EFFECT OF DIFFERENT FORCING PROCESSES ON THE LONGSHORE SEDIMENT TRANSPORT AT THE SAND MOTOR, THE NETHERLANDS

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The Sand Motor is a pilot project of a 'mega-nourishment' built in the Dutch coast in 2011. In order to understand which conditions reshape those mega-nourishments the influence of different types of forcing on the longshore sediment transport along the Sand Motor has been assessed in this paper using a process-based model. The use of numerical simulations enables the independent assessment of the different processes influencing the sediment transport magnitudes and direction. A calibrated depth-averaged model of the Sand Motor was used in order to compute the sediment transport rates around the nourishment. Results show that the overall evolution of the Sand Motor is event-driven, as the combination of energetic wave conditions, strong winds and high storm surge levels can lead to high sediment transport rates and therefore intense erosion.

Keywords: mega-nourishment, sediment transport, Sand Motor

INTRODUCTION

Around 75% of the Dutch coast consists of dune areas that provide protection of the low-lying hinterland against flooding (de Ronde *et al*., 2003; Southgate, 2011). Besides that, the sandy coast is also important for other purposes, such as ecological and recreational functions. Large sections of the Dutch coast have been constantly eroding, consequently measures were taken in order to maintain the beach-dune system.

The Sand Motor is a pilot project of a 'mega-nourishment' built in 2011 at the Delfland coast (The Netherlands) The nourishment project consists of an artificial peninsula of around 128 ha of surface and a volume of about 17 Mm3 of sand aiming to provide protection of the low-lying hinterland against flooding and increase ecological and recreational functions in a more sustainable way (Stive *et al*., 2013). It is expected that during the following 20 years the sand will be transported along the coast between Hoek van Holland and Scheveningen due to natural processes, leading to an increase of the dune area of around 33 ha (Mulder and Tonnon, 2010).

The morphodynamic behavior of mega-nourishments is still unknown, as the Sand Motor is a pioneer project of this kind. A good comprehension of the different aspects of the sediment transport in the area is important to better predict the future development of the Sand Motor. Therefore, the objective of this study is to investigate the influence of different types of forcing on the longshore sediment transport magnitudes and patterns along the Sand Motor using a process-based numerical model. The use of numerical simulations enables an independent assessment of the different processes influencing the sediment dynamics. This complements the field observations in which the superimposed effect of all the variables is present.

STUDY AREA

The Sand Motor is located at the Delfland Coast, the southern part of the Holland coast between Hoek van Holland to Scheveningen (Figure 1). The coastline is characterized by an almost uninterrupted dune row, oriented SW-NE, and the hydrodynamic conditions show almost no variation along the coast.

The Delfland coast has an asymmetrical semi-diurnal tide. The asymmetry of the tide is very well pronounced and, on average, the falling period is almost twice the rising period (8:04 hours against 4:21 hours at Scheveningen). This asymmetry also reflects on the horizontal tide, and the flood currents are generally stronger than the ebb currents. As the tidal wave propagates along the coast to the north a northward current associated with the flood tide and a southward current associated with the ebb tide are observed. Along the Dutch coast the maximum flood and ebb current velocities occur just before high and low water respectively.

The average wave climate along the Delfland coast is dominated by waves from southwest and north-northwest (Wijnberg, 2002). Due to the configuration of the North Sea, the north-northwest

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waves are generally swell waves and the southwest waves are locally wind-generated waves. Wave conditions show small longshore variations along the coast (Tonnon *et al*., 2009; van de Rest, 2004). Notwithstanding, a seasonal variation in the wave heights is observed, with higher waves occurring during the winter.

The main direction of the wind in the area is from southwest, approximately parallel to the coast, and when persisting for some time the wind can generate a longshore current due to the shear stress exerted on the sea surface. This current may facilitate the transport of sediment stirred-up by the waves in the nearshore. However, the most significant contribution of the wind is the local generation of waves and water level set-up (storm surges).

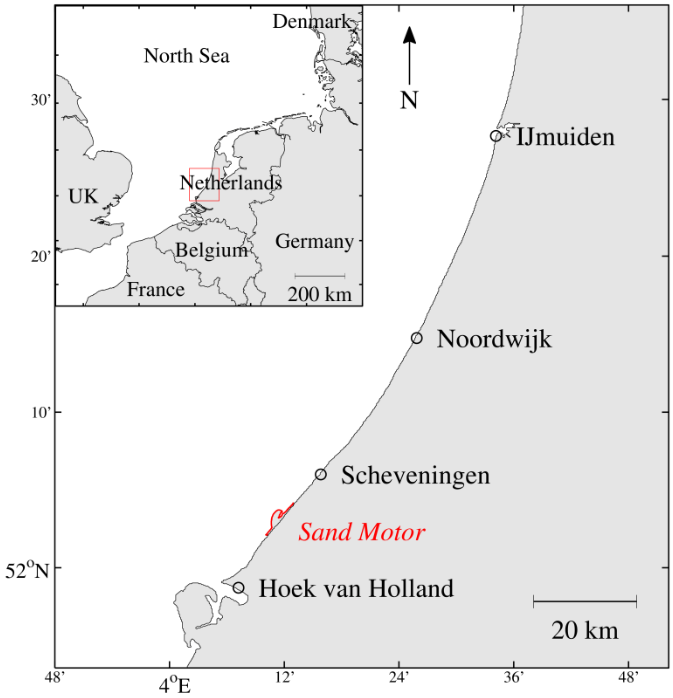

Figure 1: The Holland Coast and the location of the Sand Motor.

Effects of the Sand Motor on the hydrodynamics

The peninsula represents a big perturbation to an otherwise alongshore uniform coastline, and thus altering the local hydrodynamics. Simulations show that tidal currents are increased with a factor of about 2 due to the flow contraction at the head of the Sand Motor and eddy formation is observed at both sides of the peninsula (northeast side during flood tide and southwest side during ebb tide, Pekkeriet, 2011).

Wave-driven longshore currents are also affected by the shape of the peninsula and irrespective of the wave direction there is a point of flow separation, generating both a southward and a northward flow. The location of this point is dependent on the wave direction as it occurs where the relative angle between the incident waves and the coastline is approximately zero. The peninsula also acts as a barrier against the wave action and shadow areas are observed, especially in the case of southwest waves.

METHODOLOGY

Model overview

To understand the conditions controlling the development of the Sand Motor it is important to comprehend the nearshore processes acting in the area and the effect those processes have on the sediment transport. Delft3D is a robust process-based numerical model suite which can be applied in different coastal environments, including complex geomorphological features as spits (Dan *et al*., 2011; Grunnet *et al*., 2004). It is composed of different modules that can compute the hydrodynamics, waves, sediment transport, morphology, water quality and ecology. The base of the model is the hydrodynamic module, Delft3D-FLOW, that solves the unsteady shallow water equations in 2 (depth-averaged) or 3 dimensions, these include the horizontal momentum equations, continuity equation, transport equation and a turbulence closure model (Lesser *et al*., 2004).

Waves are simulated by the Delft3D-WAVE module that uses the spectral wave model SWAN (Simulating WAves Nearshore), which computes the evolution of random short-crested wind-generated waves in coastal areas. This module can be coupled with the FLOW module through a dynamic interaction, where the output of each module is used as an input on the other, accounting for the effects of waves on currents and the effect of flow on waves.

The sediment transport is calculated for the different fractions (as distinction is made between cohesive and non-cohesive sediment) using one of the many available sediment transport equations. The sediment transport formulation used in the model was the TRANSPOR2004 (van Rijn and Walstra, 2003; van Rijn *et al*., 2004).

The Sand Motor model

For this study a calibrated 2DH model of the Sand Motor, introduced by (Luijendijk *et al*., 2014), was used in order to compute the sediment transport rates along the area. The computational grid applied in the Delft3D-FLOW module is a curvilinear grid comprising the Delfland coast, extending 9.4 kilometers in alongshore direction and 4 kilometers in offshore direction until the -15m NAP depth contour. The computational grid has a resolution of about 30 by 30 meters near the Sand Motor, gradually decreasing towards the boundaries up to approximately 100 by 100 meters. For the Delft3D-WAVE module two nested computational grids were used: the finer grid is the same used in the Delft3D-FLOW module and it is nested to a coarser and larger grid (Figure 2).

The seaward boundary conditions of the FLOW domain are defined by a time- and space-varying water level, representing a propagating tidal wave. These values have been obtained from larger scale models covering the North Sea. At the lateral boundaries Neumann conditions are applied, thus the alongshore water level gradients at the boundaries are calculated based on the conditions at the seaward boundary. This avoids the development of boundary disturbances due to differences between the cross-shore distribution of velocity and imposed water levels resulting from the larger-scale calculations.

The bed composition is defined by two sediment fractions, a sand fraction (non-cohesive) with median grain size of 300 μm and a mud fraction (cohesive).

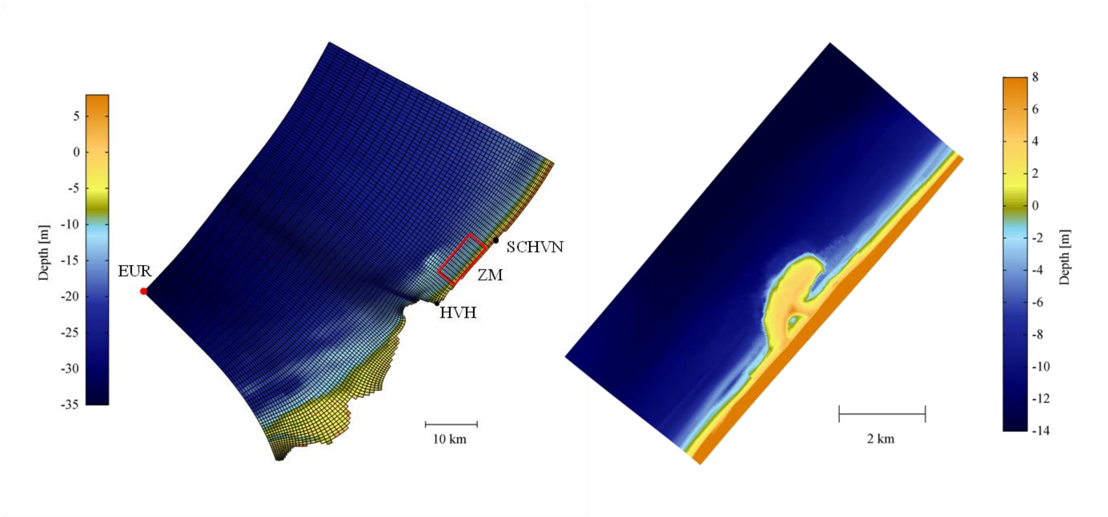

Figure 2: Coarse computational grid and bathymetry used in the Delft3D-WAVE module (left), and Delft3D-FLOW domain and the initial bathymetry of the Sand Motor soon after the construction (August 2011, right). Measuring stations are shown on the left (EUR - Europlatform, HVH - Hoek van Holland, SCHVN - Scheveningen).

Simulations

Simulations with different forcing combinations were performed in order to investigate the relative contribution of vertical tide, horizontal tidal and wind-induced currents, surge levels, and waves on the longshore sediment transport along the Sand Motor. Firstly, simulations with different wave conditions were performed. These served as a reference scenario to the subsequent simulations, in which processes such as wind, tidal currents, storm surges and waves were included or excluded in the model. The description of the several model experiments is presented in the following sections.

The wind and wave boundary conditions were assumed constant during the entire tidal cycle and sufficient time was given for the model to spin up. Hence, the simulations represent an ideal situation in which the hydrodynamic forcing is steady and wind-driven currents are already fully developed and in equilibrium. Measured data shows that variations in wave conditions within a tidal cycle are relatively small for waves higher than 1.5 m, on the other hand, the wind field shows much greater variability and this idealized scenario is normally reached only during storm events, therefore, results of simulations with mild conditions might be overestimated.

Wave scenarios

The schematized wave conditions used in the numerical experiments were derived from a 2-year time series measured at Europlatform station (starting from the moment the Sand Motor was completed, in August-2011, until August-2013). The offshore wave conditions were divided in classes of wave direction (15° sectors) and the relative weighted sediment transport of each bin was calculated using the Kamphuis (1991) equation to indicate the directional sector with most important contribution (Figure 3).

Simulations were then performed with waves coming from south-southwest (225°), the most frequent direction and the main contributor to the sediment transport (Figure 3), and wave heights ranging from 1.0 to 4.5 meters. Corresponding peak wave periods and wind speeds were defined as the mean values of the wave conditions within each bin. Wind direction is assumed to follow the wave direction. Those conditions were then uniformly applied at the seaward and lateral boundaries of the Delft3D-WAVE model. An overview of the schematized wave/wind conditions is presented in Table 1. For these simulations wind was not applied in the FLOW model as it significantly increases the complexity of the boundary conditions and the spin up time of the simulations. The contribution of the wind is analyzed separately in the following section.

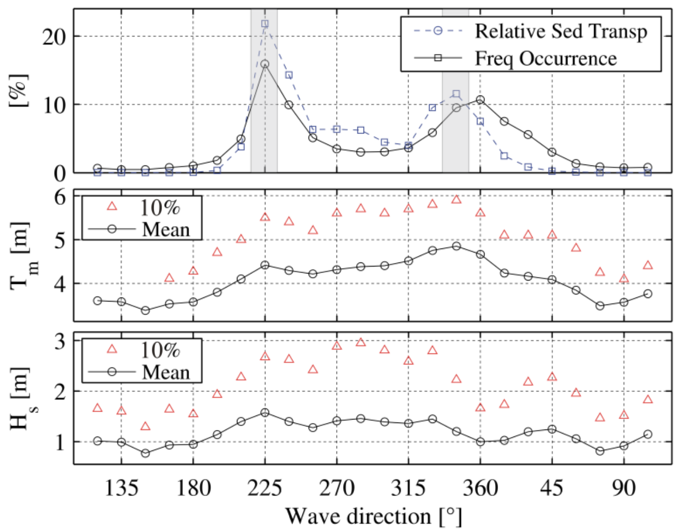

Figure 3: Wave conditions and the associated sediment transport per wave direction. Upper panel: percentage of occurrence (solid line) and relative sediment transport (dashed line) of each directional bin (15° interval). The shaded areas indicate the directions with largest contribution for the sediment transport. Middle panel: mean wave peak period of each bin and the mean wave period with 10% probability of exceedance. Lower panel: mean significant wave height of each bin and the wave height with 10% probability of exceedance.

Table 1: Overview of the different wind and wave conditions applied. The symbols are: θ, angle of wave incidence with respect to north; Hs, significant wave height; Tp, peak period; Ψ, wind direction with respect to north; W, wind speed.

Scenarios	**Wave**			**Wind**	
	θ [°]	H_s [m]	T_p [s]	Ψ [°]	W [m/s]
1	225	1.0	5.0	225	7
2	225	1.5	5.8	225	9
3	225	2.0	6.4	225	11
4	225	2.5	6.9	225	13
5	225	3.0	7.4	225	15
6	225	3.5	7.9	225	16
7	225	4.0	8.3	225	18
8	225	4.5	8.5	225	21

Decomposition into forcing processes

Four additional model experiments were designed to assess the role of tide and wind-induced currents on the sediment transport at the Sand Motor: a simulation where all processes were present (waves + vertical tide + tide- and wind-induced currents), a simulation with wind and tides but no waves and a simulation with absence of tidal currents. Those simulations were compared with the results of scenarios 2, 3 and 7 of the previous simulations (waves + tide) in order to investigate the effects of the different processes on the sediment transport.

For the simulations including wind, a uniform and constant wind field was applied over the entire FLOW domain. Wind speed and direction was the same used in the WAVE module (Table 1). The simulation without tidal currents was achieved by changing the space- and time-varying seaward boundary conditions to a uniform water level that varied only in time. Thus the propagating tidal wave is not represented in the model, and consequently tidal currents are absent while the vertical tidal movement is still present. It is important to notice that due to the alongshore extent of the domain there is a discrepancy between the water levels of this simulation and the one with the propagating tidal wave especially towards the lateral boundaries. When averaged over a tidal cycle these discrepancies are negligible, however instantaneous transports might be under/overestimated.

To account for the effect of storm surges in the sediment transport at the Sand Motor, additional water levels were imposed in the model. This was done by increasing all water level conditions by a certain level during the entire tidal cycle. Based on observed surge level records at Hoek van Holland a typical range for the surge levels was found. Simulations of scenario 7 (Table 1) were conducted with additional water levels varying from 0.2 to 1.2 meter.

Table 2: Overview of the different wind and wave conditions and forcing processes applied. The symbols are: θ, angle of wave incidence with respect to north; Hs, significant wave height; Tp, peak period; Ψ, wind direction with respect to north; W, wind speed.

Scenarios	Wave			Wind		Processes used in the FLOW model			
	θ [°]	Hs [m]	Tp [s]	Ψ [°]	W [m/s]	Waves	Tidal currents	Wind	Surge
1	225	2	6.4	225	11	✓			
2	225	2	6.4	225	11	✓	✓		
3	225	2	6.4	225	11	✓	✓	✓	
4	225	2	6.4	225	11	✓	✓	✓	✓

Calculation of sediment transport rates

To intercompare the modeling results, sediment transport rates through shore-normal transects were calculated. Transects are spaced approximately 50 m in the alongshore direction and extend from NAP +3.0 m to NAP -8.0 m. For practical purposes, some transects were chosen as representative of different zones of the Sand Motor (South, ZM1, ZM2, ZM3 and North, Figure 4).

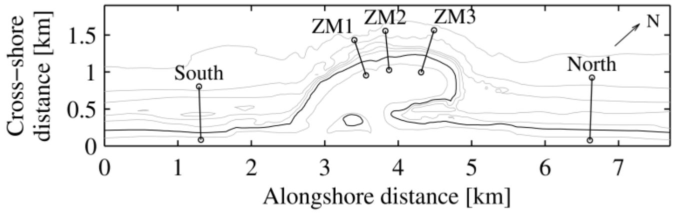

Figure 4: Location of five shore-normal transects representative for different zones of the Sand Motor from which sediment transport rates were derived.

As the transects are oriented perpendicular to the coastline (0 m contour), the transport through transects correspond approximately to the longshore sediment transport and is assumed as such. The cross-shore component is neglected in this study as oblique waves generate strong longshore currents, consequently the longshore sediment transport component is dominant over cross-shore transport.

The transport of cohesive material is also neglected. Although the gross transport of fine sediment (mud fraction) can be significant at larger depths (i.e., outside of the surf zone), its contribution to the net sediment transport is negligible. Thus, the results discussed hereafter are based on the total longshore sand transport (bed load + suspended load).

To better characterize each area and present a general alongshore trend of the sediment transport rates, results are based on the values integrated over a tidal cycle (Figure 5) and over each cross-shore transect.

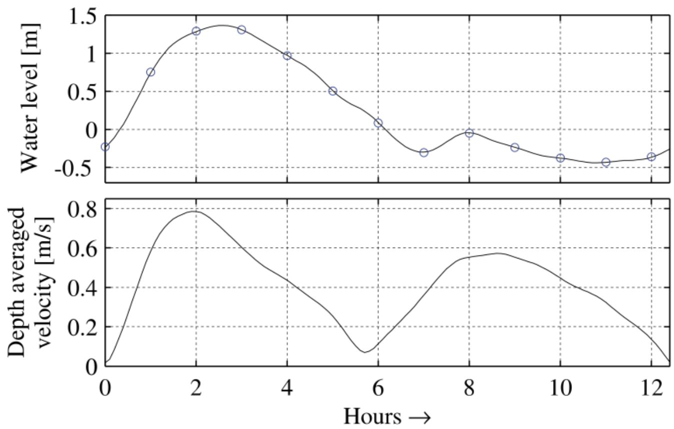

Figure 5: Water level (upper panel) and depth- averaged velocity (lower panel) at 14.5 meters water depth for the reference scenario.

SEDIMENT TRANSPORT DUE TO DIFFERENT FORCING PROCESSES

Sediment transport will respond to the changes in hydrodynamics caused by the presence of the Sand Motor. Thereby, higher transport rates are found at the head of the peninsula, where the longshore currents are stronger and the bottom slope is significantly steeper than the adjacent coastline.

Under the action of south-southwest waves (225°) the net sediment transport in the area is mainly directed northward even during ebb tide, when tidal currents are directed southward. Minimum net sediment transport occurs at the southern part of the Sand Motor, where the relative angle between waves and coastline is virtually zero, and at the area just north of the peninsula that is protected from the wave action.

Wave conditions

Sediment transport rates at the Sand Motor are highly affected by changes in wave heights / energy. Considering the same offshore wave angle (225°), more energetic events (e.g. Hs = 4.5 m and Tp = 8.5 sec) can lead to transport rates about 15 times larger than average conditions (e.g. Hs = 2 m and Tp = 6.4 sec, Figure 6). If multiplied by the frequency of occurrence of the different wave conditions, waves of about 3 m (and Tp = 6.4 m) are found to be dominant for the sediment transport at the Sand Motor (Figure 6, right panel). Mild wave conditions (e.g. Hs < 1.5 m), although occurring more frequently in the area have almost no transport capacity. On the other hand, south-southwest waves higher than 4 meters, present during approximately 0.2 % of the time, still contribute to 25,000 m3 of sediment per year (transect ZM2). At the adjacent coastline (transects South and North) this effect is less significant, therefore increasing wave power not only cause larger transport rates but also larger sediment transport gradients, which lead to erosion/sedimentation of the coast.

This dependence of the morphological development on the wave forcing is also evident on the topographic observations at the Sand Motor (de Schipper *et al*., this volume): large changes in the bottom topography were observed during periods of severe storms, while during mild conditions minor morphological changes occurred.

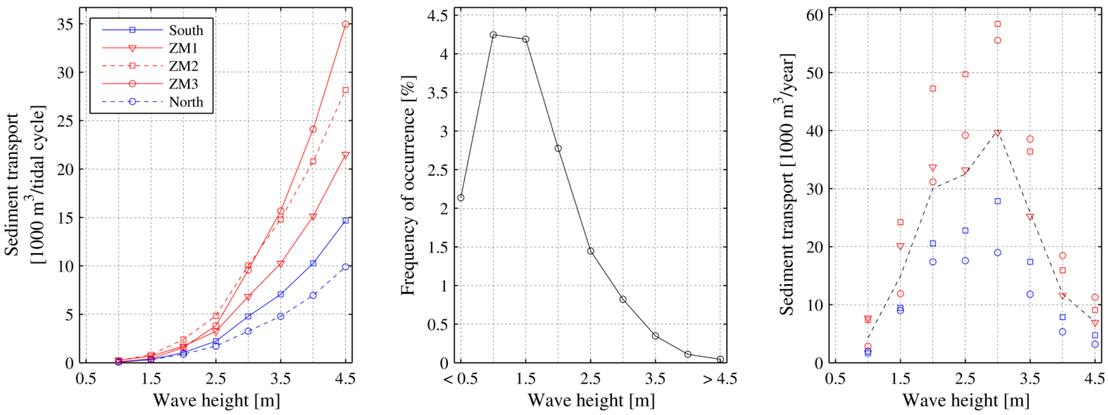

Figure 6: Left panel: Longshore sediment transport through cross-shore transects located south, north and at the head of the Sand Motor (location of the transects is shown in Fig 2). Middle panel: Frequency of occurrence of wave conditions. Right panel: Sediment transport per wave condition per year.

Wave conditions also determine the alongshore distribution of the sediment transport and location of the peak transports, due to different refraction patterns. Higher and longer waves generate maximum transports at the northern tip of the Sand Motor, while for decreasing wave height and period this zone of maximum transport shifts southward (Figure 7). This affects the gradients in sediment transport and therefore the evolution of the Sand Motor. Topographic features, such as mega-cusps and sand bars, also influence this alongshore distribution and peaks of sediment transport occurs at the horns and crests of these features, with a decrease at the embayments and troughs.

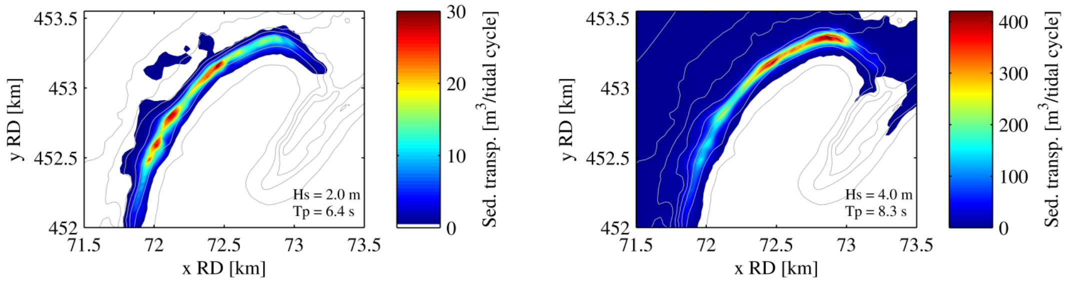

Figure 7: Distribution of the magnitude of sediment transport for different wave conditions in the case of south-southwest waves (offshore wave angle = 225°). Areas of sediment transport rates smaller than 0.5 m³/tidal cycle are shown in white.

Tidal influence

In this section, the effect of tidal currents is assessed by comparing results of a simulation without tidal currents, but with a varying water level representative of the vertical tide, with the results of the original simulations.

As the tidal flow reverses within a tidal cycle it is important to distinguish between the intra-tide and the tide-averaged sediment transport. Sediment transport is enhanced when the wave-driven longshore current and the tidal flow are in the same direction. Hence, within a tidal cycle sediment transport rates will be both increased and reduced by the tidal currents. For the long-term development of the Sand Motor, the resulting effect of the tidal currents in a tidal cycle is of greater importance and is the focus of this work.

The increase of the sediment transport due to the tide is only important at the head of the Sand Motor, due to the contraction of the tidal flow in this area and the consequent increase in current velocities. Along the adjacent coastline, this effect is not significant. Interestingly the most pronounced effect of the tide is found where the flow begins to contract, not where flow velocities are higher, decreasing towards the end of the peninsula where the flow expands. Under the action of higher waves (e.g. Hs = 4 meters), this pattern is not as clear and the effect of the tide is more or less uniform at the head of the Sand Motor (Figure 8, middle panel). Although the relative contribution of the tide seems smaller in this case (around 5%), the absolute increase in sediment transport is much larger than for milder conditions: 1600 m³/tidal cycle compared to 360 m³/tidal cycle at the head of the Sand Motor for waves of 2 meters.

The increase in sediment transport when tidal currents are present is both due to advection (enhancement of littoral drift) and stirring (increase of bed shear stress, hence increase of sediment concentration).

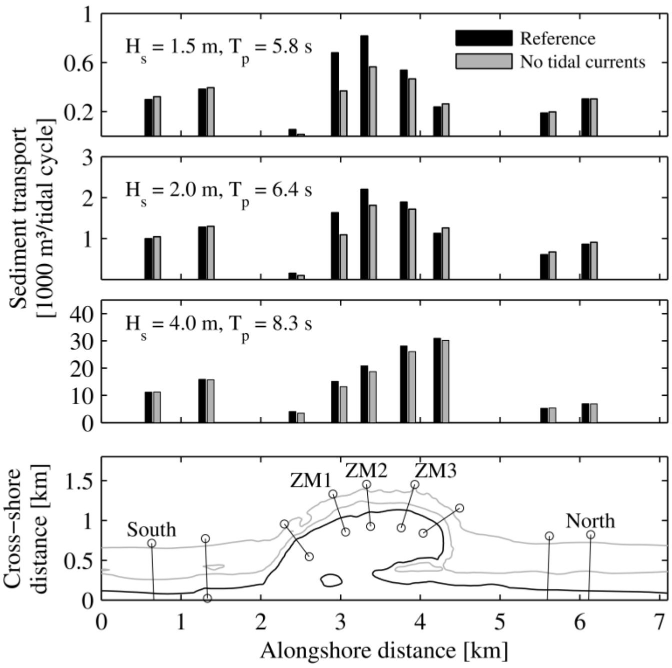

Figure 8: Sediment transport rates for a reference scenario (waves and tidal currents) and a simulation without tidal currents. Upper three panels: Longshore sediment transport through cross-shore transects for different wave conditions, Hs = 4, 2 and 1.5 meters from top to bottom. Black bars show the reference scenario and grey bars the simulation without tidal currents. Note the difference in scale of the vertical axis. Lower panel: location of transects.

Wind influence

Without the presence of waves to stir up the sediment, wind-driven currents have virtually no transport capacity. Results of the simulation including wind and tide only (no waves) correspond to less than 17% of sediment transport of the simulation with waves of 1.5 m and do not even reach 1% of the sediment transport generated by waves of 4.0 m. However, when associated with waves, they significantly increase the sediment transport in the area.

In the case of south-southwest waves (Hs = 2.0 m, scenario 3), a constant wind, with the same direction of the waves (225°) and speed 11 m/s leads to an increase from 2400 to 3100 m3/tidal cycle in the sediment transport at the head of the Sand Motor (transect ZM2), and from 1000 to 1300 m3/tidal cycle at south of the peninsula (transect South), corresponding to an enhance of about 25-35% of the sediment transport in comparison to a simulation without wind-driven currents (Figure 9). For higher waves and stronger winds (e.g. Hs = 4.0 m and wind speed = 18 m/s), an increase of more than 50% of the sediment transport is observed.

As the wind direction is constant and follows the wave direction its effect in the sediment transport is always positive, contrasting to the effect of the tidal currents that varies within a tidal cycle. Thereat, the wind has stronger influence in the net sediment transport than the tidal currents. The wind is especially important in the case of southwesterly waves and storm events, normally associated with strong and steady winds.

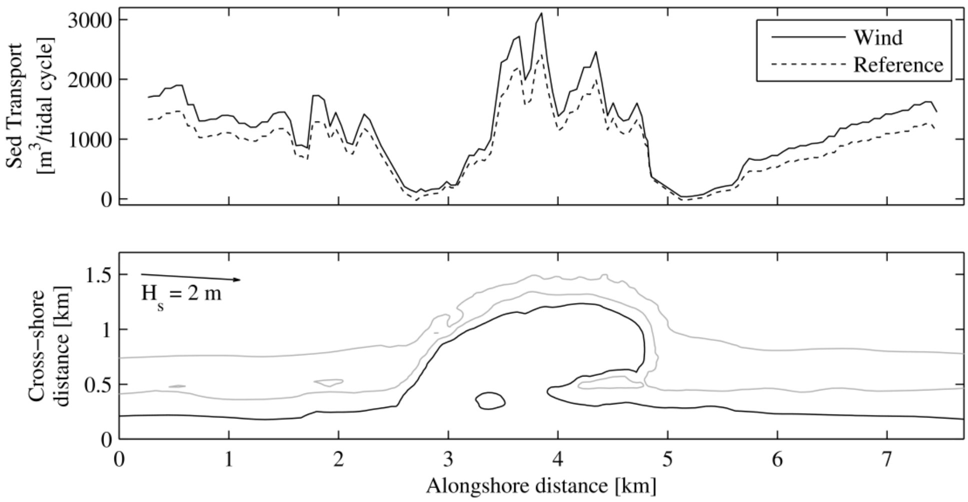

Figure 9: Tide-averaged longshore sediment transport for the reference scenario (dashed line) and the simulation including wind (solid line, upper panel). Lower panel: bathymetry of the Sand Motor in August/2011, black line indicates the coastline (0 m contour) and the gray lines indicate 4 and 12 meters depth contours. The arrow indicates the offshore wave direction.

Storm surge levels

Another important aspect controlling sediment transport rates in the area is the storm surge level. It was found that an additional water level of 1.2 meter can increase sediment transport about 10-20%.

In contrast with the influence of tidal currents, the surge level affects the whole alongshore extent of the model in a more or less uniform way. In general there is an increase of the net sediment transport, except at the areas immediately south and north of the peninsula where decrease is observed.

In the southern area this apparent decrease is due to an actual increase in the gross southern transport, as this is the area of flow separation. In the northern area this decrease occurs due to the complexity of the circulation near the lagoon inlet: velocities are controlled by the filling and emptying of the lagoon and are not in phase with the tidal currents.

Notwithstanding, the influence of the surge level is more dependent on the bottom profile than on the coastline curvature or location; and large differences can be observed even between subsequent transects. The presence of sand bars or a berm in the profile defines how strong the effect of the storm surge will be.

With the increase in water depth, only higher waves will break over the sand bar, hence the peak transport shifts nearshore and the transport curve becomes more spread (Figure 10). Although the peak transport decreases, there is an overall increase in the bulk longshore sediment transport rates and higher erosion rates are expected.

This reinforces the importance of extreme events for the development of the Sand Motor, as high surge levels are normally associated with more energetic wave conditions and stronger winds.

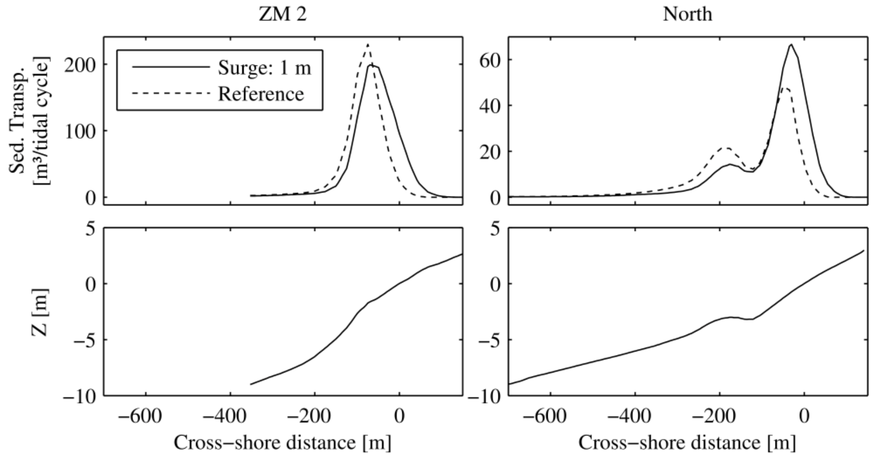

Figure 10: Cross-shore distribution of the longshore sediment transport through transects (location in Figure 4) for the reference scenario and a simulation with additional water level (upper panel). Lower panels: bottom profiles at the same transects.

DISCUSSION AND CONCLUSIONS

The relative influence of waves, tides, wind and storm surge levels on the sediment transport at the Sand Motor was investigated by means of hydrodynamic simulations and sediment transport calculations using a previously calibrated 2DH process-based model. Simulations show that waves, with a minimum significant wave height of 1.5 meter, are the main factor defining the sediment transport at the Sand Motor. Considering the frequency of occurrence and the potential transport capacity of different wave conditions, the long term development of the Sand Motor is dominated by waves of about 2.5 – 3 meters; and extreme events, although uncommon, are still more relevant than very mild conditions.

Although wind and tides alone have no transport capacity, when waves are present they play an important role in enhancing the sediment transport at the Sand Motor. In the case of SW waves, the strong tidal currents at the head of the Sand Motor lead to an increase of the sediment transport in this area, while the wind-driven currents, more alongshore uniform, reinforce the sediment transport rates along the entire coastline. The inclusion of tidal and wind-driven currents not only increases the advection of sediment stirred-up by the waves but also lead to an amplification of the bed shear stress, consequently increasing mixture and the sediment concentration in the water column.

Storm surges also enhance the sediment transport in the area. An increase in water level leads to different breaking patterns expanding and pushing the sediment transport curve to nearshore, hence increasing the sediment transport rates. This behavior highly depends on the bottom profile, however a general increase in the sediment transport is observed.

The Sand Motor has an important effect in changing the sediment transport distribution. The strong longshore currents at the head of the Sand Motor induce high transport rates in the area, while the regions adjacent to the peninsula experience very low transport, and consequently deposition of sediments.

It can be concluded that the overall evolution of the Sand Motor is event-driven, as the combination of energetic wave conditions, strong winds and high storm surge levels can lead to high transport rates and therefore intense erosion.

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