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TIDAL DYNAMICS IN THE SAND MOTOR LAGOON

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ABSTRACT

The Sand Motor is a mega-nourishment characterized by a very large sand volume of around 20 million m^3 placed along the Dutch coast. The Sand Motor is a pilot project to evaluate the performance of an alternative nourishment strategy with respect to different functions of the coastal system. Within the scope of the coastal functions, the hook-shaped design of the initial morphology of the Sand Motor involves a sheltered (man-made) lagoon. The morphology of the Sand Motor and particularly the area around the lagoon entrance has changed over time since the construction in 2011. As a result of the changing inlet and lagoon morphology, the tidal conditions inside the basin have changed. We have set up a detailed numerical model to simulate the hydrodynamic conditions inside the Sand Motor's tidal lagoon as a function of the water level at sea and the measured local morphology of the Sand Motor. It is found that the tidal response inside the lagoon changes significantly as a function of the changing morphology. The analysis reveals a prediction of the temporal development of the tidal range and mean water level inside the lagoon, which can be used to predict the closure of the Sand Motor lagoon.

Keywords: Sand Motor; Delft3D, Lagoon, Tide

1. INTRODUCTION

The Sand Motor is a mega-scale beach nourishment located along the South Holland coast in the Netherlands, see Figure 1 and Stive et al. (2013). The Sand Motor was built in 2011 as a pilot project to evaluate the performance of an alternative nourishment strategy with respect to different functions of the coastal system. Those functions are, amongst others, safety, recreation and ecology. Within the scope of the coastal functions, the hook-shaped design of the initial morphology of the Sand Motor involves a (man-made) lagoon that is largely sheltered from incoming waves, see Figure 2. The development of this lagoon is of particular interest for ecological development (the lagoon provides a sheltered, salt water habitat) and swimmer safety (tidal currents in the lagoon entrance might pose a threat to swimmers and bathers).

The Sand Motor initially consisted of around 20 million m^3 of nourished sand and was designed to feed the adjacent coastline by the spreading of the sand due to wind and waves over a large alongshore domain. The expected lifetime of the nourishment is in the order of 20 years. During this period, the development of the Sand Motor's morphology is closely monitored at monthly or bimonthly intervals. Figure 2 illustrates the development of the Sand Motor from aerial images and Figure 3 shows measurements of the morphology. It is clear from Figures 1 and 2 that the Sand Motor's morphology has been changing during the first 3-4 years since the completion of the dredging works. The morphological changes are the results of the nourished sediments being moved by the environmental forcing of wind, waves and currents.

A pronounced feature of the morphological developments is the spit formation at the lagoon entrance at the northern side of the Sand Motor. This spit is likely the result of wave driven, alongshore sediment transport in combination with the tidal currents associated with the lagoon. Many examples of spit formation due to the combination of alongshore transport in the vicinity of tidal inlets are documented and analyzed (see for instance Hayes, 1980) but to the authors knowledge this is the first man-made lagoon in a littoral system created within the scope of nourishments. Due to the formation of the spit, the morphology of the lagoon entrance has changed over time from a relatively open connection with the sea towards a narrow tidal channel. The tidal channel is expected to restrict the tidal flow, causing the tide inside the lagoon to deviate from the North Sea's tide.

Well established modelling concepts exist to estimate the geometry of a tidal channel as a function of lagoon dimensions, tidal prism and/or tidal velocities. Popular examples are the empirical relationships by O'Brien (1969) and the semi empirical work by Escoffier (1940). These concepts are based on the assumption that a certain equilibrium exists between the tide and morphological dimensions of the system. In the case of the development of the Sand Motor, dimensions deviate from natural systems and it is unclear if such an equilibrium will exist. The existence of such an equilibrium is however of interest for coastal functions where especially recreation and ecological developments are of interest.

The morphological data that is currently available allows for a detailed analysis on the existence of such an equilibrium. In this paper we assess the development of the tidal system in the Sand Motor lagoon using the measured morphology combined with a detailed hydrodynamic model. We hypothesize that the establishment of a morphological equilibrium will be reflected in the calculated tidal conditions inside the lagoon.

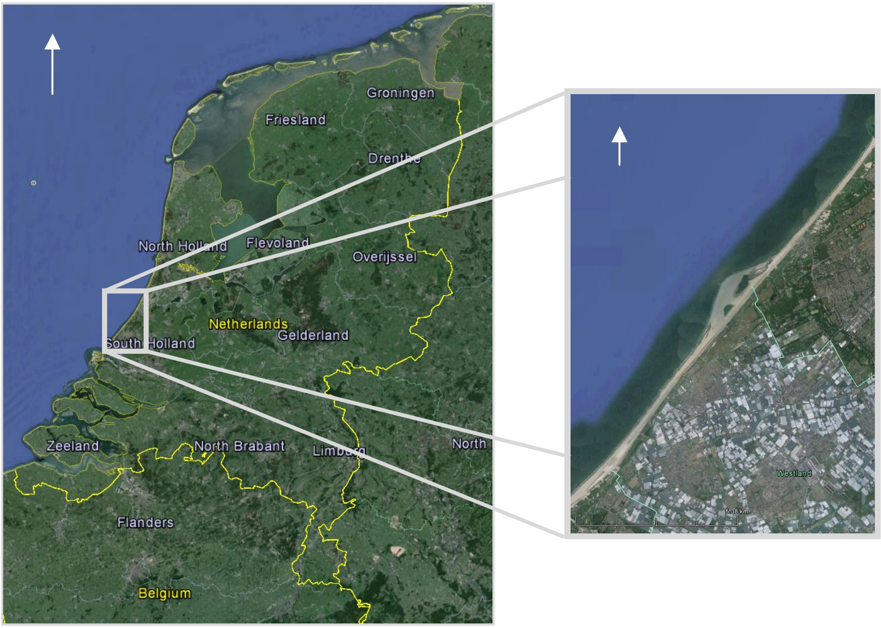

Figure 1. The Netherlands and the Sand Motor from satellite imagery (Google Earth).

Figure 2. Aerial image from the Sand Motor showing the man made lagoon; 18-7-2011 left and 20-2-2012 right (photos by Rijkswaterstaat/Joop van Houdt)

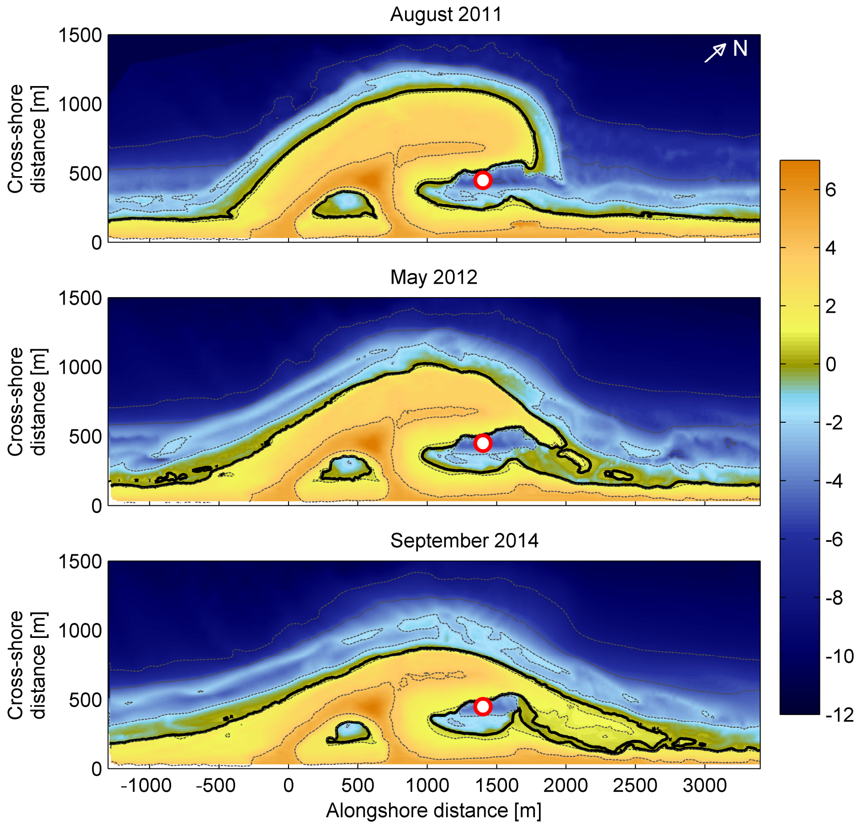

Figure 3. Development of the Sand Motor during 2,5 years after dredging works have been completed The colorbar indicates the elevation with respect to NAP which roughly coresponds to mean sea level. The white dot indicates the location for model output. The tick black lines indicates the +0.5 m NAP level. Note the development of the narrow channel.

2. METHODOLOGY AND RESULTS

At the time of writing, 25 topographic surveys of the Sand Motor have been performed over a period of 3 years upon completion of the dredging works. The topographic measurements are used to generate bathymetries, which serve as input for the hydrodynamic module of the Delft3D modelling suite. The computational grid is identical to the grid used by Radermacher et al. (2014) and covers roughly 9.6 x 3.8 km in the alongshore and cross-shore directions respectively. The grid cell resolution varies from 50 m x 50 m in the offshore corners towards 17 m x 17 m in the region of interest.

Time series of a representative astronomic spring/neap tidal cycle are imposed on the model's boundaries for each of the bathymetries. These representative time series are derived from astronomic tidal constituents for the nearby tidal gauges at Hoek van Holland and Scheveningen. To account for a propagating tidal wave inside the domain we have used a spatially varying water level boundary condition at the alongshore boundary and Neumann boundary conditions at the cross shore boundaries.

Time series of the modelled tidal conditions offshore and inside the lagoon during subsequent stages of morphological development are shown in Figure 4. The tidal range inside the lagoon deviates from the tide offshore. The mean water level is also different. Especially during low tides, the water level inside the lagoon does not follow the water level offshore. This is likely to be caused by the restricted outflow from the lagoon due to the decreasing channel dimensions with time. During high tides, the modelled water level inside the lagoon follows the offshore water level. This can be explained by the fact that the high water levels exceed the crest of the spit allowing water to flow over the large spit into the lagoon.

Temporal development of the tidal conditions inside and outside the lagoon can be described by the tidal range and mean water level as representative proxies. Figure 5 shows the development of the tidal range and mean water level inside the lagoon. Results show no significant variability in the first 6 months. After this period, the tidal range decreases with time and the mean water level increases.

Models regarding tidal basins and morphological equilibrium often use exponential functions with respect to adaptation in time towards an equilibrium (for instance Eysink et al., 1990; Stive and Wang, 2003). Such an exponential model reads:

$$y = A + B\, e^{-t/\lambda} \qquad [1]$$

where *A* can be read as the equilibrium value of *y*, *B* is an empirical coefficient and λ can be interpreted as a (morphological) timescale.

The decrease of the modelled tidal range in time is well represented by an exponential function ($A = 0.04$, $B = 0.42$, $\lambda =$ 159 days and $R^2 = 0.89$). Since $A>0$ there is no intersect with the x-axis suggesting that over time some equilibrium tidal range might be found. However, this theoretical equilibrium is negligibly small and in practice a closure of the lagoon cannot be excluded based on this extrapolation. It should also be noted that there is some stepwise development in tidal conditions that indicate faster developments during active periods in the winter months with respect to more stable periods in summer months.

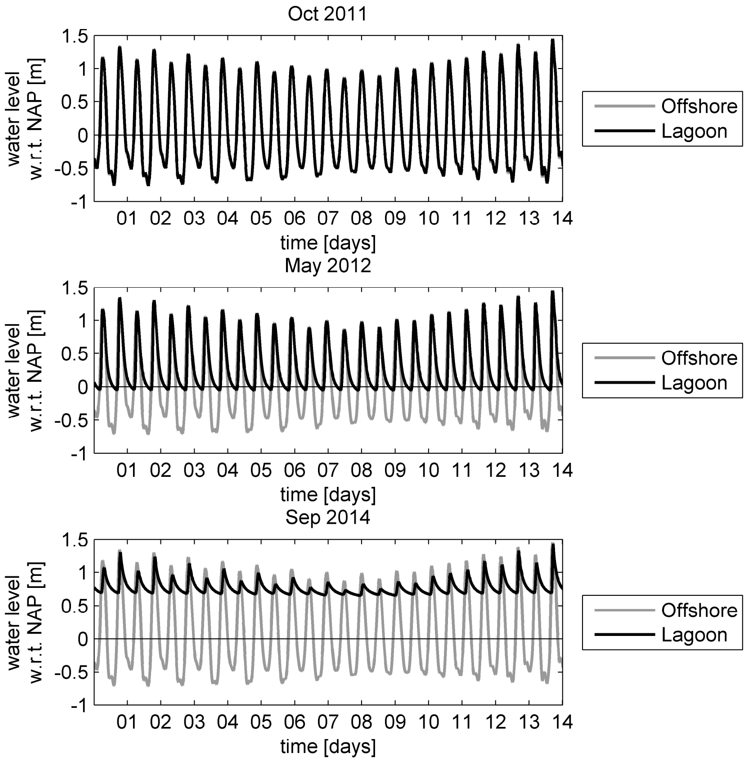

Figure 4 Modelled tides offshore and inside the lagoon for three different morphological situations in time. Note the decrease in tidal range and the increase in mean water level.

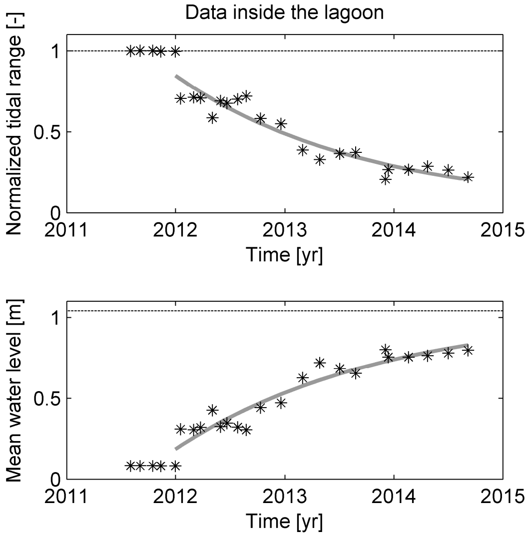

Figure 5 Tidal range and mean water level inside the lagoon as a function of temporally changing morphology. The tidal range is calculated over the full spring neap cycle using the mean difference between the crest and preceding through normalized with the mean offshore tidal range (1.77 m). The mean water level is calculated over the full spring neap cycle.

The temporal development of the modelled mean water level is also well represented by an exponential function after the first 5 months (A = 1.04, B = -0.47, λ = 142 days and R^2= 0.91) . Since A = 1.04, the horizontal asymptote has a value of 1.04 m which is in the order of the high water level at sea. Stepwise development, similar to the development of the tidal range, also occurs in the development of the modelled mean water level.

3. DISCUSSION AND CONCLUSION

We have presented the results of 25 numerical simulations with the aim of analyzing the tidal conditions inside the tidal lagoon of the Sand Motor. The simulations take only astronomical tides and measured variations of the morphology into account. The effects due to wind and waves are not accounted for in the model. Although there is currently no validation of the model procedures we can carefully conclude the following:

- The tidal characteristics inside the Sand Motor lagoon are influenced significantly by the time varying morphology of the Sand Motor domain.
- The simulated tidal range inside the Sand Motor lagoon decreased with time and the mean water level increased with time. Both the decrease of the tidal range and the increase of the mean water level approximately follow an exponential function in time. These exponential functions could suggest that the systems is approaching an equilibrium.
- There was a stepwise development in both the modelled tidal range and mean water level. These stepwise developments are a results of the difference in morphology between surveys. This difference in morphology is likely to be the result of different environmental conditions between the morphological surveys. We expect that a closure of the tidal inlet could occur due to specific environmental conditions (e.g. large waves during a storm). These conditions could change the morphology such that the modest tidal flow in the narrow channel is disrupted. This disruption might be interpreted as a (stepwise) deviation from the fitted exponential model.

Recently, we conducted a field campaign (MEGAPEX2014) where data on water levels inside the Sand Motor's lagoon was collected. We plan to use these data in the future to check the validity of our model assumptions and conclusions.

ACKNOWLEDGEMENTS

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