A novel coastal landscape model for sandy systems

Community base for interdisciplinary research on coastal evolution

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Abstract

A common measure to mitigate erosion along sandy beaches is the implementation of sand nourishments. The design and societal acceptance of such a soft mitigation measure demands information on the expected evolution at various time scales ranging from a storm event to multiple decades. Process-based morphodynamic models are increasingly applied to obtain detailed information on temporal behaviour. This paper discusses the process-based morphodynamic model applied to the Sand Motor and how the morphodynamic forecasts have benefitted from the findings of an interdisciplinary research program called NatureCoast. The starting point is the morphodynamic prediction of the Sand Motor made for an Environmental Impact Assessment in 2008 before construction began. After the construction, the model computations were optimized using the first-year field measurements and insights by applying advanced model features. Next, an integrated model was developed that seamlessly predicts the morphodynamics in both the subaqueous and subaerial domains of the Sand Motor. Decadal predictions illustrate the need to be able to resolve the marine and aeolian processes simultaneously in one modelling framework in the case of dynamic coastal landscapes. Finally, a novel morphodynamic acceleration technique was developed that allows for predicting the morphodynamics for multiple decades while incorporating storm events in one simulation. Combining the above-mentioned developments has led to a unique, open-source, process-based landscape tool for (complex) coastal sandy systems, which can stimulate further collaboration between research communities. Moreover, this work demonstrates the evolution from mono- to interdisciplinary forecasts of coastal evolution.

KEYWORDS

Sand Motor, morphodynamic modelling, decadal forecasts, interdisciplinary research, NatureCoast research program

1. Introduction[1]

Climate change is an intense challenge that our ever-increasing world population faces, and it poses special problems for those living near coasts. People have always been attracted to the coast, as a place to live and work, and to relax. By 2050, around half of the world's population is expected to live near the coast, the vast majority in developing countries. How will we cope with rapidly rising sea levels and more intense and frequent storm surges? Although retreating from coastal areas is a solution, this is an unlikely option for most coastal settlements. This means that active protection of urban areas and infrastructure against flooding will remain our primary focus. Artificial protective barriers, such as concrete dikes, dams and breakwaters have traditionally been the go-to way to deal with coastal protection. However, such hard structures have always had the single aim of providing coastal protection, without considering their impact on the coastal ecosystem. In other words, traditional coastal management solutions were treating symptoms; building coastal protection structures in nature often created new problems or moved existing problems to other nearby areas.

Throughout history, the fate of the Netherlands has always been intimately linked to the sea. Without our coastline protection and inland water management, two-thirds of the country would be under water. However, we have also realized that simply treating symptoms is no longer sufficient. Protecting people and infrastructure will always remain the primary aim of coastal management, but the impact on the environment must also be considered, as well as the wider societal context. This means that we need to fully understand how coastal ecosystems function and what their societal context is. This knowledge is crucial if we are to create integrated multifunctional coastal protection solutions that have minimal environmental impacts and are widely appreciated. The shift away from treating symptoms towards integrated, multifunctional designs requires a new approach. Throughout the Netherlands, the Building with Nature approach has been adopted. The key to this innovative approach is using prototype pilots to develop new knowledge and insights.

Building with Nature

Building with Nature (BwN) means proactively maximising the use of natural processes to improve life in delta regions. The proactive BwN approach advocates an integrated approach that harmonizes coastal management solutions with the requirements of ecosystems (de Vriend, 2015). Decisions must be made regarding desired societal and ecological functions, which means that the state and the functioning of the ecosystem must be studied and un-

1 This section is partly revised from Luijendijk and Van Oudenhoven (2019a).

derstood before a design can become a plan. The BwN approach maintains that this knowledge is crucial if environmental and nature concerns are to be integrated into coastal infrastructure projects. By considering how the local ecosystem can become part of the solution, project managers anticipate legal opposition and avoid having to create alternative nature areas. This is almost directly opposite to mainstream infrastructure approaches, which tend to focus on the current situation rather than the future and build in nature, rather than with nature. Besides being proactive, the BwN philosophy attempts to maximize the use of natural processes in infrastructure projects. The Sand Motor is one of the first large-scale applications of the BwN approach.

Figure 1. Aerial photo of the Sand Motor just after construction in July 2011.

The Sand Motor

The Sand Motor is a large sandy peninsula, constructed in 2011 on the Dutch North Sea coast near The Hague (see Figure 1). This unprecedented pilot project involved placing 21.5 million m^3 of sand on and in front of the beach with the aim that it would spread along the coast (Stive et al., 2013). Sand nourishment itself is not a new method to prevent coastline erosion. In fact, the Netherlands has had a structural nourishment program since the early 1990s. However, the Sand Motor is a unique beach nourishment project due to its size, the design philosophy behind it, and its multifunctionality. The volume of sand used for the Sand Motor is about five times that of an average nourishment. The Sand Motor is intended to feed the adjacent coasts by using the natural forces of tides, waves and wind; in a way, it is built to "disappear". Another unique aspect of the Sand Motor is that it combines the primary function of coastal protection with the creation of a new natural landscape that also provides new nature and leisure opportunities. From the outset, "learning by doing" has been a crucial part of the project (Luijendijk and Van Oudenhoven, 2019). Because of its innovations, the Sand Motor has triggered considerable political and scientific interest from all over the world. Large research consortia such as the NatureCoast program were formed to conduct interdisciplinary research on the Sand Motor.

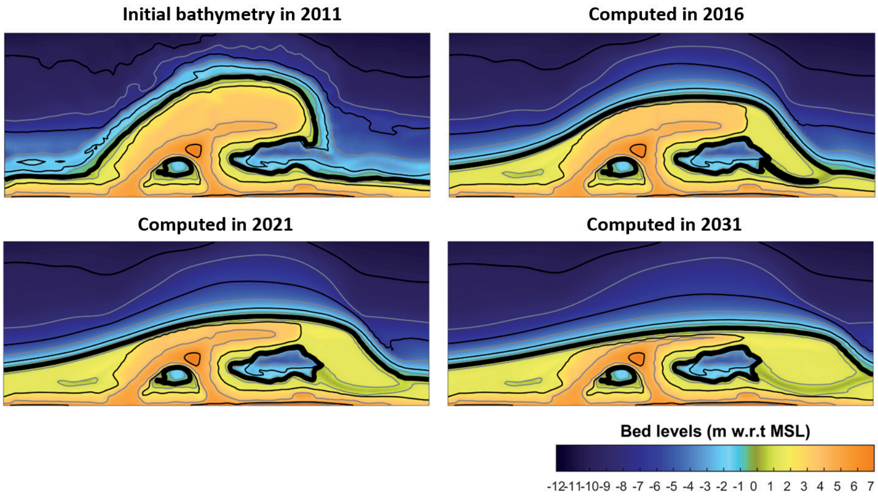

Figure 2. Predicted bed level evolution in the EIA phase for a period of 20 years (Stive et al. 2013).

As part of the Environmental Impact Assessment (EIA) in 2009, morphodynamic simulations were set up to predict the expected morphological evolution for a period of 20 years (Tonnon et al., 2009). These simulations were made for three alternative designs: a hook shape, an offshore island, and a foreshore nourishment (fully submerged). The predicted bed levels played a key role in the evaluation of the different designs and associated functions of flood protection, recreation, and nature area development. The selected hook shape design and location best fulfilled the multidisciplinary and multi-stakeholder requirements of safety in combination with recreation, development of nature, and scientific innovation. Although the results after 10 years of the three alternatives show quite similar development, the simulations with the hook shape design revealed the most heterogeneity in landscape features and ecotopes. The predicted bed levels for the selected alternatives are presented in Figure 2 up to 2031.

The Dutch Ministry for Infrastructure and Environment commissioned an extensive monitoring and evaluation project since the construction of the Sand Motor. The project evaluated the performance of the Sand Motor in terms of the three original project aims: stimulating dune growth in the project area, developing additional recreation and nature areas, and knowledge development through "learning by doing". The study was always intended to be a monitoring project, focusing on gathering data and answering the question of whether the Sand Motor works. Hence, it does not answer fundamental scientific questions regarding the Sand Motor, such as how and why the Sand Motor works. This task was left to the research programs, of which NatureCoast was the most extensive.

Measurements showed that the models overpredicted growth of the dune area by 500% after four years (Taal et al., 2016). Furthermore, the observed erosion volume in the first years after completion is significantly higher than predicted upfront. The high resolution and frequency of the measurements facilitated a unique 'numerical living lab' where the relevance of a range of environmental forcing conditions and processes can be analysed in detail. The Sand Motor provides a unique case study due to its size, resulting in a large signal-to-noise ratio and due to the comprehensive monitoring campaign, to further advance coastal morphodynamic modelling. The goal of this paper is to share the highlights of the interdisciplinary research program NatureCoast and its benefits on future model forecasts. Section 2 presents the observed behaviour of the Sand Motor in the first 6 years after construction. Findings of the NatureCoast program, relevant for the focus of this paper, are discussed in Section 3. A novel coastal landscape tool is presented in Section 4 highlighting the recent advancements made in coastal morphodynamic modelling. The overall findings are presented in Section 5.

2. The observed behaviour of the Sand Motor

This section describes the construction and observed behaviour of the evolution and dune formation at the Sand Motor.

Construction

The selected alternative was constructed with a cross-shore slope at the peninsula of 1:50, so that the toe of the nourishment reached -8 m NAP and ~1500 m from the original coastline. The northern tip of the peninsula created a sheltered area that nurtures different biotic species. A small lake of about 8 hectares was designed to prevent the freshwater lens in the dunes from migrating seaward, which would endanger groundwater extraction from the existing dune area. Sediment for the nourishment was mined offshore at two sites just beyond the 20 m depth contour at about 9 km. The sand was mined by Trailing Hopper Suction Dredgers and placed at the Sand Motor location

(Luijendijk and Van Oudenhoven, 2019). The Sand Motor was constructed in only three months between March and July 2011. Grain size analysis revealed the mean sediment diameter D50 was approx. 280 μm, which is slightly larger than the mean sediment sizes found at the natural coast here (250 μm).

Observed bed level behaviour

Monthly bed level measurements showed a rapid, predominantly alongshore redistribution of sediment in the first year after construction. The head of the peninsula eroded rapidly, leading to accretion both to the north and south. In the first half year after implementation, a spit developed from the northern tip of the peninsula, pinching the lagoon entrance. The maximum elevation of the spit and shoal were slightly below the high-water level, so they flooded during high tide (and storms). The channel landward of the shoal discharged the flow into and from the lagoon. This resulted in strong flow velocities of over 1 m/s during rising and falling tide in the spring of 2012, causing hazardous situations for swimmers. In the first three years, the coastline developed into a Gaussian bell-shaped curve. The curve widened over time, although after 2015 no further widening of the shoreline position was observed (see Figure 3). Since 2016, the shoreline has developed an asymmetrical shape (de Schipper et al., 2016).

Figure 3. Aerial photographs of the Sand Motor between July 2011 and July 2017.

After construction no sub-tidal bars were present, but these sand bars started to develop after about a year. The subtidal bars and coastline position seem to have been linked since 2013 (see Figure 4). Storms can sometimes cause a large-scale reset of the bar system. By 2018, about 3.5 million m^3 of sand had left the initial peninsula area. The erosion of the peninsula is predominantly caused by wave action, where both daily conditions and high wave events matter. In the first year after construction, the Sand Motor changed shape faster than expected based on long-term model calculations performed as part of the environmental impact assessment. Conversely, subsequent changes were slower than predicted. In 2018, the head of the Sand Motor had retreated about 300 meters since its creation in 2011 (Luijendijk, 2019b). At the same time, the Sand Motor extended up to 6 km alongshore. This shows that the intended feeder function works well. The adjacent beaches are gradually fed by the Sand Motor as the sand is spread by natural forces.

Observed dune development

The beach and the dunes are important for nature and leisure activities along the entire Delfland coast, which includes various strictly protected Natura 2000 areas. This means that the dune area landward of the Sand Motor, called Solleveld, is protected from interventions in the area. Solleveld consists mostly of “old” dunes which were deposited by the sea starting in 3000 B.C. There is a relatively narrow strip of young dunes at the seaward part of Solleveld. For decades the Delfland dunes have been growing steadily, both in height and width, mainly due to coastline maintenance activities.

Since the construction of the Sand Motor this process has continued but not as quickly in the monitoring area as before its construction. The new dune forms are highly dynamic and therefore extremely appealing in landscape terms. The area of new dunes is increasing slightly, but much slower than predicted. Only about one hectare of dune area was formed in the monitoring area in the first five years (Taal et al., 2016), which is surprisingly much smaller than predicted (23-27 hectares after 20 years). This can be partly explained by the fact that the dune lake and the lagoon capture large amounts of drifting sand and delay dune growth. The dunes are expected to continue to grow and this process should accelerate in the future, particularly once the lagoon and the dune lake have filled with sand. Furthermore, the crest of the Sand Motor has developed into a bare sandflat where lots of shells have emerged at the surface, limiting the erosion by wind. Another reason for the limited growth of the dunes is the intensive shared use of the beach. The formation of a new row of dunes in front of the old one is slowed by traffic on the Sand Motor, particularly vehicles driven by supervisors, surveyors, and researchers. The cleaning of the beach performed by the city authority of The Hague also prevents dune formation.

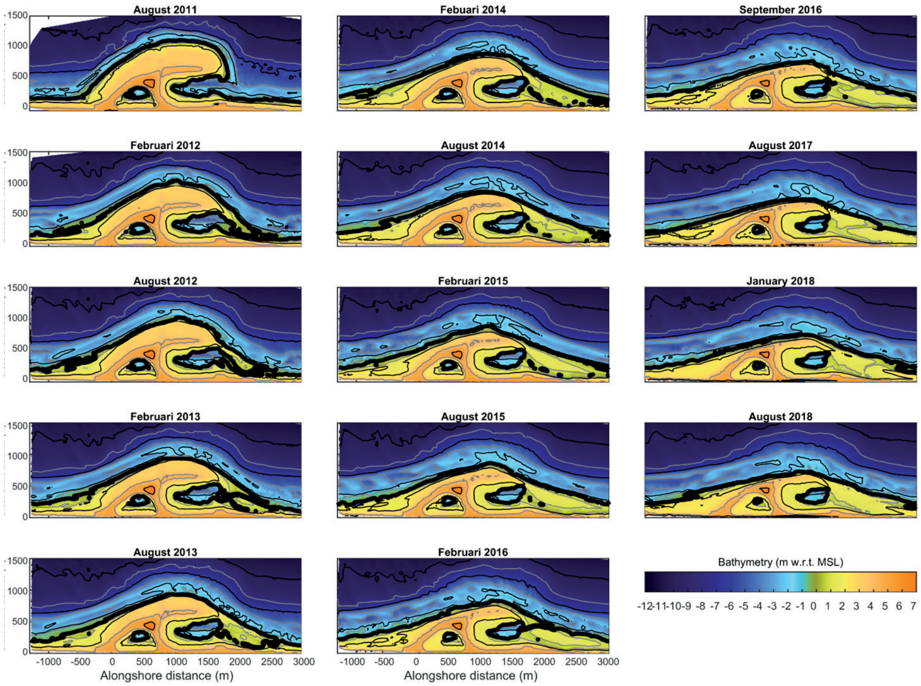

Figure 4. Measured bed levels between August 2011 to August 2018 (Luijendijk and Van Oudenhoven, 2019).

Lidar measurements show that the average dune growth of 14 m^3 per meter longshore per year in the Sand Motor domain is slightly lower than the dune growth rates along the adjacent beach stretches, while this stretch has a much wider beach compared to the other stretches. Observations after five years show that a large volume of 400,000 m^3 of sand has been blown into the dunes, lake and lagoon, which confirms the relevance of the aeolian transport in the morphological behaviour of the Sand Motor. From a sediment budget analysis of the Sand Motor it can be concluded that 58% of all sediments deposited in the dunes originate from the low-lying beach zone that is regularly reworked by waves (Hoonhout and Vries, 2017). For these reasons a model is needed that takes the interaction between both the aeolian and hydrodynamic and morphodynamic processes into account.

3. Relevant NatureCoast findings for model forecasting[2]

NatureCoast has been the largest research program focusing on the Sand Motor. The NatureCoast program was carried out by a consortium of knowl-

2 This section is a summary of and partly revised from Luijendijk and Van Oudenhoven (2019)

edge institutes and universities, and the research was conducted in cooperation with end-users from private companies, research institutes and governmental organizations. The Dutch Technology Foundation (NWO-TTW) provided the largest share of the project funds. The research in NatureCoast focused on six themes: coastal safety, dune formation, marine ecology, terrestrial ecology, hydrology and geochemistry, and governance (Luijendijk and van Oudenhoven, 2019). In this paper only the relevant findings of the first two themes are discussed.

Coastal safety

The dunes landward of the Sand Motor need to grow to increase coastal safety from flooding. Sediment composition will determine how effective this process is; this involves the mean sediment diameter, the sediment grading, and the presence of shells (see Figure 5). Simulations have suggested that if shells had not been present in the nourished sand, much more sand would have been transported from the crest of the Sand Motor. In addition, at the crest an armour layer developed which resulted in relatively limited wind-blown transport activity. This was largely due to its height. If the Sand Motor had been lower and the dry beach had experienced more frequent flooding, the development of the armour layer might have been limited, thus stimulating aeolian activity. Similarly, the dune lake and lagoon intercepted much of the sand transported from the low-lying beaches, limiting the possibilities for embryonic dunes to form. If these water bodies had been smaller or in different locations, local dune growth might have been stimulated. The long-term effects of the trapping remain to be seen, because at some point these reservoirs of fine, windblown sand will become available, as the waves and currents continue to erode the Sand Motor. Another important finding is that analysis showed that the 12 largest wave events of the first year resulted in about 60% of the total erosion observed in that year (Luijendijk et al., 2017b). Milder wave conditions, which occur more often, are thus almost as important to the erosion of the Sand Motor as storm conditions and should therefore be explicitly incorporated in the long-term (decadal) morphodynamic predictions.

Dune formation

Research on new dune development away from the existing dunes showed that the high, barren plain of sea bed material hampered perennial plants from colonizing, because root stalks transported by storms could not reach the higher elevations (van Puijenbroek et al., 2017). Wind-blown seeds that could reach these elevations found conditions that were too dry to germinate, and the steadily lowering bed level due to wind erosion did not help either. Without perennial vegetation, it was hard for permanent dunes to form on the dry beach. Thus, the sediment composition and crest height are two important factors that affected the development of vegetation at the Sand Motor. Hence, to realistically predict windblown transports, the sediment composition, crest height, and the ever-changing shape of the Sand Motor should all be included in such computations.

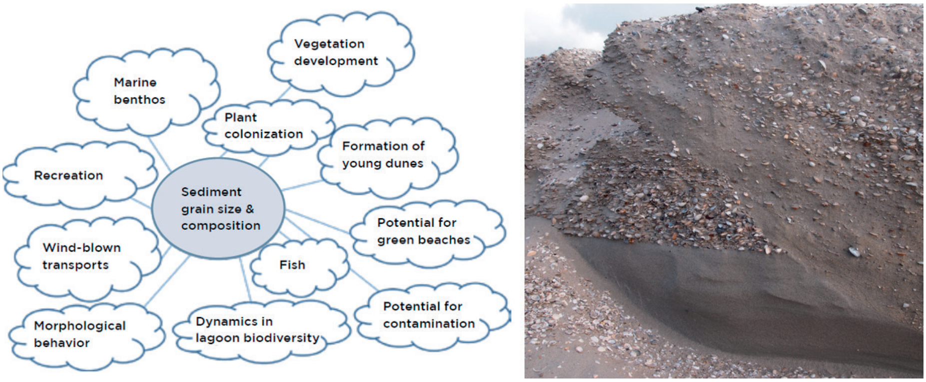

Figure 5. Left: the many relations of the sediment grain size and composition to other processes and aspects at the Sand Motor. Right: photo of the variation in grain size diameter of the nourished sand taken at the cliff (photo by Iris Pit).

The NatureCoast research has clearly illustrated the complexity of the Sand Motor's behaviour in space and time. Many interrelations were found that could only have been identified by combining knowledge across various disciplines. The most telling example is how sediment size and composition has influenced the Sand Motor's morphology and ecology and thus the ecosystem services. The driving mechanisms of the tides, waves and wind cause sediment sorting processes to act upon the nourished sand. The sediment size and composition were found to influence everything from the communities of marine benthos, fish, plant colonization, wind-blown transports, the formation of embryo dunes, development of vegetation, the dynamics in biodiversity in the lagoon, the potential for green beaches in the lagoon, the potential for contamination, morphological behaviour, and even recreation (Luijendijk and van Oudenhoven, 2019).

The next section will discuss in detail on how the abovementioned findings have influenced the numerical model approaches and computations.

4. A novel coastal landscape model

This section presents the technical advancements in coastal morphodynamic modelling and the decadal predictions of large-scale sandy interventions.

Technical advances

A process-based model has been used to hindcast the initial response of the Sand Motor. The Delft3D hydrodynamic model reproduces measured water levels, velocities and nearshore waves well (Luijendijk et al., 2017a). Applying the morphological model with its default formulations and parameter settings results, however, in a morphological evolution that is quite far from observed. The following four technical improvements have been applied to the Delft3D hindcasts and have resulted in greatly improved morphodynamic simulations for the Sand Motor.

Model features

Three key model features were found to be crucial to achieve a good agreement between the model and data (Luijendijk et al., 2017a): the erosion of dry cells, sediment transport formulation, and the formulation for nearshore wave energy distribution. Resolving the erosion of dry cells by distribution, the erosion volumes with neighbouring (dry) cells led to a better reproduction of the observed shoreline retreat. Applying a complex sediment transport formulation, including a roughness predictor, resulted in a better representation of the erosion in the shallow parts of the cross-shore profile. Explicitly resolving the roller forces of a wave, in addition to the wave forces, provided an improved distribution of the wave energy and hence the wave-driven currents. Applying the three features results in a computed morphological evolution which is consistent with the observed evolution during the study period; Brier Skill Scores in the 'Excellent' range were achieved following the classification of Sutherland et al. (2004). Model results clearly showed that sand, eroded from the main peninsular section of the Sand Motor, is deposited along adjacent north and south coastlines, accreting up to 6 km of coastline in total during just the first year of the Sand Motor.

Grid alignment

Applying the above model settings in model simulations beyond two years revealed increasing deviations with observed behaviour. The observed symmetrical, gaussian shape of the Sand Motorafter three years was not reproduced while using these settings. The deposition of the sand, eroded from the head of the peninsula, was not correctly reproduced by the model. It turned out that the alignment of the computational grid dominated the accretion patterns. Applying a curvature in the grid solved this problem and resulted in comparable Gaussian shapes between the model and the observations.

Coupling wet and dry beach models

To realistically predict windblown transport, the water levels, waves, sediment composition, and the ever-changing shape of the Sand Motor should all be included in such computations. For this reason, two morphodynamic models, being Delft3D Flexible Mesh (FM) and AeoLiS, have been seamlessly integrated and applied to the Sand Engine (Luijendijk et al., 2019a). The integrated morphodynamic simulation is capable of reproducing the observed changes between 2011 and 2016 for both the subaqueous and subaerial domain. Regarding dune growth, the simulated results of the integrated model compare well with the measured dune growth between 2012 - 2015; the measured yearly-averaged dune growth rates vary between 14 - 19 $m^3/m/yr$, while the simulated yearly-average dune growth rate is 18 $m^3/m/yr$.

When incorporating the prediction of subaqueous morphodynamic changes by a seamless coupling of AeoLiS with FM, three additional processes are explicitly resolved: 1) the reworking of sand in the intertidal zone by waves breaking up the armoured layer, 2) the erosion of the dry beach area by waves, surges and currents resulting in new beach areas exposed to aeolian transport, and 3) the widening of beaches adjacent to the Sand Motor due to alongshore dispersion.

Morphodynamic acceleration technique

A new acceleration technique for morphodynamic predictions ('brute force merged') was developed, which incorporates the full temporal variability of the wave directions and heights in the wave climate (Luijendijk et al., 2019a). This method is an attractive and flexible approach providing a combination of phenomenological accuracy and computational efficiency (factor 20 faster than the benchmark brute force technique) at both the short-medium (storm time scales) and long-time scales (20-30 years).

Impact of advancements on decadal projections of the Sand Motor

The improvement in morphodynamic modelling since 2009 (EIA phase) and notably the abovementioned technical advancements have resulted in an increase in skill of the predictions (see Figure 6). Original forecasts in 2009 (see Figure 6, EIA at second row) show the sand dispersion to both sides of the Sand Motor, while overestimating the development of a spit on the northern side of the peninsula. First year calibration improved the model results for 2016 significantly (Stive et al., 2013; see third row). The new morphological acceleration technique improved the results further both quantitative and qualitative (see fourth row). The dynamics and dimensions of the lagoon are better reproduced. Incorporating aeolian transport (see Figure 6, FMAL at lowest row) has significantly improved the skill of the dry beach, dunes, dune lake and lagoon. Incorporating these processes is not only paramount for realistic predictions of coastal dune development but also for the decadal morphological behaviour of the subaqueous domain (Luijendijk, 2019b).

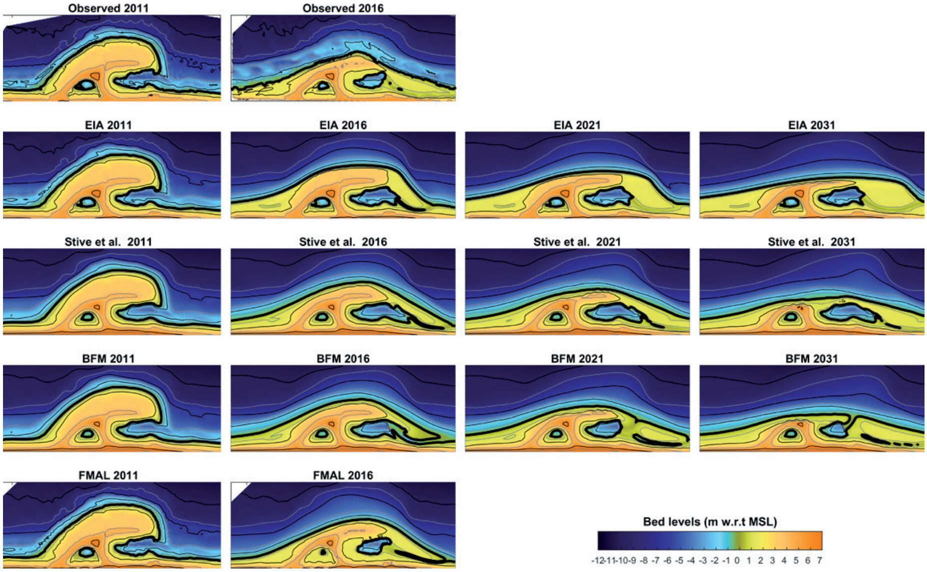

Figure 6. Advances in multi-scale morphodynamic predictions of the Sand Engine (from Luijendijk, 2019b). The four columns represent the years 2011, 2016, 2021 and 2031. The first row shows the observed bed levels, while the subsequent rows show the predicted bed levels presented in EIA, Stive et al., 2013, Brute Force techniques, and the coupled model, resp. FMAL refers to the FM coupled model with AeoLiS. The FMAL results for 2021 and beyond are not yet generated.

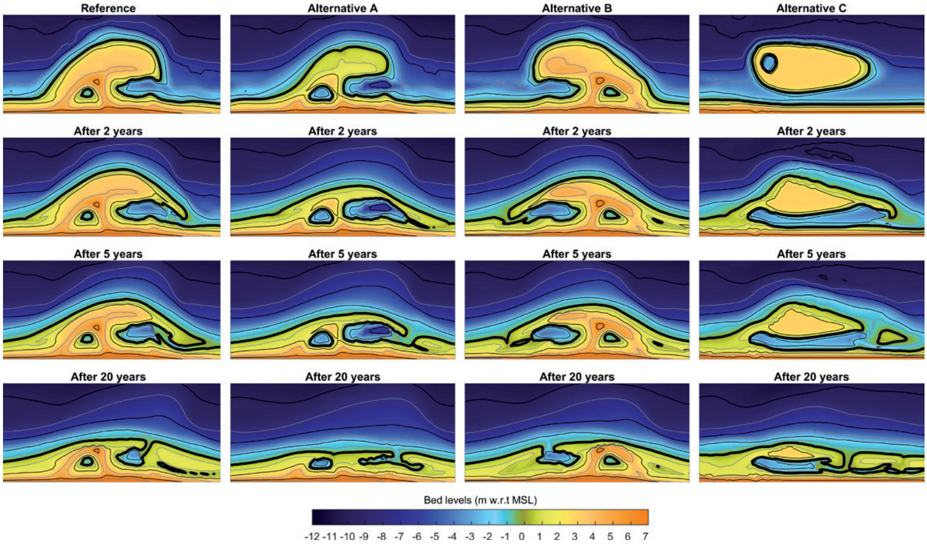

Figure 7. Predicted bathymetries for the reference case (the Sand Motor as constructed in 2011) and three alternative designs using the model discussed in Luijendijk et al. (2019a); Alternative A - the lowered Sand Motor, Alternative B - the mirror-image version of the Sand Motor, and Alternative C - the wing-shaped island.

Decadal projections of large-scale interventions

In the numerical models, many parameters can be varied when designing a sandy solution, for example, the volume, size, shape, orientation, elevation, slopes, grain size, sediment composition, chemistry of the sand, groundwater table, and features like the dune lake, lagoon, and intertidal flats. To demonstrate the impact of a few of these design parameters, the predicted 20-year evolutions of different alternative designs are presented (see Figure 7) by applying a Delft3D model as discussed in Luijendijk et al. (2019a). It is important to realise that the hook shape is just one of the possible shapes and designs. A Sand Motor is not per se a hook-shaped beach nourishment, but a concentrated nourishment that feeds the adjacent beaches at a rate that is in pace with the natural dynamics.

5. Findings

This paper discusses the process-based morphodynamic model applied to the Sand Motor and what the morphodynamic forecasts have gained from the findings of the interdisciplinary research program NatureCoast. An example of a relevant finding is that milder wave conditions, which occur more often, are almost as important to the erosion of the Sand Motor as storm conditions and should therefore be explicitly incorporated in the long-term (decadal) morphodynamic predictions. Another example is related to aeolian transport relevant for dune formation. To realistically predict windblown transports, the water levels, waves, sediment composition, and the ever-changing shape of the Sand Motor should all be included in such computations. These and other findings have triggered new developments which led to a new coastal landscape model, which integrates all relevant processes in a seamless manner (i.e. the FMAL model; the FM model coupled with AeoLiS).

The coastal landscape model was developed to seamlessly predict the morphodynamics in both the subaqueous and subaerial domains of the Sand Motor. Decadal predictions illustrate the need to be able to resolve the marine and aeolian processes simultaneously in one modelling framework; especially when dynamics of coastal landscapes and the resulting dune formation as part of the coastal flood defence are subject of interest. The coastal landscape model also incorporates a novel morphodynamic acceleration technique that allows for resolving the morphodynamics from storm to decadal time scales in one simulation.

Combining the above-mentioned developments has led to a unique, open-source, process-based landscape model for (complex) coastal sandy systems, which can stimulate further collaboration between research communities; extensions into dune dynamics and vegetation development are already planned. Moreover, this work demonstrates the evolution from mono- to interdisciplinary forecasts of coastal evolution. It is only these integrated models that can further optimize the spatial design of larger scale adaptive coastal interventions and allow for quantification of the various ecosystem services in space and over time.

Acknowledgements

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