Long-term modelling with XBeach: combining stationary and surfbeat mode in an integrated approach

L.J.C. (Laurens) Bart

Challenge the future

Photo on cover: beaches of Hoek van Holland, 's-Gravenzande and in the distance, the beach of Vlugtenburg (Rijkswaterstaat, 1993). This photo still shows the groins that were completely covered in the 2009 beach nourishment.

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Master thesis submitted for the degree of
Coastal Engineering

Graduation date: July 13th 2017

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Preface

This thesis was written as conclusion of the master Hydraulic Engineering with the specialisation of Coastal Engineering at the Technical University of Delft. Many people have contributed to this thesis. I would like to take the opportunity to thank them:

First and foremost I would like to thank Willem, my daily supervisor, for his skilled supervision, for always being available to answer both easy and difficult questions, for teaching me important modelling practices and for proof-reading chapters of my thesis.

I am grateful for the great supervision of the other committee members: Robert, Stefan and Arjen. Despite their busy schedule they were able to make time to answer my questions regarding XBeach, wave input reduction and many more topics. With their input during the progress meetings and feedback on my report, I was able to improve my research a lot.

This research was conducted at the Rotterdam office of Witteveen+Bos. I am very thankful for the opportunity Witteveen+Bos en Maarten gave me to graduate as an intern in the Hydrodynamics & Morphology group. I felt very welcome and was allowed to participate in many fun and educational activities. It was also great that I could use the computational clusters at Witteveen+Bos for running my models.

Thanks to all the other colleges at Witteveen+Bos from the Hydrodynamics & Morphology group, who were not only great company, but also very helpful in answering my questions regarding their expertises. I would also like to thank the other graduates at Witteveen+Bos, especially Cas, Guus, Lucas, Stefan, Oscar, Louwrens and Robert. It was not only great fun to graduate with you, but also very helpful to exchange knowledge and help each other out with all kinds of problems.

I am very grateful to the Technical Univesity of Delft, especially the lecturers, for providing excellent lectures and a great environment to learn and excel in different topics.

My family, especially parents, have been a great support to me during my graduation thesis, but also during the rest of my education and I am greatly indebted to them.

Acknowledgements

This research has used high quality bathymetry data that was obtained by Matthieu de Schipper (De Schipper, 2014).

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If you have any questions regarding this thesis, you can contact me via LinkedIn.

Abstract

XBeach is a process-based morphological model that has been used for modelling short term behaviour of beaches and dunes. In the past years interest has been shown by researchers and engineers to use XBeach for longer simulation periods (multiple years). XBeach has multiple modules: stationary mode is often used during calm conditions and surfbeat mode is often used during storm conditions. In this study was investigated whether the coupling of the two modes can increase the performance of long-term models compared to the separate models, while focusing on the cross-shore processes. Also the added value of (quasi-)2D models was studied. The high frequency bathymetryic data of Vlugtenburg, an alongshore uniform beach in The Netherlands, was used for creating 1D models for a period of 1 year. To compare the difference between singular and coupled models, first the potential performance of the stationary and surfbeat modules was investigated separately by optimising the settings for asymmetry, skewness and groundwater flow. It was found that the skill of the stationary and surfbeat models with default settings was negative. Erosion was overestimated (especially in surfbeat mode) and the models showed no seasonal effects. Settings for asymmetry and skewness proved to be effective measures to improve the model performance and were able to introduce seasonal effects. The optimised stationary model was able to predict the profile development reasonably well. The groundwater flow module did not affect the model stability as much as was found in the studies of Zimmermann et al. (2015) and Pender and Karunarathna (2013).

In order to validate whether a coupling between stationary and surfbeat mode would benefit the model performance, it was investigated whether stationary mode was able to restore the dune and beach erosion of the surfbeat model. Therefore surfbeat was run during the first 100 days of the year (during more extreme conditions) and stationary mode during the remainder of the year (more mild conditions). Stationary mode appeared not to be able to restore the eroded surfbeat profile. The performance of the coupled model was better than the surfbeat model, but the stationary mode was found to perform better than the coupled model for long-term modelling on the most criteria.

It was found that a deficiency in XBeach is the ability to transport sediment from the intertidal zone (and just above) further up the beach and dunes. The erosion volumes in the dunes in stationary mode were in the same order of magnitude as the onshore directed aeolian transport. Therefore was expected that the results of long-term models can be improved by coupling XBeach with a wind model.

The quasi-2D model was found to have a better performance than 1D models; in both the separate and coupled models the erosion volumes were not overestimated as much as in the 1D models.

Contents

List of Figures

List of Tables

1 Introduction

1.1 Problem definition

On Earth 200 million people live along coastlines less than 5 metres above sea level (World Ocean Review, 2017). This number is expected to increase to 400 or 500 million by the end of the 21st century. The coastal zone has always been an attractive settlement area for humans, because of the opportunities to fish, to trade, to transport, to have a tourism business and so on. However, many coastal areas are susceptible to flooding and erosion, which is a hazard for people in the coastal areas. Therefore many coastal areas that show a natural transgression (retreat of the coastline) are maintained. This is done both with soft and hard measures: for example nourishments, breakwaters and sea-dikes. In order to be able to apply the appropriate measures, it is desirable to know how the coastline is eroding.

XBeach is a process based model that is frequently used by engineering companies and researchers to determine the nearshore morphological changes. The longshore formulations are similar to the formulations of Delft3D, but XBeach covers a wider set of cross-shore processes. Return flow, wave asymmetry, wave rollers and long waves are examples of processes that are included in XBeach and not in Delft3D (Trouw et al., 2012). Because of the inclusion of long waves (infra gravity waves) XBeach is specifically suitable for models in the nearshore zone, where Delft3D is often used for larger domains.

XBeach was initially designed to determine the coastal erosion during a storm (Roelvink et al., 2009) and (Roelvink et al., 2015). Engineering companies now also show interest in using XBeach to determine the morphological changes on the time-scale of years. Recent studies show that long-term morphological models with XBeach are feasible; Zimmermann et al. (2015) evaluated the long-term evolution of a cross-shore profile with XBeach for the Belgian coast and found that a coastal profile can be kept stable for more than a year. Also was discovered that the onshore feeding of the beach by a nourishment could be successfully modelled. Pender and Karunarathna (2013) used XBeach for long-term models at Narrabean beach (Australia).

Engineering company Witteveen+Bos shows an interest in further optimising the accuracy of long-term models. They are also interested in reducing the computation time without reducing the accuracy of the models. Increasing the accuracy and/or reducing the computation time without reducing the accuracy will be referred to as increasing *the performance* of the models. The method suggested by Bodde et al. (2017) to improve the performance of long-term models was to couple two different modules within XBeach. The two XBeach modules are:

- Stationary mode: commonly used during periods with a calm wave climate. Stationary mode does not account for infra-gravity waves and therefore the computation times are smaller than for surfbeat mode.
- Surfbeat mode: used to determine storm erosion. During storms infra-gravity waves are important. Surfbeat takes these into account.

The expected benefits of this approach were that the computation time of the model could be reduced in this way. Also when stationary mode is used during calm conditions and surfbeat mode during more extreme conditions, the models combined are expected to be able to reproduce seasonal effects that are visible along the Dutch coast: the profile erodes during storms in surfbeat mode and is regenerated in stationary mode during calm conditions. The study of Bodde et al. was done for a nourishment design at a beach at the south-east side of the island of Texel in The Netherlands. It was found that a coupled model provided stable results. However, since no bathymetric measurement data was available for Texel, it was not possible to calibrate the models and the skill of the different models could not be compared. Also the east side of Texel is relatively sheltered from storms and therefore the wave climate is mainly dominated by locally generated wind waves. The results of coupled models at an unsheltered coast might be different, because infra-gravity waves play a more significant role there.

The main objective of this thesis is to further investigate whether a combination of stationary and surfbeat mode results in a more accurate and computationally efficient model.

It was decided to focus mainly on cross-shore processes and 1D simulations. Vlugtenburg, a beach in between Hoek van Holland and 's-Gravenzande, is a suitable location for this study, because of the high frequency (monthly) bathymetric survey data and because of the more or less alongshore uniform coast. This makes Vlugtenburg more suitable for 1D modelling.

In order to determine the added value of coupled stationary and surfbeat models, a comparison will be made in this study between the performance of coupled and singular models (models with only stationary or surfbeat mode). Since the added value of a coupled model can only really be determined when it is compared with singular models that have been used to their full potential, the singular models will first be calibrated and optimised. Zimmermann et al. (2015) and Pender and Karunarathna (2013) also performed optimisation studies, but settings are very dependent on the location and therefore the settings for the Australian and Belgian coast are not necessarily the best for the Dutch coast.

The XBeach settings are not only optimised in an attempt to be able to create more accurate long-term models for the Dutch coast; the sensitivity analysis also provides information on the physics of the different parameters in XBeach. With a better understanding of these physics it is possible to determine the settings that are required for the coupled model and it provides a foundation for an advice for a more generalised approach to improve long-term modelling, independent of the location. The parameters that were investigated were: the asymmetry factor (facAs), the skewness factor (facSk), the groundwater flow module (k) and the influence of long (infra-gravity) waves.

For the assessment of the Dutch coast, often 1D XBeach models were used. For the Belgian coast, the models were 2D. Another point of focus of this study is to investigate whether there are significant differences between a 1D and 2D long-term model for an alongshore uniform coast and to investigate whether the skill of 2D models for long-term morphology is better.

XBeach was initially designed for short term models. In this study was encountered that XBeach has multiple practical problems (bugs) when it is used for long-term models. In appendix D will be elaborated on these problems and the work-arounds that were used will be mentioned.

In the next section the research and sub-research questions are given.

1.2 Research questions

Main question:
Can the coupling of stationary and surfbeat mode within XBeach increase or maintain the model performance relative to a single stationary or surfbeat model?

*Improving model performance is defined as:

1. increasing the accuracy of the model compared to survey data and/or
2. reducing the computation time without reducing the accuracy of the model much

Sub-questions:

1. What is the performance of singular (non-coupled) stationary and surfbeat models for long-term modelling?
2. In what way do the following processes affect long-term morphological models and what are the optimal settings?:
    (a) Asymmetry (facAs)
    (b) Skewness (facSk)
    (c) Groundwater flow (k)
    (d) Long wave forcing (lwave)
3. Is a 2D model or 1D model preferred for a longshore uniform coast like Vlugtenburg?

1.3 Structure of report

In section 2 a background is given on important cross-shore sediment transport processes and is elaborated on previous attempts to improve long-term modelling. In section 3 a description of XBeach is given and is explained how XBeach handles the different processes. The methodology can be found in section 4. The results and observations are displayed in section 6. In the discussion (section 7) is explained whether the findings provide sufficient information for answering the research questions and will be mentioned whether the findings agree or conflict with previous studies. Also will be mentioned what the inaccuracies of the methodology in this research are. The conclusions are given in section 8, the recommendations for future research in 9. The appendices are displayed at the end of this report.

2 Literature study

2.1 Introduction

The main objective of this study is to improve long-term modelling by combining surfbeat and stationary mode in an integrated model. Both longshore and cross-shore processes are important for long-term morphology. Longshore transport influences the position of the 0m line and is a sink or source term for the cross-shore sediment balance. The cross-shore processes on the other hand redistribute the sediment in cross-shore direction. In this study has been decided to focus on cross-shore processes.

As will be explained in chapter 4, before an actual integration of stationary and surfbeat mode will be done, first the characteristics of stationary and surfbeat mode need to be studied and optimised *separately.* In order to understand the observed behaviour in the stationary and surfbeat models, an understanding of the most dominant cross-shore processes is required. In chapter 2.2 will be elaborated on the cross-shore processes that were found to be the most relevant according to literature. In the remainder of this chapter the individual processes will be discussed.

2.2 Determination of the main contributors to cross-shore sediment transport

In order to get an idea of the most relevant cross-shore processes, a closer look is taken at the near bed velocity and it is decomposed using the Roelvink and Stive (1989) decomposition.

Many different transport formulations exist, but most of them have in common that they include the shear stress (τ) to a certain power:

$$S \propto \tau^k \tag{2.1}$$

The instantaneous bed shear stress can be determined with the quadratic friction law of Grant and Madsen (1979):

$$\tau_b = 1/2 \rho f'_{cw} |u_0(t)| u_0(t) \tag{2.2}$$

In which u_0 is the time dependent near bottom horizontal velocity of combined wave and current motions. This velocity is defined at the top of the boundary layer. This leads to the following relation between velocity and sediment transport:

$$S \propto (u^2)^k \tag{2.3}$$

and with preservation of the sign and $2k = n$:

$$S \propto u|u^{n-1}| \tag{2.4}$$

The near bed velocity is decomposed into three main contributors (Roelvink and Stive, 1989):

$$u = \bar{u} + u_{lo} + u_{hi} \tag{2.5}$$

In which:
$\bar{u}$ = Time mean component
u_{lo} = low frequency motion (wave group scale)
u_{hi} = high frequency motion (short wave scale)

When the n^{th} velocity moment is taken of the near bed velocity, after using a Taylor expansion it is possible to show the contribution of the different components ($\bar{u}, u_{lo}$ and u_{hi}) (Roelvink and Stive, 1989):

$$\langle u|u|^2 \rangle = \langle \bar{u}|u_{hi}|^2 \rangle + \langle \bar{u}_{hi}|u_{hi}|^2 \rangle + \langle \bar{u}_{lo}|u_{hi}|^2 \rangle \tag{2.6}$$

In each term of the equation is visible that the sediment is stirred up by short waves ($|\bar{u}_{hi}|^2$). The transport is caused by the first term in the equation.

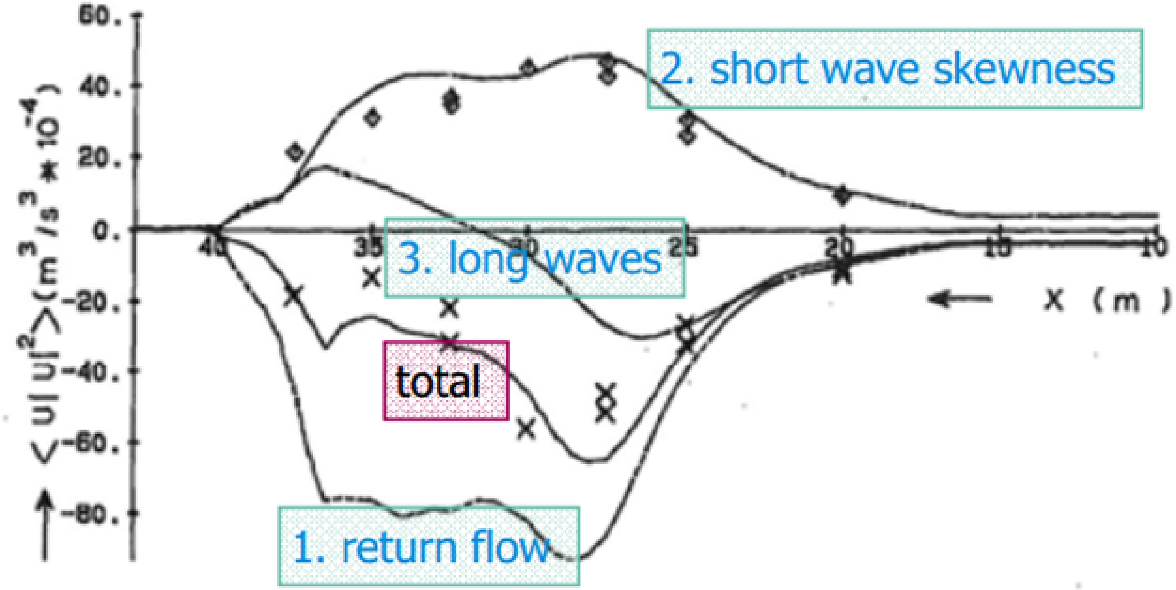


Figure 2.1: Decomposition of the near bed velocity (Roelvink and Stive, 1989).

The near bottom horizontal velocity (u_0) contains contributions of amongst other things: wave asymmetry, wave groups, bound and free long waves, mean flow, LH streaming, undertow and longshore currents.

In figure 2.1 an example of the magnitude and direction of three of the most relevant cross-shore processes is shown. These three processes correspond with the terms in equation 2.5.

In the list below a summary is given of cross-shore processes that are important according to various sources:

- Undertow is the main offshore component in combination with wave stirring (Mariño-Tapia et al., 2007).
- Sediment transport due to asymmetry and skewness are expected to be relatively minor compared to long wave and mean currents transport (Van Thiel, 2008).
- The following processes are the most relevant on a flat bed: Wave drift and streaming, undertow and asymmetry (Fredsøe et al., 1991). Currents are also very important for the net sediment transport.
- Raubenheimer and Guza (1996): Infragravity swash is dominant in storm conditions.

In section 2.4 background information is provided on various types of cross-shore processes that are of relevance in this study (not just the most relevant cross-shore processes that were mentioned in literature).

2.3 Optimisations of XBeach for long-term modelling found in literature

2.3.1 WTI parameters

XBeach contains about 250 model settings. Approximately 150 of these settings describe physical and numerical behaviour. The other 100 are case specific parameters. According to Van Geer et al. (2015) nine specific XBeach parameters have a big influence on the model results. These parameters are optimised for the

Dutch coast for 1D storm models and are called the WTI settings (Van Geer et al., 2015). The parameters might vary slightly depending on the location along the Dutch coast. The WTI settings are presented in table 2.1.

Table 2.1: The default XBeach settings and the WTI settings (Van Geer et al., 2015).

XBeach parameter	**Default settings**	**WTI settings**	**Description**
fw	0.000	0.000	Short wave friction coefficient
cf	0.003	0.001	Dimensionless friction coefficient flow
gammax	2.000	2.364	Maximum wave height to water depth
beta	0.100	0.138	Breaker slope coefficient in roller model
wetslp	0.300	0.260	Critical avalanching slope underwater
alpha	1.000	1.262	Wave dissipation coefficient
facSk	0.100	0.375	Skewness factor
facAs	0.100	0.123	Asymmetry factor
gamma (surfbeat)	0.550	0.541	Breaker parameter for Roelvink
gamma (stationary)	0.550	0.78	Breaker parameter for Baldock

2.3.2 Zimmermann et al. (2015)

Zimmermann et al. (2015) carried out a study using data of the Belgian coast in order to investigate whether certain XBeach settings could contribute to more accurate long-term models. Initially Zimmermann et al. (2015) tried to improve the results of a 1 year model by calibrating the factors for asymmetry and skewness in XBeach. Erosion was modelled well, but the sediment was not pushed back up far enough on the beach in the recovery phase. Zimmerman expected this to be due to limitations in the swash zone transport or due to the non-negligible effects of groundwater flow.

In the second test Zimmerman added a groundwater flow with a permeability of 10^{-2} m/s which lead to a stabilisation of the profile. It is unclear whether this was caused due to artificial damping of the morphological variability. Also Pender and Karunarathna (2013) experienced that it is important to include groundwater flow in the XBeach models in order to keep profiles sufficiently stable.

2.3.3 Pender and Karunarathna (2013)

Pender and Karunarathna (2013) used XBeach for a long-term simulation of Narrabean beach. Two models, a storm model and recovey model, were calibrated separately over a storm period and over a recovery period of about 20-29 days. To calibrate the model against the measured post storm profiles the Chézy coefficient (C), permeability coefficient (k) and wet cell gradient ($\delta z_b/\delta x$) prior to avalanching (wetslope), were varied. Pender used a wave height of 3m as a threshold between calm and storm conditions. The groundwater flow module was activated during the post-storm recovery period, because permeability is of importance for berm formation during the accretion phase (Jensen et al., 2009). This groundwater module simulates in- and exfiltration of groundwater (to and from the beach). The θ_{max} criterion was not implemented by Pender, because sheet flow was less likely to occur during mild conditions. The model performance was assessed with the Brier Skill Score (BSS). As a criterion the volumetric errors between measured and simulated profile and the 0 m and 2 m contour lines were used. The combined storm and recovery models showed low (good) RMAE's (Root Mean Absolute Error) for the annual profile change.

Pender indicates that the threshold (wave height of 3m) between storm and mild conditions does not allow for bar dynamics and intermediate states to be developed in the model. Pender made another recovery model that was calibrated with the entire annual time series. This model showed better RMAE's, but also a bigger error in the minimum profile envelope. Pender states that the fact that the reflective beach state is not included in the recovery simulation is limiting the accretion.

Using a statistical-process based approach (SPA), Pender was able to simulate a 10 year storm climate with reasonable predictions of the erosion volumes (it consistently overestimated the erosion). Also here the model showed the inability to simulate the full range of beach states.

2.4 Background on cross-shore processes

2.4.1 Infra-gravity waves (Free and bound long waves)

Waves are generally classified based on their period, the forces that generate the waves and the restoring forces. Munk (1950) observed that certain types of long waves were related to the variability of the incoming gravity waves. Infra-gravity waves are waves with a period between 30 seconds and 5 minutes and they are generated by gravity (wind) waves with a shorter period. Infra-gravity waves are especially important for erosion during storm conditions While offshore the infra-gravity wave height is quite small, the nearshore wave height can be in the order of meters.

A wave field consists out of different wave components with different wave lengths and frequencies. If there are waves with slightly different frequencies and periods, the wave peaks and troughs will be in phase on certain locations and out of phase in other parts. When the waves are in phase, the amplitudes add up to another. If they are out of phase the peak and trough of the waves dampen each other. Waves carry momentum; the excess momentum-flux are also called radiation stresses. The large waves carry more momentum which is exerted on the water level through radiation stresses. Therefore the water level below the large waves is lowered. The water level below the low short waves is higher. This results in a mean water level variation (a long wave) with the same wave length, frequency and velocity as the wave group. This wave is called an infra-gravity wave.

Radiation stresses are the depth and wave averaged flux of momentum due to waves (Longuet-Higgins and Stewart, 1964).

The wave induced momentum is determined by multiplying mass and velocity. For a slice in the water column this would be $\rho u_x \Delta x \Delta y \Delta z$ (Holthuijsen, 2010). The momentum in the entire column in x-direction is obtained by integrating over the depth:

$$q_x = (\int_d^\eta \rho u_x dz)\Delta x \Delta y$$

q_x can be considered as the net flux of mass between the wave trough and wave crest associated with wave propagation When considering a 1D situation (averaged over time, denoted by the over bar):

$$Q_x = \overline{\int_{-d}^{\eta} \rho u_x dz}$$

For a single harmonic component: $u_x = \hat{u} cos(\omega t)$ the depth averaged momentum is:

$$Q_x = \frac{\rho a^2}{2tanh(kd)}\omega$$

The momentum in y-direction is zero for a longshore uniform crest (there is no orbital velocity in this direction):

$$Q_y = 0$$

Radiation stresses are the *transport* of wave-induced momentum. A part of the momentum is transported by the bodily motion: $(\rho u_x)u_x \Delta y \Delta z \Delta t$ (for a slice of height Δz and width Δy). The other part is transport caused by the wave-induced pressure: $p_{wave} \Delta y \Delta z \Delta t$. For the whole column (only x-direction) this results in a radiation stress of:

$$S_{xx} = \overline{\int_{-d}^{\eta} (\rho u_x u_x + p_{wave}) dz}$$

Bound long waves are released in the surf zone when waves start to break (Longuet-Higgins and Stewart, 1964). Bound long waves are partially reflected and for regular wave groups the combination of free and the reflected bound long waves cause standing waves (Deigaard et al., 1999). Sediment accumulates in the anti-nodes where horizontal movement of sediment is minimal. It is suspected that this plays a role in the formation of nearshore bars (Short (1975) and Bowen (1980), Liu and Cho (1993), O'Hare and Huntley (1994), Aagaard et al. (1994)).

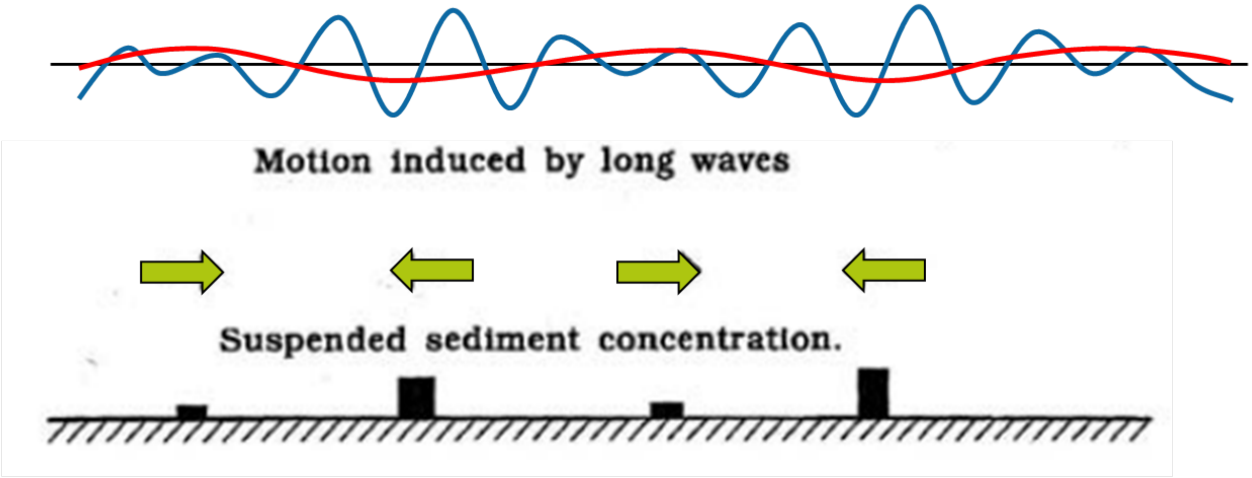


Figure 2.2: Sediment transport under bound long waves (Deigaard et al., 1999)

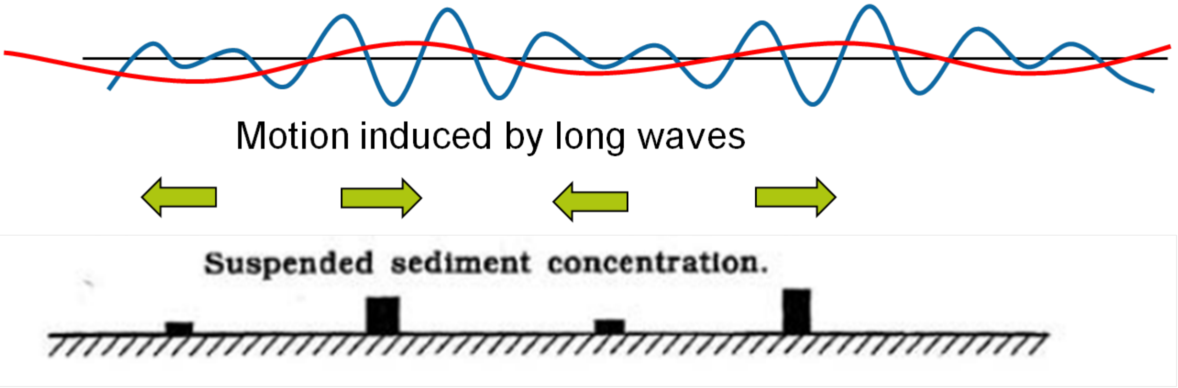


Figure 2.3: Sediment transport under free long waves (Deigaard et al., 1999)

2.4.2 Shoaling

In the coastal zone, waves start to feel the bottom and they slow down. The wave height needs to become higher in order to keep the same flux (e.g. Dally, 2010).

First waves become gradually more skewed while remaining reasonably symmetric about the vertical axis. Closer to the surf zone the harmonic waves are shifting and the wave become more asymmetric and less skewed. An indicator of both skewness and asymmetry is the Ursell parameter:

$$U = HL^3/h^3$$

2.4.3 Swash zone dynamics and groundwater flow

Infiltration and exfiltration of water into the beach can play an important role for the stability of the beach and sediment transport (Horn, 2002). Swash dynamics are not yet understood sufficiently, but it is known that beaches with a high water table tend to erode and beaches with a low water table tend to accrete. A possible explanation is that if the groundwater level is lower, the infiltration is increased, therefore the backwash of water is decreased and less sediment is transport offshore.

2.4.4 Skewness

Due to the Shoaling effect waves become more skew: the troughs are more flattened and the peaks increase (Hsu and Hanes, 2004; Mariño-Tapia et al., 2007). A skewed wave can be described by Stokes 2nd order theory. This theory explains that a non-linear wave is the sum of a number of harmonic waves. A skewed wave is the sum of two harmonic waves with the same phase speed (the waves are phase locked), but a different period and amplitude. The indicator of skewness is:

$$\langle \eta^3 \rangle / \sigma^3$$

The average wave height of skewed waves is zero:

$$\langle \eta \rangle = 0$$

but the cubed wave height is an indication of the sediment transport. The averaged cubed wave height is not equal to zero:

$$\langle \eta^3 \rangle / \sigma^3 \neq 0$$

Therefore skewed waves usually have a net onshore directed transport. The skewness of waves observed in a laboratory, reached a maximum in the inner surf zone. The skewness decreased towards midswash and then increases in shoreward direction (Cox et al., 2001).

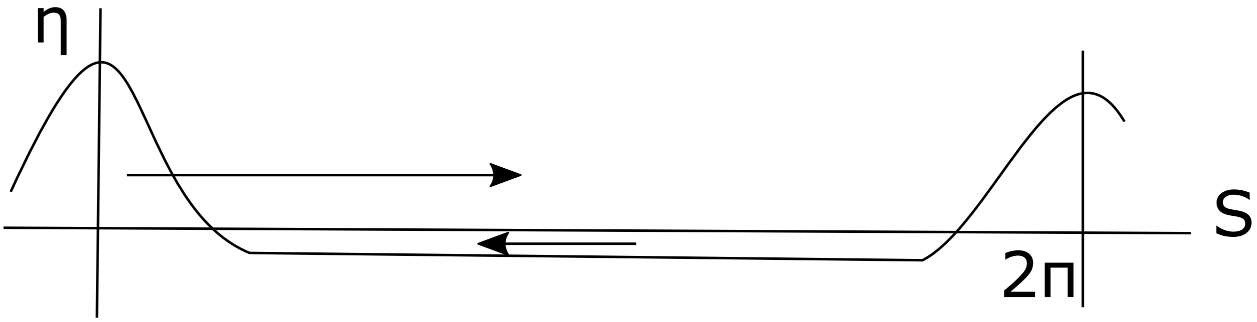


Figure 2.4: Illustration of a skewed wave with net onshore transport.

Skewed waves can also have offshore transport due to phase lag. In this scenario the sediment will be first mobilised by the crest and transported by the trough before it settles (in offshore direction). The phase lag parameter is (Dohmen-Janssen 2002):

$$P_s = \delta_s \omega / w_s = 2\pi \Delta t_{settle} / T$$

In which $s = 13d50$ is the sheet flow layer thickness.
$P_s = 0,1 - 0,3$ (unsteady flow/phase lag) (Ribberink 2008)

When the settling speed is high, mobilised sediment is quickly returned in a tranquil state and therefore there is little phase lag (quasi-steady behaviour).
$P_s <= 0,1 - 0,3$ (quasi steady behaviour)

Butt and Russel [1999] compared 15 minute time series on a gently sloping (0,014) beach. It was found that skewness in midswash was positive during moderate conditions (offshore $H_s \approx 0,80m$), but in opposite direction for storm conditions (offshore $H_s \approx 2,20m$)

2.4.5 Wave asymmetry

Wave crests travel faster in shallow water than wave troughs. Therefore waves get a pitched forward shape until they break. This is called asymmetry. The steep slope of asymmetric waves causes a fast acceleration which enhances the mobilisation of sediments (Drake and Calantoni, 2001). With Stokes theory these type of asymmetric waves can be represented with a second harmonic wave that is forward phase shifted. Elgar et al. [2001], who carried out a field study at Duck, North Carolina, provided evidence of the on-shore sediment transport of asymmetric waves. Laboratory tests by Ruessink et al. (2011) showed that sediment is mobilised more by the crest than trough.

Bar formation is said to be a combination of onshore transport by asymmetric waves and offshore transport by the wave-induced mean current (undertow) (Roelvink and Stive, 1989).

2.4.6 Wave breaking

Waves break when the slope of the waves become too steep. Wave breaking is dependent on the wave period, the local bottom slope and the wave height. Wind can cause the waves to break earlier or later, and therefore wind influences the width of the surf zone (e.g. Dally, 2010).

A breaking wave roller is a conversion of wave energy in a highly turbulent shear layer that moves at roughly the wave speed. The residual turbulence of the breaking wave roller travels downwards in the water column. This turbulence is important for the suspension of sediment and the mixing of currents in the surf zone. Breaking decay is described by Battjes and Stive (1985), Dally et al (1985).

Due to the turbulence of wave breaking the amount of suspended sediment increases, especially in the initial breaking region (Dally et al., 1984).

2.4.7 Entrainment by wave breaking and oscillatory motions

The near-bed fluid motion entrains sediment. Turbulence and vortices carry the sediment into the water column. Larger waves have stronger oscillatory velocities and suspend more sediment. Small waves maintain higher turbulence levels (Dally, 2010).

Outside the surf zone entrainment of sediment is caused by the oscillatory wave motion, currents and low frequency motions. Suspension in the upper column is caused by turbulence that is generated by ripple-wave-current interactions.

In the surf zone the flow under breaking waves enhances the entrainment of sediment. The roller is particularly effective in the suspension of sediment in the upper water column.

Near the breaking zone, long waves create a sheet flow layer in which there is strong entrainment of sediment, but only a little suspension, because there is not much turbulence. In the surf zone the sediment is kept in suspension for a longer time (Kana, 1979; Nielsen, 2002). Ripples are created in the surf zone when the surf zone currents are weak. (When waves have broken the oscillatory motion decreases.)

2.4.8 Set-down and set-up

Due to cross-shore gradients in the radiation stress, created by shoaling, the mean water level offshore of the surf zone decreases. This is called set-down. Maximum set-down is observed at the point of incipient breaking. In the surf zone the momentum flux increases when waves are breaking. Maximum set-up is at the shoreline (Dally, 2010). Wind can also create set-up or set-down.

2.4.9 Cross-shore currents (Undertow)

The net flux of non-breaking waves is nearly zero. The rollers of breaking waves however have a residual flux in direction of wave propagation. This results in onshore transport in the upper part of the column. This is compensated by an offshore directed current in the lower part of the water column: a undertow. It is the most important component for offshore sediment transport (Dally et al., 1984; Dally and Brown, 1995).

Wind can also apply an additional shear stress which must also be compensated. This means that offshore (onshore) wind leads to an onshore (offshore) current in the lower part of the water column.

Undertow is the main offshore component in combination with wave stirring (Mariño-Tapia et al., 2007).

Zhang (2016) observed a sediment resuspension of two orders of magnitude higher than during normal conditions. This was caused by a strong bottom current and increased wave-current interaction.

2.4.10 Longshore currents

The cross-shore gradient of radiation stress in Sxy direction creates a longshore component. Outside the surf zone there is no direct forcing in longshore direction, but the water inside the surf zone drags water out of the surf zone along (Svendsen and Putrevu, 1994).

The longshore component of the wind is also important for longshore currents. It can either be in the same or opposing direction as the wave driven longshore current, leading to either an enforced or attenuated current.

2.4.11 Gravity and Avalanching

When the bed slope exceeds the critical bed slope, there will be sediment exchange in order to reduce the slope to the critical slope (Roelvink et al., 2009):

$$|\delta z_b/\delta x|\; m_c r$$

Avalanching is especially triggered by infra-gravity waves. Infa-gravity waves inundate a section of the beach profile. A chain reaction is triggered as suddenly the critical slope is allowed to be less. When the sediment ends up in the wet profile, it is transported offshore by the undertow and infra-gravity backwash.

2.4.12 Aeolian transport

Dunes grow mainly due to aeolian transport: sediment transport by wind (De Vries et al., 2012). De Vries et al. (2012) used the Dutch JARKUS bathymetryic data to estimate the dune behaviour at a decadal time-scale. In the JARKUS data a positive linear trend was observed that varied alongshore. The dune volume changes were found to be dependent on the beach slope and moisture content; these parameters are limiting factors for aeolian transport. The bed slope influences two parameters: the transport capacity and the threshold that is required for the initiation of motion. No relation was found between wind forcing and dune behaviour on a yearly time-scale. The averaged erosion volumes due to extreme events appeared to be of the same order of magnitude as the growth due to aeolian transport. In the Netherlands a net average transport of 10 $m^3/m/year$ was found. This number is larger in the first couple of years after nourishments (De Vries et al., 2012). For Vlugtenburg dune growth rates were found to be about $30m^3/m/year$.

When the XBeach model results in this study are interpreted, it should be taken into account that XBeach does not include an aeolian transport module. This is not a problem for models that represent a single storm, since aeolian transport is not significant on such time-scales. In long-term models on the other hand, the aeolian transport is a very important recovery mechanism. Therefore dunes that have eroded in a XBeach model, are not able to recover. A XBeach model that predicts the dune profile perfectly might actually give a worse representation of the physics than a model that shows erosive behaviour of the dunes. This also means that evaluation methods as the Mean Squared Error Skill Score (see section 4.6.3) should be handled with great care, as this skill score only evaluates the deviation of the predicted model to the measurements.

3 Theoretical framework XBeach

3.1 General structure of XBeach

XBeach is a model that is able to simulate nearshore hydrodynamics on the time-scale of wave-groups. It is also able to simulate wave-induced currents in combination with the resulting sediment transports and morphology. The sequence of the main components of XBeach is displayed in figure 3.1. A more detailed overview of the components and the formulations is given in figure 3.2. In this section will be elaborated on the general structure of XBeach. A more detailed explanation of the different components can be found in the successive sections.

The scheme of figure 3.1 is looped through continuously until the model time exceeds the specified end time. The model starts by interpreting the initial and boundary conditions. The user can specify the following items as input for the model:

- Wave boundary conditions
- Flow, tidal and surge boundary conditions
- Wind input
- Sediment input
- Bathymetry
- Discharge input

After interpreting the boundary and initial conditions, XBeach solves the wave action balance for the first timestep (see section 3.2 for more details). The short wave action balance solves the short wave propagation. The equations that solve the long wave motions and currents are the Non-Linear Shallow Water Momentum Equations (NLSWE). The short wave action balance provides input for the NLSWE in the form of wave induced forces. It does that in two ways: both with radiation stresses that are from the wave action balance itself and from the radiation stresses that come from the roller energy balance.

Using the input from the wave action balance, the NLSWE are solved. The current velocities (u^L, v^L) and water level variations (h) are provided to the sediment transport equation, which is an advection-diffusion equation (see section 3.7). The Lagrangian current velocities (u^L, v^L) and the water level variations are input terms for the suspended sediment transport equations. The sediment transport that is determined (q_x, q_y) with these equations is corrected for the bed slope effect. Using the incoming and outgoing sediment volumes in each cell, the bottom is updated (using a mass balance). XBeach checks whether the critical wet or dry slope is exceeded and in case it is, applies a correction until the slope meets the required conditions.

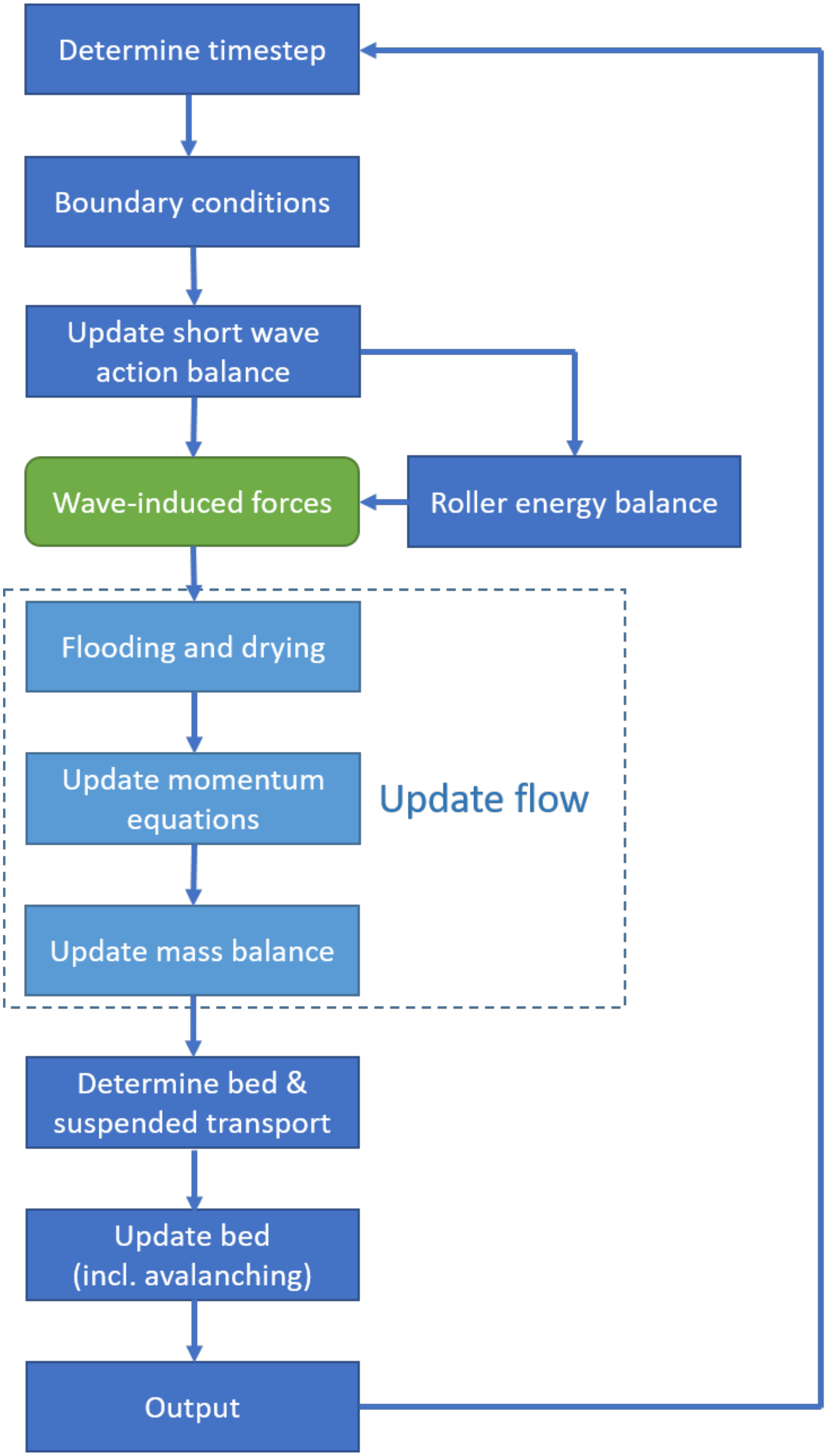


Figure 3.1: Global representation of XBeach (Smit et al., 2010).

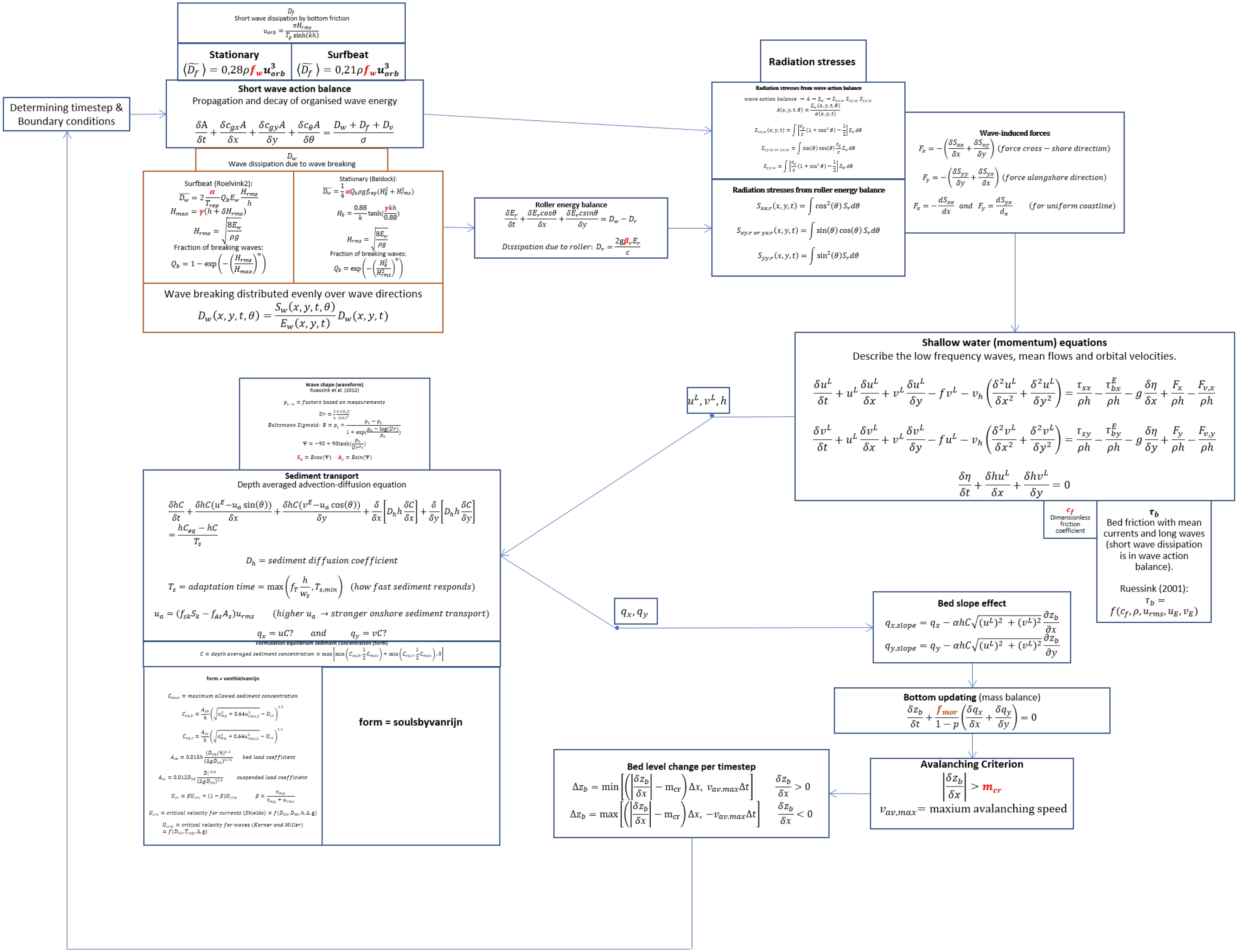


Figure 3.2: Detailed (but incomplete) theoretical framework of XBeach that displays the most important formulations in chronological order.

3.2 Short wave action balance

The propagation and decay of short waves is solved with the short wave action balance (Holthuijsen et al., 1989). This is a function based on a balance of energy, which varies in space (x, y) and time (t) and is a function of the absolute frequency (ω) and direction (θ):

$$E(\omega, \theta; x, y, t)$$

(Gelci et al., 1956). In presence of currents a more relevant parameter for wave propagation is *wave action* which is defined as (Whitham and de Vries, 1965):

$$A(x, y, t, \theta) = \frac{S_w(x, y, t, \theta)}{\sigma(x, y, t)} \tag{3.1}$$

In which:

$$S_w(x, y, t, \theta) = \text{the wave ergy density in each bin} \tag{3.2}$$

The intrinsic frequency is:

$$\sigma = \sqrt{gk \tanh(kh)} \tag{3.3}$$

The wave action balance is:

$$\frac{\delta A}{\delta t} + \frac{\delta c_{gx} A}{\delta x} + \frac{\delta c_{gy} A}{\delta y} + \frac{\delta c_\theta A}{\delta \theta} = -\frac{D_w + D_f + D_v}{\sigma} \tag{3.4}$$

The first term in this equation represents the local rate of change in time of action density. The other terms on the left hand side describe the (net) transport of wave action in the different domains (Holthuijsen et al., 1989). The wave action travels with the group velocity: $c_g(x, y, t, \theta)$. The terms on the right hand side of the wave action balance (equation 3.4) are dispersion terms and form the sink of the equation (a source term could also be added in theory):
D_w = Dispersion due to wave breaking. This term is a source term for the roller energy balance.
D_f = Dispersion due to bottom friction
D_v = Dispersion due to vegetation

The Stokes drift is obtained with the short wave energy (E_w) and direction (θ) from the wave-action balance with:

$$u^S = \frac{E_w cos\theta}{\rho hc} \; and \; v^S = \frac{E_w cos\theta}{\rho hc}$$

3.3 Roller energy balance

When waves break wave energy is temporarily stored in surface rollers.

At the point where waves start to break, the strongest radiation stress gradients would be expected resulting in set-up and longshore currents. In practice there is a delay, because the wave breaking energy is stored temporarily in surface rollers. Wave dissipation due to wave breaking (D_w) is a sink term in the short wave action balance and a source term in the roller energy balance.

The roller energy balance is represented by:

$$\frac{\partial E_r}{\partial t} + \frac{\partial E_r c cos\theta}{\partial x} + \frac{\partial E_r c sin\theta}{\partial y} = D_w - D_r \tag{3.5}$$

In which

$$D_r = \frac{2g\beta_r E_r}{c} \tag{3.6}$$

3.4 Radiation stresses

The radiation stresses form the connection between the short wave action balance and the shallow water equations. The radiation stresses from the wave action balance are obtained by first converting the wave action (A) to the wave energy density in each bin by multiplying it with the intrinsic frequency:

$$S_w(x,y,t,\theta) = A(x,y,t,\theta) * \sigma(x,y,t) \tag{3.7}$$

The radiation stresses that result directly from the energy of the wave action balance are determined with:

$$S_{xx,w}(x,y,t) = \int \frac{c_g}{c}(1+\cos^2\theta - 1/2) S_w d\theta \tag{3.8}$$

$$S_{xy,w\ or\ yx,w}(x,y,t) = \int sin\theta cos\theta \frac{c_g}{c} S_w d\theta \tag{3.9}$$

$$S_{yy,w}(x,y,t) = \int \frac{c_g}{c}(1+\sin^2\theta - 1/2) S_w d\theta \tag{3.10}$$

The roller energy balance is also responsible for the formation of radiation stresses. The roller energy is first converted to wave energy in each directional bin by taking the following partial derivative:

$$S_r(x,y,t,\theta) = \frac{\partial E_r(x,y,t)}{\partial\theta} \tag{3.11}$$

Again the wave energy in the directional bins is decomposed in radiation stresses in the xx, xy, yx and yy direction:

$$S_{xx,}(x,y,t) = \int (1+\cos^2\theta - 1/2) S_w d\theta \tag{3.12}$$

$$S_{xy,r\ or\ yx,r}(x,y,t) = \int sin\theta cos\theta S_r d\theta \tag{3.13}$$

$$S_{yy,r}(x,y,t) = \int \sin^2\theta) S_r d\theta \tag{3.14}$$

3.5 Wave-induced forces

The radiation stresses result in wave-induced forces. The wave-induced forces (F_x and F_y) are forcing terms for the Non-linear Shallow Water Equations (NLSWE).

$$F_x = -\left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y}\right) \text{(forces in cross-shore direction)} \tag{3.15}$$

$$F_y = -\left(\frac{\partial S_{yy}}{\partial y} + \frac{\partial S_{yx}}{\partial x}\right) \text{(forces in alongshore direction)} \tag{3.16}$$

For an uniform coastline (or 1D simulations) the following equations are valid:

$$F_x = \frac{\partial S_{xx}}{\partial x} \tag{3.17}$$

$$F_y = \frac{\partial S_{yx}}{\partial x} \tag{3.18}$$

3.6 Shallow water equations

The low frequency waves, mean flows and orbital velocities are described by the shallow water equations:

$$\frac{\partial u^L}{\partial t} + u^L\frac{\partial u^L}{\partial x} + v^L\frac{\partial u^L}{\partial y} - fv^L - v_h\left(\frac{\partial^2 u^L}{\partial x^2} + \frac{\partial^2 u^L}{\partial y^2}\right) = \frac{\tau_{sx}}{\rho h} - \frac{\tau_{bx}^E}{\rho h} - g\frac{\partial \eta}{\partial x} + \frac{F_x}{\rho h} + \frac{F_{v,x}}{\rho h} \tag{3.19}$$

$$\frac{\partial v^L}{\partial t} + u^L\frac{\partial v^L}{\partial x} + v^L\frac{\partial v^L}{\partial y} - fu^L - v_h\left(\frac{\partial^2 v^L}{\partial x^2} + \frac{\partial^2 v^L}{\partial y^2}\right) = \frac{\tau_{sy}}{\rho h} - \frac{\tau_{by}^E}{\rho h} - g\frac{\partial \eta}{\partial y} + \frac{F_y}{\rho h} + \frac{F_{v,y}}{\rho h} \tag{3.20}$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial hu^L}{\partial x} + \frac{\partial hu^L}{\partial y} = 0 \tag{3.21}$$

In which:

$$u^L = u^E + u^S$$

η = water level
f = Coriolis coefficient
τ_{bx}^E and τ_{sy}^E = bed shear stresses
τ_{sx} and τ_{sy} = wind shear stresses
F_x and F_y = stresses by waves (forcing from the wave action balance)
$F_{v,x}$ and $F_{v,y}$ = stresses by vegetation

The momentum and continuity equations use the Lagrangian velocity u^L. The relation between the Lagrangian velocity and Eulerian velocity is described by the Stokes velocity:

3.7 Sediment transport - Advection diffusion equation

$$\frac{\delta hC}{\delta t} + \frac{\delta hC(u^E - u_a sin(\theta))}{\delta x} + \frac{\delta hC(v^E - u_a cos(\theta))}{\delta y} + \frac{\delta}{\delta x}\left[D_h h\frac{\delta C}{\delta x}\right] + \frac{\delta}{\delta y}\left[D_h h\frac{\delta C}{\delta y}\right] = \frac{hC_{eq} - hC}{T_s} \tag{3.22}$$

When the depth-averaged sediment concentration (C) is higher than the equilibrium concentration (C_{eq}) there is deposition of sediment (sink) and vice versa sediment is entrained in the water column (source). This is represented by the term on the right side of equation 3.22. T_s is the adaptation time, which indicates how fast the sediment responds.

The total equilibrium sediment concentration is determined with:

$$C_{eq} = \max(\min(C_{eq,b}, \frac{1}{2}C_{max}) + \min(C_{eq,s}, \frac{1}{2}C_{max}), 0) \tag{3.23}$$

The equilibrium concentrations of the bed load and suspended load are determined separately. There are two transport formulations available for the equilibrium concentration in XBeach. In this study only de formulation of Van Thiel-Van Rijn is used.

v_{magu} is the Lagrangian transport velocity. u_{reps} is the Eulerian transport velocity that represents the advection velocity from wave asymmetry and skewness (u^a) and the current flow velocity (u^E):

$$u_{reps} = u^a + u^E$$

The direction and magnitude of the net sediment transport are determined by the factors for skewness and asymmetry.

3.8 Skewness and asymmetry

XBeach averages the wave energy of short waves over their wave length. Therefore the wave shape is not solved for (Van Thiel De Vries, 2009). However, when waves approach shallow water, the wave form and orbital motion become more non-linear. The effects of wave non-linearity (skewness and asymmetry) are accounted for in the advection-diffusion equation of the sediment concentration (see 3.22). Asymmetry and skewness are introduced in this equation in the form of u_a which is defined as:

$$u^a = (facSK \cdot Sk - FacAs \cdot As)u_{rms} \tag{3.24}$$

In which Sk and As are parameters for skewness and asymmetry respectively. f_{Sk} and f_{As} are two calibration factors (also referred to as facSk and facAs). Two options are available in which the wave form can be represented in XBeach: the formulation of Ruessink et al. (2012) and the formulation of Van Thiel de Vries (2009).

The formulation of Ruessink et al. is based on a data set of more than of 30000 field observations of skewness and asymmetry under non-breaking and breaking waves. Skewness and asymmetry are determined in the following way:

$$S_k = B\cos(\psi) \tag{3.25}$$

$$A_s = B\sin(\psi) \tag{3.26}$$

In which B is determined by equation 3.27. This function is fitted to measurement data using the factors $p_1\, to\, p_6$. This function is a Boltzmann Sigmoid function. A Sigmoid function is characterised by a S-shape. The top-asymptote in this function is defined by p_2 and the bottom asymptote by p_1. The inflection point is found in between, at a value of $(p_1 + p_2)/2$.

$$B = p_1 + \frac{p_2 - p_1}{1 + \exp\left(\frac{p_3 - log(Ur)}{p_4}\right)} \tag{3.27}$$

And ψ is:

$$\psi = -90 + 90\tanh(p_5/Ur^{p_6}) \tag{3.28}$$

The Ursell parameter (Ursell, 1953) indicates the non-linearity of gravity waves in shallow water and is defined as:

$$U = HL^3/h^3 \tag{3.29}$$

3.9 Bed slope effect

Most transport formulas are based on the assumption that there is a (nearly) horizontal bed. In nearshore zones the bed has a slope which influences the sediment transport as well. This is called the bed slope effect. The bed slope has different ways in which it affects sediment transport (Walstra et al., 2007):

1. Influencing the local near-bed flow velocity
2. Changing the threshold conditions for initiation of motion

3. Changing the sediment transport rate and or direction once sediment is in motion

A formulation is implemented by XBeach in order to account for the bed slope effect in the sediment transport:

$$q_{x,slope} = q_x - \alpha h C \sqrt{(u^L)^2 + (v^L)^2} \frac{\partial z_b}{\partial x} \tag{3.30}$$

$$q_{y,slope} = q_y - \alpha h C \sqrt{(u^L)^2 + (v^L)^2} \frac{\partial z_b}{\partial y} \tag{3.31}$$

These equations are the default formulations. Another option in XBeach is the formula of Soulsby (Roelvink et al., 2015).

3.10 Bed update

For bottomg updating XBeach uses a volume balance (see equation 3.32). In this balance the net incoming or outgoing sediment in x- and y-direction determines the decrease or increase in bed level.

$$\frac{\partial z_b}{\partial t} + \frac{f_{mor}}{1-p} \left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} \right) = 0 \tag{3.32}$$

In the volume balance, f_{mor} is a morphological acceleration coefficient. XBeach provides two methhods with which morphology can be accelerated:

In the first option all input times are divided by morfac (MF). This means that each wave condition lasts $1/MF$ times as short. The bottom changes are multiplied with MF. This method can be activated in XBeach with $morfacopt = 1$ and is applicable for short term simulations with extreme events (Roelvink et al., 2015).

Another option within XBeach is $morfacopt = 0$. In this option a (small) part of the hydrodynamics is taken as being representative for the entire desired period. The internal times of the model are not changed, but the resulting bed level changes are multiplied with MF. The relation between hydrodynamics and morphology is not changed as a result of this. This method is suitable for periods in which the entire period can be well represented by a small amount of the time. This means that this method is not applicable in periods with (irregular) extreme events.

In section A.1.1 (wave input reduction) is elaborated on the method that is used in this thesis to reduce the model computation time.

Avalanching
Avalanching happens when the bed slope exceeds the critical bed slope; in this case there will be sediment exchange in order to reduce the slope to the critical slope (Roelvink et al., 2009). The following criterion is used for avalanching in XBeach:

$$|\frac{\partial z_b}{\partial x}| > m_{cr} \tag{3.33}$$

In which m_{cr} is the critical bed slope. The dry critical bed slope is 1 and the wet critical slope is 0,3. There is a maximum avalanching speed defined in XBeach in order to prevent sudden bed level changes (shockwaves): $v_{av,max}$. Formulations 3.34 and 3.35 give the resulting bed level change in the timestep, including avalanching.

$$\Delta z_b = \min \left(\left[|\frac{\partial z_b}{\partial x}| - m_{cr} \right] \Delta x, v_{av,max} \Delta t \right), \frac{\partial z_b}{\partial x} > 0 \tag{3.34}$$

$$\Delta z_b = \min\left(-\left[\left|\frac{\partial z_b}{\partial x}\right| - m_{cr}\right]\Delta x, -v_{av,max}\Delta t\right), \frac{\partial z_b}{\partial x} < 0 \tag{3.35}$$

Avalanching is especially triggered by infra-gravity waves. Infa-gravity waves inundate a section of the beach profile. A chain reaction is triggered as suddenly the critical slope is allowed to be less. When the sediment ends up in the wet profile, it is transported offshore by the undertow and infra-gravity backwash.

3.11 Differences between XBeach modes

XBeach was originally designed to resolve "the short wave variations on the wave group scale and the long waves associated with them" (Roelvink et al., 2015). This is called surfbeat mode. XBeach also has two other options: non-hydrostatic mode and stationary mode:

- Stationary model: solving wave-averaged equations efficiently. Infra-gravity waves are neglected. This mode is mainly used for moderate wave conditions.

- Surfbeat/Instationary model: resolving short wave variations and associated long waves on the wave group scale. This mode is used when the focus is on swash-zone processes.

- Non-hydrostatic mode: allows non-linear shallow water equations to be solved. Accounts for phase resolved short waves. A pressure correction term is applied. Propagation and decay of individual waves can be used.

The non-hydrostatic mode is not of interest for this study.

In this section is elaborated on the differences between stationary and surfbeat mode. This is done by going through the different components of XBeach step by step (see figure 3.1).

Boundary conditions
It is possible to specify spectral and non-spectral boundary conditions. Generally a specific wave height, direction and period is specified for a certain duration, for example an hour. In stationary mode the incoming wave height, direction and period are constant during this interval. In surfbeat mode, when the option jons_table is used, each row in the table specifies a JONSWAP spectrum for a certain duration. XBeach generates wave conditions for each time-step using these spectral conditions. This results in two different types of wave fields: in stationary mode, the incoming wave height is constant. In surfbeat mode the incoming wave height varies within the interval. An example of the wave height in surfbeat and stationary mode is given in figure 3.3.

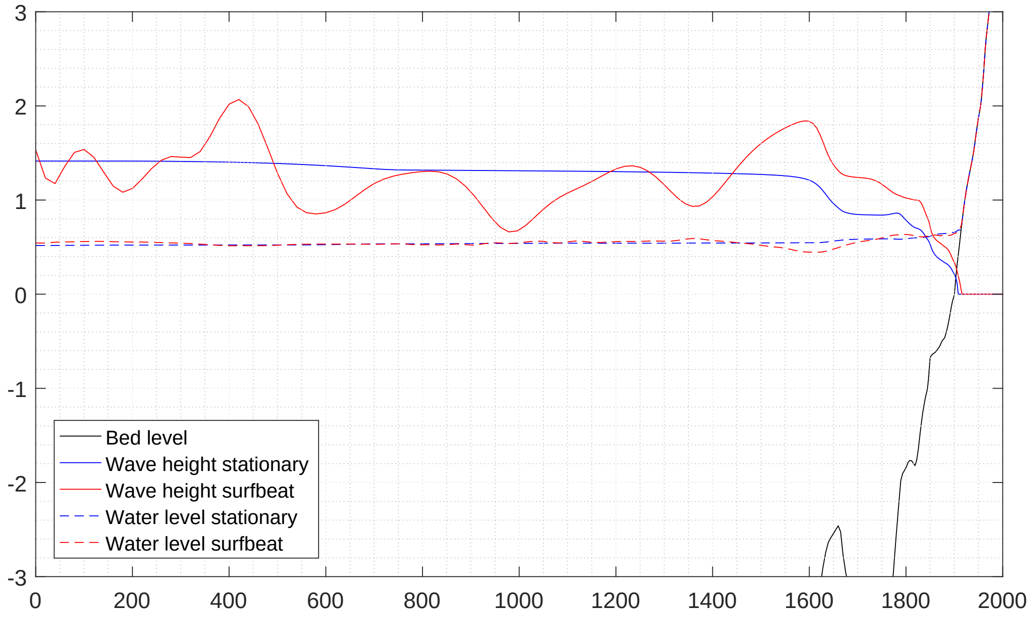


Figure 3.3: Example of wave height and water level variations along the cross-shore direction in surfbeat and stationary mode. Option used for stationary: stat_table, surfbeat: jons_table. Both models have the same boundary conditions (wave height, direction and period).

As explained in section 2.4.1 a wave field that consists out of different wave components with different wave lengths and frequencies, wave groups can be formed. Since in stationary mode solitary waves enter the domain, there will be no wave groups. Therefore also no gradient in momentum stresses is created due to variations in wave groups, hence there is no water level variation or infra-gravity wave in stationary mode. In surfbeat mode on the other hand, wave groups do form and infra-gravity waves are taken into account. In figure 3.3 is visible that the water level in the surfbeat model varies much more in deep water than in stationary mode. This shows that surfbeat mode takes into account the water level variations (or long wave motions) due to the variations in the momentum-flux that is carried by the waves.

Short wave action balance

In the short wave acion balance that is repeated here (equation 3.36) the difference between stationary mode and surfbeat mode is expressed in different ways:

- The coefficient in the formulation for the dissipation due to bottom friction (D_f) is different, although in this study D_f is 0 for both models.
- The breaker model for wave dissipation (D_w) is different: the formulation of Roelvink ($break = roelvink2$) is used in surfbeat mode and the formulation of Baldock ($break = baldock$) is used in stationary mode, because Baldock is valid for wave-averaged modelling. Also the breaker parameter (γ) is different (surfbeat: 0,541 and stationary: 0,78).
- Since the wave heights that are specified as boundary conditions in the stationary model are stationary (not varying in time) the term $\partial A//\partial t$ is zero in this model. Since no gradient in momentum stresses is created due to wave group variations the short wave action balance cannot force water level variations (or infra-gravity waves) in the shallow water equation (due to wave group variations).

$$\frac{\delta A}{\delta t} + \frac{\delta c_{gx} A}{\delta x} + \frac{\delta c_{gy} A}{\delta y} + \frac{\delta c_{\theta} A}{\delta \theta} = -\frac{D_w + D_f + D_v}{\sigma} \tag{3.36}$$

Shallow Water Equations

There are no differences in the Shallow Water Equations themselves in stationary and surfbeat mode, but the differences between stationary and surfbeat mode *do* exert themselves through the SWE. It is explained that in stationary mode the short wave action balance does not force the shallow water equations for wave group variations and therefore infra-gravity waves are not formed. Infra-gravity waves or surfbeat are very important for the location of the swash-zone.

4 Methodology

4.1 General outline of the methodology

In chapter 1.2 the research questions were described. This chapter elaborates on the methodology that will be used to answer the research questions.

This study was intended to improve the performance (accuracy or computation time) of long-term XBeach models by coupling stationary and surfbeat mode. In order to determine the added value of coupled stationary and surfbeat models, a comparison was made between the performance of coupled and singular models: models with only stationary or surfbeat mode. Since the added value of a coupled model could only really be determined when it was compared with singular models that have been used to their full potential, the singular models were calibrated and optimised first. Zimmermann et al. (2015) and Pender and Karunarathna (2013) also performed optimisation studies, but settings are very dependent on the location and therefore the settings for the Australian and Belgian coast are not necessarily the best for the Dutch coast.

In section 4.2 will be elaborated on the settings of the reference model. Also will be explained why Vlugtenburg (The Netherlands) was chosen as location for this study and will be elaborated on the boundary conditions (bathymetry, wave and tide) that are used in the reference model.

Section 4.3 elaborates on the optimisations of the singular stationary and surfbeat models. The methodology for the different sensitivity analysis for asymmetry, skewness, groundwater flow and the option lwave are displayed.

In this study also the added value of 2D models for long-term modelling was discussed. 2D models are different from 1D, even if the 2D model is longshore uniform. One of the main differences is the way in which infra-gravity waves propagate through the model. See section 4.4.

In section 4.5 will be explained in which way the coupled models are created and how they are compared with the reference models.

Section 4.6 elaborates on the evaluation criteria and methods that are used in this study.

4.2 Reference models

4.2.1 Settings

The reference model provides information on the performance of XBeach on long-term modelling using standard settings. A stationary and surfbeat reference model were created. The settings that are specific for stationary and surfbeat mode are displayed in table 4.1.

Both reference model used the WTI settings (see section 2.3). Almost all other settings were kept on the default values that were assigned by XBeach. In table 4.2 the parameters are shown that did not have a default value. These settings are also used in all other models except when described otherwise.

The Morstart parameter is set to a value of 36000s or 10 hours. The Morstart-option freezes the morphologic activity for 10 hours which provides the XBeach model time to develop the hydrodynamic action in the model (wave and currents). A morfac of 5 was used for all models. In section A.1.1 is extensively elaborated on the type of wave input reduction and morphological acceleration coefficient that was used. On the grain diameters is elaborated in the system analysis (section 5). An example of a file in which all defined settings of the XBeach reference model are defined, is shown in appendix G.1.

The results of the different optimisation strategies were compared with the reference model in order to judge whether the strategies had a positive effect on the model performance.

Table 4.1: Settings that differ for stationary and surfbeat mode.

Setting	Stationary	Sufbeat
instat (wave boundary conditions)	stat_table	jons_table
break (breaker model)	baldock	roelvink2
gamma (breaker index)	0.78	0.541

Table 4.2: Most important settings that are used in the reference models for both stationary and surfbeat mode.

Setting name	Seting value	Unit
Boundary conditions	Wave and tide	[-]
Morstart	36000	s
D50	0,0003	m
D90	0,0005	m
waveform	ruessink_vanrijn	[-]
form	vanthiel_vanrijn	[-]
turbulence	wave_averaged	[-]
morfac	5	[-]
lwave	1	[-]
XBeach revision	1.22 Kings Day (rev 5123)	[-]

In morphological modelling studies the term *long-term* is usually used for models of multiple years up to several decades. Using such models in this study was not possible due to the big cumulative computation time. The available data at the Vlugtenburg site was also limited to a couple of years. Therefore was decided to run models for *1 year* (375 days).

Assumption 4.1 *Based on the comparison of different wave directional spreading parameters in appendix B, a value of $s = 7$ was chosen for all model runs. This is close to the default XBeach parameter of $s = 10$. This value is also recommended by Goda (2010) for wind waves.*

4.2.2 Location and bathymetry

For this study was chosen not too work with a fictional case study, but to work with real data. Therefore the various settings could be calibrated and a skill could be determined of each model.

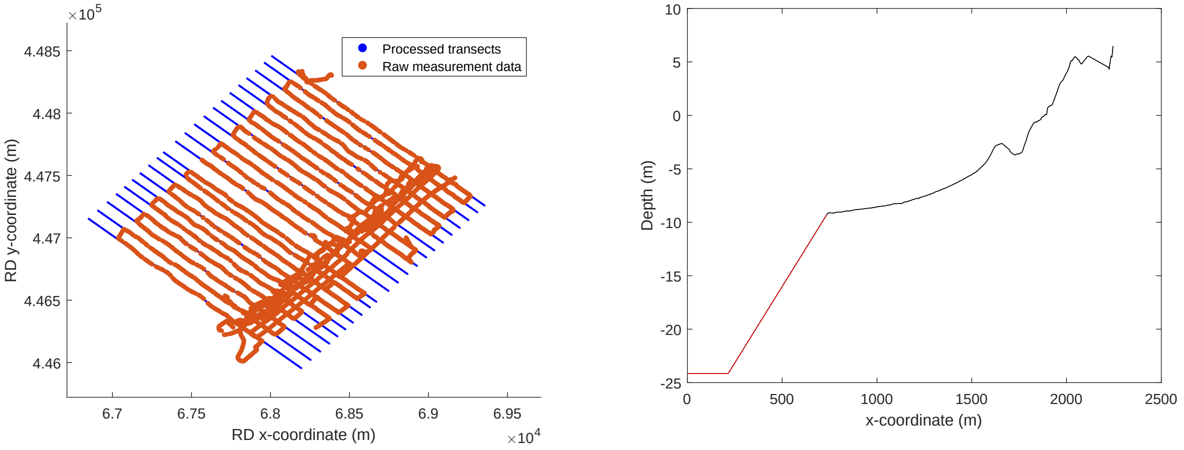
There were only a couple of sites for which long-term high frequency (multiple measurements per year) data was readily available: Duck (North Carolina, USA), Vlugtenburg (The Netherlands) and the SandMotor (Kijkduin, The Netherlands). Another condition was that the survey data was not disturbed by nourishments. Vlugtenburg was chosen, because of its suitability for 1D modelling. The SandMotor at Kijkduin, had too much longshore variability. This made the bed level changes especially sensitive for longshore transport gradients which can't be represented in XBeach 1D. A sensitivity analysis with 2D models would cost too much time. A location in The Netherlands was preferred over Duck (USA), because certain XBeach parameters are already calibrated for the Dutch coast.

The data provided by (De Schipper, 2014) was used to generate bathymetric input for the XBeach model. The data reached a depth of about -9m. In both the XBeach models and the raw data, there is hardly any morphological change below 8m depth. Still it was required to extend the depth of the model, because the available wave data was from the EURO platform which is at a location with a water depth of about 25m. The XBeach model was extended to this depth, using a slope of 1/35 (see figure 4.1b). By doing this the offshore to nearshore wave translation was included in the model. More information on the bathymetric data is provided in the system analysis (section 5).

Assumption 4.2 *Using a slope of 1/35 to extend the bathymetry instead of a more realistic gradual slope does not influence the offshore to nearshore translation of hydrodynamic properties.*

Kolokythas et al. (2016) investigated the sensitivity of the minimum distance between the grid points (dx) and found that for the Sinterklaasstorm there is not a big difference between values of $dx = 0.5$, 1 *or* 2 and therefore $dx = 2$ is used as minimum distance between grid points. The resolution of the grid is lower in offshore zones (up to a maximum of $dx = 20m$).

For all models transect 6 was used. The start date of the model was at survey 27 (16 October 2011) and the end date at survey 37 (25 October 2012), with 375 days in between.



(a) Raw survey data from survey 27.

(b) Extended bathymetry (red) and original processed bathymetry (black).

Figure 4.1: 2D and 1D Bathymetry data (De Schipper, 2014).

Grain diameter

De Vries et al. (2015) provides a value of $300\mu m$ for the D50 at Vlugtenburg. This corresponds with values found at the neighbouring nourishment, the SandMotor (Bart, 2015). The D50 at the SandMotor was on average $318\mu m$. De Vries et al. (2015) describes no value for the D90. At the SandMotor a value of about $510\mu m$ was found for the D90. This value (rounded to $500\mu m$) is also assumed for the Vlugtenburg nourishment.

Assumption 4.3 *Assuming that the grain size distribution at the SandMotor and at Vlugtenburg are similar, as both areas are nourishments, a value of* $500\mu m$ *is taken for D90 based on measurements at the SandMotor ((Bart, 2015)).*

4.2.3 Wave directional grid

The wave direction (the direction that the waves originate from) can be specified in both Cartesian (thetanaut = 0) and Nautical coordinates (thetanaut = 1). When the Nautical convention is used, the waves are specified with an angle relative to North (0°) and in clockwise direction (East = 90°). The Cartesian coordinate system is relative to the x-axis of the bathymetric grid. This means that for a grid with an x-axis from West to East (offshore to nearshore) a wave with an angle of 0° is perpendicularly incoming.

In the Vlugtenburg model, the x-coordinates are specified as distance from the most offshore point, and the y-coordinates are all zeros. XBeach needs additional input for the rotation of the bathymetric grid. This is specified by the Alfa-parameter which is the angle of the computational x-axis relative to the East and in counter-clockwise direction. For Vlugtenburg an Alfa of 318° was used (XBeach can't handle negative values of $Alfa$).

4.2.4 Wave boundary conditions

XBeach has several options for specifying wave input. For this study the *jons_table* option is used in which a series of JONSWAP spectrums is defined. Each of the spectra needs the parameters as specified in table 4.3.

Table 4.3: Parameters that need to be defined when the jons_table (JONSWAP) option is used in XBeach.

Parameter	**Unit**	**Description**
Hm0	(m)	Spectral significant wave height
Tp	(s)	Peak period
mainang	(°)	Wave direction
gammajsp	(-)	Peak enhancement factor of JONSWAP spectrum
s	(-)	Wave spreading
Duration	(-)	Duration of each condition that is specified

The following wave data was obtained from the EURO-PLATFORM: the significant wave height (H_s), wave direction and period. The EURO-PLATFORM data provides an "average wave period from spectral moments m0 + m2 from 30-500 mhz in seconds in surface water". Tm02 is defined as:

$$T_{m02} = \sqrt{m0/m2}$$

XBeach requires a peak period (Tp) to generate waves from a JONSWAP spectrum and therefore Tm02 had to be converted into Tp. Numerical simulations for a JONSWAP spectrum by Goda (2010) provide a factor to translate the mean to a peak period. This factor was used for the transformation of Tm02 to Tp:

Assumption 4.4 $T_p = \boldsymbol{1.25} \cdot T_{m02}$ *Yang et al. (2014) describe that even though Tp and Tm02 have a positive correlation, the relationship does not seem that strong. Therefore the use of this factor will introduce an inaccuracy in Tp.*

4.2.5 Tidal boundary conditions

For the tidal boundary conditions option *tideloc* = 1 is used within XBeach. This means that there is no variation in the water level in the offshore points of the model. Therefore no longshore tidal variations and currents are forced on the model.

4.3 Model settings optimisations

4.3.1 Parameters selected for optimisation

In section 2.3 was described that the WTI parameters are nine specific XBeach parameters that have a big influence on the model results (Van Geer et al., 2015). The WTI settings are optimised for the Dutch coast using measurements from the field and laboratory (1D wave flume) experiments. The WTI settings are only calibrated for 1D surfbeat mode (the parameter γ is also calibrated for stationary mode). Since the WTI settings are optimised for experiments, they do not necessarily result in the best performance of the model at Vlugtenburg. Therefore a sensitivity analysis was carried out to find settings that would result in a better performance of surfbeat and stationary mode in long-term models at Vlugtenburg. Due to time constraints it was not possible to do a sensitivity analysis for all WTI-settings. In literature 2.2 was found that the key processes in cross-shore transport are undertow, wave non-linearities (skewness and asymmetry) and long waves. Therefore only the factors asymmetry (facAs) and skewness (facSk) were selected for a sensitivity analysis.

4.3.2 Sensitivity analysis skewness and asymmetry

The parameter facSk and facAs determine the direction of the net sediment transport (Pender and Karunarathna, 2013) and therefore are expected to be of significant importance for modelling the onshore transport during calm conditions. The models that were run for the sensitivity analysis are shown in table 4.4.

Table 4.4: Models that were run for the sensitivity analysis of the skewness factor (facSk) and asymmetry factor (facAs). All models used a morfac of 5 and the WTI settings were used for parameters other than facSk and facAs.

Mode	**facSk**	**facAs**	**Note**
Stationary or surfbeat	0	0,123	
Stationary or surfbeat	0,1	0,123	
Stationary or surfbeat	0,2	0,123	
Stationary or surfbeat	0,3	0,123	
Stationary or surfbeat	0,375	0,123	Reference model (WTI settings)
Stationary or surfbeat	0,5	0,123	
Stationary or surfbeat	0,6	0,123	
Stationary or surfbeat	0,375	0	
Stationary or surfbeat	0,375	0,123	Reference model (WTI settings)
Stationary or surfbeat	0,375	0,2	
Stationary or surfbeat	0,375	0,3	
Stationary or surfbeat	0,375	0,4	
Stationary or surfbeat	0,375	0,5	
Stationary or surfbeat	0,375	0,6	

4.3.3 Sensitivity groundwater flow module

Besides the mentioned WTI settings, the permeability of the beach is also important during the accretion phase (Jensen et al., 2009). Therefore Pender and Karunarathna (2013) and (Zimmermann et al., 2015) activated the groundwater flow module in post-storm recovery simulations. In this study the influence of the groundwater flow module at Vlugtenburg was tested by switching it on in the stationary and surfbeat model. The model was run with different values for the permeability, k. The following models were compared:

Table 4.5: The permeability (k) was varied in order to investigate the sensitivity of the Vlugtenburg model to the groundwater flow module. The sensitivity analysis was done for both stationary and surfbeat mode. The models used the WTI settings and a morphological acceleration of 5.

Mode	**GW-flow module**	**Permeability**	**Note**
Stationary or surfbeat	ON	k = 0,0001	
Stationary or surfbeat	ON	k = 0,02	
Stationary or surfbeat	ON	k = 0,03	
Stationary or surfbeat	ON	k = 0,04	
Stationary or surfbeat	ON	k = 0,05	
Stationary or surfbeat	OFF	-	Reference model

4.3.4 Sensitivity lwave

When the option lwave is turned on, wave forcing on the non-linear shallow water equations and boundary conditions is possible (Roelvink et al., 2015). This means that the radiation stresses as a result of the gradients in momentum stresses in the short wave action balance are used as input for the NLSWE (through wave-induced forces). This allows for example the infra-gravity waves, set-u and set-down to be included in the XBeach model. Note that turning off the option lwave has a different effect than switching from surfbeat to stationary mode; in stationary mode, infra-gravity waves cannot exist, because the wave input can not cause gradients in momentum stresses (the wave input is stationary). However, in stationary mode the wave dissipation and breaking that is solved in the short wave action balance is still used as input for the NLSWE. When using $lwave = 0$ the communication between the NLSWE and wave action balance is switched off and wave dissipation does not result in set-up or set-down.

The different models that are run to determine the sensitivity of lwave are displayed in table 4.6.

Table 4.6: Models that are run to determine the sensitivity of lwave for stationary and surfbeat mode.

Mode	**lwave**
Stationary	OFF
Stationary	ON
Surfbeat	OFF
Surfbeat	ON

4.4 2D vs 1D

Infra-gravity waves propagate differently through a 2D model than through a 1D model. Since the effect of infra-gravity waves was found to be very significant, it was investigated whether the predictions of 1D and 2D mode were also significantly different.

Transect 6, that was used for the 1D models, was copied 29 times in alongshore direction with 200 meters in between the transects. Together the 30 transects formed a Quasi-2D grid. The reason for copying the grid 29 times was to prevent the formation of shadow zones in the model due to obliquely incoming waves.

dtheta was set to 20 degrees, dividing the wave directional grid into 9 directional bins. The remaining settings that were used in the stationary and surfbeat 2D models were exactly the same as in the 1D models.

4.5 Coupled stationary and surfbeat model

Infra-gravity waves are very important during storms and therefore should be accounted for in periods with more significant wave heights (and therefore more pronounced infra-gravity waves). Stationary mode on the other hand is often used for long-term simulations of relatively quiet climates. The expectation was that a combination of surfbeat and stationary mode would be able to simulate a destructive (erosion) and regenerative (accretion) effect. Besides being able to simulate seasonal effects, using stationary mode in certain parts of the model instead of surfbeat mode was also expected to reduce the total computation time.

The reference models (see 6.2) showed that hardly any regenerative behaviour occurred at Vlugtenburg during calm conditions. From the sensitivity analysis of facAs follows that a $facAs = 0,2$ (see section 6.3) does induce accretion and also creates an equilibrium profile that looks very much like the measurements (at the beach face). It was expected, that with these settings for the asymmetry and skewness, a profile that was eroded in rough conditions using surfbeat mode, would be able to restore to the equilibrium profile using stationary mode.

The tests that were done to investigate the performance of the integrated surfbeat and stationary model are displayed in tables 4.7 and 4.8. The wave conditions in the first 100 days of the model were quite rough. The remaining 275 days were quite calm. Therefore the first part (first 100 days) was computed with surfbeat mode and the second part (275 days) with stationary mode.

Table 4.7: This table displays the different 1D models that are run for analysing the effectiveness of a combined surfbeat and stationary model. Model nr. 1 and 2 are combined models in which first surfbeat was run for 100 days and then stationary for 275 days. The other models are models with either surfbeat or stationary mode. These models are used for reference.

Nr.	**Surfbeat**	**Settings Surfbeat**	**Stationary**	**Settings Stationary**
1	100 days	WTI	275 days	facAs = 0,2
2	100 days	WTI	275 days	facAs = 0,3
3	375 days	WTI		
4			375 days	facAs = 0,2
5			375 days	facAs = 0,3

Table 4.8: This table displays the different 2D models that are run for analysing the effectiveness of a combined surfbeat and stationary model. Model nr. 1 and 2 are combined models in which first surfbeat was run for 100 days and then stationary for 275 days. The other models are models with either surfbeat or stationary mode. These models are used for reference.

Nr.	**Surfbeat**	**Settings Surfbeat**	**Stationary**	**Settings Stationary**
1	100 days	WTI	275 days	facAs = 0,2
2	100 days	WTI	275 days	facAs = 0,3
3	375 days	WTI		
4			375 days	facAs = 0,2

4.6 Evaluation of the model performance

4.6.1 Evaluation criteria

In this study different optimisations were carried out in order to increase the model speed and accuracy; together the speed and accuracy are called the performance. In order to evaluate the accuracy, the model predictions were compared with the survey data. In order to compare the relative accuracy of the models, the models were compared with the reference models. Both qualitative and quantitative methods were used to make the comparisons.

In this study appeared that none of the reference or optimised models gave a (near) perfect prediction; where the one model scored better on the prediction of the beach slope, the other scored better on the prediction of the erosion volumes. Different readers of this thesis, for example: researchers, engineers and contractors might all use different criteria to evaluate the accuracy of the model. The models will be evaluated mainly based on the following criteria, so this needs to be kept in mind when reading the results:

- The volume changes (erosion and accretion) in the profile.
- The slope angle of the profile at different locations: the beach slope, the dune slope
- The distance from the predicted profile to the measured profile. A Mean Squared Error Skill Score (MSESS) is used for this, but this evaluation will also be done qualitatively (by eye).

It might be noted that in the list above, commonly used criteria for the evaluation of a model prediction are not present. In the list that is shown below, a reason is given for that:

- The location of the 0m line: as was mentioned in section 2.4.10 was explained the net longshore transport is the main factor that determines the location of the 0m waterline. The longshore transport is accounted for in the models that are used, but in the 1D and quasi-2D models, the net longshore transport is zero. In the measurements, longshore transport does have an influence. Therefore the location of the 0m waterline is not a good criterion to evaluate the models.
- The bar and trough formation: In some situations it appeared that XBeach was able to *maintain* the bar trough better than in other models, but generally XBeach is not able to simulate the main bar and trough formation (however, it is able to simulate a bar around 0m NAP, see section 6.3)). The bars dissipate in time and are not rebuild during calm conditions. It should be noted that the lack of XBeach to simulate the bar trough behaviour has a big influence on the skill scores.

4.6.2 Volume changes

The various types of volume changes are determined as follows:

- Total volume change $= \int [z_b - z_{b,i}]\, dx$
  This value is expected to be 0, because the net alongshore transport is 0, and no offshore disappears in the cross-shore direction either.
- Total erosion volume: $= \int^{-} [z_b - z_{b,i}]\, dx$
  All negative volume changes in the cells are added up to determine the total erosion volume (denoted with $\int^{-}$).
- Total accretion volume: $= \int^{+} [z_b - z_{b,i}]\, dx$
  All positive volume changes in the cells are added up to determine the total erosion volume (denoted with $\int^{+}$).
- Erosion volume above 0m NAP: at $t = 0$ the waterline (0m NAP) is at $x = 1900m$. The erosion volumes above 0m NAP are determined in the same way as the total erosion volume, but only for points to the right of $x = 1900m$.
- Accretion volume below 0m NAP: The accretion volumes below 0m NAP are determined in the same way as the total accretion volume, but for points left of $x = 1900m$.

In which: z_b = Bed level
$z_{b,i}$ = Initial bed level

4.6.3 Mean Squared Error Skill Score

In order to compare whether the optimisations are resulting in more efficient or accurate models, the models were compared with a reference case. A common method for evaluating the model performance is a skill score. The definition of skill is (according to the glossary of meteorology (2016)) is *"A statistical evaluation of the accuracy of forecasts or the effectiveness of detection techniques"*. The skill score that is most commonly used in comparing bed level changes in coastal engineering studies is the Brier Skill Score (BSS). This skill score should be formally called a Mean-Squared Error Skill Score (MSESS) according to Bosboom et al. (2014a):

$$MSESS\,(orBSS) = 1 - \frac{\left\langle |z_p - z_m|^2 \right\rangle}{\left\langle |z_i - z_m|^2 \right\rangle} \tag{4.1}$$

In which:
z_p is the predicted profile.
z_m is the measured profile
z_i is the initial profile.

The Mean Squared Error Skill Score (MSESS) represents how well the model predicts the bathymetry compared with the initial bathymetry. If the model prediction is equal to the initial profile (nothing happens according to the model), the skill score is 0. If the prediction for a certain moment is equal to the measurement at that moment, the skill of the model is perfect and the score is 1. When the prediction of the model is worse than the initial profile, the score becomes negative. The following classification was given for the MSESS by Van Rijn et al. (2003):

Table 4.9: Classification of Mean Squared Error Skill Scores (MSESS) by Van Rijn et al. (2003).

Score	**Classification**
<0	Bad
0,0-0,3	Poor
0,3-0,6	Reasonable
0,6-0,8	Good
0,8-1,0	Excellent

Bosboom et al. (2014a) pointed out that skill scores do not always represent the researcher's perception of model performance well. An example of this is given in figure 4.2.

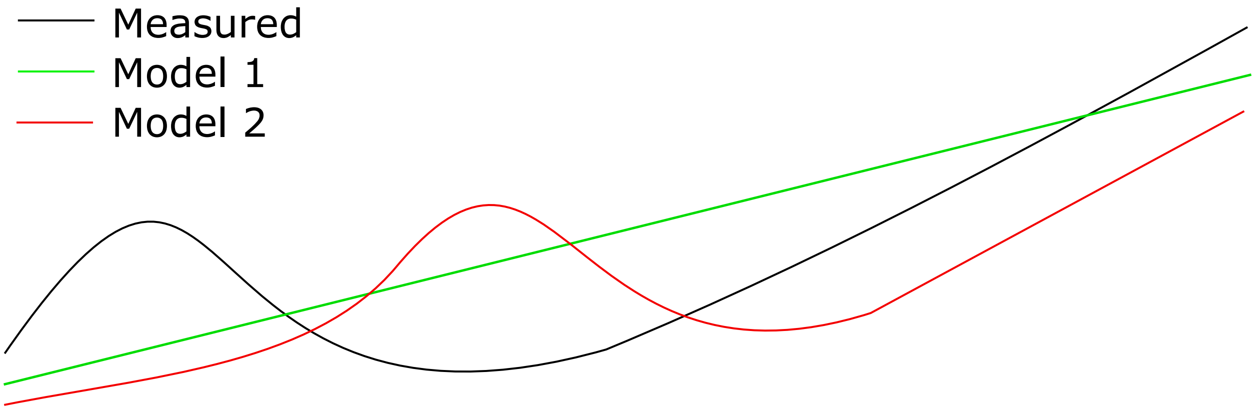


Figure 4.2: Example of different model predictions.

The MSESS is proportional with the absolute error in profile height between the measured and predicted profile. In figure 4.2 the green line (model 1) has a higher (better) MSESS than the red line (model 2) and therefore it would be considered a better model. However the bar behaviour and general profile shape is represented much more accurately by model 2. This phenomenon is called the Double Penalty Effect: *"A high resolution forecast of the same pattern as the observations but missing the observation area scores worse than a low-resolution forecast matching partly with the observation area."* (Zingerle and Nurmi, 2008). If the position of the water line or the total volume of sediment is of importance, model 1 seems to give a better prediction.

The bathymetry that was inserted in the XBeach model reached up to a depth of about 10m. The rest of the bathymetry is fictional. The MSESS is only determined for parts of the bathymetry for which *real* bathymetric data was available. Also parts that show hardly any morphological activity in the survey data and no activity in the model results, are not accounted for in the MSESS. The morphological activity behind the first dune row (at about x = 2100m) is not of interest for the XBeach model and therefore is excluded from the MSESS as well. The MSESS is determined for the entire active morphological zone, but also separately for the zones above and below 0m NAP (see figure 4.3). The boundaries of each of the zones is described in table 4.10 and visualised in figure 4.3.

Table 4.10: Boundaries of the different zones for which the skill scores (MSESS) are determined.

Skill score	**Boundary left**	**Boundary right**
Total MSESS	z-coordinate >= -9m NAP	x-coordinate <= 2100m
MSESS above 0m	z-coordinate >= 0m NAP	x-coordinate <= 2100m
MSESS below 0m	z-coordinate >=-9m NAP	z-coordinate <0m NAP

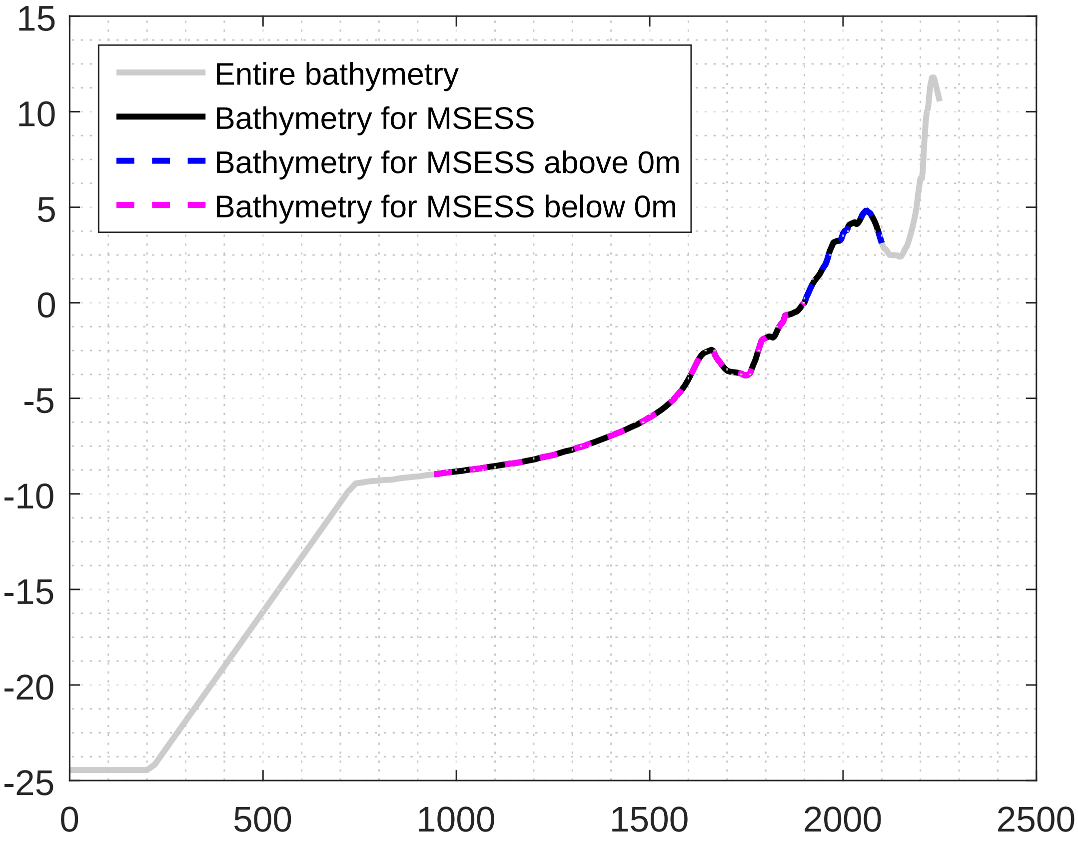


Figure 4.3: Parts of the model bathymetry that are used to determine the MSESS.

5 System analysis

5.1 General information Vlugtenburg

In section 4.2 was explained that Vlugtenburg was chosen as location for this study, because of the high measurement frequency of the bathymetry (monthly surveys) and the suitability of Vlugtenburg for 1D modelling.

Vlugtenburg is located in between Hoek van Holland and 's-Gravenzande, in The Netherlands. The location is displayed in figure 5.1. In the figure the bathymetric survey data, obtained by De Schipper (2014), is displayed. The transect that was used in this study, has been given an orange color (transect 6).

Surveys at Vlugtenburg were carried out in order to investigate a nourishment project called: "Delflandse Kustversterking" which was executed from 2008 on. The nourishment covered all existing beach morphology, including groins. A new artificial dune row was created, forming a dune valley in between the old and new dune row. The cross-shore profile was moved 300m seawards (De Schipper, 2014). From 17 July 2009 to 25 October 2012 De Schipper (2014) conducted 37 surveys in which the bathymetry was measured. Every survey consists of roughly 22 transects with a depth ranging between -9m to +7,5m. The raw data was processed by De Schipper (2014) into 22 straight and parallel transects. These transects were used as input for the 1D XBeach models. The data reached a depth of about 10m. In both the XBeach models and the raw data, there is hardly any morphological change below 8 m depth.

In figures C.1 to C.4 in the appendix the monthly bathymetric survey data is displayed. In each figure two consecutive surveys can be seen and the corresponding wave heights and directions that occurred in between the surveys. It is observed that the beach profile is quite stable, but it becomes slightly steeper during the year.

This study is aimed at the optimisation of 1D models and is focused on cross-shore processes. Vlugtenburg is a location along the Dutch coast at which alongshore processes are also relevant.

In this chapter the following topics will be elaborated on:

- Many nourishments are carried out in the vicinity of Vlugtenburg over the years. How should these be accounted for in the interpretation of the model results?
- What behaviour is observed at the Dutch coast in general?
- What behaviour is observed at Vlugtenburg?

5.2 Selecting the modelling period

As was mentioned in chapter 4 survey number 27 (measured at 16 October 2011) was chosen as starting point and survey 37 (25 October 2012) as the end point of the reference model. In this section is explained why.

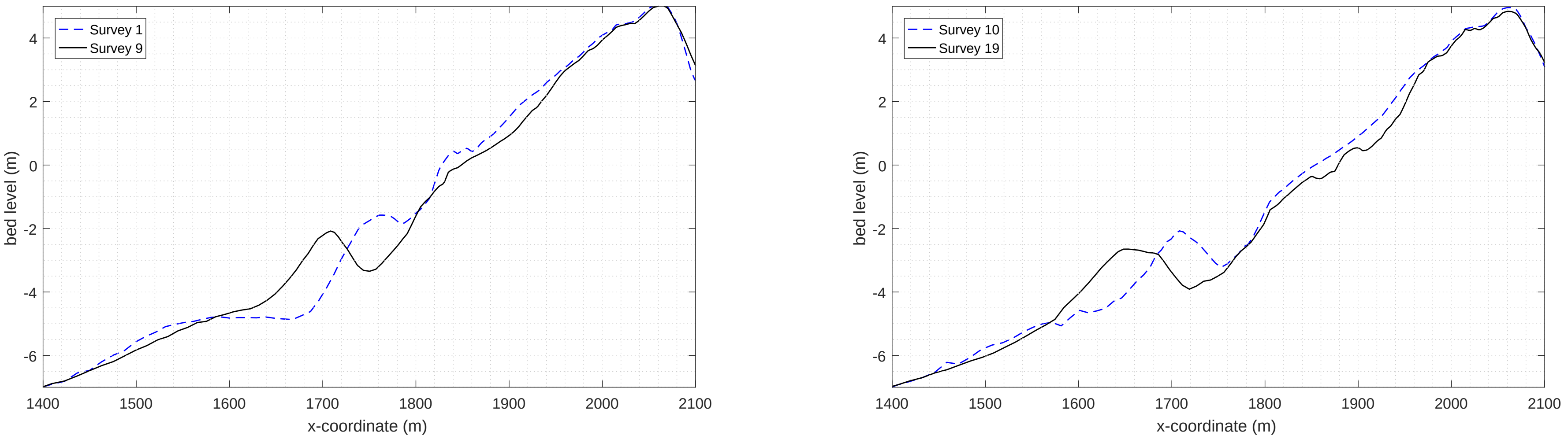
During the first nine surveys the effects of the Vlugtenburg beach nourishments are clearly visible (see figure 5.2a). In the beach nourishment the morphology has smoothed out, especially the bar and trough are much less pronounced. A more natural bar shape has formed at survey 9. XBeach would not be able to model the bar formation between survey 1 and 9. Since bar and trough formation with XBeach is not a goal of this study, the period between survey 1 and survey 9 was found to be unsuitable for the reference model.

In between survey 10-19 and between 27-37 the erosion volumes of the beach and dune are comparable (see figure 5.2). However, in period 10-19 much more bar movement is observed. In period 27-37 the bar only dissipates. Because of the the mentioned reason that bar formation and propagation is not of interest in this study, period 27-37 was found to be more suitable for the reference model.

Figure 5.1: Map that displays a part of The Netherlands, south-east of The Hague. Vlugtenburg is located in between Hoek van Holland and Kijkduin. The survey measurements are displayed in grey. The transect that is used for the reference model has an orange color.

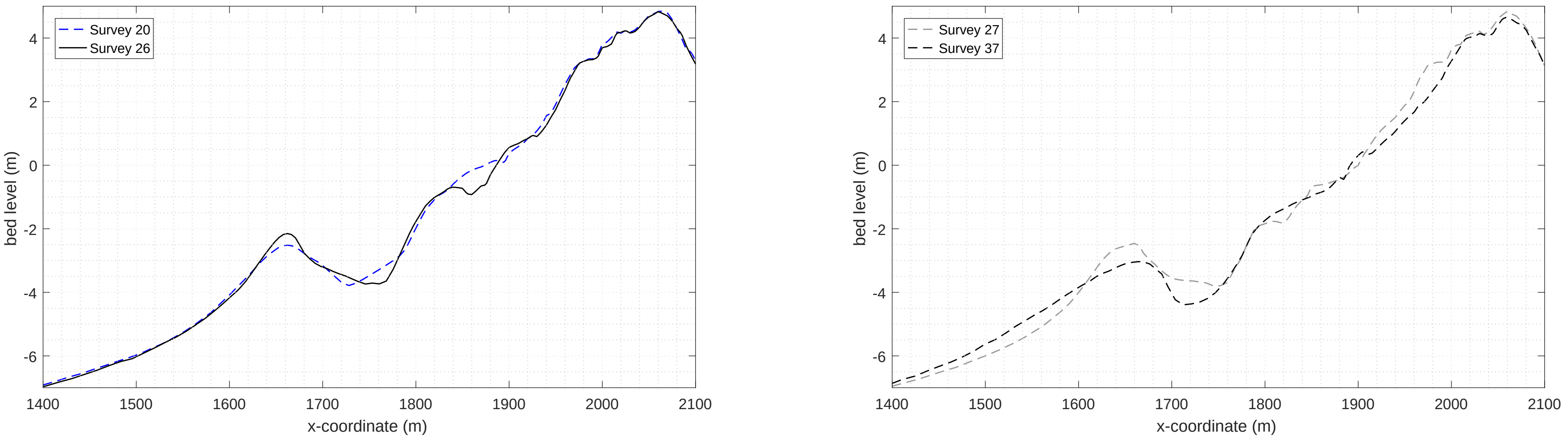
In between survey 20 and survey 26 there are calm conditions and there is not much morphological activity. Also in this period the SandMotor was constructed. In order to compare the model results with reality, it is preferred that a new source of sediment is introduced before or after, and not halfway a modelling period. This is another reason for the reference model starting at survey 27.

It is important to take into account the effect of nourishments on the survey data, because in the 1D XBeach models in this study, no extra sediment source or sink terms are added. This will be elaborated on in the next section.



(a) Survey 1 to survey 9.

(b) Survey 10 to survey 19.



(c) Survey 20 to survey 26.

(d) Survey 27 to survey 37.

Figure 5.2: Bed level changes in between different survey periods.

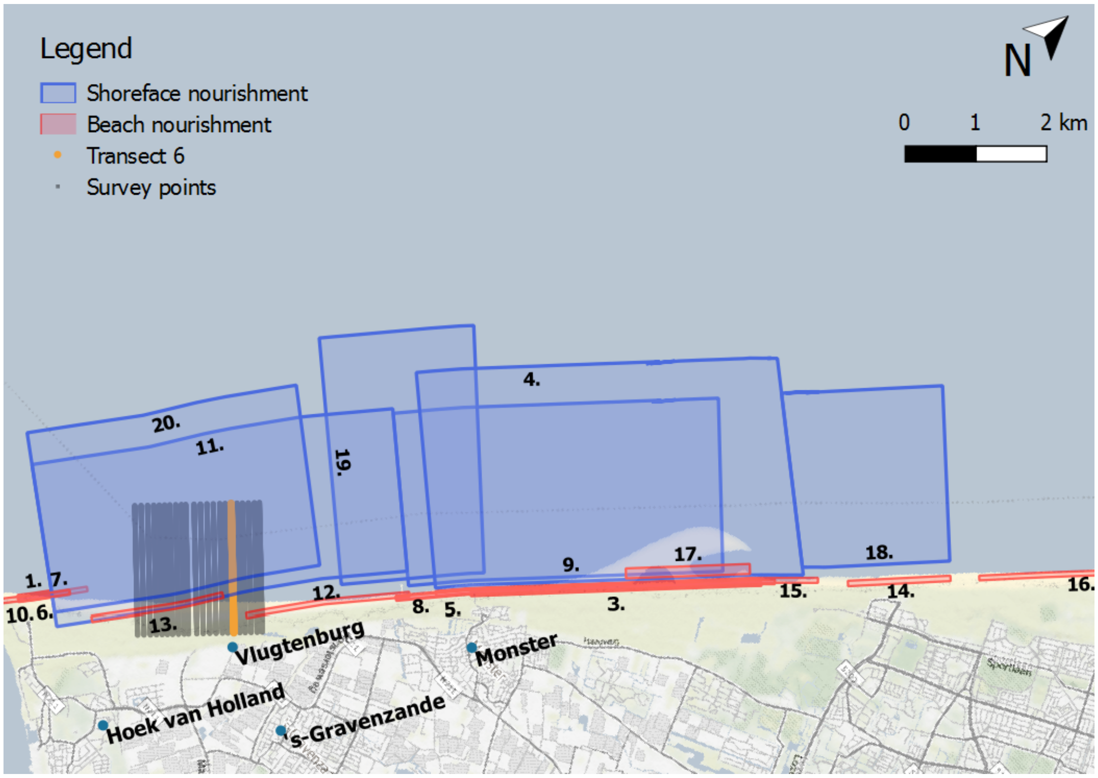
5.3 Nourishments in the vicinity of Vlugtenburg

In The Netherlands many nourishments are carried out to maintain the coastline, also at and in the vicinity of Vlugtenburg. Nourishments affect the morphology directly at the location the nourishments are realised, but also influence the morphology in the vicinity of the nourishments. Because the nourishments are not accounted for in the XBeach models in this study, it is important to take nourishments that have taken place before and during the survey of De Schipper (2014) into account in the interpretation of the results. Therefore an overview has been made of all relevant nourishments. All nourishments that were carried out in the Vlugtenburg area during the survey of De Schipper (2014) or 10 years before that, are displayed in table 5.1 and in figure 5.3. The numbers in the table correspond with the numbers in the figure. The three most relevant nourishments are: the beach nourishment at Vlugtenburg (nr. 13 in table 5.1), the SandMotor (nr. 17) and shoreface nourishment nr. 19.

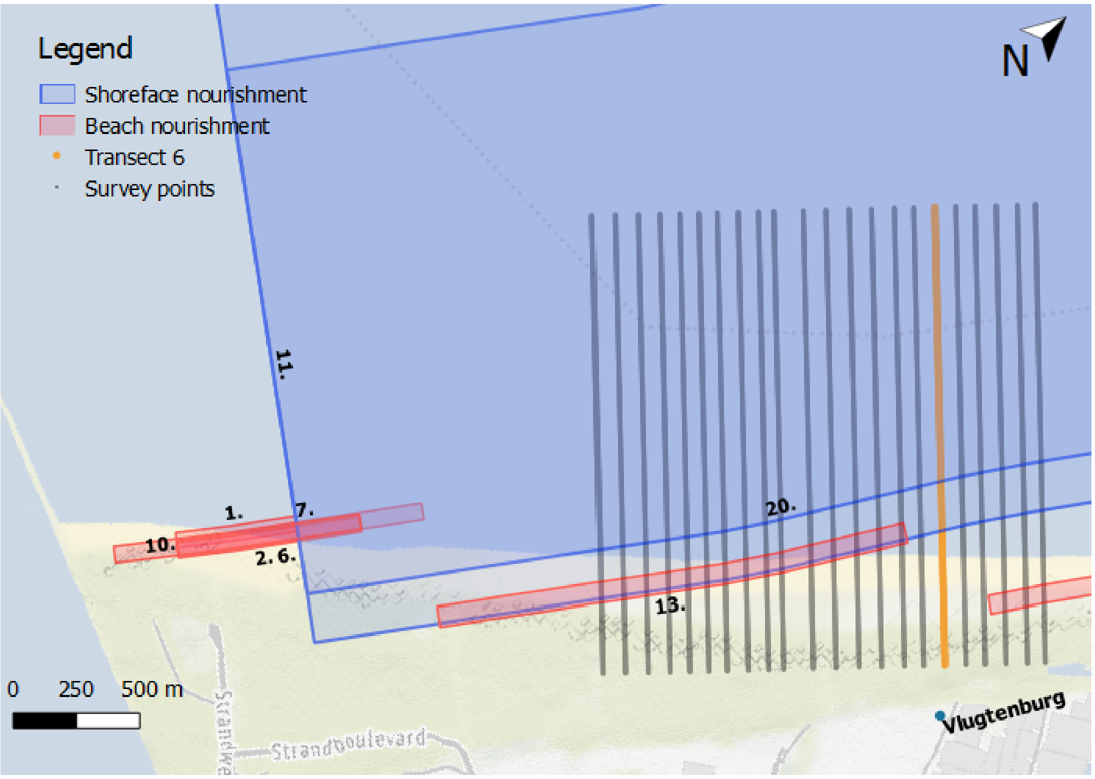
In figure 5.2 is visible that there is structural erosion of the beach and dune face at Vlugtenburg.

Table 5.1: Nourishments that are carried out from january 1999 to October 2013 at or near Vlugtenburg. The numbers in the table correspond with the numbers in figure 5.3.

Nr	**Type**	**Start**	**End**	**Volume** ($10^6 m^3$)	**Volume** ($10^6 m^3/m$)	**Comment**
1	beach	January 1999	December 1999	0.20		
2	beach	January 2000	December 2000	0.20		
3	beach	April 2001	May 2001	0.80		
4	shoreface	March 2001	November 2001	3.00		
5	beach	September 2003	November 2003	1.30		
6	beach	January 2003	December 2003	0.21		
7	beach	April 2004	May 2004	0.23		
8	beach	May 2004	June 2004	1.20		
9	shoreface	October 2005	November 2005	0.90		
10	beach	April 2007	May 2007	0.70		
11	shoreface	July 2007	November 2007	0.80		
12	beach	June 2008	January 2009	3.00		
13	beach	June 2008	October 2009	4.50	2093	Vlugtenburg
14	beach	July 2009	January 2010	3.00		
15	beach	July 2009	December 2010	5.00		
16	beach	January 2010	July 2011	2.50		
17	beach	March 2011	October 2011	17.00	8994	SandMotor
18	shoreface	August 2011	December 2011	0.50		
19	shoreface	August 2011	December 2011	2.00	917	
20	shoreface	July 2013	October 2013	1.50		



(a) Zoomed out.



(b) Zooming in.

Figure 5.3: Nourishments that are carried out between January 1999 and October 2013 are displayed in this figure. The numbers in the figures correspond with the numbers of the nourishments in table 5.3.

5.4 Aeolian transport at Vlugtenburg

De Vries et al. (2015) investigated the aeolian transport at Vlugtenburg. As was mentioned, the aeolian transport at nourished beaches can be higher than the average for the Dutch coast of $10m^3/m/year$ (see section 2.4.12). Vlugtenburg is a dissipative beach that has a sufficient sediment supply for aeolian transport. The volume of growth at Vlugtenburg was about $30m^3/m/year$. Usually an important source for the aeolian sediment transport is the upper beach. However De Vries et al. (2015) did not find a link between the dimensions of the upper beach and the dune growth: no significant erosion of the upper beach was observed due to aeolian processes. One of the explanations that was given by De Vries for the upper beach being static was that heavy deposits could have prevented the lighter deposits below the surface to have eroded by wind. This is called "armoring". Armoring does not occur at the lower beach and De Vries expects (but did not prove) that the origin of the sediment could be found at the lower beach/intertidal beach.

5.5 Vlugtenburg as part of the Dutch coast

The Dutch coast is a sandy coast which can be split into three main parts: the Delta coast in the South, the Holland Coast from Hoek van Holland to Den Helder and the Wadden coast (Mulder, 2000). Vlugtenburg is part of the Holland Coast which is a straight wave-dominated coast.

In the winter season generally erosion occurs caused by storms. In summer seasons there is accretion.

The dominant alongshore sediment transport direction is in North-eastern direction. This longshore transport is sometimes referred to as "The river of sand". However, the Dutch coastal system can be divided in 9 subsystems which are more independent of eachother (Mulder, 2000). The subsystems are divided by both natural and man-made systems. Vlugtenburg is located in the "Hoek van Holland to IJmuiden system". On the North side of this system the border is defined by the breakwaters of IJmuiden and the IJgeul (the navigation channel that has access to the ports of IJmuiden and Amsterdam). On the South of the subsystem the Maasgeul (navigation channel for the port of Rotterdam) and the breakwaters near Hoek van Holland separate the subsystem from the "Delta" subsystem. The Maasgeul and IJgeul both are hard boundaries that do not allow much alongshore sediment transport. Therefore the Holland Coast is a separate system.

Long-term morphological trends over a period of more than 10 years are observed up to depths of -15m. Between -8 and -20m NAP from 1965 to 1995 the Dutch coast had a net loss of sediments in the order of $-5\ Mm^3/year$. In the nearshore zone (above -8m NAP) the sand losses were $-1.5\ Mm^3/year$. In the IJmuiden - Hoek van Holland subsystem the sand-loss is -0.43 $Mm^3/year$ from -8 to -12m NAP (see table 5.2), but the sand balance is positive for the undeep zone (till -8m NAP): +0.25 $Mm^3/year$. (Mulder, 2000).

Table 5.2: Sand balance of the Dutch coast in the different subsystems of the Dutch Coast between 1965 and 1995. Corrected for nourishments (Mulder, 2000).

	Sand Balance ***($10^6m^3/year$)***	
	IJmuiden - Hoek van Holland	**Dutch Coast Total**
Undeep zone (till -8m NAP)	+0,25	-1,5
Deeper water (-8 to -12m NAP)	-0,43	-1,5
Outer delta's (-8m to -20m NAP)		-3,5
Total	-0,18	-6,5

The border of the active coastal zone is about -20m for the Delta Coast and the Wadden Coast, but can be found around -16m NAP for the Holland Coast, but usually also a depth of -20m is assumed as the border for the coastal zone at the Holland Coast (Mulder, 2000).

In 1990 the Dutch Government adopted the "Dynamic Preservation" policy in which a sustainable level of safety and sustainable preservation of values and functions in the dune area was stated as an objective (rws, 1990). Also as a goal was stated that the coastline should be maintained at its 1990 position: this is called the Basal Coast Line (BCL).

5.6 Hydrodynamic conditions

In this section the wave height (Hm0) is displayed during the modelled year. Also the tide and surge is displayed (figure 5.4).

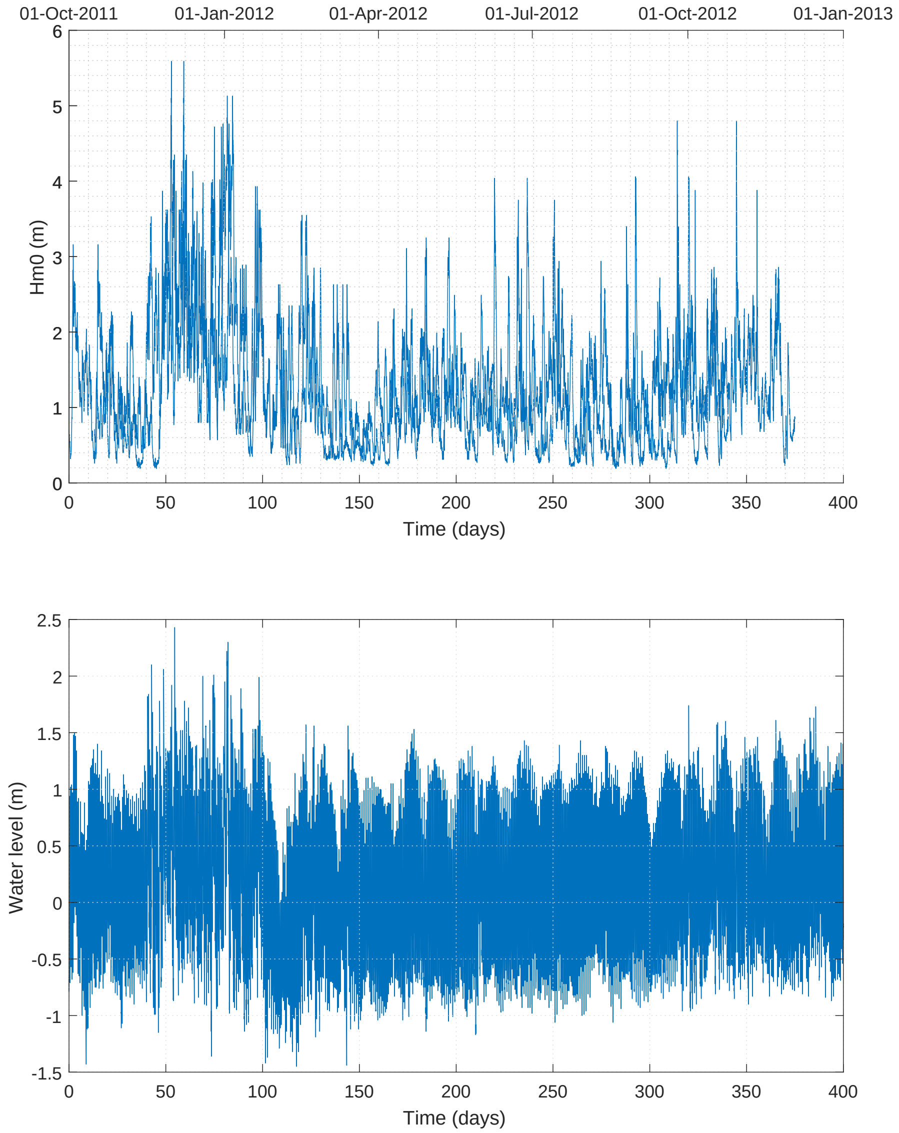


Figure 5.4: Wave height (Hm0) and water level (tide and surge) during the modelled year.

6 Results

6.1 Introduction

In chapter 4 was elaborated on the strategy that was used to be able to determine whether the coupling of a stationary and surfbeat model increases or maintains the model skill relative to a single stationary or surfbeat model. The strategy is briefly summarised here:

In order to compare the performance of an integrated stationary and surfbeat model against a single stationary and surfbeat model first reference models were made. The reference models display the status quo: what is the performance of single stationary and surfbeat without optimisation (using the WTI settings)?

Before an actual coupling of surfbeat and stationary mode was made, the *potential* of the single surfbeat and stationary mode was investigated with multiple sensitivity analysis. This was done because the added value of a coupled model can only be really determined when it is compared with single models that have been used to their full potential.

The following attempts at optimising the single stationary and surfbeat models were done:

- finding the optimal settings for asymmetry (facAs) and skewness (facSk)
- discovering whether the groundwater flow module helps to keep the beach and dune profile stable

The optimal settings themselves are not the most interesting outcome of the sensitivity studies, because the settings are very dependent on the location (in this case Vlugtenburg). However, the sensitivity studies provide a lot of insight in which way the parameters affect the model result and in which way stationary and surfbeat mode can be used in a coupled model. With this knowledge recommendations regarding long-term modelling can be given that are independent of the model site.

Stationary mode disregards the infra-gravity waves. The models can be further simplified by switching off the short wave forcing on the Non-Linear Shallow Water Equations *entirely.* This can be done with the option $lwave = 0$. This provides information on the performance of more simplified models on the long-term. Also in this way the the influence of infra-gravity waves versus processes as set-up and set-down can be compared (these processes are ignored when $lwave = 0$).

A comparison is made between 1D and 2D models, because 2D models handle the infra-gravity waves differently than 1D models and are potentially better suitable for long-term (coupled) models.

A sidestep has been made in this study; it was investigated below which wave thresholds the waves did not contribute to the model results. With these thresholds periods with waves of irrelevant heights can be skipped. The results of this study are elaborated on in appendix A.

This chapter will display the model results and describe the behaviour that is seen in the different models. Besides that it will provide information on how the different optimisations can be used in coupling the stationary and surfbeat model.

6.2 Reference models

6.2.1 Performance of reference models after 1 year

The reference models are models with the WTI settings (see section 2.3.1). The reference model starts at survey 27 and ends 375 days later, at survey 37.

In figure 6.1 can be seen how well the stationary and surfbeat reference models perform in a simulation of about 1 year (375 days) compared with the corresponding bathymetric surveys that were carried out at the start and end of the simulation period.

Both in the reference models and the bathymetric data the depth at which morphological changes are observed (depth of closure) is about -7m NAP. However, both reference models show significantly more dry shoreface and dune erosion. Both models show more accretion in the wet active zone than is observed in the surveys. Also both reference models show a much more smoothed morphology than reality; in both models the entire bar-trough feature disappeared, while in reality the bar still exists but moved in offshore direction.

Figure 6.4 displays the Mean Squared Error Skill Scores (MSESS) at various points in time within the 375 day simulation period. A negative MSESS indicates that the model does a worse job at predicting the final bathymetry than the do-nothing scenario (the initial bathymetry). A score of 0-0,3 is considered poor, 0,3-0,6 reasonable, 0,6-0,8 good and 0,8-1,0 excellent. At t = 375 days the MSESS of the stationary model is -0,6. The MSESS of the surfbeat model is about -5,6. The observation that the performance of stationary mode in long-term models is much better than the predictions of surfbeat mode is in line with Pender and Karunarathna (2013) and Zimmermann et al. (2015).

6.2.2 Observations during the modelled year

The morphological activity quickly decreases during the first few months. After this period the cross-shore profile is only changing very slightly.

In figure 6.3 the change in time of the total erosion and accretion volumes are displayed.

The figure also displays the volume and accretion volumes above and below 0m NAP. This is 0m NAP in the initial bathymetry and not necessarily in the bathymetry in other time-steps. The erosion and accretion volumes in the figure give an overview of the morphological activity in time. From the figure becomes clear that the total erosion is equal to the total accretion at all times (there is no net volume change over the whole cross-section), which is expected as no volumes are lost in cross-shore or longshore direction.

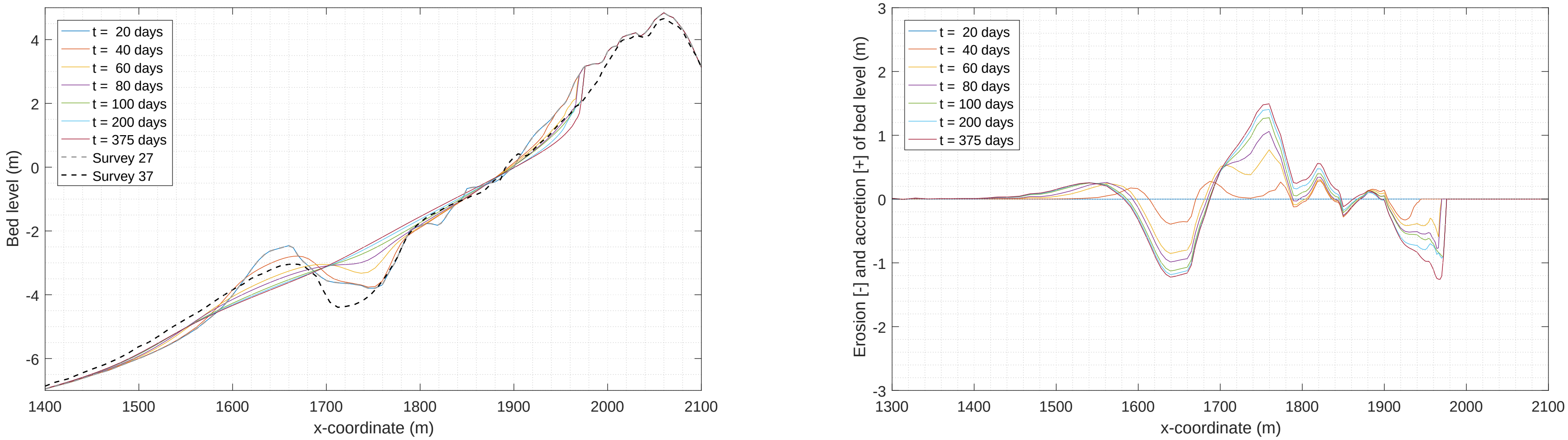
In both the stationary and surfbeat model there is only moderate morphological activity in the first 40 days, as can be seen in the stable erosion and accretion rates. At t = 50 days there is a steep increase in the cumulative erosion and accretion. This coincides with the high wave conditions (up to 5,5m offshore). Between the 40th and 100th day almost all the morphological activity takes place. It is notable that from day 150 on the gradient in the cumulative erosion volume in the stationary model is *bigger* than in the surfbeat model.

The bar does not disappear in the survey data, but it dissipates in both models and is completely gone after three months. In the surveys is observed that the location of the bar stays nearly the same (a small movement in onshore direction is observed). The bar location stays the same in the first few months in surfbeat mode. In stationary mode the bar moves more in onshore direction than the bar in the survey data. Stationary mode displays the forward tilted (saw-tooth shaped) shape of the bar better in the first months.

Between day 60 and 70 it is noticeable that the erosion volumes increase in the surfbeat model and are fairly constant in the stationary model. (verder uitwerken, wat voor type condities)

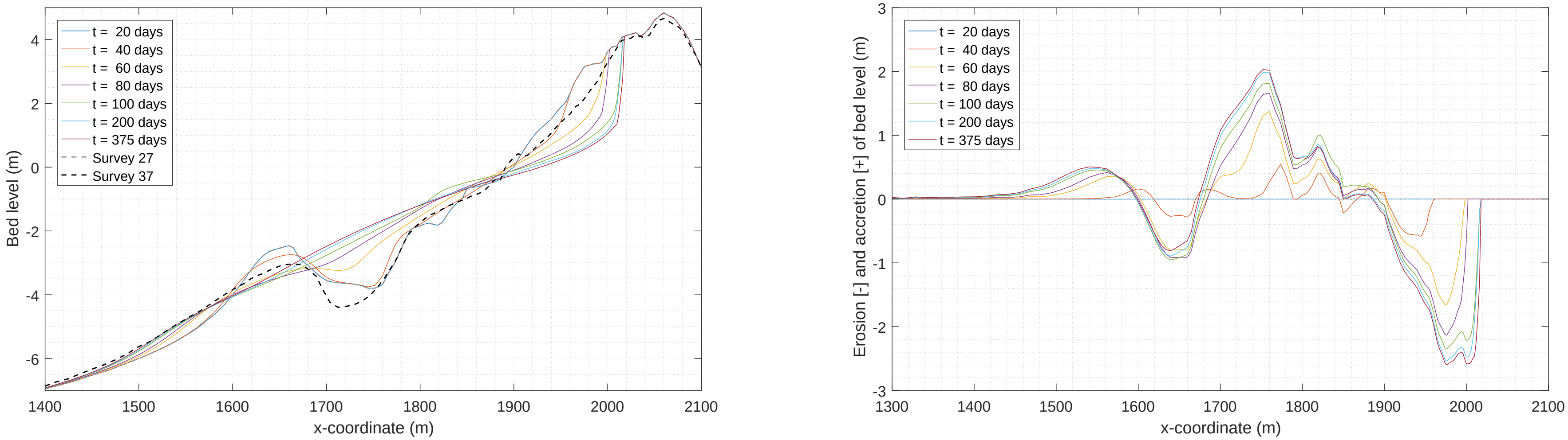
The patterns of accretion and erosion in the surfbeat and stationary simulation are almost identical, only the magnitude of the erosion and accretion differs: the cumulative erosion and accretion (ca. $140m^3/m$) in the stationary model is twice as small as in the surfbeat model (ca. $270m^3/m$). When the erosion-sedimentation-figures are compared (figure 6.1b and 6.1d) can be observed that the sedimentation and erosion in the surfbeat model is a magnitude bigger than the erosion and sedimentation in the stationary model. The most noticeable difference is observed between x-coordinate 1900-2050m (the beach and dune face).

The Dutch coast typically shows seasonal behaviour. This means that during summer a summer-profile with steeper slopes is created and during the winter a winter-profile with mild slopes. This behaviour is visible in neither the stationary and surfbeat simulation. In fact, the simulations do not show *any* signs of accretive behaviour.



(a) Stationary - Bed level change in time.

(b) Stationary - Erosion sedimentation.



(c) Surfbeat - Bed level change in time.

(d) Surfbeat - Erosion sedimentation.

Figure 6.1: Morphological activity in time from the reference models (bed level change, sedimentation and erosion).

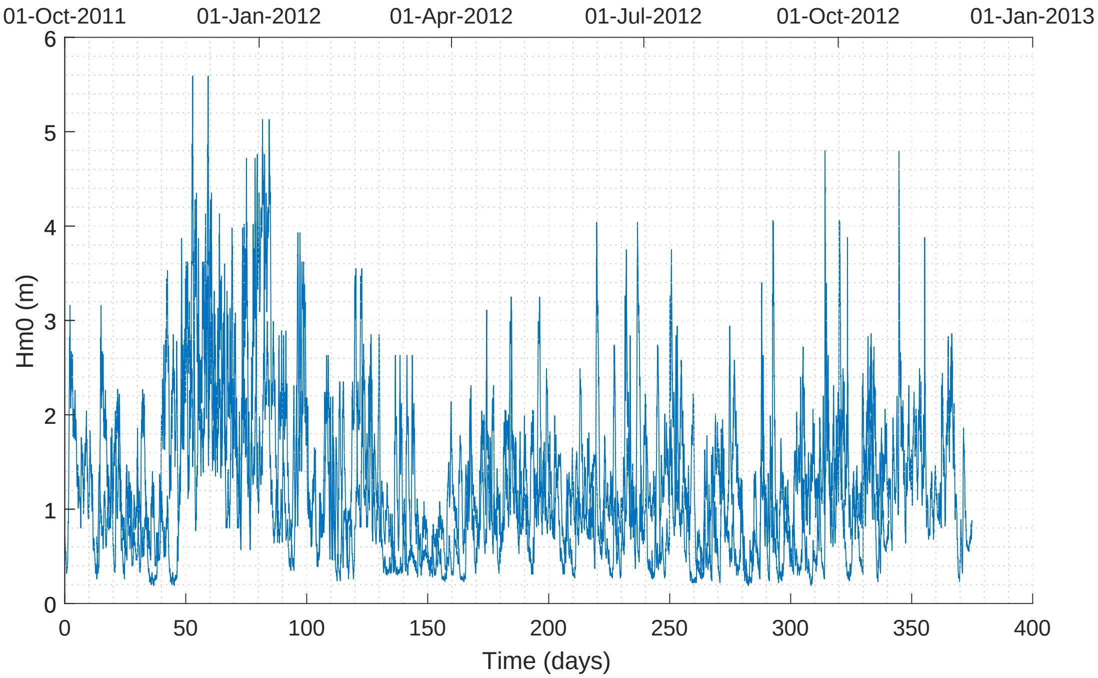


Figure 6.2: Wave height (Hm0) as measured at the EuroPlatform.

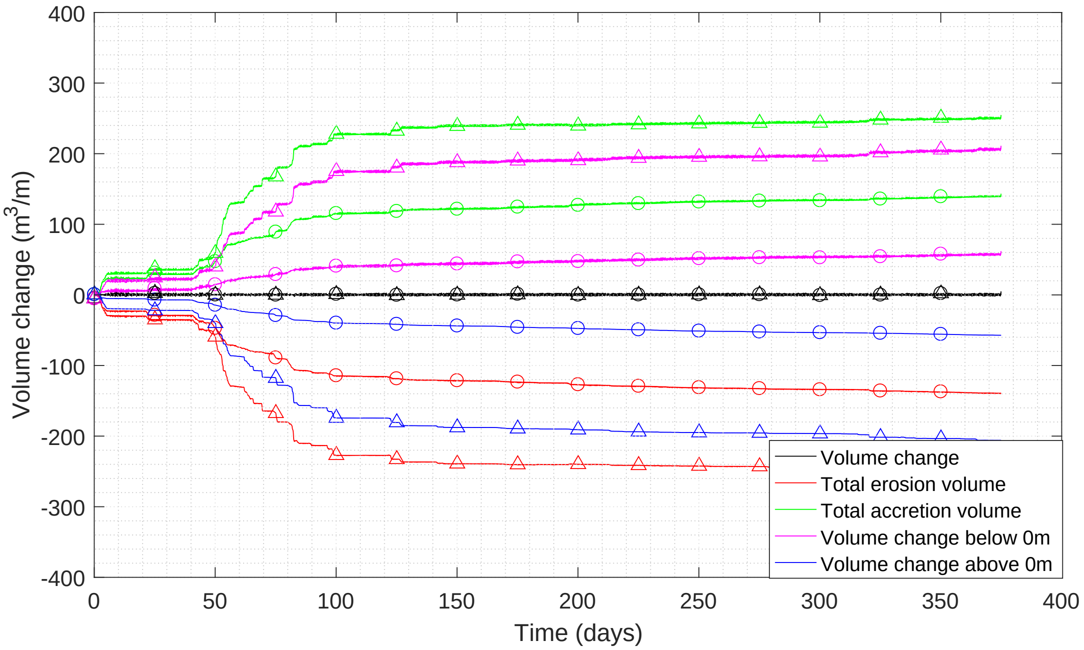


Figure 6.3: Comparing the cumulative volume change in time compared to the initial bathymetry for stationary mode (o) and surfbeat mode (Δ).

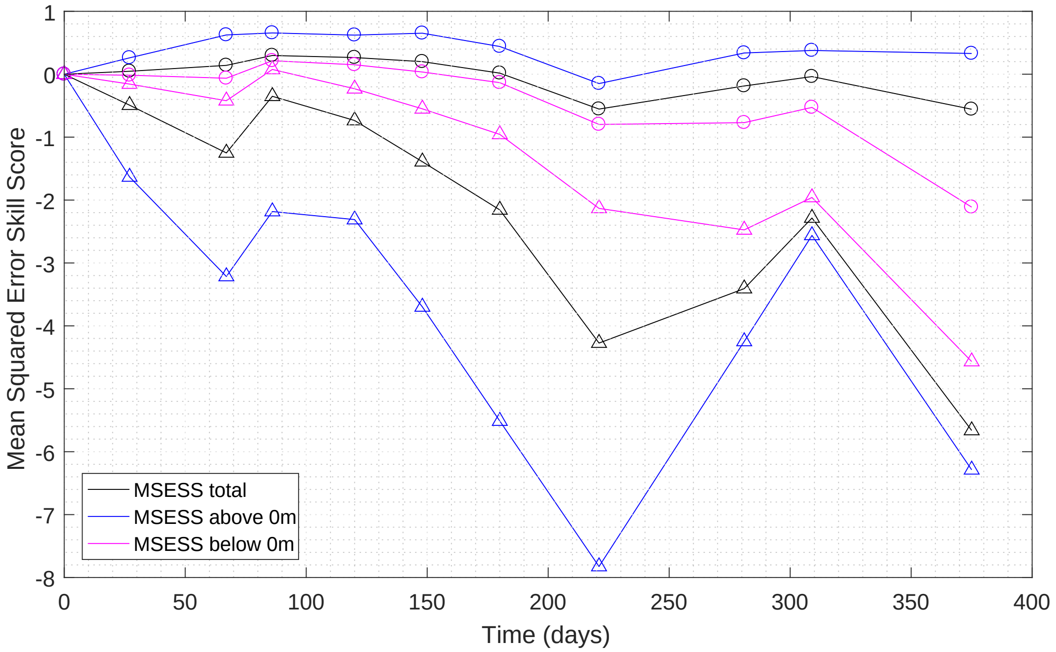


Figure 6.4: Comparing the Mean Squared Error Skill Score (MSESS) in time for stationary mode (o) and surfbeat mode (Δ).

6.3 Model settings optimisations

In section 4 is described that a sensitivity analysis was done for three parameters: facSk (wave skewness), facAs (wave asymmetry) and k (soil permeability). The sensitivity analysis were carried out in order to determine whether there are more optimal settings for long-term modelling than the default/WTI settings at this specific site in The Netherlands. With these “optimal" settings the full potential of stationary and surfbeat mode could be compared with the coupled models. Besides the contribution of the sensitivity analysis to improved settings for long-term modelling, another objective was to achieve a better understanding of what the factors facAs, facSk and k do in XBeach.

6.3.1 Sensitivity skewness and asymmetry

In the reference models no regenerative behaviour was observed. The factors for asymmetry (facAs) and skewness (facSk) can increase the onshore transport. This chapter elaborates on the sensitivity analysis for these factors that was executed in order to see whether the profile slope of the beach and dune could be better maintained or restored.

In the sensitivity analysis both factors were varied between 0 and 0,6 while keeping the other factor on a constant value (the WTI value). The results of the sensitivity analysis of facAs are displayed in figure 6.6 and the analysis of facSk in figure 6.7. In all of the figures the models go more or less through one point, this will be called the intersection point. Generally was observed that for a higher value of facAs or facSk a bigger portion of the total sediment volume ended up nearshore (or above) the intersection point and less below. Therefore the amount of dune and beach erosion decreases. Since this was overestimated in stationary and surfbeat mode, the skills score of the models increase when facAs and facSk are increased. The sediment that is transported onshore mainly ends up in the area between 0m and +1m NAP when facAs was increased and between -1m NAP and 0m NAP when facSk was increased. For higher asymmetry ($facAs => 0,2$) and skewness ($facSk => 0,5$) factors a sufficient amount of sediment was transported in onshore direction to form a bar or berm.

The bar that can be found between -3 and -5m NAP in the initial bathymetry completely disappears in all models.

Besides a change in the overall sediment volume distribution, the skewness and asymmetry factors affected the slope angle. The skewness factor seemed to be an effective parameter to adjust and calibrate the profile slope between -1,5m and 0m NAP. The asymmetry factor on the other hand mainly influenced the profile slope between +0,5m and +2m NAP. By adjusting the profile slope and reducing the eroded volume after 375 days, the skill of the stationary and surfbeat models could be increased. The skill scores (MSESS) are displayed in tables 6.1, 6.3, 6.2 and 6.4. Also a graphic representation is given in figure 6.8.

As can be seen in figure 6.8 for the stationary model the optimal skill score was found to be for a factor of ($facAs = 0,2$): the skill score increased from -0,80 (WTI) to -0,39 (facAs 0,2) and above 0m NAP the MSESS increased from 0,33 to 0,50. For surfbeat mode the skill scores also increased for certain model settings, but none of the settings contributed to a better prediction of the profile slopes. It was observed that in stationary mode the WTI settings rank among the top three best settings for the three different types of MSESS. In surfbeat mode however, the performance of the WTI settings to the other settings is average. One would expect that the WTI settings would be optimal settings, as they are calibrated for the Dutch coast (surfbeat mode), however, XBeach seems to be quite insensitive for the grain diameter according to a study by Zimmermann et al. (2015). The WTI settings are calibrated for a model with a finer grain diameter than $300\mu m$ (unknown which exact value). Normally a steeper slope is expected when the grain diameter increases in the model, but XBeach needs additional calibration of the asymmetry and skewness factors to cope with a changing grain diameter. This is the reason why the WTI settings are not the optimal settings for the nourished area at Vlugtenburg, with a more course grain diameter.

Besides the fact that the dune and beach erosion in surfbeat mode is much more significant than in stationary mode, also another important difference was observed in the regenerative behaviour of the models: the accretion area is higher above NAP in the stationary model. Sediment is deposited up till a height of +2m NAP in stationary mode and only up till a height of +1m NAP in surfbeat mode. It is expected that this difference is caused by the infra-gravity backwash in surfbeat mode.

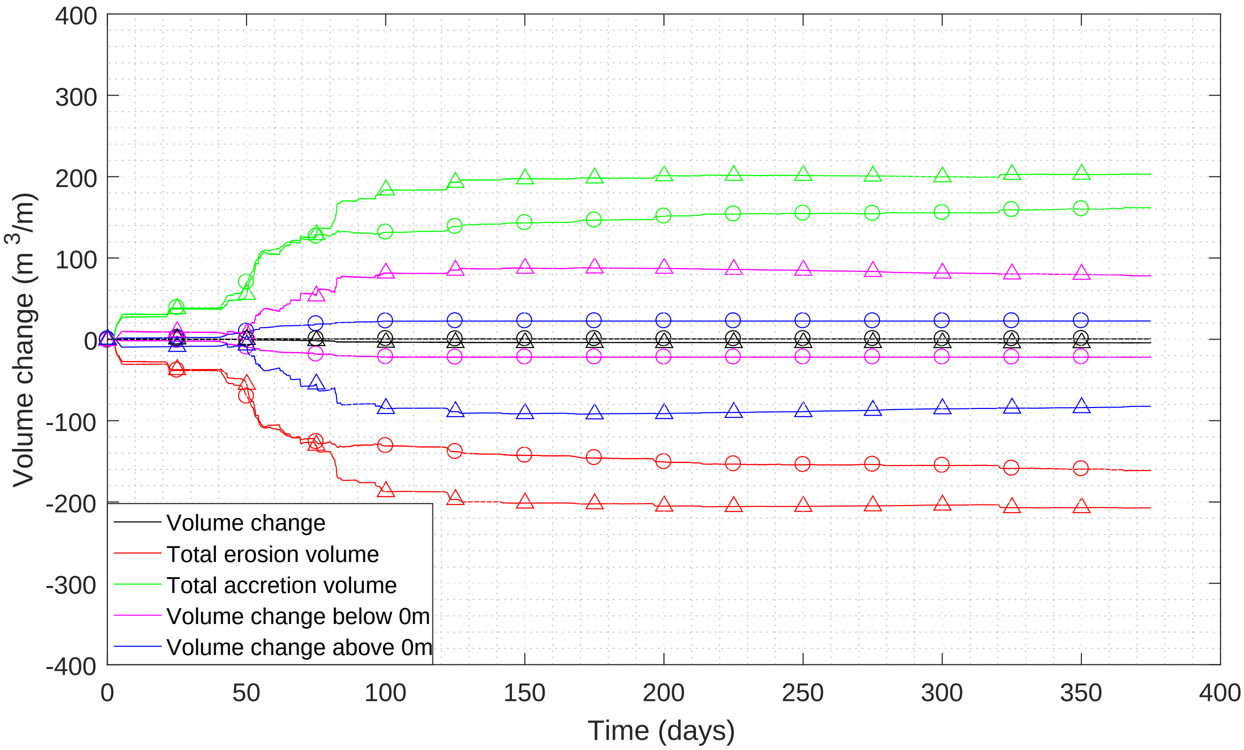
From this sensitivity analysis follows that settings for asymmetry and skewness can improve the skill of the stationary model by improving the estimation of the erosion volumes and profile slopes. Even though the onshore transport can be increased in surfbeat mode, the eroded dune volumes cannot be mitigated with increased settings for facSk and facAs. The problem is twofold:

- The dune erosion is overestimated in surfbeat mode due to the effects of infra-gravity waves. The erosion volumes that are observed in the model are not encountered in the monthly surveys.
- Sediment is not transported far enough up the beach and dunes. The capabilities of XBeach to restore an eroded dune are lacking.

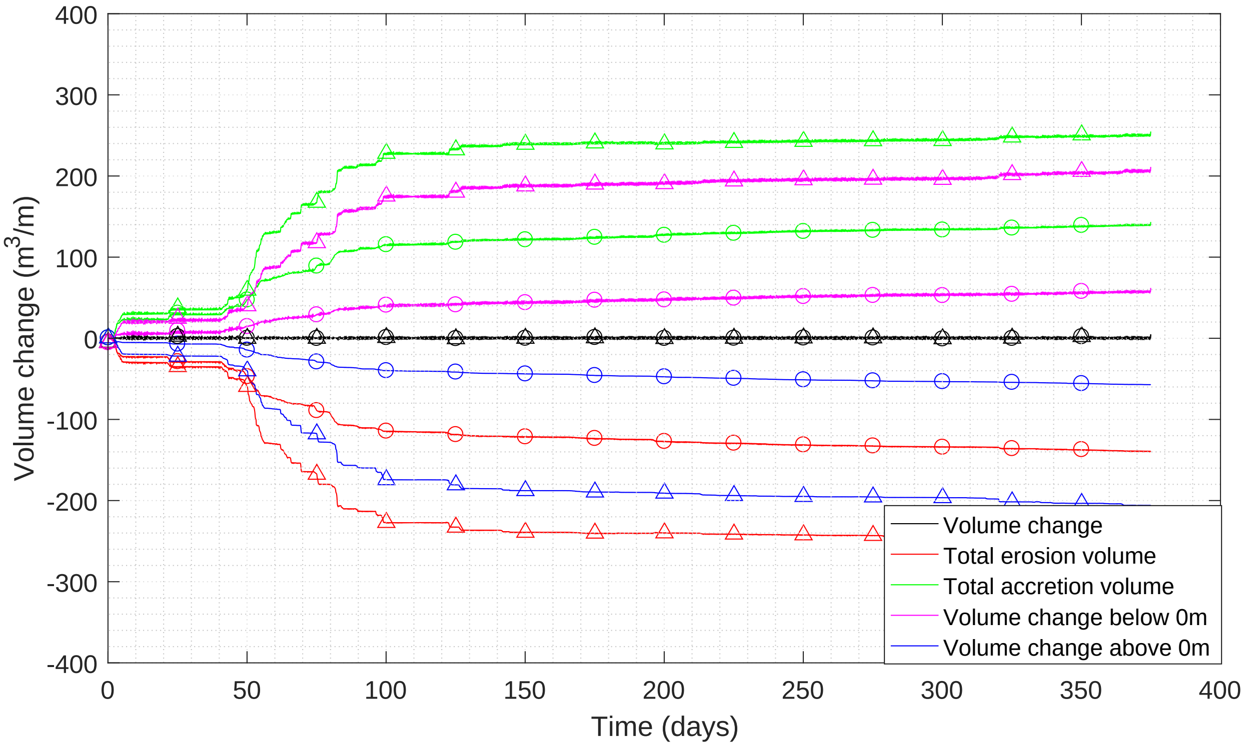
In reality aeolian transport is an important mechanism for the transport of the deposited sand in the nearshore zone to the dunes. This process is not important on the time-scale of a storm, but it is on the time-scale of a year (see section 2.4.12). The aeolian transport is even more important the first few years after a nourishment, which is the case in Vlugtenburg. The dune and upper beach growth at Vlugtenburg is about $30m^3/m/year$ (see section 2.4.12). It has to be taken into account that this volume is spread over the entire upper beach, dunes and dune valley. The exact distribution is unknown.

The overestimated dune erosion in stationary mode is of the same order of magnitude as the aeolian transport. This indicates that aeolian transport is important to take into account. The erosion volume above 0m NAP for the reference surfbeat model ($facSk = 0,375$ and $facAs = 0,123$) is about $200m^3$. Because the aeolian transport is of a much smaller magnitude, it can be concluded that aeolian transport is not the most relevant missing process in the surfbeat reference model. However, for models with increased asymmetry and skewness factors a big portion of the erosion above 0m NAP can be counteracted: for the model with $facAs = 0,6$ the dune erosion volume is only $40m^3/m$ more than is visible in the survey measurements. In this case the aeolian transport *would* be able to play a role in transporting sediment from the berm in the intertidal zone to the dunes and in this way counteracting the erosion even more.

In figure 6.5 a comparison is made between the erosion volumes of the reference model (WTI settings) and a model with an extreme setting for the asymmetry in order to demonstrate the effects of the asymmetry factor. It is visible that the erosion volumes above 0m NAP have decreased significantly compared to the WTI settings of the reference model. For stationary mode there is even a positive volume added above 0m NAP.

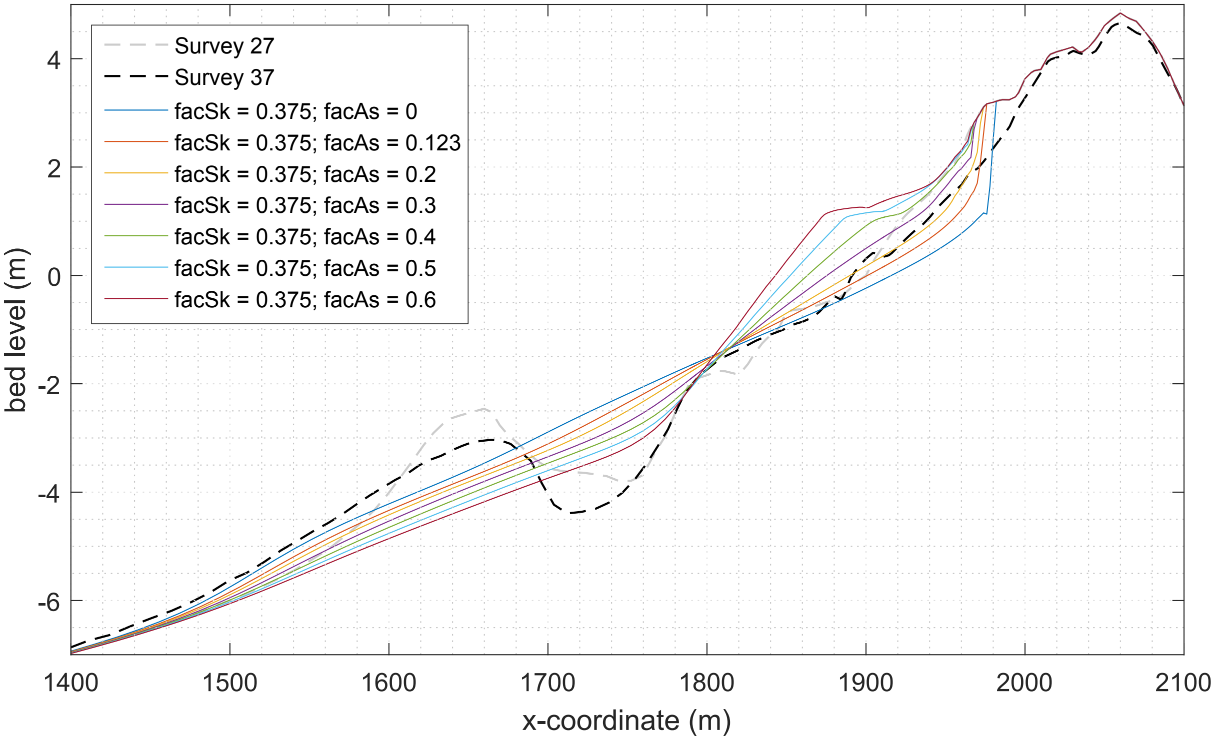


(a) $facAs = 0,6$.

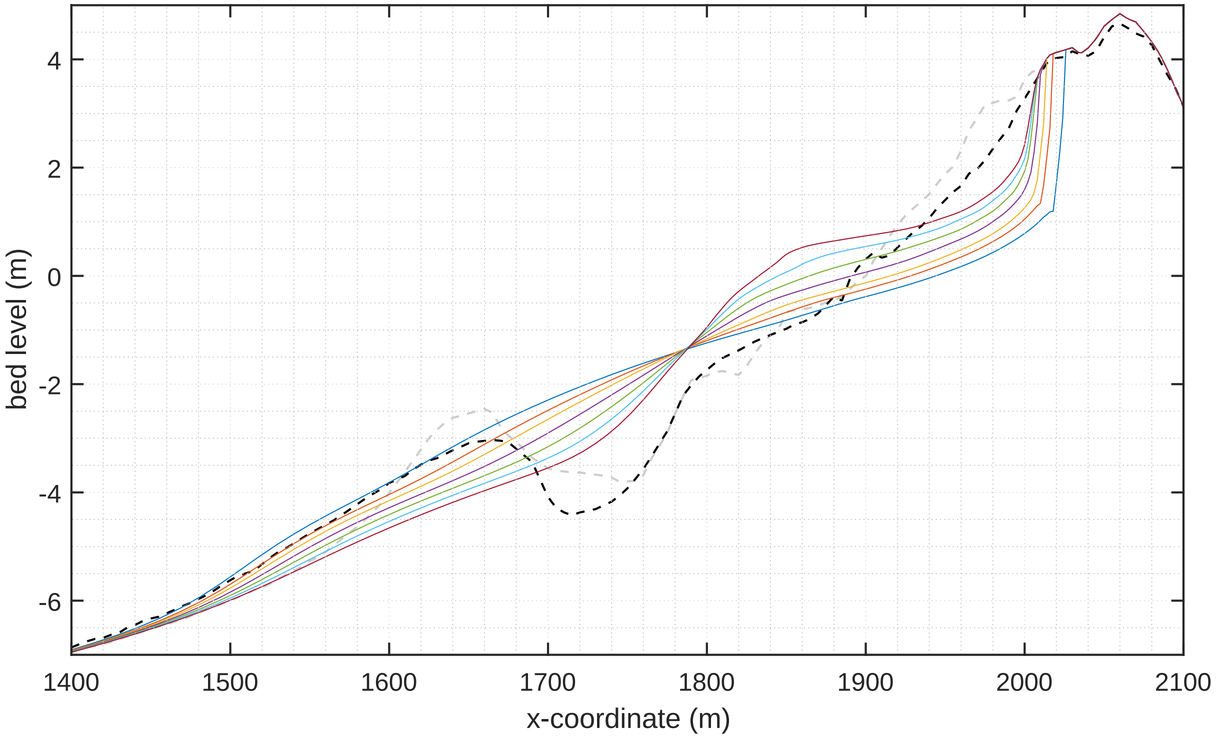


(b) WTI settings.

Figure 6.5: Comparing the cumulative volume change in time compared to the initial bathymetry for stationary mode (o) and surfbeat mode (Δ).

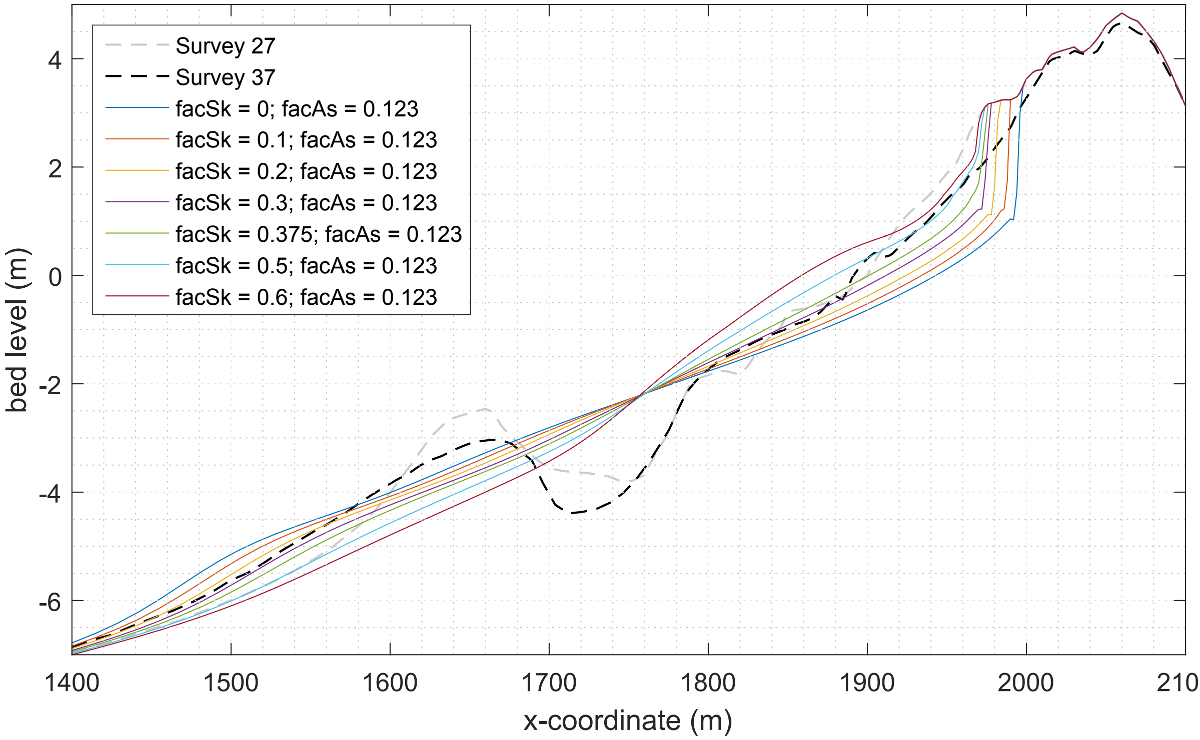


(a) Stationary mode.

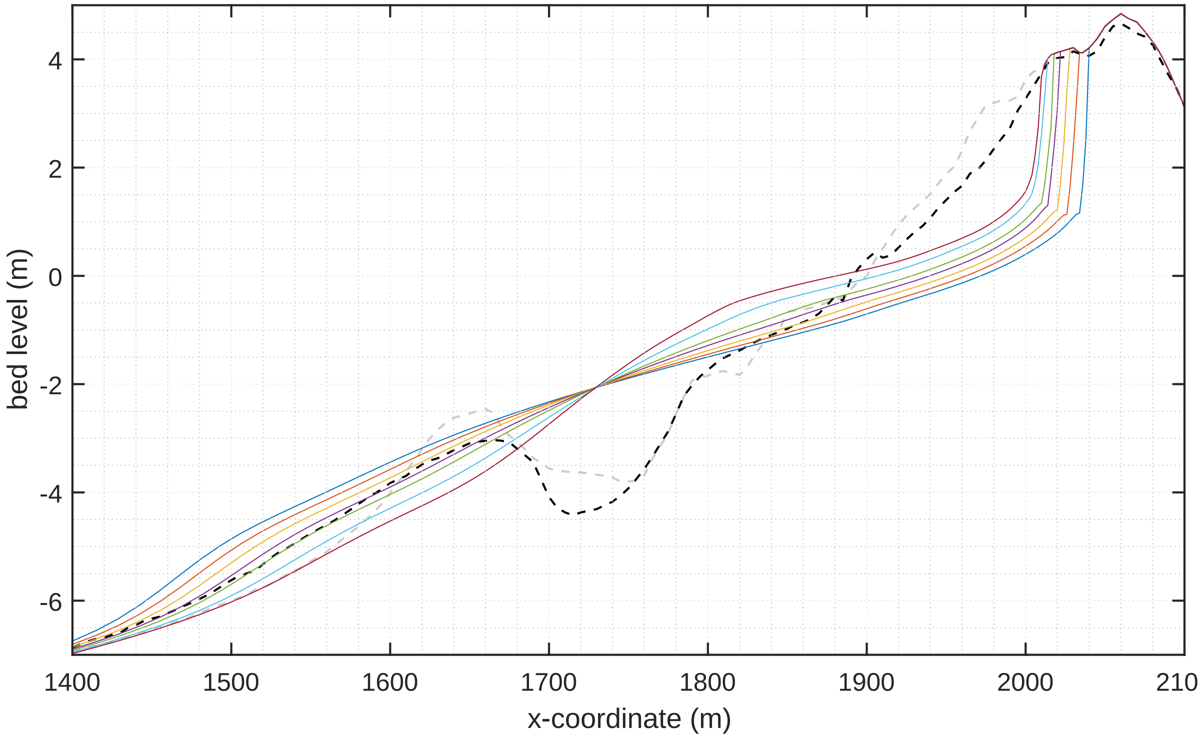


(b) Surfbeat mode.

Figure 6.6: Analysis of the sensitivity of asymmetry (facAs) in stationary and surfbeat mode. The legend of figure a is also for figure b.



(a) Stationary mode.



(b) Surfbeat mode.

Figure 6.7: Analysis of the sensitivity of skewness (facSk) in stationary and surfbeat mode. The legend of figure a is also for figure b.

Model performance

Table 6.1: Mean Squared Error Skill Scores (MSESS) for asymmetry sensitivity analysis in stationary mode.

	MSESS	**MSESS above 0m**	**MSESS below 0m**
Sk = 0,375; As = 0,0	-1.21	-0.44	-2.55
Sk = 0,375; As = 0,123 (WTI)	-0.56	0.33	-2.11
Sk = 0,375; As = 0,2	**-0.39**	**0.50**	**-1.96**
Sk = 0,375; As = 0,3	-0.63	0.28	-2.23
Sk = 0,375; As = 0,4	-1.35	-0.17	-3.41
Sk = 0,375; As = 0,5	-2.41	-0.50	-5.75
Sk = 0,375; As = 0,6	-3.63	-0.75	-8.67

Table 6.2: Mean Squared Error Skill Scores (MSESS) for asymmetry sensitivity analysis in surfbeat mode.

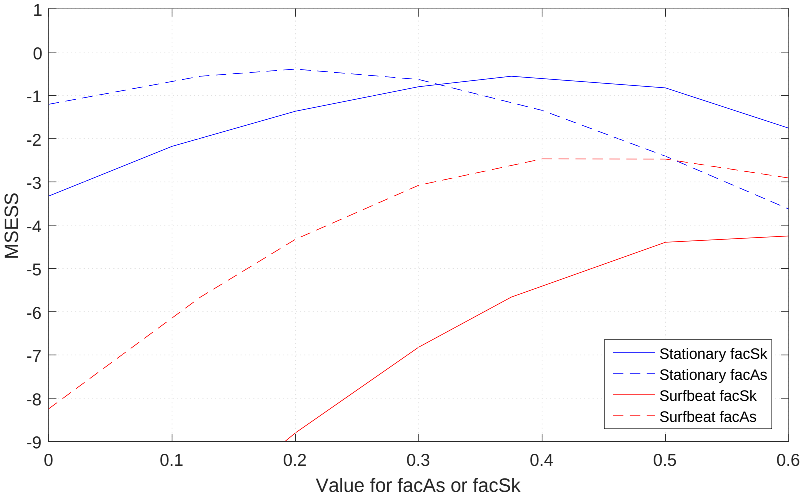
	MSESS	**MSESS above 0m**	**MSESS below 0m**
Sk = 0,375; As = 0,0	-8.24	-10.04	-5.09
Sk = 0,375; As = 0,123 (WTI)	-5.66	-6.29	-4.57
Sk = 0,375; As = 0,2	-4.33	-4.30	-4.37
Sk = 0,375; As = 0,3	-3.08	-2.34	-4.37
Sk = 0,375; As = 0,4	-2.47	-1.10	-4.86
Sk = 0,375; As = 0,5	-2.47	-0.40	-6.10
Sk = 0,375; As = 0,6	-2.91	**0.01**	-8.04

Table 6.3: Mean Squared Error Skill Scores (MSESS) for skewness sensitivity analysis in stationary mode.

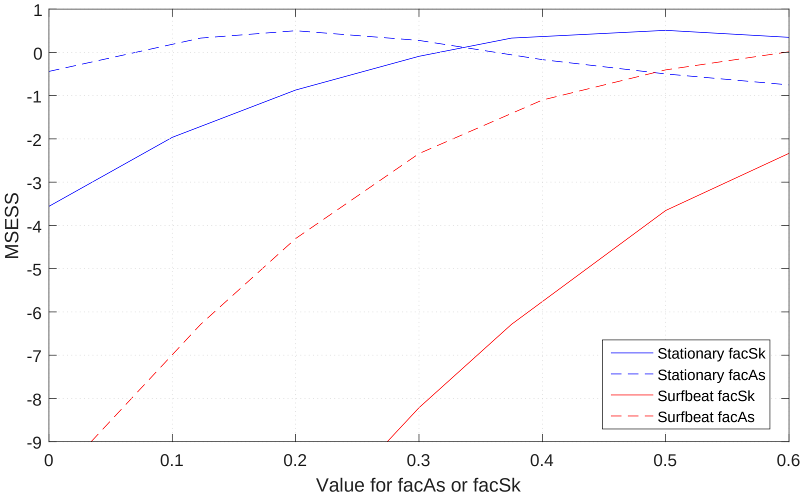
	MSESS	**MSESS above 0m**	**MSESS below 0m**
Sk = 0,0; As = 0,123	-3.33	-3.56	-2.92
Sk = 0,1; As = 0,123	-2.18	-1.96	-2.55
Sk = 0,2; As = 0,123	-1.37	-0.87	-2.23
Sk = 0,3; As = 0,123	-0.80	-0.09	-2.04
Sk = 0,375; As = 0,123 (WTI)	-0.56	0.33	-2.11
Sk = 0,5; As = 0,123	-0.83	0.51	-3.17
Sk = 0,6; As = 0,123	-1.76	0.35	-5.45

Table 6.4: Mean Squared Error Skill Scores (MSESS) for skewness sensitivity analysis in surfbeat mode.

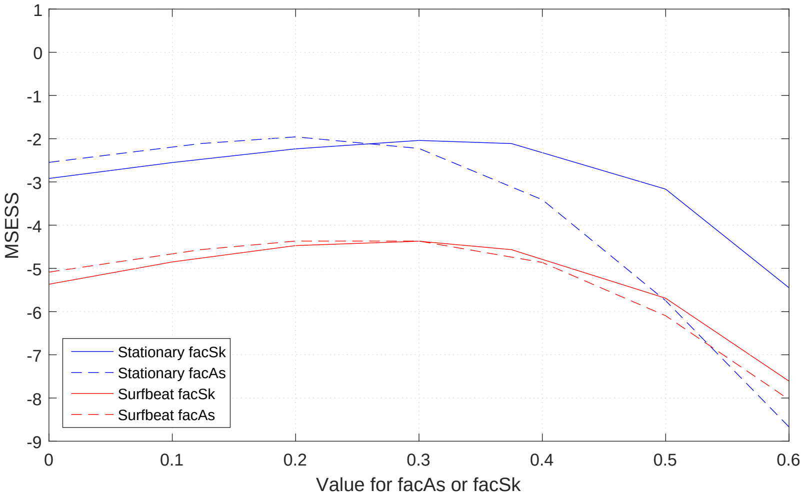
	MSESS	**MSESS above 0m**	**MSESS below 0m**
Sk = 0,0; As = 0,123	-13.88	-18.74	-5.37
Sk = 0,1; As = 0,123	-11.14	-14.72	-4.85
Sk = 0,2; As = 0,123	-8.80	-11.27	-4.47
Sk = 0,3; As = 0,123	-6.82	-8.21	-4.37
Sk = 0,375; As = 0,123 (WTI)	-5.66	-6.29	-4.57
Sk = 0,5; As = 0,123	-4.39	-3.66	-5.69
Sk = 0,6; As = 0,123	-4.25	-2.33	-7.61



(a) Total MSESS.



(b) MSESS above 0m NAP.



(c) MSESS below 0m NAP.

Figure 6.8: Skill scores (MSESS) given a certain setting of facAs or facSk while keeping the other factor constant on the WTI setting.

6.3.2 Sensitivity groundwater flow module

In XBeach the groundwater flow module is switched off by default. The reference model also does not include groundwater flow. Pender and Karunarathna (2013) and Zimmermann et al. (2015) experienced that the groundwater flow module could help to stabilise the coastal profile. The skill of their modules improved when the module was activated.

In figure 6.9 the results of the sensitivity analysis of groundwater flow for Vlugtenburg are displayed. In stationary mode hardly any difference was observed between models with and without groundwater flow. In surfbeat mode however, the model with the activated groundwater flow module showed less erosion. The difference in behaviour between stationary and surfbeat mode can be explained as follows; in stationary mode stationary wave enter the model domain (in this case the waves change every hour). If the groundwater flow module is turned on, the groundwater level in the beach has sufficient time to adapt to the incoming waves. Therefore no pressure differences are created on the beach surface. In the surfbeat model, long waves enter the domain (but much shorter than the duration of the different stationary conditions). In this case the groundwater level is not able to adapt instantaneously to the changing water level (because the permeability factor k is small) and therefore a difference is created between the water level inside and outside of the beach.

The fact that the groundwater flow module increases the stability of the surfbeat module is given in section 2.4.3; if the water table is lower, a bigger portion of the swash water is able to infiltrate, therefore the amount of backwash is decreased and less sediment is transported offshore.

In surfbeat mode the models without groundwater flow and with a k of 0,0001 m/s are similar. The models with a k of 0,02 and higher have a more stable profile. In these models the erosion at +1m NAP is reduced.

6.4 Sensitivity lwave

When the option lwave is switched off, the forcing of the short wave action balance on the NLSWE is completely switched off. This means that not only the infra-gravity waves are ignored, but also other forcings by the radiation stresses from the short wave action balance are ignored. This means that there cannot be:

- a lowering of the mean water level in the shoaling zone (set-down)
- an increasing water level in the surf zone (set-up)
- longshore currents that would normally result from radiation stresses from obliquely incoming waves

By comparing the results of models with and without lwave, more information is acquired regarding the relative importance of infra-gravity waves, set-up, set-down and longshore currents for long-term modelling.

The results of a comparison between models with and without the option lwave is shown in figure 6.10. The options *with* lwave ($lwave = 1$) are the same as the reference models for stationary and surfbeat mode.

The differences between models with and without lwave are summarised in the list below. The observations in this list are observations in figure 6.10:

- In the measurements of the high dune area +4m NAP is about the highest point that is affected by hydrodynamic action. The surfbeat model with lwave also shows that the dunes are affected up to a height of +4m NAP. This is 1 to 1,5m lower (too low) in the stationary models and surfbeat model without lwave.
- It is visible that the dune and beach erosion is more pronounced when the option lwave is switched on. The dune and beach erosion volume is severely overestimated by surfbeat with lwave. The options

without lwave do not affect the higher dune areas (above +2,5m NAP) which causes an underestimation of the erosion in that area. The stationary model produces the best volume estimate (slightly too much at one area and too little in the other).

- The slope offshore of the bar is better predicted by surfbeat with lwave on.
- The bar and trough are maintained better in models without lwave.
- The beach slope (-3m NAP to +1,5m NAP) in the model without lwave approaches the measurements very well. In the models with lwave, the slope is too gentle in this area.

Summarising, the performance of the surfbeat and stationary model without lwave is much better on most criteria than with lwave (see table 6.5). The difference is especially visible for surfbeat mode with and without lwave.

The difference between models with and without lwave indicates that set-up, set-down and longshore currents have a big influence on long-term morphology in XBeach. Below an explanation is given as to why each of these processes is expected to affect the long-term morphology. However, no investigation was done to determine how important each of the three processes is compared to each other.

In the models in this study, that are for the most part 1D models, the net longshore transport is zero (the gross transport is not) and the longshore currents do not *directly* influence the long-term morphology. However, the longshore currents are expected to have an indirect effect on morphology, because the longshore currents mobilise sediment. Sediment that is mobilised in the water column can be easier transported offshore by for example the undertow. When lwave is switched off, the sediment is less mobile in the nearshore zone and therefore less sediment is transported offshore.

Set-up is an important mechanism, because it allows waves to attack the profile at a higher level. Therefore the beach and dune profile can erode up till higher levels. The critical slope angle of parts that are inundated by set-up is also decreased (because the critical wet slope angle is less than the dry slope angle) and therefore the avalanching criterion is met earlier.

As is explained, the skill scores of the models without lwave are much better. This can be explained by the fact that the stationary and surfbeat reference models have a negative MSESS. This means that a model in which nothing happens is better that the reference models. Switching of lwave was mainly done to determine the effect of the processes that were mentioned in this section. It is not recommended to switch off lwave in long-term models. As can be seen in table 6.1 and 6.3 higher skill scores can be obtained by calibrating the skewness and asymmetry for stationary mode. Stationary mode includes more physical processes and therefore is a more robust model (more applicable in different types of situations).

Table 6.5: Mean Squared Error Skill Scores (MSESS) for models with and without the option lwave switched on.

	MSESS	**MSESS above 0m**	**MSESS below 0m**
Stationary lwave 0	0,15	0,27	-0,07
Stationary lwave 1	-0,56	0,33	-2,11
Surfbeat lwave 0	0,22	0,29	0,09
Surfbeat lwave 1	-5,66	-6,29	-4,57

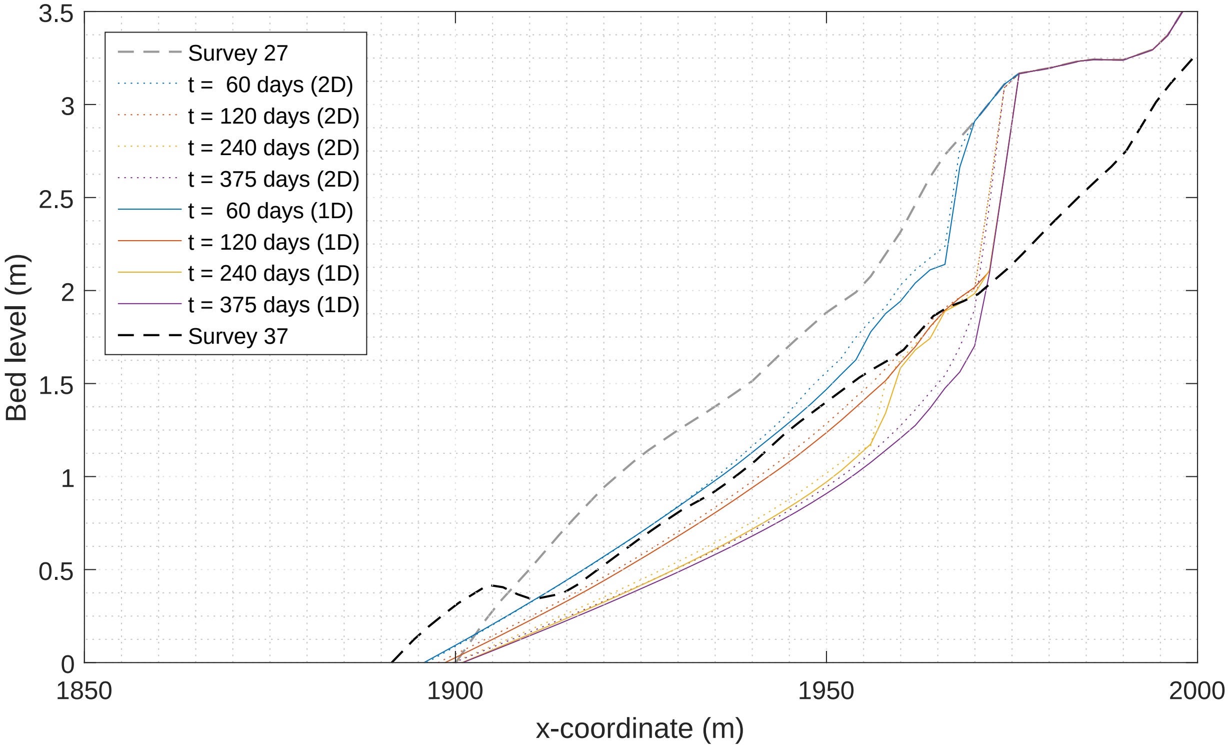
6.5 2D models

Transect 6 that was used for all 1 models, was copied in longshore direction to form a quasi-2D model. This was done to investigate whether 2D models gave more realistic erosion volumes.

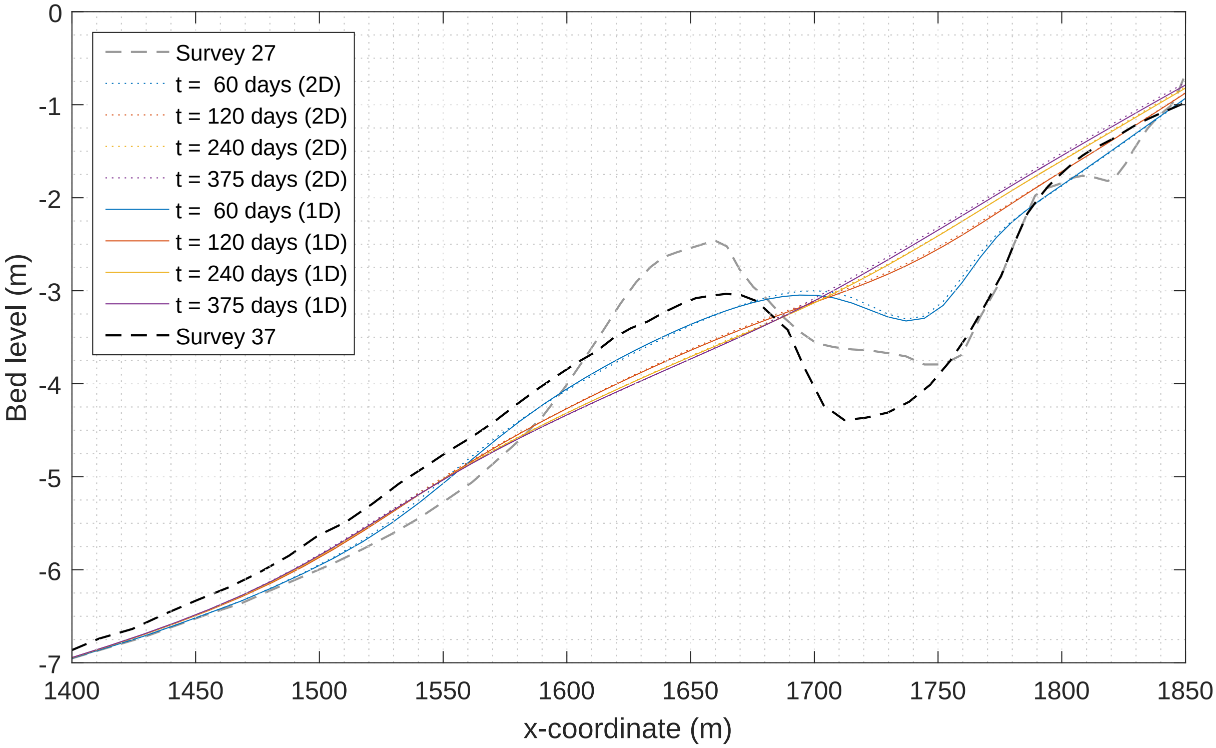
In figure 6.11a and 6.11b the 1D and 2D stationary reference model are compared. It is visible that there is only a slight difference between 1D and 2D stationary models: there is only slightly more erosion in the 1D models above +1m NAP.

In figure 6.12a the development of the bed level in time is shown for the 1D surfbeat reference model. In figure 6.12b the development of the quasi-2D surfbeat reference model is shown. In the figures is visible that the dune and beach erosion of the 1D model is much more severe than the erosion in the 2D model; the erosion in the 2D model is of the same order of magnitude as the erosion of the 1D model after 60 days. The dunes have eroded up to a meter higher and about 40m more land inward in 1D. The overall profile shape after 375 days is similar in both models except that the 1D profile is more convex and the 2D profile is more flat. The MSESS has not been determined for the 2D plot, but in the figures can be seen that the MSESS would be much higher for 2D models than for 1D model.

From this comparison follows that a 2D model has an added value for long-term modelling in surfbeat mode.

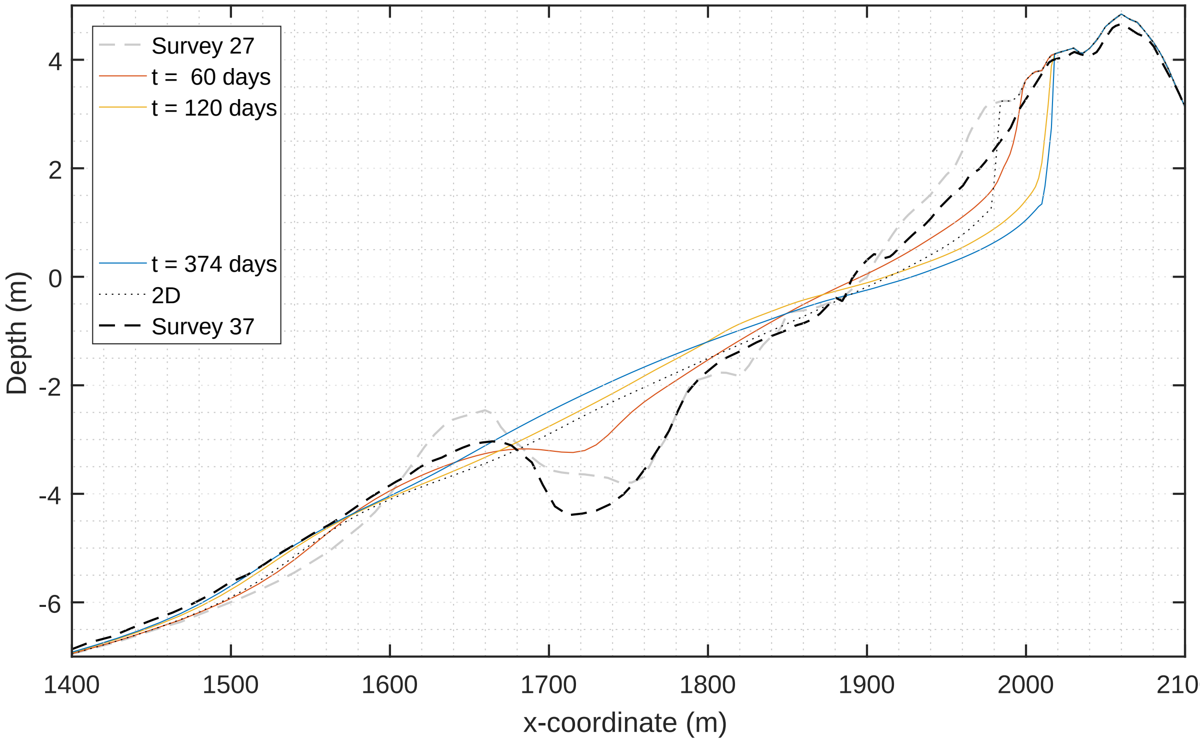


(a) Top half of the figure.

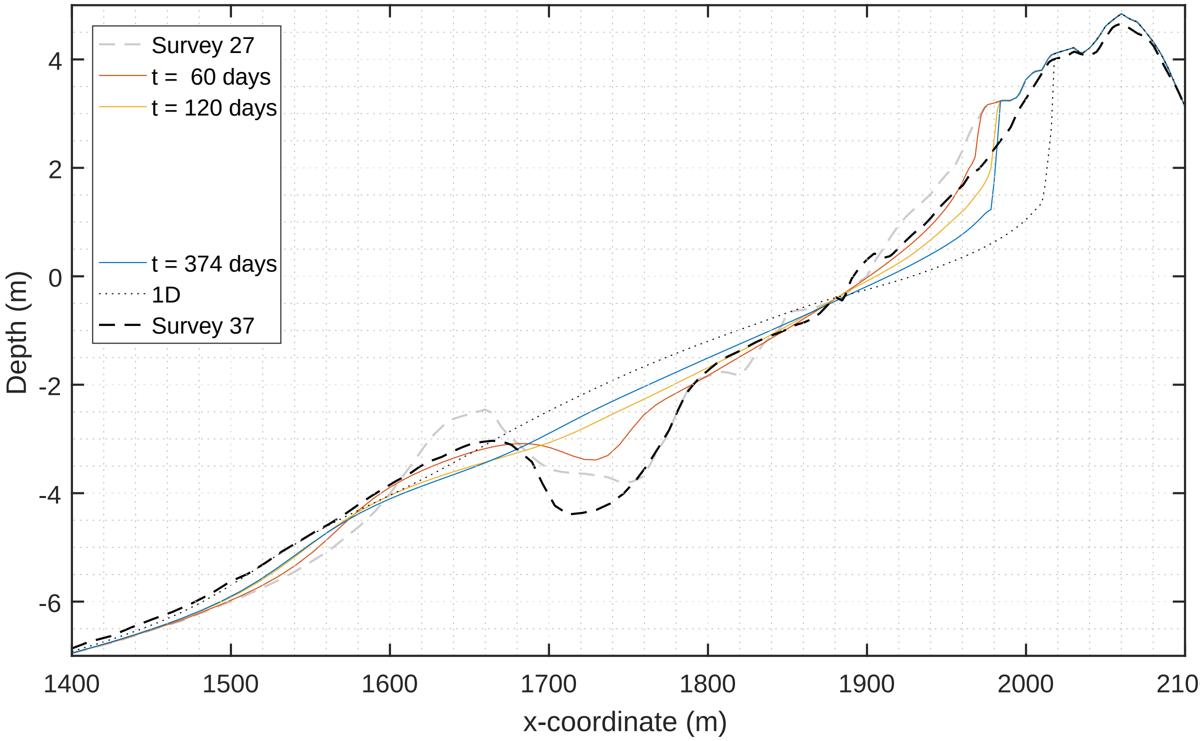


(b) Bottom half of the figure.

Figure 6.11: Comparing the 1D and 2D stationary reference model.



(a) 1D model.



(b) 2D models.

Figure 6.12: Comparison between a 1D and 2D reference surfbeat models with WTI settings and morfac 5.

6.6 Coupling of stationary and surfbeat

In the combined models the surfbeat model was run for the first 100 days, in a period with more extreme conditions than the rest of the year. For the remainder of the year (275 days) the stationary model was run using a facAs of 0,2 or 0,3. The results of the combined stationary and surfbeat model are shown in figure 6.14 and are compared with the results of the reference models that use a single mode for 375 days. The reason for running the last 275 days with stationary mode was to check whether stationary mode was able to restore the erosion of the surfbeat model. In the sensitivity analysis $facAs = 0,2$ was found to approximate the profile slope of the measurements very well and therefore this setting was used for the stationary part of the coupled model. Also a coupled model with $facAs = 0,3$ in stationary mode was used.

In the models the following was observed: in the first 100 days the surfbeat model eroded the dune and the upper beach. After 100 days the model looked very similar to the surfbeat model after 375 days. When the stationary models with an increased facAs were run from day 100 onwards, there was no further erosion of the beach and dunes. In the 275 stationary days sediment is deposited, mainly around 0m NAP in 1D and around +0,25m NAP in quasi-2D, but not higher than that. The predicted profile slope of the coupled model approximated the measured profile quite well around 0m NAP, especially in 2D mode. In 1D mode the accretion during the stationary model was not effective in restoring the erosion above 0m NAP that occurred during surfbeat mode. In 2D mode there was also no restoration of the profile above +0,25m NAP, but because the erosion in 2D did not reach up as far as in 1D, the result of the coupled model was much better than in 1D.

This seems to be conflicting with what was observed in the sensitivity analysis of the asymmetry factor, see figure 6.6. In this figure is visible that an increased asymmetry factor did in fact cause accretion up to about +2m NAP in stationary mode. This difference with the coupled model is expected to be caused by two factors:

- the slope of the surfbeat profile after 100 days is very steep. Accretion in this area needs to be build up from the bottom.
- In the sensitivity analysis of facAs was experienced, that a significant part of the accretion happened during the more extreme conditions (in the first 100 days). In the first 100 days there were higher water levels caused by storm surges (see figure 6.13) which allowed the sediment to be deposited higher in the profile. This is supported by figure F.1. In this figure is shown that the influence of tide and surge on the deposition height of the sediment is very significant: without tide, the sediment deposits stay around the water line. In the coupled model surfbeat is used in the first 100 days. In surfbeat the infra-gravity backwash dominates the onshore directed transport by wave asymmetry and skewness in the intertidal zone. Therefore the sediment is deposited lower in surfbeat mode.

Again the problem is encountered that XBeach is only able to transport sediment by hydrodynamics. Since the onshore transport is mostly during mild conditions and mild conditions usually are combined with low surges, XBeach has no ability to move sediment far up-shore. Again an aeolian module seems to be the missing requirement for better long-term modelling.

When the coupled models are compared with the stationary model can be concluded that the stationary model performs better on many aspects:

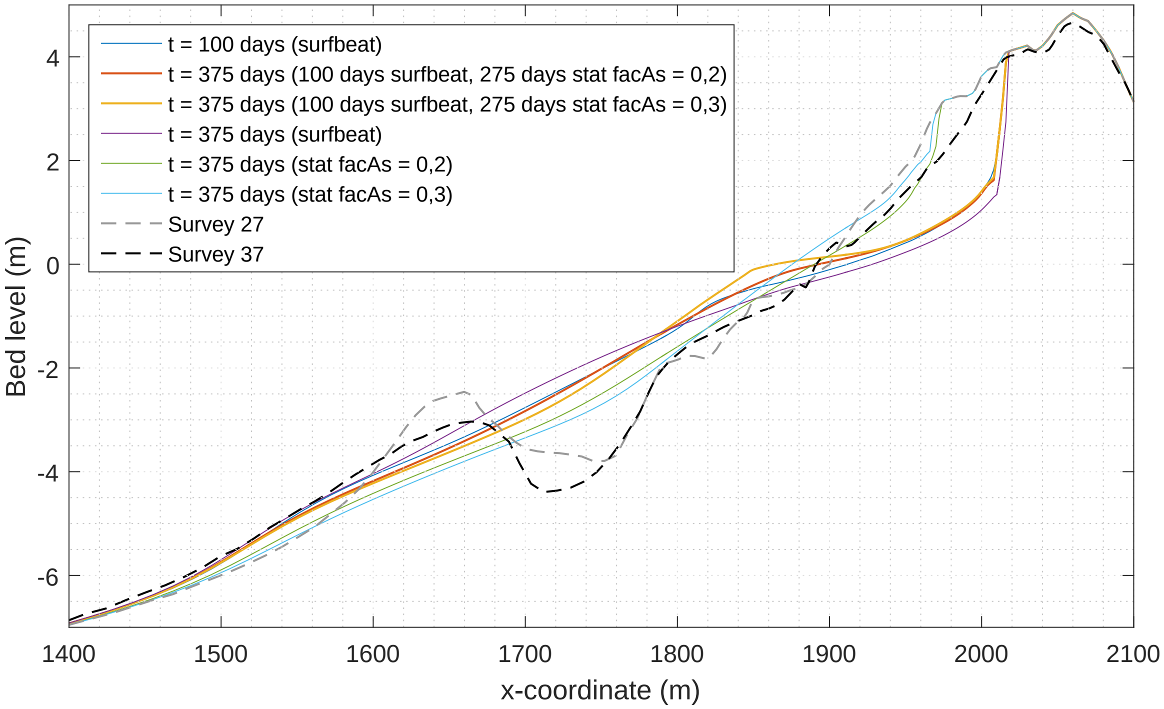
- The skill score of stationary mode is better than the skill score of the coupled models
- The erosion volumes are predicted better in stationary mode.
- The profile slope is predicted better in stationary mode.

In this study one advantage was found of the coupled model: the height up till which the dune erodes is predicted better in the coupled model than in the stationary model. The reason for this is that surfbeat predicts the height up till which the dune erodes better than stationary.

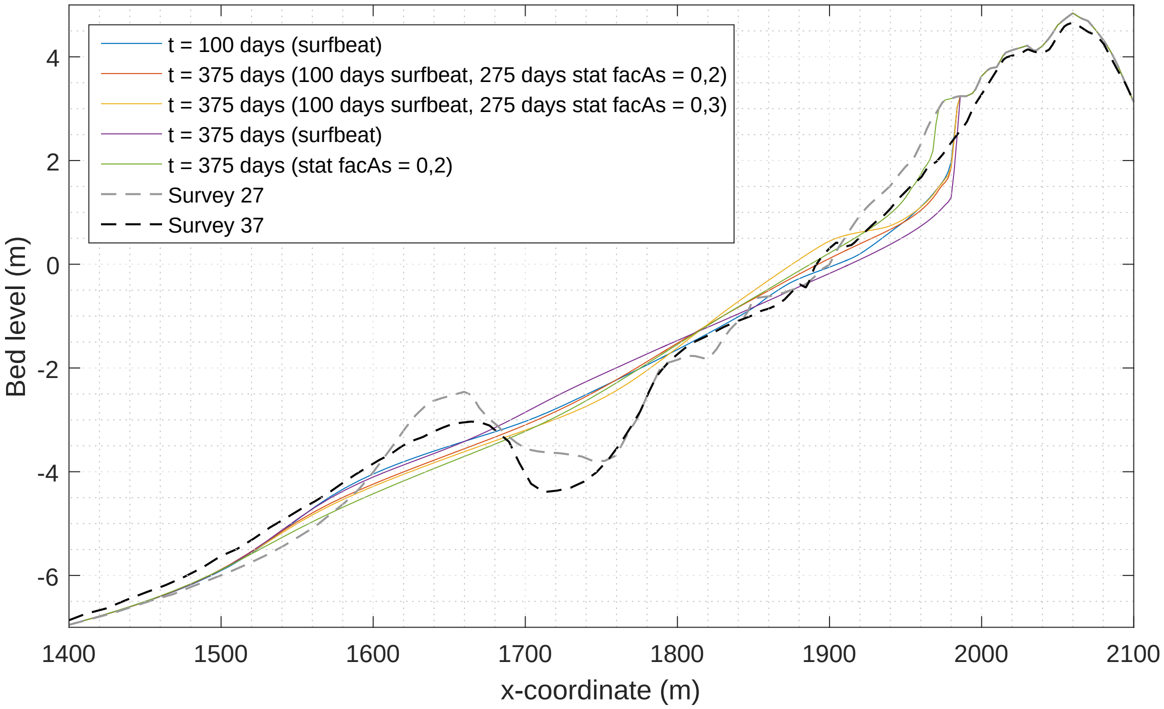
Table 6.6: Comparison of the computation times of 1D stationary, surfbeat and coupled models.

	Computation time (hours:minutes)	**Computation time (%)**
Stationary 375 days	5:37	100
Surfbeat 375 days	8:15	147
100 days stationary 275 days surfbeat	6:19	113

In table 6.6 the computation times of the different 1D models are compared. This displays that stationary mode is also on this point the most favourable model.

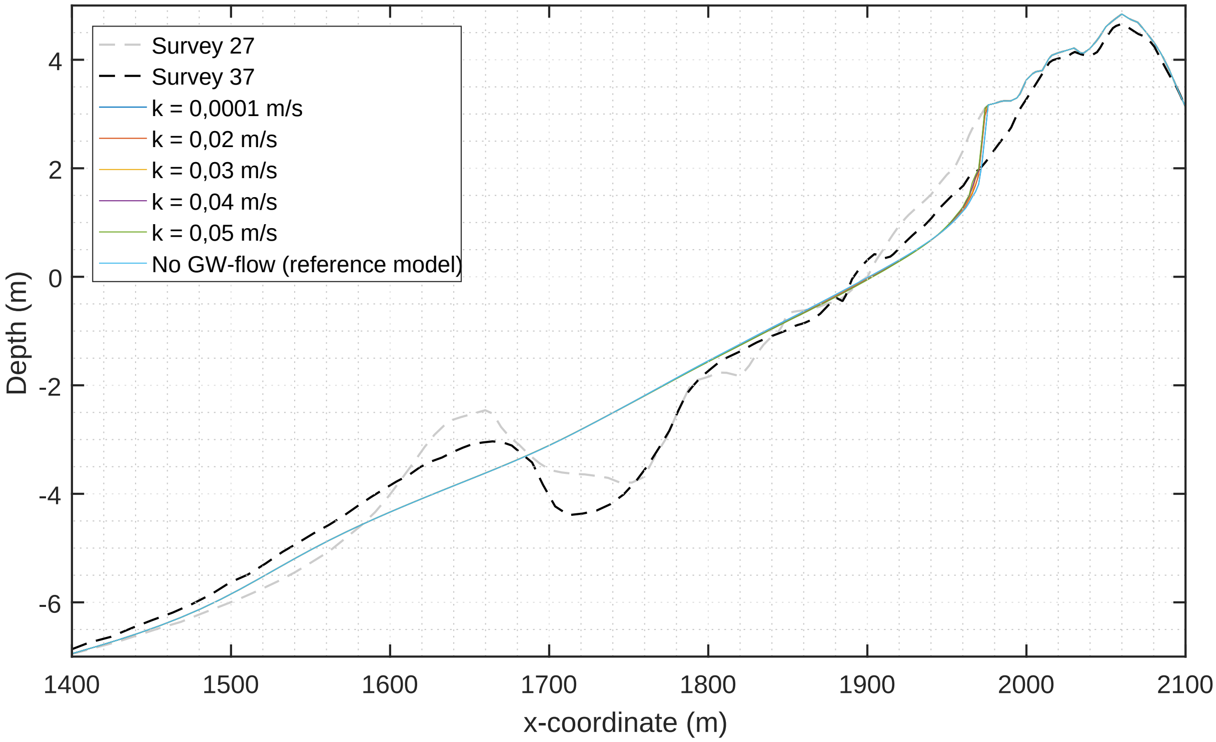


(a) 1D models.

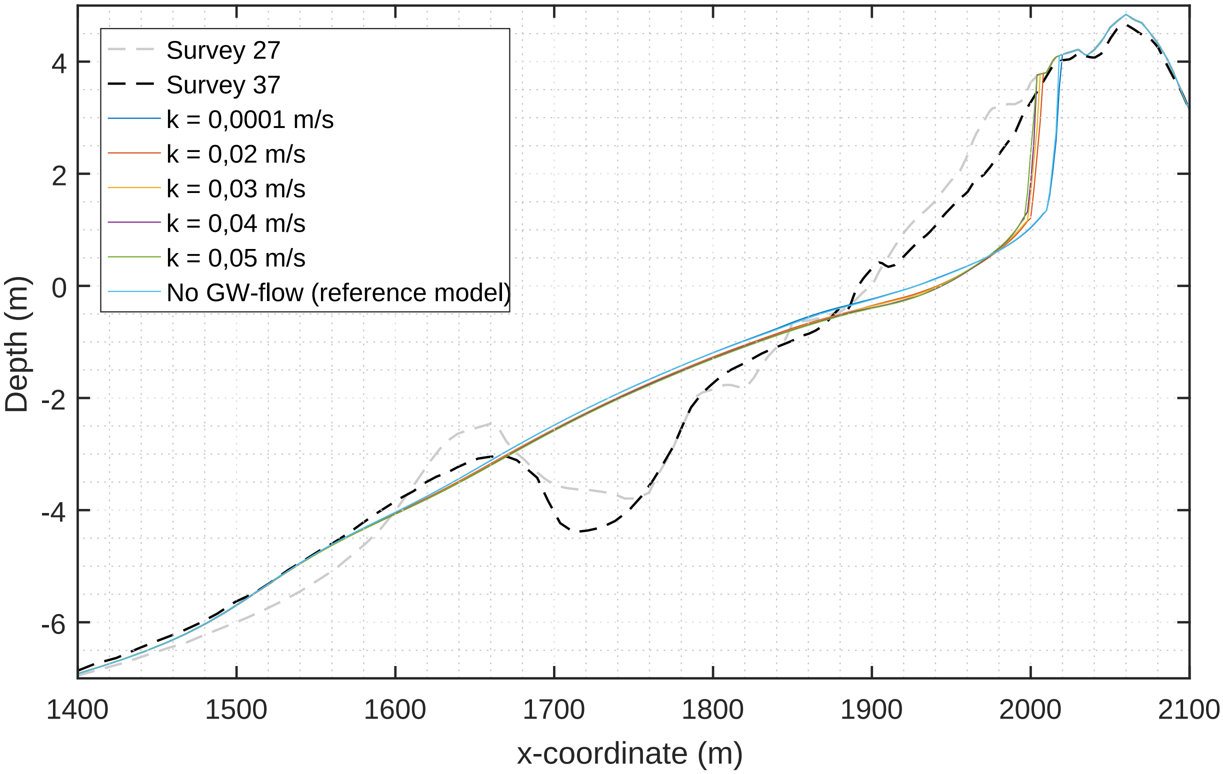


(b) 2D models.

Figure 6.14: A combination of a surfbeat and stationary model with an increased asymmetry factor is shown for both 1D and 2D models. For comparison the surfbeat reference model and the stationary model with increased asymmetry factors are displayed as well.



(a) Stationary mode



(b) Surfbeat mode

Figure 6.9: Sensitivity analysis groundwater flow variable (k).

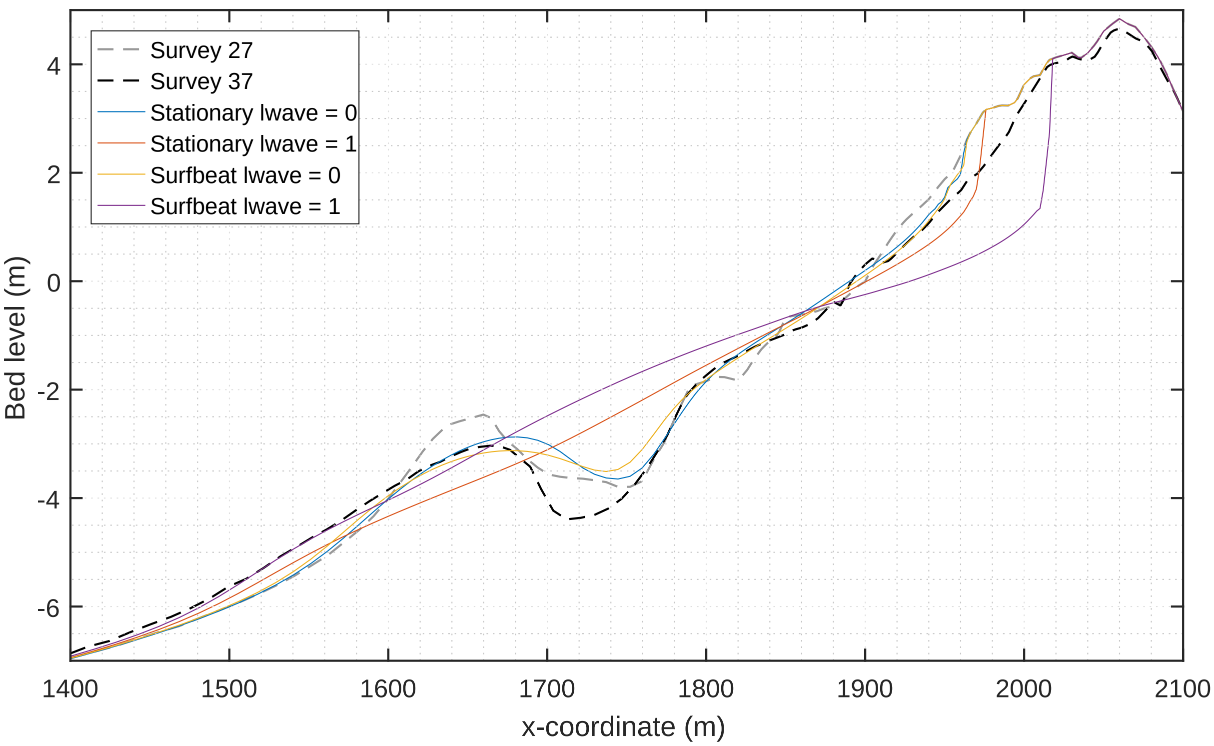


Figure 6.10: Comparing the results of models with and without the option lwave turned on.

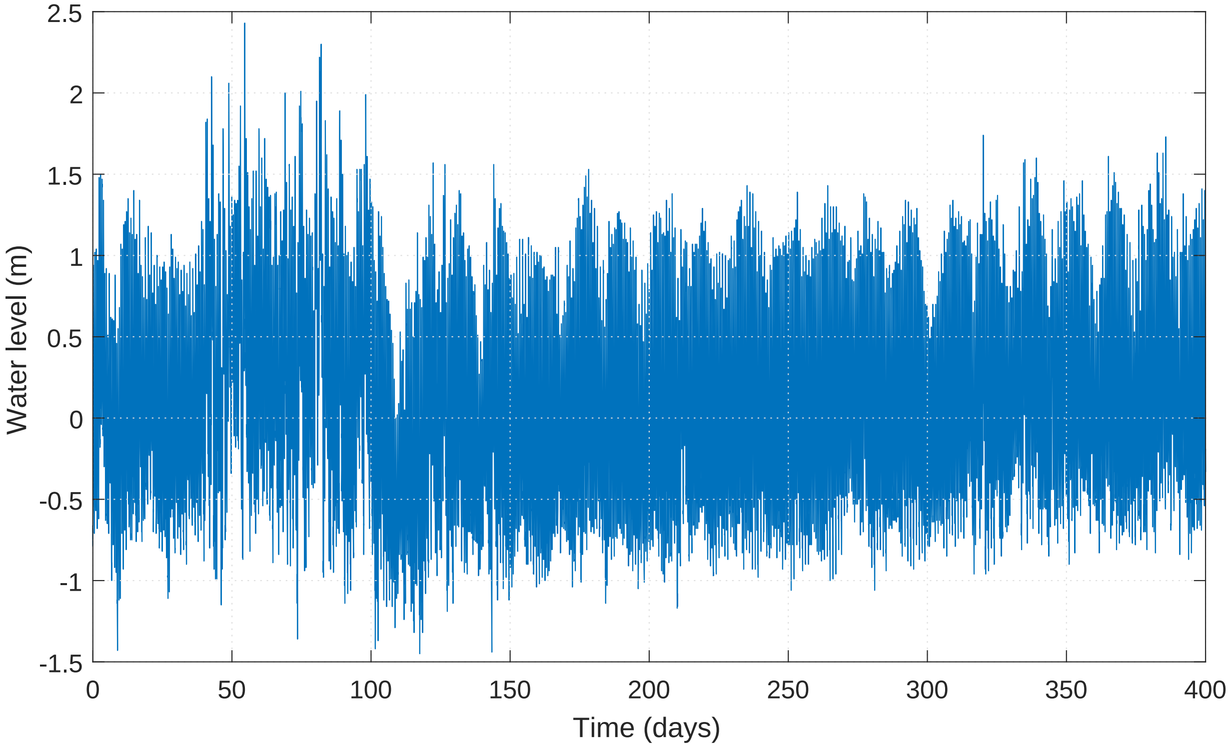


Figure 6.13: Water level (tide and surge) during the modelled year.

7 Discussion

In this chapter the findings of this study will be repeated and will be discussed whether the findings have created a solid foundation for answering the research question. It will be discussed whether the findings agree with, extend, refine or conflict with findings in literature. Another topic that will be discussed is whether the results of this study are only valid for Vlugtenburg, or could also be used for other locations.

In order to determine the added value of coupled stationary and surfbeat models, the coupled models were compared with the best possible singular models (stationary or surfbeat mode). Initially reference models were created, using the WTI (default) settings. Then several optimisations were done in order to improve the reference models.

The stationary and surfbeat reference models showed that with the WTI settings, the beach and dune erosion is overestimated. Also hardly any seasonal effects were found in the reference models: there was no accretion during mild conditions. The skill (MSESS) of the reference models was found to be negative, which means that the initial bathymetry is a better prediction of the final bathymetry than the model prediction. Pender and Karunarathna (2013) also experienced that the eroded volumes were overestimated.

Zimmermann et al. (2015) experienced that the model performance could be increased by optimising the settings for asymmetry and skewness. In order to find the optimal settings for asymmetry and skewness for Vlugtenburg, a sensitivity analysis was carried out. It was found that the model skill could be increased significantly, especially for stationary mode. The factors for asymmetry and skewness proved to be good calibration parameters for the beach slope in stationary mode. In surfbeat mode however, the settings appeared to be unable to counteract the severe dune erosion.

Even though the WTI settings were optimised for the Dutch coast, the settings for skewness and asymmetry were not found to be optimal for Vlugtenburg. This was explained by the fact that XBeach is quite insensitive to the grain diameter; an XBeach model requires calibration with the asymmetry and skewness factors to compensate for the changing grain diameter. This means that the results from this study (the settings for facAs and facSk) is not necessarily valid for models at other locations. For other locations (and other grain diameters) the settings need to be calibrated again. However, in this study has been shown that a calibration of these settings works well in combination with stationary mode.

Zimmermann et al. (2015) and Pender and Karunarathna (2013) both experimented with the groundwater flow module and found that it is an important process for the stability of the beach and dune profile. This improvement in the model skill was not observed in this study for Vlugtenburg. The surfbeat model with the groundwater flow module performed slightly better, but the eroded volumes were still overestimated. The difference between this study and the study of Zimmermann et al. can be explained by the fact that the beaches at which the Zimmermann et al. study was done (the Belgian coast), had different characteristics than the Dutch coast. The slope of the beaches in Zimmerman's study were much milder and the wave heights were less extreme. The Vlugtenburg system is more dynamic and since it is a nourished site, it is also further from the equilibrium profile. These are all factors that contribute to a faster erosion of the Vlugtenburg profile and is expected to be the reason for the Vlugtenburg profile to be less influenced by the groundwater flow.

One of the important differences between stationary and surfbeat mode is that stationary mode does not account for infra-gravity waves. The comparison of 1D stationary and surfbeat models showed that infra-gravity waves have a significant importance in the model results. It was found that stationary models perform better on the long-term prediction of the erosion volumes, profile slopes and MSESS, but surfbeat was better at predicting the height up till which dune erosion took place. The fact that stationary mode was found to be more suitable for long-term modelling agrees with findings of Pender and Karunarathna (2013) and Zimmermann et al. (2015).

In this study was experimented with a further simplification of the model in order to get a better understanding of the relative importance of different processes for long-term modelling in stationary and surfbeat mode; by switching off the short wave induced forcing on the NLSWE (by setting option $lwave = 0$), it was discovered that set-up and longshore currents are also very important processes in XBeach for long-term modelling. The skill score of models *without* the wave induced forcings on the NLSWE was much better for stationary and surfbeat mode. However, this was tested for the reference model, which has a negative skill score; therefore a model that does less, like a model without the lwave option, is automatically better. In this study tests were done with only one set of settings (the WTI settings). It should be investigated whether this model simplification is also effective at different locations and whether it still holds up when different settings for asymmetry and skewness are applied.

A coupled model was made in which surfbeat was running during the extreme conditions (the first 100 days) and stationary mode, with an increased asymmetry factor ($facAs = 0,2$), was running for the remaining 275 days. It appeared that the stationary model was only able to cause accretive behaviour up to 0m NAP in 1D and +0,25m NAP in 2D models.

In this study was focused on 1D models and cross-shore processes. However, as was mentioned in chapter 4 longshore processes are also important for long-term morphological developments. The longshore transport is important for the position of the 0m coastline and can also be a source or sink term to the cross-shore sediment balance. In the data that is used in this study, the SandMotor was already constructed and could potentially be a source term for sediment. However, in figure 5.2 can be seen that the sediment volume in transect 6 (the transect that is used in this study) is actually decreasing over the years, also after construction of the SandMotor. This is why it was justified to use this location for 1D models and cross-shore processes. Since the longshore processes are important for the location of the 0m water line, this was not used as an evaluation criterion for the performance of the models in this study.

It was shown that XBeach is unable to predict the bar behaviour. Since the bar has a dissipative effect on the wave height (waves break on the bar), this could indirectly lead to an accelerated erosion of the beach and dunes. This would be an interesting topic for further studies.

8 Conclusion

In this section each of the research questions and sub-questions will be repeated and an answer will be provided.

What is the performance of singular (non-coupled) stationary and surfbeat models for long-term modelling?

Both stationary and surfbeat models overestimated the erosion (especially surfbeat mode) and did not predict the correct profile slopes at the beach and dunes. The MSESS for the stationary reference model was -0,6 and for surfbeat mode even worse: -5,6. However, the MSESS for the part above 0m NAP was 0,3 for stationary mode. Neither stationary nor surfbeat mode showed regenerative behaviour during calm periods. In fact, almost all morphological activity took place in between the 40th and 100th day (during more extreme conditions).

In what way do the following processes affect long-term morphological models and what are the optimal settings?:

A summary of the skill scores of the different settings is given in table 8.1.

Asymmetry (facAs) and Skewness (facSk)

In the reference models was observed that there was hardly any recovery of beaches and dunes during mild conditions. The erosive behaviour of the model, on the other hand, was severely overestimated. A sensitivity analysis showed that regenerative behaviour could be introduced in the model by increasing the factor for skewness (facSk) and asymmetry (facAs). It also proved to be an effective measure to calibrate the profile slope above 0m NAP in stationary mode. The skill score of stationary mode could be increased in this way to 0,2.

In surfbeat mode the onshore transport could also be increased with higher settings for skewness and asymmetry, creating a sediment deposition zone mainly in between -2m NAP and +1m NAP. However, the severe dune erosion of the reference model could not be counteracted with these settings.

It must be taken into account that the optimal settings are site specific and should not be used indiscriminately at other locations. XBeach is too insensitive for the grain diameter which in reality influences the profile slope. The factors for asymmetry and skewness need to be used to compensate for this.

Groundwater flow (k)

As was expected, the groundwater flow module in stationary mode has a negligible influence on the bed level change. Including the groundwater flow module in surfbeat mode slightly increases model performance in the nearshore zone. In studies by Pender and Karunarathna (2013) and Zimmermann et al. (2015) the groundwater flow had a more significant effect. The extreme erosion in the surfbeat models in this study dominates the stabilising effects of the groundwater flow.

Long wave forcing (lwave)

Switching off the wave induced forcing of the wave action balance on the NLSWE, and thereby neglecting set-up and the mobilisation of sediment due to longshore currents, appeared to have a big impact on the yearly bed level change: the profile slope was predicted much better when these processes are not included. Also the bar trough system was maintained in this model. This resulted in significantly higher skill scores for both stationary and surfbeat mode. However, it is expected that this model simplification is not very robust and will not hold up when different settings for asymmetry and skewness are applied. For example set-up is very important for an accurate prediction of the sedimentation zone. When onshore processes are more relevant, this will show in the model results. Therefore it is not recommended to use the option $lwave = 0$ until it has been used successfully in combination with other locations and settings.

Is a 2D model or 1D model preferred for a longshore uniform coast like Vlugtenburg?

For stationary mode and alongshore uniform beaches, there is hardly any difference between the prediction of 1D and 2D models. For surfbeat mode however, a 2D model is preferred over a 1D model in terms of accuracy: the erosion volumes as a result of the infra-gravity waves above 0m NAP are much more realistic than in 1D models (the erosion is still overestimated).

Can the coupling of stationary and surfbeat mode within XBeach increase or maintain the model performance relative to a single stationary or surfbeat model?

In the 1D models, the coupled model showed that the severe overestimation of the erosion by surfbeat in the first 100 days could not be corrected effectively by stationary mode with an increased factor for asymmetry and skewness. In 2D models, the profile slope was restored and predicted well around 0m NAP, but the dune erosion could also not be restored in this model. Three underlying problems were found for that:

- Erosion as an (in)direct effect of infra-gravity waves (in surfbeat mode) is over-estimated.
- A mechanism is lacking to transport sediment from the intertidal zone (or just above the inter-tidal zone) further onshore to the dunes. It was found that the overestimated erosion volumes in stationary mode were of the same order of magnitude as the aeolian transport that was measured at Vlugtenburg. In the 1D reference surfbeat model the aeolian transport is only a small portion of the overestimated erosion volume, but when the onshore transport is increased with the asymmetry and skewness factor, the erosion volumes in surfbeat approach the same order of magnitude as the aeolian transport.
- In reality the regenerative behaviour takes place during calm conditions. It was found that in XBeach a big portion of the nearshore sediment deposition also takes place during extreme conditions. During the extreme conditions the surge is higher. In combination with stationary mode this provides a possibility for sediment depositions higher in the profile. However, in surfbeat mode the infra-gravity waves prevent that.

On most criteria the calibrated stationary model scored much better, but the coupled model scored better on the prediction of the height up till which the dune eroded.

At this moment the coupling of a surfbeat and stationary model is not preferred over stationary mode, because both the accuracy and computation times of the stationary model were found to be better. This statement is also expected to be valid for other coasts at which infra-gravity waves have a significant effect. At beaches where infra-gravity waves are irrelevant, the performance of the coupled and singular models is expected to be similar, just like in the case study of Bodde et al. (2017). It is recommended that XBeach is coupled to an aeolian module. After that can be investigated whether the coupling of stationary and surfbeat mode has an added value.

Table 8.1: Summary of MSESS of the optimal settings found in the sensitivity analysis.

Mode	facSk	facAs	lwave	MSESS	MSESS above 0m	MSESS below 0m
Stationary (reference)	0,375	0,123	1	-0,56	0,33	-2,11
Stationary	0,375	0,2	1	-0,39	0,50	-1,96
Stationary	0,375	0,123	0	0,15	0,27	-0,07
Surfbeat (reference)	0,375	0,123	1	-5.66	-6.29	-4,57
Surfbeat	0,375	0,6	1	-2,91	0,01	-8,04
Surfbeat	0,375	0,123	0	0,22	0,29	0,09

9 Recommendations for future studies

1. This study showed that XBeach lacks a mechanism to transport sediment from the intertidal and swash zone further up the slope. One of the mechanisms that enables this in reality is the aeolian transport with an order of magnitude of $10m^3/m/year$ and for Vlugtenburg $30m^3/m/year$. Therefore a coupling between XBeach and an aeolian model is expected to increase the ability of XBeach to simulate beach and dune regeneration.

2. In this study the focus was on a correct representation of cross-shore processes in long-term models. As was mentioned in section 2.4.10, the *longshore processes* can be important for long-term morphology as well (for example the location of the 0m line). An interesting topic for future studies would be to investigate the performance of coupled stationary and surfbeat models compared to single models, focussing on longshore processes.

3. In this study was chosen to use a "Reconstructed" wave input reduction (see section A.1.1). Another common method is to use a "Synthetic" wave input reduction, which has its advantages over the reconstructed series. It is interesting to investigate whether chronology effects would have a significant effect on the XBeach models, just like has been done with Delft3D models by Walstra et al. (2013).

4. A known problem of XBeach is the inability to model the bar behaviour correctly. This is an interesting topic for a future study.

5. Related to the inability of XBeach to model bars is the question whether the bar dissipation in XBeach is the reason for the overestimation of the beach and dune erosion in surfbeat mode, because the hydrodynamic conditions are not dampened by the bar.

6. In this study was experienced that the use of the MSESS can be tricky and misleading. Recently tools have been developed that could be an alternative or addition for the comparison and evaluation of beach profiles:

   2D Image warping tool (Bosboom et al., 2014b): this tool compares beach profiles and determines the transformation and deformation necessary to match the different profiles. It appears that this method represents the initial judgement of engineers and researchers better than traditional methods such as the MSESS. Disadvantage of this method is that the mass balance does not always hold, because sediment can be added or removed from the system by deforming the bathymetric features.

   Mol et al. (2015) presented a Root Mean Squared Transport Error (RMSTE) which represents the amount of sediment transport that needs to occur to bring the prediction closer to the observation. In this way is prevented that the displacements are penalised double.

7. In this study was stumbled upon a couple of practical problems when XBeach was used for long-term models. These problems are elaborated on in appendix D. Solving these problems could potentially save future XBeach users a lot of time.

8. In this study a sensitivity study was done in which the factors facSk or facAs were varied while keeping the other factor constant. Since the skewness and asymmetry factor both affect a different part of the beach and dune slope, a combination of an optimised asymmetry and skewness factor can potentially improve the skill of the model further.

9. Switching off the option lwave increased the skill scores of the surfbeat and stationary models. However it was expected that this simplification would not be applicable for models in which the onshore transport was increased (increased asymmetry and skewness factors). This could be a topic of further study.

A Models with reduced wave input

A.1 Methodology

A.1.1 Morphological acceleration

The 1D Vlugtenburg reference simulations of 375 days took about 70 hours to finish. This computation time was found to be inconvenient for sensitivity studies in which the model had to be run numerous times. Therefore was checked whether the reference simulation could be accelerated with a morfac value without reducing the accuracy of the results too much. Further down in this section is explained which method was used for the wave input reduction and what the (dis)advantages of the method are. In section A.2.1 the results are shown of tests with different values for morfac. It appeared that for a simulation of 375 days a morfac of 5 can be applied safely for stationary mode. Generally it is discouraged to use a morfac during storm conditions, but the surfbeat model shows that a morfac of 5 also still has a reasonable accuracy. Therefore was decided to use a morfac of 5 in all models.

Wave input reduction method
In a model with raw data, simulations are done for every time-step which means that for every time-step, a certain wave input leads to a certain morphological reaction. In a wave input-reduction a certain wave condition is assumed to be representative for a longer period of time. The morphological effect of the wave condition is therefore multiplied with a factor (morfac). This means that the number of wave inputs that needs to be simulated is reduced by morfac. This leads to a computation time that is $morfac\ times$ as short. There are two main types of wave input reductions (Walstra et al., 2013):

1. **Reconstructed series**: The raw wave data is reduced to a limited number of representative conditions. The chronology of the conditions is maintained.
2. **Synthetic series**: The raw wave conditions are grouped and combined in ascending, descending or arbitrary order. The climate is reduced by choosing one representative condition for each group of conditions. Chronology is not maintained with this method.

In this section is elaborated on the disadvantages and advantages of both methods. A summary of the characteristics of both methods can be found in table A.1.

The chronology of the wave input can be important when the morphological response of the system to the wave input is non-linear. For a linear response the results would be the same no matter the chronology. Therefore it might be of importance whether a storm occurs at the end of the simulation period or whether it is spread over the simulation period. By reducing the wave climate with a synthetic series the original chronology is disturbed and a chronology effect can be introduced.

In a synthetic series the wave conditions are sorted and combined. In case different types of model settings are used, for example surfbeat for storm conditions and stationary for mild conditions, there only needs to be one transition, since the wave conditions are sorted in ascending or descending order. When a combination of surfbeat and stationary models is applied to a reconstructed time series, the number of transitions is dependent on the number of periods with storm conditions. Therefore this number will be much higher. At each transition the model is temporarily stopped and the bathymetry output is converted to a new bathymetry input-file. Since the wave conditions disappear when the model restarts, a spin-up time is required after a transition. When the number of transitions is high the spin-up time contributes significantly to the total computation time. When there are periods in the model in which the storm conditions and calm conditions alternate quickly, there will be a lot of transitions, especially when the wave conditions fluctuate around the threshold for the transition. In this case it will be necessary to specify a minimum duration between two transitions in order to reduce the impact on the computation time.

Making a synthetic wave series requires more time than using a reconstructed input. For a synthetic series the waves first need to be grouped using wave height, period and direction as criteria. Then the conditions need to be sorted and then a representative condition needs to be found for the combined conditions using a weighted average. This master thesis is aimed at finding optimal ways to improve long-term modelling. Therefore the extra amount of time that is required for a synthetic series is considered as a disadvantage.

Another disadvantage of the synthetic time series is that it is not possible to compare intermediate model results with bathymetric data.

Many morphological changes in coastal areas are non-linear due to negative feedback mechanisms: this means that the change in morphology decreases with time elapsed since the start of a new wave condition. This effect implies that when a wave input reduction is applied, the computed morphological changes are not linearly scalable with morfac. Therefore an *overestimation* of the morphological change is expected for simulations with large morfac values.

When morfac is applied, tidal water level variations happen in $time/morfac$. When large values for morfac are applied, the steepness of the tidal wave increases. Therefore the hydrodynamic properties of the model changed. This might lead to for example more stirring of sediments.

Based on the mentioned (dis)advantages it was decided to use a *reconstructed wave time series* to reduce the computation time of the models.

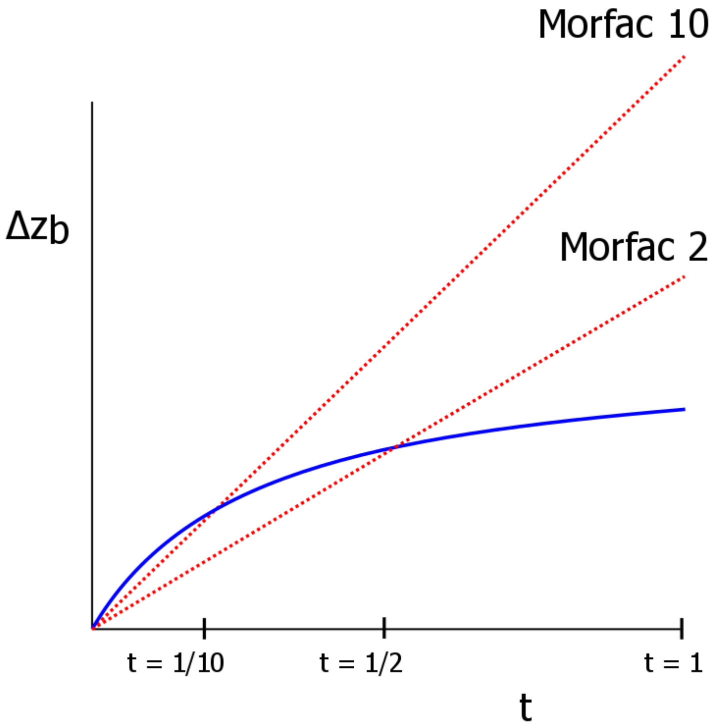


Figure A.1: Morfac assumes a linear morphological change in time where in reality the morphological change decreases in time.

A.1.2 Skipping parts of the model with waves below a threshold

Case studies at the Sand Motor with Delft3D showed that wave conditions below a certain threshold have a very limited effect on the morphological changes on the long term. This is interesting, because this means that it is not necessary to model these periods which could possibly save significant amounts of computation

Table A.1: Characteristics of two types of wave input reduction. Advantages are indicated with a +. Disadvantages with a -.

Reconstructed series	**Synthetic series**
+ No chronology effects	- Possibly chronology effects
- Nr. transitions ≈ Nr. storms	+ Only one transition
+ Wave reduction simple	- Wave reduction time consuming
+ Easy comparison with intermediate results.	- Not possible to compare with intermediate results.
- Morphological acceleration	- Morphological acceleration
- Effects hydrodynamic acceleration	- Effects hydrodynamic acceleration

time. Therefore the sensitivity of the stationary and surfbeat model of Vlugtenburg to different types of waves was investigated. This was done by running the model several times with different thresholds for the wave height (see tables A.2 and A.3). When the wave height in the boundary conditions (in the jons_table) was below this threshold, the wave height was changed to a value of 0,01m (changing it to 0,0m results in a crash of XBeach and is not possible), thereby neglecting the waves below the given threshold.

Before the wave threshold would be applied to skip certain parts of the model with non-significant waves, it had to be determined whether tidal currents (without any waves) resulted in any significant bed level changes. In order to test this, the waves of the whole year were set to a value of 0,01m in surfbeat mode (see table A.3).

Table A.2: The stationary models are run with different thresholds. Wave boundary conditions that are below this threshold are set to 0,01m.

Mode	**Wave threshold (m)**	**Note**
Stationary	0,0	Reference model
Stationary	0,5	
Stationary	1,0	
Stationary	1,5	
Stationary	2,0	
Stationary	2,5	
Stationary	3,0	

Table A.3: The surfbeat models are run with different thresholds. Wave boundary conditions that are below this threshold are set to 0,01m.

Mode	**Wave threshold (m)**	**Note**
Surfbeat	0,0	Reference model
Surfbeat	0,5	
Surfbeat	1,0	
Surfbeat	1,5	
Surfbeat	2,0	
Surfbeat	2,5	
Surfbeat	3,0	
Surfbeat	∞	Model with tide only

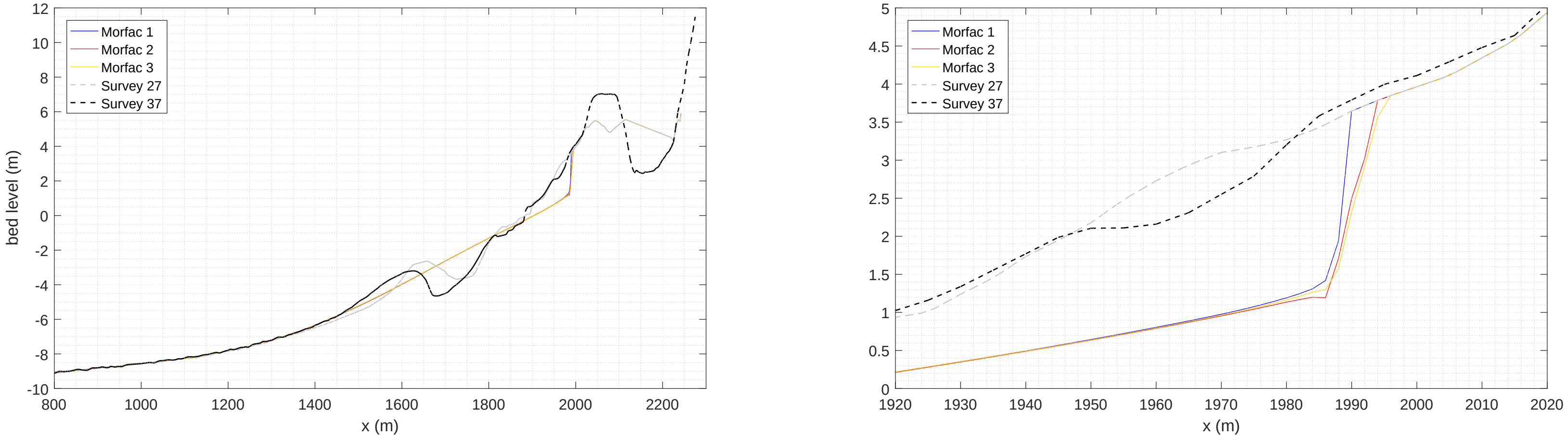
A.2 Results

A.2.1 Reducing computation time with morfac

A common way to reduce the computation time is to use a morphological acceleration coefficient, or MorFac, but this also comes at a cost of accuracy as described in section A.1.1. MorFac assumes a linear morphological change in time where in reality the morphological change decreases in time. Therefore the resulting bed level change is overestimated compared to the reference model. To determine the consequence of different morfac values, the reference model was used in combination with different morfac values. The results are displayed in figure A.2. It appears that the stationary reference model with a morfac of 5 has an inaccuracy in the bed level of about 7m at most. The surfbeat model shows a maximum deviation of about 20 meters. The deviations between the reference model with morfac 1 and morfac 5 are very small considering the difference between the reference model and the survey data. Each 1D simulation in this research took about 70 hours to finish. A morfac of 5 was used for all models in order to reduce the total simulation time without compromising the accuracy of the results.

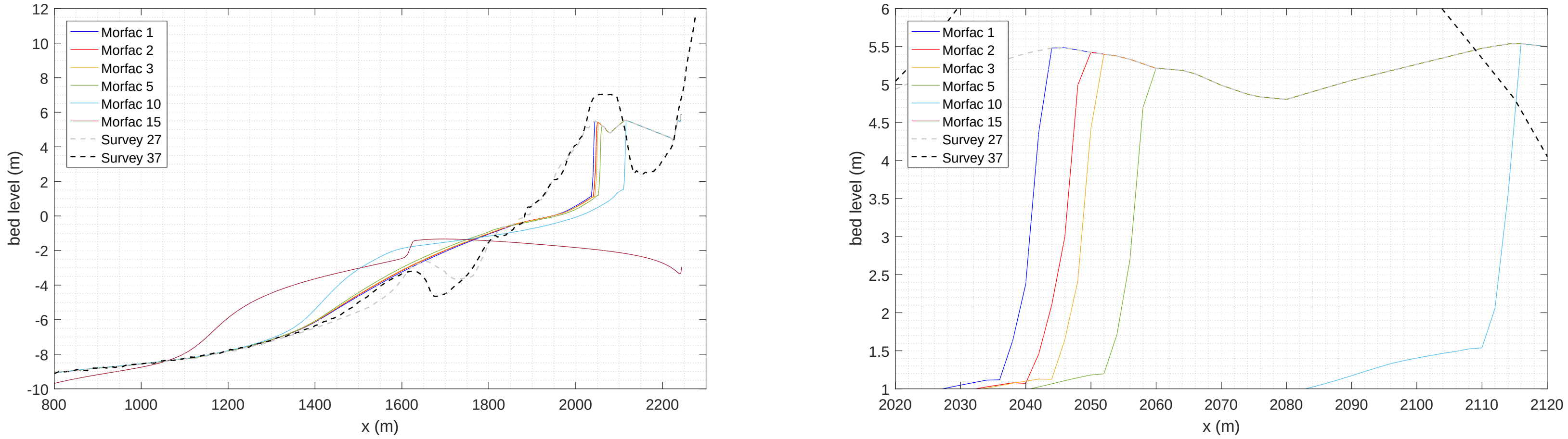
The inaccuracies of models with a MorFac of 5, were still found to be acceptable compared to models without a morphological acceleration. In other studies (for example (Pender and Karunarathna, 2013)) MorFac values of 10 and higher were used in stationary mode. In this study the MorFac was mainly used as a tool to limit the computation times of the sensitivity analysis. In order to be able to judge the results of the analysis without too much of a disturbance, the MorFac coefficients were kept on a safe value of 5. In this study models were only run for 375 days and mostly in 1D. For longer-term models in 2D, a higher MorFac is desirable. For stationary mode it is expected that also for Vlugtenburg higher values of MorFac could be used.

Influence of morfac



(a) Stationary, zoomed out.

(b) Stationary, zoomed in.



(c) Surfbeat, zoomed out.

(d) Surfbeat, zoomed in.

Figure A.2: Comparing results of different values of morfac for both stationary and surfbeat mode. Model: start at survey 27, end at survey 37, transect 12.

A.2.2 Neglecting waves below a certain threshold

Tests were carried out to find below which wave height threshold the waves did not contribute to the morphology. The results can be found in figure A.3. For both surfbeat and stationary mode it appeared that waves below 1,5m have only a slight influence on the bed level change; if the threshold became higher, the deviation from the reference model became less insignificant. In the stationary model the deviation between the reference model and the model with a threshold is most apparent in a small area at the location of the former trough. The deviation is more widely spread in the surfbeat model: from the location of the bar up to the dunes.

The influence of tidal currents alone was also tested by setting all wave input to 0,01m. The results are displayed in figure A.4. In the figure is visible that the tidal currents have a small (direct) effect on an area between -0,5 and -1,5m NAP, but the bed level changes by tidal currents alone are relatively minor compared to the morphologic activity in the reference model. Therefore it is expected that for models along the Dutch coast periods with a wave height below 1,5m can be skipped. However, this statement is only validated for the reference model; the reference model does not represent the seasonal effects well and other settings for the asymmetry are recommended (see section 6.3.1). With the recommended settings accretion *is* present during calm conditions. When the periods with low waves are skipped, this regenerative behaviour is disregarded. Therefore a wave threshold of 1,5m cannot be applied in models in which the regenerative behaviour during calm conditions balances the erosion during storm conditions. However, a smaller threshold might be applicable.

In figure A.3 can be seen that when the wave threshold is higher (ignoring more waves) the better the performance of the model. This is because the bathymetry at t = 0 is a better prediction than the model results (the MSESS is negative). Models with less wave forcing stay closer to the null-scenario and therefore perform better. When the wave threshold goes to infinity, the MSESS goes to 0 (disregarding the influence of tide for a moment).

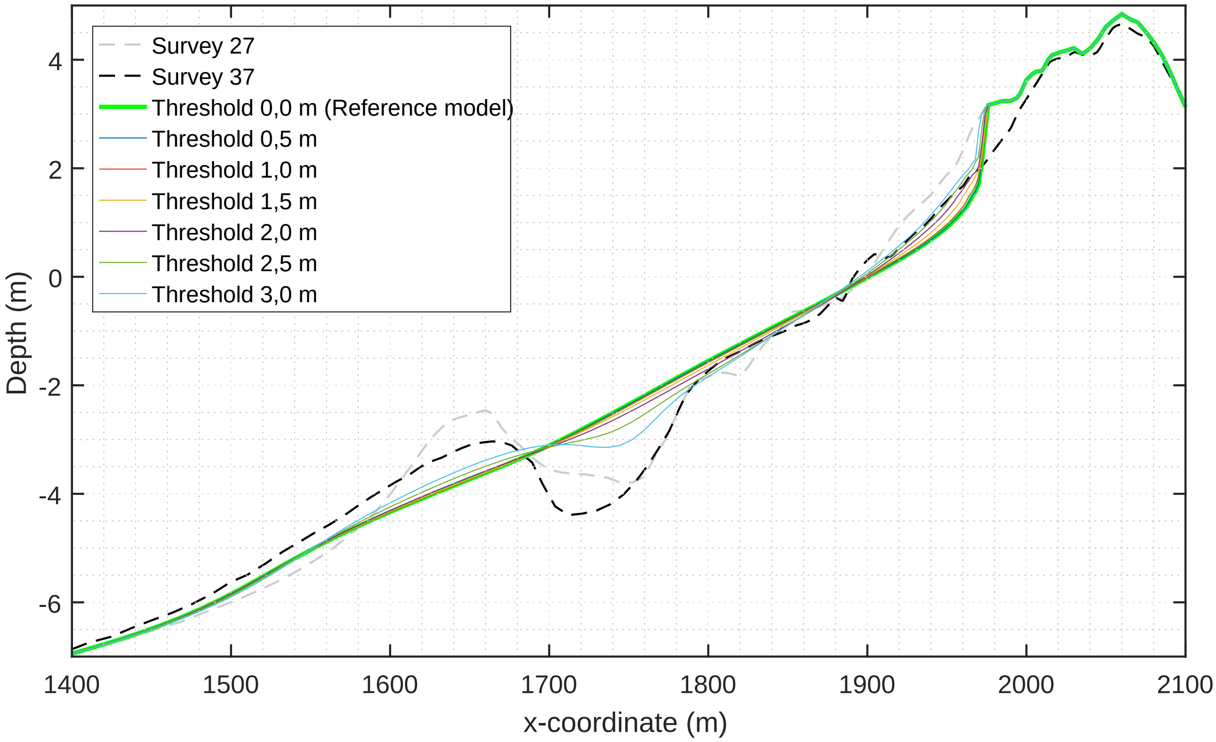
A.3 Conclusion: How can a wave input reduction contribute to more efficient long-term modelling?

How can a combination of wave input reduction and morphological acceleration reduce the computation time in an efficient way?

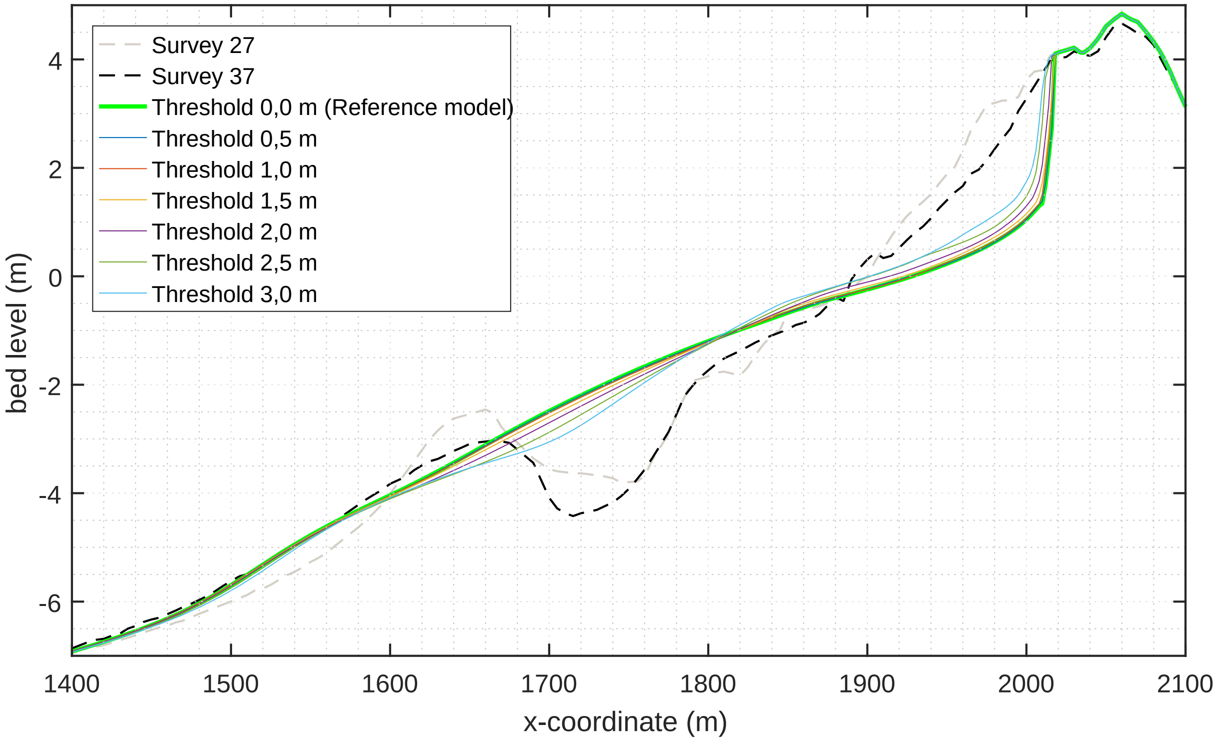
A test in which different morfac were used for a period of a year demonstrated that a morfac of 5 was usable in this study. The MorFac can be further increased for stationary mode, but since disturbances were not desired in this study, it was kept at a safe value of 5.

Can waves below a certain threshold be neglected in order to reduce the computation time?

- Waves up to 1,5m have a negligible influence on the reference case.
- The influence of the tidal wave alone is relatively small compared to the influence of waves.
- Therefore periods with waves below 1,5m can be skipped.
- Note that the sensitivity analysis for the wave threshold was only done for the reference models. In the reference models no accretive behaviour was visible during calm conditions. When the settings for asymmetry and skewness are increased, the wave threshold might not be valid anymore.

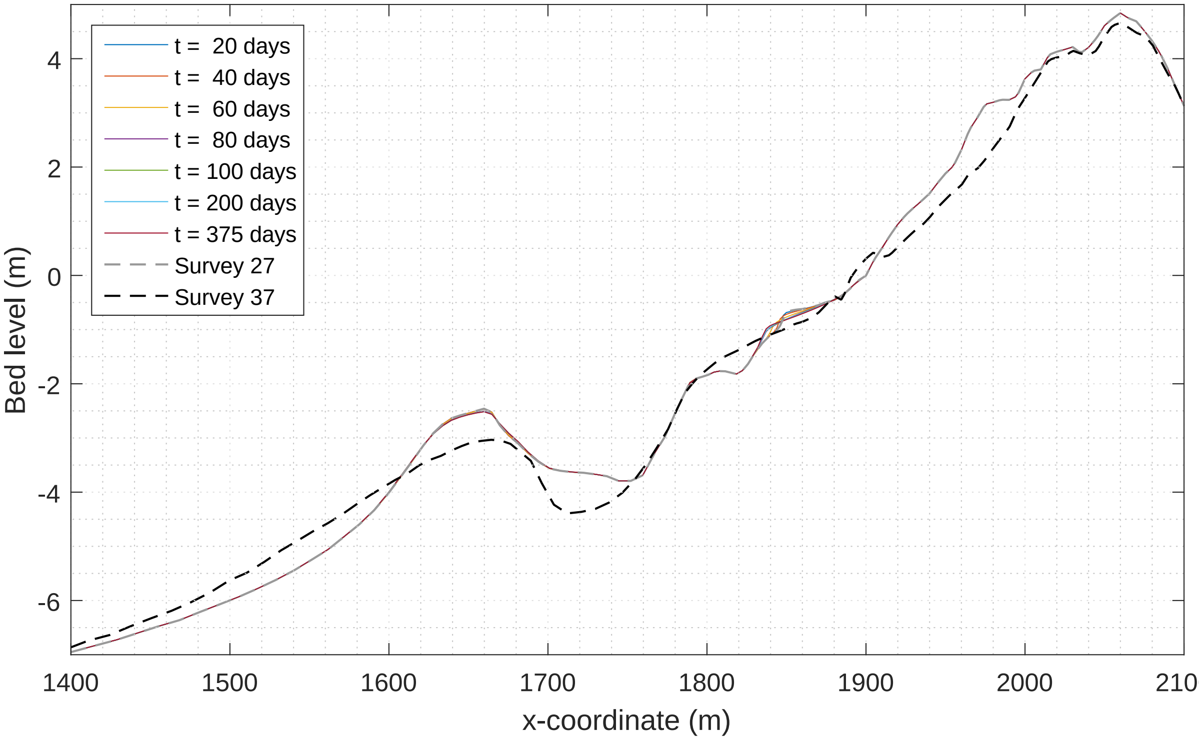


(a) Stationary mode

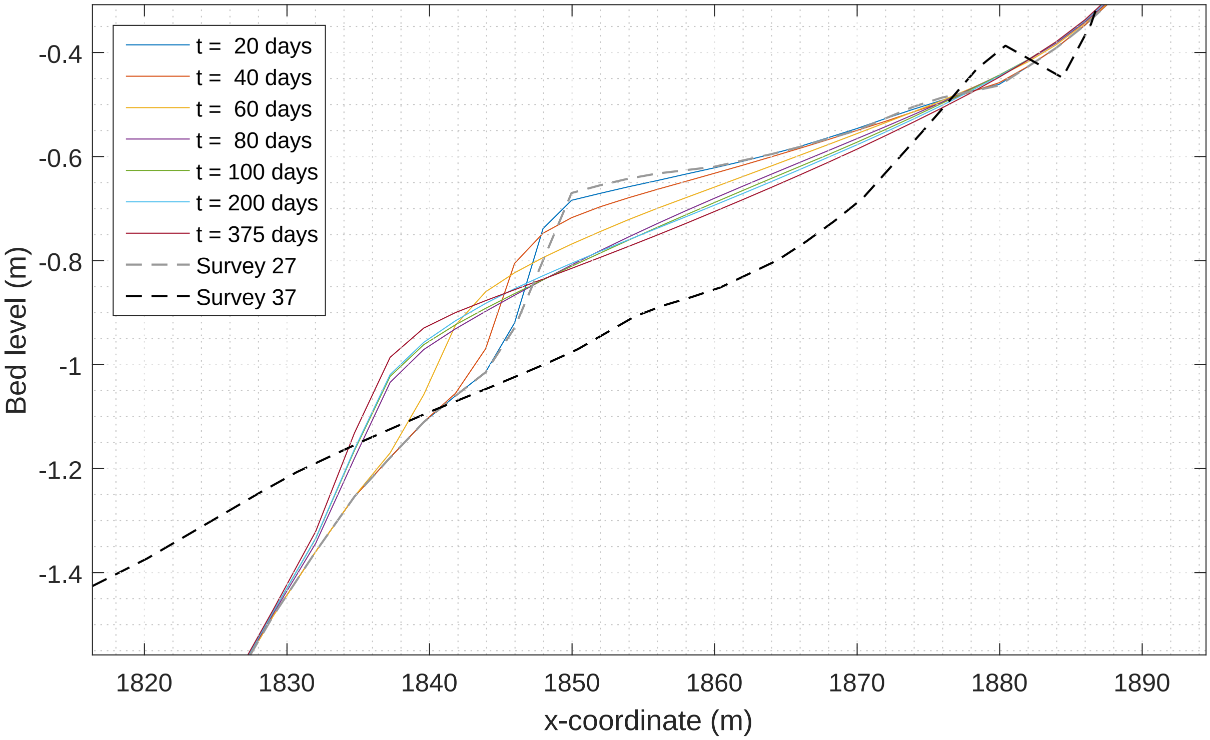


(b) Surfbeat mode

Figure A.3: Bed levels of models for which waves below the threshold are set to 0,01m.



(a) Zoomed out.



(b) Zoomed in.

Figure A.4: Bed level change in time for a model for which the wave input is set to 0,01m in the entire year.

B Wave direction and directional spreading

In a 1D XBeach model waves in the model domain are assumed to be uniform in longshore direction and therefore wave spreading is not simulated as well as in 2D. Waves that enter the domain at the offshore boundary with a wave directional spreading are translated to a longshore uniform wave. Therefore the wave height becomes more pronounced for waves with a high directional spreading as energy is converged in a single direction. This also leads to more pronounced infra-gravity waves.

Refraction is accounted for in a 1D model by assuming a longshore uniform bathymetry and applying Snells law:

Breaking results in the directional spread of of wave energy. However, refraction theory states that directional narrowing occurs when waves approach shallower water ((Herbers et al., 1999)). In low-energy wave conditions, the effect of refraction is dominant and directional narrowing occurs with decreasing depth. During high-energy wave conditions (and significant breaking occurring), there is directional spreading due to breaking between the edge of the surf-zone and the bar. Between the bar and the shoreline there is a decrease in directional spreading due to refraction.

The directional spreading is not measured at the Euro platform. The wave buoy at the SandMotor did measure the mean spreading of the direction from the wave spectrum (figure B.1). Since Vlugtenburg and the SandMotor are not that far apart, it is assumed that the directional spreading at both locations is similar.

The JONSWAP directional spreading parameter s is defined as:

$$s = 2/\sigma^2 - 1$$

In which σ is the directional spreading in radians.

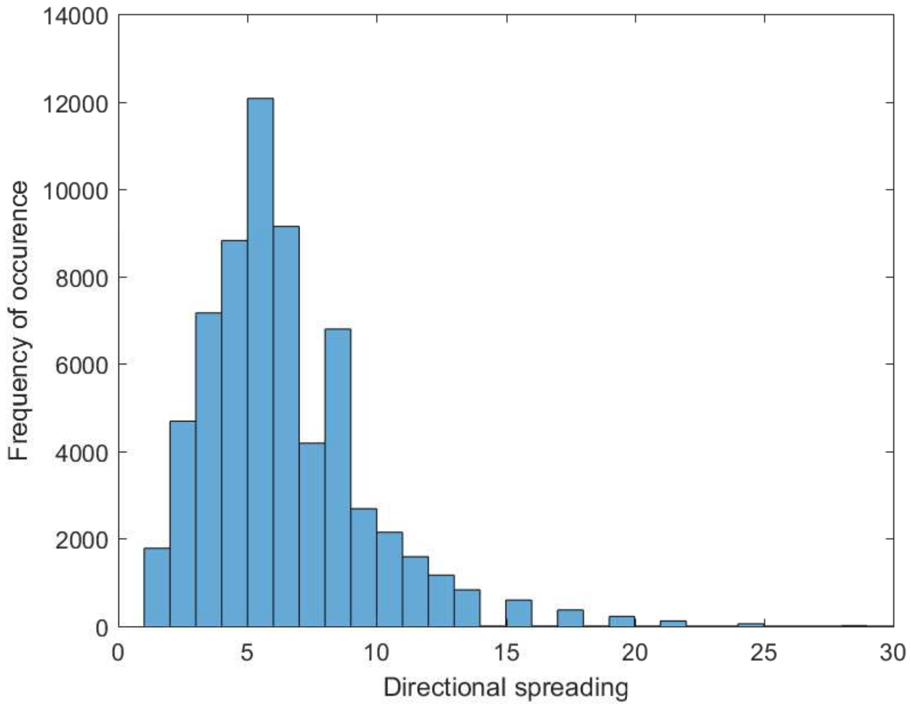


Figure B.1: Wave directional spreading measured by buoy at the SandMotor between December 2011 and November 2014.

It is most convenient to use a constant value for the wave spreading, because the wave buoy data of the

SandMotor is only available from 2011 on, the Vlugtenburg surveys are partially done before that. Therefore will be investigated whether:

1. a constant wave spreading parameter leads to a significant inaccuracy in the model compared to varying spreading parameters and
2. whether the magnitude of the constant wave spreading parameter is important

Therefore the following 1D models with wave data of the buoy at the SandMotor will be compared during a run of 19 days:

1. model wave-spreading-variable: $s = variable(measuredvalue)$
2. model wave-spreading-0: $s = 0$
3. model wave-spreading-5: $s = 5$
4. model wave-spreading-10: $s = 10$
5. model wave-spreading-15: $s = 15$

The one month simulation showed that there is a difference between using a wave spreading of s = 1 (high directional spreading, wave energy distributed more evenly in the directional spectrum) and s = varying with every time step using data from the SandMotor (see figure B.2).

In figure B.3 is visible that, apart from s = 1, varying the wave spreading parameter has only a subtle effect over a period of 19 days with many storm activity.

Based on the comparison of different wave directional spreading parameters, a value of s = 7 was chosen for all model runs. This is close to the default XBeach parameter of s = 10. This value is also recommended by Goda (2010) for wind waves.

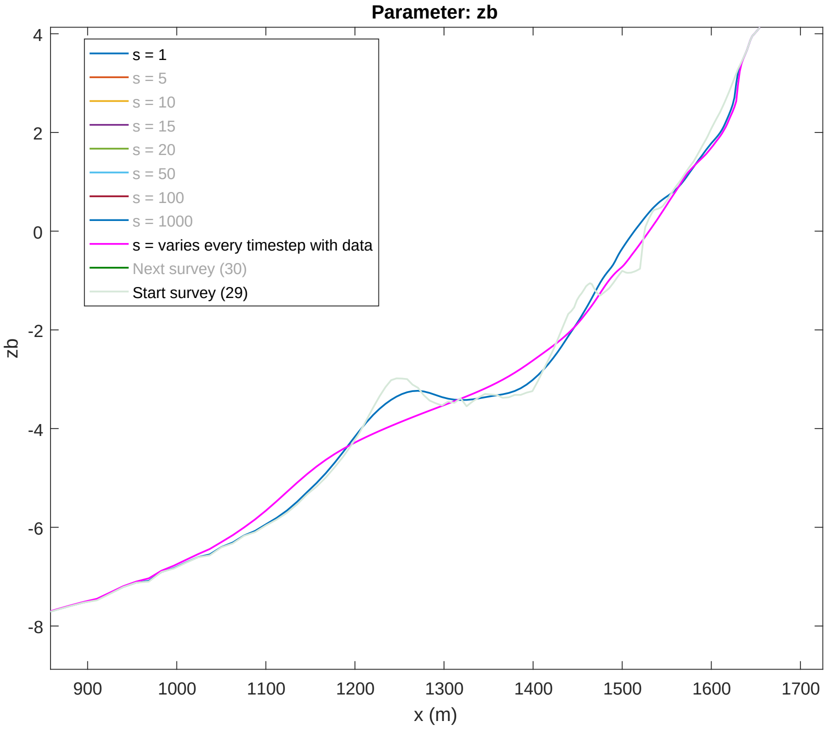


Figure B.2: Comparing differences between s = 1 (high directional spreading) and s = data.

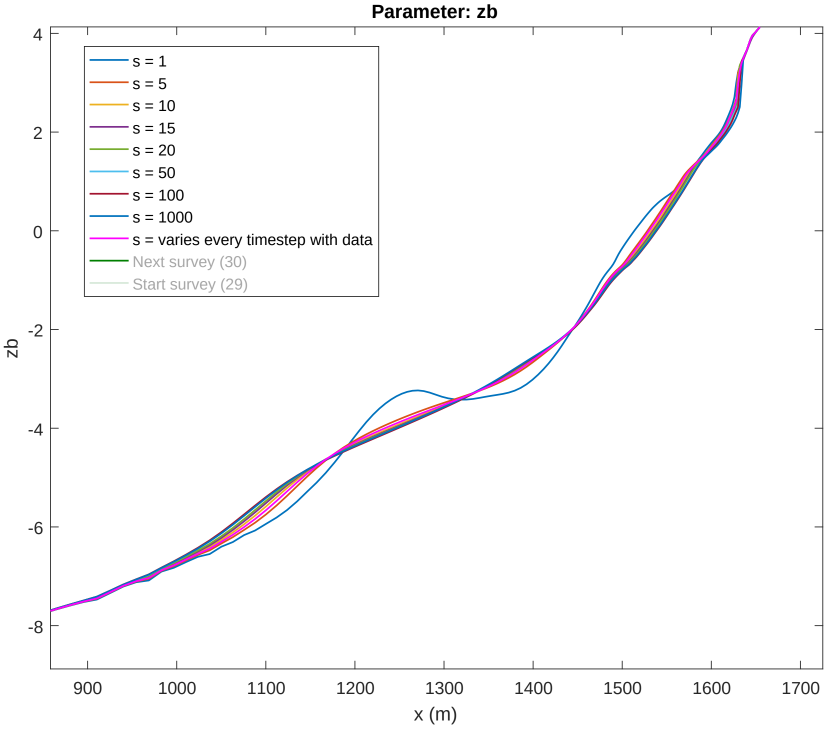
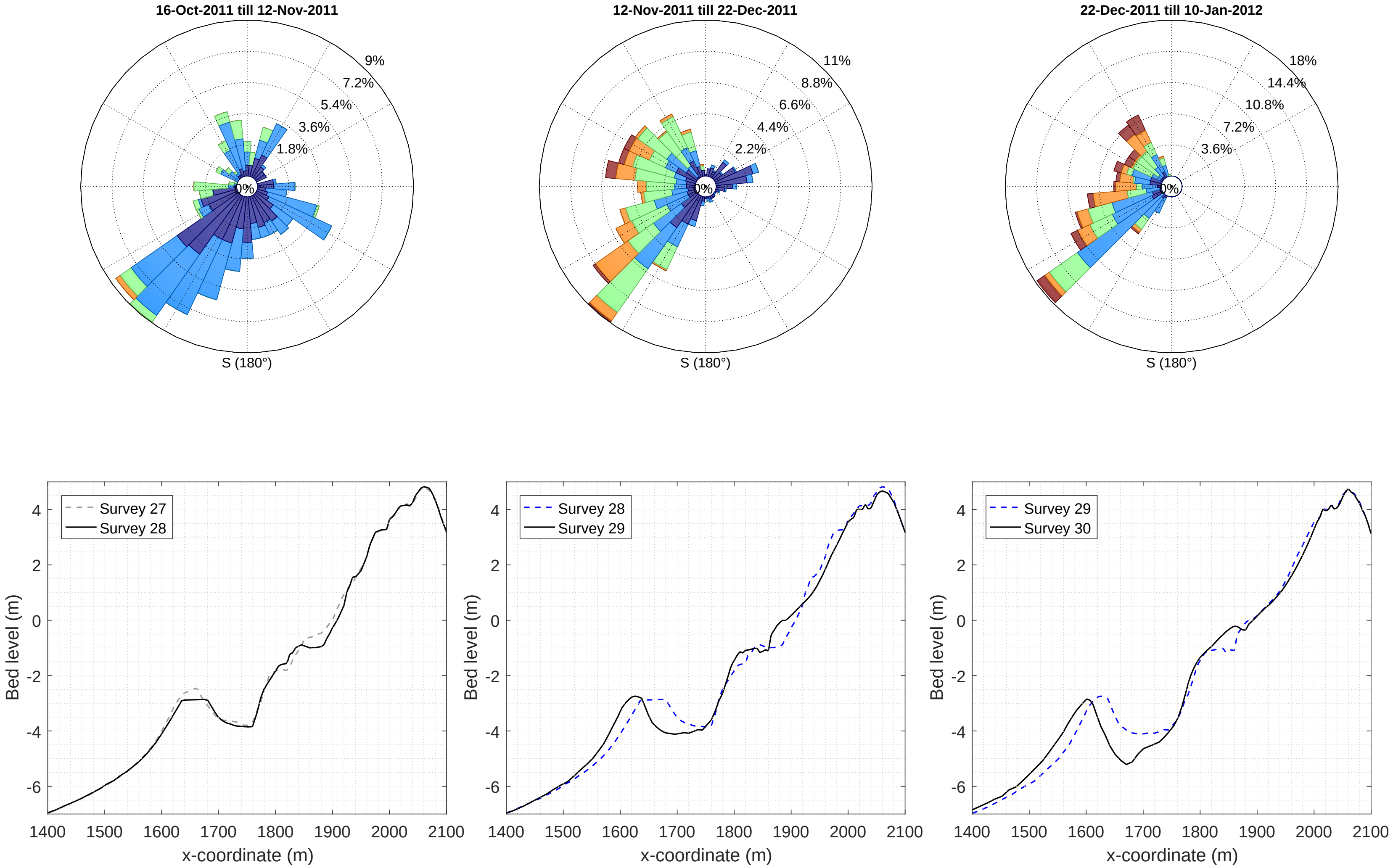


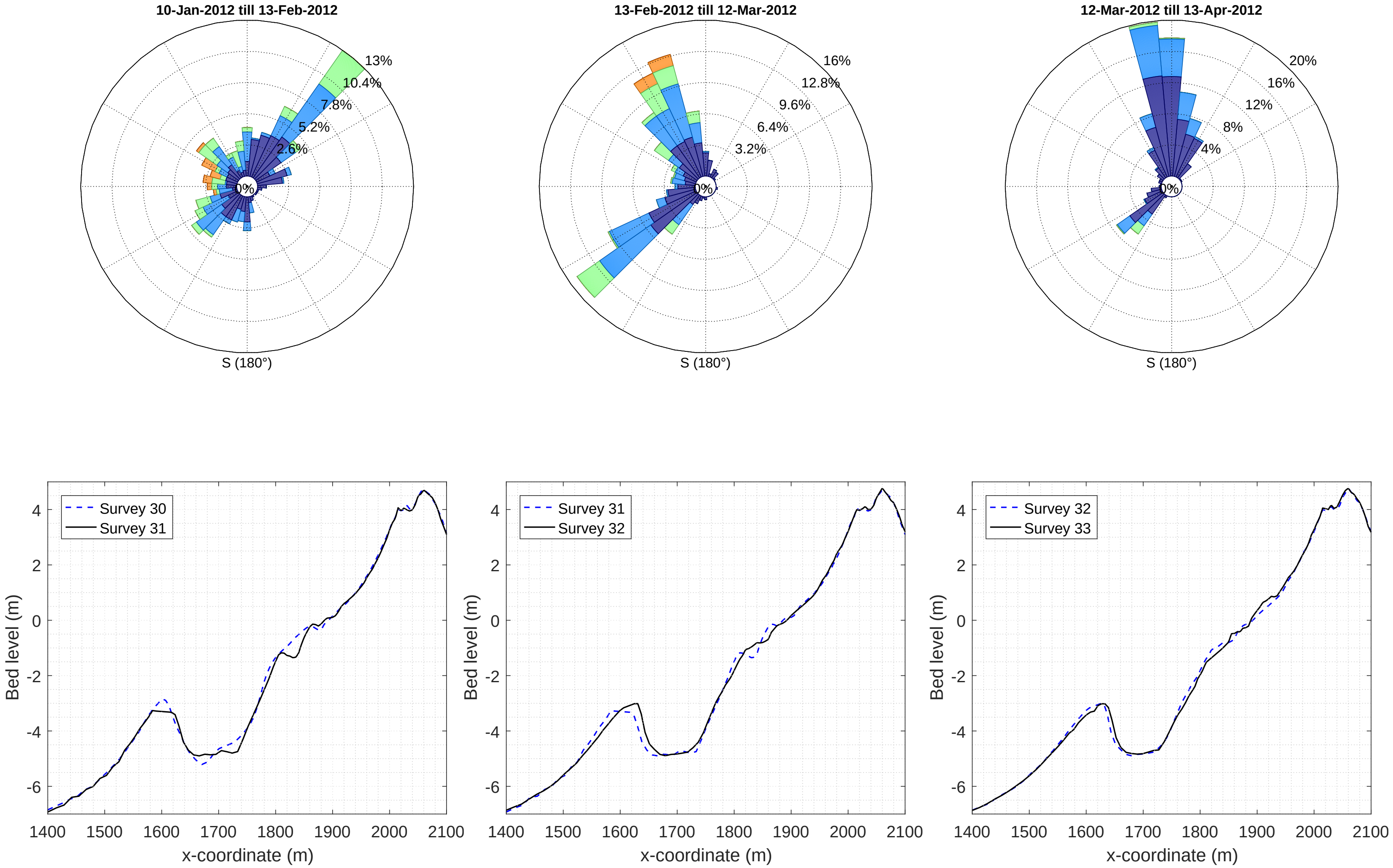
Figure B.3: Comparing different wave spreading parameters.

C Monthly surveys and wave roses



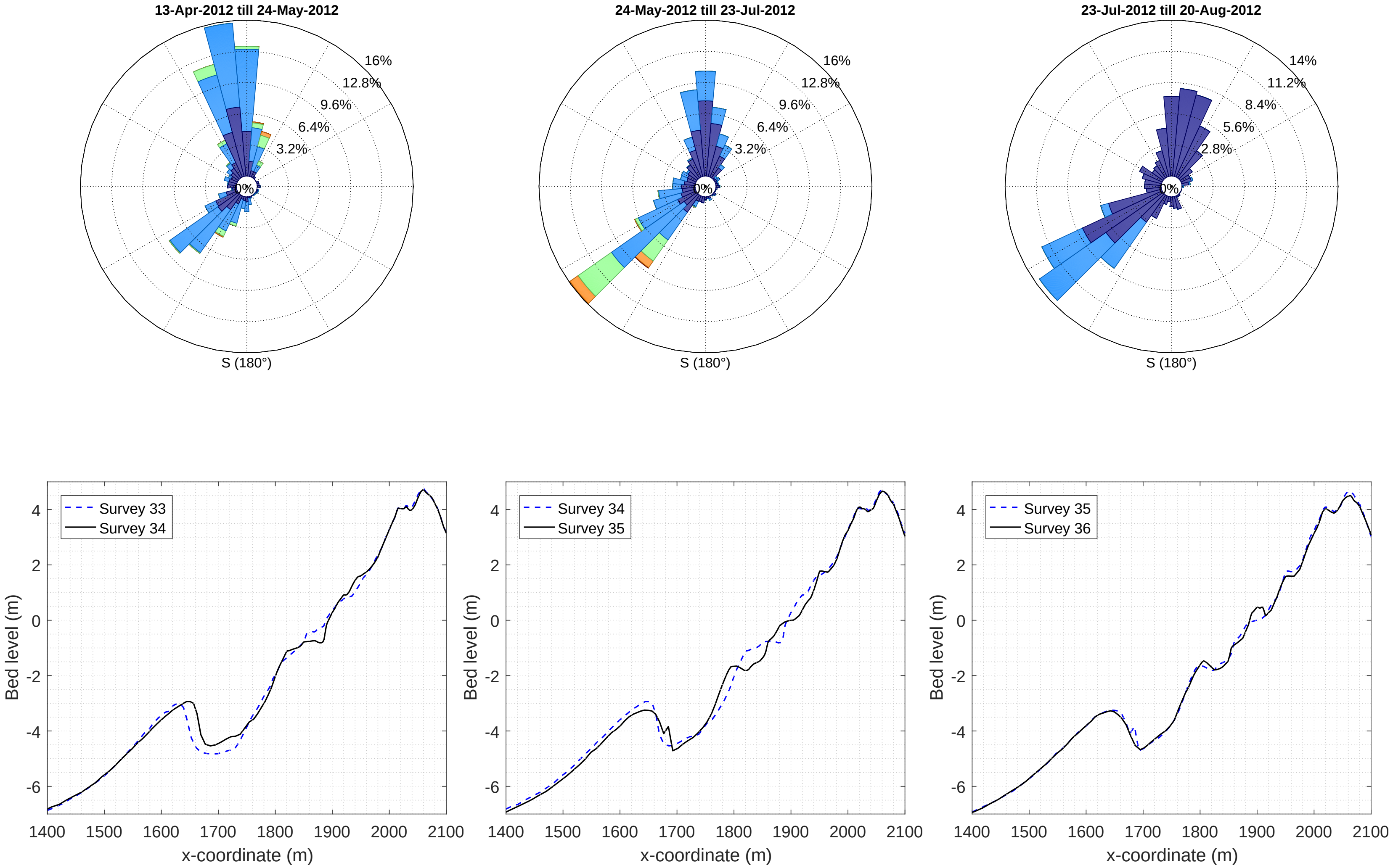
(a) (b) (c)

Figure C.1: Bed level changes of two consecutive surveys and the wave roses of the corresponding period.



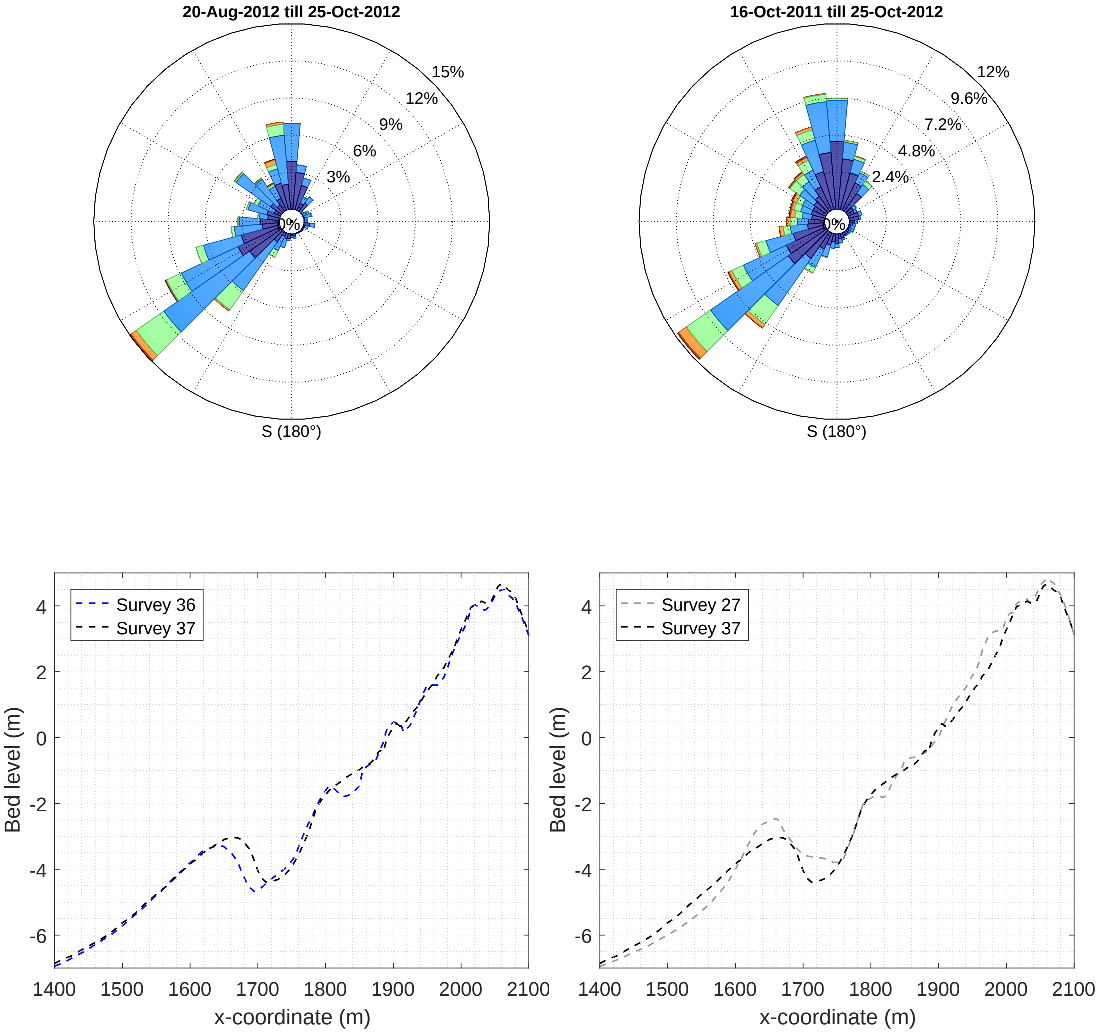
(a) (b) (c)

Figure C.2: Bed level changes of two consecutive surveys and the wave roses of the corresponding period.



(a) (b) (c)

Figure C.3: Bed level changes of two consecutive surveys and the wave roses of the corresponding period.



(a)

(b) From start survey (27) to end survey (37).

Figure C.4: Bed level changes of two consecutive surveys and the wave roses of the corresponding period.

D Practical problems encountered when using XBeach for long-term modelling

D.1 Maximum number of boundary conditions

In case the option instat = jons_table is used, XBeach generates a boundary condition file for every row in the jons_table file. In Kingsday release 1.22 revision 4867 the maximum number of boundary conditions files that can be generated is 900 (tryunit = 900). The simulation is stopped when that number is reached. XBeach displays:

"Serious problem: not enough free unit ids to create new file"

In the simulations done for this study, up to 9200 boundary condition files were required. Newer revisions have a maximum number of boundary condition files of 9999 which was sufficient for the simulations in this study.

D.2 Bug in directional grid

Many of the long-term models crashed in the newest XBeach revision at the time (Kingsday 1.22.5052). It was discovered that for stationary mode (instat = stat_table) when the direction of the incoming wave (specified in a jons_table) was equal to thetamin or thetamax, the model crashed. In stationary mode the direction of the incoming waves is exactly equal to the value that is specified in the jons_table. When surfbeat mode is used with a jons_table, a wave height, period and direction are generated based on a JONSWAP-spectrum. In this case there is a small probability that the direction of the generated wave is equal to thetamin or thetamax. Therefore these type of crashes were not observed in surfbeat mode.

This problem in the directional grid was solved by changing the directions of the wave input from $thetamin$ to $thetamin + 1$ tot 223 and directions that were equal to $thetamax$ to $thetamax - 1$.

D.3 Wave height of zero

When a wave height of 0.0m occurs in the jons_table, the model crashes.

D.4 Long computation times for high frequency output

In certain models the output frequency of 4 points was set to 5 seconds. Normally a model required about 8 hours to complete. With the high output frequency the model had to run for a week.

D.5 Memory leak in XBeach

In the XBeach revisions that were used: Kingsday 1.22.5052 and 1.22.5123, the long term models were crashing at what seemed random moments: sometimes the simulation completed, sometimes it crashed after 8000 boundary condition files were computed and sometimes already after 2000 conditions. It appeared that when $instat = jons_table$ was used, there is a memory leak when the boundary conditions are created. The memory leak in XBeach leads to an increase in memory (RAM) usage. The model crashes when the maximum amount of SWAP memory is used (see figure D.1). In the figure the model did not crash, but the increasing amount of RAM usage can be seen.

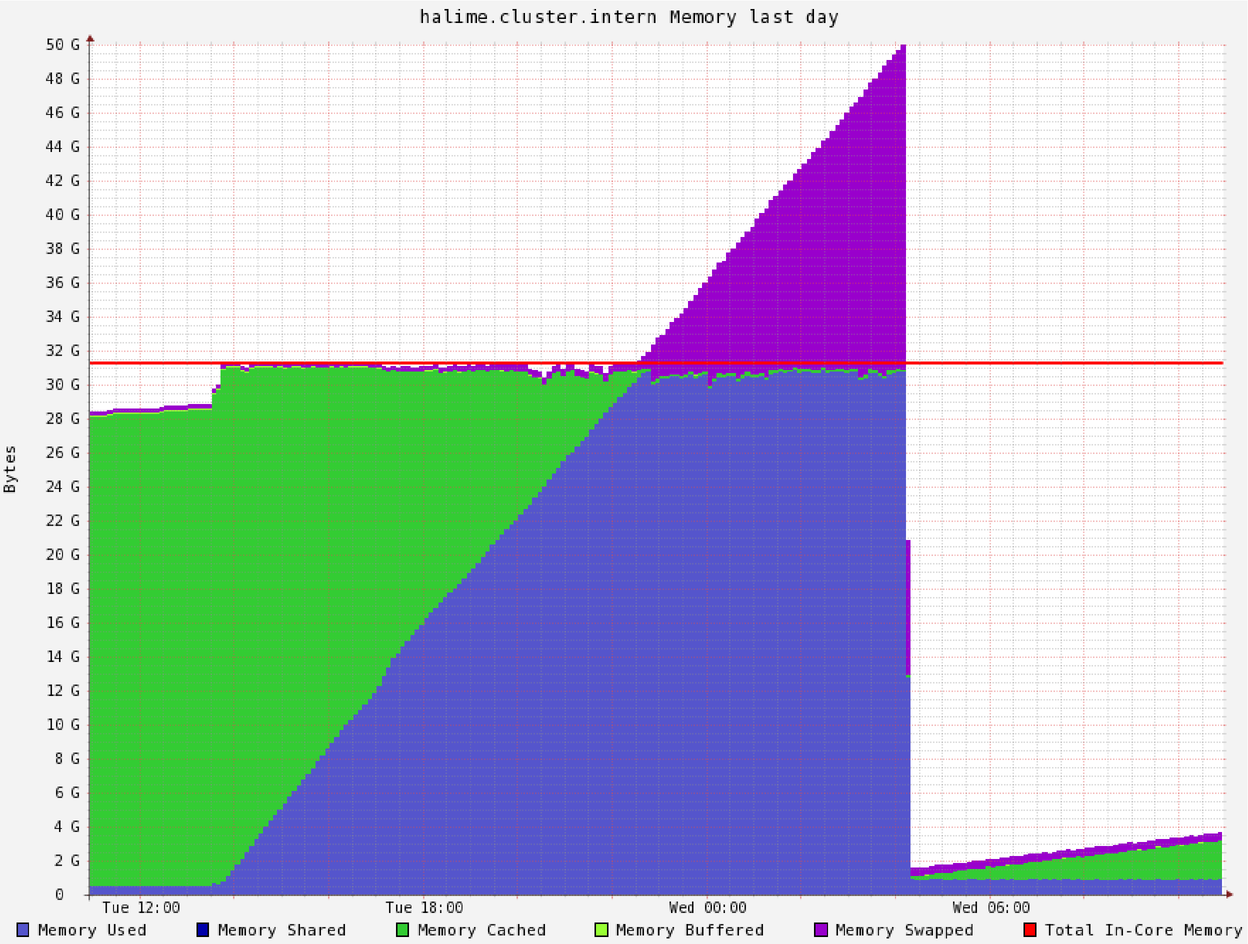


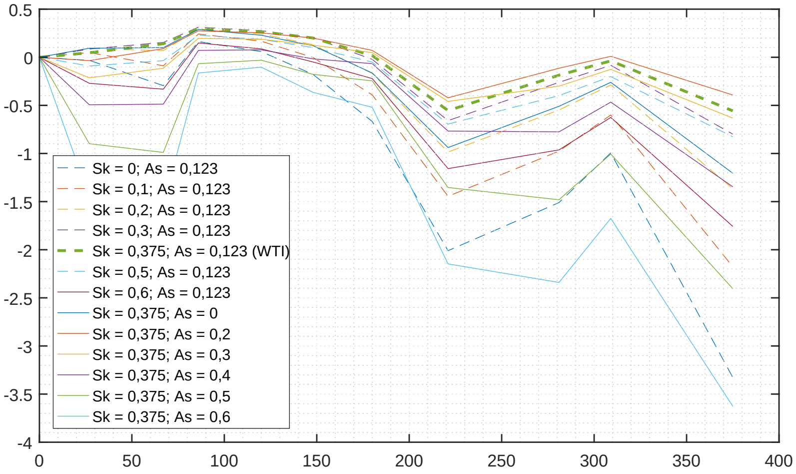
Figure D.1: Increase in Memory Used and Memory Swapped on the cluster when using instat = jons_table.

Also when using *instat* = *stat_table* the models often crash. In these models the RAM usage did not increase, but the storage space used by the model increased. The models crashed when it reached a maximum.

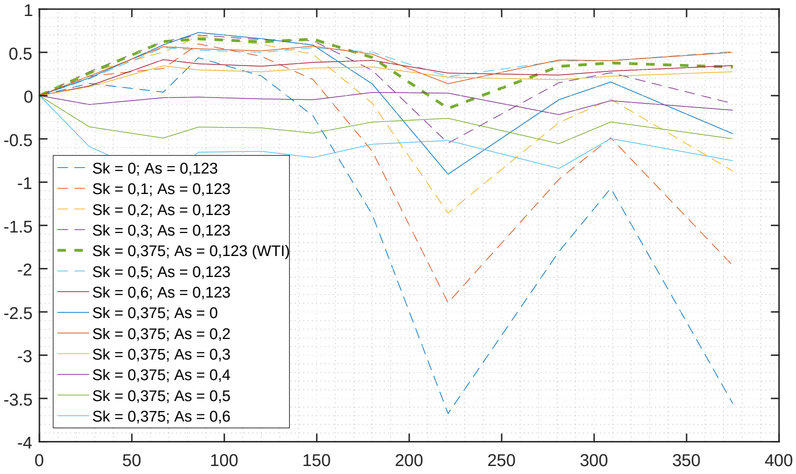
A solution for the memory leak in surfbeat mode is to use the option *instat* = *reuse* with previously generated boundary conditions. Another option is to run one model at the time on a cluster with sufficient amount of RAM. For stationary mode the boundary conditions can't be reused and the only solution found was to run it on a cluster with sufficient storage space.

E MSESS in time

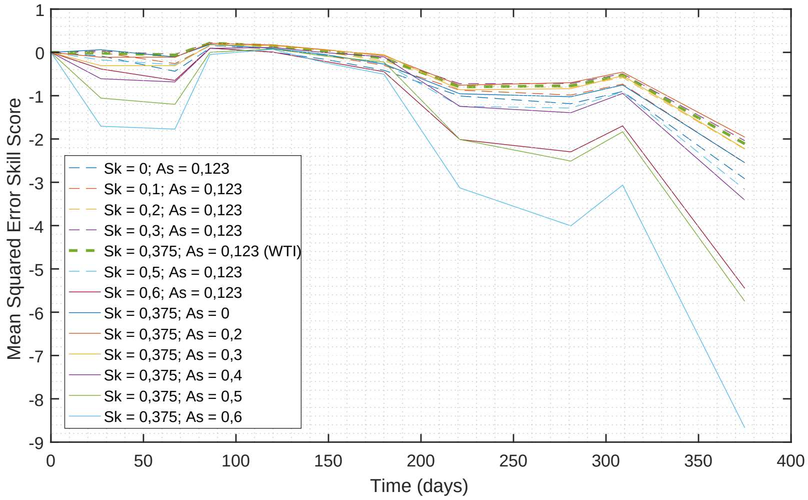
In this section the evolution of the Mean Squared Error Skill Scores (MSESS) in time of the sensitivity analysis are shown.



(a) Total MSESS.

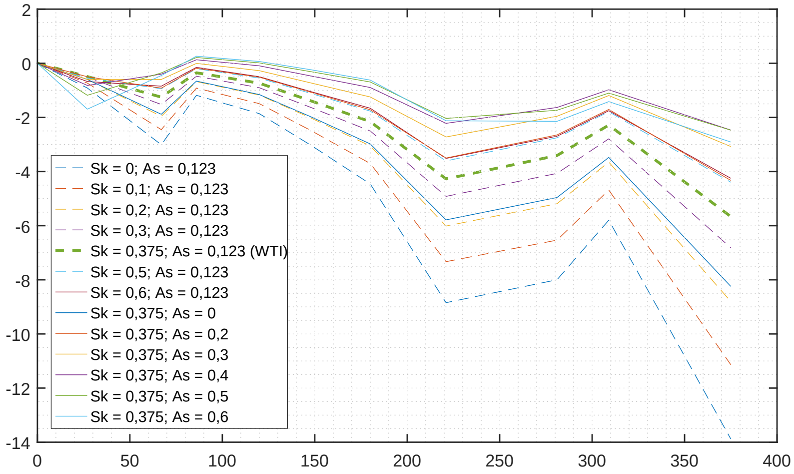


(b) MSESS above 0m NAP.

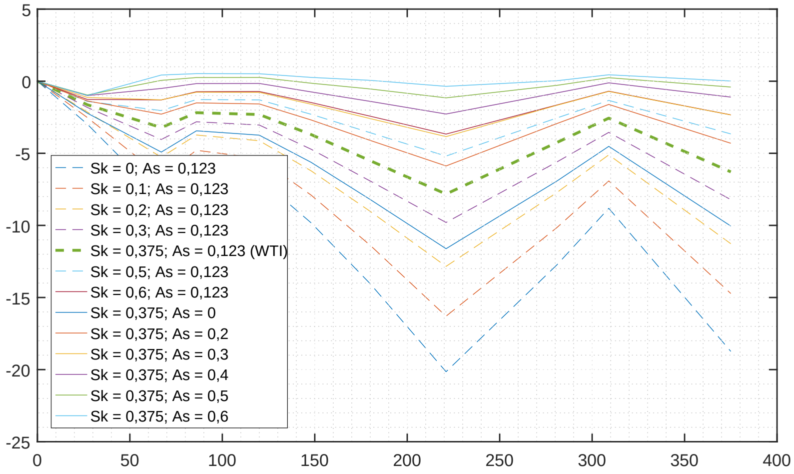


(c) MSESS below 0m NAP.

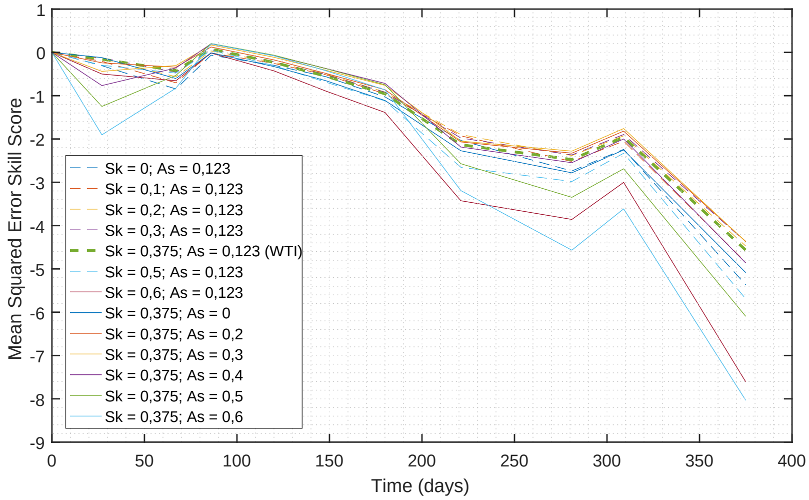
Figure E.1: Skill scores (MSESS) of different settings for facAs and facSk in the stationary model.



(a) Total MSESS.



(b) MSESS above 0m NAP.



(c) MSESS below 0m NAP.

Figure E.2: Skill scores (MSESS) of different settings for facAs and facSk in the surfbeat model.

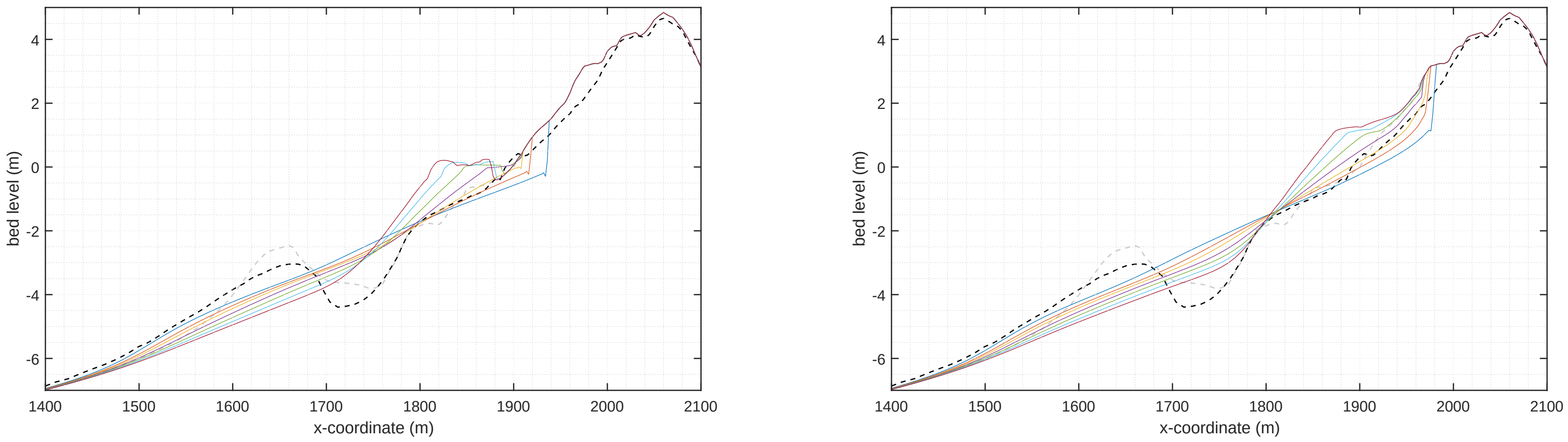
F Models without tide

The sensitivity analysis that includes tides shows different behaviour than the sensitivity analysis without tide. The region of influence of the models with tide reaches up to a higher level above NAP, which leads to more dune erosion. Besides that the models with tide have a single point at which the lines of the models intersect. The models without tide have more than one intersection point: models with a facAs of 0,4; 0,5 and 0,6 intersect near each other and have different characteristics than the models with a facAs of 0; 0,123 and 0,2. The characteristics of both groups of models are listed in table F.1.

Table F.1: Sensitivity analysis of models without tide and the two types of observed characteristics.

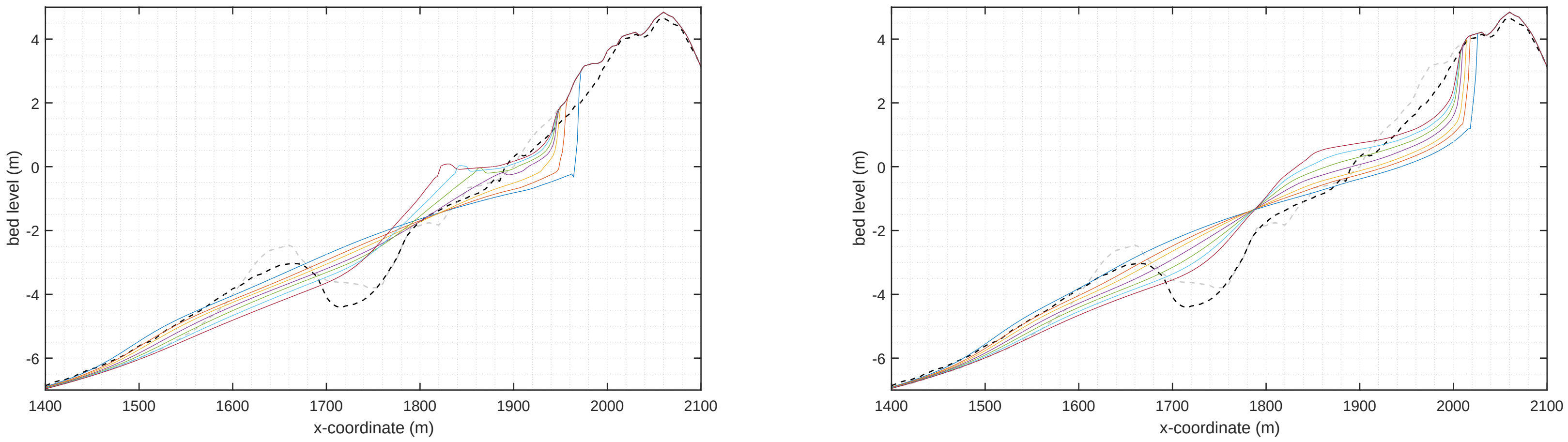
facAs	***Intersection point at (m NAP)***	***Characteristics***
0; 0,123 and 0,2	-1,75 (stationary) -1,5 (surfbeat)	Concave. Very steep dune face. No trough and bar formation.
0,3; 0,4; 0,5 and 0,6	-2,75m NAP (stationary) -2,5m NAP (surfbeat)	Convex/concave (S-shape). A bar and trough are formed at 0m NAP in combination with a wide beach with flat slope. Bar and trough are more pronounced for higher facAs. The trough is deeper for stationary mode.

For the models *with tide* there is only one intersection point (stationary: -1,5m NAP; surfbeat: -1,25m NAP). A concave shape, similar to models without tide, is observed for models with a facAs of 0; 0,123 or 0,2 and a S-shaped curve for models with a higher facAs. For the models with a high facAs there is also a wide beach with mild slope, but differently than the models without tide, there is only a little bar and trough formation for stationary mode at the high water level and none at all for surfbeat mode.



(a) Stationary without tide

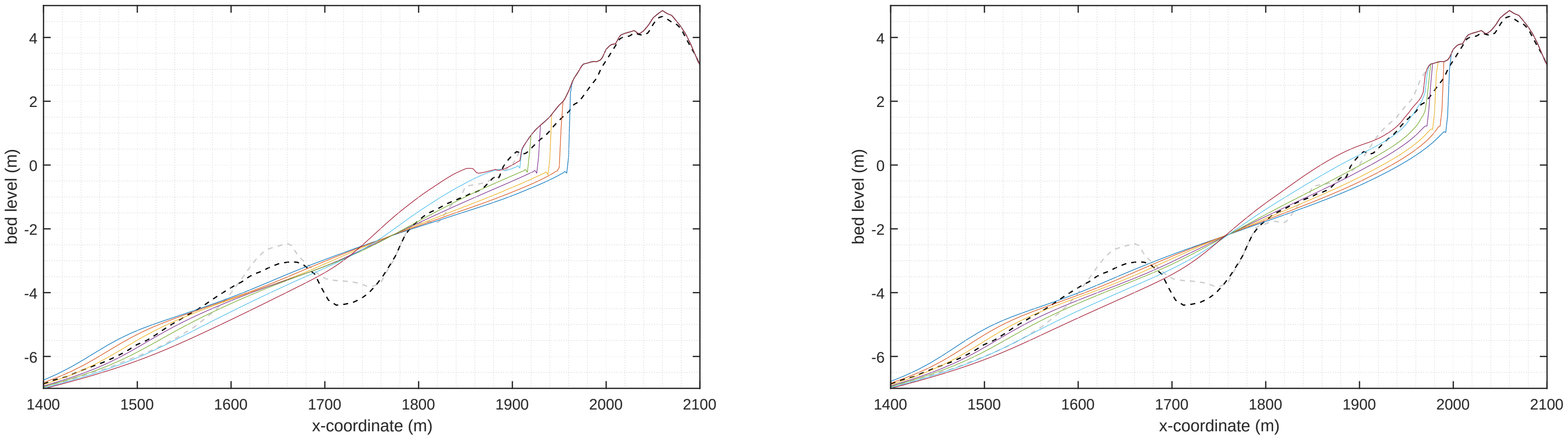
(b) Stationary.



(c) Surfbeat without tide

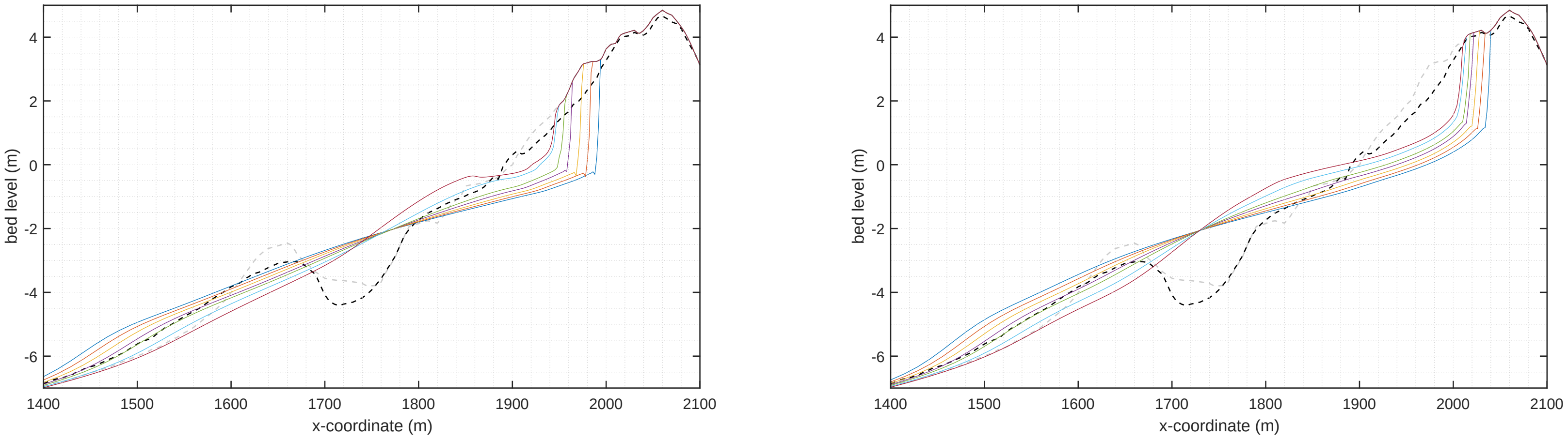
(d) Surfbeat.

Figure F.1: Analysis of the sensitivity of asymmetry (facAs) in stationary and surfbeat mode.



(a) Stationary without tide

(b) Stationary with tide



(c) Surfbeat without tide

(d) Surfbeat with tide

Figure F.2: Analysis of the sensitivity of skewness (facSk) in stationary and surfbeat mode, with and without tide.

G XBeach model files of reference model

G.1 Params.txt file

```
%%% XBeach parameter settings input file %%%
%%% %%%
%%% date: 21-Apr-2017 13:38:50 %%%
%%% function: xb_write_params %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% Bed composition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

D50 = 0.000300
D90 = 0.000500

%%% General %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% Grid parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

depfile = bed_S27_T6.dep
posdwn = 0
nx = 343
ny = 0
alfa = 318
vardx = 1
xfile = x_S27_T6.grd
yfile = y_S27_T6.grd
thetamin = -90
thetamax = 90
dtheta = 180
thetanaut = 0

%%% MPI parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

mpiboundary = auto

%%% Model time %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

tstop = 32399400

%%% Morphology parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

morfac = 5
morstart = 36000
wetslp = 0.260000

%%% Physical processes %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

lwave = 1
morphology = 1
gwflow = 1

%%% Sediment transport parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

waveform = ruessink_vanrijn
form = vanthiel_vanrijn
facSk = 0.375000
facAs = 0.123000
turb = wave_averaged

%%% Tide boundary conditions %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

zs0file = tide_16-Oct-2011_25-Oct-2012.txt
tideloc = 1

%%% Wave boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

instat = jons_table

%%% Wave breaking parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

break = roelvink2
gamma = 0.541000
alpha = 1.262000
gammax = 2.364000
fw = 0

%%% Wave numerics parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

wavint = 1200

%%% Wave-spectrum boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

bcfile = jonswap_16-Oct-2011_25-Oct-2012.txt

%%% Output variables
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

tintm = 86400
tintg = 86400

nglobalvar = 4
H
zb
hh
thetamean

nmeanvar = 21
H
```

```
zs
zs0
zb
hh
u
v
ue
ve
urms
Fx
Fy
ccg
ceqsg
ceqbg
Susg
Svsg
R
D
DR
```

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