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THE INFLUENCE OF WASHOVER DIMENSIONS AND BEACH CHARACTERISTICS ON THE SEDIMENT TRANSPORT DURING INUNDATION

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Abstract

Barrier islands need sediment input to keep up with sea-level rise. Landward directed sediment transport during storm-induced inundation can contribute to the vertical accretion of barrier islands and therefore, the partial re-opening of the artificial sand-drift dikes is considered for the Wadden Islands in the Netherlands. This XBeach model study investigates the role of the washover width and height, and the beach width and slope on the hydrodynamics and sediment transport at the washover opening during inundation. Simulations show that the washover height is the most dominant factor. Lower washover heights result in more sediment transport. Furthermore, for wider openings the total sediment transport through the entire opening firstly increases rapidly and then increases more gradually. The beach width and slope are expected to have limited effect on the sediment transport at the washover opening.

Key words: Wadden Islands, inundation, XBeach, hydrodynamics, sediment transport

1. Introduction

Many barrier islands in the world need sediment input to counteract the effects of long-term sea-level rise. Landward directed sediment transport during storm-induced overwash and inundation might contribute to the vertical accretion of barrier islands (Donnelly et al., 2006; Hoekstra et al., 2009; Lazarus, 2016; Leatherman, 1985; Masselink and van Heteren, 2014; Nielsen and Nielsen, 2006; Sallenger, 2000). The Wadden Islands in the Netherlands, Germany and Denmark are examples of barrier islands that are vulnerable to sea-level rise. The area is characterized by mesotidal conditions (2-4 m) and relatively large storm surges. Typically, Wadden Islands contain so-called washover openings, gaps in the first dune row that are low-lying, around 2.0-2.5 m (Oost et al., 2012). Some examples of Wadden Islands and their washovers are shown in Figure 1. Consequently, these washover systems are inundated several times a year, which can locally connect the water in the North Sea and Wadden Sea across the island. In the past, the closure of many of these washovers by artificial sand drift dikes has blocked this onshore sediment transport. Recently, the re-activation of parts of the Dutch washover systems is considered by the local coastal zone management to stimulate onshore sediment deposition (Oost et al., 2012), however, at the moment it is unclear if reopening will result in a net landward sediment transport.

The dominant hydrodynamic processes and their influence on sediment transport during inundation were investigated with a field campaign at the downdrift side of Schiermonnikoog in the winter of 2014-2015 and a related model study (Engelstad et al., 2017; Wesselman et al., submitted). The downdrift side lacks dunes completely and is relatively uniform in alongshore direction, and can therefore be seen as a 1D system. They conclude that cross-shore currents are strongly affected by the water level gradients between the North Sea and Wadden Sea. Typically, currents are onshore directed (i.e. from North Sea to Wadden Sea) during rising tide and can be offshore directed during falling tide caused by higher water levels in the Wadden Sea compared to the North Sea, especially under higher storm surge conditions. However, onshore currents during rising tide are dominant and therefore net sediment transport is expected to be onshore directed. In contrast to the alongshore, uniform, downdrift side the washover systems contain dunes and should be analyzed with alongshore variations taken into account.

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The aim of this study is to investigate the effect of several geometric parameters on sediment transport during inundation events: The washover opening height and width, the beach width and the beach slope. Hereby we focus on the hydrodynamic processes, with a constant water level as boundary condition (i.e. no tide). Therefore we perform a model study where these geometric parameters are changed systematically. The morphological parameters are based on washover systems at several Wadden Islands and will give more insight in how to restore the natural washovers in an effective way.

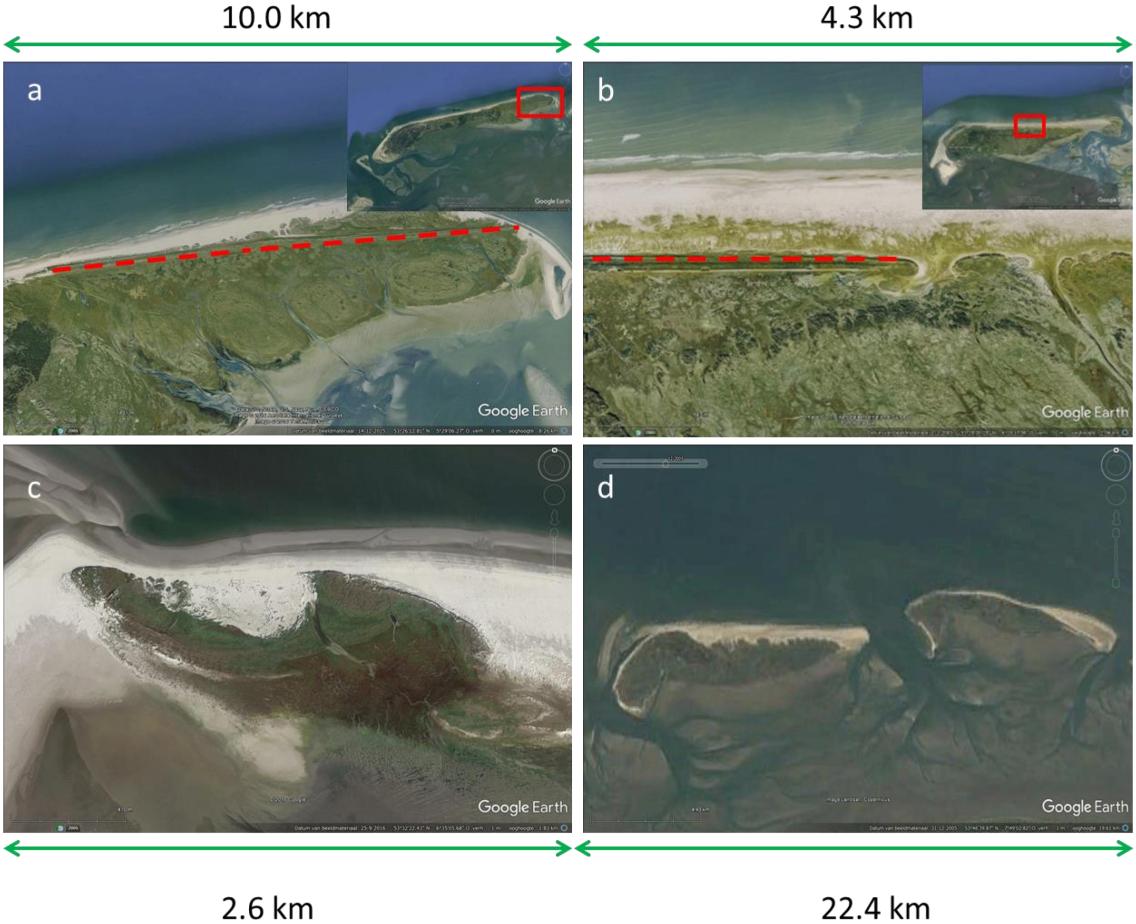

Figure1. a) Terschelling, the Netherlands. A large sand-drift dike prevents inundation. b) Schiermonnikoog, the Netherlands. The sand-drift dike is partly destroyed by a storm in 1976. c) Rottumeroog, the Netherlands. No artificial measures have been taken since 2002 at this uninhabited island. This washover is created during a storm in 2013. d) Spiekeroog (left) and Wangeroog (right), Germany. Spiekeroog did never contain sand-drift dikes at a large part of the dunes, Wangeroog is completely closed off by sand-drift dikes and other artificial measures. The North Sea is at the top of the pictures, the Wadden Sea at the bottom. For Terschelling and Schiermonnikoog, the sand-drift dikes are indicated with a red, dashed line.

2. Methods

2.1. *Area Description*

The model simulations are based on typical washover dimensions and beach characteristics we found on the Wadden Islands in the Netherlands. Lidar data from Rijkswaterstaat (RWS, Dutch Ministry of Infrastructure and the Environment) are used to investigate the geometric properties of the current washover openings of Schiermonnikoog and Rottumeroog. The largest washover openings at Schiermonnikoog (Figure 1b) were about 600 meters wide from dune to dune, before they were closed in 1959-1969 (ten Haaf and Buijs, 2008). In 1976 a large storm partly destroyed the sand-drift dike and created new openings in the dunes, but these gaps are much narrower than the original openings. The washover geometry has been more or less static since then, and in recent years vegetation started growing on the beach. This suggests the absence of beach or dune erosion and with that limited onshore sediment transport, which might be caused by the washover geometry or beach characteristics.

Based on lidar data from 2006, the most updrift washover opening at Schiermonnikoog is 200 m wide and 2.0 m above mean sea level (MSL). The dissipative beach roughly consists of two parts, which are the gently sloping foreshore (0.01 m/m) from a height of 1 m below (MSL) to the washover height, and a 300 m wide and flat beach berm that has approximately the same height as the washover opening. At Rottumeroog (Figure 1c), the washover width and height is approximately 600 m and 2.2 m respectively, based on lidar data from 2016. A typical Wadden Island washover system is illustrated in Figure 2.

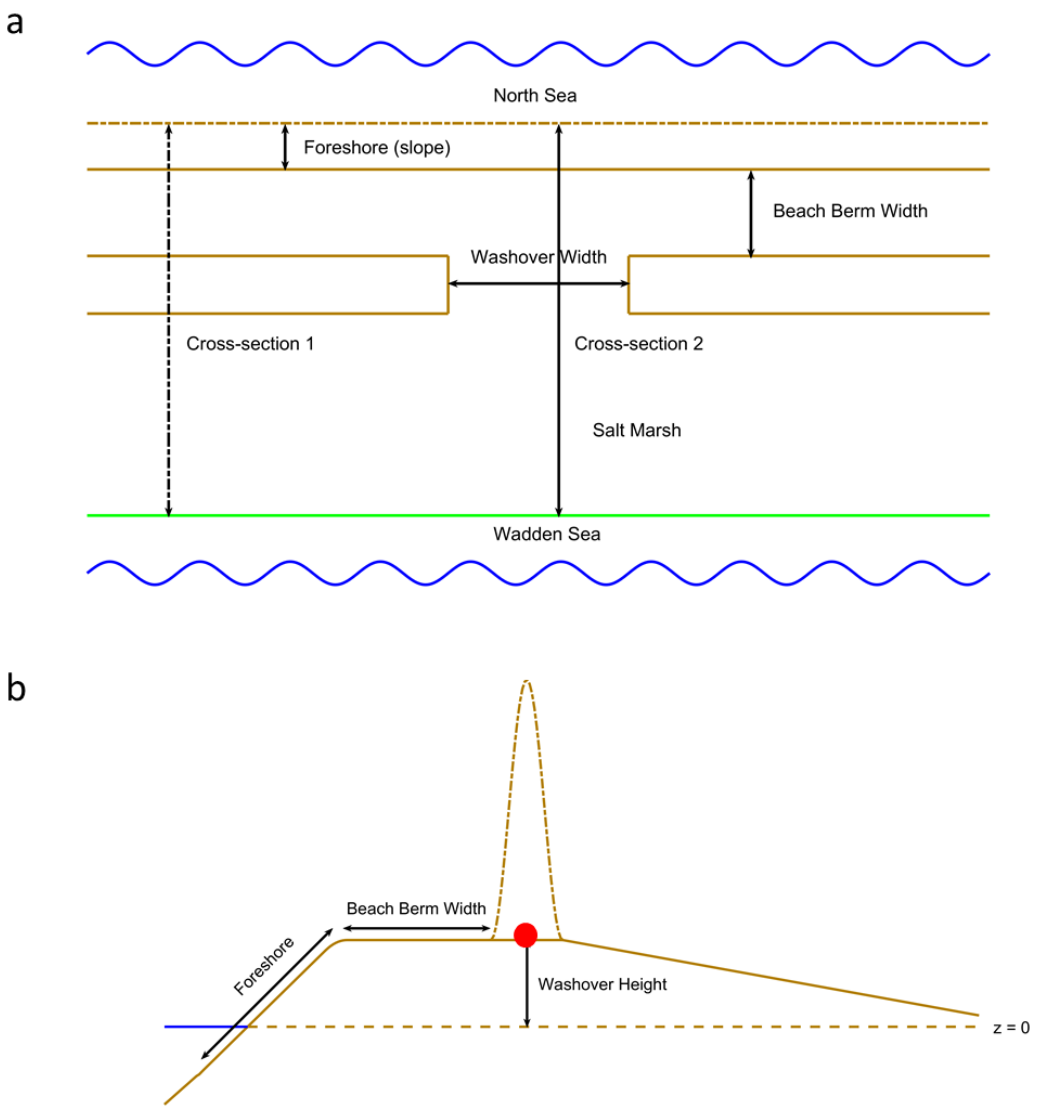

Figure 2. a) Top view of a typical washover system. The beach at the North Sea side consists of a gently sloping foreshore and a flat beach berm. The washover is an opening of the dune row. Onshore of the dunes and washover opening there is typically a salt marsh. b) Cross-sections, where the foreshore, beach berm and washover height are indicated. This profile includes a dune (dashed line) or a washover opening, depending on the alongshore location (cross-section 1 or 2). The z = 0 line is equal to MSL. The red dot marks the middle of the washover opening in cross-shore direction.

2.2. *XBeach modelling*

We use the 2D version of XBeach to model the influence of washover geometries on sediment transport during inundation events for typical Wadden Island conditions. We refer to Roelvink et al. (2009) for a full description of the XBeach model. The model is able to accurately simulate the hydrodynamics during collision or inundation events for typical North Sea conditions (de Winter, 2015; Wesselman et al., submitted). Based on field work at Schiermonnikoog and a validation study the wave breaking parameter gamma is set to 0.45 instead of the default value of 0.55. For all other parameters the default value is used. The grid is approximately 5500 m x 4000 m in cross-shore and alongshore direction respectively. The grid size in cross-shore direction gradually changes from 20 m in deep water to 5 m at the island. In alongshore direction, it changes from 30 m at the side boundaries to 10 m at the washover openings. The model is run in morphostatic mode (i.e. no bed level updates) and each run was preceded with a spin-up period of 4 hours. The parameters that are analyzed are averaged over the fifth hour of the simulation.

The bathymetry consists of a few specific sections that can be adapted to investigate their role on the sediment transport through the opening. The beach consists of two parts; the foreshore and the flat beach berm, which has the same height as the washover opening. The washover opening itself is also assumed to be flat, west and east from the gap are 8 meter high dunes. The dunes and washover opening extend 150 m in cross-shore direction before the back-barrier starts, which slopes very gently (0.002 m/m) until a final height of 1 m below MSL. The offshore part of the bathymetry contains two subtidal sand bars (Figure 3).

The influence of four geometric parameters is analyzed: The washover width, the washover height, the beach berm width and the slope of the foreshore (see Table 1). The washover width varies between 50 m and 600 m and the washover height is changed from 1.7 m to 2.3 m. The current beach bem of Schiermonnikoog is very wide compared to the past, so this 300 meters is chosen as the upper limit. The lower limit is the extreme case of a beach berm of only 10 m. Similarly, the current foreshore slope of 0.01 m/m is regarded as very gentle and acts as the lower limit, while the upper limit is 0.1 m/m. The reference profile is shown in Figure 3.

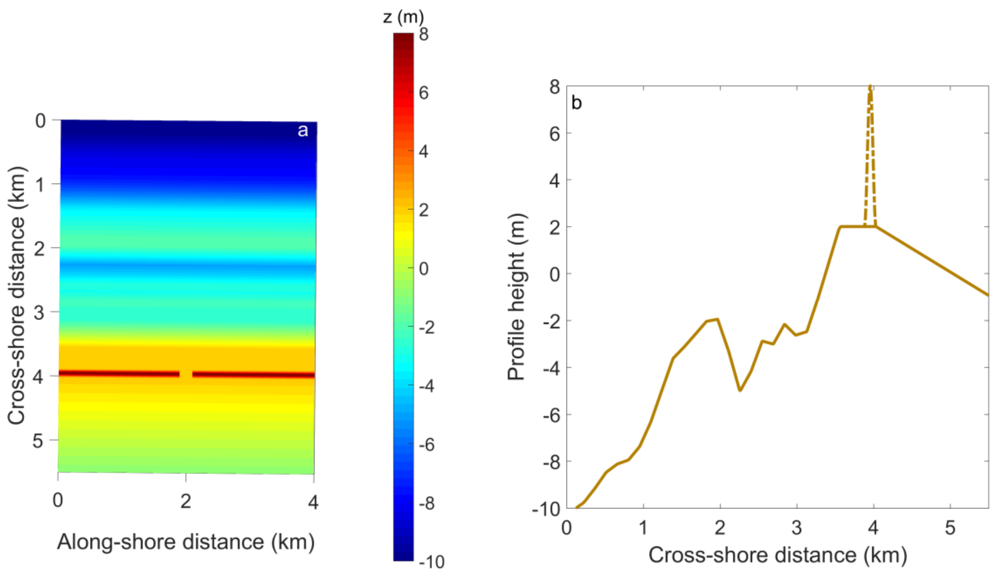

Figure 3. a) The reference profile in a) 2D and b) 1D. The washover height is 2.0 m, the washover width 200 m, the beach berm width 300 m and the foreshore slope 0.01 m/m.

The forcing represents high tide during an inundation event that occurs approximately once a year (Wesselman et al., submitted). Water levels, including storm, are constant in time with a mean height of 2.5 m above MSL at the North Sea and Wadden Sea boundary. The significant short wave height, based on an offshore buoy at a water depth of 20 m, is 5.38 m. No wave buoys are present in shallower water, so a simple 1D XBeach model was used to calculate the wave height at a water depth of 10 m (i.e. the water depth at the North Sea boundary), which is 3.52 m. The wave period is 8.53 s and the wave angle of incidence, which is 46 degrees at a water depth of 20 m, is 34 degrees at 10 m water depth based on Snell's Law. Those values are used to create a JONSWAP spectrum with a peak enhancement factor gamma of 3.3 s^{-1} and a directional spreading sigma of 18 degrees, respectively.

Table 1. Overview of all simulations

Series	Washover width (m)	Washover height (m)	Beach Berm width (m)	Forshore slope (m/m)
Reference simulation	200	2.0	300	0.01
Vary washover width and height	50, 100, 200, 300, 400, 500, 600	1.7, 2.0, 2.3	300	0.01
Vary beach berm width	200	2.0	10, 50, 100, 200, 300	0.01
Vary foreshore slope	200	2.0	300	0.01, 0.02, 0.03, 0.05, 0.1

3. Results

3.1 Reference simulation

Short waves in the reference simulation break mainly on the foreshore (Figure 4a). On the flat beach berm, short wave heights only decrease at a slow rate, which means that wave dissipation by breaking or friction is not important here. Due to wave set-up, the water level increases with approximately 30 cm until the foreshore (Figure 4b), which generates a pressure gradient across the island from North Sea to Wadden Sea. In the absence of the tide, the wave set-up is the only mechanism leading to this pressure gradient and the corresponding onshore current. The wave-driven flow field of the reference simulation shows that currents are alongshore oriented at the foreshore, representing an alongshore flow (Figure 4c). At the beach berm, the alongshore currents are smaller and get a cross-shore component in the vicinity of the washover gap. In the washover opening the currents are cross-shore oriented with maximum values of approximately 1.3 m/s. This flow increase leads to a decrease of the water level in the washover opening, as shown in Figure 4b. Behind the washover opening, flow velocities rapidly decrease. Sediment transport strongly correlates with the currents (Figure 4d) and shows the same patterns in cross-shore and alongshore direction.

3.2 Sensitivity to washover width and height

The increase of flow velocities trough a washover opening is the result of flow contraction and depends on the width of the gap. This effect is more pronounced and flow velocities and the corresponding sediment transport are larger for narrower openings (Figure 5). Maximum flow velocities at the edges of the openings range from 1.4 m/s for an opening of 50 m to approximately 1.25 m/s for openings wider than 400 m. The corresponding maximum sediment transport is 5-6 kg/m/s. Flow contraction and the corresponding velocity increase is strongest at the edges of the gaps, while this effect reduces towards the middle, leading to a flow velocity of approximately 1.05 m/s in the middle of the opening for a width of 600 m. However, the peak flow velocity and sediment transport for narrow openings (i.e. until 100 m) is largest in the middle of the washover. Flow velocities at the edges only slightly decrease for openings wider than 400 m and appear to reach a constant value. This implies that flow contraction will always play a role on the sediment transport at the edges of a washover opening, even for very wide systems.

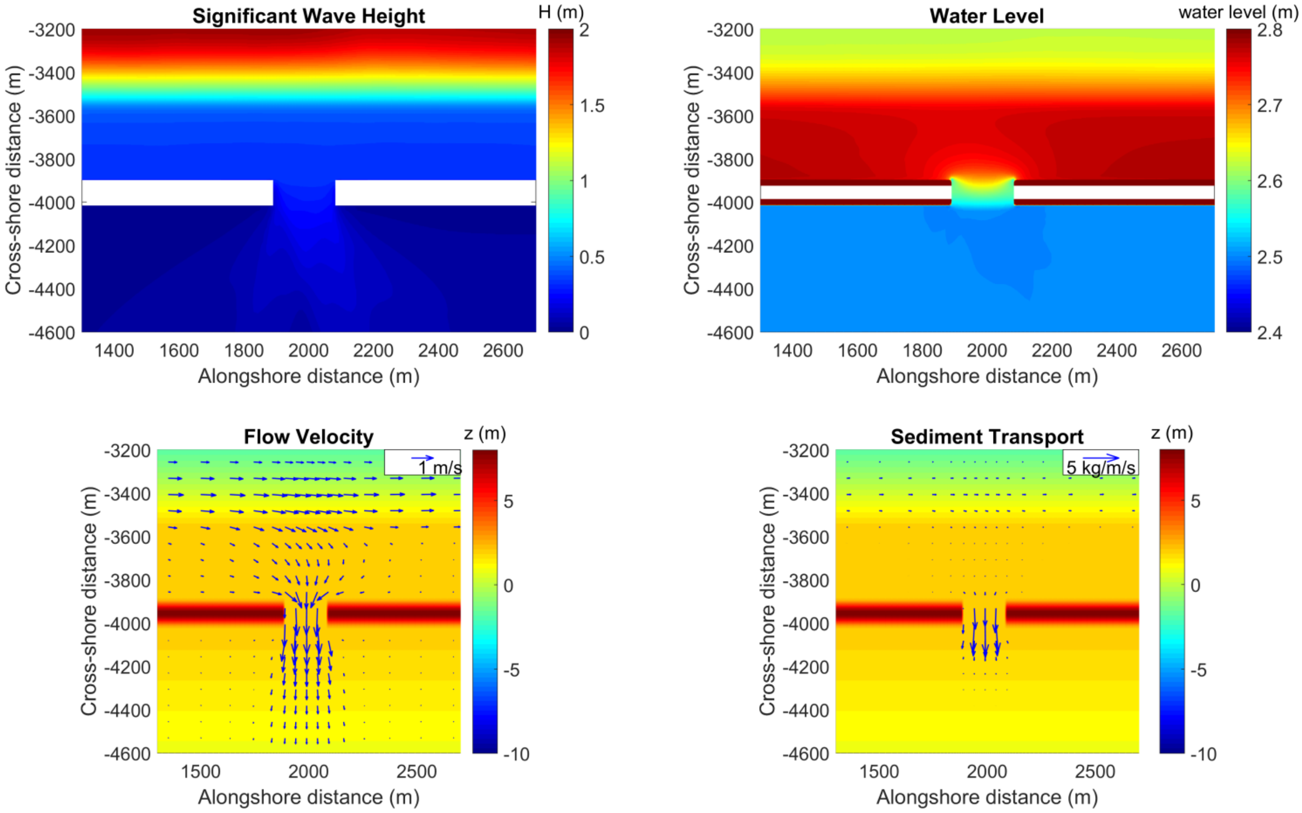

Figure 4. The hourly averaged a) Significant short wave height and b) Water level. Vector plots of c) the flow velocity and d) the sediment transport.

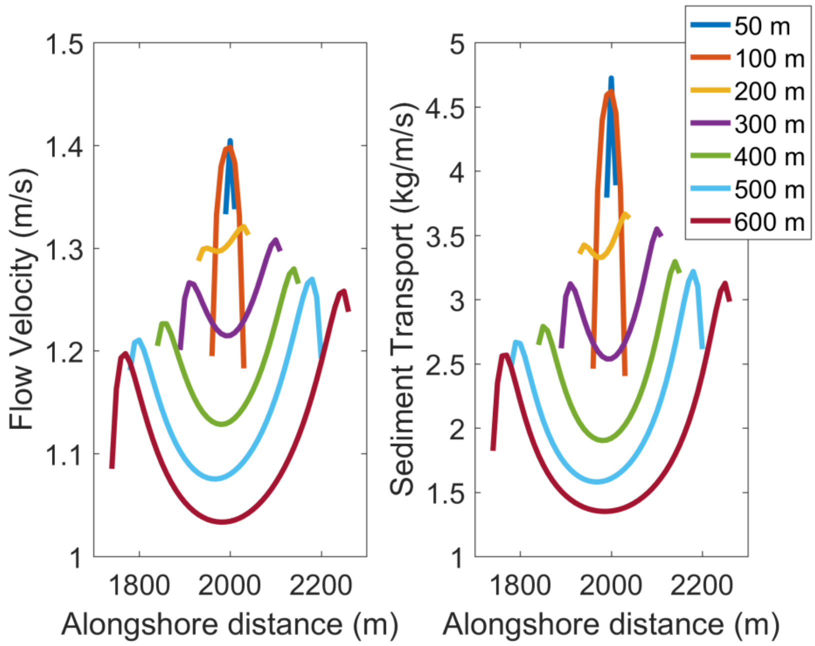

Figure 5. a) Flow velocity and b) Sediment transport along the washover opening for different washover widths for a washover height of 2.0 m.

In the previous section we have shown that short waves mainly dissipate their energy on the foreshore and less on the beach berm or in the washover opening. Short wave heights in the middle of the washover opening are only weakly dependent on the washover width (Figure 6a). The width-integrated cross-shore sediment transport through the washover (Figure 6d) is a result of two opposing effects. On one hand, for wider openings flow velocities and the corresponding sediment transport becomes smaller in the middle of the opening (Figure 6b and 6c). On the other hand, sediment can be transported over a broader width that increases the total width-integrated transport. The net result is that the total transport through the opening first strongly increases (until roughly 200-300 m) and then increases at a weaker rate.

The washover height appears to be a very important factor for washover dynamics (Figure 6). More wave energy dissipates, as expected, on the foreshore for a higher beach crest and washover opening, which results in lower wave heights. Also flow velocities and sediment transport are clearly reduced for higher washover openings. For washovers with a 30 cm lower beach crest (i.e. 1.7 m compared to 2.0 m), the total transport through the entire openings increases with approximately 30-50% depending on the width of the opening. For heights of 2.3 m, the differences with the 2.0 m case are even larger.

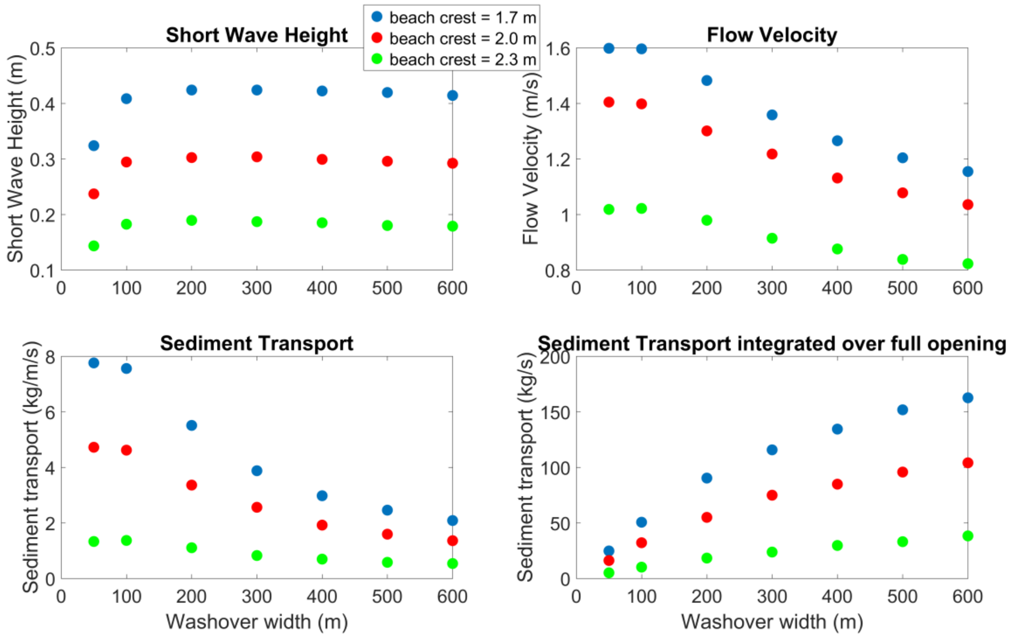

Figure 6. Parameters in the middle of washover opening for several combinations of washover width and height. a) Significant short wave height. b) Flow velocity. c) Cross-shore sediment transport. d) Cross-shore sediment transport integrated over the entire opening.

3.3 Sensitivity to beach width and slope

The width of the beach berm hardly has any influence on the hydrodynamics and sediment transport in the washover opening (Figure 7). Wave breaking mainly occurs on the foreshore, while wave dissipation on the flat beach berm by friction and breaking only has a minor contribution compared to the wave breaking on the foreshore. As a result, flow velocities and sediment transport in the washover opening are approximately the same for all beach berm widths.

Steeper foreshore slopes lead to more intense wave breaking. Consequently, the wave set-up becomes larger and flow velocities and sediment transport increases (Figure 8). However, in the range of slopes that are typically found along the North Sea coast (0.01-0.03 m/m) this effect is very small. Only for extreme slopes of 0.1 m/m the sediment transport at the washover opening significantly increases, these steep slopes are however unlikely to form at the barrier islands in the North Sea.

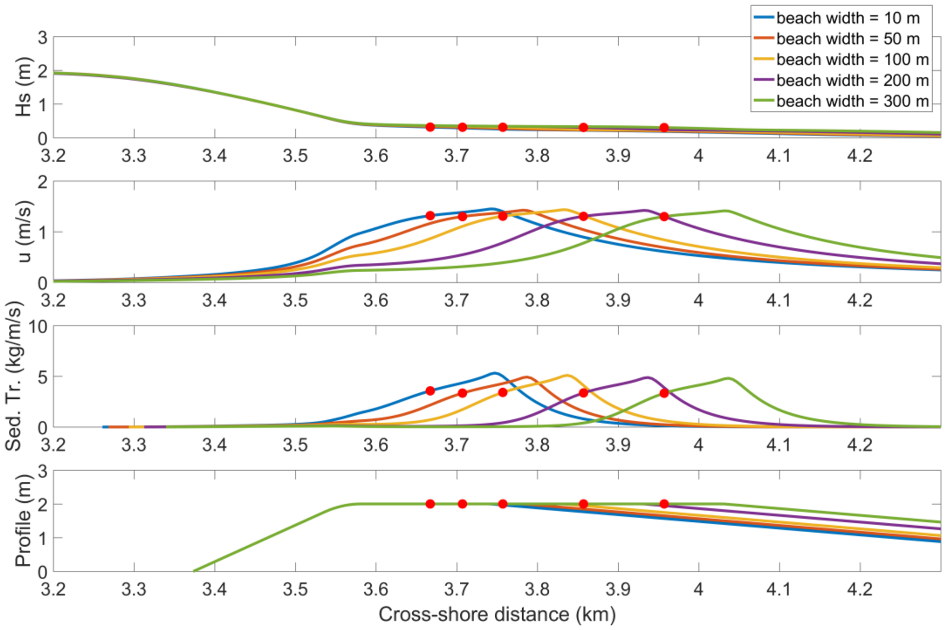

Figure 7. Parameters for different beach berm widths in cross-shore direction. For all profiles, the most onshore part of the flat profile is not the beach berm but the washover opening. a) Significant short wave height. b) Flow velocity. c) Sediment Transport d) Cross-shore profile. a-c is in the middle of the washover opening in alongshore direction. The red dots are in the middle of the washover opening in cross-shore direction, see Figure 1. This is not at the same location due to the variable beach berm width.

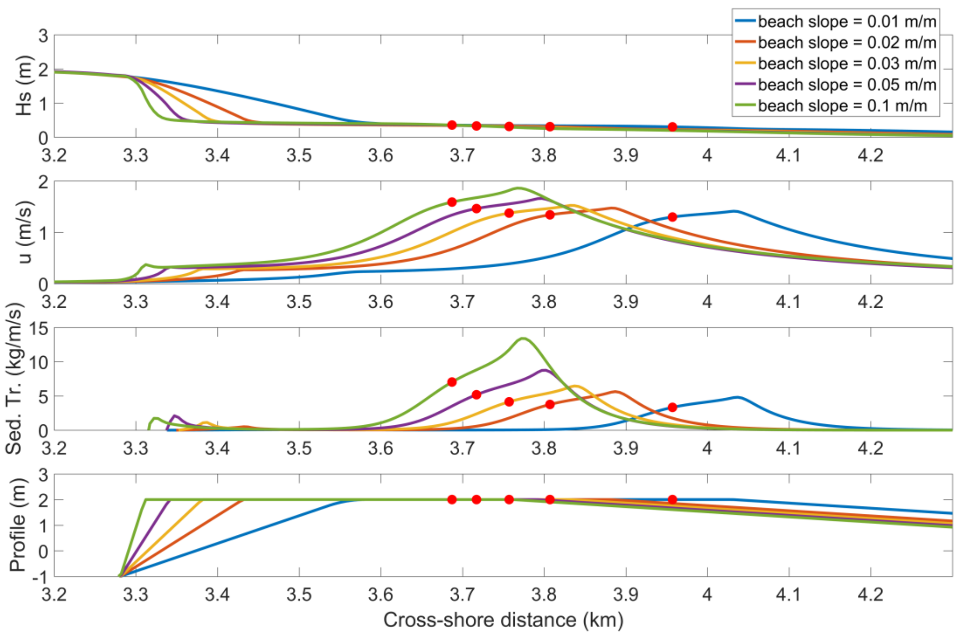

Figure 8. Parameters for different foreshore slopes in cross-shore direction. For all profiles, the most onshore part of the flat profile is not the beach berm but the washover opening. a) Significant short wave height. b) Flow velocity. c) Sediment Transport d) Cross-shore profile. a-c is in the middle of the washover opening in alongshore direction. The red dots are in the middle of the washover opening in cross-shore direction, see Figure 1. This is not at the same location due to the variable foreshore slope.

4. Discussion and Conclusions

In this study we investigate the influence of the washover dimensions (i.e. washover height and width) and beach characteristics (i.e. beach slope and width) on the sediment transport at washover openings during inundation. Based on 2D XBeach modelling we observe that the sediment transport trough a washover opening is largely determined by strong cross-shore currents. These currents are so large (1.1-1.4 m/s) that they are dominant for the sediment stirring as well as sediment transport, and consequently infragravity waves and wave stirring by short waves appear to be less important.

The cross-shore currents and thereby the sediment transport through the washover opening is influenced significantly by the washover dimensions. The washover height is one of the most dominant factors. A higher opening of 30 cm can significantly reduce (30-50%) the total sediment transport for constant water levels. This dependency on the height implies that washover dynamics can vary significantly, depending on the local geometry and common storm surge heights. Flow contraction at the washover opening results in an increase in flow velocities, mainly at the edges of the washover (also found by Hoekstra et al. (2009)). This funneling effect is strongest for narrow openings. When the openings become wider, the effect loses importance and flow velocities in the middle of the opening decrease. Until a washover width of about 200-300 m, the width-integrated sediment transport through the opening rapidly increases as function of gap width; Above these values the transport rates only show a gradual increase. Although the effect of increasing the washover width on the sediment transport is significantly hindered by the reduced flow velocity for wider openings, the depth-integrated sediment transport through the washover still increases. This implies that the narrower washover openings at Schiermonnikoog compared to the past can also contribute to the static conditions of the last decades.

For Schiermonnikoog, the lack of sediment input is often attributed to the very wide and gently sloping beach (Hoekstra et al., 2009; Oost et al., 2012). However, the beach width is found to be not important for the sediment transport for model simulations in morphostatic mode. Compared to the wave dissipation at the foreshore, wave dissipation by friction and breaking on the flat beach berm is of minor importance and therefore the beach berm does not influence the waves, water level and sediment transport at the washover opening. A wider beach can still indirectly limit sediment input by the development of a vegetated beach and dunes. Vegetation reduces the potential sediment transport, while dunes do not only increase the beach berm height, but they also increase the roughness and thereby decrease the currents. The foreshore has a larger influence (i.e. higher water levels and larger flow velocity and sediment transport for steeper slopes), however this effect is small compared to the washover height and width.

The presented XBeach simulations assume constant water levels and ignore the effects of the tide. However, Engelstad et al. (2017) and Wesselman et al. (submitted) have shown that tides largely influence flow velocities across the island. We therefore plan to add the effect of tides in future research. Furthermore, morphodynamic simulations that include bed level change would not only show the sediment transport through the washover opening, but also where this sediment is deposited and would highlight the existence of morphodynamic feedbacks.

Acknowledgements

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