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# ON THE IMPORTANCE OF TIDAL INLET PROCESSES FOR COASTAL DUNE DEVELOPMENT

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## Abstract

The cellular automata model DUBEVEG (De Groot et. al., 2011, Keijsers et. al. 2016), developed for straight coastlines, is tested to conceptually simulate coastal dune development on sandflats close to inlets. Both synthetic and real cases are considered. Results suggest that the groundwater level controls local sediment supply and, consequently, the type and size of dunes. Furthermore, groundwater levels can add intrinsically spatial variability in sediment supply which is comparable to real cases. However, spatial variability in terms of dune type could not be simulated properly, suggesting a lack of processes such as hydrodynamic erosion due to currents during storm surge flooding of the sandflat. The current model is able to qualitatively simulate spatial trends in sediment supply along the sand flat, but the mismatch in terms of dune type and size suggests a lack of important inlet specific hydrodynamic processes and limiting transport factors.

**Key words:** cellular automata model, Aeolian sediment transport, dunes and ecomorphology, sand flats, beach-dune interactions

## 1. Introduction

Dune systems that emerge close to inlets may be affected by processes from both beach and inlet. Inlet processes can produce specific characteristics that can either enhance (*e.g.* development of wide sand flats, shoal attachment) or diminish (*e.g.* high groundwater levels) potential for dune development. However, the exact effect of inlet processes on dune development is still unclear. In that perspective, the cellular automata model DUBEVEG (De Groot et. al., 2011, Keijsers et. al. 2016) may be a potential tool to evaluate, in a conceptual and qualitative way, the effects of inlet parameters on dune development. Cellular automata models are strong tools to assess the interaction between different processes and, in a qualitative way, understand underlying patterns on coastal environments. The DUBEVEG model was developed and validated to simulate the effects of climate change on dunes in an open coast setting. However, specific inlet processes that are hypothesized to be important for dune development (*e.g.* spatial patterns in sediment supply, erosion due to inlet currents during storm surges) are not yet included. The main objective of this study is to evaluate how well the current DUBEVEG model performs on a wide sand flat in a tidal inlet setting. In a case study on the island of Texel, the Netherlands, dune development on a wide sand flat bordering a tidal inlet is simulated without modifications to account for inlet specific processes. By comparison to observed developments, the applicability is evaluated, as well as the potential for adaptation of this model concept to simulate dune development near inlets.

### 1.1 *Study area*

On the island of Texel, dunes are emerging close to the inlet on the southern side of the island, where a beach plain (*de Hors*) of roughly 3 km² is located. It is situated adjacent to a mixed-energy wave dominated inlet (*Marsdiep inlet*), with a predominant wind coming from southwest (Figure 1). Large parts of the beach plain remain exposed most of the time, being flooded only during storms. The sand flat can be

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divided in three sections: one more exposed to waves, a central region, and an inner part facing the basin. The beach plain in the inner plain is, on average, lower than the exposed part, thus being flooded more frequently. The dune field associated with the beach plain has been growing and expanding in the past 18 years, with the outer and central region contributing with over 90% of the volume increase of the dunes. Roughly, embryonic dunes are found in the central part, whereas a continuous dune row with several small incipient dunes can be seen on the exposed part. The inner region has much less sediment input than the other parts (7% in volume from the total dune growth of the whole area), displaced in as a dune row.

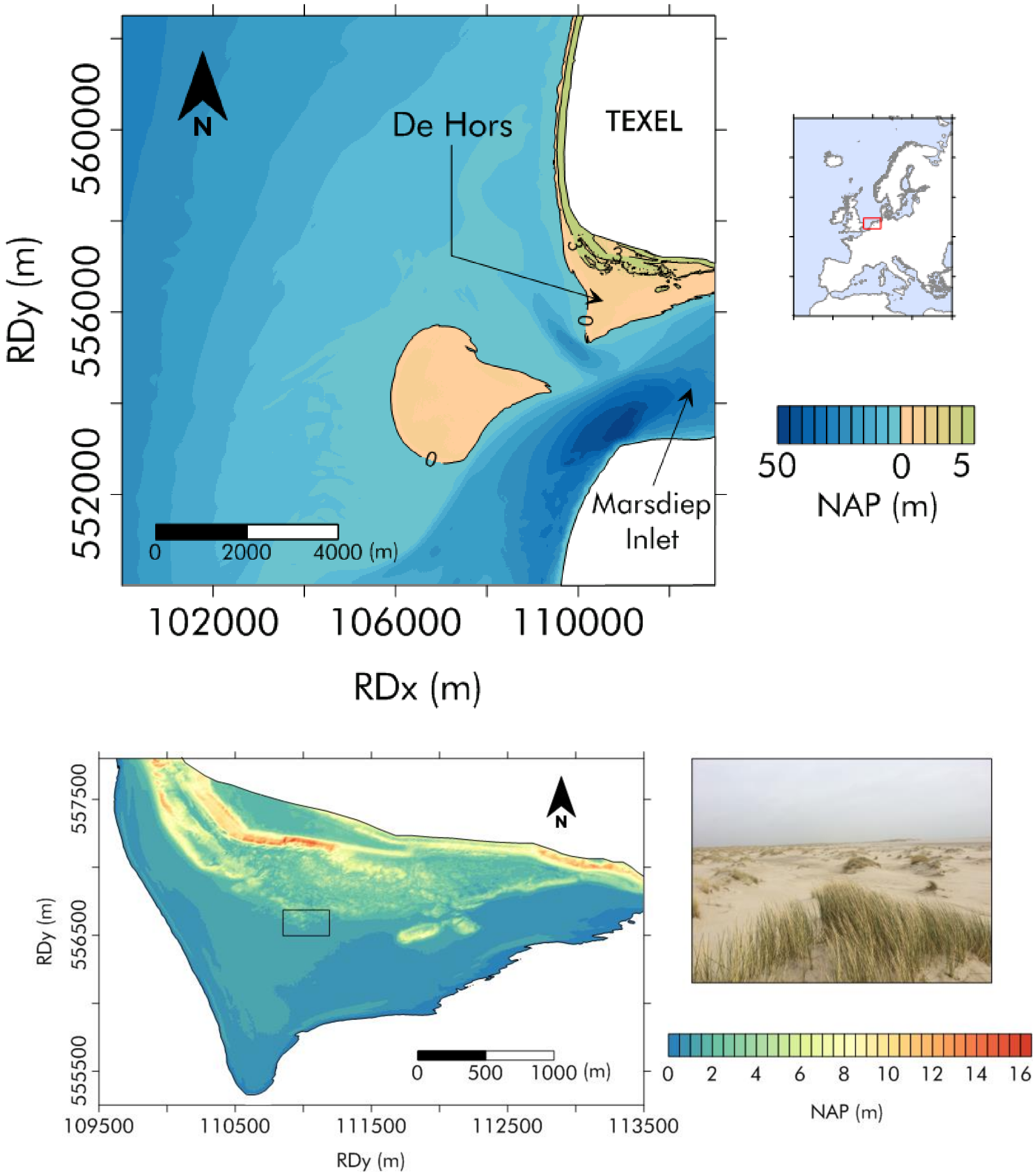

Figure 1: Upper: Map of the Marsdiep Inlet and beach plain ('De Hors') chosen as a case study for the proposed research. Lower: Elevation map of the beach plain, showing the main dune characteristics and the lower elevation of the beach plain in the eastern area. Hummocky-shaped dunes are common to the central zone, whereas dune row and foredunes are more common in the east and west part, respectively.

## 2. The DUBEVEG model

### 2.1 *Model description*

The DUBEVEG model, based on previous models by Werner (1995) and Baas (2002), simulates beach-dune development considering aeolian sand transport, biotic processes related to vegetation and hydrodynamic erosion in a probabilistic rule-based approach. The rules control the probability of discrete sand slabs to be eroded, transported and deposited over a cellular grid domain. All the rules are meant to replace complex processes which are important for dune development on coastal areas (*e.g.* hydrodynamic erosion by waves, Aeolian sediment transport, vegetation growth). The model consists of three main modules which constantly interact throughout the simulation: the transport module, the hydrodynamic module and the biotic model.

The transport module is the base of the model, on which all the others interact. Structurally within this module, individual slabs displaced over a certain domain are picked stochastically based on a probability of erosion $P_{ero}$ and transported downwind by a distance D. Based on a deposition probability $P_d$, the individual slabs can either be deposited or transported another distance D. The iterations finish when all the moving slabs are deposited. The direction of transport of each slab mimics the wind direction and can be stated either parallel or perpendicular to the Y-axis. Thus, different wind directions can be applied between iterations. The height and width of each slab are predefined and remains the same throughout the entire simulation. Their sizes can be related to a real-world scenario based on a potential Aeolian transport per meter alongshore Q (m3/m/y):

$$Q = Hs\,.\,L\,.\,(P_e/P_d)\,.\,n \tag{1}$$

where Hs is the slab height (m), L is the cell width (m), $P_e$ is the erosion probability, $P_d$ is the deposition probability and n is the number of iterations which represent one year (Nield and Baas, 2007, Keijsers et. al, 2016).

Both erosion and deposition probability are spatial dependent within the grid. Areas behind dunes, for example, are considered shadow zones which have higher deposition probability than open areas, whereas vegetated slabs will have lower probability of being eroded. Vertically, the amount of sand available to be transported depends on a defined level and a groundwater level. The groundwater level is defined as an elevation proportional to a defined equilibrium profile. The model also accounts for avalanching due to angle of repose.

The hydrodynamics module represents the sea forcing over the beach-dune system. The module is called after a number of iterations that represents roughly two weeks in order to mimic a full neap-spring tide cycle. The module uses the highest tide level (imposed as an input file) in the period and determine the inundated area (thus the potential area to be influenced by the sea) which is used to update the topography accordingly.

Wave run-up is calculated based on Stockdon et al. (2006), whilst wave dissipation is stated as a function of the remaining water depth along the X-axis. For each inundated cell an erosion probability is given due to hydrodynamic forcing. Cells to be eroded can be defined either by a stochastic term or by an imposed condition. If cells are eroded, the topography returns to its equilibrium level, defined by the equilibrium profile $Z_{eq}$. If $Z_{topo} < Z_{eq}$, an increase in the available sediment occurs representing sediment input from the sea. If $Z_{topo} > Z_{eq}$, sediment is lost and thus means hydrodynamic erosion. Sheltering from waves can be defined, which diminishes the probability of erosion behind cells higher than the estimated water level.

The vegetation module mimics the growth and decay of species which are common on dune systems based on their growth curves. In the model, two species are defined: one related to a pioneer species such as *Ammophila sp* and another related to a conservative species such as *Hippophae rhamnoides.* The curves are based on the potential of growth and decay related to a certain erosion/accretion balance. Pioneer species have an optimal growth when buried in some extent, but have less capacity to sustain big losses. The conservative species are more reliable to losses of sand. The vegetation is based on its vegetation effectiveness (Nield and Baas, 2007), which ideally relates the effect of vegetation on the sand transport. Establishment of new vegetation on bare cells and lateral expansion is included in the model, on which details can be found on Keijsers et al. (2016). The module is called less times than the hydrodynamic module, usually once or twice per model year.

### *2.2 Initial conditions*

Three different cases have been used for the simulations: one, based on LIDAR surveys from the area, is used to assess how the model performs in a real sand flat case; whereas two synthetic cases, much smaller, has been created for sensitivity analysis purposes (computational efficiency). The synthetic ones are based on areas on the west and east of the plain. All simulations have a time-span of 15 years. Water level input series were based on tide gauges available within the area. The maximum two-weeks water level measured (period for the marine update) is calculated and used as a boundary condition. All simulations were settled with a slab height of 0.1 and a consequent number of iterations which translates into a sediment transport of the same order of magnitude expected on Texel.

The case based on real data encloses the whole sand flat, with a resolution of five meters, following the resolution of the LIDAR data and a feasible computational effort/resolution balance. The initial elevation is based on the 1997 LIDAR survey, which is the oldest survey available. The conceptual equilibrium profile was built based on the same year, treated with a Gaussian low-pass filter to smooth the surface. The use of the 18-year average was tested and considered unusable due to the bias introduced by the expanding dune field. Moreover, the data suggests low variability in height for the sand flat area in a yearly time-scale, thus supporting the idea of using one field survey as a base equilibrium. The initial vegetation effectiveness for the pioneer species is defined randomly with values between 0 and 0.5 at slabs which were above 2 meters. The wind is unidirectional, from south to north (bottom to upper side in the model).

The synthetic case representing the east side of the plain is settled as a flat surface of 1.3 meters high with a small dune in the middle, resembling characteristics that can be seen in the central-inner part of the beach plain of Texel (Figure 2) and are less subject to wave action than the outer western part. The equilibrium profile used is a plan domain of 1.3 meters high, without dunes. The initial vegetation effectiveness for the pioneer species is defined randomly with values between 0 and 0.5 at slabs which were above 2 meters. For the conservative species, the initial vegetation effectiveness is settled as 0 for the whole domain. For this domain, the wave energy is settled as minimum, only to keep the marine module running and to account for small erosive effects that can happen during storms. The wind is unidirectional, from west to east (left to right, in the model). For the synthetic case representing the west side, the initial elevation is based on a small profile (400 meters) derived from the 1997 LIDAR survey, and used as constant for a longshore distance of 200 meters. The wave forcing is present in all scenarios based on this domain and is directed from west to east (left to right in the model).

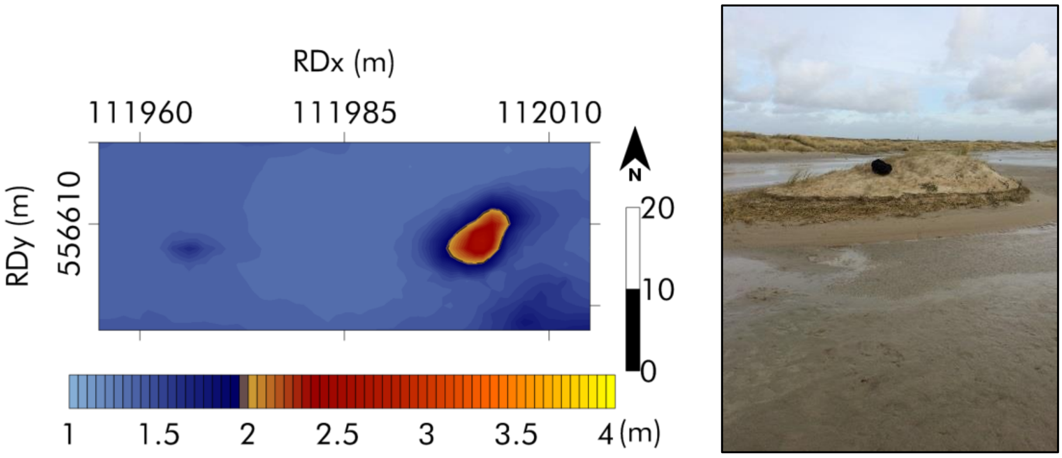

Figure 2: Left: Topographic elevation of the dune located on the central-inner part used as a base for one of the conceptual models. Right: Picture of the dune on the field after a small storm.

### *2.3 Sensitivity analysis*

One parameter that is hypothesized to be important and different between open coastline and wide sand flats is the groundwater level. Groundwater levels can bring moisture close to the surface, thus limiting the amount of sand that can be transported through Aeolian transport. In the model, the groundwater level ($Z_{gw}$) is specified as a proportion of the equilibrium profile ($Z_{eq}$), ranging from 0 (no groundwater) to 1 ($Z_{gw} = Z_{eq}$). It only limits the number of available slabs for transport by defining a upper dynamic layer on which slabs can be transported by the wind. No vertical influence on the potential of a bare slab to be eroded by wind is added by the groundwater level on the interface. Simulations using a range of values between 0 and 1 are done to evaluate how sensitive the model is to those values. For reasons of computational efficiency, simulations for the sensitivity analysis were restricted to the two synthetic domains.

## 3. Results

### *3.1 Sensitivity analysis*

The groundwater reduction conditioned the type of dunes that were formed in both scenarios (Figure 3). For the western scenario, dune rows are formed sequentially for low levels of groundwater (0.1 to 0.4). The first dune row remains without breaching until high groundwater levels (0.9), when low, barchan-shaped dunes are formed. The spacing of the dunes also increase together with the rise of groundwater level. Regarding vegetation, vegetation effectiveness values are low (below 0.1), being concentrated behind the dunes when the groundwater is low and distributed in lines when the groundwater level is high. The east side presents a different behavior, especially due to the small probability of erosion due to the wave processes. Low groundwater levels resulted in a similar sequence of dune rows as found on the western part, although in this case they grew higher and larger. Moreover, the first dune row is bigger than in the other cases, as well as its distance to the next dune row. The distance between them can be explained by the shadow zone effect induced by the first dune row, which limits the zone where sand can be eroded. Vegetation also plays a role for this development, since pioneer species have maximum growth in accretion periods. Developing vegetation increase the probability of deposition, thus increasing the dune growth and reducing the amount of sand that can reach dunes behind it. Also, values of vegetation are bigger in the eastern part related with the hydrodynamic erosive pattern that is much smaller than in the west part. The western part presents higher values of slabs eroded with lower groundwater levels than with high water levels, which tends to have values close to 0 (Figure 4). For the eastern part, the behavior is different, essentially due to the lack of stronger erosion probabilities. Low groundwater levels present an accretion pattern, with an abrupt change to values close to 0, with a small trend towards erosion. It is still unclear why this behavior appeared in the simulations for this area, although present in most of our runs. The value where the abrupt change appears is not fixed, changing between 0.3 and 0.7 levels of reduction depending the initial conditions. Regarding wind transport, there was no significant difference between the average values of transport. However, low groundwater levels presented higher variability than higher groundwater levels.

### *3.2 De Hors*

Despite the fact that specific inlet processes are missing, certain overall characteristics already emerge as a result of processes common to open coastlines. The inner part (*i.e.* the eastern part of the plain) presents less transport than the other regions. The present model suggests that groundwater can control this transport reduction to some extent (Figure 5). If the groundwater is too low, dunes emerge suggesting sediment transport in that area, even though it is, in average, lower than the rest of the plain (and consequentially prone to be inundated more frequently). Furthermore, low groundwater levels produce bedforms along most of the plain area, even close to the intertidal zone. On the other hand, raising the groundwater level shuts down great amount of the transport that can be seen in that region. Still, the model is not capable of reproducing neither the dune row that emerged since 1997 in that area nor the big dune that emerged between inner and central part. One of the reason can be the lack of morphological update due to hydrodynamic processes such as longshore currents and sediment exchange in the subtidal zone. The coastline in the area has changed since 1997, which resulted in changes in the conditions for the Aeolian transport.

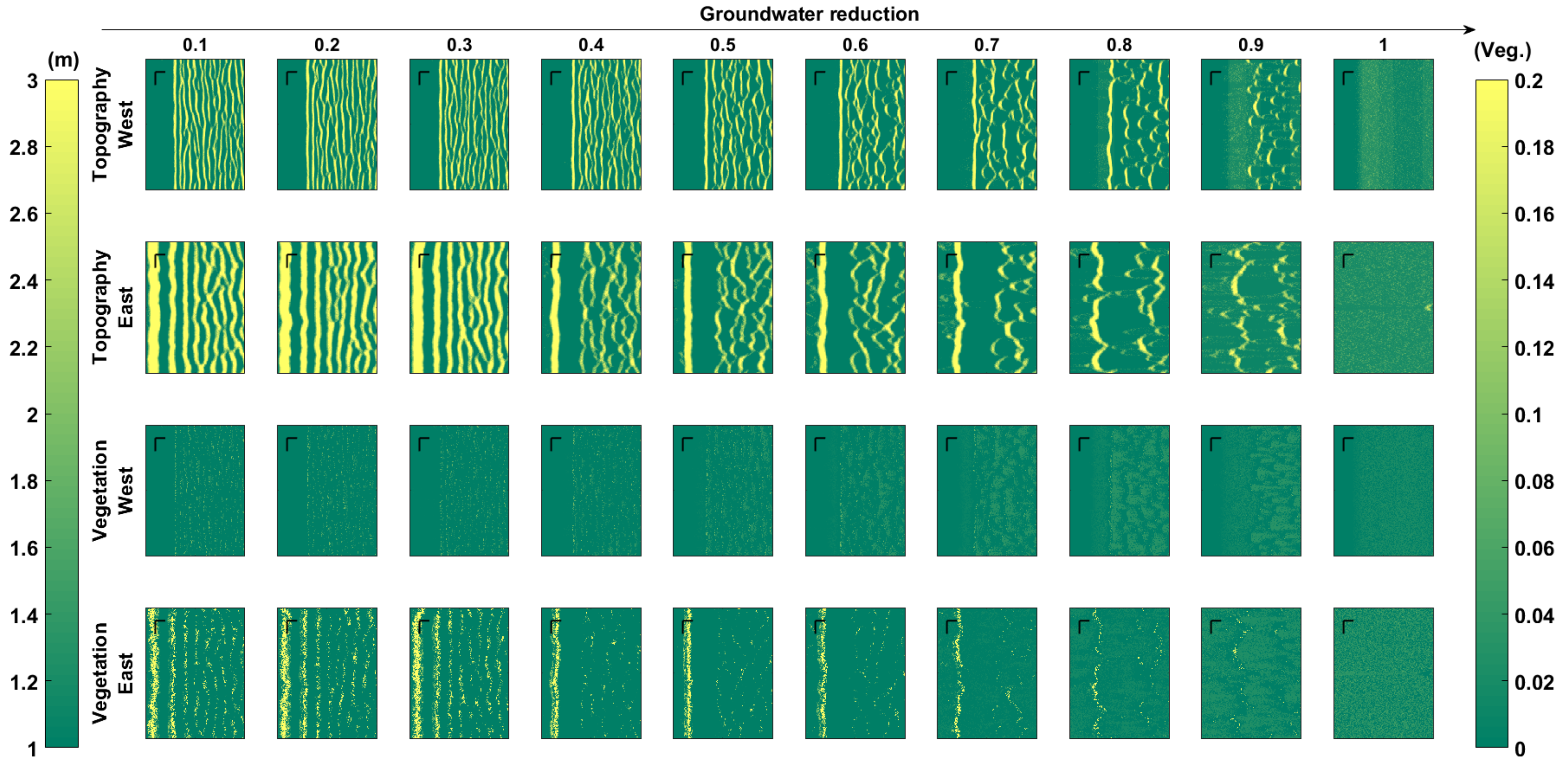

Figure 3: Model results for the synthetic domains for the east and west regions. Vegetation effectiveness plotted are the sum of both pioneer and conservative species. Black lines on the upper left of each figure represent scales of 20 meters.

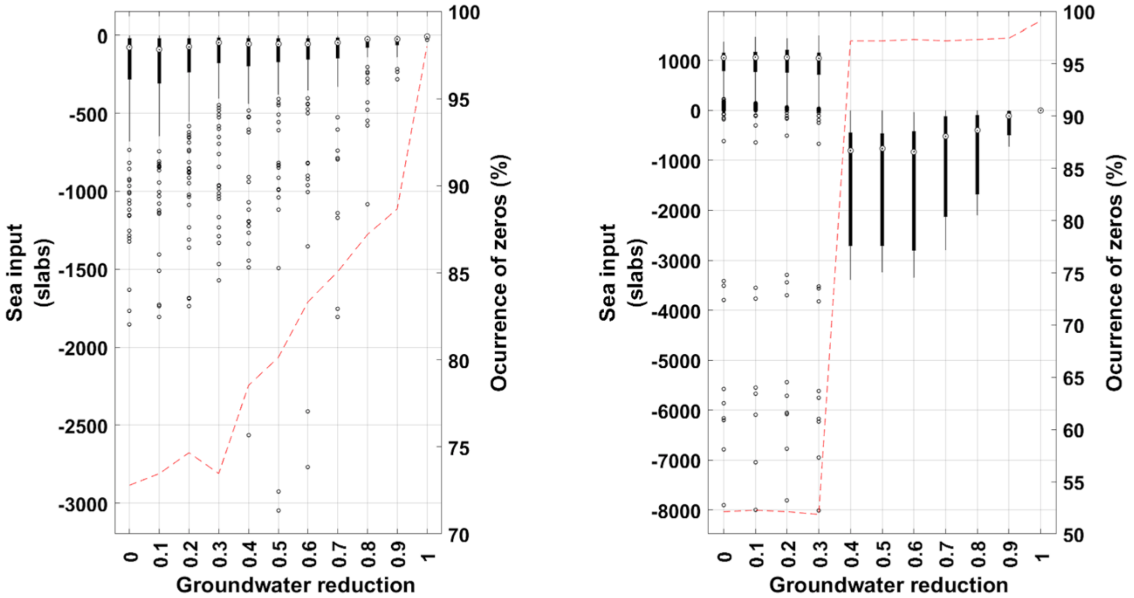

Figure 4: Boxplots representing the sea input (slabs) per iteration for different groundwater levels. Positive values represent accretion (filling of the cell by new slabs), whereas negative values represent erosion (towards the equilibrium profile). The left panel represents the western part, whereas the right panel represents the eastern domain. Zeros have been removed and its occurrence, in percentage, is shown by the red dashed line.

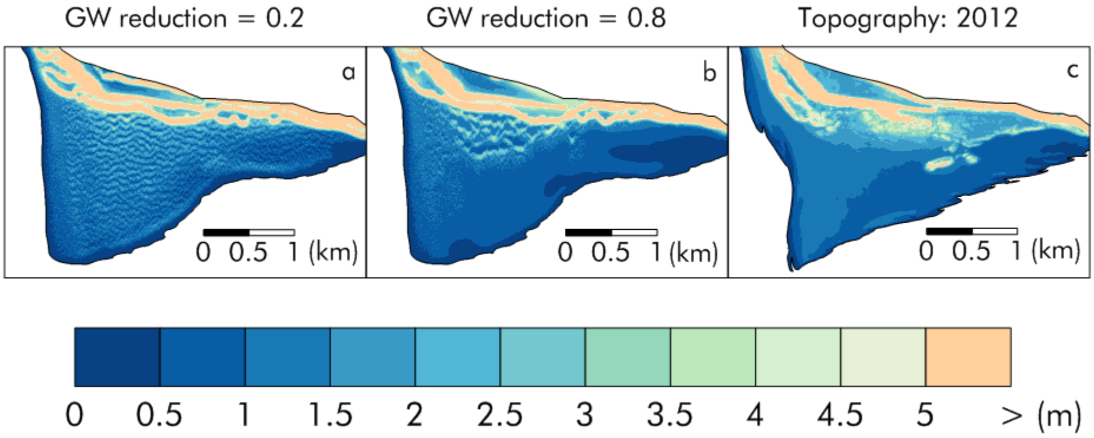

Figure 5: Topographic development based on 15-year model simulations, for groundwater reductions of 0.2 (a) and 0.8 (b), as well as the measured topography (c) for the final year. All the other conditions remained the same and are essentially based on Keijsers et. al. (2016) for open coasts.

Regarding dune shape, the model does not represent properly what is found in the area. Low groundwater levels produced uniform bedforms throughout most of the plain. Raising the groundwater level gives a spatial variability in sand transport that is, in some extent, similar to what is expected for the present area, although with distinct dune shapes. Instead of hummocky-shaped dunes, the central part produces much more spaced, defragmented dune rows. Barchan-dune can also emerge in the model, which are not expected in this region. The western area does not evolve into dunes, but rather uniformities can be seen throughout the western portion. The lack of dunes in that region can be regarded to the wave erosion processes that mostly affect this area. Also, the sudden growth of a foredune in this area might be related to coastline movement, a process that is not included in the model.

Groundwater levels controlled the amount of transported sand inversely. Low values (between 0 and 0.5) induced high values of wind transport. An exponential decay starts from 0.5 reduction reaching values close to 0 when groundwater reduction is 1. Regarding wind transport, flux values are within the order of magnitude expected for the area. Values were higher for scenarios with low groundwater levels, most probably due to the lack of transport on the east of the sandflat when groundwater is close to the surface. The transport was similar between boundaries 2 and 6 when groundwater is low, whereas a decrease trend can be seen in higher groundwater levels. Nonetheless, the model showed great capacity of transporting sand, although slabs are not able to reach long distances due to the inverse relation between probability of transport and distance of transport. Positive values of sea input were found for most of the groundwater scenarios, suggesting an accretive trend instead of an erosion. This was expected due to the area that are relative to wave erosion in opposite to the area where inundation can fill the plain, which is bigger.

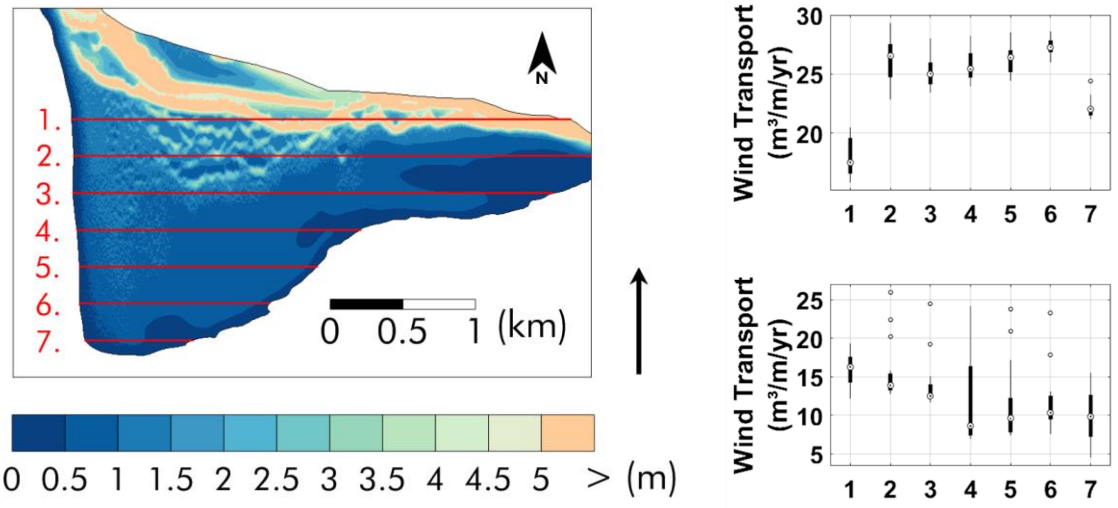

Figure 6: Left: Sand fluxes due to wind transport over seven specified boundaries, described on the map by the red lines. The direction of transport is specified by the black arrow. Right: Upper panel shows the fluxes values for a gr oundwater reduction of 0.2, whereas lower panel shows values for groundwater reduction of 0.8.

## 4. Discussion

Conceptually, sand flats such as De Hors present big areas for Aeolian sand transport and dunes to develop. Several limiting factors such as surface moisture and sediment coarsening can diminish the probability of sand to be eroded from the plain and be transported through the wind. The groundwater level can raise the relative surface moisture or even raise above the elevation, thus limiting the Aeolian transport and dune formation regardless the available space (Luna et. al., 2011). In the model, groundwater can be related, essentially, to sediment supply rather than the probability of a sediment slab to be transported or not. Low values of groundwater reduction create a bigger active layer of slabs available to transport, whereas higher values are translated into smaller layers of available slabs due to smaller distance between the topographic surface and the water table. This is comparable in some extent with the reality indirectly, although the relation with surface moisture might have a bigger influence than the layer above the groundwater level due to the time scales involved. Moreover, groundwater levels can be conditioned by extra parameters such as inundation, rainfall and evaporation (Horn, 2002), which are not included in the model.

The model is highly sensitive to sediment supply, as stated by previous authors (Nield and Baas, 2007, 2010, Keijsers et. al. 2016). Sediment supply can be represented in the model by several means, such as slab height and $P_{ero}$ (probability of erosion of a bare cell). However, most of them are introduced equally throughout the domain, thus diminishing any spatial variability that might be of interest, especially in coastal zones and systems like sand flats. The groundwater has the ability of, intrinsically, represent to some extent the spatial variability in terms of sediment supply, since it relates the amount of available sediment to the existing topographic profile, which can be variable throughout the domain. This effect can be seen in the model when comparing the western part to the eastern part of the plain. The east part is, on average, lower than the western part. That means that the groundwater levels will be higher at these location, thus inducing a reduction of the available sand for transport and, consequently, changes spatially the sediment supply. This can also be seen at De Hors, where dune growth and sediment transport is much higher in the western, less moist side than the inner, more humid and sheltered eastern part. This process could be, in some extent simulated in the model, although a mismatch in the dune shape and development could be seen.

The type of dunes that emerge in the model can also be related to sediment supply. Nield and Baas (2007) already found that sediment supply is a key part for what types of dune emerge within the model when paired together with the initial vegetation. Nebkah dunes, for example, were only simulated on limited supply situations, whereas an increase on sediment supply leads to an evolution from barchan dunes to transverse dunes. Since groundwater essentially limits the amount of sediment supply, the same aspect could be seen, with different forms of dunes emerging depending on the location at the plain. This also holds for what is seen at De Hors, where different dune types emerge along the plain, although this process could not be simulated exactly within the current model framework. Nebkah dunes could only be formed on the conceptual models within specific low supply conditions, such as really low probability of transport, but not in any scenarios using the whole plain.

Even though the total volume of sand transported over the plain is in the order of $10^4$ m³ over the plain per iteration, sand fluxes are within the expected in absolute values. However, the probability of slabs of sand to be transported along distances greater than ten hops are already really small due to the relation between transport distance and probability of deposition. That leads to a sediment source for each dune being located always within its surroundings. Sediment that is picked from the intertidal area, for example, most likely will not reach the main dune area in the northern part of the sandflat before being eroded or deposited. This may lead to uncertainties when using cellular automata models to evaluate sediment source on these environments, since the preferential source is governed by a probability limitation rather than an accounted process.

Conceptually, $P_{ero}$ also controls the sediment supply and mimics limiting transport factors such as surface moisture and sediment coarsening. There is no gradient on the interface on slabs that are in the threshold between groundwater level and topographic level to decrease the probability of erosion when closer to the groundwater level, thus more likely to be wet. Any effect of moisture due to groundwater interfaces are implicitly accounted on the $P_{ero}$ value. Since $P_{ero}$ is assumed constant throughout the plain, all the spatial variability related to these processes are neglected, thus leaving all the spatial differences related only to the sediment supply in the groundwater itself. In the model, the value of $P_{ero}$ is based on calibration values used on Keijsers et. al. (2016), for open coasts. Reducing the value might have a negative effect on the amount of sand transported, based on the concept that the plain is much less erodible than an open coast setting. Hoonhout and de Vries (2017) indicate that the intertidal area might be the primary source of sediment to the dunes in a mega nourishment setting, where also a big area for transport and dune development is available. Considering a similar scenario for De Hors, the source area would be reduced drastically, thus also reducing the amount of sand transported over the plain. Dividing $P_{ero}$ into different limiting factors components can be used to test the hypothesis, although several adaptations and probability rules should be added in the model to properly account for all the processes involved.

When wave sheltering is disabled and the probability of hydrodynamic erosion is not zero for areas without waves, the final dune volume was in the same order of magnitude, thus suggesting that the erosive process can control the final evolution in terms of dune development. Sand flats that emerge close to inlets present a hypothetical gradient on the erosion effect, being more exposed to waves from one side than another. The sheltered part, or inner part of the plain, is less likely to be eroded by waves, since part of the energy will be already dissipated in the exposed part. However, during storm surges, the plain is flooded regardless its side as long as the water level reaches higher levels than the sand flat height. If inundated, a small probability of dune erosion due to hydrodynamic forcing exists regardless the wave action (which will add an extra probability of erosion on stretches where wave action take place), being related to local currents, dune slumping and interactions between topography versus flow. The current version of the model does not have such implementation, thus being all the hydrodynamic processes related to waves. Changing sheltering and keeping a small value of probability on waves can mitigate this problem, but the exact effect of storms on these regions are still unknown.

The model does not include subtidal processes related to the inlet such as shoal attachment and coastline change due to channel migration. On systems affected by both subaerial and subtidal processes, the addition of such processes can be important to control the available sediment to be transported toward the dunes, as well as the dunes that actually emerge on more exposed zone, which tend not to develop in the same way as the more protected dune fields. At De Hors, the exposed part might be an example, on which the growth of the foredune can be related, in some extent, to coastline movements due to subtidal processes, which increased the beach width and enhanced the probability and space for these dunes to grow.

Several authors relate the biophysical feedback between vegetation and sediment supply as a key factor for dune development, growth and maintenance (Moore et. al., 2016; Zarnetsky et. al. 2015; Goldstein et. al., 2017). Dune vegetation acts as a trap, both retaining the sediment that comes from the lower beach through Aeolian processes and using the sand to grow when ideal burial and climate conditions are met. In our model, vegetation is simulated through growth curves as introduced by Nield and Baas (2007) and expanded by Keijsers et. al. (2016), which instead of simulating the processes, define the development based in the growth or decay related to erosion/accretion levels only. No relation between groundwater is introduced in the model, and the relation with erosive processes is straightforward, being removed based on a rate of survival when the cell is eroded or filled by sea processes. Since the hydrodynamic part is closely related to wave processes in the current model, some scenarios showed vegetation development in highly inundated (but no erosion/accretion) areas such as intertidal zones with really low wave energy, such as the inner part of the plain. This could be solved also by changing the minimal erosion probability for cells without waves, but a more in-depth characterization of hydrodynamic behavior in these plains are in need for further model development and adaptation for these environments.

The closest configuration yielding qualitatively similar developments to the ones observed on De Hors had expected initial conditions imposed: high groundwater levels (translating into limited sediment supply) and small probabilities of erosion due to inundation outside the wave action domain. The maintenance of the initial condition without overruling the domain with different types of dunes can be seen as positive potential for applicability of the model on systems close to inlets. The lower transport in the eastern part than the western part, as well as the dune development on the central part being different from the others (thus showing some spatial variability in the evolving dunes) show potential for adaptation and studies of dune development on systems close to inlets.

## 5. Conclusions

Although the model showed potential to create types of dunes that emerge on sandflats close to inlets on synthetic scenarios (*e.g.* Nebkah type dune) and spatial trends on sediment supply, certain characteristics cannot be modelled yet (*e.g.* dune type and size in certain locations of the plain), suggesting a lack of important processes (*e.g.* hydrodynamic erosion during inundation) that are related to inlet processes. The addition of specific rules to separate limiting factors that compose the probability of erosion of a bare cell can also be tested to improve overall supply patterns. Further research is necessary to fit a more physical based concept on the hydrodynamic erosion module for sand flats close to inlet in order to apply intrinsic characteristics of the system such as spatial erosion gradient.

## Acknowledgements

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