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Publication date
2017

Document Version
Final published version

Published in
Proceedings of Coastal Dynamics 2017

Citation (APA)
Luijendijk, A., Velhorst, R., Hoonhout, B., de Vries, S., & Ranasinghe, R. (2017). Integrated modelling of the morphological evolution of the sand engine mega-nourishment. In T. Aagaard, R. Deigaard, & D. Fuhrman (Eds.), *Proceedings of Coastal Dynamics 2017: Helsingør, Denmark* (pp. 1874-1885). Article Paper No. 157

Coastal Dynamics 2017
Paper No. 157

INTEGRATED MODELLING OF THE MORPHOLOGICAL EVOLUTION OF THE SAND ENGINE MEGA-NOURISHMENT

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Abstract

This study presents some recent developments in coastal morphological modeling focusing on flexible meshes, flexible coupling between models operating at different time scales, and a recently developed morphodynamic model for the intertidal and dry beach. This integrated modeling approach is applied to the Sand Engine mega nourishment in The Netherlands to illustrate the added-values of this integrated approach. A seamlessly coupled modeling system for Delft3D and AeoLiS has been developed and applied to compute the first years of evolution of the Sand Engine, both for the subaqueous and subaerial areas. The subaqueous bed level changes have been computed with the new Flexible Mesh version of Delft3D, resulting in comparable accuracy levels as to the standard Delft3D version. The integrated morphodynamic prediction of both subaqueous and subaerial reveals a qualitative behavior which is very similar to observations. Model results confirm that after the first year after construction the sand supply for aeolian transports is predominantly from the intertidal area. The AeoLiS model results indicate a significant intertidal erosion volume of about 230,000 m^3 over the five year period, which is a not to be neglected volume, especially in multiyear or decadal predictions. Interestingly, the model results show that the spit, developed by the wave-related processes, is also subject to aeolian transports acting on the emerged spit during lower tides. The seamlessly coupled models are now able to combine the dry beach behaviour with subaqueous morphodynamic evolution, which is important in medium-term to decadal morphodynamic predictions but also relevant for designing such sandy solutions incorporating lakes, lagoons, and relief.

Key words: morphodynamics, mega-nourishment, integrated modelling, dunes, Delft3D, AeoLiS

1. Introduction

In 2008, a Dutch State Committee (Deltacommission, 2008) advised on the protection of the Dutch coast and the low-lying hinterland against the consequences of climate change in the 21st century. The Committee put forward a vision on the interaction between coastal protection and the environment and society in search for sustainable solutions. In line with their recommendations, an innovative project was developed to achieve a more efficient and sustainable nourishment approach; the Sand Engine (*'Zandmotor'* in Dutch). This pilot project of a 'mega-nourishment' was built in 2011 along the Delfland coast and consists of a manmade peninsula of about 128 ha and a net sand volume of 17 million m^3 and two flanking shoreface nourishments bringing the total sand volume to 21.5 million m^3 (see Figure 1a). The innovative nourishment solution aims at providing protection of the low-lying hinterland against flooding and locally increasing ecological and recreational functions in a more sustainable way (Stive et al., 2013).

The Sand Engine nourishment initially spans the coastal system over a 2.4 km stretch, and extends up to 1 km offshore following a specific shape (see Figure 1a). Forces of nature, like the wind, waves and currents, have and will continue to spread the sand naturally along the coast of South-Holland (Mulder & Tonnon, 2010). The Sand Engine will gradually change in shape and will eventually be fully incorporated into the dunes and the beach enhancing coastal safety. One year after construction, a large spit has developed in the north connecting to the shore (see Figure 1b), while the lagoon is still connected to the sea.

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Figure 1. Aerial photographs of the Sand Engine a) just after construction in (September 2011) and b) five years later (September 2016). Photos by Rijkswaterstaat/Joop van Houdt.

One of the objectives of the mega-nourishment Sand Engine is to enhance coastal safety at the placement area but also at the adjacent coastal sections over time. The hypothesis is that waves and currents distribute the sand in alongshore direction while the wind blows the sand higher up the cross-shore profile. Severe storms can erode the sand from higher elevations such as the dune areas. De Schipper (2016) states that 500,000 m^3 has left the control area which has been monthly surveyed.

Large part of the ZM has not been flooded during storms. Hoonhout (2017) shows that during the first winter season large volumes of sand are transported by the wind lowering the bed levels between 0.2 – 0.5 m at the crest of the ZM. Next, the crest seems to stabilize due to armoring creates a cemented layer covering the crest. In year 2 – 4 the supply for aeolian transport comes from the intertidal area. This area is regularly mixed by waves breaking up any armoured layers. So, besides the waves, tides, and surges, also the wind influences the change in bed level in the sub-aqueous beach.

In the first years the erosion by waves and current dominate the erosion by wind, but over time the gradients in longshore transports decrease and the cross-shore slopes have adjusted to natural profiles. This implies that the contribution of aeolian transport would become more important over time and should not be neglected in decadal morphological predictions. This requires integrated morphological predictions incorporating the bed changes by waves and currents for the wet area, but also the bed changes by aeolian transports for the dry beach. In addition, the erosional process during severe storms should preferably also be fully incorporated in such an integrated modelling system.

Multi-year morphological predictions are often computed using a single morphological model commonly forced with schematized boundary conditions representing the time scale of the prediction. The goal of this paper is to present the first results of a seamlessly coupled model system that enables an integrated morphological simulation for the subaqueous and subaerial areas of the Sand Engine.

2. Processes governing the observed behavior

2.1 Observations

The bathymetric surveys indicate a strong erosion of the head in the first year, followed by a more constant erosion rate in the years after (see Figure 2). Erosion of 0.2 - 0.5m of the crest in the first year has been observed; thereafter the crest is stable. In the first year, deposition occurred at both sides whereby a spit started to develop at the north. Relatively large initial deposition volumes in lake and lagoon are observed in the first year, followed by steady, but lower deposition rates in later years.

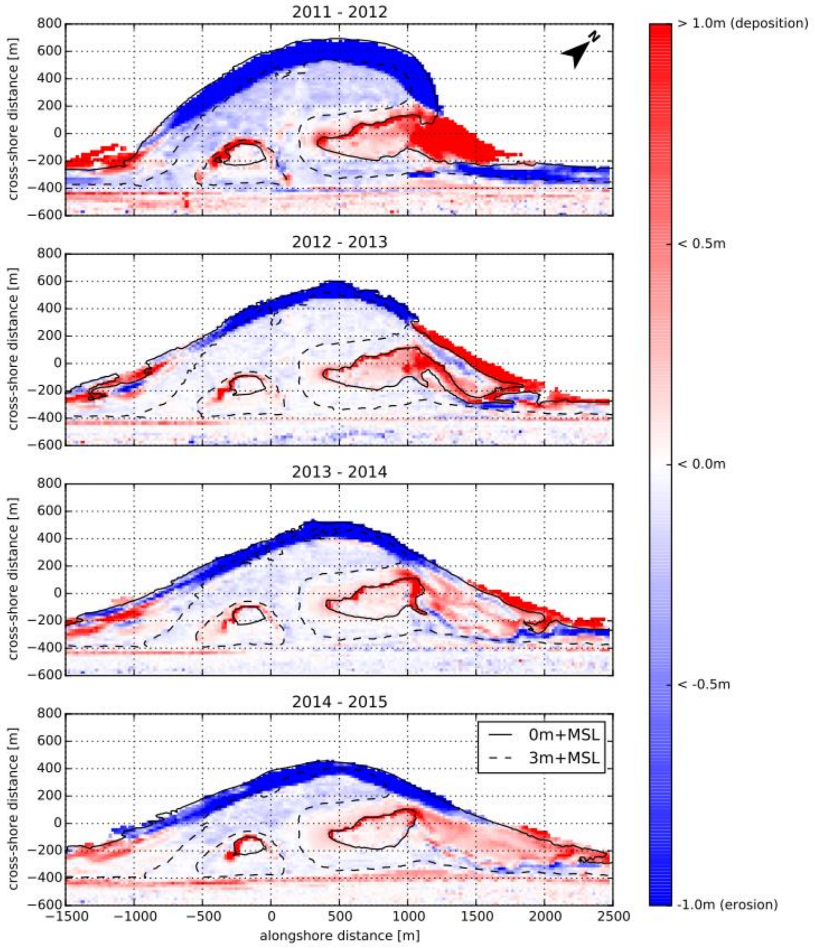

Figure 2. Annual erosion and sedimentation maps based on surveys between 2011 – 2015 (from Hoonhout, 2017).

2.2 Governing processes

Three main processes have influenced the evolution of the Sand Engine:

- Tide- and wave-driven sediment transports (sub-aqueous)
- Erosion due to storm related processes of the higher part of the beach (sub-aqueous)
- Aeolian transports picking up sediments from the crest and intertidal area (sub-aerial).

Figure 3 indicates the areas where the abovementioned processes are dominant. The lowest panel presents the measured dune growth rate (in m^3/m/yr) along this stretch of coast. Airborne lidar measurements from January 2012 until January 2015 reveal the spatial variation of the dune growth rate. The growth rates landward of the Sand Motor are somewhat smaller than the adjacent sections, with minimum rates of about 5 m^3/m/yr. This can be explained by the trapping of sand in the lake and lagoon. It is expected that when these water bodies are filled up by sand, the dune growth rates will recover to the ambient rates. However, this may take years to decades.

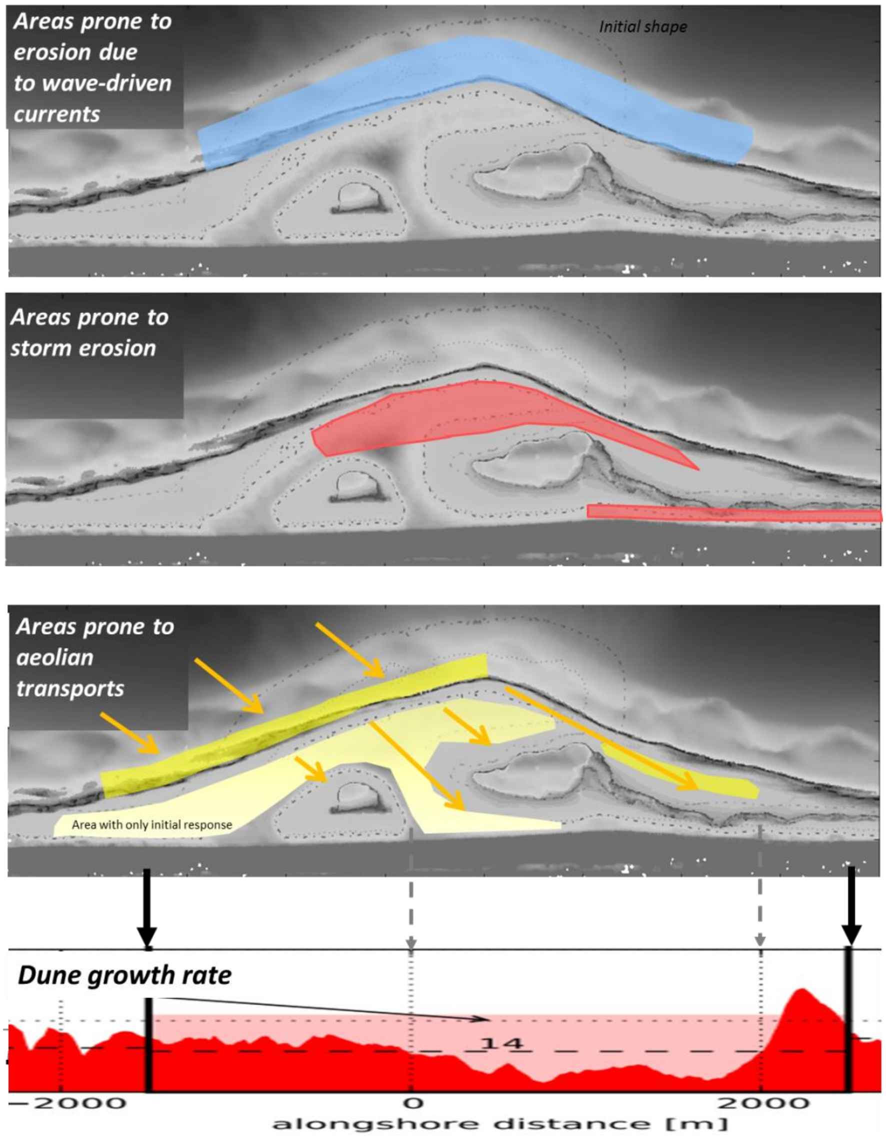

Figure 3: Sketches of the processes governing the sediment transport and morphological changes at the Sand Engine.

The above processes have been computed individually in independent studies. The evolution due to tide-, wind- and wave-driven currents has been reproduced by a Delft3D model described in Luijendijk et al. (2017). De Kort (2015) hindcasted storm events by applying XBeach, while the aeolian transports and resulting bed changes has been computed for the first five years after construction with AeoLiS (Hoonhout, 2017).

However, in order to accurately hindcast (or predict) the evolution of the Sand Engine these three processes should ideally be computed simultaneously as the evolving bathymetry influences all three types of processes. This requires an integrated modelling approach whereby the three model packages are seamlessly coupled in both space and time.

3. Integrated modeling approach

3.1 Model coupling method

In order to enable flexible couplings between the three abovementioned models, a component-based environment has been developed (see Figure 4) using the BMI method (Peckham et al., 2013). BMI (Basic Model Interface) is a software component interface. In this case the models are the software components, delivering certain functionalities like a morphodynamic computation. In order to explain what the interface means, an analogy is made with hardware in Peckham et al. (2013). They state that an interface is like a port and it allows interacting using standardized capabilities. For the components, the interface consists of a set of methods or functions to be able to use their functionalities. By implementing the interface into a (software) component it becomes possible to interact with this component by standardized methods of the interface.

Implementing BMI does not change the models, it only allows to use their functionalities and model can still be run stand alone. This is an advantage of BMI over other alternatives. As BMI is designed to allow model coupling, its interface allows interaction with the models. According to Peckham et al. (2013) a standard pattern of three main parts is often encountered in models as they usually come in the following form: a set of variables or parameters is subjected to physical laws and changes (stepwise) in time. The three parts are initializing, updating and finalizing. BMI allows to start the model (initialize), let the model do calculations (update) and finish the computation (finalize) and also read and/or change the used variables and parameters with get- and set-functions. A more detailed description of the functions is described in the paper mentioned above.

So, BMI is a set of methods and functions added to the models AeoLiS, DFlow FM and D-Waves (and therefore SWAN) to enable to interact with them. Both AeoLiS and DFlow FM are BMI-compliant. Hence, it is possible to use the functionalities of the models called from a different environment (being the controller). The amount of implemented functions still differs between the models; while the get and set functionality has not been implemented in D-Waves, it has been in AeoLiS and DFlow FM.

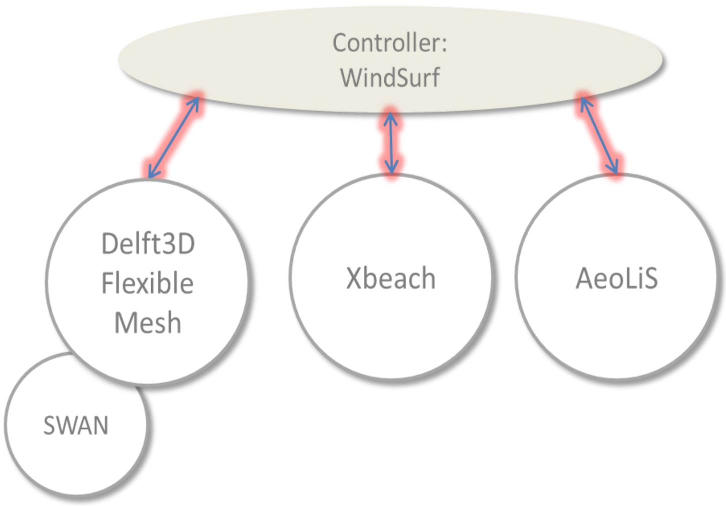

Figure 4. Graphical depiction of the different models that can be seamlessly coupled

3.2 Configuration

In this model configuration, the state-of-the-art Delft3D Flexible Mesh (FM) model is applied at the study site under moderate wave conditions (see Figure 5). The hydrodynamics computed with the FM model is validated with observed water level and currents. One of the advantages is that the flexibility of the mesh structure allows a better representation of the water exchange with the lagoon and corresponding morphological behavior than with the curvilinear grid used in the previous version of Delft3D (Lesser et al., 2004). The FM model can compute both the sand and mud transports and corresponding bed changes.

The new morphodynamic model AeoLiS (Hoonhout et al., 2016) is used to compute the bed changes in the intertidal and dry beach area. The BMI method allows a parallel coupling of Delft3D FM and AeoLiS steered by a control module that uses time series for tide, surge, wind and waves as input. The parallel online coupling steers the information exchange on a regular time interval between the AeoLiS model and the Delft3D FM model.

This configuration also facilitates a serial coupling between Delft3D FM and XBeach. Figure 5 shows an example of such a combined temporal coupling that covers both the wet and dry areas of the Sand Engine. During high wave energy events exceeding the defined threshold value, Delft3D FM is paused and waits for a new bathymetry computed by XBeach after the storm simulation. As a parallel proces, water levels, wave heights and bed levels are exchanged at a regular interval between AeoLiS and the two other models.

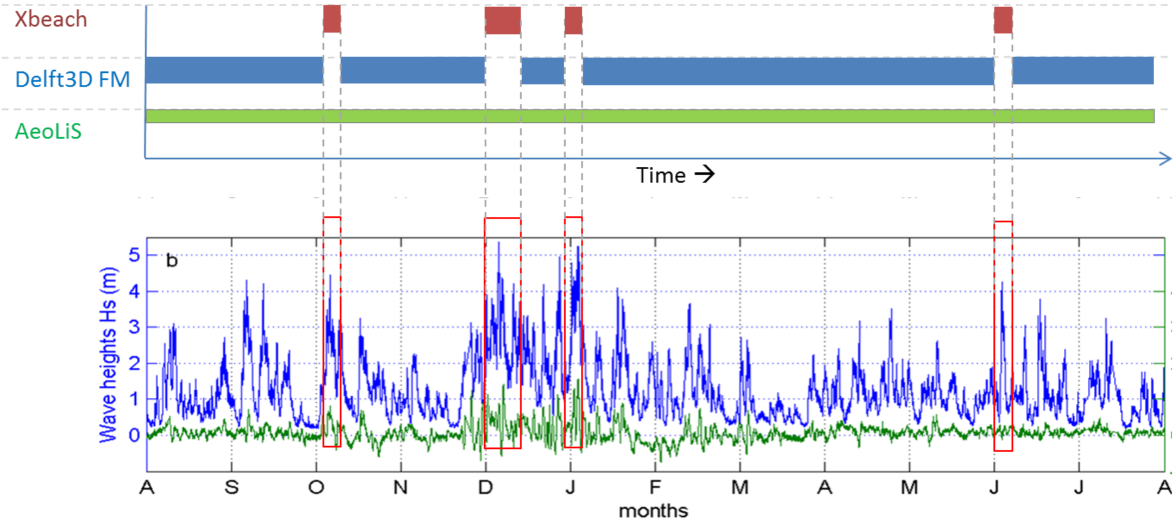

Figure 5. Time series of wave heights (H_s) (lower panel) and the serial and parallel execution of Delft3D Flexible Mesh, XBeach and AeoLiS.

The advances of this integrated simulation compared to a traditional Delft3D simulation are the following:

- pick up of sediments from the intertidal area and dry beach by aeolian transports, while predicting deposition in sheltered areas, lake and lagoon. So, resulting in morphodynamics for the subaerial.
- Temporal and spatial variations in sediment fluxes to the dunes; although dune morphology itself can not yet be computed.
- Erosion by storms and storm-induced processes (long waves and swash) of remote areas, such as dunes and the supratidal beach.
- Pick up of sediments at deeper water due to the high waves enhancing the morphological active zone
- Flexible meshes to better resolve the irregular geometry of the Sand Engine, hence the tidal filling and emptying of the lagoon.

This paper does not discuss the coupling with XBeach. The next sections briefly introduces the Delft3D Flexible Mesh and Aeolis programs.

3.3 Delft3D Flexible Mesh model

Delft3D-FM is a multi-dimensional (1D, 2D and 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing, density gradients, on structured and unstructured, boundary fitted grids. The flow model can be used to predict the flow in shallow seas, coastal areas, estuaries, lagoons, rivers and lakes. The term Flexible Mesh in the name refers to the flexible combination of rectilinear or curvilinear unstructured grids composed of triangles, rectangles, pentagons, hexagons etc. The unstructured grid approach is based on the combination of 2D/3D finite-volume cells with 1D flow networks into a single grid, as illustrated in Figure 6. In 3D simulations, the vertical grid is defined following the σ co-ordinate approach.

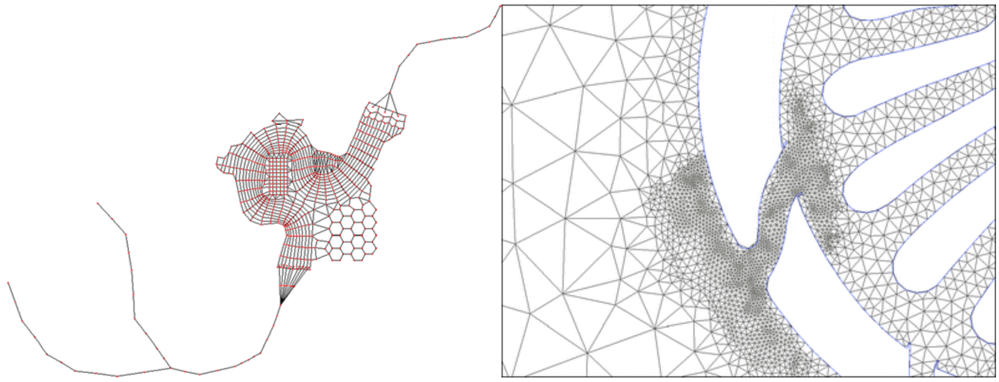

Figure 6. Examples of an unstructured mesh combining 1D flow networks and 2D/3D networks.

Delft3D-FM solves the unsteady shallow water equations in two (depth-averaged) or in three dimensions, derived from the three dimensional Navier-Stokes equation for incompressible free surface flow. The system of equations consists of the horizontal equations of motion, the continuity equation, and the transport equations for conservative constituents. The equations are formulated in orthogonal curvilinear co-ordinates or in spherical co-ordinates on the globe. The flow is forced by tide at the open boundaries, wind stress at the free surface, pressure gradients due to free surface gradients (barotropic) or density gradients (baroclinic). Source and sink terms are included in the equations to model the discharge and withdrawal of water.
The hydrodynamic conditions (velocities, water elevations, density, salinity, vertical eddy viscosity and vertical eddy diffusivity) calculated in the model can be used as input to the other modules of the Delft3D FM suite, like the D-Waves (SWAN) to compute the short wave propagation and D-SED and MOR to compute the sediment transport and morphology in a similar manner as Lesser et al. (2004). Details on this modelling framework and validation cases will be described in Reyns et al. (in prep).

A flexible mesh has been created whereby the mesh is largely aligned with the surf zone to ensure an accurate calculation of the wave-driven currents (see Figure 7). High resolution mesh is also applied to the lagoon and channel areas to be able to predict for more detailed features in the morphodynamic evolution.

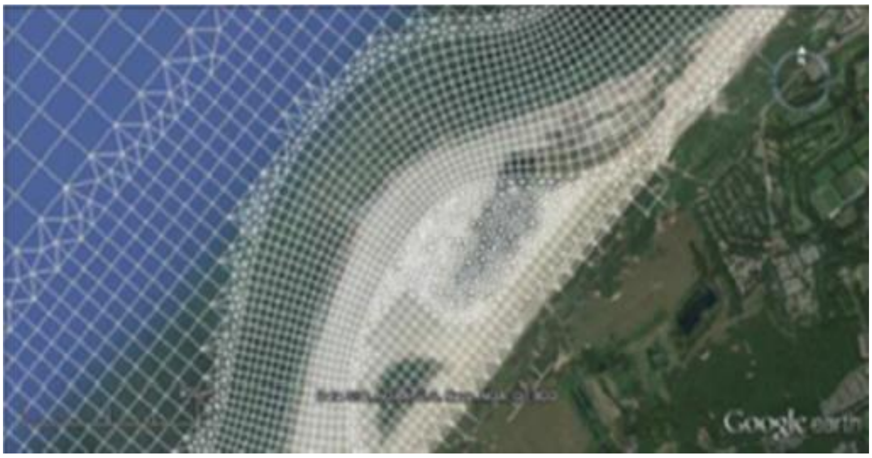

Figure 7. Examples of an unstructured mesh combining 1D flow networks and 2D/3D networks.

The FM model has been applied to compute the first year morphological evolution. The setup and approach of this morphological simulation is identical to Luijendijk et al. (2017). The model results are in large agreement with Luijendijk et al. (2017), both qualitatively and quantitatively (see Figure 8).

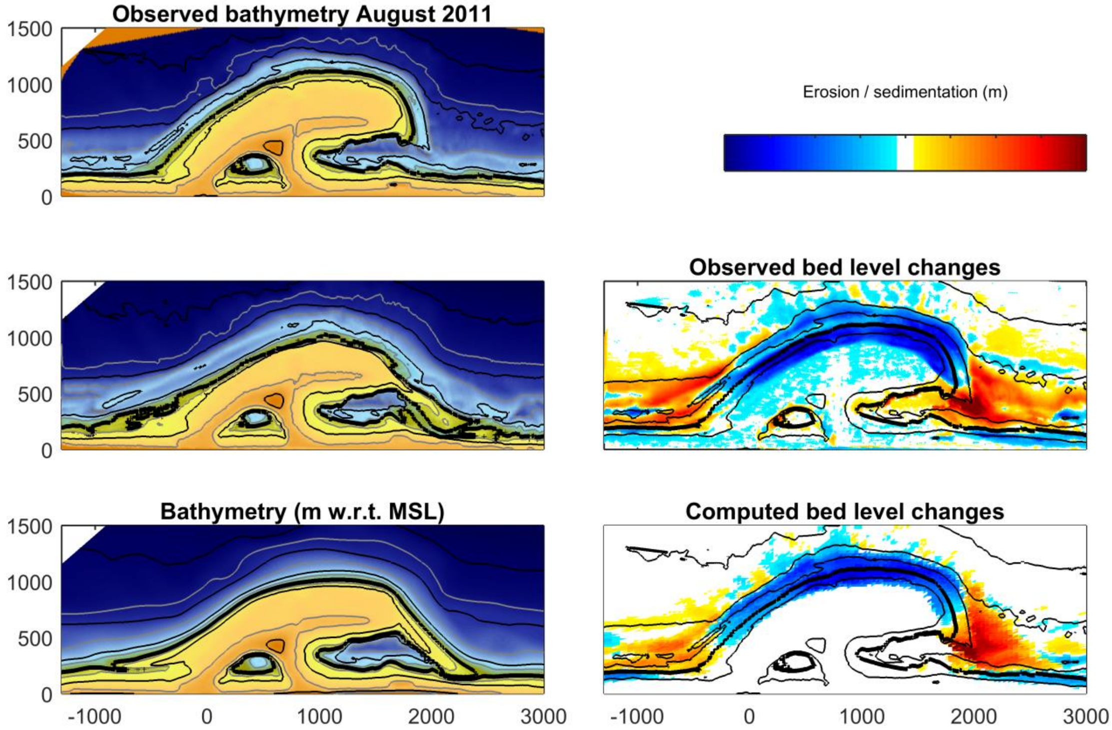

Figure 8. Observed and computed bed level changes with Delft3D Flexible Mesh after one year

3.4 AeoLiS model

The AeoLiS model by Hoonhout and De Vries (2016) is a recently developed model, based on the process-based supply limitation model of De Vries et al. (2014). A distinction is made between supply limiting factors as a result of the bed surface properties and maximal transport limiting factors being mostly the wind forcing. Also sediment supply in the intertidal area is conceptually included by introducing water level, wave energy, evaporation and infiltration input. The transport equation which is solved, is a 2DH advection equation for transport by wind.

The bed is build up of several layers all containing multiple sediment fractions. By including different fractions, or even non-erodible elements, in the sediment composition, the model is able to simulate the processes of armouring and sorting at the beach. The numerical set up is based on a first order upwind method in space and implicit Euler in time. Other schemes like central discretization in space and the μ-method are implemented but not extensively tested yet.

Hoonhout (2017) describes the calculation of the one year aeolian transports. Figure 9 presents the observed and computed annual erosion and sedimentation patterns.

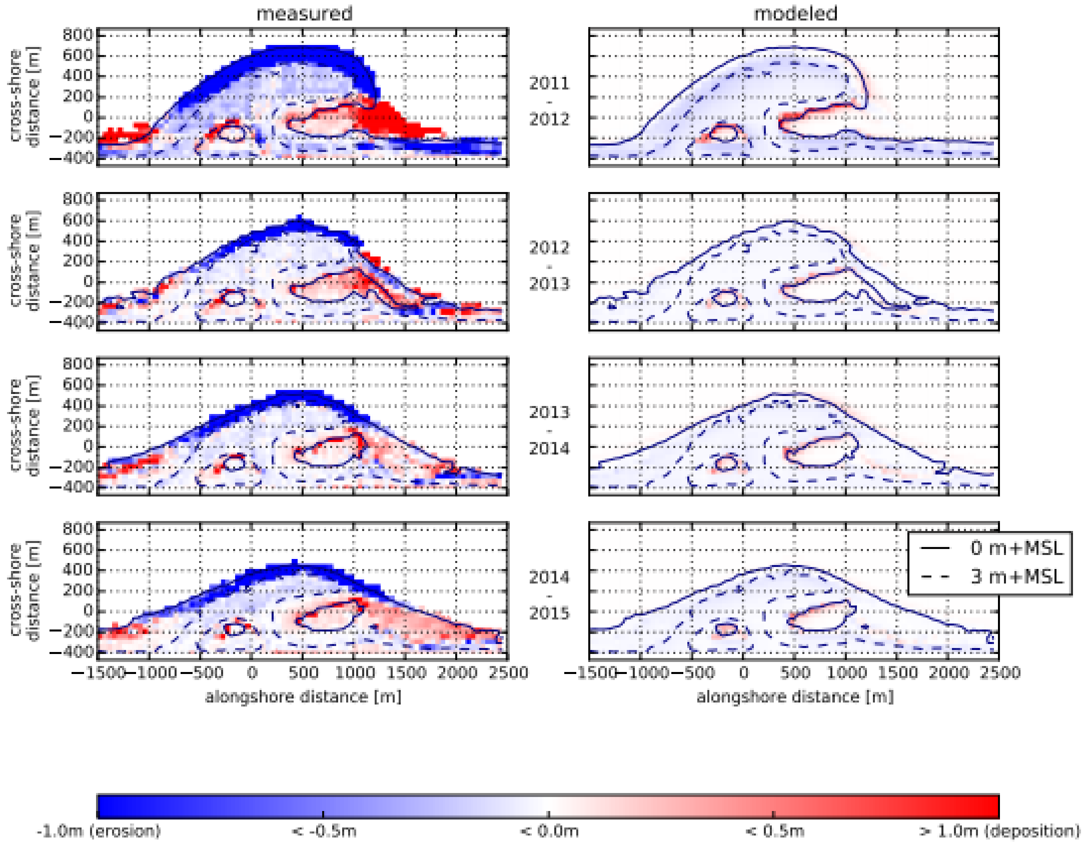

Figure 9. Comparison of annaul erosion / sedimentation patterns; the observations are prsented in the left column while the AeoLiSmodel results are presented in the right column (from Hoonhout, 2017).

Aeolian sediment supply from higher beaches diminished after half a year after construction of the Sand Motor, likely due to the formation of deflation lag deposits that resulted in an armor layer on the dry beach (Hoonhout and De Vries, 2017). That study also concludes that more than 58% of all aeolian sediment deposits originate from the low-lying beaches that are regularly reworked by waves. This means that about 230,000 m^3 (58% of 400,000 m^3) originates from the intertidal area over the first five years. Given the alongshore distance of 4 km, this gives on average about 12 m^3/m/yr erosion from the intertidal area due to aeolian transports.

As this intertidal area is also subject to bed changes resulting from the tidal, wind- and wave-driven currents resolved by Delft3D, the meshes of Delft3D and AeoLiS should overlap the migrating intertidal area at all times during a morphological hindcast or prediction.

3.5 *Exchange of variables*

A flexible, generic method has been developed in python to accuractely and efficiently interpolate information onto any type of grids (curvilinear or unstructured). A proof of concept demonstrated that the cumulative error in the mass balance remained very small. Details can be found in Velhorst (2017).
There are three crucial variables identified which need to be exchanged between the models: bed levels, water levels and wave height. The bed levels and hence its morphological development are considered as the primary output variable. The water level and accompanying water line largely determines the processes which contribute to this morphological development. The most profound physical property which is determined by the water level is whether a cell is wet or dry.

In AeoLiS, the wave height determines the depth at which reworking of the sediment occurs. By reworking sediment up to a certain depth, armoured layers become well-mixed layers, which are able to erode further. As the wave heights determine this mixing depth they are exchanged between the models.

4. Analysis

A fully coupled simulation was made for the first five years after completion. For the Delft3D FM model simulations a similar approach as Luijendijk et al. (2017) is applied. So, both models were forced with time series of observed water levels, wind and offshore waves for this five year period. Nearshore wave heights and water levels for AeoLiS are obtained from the SWAN and Delft3D FM computations, respectively. Each hour the information is exchanged between Delft3D and AeoLiS.

The combined erosion and sedimentation computed by both Delft3D and AeoLiS are shown in Figure 10 (upper panel). Besides the erosion and accretion of the subaqueous areas now the subaerial areas also show bed changes. The deposition in the lagoon for example now starts to influence the water surface area of the lagoon and hence the discharge through the channel.

The integrated simulation allows for decomposition of the results by model. Decomposing the results in waves and currents on the one hand (computed by Delft3D; lowest panel) and wind on the other hand (computed by AeoLiS; midle panel) shows the domination of the first.

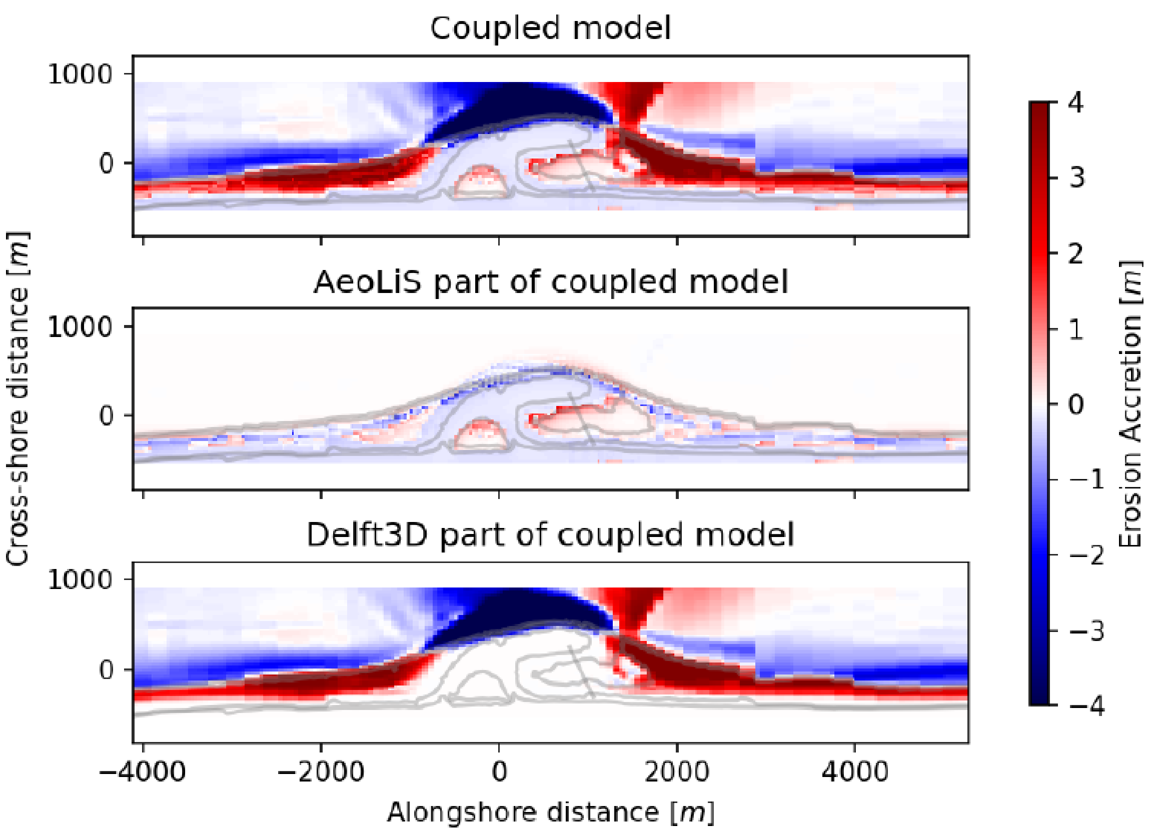

Figure 10. Erosion and deposition computed by the integrated model after five years. The lower plot presents the decomposed Delft3D results, while the middle plot presents the AeoLiS results.

The AeoLiS results clearly indicate the erosion of the dry beach at the crest of the Sand Motor (0.3 – 0.5 m) after one year but also the accretion in the dune lake and lagoon. More severe erosion by aeolian transports (O(1 m)) is computed at the intertidal area; the narrow strip along the water line. In addition, erosion by aeolian transport is also computed at the spit formed by deposition computed by the Delft3D model.

Integrating all volume changes over the five year period (2011 – 2016), results in a net sediment loss from the control area of about 1.5 million m^3 (see Figure 11). The Delft3D simulations show that ~1 million m^3 has spread beyond the lateral boundaries of the control area. Offshore losses based on the jetski surveys seem to be negligible. The AeoLis results indicate a net volume of ~ 200.000 m^3 transported landwards over the dune foot (+3 m MSL), which explains part (~20%) of the remaining loss of sediment. This adds another piece to the puzzle regarding the sediment budgets of the Sand Engine and the adjacent coasts. Unravelling the remaining 0.3 – 0.4 million m^3 is subject to ongoing research.

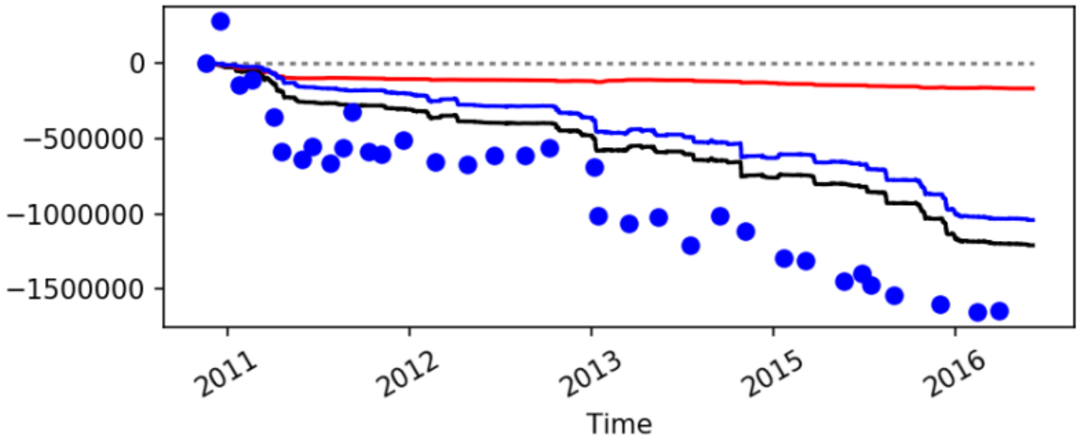

Figure 11. Sediment loss from the control area for the first five years after construction in m^3. Blue dots represent the measurements, the black line the coupled model, the blue line the decomposed Delft3D results, and the red line the decomposed AeoLiS results.

5. Findings

The research and results to date reveal the following findings:

- A dynamically coupled modeling system has been applied to compute the first years of evolution of the Sand Engine, both for the subaqueous and subaerial areas.
- The integrated morphodynamic prediction of both subaqueous and subaerial reveals a qualitative behavior which is very similar to observations. Model results confirm that after the first year after construction the sand supply from the intertidal area is predominant for aeolian transports. The model results indicate a significant intertidal erosion volume of about 230,000 m^3 over the five year period, which is a not to be neglected volume, especially in multiyear or decadal predictions.
- The subaqueous bed level changes have been computed with the new Flexible Mesh version of Delft3D, resulting in a similar accuracy compared to the standard Delft3D version. Interestingly, the combined model results show that the spit, developed by the wave-related processes in Delft3D, is also subject to aeolian transports acting on the emerged spit during lower tides.
- The seamlessly coupled models are now able to combine the dry beach behaviour with subaqueous morphodynamic evolution, which is important in medium-term to decadal morphodynamic predictions but also relevant for designing such sandy solutions, including lakes, lagoons, relief, etc.

Next addition to the coupled framework will be the incorporation of XBeach functionality in such medium-term predictions.

6. Acknowledgements

This work is funded by NatureCoast, a project of technology foundation STW, applied science division of NWO. Roshanka Ranasinghe is supported by the AXA Research Fund and the Deltares Harbour, Coastal and Offshore Research Program Coastal Developments. Bas Hoonhout is partially supported by the ERC-Advanced Grant 291206 - NEMO. Field data was collected by the Dutch Ministry of Infrastructure and the Environment (Rijkswaterstaat) with the support of the Province of South-Holland, the European Fund for Regional Development EFRO and EcoShape Building with Nature.

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