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SOLUTIONS FOR *SMART* FLOOD CONTROL

MODELLING STORM IMPACT ON COMPLEX COASTLINES: TEST-CASE WESTKAPELLE

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MANAGEMENT SUMMARY

Regular dune safety assessments in the Netherlands are presently based on a 1D model approach, which is insufficiently applicable for more complex coastal areas with structures, tidal channels or spatially strong varying bathymetry. These require more advanced methods to assess the safety in dune areas. In this study a 2D XBeach model [Roelvink et al., 2009] is applied as a demonstration for a complex coast and comparison is made with results obtained from a 1D model approach, using 1D XBeach and 1D DurosTA [Steetzel, 1993]. In addition a series of simulations is performed with super-storm conditions that result in dune breaching and flooding events. In this sense a first approach towards coastal 'hazard indicators' and 'hazard maps' is made.

This study focussed on the coastal area near Westkapelle, since this location is considered to be 'complex' for regular safety assessment studies. The near-shore zone is characterized by a (spatially) strongly varying bathymetry, due to the presence of tidal flats and channels, and a strongly curving coastline. Moreover, the Westkapelle area is protected by both coastal structures and sandy dunes, such that transition zones exist, which are difficult to assess. In this project it is demonstrated that a 2D model approach enables detailed analyses of the effects of alongshore processes on (dune-) erosion processes. A comparison with a 1D approach is made based on simulations for normative storm conditions and several settings for the angle of main wave attack.

Simulations of super-storm conditions showed the effects of processes related to dune breaching and flooding events. In this project, several types of landward boundary settings are tested in order to study their impact on the simulated inundation areas and flow characteristics, after a dune breaching event. Based on one of the model runs that resulted in flooding, examples are presented of so-called hazard maps that indicate possible safety issues along the coastline. As output of an Operational Model System (as developed in a parallel research-project) these hazard maps are useful for end-users to monitor the current state of coastal stretches, in order to identify threats in early stages.

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1 INTRODUCTION

1.1 BACKGROUND

In the Netherlands sandy dunes are an integral part of the sea defences that protect the hinterland from flooding. For the sandy coastlines safety assessments are required on a regular basis since the morphology of dunes and foreshore is highly dynamic. For the Dutch coast these assessments are performed by applying relatively simple calculation methods for dune erosion, which are extensively validated with physical scale models. The methods are based on a 1D approach and applied to a large number of predefined transects along the coastline. However, the applicability of the currently used approach for safety assessments is limited when considering more complex coastlines. Therefore, in this study the possibilities of a more sophisticated 2D model approach are examined.

In the following sections a brief introduction is presented on several aspects of safety assessments for the Dutch sandy coastal areas. Starting with the 1D approach, then the alternative: a 2D approach, and subsequently followed by a quick view on coastal safety indicators in relation to an Operational Model System for the (Dutch) coast.

1.1.1 1D approach for safety assessments

The 1D dune erosion approach is used as a quick and well-supported way to monitor the state of the sea defences along the coastline. Yearly-measured bathymetry along a large number of so-called JarKus transects provide (reasonably) up-to-date input for dune erosion modelling and the related safety assessments. The 1D approach for these safety assessments works particular well for coastal stretches with a gently sloping foreshore and a more or less alongshore uniform bathymetry, which correspond to the assumptions inherent in underlying laboratory tests.

The Dutch coast, however, (also) consists for a significant part of more complex coastal areas, with for example the presence of strongly curved coastlines, deep near-shore tidal channels, or transitions between dikes and dunes. In those complex situations the applicability of a 1D approach is doubtful, since by definition no alongshore effects are considered (or, only incorporated in a very schematized manner).

In Figure 1 an overview is presented which indicates whether the results of 1D dune erosion models are expected to be valid for certain areas along the Dutch coast. For the largest part of the central 'Holland Coast' (except the locations with coastal structures) the simple 1D dune erosion models are applicable since the foreshore is gently sloping and alongshore uniform. However, for the 'Wadden Coast' in the northern part of the Netherlands and the 'Delta Coast' in the south-west more complex, spatially varying foreshores are found, which impedes a straightforward application of 1D models. Deltares conducted that up to 40% of the dunes cannot or should not be assessed with a 1D model approach.

1.1.2 2D approach for safety assessments

For areas with complex coastlines a 2D approach might be a more suitable alternative to determine possible safety issues during (normative) storm conditions. The use of 2D dune erosion models enables a more sophisticated method to incorporate near-shore hydrodynamics and morphodynamics due to alongshore variations in bathymetry, wave field or flow velocity. These processes could have a significant effect on the amount of dune erosion and it is therefore important to account for these aspects during safety assessments.

This study focuses on the actual application of a 2D numerical dune erosion model for a so-called 'complex' coastal area along the Dutch coast. The simulation of normative storm conditions in a 2D model domain will demonstrate the advantages of a more advanced approach for dune erosion modelling.

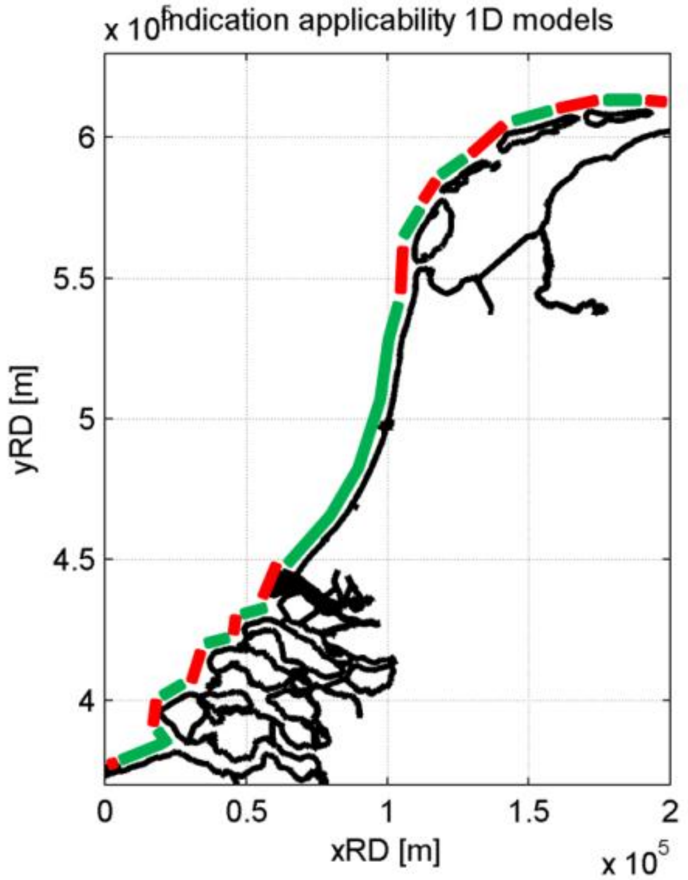

Figure 1: Indication of areas where 1D approach for dune erosion models are applicable (green) / are not applicable (red). The distinction is made based on the complexity of the foreshore bathymetry.

1.1.3 Indicators for coastal safety in Operational Model System

Most of the policymaking related to sea defences is based on the regular safety assessments for sandy coasts, which are performed in the Netherlands each five years (till present day) or six years (from now on). For local (or/and regional) authorities and administrators, who are responsible for the maintenance of the sandy sea defences, a more continuous monitoring approach is preferred such that possible safety issues are detected at earlier stages, and flood prevention can be established adequately.

A parallel project within this working-package of the project 'Real-time Safety on Sedimentary Coasts' (Flood Control 2015 program) focuses on the development of an Operational Model System (OMS) for (a part of) the Dutch coastline. An innovative step would be to combine the OMS with real-time monitoring (and prediction) of the safety against flooding. In order to integrate safety assessments in an operational system *safety indicators* are required.

The 2D approach for safety assessments of the sandy coastal areas is closely related to these *safety indicators*, since in both cases the focus lies on the spatial development of the dune area during severe storm conditions. Within this study a first attempt is made to translate the (spatial information of the) results of dune erosion models in useful safety indicators and subsequently in 'hazard maps' for the end-users.

1.2 OBJECTIVES

The main objective of this study is to demonstrate the use of a 2D model approach for a complex coastal area. New insights *due to* the consideration of dune erosion along spatial varying coastlines can be expected and will be described and compared to earlier findings. In addition comparisons are made to 1D model results and the pros and cons of both approaches will be described.

Moreover, a first step is made in the coupling of physical model output to useful safety indicators for end-users, by means of so-called ‘hazard maps’. This last point of interest is defined as a secondary objective for this project and will receive more attention in subsequent projects.

1.3 RESEARCH METHODOLOGY

The key focus of this study is on the 2D (XBeach) modelling of storm impact on complex sandy coastlines. Especially a demonstration of the abilities of such a model approach is considered as well as a comparison with the more traditional 1D approach for safety assessments of sandy coasts. In order to achieve the prescribed goals of this research project several crucial steps are defined to steer the progress.

As a first step a suitable location is selected for the application of a 2D dune erosion model. Since the 1D model approach loses its validity for coastal areas with complex, alongshore varying bathymetry, this is exactly the type of area which fits the profile for this study. After selecting a location that is characterized by complex features, a 2D morphological XBeach model is set-up [Roelvink et al., 2009]. This model is fed by gathered information about bathymetry, coastal structures, hydraulic conditions, etc.

Subsequently a large series of 1D dune erosion models is set up, for comparisons with the 2D model. The cross-shore profiles that are represented by these models are located within the 2D model domain and coincide with the 2D gridlines; approximately tangent to the coastline. Both 1D XBeach models and 1D DurosTA models are considered in this case, such that also their mutual differences can be addressed.

After the model setup for both the 1D and the 2D approaches, simulations are performed determining the storm impact on the considered coastline during normative storm conditions. Based on these simulations the pros and cons of 1D and 2D approaches of storm impact modelling are discussed; where the hypothesis is set that the 1D model results deviate significantly from the 2D results for highly complex parts of the coastline. This study contributes to the understanding of the functional limits of applicability for 1D dune erosion models.

As a next step in this research project the storm intensity in the simulations is increased stepwise to force dune breaches in the study area. The up-scaling of the storm conditions should reveal the possible weak spots along the coastline and moreover valuable insight will be obtained in the 2D effects related to dune erosion, such as water flow through dune valleys, and even massive flooding events.

The results of the up-scaled 2D simulations are also used to define safety indicators. Up-to-date indicators for the state of the (sandy) sea defences are desired by several authorities in order to act pro-actively on possible threats (i.e. flooding risks). The possibilities are studied to present (to-be-defined) safety indicators in a geographical system, which can be identified as a ‘hazard map’. Because of the high standards for coastal safety in the Netherlands and the continuous efforts of the Dutch government to maintain the current coastline position, it is expected that no ‘real’ flooding risks will be found in the study area during normative storm conditions. Therefore, the simulations with up-scaled (super) storm conditions are used to demonstrate the functionality of the hazard map.

In short, the most important aspects of this project are thus:

- Selection study location
- Model setup: 2D (XBeach)
- Model setup: 1D (XBeach / DurosTA)
- Simulations (normative storm + up-scaled storms)
- Comparison 1D and 2D models
- Safety indicators and hazard maps

1.4 OUTLINE REPORT

The outline of this report is broadly based on the different steps as defined in the previous section with the research methodology. After the introduction (Chapter 1), first a short description of the study location is given in Chapter 2. The details of the models which are set-up for this location are presented in Chapter 3, where a distinction is made between the 1D dune erosion models and the more sophisticated 2D model. In Chapter 4, all performed model simulations are discussed in detail. First, the differences and agreements between model results of the 1D and 2D simulations of the normative storm conditions are described. Subsequently, the effects of enhanced storm intensities are presented, whereby an exploratory coupling is made between the physical model output and so-called safety indicators. Finally, in Chapter 5 the most important study results are summarized and some concluding remarks and recommendations are presented.

2 STUDY LOCATION

2.1 INTRODUCTION

For a demonstration of 2D storm impact modelling a suitable study location is required. Coastal stretches that are characterized by approximate alongshore uniformity (for bathymetry, topography and hydraulic conditions) can be assessed by a relative simple, regular 1D approach in order to determine the amount of coastal erosion during storm conditions. So, a 2D model approach is particularly useful (and advantageous) for complex coastal areas, where processes related to sediment transport and dune erosion are affected by alongshore variability. In the Netherlands, typical complex coastal stretches are found along the 'Wadden'-coast (northern part of the country) and along the 'Delta'-coast (south-western part of the country). For this demonstration-project a (complex) study location is selected in the south-western part of the Netherlands: Westkapelle. In the following sections the study location near Westkapelle is described in more detail.

2.2 WESTKAPELLE

Westkapelle is selected because it is considered to be a so-called complex coastal area. Within this coastal area several complex features are present that typically impede the application of a 1D approach for storm impact modelling. Therefore, the selected study location is particularly suitable for this demonstration-case with a 2D model. In the following sections a more detailed description of the study area is given.

2.2.1 Description coastal area

Westkapelle (51^{o} 31' 45" N, 3^{o} 26' 30" E) is located in Zeeland at one of the 'Zeeuwse Eilanden', called Walcheren. The location of Westkapelle is indicated in Figure 2. It is shown that the city is situated along the coast, west of the cities Vlissingen, Middelburg and Domburg.

Walcheren is squeezed in-between the Western Scheldt estuary (to the south) and the Eastern Scheldt estuary (to the north). These estuaries are associated with complex bed level patterns that reach into the North Sea. Just seaward of both inlets large outer deltas are formed with subsequent series of shoals and tidal channels. In front of the coast near Westkapelle a very deep tidal channel has formed, close to the shoreline. Further seaward also some shallow flats are found that absorb lots of wave energy before reaching the beach area.

Moreover, from Figure 2 it is concluded that (the western part of) the region of Westkapelle is a triangular-shaped area that 'points' seaward. Westkapelle is situated in the most westerly corner of this area that, in fact, stretches out 'into sea' relatively far compared to surrounding areas. Due to the shape and orientation of the coastal stretch, and due to the presence of a near-shore tidal channel, the area is vulnerable for erosion processes that force a landward shift of the coastline. The coastline is prevented from eroding by a sea dike that is present close to Westkapelle: the Westkapelse Zeedijk. This dike is clearly shown in Figure 3 (red circle).

In Figure 3 a detailed view of the coastal area near Westkapelle is presented. In the figure several characteristic features are highlighted by coloured markers (circles, arrows and lines). The mentioned sea dike is located in the upper half of the figure and highlighted by a red circle. The coastal zone in the southern half of the figure is not protected by a dike, but the safety in that area is provided by a sandy beach and a dune area. A part of the dune area is fortified by an elongated structure that prevents the dune foot from eroding. This additional coastal structure is highlighted by the white circle.

Figure 2: Location of Westkapelle in the Netherlands. Recent bathymetric data is presented as well, to show the complexity of the near-shore sea bed. The area consists of several tidal channels and shoals that influence the hydrodynamics in the coastal zone.

An interesting location near Westkapelle is the 'central beach' between both coastal structures (yellow circle in Figure 3). This beach is positioned slightly landward of the seaward extents of the fortifications and dunes are present behind the beach. The area around the central beach is often referred to as 'Het Gat van Westkapelle'. This name originates from the effects of a bombing-event in World War II. Formerly the current sea dike extended further southward, such that the central beach did not exist. At the location of the current beach the dike is destroyed during the war and the hinterland flooded partly. This event formed the, still present, inland creek south of Westkapelle (also shown in the figure). The breached dike is repaired by closing the gap with all kinds of available material from the former dike and additionally large amounts of sand. For the model setup in this project, however, the area is considered to be entirely sandy.

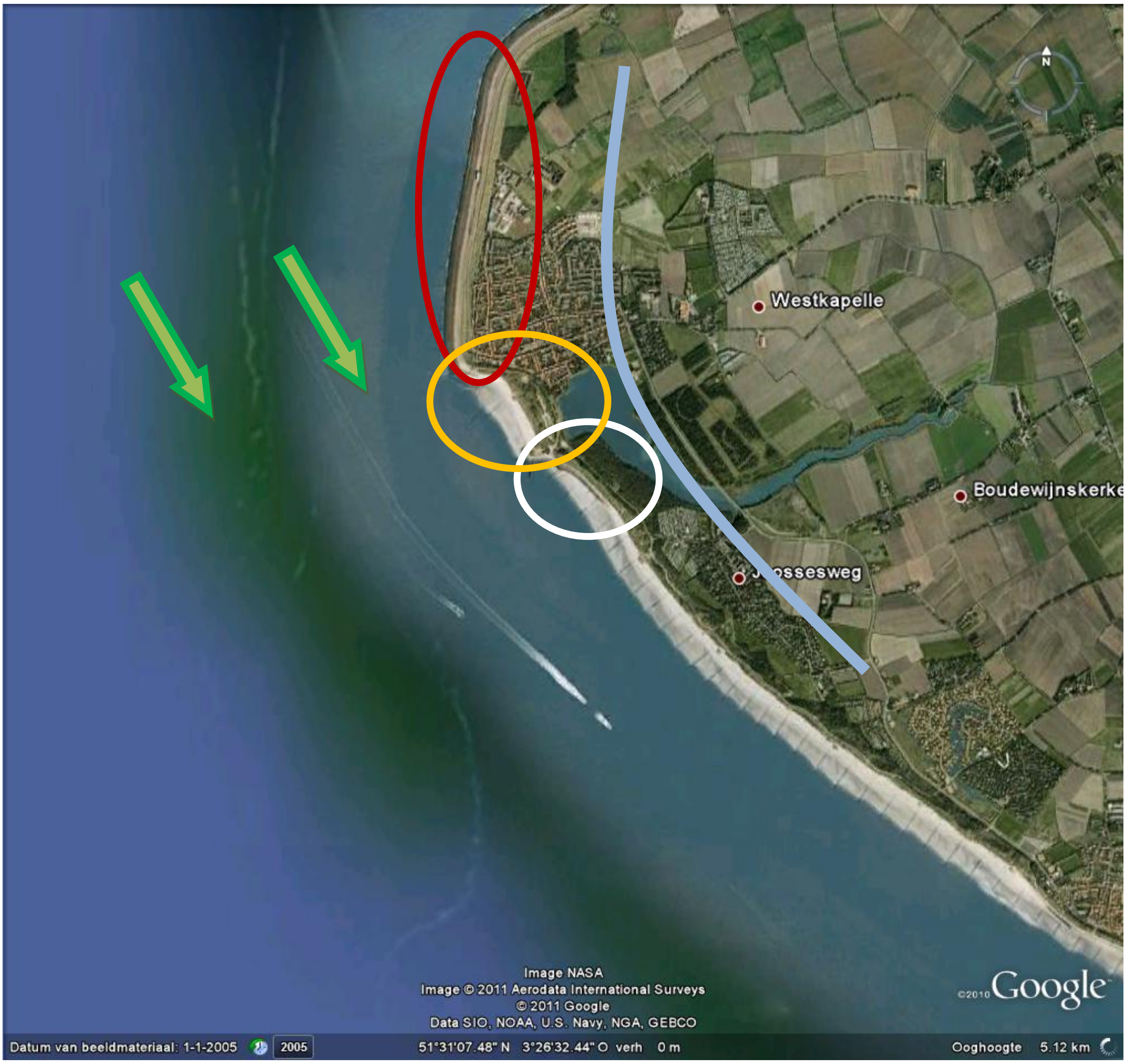

Figure 3: Coastal area near Westkapelle. The yellow circle (middle) indicates the location of 'Het Gat van Westkapelle' which is the mayor point of interest for this project. The red circle (top) highlights the position of the sea dike, while the white circle (bottom) shows the location of another coastal structure. The blue curved line indicates the amount of curvature of the coastline. And finally, the green arrows point at some complexities of the near-shore bathymetry (shoals and a tidal channel).

Further southward (south of both coastal structures) a 'normal' sandy dune area is present with (mainly) one significantly high dune row. Also an elongated (relatively wide) beach is found in front of the dune areas. Note that cross-shore elements are found at the beaches (black lines). These lines are in fact wooden groins (see also Figure 4) that reduce the amount of alongshore sediment transport during mild conditions. The wooden barriers are built in order to maintain a certain beach width by trapping sediment. The effect of this type of cross-shore dams during storm conditions is rather uncertain, but probably insignificant due to the (much) higher water levels during severe conditions. In this study the effects of those dams are *not* taken into account.

Furthermore, the blue (curved) line in Figure 3 gives an indication of the amount of coastal curvature for this particular location. The relative straight coastline in the southern part of the figure changes in a curved coastline with several small curves and two large change of coastline orientation near both sides of the sea dike in the north. The assumption of a more or less straight coastline is obviously not valid near the central beach, but seems to be more valid for the southern dune area.

Figure 4: An aerial photograph of the coastal area near Westkapelle, the Netherlands. The 'Westkapelse Zeedijk' (sea dike) is located in the back, and another coastal structure is situated in the front. In-between the beach is present near 'Het gat van Westkapelle'. Source: Rijkswaterstaat, www.kustfoto.nl.

Finally, in Figure 3 two green arrows are shown. These arrows highlight the large differences in near-shore bed levels. A deep tidal channel and shallow flats are both present just seaward of the Westkapelle coastline. Obviously, the near-shore bathymetry for this location cannot be considered as regular, so a 1D model approach is expected to have a limited applicability for this complex area; that in contrast to an approach with a 2D model.

All presented features in Figure 3 support the statement that the coastal area near Westkapelle can be identified as 'complex', such that regular a 1D approach for storm impact modelling is expected to produce doubtful or even unrealistic results due to, for example, the absence of alongshore processes in these models.

2.2.2 Coastal structures

In addition to the presented satellite images, also an aerial photograph of the considered coastal area is shown in Figure 4. The photo gives a better impression of the location, shape and orientation of the coastal structures along the coast. In the figure, Westkapelle and the sea dike are found in the background. The central beach is shown in the middle of the figure, and the extra fortifications of the shoreline (south of the central beach) are present at the front of the scene.

From the photograph it is clearly shown that the dune rows behind the central beach are located at relatively landward, compared to both of the coastal structures. In-between a transitional stretch is present where these structures gently merge with the (sandy) dunes. Especially for the sea dike it is clearly shown that the structure bends landward, towards the dune area. The maximum height of the dike gradually reduces, while increasingly large parts of the dike are covered with sand. In fact, a significantly large part of the extents of the dike is hidden underneath the dunes. The sea dike, however, is not directly connected to the coastal structure south of the central beach.

3 MODEL SETUP

3.1 INTRODUCTION

For the study location near Westkapelle both a 2D model and a series of 1D models are set-up. The main objective of the model approach in this study is to demonstrate how the more sophisticated 2D dune erosion model XBeach can be used to examine storm impact on complex coastlines, by incorporating alongshore effects and other complexities in the simulations. In this chapter a detailed description is provided for the model setup for the 2D XBeach model, as well as for the relatively simple 1D models.

3.2 2D XBEACH MODEL

To be able to simulate the morphological development of the coastal area near Westkapelle during severe storm conditions, a sufficiently large model domain is defined in order to incorporate all relevant hydrodynamics (near-shore flow, wave propagation, etc.). Within the considered domain the dynamics is driven by boundary conditions which represent proper conditions and by carefully chosen parameter settings. Moreover, all present coastal defence structures are schematized and included in the model.

All of the relevant aspects of the model setup are discussed in more detail in the following sections.

3.2.1 Grid definition

The size of the model domain in XBeach for modelling storm impact is determined based on the characteristics of the study area, and on the purpose of the simulations. The model should be able to account for all cross-shore and alongshore effects of storm impact, as well as dune breach scenarios and possible flooding of the hinterland. Due to the strong curvature of the coastline it is decided to use a curvilinear grid definition in this project. Since the possible use of a curvilinear grid is just recently implemented in XBeach, this study acts as a perfect test-case for its practical application.

For the case of Westkapelle, as presented is this report, a (curved) model domain is selected with an alongshore length of 3 – 6 km, depending on the distance from the coastline due to curvature, and a cross-shore length of about 3 km. The used grid definition for the 2D XBeach model is presented in Figure 5, where the orange lines represent the edges of the grid cells.

The length of the model (alongshore direction) is set in such a way that a coastline stretch of about 4.5 km is captured, including the transition between the sea dike and the dunes. The width of the domain (cross-shore direction) is chosen such that both the near-shore tidal channel and a substantial part of the hinterland are included. As a result the offshore boundary is located at a distance of about 1.5 km from the coastline, and the landward boundary is positioned 1.5 km landward of the coastline.

As shown in Figure 5, this size of the grid cells varies along the model domain. In order to reduce the number of cells, and thus the calculation time of the simulations, the grid resolution is decreased for the areas further away from the points of interest (near the coastline). In alongshore direction the grid size varies, near the coastline, between 10 m in the centre till 40 m at the lateral boundaries. Due to the curvature of the grid those numbers change when moving away from the coastline. In the cross-shore direction the cell size is smallest near the coastline: 5 m. Towards the offshore boundary the grid size increases to a maximum of 50 m, which is related to the wavelength of the incoming wave groups. From the coastline towards the landward boundary the size of the grid cells increases from 5 m to 20 m. In short, the (minimum) size of the grid cells in the areas of interest is about 5 x 10 m.

Figure 5: Grid definition XBeach (Westkapelle, the Netherlands).

3.2.2 Bathymetry and topography

In the previous section the extents of the model domain are presented, as well as the distribution of the grid cells within this domain. For the area within the selected domain the model requires input for the elevation of the seabed and the dry land (bathymetry and topography). These required data are obtained from several datasets which will be discussed in this section.

'Vaklodingen'

The bathymetry for the 2D XBeach model is based on the most recent set of 'Vaklodingen' data. The 'Vaklodingen' dataset consists of measurements of the bottom elevation in the Dutch near-shore coastal areas. Those measurements are performed on a regular basis, and the last usable surveying for the area near Westkapelle dates from 2005. In the previous chapter the 'Vaklodingen' were presented as an example for the complexity of the near-shore bathymetry in the surroundings of Westkapelle; and in Figure 6 the 'Vaklodingen 2005' are presented as well for the relevant area close to the model domain.

Figure 6: Bathymetry; based on 'Vaklodingen (2005)' (Westkapelle, the Netherlands).

The presence of a deep near-shore tidal channel is clearly visible in Figure 6, where the maximum channel depth (close to 40 m) seems to be found in front of the small beach near ‘Het Gat van Westkapelle’. The edge of the model domain extends up to a point seaward of the tidal channel such that this phenomenon is captured as a whole. At the offshore boundary of the grid some tidal flats are recognized, as well as a secondary (more shallow) tidal channel at the north-western corner.

‘Actueel Hoogtebestand Nederland’

The ‘Vaklodingen’ dataset only consists of information about the bed level under sea level, and sometimes up to the first dune row; but certainly no data is available for the hinterland. Tthe topographic information of the dry land is obtained from another dataset: the ‘Actueel Hoogtebestand Nederland’ (AHN data). For the considered study area two datasets were available, with different spatial resolutions. The coarsest set of data has a spatial resolution of about 25 m, while the other set has a higher resolution with in grid sizes of 5 m. The high-resolution AHN dataset is presented in Figure 7.

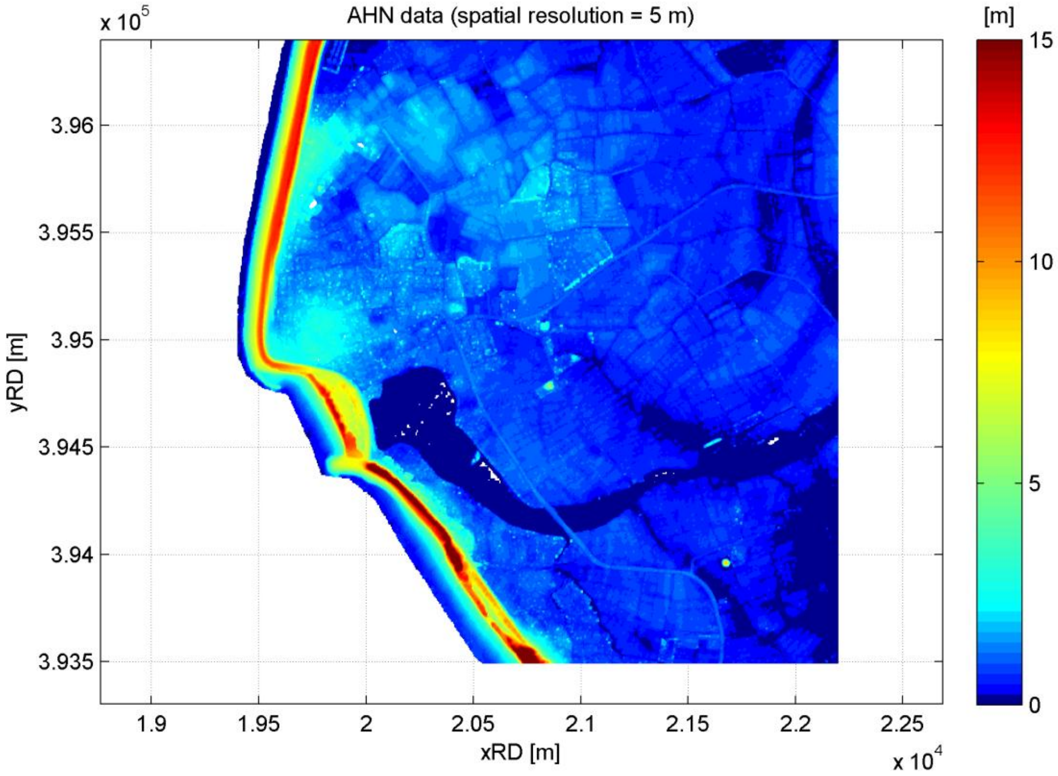

Figure 7: High-resolution AHN data for Westkapelle area.

Combined dataset

Based on both the bathymetric data ('Vaklodingen') and the topographic AHN data, a combined map is constructed that is used as input for the 2D XBeach model. The different datasets are combined by means of prioritization, which means that for areas where information is available from multiple datasets, only the data is used with the highest priority. Overlap between the datasets is only found within the dune areas, where the fine resolution AHN data has the highest priority over the 'Vaklodingen' and the coarser AHN data. Note that the decision to 'give' the highest priority *in the dune areas* also to the AHN data, instead of to the 'Vaklodingen' data, is made because of the difference in spatial resolution of both datasets. The AHN dataset has the finest resolution.

The bathymetric input for XBeach is obtained by interpolating the combined datasets of bed levels at the generated non-uniform, curvilinear, calculation grid. The result is presented in Figure 8.

Adjustments to original data

From Figure 8 it is clear that some minor and major adjustments are made to the original bathymetric data. The minor adjustments are made along the edges of the model domain. For all grid cells near the edges the bathymetry is kept constant for several cells in the direction normal to the grid boundary, in order to prescribe a zero-bathymetry-gradient at the boundaries.

Moreover, the depth of the 'Westkapelse Kreek' (the inland creek) is schematized manually, since the AHN datasets contains records of the still water level of the creek instead of records of its actual depth. The exact depth profile is not collected for this project, but it is known that the maximum depth of the creek is up to 20 m. But since no more information is available, a first guess for the average depth is set at 5 m. For the bathymetric input for the XBeach model the creek is then schematized by fixing the bed level at NAP -5 m for the whole creek-area.

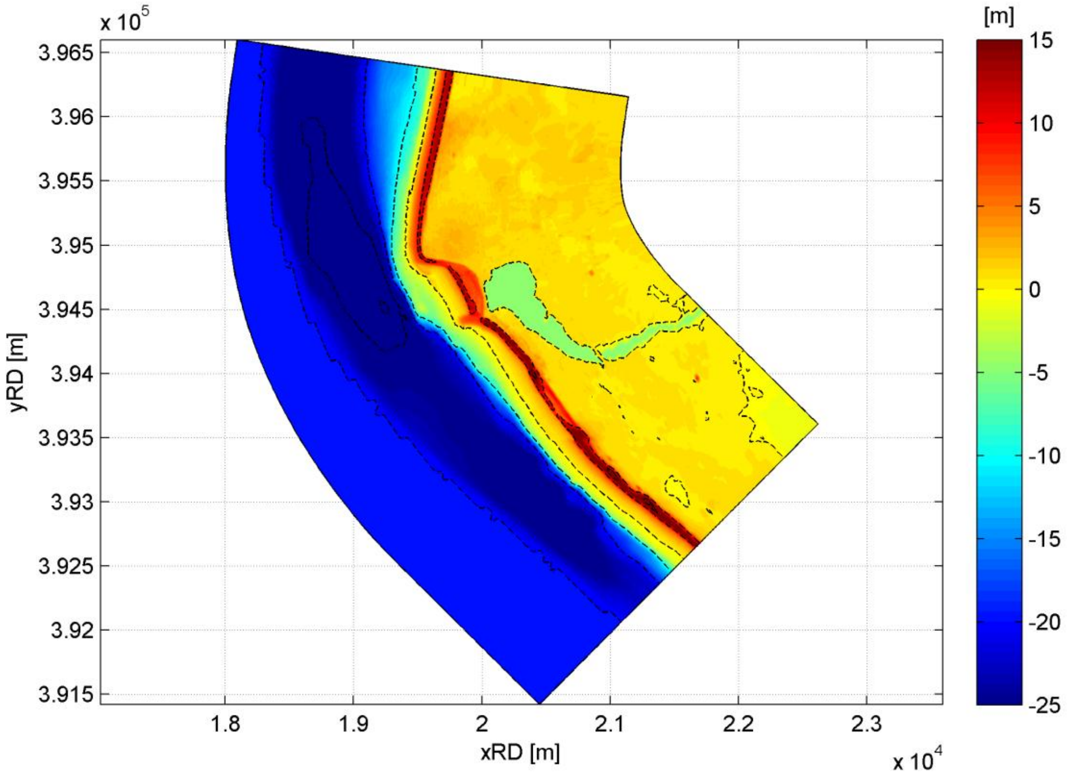

Figure 8: Bathymetry as input for 2D XBeach model. The contour lines indicate the NAP -20 m, NAP -10 m, NAP +0 m, NAP +10 m and NAP +20 m lines for convenience.

The major adjustment in the definition of the bathymetry concerns the absence of the tidal flats, which were highlighted in the previous chapter, near the offshore boundary. Seaward of the tidal channel the bathymetric dataset is adjusted in such a way that the bed level in this area is fixed to a maximum of NAP -20 m. The reason is twofold: firstly, it is convenient to define a constant bed level along the entire offshore boundary of the model, to prevent alongshore gradients at this point. Secondly, it is expected that a very shallow offshore boundary (as present here) will cause problems for the incoming wave field at this boundary. As a solution for this the offshore boundary is lowered to NAP -20 m, while the model input for the offshore wave conditions is chosen such that it corresponds to the conditions in the tidal channel, landward of the tidal flats.

However, such a major adjustment to a complex near-shore bathymetry should be omitted when possible, since the model schematization directly deviates drastically from the ‘real’ near-shore state of the coastal area. It is therefore suggested that the schematization of complex bathymetries by removing tidal flats will be studied in more detail in a later stage.

Related to the last suggestion it should be mentioned that recently an option is implemented in XBeach (which is not yet applied in this study) that enables spatially varying (wave) boundary conditions along the offshore boundary. When including XBeach in an operational model system, this option is useful to overcome the problem that the offshore bathymetry should be adjusted on forehand (based on the applied conditions).

Input for XBeach

As a summary, Figure 8 presents the bathymetric input for the 2D XBeach model, as used for modelling storm impact on sandy coastlines. The presented map consists of bed level data from multiple datasets, and is adjusted at certain points (mostly along the grid boundaries) in order to prevent instabilities in the model.

Figure 9: Schematisation coastal structures (Westkapelle, the Netherlands).

3.2.3 Coastal structures

The sea defences along the coastline near Westkapelle consists of both sandy parts and coastal structures, such as a sea dike. The bathymetric input for XBeach defines the bed level that is, by default, considered to be sandy in the XBeach model. The location, height and orientation of coastal structures are included in the model by defining a certain thickness of the sandy top layer of the bed (which is thus, by default, infinitely large). In the following sections the implementation of the coastal structures in the XBeach model is discussed in more detail.

The present structures along the coastline near Westkapelle are already discussed in the previous chapter, and it is concluded that two significant non-sandy sea defences exist within the model domain. The first one is the 'Westkapelse Zeedijk' in the northern part of the domain, stretching from the small beach in the centre till beyond the northern model boundary. And the second structure is situated just south of the central beach, between the inland creek and the shoreline.

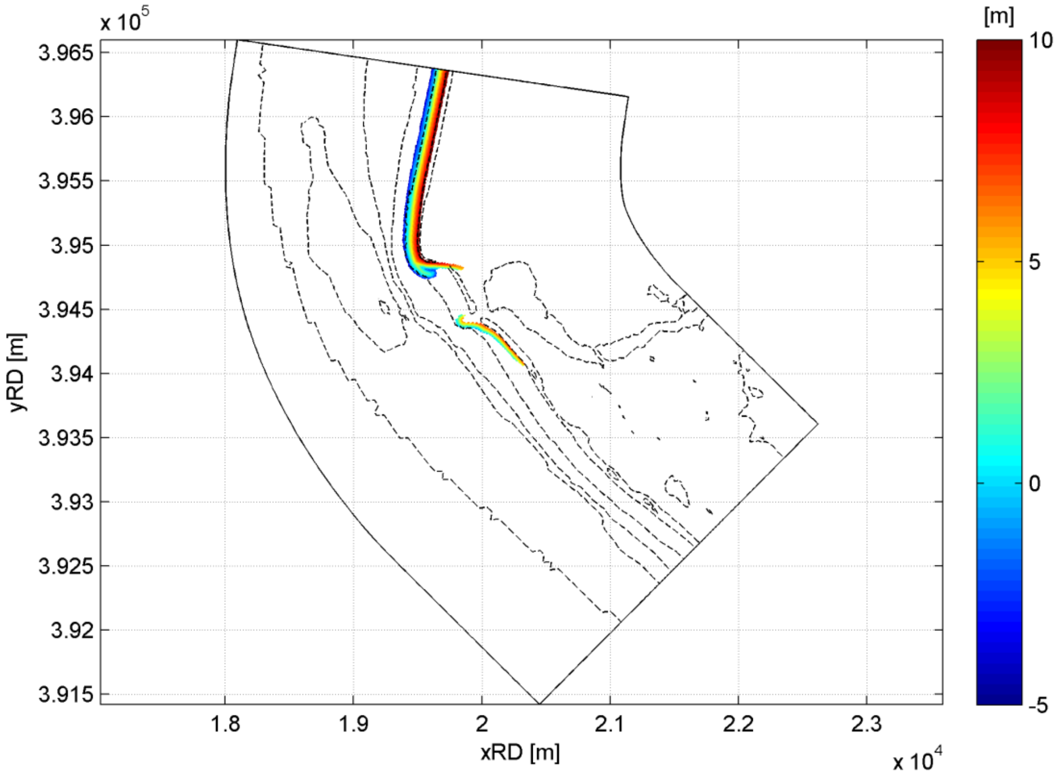

Figure 10: Schematized structure definition (with spatially varying height, position, orientation, etc.).The contour lines indicate the NAP -20 m, NAP -10 m, NAP +0 m, NAP +10 m and NAP +20 m lines for convenience.

Schematization of structures

From technical drawings of the structures' design, schematisations are made that are used as input for the XBeach model. The available set of information consists of cross-sectional profiles of several parts of the structures and of a spatial representation of the most important structural features. Some lack of information for the straight parts of the sea dike is manually added based on best guesses from available measurements for these parts of the near-shore bathymetry (JarKus measurements).

As an example of the gathered information about the coastal structures, in Figure 9 several cross-sectional profiles and alongshore connectors are visualized. It is clear that the schematization of those structures, mainly due to the complex shapes and orientations, involves quite a challenge since 1D information should be converted to a 2D representation, without losing crucial information.

Input for XBeach

In Figure 10 the final model definition of the coastal structures is presented. For both large structures (dike and dune foot fortification) the height is indicated by the colorbar. Note that this representation allows structures to be hidden under a layer of sand, whenever the height of the structure is lower than the actual level of the topography. This method enables the schematization of transitions between structures and dunes, since the structural height can decay underneath a sandy top layer.

The structural information is inserted as input for XBeach by defining a map with initial thicknesses of the sandy top layer, rather than using a 'secondary bathymetry map' with the height of the structures. In practice this means that the input for the model is a map that is constructed by subtracting the structural height from the initial bed level. Resulting negative numbers (which means that the structure is higher elevated than the measured bed level) are set equal to zero, since the measurements are considered to be more reliable than the schematized structural height. In the resulting map, a sand layer thickness of zero corresponds to an exposed coastal structure (at bed level), while all positive numbers indicate at which depth a structure is hidden.

In short, based on available information about the structural sea defences (mostly 1D profile data) a schematized 2D representation is made of the height, position and orientation of the present structures along the coastline near Westkapelle. The obtained information is included in the model input by defining the initial thickness of the sandy top layer in the model domain. Here yields: a very large thickness corresponds to the absence of structures, while an exposed coastal structure is modelled by a zero-thickness of the sandy layer.

3.2.4 Boundary definitions

Apart from the 'static' initial conditions of the XBeach model (such as bathymetry and structure definitions), also dynamic boundary conditions are prescribed in order to simulate the storm impact on the coastal stretch. The hydraulic conditions that drive the (hydro)dynamics in the model are only prescribed at the offshore boundary of the model, while the other three boundaries (landward + 2x lateral) just react to the model's behaviour in a prescribed manner.

Boundary type definitions

Both lateral boundaries of model are considered to be 'open' and therefore defined as Neumann-type boundaries, through which transport of both sediment and (wave and flow) energy is possible. The landward side of the domain is also defined as a 2D absorbing, 'open' boundary. Initially, no dynamics is expected here since the boundary is situated above dry land (except for small part where the inland creek is located).

In a later stage of this project several test-simulations are performed with deviating conditions and boundary type definitions along the landward boundary, in order to test the model's performance in simulating flooding after dune breaching: 'closed' versus 'open' boundary, with / without inland channel along the boundary (to drain abundant water), etc.

At the seaward boundary a same type of handling is defined as mentioned for the landward boundary: a 2D absorbing and weakly reflecting boundary type. Since the boundary is located offshore and therefore considered to be 'wet' during the whole duration of the storm, all incoming wave energy and water levels are prescribed at this boundary.

Boundary conditions (time dependent)

In this project, by default, normative storm conditions (for dune erosion) for the area near Westkapelle are considered. However, instead of the so-called 'rekenpeil' that is used for safety assessments with the regular dune erosion model DUROS+, the normative water level of the design conditions (= 'toetspeil') is considered in this project, since the dune erosion modelling is performed by a deterministic approach with the models XBeach and DurosTA. These design conditions have a typical (expected) return-frequency of 'once per 4000 years' for this study location, and are prescribed in [HR2006].

Since in both XBeach and DurosTA time-dependent boundary conditions are considered, the prescribed maximum storm conditions are converted to representative time series for a certain storm duration, in which tidal effects are included as well. The time-dependent storm conditions are constructed following the approach of 'standard storms', as described by [Steetzel, 1993]. The standardized time series of the hydraulic conditions are based on the maximum water level, maximum significant wave height and maximum peak period, in combination with a prescribed storm duration, simulation time and tidal wave amplitude (which is half the tidal range).

The default values for the hydraulic conditions for this project are presented in Table 1.

Table 1: Overview of hydraulic boundary conditions for normative storm impact.

Norm frequency [1/yr]	Max. water level [NAP+ m]	Max. sign. wave height [m]	Max. wave peak period [m]	Storm duration (in simulation) [hours]	Tidal wave amplitude [m]
1/4000	4.9	3.65	12.2	30	1.7

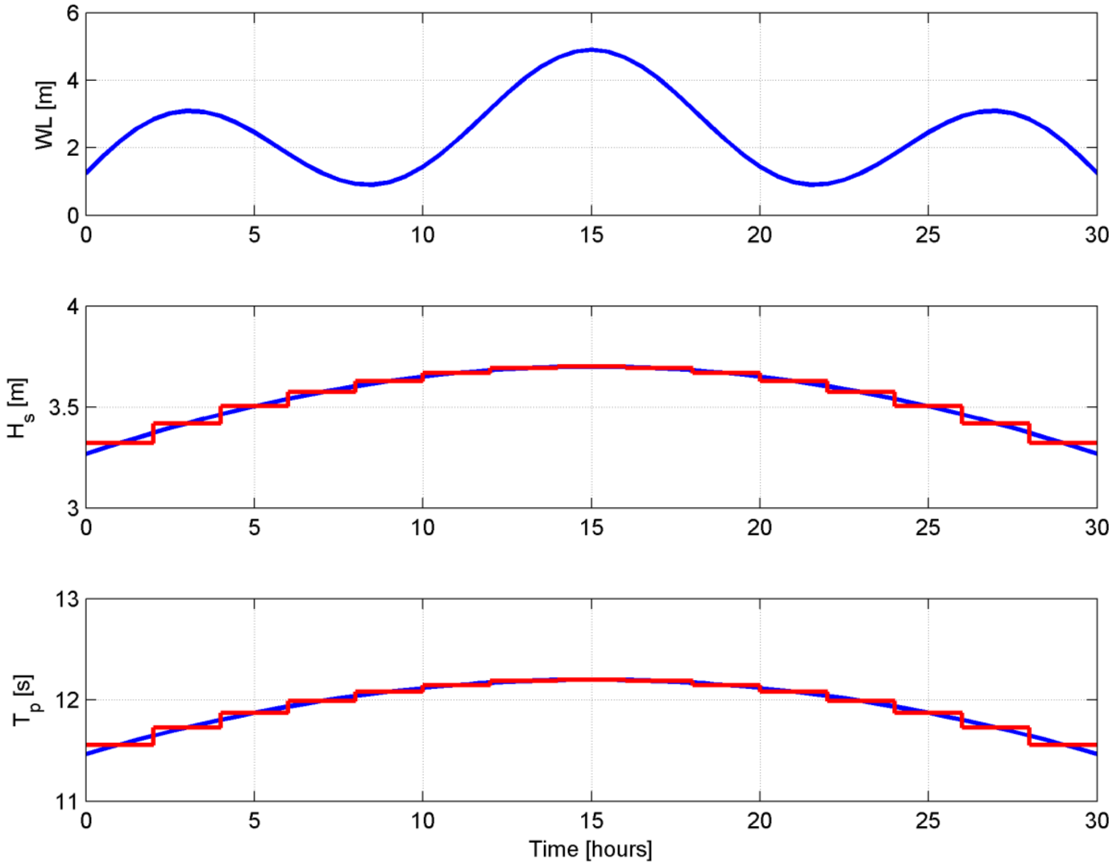

Figure 11: Time series of hydraulic boundary conditions for XBeach and DurosTA. 'Default' settings: normative storm conditions.

The time dependent definitions of the hydraulic boundary conditions for the dune erosion models, which represent standardized storms with maximum conditions according to Table 1, are presented in Figure 11. The three panels of the figure show the time series of respectively the water level, the significant wave height and the wave peak period (blue lines), for a duration of 30 hours. The red stepwise lines in the lower two panels indicate the time steps and duration for which constant wave conditions are defined in the XBeach model.

JONSWAP wave spectra

From the previous figure (Figure 11), the main characteristics of the incoming wave fields are obtained. Since it is decided to include more realistic wave fields in the XBeach simulations than just schematized monochromatic waves, the presented wave characteristics are used to build JONSWAP spectra as model input (for XBeach). For each 'step' of the red line in Figure 11, all having durations of 2 hours, one JONSWAP spectra is defined. The 'default' spectra which are used in this project are based on the parameter settings as presented in Table 2.

Table 2: Overview of parameter settings for JONSWAP spectra.

Wave height H_{m0} [m]	Wave frequency F_p [s^{-1}]	Main wave angle (Nautical) [^{o}]	Peak enhancement [-]	Directional spreading [-]	Cut-off frequency [s^{-1}]
Time-varying (H_{m0})	Time-varying ($1/T_p$)	270 (from West)	3.3	10000 / 20	1

As shown in the table, by default wave fields are considered that approach from the west. During this project also wave attacks from other directions are considered in order to test the sensitivity of this parameter setting on the calculated dune erosion patterns. Moreover, a default JONSWAP peak enhancement factor (3.3) is used to determine the spectral shape.

In the table two different values for the directional spreading are presented. The largest value (10000) reduces the directional spreading significantly, such that wave fields are formed with (more or less) elongated wave crests, perpendicular to the main direction of wave propagation. The smaller value of the directional spreading (20) enables a certain directional distribution for the wave angles, such that the main wave angle equals the given input value (by default 270^o). The default setting for this project is set at 10000.

XBeach is known for its capability to simulate (bound) long waves and related swash motion. The characteristics of the long waves are determined based on the variety of wave frequencies within the applied JONSWAP input spectra.

In short, by applying a 2D absorbing and weakly reflecting offshore boundary type, and a set of time dependent JONSWAP spectra, XBeach is able to simulate realistic, spatially- and time- varying, wave fields in the model domain. The default settings for the hydraulic conditions are presented in the previous sections and the supporting figures and tables.

3.2.5 Parameter settings

The 2D dune erosion simulations in this project are primarily used to demonstrate the possibilities of the model in dealing with complex cases. Moreover, the model's sensitivity to some input conditions and parameters definitions are studied. Clearly it is *not* an objective in this study to deliver a perfectly calibrated model setup for this specific test case. Therefore, whenever possible the default (physical and numerical) parameter settings of the current release of the XBeach model are used.

At this point revision number 2315 (date: Oct. 2011) of XBeach (in the so-called 'trunk' directory of the open-source XBeach repository) is used for the simulations of storm impact on the Westkapelle coastal area.

The remaining non-default settings are summarized in Table 3.

As mentioned earlier a simulation time of 30 hours is chosen to model the storm impact. Because of the relative small time steps needed in XBeach to calculate the hydrodynamics properly (time steps of order 0.1 s); a morphological scaling is applied in order to decrease the calculation times. A scaling factor of 10 is used for the simulations in this project. Moreover, the starting time of morphological updating is set at 120 sec to prevent bed updates due to early wave action during the spin-up time of the hydraulic conditions.

The fourth row of the column presents the user-defined settings for the directional wave bins considered in the model. Wave energy is distributed over a predefined (limited) number of wave bins. For normal (long crested) wave incidence on a straight coastline only one wave bin is required since no directional spreading is expected. For cases with alongshore non-uniform bathymetry or conditions, and for cases with off-normal wave incidence, variations in the angle of wave propagation are expected, such that more wave bins are required in order to describe the system properly. As a default case, in this project 9 wave bins are considered, for which the direction of wave propagation is always pointed into the model domain. The 9 bins are thus spread over half a circle in segments of 20^o. During the project several tests are performed with deviating wave bin definitions (more bins, less bins, other orientations, etc.).

The last parameter in the table ('*epsi*') is set to -1, which corresponds to an automatic setting of the parameter based on calculated quantities in the model. The value for '*epsi*' represents a weighting factor that is used to separate the signal of the flow field at the grid boundaries. This is required for a proper handling of the absorption and reflection of (long) waves at the boundaries.

Table 3: Overview of XBeach parameter settings.

Parameter	Description	Value
tstop	End time of simulation	108000 sec *(30 hours)*
morfac	Morphological scaling factor	10
morstart	Start time of morphological updating	120 sec
thetamin, thetamax, dtheta	Definition directional (wave) bins; nautical angles	180^o, 360^o, 20^o *(9 bins)*
epsi	Weighting factor for signal separation at boundaries	-1 *(automatic)*

3.3 1D MODELS

In addition to the 2D model approach with XBeach also, for comparison, a series of 1D models is set-up for the simulation of dune erosion during storm conditions. Both DurosTA [Steetzel, 1993] and XBeach [Roelvink et al., 2009] are used for this purpose such that mutual differences (between both transects models) can be identified as well. In the following sections the model setup is discussed in more detail, starting with the grid definition and the considered bathymetric data and afterward a short note on the offshore hydraulic boundary conditions.

3.3.1 Grid, bathymetry and structures

In contrast to the regular approach for safety assessments the bathymetric input of the 1D models in this project is not (directly) based on the yearly 'JarKus' measurements along predefined transects. The position and orientation of the transects of the 1D models are based on the grid definition of the 2D XBeach model. This choice enables a quite straightforward comparison between both model approaches.

For the 2D model setup a curvilinear grid definition is used whereby the (alongshore) grid lines are positioned more or less parallel to the coastline for the entire coastal stretch. The cross-shore grid lines are tangentially oriented to those coast-parallel grid lines, so consequently the orientation of all cross-shore transects of the grid are (with some exceptions) perpendicular with respect to the coastline; just like the JarKus transects (see Figure 12). Due to the coast-normal orientation it is possible to use the individual cross-shore transects (i.e. each grid 'row') as input for transect-based 1D dune erosion models.

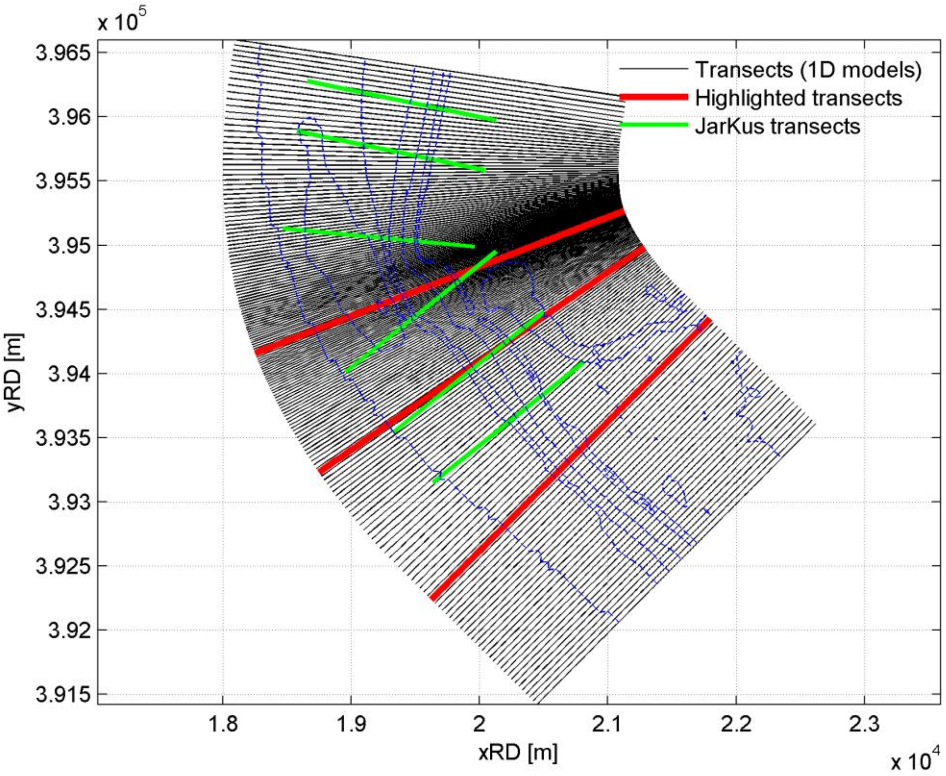

Figure 12: Overview of defined transects for the 1D models (black lines) with three highlighted examples (red). The green lines indicate the orientation of a selected group of JarKus transects along the coastline.

In this project the 2D grid definition with dimensions *n* x *m* (cross-shore x alongshore) is divided in a series of *m* different 1D transect grids (with *n* x 1 elements). In other words, the whole model domain of XBeach is alternatively represented by multiple adjacent cross-shore transects. For each of the transects the same non-uniform cross-shore grid cell sizes are considered in order to coincide with the 2D model definitions, as much as possible.

Not only the grid definition of the 2D model is represented by a *n* x *m* matrix, but also the input data for both the bathymetry and coastal structures. These features are converted to 1D model input in a similar way; just by splitting each matrix into *m* times an (*n* x 1) array. Three examples of input for the transect models are presented in Figure 13, where bathymetry and structure definition are shown along a cross-shore grid. The locations of these transects within the 2D model domain are indicated by the coloured lines in the previous figure.

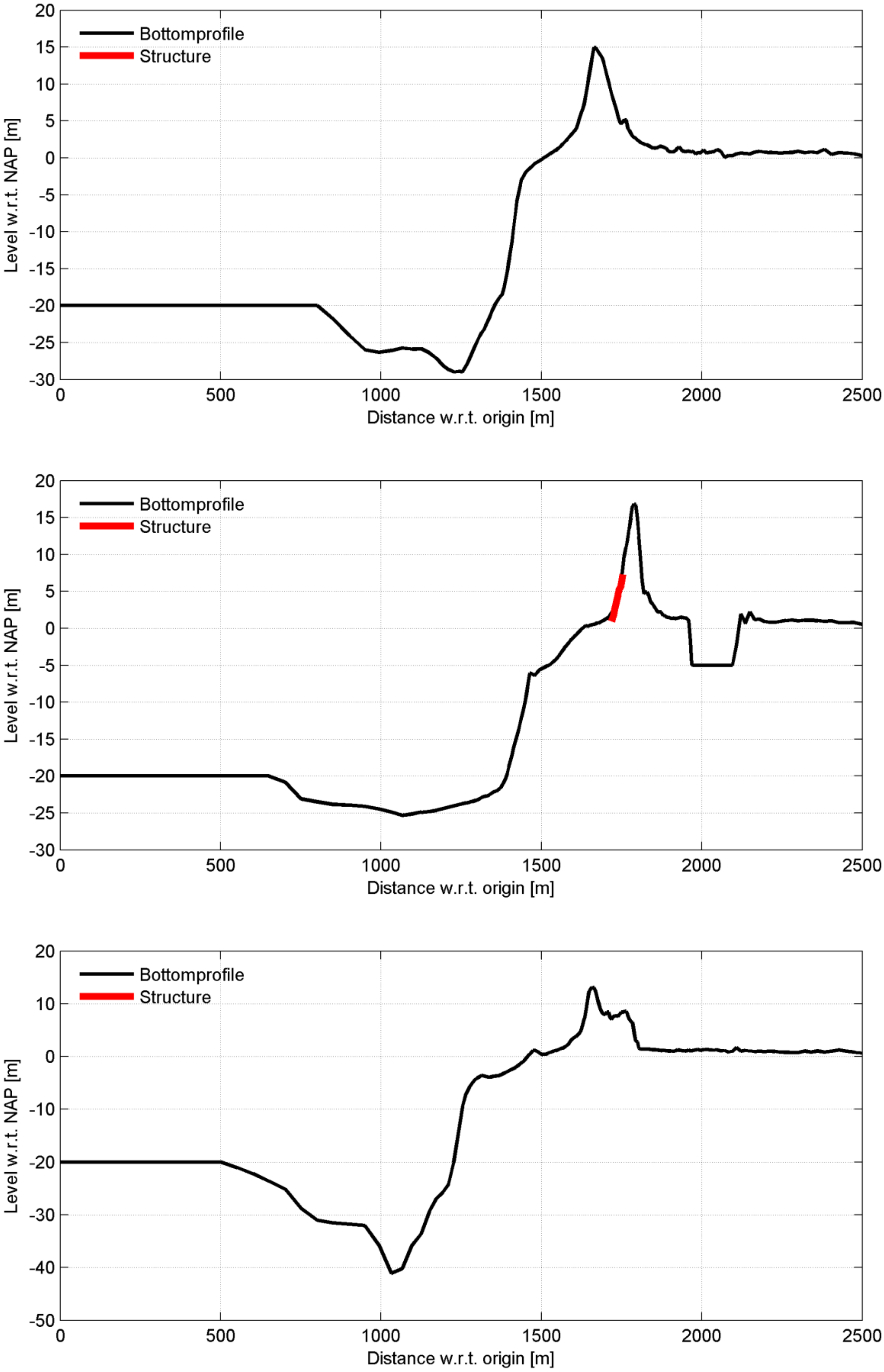

*Figure 13: Transects **'yID030'** (top), **'yID060'** (middle) en **'yID105'** (bottom). Examples of bathymetry and structure input for 1D dune erosion model.*

3.3.2 Offshore hydraulic conditions

At the offshore boundaries of the different transect models (all with local depths at NAP -20 m) water levels and waves are imposed as forcing for the hydrodynamics (and morphodynamics) during the simulated storm conditions. The offshore boundary conditions for the transects are based on exactly the same information as used as input for the 2D XBeach model. This means that, by default, water levels and waves are considered corresponding to normative (design) conditions; with a norm frequency of 10^{-4} yr^{-1}.

Time-dependent offshore conditions

As discussed in paragraph 3.2.4, a simulated storm period of 30 hours is considered with maximum storm intensity after 15 hours. The water level reaches a maximum level of NAP +4.9 m, while the significant wave height at that moment is equal to 3.7 m. The corresponding time series were presented in paragraph 3.2.4 as well, in Figure 11.

For XBeach simulations the time series of the wave conditions are used to generate a series of directional JONSWAP spectra in order to simulate 'realistic' wave field in the near-shore area. The range of different wave frequencies allows for the presence of (bound) long waves and related swash motions. For 1D XBeach calculations JONSWAP spectra are used as well, but the transect model DurosTA only deals with time varying settings of wave height and wave period, without accounting for wave groups and long waves.

Direction of wave attack

The time-dependency of the offshore boundary conditions (both for water level and for waves) is similar for the 1D models and the 2D model. However, there is one important aspect related to the definition of the offshore conditions which is quite different for both model approaches: the inclusion of the angle of wave incidence in the model domain. In a 1D transect model this is not as obvious as in a 2D model which simulates the development of an entire (spatially varying) wave field.

Regularly, for 1D dune erosion modelling a shore-normal (and alongshore uniform) wave propagation direction is assumed for simulations, such that the sediment balance along a transect is closed any time. In many cases the assumption of shore-normal wave attack is tolerated, since waves are refracted towards the coast in shallow water. However in cases with more complex coastlines cases or with a strong off-normal direction of wave attack, the direction of wave propagation can significantly influence the dune erosion processes.

In contrast to the commonly used balance-model(s) for dune erosion (i.e. DUROS+ [TRDA, 2006]), the 1D model DurosTA is able to deal with off-normal wave incidence by applying schematized corrections to the model parameters that reduce the effectiveness of the wave attack. Therefore it is decided to consider two types of 1D simulations in this project. First, by default for each transect a model is set-up with a grid-normal wave attack (and thus wave propagation along transect). And second, additional models are set-up with obliquely incoming waves, such that the incoming wave angle (per model) depends on the orientation of the considered transect within the model domain.

So, for the first type of wave angle definition the direction of wave attack is, for all 1D models, constant with respect to the orientation of the corresponding transects. And therefore, the wave angle varies with respect to world coordinates. In contrast, for the second definition type the angle of wave attack is, for all 1D models, constant with respect to world coordinates (by default: incoming waves *from* west). This means that the *relative* wave angles, with respect to the transect orientations, vary along the model domain. Both types of wave angle definition for the 1D models are illustrated in Figure 14. Note that the first definition is more commonly used as a first guess for the amount of dune erosion, while the second definition represents an alternative approach by considering the (schematized) effects of oblique wave attack.

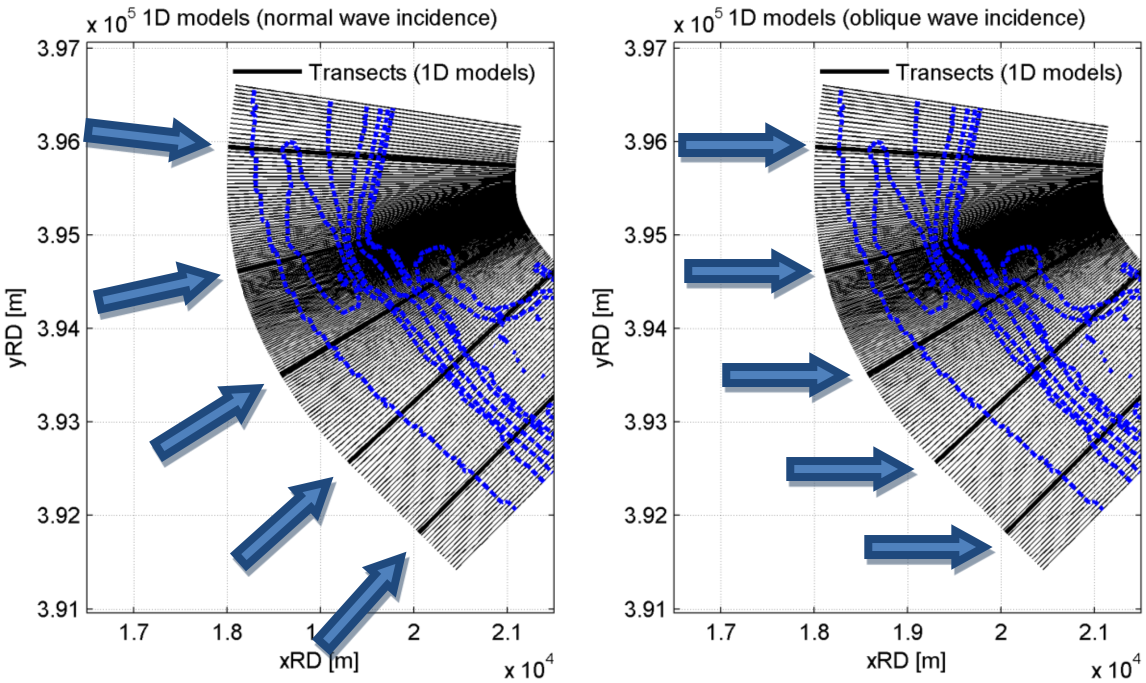

Figure 14: Illustration of two considered types of input for the direction of wave attack. Left panel: normal wave incidence for all individual 1D transects. Right panel: westerly waves are imposed, so the orientation of the individual transects determines the angle of wave incidence, per transect.

3.3.3 Other settings

Most of the 1D dune erosion models are developed (and usable) under to some basic assumptions concerning alongshore uniformity of the considered coastline. In some cases and with certain models, however, it is possible to account for alongshore variations with a 1D approach. The 1D model that is used in this project (DurosTA) has some advanced options to include several effects due to alongshore non-uniformity. Two of the considered options are: the inclusion of an alongshore current gradient and the schematized implementation of coastal curvature.

In this project, by default, both advanced options to include effects of alongshore variations are disabled. However, some tests are performed with included alongshore variability in order to investigate the sensitivity of the model and to compare the results with a 2D model approach.

Accounting for alongshore current gradients enables a net alongshore sediment transport which affects the amount of dune erosion during storm conditions. A zero-gradient in alongshore currents has no effect on the dune erosion since sediment transport away from the transect is compensated by sediment supply from upstream locations. Idea is that a combination of oblique wave attack and alongshore gradients induce net alongshore drift of sediment such that the cross-shore sediment balance is not by definition closed.

Including coastal curvature in the model has comparable effects on the handling of sediment transport along the coast, and thus on the amount of simulated dune erosion. Due to a positive curvature the amount of alongshore transport increases along the coast, resulting in a loss of sediment between two adjacent transects [Steetzel, 1993].

4 MODEL SIMULATIONS

4.1 INTRODUCTION

In this chapter a detailed description is provided of all performed simulations with both the XBeach models and the DurosTA models. First the 2D XBeach simulations, with normative storm conditions and westerly wave attack, are discussed. Then the effects of deviating angles of wave attack are presented and compared to the (default) model results for the westerly wave attack. Subsequently, the 2D XBeach results are compared to the results of large series of 1D XBeach and DurosTA models. Based on these additional simulations detailed analyses of bed level (and/or sediment volume) changes are presented.

Moreover, in this project super-storm conditions are considered in order to force dune breaches and flooding events. The results of the associated simulations are presented in this chapter as well. As a final demonstration, the results of one of the model runs are converted into so-called 'hazard maps'. These maps show the possibilities of post-processing of the XBeach results, such that useful information is obtained for end-users.

4.2 NORMATIVE STORM CONDITIONS

For the considered test-case of 2D dune erosion modelling near Westkapelle, by default normative storm conditions are considered, as discussed in Chapter 3. In the following sections the results are presented of a series of storm impact simulations using the different approaches (1D versus 2D modelling). First the results of the 2D XBeach model are discussed, followed by a brief section of the 1D model results. And afterwards a comparison is made between both model approaches.

4.2.1 2D storm impact modelling (XBeach)

Based on the considerations as presented in the previous chapter, a 2D model setup is build that simulates storm impact on a complex coastline. The results of the reference-run and some additional simulations are presented in this section. In the following several output parameters are discussed in order to demonstrate the capabilities of the XBeach model.

4.2.1.1 Waves from the west

As a reference case normative storm conditions are simulated whereby the main direction of wave attack along the offshore boundary is from the west. For clarity westerly waves are considered with elongated straight wave crests perpendicular to the direction of propagation. A more realistic wave field representation due to directional spreading of the wave field is considered as well, but not presented in this report because the results are very similar. The most important difference is the absolute amount of erosion and deposition, which is lower when considering directional spreading; because the long wave energy is distributed over a larger range of directions and is therefore effectively lower.

In the next sections the output states for several important physical parameters of the storm impact simulations are presented. First the constructed wave fields in the model domain are described, then the (GLM) velocity fields are shown in combination with the induced (bed load and suspended load) sediment transport rates. And finally the resulting erosion/deposition areas along the coastline are presented and discussed.

Waves

During the simulations a more or less regular, but time-varying, wave field with straight, elongated crests is imposed at the offshore boundary of the model domain. Since the model setup is based on a curvilinear grid definition, and thus a curved offshore boundary, it is worthwhile to check the resulting incoming wave field and the propagation of waves towards the coast. This regularity check is one of the reasons that in the reference simulation no directional spreading of the wave field is considered.

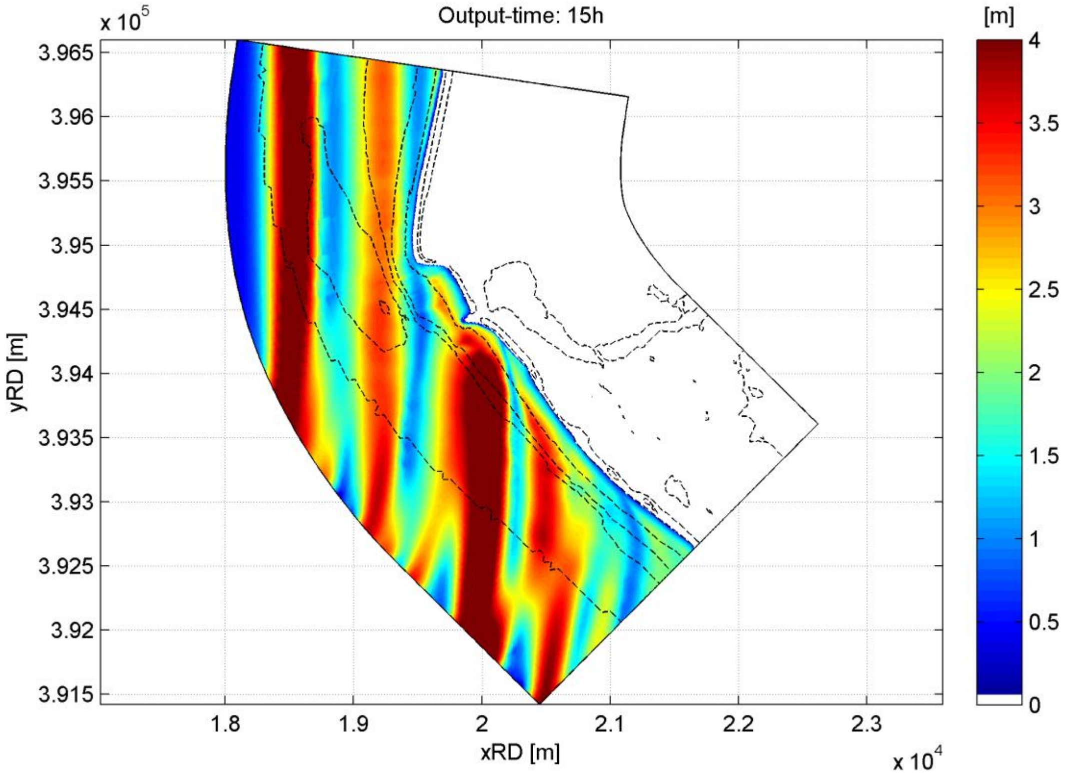

Figure 15: Significant wave height. The results are based on a simulation with westerly wave attack and normative storm conditions. The presented output is a snapshot at the time of maximum storm intensity (after 15 hours of simulation time).

In Figure 15 the simulated wave (group) field during storm maximum (after 15 hours) is presented. In fact, the shown wavy spatial pattern represents wave-groups that result from superposition of wave signals with varying periods and wavelengths. Within wave-groups the wave height varies periodically such that a larger scale wave pattern appears. As shown in this figure, the crests of the wave groups are associated with the highest magnitudes of the significant wave height of the short waves.

From the figure it is clear that the incoming wave crests are more or less oriented from north to south at the offshore boundary, despite its curved shape. Although not directly visible at one timeframe, sequences of timeframes show that the direction of wave propagation at seaside is indeed from west to east, towards the coastline. Due to bathymetry (i.e. tidal channel and shoaling) the wave direction varies slightly throughout the domain, as expected from wave theory.

The maximum wave height at the presented timeframe (storm maximum) is between over 4 m. The presence of the tidal channel closely to the shore causes only minimal wave height decay offshore. Most of the wave dissipation in this model domain thus occurs in the small area just between the landside of the channel and the shoreline. Note here that offshore shoals and flats are *not* directly considered in this model setup. In reality, a significant amount of wave dissipation occurs at those shallow locations; *however* these effects are already incorporated in the imposed wave-boundary conditions. Relatively mild normative wave conditions (wave heights up to 4 m) are considered, which reduce further in the area very close to the shore.

From the presented figure it is clear that the relative angle of wave incidence (with respect to the orientation of the shoreline) strongly varies along the coastline, due to its curvature. The off-normal wave incidence would likely generate shore-parallel currents and transports, and since the direction of wave attack also varies along the coast, gradients in the generated currents and transports are expected. Whether the near-shore flow field is simulated properly is shown in the following section.

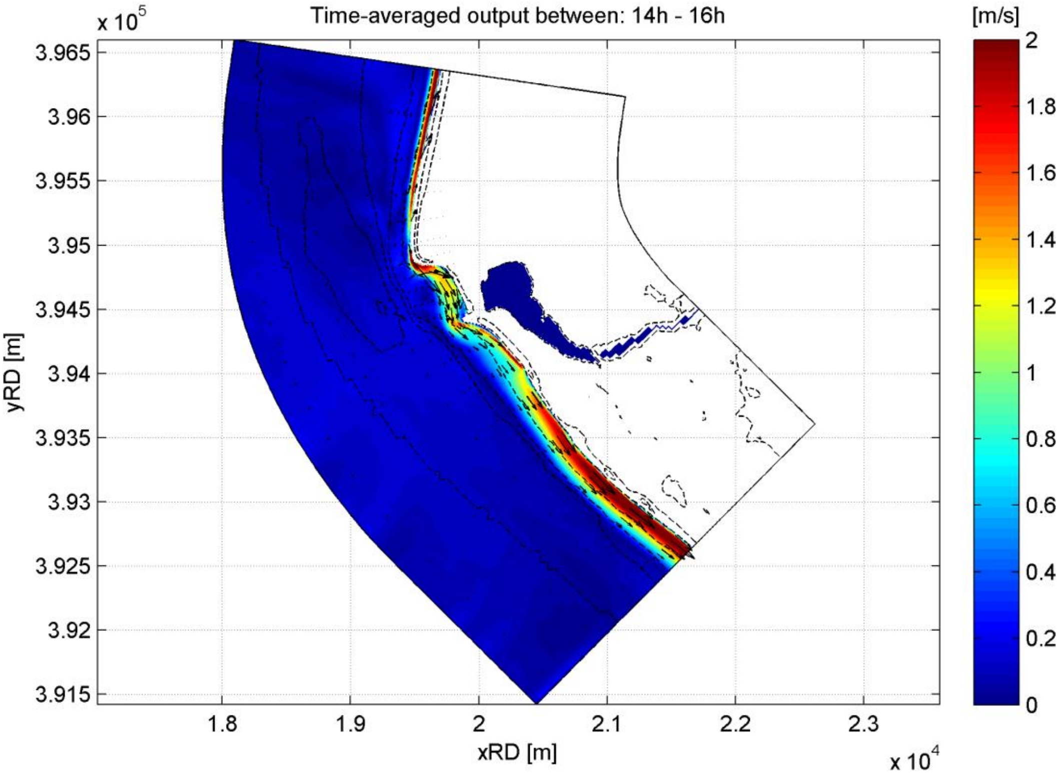

Figure 16: Time-averaged (GLM) flow velocity. The results are based on a simulation with westerly wave attack and normative storm conditions. The presented output is an averaged value for a period of 2 hours around 'storm-maximum' (after 14-16 hours of simulation time).

Velocities

It is expected that the curved coastline near Westkapelle, in combination with a more or less unidirectional wave field, results in alongshore current flow and related sediment transport. Figure 16 shows whether this is actually the case.

The presented flow field represents depth-averaged Generalized Lagrangrian Mean (GLM) velocities, visualized by both a vector field and a map with velocity magnitudes. In Figure 16 the time-averaged flow is presented for a 2-hours period around the time of maximum storm intensity (simulation times 14 h – 16 h).

The figure shows a relatively strong near-shore and shore-parallel flow with speeds up to 2 m/s in both the northern and southern areas of the domain, just as expected. The velocity field in the northern area consists of a small band of high velocities along the dike, while a wider band of high velocities is found at the foreshore in the southern part of the domain. Moreover, the sharp corners of the dike segments around the central beach are accompanied with strong current velocities, enabling sediment transport away from the small beach towards surrounding areas, and vice versa.

Sediment transport

The simulated flow field suggests that during severe storm conditions a net loss of sediment is expected for the whole model domain. In fact, the curved coastline generates flow divergence whereby significant alongshore gradients are found. To illustrate the net flow of sediment, the sediment transport rates are presented as well; in Figure 17. Similar to the flow field data in the previous figure, the presented sediment transport rates are time-averaged values over a period of 2 hours, around storm maximum.

Both in the southern part and in the central part of the model domain relatively high transport rates are found along the coast. Near the central beach, which is surrounded by coastal structures, sediment transport is simulated around the tip of the southern structure. So during storm conditions, the central beach actually loses sediment, which is transported southward.

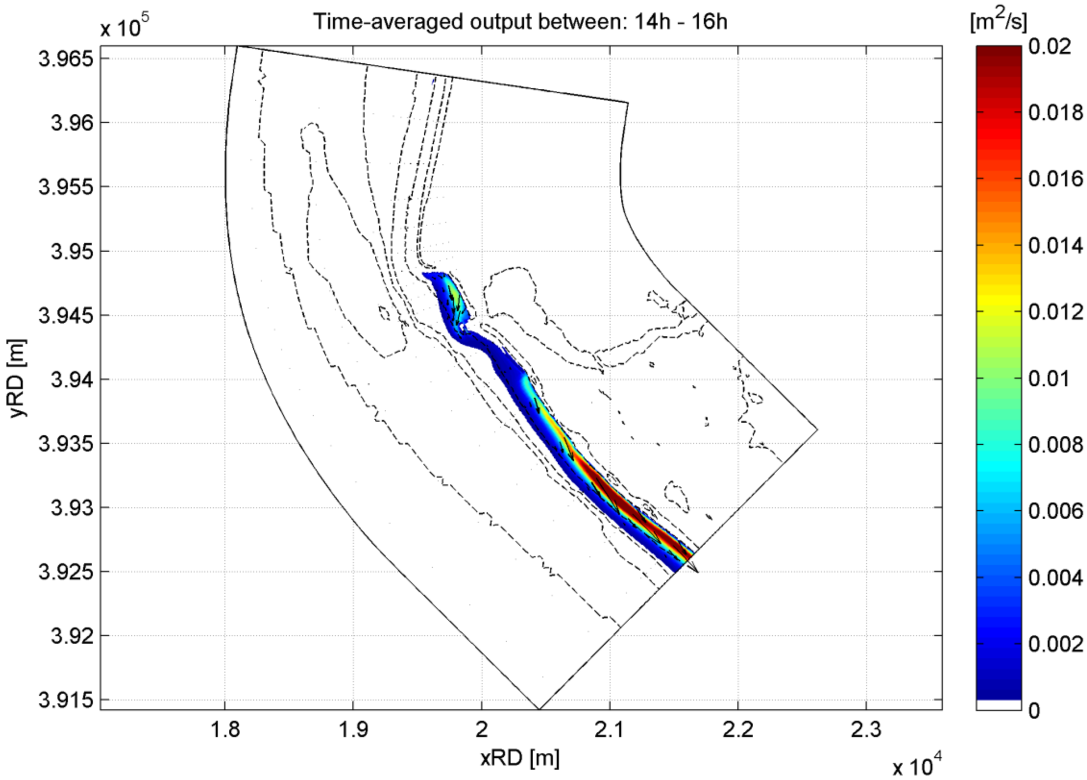

Figure 17: Time-averaged sediment transport rate. The results are based on a simulation with westerly wave attack and normative storm conditions. The presented output is an averaged value for a period of 2 hours around 'storm-maximum' (after 14-16 hours of simulation time).

The dune area in the south also experiences sediment losses due to south-eastward directed transport. Noticeable here is the strong gradient in the sediment transport rates. The rate of transport continuously increases towards the south. As a consequence it is expected that the specific coastal stretch loses sediment as well, since the sediment outflow rate is higher than the inflow rate.

In the presented figure it is, at a first glimpse, remarkable that no/very little sediment transport is found in the northern part of the model domain, while high alongshore velocities are simulated. However, it should be noted that the figure only accounts for dynamics within a 2 hours period around storm maximum, when high water levels are imposed. During this period the highest alongshore velocities (i.e. high enough to stir up sediment at the seabed) occur very close to the waterline (see Figure 16) at positions where the sea dike determines the elevation of the subsurface seabed. In other words, due to the (high) water level near storm maximum a significantly large part of the seaside of the (non-erodible) dike is under water, such that the wave- and current-induced bed-shear stresses, which are large enough to stir up sediment, only act on a non-erodible layer. It is, however, expected (and confirmed) that during other phases of the tide and the storm also in the northern parts of the domain, in front of the dike, sediment is transported; when the water level is slightly lower.

Sedimentation and erosion

As a final step in presenting the results of the reference simulation the resulting bed level changes due to the storm conditions are considered. Those bed level changes are quantified and analysed by determining the differences in bed level elevations between the initial situation and the situation after 30 hours of simulated storm conditions. From those bed level changes typical erosion- and deposition-patterns are obtained that illustrate the impact of the storm on the coastal area.

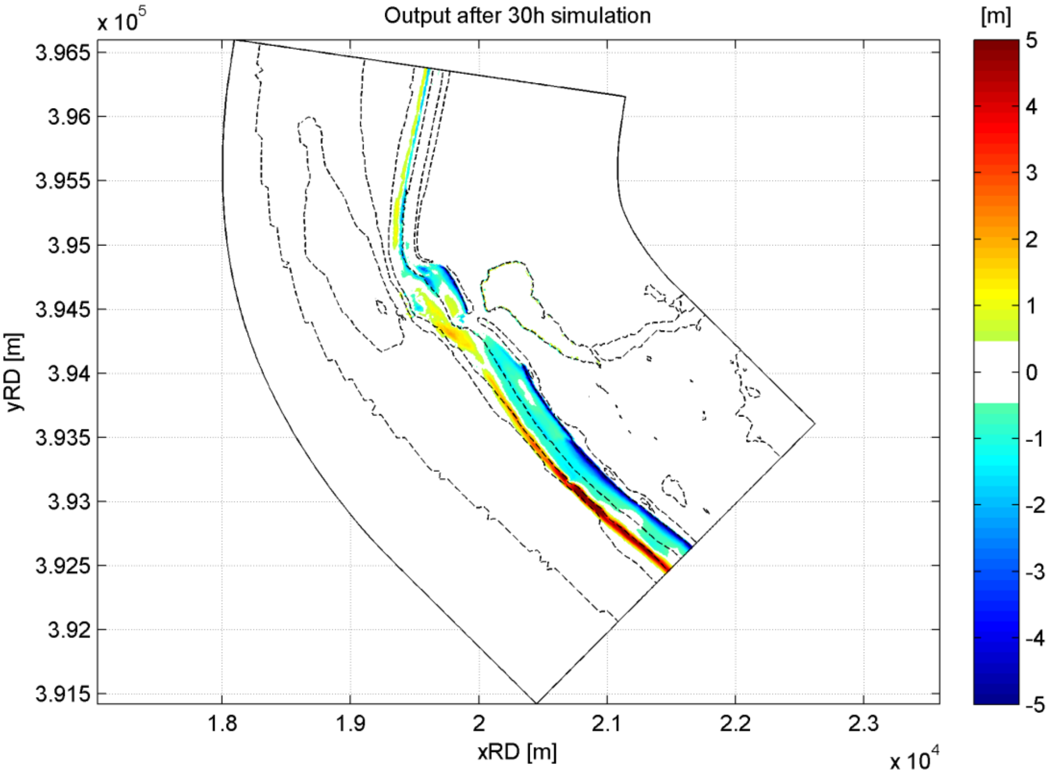

Figure 18: Bed level changes. The results are based on a simulation with westerly wave attack and normative storm conditions. The presented output is the result of 30 hours of simulation time. Redish colours indicate deposition areas, and bluish colours are associated with erosion patterns.

The bed level changes for the reference simulation are presented in Figure 18, where the absolute differences (in meters) are plotted. In the northern area only bed level changes are found just in front of the dike. Those erosion- and deposition patterns are associated with excavation near the toe of the dike. The resulting excavation pits are also (but in smaller dimensions) found in front of the coastal structure just south of the central beach.

In the southern area, where the coastline is protected by dunes (or actually one dune row), a significant amount of dune erosion is predicted. Besides only *dune* erosion also a certain amount of sediment at beach level is eroded, lowering the whole profile just seaward of the first dune row. The eroded sediment is partly deposited near the landward slope of the tidal channel and is partly transported in alongshore direction due to the southeast-directed flow.

Due to gradients in the alongshore transport rates of sediment the amount of sediment outflow is larger than sediment inflow, causing a net loss of sediment in the considered area. The effects of this asymmetry are larger for the area just south of the structural defences (in the centre of the model) then for the area near the south-eastern lateral model boundary. Therefore, some clear differences are noticeable in the erosion- and deposition patterns.

A similar and even more pronounced asymmetry between erosion and deposition is found near the central beach in-between the dike and the fortified ‘headland’. The detailed view on the bed level changes in the central area is presented in Figure 19, in which the same results are presented as in the previous figure.

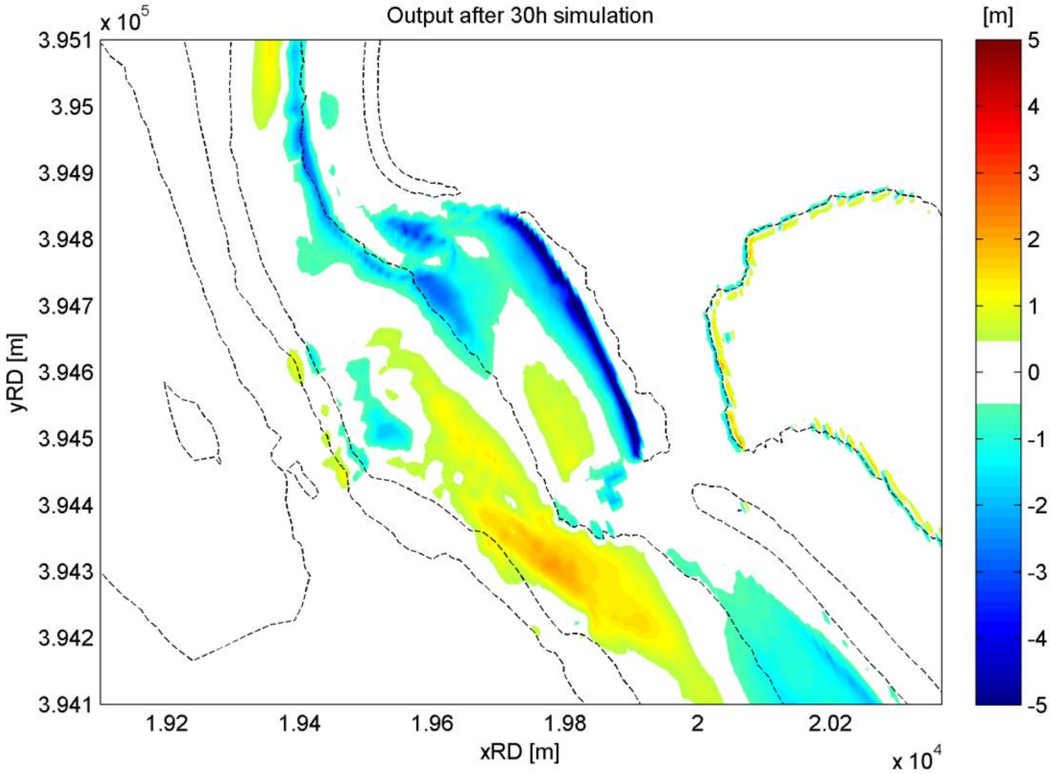

Figure 19: Bed level changes for a specific area within the model domain (central beach). The results are based on a simulation with westerly wave attack and normative storm conditions. The presented output is the result of 30 hours of simulation time. Redish colours indicate deposition areas, and bluish colours are associated with erosion patterns.

The figure shows several interesting features related to dune erosion; and in particular to dune erosion along a complex-shaped coastal stretch. Just like any 'normal' dune area, the dune row behind the central beach is eroding due to the stormy conditions at sea. But the surrounding coastal structures, the near-shore tidal channel and the strongly curved shoreline, cause alongshore effects that play an important role in the distribution of sediment over the foreshore. Moreover, it is hypothesized that an outflow of sediment at the foreshore enhances the process of dune erosion by 'clearing space' in the (subsurface) deposition area. In order to test this idea, comparisons with other (1D) model simulations are required. Later on in the report this point is discussed in more detail.

One of the most interesting features in Figure 19 is the limited amount of sediment deposition seaward of the central beach. Most of the sediment that is eroded at that location is deposited downstream 'around the corner' of the structural defence. And only a minor amount of sediment is trapped *at* the original beach (south-side) due to the presence of the non-erodible structure. Moreover, almost no sedimentation is simulated inside the tidal channel, since all sediment exchange seems to be confined to the shallower foreshore.

Another remarkable result in the presented figure is the absence of deposited sediment around the southern tip of the sea dike in the north. Due to the curved shape of the dike and the direction of wave attack, flow divergence is noticed near this location, associated with relatively high velocities, transporting the suspended sediment downstream (either to the north of to the south). As a consequence, more erosion is simulated at the seaward side of the southern tip, compared to the amount of erosion along the dike segments further northward. Also a significant amount of erosion is observed *at* the beach (north side) and landward of the breakwater that extends south of the dike.

In short, the results of the first tests with the reference simulation for the modelling of storm impact on a complex coastline, using a 2D model approach, show that alongshore effects could have a significant effect on erosion- and deposition patterns along the coast. Especially for locations with large spatial variations in bathymetry and coastline orientation, a 2D simulation is preferred in order to account for flow divergence and accelerated transport rates. More detailed comparisons with a 1D approach will follow later on in this chapter.

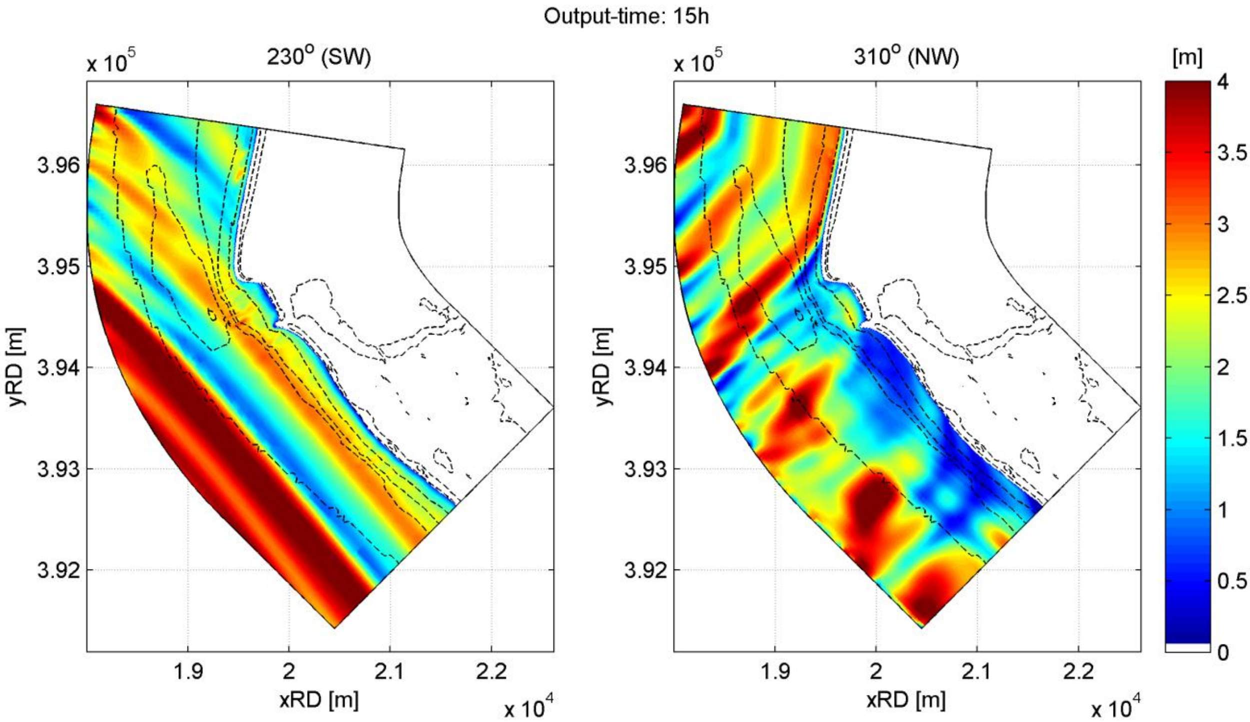

Figure 20: Significant wave height. The results are based on a simulations with incoming wave angles from 230^o N (left panel) and from 310^o N (right panel), and normative storm conditions. The presented output is a snapshot at the time of maximum storm intensity (after 15 hours of simulation time).

4.2.1.2 Waves from other directions

In the previous sections the first results of the so-called reference simulation are presented. In that particular run such a wave attack was imposed that all waves were approaching the coastline from west. In this section results are shown for simulations with other directions of wave attack. As two extremes for possible wave directions, angles are imposed that deviate plus or minus 40 degrees from the westerly wave direction. So, westerly waves have a nautical wave angle of 270 degrees (from North), and the waves for the two extra cases have nautical angles of 230 degrees and 310 degrees.

In the following, wave fields, flow fields and bed level changes are presented for both of the additional simulations, in a similar way as for the reference simulations.

Waves

The wave fields corresponding to the additional simulations with deviating offshore wave directions are presented in Figure 20. In the left panel of this figure the offshore imposed wave direction is 230 degrees, which is close to southwest. The right panel shows the wave field with waves from 310 degrees (or almost northwest).

The south-westerly waves approach the dune area in the southeast almost under a shore-normal angle, and the direction of wave propagation is also more or less parallel to the lateral boundary of the model domain. Although south-westerly storms generally do not appear to be as severe as north-westerly storms (due to the shape and size of the North Sea), in these simulations the (wave) conditions are set equal for all wave directions. So, the intensity of the south-westerly wave attack equals the intensity of the westerly wave attack, but the wave approach the coast under a shore-normal wave angle.

The north-westerly waves, however, enter the model domain under quite an off-normal angle, such that not all wave crests travel into the domain through the offshore boundary. Waves also enter the domain through the lateral boundary at the north. Elongation of the wave crests in the so-to-call ‘shading-area’ near the edges is enabled by an internal model setting in XBeach (*leftwave/rightwave* = *wavecrest*). However, the presented results are based on simulations without the ‘*wavecrest’* option, since strange velocity jets were generated at the lateral boundaries for this model setting. So, as a consequence, the presented results are based on Neumann-type wave boundaries.

For the north-westerly waves, which propagate along the axis of the tidal channel, clearly the typical process of wave refraction is visible in the right panel of the figure. From the channel-slope towards the coast, the direction of wave propagation rotates landward. Overall, the imposed angle of wave attack results in a maximum impact on the dike in the northern part of the domain, and a relatively low wave impact on the sandy coastal stretch (since that area is located ‘around the corner’).

Despite the oblique incidence of the north-westerly waves, with respect to the lateral model boundary, the wave fields (and resulting wave groups) seem to be quite satisfactorily; except for the mentioned shading area near the northern boundary. The output of other relevant parameters is presented in the next part of this section.

Velocities

In contrast to the flow field for the simulation with westerly waves, the flow patterns for other wave directions consist of some remarkable features (see Figure 21). The most remarkable result is the relatively wide band of high velocities that is simulated in front of the dike for the situation with a north-westerly wave approach (partly through the lateral boundary due to the oblique incidence).

First the flow field in the left panel, forced by south-westerly waves, is considered. Along the coastline a velocity field is simulated which corresponds to the expected behaviour for south-westerly waves. Due to the more or less shore-normal wave attack in the sandy area in the south, no steady and strong flow current is generated along the coast. In fact, the subtle curve in the coastline results in a flow separation due to divergence. The strongest current (but not as strong as the one generated by the westerly waves) is directed southward along the shoreline; out of the domain. While a weaker alongshore current is directed northward, from the dune area towards the coastal stretch of which the dune foot is protected. At that point a flow convergence is observed due to a southward directed flow which originates near the central beach near ‘Het Gat van Westkapelle’. Finally it can be seen that a relative strong current is formed in front of the dike, since the waves approach this area under a very oblique angle, generating a large velocity shear. This current is stronger than the one generated by the westerly waves.

In the right panel high velocities near the northern boundary are shown, but in contrast to the left panel, the flow is directed southward. The high velocity-band in the right panel of the presented figure is generated by the north-westerly waves that push water along the sea dike. This result is in line with the expectations, based on the orientation of the coastline at that location. Due to the southward directed near-shore flow-velocity, eroded sediment from excavation pits at the toe of the dike is transported towards the sandy area in the south. However, at a first glimpse the magnitudes in the velocity-field seem to be rather high. Whether this is a realistic scenario should be validated and tested when using this model for practical applications. At this point the simulated flow-field is considered to be doubtful (for the velocity magnitudes), while the overall flow-patterns are in line with the expectations.

More in general it is noticed that the oblique wave incidence from the north-west mainly affects the coastline which is protected by the sea dike. The dune area and the beaches are, in fact, located in a shaded area for both the wave field as the generated flow field. In the southern part of the domain the velocity magnitudes are significantly lower than for the simulations with other wave directions. So, the very strong inflow at the northern boundary has only a limited influence on the area where significant erosion can occur due to the presence of dunes. The dune area is thus indirectly protected by the dike, for waves originating from the north-west.

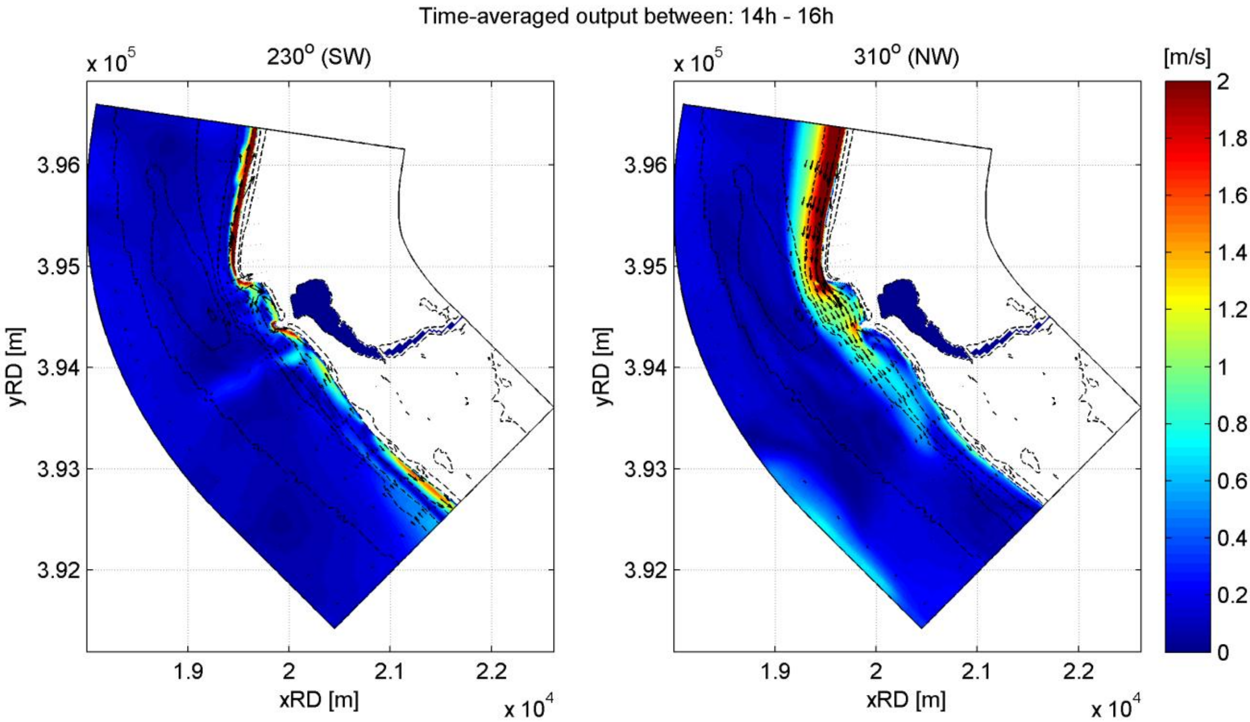

Figure 21: Time-averaged (GLM) flow velocity. The results are based on a simulations with incoming wave angles from 230° N (left panel) and from 310° N (right panel), and normative storm conditions. The presented output is an averaged value for a period of 2 hours around 'storm-maximum' (after 14-16 hours of simulation time).

'Wavecrest' option

Again it is noted that the '*wavecrest'* option is disabled for the lateral boundaries, just as mentioned in the wave-section. This choice could result in a somewhat disturbed wave field near the boundaries in case of a large obliqueness of the wave field. However, the simulations with *enable 'wavecrest'* options did result in very strange velocity jets near the side boundaries. And surprisingly the largest flow disturbances were generated near the northern boundary; for simulations with south-westerly waves. So, instabilities seem to arise not only in the shading area for the wave field, but even outside this area, where it is not expected. Further analyses, not presented in this report, showed that the boundary-type definitions could have a significant influence on the stability of the dynamics near the (lateral) boundaries, especially for a curvilinear grid definition. One of the hypotheses concerning this topic is that an increased amount of curvature of the grid towards the edges negatively affects the in- and outflow dynamics in a 2D XBeach model domain. The performed tests showed that alongshore stretching of the grid, such that rectilinear cells are formed near the lateral edges does improve the model's performance in simulating realistic flow field.

Sedimentation and erosion

The simulated sediment transport rates result in similar patterns as presented for the flow field, therefore these results are not presented in this report for the two additional wave directions. Instead, the final results for the bed level changes are presented in this section. In Figure 22 the erosion- and deposition patterns are presented, based on the differences of the bed levels between the pre-storm and the post-storm situations. Reddish colours indicate locations where sediment deposition occurred, while bluish colours represent eroded areas.

From the left panel several conclusions can be drawn. First of all, there are some remarkable features simulated in the north-eastern part of the domain, just in front of the dike. A wavy pattern is observed in the erosion/deposition patterns, which is not expected on forehand, since only some (minor) excavation pits should be formed. Apparently these features are forced by a somewhat disturbed flow field in the corner between the dike and the model boundary, possibly due to (undesired) channelling of the wave field and flow in the corner of the model. A combination of reflections near the dike and a certain type of flow-handling at the boundary in a relatively small area might induce problems. This specific topic should be studied in more detail in the near-future.

More in general view (thus excluding the features at the northern boundary); the distribution of deposition and erosion areas equals the expectations. Since the direction of wave attack is from the south-west, which is more of less perpendicular to the orientation of the sandy coastline in the south, smaller alongshore sediment transports are generated. It was already shown in Figure 21 that the alongshore currents are much weaker for this specific wave direction. The absence of strong currents (and transport rates) results in smaller erosion volumes in the dune area because most of the eroded sediment will act as a safety buffer at the foreshore of that particular location. Moreover, the converging flow in front of the protected coastal stretch just south of the central beach results in a deposition zone at that location. Also the more inland-located central beach itself acts as a trap for sediment when waves are approaching from the south-west (see detailed view in Figure 23). So, relative to the situation with westerly waves, more sediment deposition is found near the central beach, while in the prior simulation deposition occurs further southward.

The right panel of Figure 22 shows the patterns of bed level changes for the situation that waves are approaching from the north-west. The first remarkable result is that relatively large amounts of deposition are simulated in the northern part of the model domain, while this is not compensated by equal amounts of erosion in the nearby area. The only area where a significant amount of erosion is simulated is the southern tip of the sea dike, where the dike orientation changes to a more landward direction. However, it is obvious that the sediment that deposited in front of the dike originates from a location upstream and therefore is transported into the model domain through the (northern) lateral boundary. This inflow of sediment is enabled by the Neumann-type of boundary definition. Question is whether the observed patterns give a realistic representation of the dynamics in this area. This somewhat doubtful result for bed level updating (and sediment transport) contributes to the earlier findings that a more detailed analyses is desired for the inflow- and outflow- dynamics in a curved 2D XBeach model domain.

Similar to the results in the left panel the erosion and deposition patterns in the dune area (south side) are closer to the expectations. Since this area is situated in a shaded area of the flow- and wave field only a small amount of erosion is expected, while the sediment subsequently is distributed by the southward-directed flow along the coast.

Moreover, the central beach area just south of the dike is shielded as well for the most severe wave conditions. As a consequence a relatively small amount of erosion is found in this area. In contrast, lots of deposited sediment is simulated at the foreshore of the beach, which obviously not originates from the adjacent dunes. When considering the flow field for this location, it is concluded that the deposited sediment is transported by the strong jet along the dike. Deposition in this particular area is caused by the flow gradients that result in convergence of the sediment transport field. As shown in Figure 23, the erosion/deposition patterns for the simulations with north-westerly waves significantly deviate from the other cases. Especially the amount of deposited volume seems to be overestimated in the results.

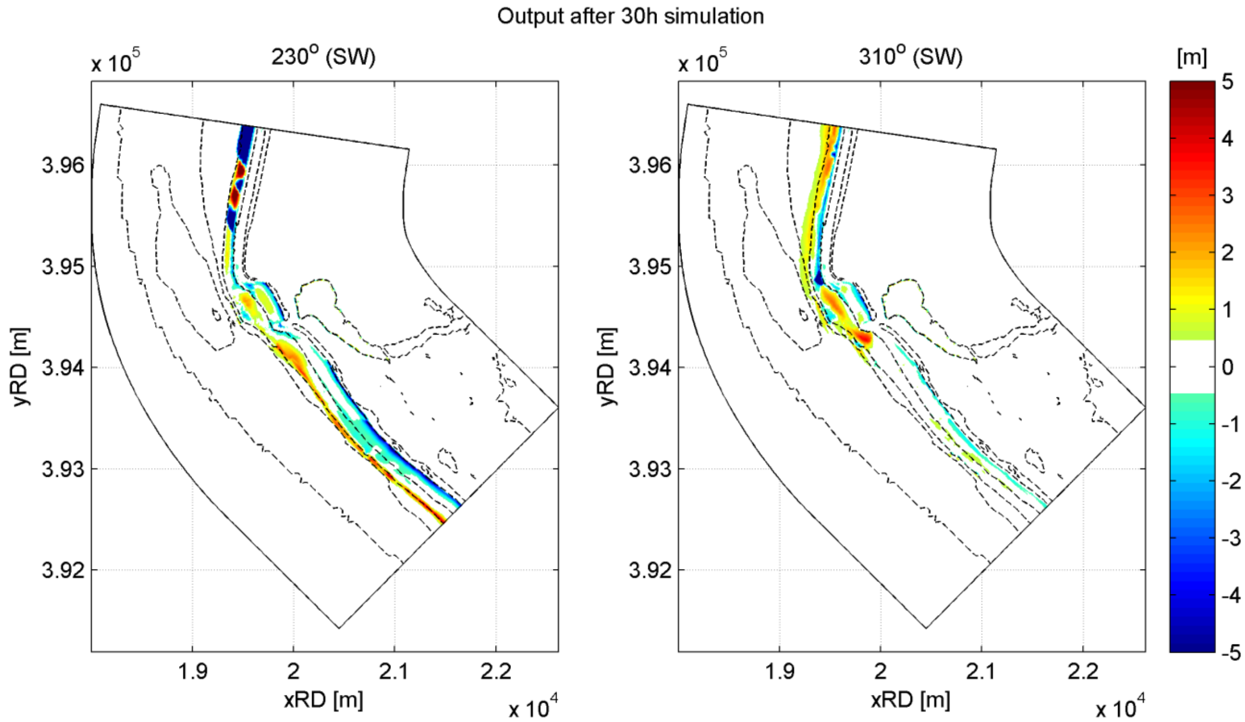

Figure 22: Bed level changes. The results are based on a simulations with incoming wave angles from 230° N (left panel) and from 310° N (right panel), and normative storm conditions. The presented output is the result of 30 hours of simulation time. Redish colours indicate deposition areas, and bluish colours are associated with erosion patterns.

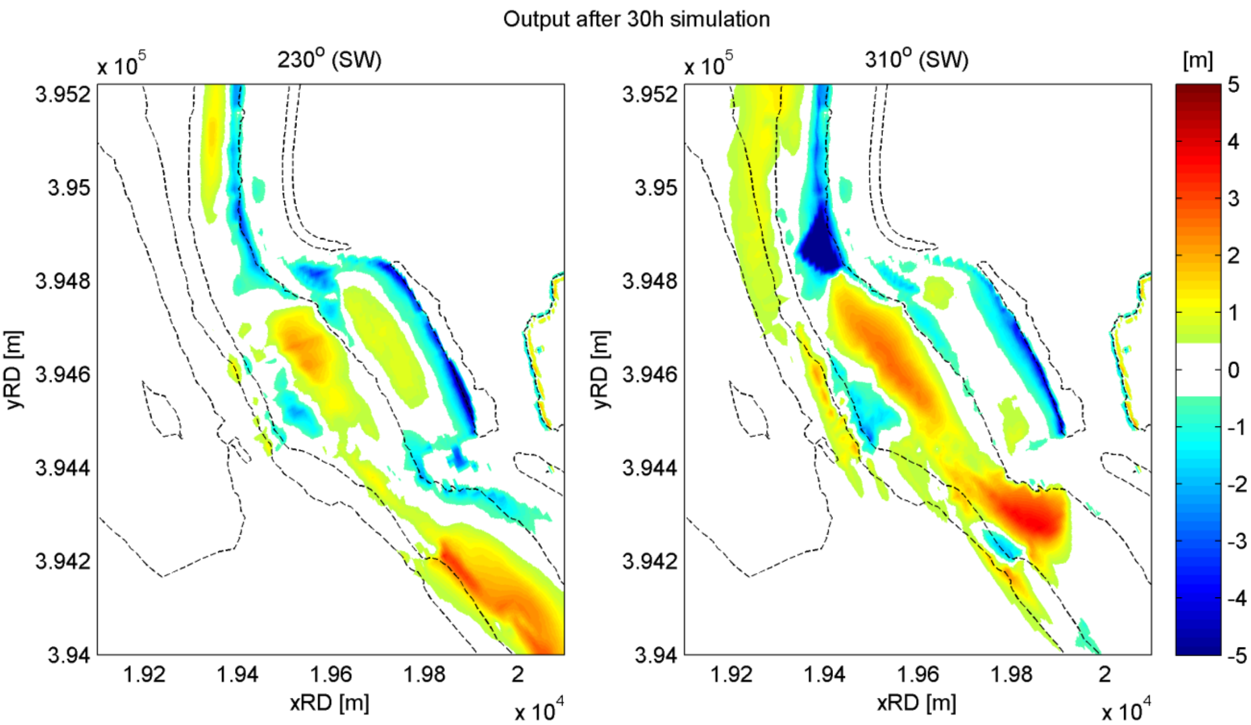

Figure 23: Bed level changes for a specific area within the model domain (central beach). The results are based on a simulations with incoming wave angles from 230° N (left panel) and from 310° N (right panel), and normative storm conditions. The presented output is the result of 30 hours of simulation time. Redish colours indicate deposition areas, and bluish colours are associated with erosion patterns.

4.2.2 1D storm impact modelling (XBeach)

In addition to the 2D dune erosion simulations with XBeach also a 1D approach with XBeach is considered to determine the amount of dune erosion during normative storm conditions. For all cross-shore components of the grid in the 2D model domain separate transect models are defined (see Figure 12), for which calculations are performed.

Obviously, for a 1D approach all alongshore components of the coastal dynamics are omitted since there is no interaction between the different transect-models. So, by definition, a sediment balance is expected to be found along the considered transects. As a consequence all eroded sediment in the dune- and beach area is deposited at the foreshore or in the near-shore tidal channel.

In the following a series of three examples is presented of results of the transect model approach for dune erosion modelling. The same transects are selected as indicated earlier in Figure 12 (red lines): transects yID030, yID060 and yID105. The model results are presented in Figure 24, where in addition to the 1D XBeach results also the output of the 2D XBeach approach is shown for the particular locations (pink solid line). Note that two different erosion profiles of the 1D model are considered in the figure. As explained in the previous chapter for each transect two simulations are performed; one with normal wave incidence and one with oblique wave incidence depending on the orientation of the considered transects (see Figure 14 for an illustration). So, the red solid line in the figure represents the result for the calculations with shore-normal wave attack, and the red dashed line is the result for an off-normal wave incidence.

Results for transect yID030

Starting with the upper panel of Figure 24, a cross-shore profile in the southerly dune area is considered, which is situated relatively far away from the actual 'complex area' around the central beach, south of the sea dike. The transect does not contain any structures and the coastline at that location is more or less straight. Under normative storm conditions both the 1D and 2D approach predict a certain amount of dune erosion such that the first dune row is not breached and the hinterland is protected from flooding by this dune row.

Comparing the two different 1D cases it can be concluded that more erosion is simulated for the case that an obliquely incident wave attack is considered. More specific, an extra amount of erosion is found near the dune face and near the original shoreline. As a consequence (and due to the 1D approach that forces a closed sediment balance), also more deposition is found for the case with oblique waves. For both 1D cases the eroded sediment is deposited along the tidal channel slope in front of the coast, such that the landward side of the channel is moved seaward. The extra eroded sediment for the case with oblique waves is deposited near the toe of the channel slope.

The fact that the 1D simulation with oblique wave incidence (and without alongshore transport capacity; due to the 1D approach) results in a larger amount of dune erosion is quite remarkable. It is expected that normal wave incidence induces a more direct wave attack with higher erosion rates. The only mayor aspect that could cause higher amount of erosion for oblique wave incidence, a gradient in alongshore sediment transport rates, is not included in a transect model. The absence of this crucial information for a 1D model approach for oblique wave incidence makes this a rather complex scenario that should be studied in more detail in future studies.

In contrast to the 1D models the 2D XBeach model does include all relevant dynamics to account for alongshore sediment transport in the near-shore. On forehand it is expected that the presence of (gradients in) shore-parallel currents and associated sediment transport will cause more dune erosion. The reason for this expectation is that the foreshore will constantly be 'cleaned-up' when the amount of sediment outflow is larger than the amount of sediment inflow. Due to this clean-up a new (dynamic) equilibrium state can be formed. This can be explained in two ways. First, more space at the foreshore means an enlarged capacity such that more eroded sediment can be deposited there. And second, a smaller amount of sediment deposition at the foreshore causes a smaller reduction of the wave height towards the shoreline, so a more intense wave attack reaches the dune face. Both aspects would likely cause a larger amount of sediment erosion in case a gradient exist in the alongshore sediment transport rates.

Since the results in Figure 17 showed that there actually exists an alongshore transport gradient for the considered part of the coastal stretch, more dune erosion is expected for the 2D model result for transect yID030 in Figure 24. The top panel of the figure indeed shows that the 2D model simulates larger amounts of erosion in both the dune area and the whole area around the shoreline. It is also clear that the sediment balance for this transect is not closed, since more erosion is found than deposition. As mentioned earlier this is caused by the diverging alongshore current (directed southward). So the eroded sediment is mostly transported southward, while this is not fully compensated by sediment that originates from locations upstream.

Results for transect yID060

The middle panel of Figure 24 shows the results of the 1D and 2D simulations for transect yID060. The coastal stretch around this transect is located south of the central beach and is protected by a dune foot fortification. It is clearly shown that the coastal structure prevents the dune row from eroding. All mayor bed level changes occurred seaward of the structure.

The results of all model runs are very similar for this specific situation. The only important difference can be found just landward of the tidal channel where deposited sediment is found for both 1D cases, while the deposition not occurred for the 2D model due to the alongshore losses in that case. So, in fact the amount of erosion is similar in all cases while there are some (minor) differences in the amount of deposited sediment.

Results for transect yID105

The last panel presented in Figure 24 corresponds to a transect that is located at the central beach just south of the sea dike. This beach is in fact situated in the area for which, on forehand, the largest differences were expected between a 1D and a 2D model approach. As described earlier in this report, the coastline at this location consists of multiple complexities, such a strong curvature, a dike/dune transition, a ‘sheltered’ dune row, etc. The figure as presented here could provide more insight in the differences of the 1D and 2D model approach for this location.

Similar to the results for transect yID030, the 1D case with obliquely incident waves, results in a larger amount of erosion compared to the simulation with normal wave incidence. For both 1D simulations it is shown that the eroded sediment from the dune row is deposited in the area around the shoreline. So both the beach and the near-shore bed have an increased level after the storm attack. Only a negligible amount of sediment is deposited inside the tidal channel a little further offshore.

In contrast to the results for transect yID030, the amount of eroded sediment for the 2D simulation is not larger than the 1D cases. So in this, even more complex, situation with a sheltered dune row, the former explanation that alongshore transport gradients will result in larger amounts of dune erosion does not tell the whole story. This specific area is subject to many different (complex) processes and obviously the alongshore components do not directly result in more dune erosion. However, the figure does show that a significant larger amount of the beach area is eroded in the 2D model result. The amount of deposition is more or less equal for all cases, so the sediment from the beach is deposited further downstream.

So, despite the absence of an increased amount of dune erosion for the 2D simulation, as might be expected from theory, it is clear that a 2D model approach for complex coastlines does provide (even unexpected) new insights in the dynamics in the coastal zone.

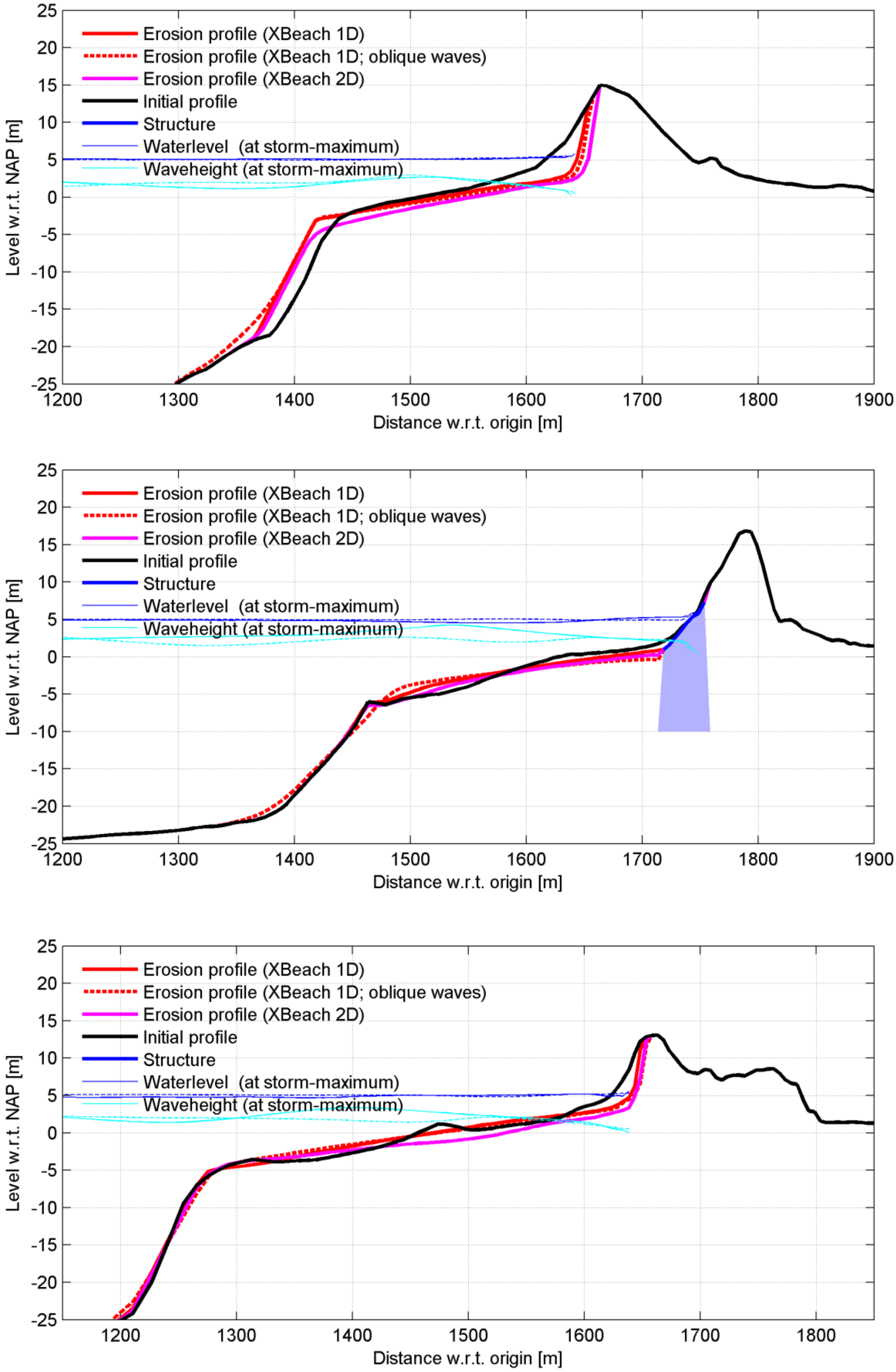

*Figure 24: Transects **'yID030'** (top), **'yID060'** (middle) en **'yID104'** (bottom). Examples of results of 1D XBeach simulations for dune erosion. In addition, the corresponding output of the 2D XBeach simulations is presented for comparison.*

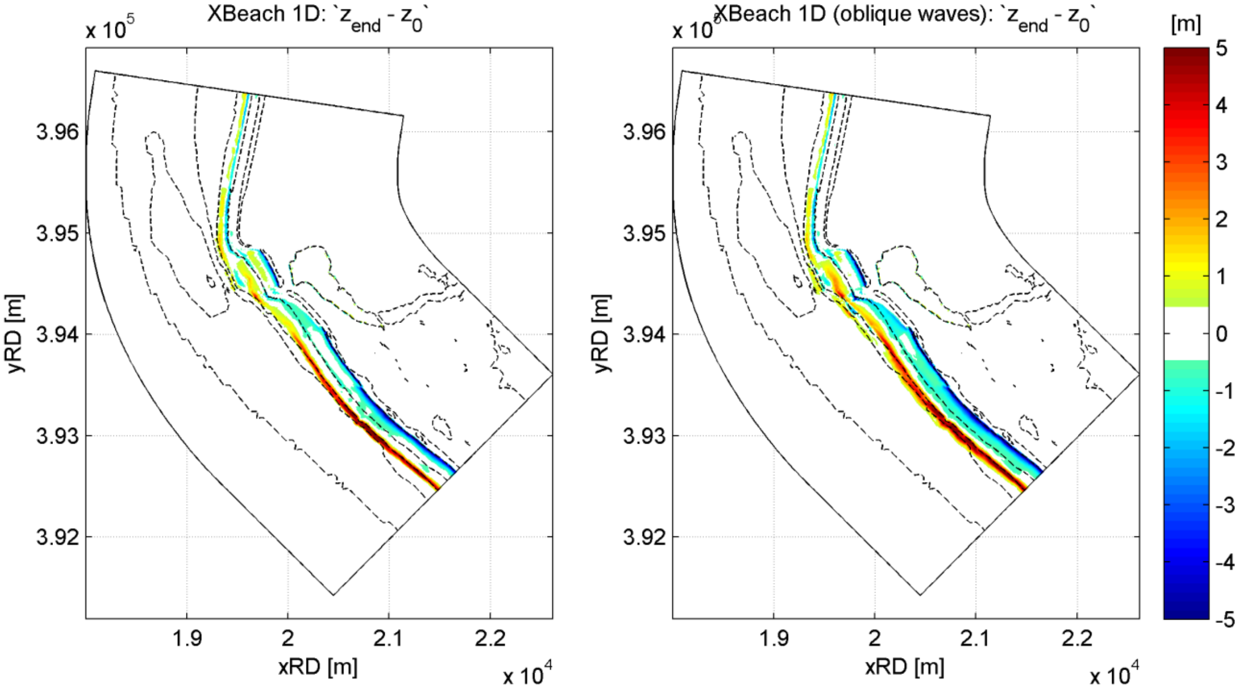

Figure 25: Bed level changes. This is a 2D representation of results from a large series of adjacent 1D XBeach models. Left panel: normal wave indidence for individual transects. Right panel: westerly waves and thus varying angle of wave indicence. Redish colours indicate deposition areas, and bluish colours are associated with erosion patterns.

Presenting 1D results in 2D overview

As a result of the 2D XBeach simulations spatial patterns of erosion and deposition are presented in Figure 18. The results of the 1D dune erosion models are presented in a similar way by combining the information of all transects in one set of data. The combination of available output for a total of 184 alongshore transects is presented in Figure 25, where per transect the bed level changes are visualized. The left panel presents the results for the simulations with normal wave incidence, while in the right panel output is presented for the simulations with westerly waves and thus off-normal wave incidence. In this last case the angle of wave incidence varies along the model domain, based on the orientation of the transects. For example, the largest angle of incidence is found for the transects in the southern part of the model domain.

As concluded from the example transects in the previous sections, the amount of dune erosion (and consequently foreshore deposition) is larger for the simulations where off-normal wave incidence is considered. This remarkable result is also clearly visualized in Figure 25. Significantly more erosion is observed in the dune area and at the beach for the whole southern part of the model domain. Much smaller differences are found between the two panels, northward of the central beach, since the orientations of the transects in the northern part are nearly west-east directed, and also due to the presence of the sea dike.

Overall, the erosion- and deposition patterns are, although different in magnitude, very similar for both cases. Erosion is simulated in the dunes and partly around the shoreline, and deposition is found just landward of the tidal channel slope.

A more detailed comparison with the 2D model results follows at the end of this chapter.

4.2.3 1D storm impact modelling (DurosTA)

So far, the storm impact modelling of the complex coastline near Westkapelle is performed using XBeach, for both the 1D and the 2D approaches. In addition another, more regularly used, 1D dune erosion model is considered in this project: DurosTA. This model is used for further analyses and comparisons with both XBeach model approaches.

For both the 1D XBeach models and the 1D DurosTA models the same model setup is used, as far as possible. An important notable difference between the model setups is the fact that the default parameter settings are used for both models. It is known that the settings for both models are (individually) optimized based on experiments, so it is not guaranteed that the default settings for physical parameters are exactly equal. Moreover, XBeach consists of a sophisticated formulation of the dynamics of bound long waves, which is not (directly) included in DurosTA.

Similar to the presented output of the 1D XBeach models, the results of the simulations with DurosTA are compared to the 2D XBeach model result. Moreover, two different 1D model results are presented per transect, since the effects of both normal wave incidence and oblique wave incidence (based on the orientation of the transects) are studied. For three example transects (yID030, yID060 and yID105) the erosion profiles are presented in Figure 26.

Results for transect yID030

The upper panel of Figure 26 shows the DurosTA model results for a transect in the southern part of the model domain. The transect is situated along a coastal stretch that is protected by dunes only. The figure shows that the dune row provides enough protection, during normative storm conditions, to prevent the hinterland from flooding. When comparing both 1D DurosTA results with the corresponding result of the 2D XBeach simulation, it is worth mentioning that the two models produce very similar results, despite the different model formulations.

The most important differences between XBeach and DurosTA are related to the typical slope of the (final) dune face and to the channel slope after sediment-deposition. The result of XBeach shows a relatively steep dune face with a clear transition level of the dune foot, and a gradual and smooth profile near/along the channel slope. On the other hand DurosTA has a smoother transition of the profile between beach and dune face, resulting in a gentler overall slope. And more seaward the final profiles of the 1D model show very steep slopes of the seaward shifted tidal channel.

In the top panel of the figure it is clearly visible that the result of 2D XBeach does not have a closed sediment balance, while the erosion- and deposition volumes for the DurosTA results are, by definition, equal. As explained in the previous section (4.2.2) gradients in the alongshore transport rates cause net sediment loss in the area of this transect. While the erosion volumes are similar for the 1D and 2D results, the 1D results present significantly larger amounts of deposition.

A comparison between the two different DurosTA results for transect yID030 shows what the effects are when considering normal wave incidence rather than off-normal wave incidence, or vice versa. DurosTA simulates the maximum amount of dune erosion for a situation with shore-normal wave incidence. The larger the off-normal angle of wave attack, the smaller the amount of erosion. Note that the difference between the resulting amount dune erosion for normal and off-normal wave incidence is opposite to the differences found for the XBeach simulations. This is quite a remarkable result that needs further consideration in future studies.

For DurosTA yields that the inclusion of oblique wave incidence is based on the assumption that waves travel a larger distance to the coast when their direction of wave propagation is off-normal; and a longer travel distance means more wave energy is dissipation. As a consequence smaller waves reach the shore, resulting in smaller erosion volumes. For clarity, the differences in near-shore wave height are shown in Figure 28.

Results for transect yID060

The middle panel of Figure 26 shows the model results of 1D DurosTA and 2D XBeach for transect yID060, which contains a dune foot fortification to protect the first dune row. Due to the more west-east directed orientation of the transect a smaller difference is found between the results of both DurosTA simulations (normal versus off-normal wave attack). Both erosion profiles show that some minor bed level changes occurred above the non-erodible structure and that small excavation pits form at the toe of the structure. Moreover, the bed level of the whole beach area decreases by approximately 2 meters, while sediment deposition takes place at the foreshore just landward of the tidal channel.

As shown before, XBeach only simulates minor profile changes above the coastal structure. Compared to DurosTA the 2D model also determines a smaller amount of beach erosion, partly because no excavation pit is formed under these conditions. However, there largest difference is, again, that the 1D XBeach model shows a much smaller amount of deposition volume at the foreshore, since most of the eroded sediment is transported downstream through the model domain.

Results for transect yID105

The last presented transect (bottom panel in Figure 26) is located at the central beach. Compared to the results of the other example locations, the similarity between the 1D DurosTA model results and the 2D XBeach output is largest. Especially the predicted amount of erosion of the dune row and the upper part of the beach is more or less equal for both models. Also the difference between the two DurosTA results (normal waves versus oblique waves) is very similar, but this is due to the orientation of the considered transect. The oblique wave incidence is based westerly waves and this transect also has approximately a west-east directed orientation. So, the wave attack is nearly identical for both types of simulations.

Compared to the 2D simulation the only notable difference is that significantly more deposition is found for the DurosTA simulations. As discussed before, the 2D approach of this area enables (southward directed) alongshore sediment transport such that only a limited amount of sediment deposits at the foreshore. In fact, for the 2D simulation even a small amount of *erosion* is found around the shoreline; due to the diverging flow field.

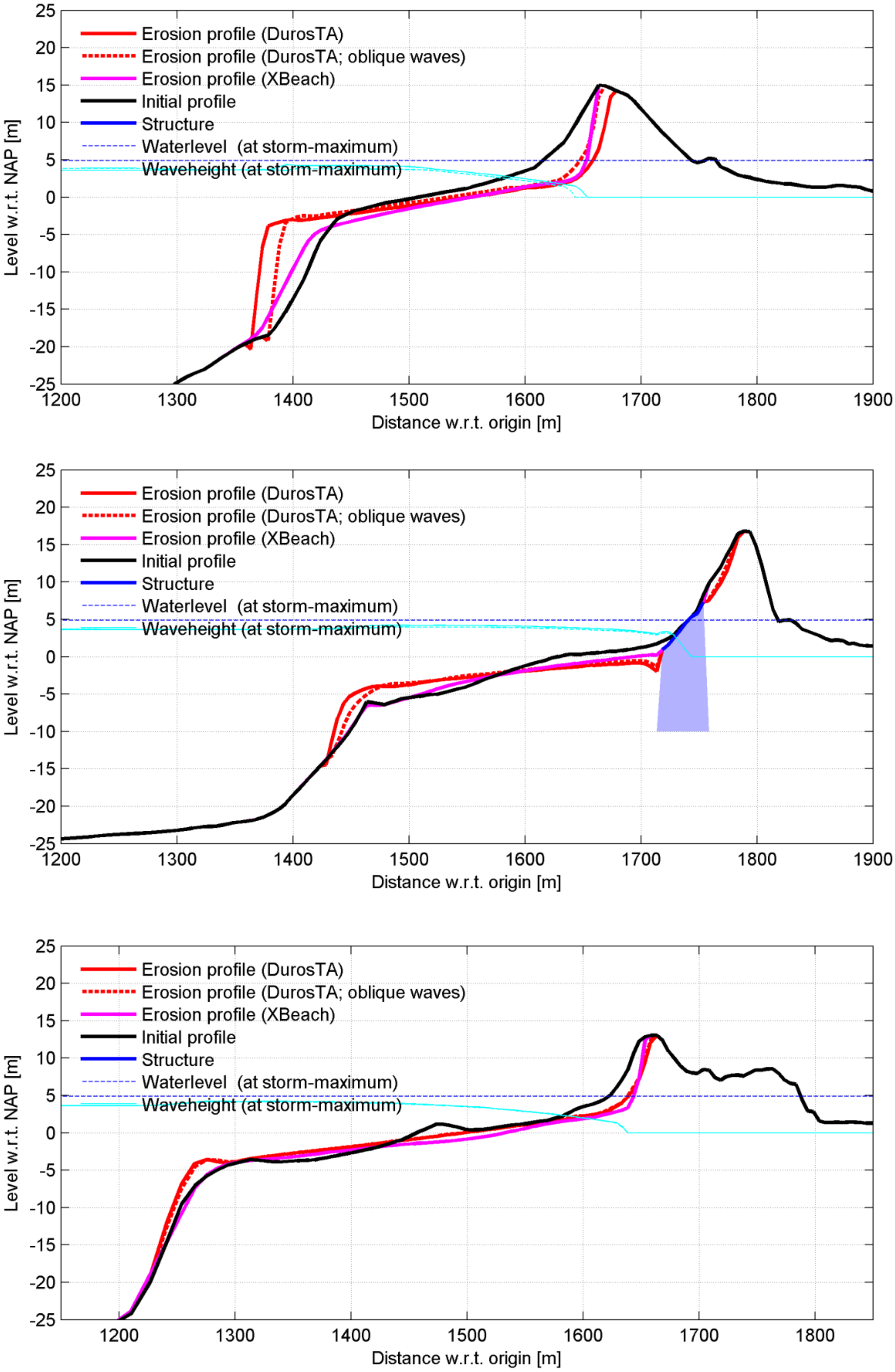

Figure 26: Transects ***'yID030'*** *(top),* ***'yID060'*** *(middle) en* ***'yID104'*** *(bottom). Examples of typical output of the 1D dune erosion model DurosTA. In addition, the corresponding output of the 2D XBeach simulations is presented for comparison.*

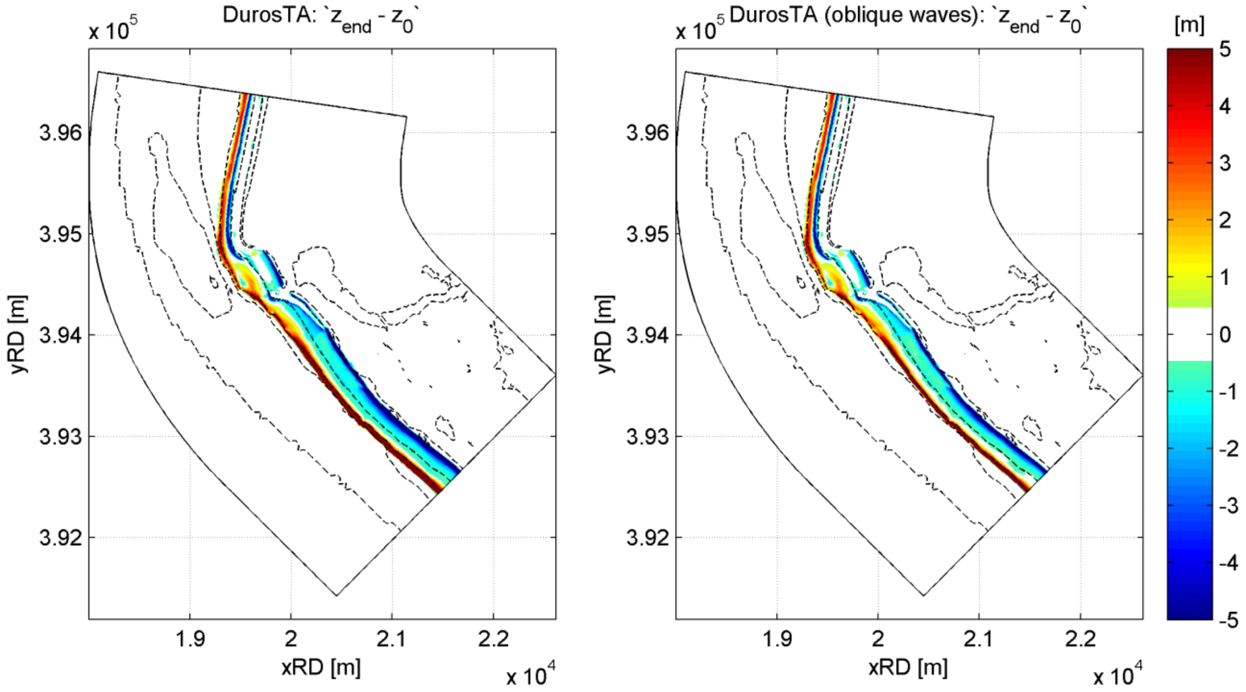

Figure 27: Bed level changes. This is a 2D representation of results from a large series of adjacent 1D DurosTA models. Left panel: normal wave indidence for individual transects. Right panel: westerly waves and thus varying angle of wave indicence. Redish colours indicate deposition areas, and bluish colours are associated with erosion patterns.

Presenting 1D results in 2D overview

Similar to the results of the 1D and 2D XBeach, the information of the simulated bed level changes for all considered transects (184) is combined and presented in a 2D overview. This 2D representation gives insight in the spatial patterns of erosion and deposition in the coastal area, based on a large series of 1D calculations. The constructed chart is shown in Figure 27, in which a comparison is made between the simulations with normal (left panel) and off-normal (right panel) wave incidence.

From the presented figure it is shown that, in general, more erosion and deposition is determined for the simulations with normal wave incidence. The same conclusion was drawn based on the presented results for the example transects. Both types of calculations show significant depths of the excavation pits that formed in front of the sea dike. In the southerly dune area more erosion of the dune face as well as more deposition at the tidal channel slope is found for normal wave incidence.

From the figure it is also clear that the difference between both panels increases southward, since the angle of wave incidence grows due to the changing orientation of the individual transects. DurosTA includes oblique wave attack by reducing the effective wave energy that reaches the shoreline, resulting in less erosion. This forced reduction of wave energy, and thus wave height, is visualized in Figure 28. The figure presents the significant wave height at the moment that the storm reaches its maximum intensity.

The near-shore wave height just landward of the tidal channel slope is significantly reduced when considering off-normal wave attack instead of shore-normal wave approach. Obviously, smaller waves result in less erosion and deposition.

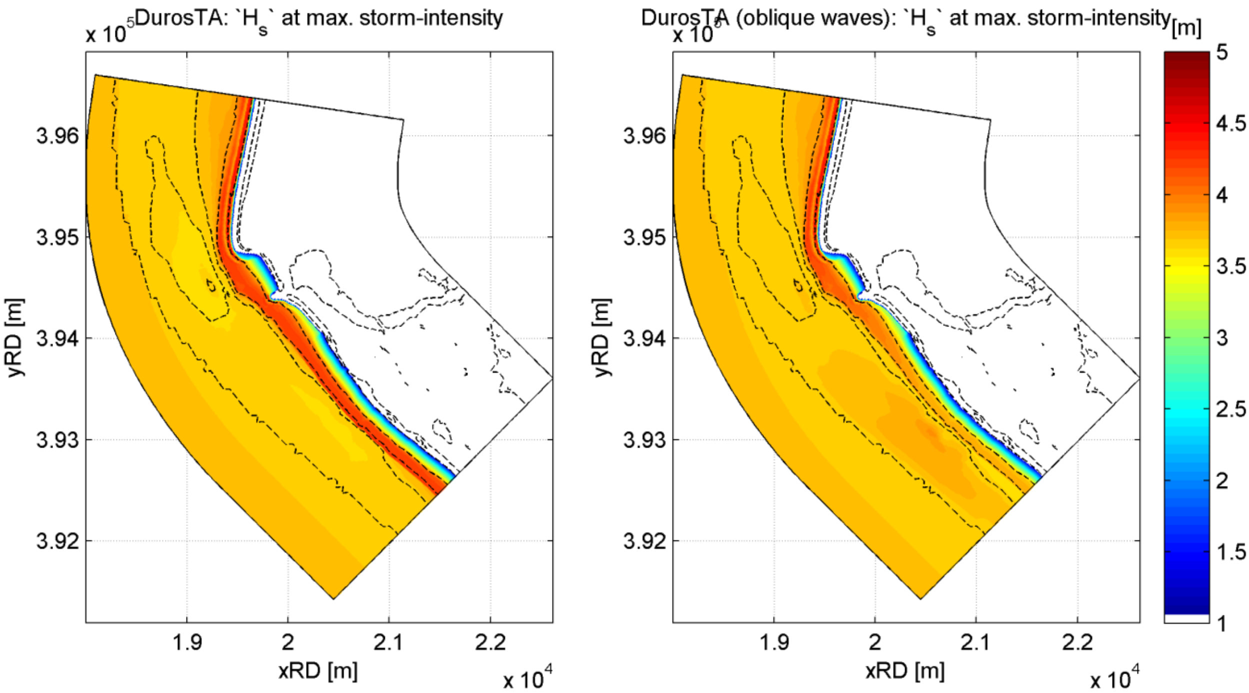

Figure 28: Significant wave height. This is a 2D representation of results from a large series of adjacent 1D DurosTA models. Left panel: normal wave indidence for individual transects. Right panel: westerly waves and thus varying angle of wave indicence.

Advanced options to schematize alongshore effects

Dune erosion model DurosTA contains some advanced options to include the effects of alongshore variations in a schematized way. One of the relevant options for this project is the possibility to include the effect of coastal curvature in the calculations. By default a straight coastline is considered in the model such that no alongshore sediment gains or losses are allowed. The definition of a certain value for coastal curvature forces the model to perform an additional calculation, for each transect, by defining a secondary transect with deviating orientation in order to determine sediment losses in the primary transect due to alongshore gradients.

It is interesting to see whether the consideration of coastal curvature in DurosTA simulations results in comparable sediment losses (or gains), as determined by the more sophisticated 2D XBeach model approach. More detailed studies are suggested at this point, but for a first impression the difference between a straight and a curved coastline definition is presented in Figure 29. For both cases normally incident waves are considered and it is shown that more erosion occurs when a curved coastline is considered. Curvature induces alongshore transport gradients and net sediment transport. And in the previous section it is explained that alongshore sediment losses result in relatively lower bed level at the foreshore, which subsequently results in less wave height reduction, more severe wave attack at the shore and therefore more dune erosion. In fact the lower level of the foreshore also means that its ‘in-take’ capacity for sediment from the dunes is larger.

Figure 29 shows, for one example transect (yID030) that coastal curvature results in a total sediment loss of 908 m^3/m along the transect. The amount of curvature is imposed by setting a typical radius of a schematized arc that represents the coastline position. For this experiment a radius of 3000 m is used, based on the change of transect orientation near Westkapelle. Obviously a smaller radius (and thus a larger curvature) results in larger sediment losses along the considered transect.

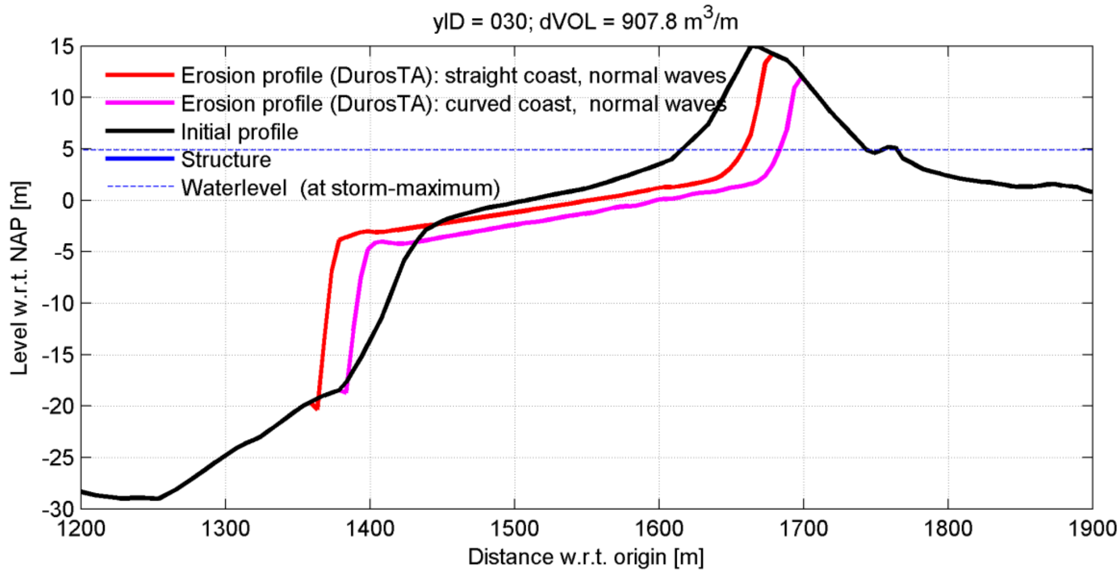

Figure 29: Result of DurosTA simulation for transect yID030. The typical difference between simulations with and without coastal curvature is shown here. The determined volume-difference between both results is 908 m^3/m.

In the next section the typical value for the amount of sediment loss is compared to the determined gains and losses, as simulated with the 2D XBeach model. This comparison contributes to the understanding of alongshore processes and the way they are implemented in relatively simple 1D dune erosion models.

4.2.4 Comparison 1D and 2D results: erosion and deposition patterns

In the previous sections the individual results of 2D XBeach, 1D XBeach and 1D DurosTA simulations are presented in order the show (some of) their possibilities regarding to storm impact modelling. It is shown that the results of a large series of 1D transect models can be combined such that a 2D overview of the results can be constructed. In the following sections the results for the 1D and 2D models are discussed in more detail, while comparing both types of approaches. Subsequently the results of the different model approaches are presented in an alternative manner such that volume differences along the coastline can be analysed in more detail.

2D XBeach versus 1D XBeach

For both the 1D and 2D results of XBeach spatial overviews with erosion and deposition patterns are presented for the whole model domain. In this section a more detailed comparison is made between the results of both approaches. In Figure 30 and Figure 31 the bed level changes are presented for two different areas within the model domain. The first figure shows a comparison between 1D and 2D XBeach for the area around the central beach, just south of the sea dike. And the second figure focuses on the dune area in the southern part of the domain. Note that only the results for westerly waves are presented, which means that the presented 1D results are based on the simulations with oblique wave incidence, instead of normal wave incidence.

Several interesting differences are found in Figure 30, where clearly the results of alongshore effects are shown for the 2D case. For example a notable alongshore difference between the northern and the southern half of the beach area exists for the 2D approach, while the right panel of the figure suggests that this difference is not caused by differences in the cross-shore profiles, since the presented patterns (left versus right) are significantly different. Apparently the presence of the sea dike, the shielded location of the beach and dune area, and the seaward-reaching coastal structure south of the beach, induce sediment transports along the coast. The loss of sediment in the northern half of the beach is partly deposited at southern part of the beach, and the largest part of all eroded sediment is deposited further southward, in front of the structure.

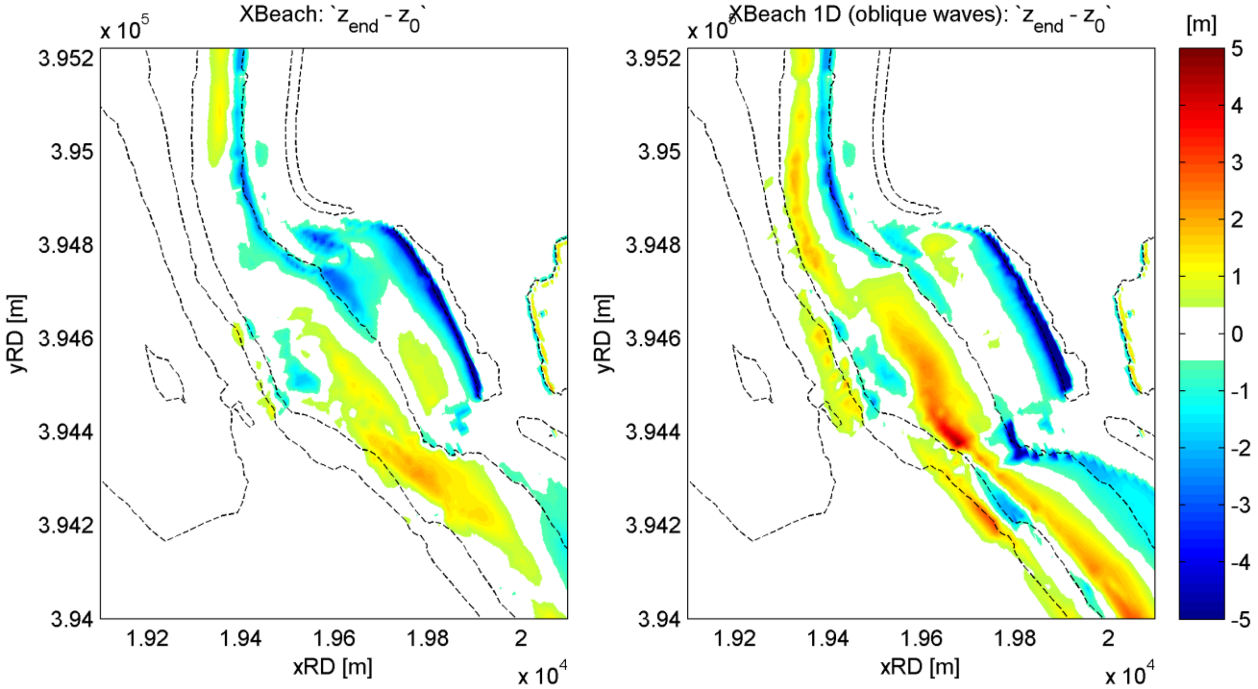

Figure 30: Bed level changes for a specific area within the model domain (central beach). The results are based on westerly wave attack, normative storm conditions and 30 hours of simulation time. Left panel: 2D XBeach. Right panel: 1D XBeach. Reddish colours indicate deposition areas, and bluish colours are associated with erosion patterns.

Similar to the 2D model run, the 1D simulation also results in a certain amount of deposition in front of the dune foot fortification just south of the central beach. But this obviously originates from another location. In contrast to the 2D simulation, the 1D model runs predict much more erosion near the toe of the structure because relatively deep excavation pits are formed. So the amount of deposition south of the central beach, just seaward of the coastal structure, is similar for both model approaches, but the sediment originates from different locations. Related to this, the eroded sediment from the dunes is, in case of the 1D approach, obviously deposited just seaward of the central beach at the foreshore.

In general, the amount of dune erosion is very similar for both the 1D and the 2D approaches; which is quite remarkable since the deposition patterns are very different. Moreover, the bed level changes around the shoreline are also different for both cases. The sediment distribution for a 2D approach is directly related to the geometry of the surrounding area.

In Figure 31 a more detailed view is presented in the dune area just south of all structural coastal defences. The last part of the dune foot fortification is included in the upper part of the figures (just landward of the erosion pattern in the north-west. When comparing both results it is obvious that very similar distances of dune retreat are determined for both model approaches. Furthermore, the amount of eroded sediment at the beach is pretty much the same. But again the deposited volumes do differ slightly for this area. It is shown that for XBeach 2D all deposition takes place at the foreshore, landward of the channel slope. All ‘missing’ sediment is deposited further downstream in the southern part of the model domain (or beyond). On the contrary, the 1D results do predict deposition inside the tidal channel, at the landward slope.

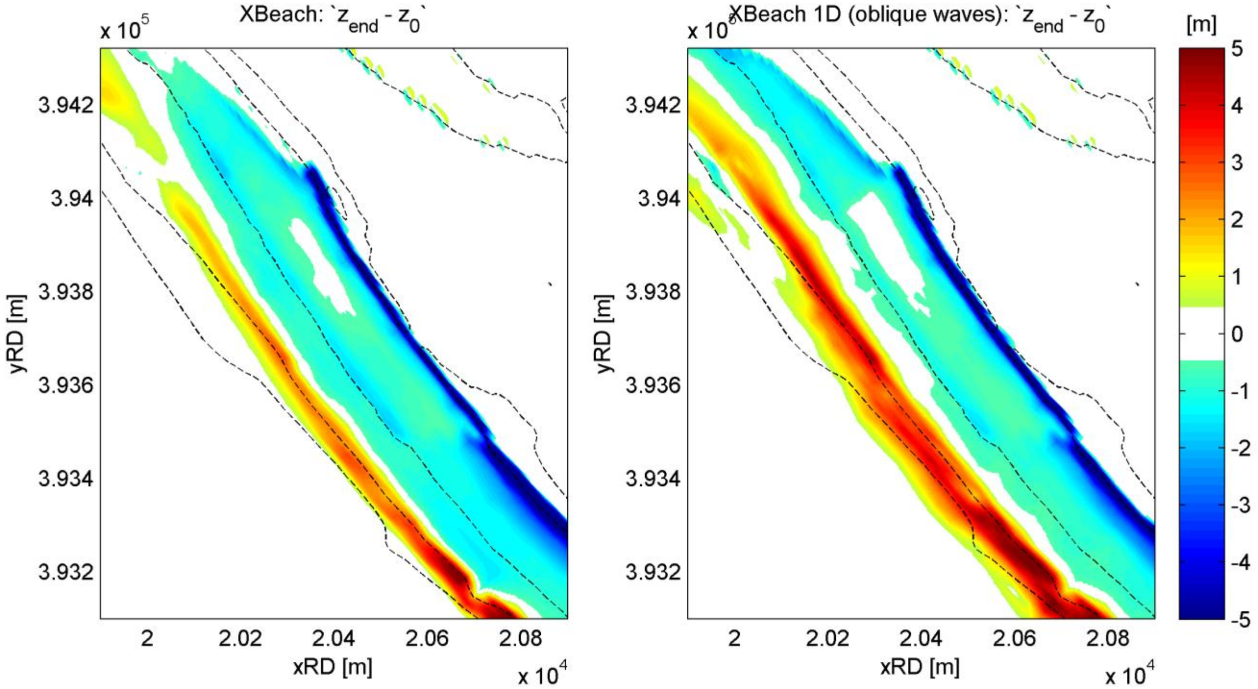

Figure 31: Bed level changes for a specific area within the model domain (southern dune area). The results are based on westerly wave attack, normative storm conditions and 30 hours of simulation time. Left panel: 2D XBeach. Right panel: 1D XBeach. Reddish colours indicate deposition areas, and bluish colours are associated with erosion patterns.

Based on both presented figures it can be concluded that the differences between a 1D and 2D model approach for the coastal area near Westkapelle are rather limited. The amount of dune erosion throughout the whole domain is very similar for both approaches. On the other hand, the deposition volumes and associated patterns show several discrepancies, mostly related to alongshore transport. Overall, the patterns (erosion and deposition) are comparable and especially on the spatial scale of the entire model domain these patterns are very similar. Only on a smaller scale significant differences are found between the models: for example near the central beach, where the complex shape of the coastline causes near-shore redistribution of sediment at the foreshore.

Although the 1D and 2D results are not drastically different, it should be noted that the 2D approach, do give lots of extra insight in the dynamics in the coastal area. These insights are necessary for a better understanding of the important processes that act during storm conditions.

2D XBeach versus 1D DurosTA

Similar to the comparisons between 1D and 2D XBeach also the differences between DurosTA and 1D XBeach are considered. The results of the associated comparisons are presented in Figure 32 and Figure 33. The first figure focuses on the central beach, while the second figure shows the most southward located dune area. Again both right panels present the 1D XBeach results, and in this case the left panels present the combined DurosTA results. All presented results are associated with westerly waves, and therefore they are based on the simulations with oblique wave incidence.

The patterns in both panels of Figure 32 show both some clear similarities and some obvious differences. Overall the same erosion and deposition patterns are simulated by both 1D dune erosion models. However, it should be emphasized that both figures consist of combined results of a large series of 1D transect calculations. So the variations in alongshore direction are mainly imposed by the initial bathymetry rather than that these variations are actual model results. The cross-shore variations of the patterns do result from differences in the model's behaviour.

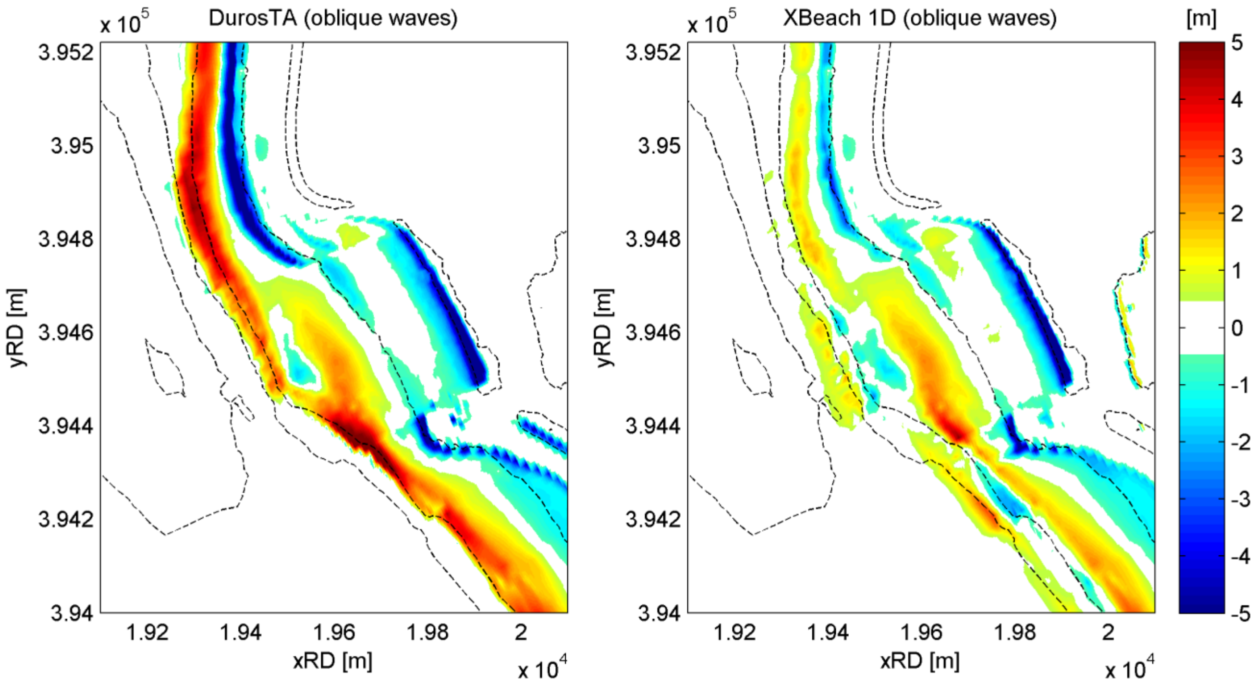

Figure 32: Bed level changes for a specific area within the model domain (central beach). The results are based on westerly wave attack, normative storm conditions and 30 hours of simulation time. Left panel: DurosTA. Right panel: 1D XBeach. Reddish colours indicate deposition areas, and bluish colours are associated with erosion patterns.

From Figure 32 several conclusions can be drawn. Starting in the northern part of the considered area, it can be concluded that DurosTA generates much larger excavation pits in front of the sea dike than XBeach. Although the patterns for erosion and deposition are very similar, the magnitudes of the bed level changes are much larger for DurosTA. In contrast, the calculated depths of the excavation pits near the toe of the dune foot fortification (south of the central beach) are quite similar for both models. The differences between the pits in front of the sea dike and the pits near the other structure are related to the typical level of the toe of the structures.

The predicted bed level changes for the central beach itself (and the dune row landward of the beach) are very similar. Both the amount of dune erosion and the amount of sediment deposition at the foreshore are approximately equal. The only (minor) difference is the way both models deposit sediment at the tidal channel slope; generally, the final bottom profiles for XBeach do have smoother transitions from disturbed to undisturbed areas. The landward channel slopes are therefore much steeper for the DurosTA results.

In Figure 33 the results for both DurosTA and 1D XBeach are presented for the dune area just south of the coastal structures. Only the southward extent of the dune foot fortification is visible in the upper part of both panels. From the figure it is concluded that minor differences are found between the erosion- and deposition patterns for both model approaches. Overall, DurosTA predicts (a little) more erosion than XBeach, resulting in a larger estimate for the dune face retreat and bed level changes landward of (or ‘above’) the coastal structure. And moreover, the final bottom profiles for DurosTA are relatively steep at the seaward extent of the deposition zones; and particularly a steeper tidal channel slope is formed. The 1D XBeach results show more smoothed profiles with deposition areas that extend further seaward.

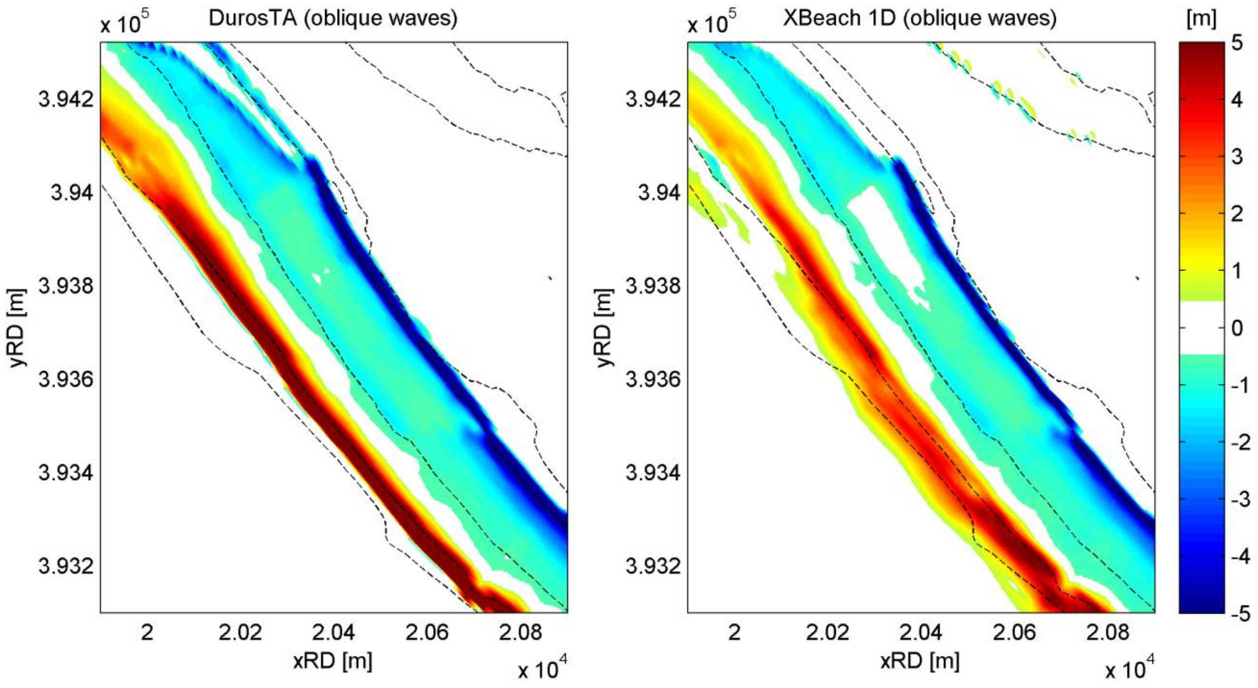

Figure 33: Bed level changes for a specific area within the model domain (southern dune area). The results are based on westerly wave attack, normative storm conditions and 30 hours of simulation time. Left panel: DurosTA. Right panel: 1D XBeach. Reddish colours indicate deposition areas, and bluish colours are associated with erosion patterns.

4.2.5 Comparison 1D and 2D results: alongshore distribution of sediment volumes

In the previous sections the results of the storm impact simulations are presented in terms of erosion- and deposition patterns inside the model domain. The presented figures with these patterns enabled a qualitative comparison between the different types of simulations and they gave insight in the dynamics of the system in the considered coastal area. In addition to this, also a more quantitative analysis is performed that relates to determined volume-differences along the coastline.

Considering the alongshore distribution of sediment volumes and the simulated volume changes, results in better insight in the effects of a 2D approach; rather than a 1D transect approach. In this section the sediment volume-effects of alongshore transport in the 2D XBeach model are quantified by considering post-storm volume-differences along the coast.

4.2.5.1 Volume-boxes

Before the results of the volume-analysis are presented, first a series of ‘boxes’ is defined within the model domain. These boxes represent areas with characteristic output, such that the description of the results can be linked to specific locations. Moreover, spatially-averaged output values can be determined for the different boxes, in order to simplify the results of the analyses.

In Figure 34 the considered boxes for the volume-analyses are presented. In total, 7 characteristic areas are defined for this particular purpose. The selected positions for the boxes are mainly based on the erosion and deposition patterns that resulted from the simulations. As shown, the boxes focus on the coastal area near the central beach, just south of the sea dike. Larger box-areas are defined near the model boundaries.

A detailed view on the box definition is given in Figure 35, such that the central beach and the nearby situated coastal structures are highlighted. The figure shows that distinction is made between the northern and the southern half of the central beach, since the 2D XBeach results showed different behaviour in both sections.

Moreover, a limited area just north of the beach area is defined because significant differences were observed in the bed level changes between the 1D and 2D approaches. And the typical deposition area (in 2D) for sediment that originates from the central beach is indicated by box-number 3.

Based on the calculated bed level changes an alongshore distribution of volume changes is determined. Per considered cross-shore profile the total amount of eroded sediment volume, deposited sediment volume, and net changed volume is calculated. So in fact, positive, negative and net bed level changes are considered and converted in volumes-per-unit-meter (m^3/m), based on grid cell sizes. By applying this method for each individual transect, alongshore variations in the volume changes are extracted from the model results.

4.2.5.2 Alongshore distribution of volume changes

The results of the volume-analyses are presented in Figure 36, in three different panels. The first panel shows the alongshore distribution of the amount of eroded sediment per transect. The second panel indicates the volumes of deposited sediment, per transect. And finally, the third panel presents the net simulated volume changes for each transect. The last panel also acts as a proper check for the 1D dune erosion models, since the volume balances should, by definition, be closed for each transect. In other words:

`EROSION - DEPOSITION = 0.`

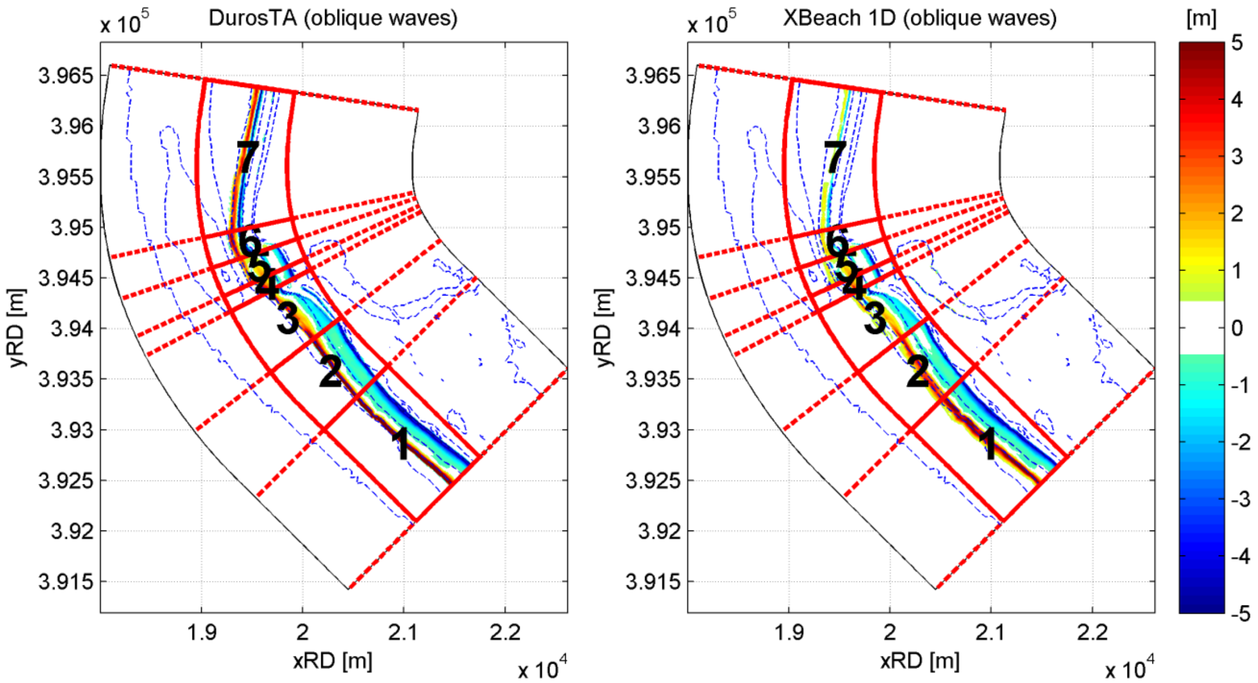

Figure 34: Definition of the so-called volume-boxes along the coastline, for further analyses.

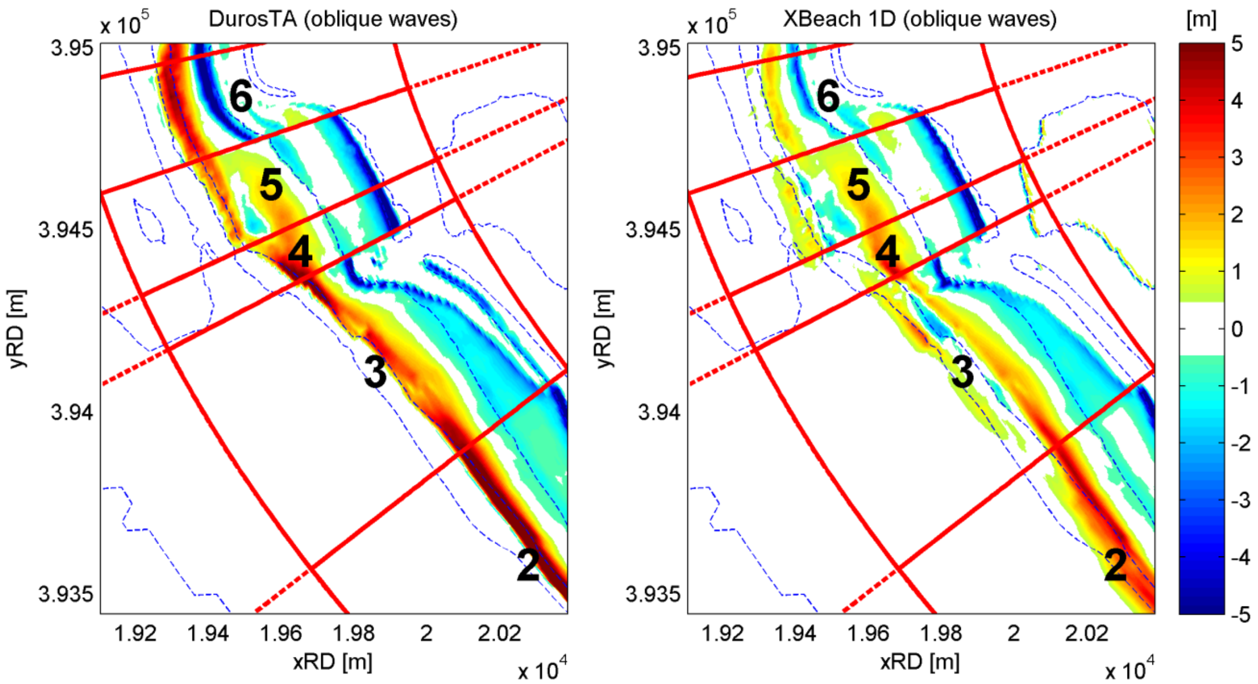

Figure 35: Definition of the so-called volume-boxes along the coastline, for further analyses. Detailed view.

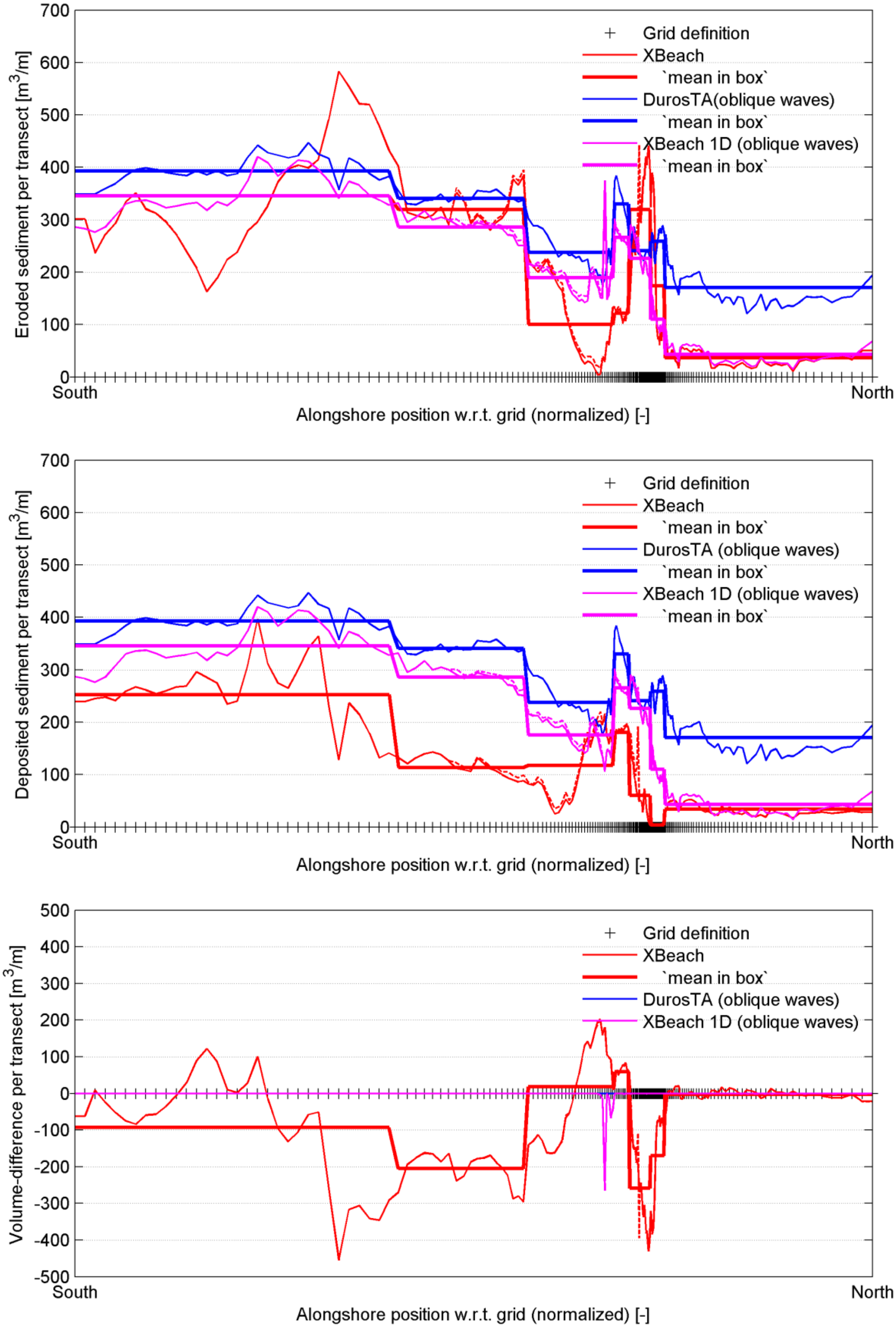

Figure 36: Results of volume-analyses. For a large series of transects along the coastline the total amounts (per cross-shore profile) of eroded sediment (top panel), deposited sediment (middle panel) and net volume changes (bottom panel) are presented. The results are alongshore distributions of sediment volume changes. All output is based on simulations (2D XBeach, 1D XBeach and DurosTA) with westerly wave attack and normative storm conditions.

In Figure 36 a large amount of data is presented. The y-axes represent indicators for volume changes (erosion, deposition or net change). The x-axes are normalized indicators for the position along the coastline: the left side of the graphs corresponds to the southern area of the model domain, and the right side is associated with the northern part of the domain. The related 2D grid definition in alongshore direction is indicated by the '+'-shaped markers at the x-axes. As mentioned earlier, larger grid distances are used near the model boundaries while a higher grid resolution is imposed near the central beach area (in this figure located at 2/3 of the horizontal extent).

In the panels of the figure different line colours are used to distinct the output of the different model approaches (2D XBeach, 1D XBeach and 1D DurosTA). Red lines are used to indicate the 2D XBeach output; magenta (/ pink) lines represent 1D XBeach results, and blue lines are related to DurosTA results. Moreover, thin solid lines represent the determined volume-information within the defined boxes, while the (mostly identical) dashed lines are associated with volumes within the full extent of the cross-shore transects. So the dashed lines only differ from the solid lines when erosion/deposition occurs at locations other than near the shoreline; for example at the edges of the inland creek. Furthermore, the thick solid lines indicate the box-averaged values for the calculated volume changes within the boxes.

In the following subsections a series of remarks and conclusions is presented, based on the graphs in Figure 36.

Erosion per volume-box

The upper panel of Figure 36 shows the erosion volumes for each transect along the coastline. In general, all erosion occurred in the first dune row and at the beach. Typically erosion volumes of 300 – 400 m^3/m are found for the dune area in the southern part of the domain (left in figure). DurosTA predicts (on average) the largest amount of erosion in the dunes (400 m^3/m), while both XBeach approaches (1D and 2D) result in equal erosion volumes that are (both) slightly lower (350 m^3/m) compared to DurosTA. Although the averaged volumes for 1D and 2D XBeach are equal, the alongshore variation for the 2D model is much larger. For this model the two extremes are found close to 200 m3/m and 600 m^3/m. This means that some non-uniformity exists within the dune area. This will be discussed in more detail later on.

In the second volume-box, that represents the sandy dune area just north of the first box, also a more or less (alongshore) constant amount of erosion is found. The volumes are slightly lower than for box 1, and for this box the 2D XBeach results lay in-between both 1D results. The typical erosion volumes are 300 – 350 m^3/m.

The third box is located in the area where the coastline is protected by a dune foot fortification. As a result a much smaller amount of erosion is simulated for all models. In Figure 24 and Figure 26 the model results are presented for an example-transect that is located in this specific area. The influence of the structure is clearly shown in these figures. The largest erosion volumes for box 3 are found for DurosTA (on average 250 m^3/m), followed by 1D XBeach (200 m^3m). The box-averaged value for 2D XBeach is half of the value for 1D XBeach and in the northern part of the box (right in figure) the amount of erosion drops till (almost) zero. The location where no erosion is simulated with the 2D model corresponds to the area where the coastal structure stretches seaward as small 'headland'. The 1D models simulate excavation pits in front of the structure, while these pits are absent in the 2D model results. This is likely caused by the sediment supply from upstream (here: northern) locations.

The fourth volume-box is one of the two boxes at the central beach. Box 4 covers the southern part of the beach and box 5 covers the northern half. The beach is represented by two boxes (instead of one) because a significant difference is found in the results for both sides of the central beach. The difference is not that big for the 1D model results, but for this location the effects of 2D modelling are clearly demonstrated. While the amount of erosion is ranging between 250 m^3/m and 300 m^3/m, for both boxes and both 1D models, the erosion volumes are completely different for both sides of the beach when considering the 2D model. At the south-side of the beach typically 100 m^3/m of erosion is found while this reaches over 300 m^3/m of sediment loss for the northern part.

Finally, two boxes are considered that are located in the area where a sea dike protects the hinterland from flooding. The first, small, box shows a varying amount of erosion near the southern tip of the dike, depending on the considered model. Most erosion (mostly excavation) is simulated by DurosTA, then 2D XBeach follows because alongshore current-effects cause relatively large amounts of erosion, compared to the 1D XBeach case. The large volume-box for the remaining part of the sea dike shows that DurosTA simulates a huge amount of excavation in front of the dike (almost 200 m^3/m), while both XBeach approaches results in much smaller amount of erosion near the toe of the structure (less than 50 m^3/m).

Deposition per volume-box

In addition to the erosion volumes also deposition volumes are presented in Figure 36; in the second panel. The alongshore variability for the determined volumes of deposited sediment is much smaller than for the erosion volumes. For the whole model domain yields that the largest amount of deposition is simulated by DurosTA. In general, the amount of deposition decreases northward, due to the presence of structures in the northern part of the model. The simulated deposition volumes for the 1D XBeach simulations are slightly lower for the dune areas, with typical volume-differences of approximately 50 m^3/m. The differences are significantly larger (up to 150 m^3/m) for the area that is protected by the sea dike.

The deposition volumes for the 2D XBeach simulations are smallest for the entire coastal stretch within the domain. For the dune areas and the central beach area the amount of deposited sediment is significantly lower than the estimated amount for both 1D models. For box 7 (sea dike) the determined volumes for both XBeach approaches are more or less equal, so the size of the generated excavation pits is comparable for the 1D and 2D simulations.

The most remarkable results for the second panel are the deposition volumes that are found in the area around the southern coastal structure (thus south, or left, of the central beach). In box 2 relatively low deposition volumes are found compared to the amount of erosion that is simulated in the same box. On the other hand the amounts of erosion and deposition are more or less equal for box 3, while clearly more sediment deposition, rather than erosion, is determined for the fourth box (= southern part of central beach). The opposite holds for the northern part of the beach, where more erosion occurred than that is compensated by deposition of sediment.

Net volume-change per box

The last panel of Figure 36 shows the net volume changes per transect. The net changes are defined as the difference between erosion and deposition. When a sediment balance exists for a certain transect, this means that all erosion is compensated by deposition. However, this does not necessarily mean that the pre-storm and post-storm bottom profiles are equal. A sediment balance, or a zero volume-difference, means that the amount of sediment is conserved along a particular cross-shore transect. For a 1D dune erosion model the sediment balance is closed, by definition, when no alongshore components are included.

In the last panel of the figure it is clearly shown that for both 1D models a closed sediment balance is found. The only exception holds for two minor outliers in the third box, where negative volume-differences are observed for the 1D XBeach model. These outliers are related to invalid bed level updating in generated excavation pits for two transects in the entire model domain.

As expected, the sediment balance for the 2D model is not closed due to alongshore sediment losses and gains. From the figure it can be concluded that the total amount of available sediment is significantly reduced during a normative storm event. In other words, alongshore processes resulted in a net outflow of sediment for the entire model domain. Especially in the southern part of the domain (left in figure) negative volume-differences are identified. In Figure 17 it was shown that a southward directed net sediment transport is simulated for the storm impact simulation with westerly waves. So obviously, most of the eroded sediment is transported outward through the southern model boundary. Due to the non-uniformity of the coastline the sediment outflow is not compensated by sediment inflow from northern directions; this results in net losses.

For the two volume-boxes in the southern dune area net volume-differences are simulated between 0 m^3/m and -400 m^3/m. The corresponding box-averaged values are respectively -100 m^3/m (box 1) and -200 m^3/m (box 2). Near the southern model boundary the sediment balance is approximately restored, such that the amount of erosion equals the amount of deposition. In fact, the inflow and outflow of sediment are balanced, since previous figures showed that significantly large transport rates are found in this area.

The largest volume-differences are expected (and found) at the locations where gradients exist in the transport rates. Flow divergence, for example, results in relatively high outflow rates compared to the inflow rates. As a consequence net sediment losses (or negative volume-differences) are determined. This particular example is nicely illustrated in the northern part of box 1, where a large negative peak is shown in the lower panel of Figure 36. At this location a small, but distinct, curve of the coastline is present that results in a diverging flow field along the coast. Due to this divergence, and the presence of erodible sediment, more dune erosion is simulated at this location.

In contrast to the simulated sediment losses in the dune area, a small net sediment gain is determined for boxes 3 and 4. Box 4 represents the southern half of the central beach, and box 3 corresponds to the area where the coastal stretch is protected by a dune foot fortification (and a structural headland). For box 3 yields that only small amount of erosion are found due to the presence of a structure, while eroded sediment from upstream locations (mostly the northern part of the central beach) deposited at the foreshore. So as a net effect the total amount of sediment increased in this volume-box. The same thing happens for box 4, where even more sediment is 'trapped' that is eroded just north of that area.

The opposite result is found for box 5 (northern half of central beach). A very large amount of erosion is simulated there at both the foreshore and above still water level. Most of the eroded sediment is transported southward to boxes 3 and 4, such that only small amount of sediment deposited at the foreshore. A similar conclusion holds for box 6 that is located near the southern tip of the sea dike. At that particular location strong alongshore currents are generated by the geometry such that erosion occurs near the toe of the structure, while the sediment is deposited downstream.

Finally, a closed sediment balance is found in box 7 for the whole coastal area that is protected by the sea dike. Both the erosion- and deposition volumes are rather small, but balanced.

1D XBeach versus DurosTA

Based on the presented panels in Figure 36 it can be concluded that both 1D model approaches (XBeach and DurosTA) show very similar results. In general, the results of the simulations with DurosTA are considered to be more conservative, because the amount of (dune) erosion is larger for the entire model domain. For the sandy part of the coastline a typical difference of 50 m^3/m is observed between both models. Moreover, the sizes of the excavation pits in front of structures are in general much larger when simulated by DurosTA than by XBeach.

2D XBeach versus 1D models

It is shown that both 1D dune erosion models give very similar results. Question is, however, what typical differences are found between the 1D and 2D model approach. The panels in Figure 36 show that alongshore processes do play a significant role in simulating (dune) erosion along a coastal stretch. In particular for areas with an alongshore non-uniform bathymetry significant volume-differences are found along the coastline. Within the considered model domain two locations are identified where the alongshore effects are clearly visible.

First, a clear southward shift of sediment is simulated in the area around the central beach. Especially the northern part of the beach area lost a significant amount of sediment, which contributes to downstream locations, even 'around the corner' of the coastal structure south of the beach.

A second, less expected, location where the effects of alongshore sediment transport are obviously present is a small coastal stretch in the centre of the considered dune area. Due to coastline curvature, flow divergence is generated that results in net loss of sediment in that area. This typical effect of coastal curvature on the sediment balance is very similar to the schematization that is incorporated in the formulations of the DurosTA model to account for curved coastlines. In Figure 29 an example is presented for a case that the advanced option of coastal curvature is enabled in DurosTA. The simulated effect of curvature is that the entire cross-shore profile shifted landward, resulting in a net loss of sediment volume of approx. 900 m^3/m. The 2D model approach simulates a maximum sediment loss of 500 m^3/m; in the same area of the domain. Note that the setting of the amount of curvature (circle radius) is quite uncertain for this type of coastline (with lots of variations in the orientation of the shoreline). But, under the assumption that a proper radius is imposed, it seems that DurosTA gives conservative results for coastal curvature as well. A more detailed and confined study should be performed in order to identify fundamental differences and similarities between the schematized way to account for curvature (by using DurosTA) and a sophisticated, physically based, approach with a 2D model (XBeach).

And finally it is noted that in Figure 36 clearly the effects of gradients in the alongshore transport rates are shown; for the entire (southerly) dune area. Mostly negative volume-differences are found in a large part of the dune area, which means that varying transport rates are present. In fact, the sediment transport rate increases southward, just as shown in Figure 17. When a zero-gradient alongshore transport is considered, the amount of inflow and outflow remains constant, independent of the size of the transport rates. Only alongshore differences in the transport rates result in convergence and divergence; and thus in net volume differences.

Normal versus oblique wave incidence for 1D models

As a final part of the volume-analyses additional model results are considered. As explained before, the 1D simulations are performed by applying two different options for the direction of wave attack. For most safety assessments a shore-normal wave attack is imposed; especially when using the dune erosion models DUROS+ or DurosTA. In this study the 1D model results are compared with 2D simulations, with westerly winds. And in order to make a proper comparison, the output of the 1D simulations with oblique wave incidence is thus presented in the previous sections and, for example, in Figure 36.

In this subsection also the results of the volume-analyses for the simulations with shore-normal wave incident are presented. In Figure 37 a comparison is made between the (1D) results for normal- and off-normal wave attack, for both XBeach and DurosTA. The dashed lines in figure correspond to cases with normal wave incidence and the solid lines are related to simulations with westerly wave attack.

As concluded in an earlier stage, based on output for individual transects, XBeach and DurosTA handle off-normal wave attack in different ways. In DurosTA the intensity of the wave attack reduces when the obliqueness increases (thus less erosion is simulated for off-normal waves), and for XBeach yields that the maximum amount of erosion is simulated under a certain angle of wave incidence (approx. 30 degrees). These differences are clearly visible in Figure 37.

In fact, when considering shore-normal wave attack for all transects, a very big difference is found between the results of XBeach and the results of DurosTA. By considering simulations with oblique wave incidence, the difference between the model results is reduced significantly, due to the opposite effects of the implemented method for dealing with wave angles.

When comparing the 1D results with the 2D model result, it can be concluded that the amount of simulated erosion for the 2D approach fits within the wide ranged area of 1D results. However, the determined deposition volumes for the 2D simulation are generally lower than most of the 1D model results, and the values are more or less equal to the results of the 1D XBeach approach with shore-normal wave attack.

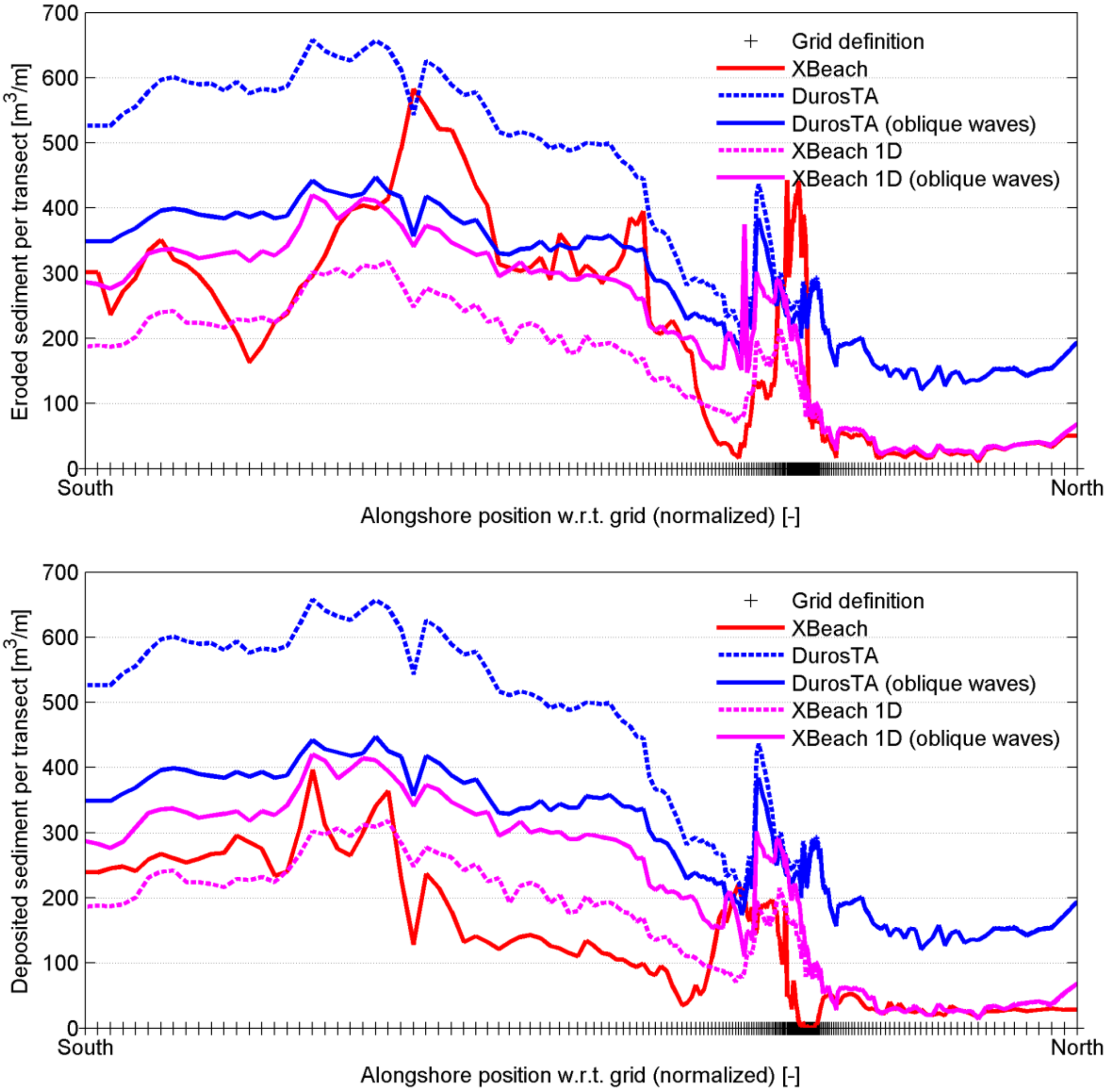

Figure 37: Results of volume-analyses. For a large series of transects along the coastline the total amounts (per cross-shore profile) of eroded sediment (top panel) and deposited sediment (bottom panel) are presented. The results are alongshore distributions of sediment volume changes. All output is based on simulations with normative storm conditions. The solid lines represent simulations with westerly waves, and the dashed lines are associated with normal wave incidence for the 1D models.

4.3 DUNE BREACHING

Up to this stage of the project, simulations are performed for normative storm conditions. The simulations suggest that the coastal sea defences in the considered coastal stretch near Westkapelle are sufficiently robust to withstand a normative storm event. The performed simulations contribute to one of the main objectives of this project: demonstrating the capacities of XBeach in modelling storm impact on a complex coastline. This is also emphasized by making comparisons with 1D dune erosion models.

Another related objective is to demonstrate that 2D XBeach can be used in an operational model system to monitor and predict the real-time safety of a coastal area; particularly focussed on dune breaching and safety against flooding. Therefore in this section the imposed storm intensity is increased step-by-step, in order to force dune breaching in the model domain; and test the model's behaviour during breaching processes and flooding events.

In the following sections a more detailed description is presented of the performed test-simulations. First the intensified boundary conditions are discussed, followed by information about different model settings concerning the landward boundary. And finally a set of model results is presented for simulations where dune breaching occurred.

4.3.1 Hydraulic boundary conditions

The simulations with normative storm conditions did not result in breaches in the dune area. In order to demonstrate how XBeach deals with dune breaching and flooding the storm conditions are intensified. Stepwise, both the water level and the wave conditions are increased such that dune breaches are enabled.

The up-scaling of conditions for this test-case is not based on any sophisticated or published method. The objective of this study is to demonstrate how XBeach simulates dune breaches, so there is no need for advanced scaling-methods. For this project the water levels and wave conditions are scaled simultaneously, and a series of 6 different storm conditions is considered. In order of increasing intensity the conditions are labelled as: *A*, *B*, *C*, *D, E* and F.

The water levels are increased in a range between NAP +5 m and NAP +7 m; in steps of 0.4 m. The settings for the significant wave height range from 4 m till 9 m, in steps of 1 m. And finally the wave period varies between 12 sec and 15 sec, in steps of 0.6 sec. The resulting time-series for all sets of hydraulic boundary conditions are presented in Figure 38.

Obviously these scaled conditions are not very realistic; but testing the 2D model for these conditions gives more insight in the dynamics and the model's behaviour when dunes are collapsing.

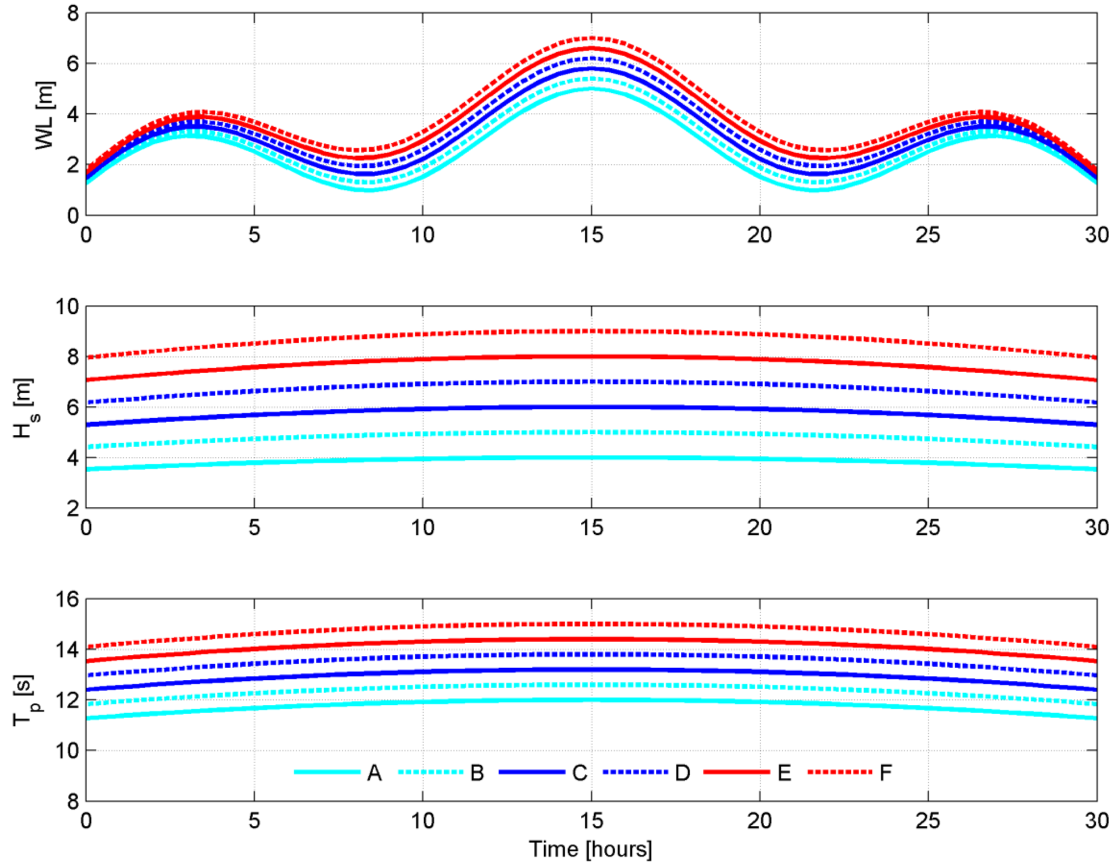

Figure 38: Time series of different sets (A, B, C, D, E, and F) of increased hydraulic boundary conditions. The storm conditions are increased stepwise in order to simulate dune breaches with XBeach.

4.3.2 Landward boundary definitions

For simulations where dune breaches are expected it is necessary to apply proper settings for the type of boundary definition at the landward side of the model domain. For the seaside of the domain ‘open’ boundaries are considered such that water, waves and sediment can enter and/or leave the model domain. Another option is to impose a ‘closed’ boundary that acts as a (reflecting) wall. In most cases a closed boundary is not favoured when considering ‘realistic’ model setups, other than laboratory experiments.

For the default simulations in this project an ‘open’ landward boundary is considered. But in fact, the landward boundary is never been used because the dunes and structures protected the hinterland from flooding, for normative storm conditions. For the simulations with intensified conditions it is expected that the hinterland will be flooded, and that (outflowing) water reaches the landward boundary. For these flooding events it is required to have a more detailed look at the landward boundary definition, since it can/will affect the dynamics inside the model domain.

Several options for boundary definitions are tested during this project. Besides ‘just’ a closed or open landward boundary, also test-runs are considered for which the bathymetry near the ‘dry’ boundary is adjusted in order to create ‘buffers’. And also the dry parts of the lateral boundaries do influence the flow- and wave dynamics.

In Table 4 a list of tested boundary definitions is presented, with a short description. Note that two types of bathymetric adjustments are considered: a landward channel and sand-walls. The (artificial) channel is used as a buffer and to enable a ‘smooth’ outflow of water. The sand-walls are artificial dunes that are used to close the boundaries (either lateral, landward or both), and simultaneously absorb parts of the (wave) energy.

Table 4: Overview of considered settings for inland model boundaries. Multiple combinations of boundary definitions and bed level adjustments are tested in order to find the most stable and realistic results for flooding events.

Landward boundary	Lateral boundaries	Description
Open	**Open (Neumann)**	All boundaries are ‘open’. + *No reflections* + *No closed box behind sea defences, such that water level keeps rising* × *Boundary is ‘end-of-the-world’; so flow acceleration and erosion at landward boundary*
Closed	**Open (Neumann)**	Landward boundary acts as a wall, while lateral boundaries are still open. + *No ‘end-of-the-world’-effects with flow acceleration* + *No closed box behind sea defences* × *Reflections at landward boundary*
Open **Landward channel**	**Open (Neumann)**	All boundaries are ‘open’, and a channel is present along landward boundary. Channel acts as a buffer that reduces boundary-effects. + *No reflections* + *No closed box behind sea defences* × *Still problems with flow acceleration and sediment losses*
Closed **Landward channel** **(Sand-wall at boundary)**	**Open (Neumann)**	Landward boundary acts as a wall, and a channel is present along landward boundary. Channel acts as a buffer that reduces reflections. Lateral boundaries are ‘open’ such that outflow is possible. Additional option: adding a sand-wall (high dune) at the landward boundary for (extra?) damping. + *Less reflections* + *No closed box behind sea defences* + *No ‘end-of-the-world’-effects with flow acceleration* × *Still some reflections at landward boundary*
Open / Closed **Sand-wall at boundary**	**Sand-walls at boundaries**	All landward boundaries are closed by sand-walls (high dunes). The thickness of the walls is sufficiently large to prevent breaches. + *No ‘end-of-the-world’-effects with flow acceleration* + *Reflections are damped* × *Closed box behind sea defences, no outflow possible at boundaries* × *Internal flow patterns are generated due to reflection and the fact that water is ‘trapped’*

4.3.3 Simulated dune breaches

The previous sections showed that a large number of simulations is performed in order to test the capabilities of XBeach in simulating dune breaching and flooding. Dune breaching is enabled by imposing a stepwise increasing intensity of the storm conditions. And when the dunes are breached under certain conditions, different types of boundary definitions are imposed in order to test their influences on the associated flooding event.

For this particular test-case dune breaching occurred for the hydraulic boundary conditions labelled as *C*. Conditions *C* consist of a imposed water level of NAP +5.8 m, a significant wave height of 6 m and a typical peak period of 13.2 seconds. For these conditions the dune area collapses and the hinterland is flooded. In this report only the results are presented for the simulations that are forced by conditions with label *C*.

From the presented list (Table 4) with different definitions for the landward boundaries two options are selected for which the erosion- and deposition patterns, after one storm event, seem to be realistic. The results of the two selected options are quite different and should not be used without expert judgement. For both options yield that the flow patterns are acceptable, without any strange outflow jets and associated sediment losses.

In contrast, some of the other options (especially those with 'open' landward boundaries) result in very unrealistic flow fields and erosion patterns. For an open boundary definition yield that 'the world ends' at the boundary, so in fact a frictionless passage is created that contracts the flow field and also accelerates the flow field towards the boundary. As a consequence, most of the available sediment in the hinterland is eroded and transported out of the model domain.

Erosion- and deposition patterns

In Figure 39 and in Figure 40 the bed level changes are presented for the two selected simulations with boundary definitions that result in proper model results. Obviously some significant differences are observed between both results. However, it is very hard to judge the quality of the model results for the flooding event, because 'the truth' is unknown. The imposed storm conditions have not been observed in the past, and probably will never be observed in the future. Only physical scale model could provide additional information at this point, in order to judge the results of the flooding event.

Figure 39 presents the erosion and deposition patterns for a simulation where a 'closed' landward boundary is considered. No flow or transport through the land boundary is allowed for this particular simulation. As a consequence, the only possible locations for outflow of water and sediment are the lateral boundaries and the 'gaps' in the dune area. In the figure it is clearly shown that a large gap has formed in the dune area due to the high flow velocities through the initially formed breaching gap. A significant part of the eroded sediment from the dune area is subsequently deposited in a wide area around the place of the dune breach. Also lots of sediment is deposited at the bottom of the inland creek. A closer look at the central beach leads to the observation that some overwash is simulated in the northern corner of the beach area.

In Figure 40 similar results are presented as in the previous figure, but the results are based on a simulation with an adjusted definition of the landward boundary. Again a 'closed' boundary is considered, but in this case an artificial channel is included within the model domain. This channel (with an initial still water level at NAP -1 m) acts as a small basin for abundant water and facilitates outflow through the lateral boundaries. To what extent this channel results in an (accidental) overestimated amount of outflow is unknown. Similar to the previous result a deep gap has formed in the dune area; however, the size *and* the location of the gap are different for both simulations. Moreover, the total amount of erosion (and deposition) is smaller for the second simulation, and most of the eroded sediment is deposited in the artificial channel.

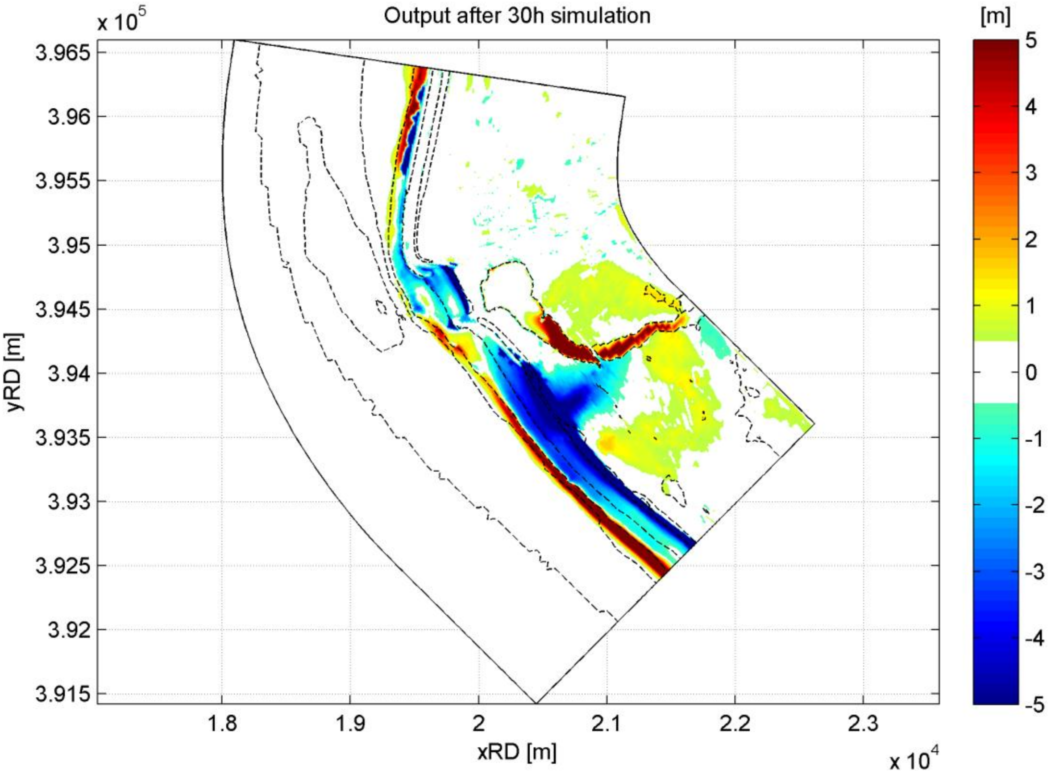

Figure 39: Bed level changes. The results are based on 30 hours of simulation with super-storm conditions (input-set C) and a 'closed' landward boundary. Redish colours indicate deposition areas, and bluish colours are associated with erosion patterns.

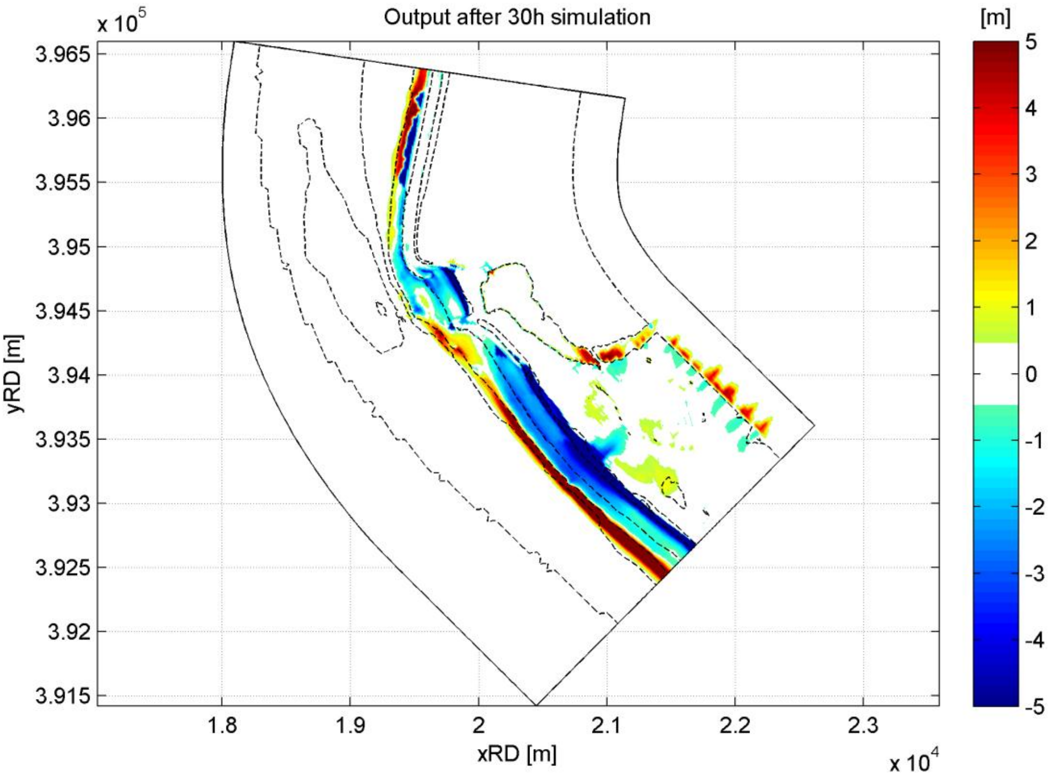

Figure 40: Bed level changes. The results are based on 30 hours of simulation with super-storm conditions (input-set C), a 'closed' landward boundary and an extra artificial landward channel. Redish colours indicate deposition areas, and bluish colours are associated with erosion patterns.

The most remarkable difference between both results is the location where the dune breaching occurred. For the first simulation (without artificial channel) a more northward located gap has formed, while the dune breach for the second simulation is simulated further southward. This remarkable result is related to a random component that is used to initialize the wave-boundary conditions. Slightly different initial settings result in deviating long wave signals and consequently different water level variations due to these long waves. This so-called swash motion has a significant influence on the short-term variations in the dune erosion-rates. Apparently, the whole dune area around both simulated gaps is critically weak at a certain moment during the storm. The short-term (temporal and spatial) variations in water level finally determine the (accidental) location of the dune breach. Due to the renewed flow field after a dune breach, the other, also critically weak, dune sections might sustain further wave attack. Note that this explanation is only a hypothesis that should be studied in more detail in future studies.

Inundation areas

In addition to the presented erosion- and deposition patterns for the two selected simulations, also the inundation areas during the storm are visualized. An important risk-indicator for safety is the predicted size of flooded areas in case of failure of the primary sea defences. For future applications of XBeach, i.e. as part of an operational model system for coastal safety, it is therefore required to visualize the process of flooding of the hinterland.

Figure 41 shows the inundation areas for the simulation with a ‘closed’ landward boundary, and ‘open’ lateral boundaries. The flooding event is presented at four subsequent moments during the second half of the simulated storm. The results are captured at respectively 18 hours, 19 hours, 20 hours and 21 hours after the starting time of the simulation. For this simulation dune breaching occurred near the storm maximum (after 15 hours).

In the figures the green colour is used to visualize the bathymetry and topography of the sandy parts in the model domain. The coastal structures are indicated by the magenta (pink) coloured areas. And the sea water level is drawn as a semi-transparent bluish layer. Note that the shading effects in the figure highlight variations of the bed level, and also the long wave patterns that are superimposed at the still water level.

The most remarkable result of Figure 41 is the fact that almost the entire model domain is flooded at a certain moment during the storm event. This means that also the city of Westkapelle is flooded during the considered storm conditions. However, the amount of flooding is most likely overestimated due to the definition of a wall-type of boundary along the landward border. The open lateral boundaries apparently do not provide a sufficiently large outflow capacity for the abundant water inflow from the sea. On the other hand, the imposed storm conditions are extremely severe, so large flooding might be expected when the primary water defences fail. At this point, no conclusions are drawn for the reliability of the simulated inundation areas; therefore a more detailed study should be performed.

Another model-result for dune breaching and inundation is presented in Figure 42. In fact, all model settings are exactly the same as for the simulation that is presented in Figure 41. The only (significant) difference is the presence of an artificial channel near the landward boundary. Note that the landward boundary is defined as a fully-reflective wall, but the artificial channel (might) enhance water outflow through the lateral boundaries. Note that initially both the inland creek and the artificial channel are filled with water (just like the previous simulations) with a fixed still water level at NAP -1 m.

From the upper left panel of the figure is it clear that the dune breaching occurred later in time, compared to the previously presented simulation (without any channel). The dune breaching occurred just before the presented snapshot at 18 hours. Actually this is a very remarkable result, since the conditions and initial model setting for the area seaward of the dunes are exactly the same for both simulations. But as explained before, the simulated differences are related to a random component for the generated (long) wave signal, which results in deviating high-frequency water level changes (or swash motion).

The upper panels also show the effects of the overwash-event, north of the central beach. A small amount of seawater is observed just north-east of the dune area behind the beach. This water subsequently flows towards the inland creek south of the town of Westkapelle. Note that the dunes at this location did not actually breach, but the high water level induced some overflow at the transition between the sea dike and the sandy dunes.

Moreover, a significant difference can be found between the results of the two simulations in the simulated impact of the flooding event. For the simulation with an artificial channel a much smaller inundation area is observed, since only the southern half of the model domain is flooded. Of course, this major difference in size of the flooded hinterland is (partly) caused by the presence of the artificial channel. But this cannot be the only reason for the different model-results; most likely also other effects play an important role here. For example, the simulated gap in the dune row is much smaller for the second simulation, such that a smaller amount of seawater entered the area behind the dunes. Probably, the combination of an enhanced water outflow at the lateral boundaries (due to the imposed channel), and a smaller gap in the dunes with consequently a smaller amount of water inflow, resulted in a significantly smaller inundation area for the second simulation.

The presented results (and their mutual differences) clearly showed that both the type of boundary definition and the (initially random) generated swash motion can have a significant effect on the results of simulations with dune breaches and flooding events. In order to use these kinds of advanced simulations for more specifically formulated consultancy questions, further analyses are required in future studies. But this test-case gives a very good impression of the possibilities of XBeach in modelling storm impact and more specifically dune breaching and flooding events. Especially those last two components will contribute to a better understanding of the risks of critical amounts of dune erosion. Therefore it is suggested that XBeach will actually be an additional improvement to the Operational Model System for the Dutch Coast that is currently under construction in a parallel development-project.

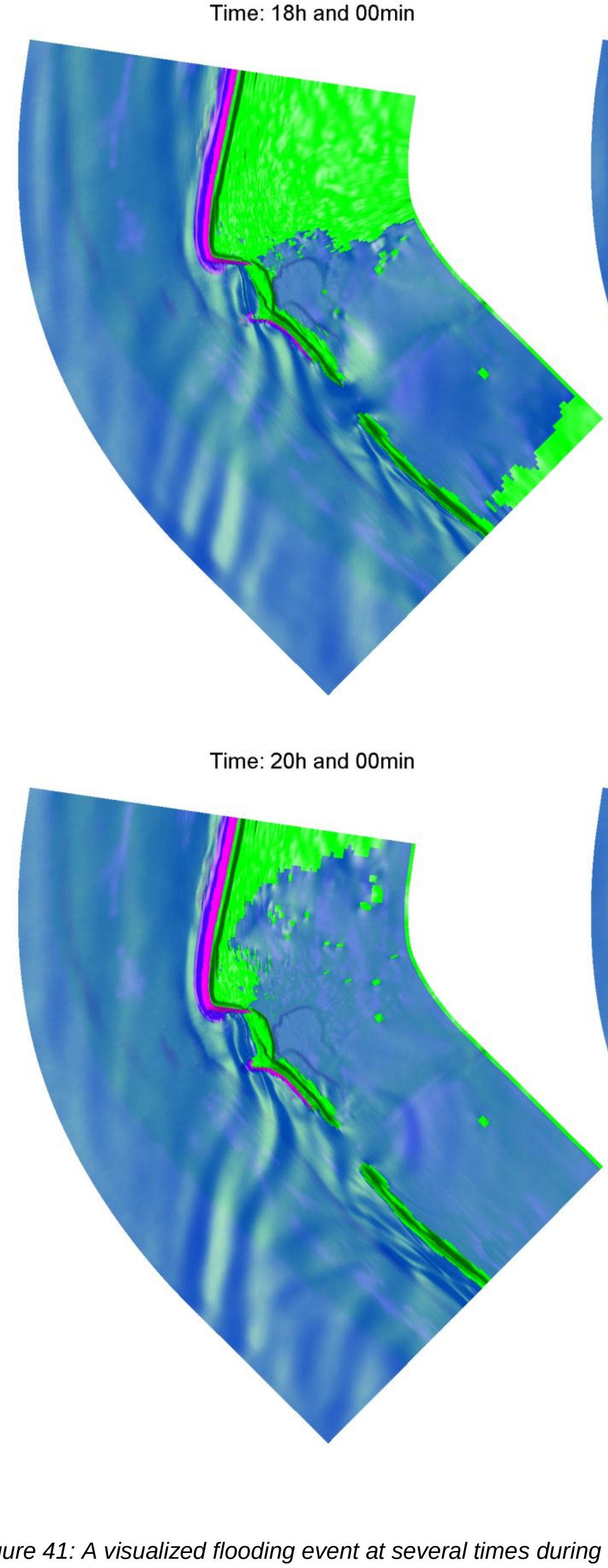

Figure 41: A visualized flooding event at several times during a super-storm simulation. The results are based on 30 hours of simulation with super-storm conditions (input-set C) and a 'closed' landward boundary. The pink colour indicates the presence of coastal structures, the green colour represents the sandy bottom, and the (semi-transparant) blue layer shows the sea surface level (still water level plus variation due to bound long waves).

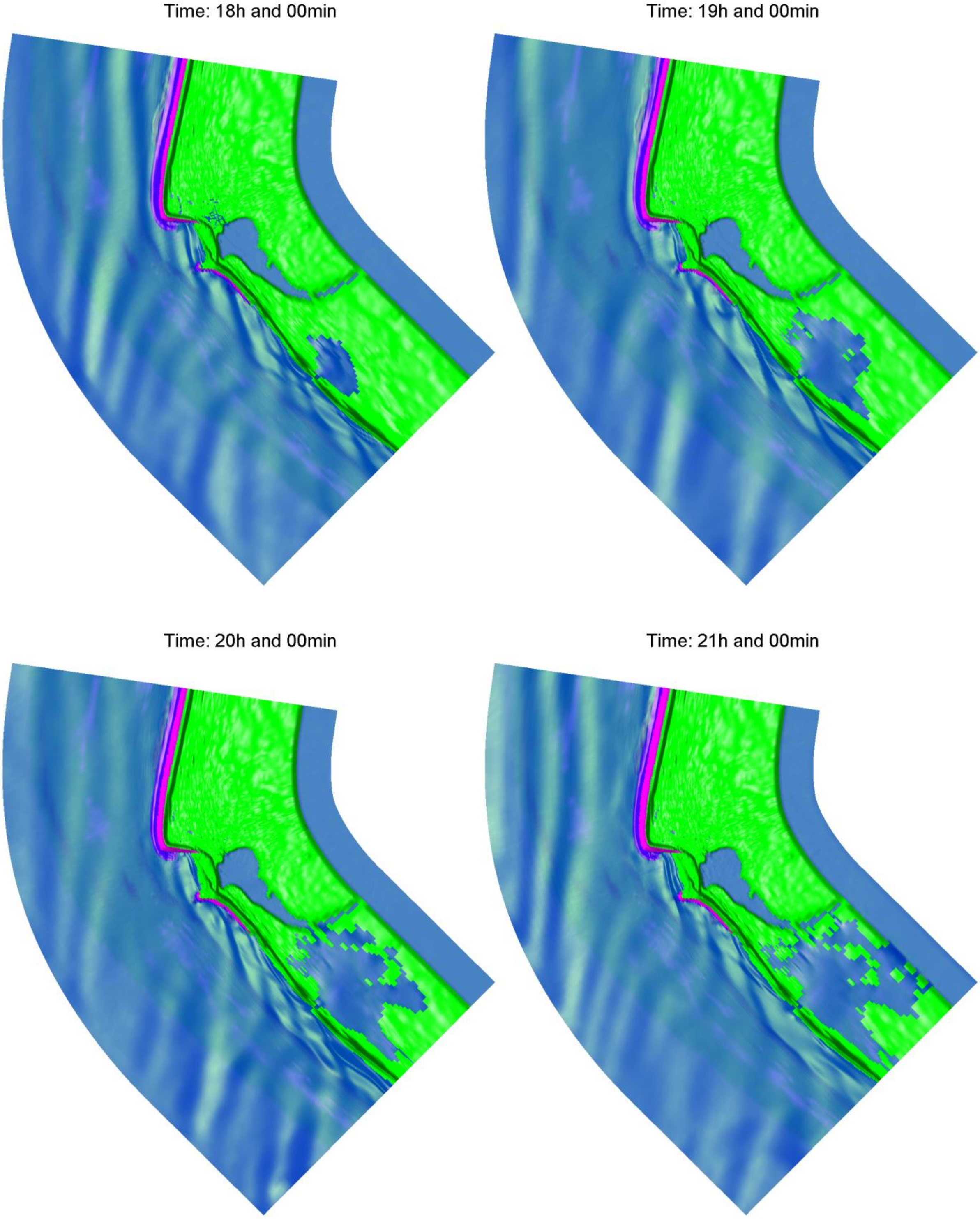

Figure 42: A visualized flooding event at several times during a super-storm simulation. The results are based on 30 hours of simulation with super-storm conditions (input-set C), a 'closed' landward boundary and an extra artificial landward channel. The pink colour indicates the presence of coastal structures, the green colour represents the sandy bottom, and the (semi-transparant) blue layer shows the sea surface level (still water level plus variation due to bound long waves).

4.4 HAZARD MAPS

End-users, such as governmental organisations and local policymakers, prefer easy-to-use and up-to-date information of coastal areas, in order to monitor important functions of these areas. Real-time data, by monitoring, enable adequate actions to (negative) changes of the current state of the coastal functions. Some basic keywords related to functions of the coastal zone are *safety*, *recreation* and *nature.* 2D storm impact modelling, as considered in this project, is closely related to the *safety* level that is provided by the coastal zone.

Maintaining proper safety levels along the coastline is top-priority for several local, regional and also national (governmental) organisations. For this purpose it is required to have spatial and temporal information of safety indicators for the coastal areas. In the Netherlands, safety assessments are based on yearly measured near-shore bathymetric datasets, for a large series of transects along the coast. This approach provides (yearly and transect-based) information about the expected amount of dune erosion and thus the size of the safety buffer in the dune area. In general, this approach gives a clear impression of the current safety level; however more detailed information, both temporal and spatial, is required in order to gain insight in the impact of low safety levels and to act adequately to changes in the (real-time) safety level of the dune areas along the coast.

A 2D modelling approach for dune erosion increases the alongshore resolution of storm impact simulations, by including all available bathymetric information of an entire coastal stretch, instead of only a limited amount of transect-data. Moreover, the inclusion of 2D XBeach models in an operational model system (with Argus video-imaging of the real-time near-shore bathymetry) will significantly improve the temporal scale for safety monitoring.

4.4.1 Hazard map demonstration

The final objective of this project, about 2D storm impact modelling of a complex coastline, is a (quick) demonstration of so-called hazard maps. These hazard maps are final ‘products’ of the storm impact simulations that provide useful information for end-users, based on a combination of relevant (physical) output parameters of the models. In other words, the hazard maps are all-in-one representations of relevant indicators for possible threats.

Hazard indicator(s)

In order to create a hazard map, first, indicators for threats should be defined. Since this part of the project only consists of a quick demonstration of the possibilities to convert XBeach results into usable output charts, no detailed explanations are provided in this report about the considered methods to define hazard indicators. In fact, there are many different ways to define hazard indicators, mostly depending on the actual required information for a specific coastal area. Several examples of safety or hazard indicators are: the position of the coastline, the width of the dune area, the width of the first dune row, the height of the dunes, the rest-volume of a dune row (after a storm event), etc. Or in case of actual dune breaching: the velocity of seawater inflow, the area of flooding, the water depth of the inundated area, etc.

For this demonstration case, the hazard indicator is defined to be the product of water depth and flow velocity:

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HAZARD INDICATOR = WATER DEPTH * FLOW VELOCITY
```

Idea behind this definition is that, in case of a flooded hinterland, high flow velocities are dangerous, especially when a substantial amount of water is present: i.e. large velocities with small water depths are less hazardous than large velocities with large water depths. And moreover, (not too) large water depths with low flow velocities are not that dangerous as well. In other words, the product of both parameters could provide useful information. Of course, for ‘real’, practical applications a more sophisticated approach can be adopted, by applying scaling factors for both of the considered parameters, or by including other physical parameters in the definitions. But for this demonstration, a relative simple approach is used.

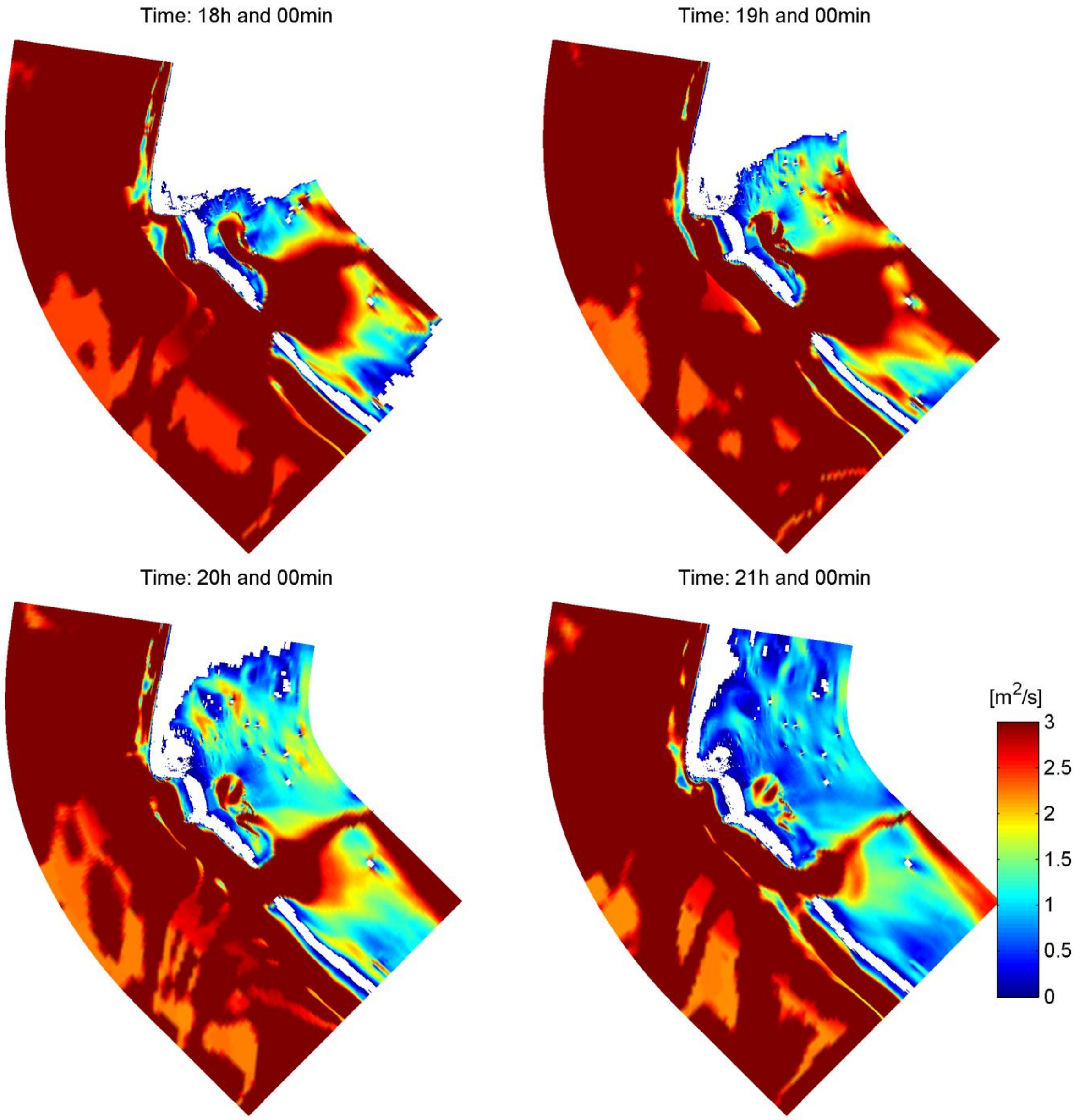

Figure 43: An example of the defined hazard indicator at several times during a super-storm simulation. The results are based on 30 hours of simulation with super-storm conditions (input-set C) and a 'closed' landward boundary. Higher values of the hazard indicator (defined as the product of water depth and flow velocity) indicate larger risks.

The results of one of the considered simulations, with dune breaching and a flooding event, are used to show the typical spatial and temporal variation of the defined hazard indicator. Some results of the selected simulation were presented in Figure 41. The determined hazard indicators for that simulation are presented in Figure 43. In the figure the product of flow velocity and water depth is presented, and obviously the resulting value for the indicator is a measure for the risk-level at a certain location. High values of the indicator are associated with areas where it is not safe to stay; due to either large water depths or high flow velocities (or both). Note that the minimum flow velocity is set to 0.1 m/s, in order to prevent low values for the indicator in very deep water without flow (offshore locations).

Obviously the largest indicator-values are found at sea and near the generated gap in the dunes due to breaching. Through this gap large inflow velocities are found, such that it is very dangerous to stay at that location. Moreover, relatively high values are found at the position of the inland creek, since the depth of the creek is associated with high risk.

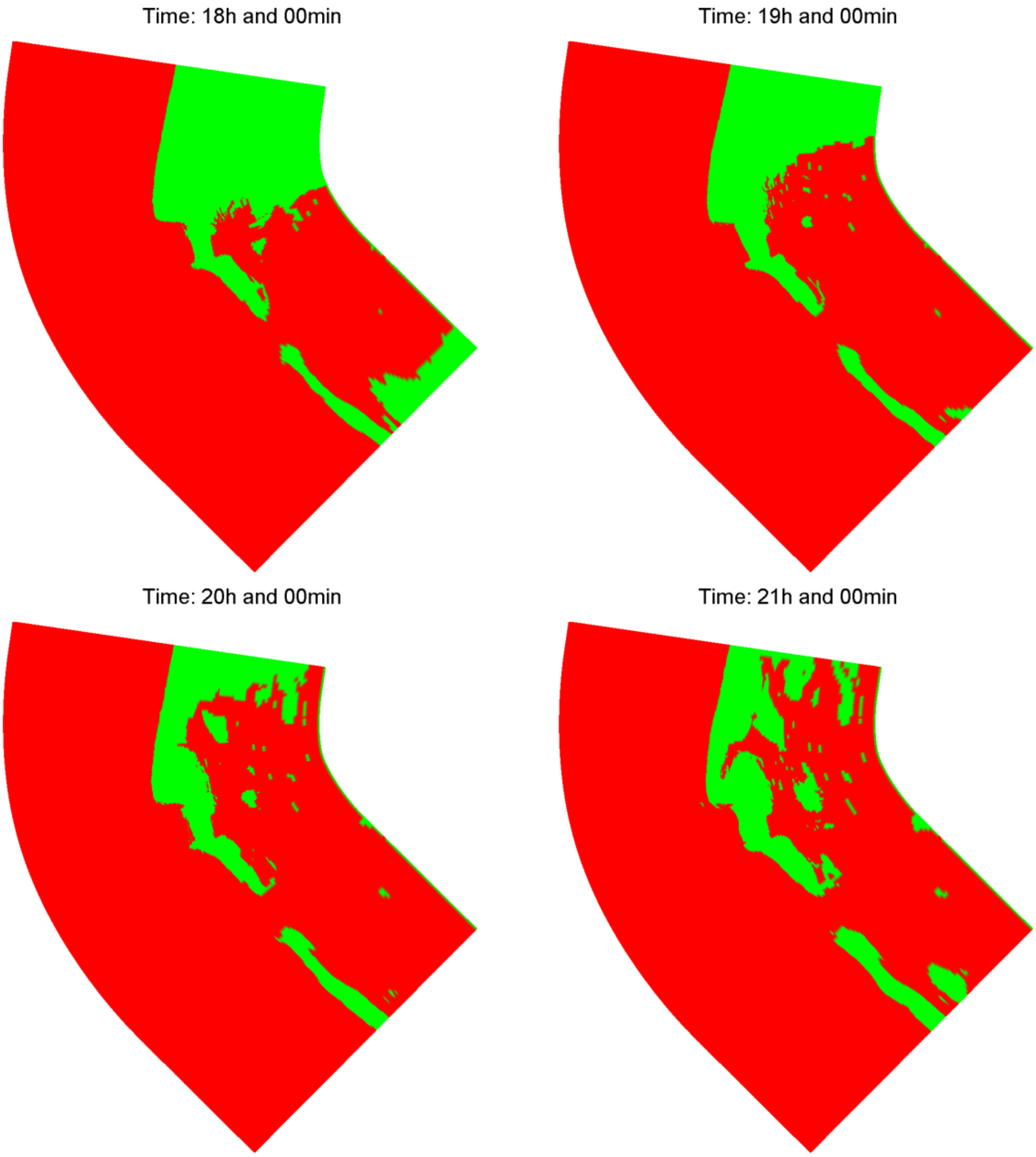

Figure 44: An example of a so-called 'hazard map' at several times during a super-storm simulation. The results are based on 30 hours of simulation with super-storm conditions (input-set C) and a 'closed' landward boundary. Depending on a specified cut-off value for the hazard indicator, a distinction is made between 'safe' (green) and 'hazardous' (red) areas. This figure is obviously presented for demonstration-purposes only, and the hazard indicator-definition and the (chosen) cut-off value should be calibrated and validated in future studies.

Hazard maps

Based in the presented charts with the hazard indicator-values, finally an example of an actual hazard map is created. The result is presented in Figure 44. This hazard map is, in fact, another representation of the previously presented figure, but here a certain cut-off value for the hazard indicator is chosen, such that areas are identified as either *safe* (green) of *not safe* (red). In this figure, the cut-off value for the indicator is set at 0.6.

Again, it should be noted that this is just a quick demonstration of the possibilities of post-processing for XBeach model results. Due to the 2D approach, it is relatively easy to convert model results into user-friendly charts with area-indications for certain hazard (or safety) indicators.

The arbitrary choice of both the definition of the hazard indicator and the cut-off value for *safe / non-safe* conditions imply that the presented results cannot be used for purposes other than demonstrations. For example, it is quite risky to stay at the top of the dunes during the considered storm conditions, while these figures suggest that it is safe, because no water flows are simulated over the remaining dunes.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The main objective of this project is to demonstrate the possibilities of 2D XBeach, regarding to storm impact modelling for complex coastal areas. A test-location near Westkapelle is selected that is characterized by rather complex features for dune erosion modelling, such as a deep near-shore tidal channel, dike/dune transitions, a strongly curved coastline, and alongshore varying bathymetry. For this specific location a regular 1D approach for storm impact modelling is considered to be doubtful due to the absence of alongshore components of sediment transport in regular 1D dune erosion models. Therefore a 2D XBeach model is set-up for the coastal area near Westkapelle. This model setup is used to simulate the effects of normative storm impact for different directions of wave attack.

In order to judge the results of the 2D XBeach model, a large number of 1D dune erosion models is set-up as well. Both XBeach (1D) models and DurosTA models are considered in this project. The 1D models are built for each cross-shore gridline in the 2D model domain, such that a series of subsequent transects (in alongshore direction) covers the entire model domain. The comparison of the results of 1D and 2D model approaches is, for this project, based on normative storm conditions.

A secondary objective of this project is to simulate dune breaching and flooding events, and to convert the results for these simulations into user-friendly output for end-users. As a demonstration-case so-called 'hazard maps' are presented, based on a particular simulated flooding event. These maps distinguish, during flooding events, the hazardous areas in the model domain from areas that are considered to be less risky, and therefore they provide useful information to end-users.

In the following sections, stepwise, the most important conclusions are presented that can be drawn based on the performed analyses.

5.1.1 2D XBeach model (normative storm conditions)

Simulations with the 2D XBeach model are performed for normative conditions and multiple wave directions. For each of the performed simulations the output of several model parameters is presented. The most important output parameters are the significant wave height, the flow velocity, the sediment transport rate and the final bed level changes.

The model results for westerly waves seem to be very trustworthy (based on qualitative analyses of the output of several model parameters) and they do give lots of insight in the dynamics of the system. The simulated erosion- and deposition patterns provide most of the required information to analyse the impact of storm conditions at the coastal area.

Simulations with relative large obliqueness of the incoming wave attack provide rather good results as well, but it should be noted that the final results are obtained after adjusting the grid definition and lateral boundary definition for the wave input. The stability of the flow field near the boundaries was significantly reduced by the obliqueness of the wave field (relative to the orientation of the lateral boundaries). Especially when the grid cells are curved near the side borders, problems arise for the model's stability. The applied solution for this problem was to extent the model domain with rectangular grid cells, such that minimal errors are induced by the Neumann-type definition at the lateral boundaries. Moreover, also a Neumann type of wave-boundary definition is used, instead of the '*wavecrest'* option that extrapolates the orientation of the crest of the wave field in the 'shading' areas near the boundaries. A drawback of this model setting is that the wave field (and thus the wave-induced alongshore currents) near the borders can be disturbed. However, a disturbed wave-field is always better than a growing instability of the flow field.

The final results for several settings of the wave obliqueness showed that significant differences in the amount of dune erosion are found when the directions of wave attack differ.

5.1.2 1D models versus 2D model (normative storm conditions)

1D dune erosion simulations are performed for a large series of transects along the coastline. All available results for these different transects are combined in a 2D representation of the 1D model output. In fact, 2D maps are created, based on the 1D model results. So finally, for both the 2D model and the combined series of 1D models maps are presented with erosion- and deposition patterns, based on the simulated bed level changes.

Furthermore, also analyses are performed by comparing the simulated volume differences along the coastline, per transect. These analyses consisted of a comparison of the amounts of erosion, deposition and net volume changes, for all model approaches (2D XBeach, 1D XBeach and DurosTA).

The results for 1D XBeach and 1D DurosTA mostly differ in the size of the simulated volume changes; the spatial sediment distribution is similar. Also, the *large-scale* erosion- and deposition patterns for both the 1D models and the 2D model are very similar. However, when comparing the amount of erosion and deposition for the 1D approach with volume differences for the 2D approach, it is concluded that alongshore processes do influence the sediment distribution along the coast substantially; especially on the more local scale. From the results it is concluded that especially the deposition areas are influenced by alongshore transport processes, while the erosion patterns are comparable for the 1D and 2D models. For example, the eroded sediment at the central beach is deposited further south, in front of the coastal structure.

The expected larger amount of erosion in the dune area due to gradients in alongshore sediment transport is not clearly confirmed, based on the performed simulations. It is most likely that another process counteracts the effect of extra (expected) erosion: the sea dike shields the central beach, so a reduced wave attack encounters the shoreline.

On the other hand, the expected extra erosion due to alongshore effects in 2D is (unexpectedly) found in the southerly dune area. A small curve in the coastline orientation resulted in flow divergence and consequently significantly larger amounts of erosion for the 2D model than simulated with both 1D models. So, it is suggested that even a bit of coastal curvature does have a significant effect on the amount of dune erosion during a storm event.

5.1.3 Dune breaching and flooding events

The 2D XBeach model is also used to simulate dune breaching and flooding events, by imposing super-storm conditions. By increasing the maximum water level by approx. 1 m, the maximum significant wave height by approx. 2 m, and the wave period by 1 second, dune breaching is forced within the considered model domain. During these simulations (with dune breaching) overwash events are observed as well. And these events mainly occurred in the transition area between sea dike and dune area.

A remarkable result of the simulations, related to dune breaching, is that different breaching locations are found for (slightly) different model runs. Small differences in the input settings for the (long) wave signal, as generated at the initial state, result in (totally) different breaching locations, and also in the associated gap-sizes.

The impact of flooding events, which occur after dune breaches, turned out to be very sensitive to model-settings for the inland boundary definitions. Largely deviating results are found for different types of settings for the boundaries. ‘Open’ boundaries at the landward side of the dune areas are mostly resulting in (very) large amounts of erosion in the entire hinterland, due to extremely large (frictionless) outflow velocities through the landward boundaries. In fact, the borders of the model domain are considered as ‘the end-of-the-world’ for these ‘open’ boundary settings. Defining the landward border as a wall-type of boundary do result in much better flow fields and in more realistic erosion- and deposition volumes. Drawback of wall-type boundaries is the fact that flow- and wave reflections are simulated near these boundaries, and when all inland boundaries are ‘closed’ the hinterland is actually filled like a closed box. A model setup with an artificial, landward channel, combined with open lateral boundaries, seems to result in the ‘best’ simulated flooding event. However, this conclusion is obviously just based on a qualitative analysis and expert judgment, since no data are available for a proper validation.

5.1.4 Hazard maps

In order to provide useful information to end-users, the XBeach output parameters are converted into function-indicators for the coastal area. For this specific test-case one hazard indicator is considered as an example. This hazard indicator is defined as the product of flow velocities and water depths, such that high flow velocities and/or large water depths indicate large treats. By imposing a well-considered cut-off values for the hazard indicator so-called 'hazard maps' can be constructed that indicate possible treats within the model domain. Some preliminary examples of hazard maps are presented in this project, based on one of the simulations with dune breaching and a flooding event.

5.2 RECOMMENDATIONS

Based on the performed simulations, analyses and comparisons several aspects are identified that should be studied in more detail in future studies. Most of the posed recommendations are related to more detailed (and more schematized) analyses that are required in order to quantify the effects of alongshore coastal processes on the amount of dune erosion.

In the following a list of recommendations is presented.

- ✓ Study alongshore sediment transport along curved coastlines with more schematized model setups.

  At the selected location for this project (Westkapelle) not only coastal curvature is affecting the erosion processes, but many other complexities do influence these processes as well. A more schematized 2D approach should provide more insight in the typical effect of curvature only.

- ✓ Study oblique wave attack for 1D XBeach models in more detail.

  Analyses in this project showed that the maximum amount erosion is simulated by 1D XBeach for slightly oblique wave incidence, rather normal wave incidence. The modelled effects of oblique wave attack in XBeach are therefore significantly different than the effects that result from simulations with DurosTA.

- ✓ Study oblique wave attack for 2D XBeach models.

  - Fix the boundary problems for '*wavecrest'* option (lateral boundaries).

    Instabilities (in the flow field) arise near the lateral boundaries when the wavecrest option is enabled in XBeach. The 'wavecrest' option should extrapolate the wave crests in the so-called shading areas near the lateral boundaries; although this seem to work, also strange velocity jets are formed through these boundaries.

  - Test, for straight coastlines, how oblique wave incidence contributes to the generation of alongshore currents and sediment transport.

    In qualitative way the effects of alongshore processes are shown in this project. However, a more quantitative relationship between the angle of wave incidence and wave-generated current velocities and sediment transport rates should be determined as well. Subsequently the schematized effect in DurosTA and the physical effects in XBeach can be compared.

- ✓ Study the amount of 'extra' dune erosion near a dike/dune transition with a schematized model.

  For safety assessments an additional landward shift of the dune face is suggested for transition areas where both a dike and a dune area are present as primary sea defences. Due to the complexities in the selected location for this project, the expected extra dune face retreat near the coastal structures is not confirmed by the performed simulations. It is suggested to set-up more schematized 2D XBeach models with dike/dune transitions, in order to study the effects of structures on the erosion volumes in an adjacent dune area.

- ✓ Study flooding events with XBeach in comparison with results from other models (either numerical models or physical scale models).

  In this project dune breaches and flooding events are simulated with a 2D XBeach model. However, variations in the type of inland boundary definitions did result in significantly different flow patterns and sizes of flooded areas behind the breached dune area. Since no data were available to validate the simulated effects of these dune breaches, comparisons with other numerical models or physical scale models are required in order to check which type of input settings for XBeach are preferred in order to perform realistic simulations related to the dynamics of flooding events and for example the size of the inundation areas.

- ✓ Study the stability of XBeach when simulating extreme storm conditions that induce dune breaching.

  Several simulations, performed during this project, did result in unrealistic high inflow velocities through the offshore boundary. Further analyses should clarify whether these 'jets' are caused by instabilities due to the extremely high conditions (large wave heights w.r.t. water depth) or by a suction-effect due to generated flow velocities through the gap(s) at a dune breach location.

- ✓ Discuss the applicability of 'hazard maps' with end-users, and study more sophisticated approaches to determine hazard indicators and safety levels.

  In this project a relatively simple demonstration-case for hazard maps is presented, but for actual applications of this type of model output more contact with end-users is required. In addition also a more detailed literature-study should be performed to compare existing methods for visualizing hazard indicators and safety levels.

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A XBEACH LOG-FILE

```
**********************************************************
                   Welcome to XBeach

            revision Range 2356 Not mixed revisions  and no local modifications
            date 2011/10/21 17:24:23
 URL: https://svn.oss.deltares.nl/repos/xbeach/trunk
**********************************************************

Simulation started: YYYYMMDD    hh:mm:ss     time zone (UTC)
                    20111104  14:02:24     +0100

General Input Module
Reading input parameters:
--------------------------------
Physical processes:
XBeach reading from params.txt
swave                   = 1 (no record found, default value used)
lwave                   = 1 (no record found, default value used)
flow                    = 1 (no record found, default value used)
sedtrans                = 1 (no record found, default value used)
morphology              = 1 (no record found, default value used)
avalanching             = 1 (no record found, default value used)
nonh                    = 0 (no record found, default value used)
gwflow                  = 0 (no record found, default value used)
q3d                     = 0 (no record found, default value used)
swrunup                 = 0 (no record found, default value used)
ships                   = 0 (no record found, default value used)
--------------------------------
Grid parameters:
gridform                = delft3d
depfile                 = depth.dep
xyfile                  = grid.grd
xori                    = 0.0000 (no record found, default value used)
yori                    = 0.0000 (no record found, default value used)
alfa                    = 0.0000 (no record found, default value used)
posdwn                  = 0.0000
thetamin                = 180.0000
thetamax                = 360.0000 Warning: value > recommended value of 180.0000
dtheta                  = 20.0000
thetanaut               = 1
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Model time parameters:
CFL                     = 0.7000 (no record found, default value used)
tstop                   = 108000.0000
--------------------------------
Physical constants:
rho                     = 1025.0000 (no record found, default value used)
g                       = 9.8100 (no record found, default value used)
depthscale              = 1.0000 (no record found, default value used)
--------------------------------
Initial conditions:
zsinitfile              = None specified
--------------------------------
Wave boundary condition parameters:
instat                  = jons
bcfile                  = filelist.txt
taper                   = 100.0000 (no record found, default value used)
nmax                    = 0.8000 (no record found, default value used)
leftwave                = wavecrest
rightwave               = wavecrest
--------------------------------
Wave-spectrum boundary condition parameters:
random                  = 1 (no record found, default value used)
fcutoff                 = 0.0000 (no record found, default value used)
```

```
nspr                     = 0 (no record found, default value used)
trepfac                  = 0.0100 (no record found, default value used)
sprdthr                  = 0.0800 (no record found, default value used)
oldwbc                   = 0 (no record found, default value used)
newstatbc                = 1 (no record found, default value used)
correctHm0               = 1 (no record found, default value used)
oldnyq                   = 0 (no record found, default value used)
Tm01switch               = 0 (no record found, default value used)
wbcversion               = 2 (no record found, default value used)
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Flow boundary condition parameters:
front                    = abs_2d
left                     = neumann
right                    = neumann
back                     = abs_2d
ARC                      = 1 (no record found, default value used)
order                    = 2.0000 (no record found, default value used)
carspan                  = 0 (no record found, default value used)
freewave                 = 0 (no record found, default value used)
epsi                     = -1.0000
tidetype                 = velocity (no record found, default value used)
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Tide boundary conditions:
tideloc                  = 4
zs0file                  = tide.txt
--------------------------------
Discharge boundary conditions:
disch_loc_file           = None specified
disch_timeseries_file    = None specified
ndischarge               = 0 (no record found, default value used)
ntdischarge              = 0 (no record found, default value used)
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Wave breaking parameters:
break                    = roelvink2 (no record found, default value used)
gamma                    = 0.5500 (no record found, default value used)
alpha                    = 1.0000 (no record found, default value used)
n                        = 10.0000 (no record found, default value used)
gammax                   = 2.0000 (no record found, default value used)
delta                    = 0.0000 (no record found, default value used)
fw                       = 0.0000 (no record found, default value used)
fwcutoff                 = 1000.0000 (no record found, default value used)
breakerdelay             = 1 (no record found, default value used)
shoaldelay               = 0 (no record found, default value used)
facsd                    = 1.0000 (no record found, default value used)
facrun                   = 1.0000 (no record found, default value used)
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Roller parameters:
roller                   = 1 (no record found, default value used)
beta                     = 0.1000 (no record found, default value used)
rfb                      = 0 (no record found, default value used)
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Wave-current interaction parameters:
wci                      = 0 (no record found, default value used)
hwci                     = 0.1000 (no record found, default value used)
cats                     = 4.0000 (no record found, default value used)
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Flow parameters:
bedfriction              = chezy (no record found, default value used)
bedfricfile              = None specified
C                        = 55.0000 (no record found, default value used)
nuh                      = 0.1000 (no record found, default value used)
nuhfac                   = 1.0000 (no record found, default value used)
nuhv                     = 1.0000 (no record found, default value used)
smag                     = 1 (no record found, default value used)
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Coriolis force parameters:
wearth                   = 0.0417 (no record found, default value used)
lat                      = 0.0000 (no record found, default value used)
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```

```
Wind parameters:
rhoa                    = 1.2500 (no record found, default value used)
Cd                      = 0.0020 (no record found, default value used)
windfile                = None specified
windv                   = 0.0000 (no record found, default value used)
windth                  = 270.0000 (no record found, default value used)
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Bed composition parameters:
ngd                     = 1 (no record found, default value used)
nd                      = 3 (no record found, default value used)
por                     = 0.4000 (no record found, default value used)
D50                     = 0.0002 (no record found, default value used)
D90                     = 0.0003 (no record found, default value used)
rhos                    = 2650.0000 (no record found, default value used)
dzg                     = 0.1000 (no record found, default value used)
dzg1                    = 0.1000 (no record found, default value used)
dzg2                    = 0.1000 (no record found, default value used)
dzg3                    = 0.1000 (no record found, default value used)
sedcal                  = 1.0000 (no record found, default value used)
ucrcal                  = 1.0000 (no record found, default value used)
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Sediment transport parameters:
form                    = vanthiel_vanrijn (no record found, default value used)
waveform                = vanthiel (no record found, default value used)
sws                     = 1 (no record found, default value used)
lws                     = 1 (no record found, default value used)
BRfac                   = 1.0000 (no record found, default value used)
facsl                   = 1.6000 (no record found, default value used)
z0                      = 0.0060 (no record found, default value used)
smax                    = -1.0000 (no record found, default value used)
tsfac                   = 0.1000 (no record found, default value used)
facua                   = 0.1000 (no record found, default value used)
facSk                   = 0.1000 (no record found, default value used)
facAs                   = 0.1000 (no record found, default value used)
turb                    = bore_averaged (no record found, default value used)
Tbfac                   = 1.0000 (no record found, default value used)
Tsmin                   = 0.5000 (no record found, default value used)
lwt                     = 0 (no record found, default value used)
betad                   = 1.0000 (no record found, default value used)
sus                     = 1 (no record found, default value used)
bed                     = 1 (no record found, default value used)
bulk                    = 1 (no record found, default value used)
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Morphology parameters:
morfac                  = 10.0000
morfacopt               = 1 (no record found, default value used)
morstart                = 120.0000
morstop                 = 108000.0000 (no record found, default value used)
wetslp                  = 0.3000 (no record found, default value used)
dryslp                  = 1.0000 (no record found, default value used)
hswitch                 = 0.1000 (no record found, default value used)
dzmax                   = 0.0500 (no record found, default value used)
struct                  = 1
ne_layer                = structures.dat
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Output variables:
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tunits                  = None specified
projection              = None specified
tstart                  = 0.0000
tint                    = 1.0000 (no record found, default value used)
tsglobal                = None specified
tintg                   = 600.0000
tspoints                = None specified
tintp                   = 3600.0000
tscross                 = None specified
tintc                   = 1.0000 (no record found, default value used)
tsmean                  = None specified
tintm                   = 3600.0000
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nglobalvar                = 19
nglobalvar: Will generate global output for variable:zb
nglobalvar: Will generate global output for variable:zs
nglobalvar: Will generate global output for variable:H
nglobalvar: Will generate global output for variable:u
nglobalvar: Will generate global output for variable:ue
nglobalvar: Will generate global output for variable:v
nglobalvar: Will generate global output for variable:ve
nglobalvar: Will generate global output for variable:Fx
nglobalvar: Will generate global output for variable:Fy
nglobalvar: Will generate global output for variable:Subg
nglobalvar: Will generate global output for variable:Svbg
nglobalvar: Will generate global output for variable:Susg
nglobalvar: Will generate global output for variable:Svsg
nglobalvar: Will generate global output for variable:Sutot
nglobalvar: Will generate global output for variable:Svtot
nglobalvar: Will generate global output for variable:sedero
nglobalvar: Will generate global output for variable:dzav
nglobalvar: Will generate global output for variable:thetamean
nglobalvar: Will generate global output for variable:structdepth
npoints                   = 0
nrugauge                  = 0 (no record found, default value used)
npointvar                 = 0
rugdepth                  = 0.0000 (no record found, default value used)
nmeanvar                  = 8
nmeanvar: Will generate mean, min, max and variance output for variable:zs
nmeanvar: Will generate mean, min, max and variance output for variable:H
nmeanvar: Will generate mean, min, max and variance output for variable:u
nmeanvar: Will generate mean, min, max and variance output for variable:ue
nmeanvar: Will generate mean, min, max and variance output for variable:v
nmeanvar: Will generate mean, min, max and variance output for variable:ve
nmeanvar: Will generate mean, min, max and variance output for variable:Sutot
nmeanvar: Will generate mean, min, max and variance output for variable:Svtot
ncross                    = 0 (no record found, default value used)
outputformat              = netcdf
ncfilename                = None specified
netcdf output to:xboutput.nc
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Drifters parameters:
drifterfile               = None specified
ndrifter                  = 0 (no record found, default value used)
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Shipwaves parameters:
shipfile                  = None specified
--------------------------------
Wave numerics parameters:
scheme                    = upwind_2 (no record found, default value used)
--------------------------------
Flow numerics parameters:
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umin                      = 0.0000 (no record found, default value used)
hmin                      = 0.2000 (no record found, default value used)
secorder                  = 0 (no record found, default value used)
oldhu                     = 0 (no record found, default value used)
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Sediment transport numerics parameters:
thetanum                  = 1.0000 (no record found, default value used)
sourcesink                = 0 (no record found, default value used)
cmax                      = 0.1000 (no record found, default value used)
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Bed update numerics parameters:
frac_dz                   = 0.7000 (no record found, default value used)
nd_var                    = 2 (no record found, default value used)
split                     = 1.0100 (no record found, default value used)
merge                     = 0.0100 (no record found, default value used)
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MPI parameters:
mpiboundary               = auto (no record found, default value used)
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```

```
 Finished reading input parameters
 ---------------------------------
Warning: Setting rugdepth to minimum value greater than eps (0.00500)
 Unknown, unused or multiple statements of parameter swtable in params.txt
 -------------------------------------
 Building Grid and Bathymetry
 -------------------------------------
 Initializing .....
 readtide: reading tide time series from tide.txt ...
 ---------------------------------
 Initializing spectral wave boundary conditions
 ---------------------------------
 NetCDF outputformat
 Creating netcdf variable: zb
 … … … …
 Creating netcdf variable: Svtot_max
 Writing file definition.
 Setting up boundary conditions
 waveparams: Reading from jonswap_1.txt ...
 XBeach reading from jonswap_1.txt
 Hm0                        = 3.3206
 fp                         = 0.0865
 fnyq                       = 1.0000
 dfj                        = 0.0050 (no record found, default value used)
 gammajsp                   = 3.3000
 s                          = 10000.0000 Warning: value > recommended value of 1000.0000
 mainang                    = 270.0000
Input checked: Hm0 = 3.321 Tp = 11.561 dir = 270.000 duration = 720.000
Derived Trep = 10.565
Changing dtbc in wave boundary conditions to satisfy Nyquist condition:
New dtbc = 0.5025 s.

 Calculating wave energy at boundary
 Calculating flux at boundary
 Warning: shallow water so long wave variance is reduced using par%nmax
 Boundary conditions complete, starting computation

Simulation   0.0 percent complete. Average dt 0.076 seconds
Time remaining 34 hours and 38 minutes
      … … … … …
      … … … … …
      … … … … …
Simulation 100.0 percent complete. Average dt 0.108 seconds
Time remaining  0 seconds

 Duration    :    64855.4218750000      seconds
 Timesteps   :       102269
 Average dt  :   0.105603848673596      seconds
 Unit speed  :   1.531799552100048E-005 seconds/1
 End of program xbeach
```