for the straight profile, simulations with morfac 3 and morfac 1 are compared (both for the 0.15 and 0.3mm sediments) (kt026 b and c and kt027 b and c), Figure 3-18 and Figure 3-19. Morfac 3 seems a good compromise between calculation time and accuracy.

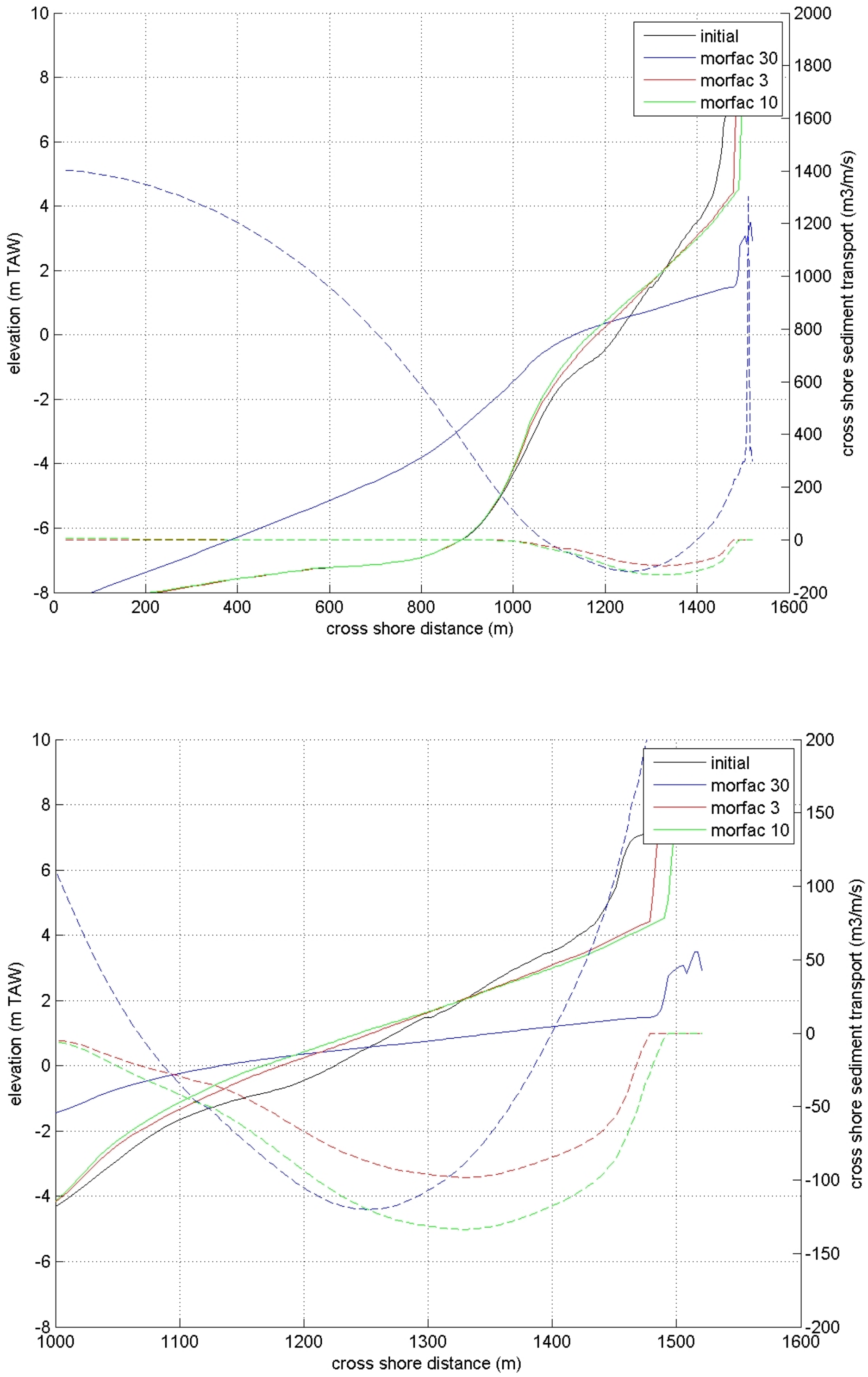


Figure 3-16 Influence of morfac on the evalution of the cross-shore profile of Mariakerke after 1 year (global (top) and zoom (bottom)). The dashed lines represent cross-shore sediment transport (negative is offshore-directed).

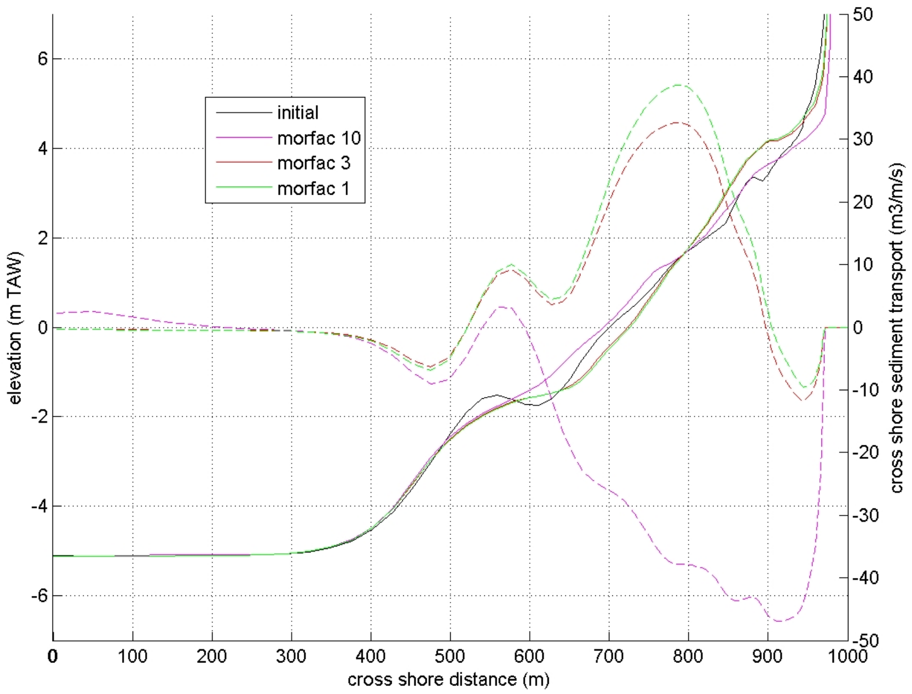


Figure 3-17 Influence of morfac on the evolution of the cross-shore profile of Bredene after 1 year. The dashed lines represent cross-shore sediment transport (negative is offshore-directed).

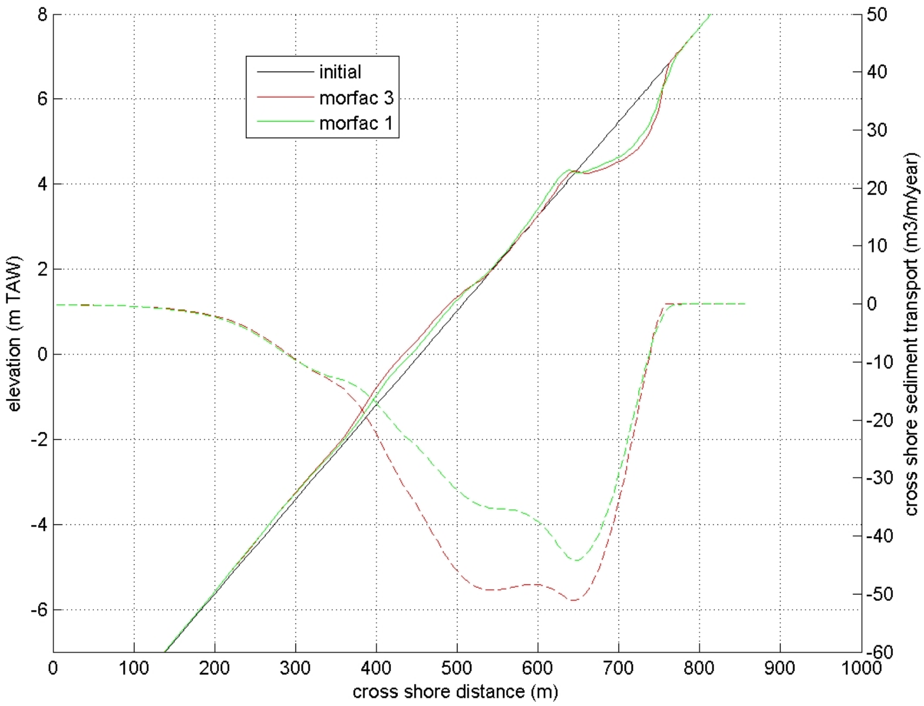


Figure 3-18 Influence of morfac on the evolution of the straight cross-shore profile - d50=0.15mm after 1 year. The dashed lines represent cross-shore sediment transport (negative is offshore-directed).

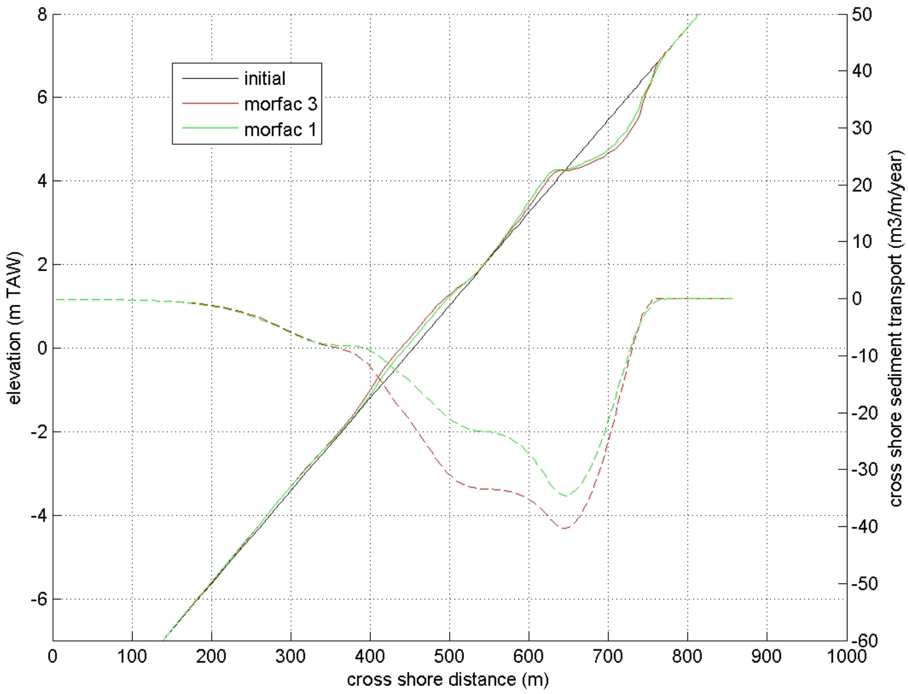


Figure 3-19 Influence of morfac on the evolution of the straight cross-shore profile -d50=0.3mm after 1 year. The dashed lines represent cross-shore sediment transport (negative is offshore-directed).

Grid resolution

A trial was made to reduce the number of cells. Instead of a grid resolution of 3m (normally used value) in the surf zone (kt003), a grid resolution of 6m (kt004) was used (with morfac 10, since only the effect of the grid resolution is examined). The effect is visible in Figure 3-20 and is judged important.

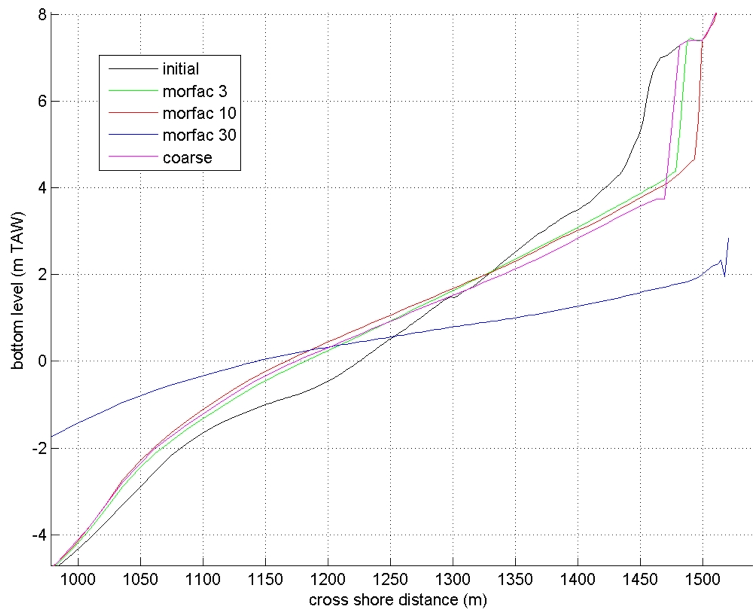


Figure 3-20 Effect of grid resolution (Mariakerke profile)

Influence of the WTI vs default settings

A number of semi-empirical parameters are used within XBeach to describe various processes. Two sets of calibration values were used within this study (Table 3-3). The first set of calibration values, the Groundhog Day (GHD) calibration set, contains the default values used in the Groundhog Day release of XBeach. Most of these calibration values were also the default values in earlier versions of XBeach.

The second set of calibration values is the WTI (Wettelijk Toetsinstrumentarium) calibration set, which was provided by Deltares, determined using an extensive calibration of XBeach based on a large database of laboratory and field measurements (van Geer *et al.*, 2015).

For the parameters other than those listed in Table 3-3, the default values were used. These are the same in the GHD and WTI calibration sets. It should be noted that the parameters are obtained using a statistical analysis of modelled and measured (in large wave flumes and nature) erosion during storm conditions. The combination of parameters is not necessarily physically supported.

Table 3-3: Calibration values for the Groundhog Day (GHD) calibration set and the “Wettelijk Toetsinstrumentarium” (WTI) calibration set

Parameter name used in XBeach	Description	GHD	WTI
fw	Bed friction factor (for waves)	0.000	0.000
cf	Bed friction factor (for flow)	0.003	0.001
gammax	Parameter for depth-induced breaking: maximum ratio Hrms/hh	2.000	2.364
beta	Breaker slope coefficient in roller model	0.100	0.138
wetslp	Critical avalanching slope under water	0.300	0.260
alpha	Wave dissipation coefficient	1.000	1.262
facSk	Calibration factor for wave skewness effect on sediment transport	0.100	0.375
facAs	Calibration factor for wave asymmetry effect on sediment transport	0.100	0.123
gamma	Breaker parameter in Baldock or Roelvink formulation	0.550	0.541

Figure 3-21 compares the WTI settings (kt010) vs. the default settings (kt011) for the Bredene profile. The default settings give about 3 times more offshore directed transport. Since the Bredene-profile is more or less in equilibrium, the use of the WTI settings seems more realistic. It should be noted that this conclusion is based on limited validation work (the WTI settings are originally derived for dune erosion under extreme storms, not for beach erosion under normal conditions). Therefore, for specific projects, a more detailed calibration is advised.

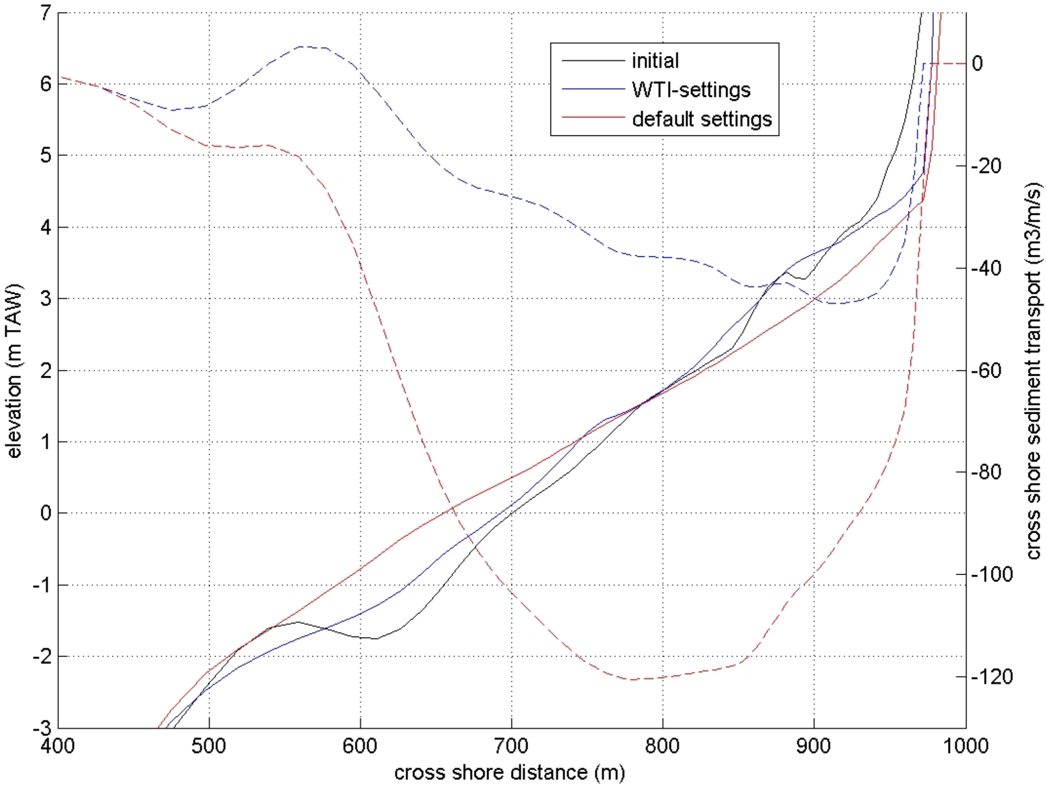


Figure 3-21 Comparison of profile development and crosshore transport using the WTI and default settings with morfac 10 on the Bredene profile. The dashed lines represent cross-shore sediment transport (negative is offshore-directed).cross-shore

In this case however, the difference between morfac 3 (kt012) and morfac 10 (kt010) is much larger (cf. Figure 3-17). Using the morfac 3 simulations (kt012 and kt013) shows that (Figure 3-22), for the Bredene profile, the WTI settings cause a net onshore directed sediment transport, while the default settings cause net offshore directed transport. The reason that the Bredene profile shows onshore transport, while all other profiles only show offshore transport might be explained by the averaged slope of the profile (1/60 between -2 and +4m TAW), while the other profiles are 1/50 or steeper. Also with morfac 3, the WTI results are much more reliable (regeneration of a stable profile) than the default settings.

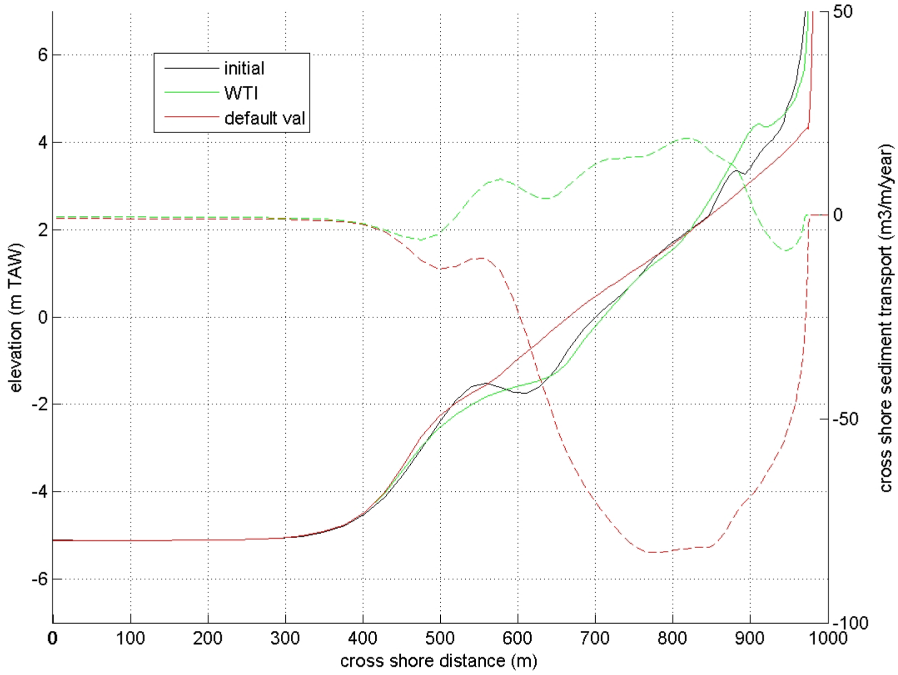


Figure 3-22 Comparison of profile development and crosshore transport using the WTI and default settings with morfac 3 on the Bredene profilecross-shore. The dashed lines represent cross-shore sediment transport (negative is offshore-directed).

In Figure 3-23 results are compared for the Knokke profile (kt014 vs kt016). Although the Knokke profile is in reality eroding (also due to longshore transport), the shape of the cross-shore profile is rather stable. This stability is best regenerated using the WTI-settings. The real erosion of the intermediate beach is partly due to longshore transport and partly (cf. net offshore transport at the wet beach in Figure 3-23) due to cross-shore transport.

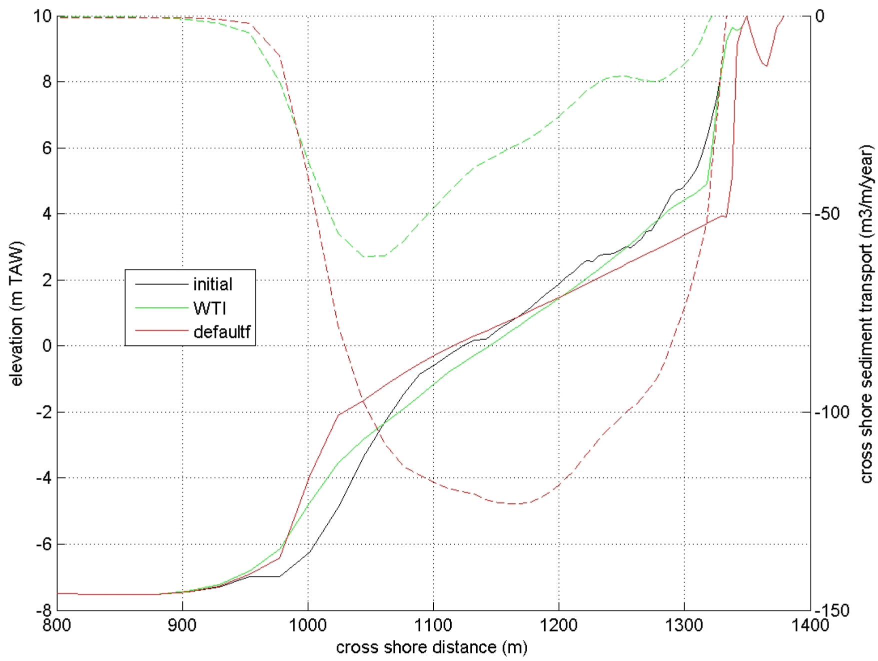


Figure 3-23 Comparison of profile development and crosshore transport using the WTI and default settings with morfac 3 on the Knokke-profilecross-shore. The dashed lines represent cross-shore sediment transport (negative is offshore-directed).

In Figure 3-24 the use of WTI-settings is evaluated for the straight profile for the 0.3mm sand (kt027 - kt029- kt030-kt031 and kt032). For all simulations cmax=10 is used. The following tests have been done:

- a) is a simulation with the WTI parameters of Xbeach
- b) is a simulation with the default parameters of XBeach,
- in c) the default parameters are used, except for the parameters that cause onshore transport (facSK and facAs, for which the WTI settings are used,
- in d) also the roughness coefficient is changed to the WTI setting (a decrease of roughness)
- and in e) also the wave parameters are changed to the WTI settings (e.g. limiting wave height in the shallow zone).

The difference between run a) and run e) is the wetslp-parameter (0.3 instead of 0.26 for the WTI-settings), which is only relevant for dune erosion. As can be seen, all parameters, except the wetslp, have an important influence on the cross-shore sediment transport. Figure 3-25 shows the result for the fine sand (0.15 mm) (kt026 vs kt028).

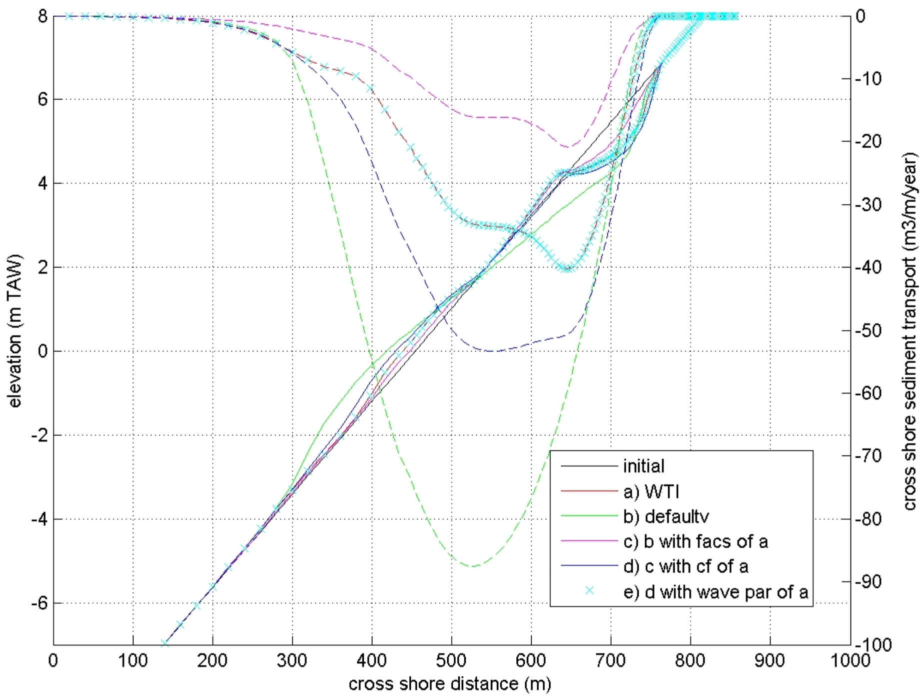


Figure 3-24 Comparison of profile development and crosshore transport using the WTI and default settings with morfac 3 on the straight-profile with d50=0.3mm (cross-shore transport is positive if onshore directed) (the red line of the cross-shore transport corresponds completely with the blue crosses of simulation e)

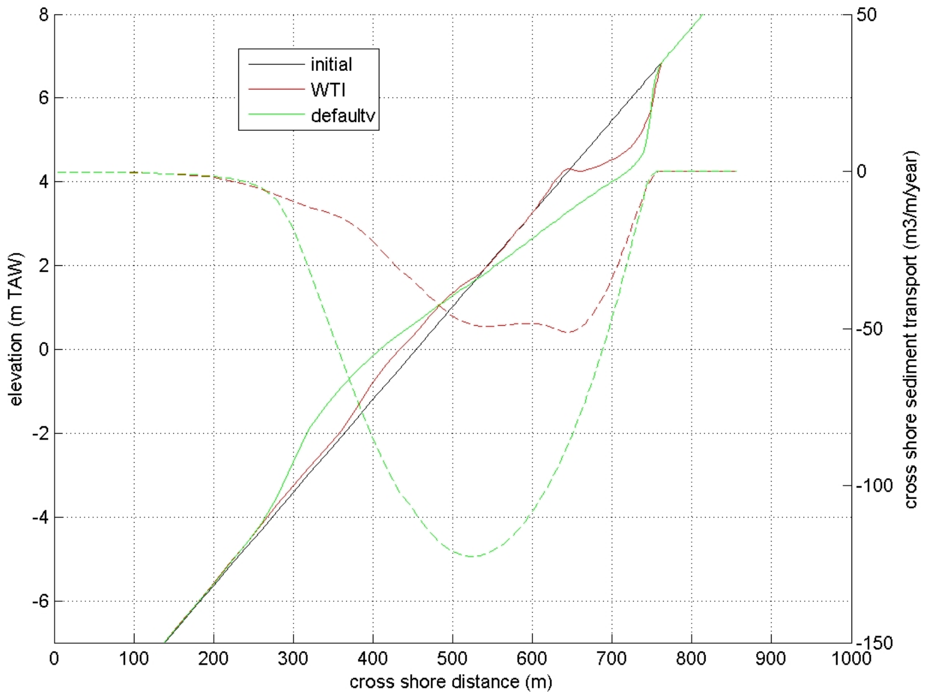


Figure 3-25 Comparison of profile development and cross-shore transport using the WTI and default settings with morfac 3 on the straight-profile with d50=0.15mm (cross-shore transport is positive if onshore directed)

Influence of cmax

The difference in maximum transport between the fine and coarse sediments depends on the use of cmax. Cmax limits the bed concentration for sheet flow conditions to a maximum value. If this value is exceeded for two different d50-values, the difference in sediment transport reduces. For the default cmax (=0.1), the maximum yearly cross-shore transport is resp. -33.4 m3/m/year and -37.6 m3/m/year for 0.3mm and 0.15mm sand. Finer sand gives 12% more transport. For a value of cmax=10.0 the transport is resp. 36.7 and 46 m3/m/year, and increase of 25% for finer sand.

For this reason, (only) for the straight profile simulations, calculations are done with cmax=10.0, in order to see more influence on the grain size.

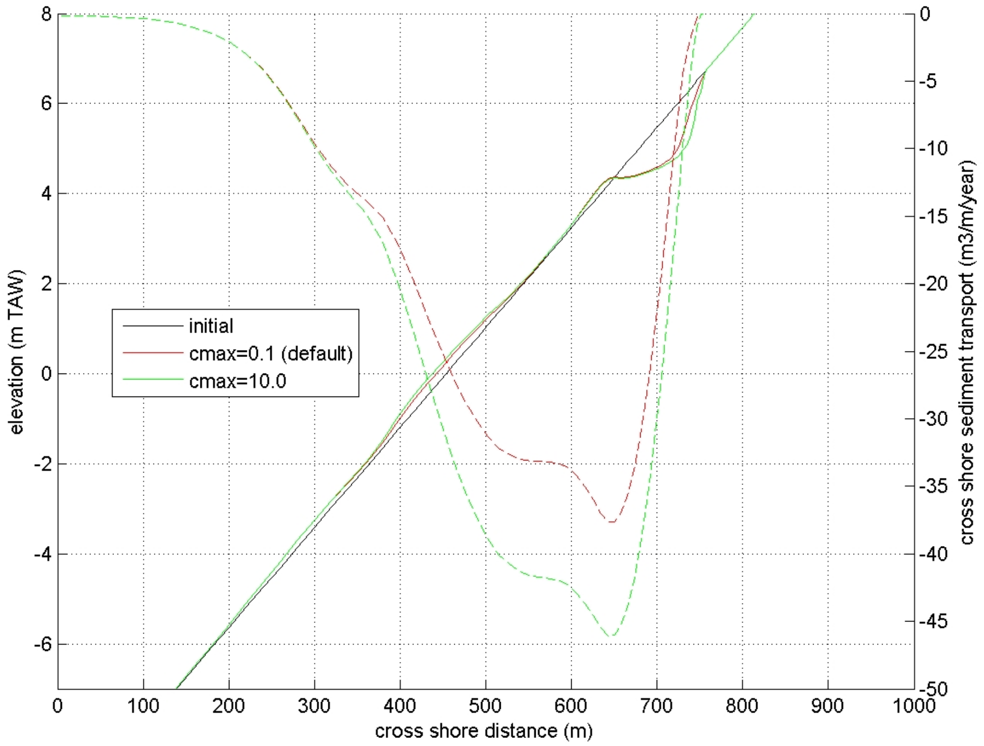


Figure 3-26 Influence of cmax (straight profile, d50=0.15mm)

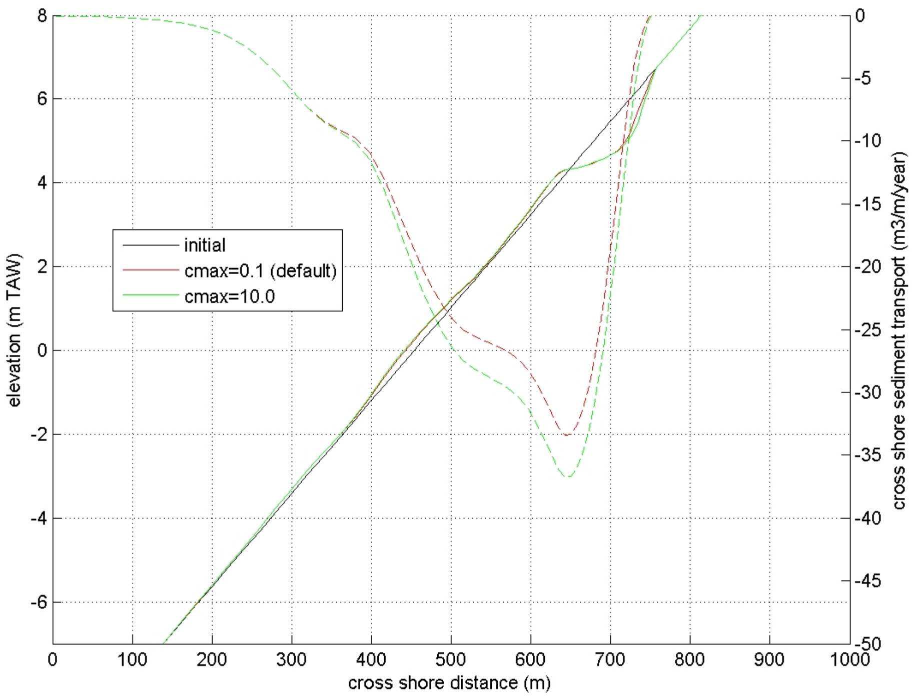


Figure 3-27 Influence of cmax (straight profile, d50=0.3mm)

Influence of grain size

The influence of the grain size is rather small. Figure 3-28 compares the results for the Knokke profile after 1 year for resp. 0.3 (kt014), 0.2 (kt015) and 0.1 (kt017) mm. The difference between 0.3mm and 0.1mm is less than a factor 2.

After 3 years (Figure 3-29, kt023 compared to kt024), the slope of the Knokke profile between LW (0.5m TAW) and HW (4.5m TAW) evolved from 1/34 to 1/36 in 3 years, with the same evolution for 0.2mm and 0.3mm sand. The only difference is that the 0.2mm sand is eroded with 3m extra compared to the 0.3mm sand. This is in contradiction with the observation that the slope of beaches strongly depends on the grain size. If the profile is observed between -2m TAW and +5m TAW some more flattening of the profile for the fine sediment is visible. Probably, over a long time span, the difference will grow. However, due to the small cross-shore transport rates (less than 50 m^3/m/year), it takes a lot of time to change the slope of a profile from 1/35 to e.g. 1/50 (between -4m TAW and +5m TAW a volume of 600m3 is involved).

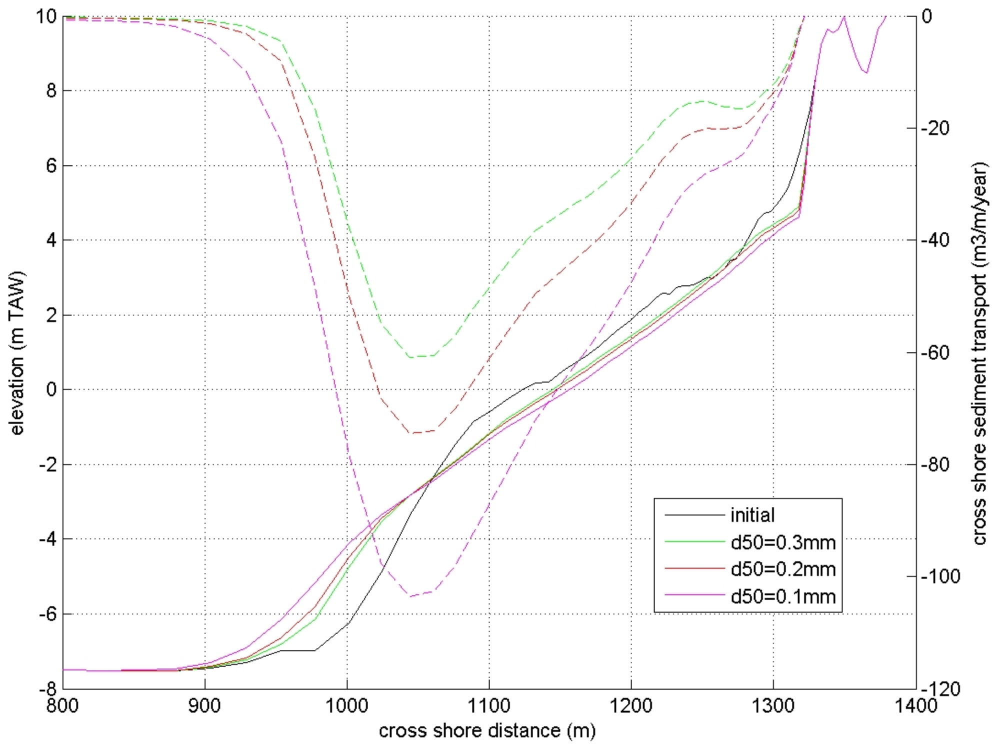


Figure 3-28 Influence of grain size on the development of the Knokke profile in the first year

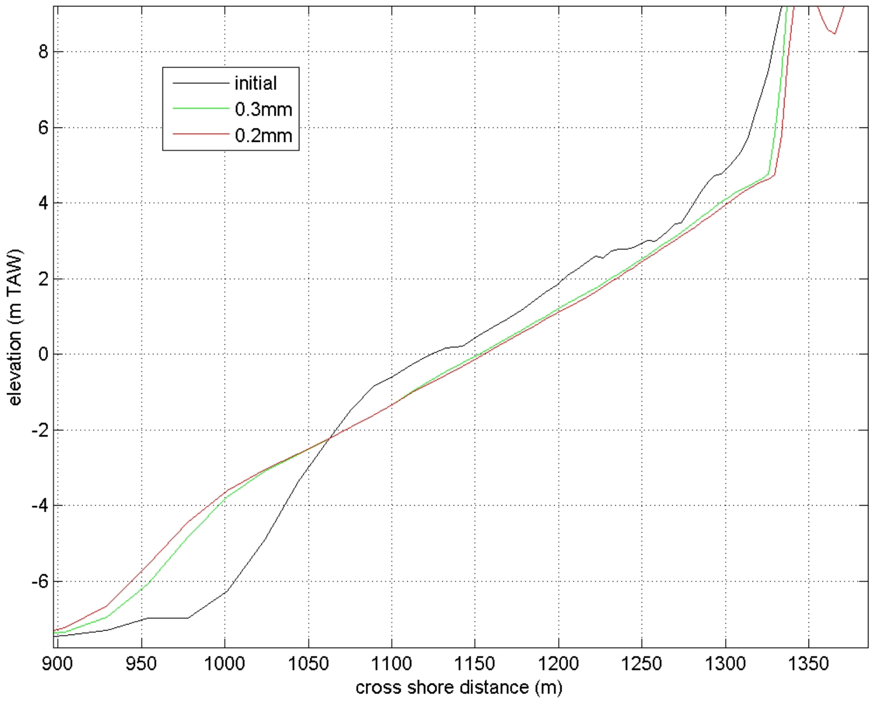


Figure 3-29 Influence of grain size on the development of the Knokke profile after 3 year

The reason for this small difference is explored with calculations for the straight profile (it should be noted that a value of cmax of 0.1 is used (default value)). For the straight profile, an increased value for cmax (=10.0) is used. Otherwise, the differences between fine and coarse sediments would have been smaller (see before). Figure 3-30 shows the influence for the WTI settings. (kt026 vs kt027). The maximum offshore transport differs a factor 1.25. For the default settings (kt028 vs kt029) (Figure 3-31) the difference is a factor 1.35, so slightly more sensitive. If onshore transport is switched off (fasSk and facAs = 0), the difference becomes a factor 1.5 (kt033 vs kt034), Figure 3-32.

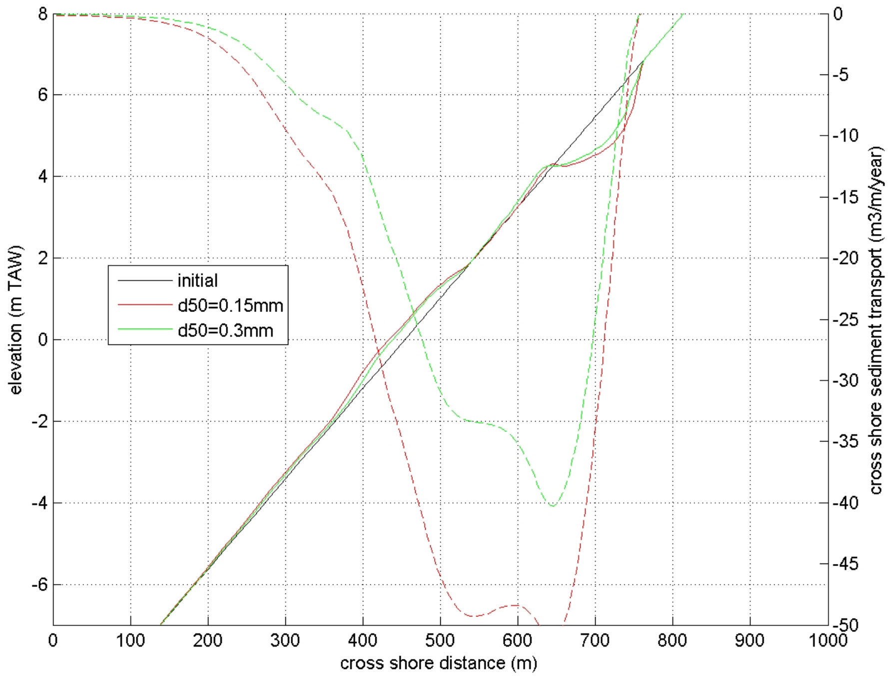


Figure 3-30 Influence of d50 on the development of the straight profile after 1 year – WTI settings

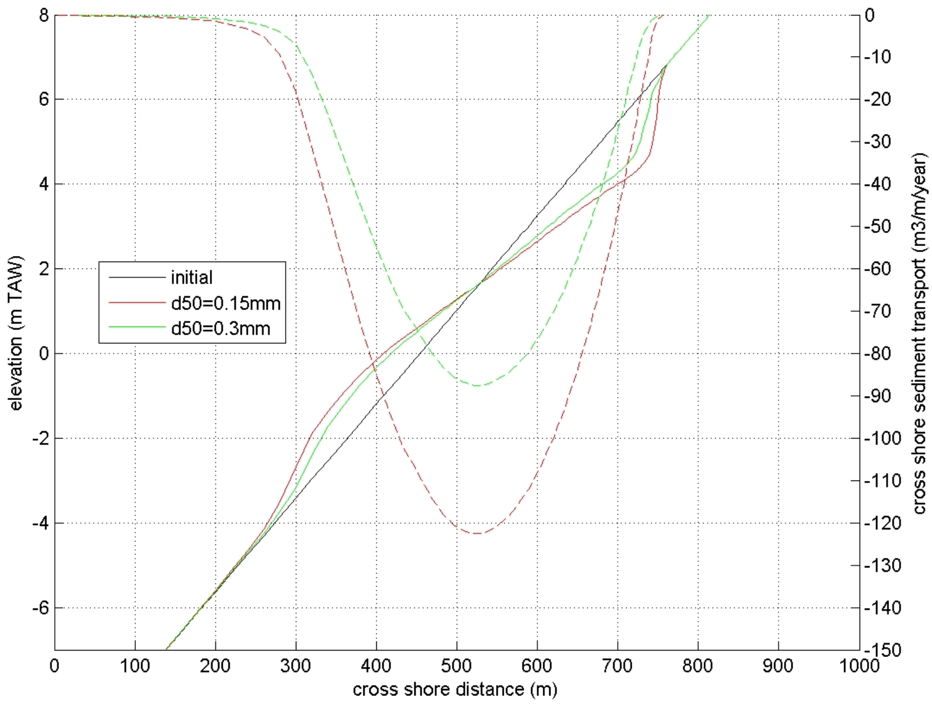


Figure 3-31 Influence of d50 on the development of the straight profile after 1 year – default settings

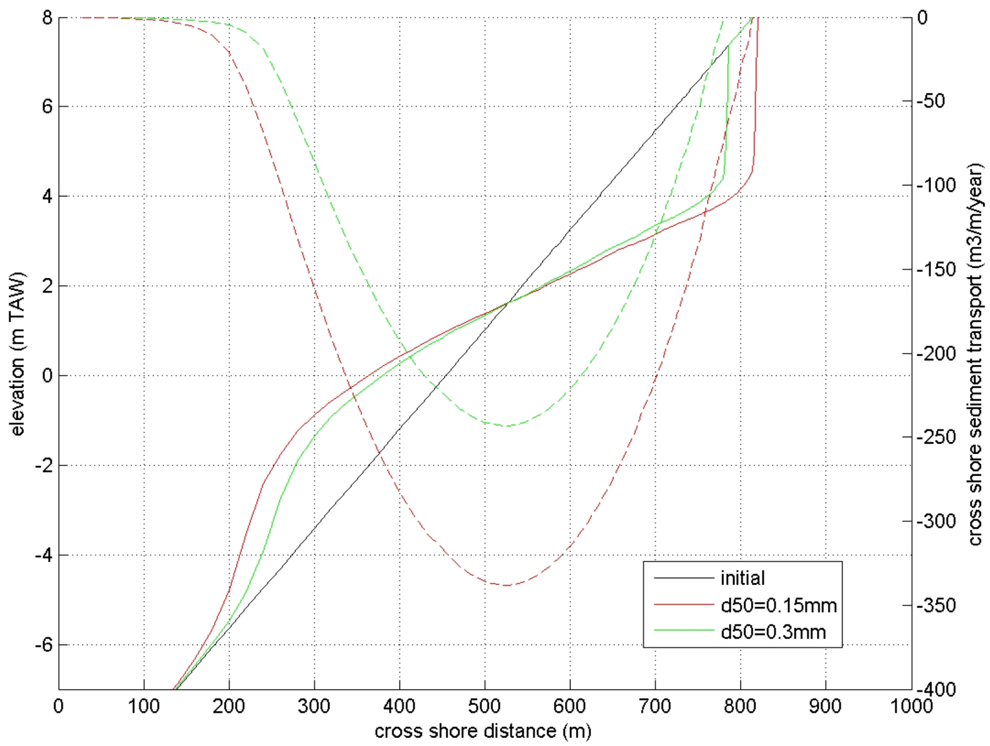


Figure 3-32 Influence of grain size on the development of the straight profile after 1 year – onshore transport switched off (facSk and facAs = 0)

Figure 3-33 and Figure 3-34 show that the effect of the grain size does not depend on the wave height.

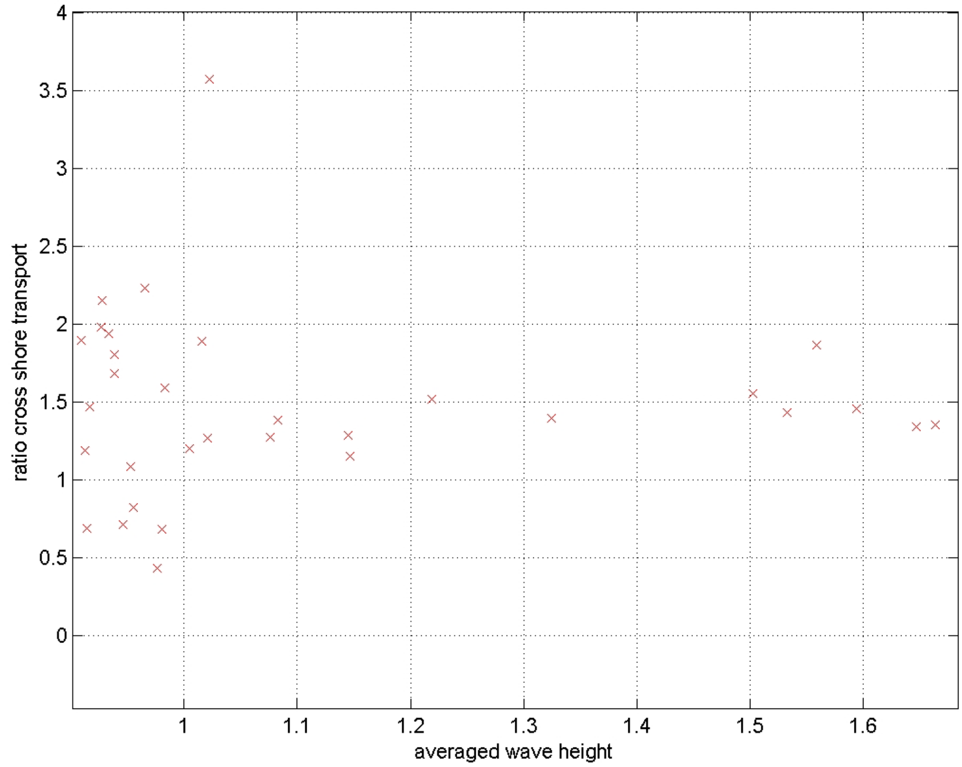


Figure 3-33 Ratio of the cross-shore transport for d50=0.15mm and d50=0.3mm at z=3m TAW

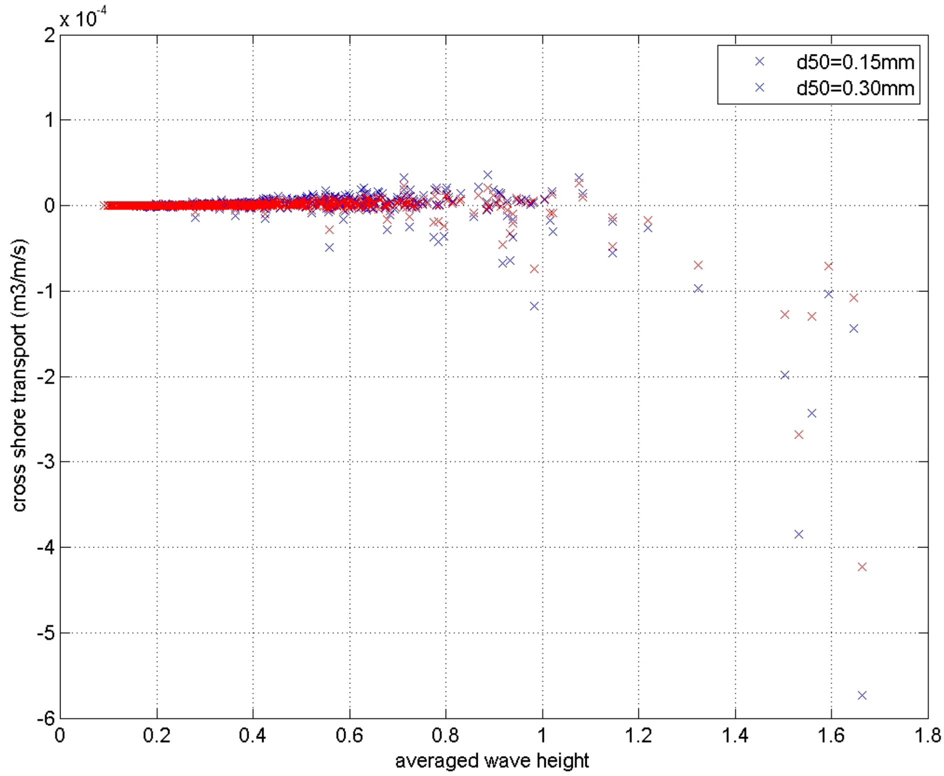


Figure 3-34 Dependency of the cross-shore transport on the wave height (averaged value over 1 tidal cycle) and the grain size

It can be concluded that the sensitivity for the grain size of the cross-shore transport is rather small (using Soulsby-Van Rijn for a typical situations, the ratio of the bed transport is 1.4, for the suspended transport 2.4 and for the total transport 2.2). It should be further explored why this difference is small and why the difference decreases slightly if the WTI settings are used. For the profile development, probably also facSk and facAs should depend on the grain size. Indeed, as shown in the theoretical test case, using similar values of facSk and facAs for both grain sizes overestimates onshore transport for fine sediment (the WTI settings are mainly based on cases with an (equivalent) grain size of 0.2mm).This also needs further investigation.

Influence of tide

Simulations are done with a simple 2D model for the Knokke profile (with uniform profiles, using 6 grid cells alongshore). Boundary conditions are generated in order to get typical longshore tidal velocities (up to 0.5m/s). Figure 3-35 compares the results with and without tide (Kt021 vs kt022). The tide increases the cross-shore transport (higher velocities cause more stirring up of sediments), but the shape of the cross-shore transport distribution over the cross-shore profile does not change. For real applications, where the time effect is important, tidal currents should be taken into account ! For specific projects, where real erosion/sedimentation rates have to be known, 2D modelling is also necessary to include longshore transport (gradients).

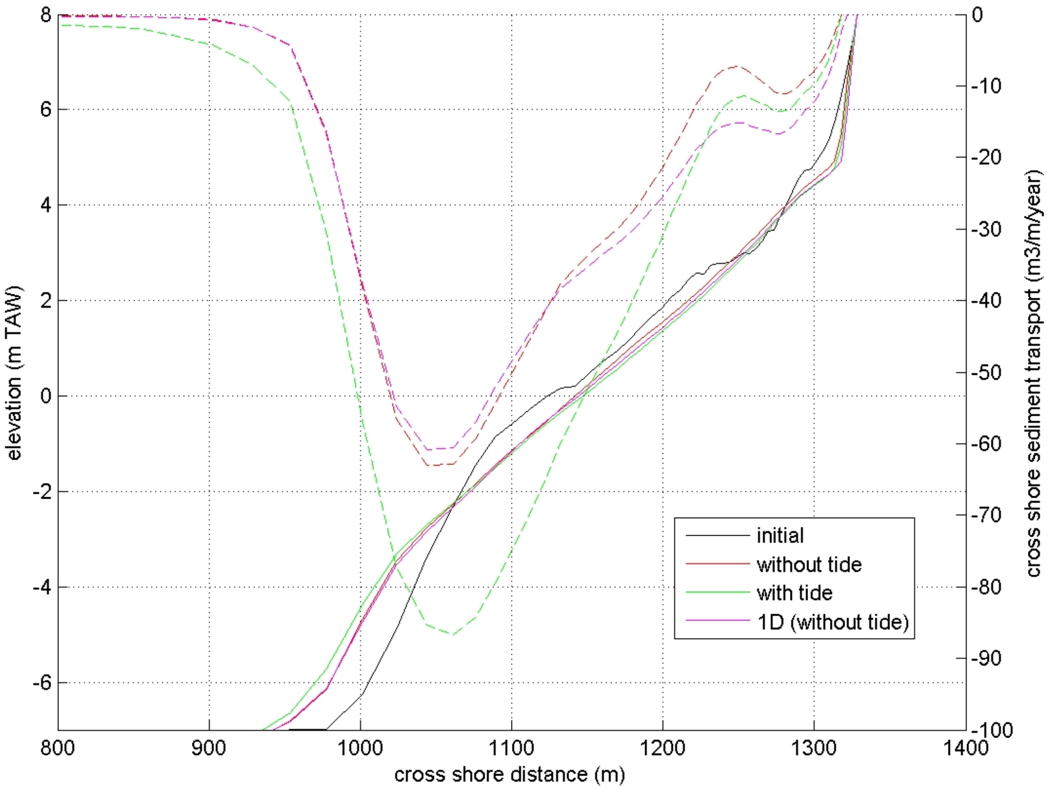


Figure 3-35: Influence of the tide for the Knokke profile

Applications

Longer term time evolution

Figure 3-36 and Figure 3-37 show the long term profile evolution of the Knokke profile for resp. 0.3mm and 0.2 mm (kt023 and kt024) using the WTI settings. It can be observed that the spin-up time is about 1 year, afterwards the profile shape does not change significantly, more gradual erosion is visible.. The stability of the profile shape shows the capacity of XBeach to generate stable profiles as observed.

It is remarkable that the long term erosion process observed qualitatively matches observations. Sand from the upper beach and dune is eroded and deposed in the Appelzak gully (see the progressive extension of the profile slope). In reality the gully is kept open by the strong tidal currents : this process is not modelled in the 1D simulation. Also the erosion caused by the local gradient in longshore transport East of Zeebrugge is not modelled. It is hence possible that the cross-shore erosion is quantitatively overestimated.

In view of these results, a theoretical way to stabilise the erosion in Knokke could be to extend the profile slope down into the Appelzak, and to displace the Appelzak gully, and therefore the tidal currents, by dredging on the limit of the Paardenmarkt. This scenario can be tested in a 2D model (Lanckriet et al., 2015).

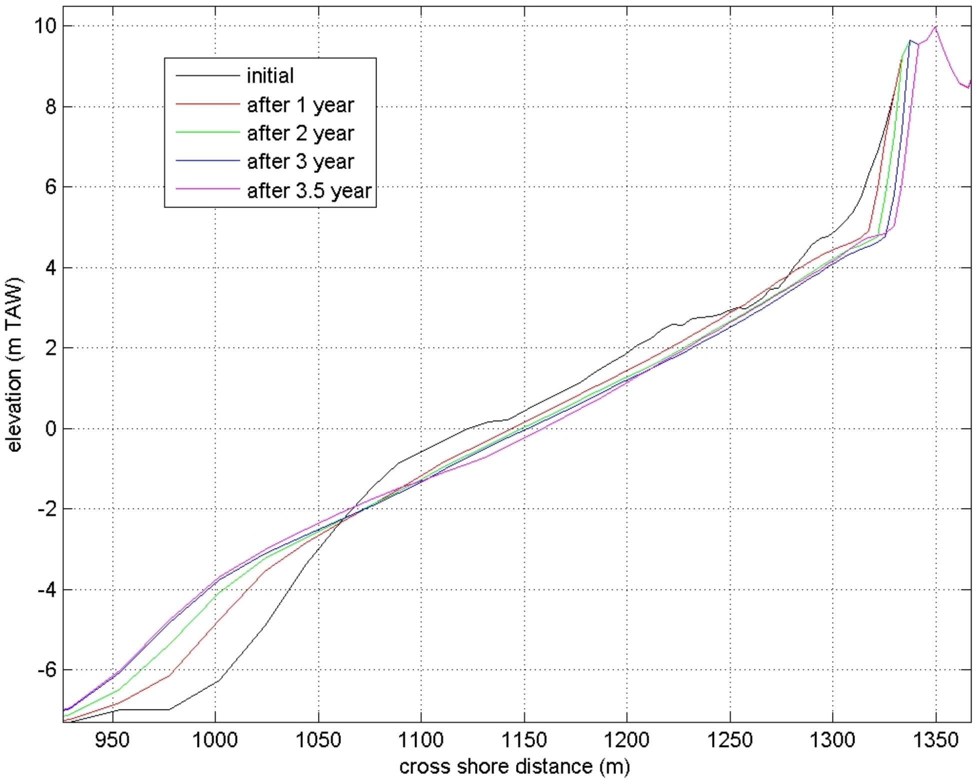


Figure 3-36 Long term profile evolution for the Knokke profile with d50= 0.3mm

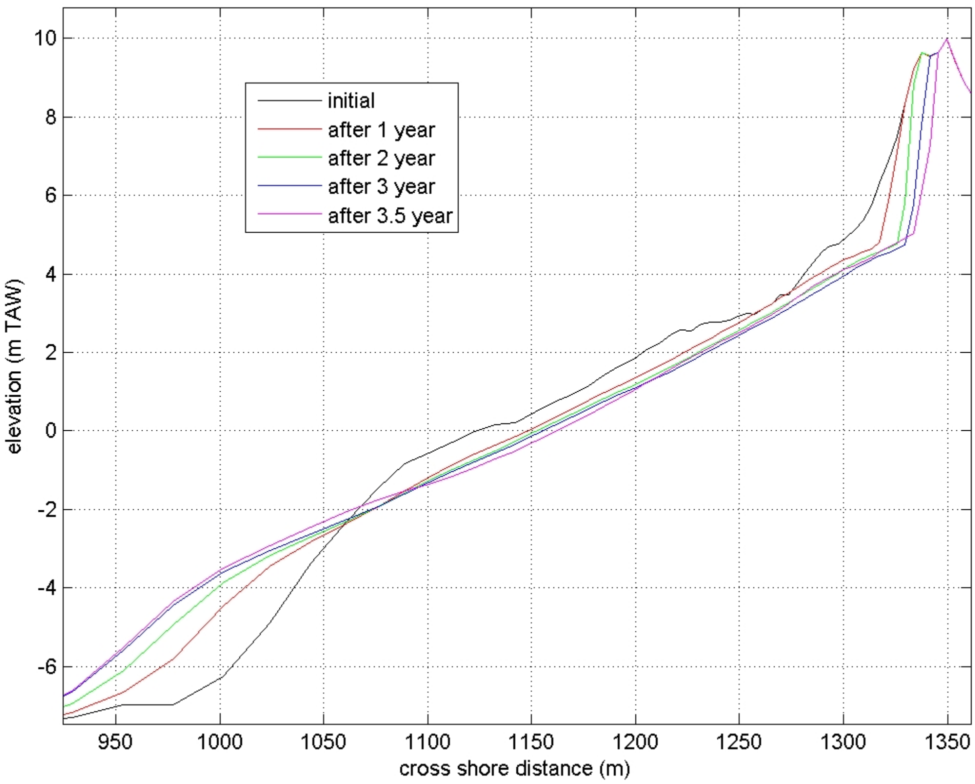


Figure 3-37 Long term profile evolution for the Knokke profile with d50= 0.2mm

Also the Bredene profile reaches its maximum nearly after 1 year (kt012) (d50=0.2mm, WTI settings) (Figure 3-39). It is observed that the equilibrium profile is somewhat steeper than the measured profile above the +2m TAW level. A flat part can be observed near HW spring (4.5m TAW), this is not very clear from the measurements. However, Figure 3-39 shows that although the profile reaches an equilibrium, through the year some larger fluctuations can be observed. At some periods of the year, the profile is less steep and the berm near HW spring is less clear.

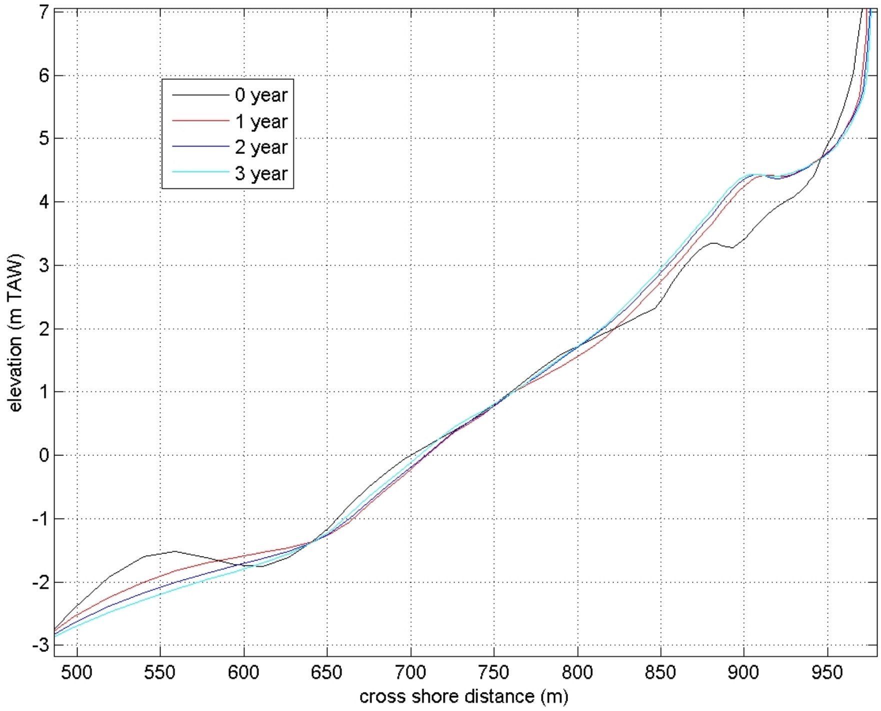


Figure 3-38 Long term evolution of the Bredene profile

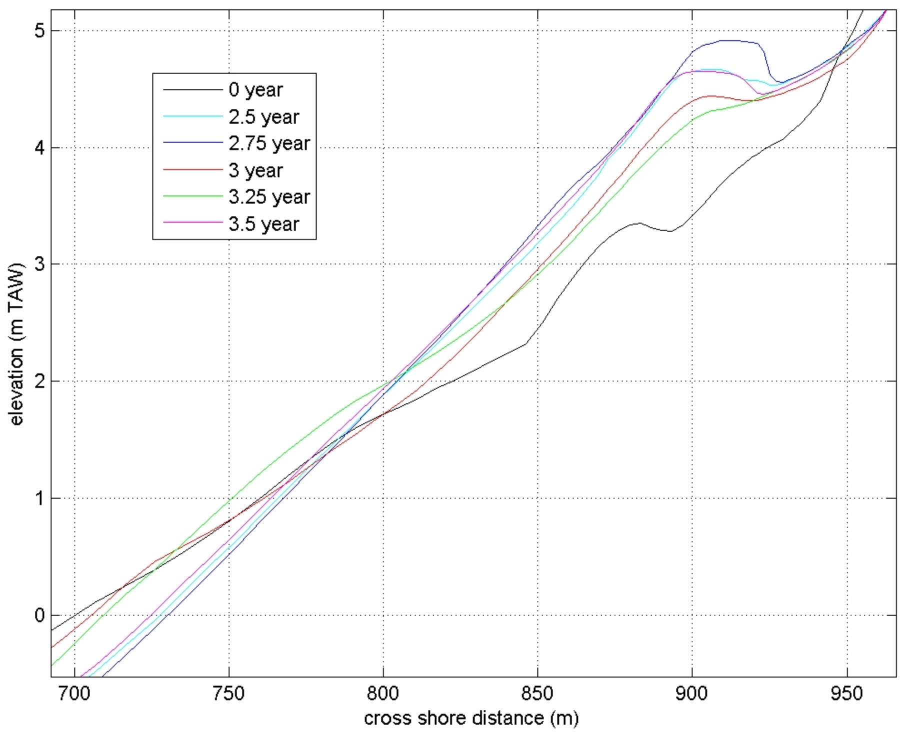


Figure 3-39 Time evolution of the Bredene profile during 1 year

The stability of the profile can also be seen in the serious reduction of cross-shore transport between the first and the third year (Figure 3-40).

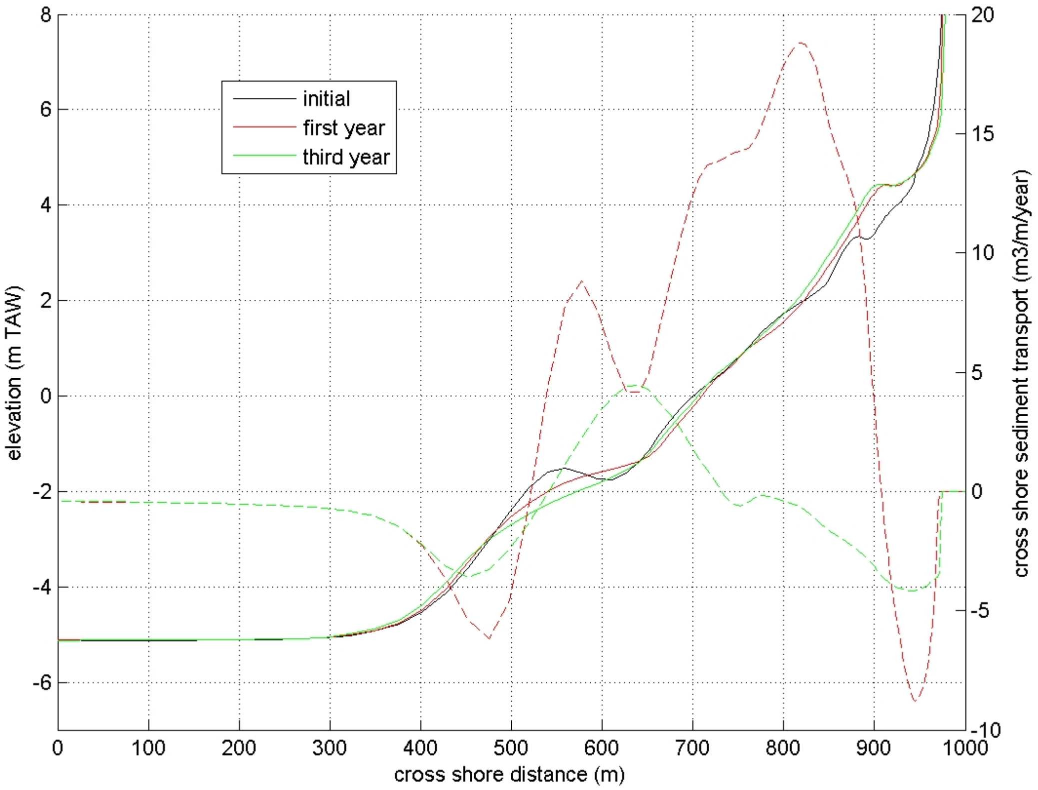


Figure 3-40 Comparison of cross-shore transport in the first and in the third year

The long term evolution is also done for the straight profile (kt026 and kt027 ; Figure 3-41 and Figure 3-42). Figure 3-43 compares the profiles after 5 year. Almost no dependency on the grain size is visible.

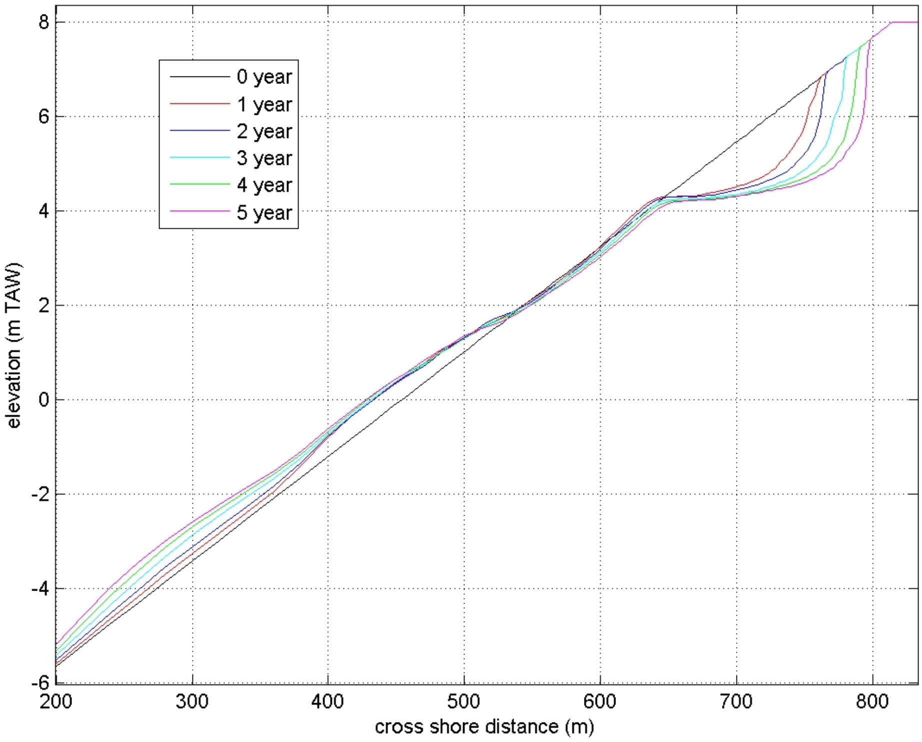


Figure 3-41 Long term evolution of the straight profile, d50=0.15mm (cmax=10)

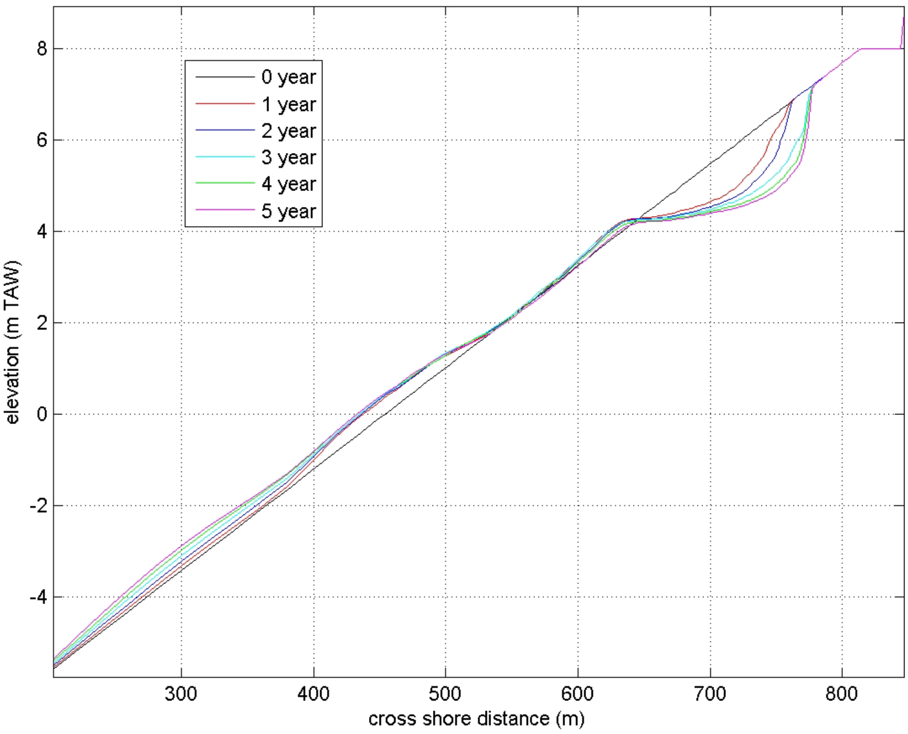


Figure 3-42 Long term evolution of the straight profile, d50=0.3mm (cmax=10 (-))

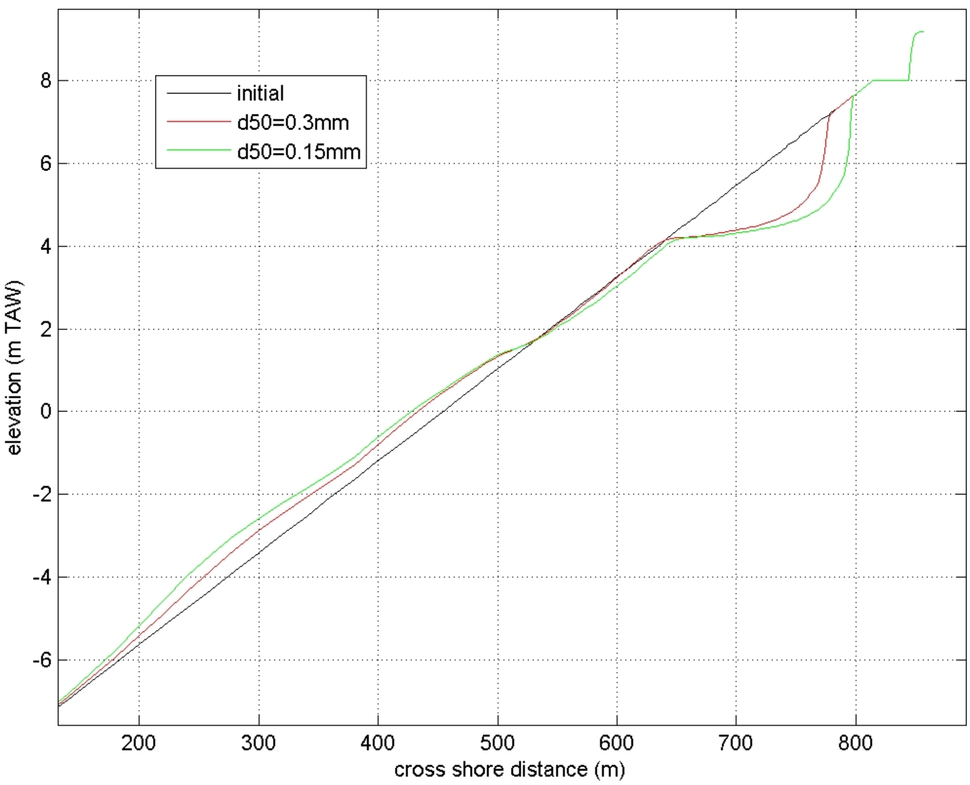


Figure 3-43 Comparison of the evolution of the straight profile after 5 years for d50 =0.3 and 0.15mm)

Shoreface nourishment

On the Bredene-profile a fictive foreshore nourishment of 400m^3/m is done (berm at -1m TAW). The evolution is shown in Figure 3-44 till Figure 3-47. It can be seen that the extra sand is slowly moving in the onshore direction. In the first year the foreshore nourishment has a negative effect of -9m3/m on the intertidal zone (between +0.5m TAW and 4.5 m TAW), in the second year a positive effect of 4m3/m (so 13m^3 sand extra has moved onshore), in the third year 37m^3/m positive (33m^3 extra) and in the last half year 50m^3/m extra (26m^3/m/year extra positive). It should be noted that these values are rather limited compared to the extra 400m^3/m sand that is dumped on the foreshore. More investigation is necessary for the longer term effect (some stabilisation seems to occur) and the effect on beaches that are eroding (the Bredene profile shows onshore transport, the other profiles offshore transport).

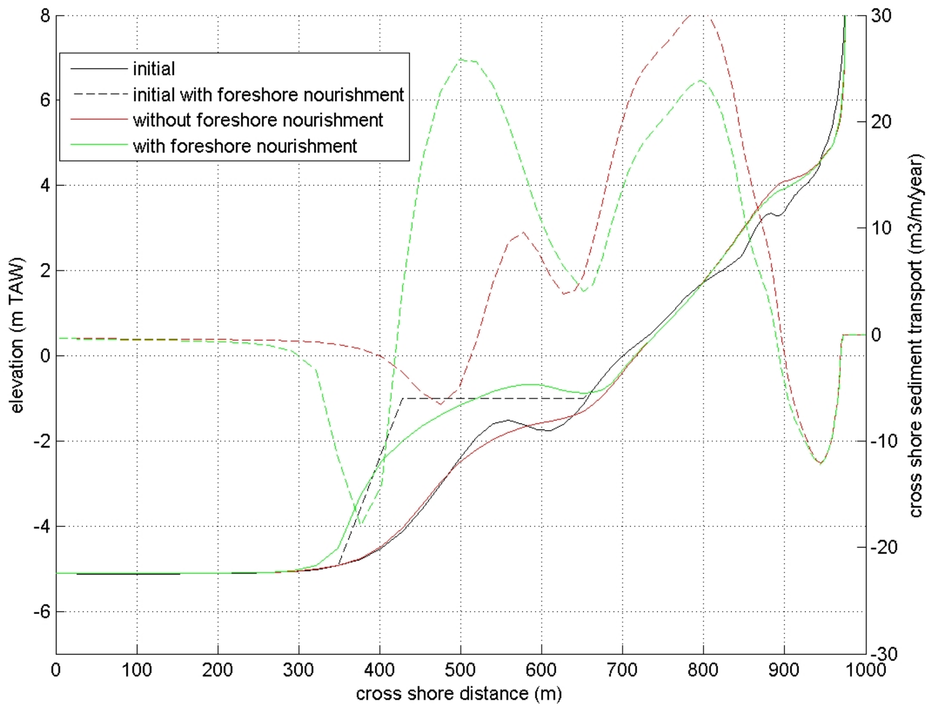


Figure 3-44 Evolution of the foreshore nourishment during the firstyear, compared to the situation without nourishment.

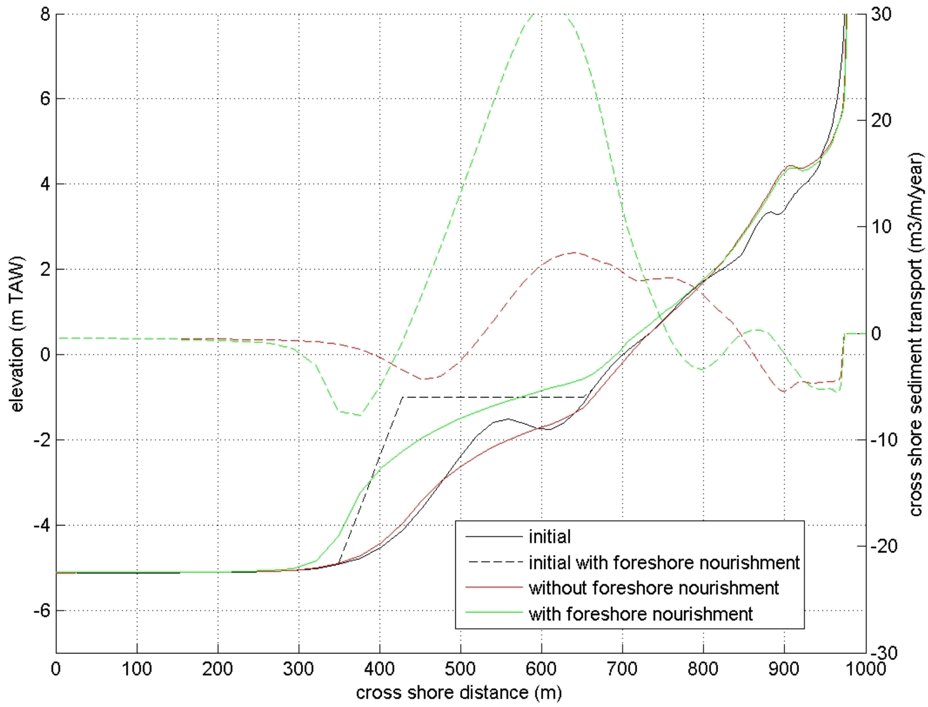


Figure 3-45 Evolution of the foreshore nourishment during the second year compared to the situation without nourishment.

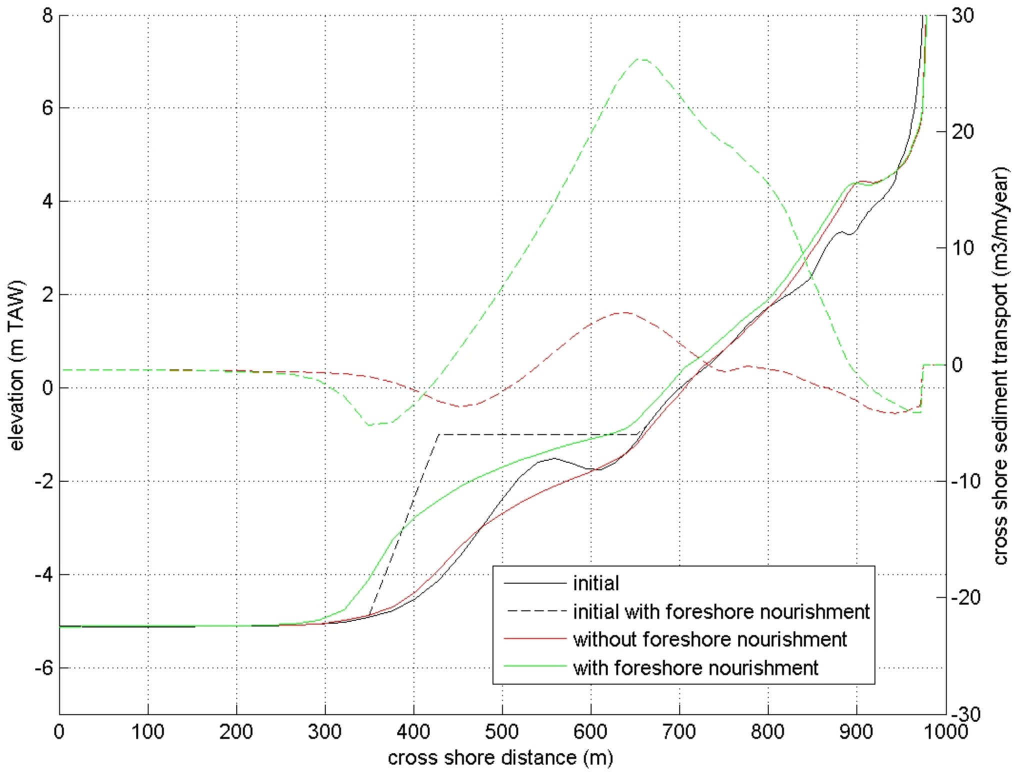


Figure 3-46 Evolution of the foreshore nourishment during the third year compared to the situation without nourishment.

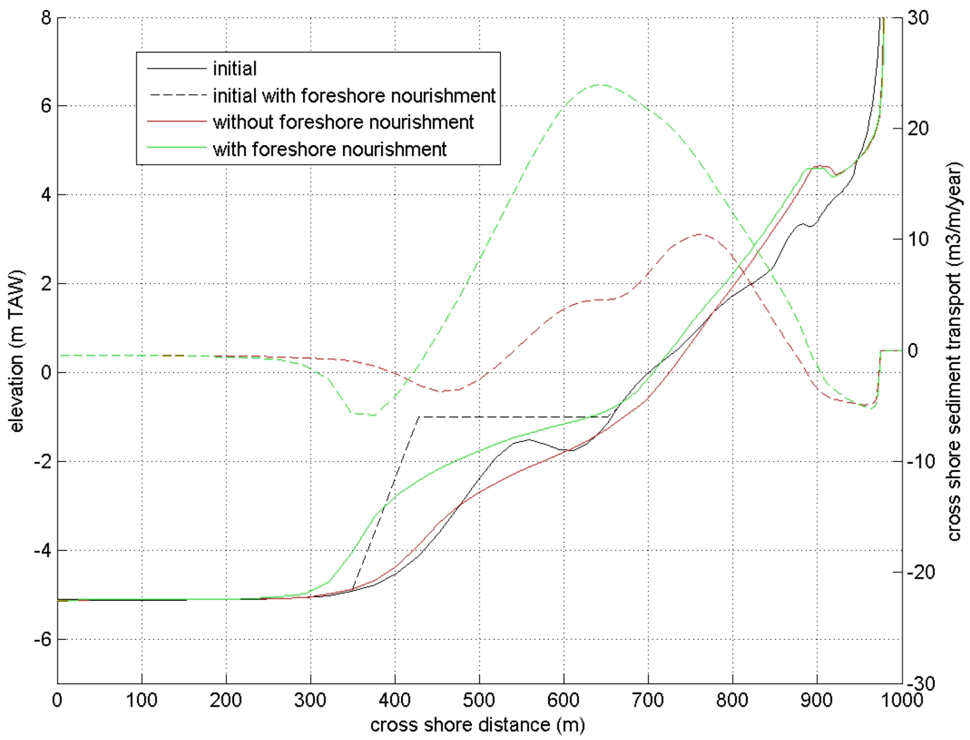


Figure 3-47 Evolution of the foreshore nourishment between year 1 and 3.5. compared to the situation without nourishment.

3.5 Conclusion

The following conclusions can be made from these exercises for the potential applications mentioned in the introduction :

Evaluation of the long term stability of the cross-shore profile

- Both the steep profiles and the measured Belgian profiles can remain stable over a period of several years. The slope is realistically reproduced with some calibration. For the (mild) Belgian profiles this calibration means applying the WTI settings. For the steep profile the inclusion of groundwater proved necessary to conserve the profile shape. Even the long term erosion in Knokke is qualitatively well-reproduced.
- The grain size is however found to influence the slope less than expected, partly because a certain insensitivity of XBeach to the grain size applied, and partly because long time horizons are needed before significant volumes of sand have been redistributed in cross-shore direction.
- The WTI settings, although yielding good results for the Belgian coast, have no physical background. They compensate errors caused by one parameter by errors caused by other parameters : onshore transport parameters, the bed roughness and the wave parameters are all important.
- The spin-up is approximately one year. After that the profile shape varies less, still important seasonal variations are predicted by the model (summer, winter).

Evolution of a coarse-sized nourishment

- XBeach contains limitations which currently prevent from using multiple sediment fractions which are too different. The calibration factors for onshore transport are in reality dependent on the grain size. Nonetheless the long term onshore feeding of the beach by a shoreface nourishment can successfully be modelled in XBeach.

Evaluation of coastal retreat due to sea-level rise

- Although the cross-shore profile can be kept stable over a period of several years, XBeach is not ready yet to evaluate the effect of sea level rise on coastal retreat. The mass balance which is not closed, with errors compounded by the morfac, forms the largest limitation to reach this objective. A second major limitation is simply the imperfect knowledge of the grain size distribution and stratigraphy along the profile, which prevent the initial profile to be in perfect equilibrium in the model (provided it is the case in reality). Finally it remains difficult to separate the long term trend from the noise due to intra-year climate variability (as in reality).
- The morfac option morfacopt=1 (impact on the hydrodynamic time scale rather than on the mophdynamic tme scale) is the largest source of error on the mass balance (see Belgian profile), but probably not the only one (see steep profile). It is incompatible with advection, i.e. with tide, because all currents are artificially amplified (cross-shore tidal filling and long waves in 1D and 2D, tidal alongshore currents in 2D). The morfac impacts the net cross-shore transport direction. For the Belgian profiles, with this method a morfac of 3 is recommended, a morfac of 10 is too large.

To conclude: XBeach is not able yet to model coastal erosion due to sea-level rise, but not far either. This exercise is to our knowledge the first attempt to model cross-shore development at such a long time scale. Some additional research is needed to address the remaining issues:

- Concerning the excessive fines on the beach, the code has been modified to include a calibration parameter for onshore transport for each fraction. It proves to be a handy workaround to prevent unrealistic behaviour.
- Concerning the mass balance issue, the Groundhog Day release of XBeach contains improvements described in the thesis of De Vet (2014). A test shows however that it does not solve the problem.
- Concerning the lack of coastal retreat, further investigations are needed to identify possible missing processes and whether this is physically possible.

- Some methodologies may need to be developed to compensate for the lack of data on grain sizes and stratigraphy of the shelf. An initialisation run for the bed composition seems a promising method.

Coastal retreat is probably difficult to model because it is a slight and progressive natural change. By contrast other long term applications are probably easier. The exercises suggest that XBeach is capable of modelling the long term evolution of beach and shoreface nourishments, which are a large departure from the equilibrum profile.

4 Conclusions

This report has investigated the capabilities of Delft3D in 2D mode and of XBeach to model cross-shore transport at different time scales. Based on the driving processes identified, XBeach is to be preferred over Delft3D for cross-shore profile modelling. The 2D mode of Delft3D does not properly treat sediment transport due to return flow.

A 3D model of Delft3D can also perform well because it includes more processes, but it is less handy from an engineering point of view (potentially complex 3D calibration, longer computation time). A model for cross-shore transport should include at the very least onshore transport by wave skewness and asymmetry, offshore transport by the return flow and avalanching for dune erosion.

Results of modelling exercises show promising results for long term profile development in XBeach. The profile can be kept stable over a time horizon of a year and longer. The resulting profile shape on the Belgian coast after a year is close to reality when using the WTI settings. However some model limitations still exist which prevent form obtaining realistic results over a time scale of 10 years:

- The mass balance is not closed. Recent improvements to the code did not solve the issue.
- The morfac still comes with several side effects, for instance on the mass balance and on the onshore-offshore transport direction. A tide should not be applied when using the acceleration method morfacopt=1.
- The onshore transport calibration factors are not dependent on the grain size, while they physically should be. The code can be easily modified to fix this issue.
- The model currently predicts coastal advance due to sea level rise instead of coastal retreat, due to a reshaping of the profile. It is not clear whether this is physically realistic.

For the Belgian coast, XBeach is able to reproduce the shape of the cross-shore profiles if the WTI settings are used and if the morfac parameter is small. The grain size dependency seems to be underestimated (further research required). XBeach is also able to reproduce the extra onshore transport in case of shoreface nourishments.

5 References

Price, T.D., Ruessink, B.G. and Castelle, B. (2014). Morphological coupling in multiple sandbar system – a review. *Earth Surf. Dynam., 2, 309–321.*

Bailard, J.A. (1981). An Energetics Total Load Sediment Transport Model for Plane Sloping Beaches. *Journal of Geophysical Research, 86 (C11),* pp. 10938-10954.

Berni, C. (2011). *Processus de mobilisation et de transport de sédiments dans la zone de déferlement.* PhD thesis at Laboratoire des Ecoulements Géophysiques et Industriels (LEGI), Grenoble University. In French.

Bijker, E.W. (1971). Longshore transport computations, *J. Waterway. Harbour. Coast. Eng. Div.-ASCE, 97 (WW4),* pp. 687-701.

Brière, C., Giardino, A. and Van der Werf, J. (2010). Morphological modeling of bar dynamics with Delft3D: The quest for optimal free parameter settings using an automatic calibration technique. Proceedings of ICCE 2010.

Cornish, V. (1898). On sea beaches and sand banks. *Geography Journal*, II: 528-647.

Dean, R.G. (1973). Heuristic models of sand transport in the surf zone. *Proceedings Conference of Engineering Dynamics in the Surf Zone*, Sydney, Australia.

Dean, R.G., Rosati, J.D. and Walton, T. (2014). Does the Bruun rule work? Poster consulted online at http://cirp.usace.army.mil/pubs/posters/BruunRule.pdf on 26/03/2014.

Deltares (2010a). *Delft3D-FLOW. Simulation of multi-dimensional hydrodynamic flow and transport phenomena, including sediments – User Manual. Version 3.04, rev. 11114.* Deltares, Delft, The Netherlands.

Deltares (2010b). *Delft3D-WAVE. Simulation of short-crested waves with SWAN – User Manual. Version 3.04, rev. 11114.* Deltares, Delft, The Netherlands.

Deltares (2011). *Delft3D-FLOW. Simulation of multi-dimensional hydrodynamic flow and transport phenomena, including sediments – User Manual. Version 3.15, rev. 17474*. Deltares, Delft, The Netherlands.

De Winter, J; Trouw, K.; Toro, F.; Delgado, R.; Verwaest, T.; Mostaert, F. (2010). *Scientific support regarding hydrodynamics and sand transport in the coastal zone: Literature review of data. Version 2.0. WL Rapporten, 744_30*. Flanders Hydraulics Research & IMDC: Antwerp, Belgium.

ENCORA (2011*).* Coastal Hydrodynamics And Transport Processes. Consulted on January 3rd, 2012 on http://www.coastalwiki.org/coastalwiki/ .

Foster, D. L., Bowen, A. J., Holman, R. A., and Natoo, P. (2006). Field evidence of pressure gradient induced incipient motion, *J. Geophys. Res., 111 (C05004).*

Galappatti, R., and Vreugdenhil, C.B. (1985). A depth-integrated model for suspended transport, *Journal of Hydraulic Research, 23 (4).*

Grasmeijer, B. (2002). *Process-based cross-shore modelling of barred beaches.* PhD thesis, pp.251, University of Utrecht, The Netherlands.

Ippen, A.T., Eagleson, T.S. (1955). A study of sediment sorting by waves shoaling on a plane beach. *USACE, Beach Erosion Board Technical Memorandum*, 63, p. 83.

Lanckriet, T.; Zimmermann, N.; Trouw, K.; Wang, L.; De Maerschalck, B.; Delgado, R., Verwaest, T., Mostaert, F. (2015b). Wetenschappelijke bijstand voor de hydrodynamica en zanddynamica in de kustzone: Advies suppletie Knokke – Effect op de morfologie van het Zwin en van de Baai van Heist: XBeach - modellering. Versie 1.0. Rapport, 12_107. Waterbouwkundig Laboratorium & IMDC: Antwerpen, België.

Longuet-Higgins, M.S. (1953). Mass transport in water waves. *Phil. Trans. R. Soc., London*, Ser. A 245 (03), pp. 535-581.

Ranasinghe, R., Swinkels C., Luijendijk A., Roelvink J.A., Bosboom J., Stive M.J.F. and Walstra D.J.R (2011). Morphodynamic upscaling with the morfac approach: dependencies and sensitivities.

Coastal Engineering, 58 (8), pp. 806-811.

Ranasinghe et al (in prep.). Unknown reference.

Reniers, A.J.H.M., and Battjes, J.A. (1997). A laboratory study of longshore currents over barred and non-barred beaches. *Coastal Engineering, 30,* pp. 1-22.

Reniers, A. (2013). Keynote lecture about rip currents in Delft3D during Delft Software Days 2013, Delft, The Netherlands.

Ruessink, B.G., Kuriyama, Y., Reniers, A.J.H.M., Roelvink, J.A., and Walstra, D.J.R. (2007). Modeling cross-shore sandbar behavior on the timescale of weeks. *J. Geophys. Res., 112*, F03010.

Ruessink, B. G., Michallet, H., Abreu, T., Sancho, F., Van der A, D.A., Van der Werf, J.J., and Silva P.A. (2011). Observations of velocities, sand concentrations, and fluxes under velocity-asymmetric oscillatory flows, *J. Geophys. Res., 116 (C03004).*

Seymour, R.J., Castel, D. (1989). Modeling cross-shore transport. *Nearshore sediment transport*, Plenum Press, New York, N.Y., pp. 387-401.

Seymour, R.J. (2005). Cross-shore sediment transport. In: Schwartz M.L. (2005). *Encyclopaedia of Coastal Science. Coastal wind effects.* Springer Netherlands.

Soulsby, R. (1997). *Dynamics of marine sands.* Thomas Telford Publications, London, United Kingdom.

Soulsby, R. (2003). Overview of Coast3D project. *Coast3D project, Paper A1,* HR Wallingford Ltd.

Stokes, G.G. (1847). On the theory of oscillatory waves. *Trans. Cambridge Phil. Society*, vol. 8, pp. 441-455.

Trouw, K.; Mathys, M.; Toro, F.; Delgado, R.; Verwaest, T.; Mostaert, F (2010). *Scientific support regarding hydrodynamics and sand transport in the coastal zone: Literature review of physical processes. Version 2.0. WL Rapporten, 744_30*. Flanders Hydraulics Research & IMDC: Antwerp, Belgium.

Van der A, D. A., O'Donoghue, T., and Ribberink, J.S. (2009). Sheet flow sand transport processes in oscillatory flow with acceleration skewness, paper 133 in *Proceedings Coastal Dynamics'09*, World Sci., Singapore.

Van Rijn, L. (2003). Sediment transport by currents and waves: general approximation formulae. Coastal Sediments. In: *Corpus Christi, USA*.

Van Rijn, L., Walstra, D. (2003). *Modelling of sand transport in Delft3D.* WL | Delft Hydraulics, project Z3624.

Van Rooijen, A., Reniers, A., Van Thiel de Vries, J., Blenkinsopp, C., and McCall, R. (2012). Modeling swash zone sediment transport at Truc Vert beach. *Coastal Engineering*.

Van Thiel de Vries, J.S.M., van Gent, M.R.A., Walstra, D.J.R., and Reniers, A.J.H.M. (2008). Analysis of dune erosion processes in large-scale flume experiments. *Coastal Engineering 55*, pp. 1028–1040.

Unesco-IHE, Deltares, TU Delft (2009). *XBeach model description and manual. Report Z4175.*

USACE (2008). *Coastal Engineering Manual.*

Walstra, D.J.R., Reniers, A.J.H.M., Ranasinghe, R., Roelvink, J.A., and Ruessink, B.G. (2011). On bar growth and decay during interannual net offshore migration. Coastal Engineering.

West, T.R. (1995). *Geology applied to engineering*. Prentice Hall, 560 pp.

Zimmermann, N., Mathys, M., Trouw, K., Toro, F., Delgado, R., Verwaest, T., Mostaert, F. (2010). *Scientific support regarding hydrodynamics and sand transport in the coastal zone: Literature review of models. Version 2_0. WL Rapporten, 744_30*. Flanders Hydraulics Research & IMDC: Antwerp, Belgium.

Zimmermann, N.; Mathys, M.; Trouw, K.; Delgado, R.; Toro, F.; Verwaest, T.; Mostaert, F. (2011). *Scientific support regarding hydrodynamics and sand transport in the coastal zone: Simplified Blankenberge case: comparison of Delft3D and Xbeach model results. Version 1_2. WL Rapporten, 744_30*. Flanders Hydraulics Research & IMDC: Antwerp, Belgium.

flanders
HYDRAULICS RESEARCH

Waterbouwkundig Laboratorium

Flanders Hydraulics Research

Berchemlei 115
B-2140 Antwerpen
Tel. +32 (0)3 224 60 35
Fax +32 (0)3 224 60 36
E-mail: waterbouwkundiglabo@vlaanderen.be
www.watlab.be