Geomorphology 327 (2019) 28–47

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

The effect of washover geometry on sediment transport during inundation events

D. Wesselman[a,*], R. de Winter[b], A. Oost[b], P. Hoekstra[a], M. van der Vegt[a]

[a]Department of Physical Geography, Faculty of Geosciences, Utrecht University, P.O. Box 80.115, TC Utrecht 3508, the Netherlands
[b]Deltares, P.O. Box 177, MH Delft 2600, the Netherlands

ARTICLE INFO

Article history:
Received 23 January 2018
Received in revised form 2 October 2018
Accepted 15 October 2018
Available online 23 October 2018

Keywords:
Wadden Islands
Washover opening dimensions
Inundation
XBeach

ABSTRACT

Storm-induced sediment transport across a barrier island can lead to vertical accretion and onshore migration of the barrier island. Many barrier islands either have high dunes that prevent inundation, or are so low-lying that they are inundated several times a year. The Wadden Islands in the Netherlands, Germany and Denmark typically have alongshore-varying topography, where high dunes alternate with low-lying washover openings. The effects of the geometry of the washover openings on hydrodynamics and sediment transport are still unknown and are the main focus of this research. First, we present data on width and for some cases also vertical elevation of bed level for all washover openings along the Wadden Islands. The mean width is 200 m but the actual width ranges from 35 to 1100 m, and the elevation is between 1.5 and 2.1 m above MSL. Further, we present results of an XBeach model study to investigate how the washover opening geometry affects sediment transport during storm-induced inundation. We identify two important effects of washover width: firstly, for narrow openings flow contraction is important, causing relatively larger sediment exchange rates per unit width; secondly, in a wider opening sediment is transported over a larger width, resulting in larger sediment mass exchange rates. Furthermore, the elevation of the washover opening is of high importance: washover openings that are 30 cm higher than the reference case significantly decrease currents and sediment transport across the island. Divergence of sediment transport occurs in the washover opening, which leads to erosional patterns. Landward from the opening, sediment transport converges which leads to depositional patterns. The pressure gradient between North Sea and Wadden Sea across the Wadden Islands is an important forcing parameter: higher water levels in the back-barrier reduce onshore-directed currents and sediment transport.

1. Introduction

Barrier islands are known for their dynamic behaviour, especially under storm conditions. Depending on the circumstances, high water levels and strong waves can erode or even breach dunes and beaches (van de Graaff, 1977; Vellinga, 1982; Nielsen and Nielsen, 2006; McCall et al., 2010; Houser et al., 2015; de Winter et al., 2015), but they can also result in deposition of sediment in the overwash or inundation regime (Leatherman, 1976; Donnelly et al., 2004; Donnelly et al., 2006; Masetti et al., 2008; Lorenzo-Trueba and Ashton, 2014). Ignoring other processes such as eolian transport, the elevation of the barrier can on the long term be in equilibrium with mean sea level (Leatherman, 1979; Lazarus, 2016), because inundation frequency increases for increasing sea level. In a situation with enough sediment supply barrier islands can increase their elevation at the same rate as sea-level rise (Masetti et al., 2008; Lorenzo-Trueba and Ashton, 2014).

The potential for barrier islands to be inundated during storms is largely determined by the profile height (e.g. the existence of dunes) and storm-induced water levels and waves. As described by Durán Vinent and Moore (2015), barrier islands do either include dunes when dune recovery dominates, or are low-lying when the effects of overwash and inundation are more important. Barrier islands of the first category are not inundated on a regular basis because typical high water levels are lower than the dune crest (Sallenger, 2000). Instead, severe and rare storms are required to first erode and lower the dunes in the collision phase (i.e. waves hit but do not overtop the dunes) and overwash phase (i.e. individual waves overtop the dunes), before inundation can occur. The second category consists of barrier islands without dunes. For example, the beach crest of the island tail of the Wadden Island of Schiermonnikoog, the Netherlands, is lower than 2 m above MSL and it is therefore inundated several times a year, even with relatively weak storms (Engelstad et al., 2017). Some parts of the islands of the Wadden Area (Fig. 1) demonstrate a

* Corresponding author.
E-mail address: d.a.wesselman@uu.nl (D. Wesselman).

https://doi.org/10.1016/j.geomorph.2018.10.014
0169-555X/

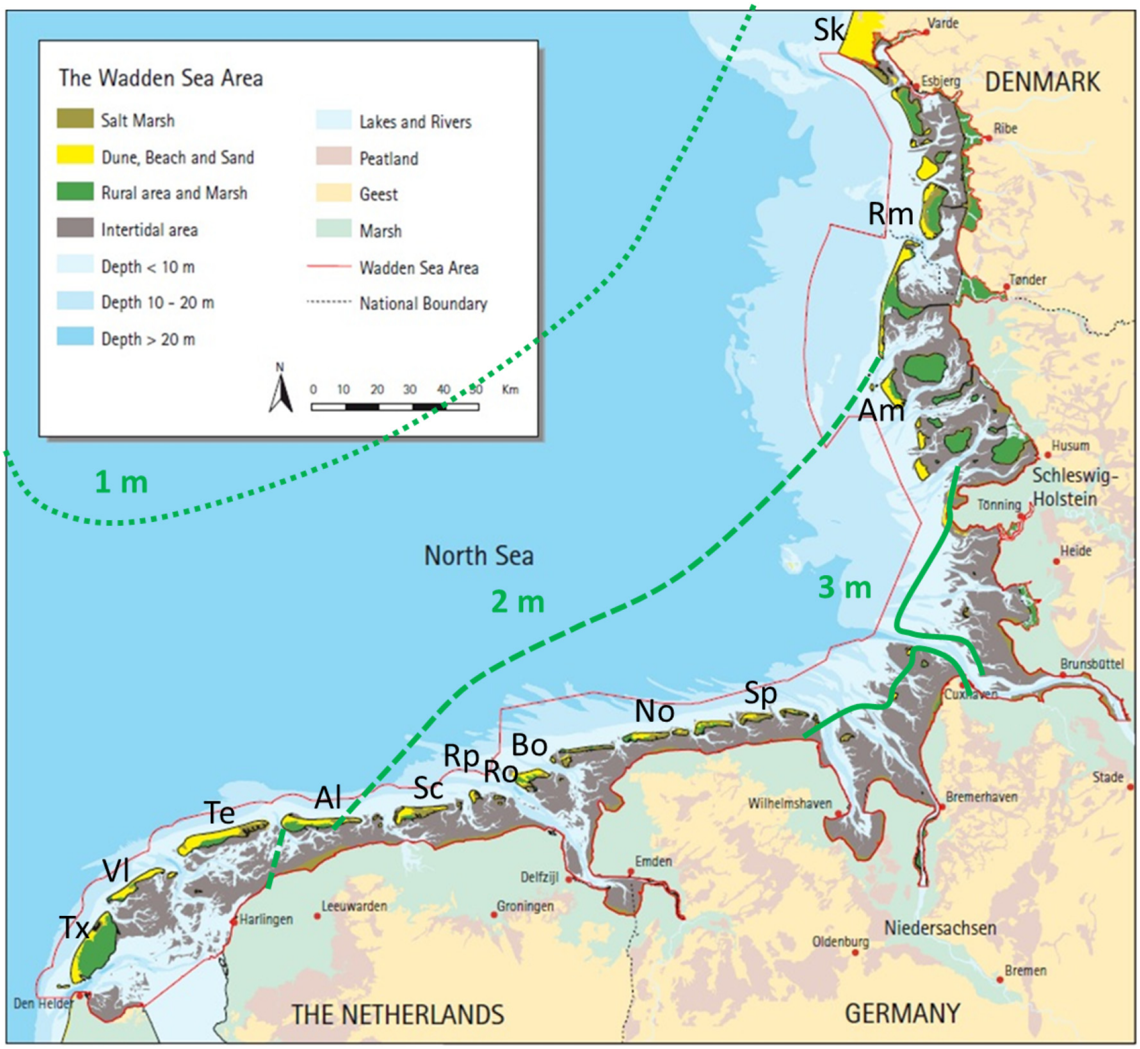

Fig. 1. Overview of the Wadden Sea region and overview of tidal range (in m) and locations of the various barrier islands discussed in the text. From W to E: Tx = Texel; Vl = Vlieland; Te = Terschelling; Al = Ameland; Sc = Schiermonnikoog; Rp = Rottumerplaat; Ro = Rottumeroog; Bo = Borkum; No = Norderney; Sp = Spiekeroog. From S to N: Am = Amrum; Rm = Romo; Sk = Skallingen peninsula. (based on: Ehlers, 1988, courtesy Balkema Books; map courtesy of the Common Wadden Sea Secretariat).

mixed character and show an alternating pattern of high dunes and low-lying areas, also known as washover openings, that are flooded regularly (de Groot et al., 2011; Tillmann and Wunderlich, 2013).

The influence of the washover opening on storm-induced sedimentation has not been studied extensively. Some studies show for example the importance of the volume of the washover opening (Lazarus, 2016), but a quantitative analysis and comparison of different factors that can influence washover processes is lacking. The Wadden Islands are examples of barrier islands where the important processes and dominant topographic characteristics during inundation are not yet identified. Engelstad et al. (2017) and Wesselman et al. (2017) show that at the island tail of Schiermonnikoog (i.e. no dunes and alongshore uniform), cross-shore currents are largely influenced by the pressure gradient from the North Sea to the Wadden Sea, which is the product of tidal effects, storm surge and wave set-up. It is, however, unknown how these currents are affected by different washover opening dimensions and how they lead to sediment transport patterns and morphological change.

The aim of this study is to get a better understanding of the role of washover opening geometry of the Wadden Islands on the short-term, storm-induced hydrodynamics and sediment transport. Factors that will be analyzed and compared are the washover opening width and height, beach slope and width, and different storm types. Therefore, in the first part of the study we describe the typical properties of the openings along the Wadden Sea area, such as elevation and width. Subsequently, we use these results to simulate storm-induced inundation for typical washover topography with the model XBeach, to determine the implications of the washover openings for sediment transport and sediment erosion and deposition patterns.

2. Topography of the Wadden Islands

2.1. Wadden Island description and data gathering

The Wadden Islands are a chain of barrier islands, separated by tidal inlets, and are located in the North Sea along the coast of the Netherlands, Germany and Denmark (Fig. 1). They are exposed to a mesotidal to macrotidal environment. The islands are separated from the mainland by shallow tidal basins, called the Wadden Sea. Many Wadden Islands have a typical “drumstick shape” with the wider part at the updrift side, which is the side where tidal and the dominant wave-induced currents are coming from and where shoals and sand merge from the ebb-tidal delta (Hayes, 1979; Ridderinkhof et al., 2016). The tails are relatively narrow and dynamic and alternately grow or erode over time. The islands are often characterized by foredunes that separate the beach from the hinterland, but these are sometimes interrupted by low-lying washover openings. Two different types of washover openings can be observed: washover openings that are restricted to the dunes and washover openings that connect to the Wadden Sea. We take both types into account for this overview. Blowouts are not taken into account, because they are too high to be inundated during storms (Abhar et al., 2015).

We gathered data on washover opening geometries in two different ways. Firstly, we made an inventory of all present-day washover openings for the Wadden Islands and determined the width of these openings based on the most recent Google Earth images by estimating the distance from dune to dune, parallel to the coast. Islands characterized by the presence of washover openings are Texel, Vlieland, Terschelling, Ameland, Schiermonnikoog, Rottumerplaat, Rottumeroog (the Netherlands), Borkum, Norderney, Spiekeroog, Amrum (Germany), Rømø and Skallingen (Denmark). Details on the locations of these washover openings can be found in Appendix A. Secondly, we used LIDAR-derived elevation maps of Schiermonnikoog and Spiekeroog to determine the elevation and to check the values of the width of the openings obtained with the Google Earth images (Fig. 2). The average elevation was calculated along the entire washover opening. However, the first 10 m on both sides of the opening were omitted. Here, the profile elevation already increases towards the dune and this would lead to an overestimation of the average elevation of the opening. For Schiermonnikoog, annual LIDAR data from Rijkswaterstaat (Dutch Ministry of Infrastructure and Water Management) for the period 2000–2011 were used with a cross-shore and alongshore grid size of 5 m. For Spiekeroog, we used data of 2014 from airborne Laserscanning and a hydrographic survey in Germany, with a grid size of 2 m. In 2014, there was only one washover opening present.

2.2. Washover opening dimensions

The washover opening width at Schiermonnikoog, based on the LIDAR data, ranges between 35 and 220 m depending on the year and the specific location (Fig. 3a). Two important trends can be deduced from these results. Firstly, the washover openings get narrower in the downdrift direction. Secondly, the width is fairly constant in time, which suggests that storms do not significantly widen the openings and also that aeolian transport does not significantly influence the width, at least for the last 15 years. The washover elevation ranges between 1.5 and 2.1 m above MSL, which means that for normal tidal conditions they will not submerge but they can easily be inundated during storms, with peak water levels during storms that can reach 3 m. The 380 m-wide and 1.8 m-high opening at Spiekeroog is wider than the current openings at Schiermonnikoog, but the elevation is in the same range. When all recent washover openings are taken into account, a wide range of widths is observed. Most washover openings are relatively narrow (i.e. 400 m or less) but much wider openings are found as well (Fig. 3b).

3. Design of XBeach simulations

We used the Kings Day release of the process-based and depth-averaged model XBeach (Roelvink et al., 2009) to investigate the effect of washover opening characteristics on hydrodynamic processes and sediment transport during inundation for typical Wadden Island storm conditions. The short waves (H_s), infragravity waves (H_{ig}), water depths (h) and cross-shore currents (u) were validated for Wadden Island inundation during storm conditions in Wesselman et al. (2017). They compared model results with hydrodynamic field data from the island tail of Schiermonnikoog. This validation was for the 1D mode of XBeach, while this study used the 2D mode. The model can also predict

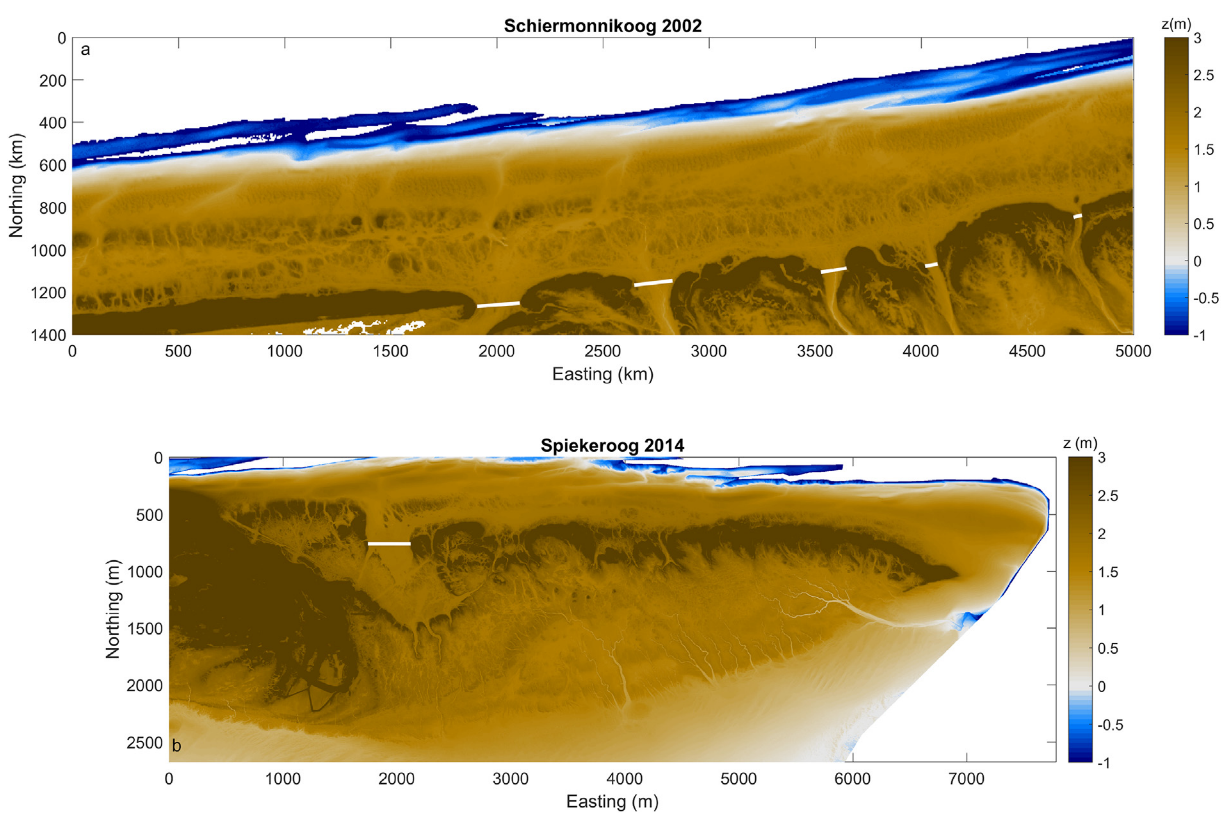

Fig. 2. LIDAR images of a) Schiermonnikoog, 2002 and b) Spiekeroog, 2014. The white lines show the positions of the washover openings.

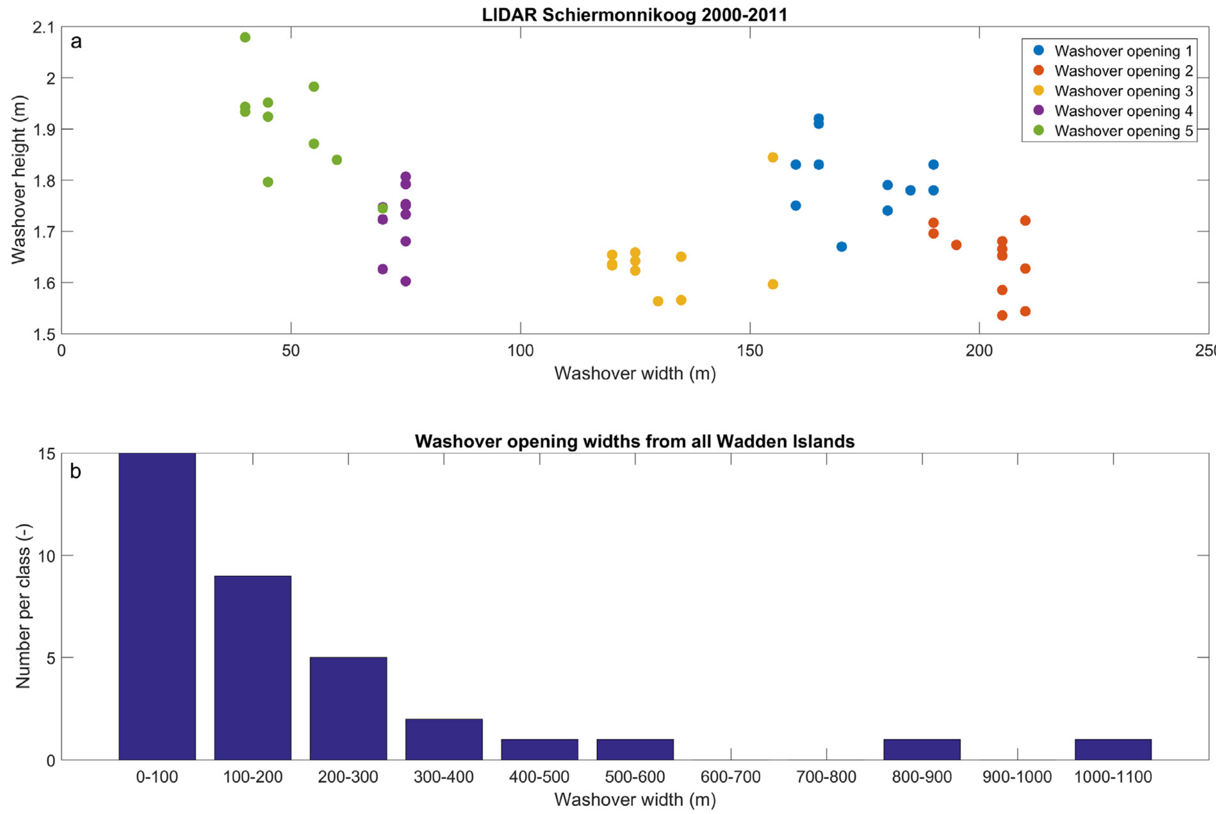

Fig. 3. a) Washover opening width versus elevation at Schiermonnikoog for the period 2000-2011. Washover opening 1 is the most updrift opening. b) Distribution of washover widths from all Wadden Islands based on the most recent geometries. The total sample number is 35.

2D patterns in bed level change reasonably well, for example at the western coast of the Netherlands (de Winter et al., 2015), Santa Rosa Island, Florida (McCall et al., 2010) and Follet's Island, Texas (Harter and Figlus, 2017). Therefore, the XBeach model is suitable to simulate 2D hydrodynamics and sediment transport for Wadden Islands with overwash and inundation conditions. We have no data to validate the model specifically for the washover openings.

The input profiles for XBeach were created to represent the washover openings observed on the islands of the Wadden Sea area (Fig. 4). It consisted, from offshore to onshore, of a few individual but interconnected parts: the offshore profile, the beach profile, the dune or washover profile and the Wadden Sea or hinterland profile. The bed profile from 10 to 1 m below MSL was constant for all simulations and was based on a bed profile from 2013 called "Vaklodingen" (gridsize of 20 m) and measured by Rijkswaterstaat. This profile was located offshore from the most updrift washover opening at Schiermonnikoog and contains a subtidal sandbar. The beach of Schiermonnikoog typically consists of a gentle sloping part (from 1 m below MSL to the washover opening elevation) and a flat part, with a total width of approximately 600 m. This is implemented in the input profiles, where the sloping part of the beach was varied between 0.01 and 0.1 m/m and the flat part between 10 and 300 m. The washover opening dimensions were taken from the analysis presented in the previous section. Onshore from the beach, the profile either continues with a washover opening or a dune, depending on the alongshore location. We studied the influence of the washover elevation from 1.7 to 2.3 m above

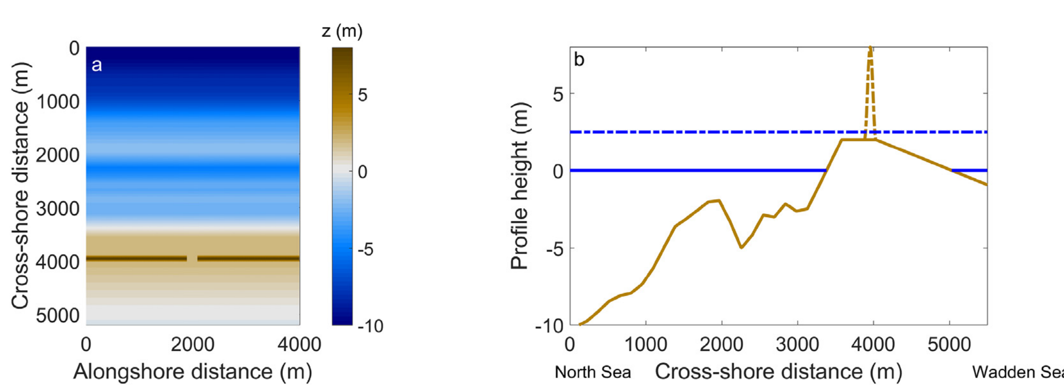

Fig. 4. a) The profile of reference simulation A0. b) 1D profile of reference simulation A0. Two cross-shore transects are shown, one in the dunes and one in the washover opening. The blue solid line is mean sea level, the blue dashed line is a water level of 2.5 m above MSL, used for the simulations with constant water level.

Table 1
Series of simulations. A0 is the reference simulation, performed with tidal curves. For Series A, the profile of A0 is always used but the hydrodynamics vary. The waves used here are shown in Table 2 and the tidal curves are shown in Fig. 5. Series B is performed with constant wave and water levels, but varying topography.

Series	Washover elevation (m)	Washover width (m)	Beach slope (m/m)	Beach width (m)	Water level (m)
A0	**2.0**	**200**	**0.01**	**300**	**Inundation class 5**
A	2.0	200	0.01	300	Inundation class 3-6
B1	1.7–2.3	50–2000	0.01	300	2.5
B2	2.0	200	0.01–0.1	10–300	2.5

MSL and the width from 50 to 2000 m. Although a washover opening width of 2000 m is greater than observed, it provides more insight in the importance of 2D processes in the opening and how these depend on width.

All simulations are summarized in Table 1. In Series A the sensitivity of the reference profile A0 (i.e. a washover opening width and height of 200 m and 2.0 m above MSL) to time-varying water levels and varying wave boundary conditions was studied. The boundary conditions were the same as defined in Wesselman et al. (2017), where class 1 represents inundation under mild storm conditions and class 6 represents severe storms (Fig. 5). The methods to create these classes are summarized in Appendix B. For this study only storm classes 3–6 were taken into account because class 1 and 2 did not result in inundation. The wave forcing per inundation class is shown in Table 2. This wave forcing was based on an offshore wave buoy where the profile is 20 m below MSL while the input profiles started at 10 m below MSL. Therefore, a correction was made to account for the wave dissipation that already occurs between -20 and -10 m. Series B had constant water levels (2.5 m at the two open boundaries of the model) and wave forcing (Class 5). Series B1 is a sensitivity analysis of the influence of the washover opening topography on sediment transport. Series B2 describes the influence of the beach slope and width. Constant water levels were used for the sensitivity analyses in Series B because it resulted in similar patterns of hydrodynamics and sediment transport as in the simulations with tide. This will be shown in more detail in the results section.

All simulations were performed in morphostatic mode. The sediment had a d50 of 200 μm and a d90 of 300 μm, respectively. Sediment transport was calculated with an advection-diffusion equation, where the equilibrium sediment concentration was obtained from the Van Thiel-Van Rijn equation (van Rijn, 2007; Van Thiel de Vries, 2009). The wave breaking parameter γ in the wave breaking formulation “Roelvink2” (Roelvink, 1993) was set to 0.45 instead of the default value of 0.55, which is in line with the study of Hoonhout and van Thiel de Vries (2012). For other model parameters the default values were used. Sediment transport is mostly expressed in kg/m/h or kg/h. For the tide simulations in series A, this means that the total sediment transport (kg or kg/m) is divided by the total inundation time during the tidal cycle to get averaged values. For Series B we focused on the hydrodynamics and resulting sediment transport, but for Series A we also calculated the divergence of the sediment transport, by using Eq. (1),

$$S_{div} = \frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y} \tag{1}$$

where S_x and S_y are sediment transport in cross-shore and alongshore direction, respectively, and S_{div} is the divergence of the sediment

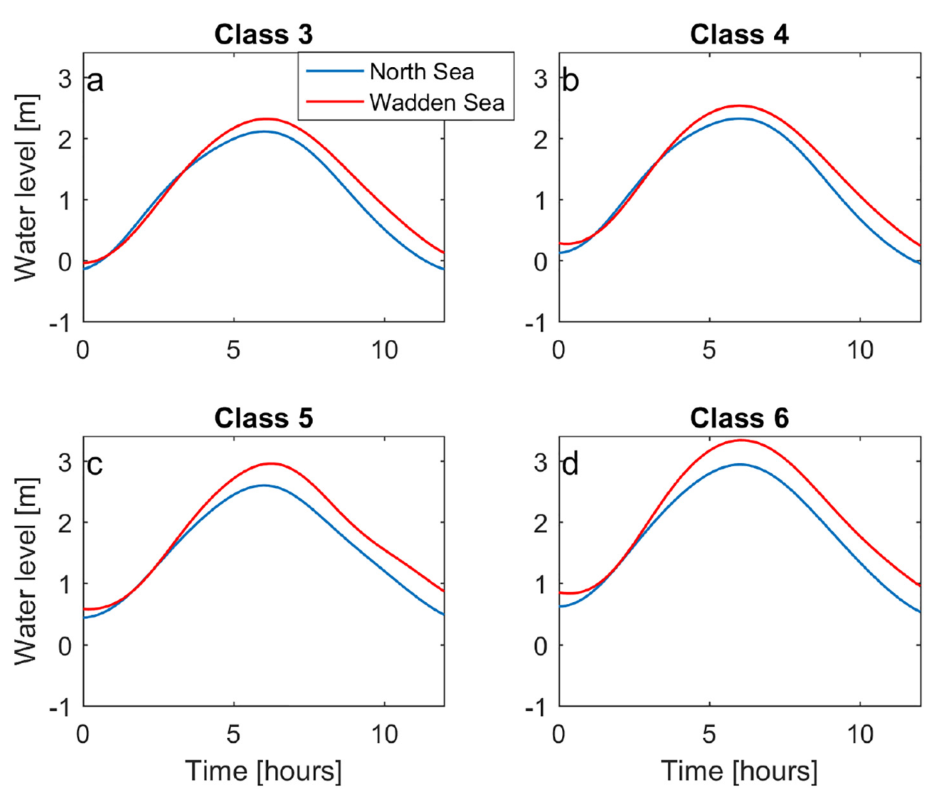

Fig. 5. Boundary conditions at North Sea and Wadden Sea side as used in the model (Series A). Water levels are above MSL. For more information see Wesselman et al. (2017) and Appendix B.

Table 2
Inundation classes based on Wesselman et al. (2017) and explained in Appendix B. Class 1 and 2 are not taken into account, because they do not lead to inundation at the reference profile. The wave forcing is used for Series A, but for Series B only class 5 is used.

Class	Wave height (m)	Wave period (m)	Wave angle of incidence (°)	Constant water level (m)
Class 3	3.98	7.34	44	2.0
Class 4	4.33	7.69	43	2.25
Class 5	**5.38**	**8.53**	**36**	**2.5**
Class 6	5.61	9.08	33	2.75

transport, which indicates erosion or deposition patterns. Positive values indicate sediment transport divergence which leads to erosion, while negative values indicate convergence which leads to deposition.

The grid size in cross-shore direction gradually changed from 20 to 5 m from deep water to the region of interest. In the alongshore direction, the grid size was 30 m at the side-boundaries and gradually decreased to 10 m in the region of the washover opening. The grid covered approximately 5500×4000 m in cross-shore and alongshore directions respectively. The simulation time depended on the type of simulation. The simulations including the tide described two tidal cycles of 12.5 h each. The first tidal cycle was used as spin-up and the second tidal cycle was analyzed. For the stationary runs (i.e. no tide), the simulation time was 5 h, where the first 4 h were used as spin-up and the fifth hour was analyzed.

4. Results

4.1. Patterns of flow, sediment transport and sediment transport divergence

In the reference simulation A0, H_s decreases in the onshore direction during maximum onshore-directed flow, typically 1.5 h before high water (Fig. 6a). The first location of significant wave dissipation is the sub-tidal sandbar with the crest at approximately 2 m below MSL (Fig. 6b). The wave energy decreases further at the foreshore and beach in shallow water, and as a result the wave height is smaller than 0.5 m at the beach and in the washover opening. The breaking waves cause higher water levels in the washover opening, while landward of the washover the wave-induced set-up decreases. This leads to a pressure gradient from washover opening to Wadden Sea. Currents are alongshore-dominated at the foreshore, caused by oblique waves (Fig. 6c). However, at the beach the alongshore currents gradually disappear and the cross-shore component becomes dominant. Through the washover opening, the currents are in the cross-shore direction. Furthermore, they increase through the opening due to flow contraction, which results in currents with a magnitude of almost 1 m/s. Onshore from the washover opening, cross-shore currents gradually decrease. The patterns in the sediment transport are similar to the patterns of the currents (Fig. 6d). The alongshore transport at the foreshore is relatively small, and sediment transport is relatively large through the washover opening and its surroundings. This sediment transport is largely dominated by suspended load transport (i.e. 95–100 %).

We investigate the influence of the tide by adding the tidal curves of Fig. 5 (i.e. a higher class means higher water levels and larger

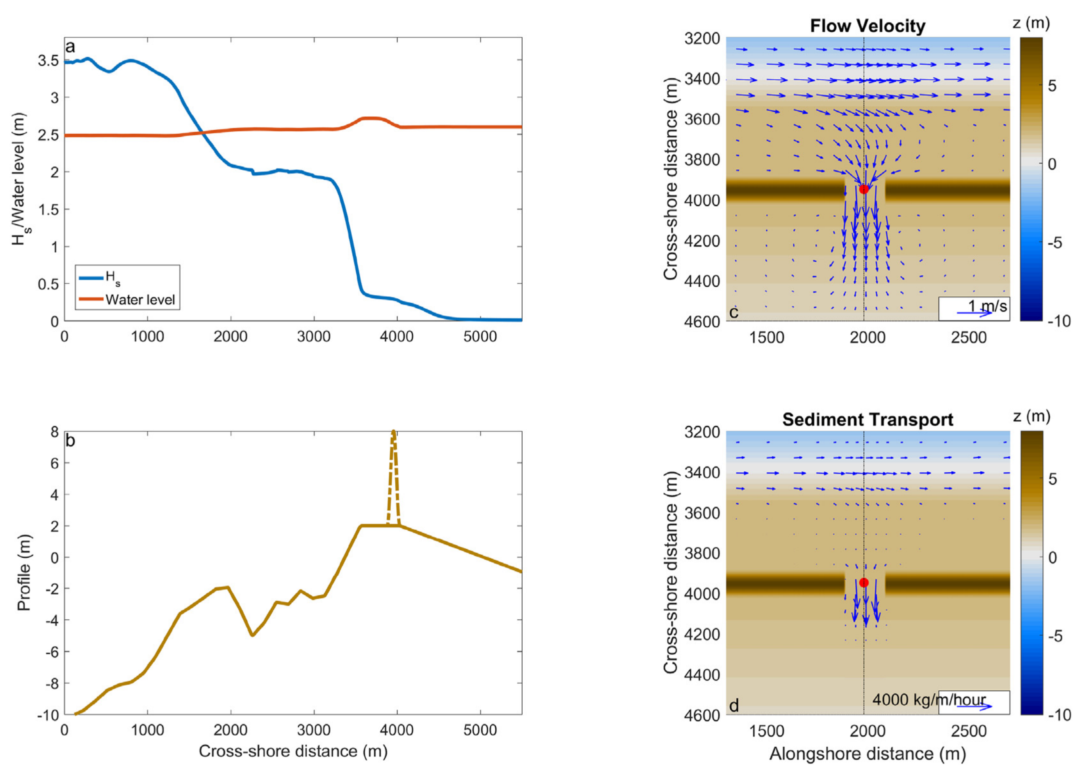

Fig. 6. Results of the reference simulation A0. a) Significant wave height and water level as function of cross-shore distance through the centre of the washover opening. b) 1D profile. c–d) Flow velocity and sediment transport averaged over 15 min and during maximum flow, approximately 1.5 h before high water. The red dot marks the center of the opening in both directions.

waves) as offshore and onshore boundary conditions to the reference profile. All these inundation classes are characterized by higher water levels in the Wadden Sea than in the North Sea. The resulting cross-shore currents and sediment transport in the middle of the washover opening show positive values during rising tide (Fig. 7). However, during falling tide currents and sediment transport disappear or even become negative when the pressure gradient between North Sea and Wadden Sea reverses. The total flux in kg/h (i.e. the onshore minus the offshore directed transport, divided by the total inundation period) is still positive (Fig. 7c).

The resulting sediment transport divergence and convergence patterns are shown in Fig. 8 a–d. Erosion occurs in regions with divergent sediment transport (red colours), while deposition takes place when sediment transport converges (blue colours). The deposition and erosion patterns are in line with the observed hydrodynamics and sediment transport, and patterns are similar for all inundation classes but magnitudes differ. At the beach, divergence of sediment transport is negligible as currents and sediment transport are minor here. Approximately 50 m offshore from the washover opening, where currents accelerate due to flow convergence, the beach has an eroding trend. This continues in the washover opening, where the net erosion trend reaches its maximum. Landward from the opening, erosion rapidly changes into a deposition trend because of decelerating currents. Although the trends are similar for all inundation classes with constant water levels, the magnitude of sediment transport divergence and convergence depends on the water levels and waves. Higher mean water levels and waves tend to increase the sediment transport divergence and convergence, however, higher water levels in the Wadden Sea than in the North Sea tend to decrease these values. The net effect is that sediment transport divergence and convergence hardly increase from inundation classes 4 to 6.

4.2. Sensitivity of currents and sediment transport to washover opening geometry

In order to analyze the impact of the elevation of the washover, we varied the elevation between 1.7 and 2.3 m in Series B1. These simulations were performed with a constant water level of 2.5 m in the North Sea and Wadden Sea. It appears that flow velocity and sediment transport are very sensitive to the elevation of the opening, especially for narrow openings (Fig. 9a–b). A washover elevation that is only 30 cm higher leads to significant smaller flow velocities and sediment transport in onshore direction. Furthermore, the importance of the opening width is visible. For narrow openings cross-shore currents and sediment transport both decrease when they become wider, but from approximately 1200 m both currents and sediment transport remain almost constant. Fig. 9c shows the sediment exchange rate, which is the width-integrated sediment transport through the whole opening for every combination of opening width and elevation. We identify two relevant and counteracting effects. On the one hand, the effect of flow contraction reduces for wider openings and results in less sediment transport per meter alongshore (kg/m/h). On the other hand, in a wider opening sediment is transported over a larger width, resulting in sediment mass exchange rates (kg/h) that tend to be larger. The combined result is that the net sediment transport (kg/h) steadily increases for wider openings. However, this rate of increase slowly diminishes. The sediment exchange rate increases by 800% for a width from 50 to 1000 m (i.e. the maximum width measured along the islands). Furthermore, also for the total sediment transport the washover elevation appears to play a crucial role during storm conditions. A 30 cm higher washover opening clearly reduces the sediment transport in the onshore direction, while washover openings with a lower bed level result in much more sediment transport.

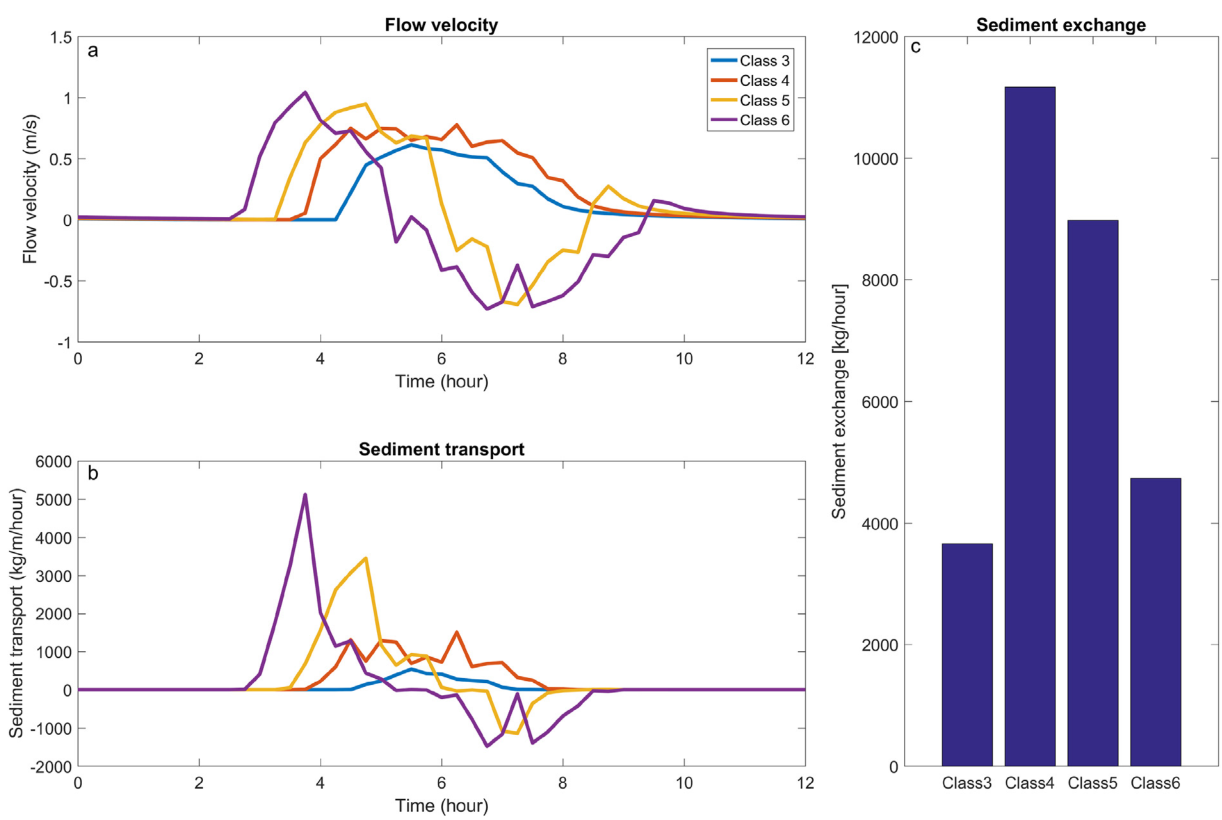

Fig. 7. a) Flow velocity and b) sediment transport in the middle of the washover opening (in both directions) for inundation classes 3-6. Positive values mean in onshore direction, while negative values are offshore directed. c) Net sediment exchange during the full tidal cycle for inundation classes 3–6. This is calculated as the onshore minus the offshore directed transport and averaged over the total inundation period.

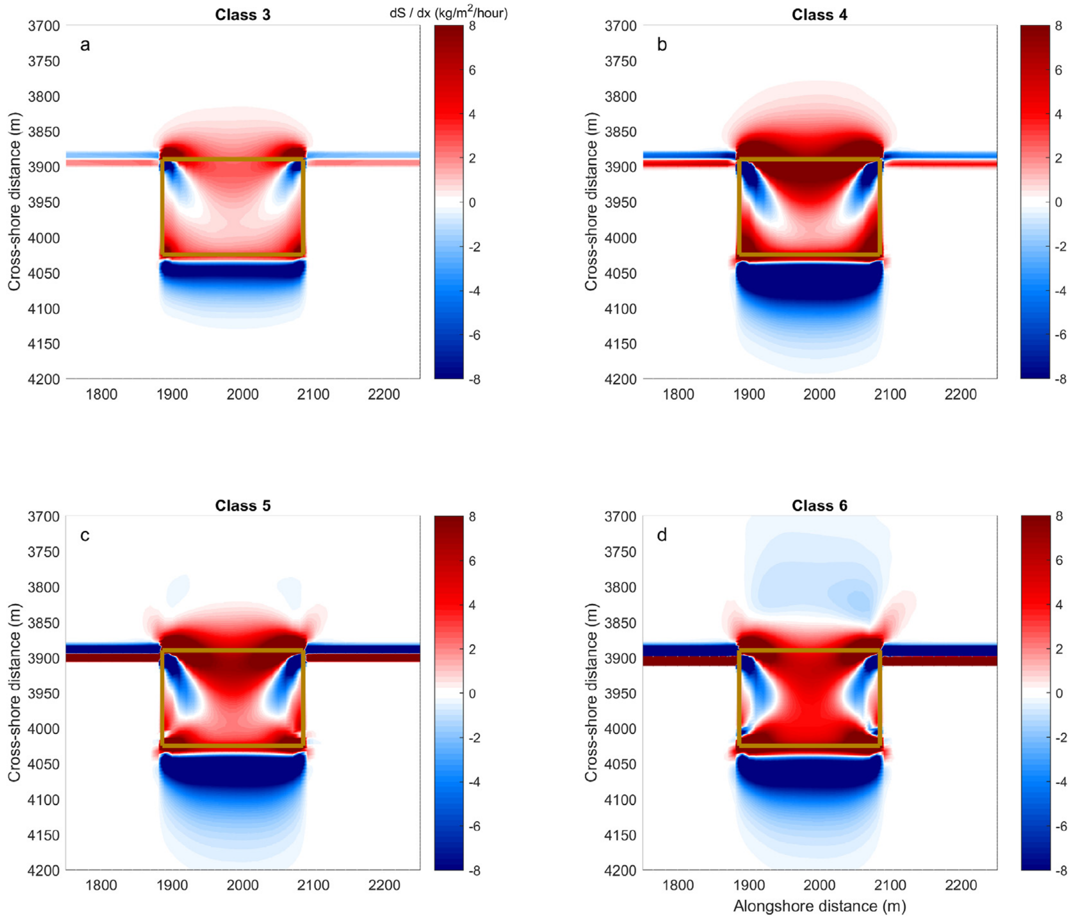

Fig. 8. Sediment transport divergence and convergence for Series A. Blue colours mean sediment transport convergence (deposition) and red means sediment transport divergence (erosion). The area enclosed by the brown box is the location of the washover opening.

From 2.3 to 1.7 m, the sediment exchange rate increases with 400%. Fig. 9c also demonstrates that the trends in sediment exchange rates for simulations with constant water levels and tidal curves are similar. This indicates that the application of constant water levels, which requires less computational effort than tidal curves, can be used to perform the sensitivity analyses from Series B.

The influence of the width of the washover opening is shown in more detail in Fig. 10 (part of Series B). The flow velocity in the 100 m-wide opening peaks in the middle and decreases towards the dunes. However, for openings wider than 200 m the effect of flow contraction is the greatest near the dunes and it loses part of its effect towards the middle of the opening. The effect of flow convergence is always substantial and visible in the results, even for the widest opening of 2000 m. The flow velocity near the dunes is only slightly dependent on washover width, but the velocity magnitude in the middle is more sensitive to width. This flow velocity asymptotically reaches the value that would occur in an alongshore uniform case, and simulations showed that this value is approximately 0.92 m/s. Again, the sediment transport patterns correlate strongly with the currents. This suggests that sediment stirring by currents (that are partly wave-induced) is dominant and the impact of H_s and H_{ig} on sediment stirring is of minor importance. Because currents are larger at the edges of the washover opening, sediment transport is also maximal at those locations.

4.3. Sensitivity of currents and sediment transport to beach characteristics

In series B2 we varied the beach slope between 0.01 and 0.1 m/m and the width of the flat part of the beach between 10 and 300 m. The beach slope has an effect on the sediment exchange rate (Fig. 11a). Steeper slopes lead to more intense wave set-up, higher water levels, a larger pressure gradient between the North Sea and Wadden Sea, larger currents and more sediment transport. In the range 0.01 – 0.03 m/m, which is assumed to be realistic for the Wadden Sea coast, the sediment exchange rate increases by 25%. This effect is significantly smaller than the effect of the washover opening width and height. The beach width has hardly any effect (Fig. 11b). The pressure gradient between the North Sea and Wadden Sea, and thereby the other processes, remain unaltered when the beach width increases.

5. Discussion

5.1. Implications of XBeach simulations

As illustrated by the data from Schiermonnikoog, the dunes (i.e. remnants of the former sand drift dike) and washover openings are rather stable since the first LIDAR measurements in 2000. Furthermore, landward deposition of sediment behind the dunes is limited, which is also supported by ten Haaf and Buijs (2008). The XBeach simulations suggest that there are a number of reasons to explain these observations. Firstly, there is limited sand supply. Although the wide beach of Schiermonnikoog provides significant amounts of sediment, the currents and waves at the beach are too small to effectively pick up this sand and transport it landward (Fig. 6). Only at the location just before and at the opening are the currents large enough to stir, resuspend and transport sediment. The limited width of the opening further decreases the landward transport.

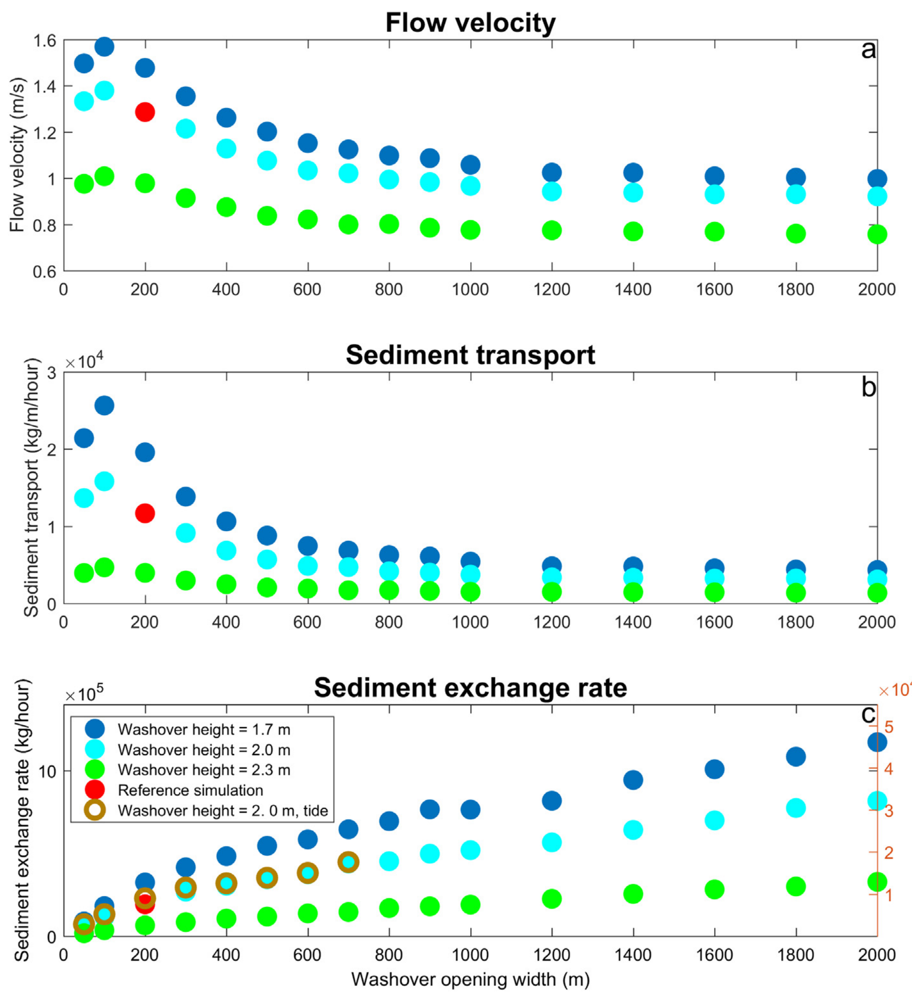

Fig. 9. Series B1: a) Cross-shore flow velocity, b) cross-shore sediment transport at the position of the red dot in Fig. 6. This is the middle of the opening in both directions. c) Sediment exchange rate through the whole opening. The filled dots were performed with constant water levels and belong to the left y-axis, while the open dots (belonging to the right y-axis) were performed with the tidal curves. Different colours represent different washover opening elevations for the filled dots. The red dot in this figure is reference simulation A0.

In addition, the pressure gradient during storm surges creates an opposing mechanism and results in limited deposition behind the dunes (Fig. 7).

The patterns of the currents, sediment transport and sediment transport convergence and divergence depend on the width of the washover opening in the model simulations. The currents accelerate through the washover opening and are in a cross-shore direction, which was also found by van Dongeren and van Ormondt (2007) and by Hoekstra et al. (2009), and decelerate onshore from the opening. These velocity gradients lead to erosion in the opening. The smaller the opening, the larger the sediment transport divergence. Therefore it seems logical to assume that on average smaller washover openings will also be characterized by lower elevations. The results from Fig. 3a do not contain enough washover openings to confirm this and more research is needed to investigate this hypothesis.

5.2. Factors influencing washover processes

Previous studies observed a large role for the cross-shore currents when inundation depths are large (Sherwood et al., 2014; Engelstad et al., 2017) or a large role for the waves when inundation dephts are small (e.g. Figlus et al., 2010; Matias et al., 2017; Phillips et al., 2017). The Wadden Islands are often exposed to large inundation depths, and therefore results show that storm-induced sediment transport through washover openings for the Wadden Islands is almost entirely caused by the cross-shore currents that are the net product of tidal water levels, storm surge levels and local wave set-up upon the barrier (e.g. Fig. 10). Although (breaking) waves are responsible for this local wave set-up they appear to be too small and insignificant to locally and effectively stir the bed and resuspend sediment. This means that topographic factors that influence these currents dominate washover sedimentation. Therefore, the height of the washover opening is one of the crucial parameters that leads to an increase in sediment transport of 400% when it decreases from 2.3 to 1.7 m above MSL (Fig. 9). The beach characteristics are less important. Steeper beach slopes result in slightly more wave set-up, but this leads to only 25% more sediment transport through the opening when the slope increases from 0.01 to 0.03 m/s. The beach width is not capable of influencing the pressure gradient and therefore has no influence on the cross-shore currents (Fig. 11). Wider openings decrease the magnitude of the currents and thereby the sediment transport per meter width, however, wider openings lead to more capacity for transport. This results in an increase of 800% in sediment transport through the opening and is thereby the most important factor investigated in this study. The magnitude of the storms, represented as inundation classes, is less important than the washover opening geometry: higher water levels in general and larger waves are counteracted by higher water levels in the Wadden Sea than in the North Sea.

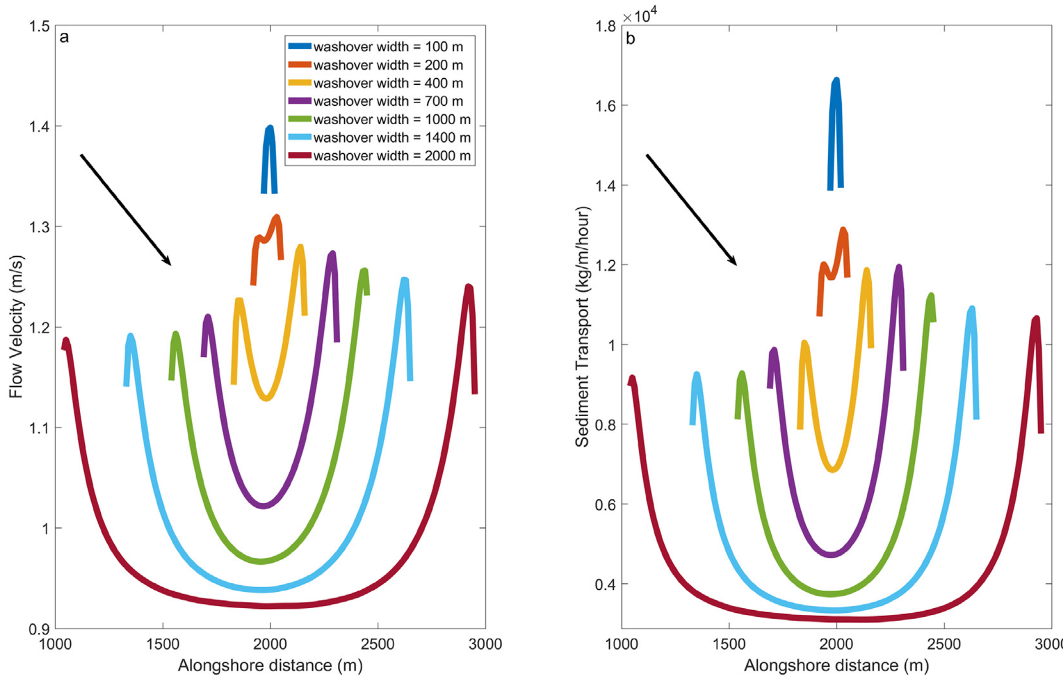

Fig. 10. a) Cross-shore flow velocities and b) cross-shore sediment transport along the washover opening for different opening widths for Series B. The washover opening elevation is 2.0 m. The arrows indicate wave direction.

The significant role of the pressure gradient between North Sea and Wadden Sea through the washover openings suggests that the hydrodynamic processes and the resulting sediment transport are different for barrier islands where offshore waters and landward tidal basins are not connected during storms, which was also recognized by Lazarus (2016). This is illustrated in Figs. 12 and 13, where a secondary dune system is added to the reference simulation that blocks the North Sea from the Wadden Sea. When the inundation phase starts after approximately 3.5 h, currents start increasing until 0.5 m/s. However, after one hour the washover basin is filled, the pressure gradient disappears and currents slow down. As a result, sediment transport is negligible throughout the whole tidal cycle,

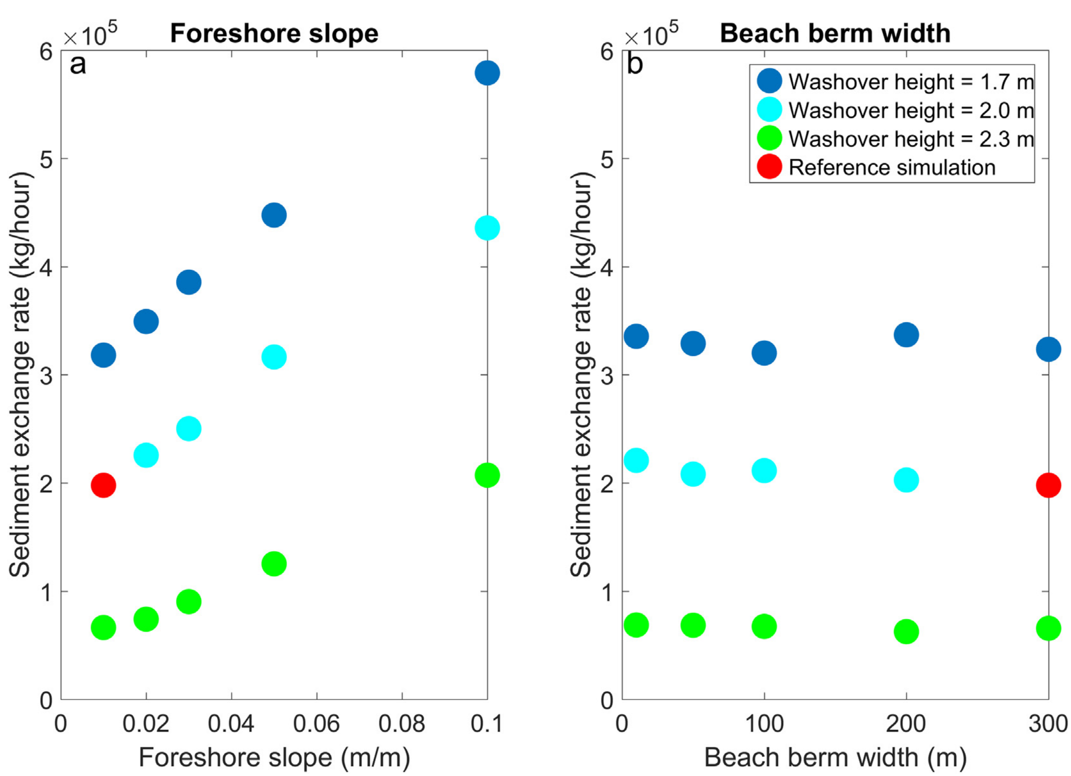

Fig. 11. Series B2: Sediment exchange rate for a) varying beach slope and b) varying beach width. This is the middle of the opening in both directions. Different colours represent different washover opening elevations. The red dot in this figure is reference simulation A0.

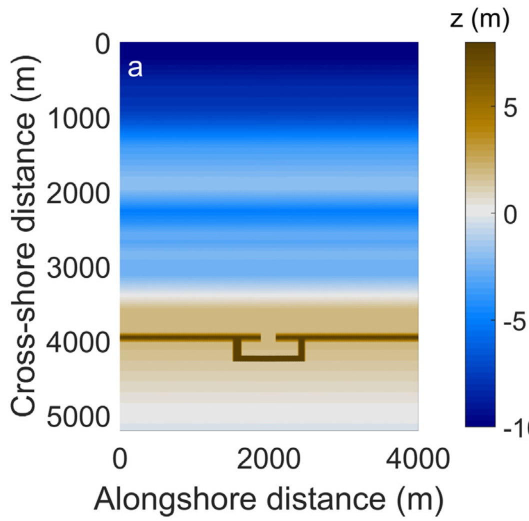

Fig. 12. Profile with a secondary dune system, based on reference simulation A0, that blocks the North Sea from the Wadden Sea.

compared to a situation where the North Sea and Wadden Sea are connected.

6. Conclusions

In this paper we studied the influence of several topographic characteristics of Wadden Islands on the hydrodynamics and sediment transport during storm-induced inundation, with a focus on natural gaps in the foredunes known as washover openings. The washover opening geometries used for the XBeach simulations were based on the ones that are present across the Wadden Islands. The mean width was 200 m but the actual width ranged from 35 to 1100 m, and the elevation was between 1.5 and 2.1 m above MSL. The simulations show that cross-shore currents are for a large part responsible for the sediment transport patterns, which are significantly affected by the elevation and width of the washover opening. Differences in opening height investigated in this study demonstrate a decrease in sediment transport by 400% for higher openings. Narrower openings result in stronger flow convergence and larger currents, but on the other hand, wider openings have more capacity to transport sediment. Both effects combined results in increasing sediment transport for wider openings, up to 800% for the range that is analyzed. The beach slope leads to a 25% change in sediment transport and is less important than the washover opening dimensions. The patterns of sediment transport convergence and divergence, which are a measure for morphological change, show that during inundation the washover opening erodes, and the area just onshore from there receives sediment, resulting in deposition. Lower and smaller openings lead to larger erosion depths, however, the total area of deposition increases for wider openings. The higher water levels in the Wadden Sea at the location of Schiermonnikoog during storm surges significantly decrease the potential for large currents and high deposition rates for the washovers, however, it is still much greater than in a system without a connection between the North Sea and Wadden Sea. This indicates that the regional hydrodynamic forcing must be taken into account under all circumstances.

Acknowledgements

Daan Wesselman is supported by Climate-KIC, as well as by the Netherlands Organisation for Scientific Research (NWO), Natuurmonumenten, the National Forest Service (Staatsbosbeheer) and the Wadden Academy.

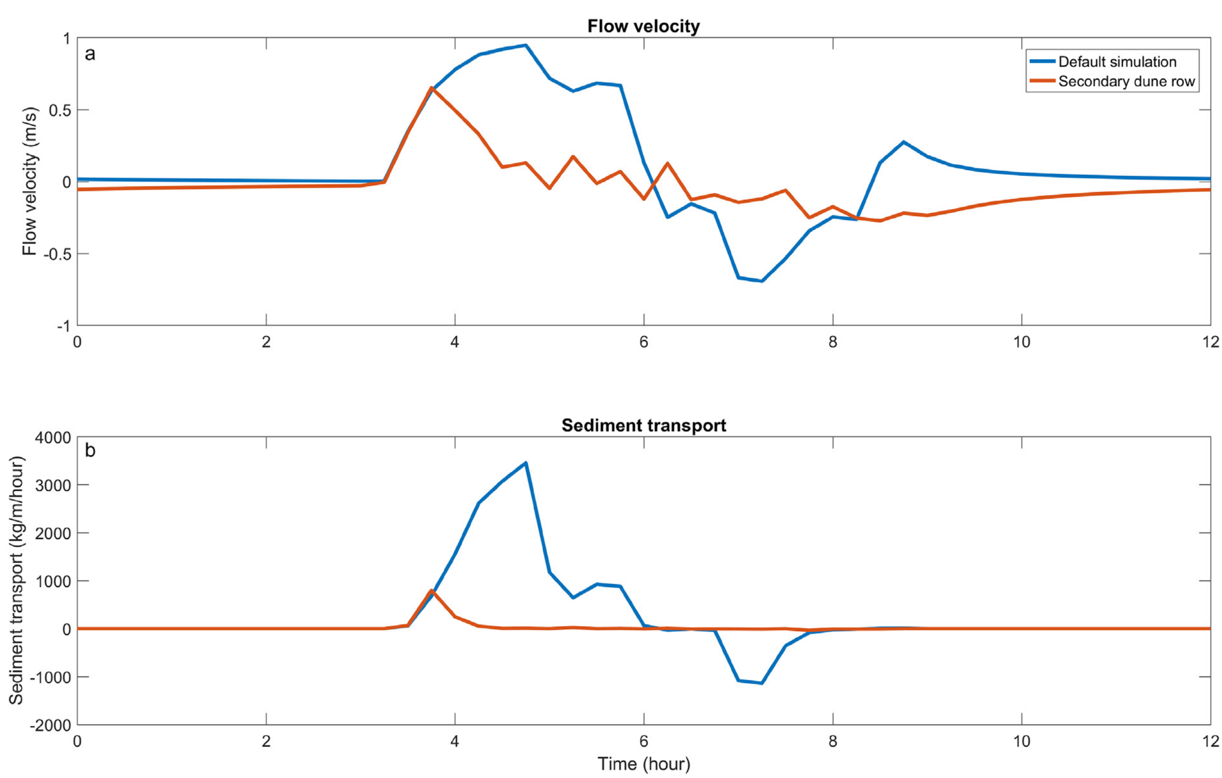

Fig. 13. a) Flow velocity and b) sediment transport for the default simulation A0 and the simulation with a secondary dune system.

Appendix A

Google Earth was used to investigate the range of widths of the washover openings at all Wadden Islands where these openings exist, which are Texel, Vlieland, Terschelling, Ameland, Schiermonnikoog, Rottumerplaat, Rottumeroog, Borkum, Norderney, Spiekeroog, Amrum, Rømø and Skallingen (Fig. 1). If possible, the width was calculated parallel to the coast and the location of the vegetation was used, as this often indicates the dune position. In this Appendix, an overview is given of all the washover openings at these islands, including a brief description of the local situation. Based on personal communication and field observations, we know that some of the openings in the dunes are blowouts instead of washover openings, which are consequently never inundated. These blowouts are not taken into account. Furthermore, many variations are found along the Wadden Islands. For example, some washover openings connect the North Sea and Wadden Sea during storms, while others are (partly) backed by a secondary dune row. Furthermore, some openings contain an active channel (e.g. the Slufter at the island of Texel) while the majority is completely dry during calm weather conditions. For the goal of this study, they were all considered as washover openings and described below.

A.1. Texel

Texel contains two washover openings. The first one is located at the Hors, a wide beach plain at the South Western part of the island and is 40 m wide (Fig. A1). This one is different from most other openings because it is not orientated towards the North Sea. Instead, it is attached to the Marsdiep, the deep tidal inlet between Texel and the mainland. The second one is also known as the Slufter (Fig. A2) with an opening that is 420 m wide. The Slufter contains a large and fast-migrating channel and this area is completely backed by dikes that prevent the inhabited part of Texel from flooding (van der Vegt and Hoekstra, 2012).

A.2. Vlieland

The western part of Vlieland, called the Vliehors, was a low-lying beach plain without dunes for a long time (Fig. A3). Recently, a small dune complex formed so that nowadays a washover opening of 1040 m can be defined.

A.3. Terschelling

At Terschelling, three narrow washover openings of less than 100 m in width can be found (Fig. A4). They are not connected with the hinterland of Terschelling, because a large and artificial sand-drift dike is in between. In January 2017, a large storm breached the upper end of the sand-drift dike, which is probably caused by the eroding island tail that makes this area more vulnerable to storms. This created the fourth washover opening of 380 m wide.

A.4. Ameland

Ameland contains, similar to Terschelling, a large sand-drift dike that made an end to the majority of previously existing washover openings. Nevertheless, three openings narrower than 100 m can still be found at the island tail (Fig. A5).

A.5. Schiermonnikoog

Schiermonnikoog is the island where nowadays most washover openings can be found (Fig. A6). However, they are relatively young: in the sixties, a large sand-drift dike was created that closed several wide washover openings (ten Haaf and Buijs, 2008). A large storm in 1973 breached this sand-drift dike at several locations, which enhanced the formation of new but smaller washover openings. Nowadays, they are between 40 m and 210 m wide.

A.6. Rottumerplaat and Rottumeroog

Rottumerplaat and Rottumeroog are two uninhabited islands in the Netherlands which both contain a washover opening (Figs. A7 and A8). Although the coasts of these islands are no longer maintained, still remnants of artificial measures can be observed. For example, a large sand-drift dike in the middle of Rottumerplaat separates the islands into two parts. This results in the fact that the North Sea and Wadden Sea are not connected here during storms through the 860 m wide opening. At Rottumeroog, the washover opening of 590 m wide only exists since a large storm in 2013 breached part of the dunes, also known as the Sinterklaasstorm.

A.7. Borkum

Borkum is the first German Wadden Island from west to east (Fig. A9). The most updrift part of Borkum is protected by concrete structures and sand-drift dikes, however at the island tail three washover openings are present, ranging in width from 30 m to 260 m.

A.8. Norderney

The island tail of Norderney (Fig. A10) never experienced the existence of a sand-drift dike and therefore it contains several washover openings. The most updrift opening is the widest one (270 m) and contains a channel. The other washover openings are between 50 m and 210 m.

A.9. Spiekeroog

Similar to Norderney, the island tail of Spiekeroog was not closed off by artificial sand-drift dikes in the past (Fig. A11). The most updrift washover opening is 380 m wide. Spiekeroog used to have more washover openings, but nowadays they have almost disappeared due to the formation of natural dunes in the openings. Therefore, only the most updrift washover opening of Spiekeroog was taken into account in this study.

A.10. Amrum

Amrum contains one washover opening of 170 m wide that is in front of a sand drift dike dike (Fig. A12).

A.11. Rømø

Rømø, one of the Wadden Islands in Denmark, contains three washover openings ranging from 60 to 100 m wide (Fig. A13). They arose in a new, young series of foredunes onshore from the old beach plain, which is now partly enclosed.

A.12. Skallingen

Skallingen is a barrier spit that is partly separated from the mainland of Denmark with a tidal basin (Fig. A14). Two washover openings exist here of 140 and 200 m wide. The latter exists since a breach during a storm in 1990 (Nielsen and Nielsen, 2006).

Fig. A1. Washover opening one at Texel, the Netherlands.

Fig. A2. the Slufter, washover opening two at Texel, the Netherlands.

Fig. A3. Washover opening at Vlieland, the Netherlands.

Fig. A4. Washover openings at Terschelling, the Netherlands.

Fig. A5. Washover openings at Ameland, the Netherlands.

Fig. A6. Washover openings at Schiermonnikoog, the Netherlands.

Fig. A7. Washover opening at Rottumerplaat, the Netherlands.

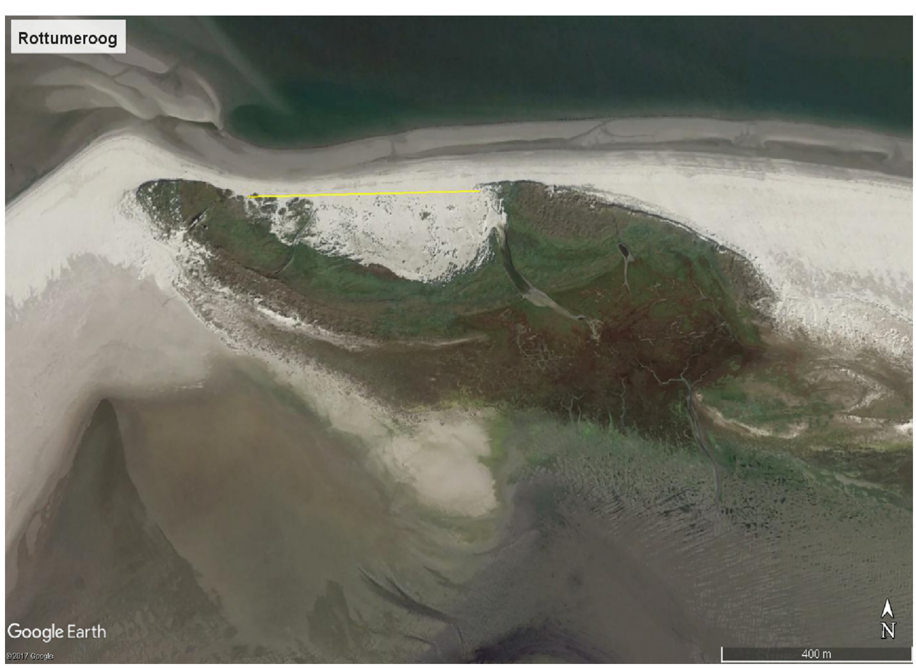

Fig. A8. Washover opening at Rottumeroog, the Netherlands.

Fig. A9. Washover openings at Borkum, Germany.

Fig. A10. Washover opening at Norderney, Germany.

Fig. A11. Washover opening at Spiekeroog, Germany.

Fig. A12. Washover openings at Amrum, Germany.

Fig. A13. Washover openings at Rømø Denmark.

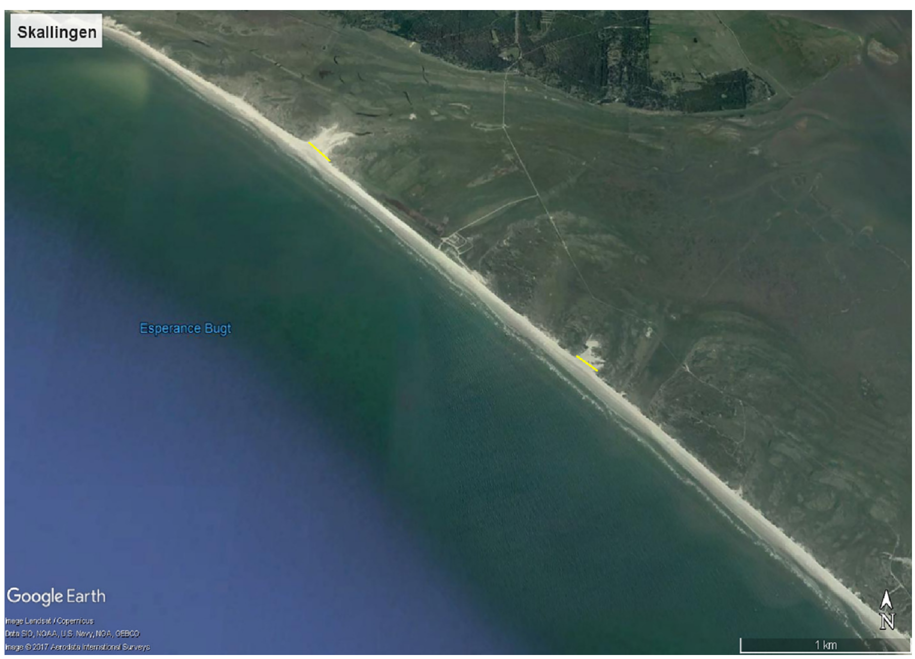

Fig. A14. Washover openings at Skallingen, Denmark.

Appendix B

The inundation classes used in the simulations of this paper were created in Wesselman et al. (2017). This appendix summarizes how these inundation classes were defined. It should be noted that for this paper only classes 3–6 were used, because classes 1 and 2 do not lead to inundation for most profiles in this paper, in contrast to the profiles used in Wesselman et al. (2017).

The classes consist of water levels in the North Sea and Wadden Sea (measured every 10 min) and offshore wave forcing (measured every hour), based on the period 1990–2014. The first step was to collect all individual tidal cycles where the peak offshore water level (a combination of tide and storm surge) is higher than 1.5 m, which would cause inundation on the profile used in Wesselman et al. (2017). Then, all these tidal cycles were sorted into classes, with a separation of 0.25 m per class. Thus, for class 1 all tidal cycles with an offshore peak water level between 1.50 and 1.75 m were collected, etc. Averaging all these tidal cycles within one class led to an average tidal cycle which represented the specific class.

The same averaging of all tidal cycles within one class was performed for the Wadden Sea, however, the moment of peak water level was still based on the North Sea. The reason to define the tidal curves in the Wadden Sea based on the peak water level in the North Sea was that there is often a time lag between the North Sea and Wadden Sea, which can be demonstrated more easily by following this method. Fig. 5 shows the resulting representative tidal curves for inundation classes 3–6, demonstrating that besides the time lag, water levels in the Wadden Sea during storms are also higher than in the North Sea.

The offshore wave forcing (height, period and direction) is also averaged for all tidal cycles within one class, which leads to constant wave forcing per class (Table 2). The wave height and period increases for larger storms and the wave direction becomes more northwest, which means more perpendicular to the shore.

References

Abhar, K.C., Walker, I.J., Hesp, P.A., Gares, P.A., 2015. Spatial-temporal evolution of aeolian blowout dunes at Cape God. Geomorphology 236, 148–162.

de Groot, A.V., Veeneklaas, R.M., Bakker, J.P., 2011. Sand in the salt marsh: contribution of high-energy conditions to salt-marsh accretion. Mar. Geol. 282, 240–254.

de Winter, R., Gongriep, F., Ruessink, B., 2015. Observations and modeling of alongshore variability in dune erosion at Egmond aan Zee, the Netherlands. Coast. Eng. 99, 167–175.

Donnelly, C., Kraus, N., Larson, M., 2006. State of knowledge on measurement and modeling of coastal overwash. J. Coast. Res. 965–991.

Donnelly, C., Kraus, N.C., Larson, M., 2004. Coastal overwash: part 1, overview of processes. Tech. rep. DTIC Document.

Durán Vinent, O., Moore, L.J., 2015. Barrier island bistability induced by biophysical interactions. Nat. Clim. Chang. 5, 158–162.

Engelstad, A., Ruessink, B.G., Wesselman, D., Hoekstra, P., Oost, A., van der Vegt, M., 2017. Observations of waves and currents during Barrier island inundation. J. Geophys. Res. 122 (4), 3152–3169.

Figlus, J., Kobayashi, N., Gralher, C., Iranzo, V., 2010. Wave-induced overwash and destruction of sand dunes. Coastal Engineering. vol. 32.

Harter, C., Figlus, J., 2017. Numerical modeling of the morphodynamic response of a low-lying barrier island beach and foredune system inundated during Hurricane Ike using XBeach and CSHORE. feb. Coast. Eng. 120, 64–74. https://doi.org/10.1016/j.coastaleng.2016.11.005.

Hayes, M.O., 1979. Barrier Island Morphology as a Function of Tidal and Wave Regime. Barrier islands. , pp. 1–27.

Hoekstra, P., ten Haaf, M., Buijs, P., Oost, A., Klein Breteler, R., van der Giessen, K., van der Vegt, M., 2009. Washover development on mixed-energy, mesotidal Barrier island systems. Coastal Dynamics. vol. 83. pp. 25–32.

Hoonhout, B., van Thiel de Vries, J.S.M., 2012. Modelling dune erosion, overwash and inundation of barrier islands. Proceedings of the 33rd International Conference on Coastal Engineering. Coastal Engineering Research Council.,

Houser, C., Wernettte, P., Rentschlar, E., Jones, H., Hammond, B., Trimble, S., 2015. Post-storm beach and dune recovery: implications for barrier island resilience. Geomorphology 234, 54–63.

Lazarus, E.D., 2016. Scaling laws for coastal overwash morphology. Geophys. Res. Lett. 43 (23), 12,113–12,119.

Leatherman, S.P., 1976. Barrier island dynamics: overwash processes and eolian transport. Coast. Eng. Proc. 1 (15).

Leatherman, S.P., 1979. Migration of Assateague Island, Maryland, by inlet and overwash processes. Geology 7, 104–107.

Lorenzo-Trueba, J., Ashton, A.D., 2014. Rollover, drowning, and discontinuous retreat: distinct modes of barrier response to sea-level rise arising from a simple morphodynamic model. J. Geophys. Res. Earth Surf. 119 (4), 779–801.

Masetti, R., Fagherazzi, S., Montanari, A., 2008. Application of a barrier island translation model to the millennial-scale evolution of Sand Key, Florida. Cont. Shelf Res. 28 (9), 1116–1126.

Matias, A., Rita Carrasco, A., Loureiro, C., Andriolo, U., Masselink, G., Guerreiro, M., Pacheco, A., McCall, R., Ferreira, Ó., Plomaritis, T.A., 2017. Measuring and modelling overwash hydrodynamics on a barrier island. Proceedings of the Coastal Dynamics. pp. 1616–1627.

McCall, R., De Vries, J.V.T., Plant, N., Van Dongeren, A., Roelvink, J., Thompson, D., Reniers, A., 2010. Two-dimensional time dependent hurricane overwash and erosion modeling at Santa Rosa Island. Coast. Eng. 57 (7), 668–683.

Nielsen, N., Nielsen, J., 2006. Development of a washover fan on a transgressive barrier, Skallingen, Denmark. J. Coast. Res. Spec. (39), 107–111.

Phillips, B.T., Brown, J.M., Bidlot, J.-R., Plater, A.J., 2017. Role of beach morphology in wave overtopping hazard assessment. J. Mar. Sci. Eng. 5 (1).

Ridderinkhof, W., Hoekstra, P., van der Vegt, M., de Swart, H., 2016. Cyclic behavior of sandy shoals on the ebb-tidal deltas of the wadden sea. Cont. Shelf Res. 115, 14–26.

Roelvink, D., Reniers, A., van Dongeren, A., de Vries, J.v.T., McCall, R., Lescinski, J., 2009. Modelling storm impacts on beaches, dunes and barrier islands. Coast. Eng. 56 (11), 1133–1152.

Roelvink, J., 1993. Dissipation in random wave groups incident on a beach.feb. Coast. Eng. 19 (1-2), 127–150.

Sallenger, A.H., 2000. Storm impact scale for barrier islands. J. Coast. Res. 16, 890–895.

Sherwood, C.R., Long, J.W., Dickhudt, P.J., Dalyander, P.S., Thompson, D.M., Plant, N.G., 2014. Inundation of a barrier island (Chandeleur Islands, Louisiana, USA) during a hurricane: observed water-level gradients and modeled seaward sand transport. J. Geophys. Res. Earth Surf. 119 (7), 1498–1515.

ten Haaf, M.E., Buijs, P.H., 2008. Morfologie en dynamiek van washoversystemen (Dutch report). Tech. rep., Department of Physical Geography, Utrecht University.

Tillmann, T., Wunderlich, J., 2013. Barrier rollover and spit accretion due to the combined action of storm surge induced washover events and progradation: insights from ground-penetrating radar surveys and sedimentological data. J. Coast. Res. Spec. Issue 65 - Int. Coast. Symp. 1, 600–605.

van de Graaff, J., 1977. Dune erosion during a storm surge. Coast. Eng. 1, 99–134.

van der Vegt, M., Hoekstra, P., 2012. Morphodynamics of a storm-dominated, shallow tidal inlet: the Slufter, the Netherlands. J. Geosci. 91, 325–339.

van Dongeren, A., van Ormondt, M., 2007. H&I zeereep: aspect verdiepende studies morfologie: hydraulica (Dutch report). Tech. rep. WL | Delft Hydraulics.,

van Rijn, L.C., 2007. Unified view of sediment transport by currents and waves. II: suspended transport. J. Hydraul. Eng.

Van Thiel de Vries, J.S.M., 2009. Dune Erosion during Storm Surges.Ph.D. thesis. TU Delft, Delft University of Technology.

Vellinga, P., 1982. Beach and dune erosion during storm surges. Coast. Eng. 6, 361–387.

Wesselman, D., de Winter, R., Engelstad, A., McCall, R., van Dongeren, A., Hoekstra, P., Oost, A., van der Vegt, M., 2017. The effect of tides and storms on the sediment transport across a Dutch barrier island. Earth Surf. Process. Landf.