

Washover inundation and barrier island accretion

Overstroming in washover systemen en de aangroei van Waddeneilanden

(met een samenvatting in het Nederlands)

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Samenvatting

Barrière-eilanden zijn zandige, langgestrekte eilanden parallel aan de kust die zijn opgebouwd door golven, stromingen en wind. Ze beschermen het vasteland tegen stormen, geven ecosystemen ruimte om te ontwikkelen en dienen als een toeristische attractie. Meestal hebben barrière-eilanden aanvoer van sediment nodig om te groeien in verticale richting, zodat erosie ten gevolge van zeespiegelstijging op de lange termijn kan worden gecompenseerd. In het gebied landinwaarts van de stranden en duinen, zoals voormalige duinvalleien, vindt meestal alleen sediment transport en bijbehorende bodemverandering plaats als de waterstand door storm verhoogd is. Natuurlijke laaggelegen gaten in de duinen die bekend staan als washover openingen zouden sediment transport in landinwaartse richting kunnen stimuleren. Deze washover openingen zijn hogergelegen dan normaal hoog water, maar lagergelegen dan hoog water tijdens stormen. Dit betekent dat ze droog blijven tijdens rustig weer, maar overstromen tijdens stormen.

Het hoofddoel van deze studie was om het belang van washover openingen op de Waddeneilanden voor stormgerelateerde sediment transporten in kustdwarse richting beter te begrijpen, zowel voor de korte termijn (individuele stormen) als de middellange termijn (jaren tot decennia). De Waddeneilanden samen vormen een keten van barrière-eilanden in de Noordzee langs de Nederlandse, Duitse en Deense kust. Waddeneilanden in een natuurlijke staat bevatten vaak meerdere washover openingen, maar in het verleden zijn veel van deze openingen gesloten door kunstmatige stuifdijken. Dit zorgt ervoor dat het gebied achter de duinen niet kan overstromen vanaf de Noordzee, maar als neveneffect wordt ook het potentiële zandtransport richting het land tegengehouden tijdens stormen. Managementorganisaties in Nederland overwegen om de washovers weer te heropenen door (delen van) de stuifdijken te verwijderen, wat uiteindelijk zou kunnen leiden tot bodemophoging achter de duinen. In deze studie heb ik velddata gebruikt van de Waddeneilanden Schiermonnikoog en Rottumeroog, maar ook het procesgedreven XBeach model. De data zijn voornamelijk gebruikt om XBeach te valideren en kalibreren. Om de hoofdvraag te beantwoorden is XBeach echter voornamelijk gebruikt.

De invloed van golven, getij en waterstanden tijdens storm op sediment transport over het strand van een typisch Waddeneiland tijdens overstroming (inundatie) is onderzocht met een morfostatische 1D XBeach studie (Hoofdstuk 2). Ten eerste is XBeach gevalideerd en gekalibreerd met velddata van waterstanden, golven en stromingen tijdens stormen die gemeten zijn op de laaggelegen en duinloze eilandstaart van Schiermonnikoog. Voor dit gebied werd uitgegaan van een uniforme geometrie in kustlangse richting. Ten tweede is het sediment transport over de eilandstaart onderzocht voor de middellange termijn. Zes representatieve inundatieklassen zijn bepaald, die variëren van laag-energetisch en veelvoorkomend tot hoog-energetisch en zeldzaam. Voor deze zes klassen zijn de hydrodynamica en het sediment transport gesimuleerd. Een analyse van deze modelsimulaties liet zien dat grotere stormen meer kustdwarse sediment transport veroorzaken door sterkere stromingen en grotere golven. Het netto landinwaartse sediment transport tijdens een storm blijft echter hetzelfde of neemt zelfs af naarmate de inundatieklasse hoger wordt, doordat

de gemiddelde waterstand in de Waddenzee sneller stijgt dan in de Noordzee tijdens storm. Dit zorgt voor een veel lagere of zelfs negatieve sediment transport (richting de Noordzee). Als de frequentie van de inundatieklassen wordt meegewogen dan blijkt het cumulatieve effect van relatief kleine stormen op de middellange termijn veel belangrijker dan die van de grote maar zeldzame stormen.

De effecten van de geometrie van de washover openingen op de hydrodynamica en het sediment transport tijdens inundatie zijn onderzocht met een morfostatische 2D XBeach studie (Hoofdstuk 3). Hiervoor zijn eerst data verzameld van de breedte en soms ook van de bodemhoogte van alle washover openingen op de Nederlandse, Duitse en Deense Waddeneilanden. Hiervoor is gebruik gemaakt van luchtfoto's en satellietbeelden. De waargenomen gemiddelde breedte is 200 m maar varieert van 35 tot 1100 m. De bodemhoogte is overal tussen de 1,5 en 2,1 m NAP. XBeach simulaties lieten vervolgens zien dat de variatie in breedte twee belangrijke effecten heeft: Ten eerste treedt voor smalle openingen samentrekking (contractie) op van de stroming, zodat deze toeneemt en daardoor ook de mate van sediment uitwisseling per meter breedte. Ten tweede wordt sediment getransporteerd over een breder gebied als de breedte van de opening toeneemt, wat resulteert in meer uitwisseling van sediment. De combinatie van beide effecten zorgt altijd voor meer sediment transport door een washover opening als de breedte toeneemt. Bovendien is ook de bodemhoogte erg belangrijk. Openingen die 30 cm hoger zijn dan de standaardsimulatie (met een bodemhoogte van 2,0 m NAP) leveren beduidend kleinere stromingen en minder sediment transport op in kustdwarse richting. In de opening treedt divergentie van het sediment transport op, wat resulteert in erosiepatronen. Landinwaarts van de opening convergeert het sediment transport juist, wat leidt tot depositiepatronen.

Morfologische ontwikkelingen op de middellange termijn, inclusief terugkoppelingen tussen morfologie, hydrodynamica en sediment transport in en nabij washover openingen zijn onderzocht met een morfodynamische 2D XBeach studie (Hoofdstuk 4). Drie verschillende geometrieën zijn gebruikt, waarvan twee een washover opening bevatten met een breedte in kustlangse richting van 200 respectievelijk 600 m. De derde geometrie bevatte geen duinen en was uniform in kustlangse richting. Resultaten lieten zien dat stormgerelateerde inundatie de openingen eroderen met in totaal meer dan 0,5 m en vervolgens dit sediment afzetten in landinwaartse richting. Deze afzetting heeft een vergelijkbare dikte van 0,5 m. Breder washover openingen leiden tot grotere washover volumes. De geometrieën ontwikkelen zich niet naar een evenwicht maar in plaats daarvan blijft de mate van depositie landinwaarts van de openingen min of meer constant. Depositie neemt met 60% toe als een sterke zeespiegelstijging van 10 mm/y wordt meegenomen in de simulaties. Echter, de totale extra accommodatieruimte die wordt veroorzaakt door de zeespiegelstijging wordt niet compleet gecompenseerd door deze depositie. Verschillende sequenties van stormen (van laag-energetisch naar hoog-energetisch en andersom) veroorzaken een verschil van 20-25% in de sedimentatie volumes.

De natuurlijke ontwikkeling van een Waddeneiland en meer in het bijzonder de ontwikkeling van een washover opening waar geen menselijke ingrepen meer plaatvinden is onderzocht op Rottumeroog (Hoofdstuk 5). Sinds 2005 worden de stranden en duinen van dit eiland niet meer onderhouden. Bovendien is er een natuurlijke washover aanwezig door een doorbraak in de duinen. Eerst zijn de vijf bestaande digitale bodemhoogtekaarten sinds 2005 van dit gebied onderzocht. De eerste jaren na 2005 worden gekenmerkt door sterke erosie van het strand en duinen, gevolgd door de ontwikkeling van een 600 m brede doorbraak in de duinen. Deze doorbraak ontwikkelde zich in een washover en is nog steeds actief. Bodemhoogte in de washover is plaatselijk gestegen met waarden tot aan 0,8 m, wat neerkomt

op een sedimentaanvoer van ongeveer $62 \text{ m}^3/\text{m}$ (volume per meter kustlijn) in één stormseizoen. Vervolgens zijn 2D morfodynamische XBeach simulaties uitgevoerd voor de winter van 2016-2017 om uit te zoeken welke processen deze bodemverandering veroorzaken. Bovendien werd op deze manier de toepasbaarheid van XBeach onderzocht voor de voorspelling van bodemverandering op een Waddeneiland tijdens storm. Kwalitatieve patronen van stranderosie en sedimentatie in de washover bleken meestal overeen te komen, kwantitatieve waarden werden echter sterk onderschat. Mogelijke redenen hiervoor zijn de kustlangse getijde- en windgedreven stromingen die niet zijn meegenomen in het model, en de beschermde ligging van Rottumeroog voor Noordzeegolven. Daarom zou een grootschaliger model van het volledige gebied de resultaten kunnen verbeteren.

Summary

Barrier islands are sandy, elongated islands parallel to the shore that are built up by the action of waves, currents and wind. They protect the mainland from storms, provide conditions for unique ecosystems to develop and act as a touristic environment. In general, barrier islands need sediment input to accrete in vertical direction and thereby to counteract the erosional effects of sea-level rise on the long term. The area landward from beaches and dunes, such as former dune valleys, often only experience sediment transport and corresponding morphological change during times of storm-induced elevated water levels. The existence of natural low-lying gaps in the foredunes, also known as washover openings, may stimulate onshore-directed sediment transport. These washover openings are typically located at a higher elevation than high-tide water levels but lower than the combination of high tide and storm surge. This means that they remain dry during calm weather but may inundate during storms.

The overall aim of this PhD-thesis was to improve the understanding of the role of the washover openings on the Wadden Islands on the storm-induced and cross-shore directed sediment transport on the short- (event scale) as well as medium-term (annual to decadal time scale). The Wadden Islands form a chain of barrier islands, located in the North Sea along the coast of the Netherlands, Germany and Denmark. Wadden Islands in a natural state often are characterized by the presence of several washover openings. In the past though many of these openings were closed off by artificial sand-drift dikes. This measure prevents the area behind the (artificial) dunes from flooding, but has as side effect that potential onshore-directed and storm-induced sediment transport is blocked. Coastal zone management organizations in the Netherlands consider the re-opening of the washovers by removing parts of the sand-drift dikes and it is hypothesized that this might lead to vertical accretion behind the dunes. In this PhD-thesis I used both field data from the Wadden Islands Schiermonnikoog and Rottumeroog, and a process-based model (XBeach). The field data were mainly used to validate and calibrate XBeach. To fulfill the overall aim, the XBeach model was mostly applied.

The influence of wave, tide and storm surge conditions on sediment transport across the beach of a typical mesotidal Wadden Island during inundation was explored with a morphostatic 1D XBeach model study (Chapter 2). Firstly, XBeach was validated and calibrated with field data on water levels, waves and currents measured during inundation events at the low-lying and dune-lacking island tail of the island of Schiermonnikoog. The area was considered to have alongshore-uniform geometry. Secondly, the medium-term sediment transport across the barrier island was studied. Six representative inundation classes were distinguished, ranging from frequently occurring, low-energy events to infrequent, high-energy events, and the hydrodynamics and sediment transport during these events were simulated. An analysis of the model simulations showed that larger storm events cause larger cross-shore sediment transport due to stronger currents and larger waves. However, the net onshore directed sediment transport during a storm levels off or even becomes smaller for the largest inundation classes because it is counteracted by larger mean water levels in the Wadden Sea (back-barrier). This opposes or even reverses sediment transport during inundation. When

taking into account the frequency of occurrence of storms, it appeared that the cumulative effect of relatively mild storms on long-term cross-shore sediment transport is much larger than that of the large storm events.

The effects of the geometry of the washover openings on hydrodynamics and sediment transport during inundation were investigated with a morphostatic 2D XBeach model study (Chapter 3). To this end, first data on width and for some cases also bed level elevation for all washover openings along the Dutch, German and Danish Wadden Islands were investigated, making use of aerial photographs and satellite images. The observed mean width is 200 m but the actual width ranges from 35 to 1100 m, and the elevation is between 1.5-2.1 m above MSL. Based on the XBeach simulations, two important effects of washover width were identified: 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. These effects combined lead to a larger sediment load that is transported through a washover opening when the opening is wider. Furthermore, the elevation of the washover opening is of high importance: washover openings that are 30 cm higher in elevation than in the scenario for the reference case (with a bed level of 2.0 m above MSL) result in a significant decrease in 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 again which leads to depositional patterns.

Medium-term morphological developments (25 years), including feedbacks between morphology, hydrodynamics and sediment transport around washover openings were explored in a morphodynamic 2D XBeach model study (Chapter 4). Three different geometries were used. Two of them contained a washover opening with an alongshore width of 200 m and 600 m respectively, while the third geometry lacked dunes and was alongshore uniform. Results showed that inundation events erode the washover openings with values of more than 0.5 m in total and deposit this sediment onshore. This leads to a vertical local accretion of the island with the same magnitude. Wider washover openings lead to larger washover volumes. The geometries do not evolve towards an equilibrium but instead the rate of deposition landward from the opening stays approximately constant. When a high rate of sea-level rise is taken into account (10 mm/y), deposition values increase with approximately 60%, and likewise vertical accretion rates increase as well. However, the accommodation space created by sea-level rise is not completely compensated by washover deposits. Different sequences of storms (from low to high energetic conditions and vice versa) cause a difference of 20-25% in sedimentation volumes.

The natural evolution of a barrier island in absence of coastal management, and specifically the evolution of washover openings and the landward supply of sediment was investigated in a case study at the island of Rottumeroog (Chapter 5). Since 2005 beaches and dunes at the island are no longer maintained. Furthermore, the island is characterized by a natural washover, interrupting the dune system. To this end, first all five digital elevation maps (DEMS) available for this area since 2005 were investigated. The first years since 2005 were characterized by strong erosion of the beach and foreshore, followed by the development of a 600 m wide breach in the dunes. This breach developed into a washover and has been active since then. Bed level elevation in the washover increased with values up to 0.8 m, reflecting cross-shore supplies of sediment in a single storm season of about $62 \text{ m}^3/\text{m}$ (volume per meter coastline). Secondly, 2D morphodynamic XBeach simulations were performed to analyze the processes that caused the morphology change in the winter of 2016-2017 and to test the performance of XBeach for inundation-induced morphology change at a Wad-

den Island. Qualitative patterns of beach erosion and sedimentation in the washover and at the island tail were simulated reasonably well, however, magnitudes were strongly underestimated. Possible reasons are alongshore tide- and wind driven currents that were not taken into account and the sheltered location of Rottumeroog against North Sea waves. Using a larger-scale model of the entire area might improve the modelling results.

Chapter 1

Introduction

1.1 Context

Barrier islands are sandy, elongated islands parallel to the shore that are built up by the action of waves, currents and wind. Worldwide, 10% of the coastline is bordered by these islands (Stutz and Pilkey, 2011). They protect the mainland from storms, provide conditions for unique ecosystems to develop (Wang et al., 2012) and act as a touristic environment. In general, barrier islands need sediment input to counteract the erosional effects of sea-level rise on the long term (Morton and Sallenger, 2003). Therefore, it is crucial to understand the processes that determine the morphological evolution of barrier islands. Beaches and dunes can receive sediment during calm weather conditions by onshore wave- or aeolian transport. However, the area landward of beaches and dunes, such as former dune valleys, often only experience morphological change during times of storm-induced elevated water levels or during conditions that allow aeolian transport to occur. Many studies have shown that storms or hurricanes led to sedimentation landward of the beach or dunes, as studied amongst others by Pierce (1970), Leatherman (1976), Leatherman (1979), Dolan and Hayden (1981), Penland et al. (1985), Storms et al. (2002), Donnelly et al. (2004), and Donnelly (2007). However, Sanders and Kumar (1975) concluded that on the shelf of Fire Island, New York, barrier islands drowned at different times within the Holocene period. Similarly, Mellett et al. (2012) found evidence of a drowned barrier island in the Hastings Bank area in the north-eastern English Channel. This suggests that the actual response of barrier islands to storm-induced processes very much depends on local hydrodynamical and morphological conditions.

In this PhD-thesis the focus is on the Wadden Islands, a chain of barrier islands located in the North Sea along the coast of the Netherlands, Germany and Denmark (Figure 1.1). Between the islands and the mainland a system of inter-connected tidal basins is present, called the Wadden Sea. Wadden Islands in a natural state often have several low-lying gaps in the foredunes, also known as washover openings, which are regularly flooded during storms (Hoekstra et al., 2009). In the previous century, many of these washover openings were closed off by artificial dunes, known as sand-drift dikes, to increase the safety during storms (Oost et al., 2012). This measure prevents the area behind the (artificial) dunes from flooding, but has as side effect that potential onshore-directed storm-induced sediment transport is blocked. Coastal zone management organizations in the Netherlands consider the re-opening of the washover openings by removing parts of the sand-drift dikes. It is hypothesized that this might have two potential pay-offs: Firstly, it compensates the effects of sea level rise by restoring the natural processes that can lead to storm-induced vertical accretion. Secondly, it enhances the dynamic character of coastal ecosystems. The absence of sediment transport and salt-water influence has resulted in severe ecosystem degradation, illustrated by a shift from species-rich plant mosaics to mono-specific reed stands.

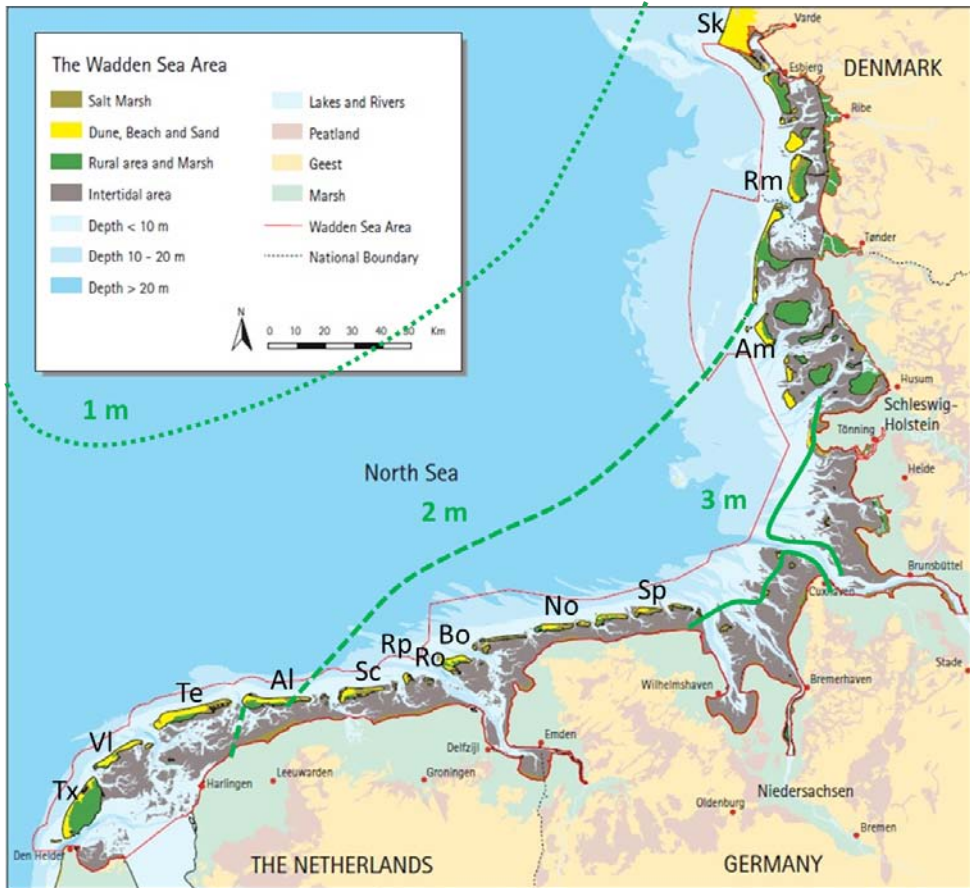


Figure 1.1: The Wadden Area in the Netherlands, Germany and Denmark including the North Sea, Wadden Islands, the Wadden Sea and the mainland. The green lines represent tidal range zones. The islands that include washover openings are indicated: Tx = Texel, VI = Vlieland, Te = Terschelling, Al = Ameland, Sc = Schiermonnikoog, Rp = Rottumerplaat, Ro = Rottumeroog, Bo = Borkum, No = Norderney, Sp = Spiekeroog, Am = Amrum, Rm = Rømø and Sk = Skallingen. Based on: Ehlers, 1988, courtesy Balkema Books; map courtesy of the Common Wadden Sea Secretariat.

The overarching aim of this PhD-thesis is to improve the understanding of the role of the washover openings on the Wadden Islands on the storm-induced and cross-shore directed sediment transport on the short- (event scale) as well as medium-term (annual to decadal time scale). To satisfy this objective, the PhD-thesis will unravel the dominant hydrodynamic processes across an island and the corresponding sediment transport and morphology change during a range of storm conditions.

1.2 Hydrodynamics, sediment transport and morphological development of barrier islands

1.2.1 Swash regime and dune collision regime

Sallenger (2000) developed a storm impact scale depending on profile elevation, water level and waves that consists of four regimes: swash, (dune) collision, overwash and inundation. All regimes are illustrated in Figure 1.2. In a system with a closed coast where the water level is lower than the beach berm (swash regime, Figure 1.2a), the direction of net cross-shore sediment transport largely depends on the water level, wave forcing and wave-induced currents. The time-varying water level in shallow water is determined by the tides, storm surge, wave-induced set-up and set-down (Longuet-Higgins and Stewart, 1964; Symonds et al., 1995) and the infragravity and sea-swell/short waves (0.005 - 0.05 and 0.05 - 1 Hz respectively). Short waves result in onshore directed transport in shallow water caused by their skewed shape, which leads to beach accretion (Ruessink et al., 1998). On the other hand, cross-shore wave-induced currents (undertow) result in offshore directed transport and beach erosion (Osborne and Greenwood, 1992). During calm-weather conditions, wave set-up and undertow are small and the net cross-shore sediment transport direction is onshore. However, during storm-conditions the undertow dominates and the net direction is offshore.

Infragravity (IG) waves receive their energy from the sea-swell waves through nonlinear energy transfers (e.g. Herbers et al., 1994; de Bakker et al., 2015). The magnitude of the IG waves increases while traveling towards the coast and can reach up to more than a meter in height during storms (Baumann et al., 2017). They are able to stir and transport sediment in an onshore or offshore direction (Beach and Sternberg, 1988; Engelstad et al., 2018). IG waves can also affect currents by periodically increasing the water level in shallow water and thereby altering pressure gradients.

In the collision regime (Sallenger, 2000), the system is still 'closed', i.e. water levels and waves do not overtop the dunes (Figure 1.2a). However, during storms short and IG waves are able to reach the dunes, which can lead to severe dune erosion (de Winter et al., 2015) and collapse of dunes when these dunes are getting steeper due to avalanching. Patterns in currents such as undertow are similar to those of the swash regime, but will be located further onshore due to higher water levels. For both regimes, water levels and waves do not overtop the dunes and morphology change behind dunes and washover openings is limited (Harter and Figlus, 2017).

1.2.2 Barrier island overwash and inundation

Overwash and inundation are the third and fourth regime in the storm impact scale of Sallenger (2000) and cover events that result in water that overtops the dune or beach crest. In the overwash regime (Figure 1.2b), the mean water level is still lower, but individual waves can overtop the dune or beach crest. When large waves overtop the dunes, the crest is often exposed to strong erosion and this sediment is deposited immediately landward of the dunes (Figlus et al., 2010). However, when smaller waves just overtop the dune crest, the crest can also increase in elevation and sedimentation barely occurs landward of the dune crest (Matias et al., 2009). IG waves are often important in this regime, as short waves are typically dissipated before they reach the dunes.

In the inundation regime (Figure 1.2c), the mean water level is higher than the beach or dune crest, resulting in continuous flow and sediment transport. When the sea or ocean is connected with the back-barrier basin across a barrier island during storms, currents are no

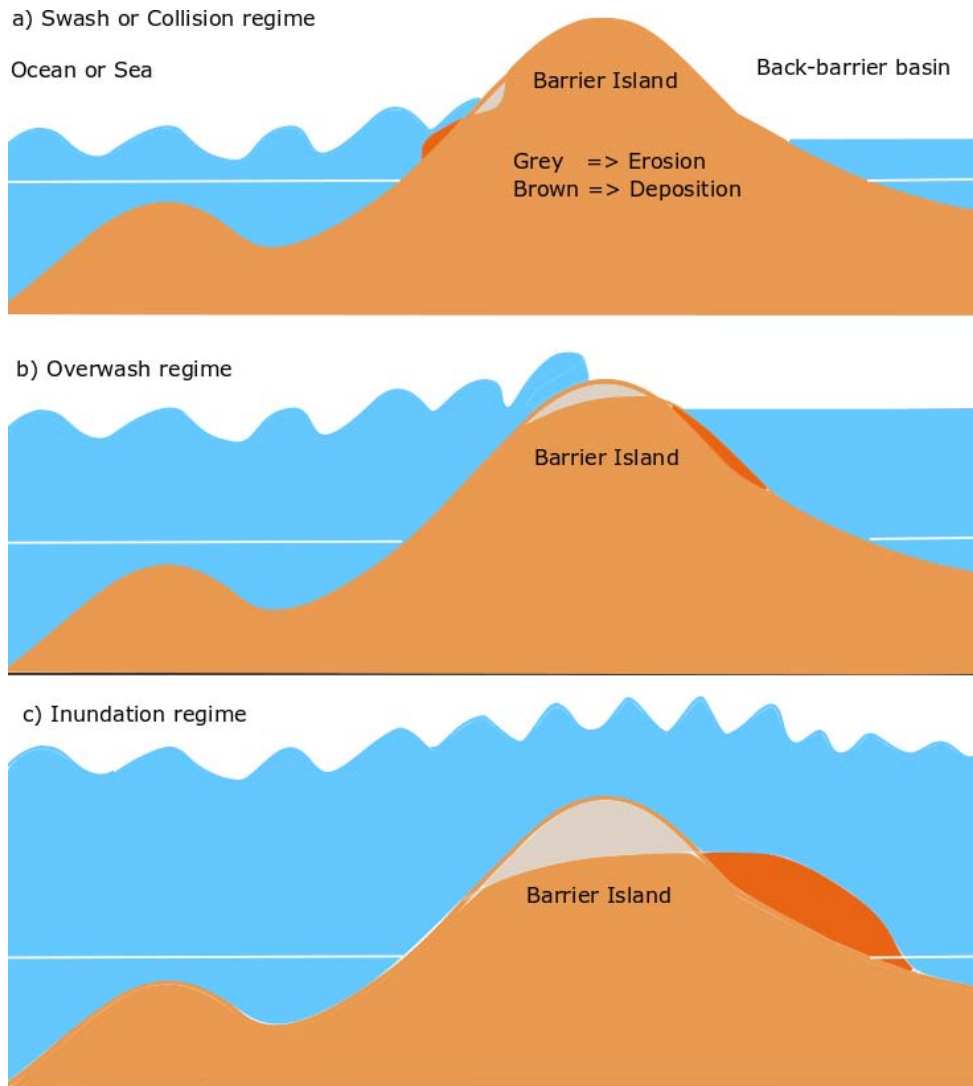


Figure 1.2: An illustration of all storm-impact regimes from Sallenger (2000). a) Swash and Collision regime, b) Overwash regime and c) Inundation regime. Grey means erosion and dark brown means deposition. The white line represents mean sea-level.

longer exclusively wave-induced but also depend on the pressure gradient caused by different water levels on both sides of the island (e.g. Sherwood et al., 2014; Engelstad et al., 2017; Engelstad et al., 2018). Water levels offshore of the barrier can be higher than in the back-barrier because of the combined effect of tide, wind and wave set-up. This leads to onshore-directed sediment transport due to both wave- and current-driven processes; a contrasting pattern in comparison with conditions for a closed coast. A few studies described offshore directed currents and resulting offshore directed sediment transport under conditions where the water level in the back-barrier basin is higher than in the ocean or sea during part of the

inundation phase (Sherwood et al., 2014; Harter and Figlus, 2017; Passeri et al., 2018). This is further discussed in section 3 of this chapter. IG wave orbital motions can stir and transport sediment by the orbital motions. Furthermore, IG waves can indirectly contribute to larger sediment transport in the inundation regime by periodically increasing the water level in shallow water and thereby increasing the pressure gradient between the back-barrier basin and the ocean/sea. Moreover, short waves can increase sediment stirring while traveling on a IG wave crest (Engelstad et al., 2018). Therefore, IG waves should be taken into account while investigating the hydrodynamics and resulting sediment transport during inundation.

Based on their morphological response to these four regimes, one distinguishes two types of barrier islands. The first type is dominated by recovery processes during relatively calm weather conditions and includes high dunes that block offshore water levels and waves from the area behind the dunes. The second type contains low-lying islands, where storm-induced floodings dominate (Orford and Carter, 1982; Morton and Sallenger, 2003; Durán Vincent and Moore, 2015; Houser et al., 2015). However, barrier islands can also be in between those states, with an alongshore alternation of high dunes and low-lying gaps (Lazarus and Armstrong, 2015).

1.2.3 Morphological effects during overwash and inundation

The morphological effects during the overwash and inundation regimes can be split into erosional and depositional patterns. Storm-induced erosion is often being found along the beach and/or dunes, while storm-induced sedimentation typically occurs landward of the dunes. Literature tends to focus on specific conditions that often occur along the Atlantic or Gulf Coast of the USA. These coasts are often wave-dominated environments exposed to hurricanes (Buynevich and Donnelly, 2004; Wang et al., 2006), and including narrow-banded islands with relatively low dunes. For example, McCall et al. (2010) and Plant and Stockdon (2012) investigated the effects of Hurricane Ivan (2004) on Santa Rosa Island, a 85 km long and 150 - 1000 m wide barrier island in the Gulf of Mexico which has small dunes (3-4 m above MSL). Although the tidal range is small, the overwash regime was still reached due to storm surge and large hurricane-induced waves. This led to dune breaching and the formation of a washover fan with sedimentation up to 0.5-1.0 m in thickness. Another example is the study of the effect of Hurricane Dennis (2005) on St. George Island, Florida (Priestas and Fagherazzi, 2010). This narrow-banded, wave-dominated island shows post-hurricane dune erosion and washover fan formation with similar bed level change as Santa Rosa Island. The small tide implies that the storm-induced water level is still lower than the dunes, so that first dune lowering/breaching is required before the inundation regime can develop. During inundation, morphology change is often larger than during overwash and sediment can sometimes even reach the back-barrier basin (see Figure 1.2c for an illustration).

Studies that investigated morphological development during overwash or inundation of barrier islands that are similar to the Wadden Area (i.e. mesotidal, often mixed-energy coastal conditions without hurricanes, wider islands and higher dunes) are scarce. Matias et al. (2009) showed that overwash and the corresponding dune erosion/growth and washover formation also occurs in a mesotidal and extra-tropical environment at Barreta Island, Portugal. Historic washover deposits are being found landward of the dunes on the island of Schiermonnikoog, the Netherlands (de Groot et al., 2011), at the island of Spiekeroog, Germany (Tillmann and Wunderlich, 2013) and at Skallingen, a barrier-spit in Denmark (Christiansen et al., 2004; Nielsen and Nielsen, 2004). This demonstrates that overwash occurs on the Wadden Islands. Studies on the evolution and character of washover deposits include a large variety of research methods, such as measuring pre- and post-storm topography (Don-

nelly et al., 2006), sedimentological studies (Shaw et al., 2015), analyzing aerial photographs (Matias et al., 2008; Leatherman, 1979) or experiments (Matias et al., 2016). Furthermore, exploratory models are used that simplify certain processes, which allows analyzing the long-term (decades-centuries) development of barrier islands (Masetti et al., 2008; Moore et al., 2010; Lorenzo-Trueba and Ashton, 2014).

Not only hydrodynamic forcing and initial bathymetry (dune elevation, beach elevation, etcetera) affects storm-induced sediment transport, but also the sediment source and availability plays a role (Brenner et al., 2015). Pre and post-storm profile measurements (based on shortterm, individual storm events or a series of storms) show that the sedimentation behind the dunes can have different sources, such as upper foreshore or surfzone, or beaches and dunes (Williams, 2015). The degree of sediment availability may be one of the major factors for the potential washover formation.

1.3 The Wadden Area

The storm-induced hydrodynamic processes during overwash or inundation and the corresponding sediment transport and morphology change, as described in the previous sections, strongly depend on local conditions such as the initial bathymetry/island profile, wave and tidal conditions and back-barrier basin characteristics. The impact of these specific hydrodynamic and morphological conditions on overwash and inundation is barely investigated for the Wadden Islands.

The Wadden Islands are exposed to a meso- to lower-macro tidal regime with a tidal range from 1.4 m in the West to 3.5 m at Germany. Storm surges are not resulting from hurricanes but from extra-tropical storms above the North Sea and peak water levels can be 3.5-4 m above MSL (Oost et al., 2012). Offshore wave heights can reach maximum values of 8-11 m. The Wadden Islands often have a "drumstick shape" with the wider part at the updrift side (element 1 in Figure 1.3), which is caused by sandy shoals that periodically attach from the ebb-tidal deltas (Ridderinkhof et al., 2016). This sediment is slowly transported in downdrift direction (from west to east) by wave- and wind-induced currents, which periodically widens the beaches of the islands (Hayes, 1979; Grunnet, 2004). While the western part contains a large dune arc complex (element 2 in Figure 1.3), more to the east an alternation of dunes and washover openings is visible with a salt-marsh landward of the dunes/openings (element 4 in Figure 1.3). A washover opening on the island of Schiermonnikoog is illustrated in Figure 1.4. Two types of washover openings can be distinguished: 1) openings that directly connect the North Sea and Wadden Sea during storms (such as the examples in Figure 1.3) and 2) openings that are bordered by a secondary dune system, such as the Slufter at Texel, the Netherlands (van der Vegt and Hoekstra, 2012). The focus in this PhD-thesis will mainly be on the first category, as the open systems can contribute to the sediment input to larger areas than the second category. For washover openings of the second category, by definition the landward supply and deposition of sediment will be limited.

With the different characteristics of the Wadden Islands – compared to the typical USA barrier islands – in mind, several knowledge gaps can be identified. Firstly, it is unknown which large-scale hydrodynamic processes (e.g. tide, short waves, IG waves, currents) are relevant for sediment transport and morphology change during overwash or inundation. More in detail, the importance of water level differences between North Sea and Wadden Sea on hydrodynamics and sediment transport is unknown. For example, some studies (Sherwood et al., 2014) show a reversed, offshore directed current when the water level is higher in the back-barrier than in the sea/ocean. Hoekstra et al. (2009) observed higher water levels in the

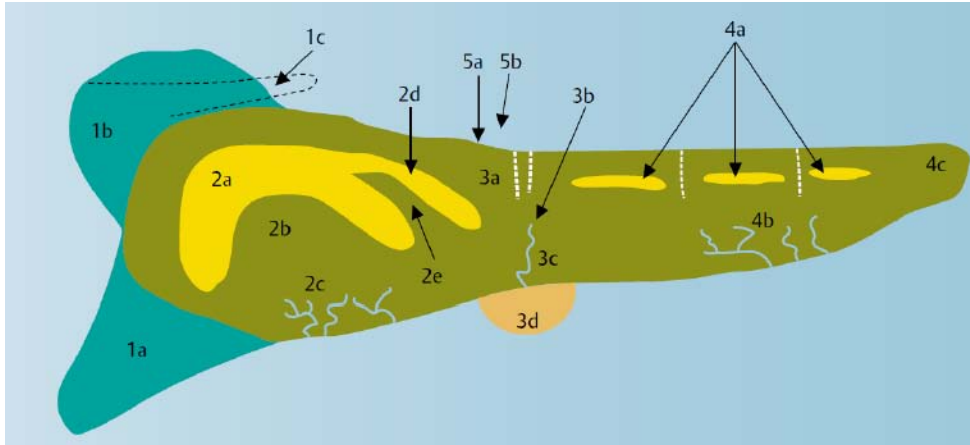


Figure 1.3: A conceptual model of a Wadden Island, containing an island head (elements 1), dune arc (2), washover complex (3), island tail including dunes/washover openings/salt marsh (4) and beach/foreshore (5). Figure from Oost et al. (2012)

Wadden Sea in comparison to the North Sea. Recent field studies indicate that there is a subtle balance between North Sea and Wadden Sea water levels, forced by tides, surges and wave set-up, which all affects the cross-shore direction and magnitude of the currents (Engelstad et al., 2017).

Secondly, the systematic alternation of high dunes and washover openings means that potential erosion and deposition patterns will vary in alongshore direction (Durán et al., 2016). These openings vary in elevation, width and alongshore spacing (ten Haaf and Buijs, 2008). It is hypothesized that existing washover systems act as important gateways to facilitate the cross-shore transport of water and sediment during storms. However, knowledge on the role of these washover openings on the cross-shore sediment transport is largely missing. This includes knowledge on the influence of washover geometry, such as the width and elevation of the opening on the effectiveness to deposit sediment landward of the openings and dunes (Lazarus, 2016). This information is in particular relevant if coastal zone management intends to remove parts of the sand-drift dikes.

Finally, most research on overwash or inundation focused on extreme storms such as hurricanes, because they are often required to erode or even breach high dunes before the area landward of the dunes will be affected. However, in areas without hurricanes but with (partly) low-lying islands such as the Wadden Islands, both storm frequency and magnitude may play a role, where more gentle storms have weaker wave forcing and lower water levels but a larger frequency of occurrence (Masselink and van Heteren, 2014). The effect of severe versus gentle storms has not yet been investigated.

1.4 Research Aims

The main aim of this PhD-thesis is to improve the understanding of the role of the washover openings on the Wadden Islands on the storm-induced and cross-shore directed sediment transport on the short-term (event scale) as well as on the medium-term (annual to decadal time scale). The focus is on the inundation regime. The short term is investigated to unravel



Figure 1.4: One of the washover openings at the island of Schiermonnikoog. Source: Rijkswaterstaat.

the dominant processes, while the annual- to decadal term gives insight in the contribution of mild storms with frequent occurrence versus severe but rare storms. Moreover, analyzing the medium term improves the understanding of how a sequence of successive storms contributes to the cumulative growth and accretion of parts of Wadden Islands. To fulfill this aim, three research questions are defined, each divided in sub-questions, which will be investigated for the Wadden Area:

1. *What are the dominant cross-shore hydrodynamic processes during inundation and how do they affect resuspension and transport of sediment?*

The importance of short waves, IG waves and currents on sediment stirring and transport in the inundation regime is analyzed. Alongshore uniform geometry is assumed to exist and the focus will be on the cross-shore patterns. Sub-questions that will be answered are:

- 1a. *What is the effect of tides on cross-shore hydrodynamics and sediment transport?*
- 1b. *What is the relative importance of severe, but infrequent storms versus mild, but frequently-occurring storms?*

The second research question is:

2. *What is the influence of island geometry and local washover morphology on storm-induced sediment transport patterns and magnitudes?*

Washover openings largely vary in width (in alongshore direction) and elevation above MSL. Furthermore, beach and foreshore width and slope in a system with an open landward boundary might influence the hydrodynamics and sediment transport. The sub-questions that will be investigated are:

- 2a. *What are typical washover dimensions (width and elevation) at the Wadden Islands?*
- 2b. *What is the influence of the washover geometry on storm-induced sediment transport patterns and magnitudes?*
- 2c. *What is the influence of foreshore morphology on storm-induced sediment transport patterns and magnitudes?*

The third and final research question reads as:

3. *What is the expected medium-term storm-induced morphological evolution of washovers due to inundation on Wadden Islands?*

For this research question the focus moves from short-scale (individual storm events) to annual to decadal-scale (maximum 25 years). In this case both alongshore uniform geometry (island tails, washover plains) and alongshore varying conditions (washover openings) are studied. This research question will be analyzed for a 'synthetic' and an existing Wadden Island (Rottumeroog). This latter case covers a period of more than a decade (2005-2017). Sub-questions that will be answered are:

- 3a. *What is the medium-term storm-induced morphological evolution for alongshore-uniform conditions?*
- 3b. *What is the medium-term morphological evolution for alongshore-varying conditions (washover openings)?*
- 3c. *What are the morphological feedbacks at the location of a washover in relation to washover geometry?*

This thesis is part of a project that also resulted in another thesis of Anita Engelstad (Engelstad, 2019). The main aim of both research projects was comparable, but the approach was complementary. In this thesis I have chosen a process-based modeling approach, whereas Anita Engelstad mainly analyzed field data. Furthermore, in this thesis I focus partly on the annual- to decadal scale and the importance of washover opening geometry. Anita Engelstad focused on the event-scale.

1.5 Methods

1.5.1 Approach

In this PhD-thesis I used both field data and a process-based model (XBeach). The field data are mainly used to validate and calibrate XBeach. However, the research questions will mainly be answered using XBeach.

1.5.2 Field Data

Data collected during two field campaigns were used, one was located at Schiermonnikoog and the other one at Rottumeroog, both in the Netherlands. Observations on hydrodynamics (currents, water levels, short waves and IG waves) were obtained during a measurement campaign at the Eastern tip of the barrier island Schiermonnikoog, from November 4, 2014 to January 31, 2015 (Figure 1.5). This island tail was chosen, because the beach crest is approximately 20-30 cm lower than most washover openings closer to the updrift side, which makes flooding a more common event and increases the opportunity to actually measure the impact of inundation. Additionally, the beach morphology and nearshore bathymetry are almost uniform in the alongshore direction and dunes are absent.

In the winter of 2016-2017, water levels, waves and morphology change were measured on Rottumeroog, a small uninhabited Wadden Island of 0.5-1 km wide (Figure 1.5). The shoreline of Rottumeroog contains from west to east 4-6 m high dunes, a washover opening, 6-8 m high dunes and subsequently a sandy and relatively flat island tail. The area landward



Figure 1.5: Schiermonnikoog and Rottumeroog, the locations of the two field campaigns.

of the dunes and washover opening is vegetated. Since 2005, Rottumeroog is, in contrast to other Wadden Islands in the Netherlands, not influenced by artificial measures. Therefore, Rottumeroog was an ideal location to measure morphology change caused by inundation events.

In addition, I used existing field data from which washover geometries can be obtained. For this purpose, I analysed bed level data from Rijkswaterstaat (echo soundings or lidar data), supplemented with estimated washover opening widths from Google Earth.

1.5.3 Modeling with XBeach

Model simulations in this PhD-thesis were performed with XBeach (Roelvink et al., 2009), a process-based numerical model based on the storm impact scheme of Sallenger (2000). The model contains all relevant hydrodynamic processes, sediment transport formulations and bed level updates, which makes it suitable to use for simulating and analyzing overwash and inundation events at the Wadden Islands. In contrast to other models such as Delft3D, XBeach explicitly solves the hydrodynamics at the IG time-scale. For this study, hydrodynamic field data measured during storms were available and this yields a powerful combination of field data and model simulations for the same location. In this way the applicability and the reliability of the model could be analyzed. The Kings Day version of XBeach (released on October 22, 2015) was used in all chapters. A description of relevant processes and parameters can be found in appendix A.

A number of studies used XBeach for predicting/hindcasting bed level changes after storm or hurricane events (McCall et al., 2010; de Vet et al., 2015). A few recent XBeach studies focused more on the hydrodynamic forcing and its influence on morphology change (Phillips et al., 2017; Mickey et al., 2018). The model was mainly used for short-term, individual storm events, with the study of Pender and Karunaratna (2013) in the 1D mode and the study of Splinter et al. (2014) in the collision regime as notable exceptions. Here I will also use it to simulate washover events from event scale to decadal time scales.

1.6 Thesis Outline

Chapter 2 describes the study performed to answer research question 1. For this analysis, the 1D mode of XBeach was first validated and calibrated with the data from the field campaign on Schiermonnikoog. Secondly, the sensitivity of modeled onshore sediment transport to water levels and waves was analyzed. Lastly, a storm classification was created based on 25 years of water level and wave data that describes gentle, frequently-occurring versus severe and rare storms and their effect on total sediment transport.

Research question 2 will be answered in Chapter 3. An overview is presented of the characteristics of existing washover openings along the Dutch, German and Danish Wadden islands. Furthermore, XBeach was used in 2D mode to study the influence of washover geometry on sediment transport.

Research question 3 will be addressed in Chapters 4 and 5. A methodology had to be developed to use XBeach, originally created to simulate individual storm events, to simulate the morphological evolution for a period of 25 years (Chapter 4). Next, the effect of 25 years of inundation events on sediment transport and morphology change was analyzed. In Chapter 5, the medium-term effects of the island characteristics that are investigated in Chapters 2, 3 and 4, such as washover opening and island tail geometry, were investigated for the island of Rottumeroog. Digital Elevation Maps from 2005 until 2017 were analyzed to determine the changes in coastal morphology and associated sediment volumes. In addition, the performance of XBeach in predicting hydrodynamics, and morphology change was tested. In Chapter 6, the answers to all research questions will be summarized and a synthesis will be presented. Furthermore, a final evaluation will be given on the performance of XBeach on hydrodynamics, sediment transport and morphology change.

Chapter 2

The effect of tides and storms on the sediment transport across a Dutch barrier island

Based on: Wesselman, D., de Winter, R., Engelstad, A., McCall, R., van Dongeren, A., Hoekstra, P., Oost, A. and van der Vegt, M. (2017), The effect of tides and storms on the sediment transport across a Dutch barrier island. *Earth Surface Processes and Landforms* 43, 3, 579-592.

Abstract

Under natural conditions, barrier islands might grow vertically and migrate onshore under the influence of long-term sea level rise. Sediment is transported onshore during storm-induced overwash and inundation. However, on many Dutch Wadden Islands, dune openings are closed off by artificial sand-drift dikes that prevent the influx of sediment during storms. It has been argued that creating openings in the dune row to allow regular flooding on barrier islands can have a positive effect on the sediment budget, but the dominant hydrodynamic processes and their influence on sediment transport during overwash and inundation are unknown. Here, we present an XBeach model study to investigate how sediment transport during overwash and inundation across the beach of a typical mesotidal Wadden Sea barrier island is influenced by wave, tide and storm surge conditions. Firstly, we validated the model XBeach with field data on waves and currents during island inundation. In general, the XBeach model performed well. Secondly, we studied the medium-term sediment transport across the barrier island. We distinguished six representative inundation classes, ranging from frequently occurring, low-energy events to infrequent, high-energy events, and simulated the hydrodynamics and sediment transport during these events. An analysis of the model simulations shows that larger storm events cause larger cross-shore sediment transport, but the net sediment exchange during a storm levels off or even becomes smaller for the largest inundation classes because it is counteracted by larger mean water levels in the Wadden Sea that oppose or even reverse sediment transport during inundation. When taking into account the frequency of occurrence of storms we conclude that the cumulative effect of relatively mild storms on long-term cross-shore sediment transport is much larger than that of the large storm events.

2.1 Introduction

Many barrier systems all over the world are threatened by the effects of long-term sea level rise (Flato et al., 2013). If sediment is abundant and the rate of sea level rise is small, barrier islands can maintain their shape by moving landward, a process called rollover (Leatherman, 1985; Donnelly et al., 2006; Masselink and van Heteren, 2014; Williams, 2015). The land-

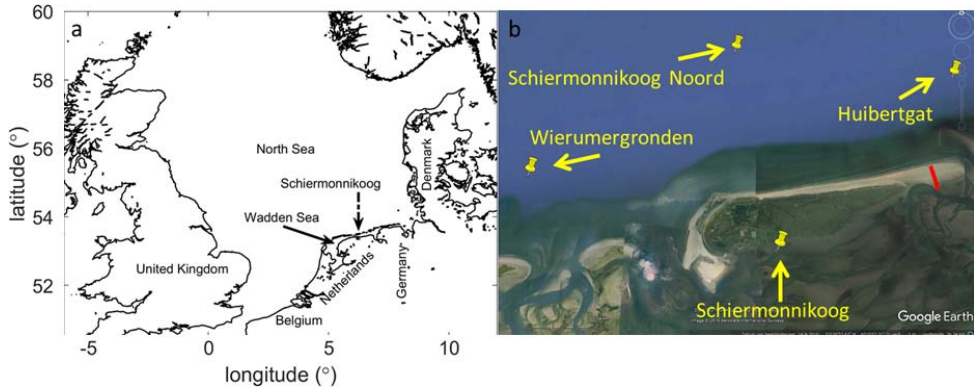


Figure 2.1: a) The Wadden area in the Netherlands, Germany and Denmark, including the North Sea, barrier islands, tidal inlets and a series of tidal basins (Wadden Sea). The dashed arrow indicates the Wadden Island Schiermonnikoog, the Netherlands. b) Schiermonnikoog in more detail. The red line is the location of the cross-shore field array. Schiermonnikoog Noord is a wave buoy; Wierumergronden, Huibertgat and Schiermonnikoog are water level stations, respectively.

ward transport of sediment can take place during overwash and inundation, which typically occurs during storm surge conditions. During the overwash regime, waves overtop the maximum barrier island height (*i.e.* the beach or dune crest), whereas during the inundation phase the water level also exceeds the island crest (Sallenger, 2000). The associated gradients in sediment transport can result in vertical accretion of barriers by sediment deposited landward in the form of washover fans and terraces (Leatherman, 1976; Hoekstra et al., 2009; Masselink and van Heteren, 2014).

Existing studies on overwash and inundation often focused on microtidal regimes and narrow barrier islands with hurricane-driven wind and wave conditions or morphology change after a storm (*i.e.* the end product: The post-storm morphology) rather than the processes during overwash and inundation itself (Morton and Sallenger, 2003; Donnelly et al., 2004; FitzGerald et al., 2007; McCall et al., 2010; Plant and Stockdon, 2012; Schupp et al., 2013; Williams, 2015). Hurricane-driven storms typically result in a large wind set-up (Androulidakis et al., 2015) and wave set-up (Longuet-Higgins, 1983; Lazarus and Armstrong, 2015). Here, strong erosion of the dunes or even breaching of the barrier islands can occur during overwash and inundation. The scarce studies on overwash and inundation processes at barriers in mesotidal, extra-tropical conditions focused on the influence of island geometries on the occurrence of overwash and inundation (Matias et al., 2009) or on morphological change after a storm (for example Nielsen and Nielsen (2004)), but the underlying processes have not been studied in detail yet (Lazarus, 2016). One of the reasons for this is that it is difficult to measure the hydrodynamics and sediment transport during storm conditions (Donnelly et al., 2006; VanDusen et al., 2016). To develop a better understanding of the role of overwash and inundation processes on the vertical accretion of barriers, insight into hydrodynamic processes and sediment transport during these regimes is crucial (Lapetina and Sheng, 2015), and this knowledge should preferably be developed based on field studies interacting with process-based models.

Here, we focus on the barrier islands in the Wadden Sea, which are exposed to a mesotidal environment (*i.e.* a tidal range of 2-4 m, depending on the location) characterized by

strong autumn and winter storms that generate waves and storm surges in the North Sea. The Wadden area along the coast of the Netherlands, Germany and Denmark is a chain of barrier islands, tidal inlets and back-barrier basins (Figure 2.1a). Typical Wadden Island beaches are wide and slope relatively gently (Hoekstra et al., 2009). The barrier islands have a typical drumstick shape (Hayes, 1979). The Wadden Islands are examples of barrier islands that can experience overwash and inundation during storm events (Hoekstra et al., 2009). The characteristic North Sea and Wadden Sea wave, tide and storm surge conditions affect sediment transport during overwash and inundation. The storms in the Wadden area can result in severe wave and wind set-up. The combination of wave- and wind-induced set-up and tidal variations, both in the North Sea and Wadden Sea, affects the magnitude and direction of the flow velocity across the island in the inundation regime (Hoekstra et al., 2009; Sherwood et al., 2014; Engelstad et al., 2017; Harter and Figlus, 2017). The short waves (< 20 s) move to the shore in wave groups, creating infragravity (IG) waves with a period of 20-200 s (Longuet-Higgins and Stewart, 1962; Battjes, 1974; Herbers et al., 1994). These IG waves have been found to be important on gentle slopes such as those of the Wadden Islands (de Bakker et al., 2015), which enhances the stirring and transport of sediment (Beach and Sternberg, 1988). For gentle sloping, dissipative Wadden coasts the importance of these hydrodynamic processes for sediment transport during overwash and inundation have not been studied so far. Furthermore, no research has been done yet on the role of relatively small, more frequently-occurring North Sea storms versus larger, exceptional storms.

The aim of this study is twofold. The first aim is to validate the 1D version of the process-based model XBeach for hydrodynamic processes (*i.e.* water levels, short and IG wave heights and flow velocities) during overwash and inundation for North Sea conditions. XBeach includes all these processes and is therefore a useful tool to analyze hydrodynamics and the resulting sediment transport during overwash and inundation (Roelvink et al., 2009). To this end, we gathered a unique field-data set at the island tail of Schiermonnikoog where we measured these hydrodynamic parameters during several overwash and inundation events over three months in the winter of 2014-2015. The second aim is to extend our knowledge on hydrodynamic processes and sediment transport during overwash and inundation for mesotidal conditions. This is done by using the validated XBeach model. To reach this aim, we investigate how sediment transport during overwash and inundation across the beach of a typical Wadden Sea barrier island is influenced by wave, tide and storm surge conditions. Subsequently, we study the potential decadal overwash- and inundation- induced sediment transport across the barrier island.

2.2 Methods

2.2.1 Field data

Data on hydrodynamics are obtained during a measurement campaign at the Eastern tip of the barrier island Schiermonnikoog, the Netherlands (Figure 2.1b), from November 4, 2014 to January 31, 2015. The field data are used to validate the XBeach model. Overwash and inundation can take place at several locations along the island (Figure 2.2). The so-called washover openings, gaps between the dunes, are typically below 2.0 m above mean sea level (MSL) and will be flooded during storm conditions. Furthermore, the island tail lacks dunes completely and has a beach crest at 1.6 m above MSL (*i.e.* the highest point of the cross-shore profile), which means that it will be inundated completely several times a year. This island tail is chosen for our field campaign because of two reasons. Firstly, the beach crest is approximately 20-30 cm lower than many washover openings closer to the updrift side,

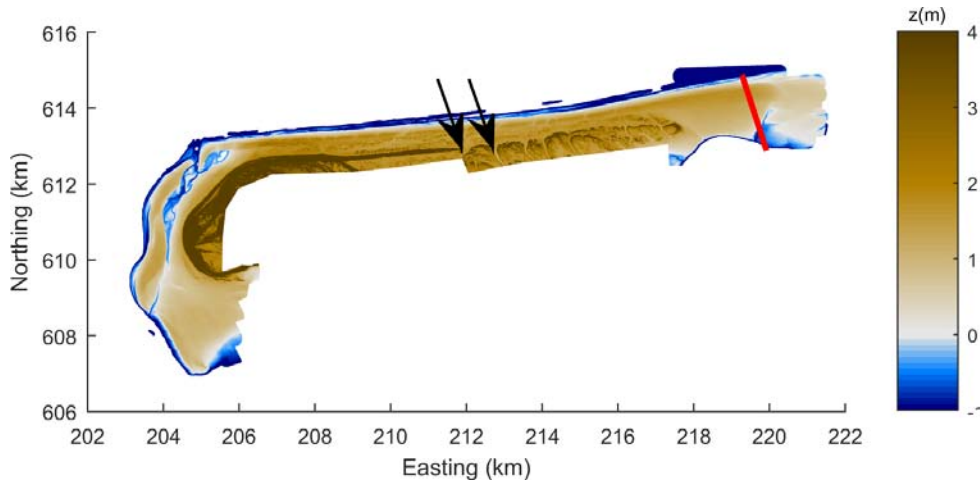


Figure 2.2: A lidar image from Schiermonnikoog, 2002. The color represents the height and the red line shows the location of the field area. The height corresponds to MSL. The black arrows indicate the two most updrift washover openings. Coordinates are given in the local RD2008 system.

which makes the chance of actually measuring overwash and inundation events at this site higher. Secondly, beach morphology and nearshore bathymetry are almost uniform in the alongshore direction and vegetation is lacking. The alongshore uniform conditions are ideal to validate the XBeach model, since the focus will be on the dominant cross-shore patterns. The foreshore has a very mild slope (approximately 1:100), with three offshore bars (Figure 2.3a). The beach crest is located a few hundred meters onshore, and inland of the beach crest, the barrier height gradually decreases (Figure 2.3b). The offshore high water levels range between 0.7 m above MSL at neap tide and 1.2 m above MSL at spring tide, while the highest storm surge level in the last 25 years is 3.5 m. In the discussion section a brief elaboration will be given on the potential differences during overwash and inundation between the island tail and the washover openings.

Ten stand-alone pressure transducers (PT; Ocean Sensor Systems Wave Gauges, OSSI-010-003C) and two instrument rigs containing an Acoustic Doppler Velocimeter (ADV; Nortek Vector, cabled version) are installed in a cross-shore array from the North Sea side to the Wadden Sea side of Schiermonnikoog (Figure 2.3b). The PTs record at 10 Hz, continuously. While fully submerged, the PTs measure mean water levels and water level variations. The ADVs measure flow velocities, recorded at 16 Hz and are located 13-17 cm above the bed. Water levels (Z), water depth (h) and flow velocities (u) are decomposed into a cross-shore and alongshore component and averaged over 15 minutes. Short and IG wave heights are determined from the variance of the second-order detrended sea surface elevation, using a highpass filter (0.05-1 Hz) and a lowpass filter (0.005-0.05 Hz). The bed profile of the intertidal and subtidal part of the profile is measured with a RTK- dGPS system at the beginning and at the end of the field campaign. The offshore bed-level profile is obtained from Vaklodingen (annual depth and height measurements of the Dutch sandy coast) and merged with the measured island profile.

Water level data are available at a ten minute interval in the North Sea and Wadden Sea and are obtained from the Rijkswaterstaat (RWS, Dutch Ministry of Infrastructure and Water

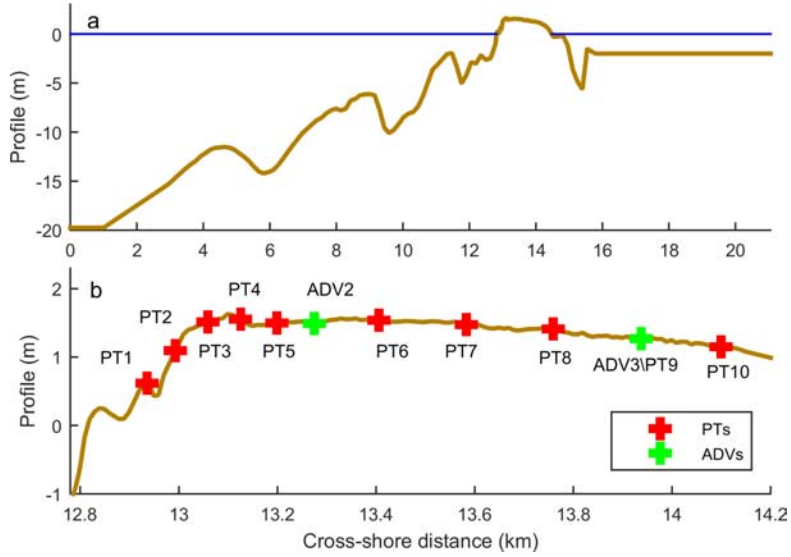


Figure 2.3: a) Schiermonnikoog cross-shore profile. North Sea is to the left, Wadden Sea to the right. The blue line represents MSL. b) Locations of the instruments during the field campaign at Schiermonnikoog. Two ADVs are placed and 10 PTs.

Management). For the North Sea, the water level stations Wierumergronden and Huibertgat are used, and for the Wadden Sea, it is the station Schiermonnikoog (Figure 2.1b). Hourly data on significant short wave height (H_s), peak period (T_p), wave direction (D), and directional spreading are obtained from the wave buoy Schiermonnikoog Noord, which is located at a water depth of approximately 20 m. Additionally, for the inundation events during the field campaign, directional wave spectra for every three hours are obtained from RWS.

2.2.2 XBeach

In this study, we use XBeach (Kings Day release) for the modelling of hydrodynamic processes and sediment transport during overwash and inundation for North Sea storm conditions. XBeach is a process-based numerical model developed to simulate storm events, and it includes the impact of overwash and inundation. The model has been shown to predict storm-driven morphological change well (McCall et al., 2010; de Winter et al., 2015). Furthermore, the studies of Stockdon et al. (2014) and de Winter et al. (2015) demonstrated that wave run-up and wave height in the swash and collision regime can be simulated accurately. We refer to the Appendix A for an overview of the governing equations regarding hydrodynamics and sediment transport, and to Roelvink et al. (2009) for a full description of the XBeach model.

The simulations consist of two parts. In the first part XBeach is validated with the field data; in the second part the various storm simulations are performed. XBeach is run in 1D mode and the cross-shore bed level profile from Figure 2.3a is used for all simulations. The grid size gradually changes from 20 m offshore to 2 m in shallow water. The prescribed offshore boundary conditions consist of water level data from offshore stations. The tide propagates along the shore from west to east, and the tidal amplitude increases. Therefore, the water level used for the validation run is determined by linearly interpolating the water level data

at Wierumergronden and Huibergat, the two nearest stations. At the Wadden Sea boundary, tidal water levels are prescribed with data from the Schiermonnikoog tidal station for all simulations. Wave forcing at the offshore boundary is prescribed using measured directional wave spectra for the validation runs, and JONSWAP spectral parameters (significant wave height, peak wave period, mean wave direction and directional spreading) for the other storm simulations. The wave data are obtained from the offshore buoy Schiermonnikoog Noord. To aid the representation of observed IG waves in the 1D XBeach cross-shore transect model, oblique waves at the boundary are rotated to the shore-normal direction before being imposed in the model. To compensate for the expected overestimation of the short- and IG wave heights, a refraction coefficient is applied as explained in Holthuijsen (2007), which compensates for the energy loss of oblique waves from deep water to the breaking zone. The breaking formulation "Roelvink2" is used (Roelvink, 1993), where the breaking parameter γ is set to 0.45 for all simulations instead of the default value of 0.55, which improved the model-data comparison. This is in line with Hoonhout and van Thiel de Vries (2012), where a γ of 0.45 yielded better results for profiles with a gentle foreshore slope. The D_{50} of the sediment is $200 \mu m$ and the D_{90} is $300 \mu m$. At the offshore and onshore boundary, the cross-shore suspended sediment transport gradients are set to zero. Each run is preceded with a spin-up period of one tidal cycle of 12.5 hours and constant wave conditions, based on the first values of the actual simulation. The XBeach simulations are performed in morphostatic mode, which means that although sediment concentrations and transport are computed, it does not lead to morphology change. The minor morphology change at the field site during the campaign allowed us to use this mode for the validation simulations. For all model parameters not mentioned here default values are used.

The following model data output (every second) is analyzed: water depth (h), flow velocity (u), significant short wave height (H_s), sediment concentration and sediment transport. From the water level data, IG wave heights are calculated in the same way as from the field data. To calculate all mean values, the output is averaged over 15 minutes.

2.2.3 Model validation

We aim to validate the hydrodynamics in XBeach during overwash and inundation with the collected field data. For this goal, the squared correlation coefficient (r^2) and bias is calculated for all PTs (*i.e.* water levels, and short and IG wave heights) and ADVs (flow velocities) with equations 2.1 and 2.2 respectively.

$$r^2 = \frac{\left[\sum_{i=1}^n (P_{model,i} - \bar{P}_{model}) * (P_{data,i} - \bar{P}_{data}) \right]^2}{\sum_{i=1}^n (P_{model,i} - \bar{P}_{model})^2 * \sum_{i=1}^n (P_{data,i} - \bar{P}_{data})^2} \quad (2.1)$$

$$bias = \frac{\sum_{i=1}^n (P_{model,i} - P_{data,i})}{n} \quad (2.2)$$

Here, n is the number of data points, and P is one of the parameters used for the validation. Eleven overwash and inundation events are measured, varying in magnitude, wind direction and duration, and are all used for the validation. All events occurred between December 11, 2014 and January 29, 2015 (Engelstad et al., 2017). Figure 2.4a shows, as an example, the water level curve of the inundation event with the highest measured water level during the campaign together with the tidal cycles before and after the largest one. This storm occurred

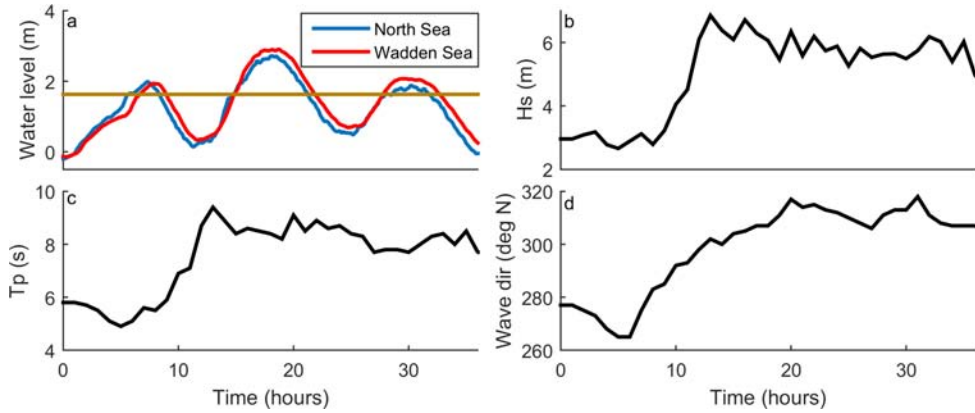


Figure 2.4: 3 out of 11 inundation events in the North Sea and Wadden Sea as function of time, used as boundary conditions for the validation runs. These three tidal cycles are from January 10, 7 a.m., to January 11, 7 p.m. a) Water level curves. The brown line represents the height of the beach crest. b) Significant wave height. c) Wave period. d) Wave direction.

at January 10 and 11, 2015. The first tidal cycle contains a tidal phase lag between the North Sea and Wadden Sea. During the second and third tidal cycle, the mean and peak water level in the Wadden Sea is larger than in the North Sea. During the entire period of 36 hours, the offshore wave height varied between 2.5 and 6.9 m and the wave period between 5.0 and 9.5 s. The wave direction gradually changed from SW to NW (Figure 2.4b-d).

2.2.4 Long-term sediment transport

To study the contribution of overwash and inundation to sediment transport across the island, we analyze the net sediment transport at the beach crest, the highest point of the profile, because this sediment that is transported over the beach crest during overwash and inundation potentially becomes available for deposition on the island. To calculate the sediment transport across the beach crest for the medium term (here we consider 25 years), three steps are taken. Firstly, an inundation classification scheme is developed (next section) based on the peak water level during a tidal cycle. This scheme represents the typical North Sea storms at Schiermonnikoog, ranging from gentle, frequently occurring storms (class 1) to large, high-energetic storms (class 6). Secondly, those inundation classes are simulated with XBeach, so that the typical hydrodynamic processes and their influence on sediment transport across the Wadden Island can be analyzed. Lastly, the total sediment transport per class is multiplied by the frequency of occurrence. In this way it can be analyzed how each class of storms contributes to the total sediment transport at the beach crest.

2.2.5 Inundation classes

We categorize the measured storms and resulting water levels into what we call inundation classes. The aim of the inundation classification is to study the effect of different storm types in a systematic way based on storm records of the last 25 years, from 1990 to 2014. The inundation classes give an overview of the dominant hydrodynamic patterns and their influence on sediment transport across the island during inundation. The classification procedure for the water levels is illustrated in Figure 2.5.

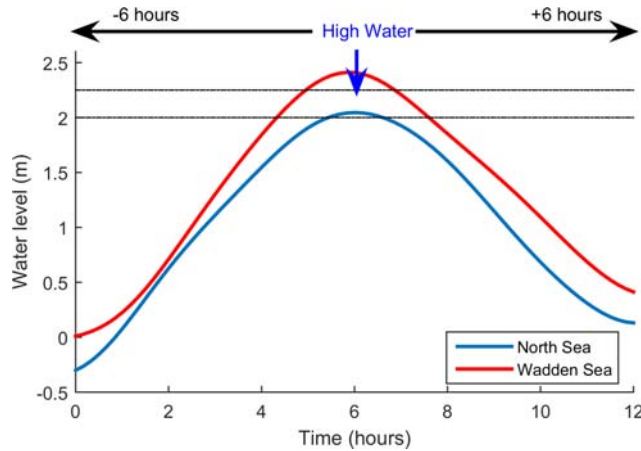


Figure 2.5: Diagram to illustrate the definition of the inundation classes. The water level curves act as an example of how the inundation classes are defined. This example belongs to class 3, based on the peak water level in the North Sea. This means that, for the final averaging, class 3 gains one tidal cycle in the North Sea and Wadden Sea, and 13 hourly values of the short wave height, peak period and wave direction.

The classes are based on the peak water level in the North Sea (station Huibertgat) during an inundation event. An inundation event is defined as a single tidal cycle with an offshore peak water level of at least 1.50 m above MSL. Peak values lower than 1.50 m hardly result in overwash or inundation based on the selected profile of Schiermonnikoog, and are therefore not included. The considered offshore peak water levels range from 1.50 m to a maximum of 3.00 m, with a separation of 0.25 m per class. Thus, class 1 contains all individual inundation events with a peak water level in the North Sea between 1.50 and 1.75 m, and so forth. Due to our definition of an inundation event, there can be multiple events in a row during one storm. For every inundation event a tidal cycle of 12 hours is obtained from the North Sea water level data, with the peak water level in the center of the time series. Finally, all the individual events in one specific class are averaged to create a representative water level curve per class.

In addition, for every inundation event a tidal cycle for the same time frame is constructed in the Wadden Sea (station Schiermonnikoog). Since the classes are initially not based on the peak water level in the Wadden Sea, the peak water level in the Wadden Sea is not necessarily in the center of the water level curve, as there is often a phase difference between the North Sea and Wadden Sea. Besides, the peak water level in the Wadden Sea can be higher than its specific class. For the Wadden Sea, the individual events per class are averaged as well.

In addition to the water levels, the offshore wave data are analyzed and used for the inundation classes (wave buoy Schiermonnikoog Noord). For every inundation event for the 25 years that are analyzed, 13 values in the same time frame (*i.e.* one per hour) for the significant short wave height, average short wave period and wave direction are added to one specific class. In total, one class contains $n = 13 \times m$ values of the above mentioned parameters, where m is the number of inundation events in one class and n the total number of values. The representative values for those parameters are calculated with equations 2.3, 2.4 and 2.5 respectively.

Table 2.1: The squared correlation coefficients (r^2) and bias for the water depths, short and IG wave heights and flow velocities for all instruments.

Instrument	Water Depth (m)		Short Wave Height (m)		IG Wave Height (m)		Flow Velocity (m/s)	
	r^2	bias	r^2	bias	r^2	bias	r^2	bias
PT1	0.94	0.13	0.92	0.19	0.37	-0.11		
PT2	0.90	0.14	0.86	0.26	0.27	-0.07		
PT3	0.92	0.07	0.87	0.14	0.38	-0.04		
PT4	0.92	0.14	0.87	0.10	0.54	-0.04		
PT5	0.92	0.09	0.87	0.08	0.70	-0.02		
PT6	0.95	0.02	0.89	0.07	0.76	-0.02		
PT7	0.95	-0.01	0.91	0.02	0.84	-0.02		
PT8	0.96	-0.06	0.91	-0.02	0.85	-0.03		
PT9	0.96	-0.02	0.91	-0.05	0.85	-0.03		
PT10	0.96	-0.06	0.89	-0.11	0.87	-0.04		
ADV2							0.63	0.16
ADV3							0.47	0.19

$$H_s = \sqrt{\frac{\sum_{i=1}^n H_{s,i}^2}{n}} \quad (2.3)$$

$$T_p = \frac{\sum_{i=1}^n (H_{s,i}^2 * T_{p,i})}{\sum_{i=1}^n H_{s,i}^2} \quad (2.4)$$

$$D = \frac{\sum_{i=1}^n (H_{s,i}^2 * D_i)}{\sum_{i=1}^n H_{s,i}^2} \quad (2.5)$$

Here, H_s is the significant short wave height, T_p the average wave period and D the wave direction. In this way, T_p and D are weighted with their energy ($\sim H_s^2$) and the weighted mean is calculated. Those values are then used to create a JONSWAP spectrum for each inundation class. For the JONSWAP spectra, the values for the peak enhancement factor γ and the directional spreading σ are 3.3 s^{-1} and 18 degrees respectively. We are not able to find a trend in the offshore wave forcing during one inundation event (for example, larger waves during high water). Therefore, the wave forcing per inundation class is constant but varied between different classes.

2.3 Results: Model Validation

The model-data comparison shows good agreement, which is illustrated with all the r^2 and bias values (Table 2.1) and the scatter plots at the instruments PT5 and ADV2, close to the beach crest (Figure 2.6). The results show that both the short wave height and the water depth, which contains the tide, storm surge and wave set-up, have very high r^2 values (ranging from 0.86 to 0.96), which means that the trend is accurately simulated. The positive bias shows that

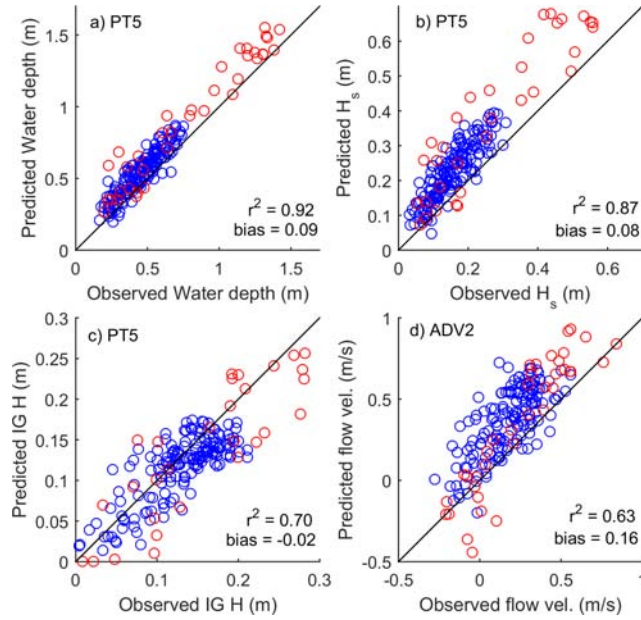


Figure 2.6: Observed versus predicted mean parameters for all inundations, for PT5 and ADV2. The black lines indicate the 1:1 position. The red circles are the two inundation events that are used for further analysis in Figure 2.7. a) Water depth b) Short wave height c) IG wave height d) Flow velocity

the water depth and short wave heights offshore from the beach crest (*i.e.* around PT4-PT5) are somewhat overpredicted. Further onshore, there is a bias towards negative values, but the r^2 values remain high. The IG wave height shows low r^2 values and a negative bias at the offshore part of the island. However, closer to the beach crest, the r^2 increases and the bias is close to zero, which means that the development of IG waves across the island is predicted accurately. The flow velocity at the beach crest (*i.e.* ADV2) is, although overpredicted with a bias of 0.16 m/s, also simulated sufficiently (r^2 of 0.63). Both the observed and the predicted flow velocities result in positive as well as negative velocities, while the latter is only observed during some of the falling tides when the water level at the Wadden Sea side is higher.

To analyze the model-data comparison of the water depths, short- and IG wave heights in more detail, the variation of the mean parameters in cross-shore direction during high tide is investigated for two inundation events (Figure 2.7). The first two tidal cycles of Figure 2.4 are chosen, which are indicated by the red colour in Figure 2.6. The first one represents the majority of the 11 inundation events, with peak water levels around 2 m in the North Sea, and the second one is the largest flooding event with a peak water level in the North Sea of 2.7 m. Water depths are represented very accurately, for both inundations. Short wave heights are slightly overestimated at the offshore part of the island, especially for the large flooding. From PT7-PT8, the observed short wave height increases again in onshore direction. This is probably caused by waves entering the island tail from the Wadden Sea side, which is not included in this model, and results in the negative bias for this part of the island (Engelstad et al., 2017). The IG waves are underestimated for the offshore part of the island, both for the large as well as for the smaller inundation. However, closer to the beach crest the negative

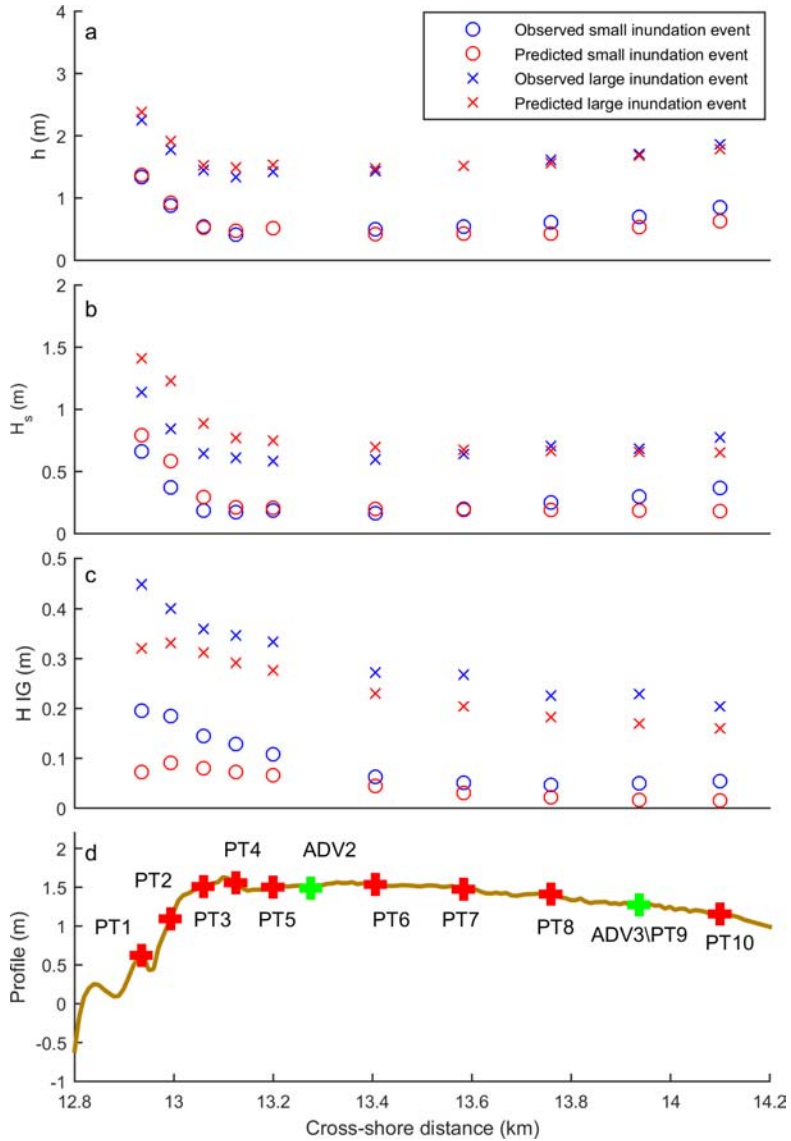


Figure 2.7: Observed and predicted a) water depth, b) short wave height and c) IG wave height for all PTs at d) the island part of the cross-shore profile. All values are averaged over 15 minutes. The circles represent one of the smaller inundation events and the crosses show the large inundation event (*i.e.* the middle tidal cycle in Figure 2.4).

bias becomes less pronounced and the development of the IG waves in cross-shore direction is predicted accurately.

Although we consider the biases to be small enough, it is useful to discuss the source of the deviations between model output and data. Firstly, it was found by Hoonhout and van Thiel de Vries (2012) that short wave heights tend to be overestimated by the model on shallow

Table 2.2: Hydrodynamic conditions per class: Peak water level; Significant wave height; Wave period; Wave direction (270 = W, 360 = N); Angle with shore; Occurrence per year, based on 25 years of data.

Class	Peak Water Level [m]	H_s [m]	Wave Period [s]	Wave Direction [°N]	Angle with shore [°]	Occurrence (per year)
1	1.50 < wl < 1.75	2.61	6.29	304	46	23.0
2	1.75 < wl < 2.00	3.42	6.97	306	44	7.4
3	2.00 < wl < 2.25	3.98	7.34	306	44	2.6
4	2.25 < wl < 2.50	4.33	7.69	307	43	0.8
5	2.50 < wl < 2.75	5.38	8.53	314	36	0.5
6	2.75 < wl	5.61	9.08	317	33	0.3

and gently-sloping foreshores. Furthermore, the overestimation of the currents can possibly be related to the positive bias of both short waves and water depths. Moreover, the currents are measured at a certain height above the bed while the model values are depth-averaged, which can result in a discrepancy between data and model output. Except for model issues, uncertainties could have been introduced by using the water level stations in the North Sea and Wadden Sea, and the wave buoy in the North Sea. Those locations are not exactly in line with our cross-shore profile, which can cause somewhat deviating model results.

2.4 Results: Long-term sediment transport

2.4.1 Inundation classes

The water levels in the North Sea and Wadden Sea that are incorporated in the inundation classification are a combination of tide and storm surge (Figure 2.8), and they reveal two interesting trends. Firstly, the water level in the Wadden Sea lags behind the water level in the North Sea, which is probably a tide-induced effect as it also occurs during calm-weather conditions. This results in higher water levels in the Wadden Sea than in the North Sea during the falling stages of the tide. Secondly, storm surges result in a larger increase of the mean water level in the Wadden Sea than in the North Sea side for larger storms and result in a smaller phase lag. As a result, only during part of the rising tide are water levels in the North Sea higher than in the Wadden Sea, while for the rest of the time Wadden Sea water levels are higher. The reverse of the water level gradient from North Sea to Wadden Sea occurs earlier as storms become more severe. For class 6, the water level in the Wadden Sea is higher than in the North Sea in deep water for the entire tidal cycle.

The wave forcing increases as expected with increasing storm magnitude (Table 2.2). The offshore wave direction gradually changes from 304-317°N, concurrent with the change in wind direction which generated the storm surge. The frequency of occurrence exponentially decreases with increasing peak water levels. For example, class 1 occurs 23 times per year, while class 6 occurs only 0.3 times per year.

2.4.2 Processes per inundation class

Field observations and model results both indicate that the duration of overwash during storms, compared to the duration of inundation, is very limited due to the large tidal range, and the low profile at the chosen location. As a consequence, model simulations also suggest that sediment transport in the overwash phase only has a small contribution to the total transport during a flooding event (less than 1% of the total transport during one inundation

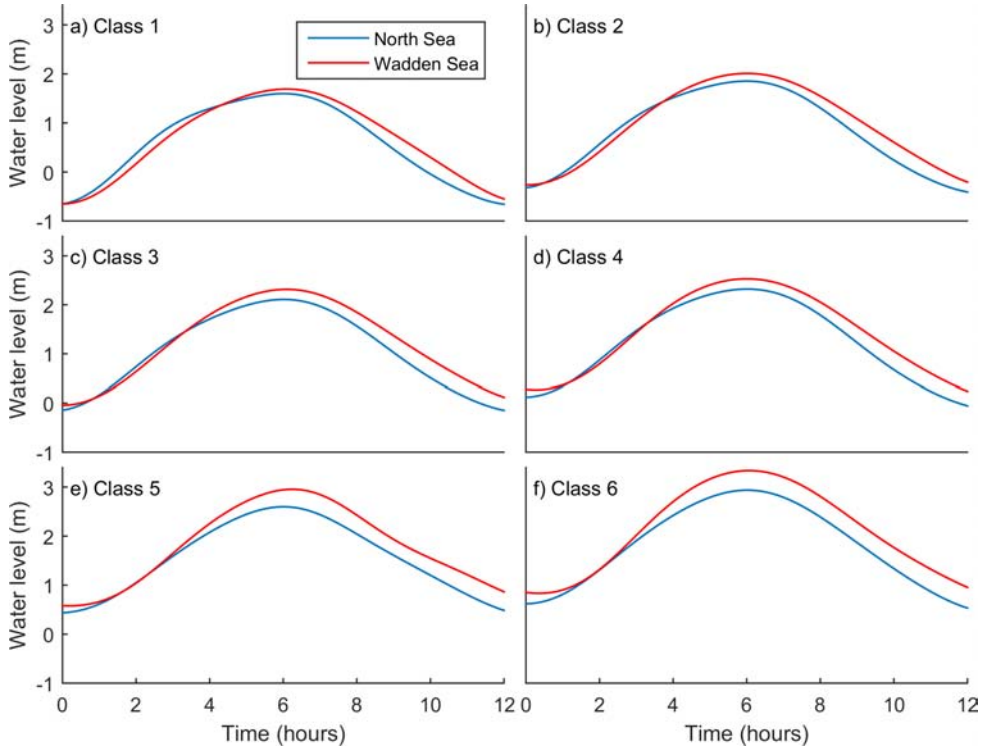


Figure 2.8: Water level curves used as boundary conditions for each class. Red is station Schiermonnikoog (Wadden Sea), blue is station Huibertgat (North Sea).

event). Therefore, the analysis of the model results will focus on the inundation phase rather than the overwash phase.

The storms of the six inundation classes (Figure 2.9a) have a profound effect on the relevant hydrodynamic processes and the resulting sediment transport over the beach crest (Figure 2.9b-f, where positive means in onshore, Wadden Sea direction and negative means in offshore, North Sea direction). For every class, short wave heights peak during high water, when the water depth is largest (Figure 2.9b). For IG wave heights, this is less clear (Figure 2.9c). During the inundation phase, they stay more or less constant for several hours. The maximum values are larger with increasing inundation class for both short- and IG wave heights, because higher classes have larger water depths (less energy dissipation) and larger offshore waves.

Flow velocities (Figure 2.9d) demonstrate similar trends for all inundation classes during the rising tide. Flow is in the positive direction (*i.e.* towards the Wadden Sea). Furthermore, the positive peak typically occurs a few hours before high water and slightly increases in magnitude for higher classes. This peak occurs earlier for higher inundation classes. Both the magnitude and timing of the flow velocity peak is the result of a complex interplay between the water level dynamics in the North Sea and Wadden Sea, which is the combination of tide, storm surge and wave set-up (see conceptual model in Engelstad et al. (2017)). The earlier flow velocity peak for higher classes is mainly determined by the fact that the water level in the

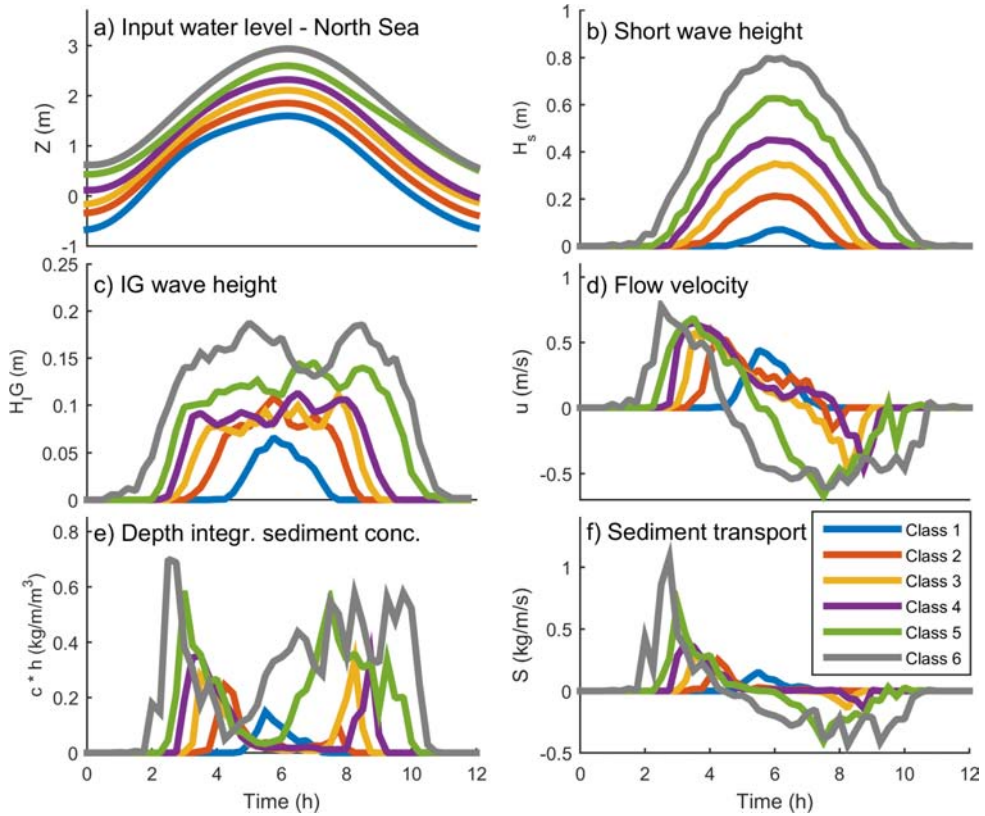


Figure 2.9: a) Input North Sea water level curves. Those are the same as in Figure 2.8. b-f) Output of all inundation classes as function of time, averaged over 15 minutes and calculated at the beach crest. b) Short wave height. c) IG wave height. d) Cross-shore flow velocity. Positive is in the direction of the Wadden Sea e) Depth-integrated sediment concentration f) Sediment transport. Positive is in the direction of the Wadden Sea.

Wadden Sea exceeds the water level in the North Sea in an earlier stage. For lower classes, the phase difference results in higher water levels in the North Sea during rising tide. For higher classes the higher water levels in the Wadden Sea become more dominant, which results in the earlier flow velocity peak. The magnitude of the peak tends, on one hand, to decrease for higher classes because of the larger mean water level in the Wadden Sea. On the other hand, it tends to increase because of the larger wave set-up (larger waves result in more wave breaking), which increases the hydraulic gradient across the profile. The combined effect is that the magnitude of the flow velocity peak only slightly increases from class 1 to class 6.

During falling tide, the flow velocity gradually decreases to zero under the influence of the higher water level in the Wadden Sea. For the higher classes, the direction of the flow velocity even reverses, especially for class 5 and 6. For class 6, this flow reversal already takes place before high tide. However, the magnitude of the negative flow velocity is significantly smaller than the positive values during rising tide. This is probably a result of the wave set-up that increases the hydraulic gradient during rising tide, but decreases the reversed hydraulic gradient during falling tide.

Sediment can be stirred from the bed by short waves, IG waves and by currents. The depth-integrated sediment concentration, which is dominated by suspended load transport (Figure 2.9e), partly correlates with the flow velocity, both during rising tide and falling tide. More in detail, two concentration peaks arise, while the time in between the sediment concentration is much smaller, which is in phase with the flow reversal (*i.e.* when it is close to zero). However, especially the larger classes show that the concentration is not completely zero during the flow reversal, which implies that also the short waves and/or the IG waves stir sediment from the bed. Furthermore, the second concentration peak during falling tide is not always at the same time as the negative velocity peak. For example, the second concentration peak of class 6 is approximately 2 hours later than the negative flow velocity peak. This suggests that the concentration also depends on the water level (*i.e.* less sediment stirring in deeper water).

Generally, suspended sediment transport (Figure 2.9f) is a function of flow velocity and depth-integrated sediment concentration. Therefore, the simulations show a strong correlation with the flow velocity during rising tide, with peak values that are higher and occur earlier for higher classes. During falling tide, sediment transport is negative for class 5 and 6, but is relatively small for all classes. This is caused by the negative flow velocities, which are close to or lower than the flow velocity threshold for sediment stirring.

2.4.3 Net sediment transport per inundation class

To investigate the effect of different inundation classes on the net sediment transport across the beach crest, the net transport is calculated as the positive transport during rising tide minus the negative transport during falling tide. It appears that the net sediment transport is always positive, towards the Wadden Sea (Figure 2.10, the blue bars). Furthermore, it increases from class to class until class 5, which means that the factors that tend to increase the transport (e.g. higher water level, larger waves) are more important than the relatively higher water level in the Wadden Sea. However, from class 5 to class 6 the transport decreases, which is mainly an effect of the falling tide phase of the inundation events. During rising tide the net onshore transport is slightly larger for class 6, but during falling tide there is more offshore transport for class 6 as well.

The same inundation classes are simulated two more times by excluding once the short wave stirring and the other time the IG wave stirring. Note that only the sediment stirring is adapted, not the wave itself. For example, when the short wave sediment stirring is excluded, the short waves still influence the hydraulic gradient by creating wave set-up. More details can be found in Appendix A. Excluding the sediment stirring by short waves or IG waves decreases the net sediment transport at the beach crest, however, an important part is stirred by the current (Figure 2.10). From class 5 to class 6, the simulations without the sediment stirring by the IG waves show an increase in the net transport, while it decreases for the default simulations. This indicates that this decrease for the default simulations is mainly caused by sediment that is stirred by the IG waves and transported in North Sea direction by the current, during falling tide.

The net transport over the beach crest is 4 to 5 times larger for high inundation classes than for class 1 events, however if net transport is combined with the frequency of occurrence (based on 25 years) the total cumulative transport is largest for less severe storms. Class 1 inundation events (peak water levels between 1.50 and 1.75 m) typically occur several times a year, for example when a small storm surge coincides with spring tide. Class 5 and 6 (peak water levels higher than 2.50 m) are relatively exceptional NW storms that occur less than once a year. Therefore, the frequency of occurrence from class 1 to class 5-6 decreases by 1-2

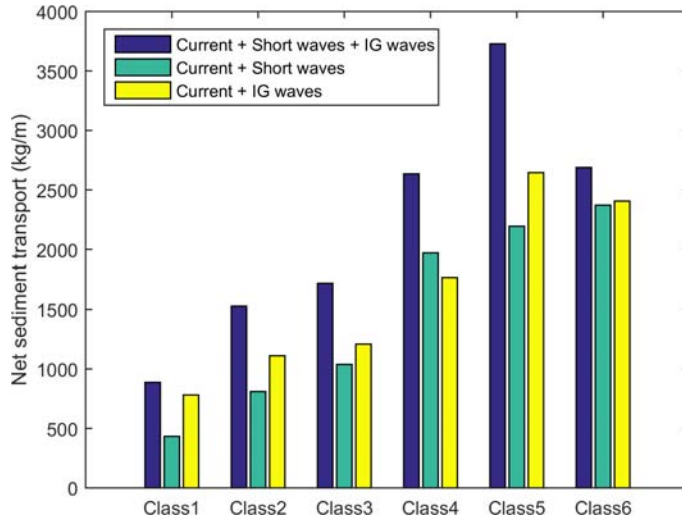


Figure 2.10: Net sediment transport for all classes at the beach crest, for the entire tidal cycle. The blue bars contain all sediment stirring mechanisms (*i.e.* short waves, IG waves and the cross-shore current). The green and yellow bars miss one component.

orders of magnitude. When the net sediment transport of each inundation class is multiplied with the frequency of occurrence, the larger net sediment transport during larger storms is not enough to compensate for their lower frequency of occurrence and to make these storms the most dominant ones in terms of net sediment transport (Figure 2.11). This implies that those frequently occurring inundation events have to be taken into account when the potential contribution of inundation events to the long-term vertical accretion of the Wadden Islands is investigated.

2.5 Discussion

2.5.1 XBeach performance

We were able to validate the hydrodynamic settings of an XBeach model under inundation regimes. Despite a gamma value of 0.45 in the wave breaking formulation, the short wave heights and water depths, and therefore the flow velocities as well, are still slightly overestimated. On the other hand, the simulated IG wave heights are slightly underestimated, especially offshore. This is in line with other studies which compared the hydrodynamic processes in XBeach with field data or lab experiments (Hoonhout and van Thiel de Vries, 2012; de Winter et al., 2015). Our results are probably slightly influenced by this bias, especially the relative role of currents and waves on sediment stirring. However, this mainly influences the amount of sediment transport, but does not change our conclusion that gentle, weaker storms have more impact on the long-term, cumulative transport than the large, less frequent storms.

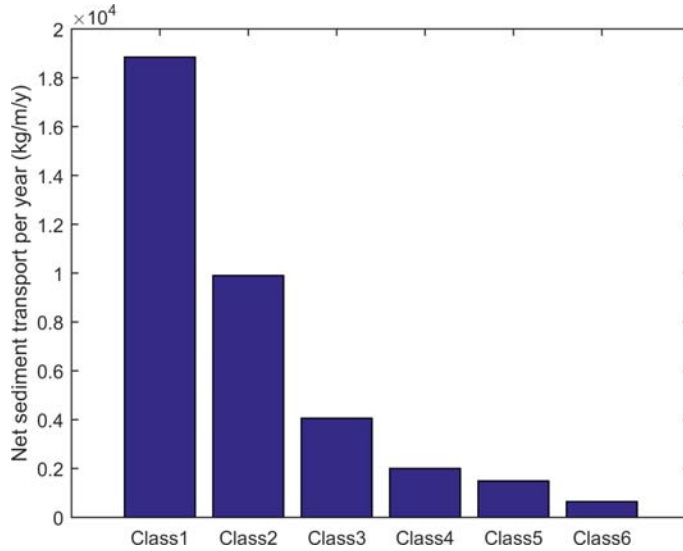


Figure 2.11: Total sediment transport per year at the beach crest. Compared to the blue bars in Figure 2.10, the net transport is multiplied by the average number of storms per year in each class, defined in Table 2.2.

2.5.2 Overwash and inundation at the island tail of Schiermonnikoog

The sediment transport is only weakly increasing for higher inundation classes, which is related to the effect of the reversed flow in offshore direction during falling tides. This is investigated in more detail with a new set of simulations, where for every inundation class the prescribed water levels at the North Sea and Wadden Sea boundary are the same, hence, no time lags and storm surge differences are considered. In this scenario, the hydraulic gradient across the island is solely determined by the wave set-up. Sediment transport is then only in Wadden Sea direction. Comparing Figure 2.12 and Figure 2.9f clearly demonstrates that the higher mean water level in the Wadden Sea during storms has a strong impact on the net sediment transport over the beach crest. The total transport during an inundation event is much smaller in the original simulations than in the simulations with equal water level in the North Sea and Wadden Sea, ranging from a decrease of 20% to 90% from class 1 to class 6. The important role of the back-barrier basin when it is connected with the ocean or sea during inundation is also recognized in other studies, for example by Hoekstra et al. (2009), Sherwood et al. (2014) and de Vet et al. (2015). Sherwood et al. (2014) also found reversed currents as a result of higher back-barrier water levels for the Chandeleur Islands in Louisiana, while Hoekstra et al. (2009) concluded as well that water can reach Schiermonnikoog from both sides of the island.

The inundation events at the low-lying island tail (*i.e.* a beach crest of 1.6 m) undergo all four stages of the regime of Sallenger (2000). The occurrence and duration of the inundation phase in general is mainly determined by the combination of beach- or dune crest height and the mean water level. Obviously, inundation is always preceded by an overwash phase during rising tide. However, at this specific field site, the duration of the overwash phase is very short compared to the duration of the inundation phase. In addition, results have also shown that the cross-shore current during inundation, induced by water level gradients between North Sea and Wadden Sea and by wave set-up, is one of the most dominant mechanisms

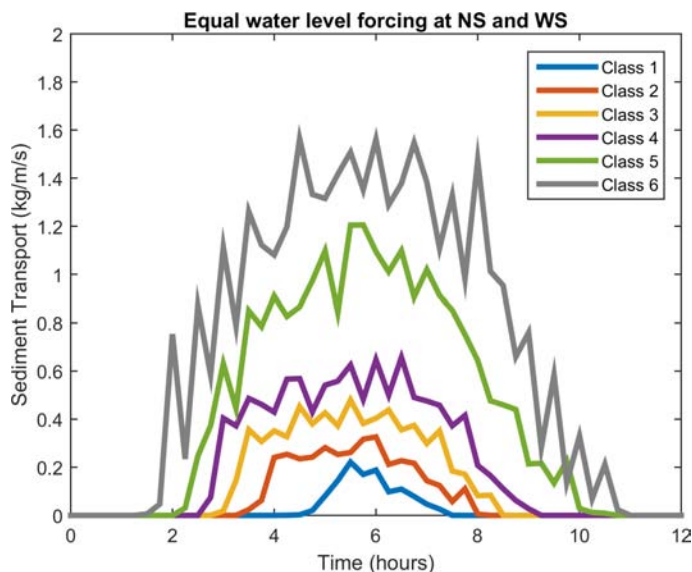


Figure 2.12: Sediment transport at the beach crest, without the hydraulic gradient caused by storm surges and tidal phase differences. Therefore, sediment transport is always in Wadden Sea direction.

for sediment stirring and transport across the island (Figure 2.10). Consequently, the net sediment transport across the beach crest during overwash is one or two orders of magnitude smaller than the transport during inundation at this specific location, which leads to the conclusion that the overwash phase plays a minor role in the net sediment transport across the island tail of Schiermonnikoog. This is in line with the findings of Harter and Figlus (2017), who concluded that the currents during the inundation regime leads to more bed level change than the wave overtopping during the overwash regime at Follets's Island, Texas, based on their XBeach simulations. However, the main difference between our study site and the location of many other studies (for example McCall et al. (2010)) is the absence of dunes, the low level of the beach crest and the mesotidal conditions.

Another difference between our field site and other barrier systems related to the very low-lying beach crest is the importance of smaller, frequently occurring storms compared to larger and more exceptional storms for the long-term cumulative sediment transport. Other studies investigating barriers with a higher beach- or dune crest often tend to focus on these severe storms because they are needed to create significant dune erosion or even breaching before inundation occurs. Examples are the work of Morton and Sallenger (2003) and Nielsen and Nielsen (2004), which described a large storm in 1990 that caused a breach at the dunes of Skallingen, Denmark. Our research shows that for typical Wadden Island conditions, where washover openings already exist, also the more frequently occurring inundation events should be taken into account for the analysis of the long-term sediment budget.

2.5.3 The Schiermonnikoog island tail versus the 2D washover openings

Typically, in natural conditions the dune rows at the Wadden Islands are not closed over the full length of the island and have natural gaps, so-called washover openings. During storms, when critical water levels are exceeded, water and sediment can flow across the island

via these openings. To protect the Wadden Islands from flooding, artificial sand-drift dikes that close these gaps were constructed in previous centuries (Oost et al., 2012). Sediment transport across the island caused by overwash and inundation is thus significantly reduced. Therefore, the areas located directly behind the dunes tend to become lower-lying relative to rising sea level. At Schiermonnikoog, a large storm in 1973 partly destroyed the sand-drift dike, which created the current openings, but these are much smaller than the natural openings before the sand-drift dike was built.

Recently in the Netherlands, the re-activation of the washover openings was considered by nature organizations to stimulate sediment deposition behind the dunes. An additional advantage of this would be the development of a more dynamical ecosystem. Our study contributes to the knowledge that is required to make this decision, however, potential differences between the 1D island tail and the 2D washover openings have to be considered. The first difference between those locations is the beach crest or washover crest height (Figure 2.2). Many washover openings are 20-30 cm higher than the beach crest at the island tail. At first sight this seems to be a small difference, however, this would mean that the class 1 inundation events, which on the long term lead to the most sediment transport at the island tail, do not occur at the washover openings. Furthermore, 2D effects must be taken into account at those locations. For example, flow contraction through an opening can accelerate currents which enhances sediment transport. Sediment slumping from the side walls of the dunes can affect the sediment transport as well and deposition patterns behind the dunes can vary in alongshore direction. The influence of these properties of the 2D washover openings on the hydrodynamics, sediment transport and morphology change will be investigated in future studies.

2.6 Conclusions

In this chapter we study the influence of inundation events on the hydrodynamics and sediment transport across the low-lying Wadden Islands in mesotidal conditions. Firstly, the model XBeach is validated with field data gathered at the barrier island tail of Schiermonnikoog, the Netherlands, during overwash and inundation events. Water depths and short wave heights across the island are simulated accurately with r^2 values of 0.85 and higher, and a small positive bias. IG wave heights are slightly underestimated. Cross-shore flow velocities result in somewhat lower but still sufficient r^2 values and a slightly higher bias. We conclude that the model-data comparison is robust enough to use the model for further analysis. Secondly, we use XBeach to simulate the cross-shore sediment transport for a wide range of waves, tides and storm surge conditions. Tidal phase differences and storm surge dynamics result in higher water levels in the Wadden Sea compared to the North Sea. This is a crucial aspect for the sediment transport across the island tail, resulting in a smaller or even reversed current and a reduced net sediment transport. Over a tidal cycle, the net sediment transport direction is still towards the Wadden Sea. We conclude that the cumulative effect of relatively mild storms is more important for the long-term sediment transport than the cumulative effect of large, more exceptional North Sea storms. Per storm, more sediment is transported across the island when the magnitude of the storm increases. However, combined with the decreasing frequency of occurrence of larger storms, we conclude that exceptional storms in mesotidal settings are not crucial for the potential vertical accretion of the island tails during overwash and inundation events.

Chapter 3

The effect of washover geometry on sediment transport during inundation events

Based on: Wesselman, D., de Winter, R., Oost, A., Hoekstra, P. and van der Vegt, M (2018), The effect of washover geometry on sediment transport during inundation events. *Geomorphology* 327, 28-47.

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 1.5-2.1 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.

3.1 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, 2004; 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. 3.1) demonstrate a 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 openings 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. Chapter 2 and Engelstad 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.

3.2 Topography of the Wadden Islands

3.2.1 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. 3.1). They

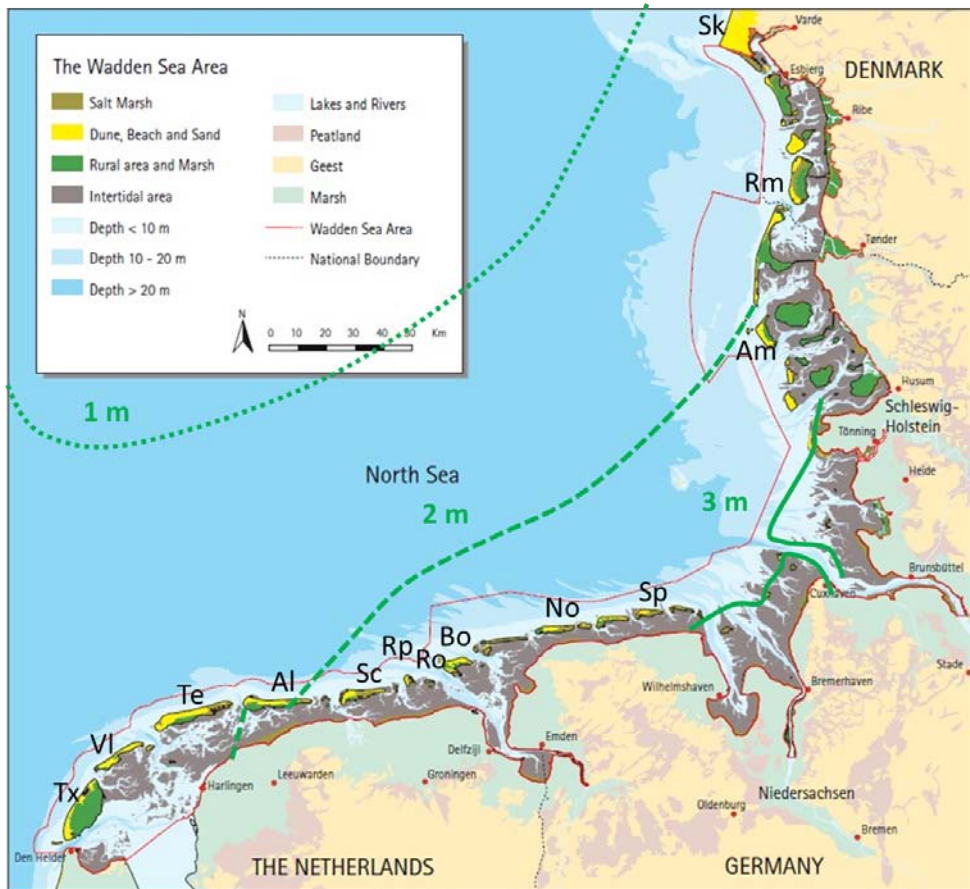


Figure 3.1: Overview of the Wadden Sea region and overview of tidal range (in m) and locations of the various barrier islands discussed in the text. From W to E: Tx = Texel; VI = Vlieland; Te = Terschelling; Al = Ameland; Sc = Schiermonnikoog; Rp = Rottumerplaat; Ro = Rottumeroog; Bo = Borkum; No = Norderney; 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).

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

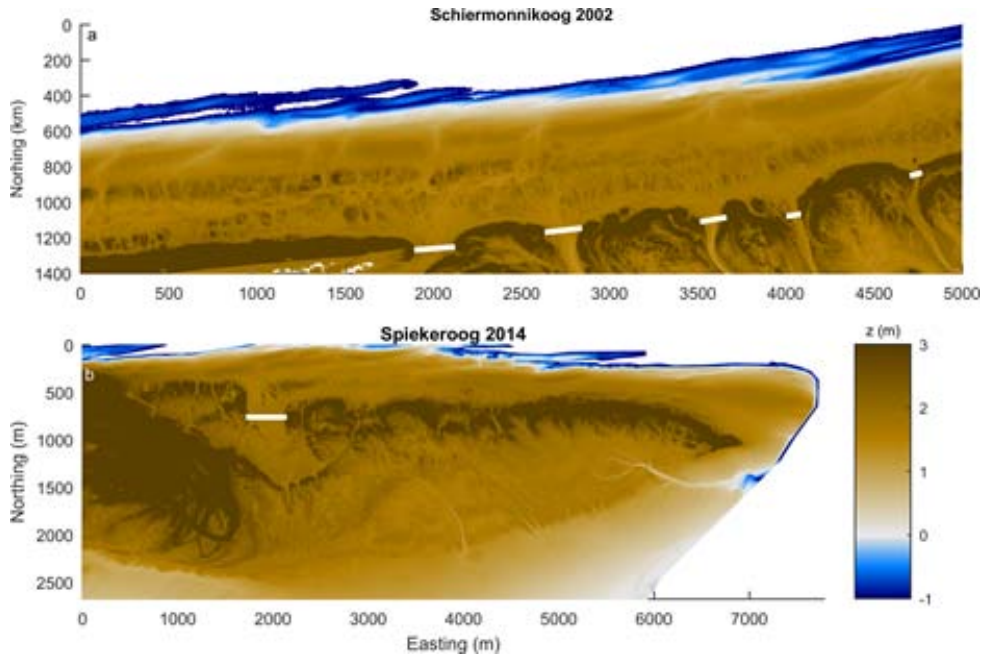


Figure 3.2: LIDAR images of a) Schiermonnikoog, 2002 and b) Spiekeroog, 2014. The white lines show the positions of the washover openings.

are not taken into account, because they are too high to be inundated during storms (Abbar 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 the Appendix at the end of this chapter. 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. 3.2). 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.

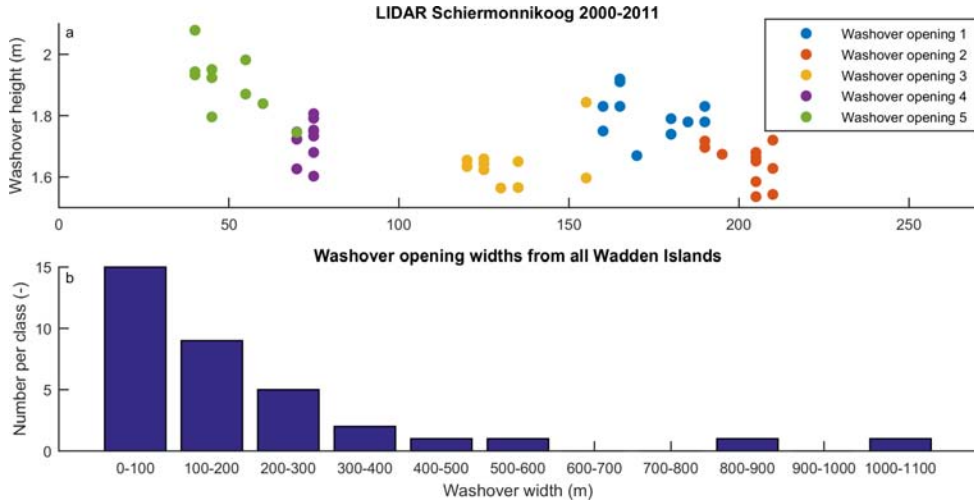


Figure 3.3: a) Washover opening width versus elevation at Schiermonnikoog for the period 2000-2011. Washover opening 1 is the most updrift opening. b) Distribution of washover widths from all Wadden Islands based on the most recent geometries. The total sample number is 35.

3.2.2 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. 3.3a). 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. 3.3b).

3.3 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 Chapter 2. Model results were compared 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 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,

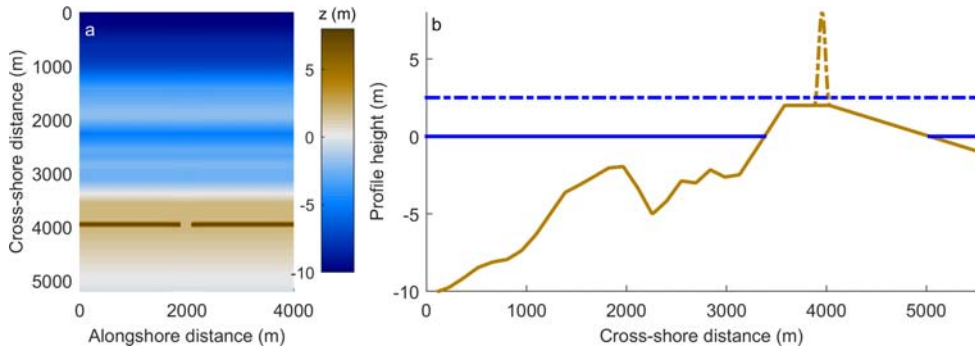


Figure 3.4: a) The profile of reference simulation Ao. b) 1D profile of reference simulation Ao. Two cross-shore transects are shown, one in the dunes and one in the washover opening. The blue solid line is mean sea level, the blue dashed line is a water level of 2.5 m above MSL, used for the simulations with constant water level.

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. 3.4). 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 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 3.1. In Series A the sensitivity of the reference profile Ao (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 Chapter 2, where class 1 represents inundation under mild storm conditions and class 6 represents severe storms (Fig. 3.5). 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 3.2. 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

Table 3.1: Series of simulations. Ao is the reference simulation, performed with tidal curves. For Series A, the profile of Ao is always used but the hydrodynamics vary. The waves used here are shown in Table 3.2 and the tidal curves are shown in Figure 3.5. 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)
Ao	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

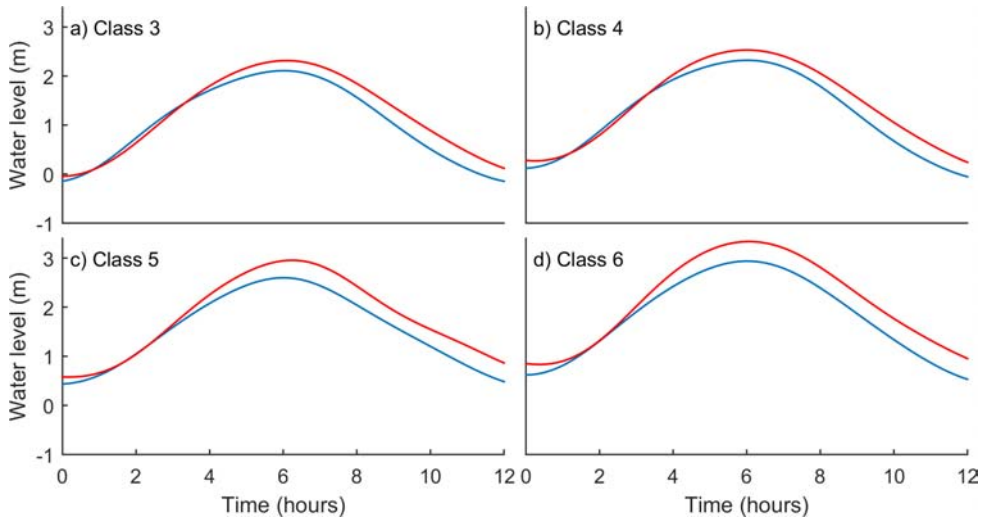


Figure 3.5: Boundary conditions at North Sea and Wadden Sea side as used in the model (Series A). Water levels are above MSL. The North Sea curves are based on water level station Huibertgat, the Wadden Sea curves on station Schiermonnikoog.

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 d_{50} of $200 \mu\text{m}$ and a d_{90} of $300 \mu\text{m}$, 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/hour or kg/hour . 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 hydrody-

Table 3.2: Inundation classes based on Chapter 2. 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

namics and resulting sediment transport, but for Series A we also calculated the divergence of the sediment transport, by using equation 3.1,

$$S_{div} = \frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y} \quad (3.1)$$

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 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 x 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 hours 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 hours, where the first 4 hours were used as spin-up and the fifth hour was analyzed.

3.4 Results

3.4.1 Patterns of flow, sediment transport and sediment transport divergence

In the reference simulation Ao, H_s decreases in the onshore direction during maximum onshore-directed flow, typically 1.5 hours before high water (Fig. 3.6a). The first location of significant wave dissipation is the sub-tidal sandbar with the crest at approximately 2 m below MSL (Fig. 3.6b). 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. 3.6c). 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. 3.6d). The alongshore transport at the foreshore is relatively small, and sediment transport is rela-

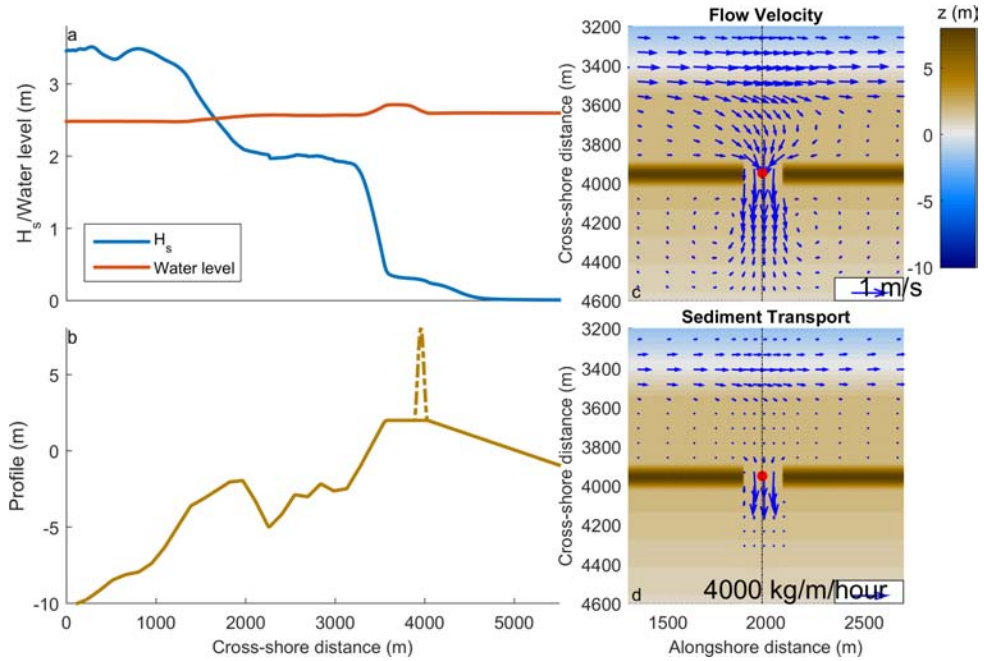


Figure 3.6: Results of the reference simulation Ao. a) Significant wave height and water level as function of cross-shore distance through the center of the washover opening. b) 1D profile. c-d) Flow velocity and sediment transport averaged over 15 minutes and during maximum flow, approximately 1.5 hours before high water. The red dot marks the center of the opening in both directions.

tively 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. 3.5 (i.e. a higher class means higher water levels and larger 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. 3.7). 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/hour (i.e. the onshore minus the offshore directed transport, divided by the total inundation period) is still positive (Fig. 3.7c). These patterns are similar as in Chapter 2.

The resulting sediment transport divergence and convergence patterns are shown in Fig. 3.8a-d. Erosion occurs in regions with divergent sediment transport (red colors), while deposition takes place when sediment transport converges (blue colors). 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

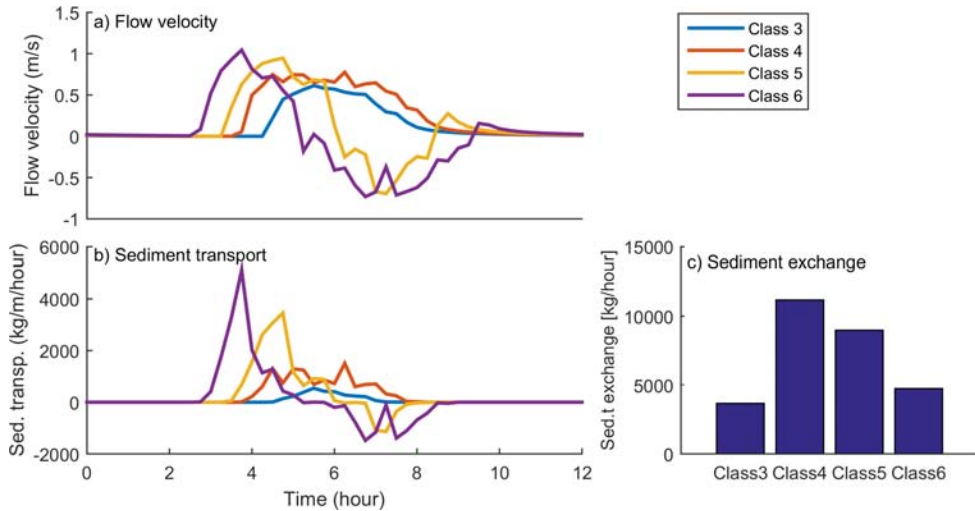


Figure 3.7: a) Flow velocity and b) Sediment transport in the middle of the washover opening (in both directions) for inundation classes 3-6. Positive values mean in onshore direction, while negative values are offshore directed. c) Net sediment exchange during the full tidal cycle for inundation classes 3-6. This is calculated as the onshore minus the offshore directed transport and averaged over the total inundation period.

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 increases from inundation classes 4 to 6.

3.4.2 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 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. 3.9a-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. 3.9c 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 one hand, the effect of flow contraction reduces for wider openings and results in less sediment transport per meter alongshore (kg/m/hour). On the other hand, in a wider opening sediment is transported over a larger width, resulting in sediment mass exchange rates (kg/hour) that tend to be larger. The combined result is that the net sediment transport

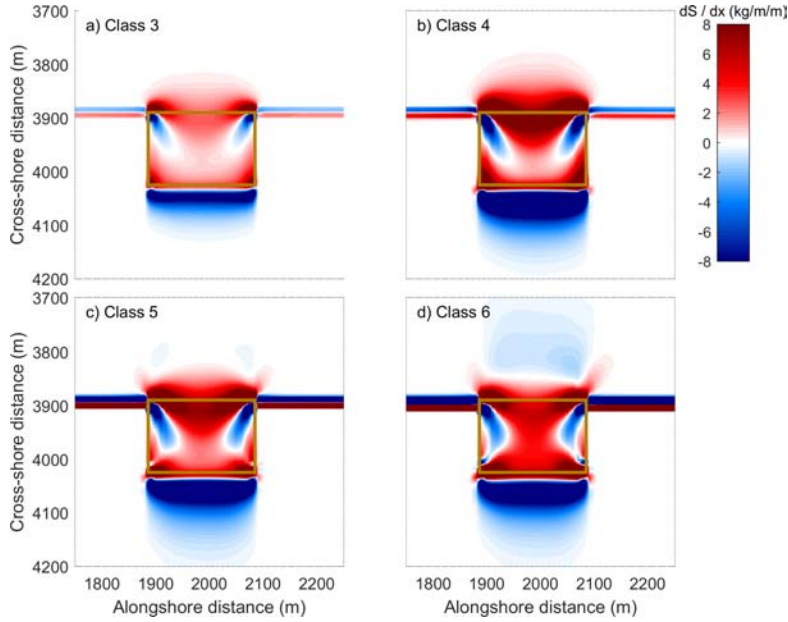


Figure 3.8: Sediment transport divergence and convergence for Series A. Blue colours mean sediment transport convergence (deposition) and red means sediment transport divergence (erosion). The area enclosed by the brown box is the location of the washover opening.

(kg/hour) 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. From 2.3 to 1.7 m, the sediment exchange rate increases with 400%. Fig. 3.9c 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. 3.10 (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 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}

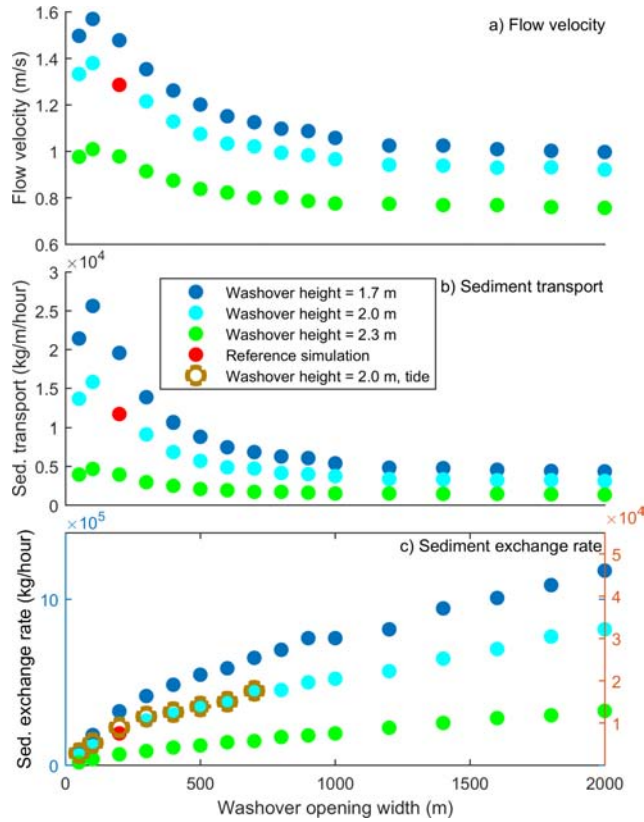


Figure 3.9: Series B1: a) Cross-shore flow velocity, b) Cross-shore sediment transport at the position of the red dot in Figure 3.6. This is the middle of the opening in both directions. c) Sediment exchange rate through the whole opening. The filled dots were performed with constant water levels and belong to the left y-axis, while the open dots (belonging to the right y-axis) were performed with the tidal curves. Different colors represent different washover opening elevations for the filled dots. The red dot in this figure is reference simulation Ao.

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.

3.4.3 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. 3.11a). 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. 3.11b). The pressure gradient between the North Sea and Wadden Sea, and thereby the other processes, remain unaltered when the beach width increases.

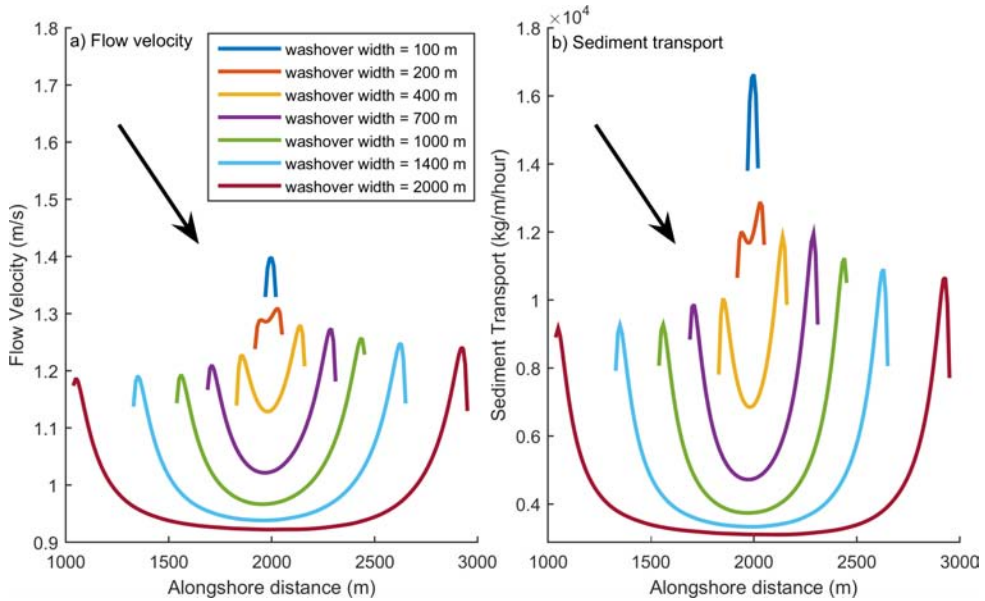


Figure 3.10: a) Cross-shore flow velocities and b) Cross-shore sediment transport along the washover opening for different opening widths for Series B. The washover opening elevation is 2.0 m. The arrows indicate wave direction.

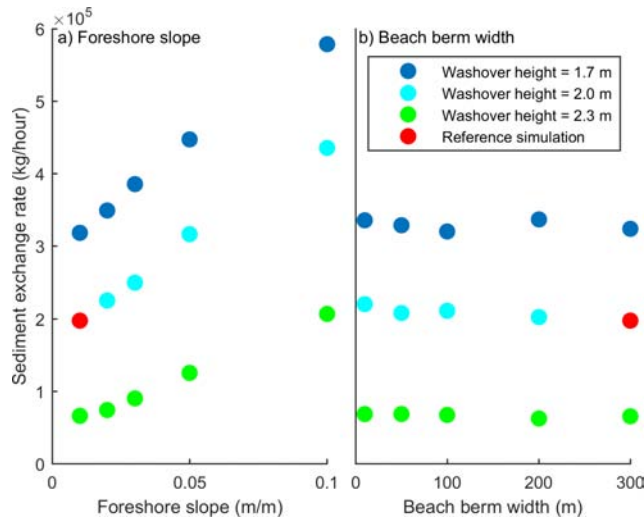


Figure 3.11: Series B2: Sediment exchange rate for a) varying beach slope and b) varying beach width. This is the middle of the opening in both directions. Different colors represent different washover opening elevations. The red dot in this figure is reference simulation Ao.

3.5 Discussion

3.5.1 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. 3.6). 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. In addition, the pressure gradient during storm surges creates an opposing mechanism and results in limited deposition behind the dunes (Fig. 3.7).

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 is, 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. 3.3a do not contain enough washover openings to confirm this and more research is needed to investigate this hypothesis.

3.5.2 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 depths 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. 3.10). 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. 3.9). 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. 3.11). 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.

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

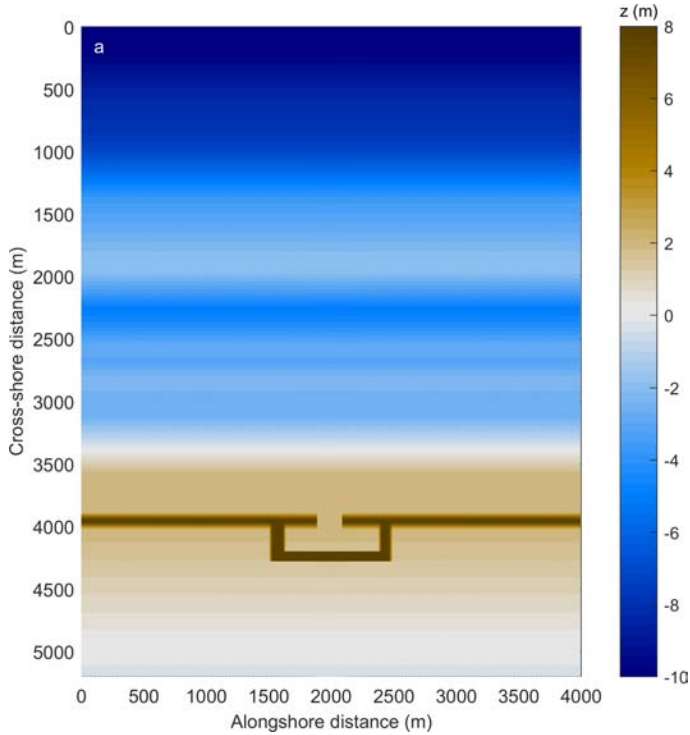


Figure 3.12: Profile with a secondary dune system, based on reference simulation Ao, that blocks the North Sea from the Wadden Sea.

in Fig. 3.12 and 3.13, 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 hours, 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, compared to a situation where the North Sea and Wadden Sea are connected.

3.6 Conclusions

In this chapter 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 1.5-2.1 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 elevation 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

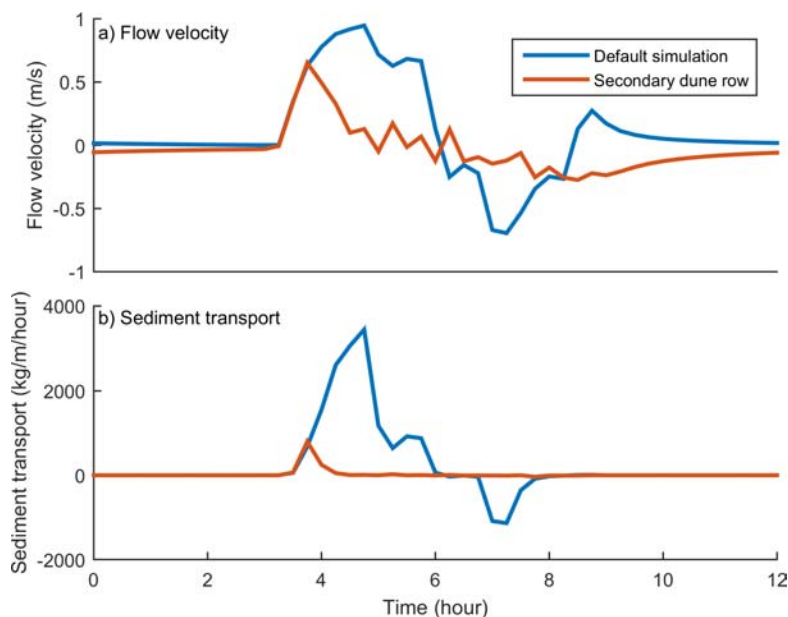


Figure 3.13: a) Flow velocity and b) Sediment transport for the default simulation Ao and the simulation with a secondary dune system.

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 is 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.

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. 3.1). 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 ac-

count. 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.

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. 3.14). 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. 3.15) 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 prevents the inhabited part of Texel from flooding (van der Vegt and Hoekstra, 2012).

Vlieland

The western part of Vlieland, called the Vliehors, was a low-lying beach plain without dunes for a long time (Fig. 3.16). Recently, a small dune complex formed so that nowadays a washover opening of 1040 m can be defined.

Terschelling

At Terschelling, three narrow washover openings of less than 100 m in width can be found (Fig. 3.17). 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.

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. 3.18).

Schiermonnikoog

Schiermonnikoog is the island where nowadays most washover openings can be found (Fig. 3.19). 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.

Rottumerplaat and Rottumeroog

Rottumerplaat and Rottumeroog are two uninhabited islands in the Netherlands which both contain a washover opening (Fig. 3.20 and 3.21). 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 island 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.

Borkum

Borkum is the first German Wadden Island from west to east (Fig. 3.22). 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.

Norderney

The island tail of Norderney (Fig. 3.23) 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.

Spiekeroog

Similar to Norderney, the island tail of Spiekeroog was not closed off by artificial sand-drift dikes in the past (Fig. 3.24). 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.

Amrum

Amrum contains one washover opening of 170 m wide that is in front of a sand drift dike (Fig. 3.25).

Rømø

Rømø, one of the Wadden Islands in Denmark, contains three washover openings ranging from 60 to 100 m wide (Fig. 3.26). They arose in a new, young series of foredunes seaward from the old beach plain, which is now partly enclosed.

Skallingen

Skallingen is a barrier spit that is partly separated from the mainland of Denmark with a tidal basin (Fig. 3.27). 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, 2004).



Figure 3.14: Washover opening one at Texel, the Netherlands.



Figure 3.15: the Slufter, washover opening two at Texel, the Netherlands.



Figure 3.16: Washover opening at Vlieland, the Netherlands.



Figure 3.17: Washover openings at Terschelling, the Netherlands.



Figure 3.18: Washover openings at Ameland, the Netherlands.



Figure 3.19: Washover openings at Schiermonnikoog, the Netherlands.



Figure 3.20: Washover opening at Rottumerplaat, the Netherlands.



Figure 3.21: Washover opening at Rottumeroog, the Netherlands.



Figure 3.22: Washover openings at Borkum, Germany.

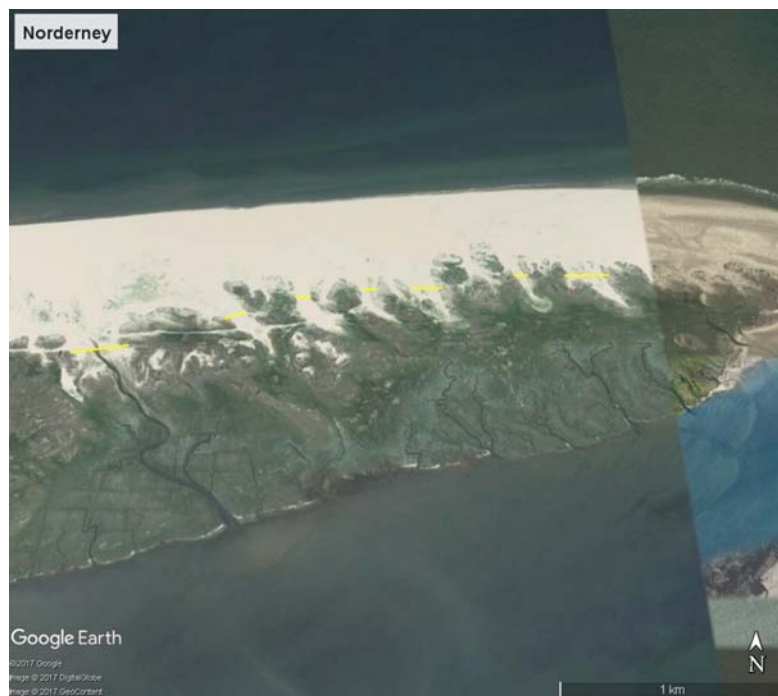


Figure 3.23: Washover opening at Norderney, Germany.



Figure 3.24: Washover opening at Spiekeroog, Germany.

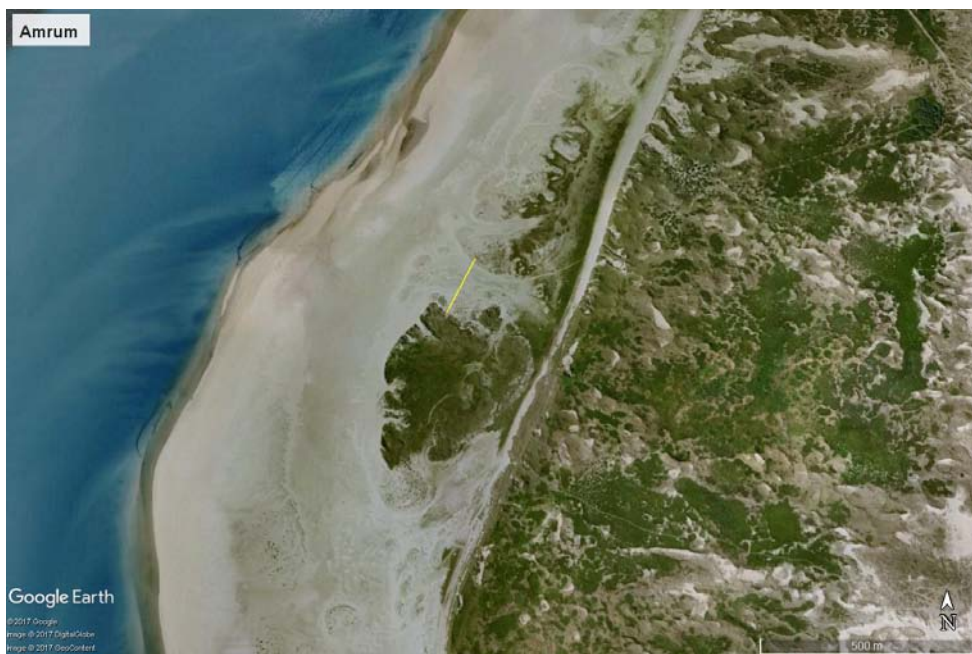


Figure 3.25: Washover openings at Amrum, Germany.



Figure 3.26: Washover openings at Rømø Denmark.

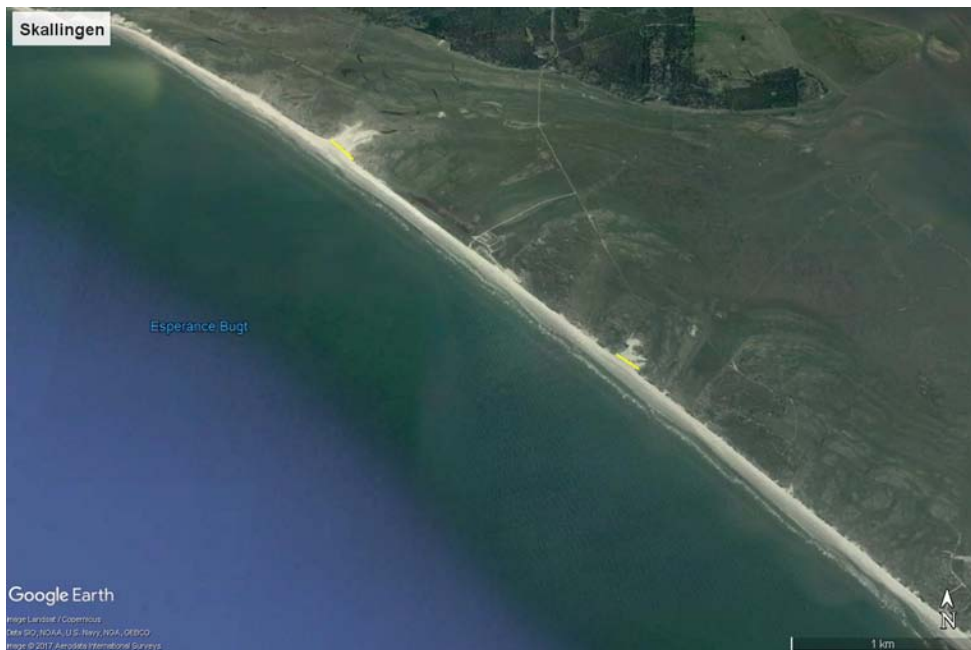


Figure 3.27: Washover openings at Skallingen, Denmark.

Chapter 4

Simulating the medium-term (25 years) evolution of washover deposits on a barrier coast with a process-based model

Abstract

It has been considered by coastal management organizations in the Netherlands to remove parts of the sand-drift dikes on the Dutch barrier islands and re-open washover openings to enhance storm-induced sedimentation behind the dunes. However, it is unclear whether the transport magnitudes are large enough to keep up with sea level rise, how such a constructed opening evolves over time, what the morphological feedbacks are and how that depends on opening geometry. To this end, the process-based model XBeach was used to investigate the medium-term (25 years) storm-induced washover development for a representative typical Wadden Sea barrier island system. Three different geometries were used. Two of them contain a gap in the dunes (washover opening) with an alongshore width of 200 m and 600 m respectively, while the third geometry lacks dunes and is alongshore uniform. Results show that inundation events erode the washover openings with values of more than 50 cm in total and deposit this sediment onshore. This leads to a vertical local accretion of the island with the same amount. Wider washover openings lead to larger washover volumes. The geometries do not evolve towards an equilibrium but instead the rate of deposition landward from the opening stays approximately constant. When a high rate of sea-level rise is taken into account (1 cm/y), deposition values increase with approximately 60% and thereby it accelerates vertical accretion rates. However, the accommodation space created by sea-level rise is not completely compensated by washover deposits. Different sequences of storms (from low to high energetic conditions and vice versa) cause a difference of 20-25% in sedimentation volumes.

4.1 Introduction

Barrier islands, which exist all over the world, often have an important role in protecting the mainland from storms. However, they are potentially threatened by sea-level rise (Bruun, 1962; Nicholls and Cazenave, 2010; Wang et al., 2012; Enríquez et al., 2017), which is expected to accelerate in the future (Flato et al., 2013). Storm-induced overwash or inundation can result in sediment deposition landward so that the islands can grow in elevation, migrate onshore (Leatherman, 1979) and keep up with sea-level rise. Although roll-over process occurred for many barrier islands in the past (Engelhart et al., 2009; Thieler and Ashton, 2011), examples are known as well of barrier islands that drowned under influence of a fast increase of sea level (Sanders and Kumar, 1975; FitzGerald et al., 2007; Mellett et al., 2012). For the Wadden Islands, it is unclear whether storm-induced sediment transport is large enough

to let the barrier islands keep-up with sea-level rise when washover openings are created. Therefore, in this study I investigate the medium-term (decadal scale, 25 years in this study) onshore sediment supply and deposition in response to inundation at the Wadden islands and the morphological feedbacks.

Simulating storms and studying their effect on morphology change at a barrier island can improve insights in the capability of the barriers to survive rising sea levels. Until now, the evolution of barrier islands is either investigated with exploratory models (Rosati and Stone, 2007; Lorenzo-Trueba and Ashton, 2014) for long-term evolution or process-based models such as XBeach to study the impact of individual storms (Chapter 2-3; McCall et al., 2010). In the exploratory models the processes are simplified and used in a more aggregated manner, often in a conceptual way to facilitate upscaling to larger timescales. The process-based models, which require local input values such as water levels, waves and profile elevation, include all the relevant processes but this makes it difficult to apply these models for long-term barrier island development. Ideally, a process-based model that can be used to analyze and predict the cumulative effect of a great number of storms over a large series of consecutive years would contribute to a better understanding of how storms and sea-level rise would influence the sediment deposition on the island landward from the beach or dunes. Recently, process-based models were applied for long-term predictions in a 1D cross-shore mode, for example in Pender and Karunarathna (2013). To our knowledge, no studies have been performed in a 2D mode that use process-based models such as XBeach for covering a multi-year period.

Most studies that investigated effects of overwash and inundation on barrier island morphology focused on relatively severe, but infrequently occurring storms. For example, Nielsen and Nielsen (2004) described the evolution of a breach of the dunes at Skallingen (Denmark) caused by high water levels and large waves. At locations with high dunes, large storm events are required to generate a landward-directed sediment transport. The water level during smaller storms is not sufficient to reach the overwash or inundation regime (see introduction of this thesis) and areas behind the dunes remain disconnected from the offshore side. This would imply that analyzing individual storm events is sufficient to explain the morphological change, assuming that aeolian transport is not important. Nevertheless, at low-lying areas that frequently inundate (i.e. at least several times per year), also the effect of smaller storms must be taken into account that individually have little impact on island morphology but may have a larger cumulative effect than a single large storm. (Chapter 2; Mickey et al., 2018). Furthermore, Dissanayake et al. (2015) demonstrated that not only the frequency and magnitude of storms is important but also the sequence in which they occur. This sequence has impact on the erosional or depositional patterns.

The Wadden Islands typically contain washover openings, low-lying gaps in the dunes that are frequently inundated during storms (Oost et al., 2012). The dunes are often too high and too wide to be breached or inundated and therefore the washover openings play a crucial role in the storm-induced cross-shore sediment supply. Large variations in washover opening width and elevation exist (Chapter 3). The mean width is 200 m but it ranges from 35 to 1100 m, and the elevation is between 1.5 and 2.1 m above mean sea level (MSL). Cross-shore currents, affected by the pressure gradient between the North Sea and back-barrier basins of the Wadden Sea largely determine patterns of sediment transport and erosion/deposition (Engelstad et al., 2017). However, it is still unknown whether the washover openings remain active on a time scale of 25 years or that a quasi-dynamic equilibrium is established where depositional processes are balanced by erosional processes.

In this study I investigate the medium-term morphological development of washover openings as a function of washover geometry and external forcing by applying a process-based model in a more or less aggregated approach. I will take the Wadden region as a pilot site and use parameters that are exemplary for this region. To this end, a computational method was constructed to simulate time-varying water level and wave conditions by representing their net effect by using single water levels and wave conditions. This drastically reduced the calculation time. Morphological changes of washovers for varying storm sequences were simulated for a period of 25 years. This is short enough to have realistic calculation times and long enough to be able to investigate morphological feedbacks. In addition a first order assessment was made of the impact of SLR on the storm-induced, cross-shore sediment supply.

4.2 Methods

4.2.1 XBeach

XBeach is a process-based model that simulates the morphological effects such as beach and dune erosion by individual storms. We used the Kingsday release in this study and refer to Roelvink et al. (2009) for a detailed explanation of XBeach (see also Appendix A). For most model parameters the default value was used. However, the breaking parameter γ was changed from the default value of 0.55 to 0.45, similar to Chapter 2 and the study of Hoonhout and van Thiel de Vries (2012).

Three representative washover geometries were defined (Figure 4.1), based on the geometry at Schiermonnikoog. Geometries 1 and 2 both include dunes with a washover opening, where dune to dune width of the opening was 200 m for Geometry 1 and 600 m for Geometry 2. Geometry 3 is alongshore uniform and lacks dunes. All geometries start offshore at a bed level of 10 m below MSL and contain a subtidal sand bar in the surf zone. The beach gradually slopes with 0.01 m/m to the maximum beach elevation of 2.0 m above MSL. Further onshore, the beach continues with a flat part of 300 m wide, which means that the total beach width (i.e. the sloping part above MSL and the flat part) is 500 m. At dune-lacking cross-shore profiles, such as at the washover openings at Geometry 1 and 2, and Geometry 3, the flat part extends with 150 m which makes the total flat part here 450 m. The dune width is also 150 m in cross-shore direction and the dunes have a maximum elevation of 8 m above MSL. Onshore from the dunes or flat part, the elevation of the barrier gradually decreases to 1 m below MSL for all three geometries.

The grid size in cross-shore direction gradually changed from 20 m offshore to 5 m in the region of interest. In alongshore direction, the grid size was 30 m at the sides and gradually decreased to 10 m in the region of the washover opening. The grid covered approximately 5500 x 4000 m in cross-shore and alongshore direction, respectively. Depending on the approach either time series or constant water levels were prescribed at the offshore boundary. This will be explained in more detail in section 4.2.2. Furthermore, wave characteristics were prescribed at the offshore boundary, where a JONSWAP spectrum was used to translate wave height, period, direction and spreading into a directional wave spectrum. At the onshore boundary, in this case the Wadden Sea, water levels were prescribed. The spin-up time for bed levels was 4 hours. The morfac factor, which accelerates bed level updates and decreases calculation time (Roelvink et al., 2009), was set to 5. The sediment had a d_{50} of 200 μm and a d_{90} of 300 μm respectively, similar to the other simulations in this thesis (see also Chapter 2 and 3). The suspended load transport was calculated with an advection-diffusion equation,

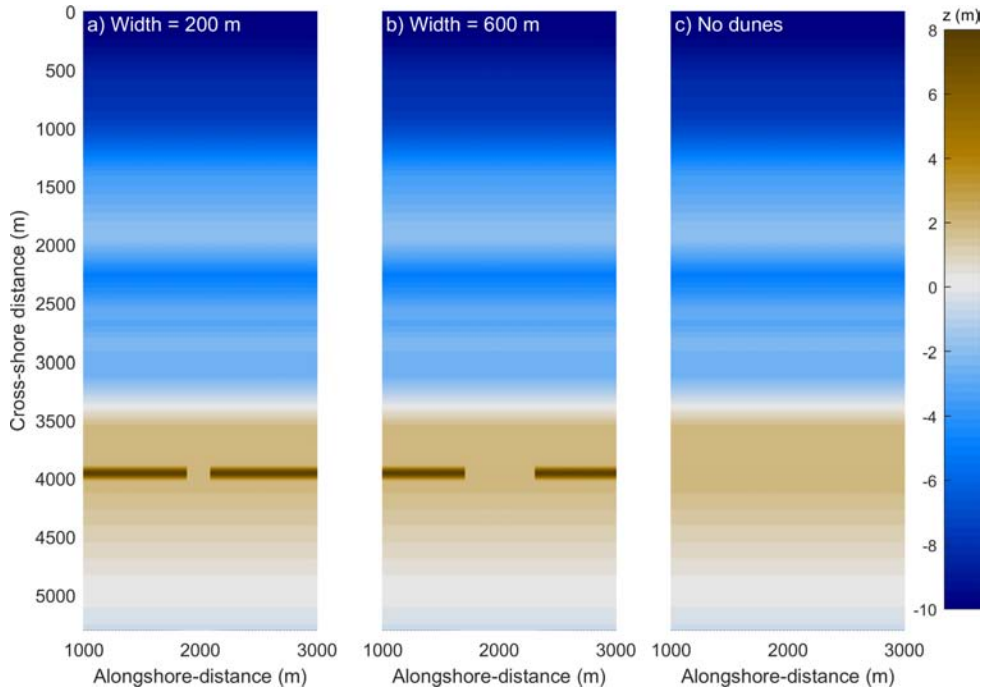


Figure 4.1: Geometries 1, 2 and 3. Characteristics of all profiles are the same, except for the washover width, which is 200 m and 600 m for profiles 1 and 2 respectively. Geometry 3 lacks dunes and is alongshore uniform.

where the equilibrium sediment concentration was obtained from the Van Thiel - Van Rijn equation (van Rijn, 2007; Van Thiel de Vries, 2009).

4.2.2 Converting short-term simulations to medium-term results

The aim of this study was to analyze medium-term (25 years) morphological evolution of the washover openings. For this purpose, two steps were taken. First, the hydrodynamic forcing was schematized using the same inundation class approximation as previously used in Chapter 2 and Chapter 3. In the inundation scheme, class 1 represents mild but frequently occurring inundation events and class 6 represents severe storms (Figure 4.2). All storm classes have a corresponding time-varying water level curve in North Sea and Wadden Sea, and offshore wave forcing that were used as boundary condition at the open boundaries. For a full explanation and analysis of the inundation classes I refer to Chapter 2. In 25 years 250 inundation events occurred and since each storm is characterized by specific time-dependent water levels and wave conditions, it is not possible to simulate the morphological evolution based on all individual storms. Therefore, a second step was needed. A computational method was constructed to represent time-varying water level and wave conditions with single water level and wave conditions. The water level was constant in time and space (i.e. similar in North Sea and Wadden Sea).

In Chapter 3 it was demonstrated that the qualitative erosion-deposition patterns that occurred with time-varying water levels are similar as with simulations performed with constant water levels during peak water level conditions (Figure 4.3a-b). This is because these

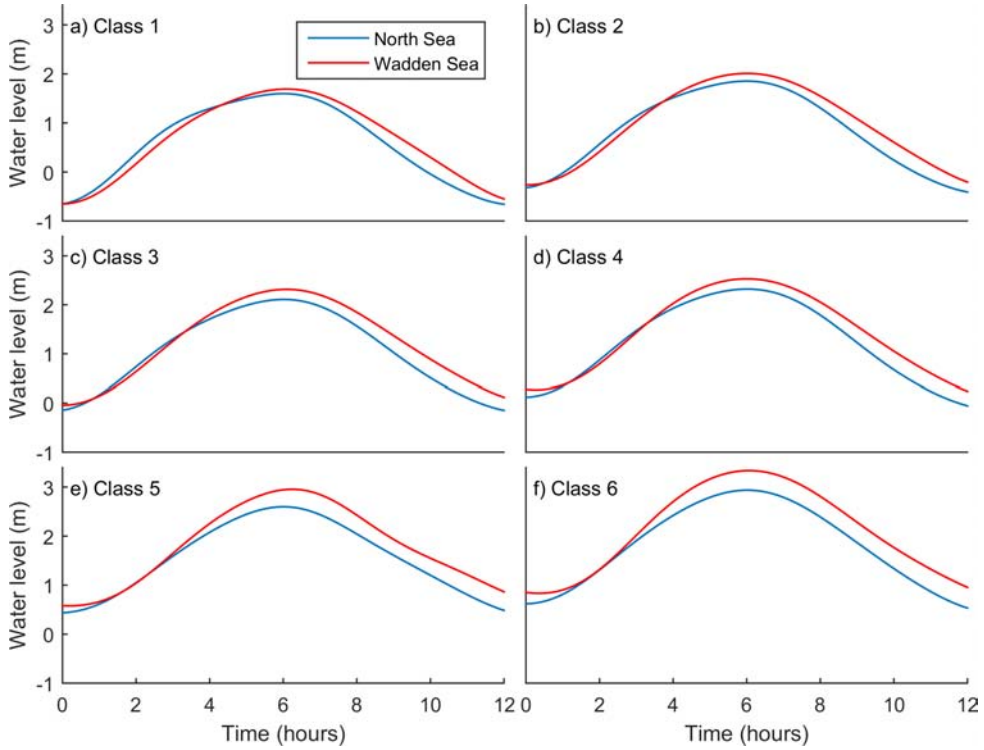


Figure 4.2: Tidal curves in North Sea and Wadden Sea from the six inundation classes, based on Chapter 2.

Table 4.1: Characteristics of each inundation class: The wave height and period, the correction factor, the occurrence in 25 years and the number of hours for the simulations. For class 1 and 2, with conditions during which inundation will not or hardly occur in the selected profiles of this study, the correction factor of class 3 is used.

Class	Wave height (m)	Wave Period (s)	Correction factor	Occurrence in 25 years	Number of hours of simulation
1	2.6	6.3	0.32	575	185.5
2	3.4	7.0	0.32	185	59.7
3	4.0	7.3	0.32	65	21.0
4	4.3	7.7	0.37	20	7.4
5	5.4	8.5	0.23	12.5	2.8
6	5.6	9.1	0.19	7.5	1.4

patterns are mainly determined by strong cross-shore currents that accelerated through the washover opening and decelerated again further onshore. The reversal of the flows that sometimes can occur with time-varying water levels had small influence on the general erosion-deposition patterns (Chapter 2). Furthermore, short waves only influence stirring of sediment but not the transport direction. Infragravity waves are, depending on the phase, more important than short waves for the stirring of sediment (Engelstad et al., 2018)). Although the qualitative patterns are similar, the magnitudes of sediment convergence and divergence were much larger for peak water level conditions than for time-varying water level condi-

tions, with a two orders of magnitude difference. Therefore we used constant water level boundary conditions and applied a scaling factor to calculate how bed level change during one hour of constant water levels relates to the bed level change that occurs during one full storm tidal cycle with time-dependent hydrodynamic boundary conditions. The correction factor (CF) must be determined for each class. First, bed level change per unit time was calculated as:

$$\frac{\partial z_b}{\partial t} = -\frac{\partial S}{\partial x} - \frac{\partial S}{\partial y} \quad (4.1)$$

Here, z_b is the bed level, S is sediment transport. Bed level change for a simulation including the tidal cycle is then linked to a simulation including constant water levels with equations 4.2 and 4.3:

$$\int_0^{tide} \frac{\partial z_b}{\partial t} \text{ tide} \cong CF * \int_0^{1h} \frac{\partial z_b}{\partial t} \text{ const wl} \quad (4.2)$$

$$CF = \frac{\int_0^{tide} \int_A \frac{\partial z_b}{\partial t} \text{ tide} dA dt}{\int_0^{1h} \int_A \frac{\partial z_b}{\partial t} \text{ const wl} dA dt} \quad (4.3)$$

Here, A is the area behind the dunes (where deposition occurred). Using the correction factor for each inundation class, total bed level change was determined by:

$$\Delta z_b = \Delta t \sum_i CF_i * O_i \frac{\partial z_b}{\partial t_{\text{const wl},i}} \quad (4.4)$$

Here, O represents the occurrence per class i . The results are summarized in Table 4.1. In general, the correction factor is smaller for higher classes. This is caused by the trend that surge height in the Wadden Sea rises faster for higher classes than in the North Sea. Therefore, onshore-directed currents are reduced more by this effect for higher classes (Chapter 2). For the constant water level simulations, this effect is not incorporated so that convergence values increase faster than for the simulations with tidal curves and as a result the correction factor decreases.

To test the robustness of this method, we simulated the morphology change caused by class 6 storms during 25 years. This exercise was performed for both the newly developed method and with all inundation class 6 cycles that occurred in 25 years. As depicted in Figure 4.3c-d, erosion in the washover opening and deposition onshore from there occurs. The resulting morphology change for both methods is similar, both in patterns and in magnitudes. Although differences arise, such as the small channel and the larger scour channels that are evolving in the simulation including the tide, simulations with class 6 storm conditions demonstrate that this method can be used to analyze the patterns and magnitudes of morphology change caused by storm-induced inundation for a period of 25 years. However, it is important to note that beach-recovery and aeolian transport during calmer weather conditions are ignored. A short elaboration on how this may influence the results will be given in the discussion section.

4.2.3 Overview of simulations

The simulations can be separated in 3 parts (Table 4.2). To investigate the effect of different classes on morphology change separately for 25 years, they were first simulated stand-alone

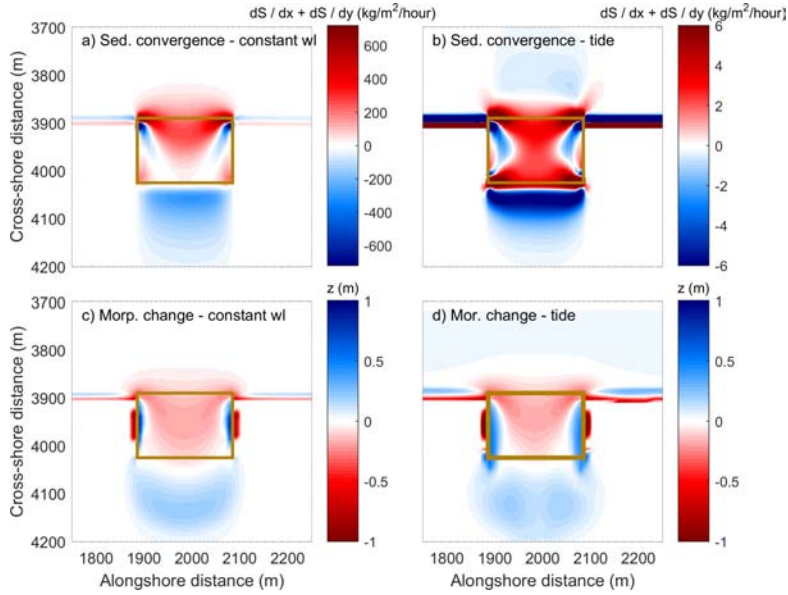


Figure 4.3: Sediment transport divergence and convergence for class 6 for a) constant water levels and b) tidal curves. The values for the tide simulations are averaged over one tidal cycle (12 hour). Morphology change for class 6 for c) constant water levels and d) tidal curves.

(Series A). Series A1 obtain the appropriate simulation time and corresponding morphological duration by using the correction factor from Table 4.1. Series A2 (performed for class 5 storms only) represents a morphological time scale of 1500 years; simulation time is 180 hours. These simulations are performed to investigate whether the washover geometries develop towards an equilibrium. In Series B we simulated all the inundation classes, either from low to high energetic conditions (B1) or from high to low (B2), to investigate the importance of storm order. In Series C, sea level rise is incorporated. Sea-level rise projections are highly uncertain and can vary on a regional scale (Flato et al., 2013; de Winter et al., 2017). For the next 25 years, an extreme sea-level rise of 25 cm may be considered (van der Spek, 2018; Vermeersen et al., 2018). This can have a strong effect on inundation processes and the question is whether this affects the onshore sediment transport rates as well. For Series B and C, transitions between different classes would cause sudden changes in water levels. Therefore, for every transition the simulation was interrupted and the output of this simulation was used as input for the next one (with again 4 hours of spin-up). Class 1 and 2 did not lead to morphology change for Series A and B as water did not reach or overtop the elevation of the washover opening. Therefore, these classes were omitted in the analysis. For series C, class 2 was added again due to the higher mean water levels caused by sea-level rise.

4.3 Results

4.3.1 Individual inundation classes (Series A)

The erosion and deposition patterns for all classes (Series A1) are roughly similar for all combinations of inundation class and washover opening width (Figure 4.4 and 4.5). Chap-

Table 4.2: Series of simulations. In Series A, the inundation classes are simulated individually. In Series B, the classes are combined in different orders. In Series C, sea-level rise (SLR) is added.

Series	Description
A1	Individual classes based on correction factor
A2	Class 5, morphological duration is 1500 years
B1	All classes from low to high
B2	All classes from high to low
C1	All classes from low to high including SLR
C2	All classes from high to low including SLR

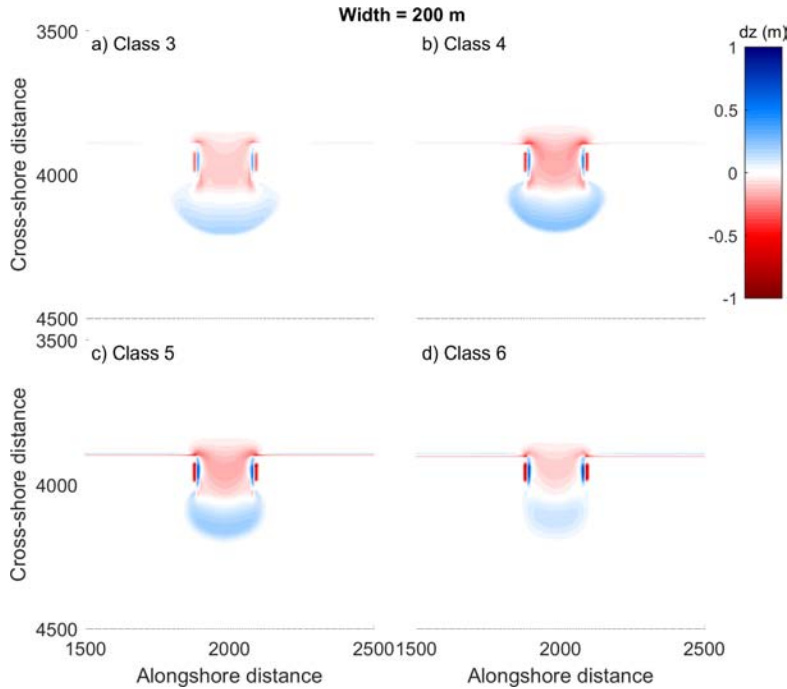


Figure 4.4: Series A1: Bed level change for different inundation classes and a washover opening width of 200 m. Positive (blue) means deposition and negative (red) means erosion.

ter 2 and 3 showed that the cross-shore current is for a large part responsible for sediment transport through a washover opening at a Wadden Island and that these currents accelerate through the opening and decelerate further onshore. Morphology change is in line with these findings (i.e. $\frac{dS}{dx}$ is much larger than $\frac{dS}{dy}$ in equation 4.1). At the wide beach though, currents and sediment transport are small and morphology change negligible. In the washover opening, accelerating currents lead to erosion and onshore transport and sediment is deposited in a fan-shaped feature. Magnitudes of erosion and deposition depend on the combination of opening width and forcing, and can locally be more than 0.3 m.

The simulations without dunes show in cross-shore direction similar patterns, with erosion at the location of the 'washover opening' and beach crest and deposition more landward (Figure 4.6). Currents are not hindered anymore by dunes and therefore morphology change

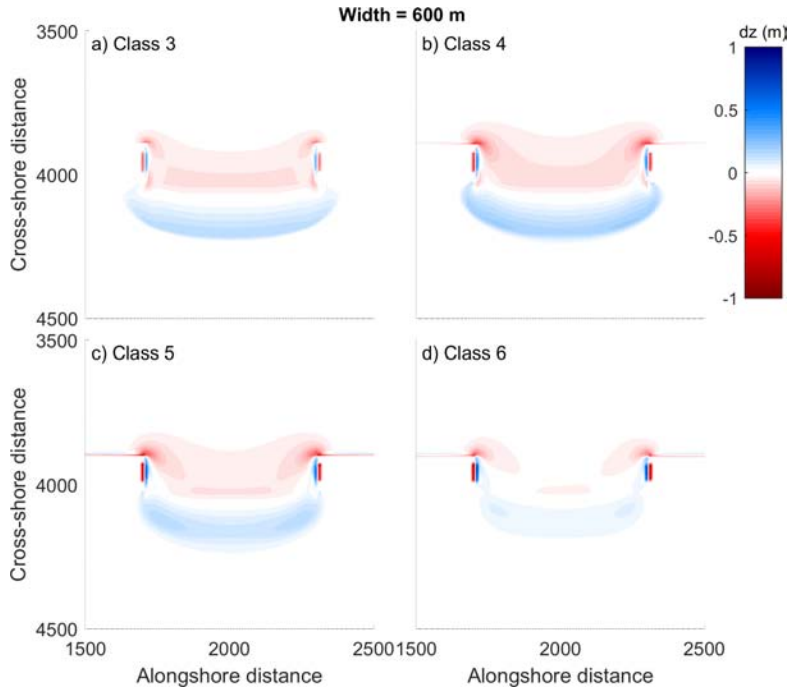


Figure 4.5: Series A1: Bed level change for different inundation classes and a washover opening width of 600 m. Positive (blue) means deposition and negative (red) means erosion.

is uniform in alongshore direction. Currents are on average smaller than for the simulations with dunes, because they lack the acceleration effect due to flow contraction. Therefore morphology change is smaller. For class 6 this means that, next to their low frequency of occurrence, currents are not large enough to cause any visible morphology change (Figure 4.6d).

The total volume of sediment deposited landward of the washover opening (Figure 4.7) for different classes depends on two opposing mechanisms: Higher classes have higher water levels and larger waves (and consequently more wave set-up), which increases the cross-shore flow velocities and thereby the sediment transport and its divergence. On the other hand, the total inundation time decreases for higher classes. As a result, total sedimentation volumes have the same order of magnitude for class 3-5, while class 6 is slightly lower. Class 3 has smaller deposition values than class 4, which is caused by the fact that the water levels of class 3 are close to the threshold level or elevation of the washover opening. Consequently, water depths are so small that currents significantly decrease due to friction and this effect appears to be more important than the longer duration. The simulations with 600 m wide openings lead to more sedimentation than the simulations with 200 m wide openings. However, the increase in deposition is not proportional to the increase in width because the acceleration effect of currents through an opening is stronger for smaller openings (Chapter 3). As expected, simulations without dunes result in much more deposition as sediment can be transported cross-shore along the entire 4000 m wide barrier instead of only through the washover opening.

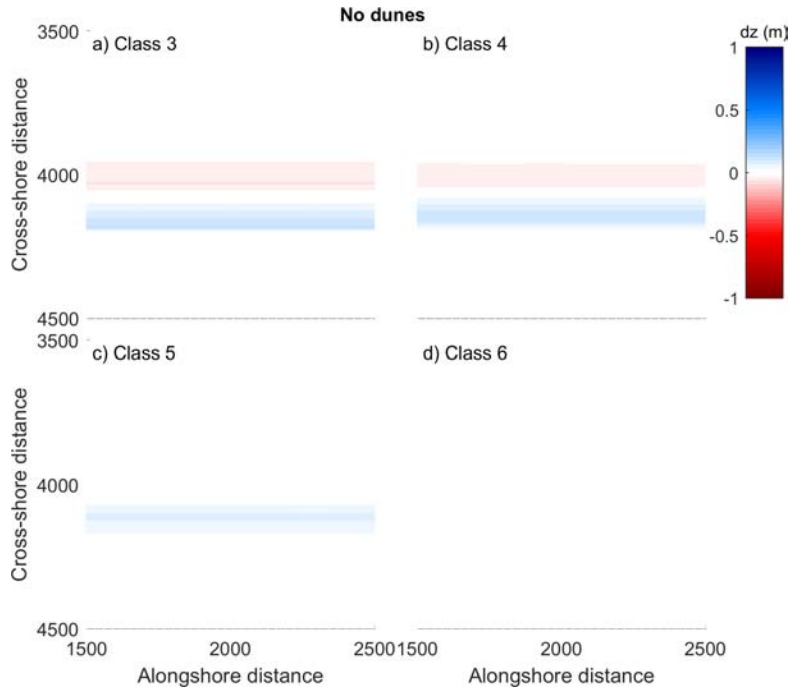


Figure 4.6: Series A1: Bed level change for different inundation classes for the simulation without dunes. Positive (blue) means deposition and negative (red) means erosion.

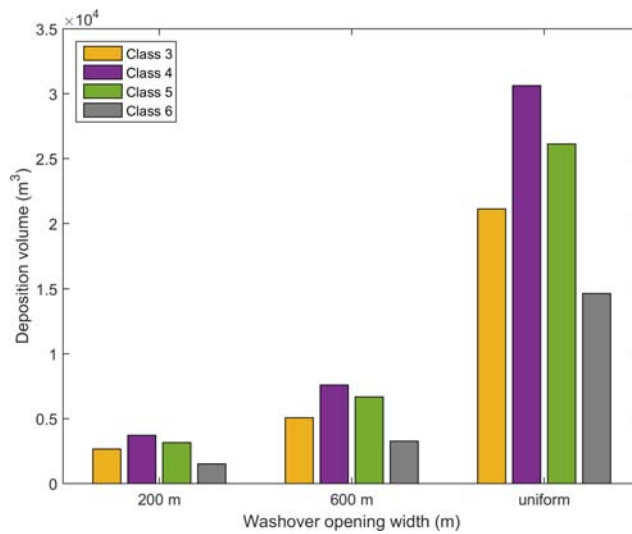


Figure 4.7: Series A1: Total volume of deposition onshore from the washover opening for different inundation classes for both opening widths.

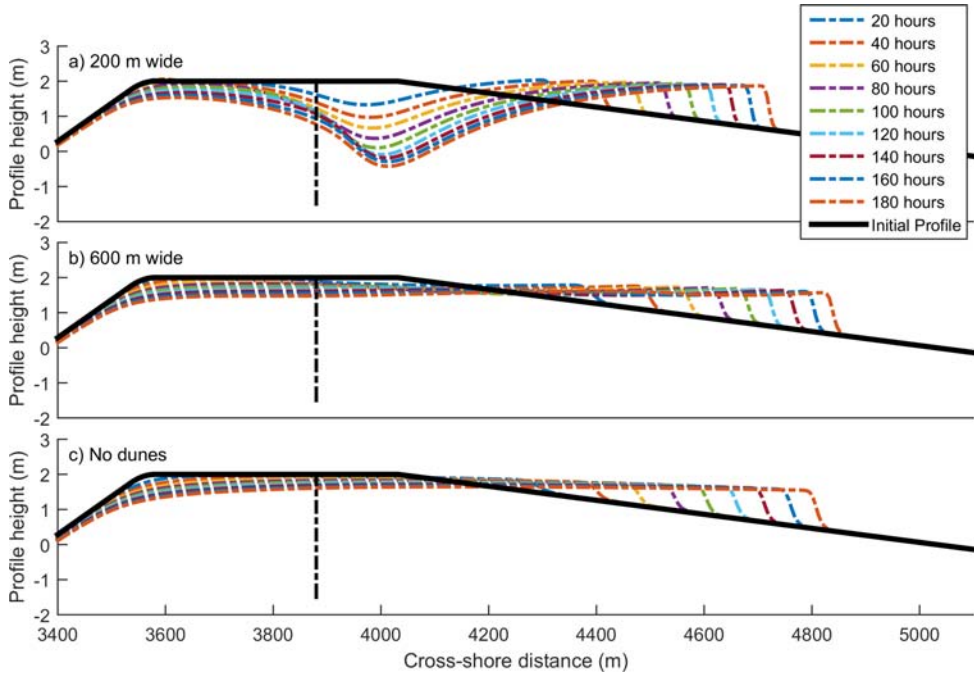


Figure 4.8: Series A2, class 5, for a washover opening width of 200 m and 600 m wide, and for the profile without dunes. The 1D profiles are located in the middle of the openings in cross-shore direction. The black dash-dotted line indicates the transition between beach and washover opening.

Class 5 storms were also simulated for a longer time (morphological time 1500 years) to investigate whether the system evolves towards equilibrium. Figure 4.8 shows 1D profiles in cross-shore direction in the middle of the washover opening for geometries 1 and 2. At the 200 m wide washover opening, bed levels keep decreasing by ongoing erosion. The gradients in the cross-shore current from beach to opening, responsible for this trend, are affected by three important and opposing mechanisms: Firstly, currents tend to accelerate through a gap due to flow contraction. Secondly, currents tend to increase when water depths become larger, for instance due to decreasing bottom friction. Thirdly, currents tend to decelerate when the water depth locally increases due to continuity effects. The spatial changes in flow magnitude directly affect the sediment transport, and flows that increase in landward direction result in erosion and the other way around for decreasing flows. The third mechanism is illustrated with a schematic picture (Figure 4.9). Although on a larger scale erosion would lead to larger water depths and larger currents, this is different when erosion occurs on a more local scale. In order to fulfill the rules of continuity currents decelerate. The first mechanism is more important than the third for both geometries, as erosion occurs in the opening for all time steps. The erosion rate is larger for the smaller opening, caused by the stronger flow contraction effect. Where the beach first stays relatively intact for both geometries, eventually it starts eroding as well. Geometry 3 has a similar morphological evolution as the middle transect of the 600 m washover opening. This indicates that the processes in the middle of the 600 m washover opening are hardly affected by the dunes, in contrast to the geometry with a width of 200 m opening.

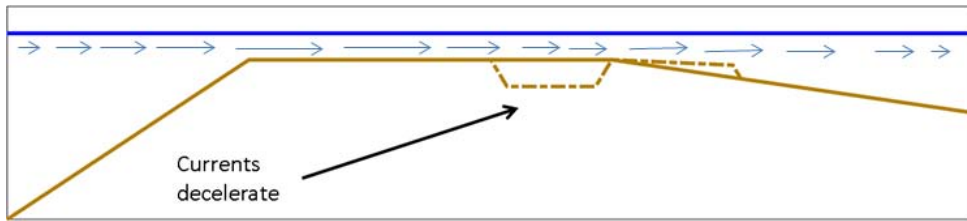


Figure 4.9: Schematic pictures that illustrates why currents in the washover opening become smaller when erosion occurs. The blue arrows indicate patterns in flow velocity.

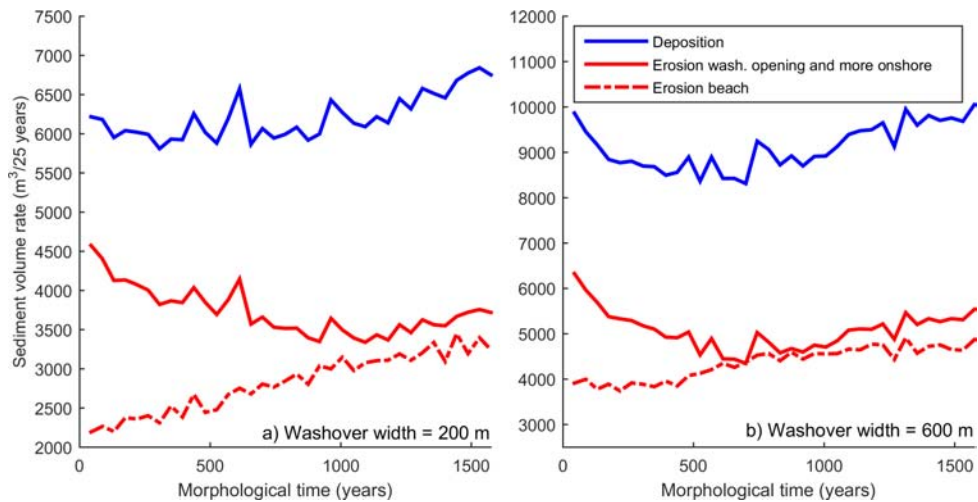


Figure 4.10: Deposition onshore from the washover opening and erosion at the beach and in the washover opening (and further onshore) for 1500 years of morphological time

Deposition rates as function of time show that the geometries do not evolve towards equilibrium (Figure 4.10). For the 200 m wide opening deposition rates stay approximately constant until roughly 700 years of morphology time. After this period the volume rates even slightly increase. This means that the fan-shaped feature keeps expanding over time. The 600 m wide opening shows similar patterns, although first a decreasing instead of constant trend is visible until 700 years. The erosion rate in the washover opening and further onshore decreases until this moment in time. After that, it stays constant or even increases again. This is caused by two opposing mechanisms: Currents in the opening get smaller due to larger water depths (Figure 4.9), which decrease erosion values. However, erosion in between the opening and the area where deposition starts increases. This area moves further onshore as function of time and results from a morphological feedback: Initially the area accretes due to decelerating currents immediately onshore from the washover opening. Consequently, water depths become smaller, currents accelerate and deposition changes into erosion. This last mechanism becomes more dominant over time and stops the decreasing erosion trend onshore from the beach. The erosion at the beach (ie. the area offshore from the dunes and washover opening) keeps increasing as function of time, which is one of the reasons why deposition rates do not decrease on the long-term.

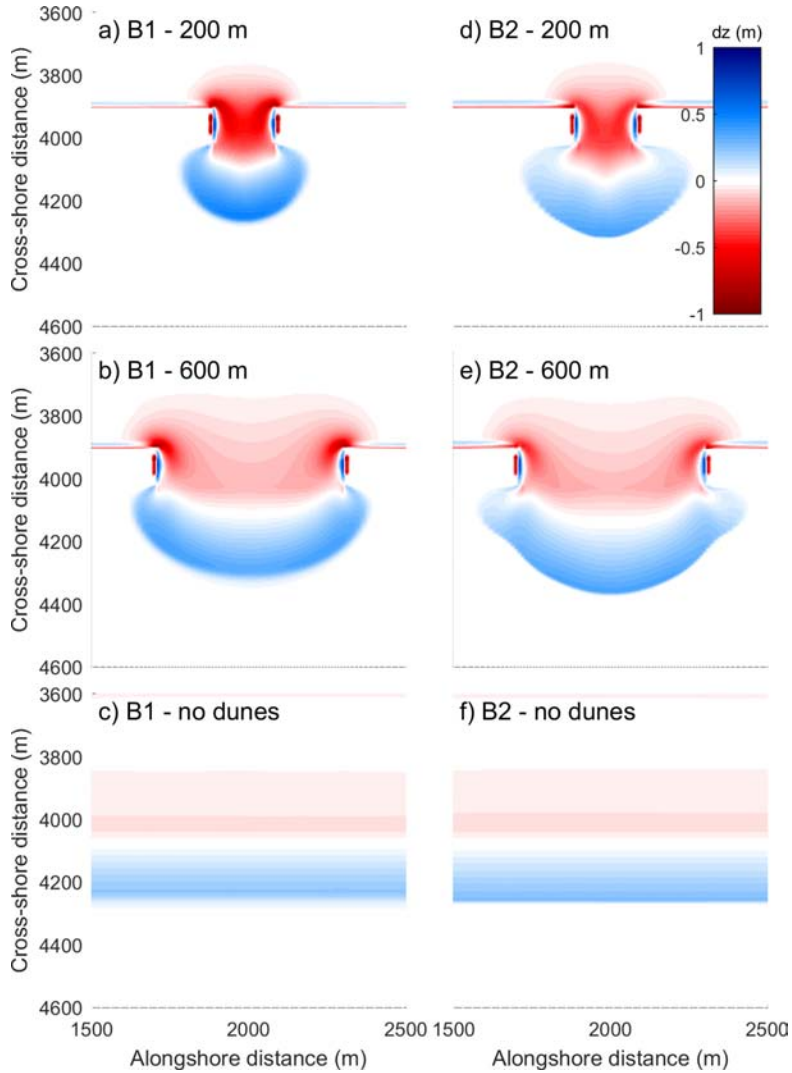


Figure 4.11: Morphology change for series B1 and B2 for a washover opening width of 200 m and 600 m and for Geometry 3. Positive means deposition and negative means erosion.

4.3.2 Morphological evolution including all storm events (Series B)

Series B1 and B2 show similar patterns of erosion and deposition as the individual classes, but magnitudes are larger because these series include the effects of all storms during 25 years (Figure 4.11). Bed levels increase, depending on the specific simulation and location, more than 0.5 m. Total deposition volumes of Series B1 (from low to high energetic conditions) are approximately 25% and 20% larger than of Series B2 (from high to low) for the 200 m and 600 m wide opening, respectively.

The difference between Series B1 and B2 is mainly caused by class 5 and 6 (Figure 4.12), which results in larger deposition volumes when high energy events take place after the

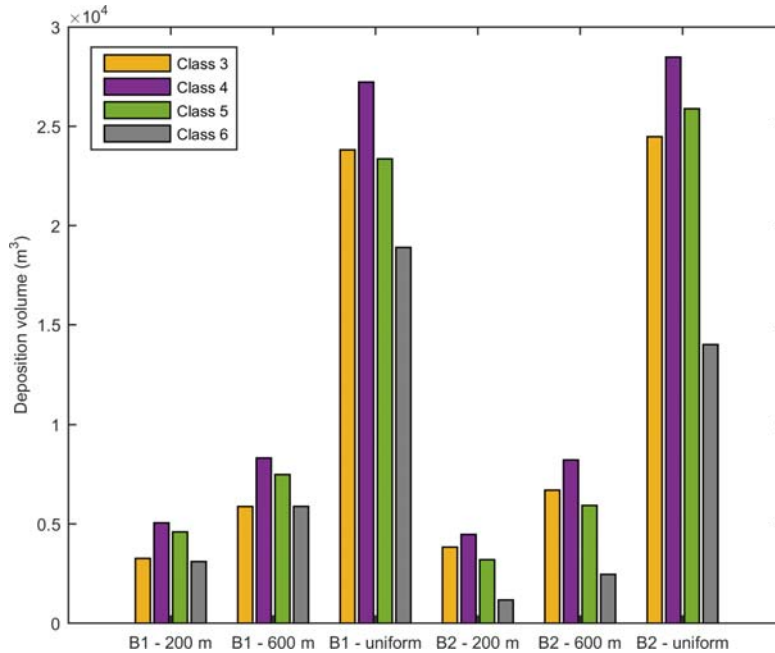


Figure 4.12: Contribution of each class to the total deposition volume onshore from the washover opening. For Series B1 classes were simulated from low to high energy conditions and vice versa for Series B2.

smaller storms. Class 4 resulted in similar deposition values, and class 3 caused more sedimentation for Series B2, however, this effect is smaller than the reversed effect of class 5 and 6. The highest classes lead to more sedimentation when they are simulated after the lower classes, because the beach or washover elevation is already slightly lowered due to erosion during the smaller inundation events. Larger water depths during class 5 and 6 then result in larger currents, more sediment transport and more deposition onshore from the washover opening.

4.3.3 The effect of sea-level rise (Series C)

The erosion and deposition patterns for the simulations with sea-level rise are similar to the ones without. Series C1 (from low to high energy) leads to more erosion and deposition than Series C2, similar as in Series B. Total sedimentation volumes are up to 60% larger when sea-level rise is included. This indicates that sea-level rise can accelerate sedimentation onshore from dunes and washover openings at the Wadden Islands.

To investigate whether the synthetic island is able to keep up with sea level rise in the simulations, the accommodation space created by 25 cm of sea level rise is compared with total deposition volumes onshore from the washover opening or dunes. To define the accommodation space, only the area onshore from the dunes higher than 1 m above MSL is taken into account: The area lower than that is not morphologically active during storms due to the large width of the island. Figure 4.14 shows that deposition volumes are strongly restricted by the presence of dunes. For the dune-lacking simulation, the total area in alongshore direction is morphologically active during storms from the North Sea while this is not the case for the geometries including dunes and washover openings. However, even for the Geometry 3, the

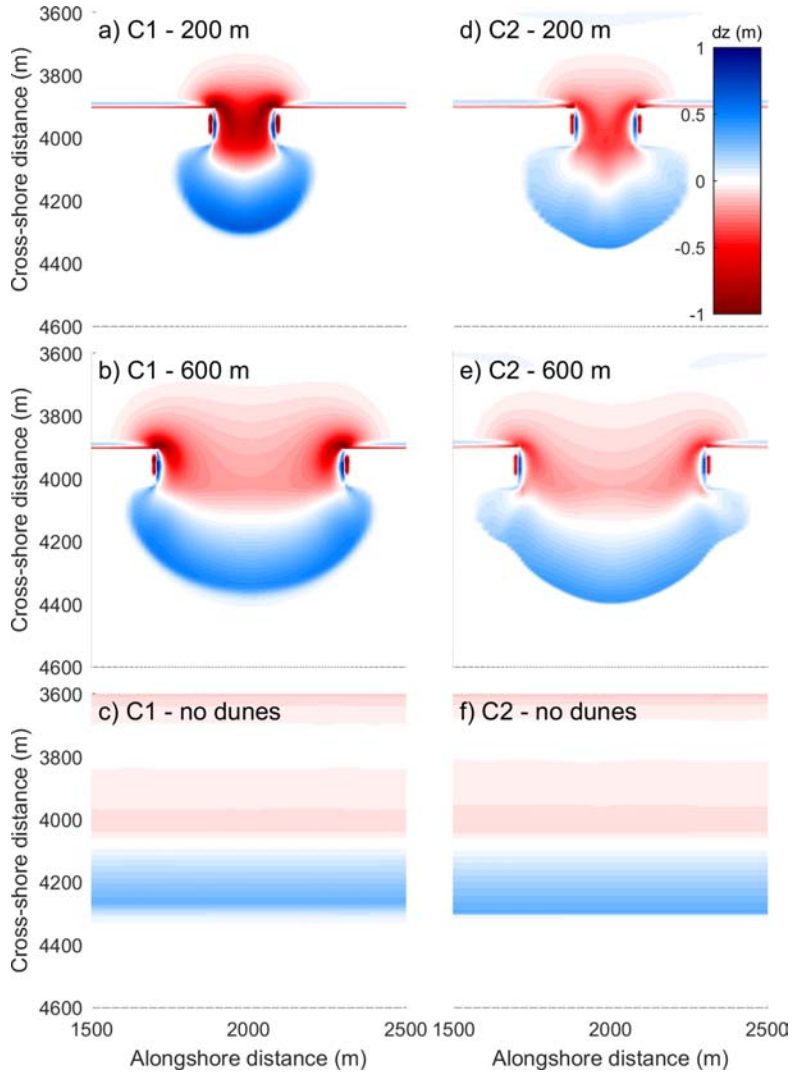


Figure 4.13: Morphology change for series C1 and C2 for a washover opening width of 200 m and 600 m and for Geometry 3. Sea-level rise is added. Positive means deposition and negative means erosion.

deposition volume is only 34% of the accommodation space created by sea level rise, which shows that this island is only partly capable to keep-up with sea level rise.

4.4 Discussion

4.4.1 Deposition volumes

This study investigated the medium-term (25 years) effects of storm-induced inundation on morphology change at the Wadden Islands, and more specific at the beach, washover open-

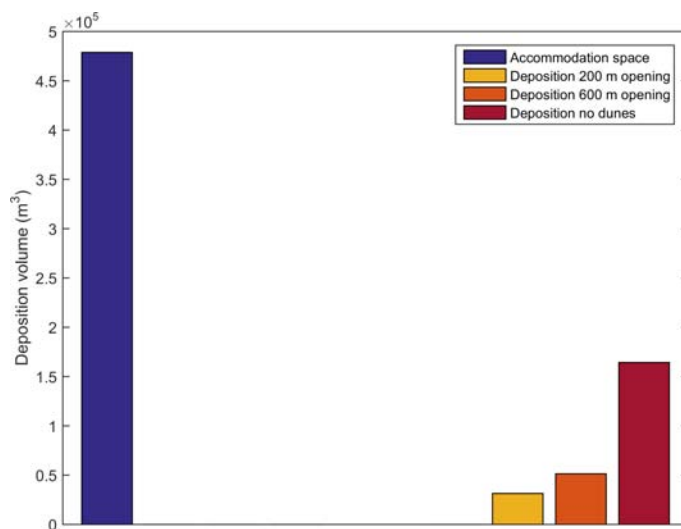


Figure 4.14: Accommodation space created by 25 cm of sea level rise versus sedimentation volumes for the three different profiles, based on series C1.

ings and washover fans (from offshore to onshore). This was done by using the process-based model XBeach. A total deposition volume per meter coastline of approximately 85 m^3 is found in 25 years, based on the 200 m wide opening. Comparable model studies in the Wadden Area to validate this value are scarce, however, Nielsen and Nielsen (2004) monitored the development of a washover system after a breach at Skallingen, Denmark. They found that in 13 years (after which the opening was closed due to aeolian transport) the total deposition volume in the washover fan per meter coastline was $345 \text{ m}^3/\text{m}$, approximately 4 times larger than simulated in this study for a period that is approximately 50% in length. This suggests that XBeach underestimates sediment transport through and deposition onshore from a washover opening. However, differences in tide, wave climate and washover geometry may also play a role. For example, the elevation of the washover opening at Skallingen was with 1.8 m above MSL relatively low: Chapter 3 shows that transport magnitudes are very sensitive to the elevation of the opening relative to the height of the water level.

Deposition volumes per meter coastline as a result of one single extreme storm or hurricane were determined for various locations in the world. For example, at Miami Beach, USA, 54 m^3 (Reardon, 1926), Long Island, USA, 75 m^3 (Redfield and Miller, 1957), Assateague Island, USA, 20 m^3 (Leatherman et al., 1977) and Cozumel, Mexico, 28 m^3 (Morton and Sallenger, 2003) were measured. Although these values are lower than found in this study, they represent results of only one event instead of 25 years. This difference may be related to the sediment source. During the storm/hurricane at these locations and due to the local geometry of the coast, the relatively low dunes will be initially breached before overwash and inundation can develop. Due to their destruction though these dunes may act as an important source of sediment. Moreover, XBeach may underestimate erosion and deposition volumes. I refer to Chapter 5 for a further assessment and discussion of the performance of XBeach.

4.4.2 Aeolian processes and beach recovery

Aeolian transport during dry-beach conditions with sufficient wind was not yet taken into account, while this can be an important factor for amongst others beach recovery, dune growth or the growth/closure of washover openings (Oost et al., 2012). In the past, coastal models that describe aeolian transport were always developed independently from models describing hydrodynamics (Sherman and Bauer, 1993). The first generation of aeolian models mainly used parameterizations based on the velocity threshold for wind transport (e.g. Bagnold, 1937; Owen, 1964; Sorensen, 2004). Currently, process-based models for aeolian transport become available, such as the AEOLIS model (Hoonhout and de Vries, 2016). This gives opportunities to couple wind transport models with process-based hydrodynamic models such as XBeach, which recently indeed has been performed for AEOLIS (Cohn et al., 2019) and another dune profile model Duna (Roelvink and Costas, 2019).

The results in this study show erosion of the beach during inundation which is not being recovered (Figure 4.8). However, beach recovery often occurs caused by hydrodynamic processes during calm-weather conditions. This can lead to an extra source of sediment for washover deposits during storms. Moreover, a recovered high and wide beach provides better conditions for aeolian transport which can lead to extra washover deposits as well.

4.5 Conclusions

In this study I used XBeach for simulating medium-term (25 years) effects of inundation events on morphology change at washover openings on barrier islands. By using a modeling approach that is based on the use of constant (and equal) water levels in both North Sea and Wadden Sea, a proxy is developed for the morphological impact of full tidal cycles. Due to this methodology I was able to reduce calculation times by a factor 100 while maintaining approximately the same morphological results. Results show that inundation events erode the washover openings with values of more than 50 cm in 25 years and deposit this sediment further onshore. This results in similar amounts of vertical accretion just landward of the washover openings. When a high rate of sea-level rise is taken into account (1 cm/y), deposition values increase with approximately 60%. And although vertical accretion rates increase as well, it is clear that inundation events do not entirely counteract the effects of sea level rise. Due to the low-lying character of the washover openings, relatively mild but frequently occurring inundation events must be considered for their long-term development. Different sequences of storms (from low to high-energetic and vice versa) cause a difference of 20-25% in sedimentation. The cumulative effect is largest for a storm sequence that develops from low energetic to high energetic conditions.

Chapter 5

The morphological response to storms at Rottumeroog; an island without active coastal management since 2005

Abstract

Since 2005, beaches and dunes are no longer maintained at Rottumeroog, an uninhabited island in the Netherlands. Furthermore, the island is characterized by a natural washover, interrupting the dune system. This makes this island an ideal case study to investigate the natural evolution of a barrier island in absence of coastal management, and specifically to study the evolution of washover openings and the landward supply of sediment. To this end, first all five digital elevation maps (DEMS) available for this area since 2005 were investigated. The first years since 2005 are characterized by strong erosion of the beach and foreshore, followed by the development of a 600 m wide breach in the dunes. This breach developed into a washover and has been active since then. Bed level elevation in the washover increased with values up to 80 cm and with $62 \text{ m}^3/\text{m}$ (volume per meter coastline) in one winter. Secondly, XBeach simulations were performed to analyze the processes that caused the morphology change in the winter of 2016-2017 and to test the performance of XBeach for inundation-induced morphology change at a Wadden Island. Qualitative patterns of beach erosion and sedimentation in the washover and at the island tail were simulated reasonably well, however, magnitudes were strongly underestimated. Possible reasons are tide- and wind driven currents that are not taken into account and the sheltered location of Rottumeroog against North Sea waves. Using a larger-scale model of the entire area might improve the modeling results.

5.1 Introduction

Coasts of Wadden Islands in the Netherlands, Germany and Denmark are originally diverse containing areas with high dunes and beaches, lower dunes that erode at times and lower sandy areas. However, the Wadden Islands have experienced major changes due to the implementation of a range of coastal protection measures (Oost et al., 2012). For example, in the past natural gaps in the dunes, known as washover openings, were closed by artificial sand drift dikes and more recently the islands were nourished with sand to maintain the coastline. This followed a global trend where many dunes or dikes at barrier islands were strengthened in the last decades (McNamara and Lazarus, 2018). However, the lack of inundation events in the area landward from the dunes has several consequences for the long-term development of barrier islands. First of all, storm-induced sediment input, assumed to be important for the long-term vertical growth of the island, is lacking (e.g. Moore and Murray, 2018). As a result, the closure of the washover openings prevents the islands from the possibility to keep up with sea-level rise in a natural way. Secondly, the lack of flooding and salt-water intrusion

during storms limits the development of coastal ecosystems and reduces the biodiversity of the islands. A solution for both problems could be the re-opening of the washovers, which is considered by Dutch coastal zone management authorities for the uninhabited areas such as the nature reserves at the island tails of Schiermonnikoog and Terschelling.

Before taking and implementing this decision, more research is needed to analyse and predict how Wadden Islands will respond to such a measure. More specifically, better insights in erosion and deposition patterns caused by storm-induced inundation in natural conditions are required. However, nowadays all the large Wadden Islands are characterized by artificial measures such as the man-made or anthropogenic sand-drift dikes. Therefore, in this chapter I study the morphological response of Rottumeroog, a small barrier island that is subject to natural processes since 2005 (Figure 5.1). The last human intervention (a beach nourishment) was carried out in 2005 and since then no measures have been implemented.

The first aim of the present morphological study is to determine the erosional and depositional patterns in an area characterized by a washover opening and the frequent occurrence of inundation. Based on Digital Elevation Models (DEM's) a quantitative assessment will be made of the deposition and accretion volumes in the local area of the washover. The second aim is to compare this data with the morphological developments in reference areas to analyse the effectiveness of a washover in facilitating a landward gain of sediment and vertical accretion. Reference areas can contain high dunes or can be dune-lacking island tails. For example, Nielsen and Nielsen (2004) showed that although erosion and deposition both took place in an area with a washover at Skallingen, Denmark, net sedimentation occurred due to the formation of washover deposits. However, cross-shore profiles that contained high dunes experienced net erosion, as the dunes eroded but this sediment could not develop into washover deposits. The third aim is to apply the XBeach model and to test the applicability and validity of the model. The use of a process-based model can contribute to a better understanding of morphological patterns and improve coastal zone management, for example in developing the design parameters of washover openings. In Chapters 2-4 I used XBeach (Roelvink et al., 2009) as modeling tool to investigate the effects of inundation events at island tails or washover openings, but for a 2D real-case scenario like Rottumeroog, it was not yet validated for parameters such as sediment volumes and erosion-deposition patterns.

This chapter starts with the methods (section 2) and results (section 3) of the analysis of the DEMs, where research aims 1 and 2 are investigated. It continues with the methods and results of the XBeach simulations, where research aim 3 is investigated. The chapter ends with a discussion (section 5) and conclusions (section 6).

5.2 Methods: analysis of morphological development of Rottumeroog

Rottumeroog is a small Wadden Island in the Netherlands that is 0.5-1 km wide and approximately 3 km long (Figure 5.1). At both sides of the barrier island a tidal inlet or tidal channel is located and the Eems-Dollard estuary is located more to the East. Rottumeroog is characterized by a shallow subtidal part and small beach plain in the west, a dune area in the middle and an island tail in the east. Dunes in the middle are nowadays interrupted by a 600 m wide washover opening. A vegetated area is present onshore from the washover opening. In 1990, it was decided to maintain the coastline at its position as it was recorded in the same year; the "1990 shoreline" became the benchmark for future coastal zone management. However, since 2005 the Rottum area (i.e. Rottumeroog and Rottumerplaat) is excluded and no longer nourished. In this chapter, the morphological development of Rottumeroog since then is analyzed by using all available DEMs. The morphology of Rottumeroog below and above mean



Figure 5.1: Overview of Rottumeroog and the surrounding area, including tidal inlets, neighbouring Wadden Islands and the Eems Dollard estuary. Source: Google Earth.

sea level (MSL) has been measured by Rijkswaterstaat (Dutch Ministry of Infrastructure and Water Management) for five different years since 2005. For 2005 and 2013, the DEMs are based on so-called Vaklodingen; the bathymetry was measured with a grid size of 20 m in both directions using a single-beam echo sounder (Perluka et al., 2006). The area above MSL was measured with a LiDAR system. For 2007, 2016 and 2017, coastal LiDAR data were obtained with a resolution of 5 m (2007) or 2 m (2016, 2017).

Two different volumes were defined. Firstly, total volumes for the entire area higher than 0.5 m above MSL were calculated. This boundary was chosen, because Rottumeroog sometimes connects with the 'Zuiderduintjes', a very small island south from Rottumeroog, when this boundary would be equal to 0 m (above) MSL (Figure 5.1). The area will be considered as the "entire island" in the present analysis. Secondly, volume calculations for this study mainly focused on the area indicated by the green box as shown in Figure 5.2. The green box is the area of Rottumeroog that includes dunes and the large washover fan, but excludes the low-lying parts in the west and the east of the island. The green area is fixed in contrast to the area bounded by the 0.5 contour line and will be regarded as the "central part" of the island.

The central part was further subdivided into morphological units (Figure 5.3). The beach is defined as either the sandy area below 3 m in front of the dunes, or as being an open area which connects at both sides with the sea. The beach was separated into two parts (beach west and beach east) to illustrate an opposing trend for both beaches. The boundary between both systems was slightly arbitrary. The dunes are the vegetated area higher than 3 m above MSL and were separated into two parts as well for the same reason and at the same alongshore location. The washover is the sandy area higher than 2 m and behind the (hypothetical) dune row. Offshore it either connects to the dunes or beach, onshore it connects to the salt marsh, which is the vegetated area below 3 m. The boundary between washover and salt marsh is manually determined with Google Earth for different years. In addition to the 3D morphological analysis, three different cross-shore transects were studied in more detail (locations are shown in Figure 5.2) that represent the washover area, the dune area east from it and the eastern island tail, respectively.

5.3 Morphological analysis

5.3.1 Analysis of DEMs Rottumeroog

Comparing DEMs of 2013 with 2007 and 2005 (Figure 5.2) and the development of the morphological sub-units in the central part in the same years (Figure 5.3) indicates strong beach erosion in the middle, whereas the east and west part of the beach have expanded. Furthermore, dunes eroded in the middle, while the dunes in the south-eastern corner of the central part grew in elevation. This dune growth continued until 2017. The washover system partly developed and became visible in the DEM of 2013 (i.e. a part of the dunes eroded to values lower than 3 m above MSL), but a large part of the dunes in front of the salt marsh was still in place. The washover partly covered the previously existing salt marsh. From 2013 to 2016, the beach was characterized by ongoing retreat. The breach in the dunes was expanding and reached a width of approximately 600 m, creating the present washover system. Since then the washover system was characterized by vertical accretion. From 2016 to 2017, the beach maintained its declining trend while the washover system and the more onshore part of the island tail is characterized by expansion.

Three transects across the island (see Figure 5.2a for locations) illustrate the morphological patterns that emerge in time (Figure 5.4). The first transect, located in the washover opening, shows the continuous beach erosion since 2005, where the shoreline migrated onshore over a distance of about 200 m (Figure 5.4a,d). Furthermore, dune breaching took place. Firstly, dune erosion occurred in the form of the steepening of the dune face, a landward displacement of the dune front and subsequently a narrowing of the dune. Finally, the dune breached. From 2016-2017 (the purple versus the green line), it can be observed that beach erosion continued while sedimentation occurred in the washover. More specifically, the washover elevation increased with values up to 0.8 m in the winter of 2016-2017, and the volume of sedimentation per meter coastline in this period was $62 \text{ m}^3/\text{m}$. The second transect shows similar beach erosion patterns, however, dune development is in contrast to transect 1 in opposite direction, because in 12 years time the dune crest grew to 9 m above MSL (Figure 5.4b,e). The third transect at the eastern island tail shows beach accretion between 2005-2013. Similar to transect 1, beach erosion occurred from 2016-2017, while areas located more onshore gained sediment (Figure 5.4c,f). Increase in elevation was slightly smaller than in the washover area (increase up to 0.5-0.6 m), but as the cross-shore extent of the area of sedimentation was slightly larger, sedimentation volume per m coastline was roughly similar.

The evolution of the total volume of sediment for the central part and entire island are shown in Figure 5.5a. The central part first gained sediment but overall slightly lost volume, which mainly happened in the period 2013-2016. However, for the entire island the volume increased. Volume changes of the dunes and beaches in the central part are illustrated for two areas (Figure 5.5b). For the western part (dark blue line in Figure 5.5b), dune erosion occurred from 2007 to 2017 and volumes decreased with 50%. For the eastern part (light blue line in Figure 5.5b), dune volume slightly increased but with smaller magnitudes than at the western part. The volume of the beach at the western part strongly decreased until 2013 but slightly increased again after 2013. The decreasing trend of the beach volume in the west was compensated by the growth of the beach at the eastern part from 2007 until 2013. As a result the total beach volume stays relatively constant but the "center of gravity" moves eastward, which is in line with the general migration direction of Wadden Islands. The volume of the washover opening increased from zero to $200\,000 \text{ m}^3$ due to the dune breach in 2013 and the corresponding shift from salt marsh to washover. The salt marsh volume decreased with slightly larger amounts. One would expect that the combination of salt-marsh and washover

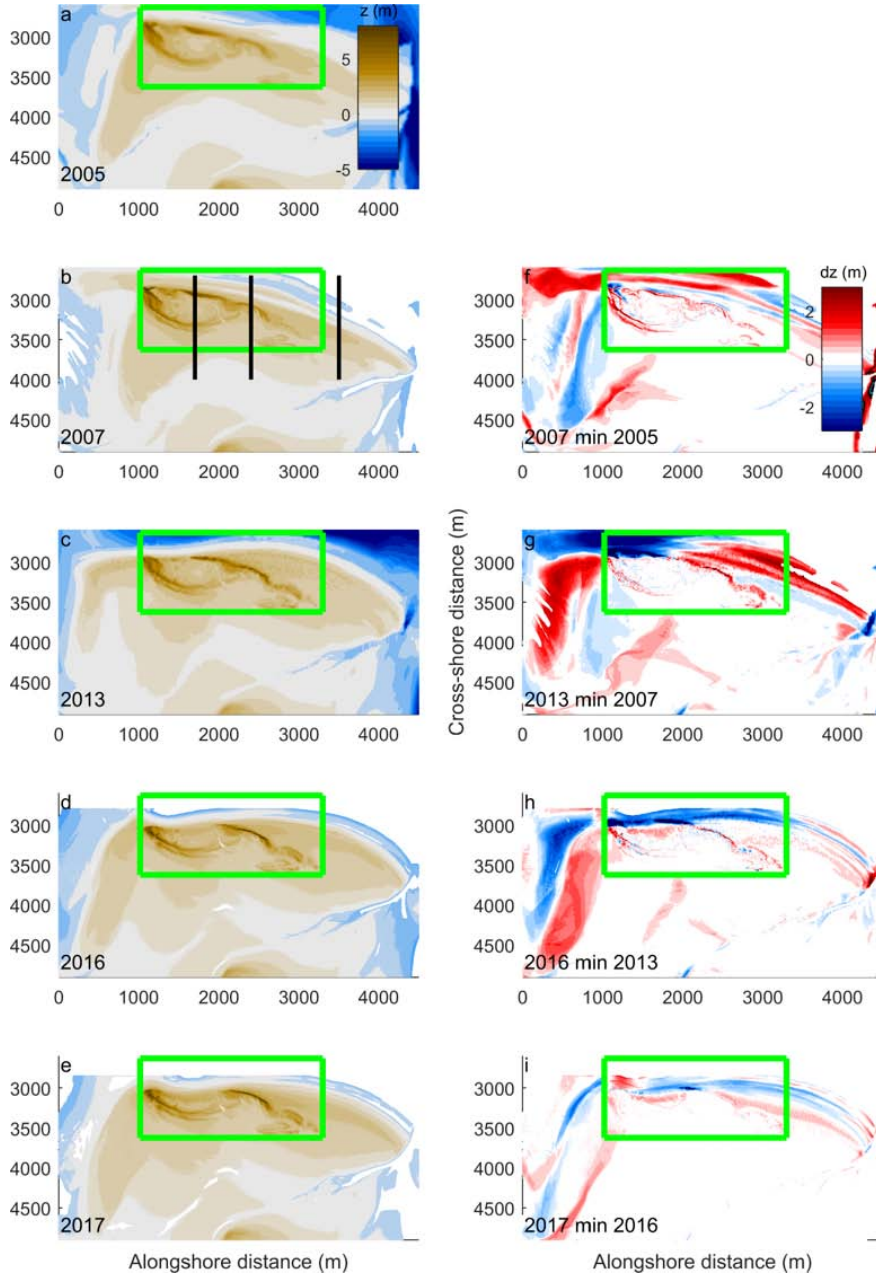


Figure 5.2: Digital Elevation Maps (panels a-e) and elevation difference maps (panels f-i) of Rottumeroog of 2005, 2007, 2013, 2016 and 2017. The green boxes (central part) represent the main part of Rottumeroog including the dunes. The black lines in panel b represent three transects that are used for further analysis.

would increase in volume due to the storm-induced sedimentation. However, this is not the case because the beach moves southward at the expense of the washover area.

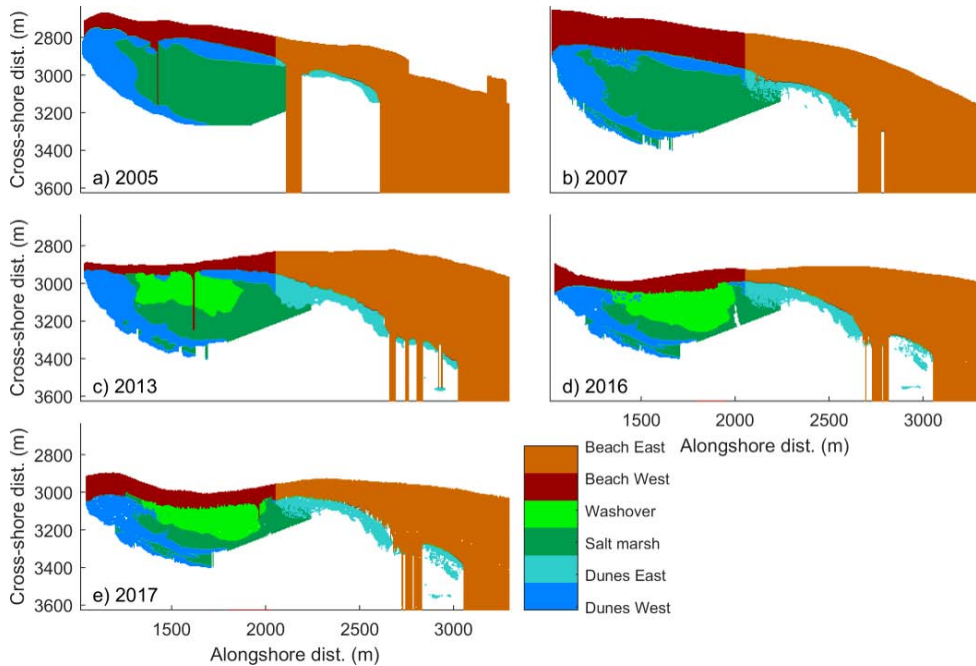


Figure 5.3: The central part subdivided into the beach (west and east), dunes (2 parts), salt marsh and washover for all years.

The area per bed level height for the central part is used to investigate at which elevation bed level change has occurred (Figure 5.6). For all years, the majority of the island has bed levels below 3 m. The bed level composition in 2007 and 2013 was similar for the beaches as well as the dunes (red and yellow line respectively in Figure 5.6), although strong morphologic changes were observed in between these years as shown in Figure 5.2 and Figure 5.3. The decrease in surface area between 2013 and 2016 was mainly occurring at the beach at a profile elevation between approximately 1.0 and 1.5 m above MSL, as depicted by the lowering of the yellow 2013-line compared by the purple 2016-line in Figure 5.6. From 2016 to 2017 the surface of the central part stayed the same, but the distribution changed. The beach and washover opening showed a sediment shift from lower to higher areas, as shown in Figure 5.3. The contribution of the area between 1 and 2 m above MSL decreased, while the contribution of the area between 2 and 3 m above MSL increased. The dune surface remained nearly constant.

The morphological development of the central part is further analyzed by investigating total erosion and deposition volumes as function of alongshore direction (Figure 5.7). To this end, erosion is regarded as negative bed level differences, while deposition is regarded as positive bed level difference. The only period that is characterized by net deposition over the entire island is 2005-2007, especially in the western section of the central part. The period 2007-2013 shows erosion at the western part and deposition at the eastern part. In the period 2013-2016 (Figure 5.7c), strong erosion dominates along the whole area. From 2016 to 2017, total deposition volumes roughly match with total erosion volumes, similar to what is observed in Figure 5.5a (green line). Deposition values along the washover and island tail

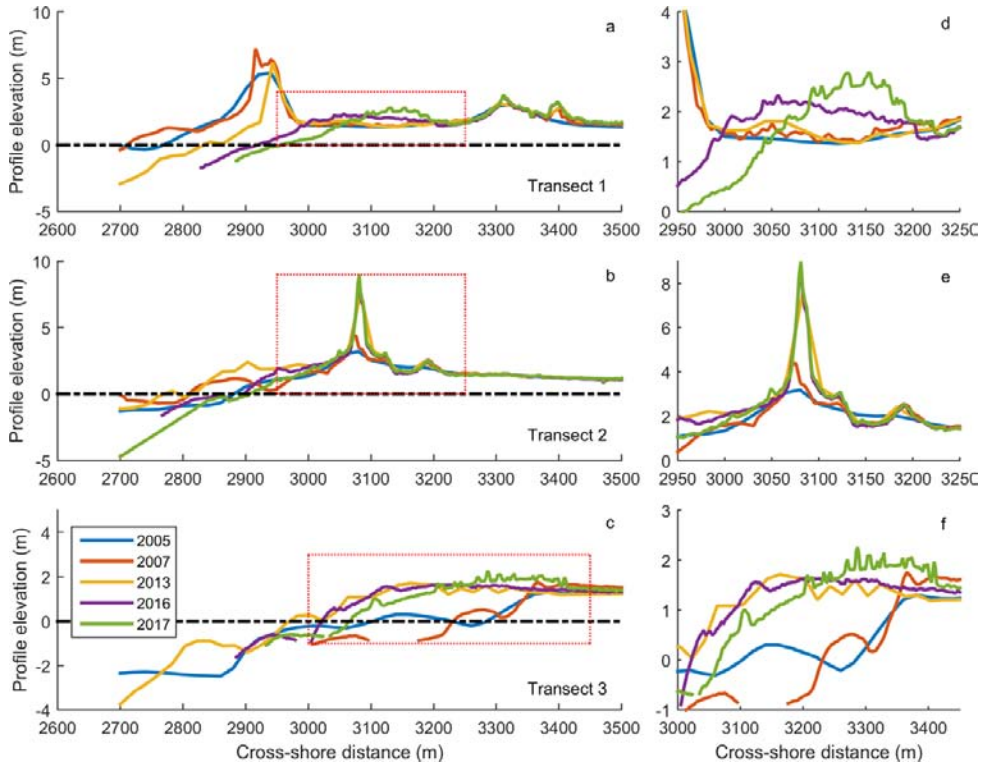


Figure 5.4: Three 1D transects of all years in the washover, dune area and island tail. Locations are shown in Figure 5.2. Panels d-f show a the area that is indicated with a red dotted box in panels a-c in more detail.

are similar. As expected, these values are lower at the dune area in between as sediment is blocked by the dunes. The high deposition values at the western part are caused by the beach plain outside the central part at the west that slowly migrates from west to east and starts affecting the beach in the central part.

5.3.2 Summary analysis of DEMS

From the analysis of the DEMs of Rottumeroog, it can be concluded that 1) From 2005 to 2017, the beach of Rottumeroog was characterized by strong retreat of approximately 200 m. 2) The total sediment volume of the central area slightly decreased, while the volume of the entire island increased. 3) Strong dune erosion occurred seaward from the area that is nowadays the washover, but total dune volume in the central part stayed constant due to dune growth more to the east. 4) Since 2016 the washover strongly increased in elevation with values up to 0.8 m. This showed that the washover at Rottumeroog is effective in stimulating vertical accretion of the area landward from the opening. 5) Patterns at the washover and island tail were similar: Erosion on the foreshore/offshore part of the beach, and deposition at the washover/onshore part of the beach. Deposition volumes per m coastline in the washover opening and island tail in the winter of 2016-2017 were similar as well. 6) The net sedimentation along cross-shore profiles in the washover and island tail in the winter of 2016-2017 was approximately zero, as erosion at the foreshore/beach was compensated by deposition

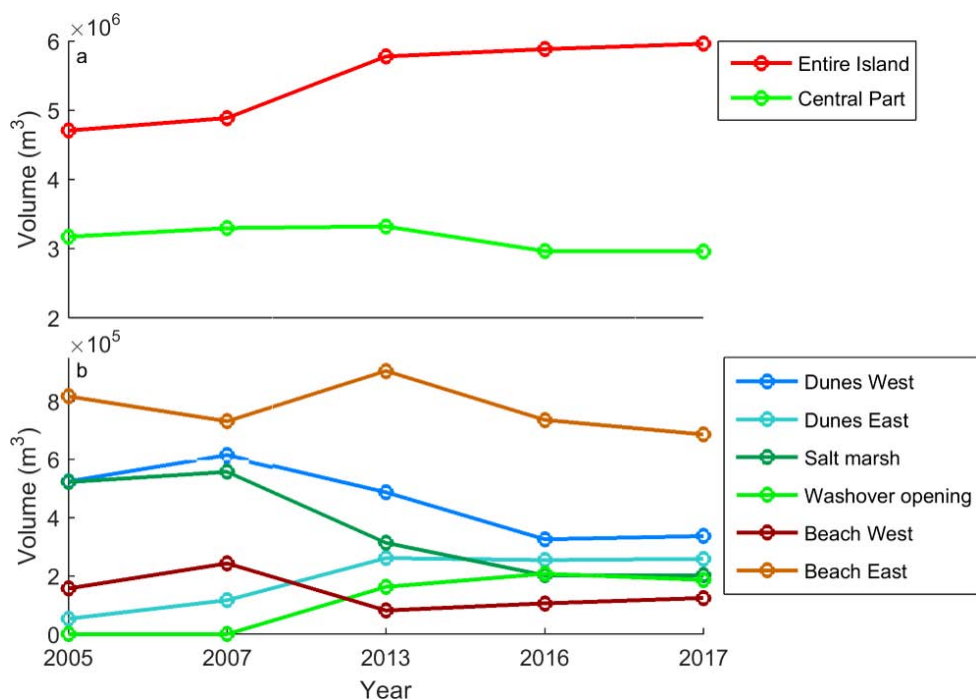


Figure 5.5: Volumes of a) The entire island and the central part and b) The subareas

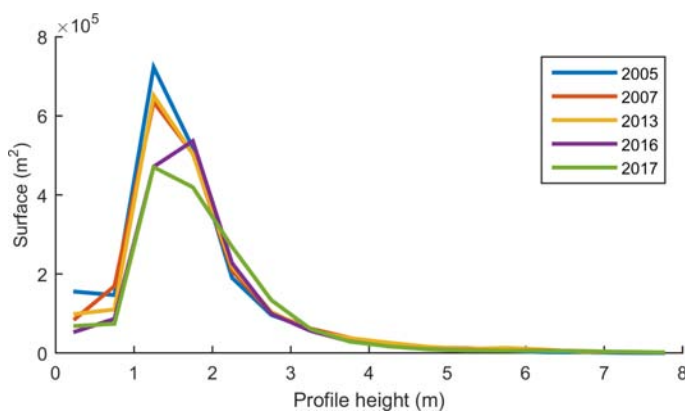


Figure 5.6: Distribution of surface area for 2005, 2007, 2013, 2016 and 2017, binned per 0.5 m.

more landward. However, cross-shore profiles containing dunes showed an eroding trend, because these dunes blocked storm-induced sediment supply for area landward from there.

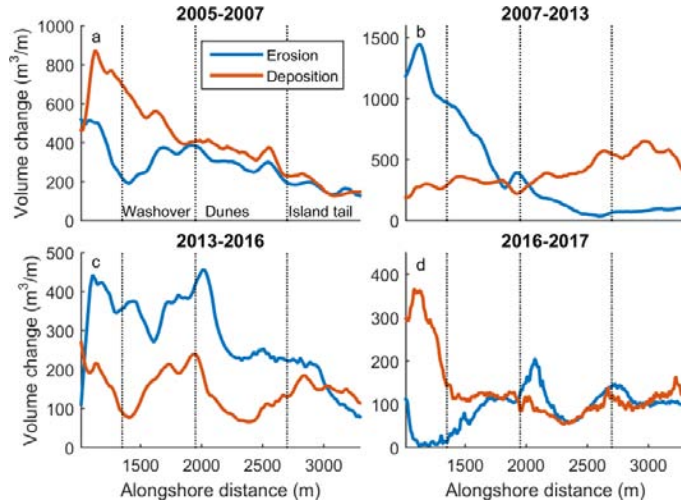


Figure 5.7: Erosion and deposition volumes as function of alongshore distance for the central part. For each figure, two consecutive digital elevation maps were compared.

Table 5.1: Summary of the hydrodynamics for all inundation events in the period 2013-2016 and 2016-2017, based on the inundation scheme from Chapter 2 of this thesis. Only classes 3-6 are taken into account because classes 1-2 hardly lead to overwash or inundation at Rottumeroog.

Class	2013-2016			2016-2017		
	Number of events	Wave height (m)	Wave period (s)	Number of events	Wave height (m)	Wave period (s)
3	7	4.3	7.1	2	5.1	7.9
4	3	4.4	7.1	3	5.3	8.0
5	2	6.1	8.6	1	5.6	8.4
6	2	3.2	7.1	0		

5.4 XBeach modelling

5.4.1 Methods

The analysis of the DEM's of Rottumeroog indicates that washover openings can indeed result in storm-induced sedimentation landward from the beach. In the winter of 2016-2017 water levels and waves were measured at in total three locations in an array from North Sea to Wadden Sea through the washover (Figure 5.8) with pressure transducers (PT; Ocean Sensor Systems Wave Gauges, OSSI-010-003C). The PTs record at 10 Hz, continuously. While fully submerged, the PTs measure mean water levels and water level variations. Therefore, all the inundation events from the winter of 2016-2017 were simulated in the morphodynamic 2D mode. For this period bed level change could be compared with the DEMs of 2016 and 2017 and the modeled hydrodynamics with the field measurements.

The grid covered approximately 3500 by 4500 m in cross-shore and alongshore direction respectively (Figure 5.8). The grid size in cross-shore direction gradually changed from 20 to 5 m from deep water to the areas above MSL. In 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 wave breaking parameter γ in the wave breaking formulation "Roelvink2" (Roelvink,

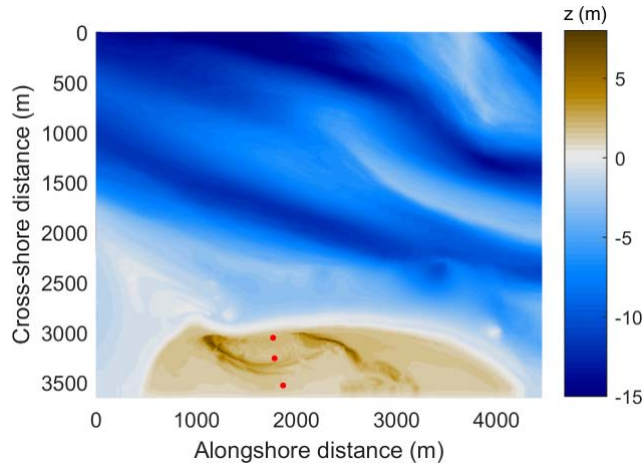


Figure 5.8: Bed level (from 2016) for the simulation, based on coastal lidar for the area higher than 1 m below MSL and Vaklodingen 2016 for the area lower than that. The three dots represent the locations of the pressure transducers during the field campaign in the winter of 2016-2017. The two most seaward located are used for model validation, the most southern one is used as water level boundary condition in the Wadden Sea.

1993) was set to 0.45 instead of the default value of 0.55, which is based on the studies of Hoonhout and van Thiel de Vries (2012) and Chapter 2. For other model parameters the default values were used. The sediment had a d_{50} of 200 μm and a d_{90} of 300 μm respectively. For all simulations, a spin-up tidal cycle without morphological change was used.

Input data used for the simulations were bed levels, water levels and wave forcing. The input bed level was based on the 2016 DEM (Figure 5.8). Offshore water levels were obtained from the station Huibertgat, located approximately 12 km west from Rottumeroog. No permanent water level station was available in the Wadden Sea at the location of Rottumeroog and therefore the most landward located pressure transducer from the field campaign was used for this goal. Offshore wave forcing was measured by the offshore station Huibertgat and prescribed at the seaward boundary. The winter of 2016-2017 resulted in 7 inundation events (Figure 5.9 and Tabel 5.1). Water levels in the North Sea had peak values between 2.0 and 2.5 m, significant wave heights were up to 7 m, and peak wave periods up to 10 s. The wave direction was almost perpendicular to the coast of Rottumeroog. Only the tidal cycles that led to inundation were simulated and the periods in between were ignored. This means that the tidal cycles that led to inundation were merged to one time series.

5.4.2 Modelling results

The simulated bed level change for 2016-2017 shows similar patterns in the washover as found with the DEM analysis: Erosion at the beach/seaward part of the washover and deposition at the landward part of the washover (Figure 5.10). The same patterns of erosion and deposition are found at the western part of the island tail ($x = 2700\text{--}3200\text{ m}$), which is similar to data as well. However, the most eastern part is characterized by erosion only (in contrast to field measurements). Although the patterns are similar (except for the eastern part of the island tail), the magnitudes of erosion and deposition are strongly underestimated by XBeach. This is also visible from three cross-shore transects shown in Figure 5.11, which are the same profiles as in Figure 5.4. The total simulated deposition volume in the washover

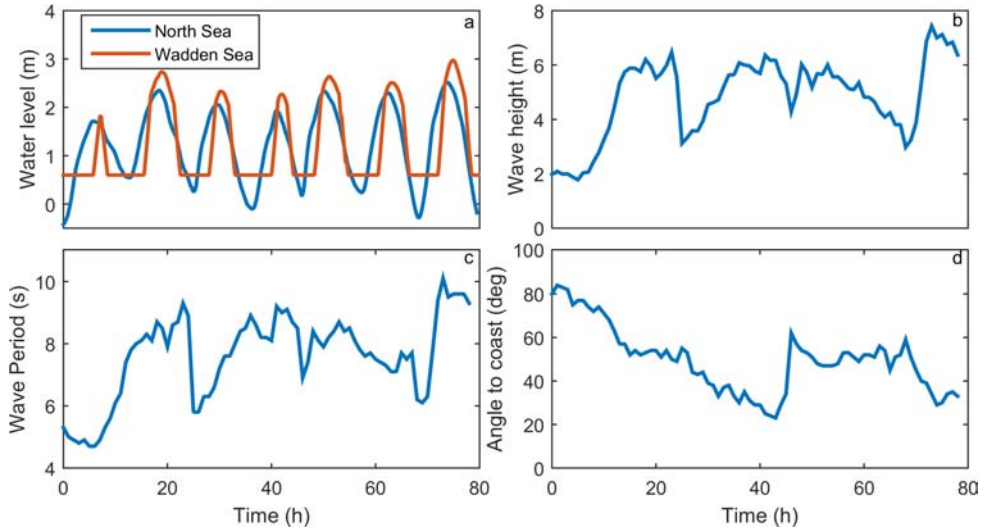


Figure 5.9: Hydrodynamic boundary conditions for 2016-2017. a) Water level in North Sea and Wadden Sea. All the tidal cycles that led to inundation at Rottumeroog are merged to one time series. During low water conditions, the pressure transducer at the Wadden Sea side falls dry. This explains the cut-off. b) Wave Height c) Wave Period d) Wave Angle with the coast.

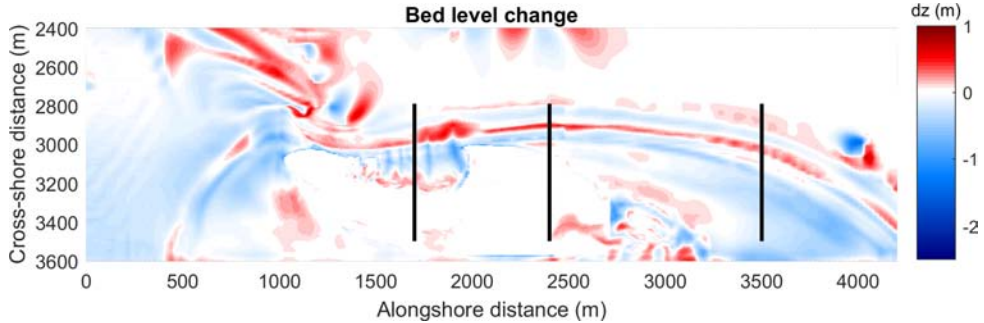


Figure 5.10: Total bed level change for the simulation of the inundation events in the winter of 2016-2017. The three transect are the same as in Figure 5.4 and are in the washover area, dune area and island tail respectively.

area is approximately 8 times smaller than what is measured (Transect 1). Transect 2 shows that a profile at the dune area hardly changed for the simulation, although the DEMs show that the dune grew in elevation. The third transect shows accretion for the island tail based on the DEMs but erosion based on the simulation.

One could argue whether the model is able to simulate the water levels and wave height correctly or that a poor representation of the hydrodynamics is the cause of the relatively small erosion and sedimentation volumes in the model. Therefore, the water levels and short waves are compared with data from the pressure transducers from the field campaign (Figure 5.12). For PT1 and PT2, the water level is underestimated by XBeach with 10-20 cm during rising tide and high water. PT1 shows good agreement between model and data for

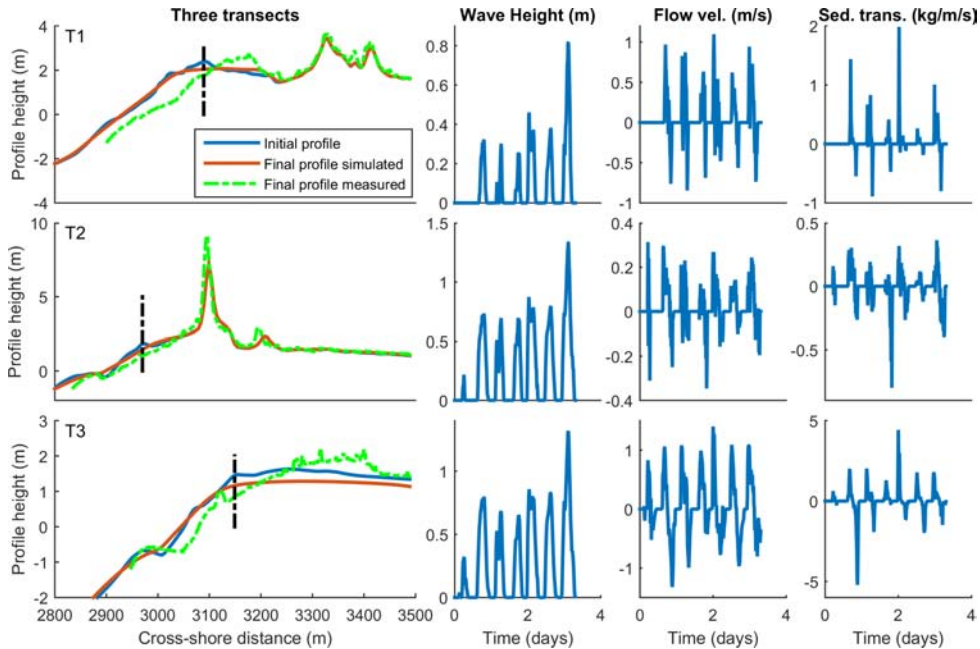


Figure 5.11: Initial and final bed level (modeled and measured) for three representative profiles, indicated in Figure 5.10, and the corresponding wave heights, flow velocities and sediment transport as function of time. The black lines indicate the position where the hydrodynamic parameters are determined.

the short waves, but XBeach overestimated the short waves with 0.05-0.1 m for PT2. These differences might be a result of the fact that the offshore water level and wave stations used as boundary condition are located relatively far from Rotumeroog (approximately 15-20 km to the west). The patterns of the currents are similar in the washover opening and island tail, which both have strong onshore directed currents during rising tide and smaller, offshore directed, currents during falling tide. Although this cannot be compared with data, these trends are similar as found at Schiermonnikoog (Chapter 2 and Engelstad et al. (2017)).

To verify whether the mismatch between model and data can be attributed to uncertainty in the boundary conditions, grain size or a certain model parameter, a sensitivity analysis was performed to test the XBeach results. All different model simulations are summarized in Table 5.2. Firstly, the boundary conditions are varied, which are 1) higher water levels in the North Sea, 2) larger waves and 3) higher water levels in the North Sea and larger waves. Offshore water levels were increased with 0.2 m, wave heights with 1 m and wave periods with 3 s. This will most likely lead to an increase in sediment transport and bed level change. Secondly, the sensitivity to grain size was studied (D_{50} of 100 and 150 μm instead of 200 μm) since grain size data is not available for the field site. A smaller grain size is expected to result in larger deposition values as well. Thirdly, also the sensitivity of the model results to the wave skewness factor is evaluated. This parameter is often used as calibration factor for bed level change. Increasing this parameter from 0.1 to 0.5 will increase sediment transport and deposition as well. Finally, the sensitivity to removing the berm was studied. This berm might hinder cross-shore flow over the washover and thereby limit sediment transport and erosion

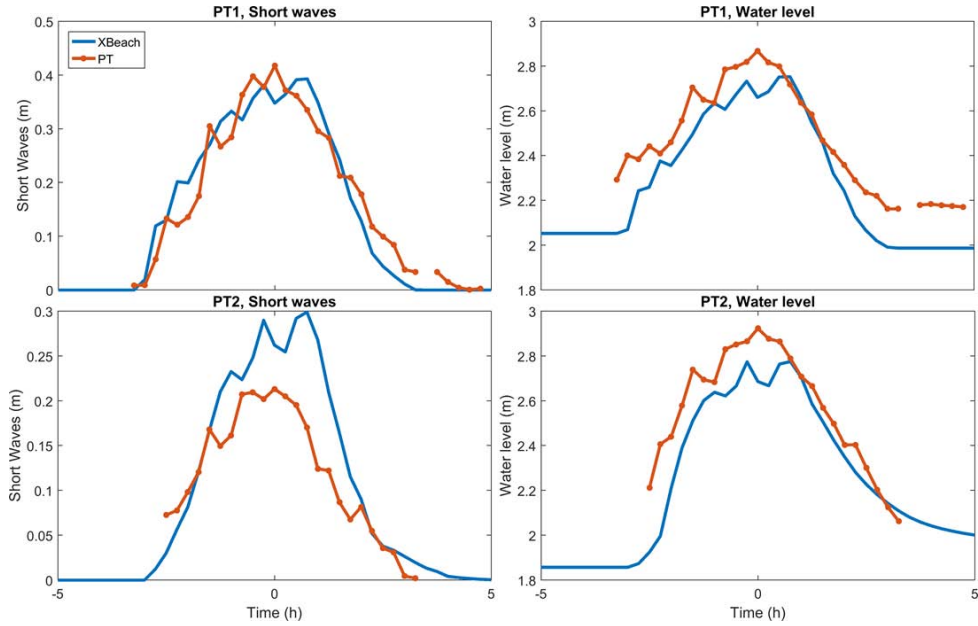


Figure 5.12: Comparison of short wave heights and water levels for the pressure transducers located in the washover during the inundation events in the winter of 2016-2017. Only the first event is taken into account. After that, the profile might have changed too much, which influences the hydrodynamics.

Table 5.2: Additional simulations to investigate the sensitivity of XBeach to certain boundary conditions and parameters and their effect on simulated deposition volumes (last column).

Simulation	Water level	Hs, Tp	D50 (m)	FacSK	Berm	Deposition (*10 ³ m ³)
Default	Normal	Normal	0.00020	0.1	Yes	4.9
Higher wl	+20 cm					6.1
Larger waves		+1 m, +3 s				6.4
Higher wl and larger waves	+20 cm	+1 m, +3 s				8.0
Smaller d50 1			0.00015			5.3
Smaller d50 2			0.00010			5.7
Wave skewness				0.5		6.4
No berm					No	5.1
Measured						37.5

and deposition values. The berm South of the washover area that might hinder cross-shore currents across the island has been removed.

In all sensitivity runs the deposited volume of sediment increased compared to the default run (Table 5.2). However, the maximum increase in deposition volumes for a higher water level and larger waves is only 60% while the measured deposition volume is nearly a factor 8 larger. Therefore, the cause of the discrepancy between model and data is not the sensitivity to these boundary conditions and/or model parameters.

5.5 Discussion

5.5.1 Deposition in the washover and at the island tail

The main aim of the DEM analysis was to investigate the effectiveness of a washover opening in relatively natural conditions for improving vertical accretion landward from the opening, and how that relates to a 'reference area' (i.e. the island tail) where inundation occurs as well. Vertical accretion values up to 0.8 m in the winter of 2016-2017 were measured in the washover area. Accretion volumes per meter coastline in this period were found to be about $60 \text{ m}^3/\text{m}$ in the washover opening, which is remarkably large compared to other studies. In Chapter 4 of this thesis, a volume per m coastline of $85 \text{ m}^3/\text{m}$ was found, based on a period of 25 years instead of one winter covered by XBeach simulations. Other studies that were discussed in Chapter 4 focussed on single extreme storm or hurricane events that led to dune erosion or breaching, resulting in volumes per m coastline from 20 to $75 \text{ m}^3/\text{m}$. This shows that the deposition found at Rottumeroog in 2016-2017, in which dune breaching hardly occurred, is in the same range as caused by extreme storms where dune breaching provided a large source of sediment. The deposited sediment did not come from the dunes, but the main sediment source here was the eroding beach. The coast strongly migrated onshore over hundreds of meters since 2005 and with tens of meters in the winter of 2016-2017 (Figure 5.4). In this winter, the volume of beach erosion was approximately equal to the amount of deposition in the washover, which suggests that the sediment of the eroded beach is mainly being deposited at the island instead of being lost in the North Sea.

Two studies can be used to compare the results from this chapter with other locations in the Wadden Area where bed level changes in a washover or at an island tail were measured. Firstly, Engelstad et al. (2018) measured bed level change at the island tail of Schiermonnikoog for exactly the same period in the winter of 2016-2017 as used in this chapter for Rottumeroog. Trends were similar with an eroding beach and deposition more onshore. However, while Rottumeroog experienced beach erosion from at least -1 m MSL (i.e. the location where measurements started) until approximately 2 m above MSL, the erosion at Schiermonnikoog started at 0.5 m above MSL. Nevertheless, the resulting erosion and deposition volumes per m coastline were only approximately 30% smaller than at Rottumeroog. The maximum accretion height was only 0.3 m, but sedimentation extended over a cross-shore length of 200 m. Secondly, Nielsen and Nielsen (2004) monitored a washover area at Skallingen, Denmark during its 13 years lifetime. In 1990, this washover was formed due to a breach of the dunes. A similar deposition volume per m coastline in the washover area of $50 \text{ m}^3/\text{m}$ as at Rottumeroog was found in the first winter. In this 13 years period, the coast eroded with on average 3-4 m per year but the dunes and washover area accreted. The total volume per m coastline increased with $557 \text{ m}^3/\text{m}$ from 1990 to 2000. However, during the last 3 years when the washover was almost closed by new dunes, the total volume per m coastline no longer increased. This was due to the fact that sedimentation landward from the dunes was no longer possible. The lack of sedimentation in areas containing dunes is in line with what was found at Rottumeroog.

Although vertical accretion levels at the island tail of Rottumeroog were slightly lower, the cross-shore extent of the accretion area where accretion occurs is slightly larger, resulting in similar deposition volumes per meter coastline. This suggests that specific washover opening conditions (for example flow acceleration due to 2D effects, described in Chapter 3) were not dominant in determining deposition volumes.

5.5.2 XBeach performance

The hydrodynamic processes during storm-induced inundation were probably sufficiently captured by XBeach, similar to what was found in Chapter 2. Water levels and short waves were roughly comparable with data from pressure transducers installed during a field campaign in the winter of 2016-2017, but the measured and applied input values may include potential errors due to uncertainties in the hydrodynamic boundary conditions. Although flow velocities were not validated with data, the cross-shore component of the velocities were in the same range as currents that were measured at the island tail of Schiermonnikoog (Chapter 2; Engelstad et al., 2017), where local trends and conditions in storm-induced water levels in North Sea and Wadden Sea are similar as for Rottumeroog. At Schiermonnikoog, cross-shore currents up to 0.8 m/s were measured, while cross-shore currents up to 1.0 m/s were simulated for Rottumeroog.

Trends in morphology change were, except for the island tail, similar to observations, with erosion at the beach and deposition in the washover area. However, the magnitudes of erosion and deposition values were largely underestimated. A few other studies have been performed where XBeach simulations of morphological changes caused by hurricanes (i.e. dune breaching and associated landward deposition) were compared with field measurements. Lindemer et al. (2010) found similar results for the effects of Hurricane Katrina at the Chandeleur Islands, Louisiana, where patterns of erosion (in this case dune breaching) and deposition were comparable but magnitudes strongly underestimated. On the other hand, morphological change was overestimated with one order of magnitude by XBeach simulations in McCall et al. (2010) for the effects of Hurricane Ivan in 2005 at Santa Rosa Island, Florida. This was improved by applying a sheet flow sediment transport limiter. Furthermore, Harter and Figlus (2017) simulated the effects of Hurricane Ike (2008) at Follet's Island (Gulf of Mexico) with XBeach and they found that large-scale 2D-features (e.g. dune breaching) were accurately captured but that smaller-scale features at locations with dunes were underestimated or even missing. To my knowledge, other XBeach studies where morphology change in the inundation regime is simulated at locations where dunes are missing and where these results are compared with field measurements do not exist.

The underestimation in the XBeach simulations of the morphology change at Rottumeroog may be related to a number of issues. Firstly, wind- and tide-driven alongshore currents were not incorporated. However, sediment stirring is influenced by the magnitude of the current and the alongshore current can contribute to that. Engelstad et al. (2018) measured alongshore flow velocities of roughly 1 m/s at the island tail of Schiermonnikoog during inundation in the winter of 2016-2017, which indicates that these currents can indeed be large. Secondly, alongshore currents can lead to (gradients in) alongshore sediment transport. For example, Rottumeroog contains an obliquely-oriented dam (used in the past to protect the coast) which probably causes gradients in alongshore currents and transport. Furthermore, a large ebb-tidal delta at the west of the island is missing, which is typical for most other Wadden Islands and usually provides an extra source of sediment for the islands on the long-term. This issue gives rise to the consideration of nesting XBeach into a large-scale model for the entire area instead of only using XBeach for a relative small area. Although this was outside the scope of this study, it is recommended for future studies related to Rottumeroog. Thirdly, a process-based model is always an approximation of reality and therefore it cannot be excluded that imperfections in how the processes are implemented in the model influence the results.

5.6 Conclusions

In this chapter, the Wadden Island Rottumeroog has been investigated to study the storm-induced morphological impact on an island that is no longer maintained since 2005. Five DEMs measured between 2005 and 2017 have been analysed. This analysis shows that Rottumeroog experienced strong beach erosion of up to 50 m per year. Nevertheless, since 2013 significant deposition took place in the washover and island tail with values up to 0.8 m (in elevation) and $62 \text{ m}^3/\text{m}$ (volume per meter coastline) in the winter of 2016-2017. This shows that a washover opening effectively creates space for landward deposition when conditions are favorable. Overall, erosion and deposition volumes were similar for the winter of 2016-2017 and the island volume remained more or less constant. XBeach was capable of reproducing the trends of beach erosion and deposition onshore from the beach, however, the magnitudes of bed level change were strongly underestimated. There may be various reasons to explain this underestimation such as the lack of tide- and wind-driven flow in the modeling approach. This suggests that for Rottumeroog a large-scale flow- and wave-driven model may be more suitable to apply.

Chapter 6

Synthesis

6.1 Main findings

In natural conditions, Wadden Islands may demonstrate vertical accretion due to storm-induced water levels and onshore-directed currents and corresponding sediment transport. However, on many Dutch Wadden Islands, dune openings are closed off by artificial sand-drift dikes that prevent the influx of sediment during storms. It has been argued that creating openings in the dune row to allow regular flooding on the Wadden Islands can have a positive effect on the sediment budget, but the dominant cross-shore hydrodynamic processes and their influence on cross-shore sediment transport during inundation were unknown. The main aim of this PhD-thesis was to improve the understanding of the role of the washover openings on the Wadden Islands on the storm-induced and cross-shore directed sediment transport on the short-term, event scale as well as medium-term, annual to decadal time scale. The focus was on the inundation regime. To satisfy this objective, use was made of the XBeach model in combination with a set of hydrodynamic field measurements for calibration and validation of the model and a series of morphological surveys on the island of Rottumeroog. Three separate research questions were formulated in Chapter 1 and studied in Chapters 2-5. Here, these questions will be answered.

1. *What are the dominant cross-shore hydrodynamic processes during inundation and how do they affect resuspension and transport of sediment?*

A 1D XBeach model study was set up in Chapter 2 to investigate how cross-shore sediment transport during inundation across a representative cross-shore profile along the island tail of Schiermonnikoog is influenced by wave, tide and storm surge conditions. The resulting short- and IG wave heights, cross-shore currents and water levels were validated with existing field data.

Cross-shore currents during inundation strongly depend on the water level gradient between North Sea and Wadden Sea, which is influenced by tide, storm surge and wave set-up processes. The tidal wave propagates from the North Sea into the Wadden Sea creating a time lag of approximately 20-30 minutes. This favours onshore directed currents during rising tide and offshore directed currents during falling tide. Nevertheless, storm surge levels are often higher in the Wadden Sea than in the North Sea, which favours offshore directed currents. Wave set-up at the North Sea coast during storms is a third relevant process. If large enough – with high incoming waves - it may compensate or even overrule the impact of the offshore directed gradient in water level. Results showed that all components together mostly lead to a strong water level gradient and large cross-shore

current (up to 1 m/s) from North Sea to Wadden Sea across the island tail of Schiermonnikoog during rising tide. During falling tide, this water level gradient is much weaker and sometimes even reverses, which can result in a small (up to 0.4 m/s) offshore directed current. This pattern of alternating onshore and small offshore directed currents during a tidal cycle with storms was recently confirmed by our field measurements at the barrier island of Schiermonnikoog (Engelstad et al., 2017). Furthermore, Sherwood et al. (2014) simulated similar offshore directed currents with XBeach for the Chandeleur Islands, USA, when the bay water levels were higher than the ocean water levels. They found offshore directed currents of approximately 0.2 m/s.

Sediment transport largely follows the trends of the cross-shore currents. During rising tide, sediment transport is onshore directed. During falling tide, sediment transport is close to zero or even offshore directed. Wave dissipation mainly occurs on the gentle foreshore, and waves only marginally contribute directly to sediment transport across the island (less than 5%). Therefore, the inundation regime clearly differs from the swash and collision regime. In both the swash and collision regime, short waves in the surf zone are often found to be crucial for both the stirring and transport of sediment (e.g. Ruessink et al., 1998). However, short waves indirectly affect sediment suspension and transport by creating wave set-up and thereby modifying the water level gradient. IG waves maintain most of their energy across the beach and contribute more to sediment stirring than the short waves (10-20%). Nevertheless their contribution is still much smaller than found for the overwash regime, where IG waves are often the dominant source for sediment transport (e.g. Figlus et al., 2010).

Based on 25 years of water level and wave data in the North Sea and corresponding water level data in the Wadden Sea, I created an inundation classification scheme, where class 1 represents small inundation events that occur on average 23 times per year and class 6 characterizes severe storms that occur approximately once per 3 years. Factors that lead to more onshore-directed sediment transport for higher classes are higher elevated water levels due to more energetic storms, larger waves and the associated increase in wave set-up. Simultaneously though, storm surge levels increase faster for higher classes in the Wadden Sea than in the North Sea, which tends to decrease the water level gradient. Although the net effect is an increase in sediment transport for larger storms, the faster increase of Wadden Sea water levels significantly reduces potential onshore-directed sediment transport. When the frequency of occurrence is taken into account, which decreases for higher classes, the cumulative effect (i.e. the net onshore transport for a period of 25 years) of large storms is less important than the cumulative effect of smaller storms. More specifically, the cumulative effect of class 6 storms is only 5% of the cumulative effect of class 1 storms.

2. *What is the influence of island geometry and local washover morphology on storm-induced sediment transport patterns and magnitudes?*

In reality, for our Wadden Sea barrier island system washover openings are alongshore-varying features and furthermore, they exist in a large variety of dimensions. van Dongeren and van Ormondt (2007) and Hoekstra et al. (2009) found that currents accelerate through a washover opening, but it was unknown how that depends on washover geometry such as elevation and width of the opening, and foreshore/beach width and slope. Likewise it remained unknown how this affects the local sediment transport processes. It was clear though that in these non-uniform, alongshore conditions a cross-shore profile

approach is no longer valid or applicable. As a first step in the analysis an inventory was made in Chapter 3 of the geometrical properties of all currently existing washover openings on Dutch, German and Danish Wadden Islands. As a second step an XBeach model in a 2D mode was set up to investigate the influence of washover geometry on hydrodynamics and sediment transport.

The mean washover opening width is 200 m, however, there are large variations between the washover openings with widths from 35 to 1100 m. The mean washover height varies between 1.5 and 2.1 m above MSL. For the default simulation, a width of 200 m and an elevation of 2 m above MSL were used. For other simulations, they ranged from 50-2000 m and from 1.7-2.3 m above MSL respectively. Compared to the 1D simulations in Chapter 2, cross-shore currents experience an extra flow acceleration through an opening due to flow contraction. This effect mainly occurs at the edges of the washover opening and is less pronounced in the middle of the washover, far from the dunes-washover opening boundary. Nevertheless, model simulations show that even for a 1000 m wide opening the effect of flow acceleration still plays a role in the middle of the opening, as sediment transport per m coastline is approximately 25% larger than in the middle of a 2000 m wide opening.

Narrower openings result in stronger flow contraction and therefore larger sediment transport per meter width, but on the other hand, for wider openings a larger width-integrated sediment transport is observed. Both effects combined results in increasing sediment transport for wider openings, with a difference of 800% between a washover opening of 50 and 2000 m. Furthermore, currents and sediment transport are very sensitive to the washover opening elevation. A 0.3 m lower than default washover elevation (2 m above MSL) results in approximately two times larger onshore sediment transport. On the other hand, a 0.3 m higher than default washover elevation results in a reduction of approximately 60% of the onshore sediment transport. The beach widths and foreshore slopes that are analysed are 10-300 m and 0.01 m/m to 0.1 m/m respectively. They only have mild influence of modeled sediment transports with differences up to 25%.

3. *What is the expected medium-term storm-induced morphological evolution of washovers due to inundation on Wadden Islands?*

In Chapter 2 and 3, hydrodynamic processes and sediment transport were analysed with XBeach in the 1D and 2D mode, however, morphology change was not yet taken into account. Furthermore, these studies focussed on the event-scale while storm-induced vertical accretion is in particular relevant for the annual to decadal time scale. To investigate the morphological changes over medium-term time scales, including morphological feedbacks on sediment transport processes, XBeach was again applied in 2D mode by incorporating morphological change. XBeach was originally developed to simulate morphological change during individual storm events. In Chapter 4, a computational method was constructed to represent time-varying water level and wave conditions with single water level and wave conditions. This decreased calculation times with approximately a factor 100 and made it possible to simulate a period of 25 years. In this approach, calm-weather conditions and aeolian transport were not taken into account.

XBeach simulations show that inundation events are able to erode the washover openings with values of more than 0.5 m. The eroded sediment is deposited further onshore due to gradients in cross-shore currents. This resulted in local vertical accretion of the island with values of more than 0.5 m as well. Deposition rates onshore from the washover opening

stay approximately constant despite the erosion of the opening and beach, which is not being recovered as calm-weather conditions are not taken into account. This suggests that the cross-shore storm-induced sediment transport can continuously lead to vertical accretion of parts of the Wadden Islands. When a high rate of sea-level rise (10 mm/year) is taken into account, deposition values increase with approximately 60%, accelerating the rate of vertical accretion but not fully compensating for sea level rise. This is caused by a higher storm-induced elevated water level, which is in agreement with findings of Chapter 3, in which I showed that transport rates are very sensitive to the elevation of the washover opening. The application of different storm sequences in the model runs causes a difference of 20-25% in sedimentation (from gentle to severe storms results in more transport than vice versa) and is thereby less important than sea-level rise or other factors investigated in the previous chapters.

Based on the default case with a washover opening of 200 m in width, a total deposition volume per meter coastline in 25 years of $85 \text{ m}^3/\text{m}$ was found. This is rather low compared to a washover opening at Skallingen, Denmark, where a value of $345 \text{ m}^3/\text{m}$ was found in 13 years based on measurements. Although differences in tide, wave climate and washover geometry may play a role, it cannot be excluded that XBeach underestimated morphology change at the washover openings. Other field studies found values of sediment transport per m coastline based on a single storm event that are close to the present results obtained with the XBeach model for simulations over a period of 25 years. For example at Miami Beach, USA, $54 \text{ m}^3/\text{m}$ (Reardon, 1926), Long Island, USA, $75 \text{ m}^3/\text{m}$ (Redfield and Miller, 1957), Assateague Island, USA, $20 \text{ m}^3/\text{m}$ (Leatherman et al., 1977) and Cozumel, Mexico, $28 \text{ m}^3/\text{m}$ (Morton and Sallenger, 2003). These values though were based on hurricane conditions and are therefore hard to compare with Wadden Island conditions.

In Chapter 3 and 4, a more or less 'synthetic washover area' was used, although inspired by the properties of Dutch barrier islands, to analyse the hydrodynamics, sediment transport and morphology change during inundation. To gain further insight in the natural processes on a medium-term time scale the study was extended to a natural barrier island in the Netherlands, the island of Rottumeroog (Chapter 5). This island contains a natural washover opening and no human interventions or maintenance took place after 2005. This makes this island an ideal location for a case study to investigate the natural evolution of a barrier island in absence of coastal management, and specifically to study the evolution of a washover opening in relation to the landward development of the island.

To this end, all five digital elevation maps (DEMS) of the area from 2005 to 2017 were investigated. The first years since 2005 were characterized by strong erosion of the beach and foreshore, followed by the development of a 600 m wide breach in the dunes. This breach developed into a washover and has been active since then. Bed level elevation in the washover increased with values up to 0.8 m and with $62 \text{ m}^3/\text{m}$ (volume per meter coastline) in one winter. This was much larger than the values found in Chapter 4.

Chapter 2 showed that at the island tail of Schiermonnikoog, the cumulative effect of storms on bed level change is more important than the effect of larger, individual storms. At Rottumeroog, the bed level was only measured before and after a period that contained at least 7 inundation events, which makes it difficult to confirm that this conclusion can be drawn here as well. However, the pressure data from the transducer at the washover of Rottumeroog suggest that it was indeed the cumulative effect of several inundation events that caused the strong sedimentation here. These data show that the pressure transducer got buried during the fourth inundation event. After 7 inundation events (at the end of the field campaign), the transducer was covered by 0.8 m of new deposits.

XBeach simulations in 2D mode were performed to analyze the processes that caused the morphology change in the winter of 2016-2017 and to test the performance of XBeach for inundation-induced morphology change at a Wadden Island. Patterns of beach erosion and sedimentation more landward in the washover were sufficiently simulated. This was similar at the western part of the dune-lacking island tail. For the eastern part of the island tail, erosion was simulated whereas deposition was measured. For all areas, magnitudes were strongly underestimated. This was in line with the study of Harter and Figlus (2017), where a strong underestimation of morphology change by XBeach was found for the effects of Hurricane Ike (2008) at Follet's Island, Gulf of Mexico. In contrast though McCall et al. (2010) found an overestimation of the morphology change at Santa Rosa Island during Hurricane Ivan (2005). A more detailed elaboration on possible reasons for the underestimation of magnitudes of morphological change in Chapter 5 will be given in the next section.

6.2 XBeach performance and perspectives

XBeach was used in most chapters of this thesis. In Chapter 2, XBeach was used in the 1D and morphostatic mode (i.e. no bed level updates). From Chapter 3 the simulations were performed in the 2D mode. In Chapters 4 and 5 morphology change was added. The most important aspect of XBeach, for example compared to Delft3D, is the explicit calculation of IG waves. Many studies found that IG waves are crucial in the overwash and inundation regime (e.g. Sallenger, 2000). In the overwash regime, IG waves are often required to overtop the dunes as short waves are already dissipated. In the inundation regime, both short waves heights and flow velocities increase during the passage of a IG wave crest (Engelstad et al., 2017). Furthermore, IG waves play a role in the stirring of sediment. This suggests that IG waves must be incorporated during the modelling of overwash and inundation. Therefore XBeach was anticipated to be a proper tool for this purpose. This section elaborates on the performance of XBeach in terms of 1D/2D hydrodynamics and morphology change.

6.2.1 XBeach 1D hydrodynamics

In the recent past, XBeach was mainly validated for the overwash and inundation regime with pre- and post-storm profile data (e.g. McCall et al., 2010; de Vet et al., 2015) or hydrodynamic data based on laboratory experiments (Hoonhout and van Thiel de Vries, 2012; Stockdon et al., 2014), but not yet with hydrodynamical data from the field. The present study (Chapter 2) showed that XBeach is capable to accurately predict water levels, cross-shore currents, short waves and IG waves in the inundation regime in the 1D mode by adapting only one parameter, the wave breaking parameter γ , similar to other studies containing a gentle-sloping coast (Hoonhout and van Thiel de Vries, 2012).

In the 1D mode, short waves can be imposed on the North Sea boundary with an angle to the coast. According to the validation of the short waves in Chapter 2, this resulted in accurate prediction of wave heights. However, the IG waves were strongly underestimated with approximately 50% when a wave angle was applied at the boundary. This underestimation was not present when shore-normal waves were imposed, even when wave spreading was included. This is caused by the fact that in the 1D mode of XBeach, only the cross-shore component of the full infragravity field is prescribed which leads to an underestimation of the IG wave height. Therefore I used shore-normal waves in Chapter 2. To correct for the corresponding overestimation of the short-wave energy when waves are oblique-incident in reality, a wave forcing correction such as described in Holthuijsen (2007) and used in Chap-

ter 2 should then be applied. This approach resulted in the most optimal results for both short- and IG waves.

6.2.2 XBeach 2D hydrodynamics

The hydrodynamics in the 2D mode of XBeach were the same as in the 1D mode, which was tested by converting the 1D profile from Chapter 2 to a 2D alongshore-uniform area. This led to equal wave heights, water levels and flow velocities. In contrast to the 1D mode, oblique-incident waves can be imposed at the boundary correctly. More realistic wave angles were therefore applied in Chapters 3-5.

XBeach gives two options to investigate the role of the IG waves in the simulations. Firstly, wave stirring by IG waves can be turned off ($lws = 0$). By using this option, the hydrodynamics are unaltered but sediment is only stirred by the currents and short waves. This option was used in Chapter 2 to quantify the contribution of the IG waves to total wave stirring, which was approximately 10-20%. Secondly, IG waves can be excluded completely ($lwave = 0$). However, the corresponding model output cannot directly be compared with the default version as the model turns to another wave-breaking module of Baldock et al. (1998). Therefore, in XBeach the importance of IG waves could only be investigated in an indirect way. However, Engelstad et al. (2018) demonstrated with field measurements at the island tail of Schiermonnikoog that for most cases the relative importance of sediment transport by IG waves during rising tide is only 5-20% of the total transport by waves and currents. During falling tide the relative contribution of IG waves can be larger (up to 50%) but their absolute contribution of sediment transport during falling tide remains relatively small and is about 20%.

6.2.3 XBeach 2D morphodynamics

Morphology change was validated for the overwash and inundation regime in XBeach in a number of studies (e.g. McCall et al., 2010; Lindemer et al., 2010; Harter and Figlus, 2017). At the locations of these studies, strong dune erosion or breaching occurred. However, for predicting morphology change at locations with already low-lying bed levels, such as washover openings, XBeach studies did not yet exist. In Chapter 4, XBeach simulations based on Schiermonnikoog showed that inundation can lead to sedimentation landward from the opening with the opening and beach acting as a local source of sediment. In Chapter 5, simulated morphology change at Rottumeroog showed similar patterns but compared to available DEMs the magnitudes were strongly underestimated. Landward-directed sedimentation mainly depends on the existence of the cross-shore current and the sediment source. Cross-shore currents were probably sufficiently modeled and comparable with results from earlier chapters. Furthermore, short wave heights were accurately simulated as well. However, the strong beach erosion as observed in reality was not accurately modeled with XBeach and this might be a major reason for the mismatch of deposition rates between model and data. Investigating the processes behind the strong beach erosion at Rottumeroog was outside the scope of this thesis. Possibly, alongshore tidal or wind-induced currents were underestimated which add extra bed-shear stress to the system. This, in combination with wave forcing, can contribute to extra stirring of sediment and consequently an increase in alongshore and cross-shore transport.

Modelling the above-mentioned processes accurately requires modeling of a larger area than the few km grid in alongshore and cross-shore direction that is typically used for XBeach. Larger grids though would lead to unrealistic calculation times. Therefore, a future approach may be the nesting of XBeach in a larger-scale model such as Delft3D. This

is already possible and for example used for a dune-fronted sandy beach in the study of Karunarathna et al. (2018). In this way, the larger-scale features and nearshore processes can be better incorporated.

6.2.4 Using XBeach for medium term simulations

XBeach was originally created to analyse the morphological impact of single storm events (Roelvink et al., 2009). In Chapters 4 and 5 I used XBeach for the decadal and annual time scale respectively. By excluding the morphological developments in the time intervals between successive storms, effects of beach recovery by waves and tides and aeolian processes were not taken into account.

In this thesis I only investigated morphology change caused by storms on the short term or medium term (25 years). However, the calm-weather conditions where beaches can recover by hydrodynamic processes and aeolian transport can facilitate dune growth and potentially even close washover openings again by aeolian deposition. This can significantly affect barrier island evolution. Recently, studies were performed that investigate which conditions are ideal for aeolian transport (e.g. Delgado-Fernandez and Davidson-Arnott, 2011; Hage et al., 2018). Using these insights and coupling them to storm-driven models would enhance the understanding of medium-term barrier island development. Currently, process-based models for aeolian transport become available, such as the AEOLIS model (Hoonhout and de Vries, 2016). This provides new opportunities to couple wind transport models with process-based hydrodynamic models such as XBeach, which recently indeed has been performed for AEOLIS (Cohn et al., 2019) and another dune profile model Duna (Roelvink and Costas, 2019). Using such integrated approaches could enhance insights in medium-term washover development.

6.3 Future options for the management of sand-drift dikes

In the previous century, many of the washover openings on the Dutch barrier islands were closed off by artificial dunes, known as sand-drift dikes, to increase the safety during storms (Oost et al., 2012). This measure prevents the area behind the (artificial) dunes from flooding, but has as side effect that onshore-directed storm-induced sediment transport is blocked. Coastal zone management organizations in the Netherlands consider the re-opening of the washover openings by removing parts of the sand-drift dikes. This may contribute to storm-induced vertical accretion. In this thesis I investigated the washover openings from a scientific perspective. Nevertheless the study – in combination with the previous study of Engelstad (2019) – can have important practical spin-off in terms of recommendations for the creation or re-activation of washovers. In this section I elaborate on the most important design criteria and area characteristics based on the results.

1. Hydrodynamics

Results in all chapters demonstrated that approximately 80-90% of the cross-shore sediment transport during inundation is caused by currents. At the island tail of Schiermonnikoog, currents reach values up to 1 m/s (Chapter 2). Model simulations with the XBeach model indicated that flow velocities are even higher through washover openings due to the effect of flow contraction (Chapter 3) and can reach values up to 1.6 m/s. In addition, when currents are smaller than approximately 0.5 m/s, sediment is hardly stirred and transported. The presence of a strong cross-shore current is therefore a crucial component for storm-induced sediment transport and vertical accretion.

2. *Presence of vegetation and embryonic dunes*

Although not investigated in this thesis, vegetation most likely reduces the currents by adding friction. Moreover, vegetation strongly limits the mobility of sediment. The vegetation on the wide beach of Schiermonnikoog in front of the washover openings may be one of the reasons why the washover area has been morphologically inactive in the last decades, as shown in Chapter 3. Similar to vegetation, embryonic dunes that grow on the beach of Schiermonnikoog may reduce currents in the inundation regime as well. Therefore I conclude that a not too wide and vegetation-free beach leads to better conditions for washover development.

3. *Washover opening elevation and width*

Results presented in Chapter 3 demonstrated the important effect of washover geometry on currents and sediment transport. For a washover opening with an elevation of 1.7 m above MSL, sediment transport is approximately 400% higher than for an elevation of 2.3 m above MSL. This means that washover areas with a lower opening have more potential for vertical accretion. The washover openings at Schiermonnikoog have an elevation between 1.5 and 2.1 m above MSL and can be considered as relatively low (Chapter 3). The washover opening at Rottumeroog is with 2.2 m above MSL slightly higher (Chapter 5). However, the tidal range at Rottumeroog is slightly higher as well which may compensate for the higher washover opening. Based on the results, I conclude that the lower the elevation of the washover opening is, the larger washover deposition rates will be.

A washover opening width of 2000 m generates approximately 800% more sediment transport than an opening of 50 m wide. On the other hand, the sediment transport per meter coastline (m^3/m) decreases for wider openings. At Schiermonnikoog, the washover openings are relatively small (200 m or less). At Rottumeroog, the opening is wider (approximately 600 m). The optimal design width of a (re-activated) washover opening is slightly arbitrary since sediment transport increases for wider openings, but the costs for creating a gap and the removal of sediment will rapidly rise for increasing width. Based on the simulations in Chapter 3, the reduction of sediment transport per m coastline is roughly constant until 600 m. For a washover width between 600-1000 m, sediment transport per m coastline reduces more strongly. Furthermore, natural washover openings before the construction of sand-drift-dikes were often approximately 600-800 m in width (Chapter 3). Therefore, 600-800 m would probably be an optimal width for construction of new washover openings.

4. *Sediment Source*

Another important factor is the sediment source. Many studies showed that on the short term (i.e. individual storms or a series of storms during one winter) the sediment that is deposited landward mainly comes from a local source (e.g. Williams, 2015), for example by dune breaching (e.g. Nielsen and Nielsen, 2004; McCall et al., 2010). In this thesis, the focus was mainly on beach erosion as the dominant sediment source. At Rottumeroog, strong beach erosion occurs at least since 2007 with approximately 30 m retreat of the coast per year. Beach erosion volumes during the winter of 2016-2017 roughly matched with more landward directed sedimentation volumes (Chapter 5). This suggests that storm-induced beach erosion is crucial to create a positive cross-shore directed sediment transport.

Appendix A

XBeach formulations

This Appendix describes the governing XBeach equations that compute the hydrodynamics, sediment concentration/transport and bed level change. All details can be found in Roelvink et al. (2009). I focus on the relevant processes and ignore the parts or processes that were not used in this thesis, such as wind forcing. In the surf beat mode, the short waves are solved with the wave action balance on the scale of wave groups. The infragravity waves and mean flows are then computed with the shallow water equations. The sediment transport is calculated with an advection-diffusion equation, while the equilibrium sediment concentration is derived with the Van Thiel - Van Rijn equation.

A.o.1 Short wave action balance

The wave forcing is computed with a time-varying version of the wave action balance (equation A.1), which is a simplified balance compared to for example SWAN.

$$\frac{\partial A}{\partial t} + \frac{\partial c_x A}{\partial x} + \frac{\partial c_y A}{\partial y} + \frac{\partial c_\theta A}{\partial \theta} = -\frac{D_w + D_f}{\sigma} \quad (\text{A.1})$$

Where c_x , c_y and c_θ is the wave action speed in x, y and directional space respectively. D_w and D_f are energy dissipation terms caused by wave breaking and bottom friction, σ is the intrinsic frequency and A is the wave action computed as:

$$A(x, y, t, \theta) = \frac{S_w(x, y, t, \theta)}{\sigma(x, y, t)} \quad (\text{A.2})$$

In which S_w is the wave energy density in each directional bin. The intrinsic wave frequency σ is obtained from the linear dispersion relation:

$$\sigma = \sqrt{gk \tanh(kh)} \quad (\text{A.3})$$

Where k is the wave number. The wave breaking dissipation term is based on the extended Roelvink formula, where the fraction of breaking waves (Q_b) is multiplied by the dissipation per breaking event (equations A.4 - A.6).

$$D_w = 2 \frac{\alpha}{T_{rep}} Q_b E_w \frac{H_{rms}}{h} \quad (\text{A.4})$$

$$Q_b = 1 - \exp\left(-\left(\frac{H_{rms}}{H_{max}}\right)^n\right), H_{rms} = \sqrt{\frac{8E_w}{\rho g}}, H_{max} = \gamma \cdot (h + \partial H_{rms}) \quad (\text{A.5})$$

$$E_w(x, y, t) = \int_0^{2\varphi} S_w(x, y, t, \theta) d\theta \quad (\text{A.6})$$

In which α is a wave dissipation coefficient, T_{rep} the representative wave period, E_w the energy of the wave, H_{rms} and H_{max} the root-mean-square and maximum wave height respectively, and n and γ are free parameters. For this thesis, for γ a value of 0.45 instead of the default value of 0.55 is used (see Chapter 2 for motivation).

A.o.2 Shallow water equations

The infragravity waves and mean flows are calculated with the Generalized Lagrangian Mean (GLM) shallow water equations (Walstra et al., 2000). The Lagrangian velocities are related to the Eulerian velocities and the Stokes drift:

$$u^L = u^E + u^S, v^L = v^E + v^S \quad (\text{A.7})$$

The Stokes drift is calculated as follows:

$$u^S = \frac{E_w \cos \theta}{\rho h c} \quad (\text{A.8})$$

$$v^S = \frac{E_w \sin \theta}{\rho h c} \quad (\text{A.9})$$

The GLM momentum equations are then:

$$\frac{\partial u^L}{\partial t} + u^L \frac{\partial u^L}{\partial x} + v^L \frac{\partial u^L}{\partial y} - v_h \left(\frac{\partial^2 u^L}{\partial x^2} + \frac{\partial^2 u^L}{\partial y^2} \right) = -\frac{\tau_{bx}^E}{\rho h} - g \frac{\partial \eta}{\partial x} + \frac{F_x}{\rho h} \quad (\text{A.10})$$

$$\frac{\partial v^L}{\partial t} + u^L \frac{\partial v^L}{\partial x} + v^L \frac{\partial v^L}{\partial y} - v_h \left(\frac{\partial^2 v^L}{\partial x^2} + \frac{\partial^2 v^L}{\partial y^2} \right) = -\frac{\tau_{by}^E}{\rho h} - g \frac{\partial \eta}{\partial y} + \frac{F_y}{\rho h} \quad (\text{A.11})$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial h u^L}{\partial x} + \frac{\partial h v^L}{\partial y} = 0 \quad (\text{A.12})$$

v_h the horizontal viscosity, calculated as:

$$v_h = c_s^2 * 2^{0.5} * \sqrt{\frac{\partial u^2}{\partial x} + \frac{\partial v^2}{\partial y} + \frac{1}{2} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)^2} \Delta x \Delta y \quad (\text{A.13})$$

In which c_s is the Smagorinsky constant, set at 0.1. τ_{bx} and τ_{by} are the bed shear stresses, η the water level, g the gravitational acceleration and F_x and F_y the wave-induced stresses. The bed shear stress is calculated with:

$$\tau_{bx}^E = c_f \rho u_E \sqrt{(1.16 u_{rms})^2 + (u_E)^2} \quad (\text{A.14})$$

$$\tau_{by}^E = c_f \rho v_E \sqrt{(1.16 u_{rms})^2 + (u_E)^2} \quad (\text{A.15})$$

Where c_f is the dimensionless friction coefficient and u_{rms} the wave orbital velocity magnitude.

A.o.3 Surf beat mode and infragravity waves

In this thesis I performed all simulations in the surf beat mode. Here, the variation of short-wave envelope is solved on the scale of wave groups. It includes a dissipation model for use with wave groups. Radiation stress gradients drive infragravity waves. In the 1D mode of XBeach, only the cross-shore component of the full infragravity field is prescribed which leads to an underestimation of the IG wave height. Therefore, I used the 2D mode (Chapter 3-5) or the 1D mode with shore normal waves (Chapter 2).

A.o.4 Sediment transport

The sediment concentrations are computed with a advection-diffusion equation with a source-sink term based on the equilibrium sediment concentration:

$$\frac{\partial hC}{\partial t} + \frac{\partial hCu^E}{\partial x} + \frac{\partial hCv^E}{\partial y} + \frac{\partial}{\partial x} \left(D_h h \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_h h \frac{\partial C}{\partial y} \right) = \frac{hC_{eq} - hC}{T_s} \quad (A.16)$$

In which C is the depth-averaged sediment concentration (varying on the wave-group timescale), D_h the constant sediment diffusion coefficient, T_s an adaptation time related to the entrainment of sediment and C_{eq} the equilibrium equation, computed with the Van Thiel - Van Rijn equation (van Rijn, 2007; Van Thiel de Vries, 2009):

$$C_{eq,b} = \frac{A_{sb}}{h} \left(\sqrt{v_{mg}^2 + 0.64u_{rms,2}^2} - U_{cr} \right)^{1.5} \quad (A.17)$$

$$C_{eq,s} = \frac{A_{ss}}{h} \left(\sqrt{v_{mg}^2 + 0.64u_{rms,2}^2} - U_{cr} \right)^{2.4} \quad (A.18)$$

Where $C_{eq,b}$ and $C_{eq,s}$ are the equilibrium concentration for bed load and suspended load respectively, A_{sb} and A_{ss} are coefficients and U_{cr} is the critical velocity. v_{mg} is the Eulerian flow velocity magnitude. When long wave stirring is turned on ($lws = 1$), v_{mg} is simply the magnitude of the Eulerian velocity:

$$v_{mg} = \sqrt{(u^E)^2 + (v^E)^2} \quad (A.19)$$

However, if $lws = 0$ then v_{mg} is calculated with two terms, a factor of v_{mg} of the previous time step and a current-averaged part, based on a factor f_{cats} :

$$v_{mg}^n = \left(1 - \frac{dt}{f_{cats}T_{rep}} \right) v_{mg}^{n-1} + \frac{dt}{f_{cats}T_{rep}} \sqrt{(u^E)^2 + (v^E)^2} \quad (A.20)$$

This is in fact calculating the average over one wave period, so that wave stirring by the IG waves is excluded. When short wave stirring is turned on ($sws = 1$), equation A.17 and A.18 are used for determining the equilibrium concentration. However, when $sws = 0$, the term $0.64u_{rms,2}^2$ is left out of the equations.

A.o.5 Bottom updating

Based on the gradients in the sediment transport the bed level (z_b) changes according to:

$$\frac{\partial z_b}{\partial t} + \frac{f_{mor}}{1-p} \left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} \right) = 0 \quad (A.21)$$

In this equation, f_{mor} is a morphological acceleration factor, ρ the porosity, and q_x and q_y represent the sediment transport rates in x and y direction.

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About the author

Daan Wesselman was born at the 13th of April 1990 in Nieuwegein, where he grew up and attended secondary school at Cals College. In 2008, he started his bachelors in Earth Sciences at Utrecht University. Daan got intrigued by beaches, waves and morphodynamics during several courses and decided to continue with a masters in Earth, Surface & Water with coastal processes as specialisation. During his masters he wrote his thesis on the development of spectra and bispectra in the surf zone, based on wave flume data. Thereafter, he went for a six-month internship to Deltares in Delft to study how sandbars move over time and which factors determine the migration speed. The experience with doing research convinced him to continue in research and find a PhD position. In May 2014, Daan started as PhD candidate with a Climate-KIC project at Utrecht University, where he improved his skills in collecting and analysing data, modelling, writing and teaching. Since November 2018, he works for WaterProof B.V. in Lelystad, the Netherlands.

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