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Methodology for Safety Assessment 2021

XBeach BOI – sensitivity analysis and model validation

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Methodology for Safety Assessment 2021

XBeach BOI – sensitivity analysis and model validation

De Roo, S.; Trouw, K.; De Maerschalck, B.

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Abstract

Since the 2015 Coastal Safety Assessment, XBeach is applied for the morphodynamic modelling of the normative storm conditions. Being under continuous development, a further validation of the newest XBeach version was necessary upon use in the 2021 Coastal Safety Assessment (SA21).

A thorough sensitivity analysis learned about the differences between the released XBeach versions. Some physics got integrated or improved and the model's architecture was adjusted at some points. Based on a (limited) model validation with field measurements, it was found that the BOI (*Beoordelings- en OntwerpInstrumentarium)* settings, calibrated in the framework of the methodology update of the Dutch Coastal Safety Assessment, are also suitable for use along the Belgian coast. Only the *wetslp* parameter, determining the critical avalanching slope under water, was slightly lowered to 0.10 (instead of 0.15). No structural bias was found in the model's performance and the scatter index was acceptably low, being 0.14 and 0.30 for the modelled retreat distance and erosion volume respectively.

The XBeach model set-up and settings for the 2021 Coastal Safety Assessment are now based on the validated 2DH application of XBeach as described in this report. For this assessment, the entire Belgian coast will be divided into 28 coastal areas. For each of these coastal areas, the morphodynamic response to a 45-hour normative storm will be assessed and the safety level will be evaluated.

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1 Introduction

1.1 Background: the 2021 Coastal Safety Assessment

In 2011, the Flemish government approved the Coastal Safety Master Plan, a flood risk management plan aimed at protecting the 67-kilometre-long Belgian coastline against the design storm surge having a return period of 1000 years. The Master Plan proposed various protection measures to maintain (or increase) the coastal defence's structural integrity. Numerous measures have been gradually implemented, ranging from beach nourishments to new robust dikes. These measures ensure coastal safety until 2050 by taking into account a moderate sea level rise and adaptive beach nourishments.

To maintain a resilient, safe, and climate-adaptive coastal defence, its as-is safety level against the design storm surge must be assessed every six years. The year 2021 marks the third safety assessment, hereafter referred to as the 2021 Coastal Safety Assessment (SA21).

1.2 Objective of this report: XBeach in 2021 Coastal Safety Assessment

XBeach was used for the first time in the 2015 Coastal Safety Assessment. At that time, validation efforts focused on 1D cross shore cases. Being under continuous development a further calibration and validation of the new XBeach version is necessary and hence, the objective of this report.

1.3 Reader's guide

Chapter 2 briefly tackles XBeach' history and relevant developments to our work, like calibrated parameter settings.

Chapter 3 gives an overview of sensitivity analyses carried out using XBeach versions X and (beta-)Halloween.

Chapter 4 lists the validation methodology whilst Chapter 5 describes the validation cases.

Chapter 6 concludes the model settings for SA21.

Chapter 7 elaborates on a special case: breaching in a complex dune area.

Chapter 8 reflects on the work carried out to meet the objective and identifies some challenges yet to tackle.

2 XBeach developments: from Groundhog Day to Halloween

2.1 XBeach: general

Infragravity waves dominate nearshore hydrodynamics on dissipative beaches under storm conditions and play a key role in the dune (and nourished beach) erosion process. XBeach is a process-based 2DH morphodynamic numerical model for the nearshore and coast (Roelvink *et al.*, 2009), being specifically developed to predict beach and dune erosion, breaching and flooding during storm events. The XBeach surfbeat mode, focus of this study, solves the variation of short wave energy on the scale of wave groups, which drives lower frequency motions (infragravity waves) and unsteady currents being fully resolved in the model (Roelvink *et al.*, 2018). These hydrodynamic processes are fully coupled with sediment transport, avalanching of dune faces and resulting bed level changes.

In the 2015 Coastal Safety Assessment (SA15) XBeach was used for the first time. At that time, the XBeach Groundhog Day version was the latest one. XBeach continues to be developed; meanwhile, XBeach versions Kingsday and X were consecutively launched. The latest version, XBeach 'Halloween' was released in late 2023, after the 2021 Coastal Safety Assessment. However, its beta version 'XBeach BOI' was being developed during the preparation of the SA21 methodology and used for the validation cases (cf. Chapter 5). It will be referred to as XBeach BOI throughout this document.

Table 1 summarises the main progress made in XBeach' developments over the past decade.

Table 1 – Summary of XBeach versions (and model developments) between the 2015 and 2021 Coastal Safety Assessments.

	Summary
XBeach v 1.21 'Groundhog day' (2014)	Used in SA15, using WTI calibrated parameter settings (Van Geer *et al.*, 2015) MPI bug -> no parallel computation: very long calculation times for 2DH models (4-6 weeks)
XBeach v 1.22 'King's day' (2015)	MPI bug fix: parallel computation ok Inclusion of *single_dir* functionality: preservation of wave groupiness (Roelvink *et al.*, 2018)
XBeach v 1.23 'XBeach X' (2018)	Used in SA21: initial phase of sensitivity analysis Additional sediment transport formula: Van Rijn (1993) to improve grain size dependency
XBeach v 1.24 'Halloween' (2023)	Beta version v23.5917M 'BOI' used in SA21 methodology, generally using BOI calibrated parameter settings (McCall *et al.*, 2022) -> later on officially released in v1.24: BOI calibrated parameter settings are the default settings Improved implementation of varying tides to reduce artificial waves: tidetype = *hybrid*

	Improvements in (consistency of) Roelvink-Daly model for wave breaking in 1D and 2DH Efforts to account for wave directional spreading effect in 1D: *wbcEvarreduce* parameter Efforts to improve grain size dependency (similar to Durosta): *alfaD50* parameter

2.2 XBeach: calibrated parameter settings

Like every numerical model, XBeach needs calibration and validation to use it as storm-induced erosion predictor along the Belgian coast. In SA15 the XBeach Groundhog Day version was used with the WTI parameter settings (Table 2). These parameter settings were calibrated in XBeach 1D, making use of 30 model scale tests of dune experiments following the DUD algorithm (Van Geer *et al.*, 2015). Calibration was carried out focusing on minimising the Root Mean Squared Error (RMSE) of the erosion volume above the maximum storm surge. Derived model uncertainty was calculated to be an underestimation of 6 % (structural error) and a standard deviation of 13 % (model uncertainty).

Meanwhile, the safety assessment framework in the Netherlands underwent some changes and was renamed from WTI to BOI, still with the objective of replacing Duros+ with XBeach (1D and later on, 2DH). During the preparation of the SA21 methodology, the BOI phase was ongoing to implement XBeach (in 1D) in the Dutch Coastal Safety Assessment of the dunes. Valuable work that we were able to make grateful use of.

Within this BOI phase, time was dedicated to the reformulation of XBeach' dimensional parameters to non-dimensional equivalents based on physical relationships. By doing so, the dependency of these parameters to model scale is solved, making calibration easier and the combined use of scale model and prototype tests less complicated.

Subsequently, a new calibration was carried out in XBeach 1D (McCall *et al.*, 2022) using the same DUD algorithm yet calibrating the hydrodynamics and morphodynamics sequentially (Table 2). The hydrodynamic calibration focused on an accurate prediction of the short waves using data of 2 model scale tests. The morphodynamic calibration targeted the erosion volume above the maximum storm surge, the retreat distance of the dune front and the wet slope, using the same model scale tests as the WTI calibration. McCall *et al.* (2022) states that both calibrated parameter sets result in a similar prediction capacity of morphological changes (within calibrated boundary conditions, e.g. profile slope). Derived model uncertainty was calculated to be 16% with regard to erosion volumes, 21% for dune retreat distances and 12% for the wet slope.

Arcadis/Deltares (2022) carried out a validation of these BOI parameter settings using XBeach 1D for dune erosion modelling. A relative bias of -4 to 22 % was found for the infragravity wave height (based on 3 field cases). With regard to erosion volumes and retreat distance, a relative bias of resp. 3 % and -21 % was found whilst the scatter index amounted to resp. 24 % and 37 % (based on 7 field cases).

When using the model in 1D, the infragravity wave energy tends to be overestimated because directional wave spreading is not accounted for. By introducing the parameter *wbcEvarreduce* (cf Table 2) it is tried to mimic the energy reduction because of wave spreading. In our validation cases, this parameter is not used since a quasi 2D (alongshore repetition of a cross shore profile) or full 2D (real bathymetry along- and cross shore) model bathymetry is opted for.

Table 2 – Calibrated parameter settings: WTI (Van Geer *et al.*, 2015) and BOI (McCall *et al.*, 2022)

WTI parameter settings		BOI parameter settings	
break	Roelvink2	break	Roelvink_Daly
gammax	2.364	gamma2	0.34
gamma	0.541	gamma	0.46
beta	0.138	beta	0.08
wetslp	0.260	wetslp	0.15
facSk	0.375	facSk	0.15
facAs	0.123	facAs	0.20
alpha	0.541	alpha	1.38
		alfaD50	0.4
cf	0.001		
		wbcEvarreduce	0.3

3 XBeach X and BOI: sensitivity analysis

3.1 Sensitivity analysis: focus on hydrodynamics

3.1.1 CREST wave basin tests

3.1.1.1 Case description

Within the framework of the SBO Climate REsilient coaST (CREST) project, a series of physical model tests was carried out in the wave basin at Flanders Hydraulics (Figure 1). The scope of the CREST-project was to gain knowledge on the main physical processes that drive coastal flooding and determine the resilience of the coastal system (Belgian coast).

The physical modelling test campaign (model scale of 1/50) focused on the wave overtopping processes (layer thickness, velocities, overtopping volumes and wave forces) over a dike (with/without storm wall on top) in shallow foreshore conditions. An overview of the measurement set-up and test matrix can be found in the factual data report (Verwaest *et al.*, 2019).

Figure 2 depicts the experimental lay-out and measurement set-up of the selected test. At the wave paddle, deep water conditions are considered; ratio $H_s/h = 0.14$ and $c_g/c \approx 0.7$. Making use of a transitional steeper slope of 1/10, a shallow foreshore having a slope of 1/35 was built in over a distance of 9 m (450 m in prototype). In a first series of tests, the foreshore ends with a dike; in a second series of tests, the foreshore stops at the position of the dike's toe in a horizontal plane, to mimic incident wave conditions. The selected test is part of the latter test series.

To validate the hydrodynamic performance of XBeach, a test set-up of a rather extreme storm event (w.r.t. water level) was selected. Table 3 summarizes its main hydraulic characteristics: 1000 year RT water level and perpendicular attack of moderately high waves (yearly RT H_s and 100 year RT T_p). Test duration was set to simulate a wave train of at least 1000 waves; second order wave generation was used.

Table 3 – Input hydraulic conditions of test CREST131 (prototype scale)

	Water level [m TAW] (water depth [m])	Significant wave height [m]	Peak wave period [s]	Spectrum shape	Wave direction [w.r.t. wave paddle] – wave directional spreading
Imposed at wave paddle	+7 (22.1)	3	10	Jonswap	0° - 16°
Measured at offshore 7star gauge array	(22.14)	2.9	9.8	Not verified	0° - 12.40°

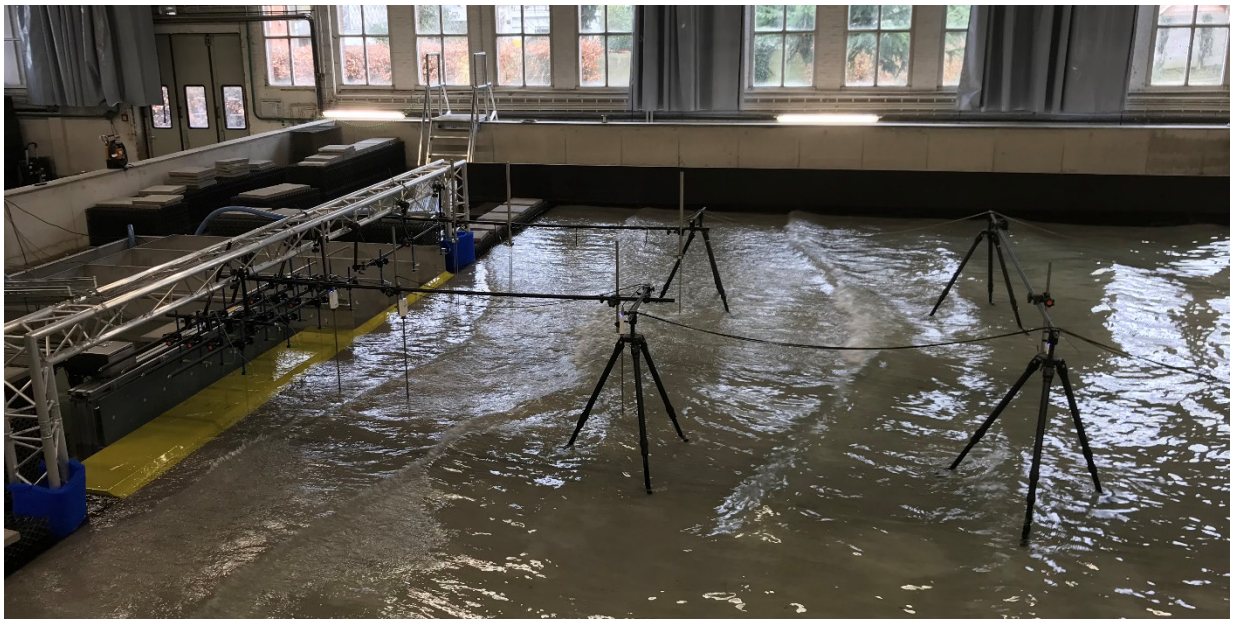


Figure 1 – Snapshot of wave basin test of stormy conditions

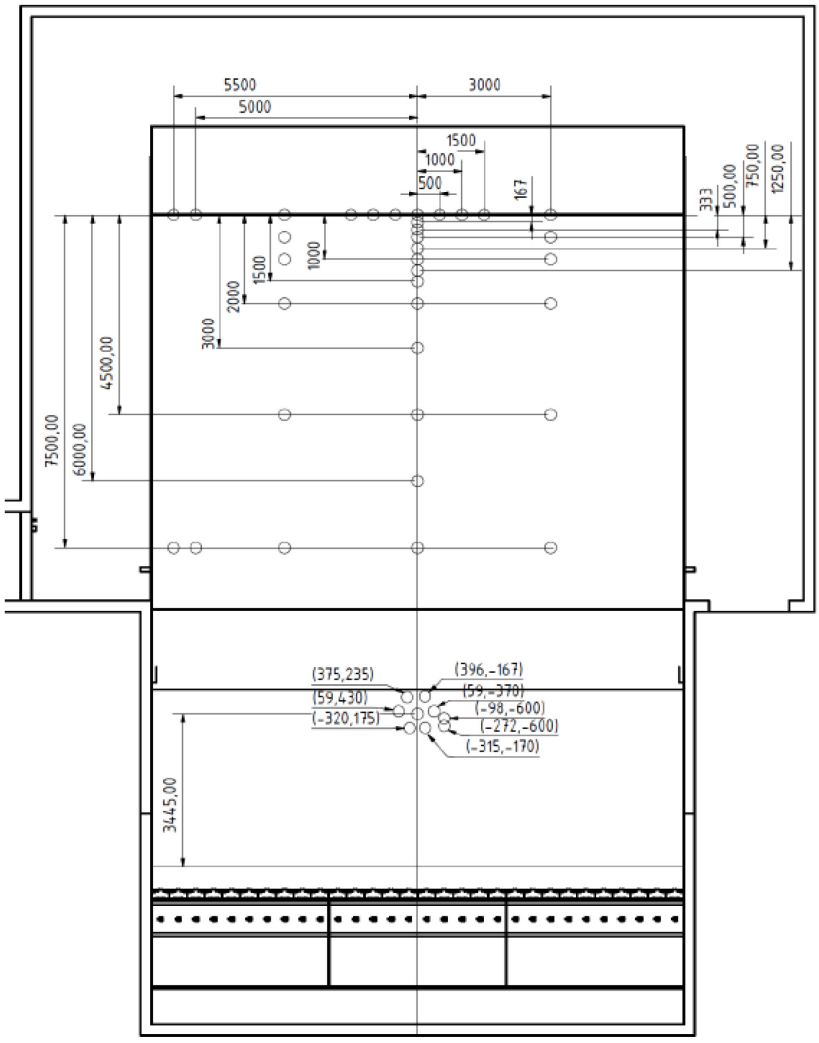


Figure 2 – Experimental lay-out and measurement set-up in the wave basin [dimensions in mm] (Verwaest *et al.*, 2019)

3.1.1.2 Model setup

The basin lay-out is translated into a XBeach bathymetry on prototype scale. Figure 3 depicts the model area and position of the wave gauges. In the sensitivity analysis, focus is laid on the wave gauges at the center line. Landward of the wave gauges at the 'toe' position a horizontal distance of 200 m is added and an absorbing-generating weakly reflective boundary condition is opted for.

Figure 4 illustrates the model bathymetry in 3D. Cross shore grid size gradually varies between 1 m in shallow water and 10 m in deep water, taking into account at least 40 points per wavelength. Alongshore grid size gradually varies between 10 m in the central zone of the model area (cf. blue rectangle in Figure 4) and 20 m at the lateral model boundaries.

Like in the wave basin tests, (more than) 1000 waves were simulated including ramp up time for hydrodynamics. Morphodynamics were turned off. Wave boundary conditions are half hourly imposed; a directional spreading value s of 25 corresponds to 16°.

Note that simulations were carried out using XBeach X . This means that, by default, *single_dir* was switched off (unless stated differently) and wave breaking was based on the extended Roelvink formula (*Roelvink2*) (instead of Roelvink and Daly in XBeach BOI). Default parameter settings were used (unless stated differently), i.e. a *gamma* of 0.55 and *alpha* of 1.

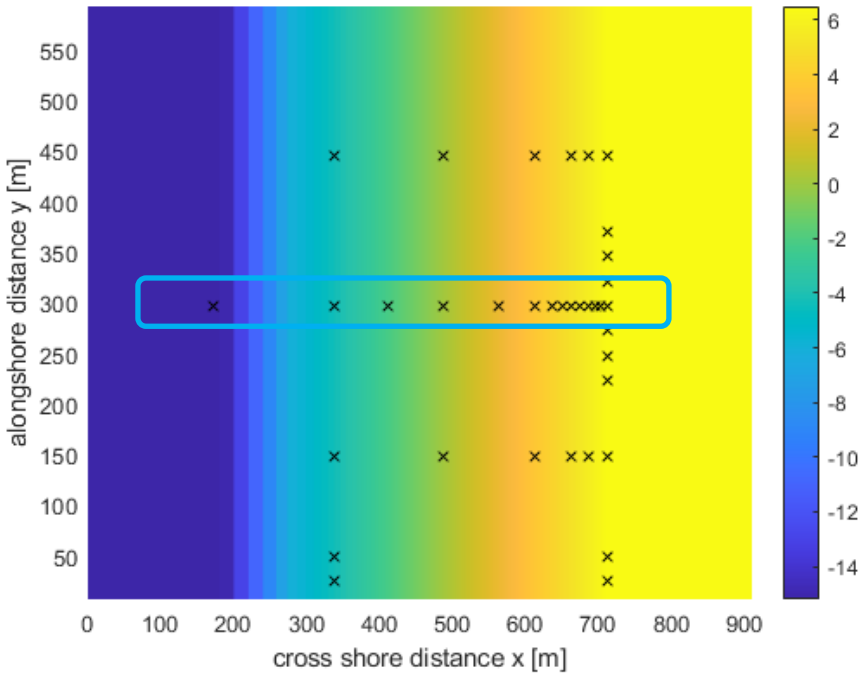


Figure 3 – XBeach: model bathymetry with wave gauges' position (in rectangle: wave gauges used in sensitivity analysis)

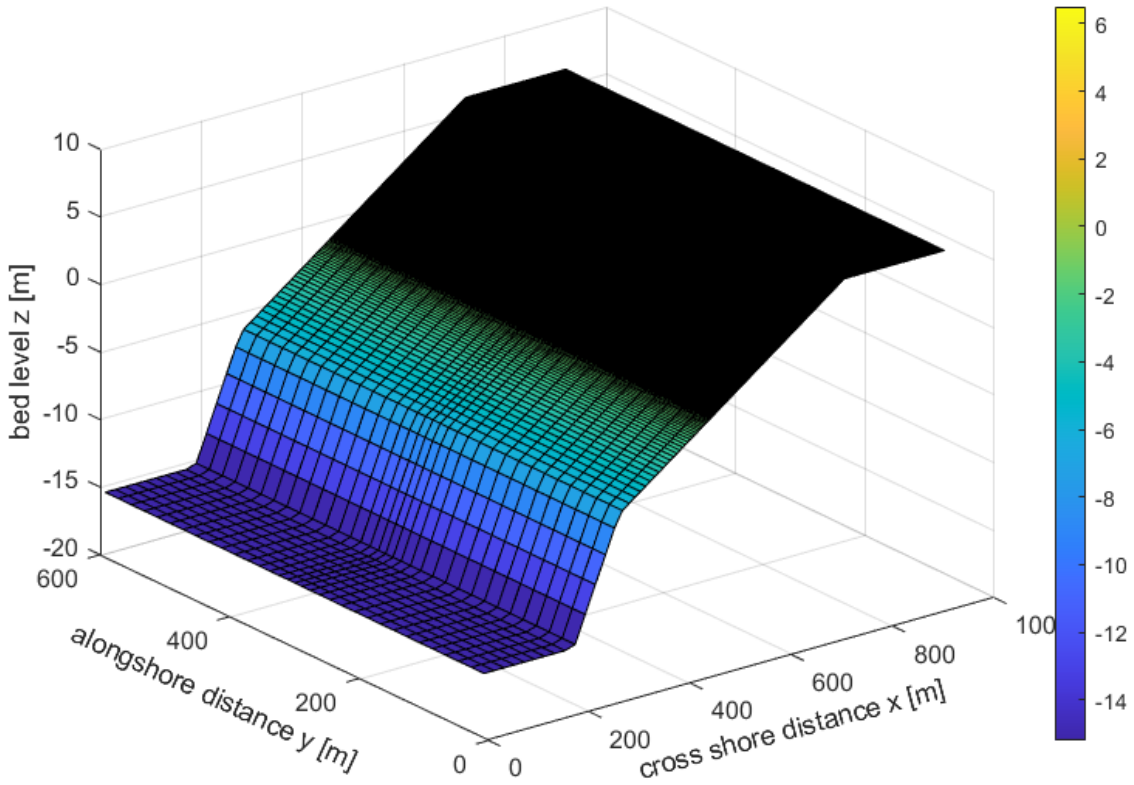


Figure 4 – XBeach: model bathymetry in 3D – illustration of grid size

3.1.1.3 Results and discussion

- General results:

Grid size dependency was tested using cross shore grid resolutions of 1 – 10 m, 2 – 10 m and 2 – 20 m (alongshore grid size was fixed). Wave propagation was slightly smoothed for the coarsest resolution but no significant differences were found in wave-induced velocities and surface elevations. A cross shore grid size of 1 – 20 m was further applied in the sensitivity analysis below.

Two modes are tested with regard to wave propagation inside the (uniform) 2DH model domain. Wave refraction being resolved using the standard propagation scheme (*single_dir* = 0, *dtheta*) where wave energy from the different directional bins is added up with considering interference among them (Figure 5, left pane) and using a stationary solver (*single_dir* = 1, *dtheta_s*) solving the wave direction periodically and then, propagating the short wave energy along that mean wave direction (Figure 5, right pane). Figure 5 illustrates that the former method results in too much smoothing of the alongshore wave groupiness while the latter method preserves it, seeing the typical short crested surface elevation. The more the alongshore groupiness is kept, the higher the infragravity wave forcing will be. Variation in the directional resolution *dtheta* and *dtheta_s* resp. shows an upper limit of *dtheta* = *dtheta_s* = 10° to obtain good results in (shallow water) wave-related output (whilst maintaining acceptable runtimes).

Comparing the modelled to measured wave heights on the center line, no clear difference is observed between the two wave propagation methods (except for the 4th wave gauge from offshore, which malfunctioned during the test) (Figure 6). Root-mean-square wave heights, being the XBeach output, are converted to the spectral significant wave height H_{m0} by multiplying the value with root(2) or 1.32 (based on Height-to-depth ratio H_0/h (Goda, 2000)). Wave propagation seems to differ between the physical model and XBeach. In deeper water, XBeach underestimates the wave heights while in shallow water, wave heights are overestimated.

Separation of the short and long wave energy is done at 0.05 Hz, the lower limit of the IG waves band being 0.005 Hz. Figure 7 shows that the ratio of short to long waves differs between XBeach and the data. XBeach overestimates the short waves while underestimating the long waves (see further: sensitivity analysis). The parameter *single_dir* turned on leads, as expected, to a higher amount of IG waves. It is not clear what causes the different wave propagation behaviour.

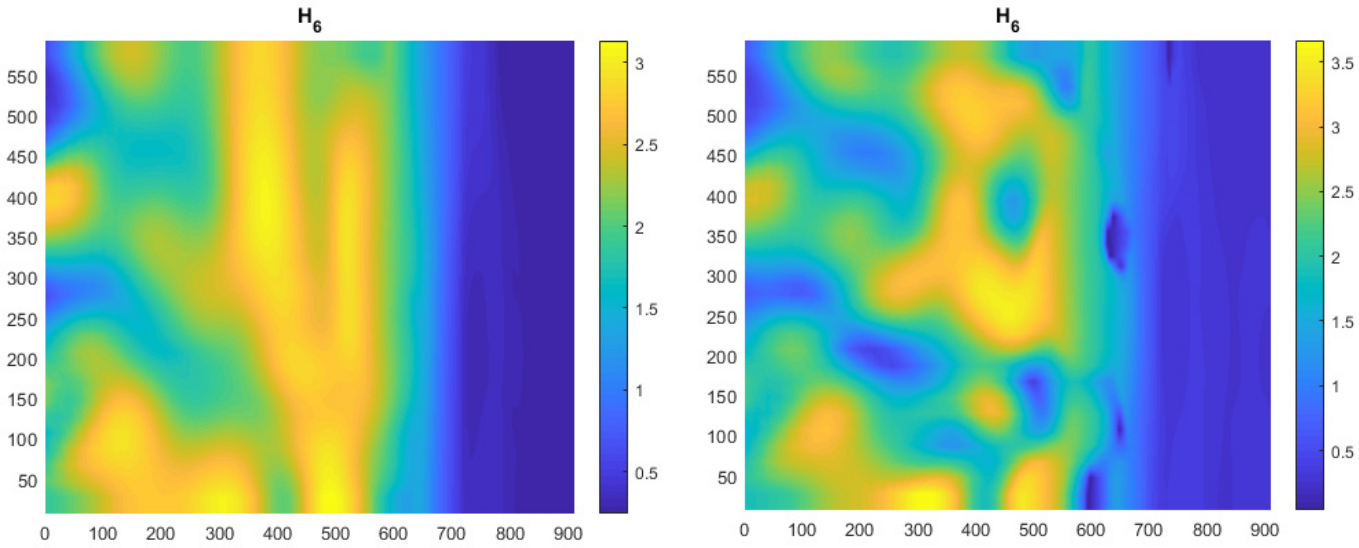


Figure 5 – Wave height distribution in 2DH using *multi_dir* mode (left) and *single_dir* mode (right)

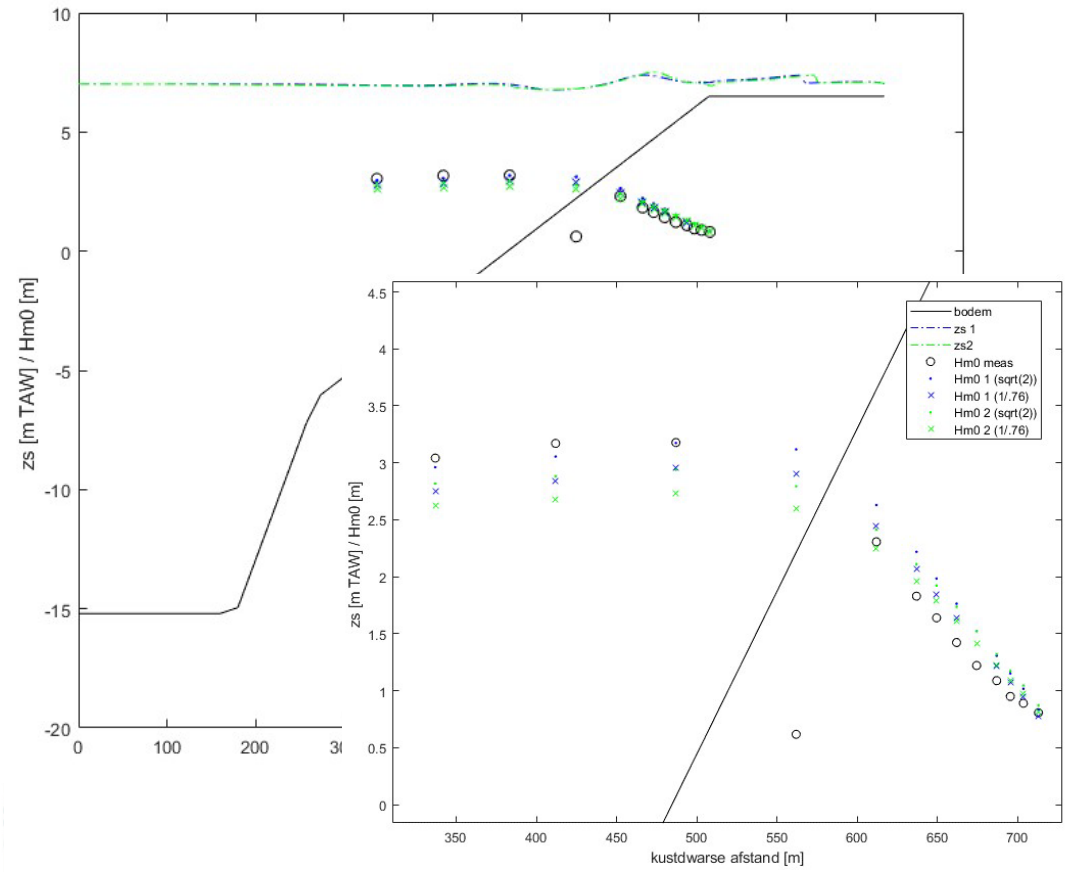


Figure 6 – XBeach result: cross shore wave height propagation (*single_dir* on (green) /off (blue))

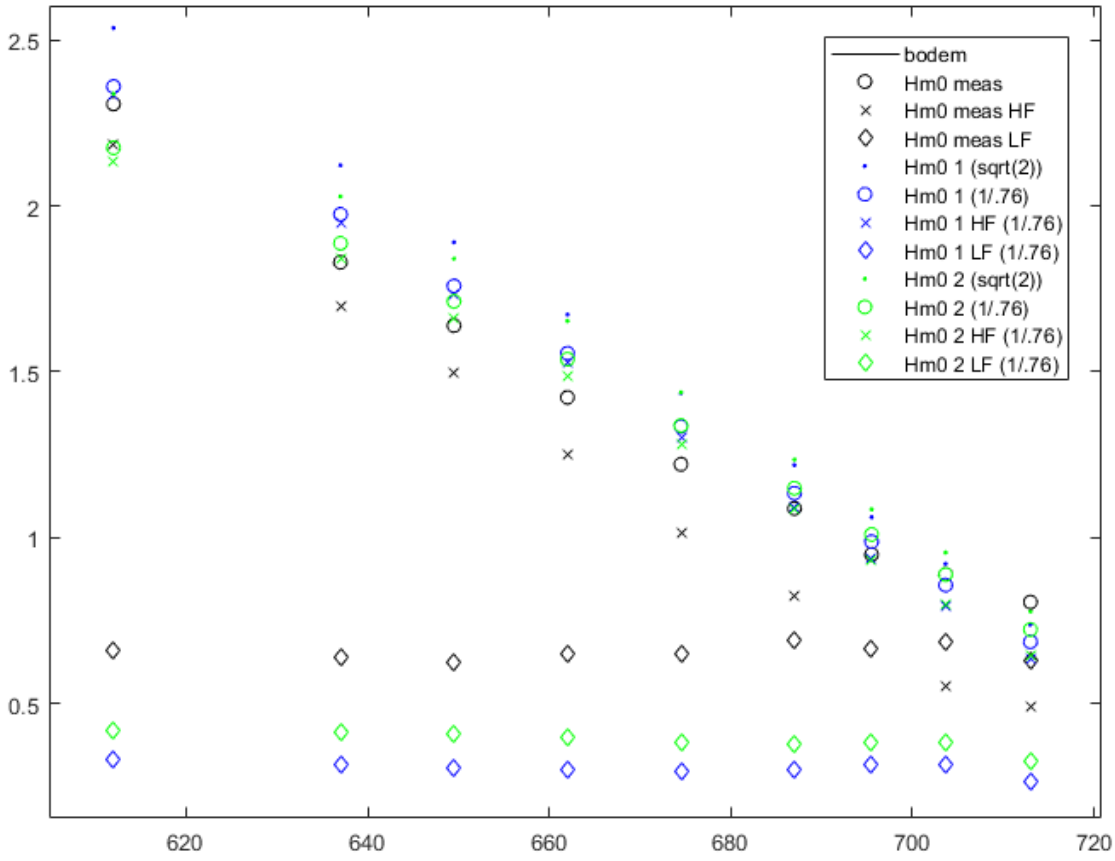


Figure 7 – XBeach result: cross shore short and long waves' propagation: zoom on surf zone (*single_dir* on (green) /off (blue))

- Sensitivity analysis:

A sensitivity analysis (*single_dir* switched off) is carried out focusing on the parameters *gamma* (breaker index, depending on bed slope) and *alpha* (wave dissipation coefficient), since they influence wave breaking. In addition, the XBeach results are compared to Swash results.

Figure 8 gives an overview of the parameters' sensitivity study. The higher *alpha*, the more waves break and dissipate. The higher *gamma*, the higher the maximum wave height becomes before waves break. The optimal parameter combination for the CREST wave basin tests is *gamma* = 0.45 and *alpha* between 1.5 and 2. Hence, the default settings, used under 'general results', are too high resp. low, being *gamma* of 0.55 and *alpha* of 1.

Wave dissipation using the extended Roelvink formula implies that wave breaking is proportional to H^3/h while the Roelvink and Daly formula allows waves to fully break when they exceed a threshold (parameter to calibrate).

Comparing Swash and XBeach results indicates that Swash and XBeach (with *gamma* = 0.45 and *alpha* = 1.5-2) closely match to the measured short waves' propagation. The IG wave height however is underestimated in the surf zone where Swash results compare better to the measurements than XBeach. XBeach seems to dissipate too fast the wave energy. This might be (partly) related to the imposed (design) water level in the XBeach model. Because of physical model effects, the water level appeared to be (on average) 2 to 6 mm lower than the design water level; hence, resulting in a water level drop of 0.15 to 0.30 m in prototype scale (Suzuki *et al.*, 2025). In the shallow foreshore conditions of this test, this changes wave transformation, enhancing wave breaking and hence, the release of IG waves.

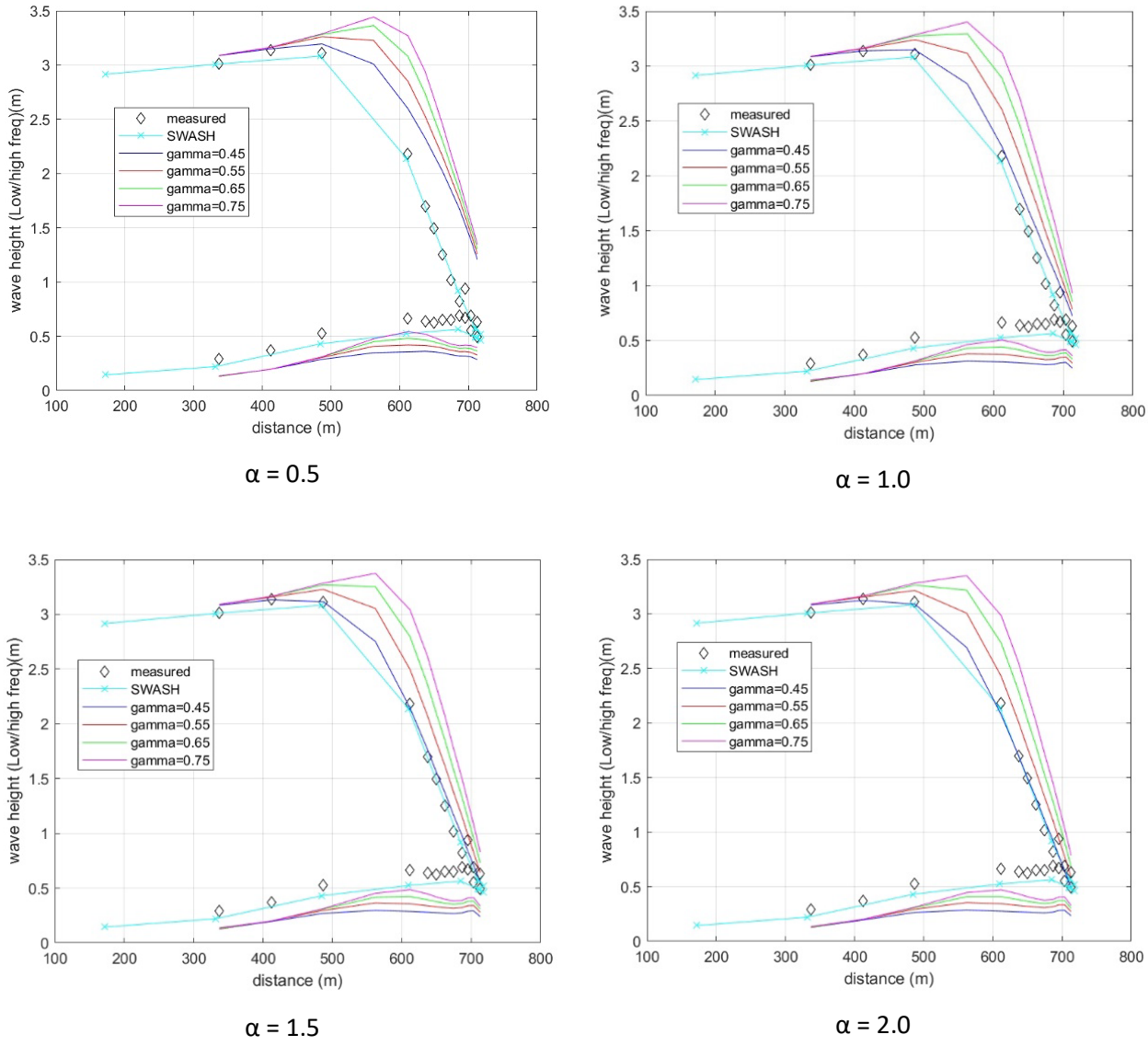


Figure 8 – XBeach and Swash result: sensitivity analysis of parameters *gamma* and *alpha*: influence on wave propagation

For all parameter settings that are not included in Table 2-3, the default XBeach settings are used, such as epsi = -1 and single_dir = 0. Moreover, random = 0 has been used for all validation cases.

3.2 Sensitivity analysis: general

Starting point of the validation of the XBeach X release was a quick check to verify its response to storm Xaver using both default and WTI settings (calibrated on XBeach GHD, cf. Van Geer *et al.*, 2015) (more details on case 'storm Xaver' in Section 5.1).

Figure 9 illustrates the difference in erosion volumes between the XBeach versions and parameter settings. In Figure 10 the sensitivity of the morphological response to every parameter is shown. The defaults settings of parameters *Cf* (bottom roughness), *FacSk* (wave skewness) and *beta* (breaker slope coefficient) (compared to the WTI values) influence the erosion volumes the most. Note that *facAs* (wave asymmetry) also has an important effect on erosion volumes but its calibrated WTI value does not differ significantly from the default value.

The newly added Van Rijn sediment transport equation was also tested, intended to increase XBeach' sensitivity to grain size. The results were however not satisfactorily better compared to the Van Thiel Van Rijn sediment transport equation and it was decided to keep the latter.

Focus was then put on testing the sediment grain size dependency parameter *alfaD50* (available since version XBeach BOI). The parameter *alfaD50* adapts the equilibrium sediment concentration (making it smaller/larger for larger/smaller grain sizes resp. compared to the reference grain size of $D_{50,ref}$ = 225 mu) and nonlinear wave-driven transport (higher/smaller for grain sizes larger/smaller than $D_{50,ref}$). Its implementation is based on the work of Steetzel (1993), which presented an empirical relation between grain size and sediment transport. Note that the calibration is based on (a limited amount of) flume experiments and a few field cases also used for XBeach validation (Arcadis/Deltares, 2022).

A first implementation of *alfaD50* was verified using a value of 2.5 (Figure 11, for illustrative purposes only). Later on during this study, the implementation was changed and a new calibration needed to be carried out (McCall *et al.*, 2022). The (final) parameter *alfaD50* was set to 0 and 0.4 and tested on the profiles of storm Xaver (Section 5.1). No difference in erosion volumes was found. It was decided to keep the parameter *alfaD50* equal to 0 in the SA21 methodology.

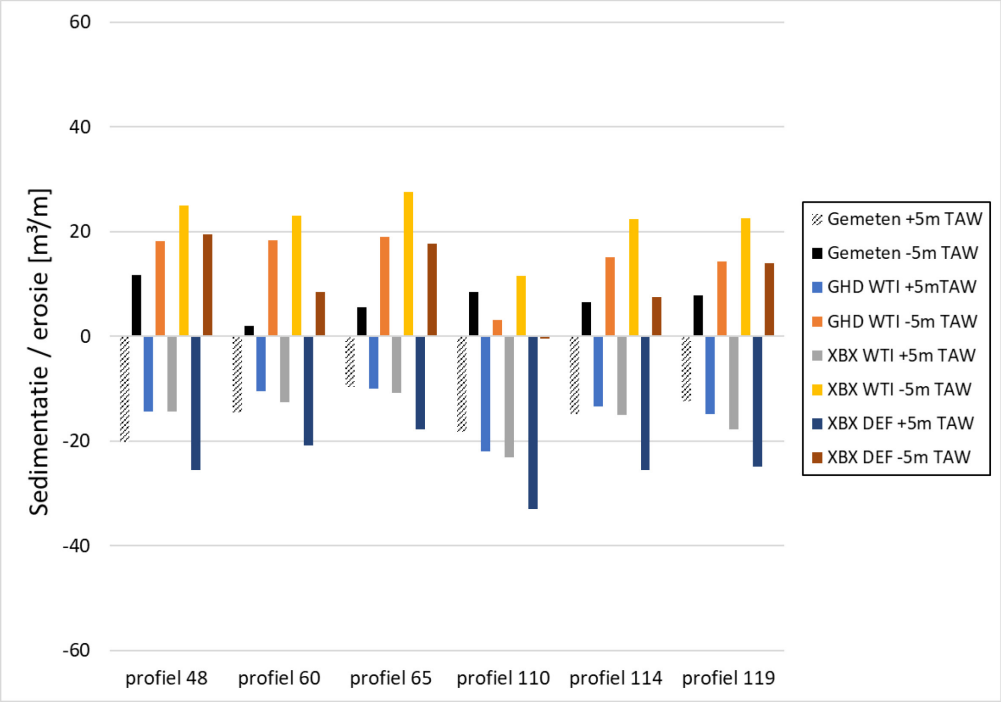


Figure 9 – XBeach result 'Groundhog day' and 'XBX' – default and WTI parameter settings: erosion volumes

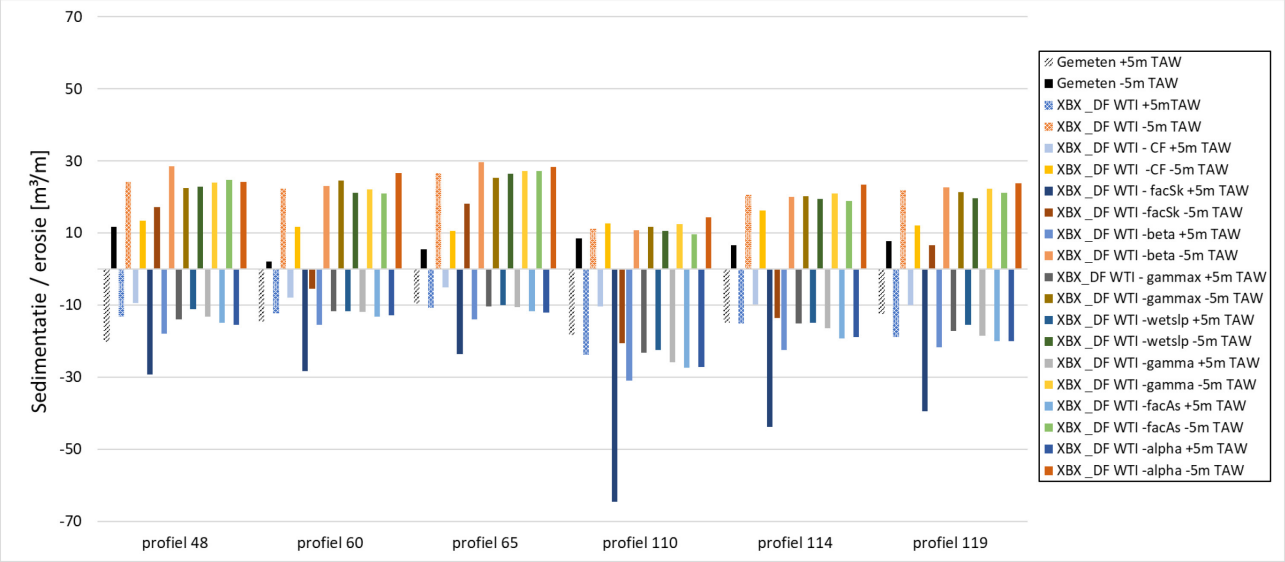


Figure 10 – XBeachX: sensitivity of erosion volumes to every WTI parameter

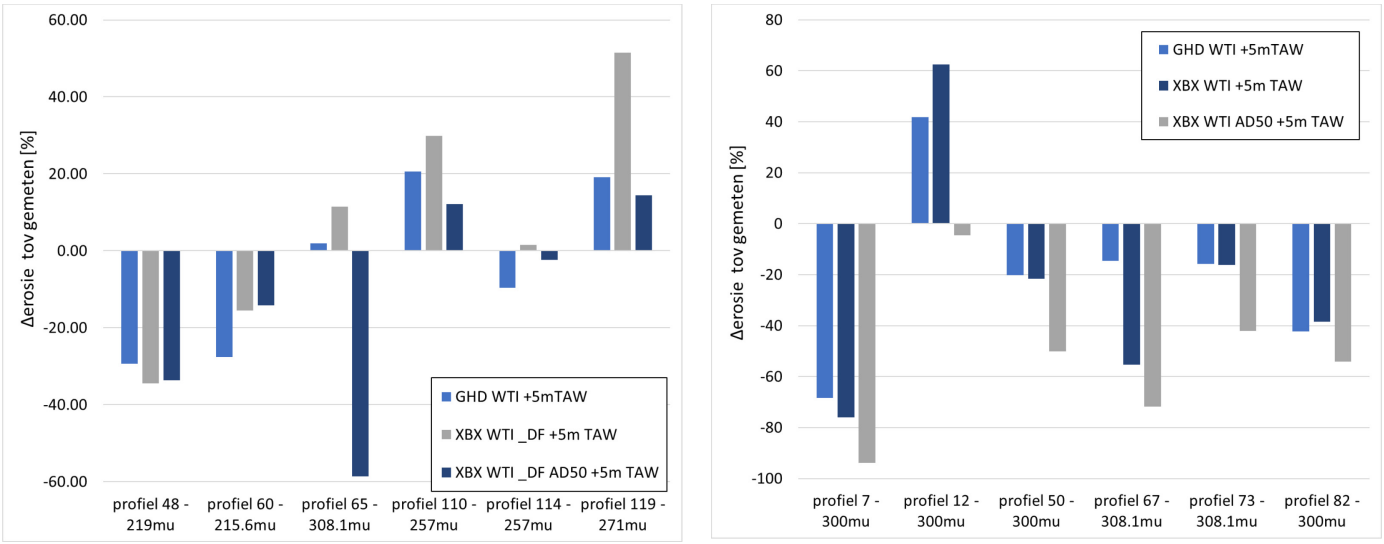


Figure 11 – XBeachX: sensitivity of grain size D_{50} (using WTI parameter settings)

3.2.1 Danish coast

3.2.1.1 Case description

The January 2005 storm caused a lot of dune erosion along the Danish North Sea coast. The location of Vedersoe is exposed and located on a high energy coastline, hence the longshore sediment transport is significant continuously changing the sandbar system, which acts as a natural wave breaker. A foreshore, containing a weak berm being one meter high, is followed by a 100 m wide beach. The beach is followed by a sandy dune, having a crest level at 14 m (DVR90) and the dune foot located at 2 m (DVR90).

The sand on the beach has a median grain size D_{50} of 400 µm, no information is available on the sediment characteristics of the dunes (Geertsen, K-S; Sorensen, 2021).

Data obtained from the Danish Coastal Authority include both pre and post storm profiles at Vedersoe (Figure 12), (deep water) waves measured using wave buoys outside Nymindegab (probably 10km offshore) and water levels outside Ferring. The coastal orientation of the profiles is close to 270°.

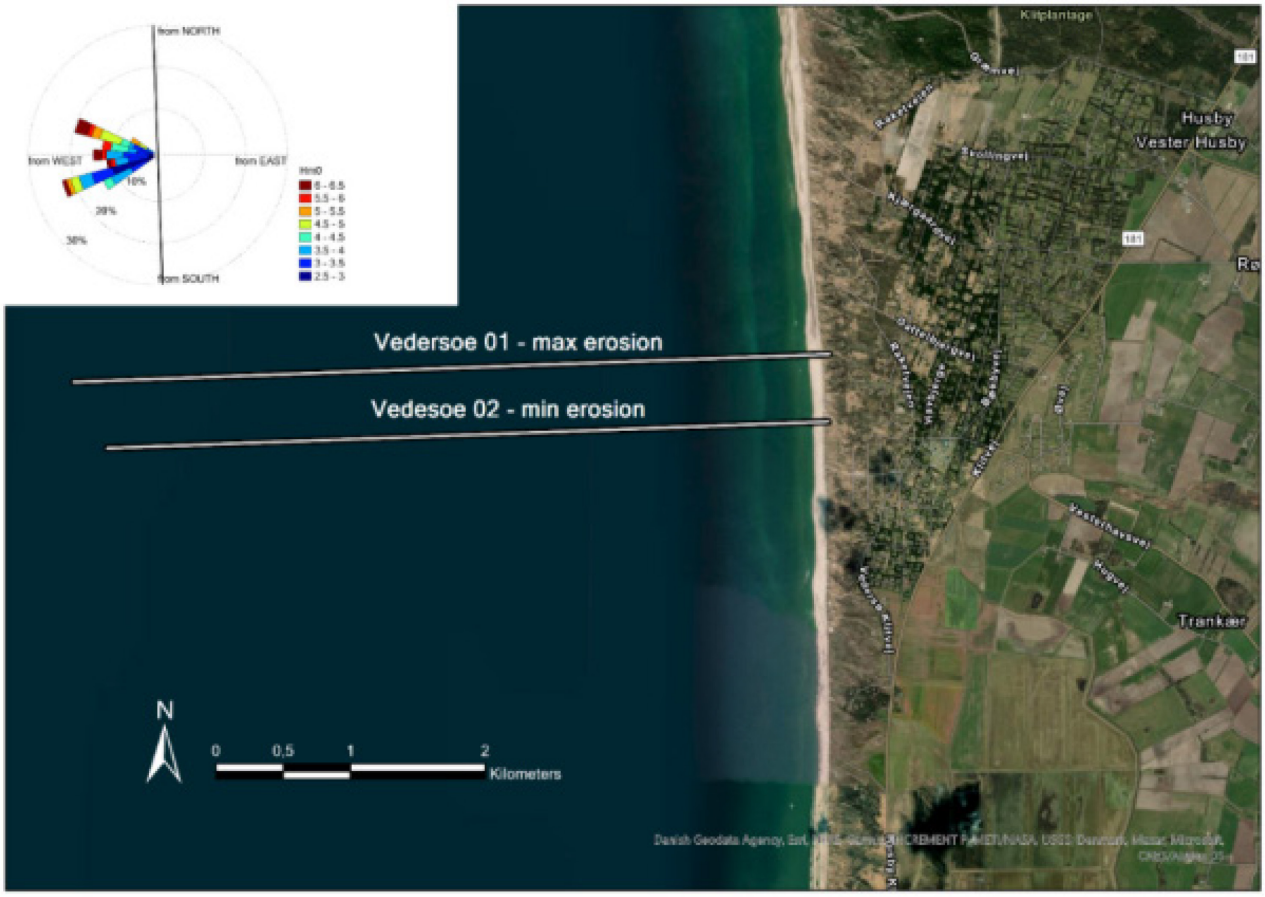


Figure 12 – Vedersoe, West coast of Denmark: location of yearly measured cross shore profiles ((Geertsen, K-S; Sorensen, 2021)

3.2.1.2 Model setup

Simulations are carried out using XBeach Groundhog (limited), Kingsday and BOI (with *single_dir* =0 and =1) in 1D (for XBeach BOI only) and q2D mode. The latter domain has an alongshore length of 1000 m and a uniform grid resolution of 30 or 50 m (except for grid sensitivity analysis).

2 wave climates are considered:

- The “Belgian” climate with a rather narrow directional spreading of 16° (*s*-value = 28) and slightly oblique waves (varying in time as measured, most of the time about 20° deviation from perpendicular wave attack)
- The “Dutch” climate with a broader directional spreading (s=6) and identical oblique wave attack

To check grain size sensitivity, simulations are carried out with median grain size D_{50} of 0.2 mm and 0.4 mm (without use of the parameter *alfaD50*) .

Note that the first simulations were done with minimum cross shore grid resolution dx_min = 2 m. Later on it became clear that the results were still grid size dependent and additional runs were done with dx_min = 1 m. Yet, the grid size dependency did not influence the comparisons, so the results with dx_min = 2 m are still used.

Calibrated WTI parameter settings were used for XBeach Groundhog Day and Kingsday runs (Table 2); the first set of calibrated BOI parameter settings was used for XBeach BOI (Table 12, column 'BOI init'). When 1D cross shore profiles are simulated, the parameter *wbcEvarreduce* reducing the incoming wave groupiness (and hence, IG wave energy) is included and set to 0.3.

Morphological acceleration factor (*morphac*) was 3.

Table 4 gives an overview of the applied model settings.

Table 4 – Case specific model settings for sensitivity analysis

XBeach versions	Wave conditions	Grid resolution	Median grain size D_{50}
Belgian waves	Belgian & Dutch waves	Belgian & Dutch waves	Belgian & Dutch waves
Ny = 12 and dy = 50 m	Ny = 17 and dy = 30 m	1D Ny = 8 and dy = 50 m Ny = 17 and dy = 30 m Ny = 40 and dy = 20 m	Ny = 17 and dy = 30 m
D_{50} = 0.4 mm	D_{50} = 0.2 mm	D_{50} = 0.2 and 0.4 mm	D_{50} = 0.2 and 0.4 mm
dx_{min} = 2 m	dx_{min} = 1 m	dx_{min} = 1 and 2 m	dx_{min} = 1 and 2 m

3.2.1.3 Results and discussion

- XBeach version

Figure 13 illustrates the post storm cross shore profiles of the different XBeach versions and parameter setting of *single_dir*. The maximum retreat distance X_d is calculated at the maximum water level and X_e at the dune crest. Table 5 summarizes the erosion volumes and retreat distances. Most of the results are close to the measurements, except for Kingsday with *single_dir*=1. As both median grain size and directional spreading of the waves are not known and also the dune profile above +4 m before the storm is not exactly known (they assumed a profile starting at +4), it does not make sense to further calibrate simulations but rather focus on the results' sensitivities.

Following observations are made, using XBeach BOI with parameter *single_dir* = 0 as base simulation:

- XBeach Groundhog and Kingsday, *single_dir* =0 give about 30% more erosion than XBeach BOI, *single_dir* = 0
- XBeach BOI *single_dir* =1 gives 13% more erosion than XBeach BOI *single_dir* =0
- Difference between *single_dir* = 0 and 1 is much larger in XBeach Kingsday compared to XBeach BOI

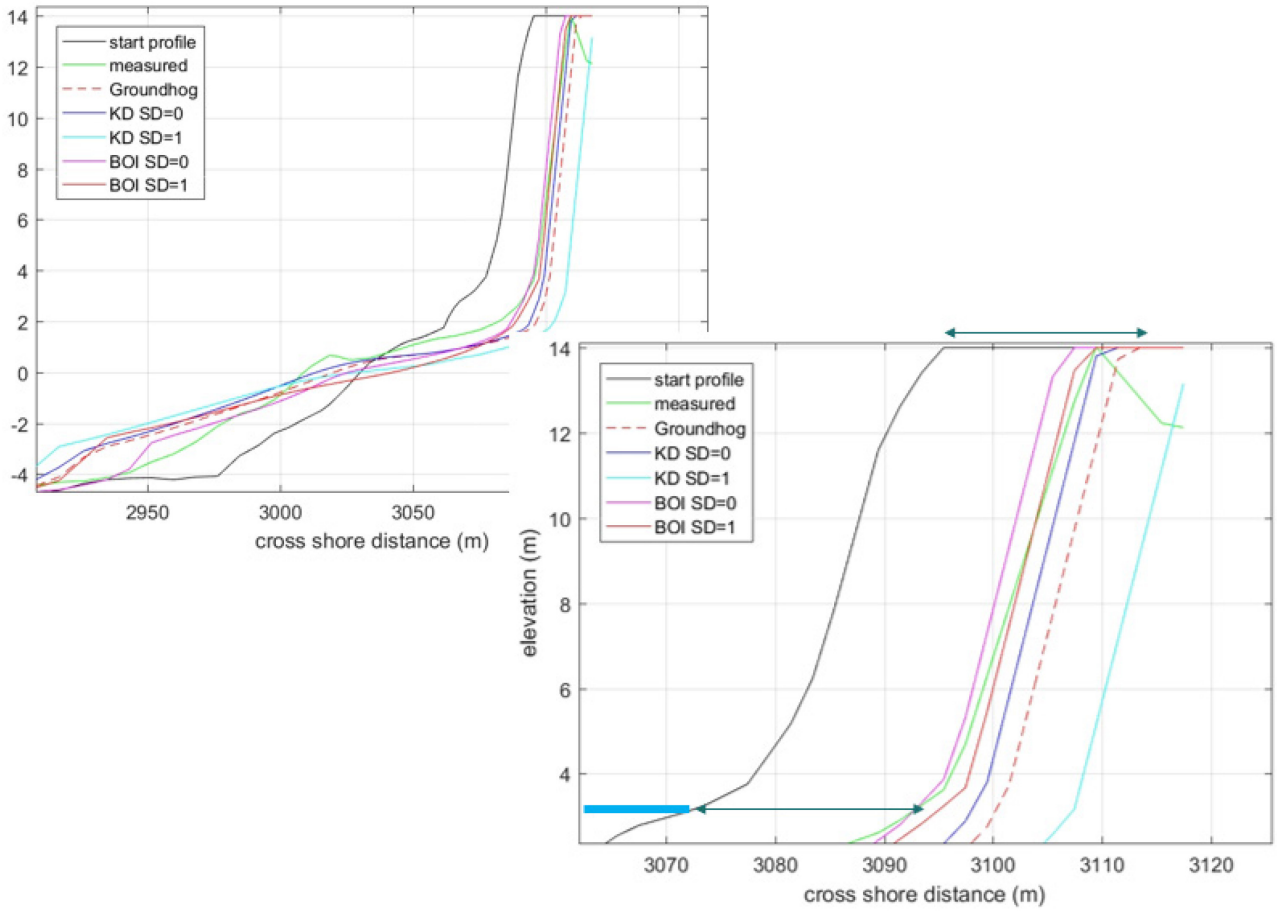


Figure 13 – XBeach versions: post storm profile

Table 5 – XBeach versions: erosion volumes and retreat distances (base simulation BOI SD=0)

XBeach version	Erosion volume (m^3/m)	Retreat distance X_d (m)	Retreat distance X_e (m)	Erosion (%)	$d(X_d)$ (m)	$d(X_e)$ (m)
Groundhog	222.0	27.5	16.1	37	7.3	5.6
Kingsday SD=0	200.0	25.5	13.4	24	5.3	2.8
Kingsday SD=1	294.0	35.3	22.7	82	15.1	12.2
BOI SD=0	161.5	20.2	10.6	0	0.0	0.0
BOI SD=1	181.9	22.4	12.4	13	2.2	1.9
Measured data	189.1	20.2	13.4	17%	0.0	2.9

- Input wave conditions

The influence of "Dutch" (thet=0°, s=6) and "Belgian" (thet=20°, s=28) wave conditions on morphological response is investigated using XBeach BOI (Table 6).

Following observations are made:

- In a q2D model domain slightly oblique waves (thet=20°) and relatively small directional spreading gives much more sediment transport and influence of the *single_dir* parameter setting (SD) is much larger compared to perpendicular waves with larger directional spreading
- In a 1D model domain no influence of the wave conditions is visible
- It is remarkable that the effect of the wave direction and the *single_dir* parameter setting is already visible at the offshore part of the model domain (at a water depth of 20m)

Table 6 – XBeach result: sensitivity of input wave conditions on erosion volumes and retreat distance (base simulation thet=0°, s=6)

Wave conditions	Model domain	Erosion volumes (m^3/m)	Retreat distance X_d (m)	Retreat distance X_e (m)	Erosion (%)	$d(X_d)$ (m)	$d(X_e)$ (m)
thet=0°; s=6	q2D, SD=0	143.0	19.5	8.9	0	0.0	0.0
thet=0°; s=6	q2D, SD=1	137.0	18.8	8.3	-4	-0.7	-0.6
thet=20°;s=28	q2D, SD=0	231.0	26.8	17.0	62	7.3	8.1
thet=20°;s=28	q2D, SD=1	252.0	29.4	18.9	76	9.9	10.0
thet=0°; s=6	1D, SD=0	141.8	18.7	8.7	-1	-0.8	-0.2
thet=20°; s=28	1D, SD=0	140.2	17.9	8.6	-2	-1.6	-0.3

- Grid resolution (alongshore and cross shore)

Table 7 shows the influence, being minor, of the alongshore grid settings on XBeach morphological response (all simulations with XBeach BOI SD=0). Only for the "Belgian" waves, having a narrow directional spreading, the difference between 1D and q2D is significant, indicating less erosion in 1D.

Table 8 shows the influence, being minor, of the minimum cross shore grid resolution in the avalanching zone. A finer cross shore grid (dx=1 m) gives slightly more erosion than a coarser grid (dx=2m) and the difference depends only slightly on the other parameter settings.

Table 7 – XBeach result: sensitivity of alongshore grid resolution on erosion volumes and retreat distances (base run : 1D for resp. Dutch and Belgian waves)

Alongshore dy (m) (ny)	Wave conditions	Erosion volumes (m^3/m)	Retreat distance X_d (m)	Retreat distance X_e (m)	Erosion (%)	$d(X_d)$ (m)	$d(X_e)$ (m)
0 (1)	s=6	154.4	19.8	9.9	0	0.0	0.0
50 (8)	s=6	152.2	19.9	9.7	-1	0.1	-0.2
30 (17)	s=6	145.9	20.1	9.1	-5	0.3	-0.9
20 (40)	s=6	138.9	18.8	8.4	-10	-1.0	-1.5
0(1)	s=28	119.5	15.8	6.8	0	0	0
12 50	s=28	161.5	20.2	10.6	35	4.4	3.8

Table 8 – XBeach result: sensitivity of cross shore minimum grid resolution on erosion volumes and retreat distances (base run resp 1D – dx=2 with Dutch waves and Q2D – dx=2 Belgian waves)

Model domain and cross shore $d_{x,min}$ (m)	Wave conditions	Grain size D_{50} (µm)	Erosion volumes (m^3/m)	Retreat distance X_d (m)	Retreat distance X_e (m)	Erosion (%)	$d(X_d)$ (m)	$d(X_e)$ (m)
1D - dx=2	s=6;theta=0;SD=0	200	148.8	18.3	9.5	0	0.0	0.0
1D - dx=1	s=6;theta=0;SD=0	200	155.4	20.1	12.1	4	1.8	2.6
q2D - dx=2	s=28;theta=20;SD=0	400	161.0	20.2	10.6	0	0.0	0.0
q2D - dx=1	s=28;theta=20;SD=0	400	174.0	21.7	11.7	8	1.5	1.2
q2D - dx=2	s=28;theta=20;SD=1	400	181.9	22.4	12.4	0	0.0	0.0
q2D - dx=1	s=28;theta=20;SD=1	400	203.0	25.4	15.4	12	3.0	3.0

- Median grain size D_{50}

Table 9 summarizes that a finer median grain size of 200 µm results in 20 to 30% more erosion compared to the coarser grain size of 400 µm.

Table 9 – XBeach result: sensitivity of median grain size on erosion volumes and retreat distances (base run resp. 1D dx=2 and Q2D dx=1m, both with D_{50}=400 µm)

Model domain and cross shore $d_{x,min}$ (m)	Wave conditions	Grain size D_{50} (µm)	Erosion volumes (m^3/m)	Retreat distance X_d (m)	Retreat distance X_e (m)	Erosion (%)	$d(X_d)$ (m)	$d(X_e)$ (m)
1D - dx=2	s=28;theta=20;SD=0	400	117.5	15.6	6.6	0	0.0	0.0
1D - dx=2	s=28;theta=20;SD=0	200	140.2	17.9	8.6	19	2.4	2.0
q2D - dx=1	s=28;theta=20;SD=0	400	178.0	21.8	12.1	0	0.0	0.0
q2D - dx=1	s=28;theta=20;SD=0	200	231.0	26.8	17.0	30	5.0	4.9
q2D - dx=1	s=28;theta=20;SD=1	400	202.9	25.2	14.3	0	0.0	0.0
q2D - dx=1	s=28;theta=20;SD=1	200	252.0	29.4	18.9	24	4.2	4.6

3.2.2 Simplified case

3.2.2.1 Case description

Figure 14 depicts the 2 types of simplified profiles being tested: a beach + dike (left figure) and a dune cross section (right figure) along the Belgian coast. For both cases the beach slope is set equal to resp. 1/30 ; 1/45 and 1/60. It starts at -5 and ends at +5.5 m TAW for a dune and at +7 m TAW for a dike. Furthermore, the dike profile has a berm at +7 m TAW, having a width of 30 m, backed with a dike having a slope of 1/2. The dune profile does not have a berm; the beach slope ends in a dune slope of 1/4 up to +14 m TAW. Between -5 and -15 m TAW the bed was artificially deepened using a slope of 1/35 to account for realistic wave boundary conditions.

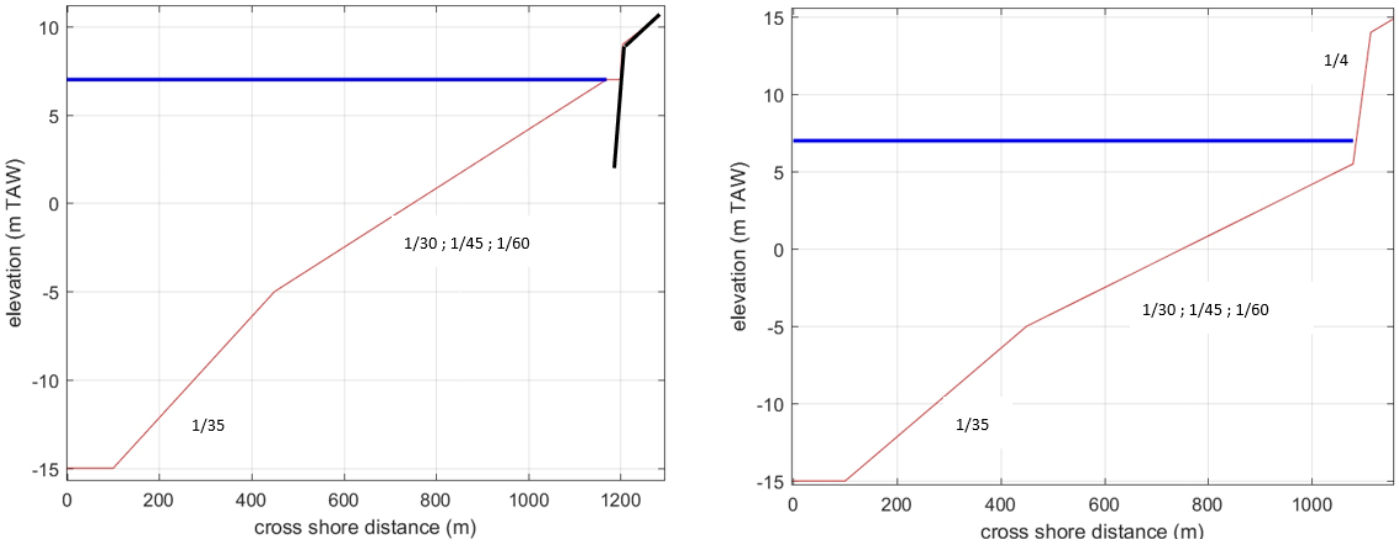


Figure 14 – Simplified case: beach + dike (left) and dune (right) cross shore profiles

3.2.2.2 Model setup

A quasi 2D model domain consists of the (copied) simplified profile over an alongshore distance of about 500 m using a uniform grid resolution of dy = 30 m. The cross shore grid resolution varies gradually up to a minimum of dx = 1 m. For the 'hydrodynamics' case also runs with a uniform grid resolution of dy = 20 m and an alongshore length of 1000 m are done. Median sediment grain size D_{50} is 200 µm.

XBeach BOI is also used in 1D mode including the parameter *wbcEvarreduce* that reduces the incoming wave groupiness (and hence, IG wave energy). It is set to 0.3. The first set of calibrated BOI parameter settings was used (Table 12, column 'BOI init').

Figure 15 illustrates the time dependent (normal incident) wave height and water level of a 46 h lasting storm surge (incl. decimation height) being used as input.

For the dike resp. dune profiles, the erosion volumes are evaluated above +6 m TAW and +7 m TAW resp.

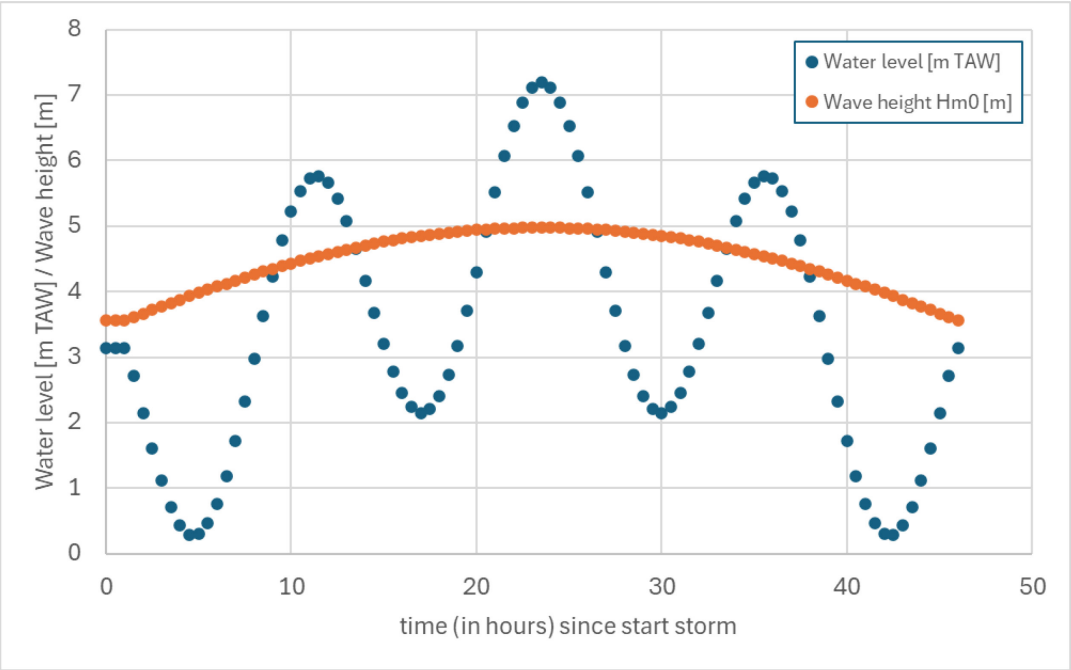


Figure 15 – XBeach input: Water level and wave height during 46h lasting storm surge

3.2.2.3 Results and discussion

- Hydrodynamics

Figure 16 (left) shows the evolution of the significant wave height (short waves) along the cross shore profile at the peak of the storm ('hydrodynamics' run, i.e. without morphology, to get the same bed profile for all settings). The profile is situated, for q2D mode, in the center of the alongshore domain. At this location, both alongshore grids (18 x 30 or 51 x 20) give similar results except at the offshore end of the breaking zone (difference of 3%).

In the surf zone, the differences in breaking behaviour between the extended Roelvink formula, being default in XBeach Groundhog Day, and the Roelvink and Daly formula, being default in XBeach BOI, are noticeable. The former formula with calibrated WTI settings gives higher waves; hence, slower wave dissipation (although waves are somewhat smaller offshore).

Figure 16 (right) illustrates the long waves' propagation. Logically, when switching the parameter *single_dir* on, this results in higher infragravity waves.

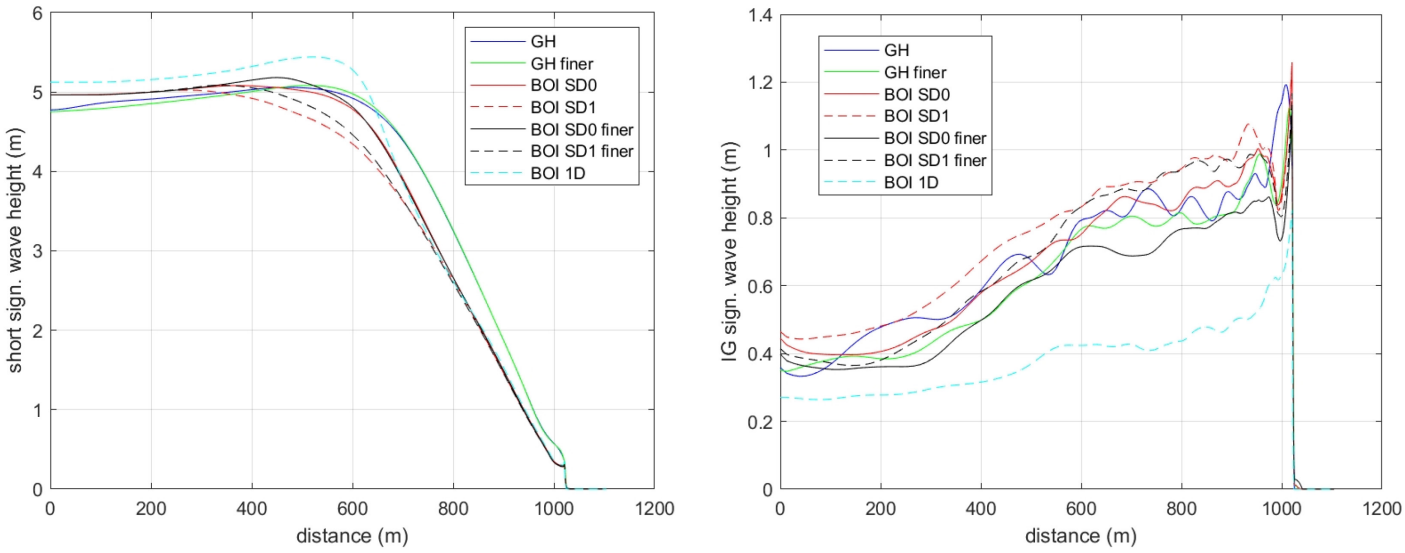
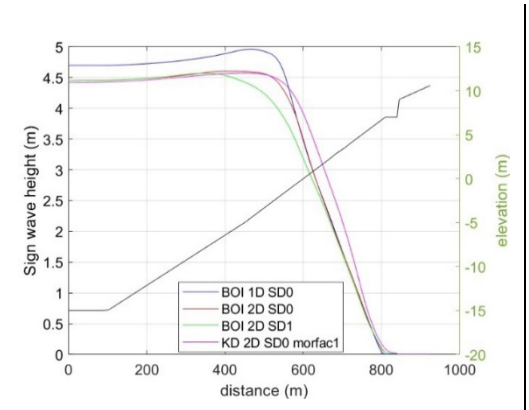


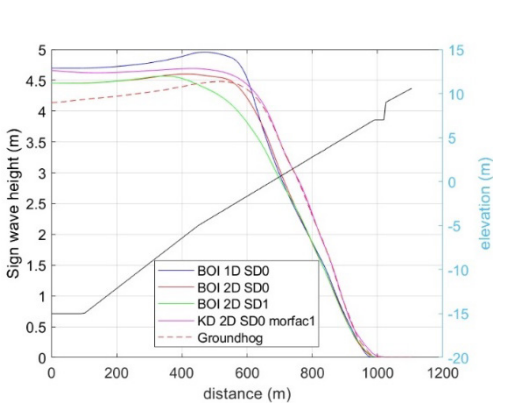
Figure 16 – XBeach: hydrodynamics: propagation of the short waves (left) and long waves (right) along the cross shore profile

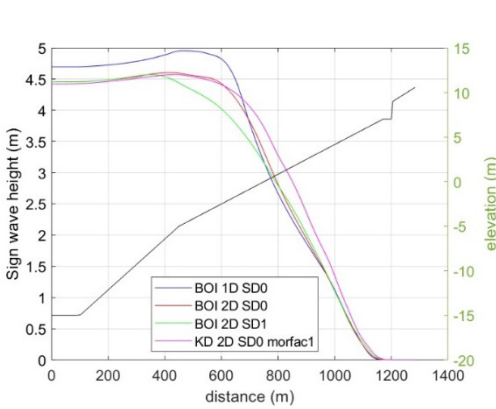
The evolution of hydrodynamics and cross shore sediment transport is examined for the simplified dike cases (dune cases are equivalent). Results are shown of the first high water of the storm (water level at +5.5 m TAW) because at that time the profile shape did not significantly differ among the simulations.

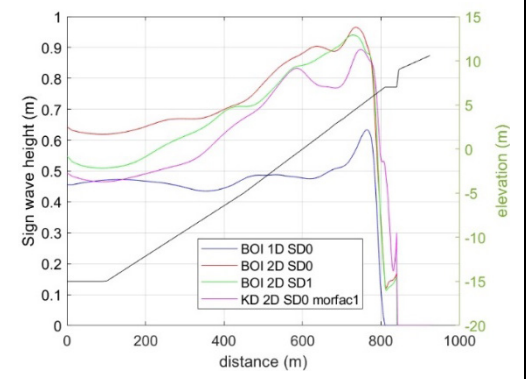
Looking at Figure 17, it can be seen that:

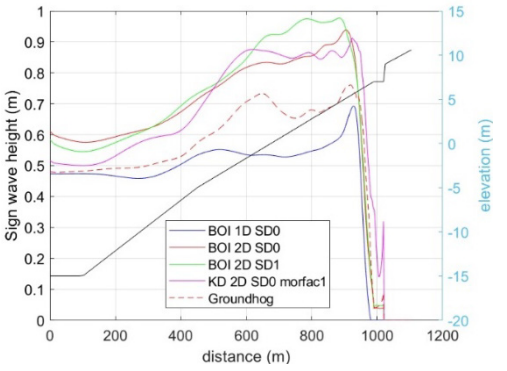
- Already at the offshore boundary differences in short wave height are visible (*random* = 0: no random seed selection).
- The short wave height is highest in the XB 1D model and (in deep water) smallest in XBeach Groundhog Day
- Wave breaking occurs most offshore in XBeach BOI in *single_dir* mode and most shallow in XBeach Kingsday
- IG waves are too much reduced in the XB 1D model
- IG waves are smaller in XBeach Groundhog Day and, logically, slightly higher in XBeach BOI in *single_dir* mode compared to Kingsday/BOI in *multi_dir* mode
- Version and parameter differences are the largest for the mildest beach (dune) (1/60) slope
- The IG wave height's maximum is the highest on the 1/30 beach slope in XBeach BOI with *multi_dir* mode and XBeach Kingsday (difference of 10-15cm), while it is the highest on the 1/60 slope in XBeach BOI with *single_dir* mode and XBeach BOI 1D, although the effect of the slope is rather limited
- Wave set-up is similar in all XBeach versions
- Cross shore velocity (*u_mean*) is significantly higher in XBeach Kingsday in the inner surf zone compared to the other XBeach versions. Xbeach Groundhog Day and XBeach BOI q2D give similar velocities, XBeach BOI 1D logically results in the smallest velocities.
- Cross shore sediment transport is highest for the 1/30 slope, and significantly higher for XBeach Kingsday compared to XBeach BOI: 3 to 5 times more. XBeach BOI in *single_dir* mode gives a higher result compared to *multi_dir* mode. Xbeach Groundhog Day's result is somewhat less than Kingsday yet much larger than BOI

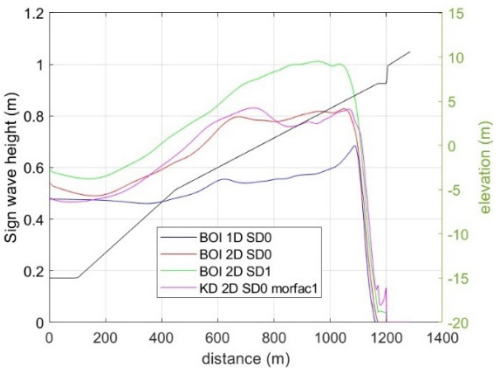

Sign wave height (m)
elevation (m)
distance (m)
BOI 1D SD0
BOI 2D SD0
BOI 2D SD1
KD 2D SD0 morfac1

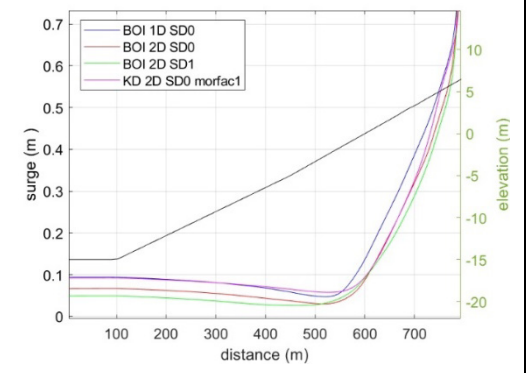

Sign wave height (m)
elevation (m)
distance (m)
BOI 1D SD0
BOI 2D SD0
BOI 2D SD1
KD 2D SD0 morfac1
Groundhog

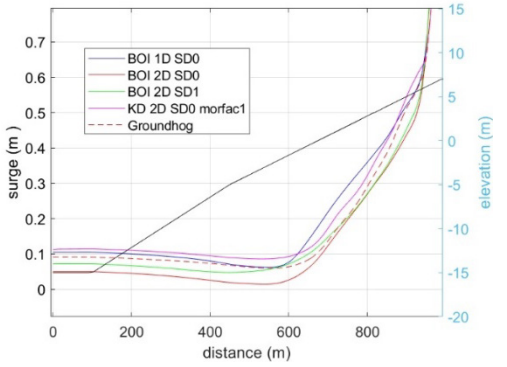

Sign wave height (m)
elevation (m)
distance (m)
BOI 1D SD0
BOI 2D SD0
BOI 2D SD1
KD 2D SD0 morfac1

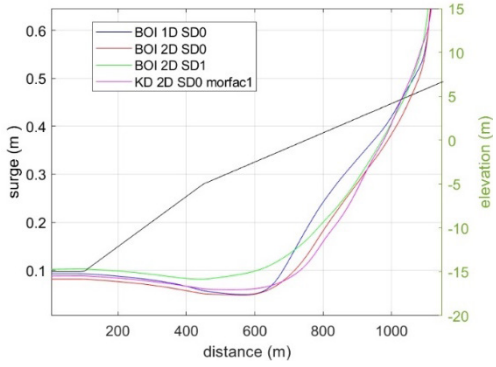

Sign wave height (m)
elevation (m)
distance (m)
BOI 1D SD0
BOI 2D SD0
BOI 2D SD1
KD 2D SD0 morfac1

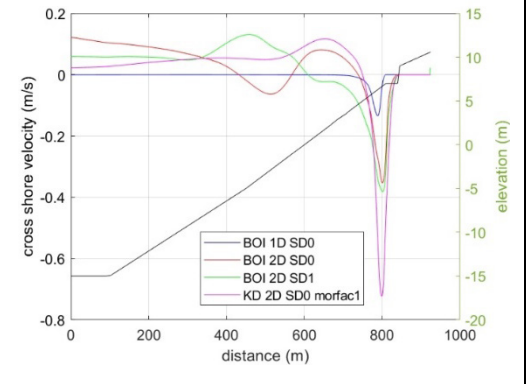

Sign wave height (m)
elevation (m)
distance (m)
BOI 1D SD0
BOI 2D SD0
BOI 2D SD1
KD 2D SD0 morfac1
Groundhog

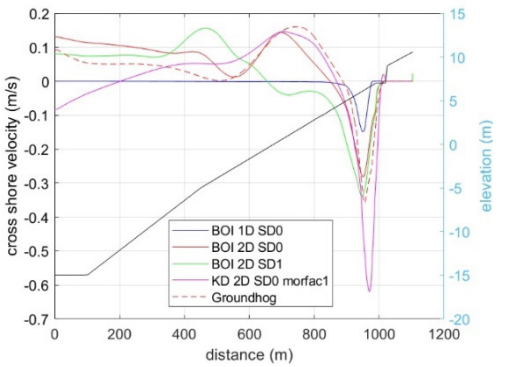

Sign wave height (m)
elevation (m)
distance (m)
BOI 1D SD0
BOI 2D SD0
BOI 2D SD1
KD 2D SD0 morfac1

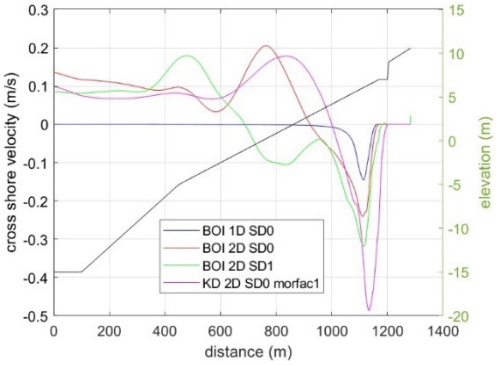

surge (m)
elevation (m)
distance (m)
BOI 1D SD0
BOI 2D SD0
BOI 2D SD1
KD 2D SD0 morfac1


surge (m)
elevation (m)
distance (m)
BOI 1D SD0
BOI 2D SD0
BOI 2D SD1
KD 2D SD0 morfac1
Groundhog


surge (m)
elevation (m)
distance (m)
BOI 1D SD0
BOI 2D SD0
BOI 2D SD1
KD 2D SD0 morfac1


cross shore velocity (m/s)
elevation (m)
distance (m)
BOI 1D SD0
BOI 2D SD0
BOI 2D SD1
KD 2D SD0 morfac1


cross shore velocity (m/s)
elevation (m)
distance (m)
BOI 1D SD0
BOI 2D SD0
BOI 2D SD1
KD 2D SD0 morfac1
Groundhog


cross shore velocity (m/s)
elevation (m)
distance (m)
BOI 1D SD0
BOI 2D SD0
BOI 2D SD1
KD 2D SD0 morfac1

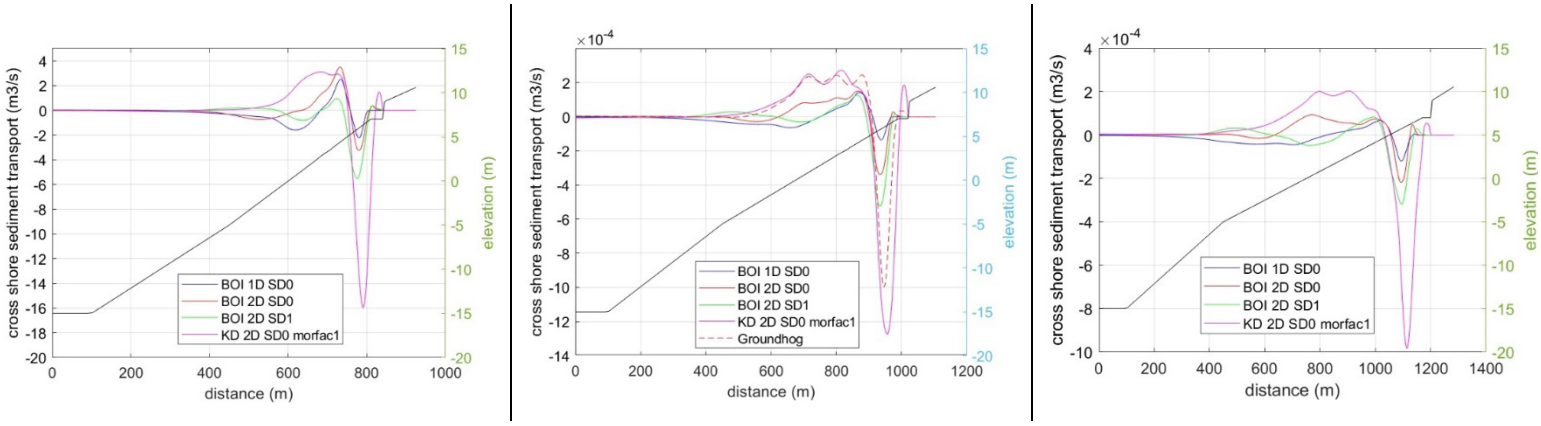


Figure 17 – Simplified dike with beach slope of 1/30, 1/45 and 1/60 (left – middle – right subfigures resp.): short and long waves' propagation, wave set-up, cross shore velocity and sediment transport (rows 1 to 5 resp.)

- Morphological response of simplified beach + dike profile

Figure 18 and Table 10 illustrate the morphological response of a simplified beach with slope 1/45 backed by a dike with slope 1/2; results of the other slopes 1/30 and 1/60 are alike (see Appendix 1). Figure 19 summarizes the erosion volumes of all beach slopes.

Following observations are made:

- In 1D mode, erosion volumes are much smaller compared to q2D mode
- Using parameter setting *single_dir* = 1 instead of 0 gives twice as much erosion (because of higher cross shore velocities cf. Figure 17)
- In XBeach BOI, using a morphological acceleration factor *morfac* = 1 or 3 gives only a small difference (10%) in erosion volumes
- XBeach Kingsday gives 4 times more erosion compared to XBeach BOI, XBeach Groundhog 3 times more than XBeach BOI (using the respective calibrated parameter settings)
- Setting the factor *facsl* = 1.6 (previous default value) in XBeach BOI gives about 50% more erosion, but still much less than XBeach Kingsday/Groundhog Day

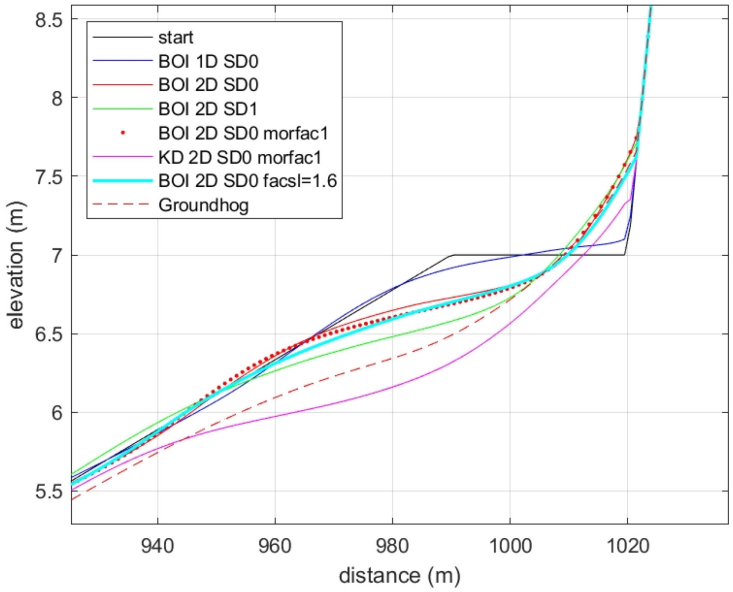


Figure 18 – Simplified dike with beach slope of 1/45: cross shore post-storm erosion profile

Table 10 – Simplified dike with beach slope of 1/45: erosion volumes above +6 m TAW

XBeach Version	*single_dir*	morfac	net erosion above +6 m TAW (m^3/m)	gross erosion above +6 m TAW (m^3/m)
BOI 1D	0	3	1.56	2.90
BOI 2D	0	3	7.28	11.68
BOI 2D	1	3	15.20	19.45
BOI 2D	0	1	8.28	13.12
Kingsday	0	1	34.14	35.69
BOI 2D facsl=1.6	0	3	11.40	14.70
Groundhog Day	-	3	28.88	31.44

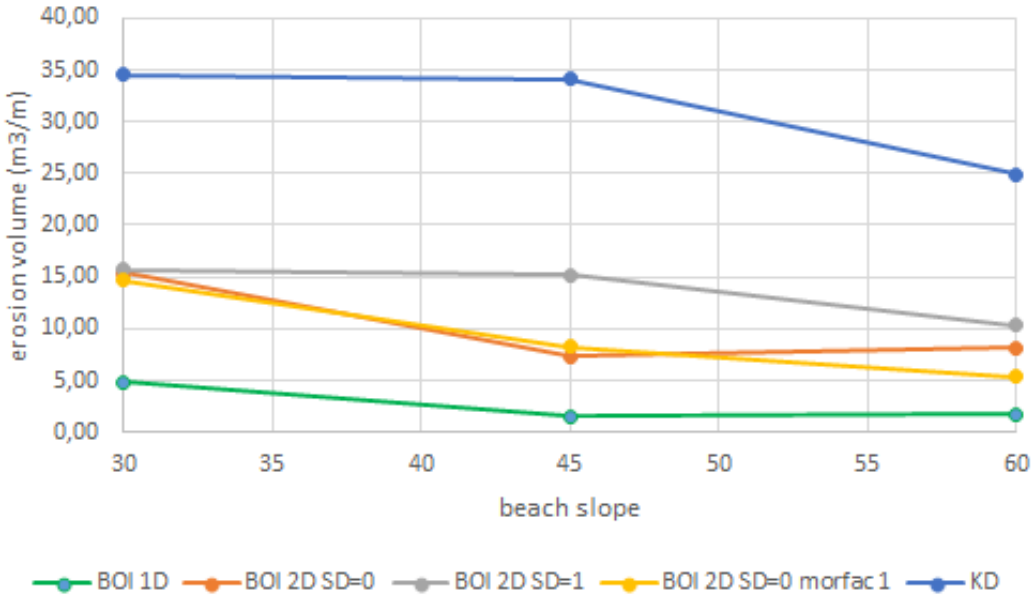


Figure 19 – Simplified dike with beach slope of 1/30, 1/45 and 1/60: erosion volumes

- Morphological response of simplified dune profile

Figure 20 illustrates the morphological response of a simplified beach with slope 1/45 backed by a dune with slope 1/4; results for the other beach slopes 1/30 and 1/60 are alike (see Appendix 1). Figure 21 summarizes the erosion volumes of all beach slopes.

Following observations are made:

- In 1D mode, erosion volumes are similar to q2D mode (especially for slope 1/60)
- Using parameter setting *single_dir* = 1 instead of 0 gives no significant difference in erosion volumes
- In XBeach BOI, using a morphological acceleration factor *morfac* = 1 or 3 gives only a small difference (up to 10%) in erosion volumes
- XBeach Kingsday gives up to 2 times more erosion compared to XBeach BOI, the difference depends on the beach slope, being the highest for the steepest beach (1/30) and the lowest for the mildest beach (1/60)

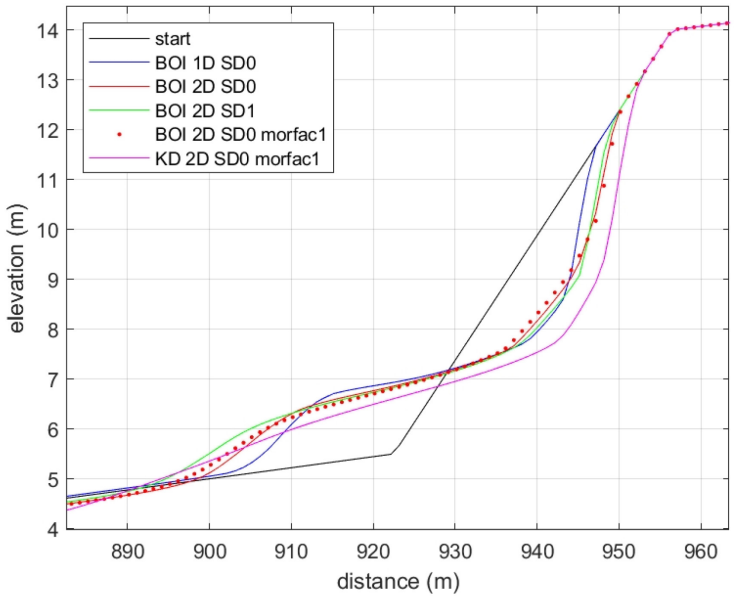


Figure 20 - Simplified dune with beach slope of 1/45: cross shore post-storm erosion profile

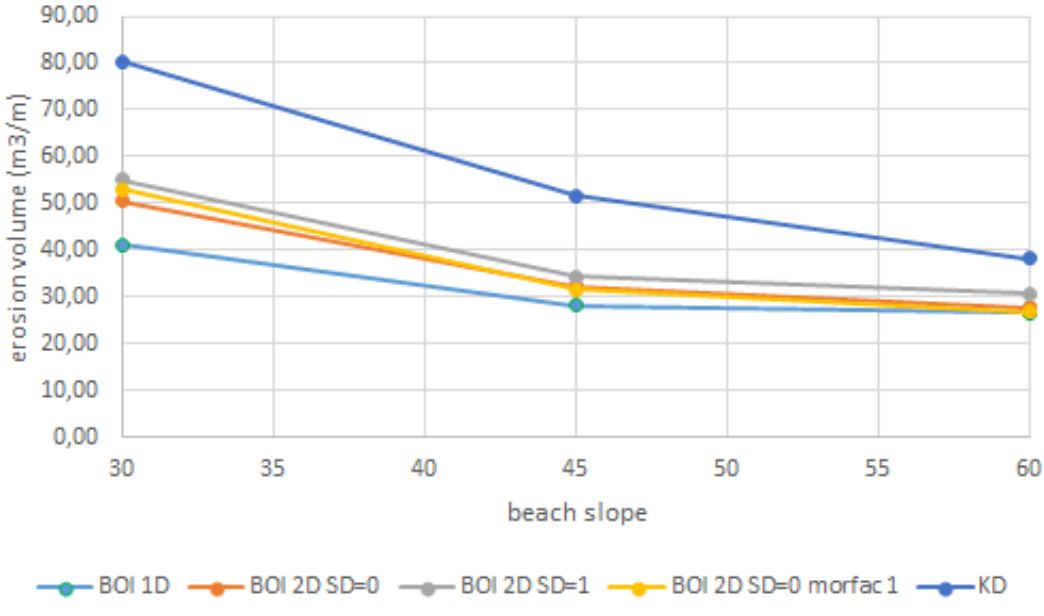


Figure 21 – Simplified dune with beach slope of 1/30, 1/45 and 1/60: erosion volumes

4 XBeach BOI: model validation – set-up

4.1 Model performance indicators

Quantitative model predictions can be evaluated using various Goodness of Fit indicators. In this study, following model performance indicators are calculated:

- Root Mean Squared Error (RMSE)
- Scatter Index (SI): normalised measure of error
- Bias
- Relative Bias

Generally, the lower the indicator's value, the better the model performed.

The Root Mean Squared Error (RMSE) of a quantity *q* is calculated as

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(q_{XB,i} - q_{meas,i}\right)^2}$$

In which i denotes every cross shore profile.

The Scatter Index (SI) is a normalised measure of the RMSE, in which the denominator holds an indication of the mean of the measured quantity:

$$SI = \frac{RMSE}{\max\left(\bar{q}_{meas}, RMSM\right)}$$

In which the Root Mean Squared Mean (RMSM) of a quantity *q* is calculated as

$$RMSM = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(q_{meas,i}\right)^2}$$

To prevent that low values of the quantity's mean result in high values of the Scatter Index, the denominator reflects the maximum of its mean or its RMSM. In this study, the RMSM is always the highest value.

The Bias (BI) (or structural error) of a quantity *q* is calculated as

$$Bias = \frac{1}{n}\sum_{i=1}^{n}\left(q_{XB,i} - q_{meas,i}\right)$$

Likewise the Scatter Index, the Relative Bias (RB) is a normalised measure of the Bias:

$$RB = \frac{Bias}{\frac{1}{n}\sum_{i=1}^{n} q_{meas,i}}$$

4.2 Validation measures

The accuracy of the modelled erosion is assessed using two quantitative measures, being the erosion volume and the retreat distance.

The maximum water level during the storm surge is considered to be leading and hence, the erosion volume is calculated above it and the retreat distance, being the change in horizontal distance of a certain point between the pre and post storm profile, is calculated at it and some distance above it (in order to capture the retreat of the slumped area). Figure 22 illustrates these morphological indicators.

Qualitatively, the modelled change in cross shore profile shape is evaluated against the measured post storm profile.

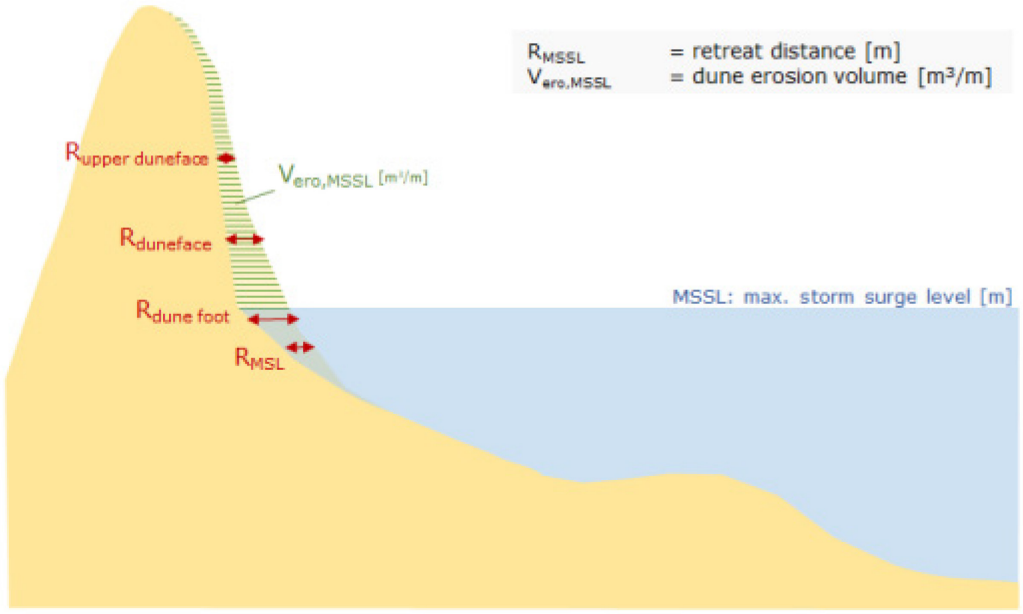


Figure 22 – Illustration of the morphological indicators: erosion volume and retreat distance (source: Hillman *et al.*, 2021)

5 XBeach BOI: model validation – cases

5.1 Storm Xaver ('Sinterklaasstorm') – Belgian coast

5.1.1 Case description: Meteorological conditions and study area

Around December 6th, 2013 storm Xaver hit the coast of several North-western European countries. While at the Belgian coast (measurement locations 'MP0' and 'ZMP'), moderate wind speeds of 15 to occasionally 20 m/s were measured, mainly coming from WNW ('MP0') at sea and NW at land ('ZMP'), the storm's intensity was much higher in the northern North sea. In the afternoon of December 5th, the wind's turning from SW to (W)NW pushed that storm surge (having a long fetch) towards the Belgian coast. This caused a very high surge (of roughly 1.5 m) at the high tide of December 6th around midnight, resulting in a water level of +6.33 m TAW (tide station in harbour of Ostend). The locally moderate wind speeds (and direction) led to moderately high wave heights of 2.5 to 3m nearshore (Oceanografisch Metereologisch Station, 2013). Trouw *et al.*, 2015 translated these meteorological conditions to input hydraulic boundary conditions for every cross shore profile using SWAN modelling. Figure 23 illustrates the hydrodynamics of storm Xaver in the nearshore.

A few days before the storm (2-4 December 2013), 122 cross shore profiles were surveyed along the entire Belgian coastline on behalf of Coastal Division (Flemish government). The cross shore resolution varied between 2 to 15 m, depending on the local bathymetry, whilst alongshore spacing was roughly 500 m. By doing so, the variability of the topography (dunes and nourished beaches) was accounted for. The survey's extent ranged from the toe of the dune/dike until the low tide contour. More seaward, the profiles were combined with single or multibeam measurements; more landward, they were extended using Lidar data (Trouw *et al.*, 2015).

On December 10th, a post storm Lidar survey was carried out along the entire coastline, covering roughly the same cross shore range as the pre storm profile survey (yet, including the entire alongshore area). Subsequently, a similar approach was followed to aggregate the data from several sources to obtain cross shore profiles (Trouw et al., 2015). Table 11 gives an overview of the morphologic characteristics of the selected cross shore profiles. Note that the profile number does not correspond to the coastal section number.

Table 11 – Storm Xaver: selected cross shore profiles along the Belgian coast

Profile number	7	10	12	44	48	50	59
Profile shape	Beach	Dune	Beach	Beach	Beach	Beach	Beach
D50 [µm]	300	179.3	300	219.4	219	300	215.6
Profile number	60	65	67	73	82	91	110
Profile shape	Dune	Dune	Dune	Beach	Beach	Beach	Beach
D50 [µm]	215	308.1	308.1	308.1	300	218	257
Profile number	114	119					
Profile shape	Beach	Dune					
D50 [µm]	257	271					

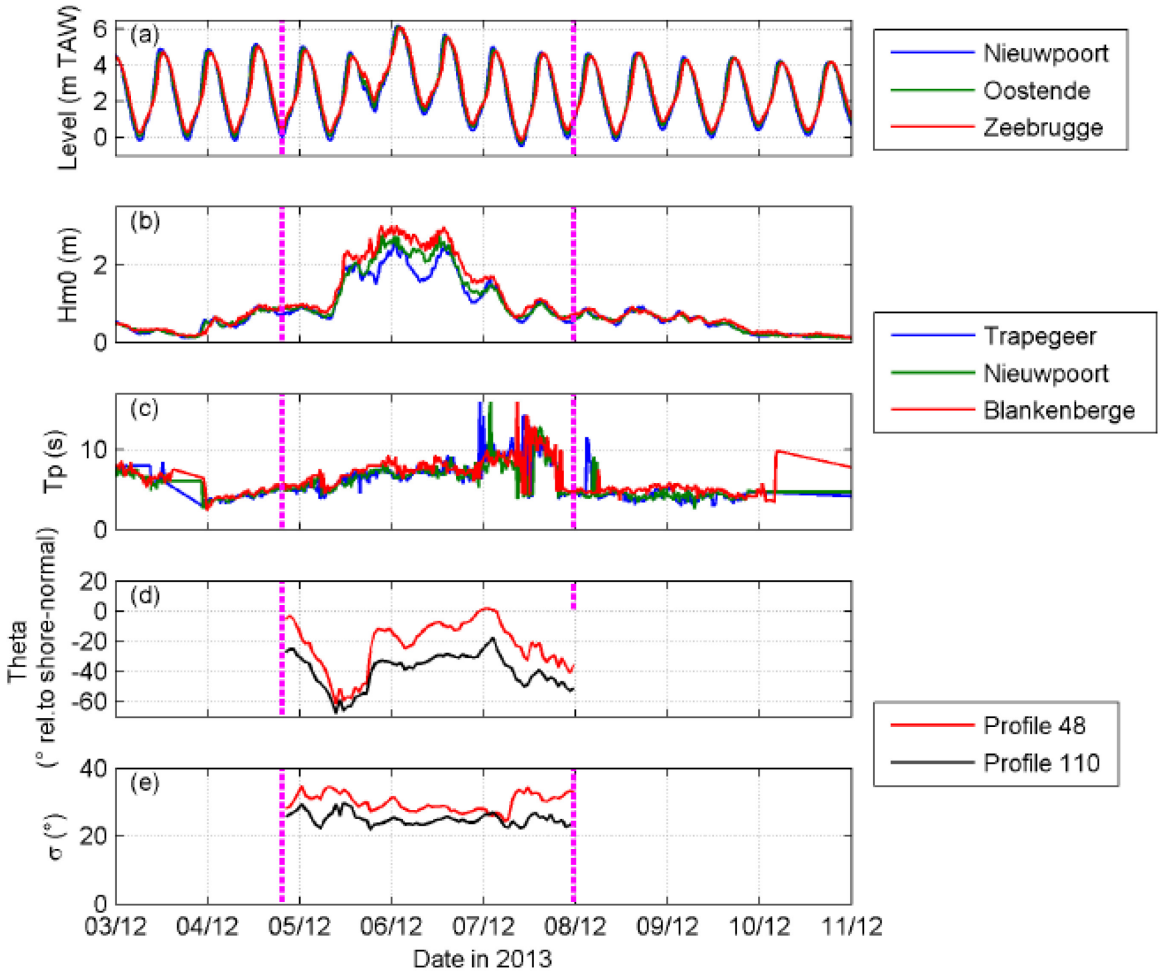


Figure 2-3: Hydrodynamic conditions recorded during the December 2013 storm.
(a) Water level; (b), significant wave height; (c) peak wave period;
(d) Incident wave angle (from SWAN model); (e) Directional spreading width.
Vertical dashed lines indicate the start and stop times for the hindcast simulations.
Measurement locations are shown in Figure 2-4.

Figure 23 – Synopsis of storm Xaver nearshore Belgium (source: Lanckriet *et al.*, 2015)

5.1.2 Model setup

1. From detailed to generalised test set-up

Based on Lanckriet et al., 2015, six profiles (profiles 48, 60, 65, 110, 114, and 119) were initially selected that cover the variability of the Belgian coastline geographically and morphologically (profile shape: dune / nourished beach). Median grain size D_{50} ranges from 215 to 308µm (cf. Table 11).

The XBeach grid of 2015 was refined, taking into account at least 40 points per wavelength and a minimum cross shore grid size (dx) of 1m (whilst keeping the same maximum of 20m), and extended seaward to deeper water for realistic long wave boundary conditions (and no wave breaking at the boundary). Alongshore the surveyed profile was copied over 1000 m with a uniform resolution of dy = 20 m (quasi 2D model).

The profile specific and time dependent SWAN spectra were used as input hydrodynamic boundary conditions over the 76 h lasting storm surge (from 04/12/2013 until 07/12/2014, i.e. between the vertical dashed lines of Figure 23). To speed up run time, simulations were reduced to the 21 most energetic hours of the storm surge focusing on the 2 tidal cycles with highest highwaters. Later on, these 2D wave spectra were parameterised as a Jonswap spectrum with corresponding wave height and peak period.

Main wave direction was initially kept and afterwards, redirected to perpendicular wave attack whilst maintaining directional spreading values (cf. Table 13).

2. Selection of parameter settings

Further validation of the BOI settings takes place using the model set-up of JNWSP 90° wave boundary conditions and a reduced 21h storm course. Ten other profiles were additionally selected, having a significantly higher or lower median sediment grain size, totalling the number of profiles to 16. 5 profiles are located in a dune area and 11 profiles in a (nourished) beach area (cf. Table 11).

Table 12 gives an overview of the non-default XBeach parameters used to validate the model results. Except for the software version update (including the change to the Roelvink Daly formulation for instationary wave breaking; see details in Section 2.1), GHD and BOI calibrated parameters are identical. Between the various BOI settings, differences focus on the *wetslp* and *facAs* parameters.

Table 12 – XBeach non-default parameters: GHD and BOI versions

	XB GHD	XB BOI init	XB BOI 0	XB BOI 2	XB BOI NL	XB BOI VL	XB BOI LO
Beta	0.138	0.08	0.11	0.08	0.08	0.08	0.08
Wetslp	0.26	0.18	0.25	0.21	0.15	0.10	0.25
facSk	0.375	0.15	0.13	0.15	0.15	0.15	0.15
facAs	0.123	0.25	0.10	0.18	0.20	0.20	0.20
Gamma	0.541	0.46	0.51	0.46	0.46	0.46	0.46
Gamma2	-	0.34	0.31	0.34	0.34	0.34	0.34
Alpha	1.262	1.38	1.37	1.38	1.38	1.38	1.38

5.1.3 Results and discussion

1. From detailed to generalised test set-up

A two step approach for validation was followed, see Table 13. First, identical input (of 2015) was used to rerun the XBeach GHD version (2014). Then, the bathymetric grid was refined, which leads to somewhat more erosion using the same XB version (Table 13, column 3). Applying the initial BOI settings (Table 12, column 3), the impact of modelling only the storm peak and using Jonswap parameterised wave conditions perpendicular to the coast (instead of SWAN spectra) was quantified. These simplifications were taken to speed up the run time and to align with the SA21 methodology (De Roo *et al.*, 2021).

To summarize, the initial BOI parameter settings generally introduce less erosion compared to the GHD settings; on average, the former settings caused an underestimation of 15% compared to the measured erosion volumes. Reducing the storm course of 76 h to the 21 peak storm hours leads to comparable erosion volumes (on average 3% less). Parametrisation of the wave conditions to a Jonswap spectrum resulted in, on average, roughly 13% more erosion compared to the reduced 21 h storm (and closely corresponds to the measured volumes (5% difference)). Changing the incident wave direction towards perpendicular (short-crested) wave attack and hence, reducing the alongshore sediment transport leads to, on average, erosion volumes being 30% underestimated compared to the measured volumes.

Figure 24 illustrates the response of a cross shore profile on these simplified hydrodynamic boundary conditions, being dependent on a.o the (wet) beach slope around the fluctuating water level. During the 21 most intensive storm hours the erosive process is captured reasonably well (compared to the 76 h XBeach result), only the redistribution of the deposited sediments lacks a further seaward migration. Note that generally the beach profile response was that sediment was eroded landward of the +5.5 m TAW contour. The erosion volumes are however calculated above the maximum storm surge level (rounded to +6 m TAW).

Besides, it is worth noting that run times are much lower using XBeach BOI compared to XBeach GHD since the latter could not be run in parallel (because of a software bug). The 76 h lasting storm surge (Table 13, column 4 compared to column 3) was finished in 26 hours using 6 cores on FH's Bernouilli queue (CPUtype/node (48cores/node): 2 x AMD EPYC 7451 24-Core Processor) compared to 23.6 days on 1 core of FH's Stevin queue (CPU: 2 x Intel Xeon Nehalem L5640 - 2.26 GHz Six Core).

Table 13 – Erosion of 6 cross shore profiles: from detailed to generalised test set-up on hydrodynamics input

Profile	Measured [m³/m]	GHD 2015 (2022) (2022 – refined) [m³/m]	BOI init (storm: 76h) [m³/m]	BOI init (storm: 21h) [m³/m]	BOI init (JNSWP obli) [m³/m]	BOI init (JNSWP 90°) [m³/m]
48	-20.21	-14.29 (-14.29 – -15.69: -22.4%)	-16.43 (-18.7 %)	-15.42 (-23.7%)	-14.43 (-28.6%)	-10.99 (-45.6%)
60	-14.54	-10.35 (-10.52 – -11.85: -18.5%)	-12.95 (-10.9%)	-12.78 (-12.1%)	-15.43 (+6.12%)	-11.18 (-23.1%)
65	-9.72	-10.12 (-9.91 – -11.31: +16.3%)	-7.89 (-18.8%)	-7.43 (-23.5%)	-9.57 (-1.5%)	-6.12 (-37%)
110	-18.27	-22.24 (-22.03 – -21.21: +16.1%)	-13.53 (-25.9%)	-12.65 (-30.7%)	-14.83 (-18.8%)	-12.11 (-33.7%)
114	-14.86	-13.58 (-13.43 – -17.19: +15.7%)	-12.34 (-16.9%)	-12.73 (-14.3%)	-13.87 (-6.7%)	-11.44 (-23%)
119	-12.45	-14.77 (-14.83 – -16.34: +31.2%)	-12.27 (-14.4%)	-11.53 (-7.4%)	-14.63 (+17.5%)	-8.11 (-34.8%)
Average difference	-	+6.4%	-15.5%	-18.6%	-5.3%	-32.9%

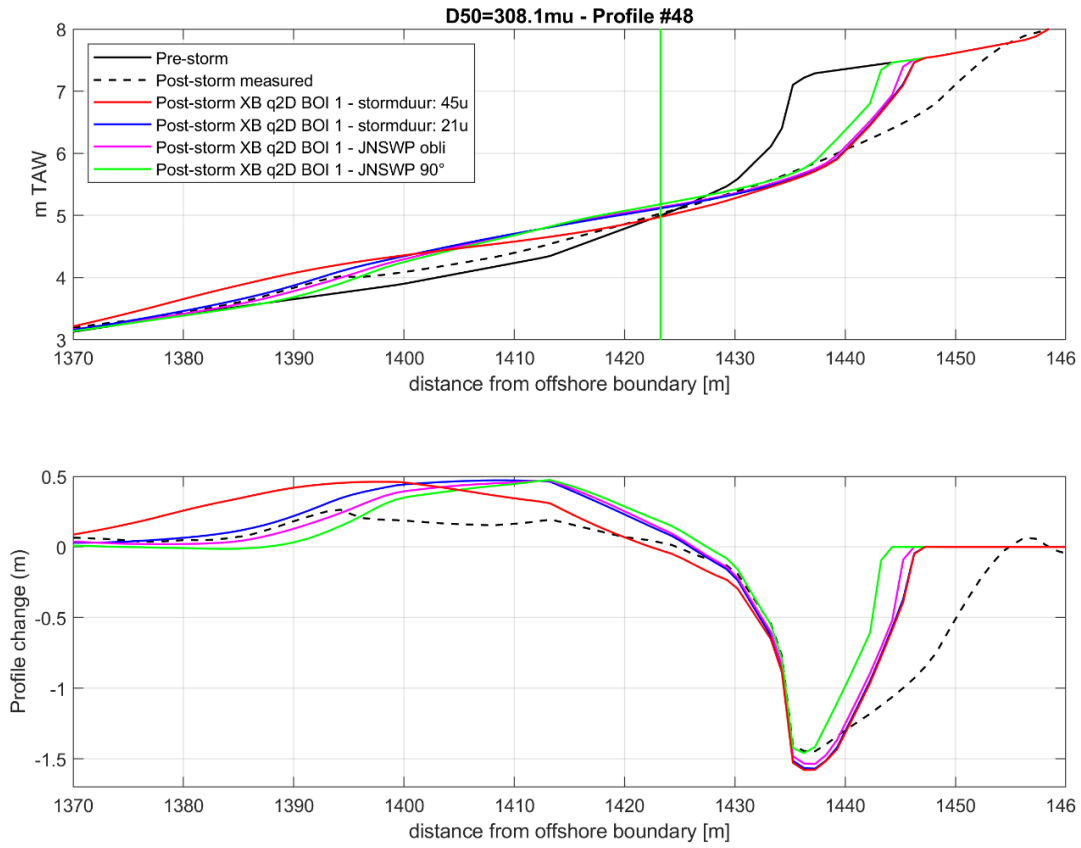


Figure 24 – Storm Xaver: profile #48: XBeach profile change - simplified input hydrodynamic boundary conditions ('BOI 1' = 'BOI init' in Table 12

2. Selection of parameter settings

Figure 25 gives an overview of the XBeach model's prediction capacity of the erosion volume (cf. parameter combinations of Table 12). Given the 'reduced 21h + JNSWP 90°' storm set-up, XBeach has a tendency to underestimate the erosion volume. The lower the *wetslp* parameter given a fixed *facAS*, the closer the modelled erosion volumes correspond to the measured volumes. Tuning both *wetslp* and *facAs* towards higher resp. lower values roughly cancels out the parameter changes. Comparing the entire 76 h storm set-up, i.e. including SWAN wave spectra, with the preferred BOI settings leads to a rather good agreement with the measured erosion volumes. There seems no grain size dependency on the predictive quality of XBeach.

Retreat distances at the maximum storm surge level (+6 m TAW) generally closely correspond to the measured retreat, indicating that the onset of the slumping zone is well predicted except for profiles where little erosion occurred (Figure 26, left subfigure). The tendency to underestimate the measured erosion volumes is confirmed by the underestimated retreat distance in the slumping zone, where differences between the parameter settings are larger (Figure 26, right subfigure). Overall, a *wetslp* = 0.10 or 0.15 while *facAs* = 0.20 show the best agreement with the measured retreat.

Figure 27 and Figure 28 illustrate the response of resp. a nourished beach and dune profile. Differences between the two *wetslp* values (given a fixed *facAs*) indicate that the lower its value the higher the inflection point, characterising the onset of the eroded dune/beach front, in the post storm profile will be and the more erosion occurs higher up in the profile. Given that XBeach calculates a rather steep eroded dune/beach front a better correspondence between model and measurements will be for these profiles (cf. profile 48).

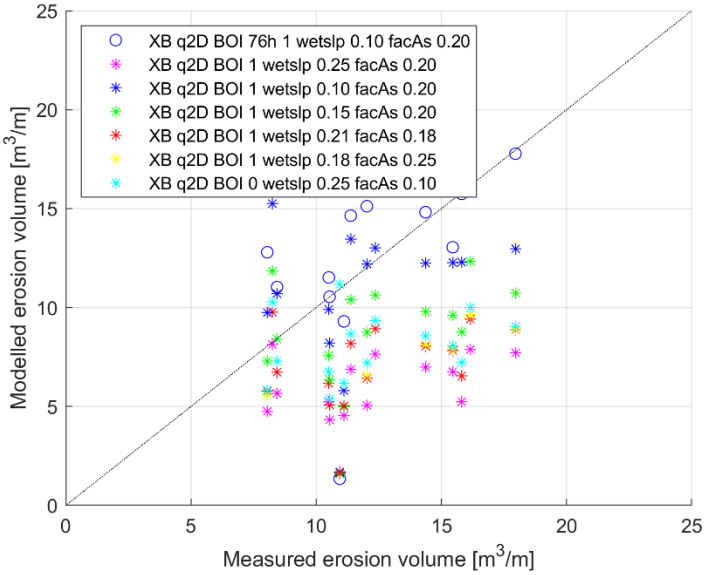


Figure 25 – XBeach result 'reduced storm + JNSWP 90°' (except for blue cirkels: '76 h storm + JNSWP 90°') – all parameter combinations: erosion volumes

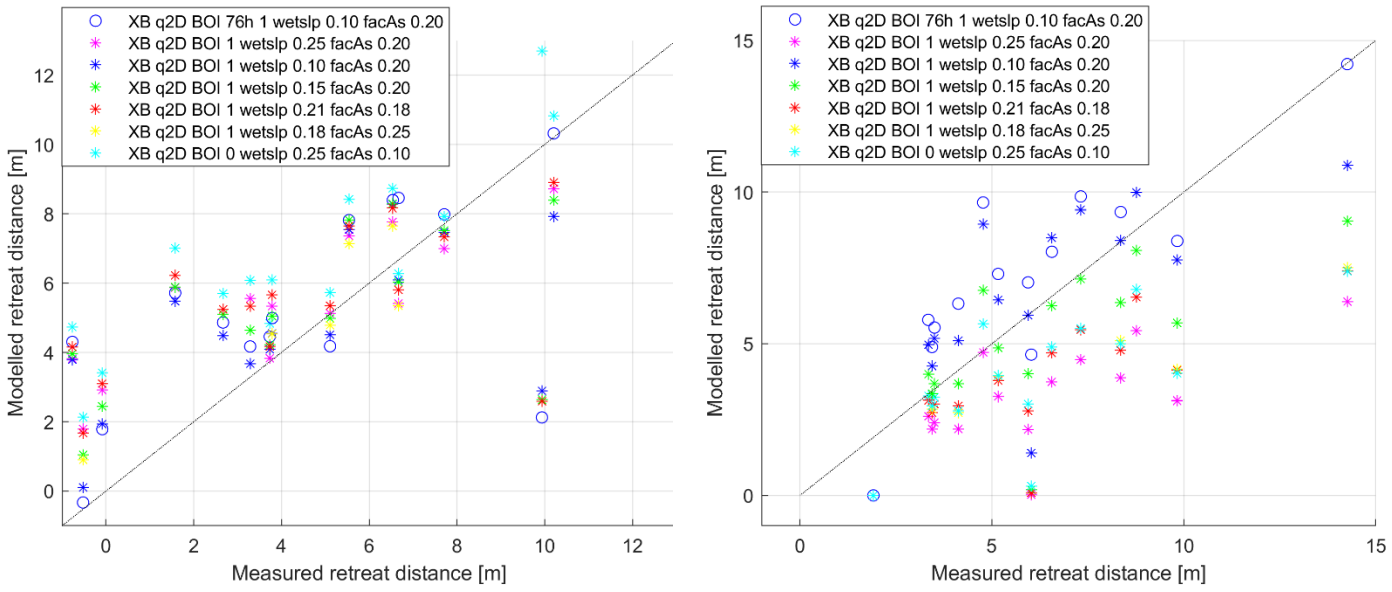


Figure 26 – XBeach result 'reduced storm + JNSWP 90°' (except for blue cirkels: '76 h storm + JNSWP 90°') – all parameter combinations: retreat distance at maximum water level (left) and at the dune/beach front (right)

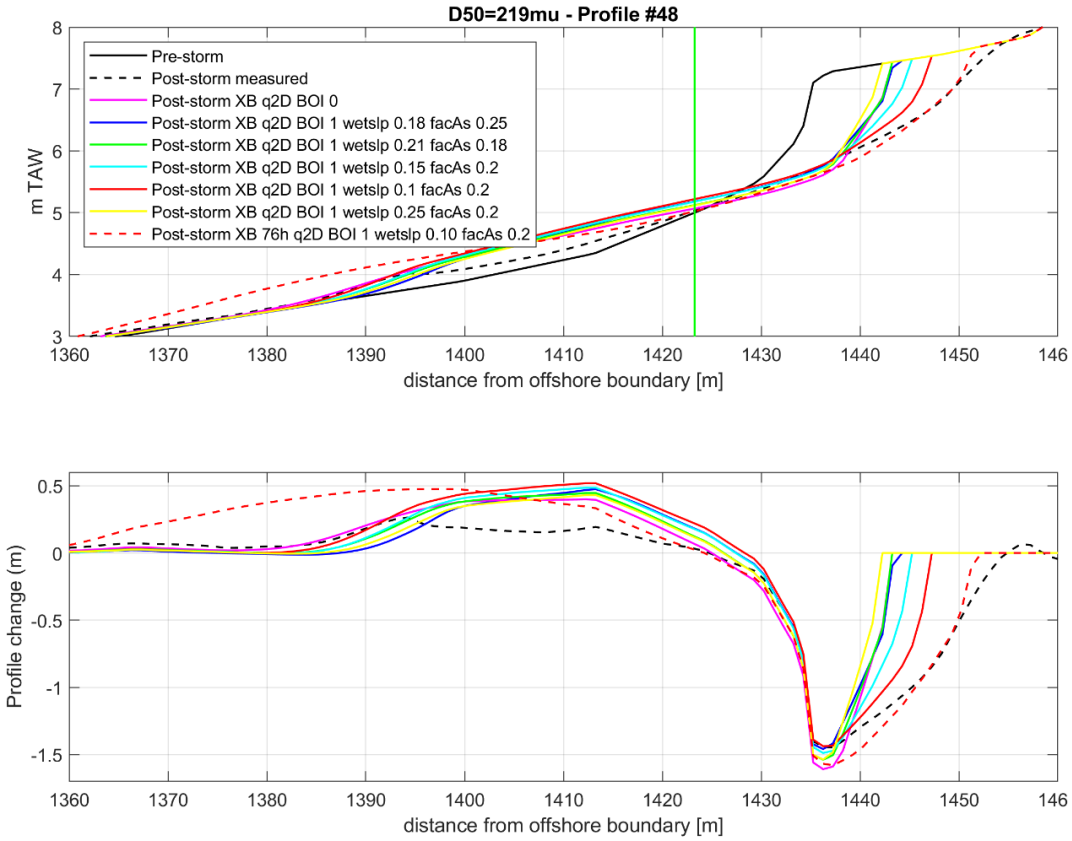


Figure 27 – Storm Xaver: profile #48 (nourished beach): XBeach profile change – all parameter combinations

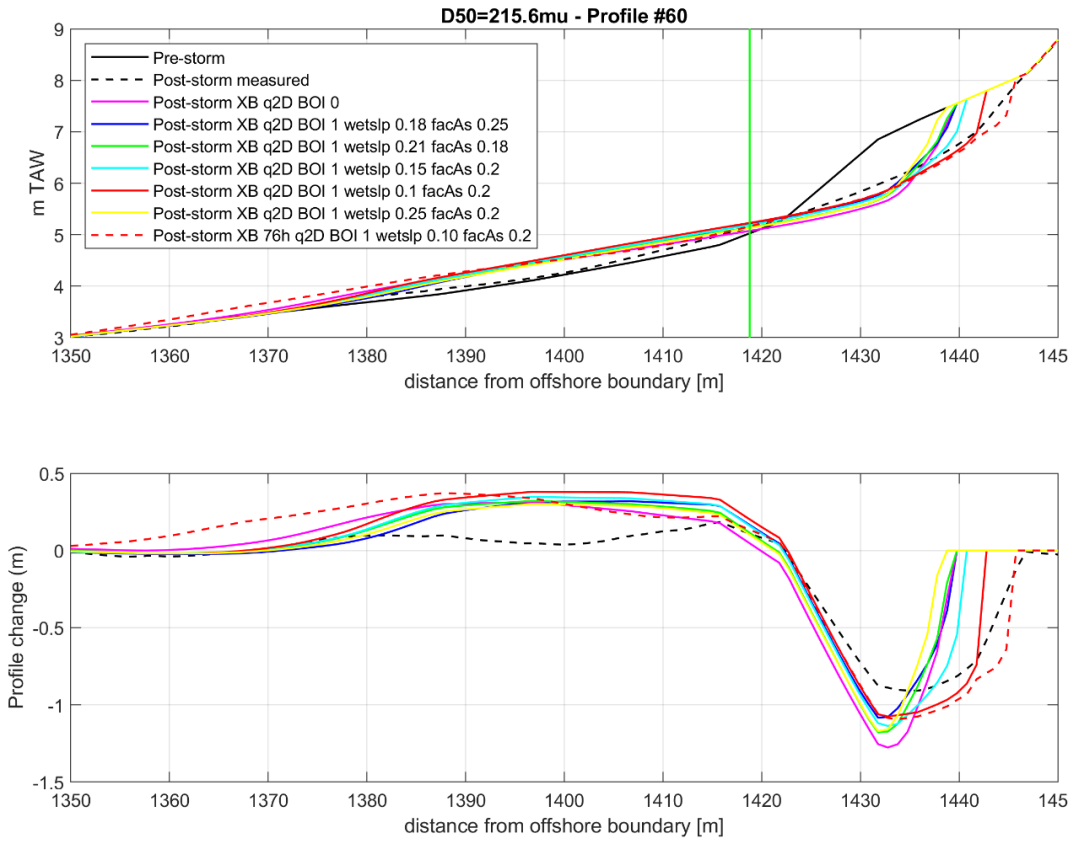


Figure 28 – Storm Xaver: profile #60 (dune): XBeach profile change – all parameter combinations

Table 14 summarizes the Goodness-of-fit indicators for all parameter combinations. The parameter combination where the lowest *wetslp* of 0.1 is used (BOI VL in Table 12) leads overall to the best model performance. The estimation of erosion volumes and retreat distances resulted in a relative bias of -0.09 and 0.04 to 0.09 resp., indicating that the structural error on these results is rather small. The scatter index, being a measure of the model's uncertainty, is resp. 0.31 and 0.33 to 0.49.

Table 14 – Xbeach result 'reduced storm + JNSWP 90°' – all parameter combinations: performance indicators (Vero: erosion volume – retreat_zs/df: retreat distance at the max water level and at the dune face)

Indicator		XB BOI init	XB BOI 0	XB BOI 2	XB BOI NL	XB BOI LO	XB BOI VL	XB BOI VL_{76h}
RMSE	Vero	4.14	5.88	5.31	4.84	6.94	3.94	4.18
	retreat_zs	0.74	3.15	2.76	2.88	2.95	2.68	2.92
	retreat_df	2.48	3.24	3.18	2.52	3.82	2.26	2.19
SI	Vero	0.33	0.47	0.42	0.38	0.55	0.31	0.33
	retreat_zs	0.13	0.57	0.50	0.52	0.53	0.49	0.53
	retreat_df	0.36	0.47	0.46	0.36	0.55	0.33	0.32
Bias	Vero	-2.49	-5.10	-4.31	-3.62	-6.33	-1.17	1.15
	retreat_zs	0.22	1.27	2.14	0.84	0.85	0.50	0.92
	retreat_df	-1.26	-2.39	-2.32	-1.35	-3.11	0.26	1.29
RB	Vero	-0.20	-0.41	-0.34	-0.29	-0.50	-0.09	0.09
	retreat_zs	0.04	0.23	0.39	0.15	0.15	0.09	0.17
	retreat_df	-0.18	-0.34	-0.34	-0.19	-0.45	0.04	0.19

5.2 Storm Xaver ('Sinterklaasstorm') – German coast: Langeoog

5.2.1 Case description

Around December 6th, 2013 storm Xaver hit the coast of several North-western European countries. A maximum water level of +3.95 m NHN (Normalhöhennull, = +1.62 m TAW) was measured at the Langeoog gauge station around midnight December 6th, 2013 (Figure 30). Wave heights, periods and directions were obtained using a SWAN model of the German Bight area at an output point 10km offshore of the island (project: EasyGSH-DB; (BAW, 2020)). Maximum significant wave height reached to 6.85 m around that highest highwater (Hillman *et al.*, 2021).

Being one of seven inhabited barrier islands of Germany, the island Langeoog is situated along the East Frisian German North Sea coast (Figure 29, left subfigures). Its mildly sloping and shallow shoreface (~1/300) is characterised by migrating sand shoals through the ebb-tidal delta and a breaker bar system that migrates in eastern direction (Arcadis/Deltares, 2022). Two months prior to the storm, in October 2013, a beach nourishment was deployed on the North-Western part of the island (alongshore length indicated in Figure 29, right subfigure). Because of the gentle sloping shallow foreshore and topography consisting of both nourished beach and natural dune areas, it is similar to the characteristics of the Belgian coast.

Topographic (LIDAR) measurements of the nourished beach and dunes were collected after the beach nourishment was completed, on October 18th, 2013. Post-storm topography was collected a few days after storm Xaver in the area of the beach nourishment, on December 13th, 2013 and unfortunately only next spring, on April 30th, 2014 in the adjacent dune area in the Eastern part of the island. Bathymetric data of the shoreface was collected during summer, in August 2013 (Hillman, S. *et al.*, 2021). The model bathymetry combined the bathymetric shoreface data with the topographic beach and dune measurements.

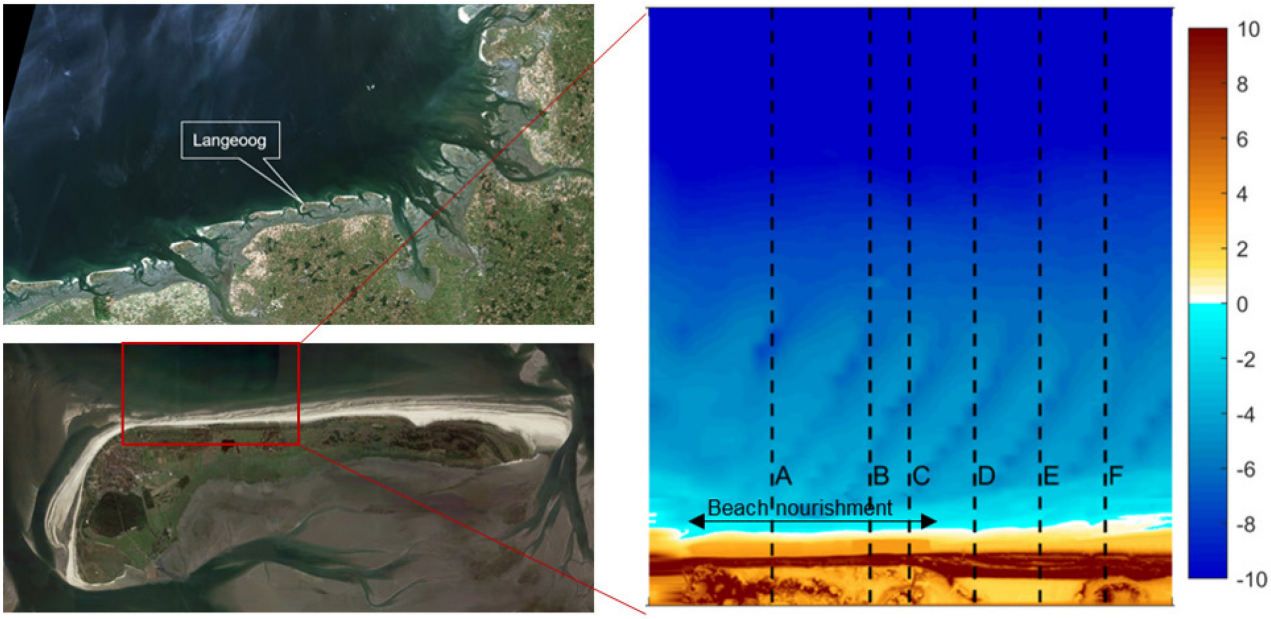


Figure 29 – Overview of the modelled area at Wadden island Langeoog: A-B-C profiles are at a nourished beach; D-E-F are at a dune area

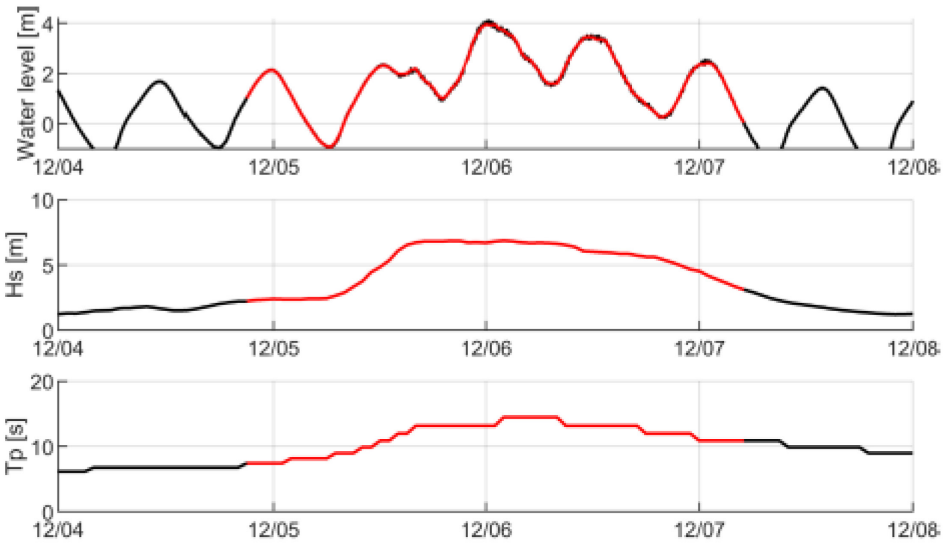


Figure 30 – Hydrodynamic conditions during storm Xaver close to Langeoog (red line: simulated period in XBeach)

5.2.2 Model setup

The 6 cross shore profiles of the XBeach skillbed (retrieved of the Subversion of Deltares), based on Hillman *et al.*, 2021, were used, i.e. profiles A-C located at the nourished beach area and profiles D-F at the dune area. Median grain size D_{50} varies cross shore being about 300 µm in the surf zone and around 200 µm in the dry beach and dune foot area. In the model, a D_{50} of 250 µm is applied. The XBeach grid has a cross shore length of roughly 4.5 km and a varying grid size ranging from 8 m offshore gradually refining to 1 m near- and onshore. The shallow shelf's bathymetry is cut-off at -12 m and artificially deepened until -23 m to obtain a seaward boundary in deeper water for realistic long wave boundary conditions.

When 1D cross shore profiles are simulated, the parameter *wbcEvarreduce* reducing the incoming wave groupiness (and hence, IG wave energy) is included and set to 0.3. With regard to quasi 2D simulations, the surveyed profile is copied alongshore over 1000 m, being uniformly spaced at dy = 20 m.

Hydrodynamic boundary conditions consist of the measured water level at Langeoog gauge station and half hourly JONSWAP wave spectra. Based on the SWAN model output, XBeach wave input was simplified to a 30° directionally spread JONSWAP spectrum and wave attack perpendicular to the coast. Focusing on the peak of the storm, a 56 h simulation period was selected (red lines in Figure 30).

5.2.3 Results and discussion

Figure 31 gives an overview of the XBeach model's prediction capacity of the erosion volume (cf. selection of parameter combinations in Table 12) for simulations of both 1D cross shore profiles and (corresponding) q2D(H) areas. 'Nourished beach' profiles A to C and 'dune' profiles D to F respond in a different way: XBeach clearly underestimates erosion volumes at the beach nourishment while a better agreement with the measurements is found in the dunes. The biggest difference between these profiles is the bed slope around the maximum water level, see 'nourished beach' and 'dune' example in Figure 32 and Figure 33 resp. Besides, it can be questioned whether this typical initial profile shape of the nourishment is still realistic after some months.

This bed slope is focused on in the simulated scenarios, differing from one another in the *wetslp* setting except for the 'BOI 0' run (cf. Table 12). The higher the *wetslp* value, the better the agreement with the post-storm measurement since it results in a downward shift of the inflection point between erosion and sedimentation. Between the modelling modes '1D' or 'q2D', the '1D' simulation always results in higher erosion volumes. The lower the *wetslp* value, the bigger the difference between both modes.

Retreat distances at the maximum storm surge again show the different response of 'nourished beach' and 'dune' profiles. Although the *wetslp* value of 0.25 leads to an improved eroded profile, the inflection point is still too high specifically in the 'nourished beach' area, resulting in sedimentation around the maximum water level instead of the measured retreat. Besides, profile response does vary from one another in the same area. Between the modelling modes '1D' or 'q2D', the 'q2D' simulation always results in the better agreement with the measured retreat. The measurements indicate that alongshore gradients in sediment transport took place during the storm so ideally, a 2D model set-up is preferred given the non-uniform coastal outline . The angle of wave attack needs reconsideration.

Table 15 summarizes the Goodness-of-fit indicators for all parameter combinations, indicating the better fit of the 'q2D' simulations. The parameter combination with the highest *wetslp* of 0.25 (BOI LO in Table 12) leads overall to the best model performance. The estimation of erosion volumes and retreat distances resulted in a relative bias of 0.04 and -0.65 to -0.95 resp., indicating that the structural error on these results is acceptable. The scatter index, being a measure of the model's uncertainty, is resp. 0.41 and 1 to 1.35.

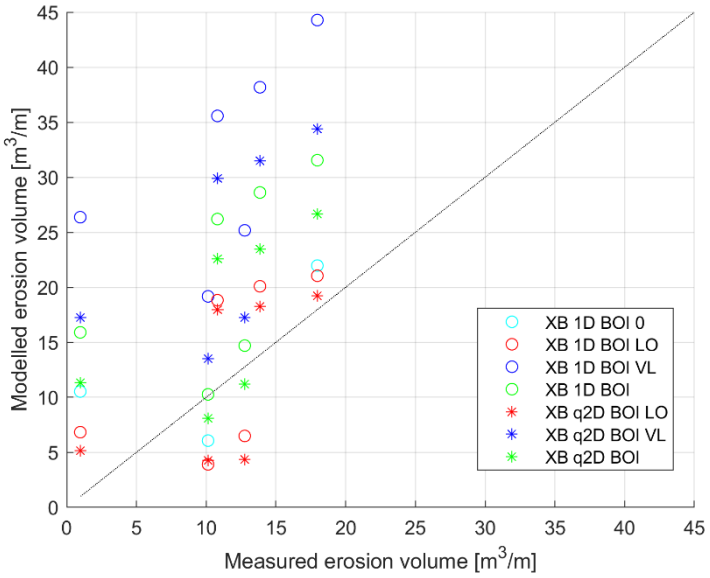


Figure 31 – XBeach result '1D & q2D bathy' – all parameter combinations: erosion volumes

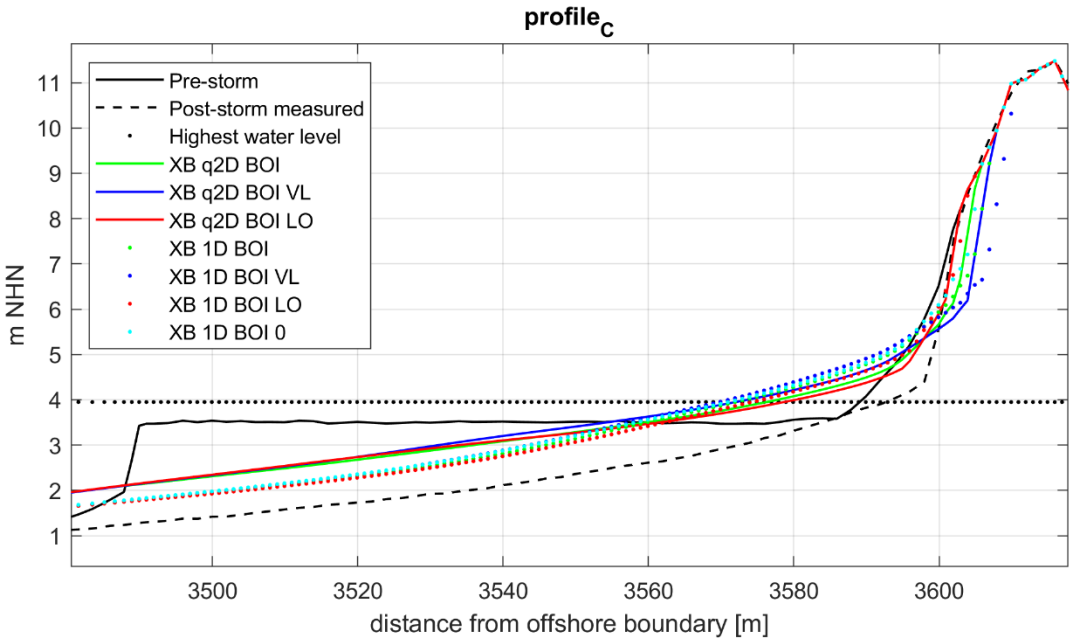


Figure 32 – Storm Xaver: profile C: XBeach profile change in nourished beach area – all parameter combinations

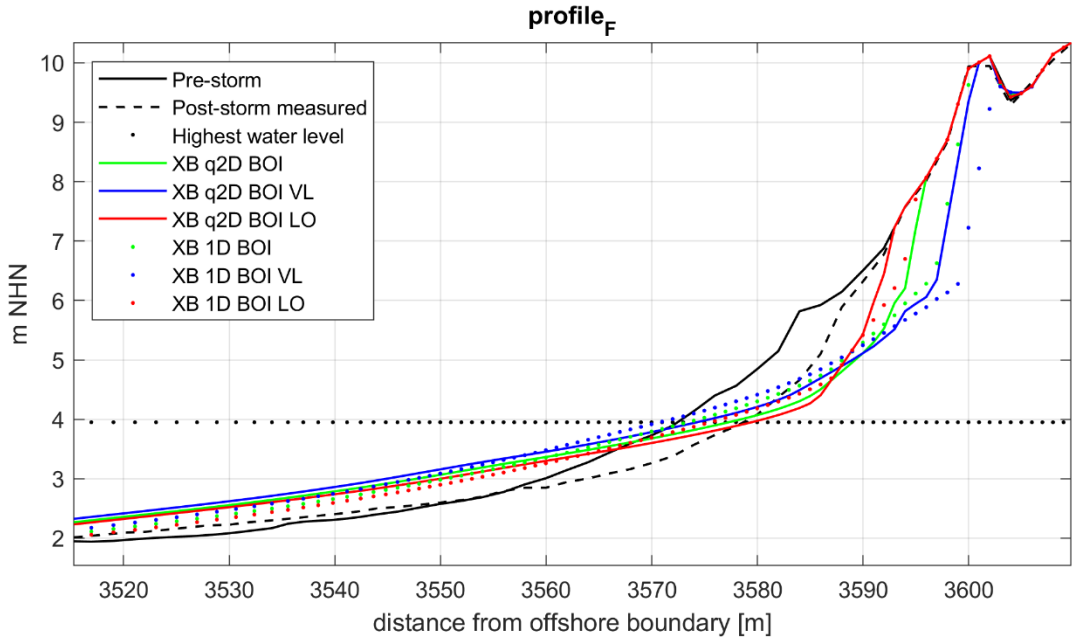


Figure 33 – Storm Xaver: profile F: XBeach profile change in dune area – all parameter combinations

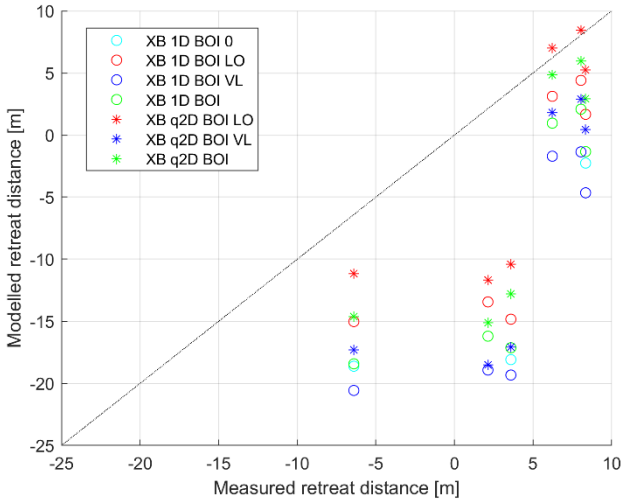


Figure 34 – XBeach result '1D & q2D bathy' – all parameter combinations: retreat distance at maximum water level

Table 15 – XBeach model performance indicators: storm Xaver – German coast
(Vero: erosion volume – retreat_zs/df: retreat distance at the max water level and at the dune face)

		1D BOI LO	1D BOI VL	1D BOI NL	q2D BOI LO	q2D BOI VL	q2D BOI NL
RMSE	Vero	6.12	21.52	12.01	5.70	14.39	8.37
	retreat_zs	10.98	15.76	13.34	8.37	13.42	10.56
	retreat_df	0.78	2.42	1.43	0.75	1.46	0.96

SI	Vero	0.50	1.76	0.98	0.47	1.18	0.68
	retreat_zs	1.77	2.54	2.15	1.35	2.16	1.70
	retreat_df	1.04	3.25	1.92	1.00	1.95	1.29
Bias	Vero	1.78	20.38	10.12	0.45	12.89	6.14
	retreat_zs	-9.34	-14.75	-12.00	-5.75	-11.61	-8.46
	retreat_df	-0.36	0.48	0.05	-0.49	0.06	-0.20
RB	Vero	0.15	1.67	0.83	0.04	1.05	0.50
	retreat_zs	-1.50	-2.37	-1.93	-0.93	-1.87	-1.36
	retreat_df	-0.48	0.65	0.06	-0.65	0.08	-0.27

5.3 Storm February 1990 – Belgian coast: De Haan

5.3.1 Case description

From February 26 to March 3, 1990 a storm (coinciding with spring tide) resulted in 8 high tides above +5 m TAW at De Haan; +5.70 m TAW being the highest water level. Water level was obtained by interpolating the gauged water levels in the harbours of Ostend and Zeebruges. Until the end of February, westerly wind prevailed, having speeds around 23 m/s; later on wind turned towards NW and wind speeds decreased to 15 m/s and lower. Wave heights and periods were deducted from the A2-buoy, roughly 4.5 km offshore the coast (about 11 km from De Haan as the crow flies). Using a SWAN model of the Belgian continental shelf, wave conditions were translated to the edge of the breaking zone nearshore De Haan ('-5 m TAW').

Figure 35 to Figure 37 illustrate the damage caused by the storm at the village of De Haan. The beach was severely eroded, up to the toe of the dike revetment (whereas the pre storm beach level was up to the crest of the lower dike part (Figure 36)).



Figure 35 – De Haan center: eroded beach in front of the dike – pre storm beach level was up to the crest of the lower dike part (see Figure 36)



Figure 36 – Close-up of the eroded beach at De Haan – erosion up to the toe of the dike (pre storm beach level at location of people in this figure)



Figure 37 – De Haan towards dunes west of the village – erosion up to Longard protection system

Maps of the autumn survey of 1989 (SIT1989MIWE26 and SIT1989MIWE27, dated October 22, 1989) and of the post February 1990 storm were digitized (including the dike/promenade) (SIT1990MIWE26 and SIT1990MIWE27; dated March, 16 1990). Digitisation was carried out by scanning in MATLAB using reference points/coordinates. These digitized maps were combined with the available shoreface soundings (Vooroeverloding De Haan-Wenduine, MOW - Dienst der Kust (survey maps of resp. November, 3, 26 and 27 1989 and March, 13 and 14 1990)) to build the model bathymetry. The model domain covers a 5 km stretch alongshore, including the dunes east and west of De Haan, as well as the De Haan centrum itself (where a dike and promenade protect the buildings). Cross shore it extends offshore the breaking zone (-5 m TAW contour)

Additionally, the KP40 profile from the publication of De Moor (1991) was digitized, using measurements from February 14 and February 28, 1990. This profile is located in De Haan center (where a dike and promenade protect the buildings). Using the February 14, 1990 measurement, an estimate was made of De Haan's topographic changes between October 1989 (for which a DEM was derived from digitized contour lines) and February 14, 1990. The result is DTM_14feb1990.txt (in m Z). This bathymetry represents the morphological conditions at the beginning of the storm.

To correct the XBeach model bathymetry with these findings, the 'DTM_14feb1990' was converted to m TAW (-0.1 m). The applied corrections to the bathymetry include:

- Dunes west of De Haan: Up to 2 m erosion within a (cross shore) 30 m wide zone around the dune front (based on the profile at KP37 ('Vosseslag')).
- Dike of De Haan: Up to 1 m erosion within a 70 m wide zone (based on the profile at KP40).
- Dunes east of De Haan: Up to 2 m erosion within a (cross shore) 15 m wide zone around the dune front (based on the profile at KP42 ('Vlissegem'); first, a vertical shift of the profile was applied to maintain an average balance.

An alternative bathymetry was also created, in which the erosion observed between October 1989 and February 14, 1990, was doubled.

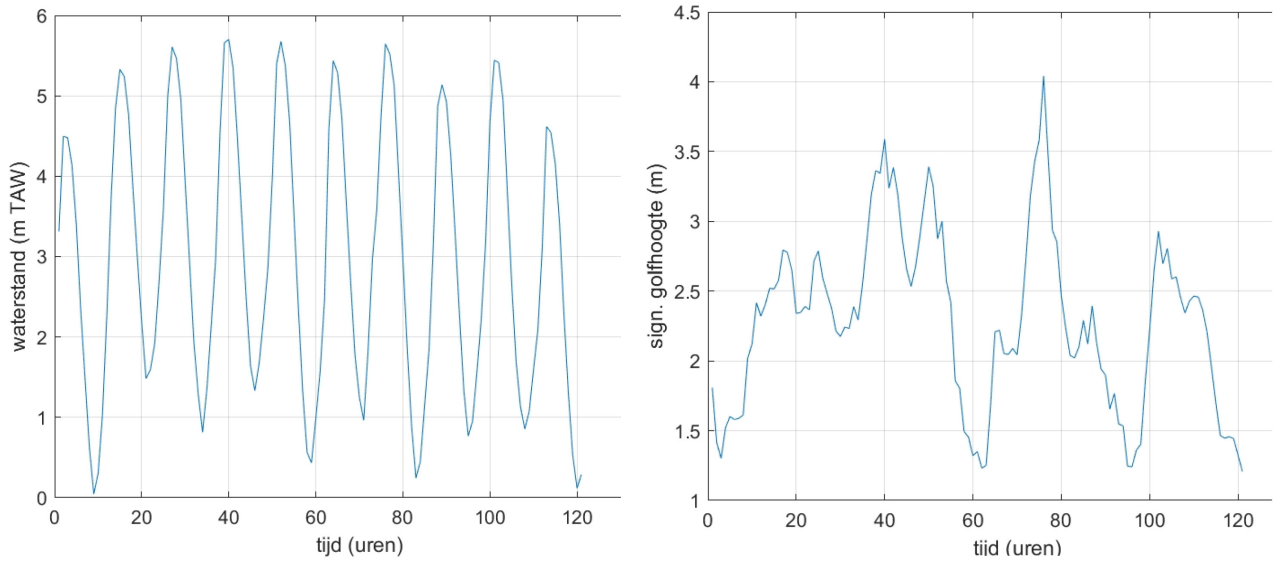


Figure 38 – Water level and significant wave height during the storm of end of February 1990
(t = 0 = 26/02/1990 0h - t=120 = 03/03/1990 0h)

5.3.2 Model setup

The model domain consists of 166 grid points alongshore (dy = 30 m) and 460 grid points cross shore (dx varies between 10 m offshore and 1 m above 3 m TAW. Median grain size d50 of 0.2 mm is used. Figure 39 and Figure 40 illustrate resp. the 2D model domain, consisting of De Haan centrum and adjacent dune areas, and a zoom on De Haan centrum.

All simulations were carried out using the model settings of the 2021 Coastal Safety Assessment (cf. Section 6.2). In total, 5 scenarios are considered:

- Basic scenario
- Basic scenario + 0.2 m higher water levels and 20% higher wave heights
- Basic scenario + lowering the initial model bathymetry: the difference in bed level between February 14, 1990 and November 1989 (= the correction) is doubled (to anticipate possible underestimation of the erosion during this period)
- Basic scenario including tidal currents
- Basic scenario + more perpendicular wave attack (wave direction at least 320°)

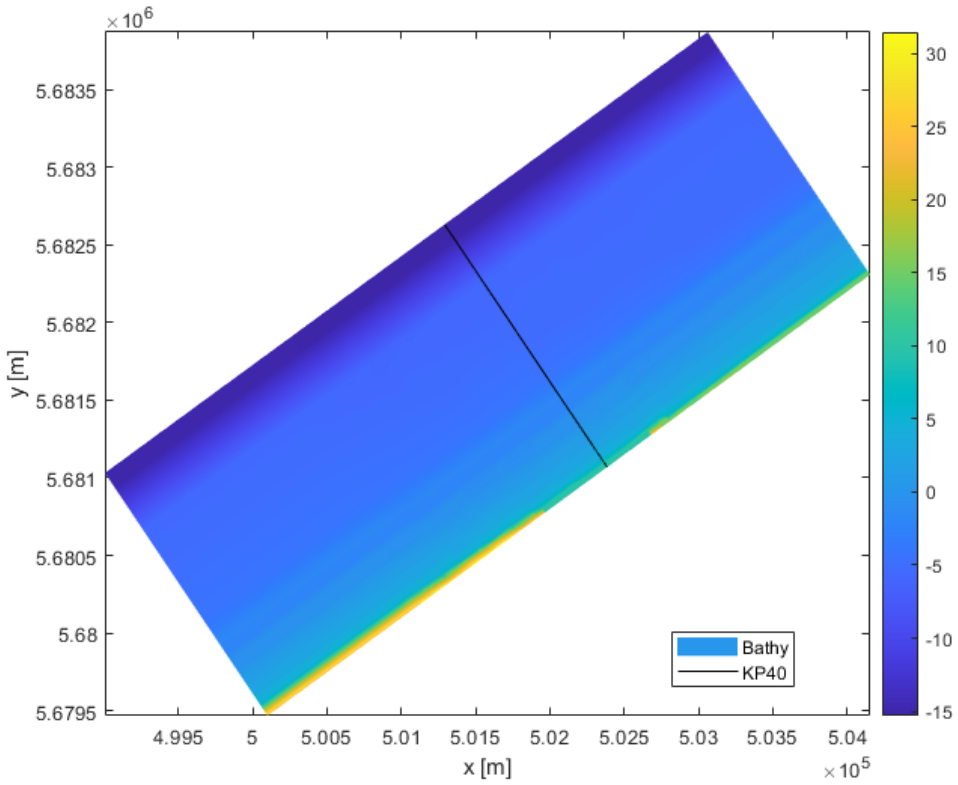


Figure 39 – XBeach: model bathymetry with indication of the KP40 profile at De Haan centrum

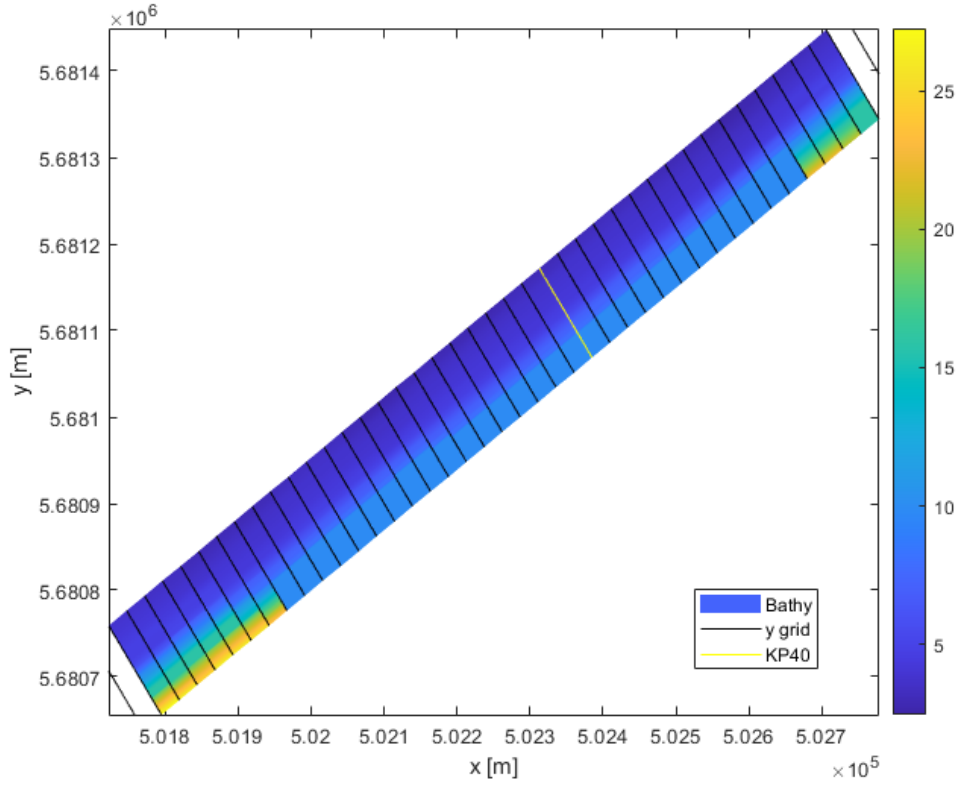


Figure 40 – Xbeach: model bathymetry: zoom on De Haan centrum, indicating alongshore resolution (black lines) and KP40 profile

5.3.3 Results and discussion

Figure 41 (left) shows the XBeach result at the location of profile KP40. The difference between the dashed line and the full black/cyan line indicates the morphological change that took place at the location because of smaller storms in the months before the stormy days (between October 1989 and February 14, 1990).

The full black line (XBeach start = “corrected” DEM just before the storm) differs from the pre-storm De Moor profile due to interpolation errors and uncertainties about the De Moor profiles. It gives a measure for the accuracy of pre storm measurement data. The same holds for the green and full blue line, both post-storm profiles. As can be seen, the erosion in front of the dike (at distance x = 1860 m) is strongly underestimated. In XBeach, a lot of sediment is deposited just in front of the dike (between x = 1800 and 1840 m). A possible reason is that the BOI settings result in too low wave-induced longshore transport. Figure 41 (right) includes the results of the 5 scenarios. Starting from a lower initial bed level or higher hydraulic boundary conditions (equivalent to a lower bed level) result in a slightly better end profile, being a lower beach. These results are however still far above the measured post-storm bed level.

Figure 42 shows the erosion volume above +5.9 m TAW for all scenarios. At De Haan centrum, this is almost equal to the measured volumes because the beach was entirely eroded above +5.9 m TAW. With regard to the dune areas, a difference of factor 2 is observed between the scenarios with higher hydraulic boundary conditions or a lowered bed level compared to scenarios without. The former scenarios seem to reflect closer the measured post-storm bathymetry. Looking to erosion above +4 m TAW however, the close resemblance disappears and the higher boundary conditions scenario being the ‘best guess’. The introduction of tide or more perpendicular waves hence only has a minor effect to the results.

Figure 43 illustrates in detail the results of two nearby cross shore profiles that significantly differ in goodness-of-fit compared to the resp. measured post-storm profiles. Again, clearly the fast depositing of sand at the toe of the dune front causes that difference.

Table 16 summarizes the Goodness-of-fit indicators for all scenarios, using the BOI VL parameter settings (‘BOI VL’ in Table 12). The ‘base’ and ‘20% higher hydraulic boundary conditions’ scenarios score the lowest values on retreat distance at the (highest) water level and erosion volume resp. and hence, are the best results. Because the scenario with higher hydraulic boundary conditions results in the closest match with the measured eroded volumes, this scenario is opted for in the final summary in Section 5.4.

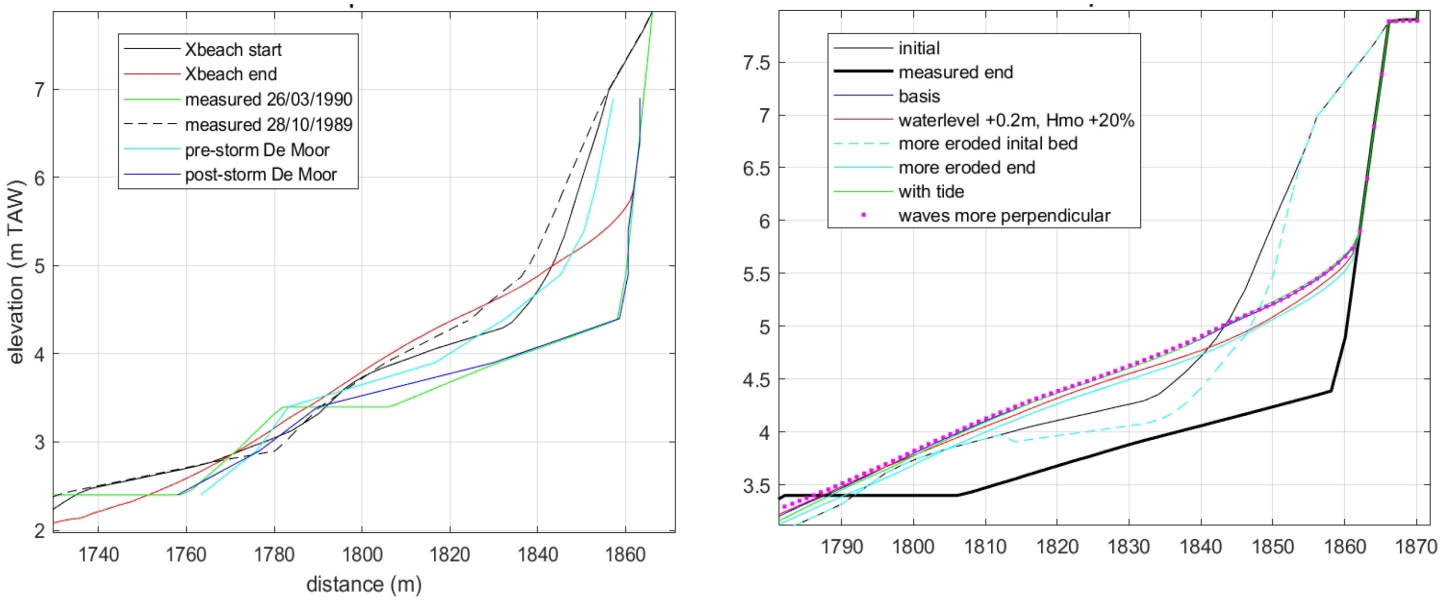


Figure 41 – XBeach result KP40 profile: basic scenario compared to measurements (left) – all scenarios (right)

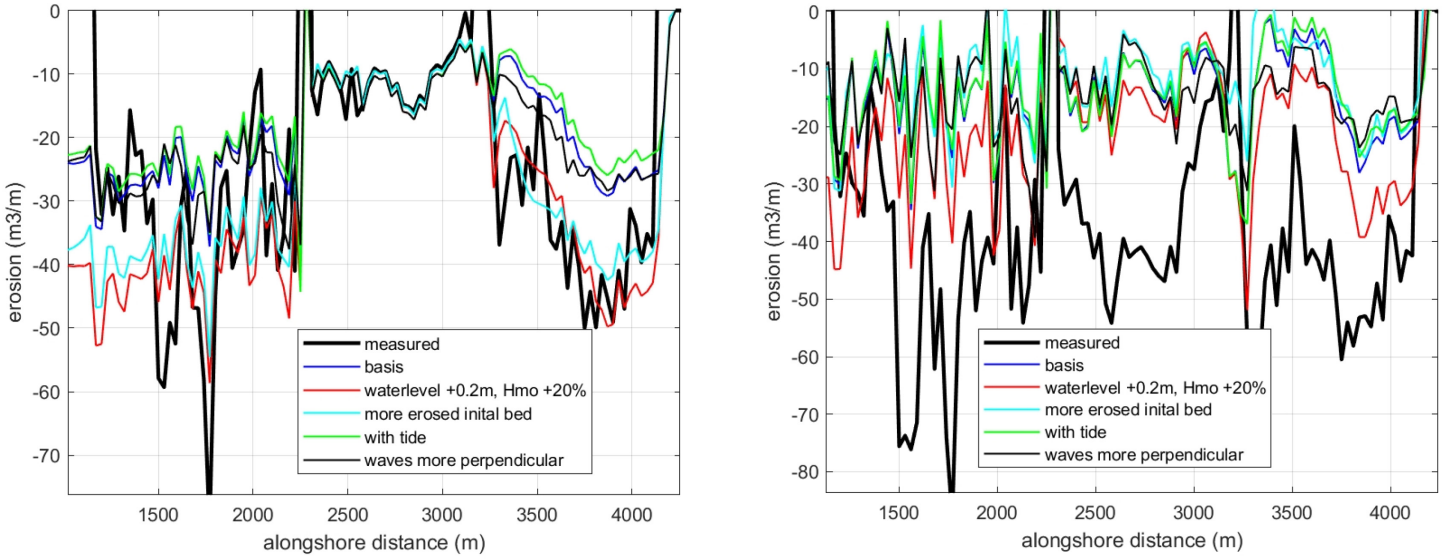


Figure 42 – XBeach result alongshore model domain: Erosion volume above +5.9 (left) and +4 (right) m TAW for all scenarios

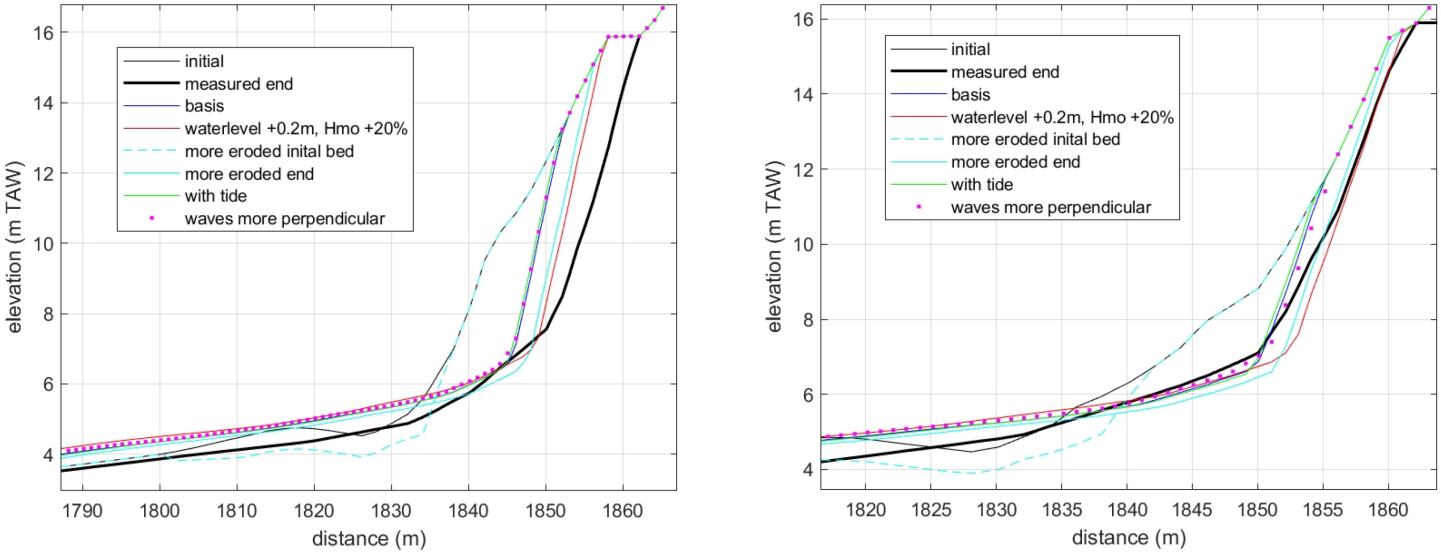


Figure 43 – XBeach results at dunes west of De Haan: 2 cross shore profiles – all scenarios

Table 16 – XBeach model performance indicators: storm february 1990 – De Haan
(Vero: erosion volume – retreat_zs: retreat distance at the max water level)

		basis	water level +0.2m, Hm0 +20%	with tide	waves more perpendicular	more eroded bed
RMSE	Vero	27.57	15.43	28.71	28.84	16.81
	retreat_zs	1.74	3.00	1.80	2.14	2.15
SI	Vero	0.53	0.29	0.55	0.55	0.32
	retreat_zs	0.21	0.36	0.21	0.25	0.25
Bias	Vero	-18.29	-6.35	-19.18	-18.92	-7.99
	retreat_zs	-0.80	-2.37	-0.79	-1.50	1.15
RB	Vero	-0.35	-0.12	-0.37	-0.36	-0.15
	retreat_zs	-0.09	-0.28	-0.09	-0.18	0.14

To get a feeling about the alongshore velocities, a comparison of the alongshore velocity and sediment transport between XBeach BOI and the older XBeach Kingsday (with the same BOI VL settings) was made (Figure 44). This alongshore transport might (!) (only if gradients occur) erode the deposited sediment, explaining the overestimated beach level below +6 m TAW in the model results. Or the higher current velocities might bring a lot of sediment in suspension.

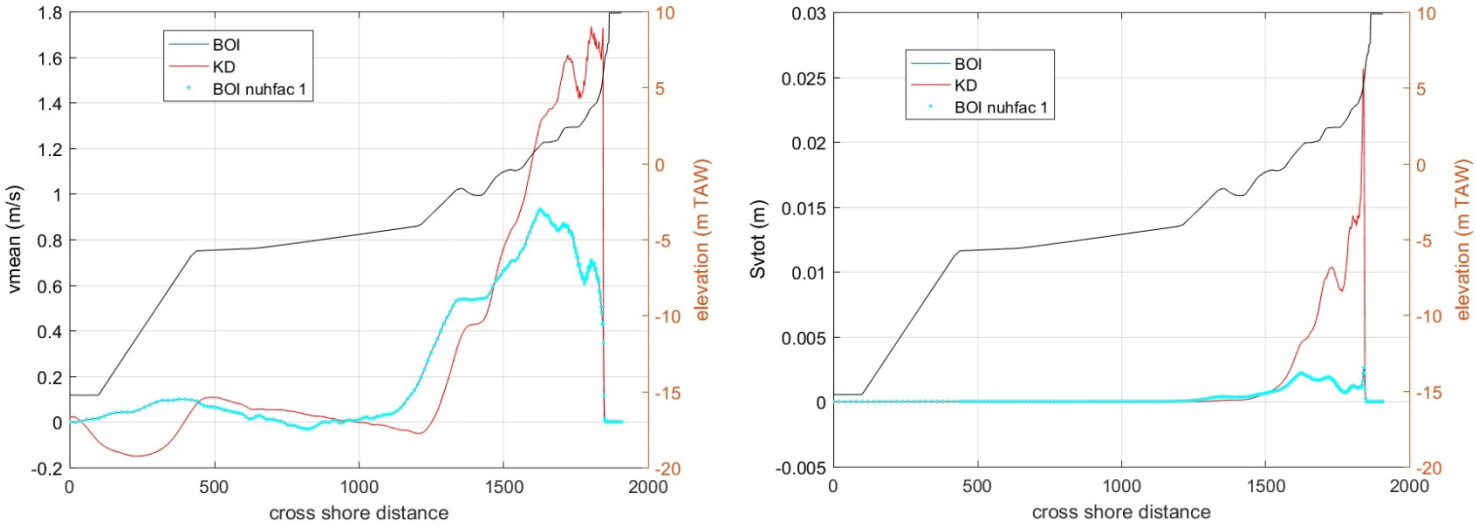


Figure 44 – XBeach post-storm KP40 profile: comparison of longshore velocity (left) and sediment transport (right) between XBeach BOI and Kingsday

5.4 Summary and conclusion

Focusing on the Belgian coast, XBeach model performance is best when BOI settings with a slightly lower *wetslp* = 0.1, 'BOI VL', are used (cf. Table 12. Table 17 summarizes the model quality using the results of storm Xaver at the Belgian coast and the February 1990 storm.

The estimation of erosion volume and retreat distances resulted in a relative bias of -0.0041 and -0.041 resp., indicating that the structural error on these results is negligible. The scatter index, being a measure of the model's uncertainty, is resp. 0.30 and 0.14.

Table 17 – Xbeach model performance indicators: summary for Belgian coast
(Vero: erosion volume – retreat_zs: retreat distance at the max water level)

	Vero	retreat_zs
RMSE	7.36	0.87
SI	0.30	0.14
Bias	-0.099	-0.25
RB	-0.0041	-0.041

6 XBeach BOI: Model settings for SA21

Based on the sensitivity analysis and model validation of XBeach BOI, a SA21 methodology with specific parameter settings was developed.

6.1 XBeach: model set-up

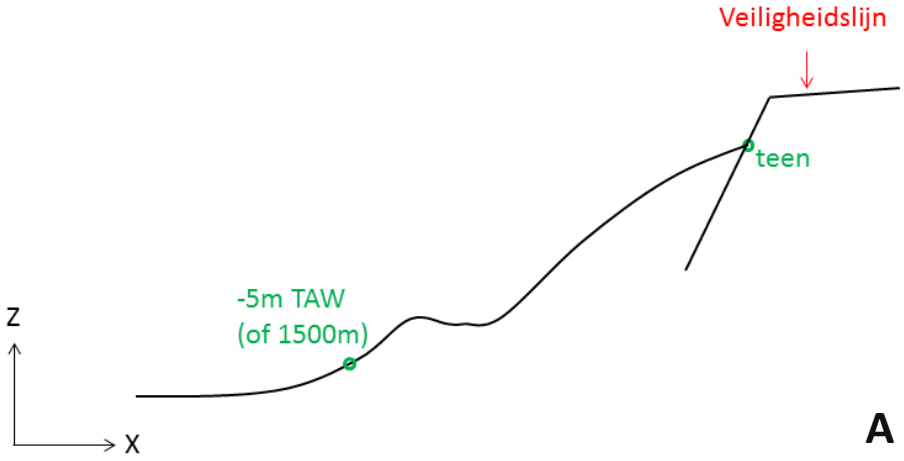
A digital elevation model, based on the to-date (spring 2021) situation of the coastal defence, is the bathymetric base to built the XBeach model domains. Alongshore subdivision of the coastal defence in adequate model domains is done based on median grain size and type of coastal section.

The model domain is oriented in such a way that perpendicular wave attack can easily be modelled; i.e. the offshore boundary is parallel to the coastline. The model domain and its alongshore and cross shore grid resolutions however, need to be defined according to following methodology.

6.1.1 Grid resolution

First: take a look to both the offshore and land area of the model domain (Figure 45):

- Identify the output points
- Determine the position of the -5 m TAW contour (or distance of 1500 m out of the coast) Note that, if multiple -5 m TAW contours are present, the most seaward one needs to be taken (Figure 45B), or if the seaward boundary lies above -5 m TAW, this seaward boundary is used as the (initial) seaward limit of the model domain (Figure 45C).
- Determine the position of the safety line



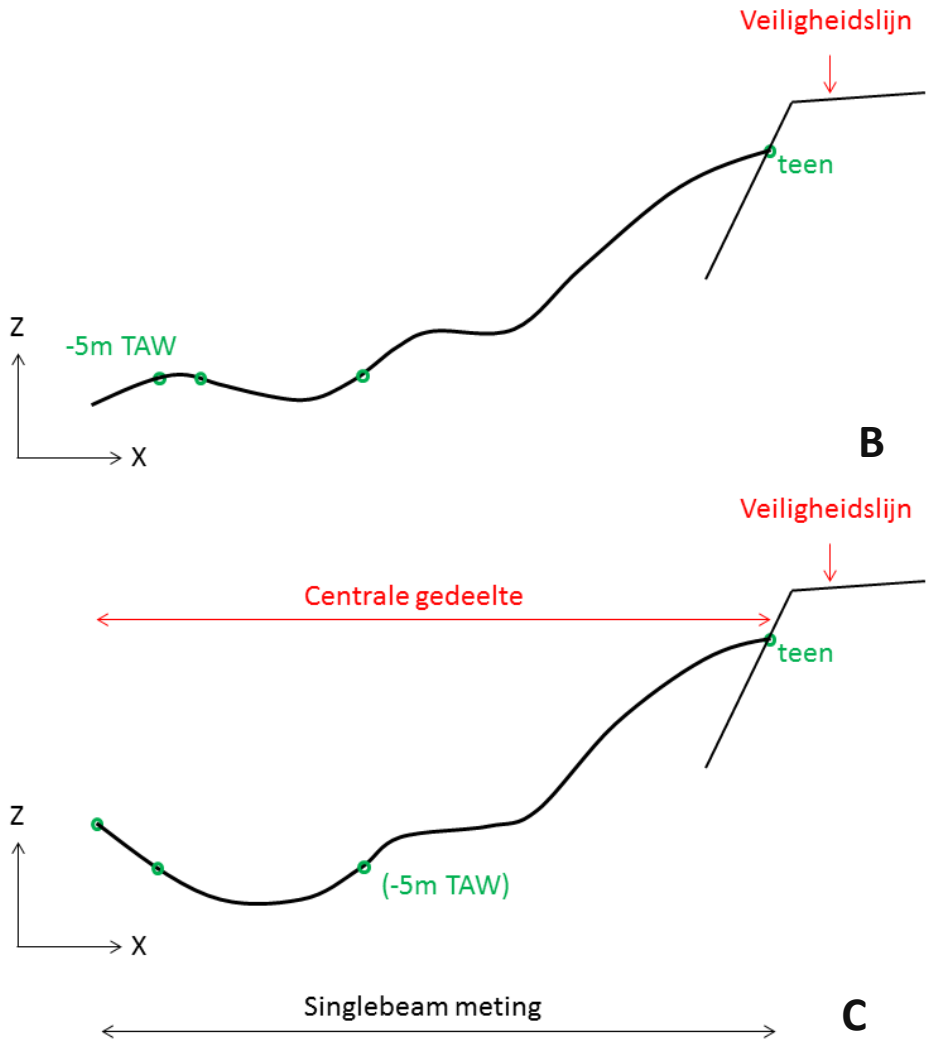


Figure 45 – XBeach model set-up: identifying the offshore and land boundaries

Optimise the varying cross shore resolution considering:

- At least 40 points per wavelength in deeper water
- Maximum grid size dx of 1 m in the expected active erosion area
- Maximum grid size dx of 2 m in dunes
- Smooth transition between varying grid sizes

Optimise the varying alongshore resolution considering:

- Maximum grid size dy of 20 m
- Maximum grid size dy of 10 m near transitions between a dune and a dike (at least 100 m at both sides)
- Exceptionally: grid size dy of 2 m when (3D) geometric features require a higher resolution (e.g. a dune passage)
- Smooth transition between varying grid sizes

6.1.2 Model domain

Extend the model domain seaward to –15 m TAW under a negative slope of 1/35, and add at least 100 m of horizontal seabed at –15 m TAW (Figure 46).

Extend the model domain landward of the safety line with at least 100 m of the actual topography, ending with (at least) 3 grid points having the same bed level (Figure 46).

Extend the model domain laterally by 250 m of actual bathymetry and 1000 m of artificial bathymetry, gradually increasing the alongshore resolution (dy) up to 100 m. The bathymetry of these artificial extensions is a copy of the original lateral boundaries (e.g., coastal section 99 + 250 m and coastal section 107 + 250 m) (Figure 47).

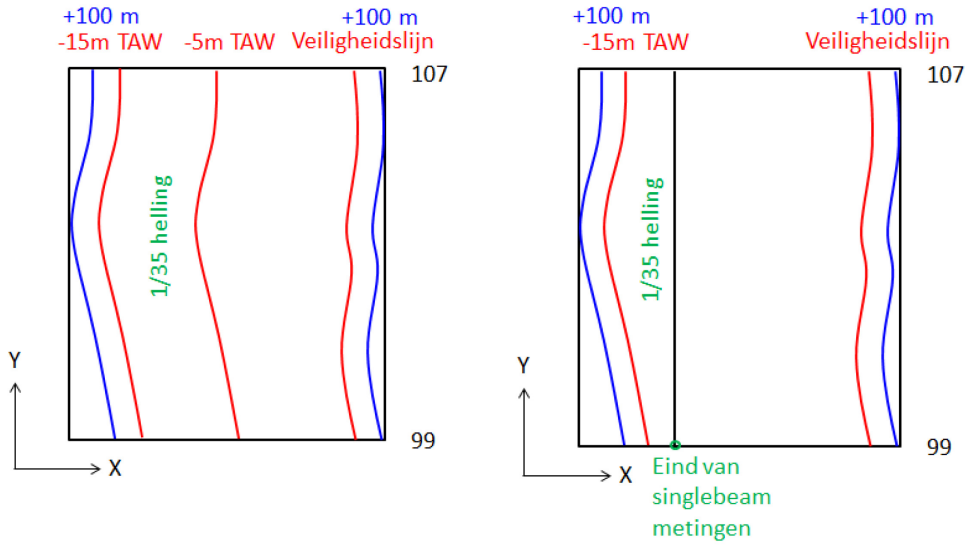


Figure 46 – XBeach model domain: indication indication of sea- and landward model boundaries

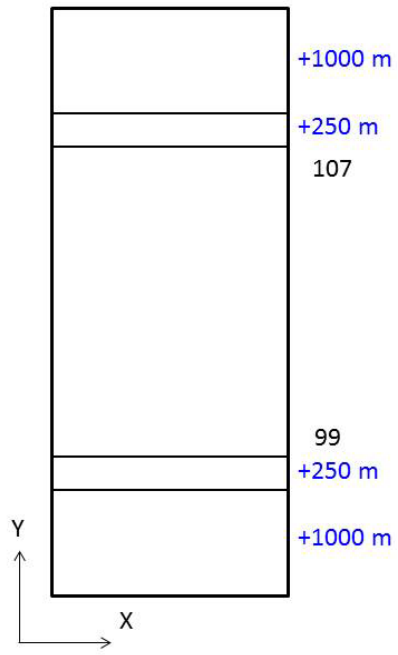


Figure 47 – XBeach model domain: indication of lateral model boundaries

6.2 XBeach: model settings

In the 2021 Coastal Safety Assessment, XBeach version: XBeach BOI, revision 5922, needs to be used with the predefined parameter settings and values listed in Table 18. (McCall et al., 2021, 2022). Parameters/functions not listed are either not activated or used with default values. Note that the table below also includes some parameters with their (presumed) default values; it is advisable to verify these values. In Appendix 2, an example of an input *params* file can be found.

Parallel computing is allowed.

Table 18 – XBeach BOI rev5922: SA21 parameter settings

wavemodel = surfbeat	Hydrostatic modelling
D50 D90	Grain size of resp. D_{50} and D_{90}
nx	Number of cross shore grid points
ny	Number of along shore grid points
vardx = 1 posdown = 0	Varying cross shore grid resolution
xfile = x.grd yfile = y.grd depfile = bed.dep ne_layer = nebed.dep	Name of input files
struct = 1	If a hard layer is present
thetamin thetamax dtheta = 140	Directional lower and upper limits; the angle between both parameters must be 140° (= dtheta), the value to be entered (in [°]) depends on the main wave direction. (In principle, the parameter “dtheta” does not need to be entered; it is calculated automatically if single_dir=1)
single_dir = 1 dtheta_s = 10	Average main wave direction is periodically determined, waves are propagated in that direction (in order to preserve wave groupiness).
random = 0	No random (run specific) wave generation
tstart = 0 tstop = 165600	The start and end times of a simulation, including a one-hour warm-up period
morstart = 3600	Morphological processes are initiated after one hour of computation time

bedfriction = manning bedfriccoef = 0.02	Bottom friction according to Manning formula
nuhfac = 0	Factor to include roller induced turbulent horizontal viscosity
wbctype = jonstable nspectrumloc = x bcfile = loclist.txt	Wave boundary conditions are time dependent JONSWAP spectra x indicates the number of locations having wave boundary conditions; their coordinates are included in the 'loclist.txt' file
tidetype = hybrid epsi = -1	Formulation of tidal boundary conditions Ratio of average flow to time dependent flow at the offshore boundary
zs0file = getij.txt tideloc = 2 paulrevere = land	Input file with tidal boundary conditions A tidal time series is imposed at two locations, at the offshore and landward boundary of the model (cf. paulrevere)
break = roelvink_daly gamma = 0.46 gamma2 = 0.34 alpha = 1.38	Short wave breaking according to Roelvink Daly formulation Breaker parameter End of wave breaking parameter Wave dissipation coefficient
beta = 0.08	Breaker slope coefficient in roller model
deltahmin = 0.1	Dimensionless coefficient to determine the threshold water depth above which stokes drift is included
wbcEvarreduce = 1 wbcScaleEnergy = 1 wbcRemoveStokes = 1	Reduction factor of short wave group variance at the boundary Switch to correct random time series of wave height to exactly match input Hm0 Switch to remove long wave Stokes drift component at the offshore boundary
sedtrans = 1 morphology = 1	Sediment transport and morphological processes are switched on
form = vanthiel_vanrijn	Equilibrium sediment concentration formulation according to Van Thiel – Van Rijn transport equations

waveform = vanthiel facSk = 0.15 facAs = 0.20	Wave non linearity taken into account using the Van Thiel de Vries formulation Calibration factors time averaged flows due to wave skewness and wave asymmetry resp.
alfaD50 = 0	Calibration term for grain size dependency
wetslp = 0.10 Hswitch = 0	Critical avalanching slope under water Water depth where switch from dryslp to wetslp is made (and vice versa)
fixedavaltime = 0 nTrepavaltime = 1	Speed for bed level update due to avalanching is limited to a maximum speed, defined by a characteristic time and length scale (dependent on wave period). It is proportional to the number of wave periods (Trep) in the nTrepAvaltime parameter
oldTsmin = 0 dtlimTs = 5 oldhmin = 0	Use is made of dtlimts to determine the numerical limiter of the adaptation time (instead of the old tsmin parameter) Number of numerical time steps for minimum adaptation time scale for sediment concentration Use is made of deltahmin to determine threshold water depth (instead of the old hmin parameter)
eps = 0.005 eps_sd = 0.5	Threshold water depth above which a cell is considered to be wet Threshold velocity difference to determine conservation of energy head versus momentum

6.3 XBeach: model output and post-processing

The simulation duration is 45 hours.

The purpose of the XBeach modelling is to determine the bed profile during and as a result of the design storm surge. To this end, hourly output is requested for several global and mean variables: H, ue, ve, zs, zb, qx, thetamean.

▪ Model uncertainty

On a post storm eroded profile, model uncertainty is accounted for by adding 15 % to the modelled erosion volume above the calculation water level (McCall *et al.* (2022).

This surcharge causes a landward shift of the post storm eroded profile, limited to a maximum cross shore shift of the dune foot of 15 m (Boers, 2012). If the crest of the post storm eroded profile Xe is below +8 m TAW (e.g. beach in front of a dike), the surcharge should not be taken into account.

▪ **Wave overtopping**

XBeach is primarily used to calculate dune and beach erosion during and after the design storm surge. However, the model can also provide wave overtopping at given output time step(s) (parameter qx_mean).

o dunes with a dune toe protection without habitation

The grid cell landward (or close by) the crest of the remaining dune volume seaward of the safety line is the position that should be used to determine the wave overtopping. The overall maximum of time-dependent wave overtopping discharges is then the average wave overtopping for this coastal section. This maximum qx_mean value should be reported.

o dunes with a dune toe protection including habitation, and dikes

The average wave overtopping q must be determined at the position of the safety line Xv. The overall maximum of time-dependent wave overtopping discharges is then the average wave overtopping for this coastal section. This maximum qx_mean value should be reported.

7 SA21: special case in dunes of De Panne

During the 2021 Coastal Safety Assessment, a conflicting feature related to 3D physical processes was found in a low lying area of the dunes at De Panne.

7.1 Sports ground at De Panne

In coastal section 8, a sports ground is located in between the first, relatively low, dune belt and the residential area. Next to it, a low dune passage is located connecting the residential area with the beach; its highest level being at +9.8 m TAW (Figure 48).

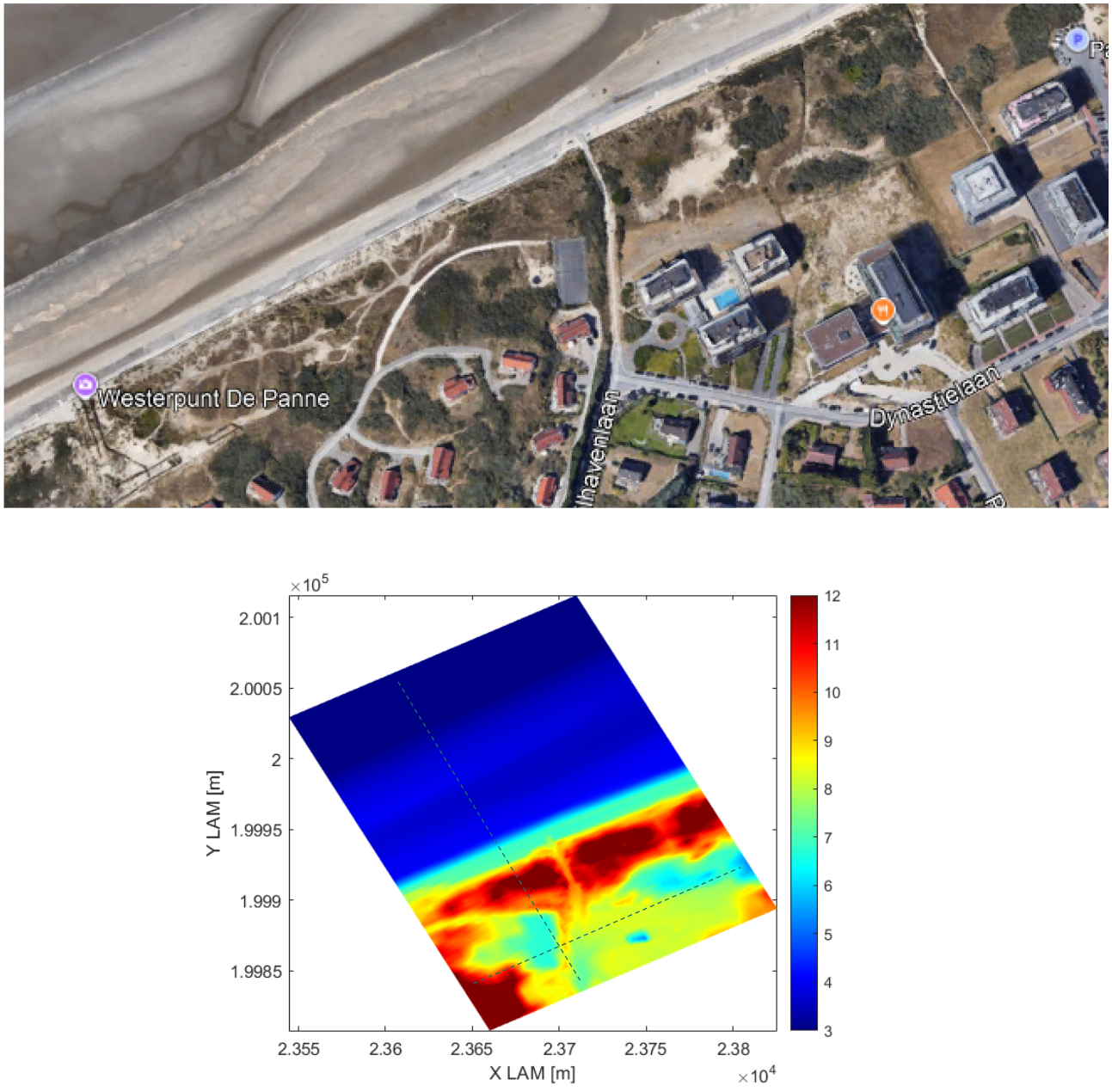


Figure 48 – Location of the sports ground in the dunes of De Panne: Google Earth image and XBeach model bathymettry (W+B, 2023): dashed line indicates cross shore and alongshore profiles of Figure 49)

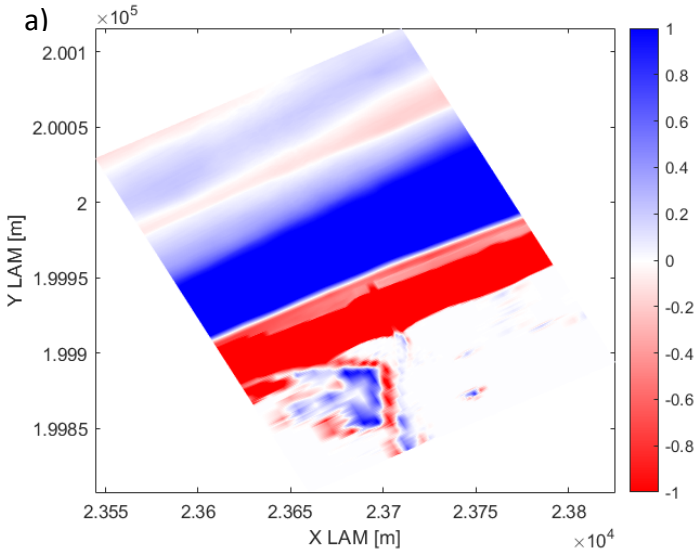
Carrying out XBeach modelling using the settings listed in Section 6.2 led to an unrealistic failure mechanism around the sports ground – in what follows, the erosion and sedimentation processes are summarized (Figure 49a):

> During the second (and highest) high tide of the 45 h lasting storm surge, the first dune belt to the northwest of the sports field breaches and water flows towards and on the sports field, leading to erosion of (part of) its adjacent berms. Because of the berms' erosion, water flows further inland. The sandy volume being eroded from the berm settles on the sports ground increasing its bottom level. The water stagnates on the sports field at around 0.8 m water depth between the second and third high tides, rising to 1 m water depth as a result of the third, and last, high tide of the storm surge.

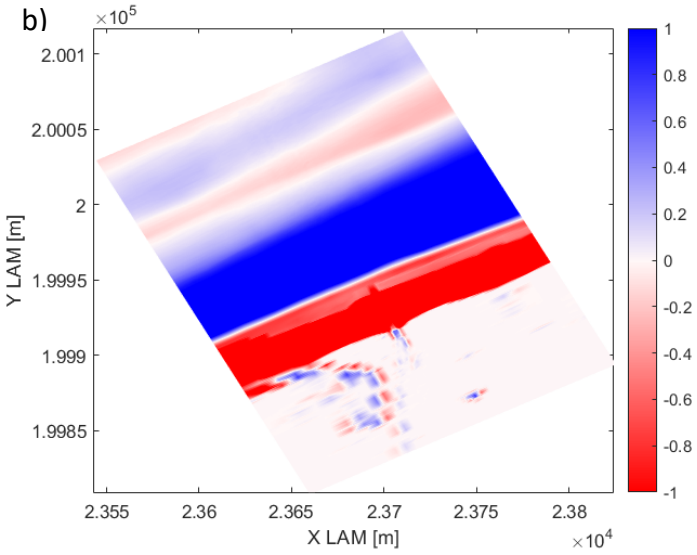
Figure 49c illustrates in detail the morphological changes in a cross section at the sports ground during the 45 h storm surge. During the first high tide only the dune foot is attacked by waves while the second (and highest) high tide results in waves overtopping the first dune belt, eroding its crest until +11 m TAW. The water level rises from 0.8 to 1 m water depth on the sports ground on the third high tide, eroding the landward berm of the sports field and further landward water flow.

Figure 49e illustrates in detail the morphological changes in an alongshore section at the sports ground during the 45 h storm surge. During the second high tide water flows onto the sports field and causes the slumping of the berm at both sides, leading to overflow over the berm to the right.

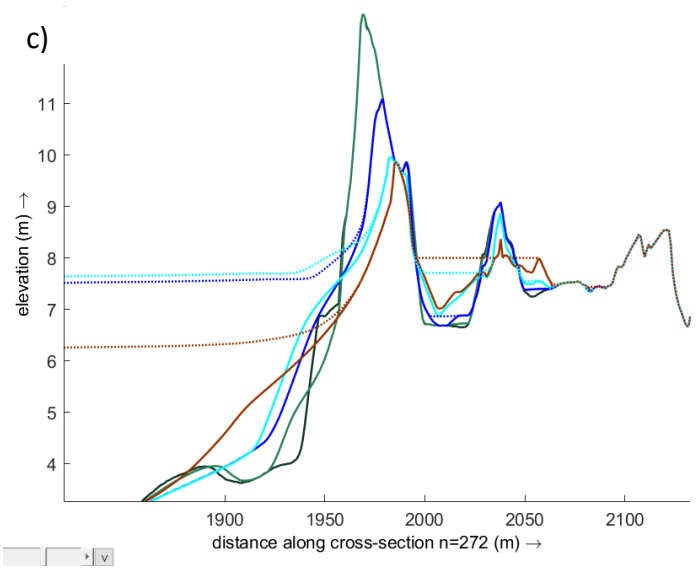
These erosion phenomena are the result of the parameter *wetslp*, which adapts the dune slope towards the (validated) equilibrium slope of 0.1 upon wave attack. However, in this particular situation it has the (negative) side effect of slumping the sports ground's berms as water stagnates on the field (and hence, cells are wet). To overcome this issue, a simulation was carried out using a *wetslp* value of 0.15. As can be seen in Figure 49b, d and e, a small increase of the wet equilibrium dune slope led to less erosion of the berms being a more likely situation.



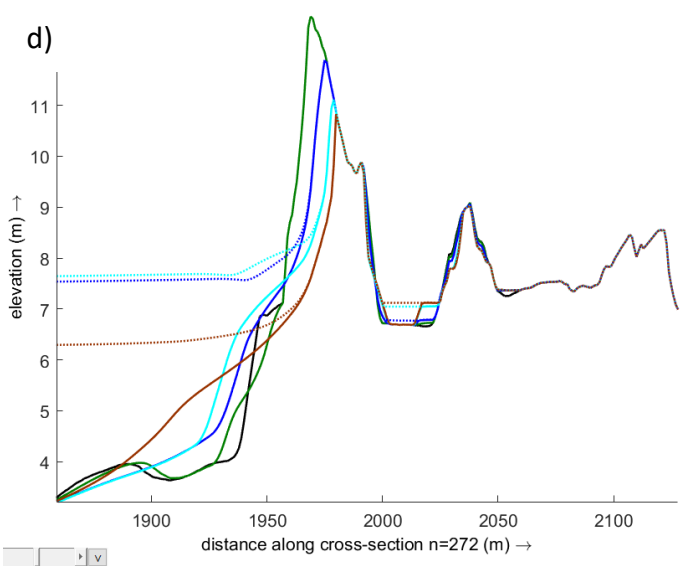
Post storm sedimentation and erosion – *wetslp* = 0.10 (red: erosion – blue: sedimentation)



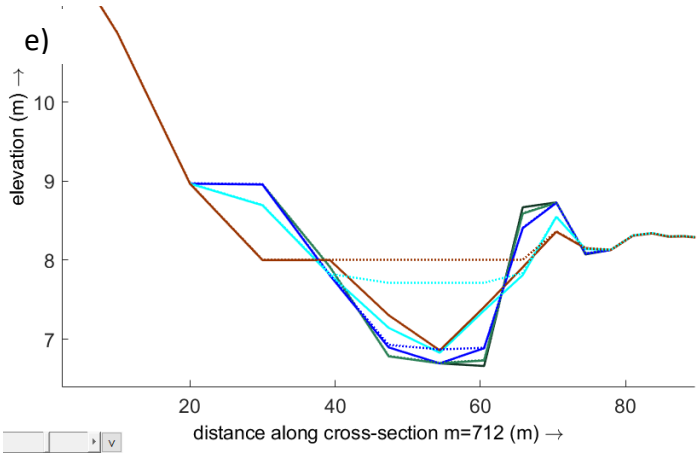
Post storm sedimentation and erosion – *wetslp* = 0.15 (red: erosion – blue: sedimentation)



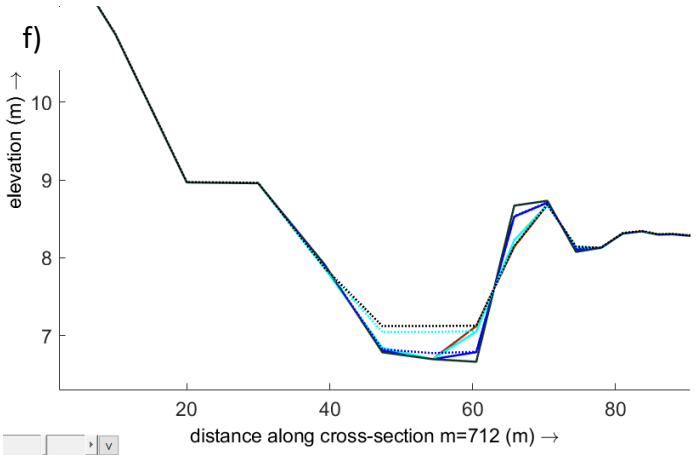
Cross shore (normative) profile – *wetslp* = 0.10 (profile and water level (dotted line) at t = 0, 7, 19, 20 (around highest high tide HW2), 31 h (around high tide HW3) since start of storm surge in black, green, blue, cyan and brown resp.)



Cross shore (normative) profile – *wetslp* = 0.15 (profile and water level (dotted line) at t = 0, 7, 19, 20 (around highest high tide HW2), 31 h (around high tide HW3) since start of storm surge in black, green, blue, cyan and brown resp.)



Alongshore profile at the sports ground – *wetslp* = 0.10 (profile and water level (dotted line) at t = 0, 7, 19, 20 (around highest high tide HW2), 31 h (around high tide HW3) since start of storm surge in black, green, blue, cyan and brown resp.)



Alongshore profile at the sports ground – *wetslp* = 0.15 (profile and water level (dotted line) at t = 0, 7, 19, 20 (around highest high tide HW2), 31 h (around high tide HW3) since start of storm surge in black, green, blue, cyan and brown resp.)

Figure 49 – XBeach results: left subfigures: wetslp = 0.1 – right subfigures: wetslp = 0.15

8 Conclusion

Since the 2015 Coastal Safety Assessment, XBeach is applied for the morphodynamic modelling of the normative storm conditions. Being under continuous development, a further validation of the newest XBeach version was necessary upon use in the 2021 Coastal Safety Assessment (SA21).

A thorough sensitivity analysis learned about the differences between the released XBeach versions. Some physics got integrated or improved and the model's architecture was adjusted at some points. Based on a (limited) model validation, it was found that the BOI settings, calibrated in the framework of the methodology update of the Dutch Coastal Safety Assessment, are also suitable for use along the Belgian coast. Only the *wetslp* parameter, determining the critical avalanching slope under water, was slightly lowered to 0.10 (instead of 0.15). It implies that avalanching occurs somewhat faster. No structural bias was found in the model's performance and the scatter index was acceptable, being 0.14 and 0.30 for the modelled retreat distance and erosion volume respectively.

The XBeach model set-up and settings for the 2021 Coastal Safety Assessment are now based on the validated 2DH application of XBeach as described in this report. For this assessment, the entire Belgian coast will be divided into 28 coastal areas. For each of these coastal areas, the morphodynamic response to a 45-hour normative storm will be assessed and the safety level will be evaluated.

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Appendix 1 Extra figures of morphological response of simplified dune and dike profiles

Figure 50 – Beach profiles at the end of the storm for the 1/30 beach slope

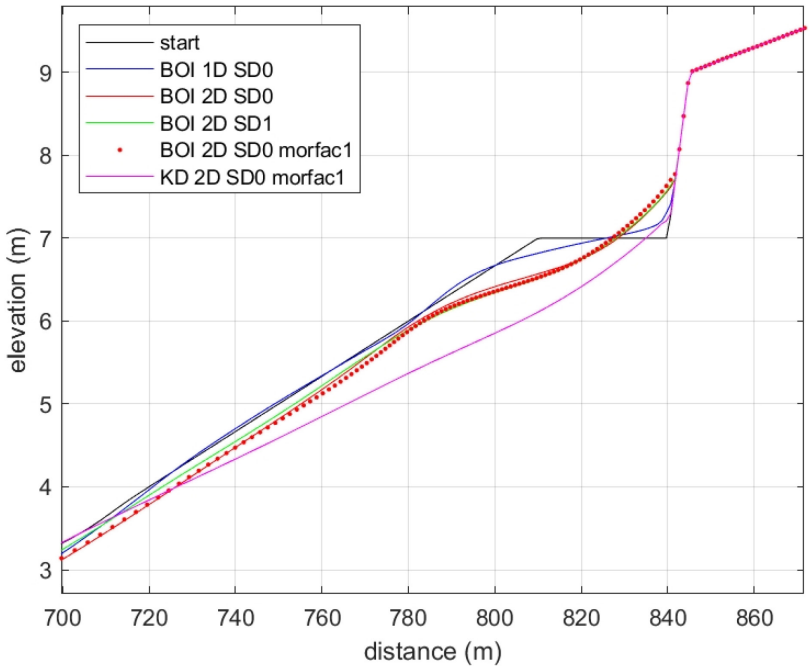


Table 19 – Results for Dike with beach slope 1/30

XBeach Version	*single_dir*	morfac	net erosion above +6 m TAW (m^3/m)	gross erosion above +6 m TAW (m^3/m)
BOI 1D	0	3	4,80	7,14
BOI 2D	0	3	15,39	19,75
BOI 2D	1	3	15,68	20,09
BOI 2D	0	1	14,67	19,71
KD	0	1	34,55	35,17

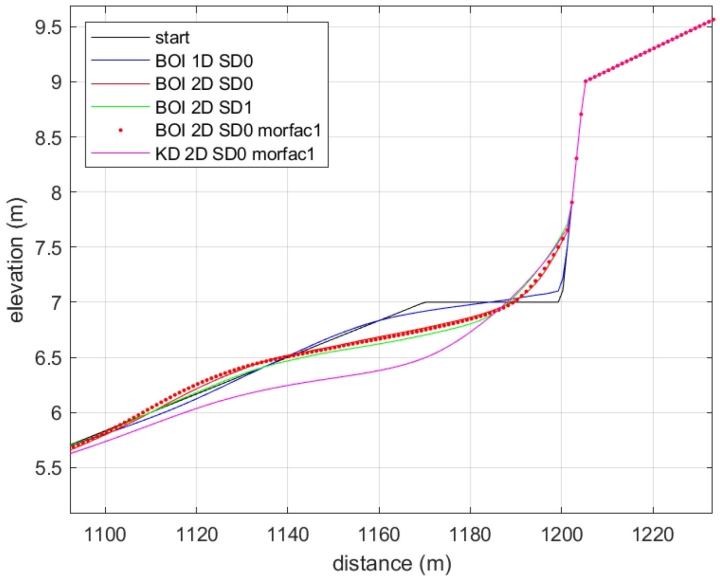


Figure 51 – Beach profiles at the end of the storm for the 1/60 beach slope

Table 20 – Results for Dike with beach slope 1/60

XBeach Version	*single_dir*	morfac	net erosion above +6 m TAW (m^3/m)	gross erosion above +6 m TAW (m^3/m)
BOI 1D	0	3	1,69	3,09
BOI 2D	0	3	8,15	12,28
BOI 2D	1	3	10,34	15,10
BOI 2D	0	1	5,36	9,68
KD	0	1	24,90	29,29

Appendix 2 Example of input file params.txt

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% XBeach parameter settings input file                         %%%
%%%                                                             %%%
%%% date:                                                       %%%
%%% function: xb_write_params                                   %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
wavemodel       = surfbeat
%%% Bed composition parameters  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
D50         = 0.000207
D90         = 0.000311
%%% Flow parameters  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
tidetype = hybrid

bedfriction = manning
bedfriccoef = 0.02

nuhfac=0
%%% General %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
deltahmin     = 0.10
fixedavaltime = 0
oldTsmin      = 0
oldhmin       = 0
random = 0
wbcEvarreduce = 1
wbcScaleEnergy = 1
wbcRemoveStokes = 1
%%% Flow boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
epsi        = -1
%%% Grid parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
depfile     = bed.dep
posdwn      = 0
nx          = 462
```

```
ny          = 247
vardx       = 1
xfile       = x.grd
yfile       = y.grd
thetamin    = -127
thetamax    = 13
dtheta      = 140
single_dir=1
dtheta_s=10
%%% Model time %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
tstop       = 165600
%%% Morphology parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
morstart    = 3600
wetslp      = 0.100
struct      = 1
ne_layer    = nedep.dep
%%% Roller parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
beta        = 0.08
%%% Sediment transport parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
waveform  = vanthiel
facSk       = 0.15000
facAs       = 0.20000
bulk = 0
alfaD50 = 0
%%% Tide boundary conditions %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
zs0file     = getij.txt
tideloc     = 2
paulrevere   = land
%%% Wave breaking parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
break        = roelvink_daly
gamma        = 0.460000
gamma2       = 0.340000
alpha        = 1.380000
%%% Wave-spectrum boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%
wbctype      = jonstable
nspectrumloc = 11
```

```
bcfile      = loclists.txt
%%% Output variables %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
outputformat = netcdf
tintm       = 3600
tintg       = 1800
tstart      = 0

nglobalvar   = 6
H
ue
ve
zb
zs
thetamean

nmeanvar     = 7
H
ue
ve
zs
zb
thetamean
qx
```

DEPARTMENT **MOBILITY & PUBLIC WORKS**
Flanders hydraulics

Berchemlei 115, 2140 Antwerp
T +32 (0)3 224 60 35
F +32 (0)3 224 60 36
flanders.hydraulics@vlaanderen.be
www.flandershydraulics.be