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LONG-TERM MORPHOLOGICAL MODELLING: COMBINING STORM IMPACT AND DAILY CONDITIONS IN AN INTEGRATED MODELING FRAMEWORK

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Abstract

For morphological behavior of coasts on the long term (years to decades), both storm events and daily conditions can play a role. It can be a challenge to combine the modeling of both types of conditions, because they act on different time scales and the dominant processes are different. This paper presents an assessment of three approaches for long term modeling (5 year), combining different time scales in an integrated modeling framework using the stationary and instationary modes of the XBeach morphological model for a nourishment in The Netherlands. All three methods lead to stable results providing insight in the long term behavior of the nourishment. The results are similar, suggesting the impact of storm events at the study site is limited for the considered period of five years. It was found that nearshore wave height was 20-40% higher using the instationary compared to the stationary mode of the model.

Key words: coastal morphology, long term morphology, sand nourishment, building with nature, XBeach

1. Introduction

For the morphological behavior of coasts on the long term (years to decades), both storm events and daily conditions can play a role. Particularly when looking at unprotected beach nourishments and land reclamations, one is interested in assessing the design on safety, stability and sediment losses on short time scales during storm events, and in morphological developments and required maintenance volumes under more averaged, daily conditions on longer time scales.

During storm events, infragravity (IG) waves forced by the wave groups are largely responsible for erosion, overwash and breaching on dissipative beaches. In the North Sea these storm events occur typically on a time scale of hours to days during which erosive processes are dominant. This requires a model which is able to accurately represent these erosive processes, which partly take place above the water line in the collision, overwash and breaching regime (Sallenger, 2000), such as the XBeach morphological model (Roelvink et al., 2009). XBeach in its default mode is wave- averaged and uses the wave-group resolving short wave action balance equations as a forcing term for IG waves, which are fully resolved using the non-linear shallow water equations (Roelvink, et al., 2009).

Under milder, daily wave conditions recovery processes start up and wave skewness and asymmetry and tidal currents determine the morphological development on the longer term. For long term development of beaches both storm conditions and daily wave condition are important. It can be a challenge to combine the modelling of both types of conditions, because they act on different time scales and the dominant processes are different. This research presents a comparison of approaches for long term modeling using the stationary and instationary modes of XBeach and shows how it affects the long-term morphological development for a case study on the island of Texel in The Netherlands (figure 1).

For this case study a new approach was used in which the morphological model XBeach was applied for storm events, as well as for the daily conditions, combining simulations for both type of conditions in a modeling framework. A similar approach was applied with good results by Pender and Karunarathna (2012) for a 1D case at Narrabeen beach, Australia.

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This paper aims to assess the added value of this approach by comparing it with an approach using only stationary simulations (no IG waves, approach B) and using only instationary simulations (with IG waves, approach C), as summarized in table 1.

Table 1, wave solver used for simulations in approach A, B and C

Approach	Daily conditions	Storm events
A	stationary	instationary
B	stationary	stationary
C	instationary	instationary

In chapter 2 the research methodology and case study are described. Chapter 3 presents the model results and the assessment of the modeling approach. Subsequently the results are discussed in chapter 4. Finally chapter 5 will provide conclusions and recommendations for further research on the topic of long term modeling with XBeach.

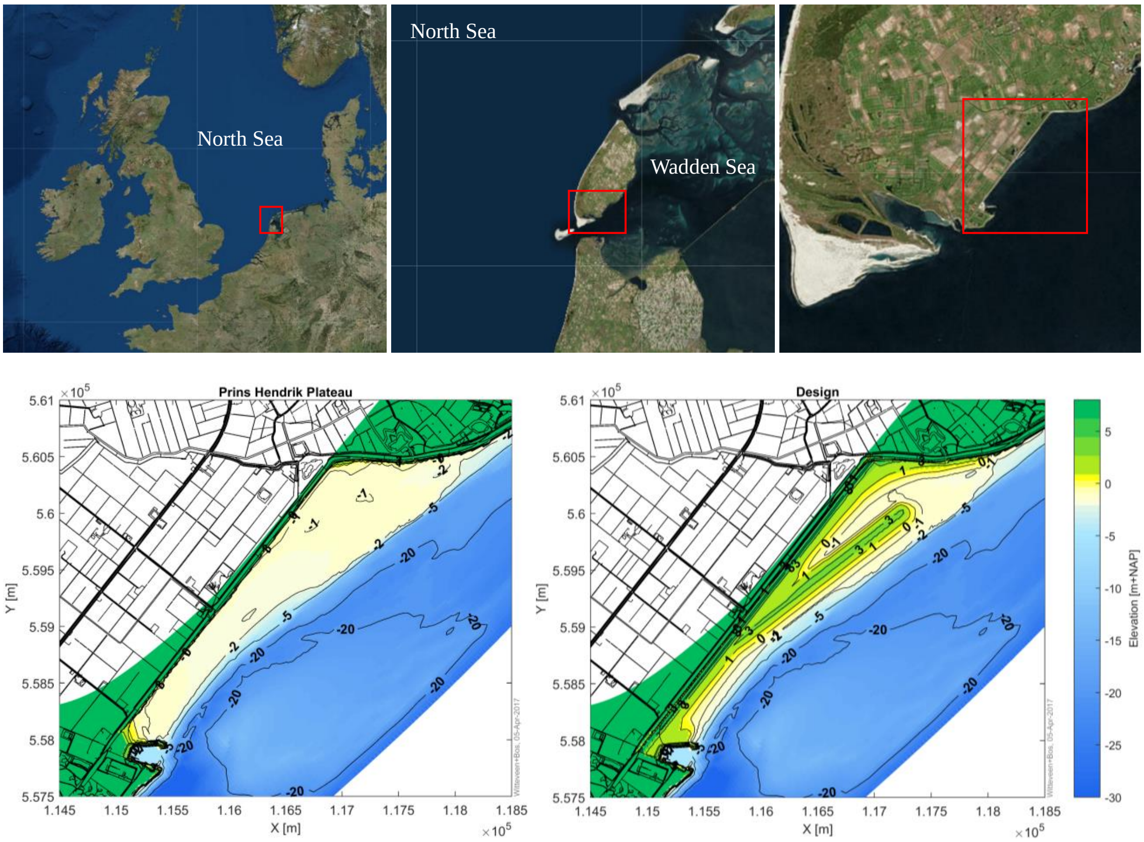

Figure 1, Case study location and design; top panel: geographic location; middle left panel: bathymetry of the area of interest; middle right panel: bathymetry and elevation of the nourishment design; bottom panel: ecological habitats

2. Methodology

2.1. *Modeling framework*

A modeling framework was set up to model five years of morphological development for the design layout of the nourishment. Separate configurations were set up for the daily conditions and the storm events. The configuration for daily conditions is used to simulate the morphological development over a one-year period based on an averaged wave climate. For this purpose the XBeach model was run using the stationary wave module which solves wave-averaged equations, but neglects IG waves. This methodology is computationally efficient for longer term simulations.

A separate configuration was set up to model storm events for each year using the instationary wave module of XBeach (also referred to as surf-beat). This module resolves the short wave variations on a wave group scale (short wave envelope) which act as a forcing term in the shallow water equations for the long (IG) waves. This allows for modeling of the processes associated with storms such as collision, overwash and breaching and corresponding morphodynamics.

In this study these simulations were combined to obtain the morphological behavior of the design for five years. A modeling framework was set up in which a simulation of one year morphology under daily conditions results in a bathymetry for a storm event simulation, which in turn gives the bathymetry for the next year, and so on (figure 2).

Wave and water level boundary conditions were provided from regional SWAN and Delft3D models.

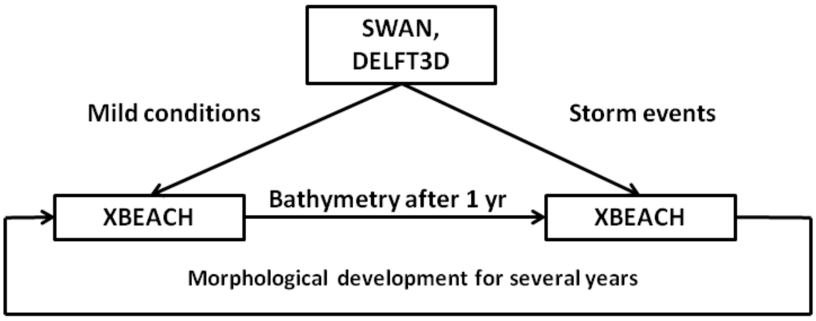

Figure 2, Modeling framework combining storm impact and daily conditions

The complete framework to model five years of morphology consists of five simulations with daily conditions and five simulations with three storms. Assuming that IG waves are only important during storm conditions, storm events were run in instationary mode and simulations for daily conditions were run in stationary mode in the original approach for the modeling study, referred to as approach A. In approach B all simulations are run in stationary mode and in approach C all simulations are run in instationary mode (Table 1).

2.2. *Case study*

2.2.1. *Location and background*

The location of the case study is at the southeast side of the Wadden Island of Texel, in the Wadden Sea adjacent to the Prins Hendrikpolder in The Netherlands (figure 1). The polder is currently protected by a dike with a length of 3.2 km. A natural shallow plateau at on average 1-2 m-NAP (NAP is the Dutch reference level and corresponds roughly to mean sea level) and a width ranging from 400 - 700 m is located at the seaward side of the dike. From the shallow plateau there is a steep transition to a deep channel with a depth varying from 15-30 m (Texelstroom). The shallow plateau is morphologically stable and the steep slope towards the Texelstroom is stabilised with a rock revetment.

Traditionally flood safety at the Wadden Sea side of Texel is provided by dikes. In the 2006 safety assessment large stretches of dike were found not to be at the required safety level and so a dike reinforcement program was initiated. For the stretch of dike at the Prins Hendrikpolder a nature-based solution was selected with a sandy dune providing the required flood safety level.

This side of the island and particularly the plateau is largely sheltered from wave attack by storms on the North Sea from the dominant SW-NW direction. Waves penetrate into the Wadden Sea and obliquely reach this area, but the short waves and corresponding IG wave action are relatively small. The wave climate is therefore dominated by locally generated wind waves.

The shallow plateau is located next to the Texelstroom. The currents in the Texelstroom are relatively strong with ebb and flood tidal velocities ranging between 1 and 2 m/s. The tidal velocities on the shallow plateau are small though, <0.5 m/s.

2.2.2. *Design*

The design of the case study should guarantee the required level of flood safety and should enhance the ecological value of the area. The required level of flood safety is provided by a straight, almost dike shaped, sandy dune parallel to the existing dike. The main dimensions are based on Dutch empirical safety rules applicable for dunes at the North Sea coast. The required crest level of the dunes is about NAP+8m and the width is over 25m.

The layout of the spit and the remaining foreshore is designed in a concave shape to provide a stable coast with a minimum of sand losses, maintaining the habitat areas as much as possible. The spit is designed sufficiently high to prevent overwash. At the dune foot and the spit, in the morphologically active zone, an additional volume of sand is included as a sand buffer for sand losses due to alongshore sediment transport.

The shallow plateau has an area of approximately 200 hectares and the case requires an initial nourishment of about 4 million m^3 of sand. Sand nourishments with a frequency of 1/10 year are foreseen to compensate for erosion caused by sediment transport (maintaining the sand buffer).

2.3. *Model setup*

A curvilinear grid was created to allow waves to enter through the offshore boundary from all shore-incident directions from 62°N to 217°N (figure 3). The cross-shore grid size varies from approximately 10 m nearshore to 35 m offshore. The alongshore grid size varies from 20-60 m.

The bathymetry was based on recent detailed surveys of the area with a resolution of 1x1 m or 2x2 m by grid cell averaging. The bathymetry of the current situation is implemented in the model as a non-erodible layer on top of which the nourishment is applied as an erodible sediment layer.

The wave directional grid covered directions from 0°N to 240°N using 16 directional bins of 15° each.

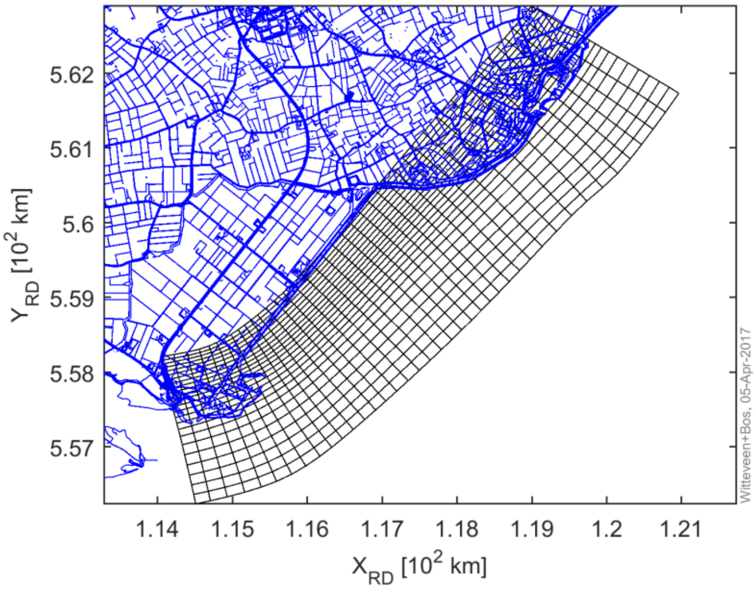

Figure 3, XBeach model grid

2.4. *Boundary conditions*

The modeling framework consisted of a model configuration for daily conditions and a model configuration for storms. Below, the wave and water level boundary conditions for both configurations are discussed in separate sections.

2.4.1. *Models with daily conditions*

For the simulations with daily conditions a 7.5 day tidal signal was selected from a spring-neap cycle such that it was representative for an average tide in this area. In order to drive an alongshore tidal current in XBeach a time series of water levels at the two offshore corners of the grid are required. The water levels are modeled with Delft3D in order to obtain boundary conditions for XBeach at the desired locations.

Based on 34 years of hourly wind measurements at a nearby location (De Kooy) a wind climate was created. In total 113 wind and wave conditions were modeled with SWAN (WTI version) to obtain wave conditions at the XBeach model boundary. 21 conditions were selected based on the expected contribution to sediment transport over one year based on a simplified transport formulation ($S = H_s^3 \sin 2\varphi$). The total duration of these conditions is about 70 days. With a morphological acceleration factor of 10 the total required simulation time is 7.5 days, including 0.5 day spin up time for hydrodynamics.

The wave climate with 21 conditions is representative for one year. The conditions are randomly mixed each year to prevent chronology effects and to vary the combination of wave height and water level. Wave boundary conditions are applied uniformly over the offshore model boundary as a time series of Jonswap spectra (H_s, Tp, wave direction and directional spreading). The wave and water level boundary conditions are summarized in figure 4 (left).

2.4.2. *Models with storms*

Each storm simulation consists of a time series of three consecutive storms. The storms were selected as the three highest wave conditions that would on average at least occur once per year based on the available wind statistics data. The corresponding (average) water levels were increased with half the tidal amplitude (0.7 m) to obtain the peak water level during each of the storms. This resulted in storms 1A, B and C for year 1, presented in table 2.

To increase the storm impact, for the storms in year 2 and 3 it is assumed that surge events with a return period of 1 year (RP1, 2.25 m+NAP) and 5 years (RP5, 2.70 m+NAP) occur simultaneously with peak wave conditions. In addition the surge events were set to a minimum water level of 1 m+NAP.

Typically, the assumption that peak wave height coincide with peak surge levels is correct in the North Sea, but for this sheltered area this is a conservative assumption, because waves generated by northwest winds generating the surge, do not reach the area of the case study.

In the storm simulations the water levels due to surge are applied uniformly over the offshore model boundary. The storm duration was based on the surge level which was assumed to follow a $\cos^2$ function. Morphology during storms is assumed to be dominated by the surge in water levels, so the tidal signal is not included in these simulations. All storm conditions modeled in the storm simulations are summarized in table 2 and figure 4.

Table 2, selected storms for storm simulations per year

year	**storm id**	**Hs [m]**	**Tp [s]**	**Dir [°N]**	**max. WL [NAP + m]**
1	1 A	1.0	3.5	93	0.60
	1 B	1.4	3.9	212	0.93
	1 C	1.6	4.2	212	1.03
2	2 A	1.0	3.5	93	1.00
	2 B	1.4	3.9	212	1.00
	2 C	1.6	4.2	212	2.25
3	3 A	1.0	3.5	93	1.00
	3 B	1.4	3.9	212	2.25
	3 C	1.7	4.4	214	2.70
4+5	The storms of year 1 are repeated in year 4 and year 5				

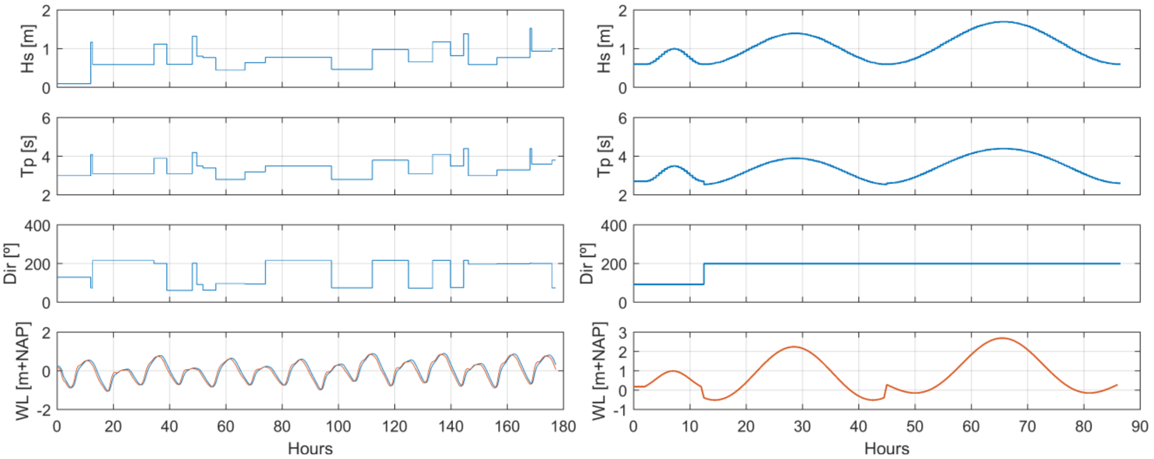

Figure 4, XBeach model boundary conditions; left: wave climate for daily conditions (year 1); right: three consecutive storms in year 3; figures show from top to bottom: time series of H_s, T_p, wave direction °N, water level

2.5. *Model validation*

The validation of the hydrodynamics was based on an inter-model comparison between XBeach and SWAN for waves and Delft3D for the tidal currents which showed good agreement.

The case study involved the modeling of a future nourishment at a location where currently hardly any sediment is available. It was therefore not possible to validate the morphology other than by expert judgement and a basic comparison with bulk transport formulations.

The outcome of the XBeach calculations are compared with the results of hand calculations using different types of bulk transport formula such as the CERC formula (Shore Protection Manual, US Army Corps of Engineers, 1984) and the Kamphuis formulae (Kamphuis, 1986, 1991). The long shore transport of both methods is in the same order of magnitude (1,000 m^3/yr to 25,000 m^3/yr).

3. Results

This section describes the results of the comparison of approach A, B and C. The comparison is focused on morphodynamics, but a significant difference in wave height was found on the shallow plateau, which is analysed in the section below as it is the main driver of morphodynamics for this case. Subsequently erosion and sedimentation and sediment transport are analysed and compared.

3.1. *Wave height*

The wave height difference between both solvers is illustrated in figure 5 based on the first year simulation of daily conditions with approach B and C. The figure shows a scatter plot of the hourly mean significant wave height for the entire simulation of year one for five different nearshore locations (figure 5, right). In the nearshore zone, roughly from the -2 m depth contour and upward, the computed wave height is significantly higher using the instationary wave solver. On average the nearshore wave height is 20-40% higher with the instationary solver compared to the stationary solver. For the higher wave conditions (H_s>0.4m) the difference tends more to 20%, whereas for the lower wave heights (H_s<0.4m) the difference tends to 40%.

It appears that the propagation of waves over the steep slope from the deep channel onto the shallow plateau is affected significantly by the wave solver. A large part of the wave energy is lost with the stationary solver, whereas most energy is conserved using the instationary solver. This may be caused by the difference in the breaker formulation and the breaker parameter that is used in both solvers.

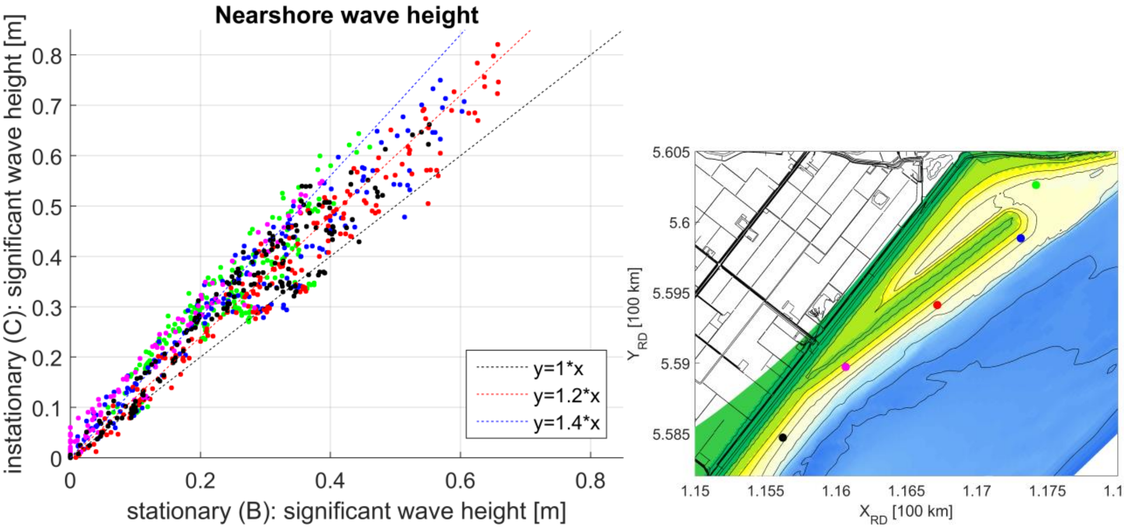

Figure 5, left panel: scatter plot of nearshore significant wave height for the stationary solver (B) versus the instationary solver (C). The markers indicates the hourly mean significant wave height at all output timesteps for the year one simulation. Colors are related to the locations shown in the right panel; right panel: locations for comparison of nearshore wave height.

3.2. ***Morphological development of nourishment after 5 years***

Using model approach A, the entire nourishment and spit remain fairly stable and unchanged after five years of simulations (figure 6 and figure 7). Due to the absence of extreme water levels (>3 m + NAP) only the spit and the lower parts of the beach are subject to wave attack and the safety dune is not reached. The seaward slopes of the nourishment erode between the -1 m and 3 m contour and become milder. Eroded sediment is partly deposited lower in the cross-shore profile and partly at the northeast tip of the spit. The position of the area of sedimentation at the tip of the spit is further landward than the observed erosion. The spit grows about 150 m towards the northeast measured at -1 m. This suggests the presence of a dominant sediment transport towards the northeast. The spit is sufficiently high to prevent overwash during an RP5 surge event. In earlier versions of the design the spit was lower, which led to overwash over the spit with sand depositing at its leeside. This was undesired because it resulted in significant changes in bed level elevation and therefore in changes in habitat areas, such that maintenance would be required with some years after completion.

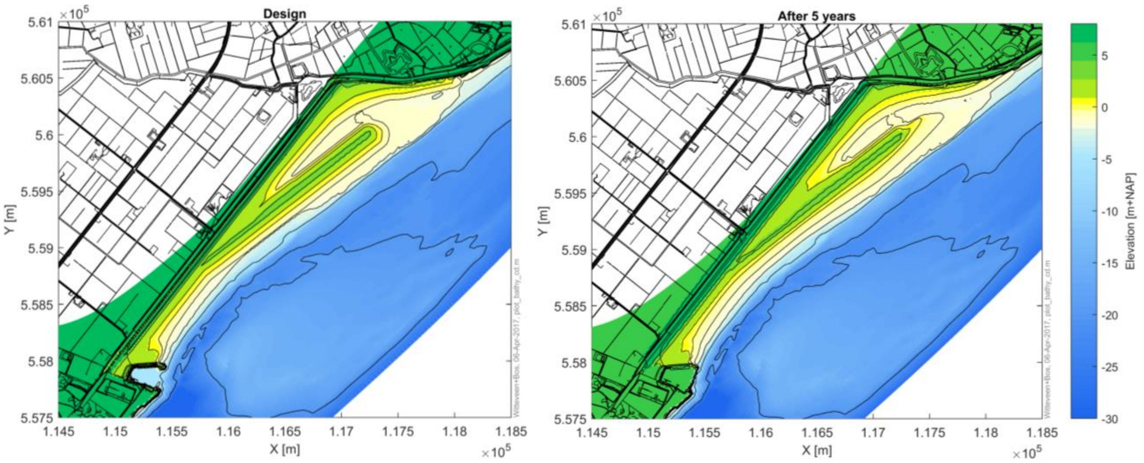

Figure 6, Method A; left panel: initial bathymetry; right panel: bathymetry after 5 years;

By comparing the bed level after five years for method A and B the effect of modeling the storms with the instationary solver can be assessed (figure 7, middle and bottom left). The sedimentation and erosion patterns are very similar for A and B. Small differences can be observed: the bed level along the slope of the beach and the spit is slightly higher for method B in the order of 0.2-0.3 m in the vertical (orange/yellow area), indicating that modeling the storms with the instationary solver leads to slightly more erosion in the cross-shore. At the northeast tip of the spit is a small area where there is more sedimentation with method A than with method B.

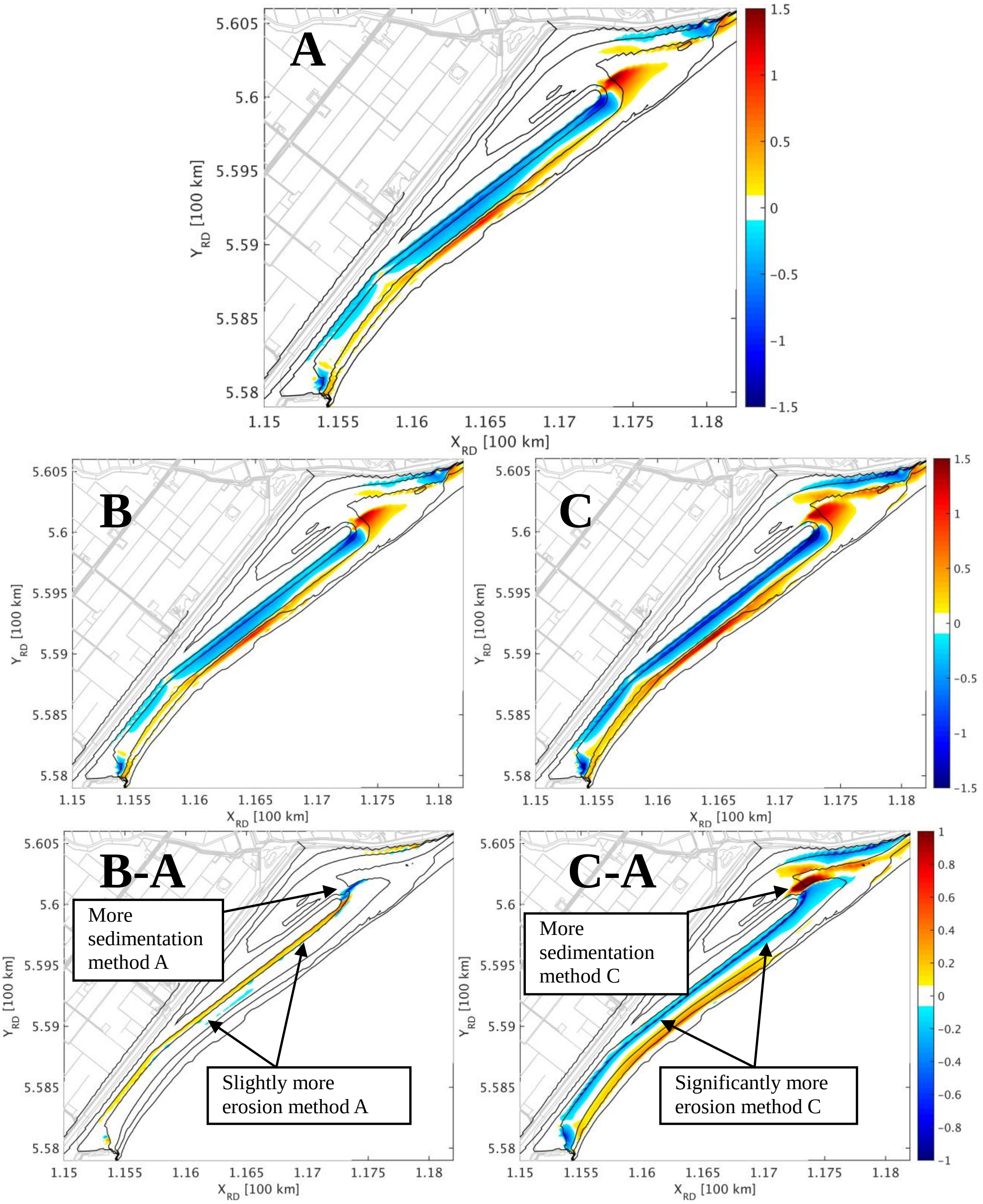

Figure 7, Top: bed level change after 5 years in meters indicating areas of sedimentation (red) and erosion (blue) for method A; Middle: Bed level changes after 5 years with method B (left) and method C (right); Bottom: bed level difference after 5 years; method B-A (left) and method C-A (right)

The observation that the instationary solver leads to higher erosion rates in the cross-shore is more clearly visible when method A and C are compared (figure 7, middle and bottom right). The sedimentation and erosion pattern for method C is similar to method A, but the patterns are more pronounced, indicating slightly more erosion and consequently more sedimentation. Along the entire nourishment area more erosion (up to 1 m more in the vertical) occurs in the cross-shore profile between 0 and 3 m+NAP, which has partly been deposited at lower cross-shore locations. Furthermore there is significantly more sedimentation at the northeast tip of the spit with method C (> 1 m in the vertical).

The higher erosion rates with the instationary wave solver are at least partly explained by the fact that the nearshore significant wave height is higher when using the instationary solver than when using the stationary solver as discussed in the previous section.

3.2. *Sediment loss in time (volume balance)*

The amount of erosion in the nourishment area provides an indication of the maintenance that will be required on the long term to maintain the flood safety and the ecological values of the design. To assess the sediment loss in time a balance area is defined that contains the complete nourishment and is limited at the -5 m depth contour (figure 8, left). Sediment that is transported out of this balance area is considered to be lost and needs to be replaced on the long term.

Over the simulated five year period approximately 25,000 m^3 of sediment is lost, which is about 5,000 m^3/year on average (figure 8, right). The initial sediment loss in year 1 and 2 is below average, while in year three and four the sediment loss is slightly above average. In year five the sediment loss is stable again at about 5,000 m^3/year.

During the storm simulations there is hardly any loss of sediment out of the balance area. The highest waves occur during these storm simulations, but there is no tidal current and only vertical variations in water level. The waves are obliquely incident and will drive alongshore sediment transport. The observation that there is no sediment loss out of the balance area indicates that a tidal current is required to enhance the alongshore transport and to enable transport of sediment to deeper water.

The sediment loss over the -5 m depth contour is equal for method A and B which both use the stationary solver for daily conditions. With method C the total sediment loss is smaller with about 23,000 m^3 instead of 25,000 m^3 with methods A and B.

Even though the differences are small, it is remarkable that the sediment loss is lower as the nearshore wave height and erosion are higher for method C than for A and B under daily conditions. Accordingly, due to the higher waves the alongshore sediment transport is higher with method C. The peak of the alongshore transport is found near the northeast tip of the spit and is about 8,000 m^3/yr with method C and about 6,000 m^3/yr with method A (figure 9). The spatial distribution of sediment transport near the northeast tip of the spit is slightly different for A and C which leads to more transport over the -5 m depth contour with method A compared to method C (figure 10).

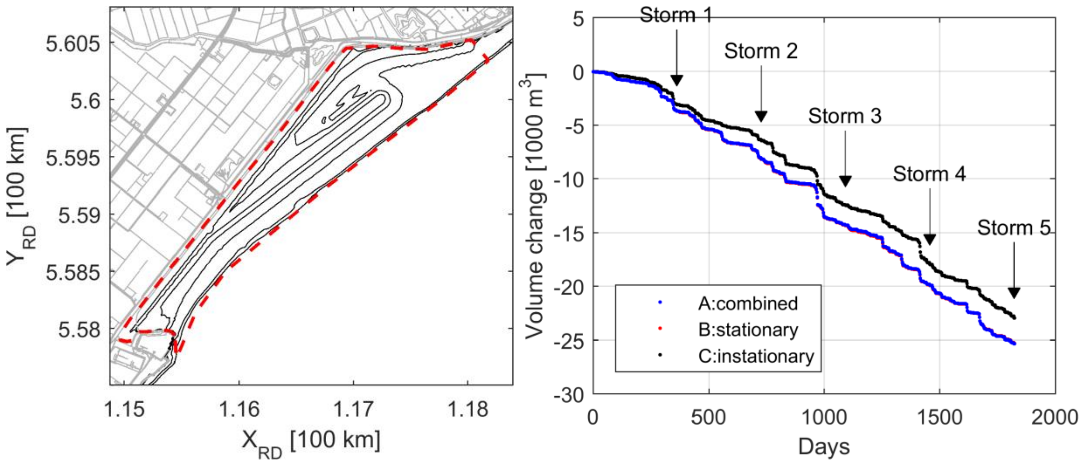

Figure 8, left: nourishment area for volume balance; right: sediment loss over 5 years of simulation with method A/B/C

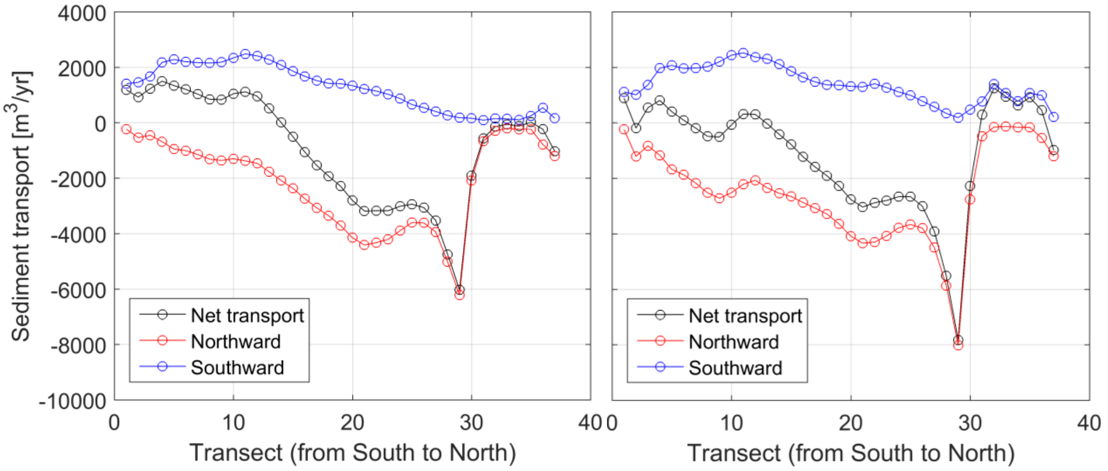

Figure 9, total alongshore sediment transport in year one: stationary solver (A, left) and instationary solver (C, right)

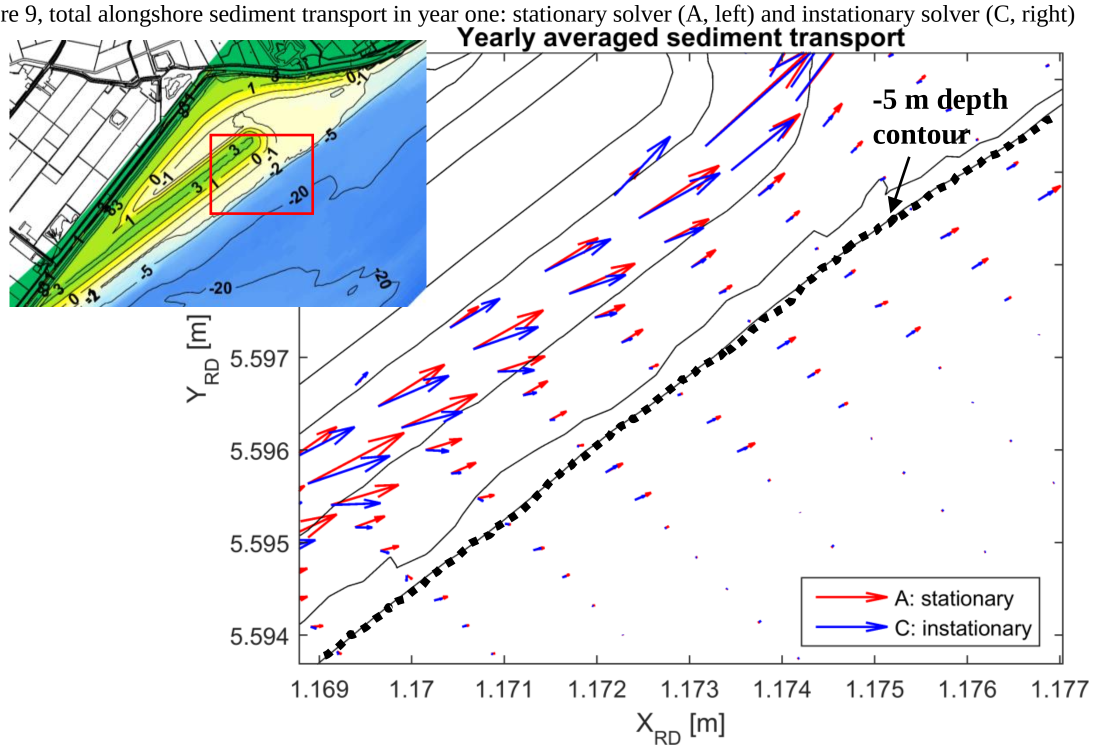

Figure 10, yearly averaged sediment transport direction near the northeast tip of the spit (see insert for location). Red arrows indicate sediment transport magnitude and direction for stationary (A) and blue arrows for instationary (C)

4. Discussion

The aim of this research was to assess the integrated modeling approach to combine storm impact and daily conditions for long term morphology based on the presented case study. The results show that the three methods that were assessed provide similar results, suggesting that in this case the combined modeling approach (method A) does not lead to significantly different results than straightforward modeling all conditions with XBeach in stationary mode (method B).

There are several reasons why the storm events are not distinctive enough from the daily conditions for this case study. First of all the wave height and period during storm events are slightly higher than during daily conditions and remains below 1.7 m and 5 s. The corresponding IG wave height is therefore quite low and insufficient to drive typical storm impact processes as described by Sallenger (2000) and may therefore be negligible for the wave conditions that were assessed. A second reason is the fact that there is no calibration and validation available. It is therefore not possible to calibrate the stationary models more towards recovery processes and the instationary models towards the more extreme (for this location) conditions.

The integrated approach of method A assumes different morphological behavior during storms than during daily conditions. During daily conditions in the year one simulation there is a narrow band of erosion along the entire nourishment with an erosion rate of about 0.2-0.5 m (figure 11, left). The erosion rate is lower in the southern parts and is more pronounced along the spit as it is more exposed to the higher waves from the southwest due to the geometry of the area and its orientation. At the northeast tip of the spit sedimentation takes places indicating alongshore transport of sediment in a northeasterly direction leading to deposition at this location. These results show that the behavior during daily conditions is driven by cross-shore and alongshore processes and tidal currents (as discussed in the previous section).

The band of erosion after the storm simulation in year three is more pronounced than the erosion band during daily conditions. The erosion rates are higher ranging from 0.3-0.6 m. At lower cross-shore locations and northeast of the spit there is a band of sedimentation, showing a deposition of about 0.2-0.5 m. Even though the waves during storms are obliquely incident (90°N and 200°N) the ratio of cross-shore versus alongshore transport of sediment is higher than during daily conditions. This can partly be explained by the absence of a tidal current in the storm simulations.

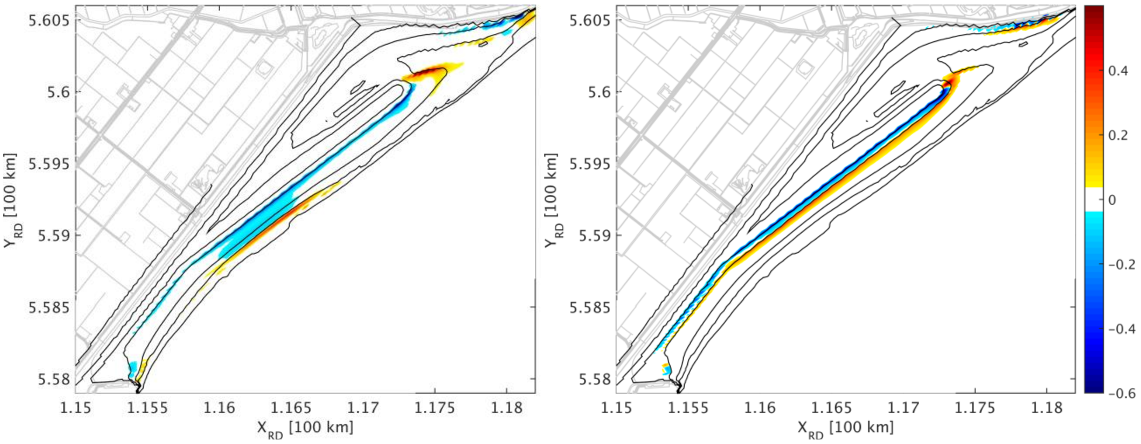

Figure 11, Method A: bed level changes showing areas of sedimentation (red) and erosion (blue); left: year 1 of daily conditions; right: storm simulation in year 3

Based on the above it is recommended to further calibrate and validate the modeling framework which was developed for this case study by monitoring the nourishment and offshore wave conditions after construction. Since the modeling framework is set up for situations where long term morphology is determined by both recovery processes and storm events, it is recommended to apply the framework at more energetic locations where both types of behavior are clearly observed.

5. Conclusions and further research

For all three methods the models provide stable results suitable for the assessment of the design for this case study. The sedimentation and erosion patterns, sediment transport rates and sediment losses for all three methods are almost similar. Modeling storms with the instationary solver compared to the stationary solver leads to slightly more cross-shore erosion. Because IG wave height is low and no overwash occurs, the added value of modeling storms with the instationary solver in method A is limited.

In general the instationary wave solver results in higher nearshore wave heights and consequently more erosion than the stationary solver for both daily conditions and storm events. Over a five year period the morphological development of the design is therefore similar, but more pronounced with method C. For the case study this means that changes in habitat areas are larger, so that method C provides the most conservative estimate of the stability of the design and the ecological values on the long term.

The wave height nearshore on the shallow plateau is quite different with the stationary and instationary wave solvers. The nearshore wave height is on average 20-40% higher with the instationary solver than with the stationary solver, resulting in higher erosion and transport rates with the instationary solver. It is recommended to further investigate these differences, which are possibly related to the breaker formulation and breaker parameter.

The computed volume losses are higher with the stationary solver than with the instationary solver, while the sediment transport rates are lower. This is probably due to small differences in the spatial distribution of sediment transport, leading to more transport (and sediment loss) over the -5 m depth contour with the stationary solver.

To further develop and assess the presented modeling framework it is recommended to start monitoring at the case study location after construction for model validation. A monitoring program is currently being set up for this purpose. Since the modeling framework is set up for situations where long term morphology is determined by both recovery processes and storm events, it is recommended to apply the framework at more energetic locations where both types of behavior are clearly observed. The influence of horizontal tide during storms also has to be investigated.

Acknowledgements

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