Memo

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Subject
TKI Dutch Coastline Challenge: Evaluation of the morphological predictive skills of the Delft3D FM model based on simulations of the Sand Engine

Contents

Reviewing procedure.
This memo is reviewed internally by the DCC project team at TUDelft (Bart van Westen, Arjen Luijendijk and Matthieu de Schipper) and aims to support the overall DCC report (DCC Syntheserapport 2023; in Dutch). Further details on the workflow and the model setup are available from the author upon request.

1 Introduction

The overall objective of the Top consortia Knowledge & Innovation project Dutch Coastline Challenge (hereafter, TKI-DCC) is to provide building blocks for climate-neutral and scalable coastal maintenance by designing and evaluating concrete coastal maintenance alternatives for the IJmuiden-Texel coastal section until 2035. The project will focus on (1) sustainable and scalable coastal maintenance concepts and (2) sustainable collaboration in the “triangle” (government, private sector, and knowledge institutions) based on smart methods of collaboration and contracting.

Within work package 2 (WP2), the main question is: Which alternative coastal maintenance concepts are available and what is their impact on the physical and ecological system? This question will be investigated on the basis of three tasks:

1) Generating a set of alternative nourishment concepts and their potential impact.
2) Evaluating the morphological predictive skill of current state-of-the-art modelling.
3) Evaluating the morphological and ecological impact of selected coastal nourishment concepts.

This memo is the second of five memos that collectively constitute the deliverables from Work Package 2 (WP2). These memos are (see Figure 1):

- Memo 1 (M1): Description of the inventory of nourishment alternatives. (*in Dutch: Inventarisatie kustonderhoudsconcepten voor de Dutch Coastline Challenge*)
- Memo 2 (M2): Description of the setup of the Delft3D Flexible Mesh model and validation of the hydrodynamics.
- Memo 3 (M3): Evaluation of the morphological predictive skills of the Delft3D FM model based on simulations of the Sand Engine.
- Memo 4 (M4): Morphological and ecological indicators for the Dutch Coastline Challenge nourishment evaluation (M5).
- Memo 5 (M5): morphological and ecological evaluation of nourishment concepts.

Several alternative nourishment concepts are presented (*Memo 1*). To predict the (eco)morphological development of these alternatives, a process-based model is set-up (*Memo 2*) and morphologically validated (*Memo 3*). Multiple indicators are defined (*Memo 4*) and used to evaluate a selection of alternative nourishment concepts (*Memo 5*).

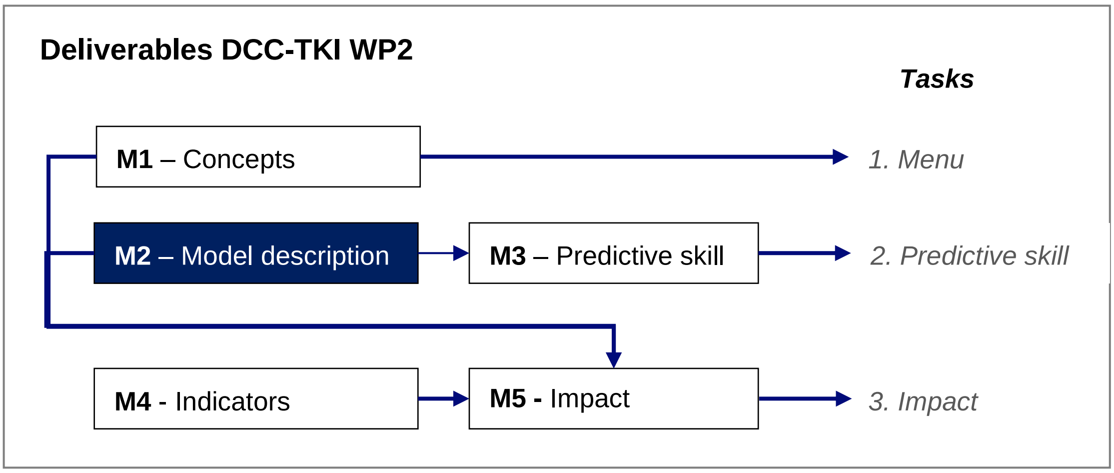

Figure 1 Overview of deliverables (memos) within the DCC-TKI project, relationship with WP2 tasks and interrelationships.

1.1 Scope

The current memo evaluates the forecast skill for morphological evolution of nourishments. The focus is on skill for aggregated parameters (e.g. remaining volume in the nourished zone) rather than a point wise comparisons and skill scores (e.g. a Brier Skill Score like in Luijendijk et al. 2017).
Predictions for small scale nourishments are notoriously difficult, with various authors reporting limited skill (Van Duin et al 2004, Huisman et al 2019). We therefore evaluate the skill for an extreme case, a mega feeder nourishment. Neither smaller scale nourishments nor unnourished beach behavior is tested. Dunes and Aeolian transport modelling are not included in this study.

1.2 Reader

The approach of the study is elaborated upon in Chapter 2. This chapter also provides the key elements of the model used. Chapter 3 provides results on the model data comparison and examines an empirical tool for mega nourishment evolution. Results are further in the discussion chapter (Chapter 4) and summarized in the conclusions (Chapter 5).

2 Methodology

The current study examines predictions of morphological evolution at nourished beaches. The approach contains two elements:

1. A 5 year hindcast of the Sand Engine nourishment case. Here we compare an empirical and a state-of-the-art numerical tool with the a large set of observations.
2. A hypothetical case of a Sand Engine-like nourishment at Egmond aan Zee. Here we examine a smaller scale nourishment, more suited to the aims of the DCC project. In absence of observations we compare the empirical tool with the state-of-the-art numerical tool.

Sand Engine 5 year hindcast

The Sand Engine project is used for the hindcast study. The Sand Engine is a 21.5 Mm^3 mega nourishment project located along the Delfland coast (Stive et al., 2013). The main part of the Sand Engine is a sandy, man-made peninsula of 17 Mm^3. Since construction in 2011, over 40 combined bathymetric and topographic surveys have been undertaken, making the Sand Engine an ideal location to perform a morphological validation on the timescale of years.

The morphological model is based on the DCC Delft3D Flexible Mesh model approach and settings proposed in Luijendijk et al., 2017. We build on the DCC Delft3D Flexible Mesh model schematization, which showed good skill in replicating the hydrodynamics (Technische Universiteit Delft, 2023b).
Luijendijk et al., (2017) utilized an older Delft3D schematization to hindcast the first 1.5 years of morphological development of the Sand Engine. The optimized model settings of this 2017 study are used as a starting point for the morphology settings in Flexible Mesh in this study. The main modifications to the morphological settings in this setup compared to Luijendijk et al., (2017) are changes to the sediment transport factors for suspended and bedload transport (*sus, bed* = 2), determined after calibration for the longshore spreading and wave-related transport factors (*susw, bedw* = 0.2) for stabilization of cross-shore developments.

The Delfland coast is located outside the coastal stretch that is evaluated in the DCC project. Therefore, the model schematization is based on the DCC FM model setup (Technische Universiteit Delft, 2023b) but computational grids, bathymetry and hydrodynamic and meteorological forcing are redefined for this study. The computational grid has a similar longshore and cross-shore resolution as the DCC FM model. The forcing of the numerical model is based on a bruteforce compressed approach, representing a realistic timeseries (i.e. including storms) but compressed in time to accelerate the computations. This is comparable to the DCC FM model discussed in Technische Universiteit Delft (2023b), with a compressed timeseries and morfac of 3. In total 5 morphological years are hindcasted by the model. More details on the model setup are given in the Appendices.

Next to the state of the art Delft3D FM model we also examine an empirical tool to predict the sediment losses at mega feeder nourishments. Tonnon et al., (2018) propose a generic relation for erosion rates of mega nourishments based on Sand Engine measurements and modelling results, with the main purpose of being supportive in project initiation phases and feasibility studies. They postulate that the lifetime of these nourishments can be predicted using:

$$T_{1/2} = 1.91 \cdot 10^{-2} \cdot V_{ini} \cdot \left(0.2 \cdot \frac{L_{ini}}{W_{ini}} + 1\right)\left(\frac{\delta Q_s}{\delta \theta}\right)^{-1}$$

$$V_t = V_{ini} \cdot e^{-\frac{T}{T_{1/2}}}$$

$$\Delta V_t = V_t - V_{ini}$$

With:

$T_{1/2}$ Half-time of the nourishment [yrs]
V_t Remaining volume at T years after construction [m^3]
ΔV_t Eroded volume at T years after construction [m^3]
V_{ini} Initial volume of the nourishment [m^3]
L_{ini} Initial length of the nourishment [m]
W_{ini} Initial cross-shore width of the nourishment [m]
$\frac{\delta Q_s}{\delta \theta}$ Longshore transport intensity parameter (LTI) [m^3/yr/degree]

We will use this empirical tool in the 5 year hindcast to evaluate its skill. Parameters are chosen to fit the Sand Engine case (V_{ini} =17·10^6, L_{ini} =3000,W_{ini} =1000 and $\frac{\delta Q_s}{\delta \theta}$ =30.000 from Tonnon et al. (2018)).

Sand Engine-like nourishment at Egmond aan Zee

Ultimately, we aim to evaluate nourishments in the DCC coastal stretch IJmuiden-Texel. This stretch has a different coastal profile and exposure to forcing than the Delfland coast where the Sand Engine is positioned. To examine the performance of the model on the DCC coastal stretch a hypothetical Sand Engine-like nourishment is implemented at Egmond aan Zee. Egmond is within the coastal stretch of interest of the DCC project and inside the DCC Delft3D FM model grid reported in Technische Universiteit Delft (2023b). Next to the state of the art model we also used the Tonnon et al. (2018) relationship for this Egmond case.

3 Results

The Delft3D FM model hindcast data shows a good spreading to lateral sides in the five years after construction of the model (Figure 2). Large erosion is present at the most protruding part of the peninsula (Figure 3, red patch between alongshore location 0 and 2000 m). Large zones of sedimentation are visible at both adjacent beaches. The nature of the model means that smaller subtidal features (e.g. sandbars and rip channels) are not replicated by the model. The lagoon entrance shows sedimentation in both data and model results. However, the entrance of the lagoon in the model computations shows a single channel with a depth below the low water level. In the observations the bed level in this zone is much shallower and above MSL, with several small channels connecting the lagoon with the open ocean. Quantitative analyses of the model and observation data are presented in the upcoming sections.

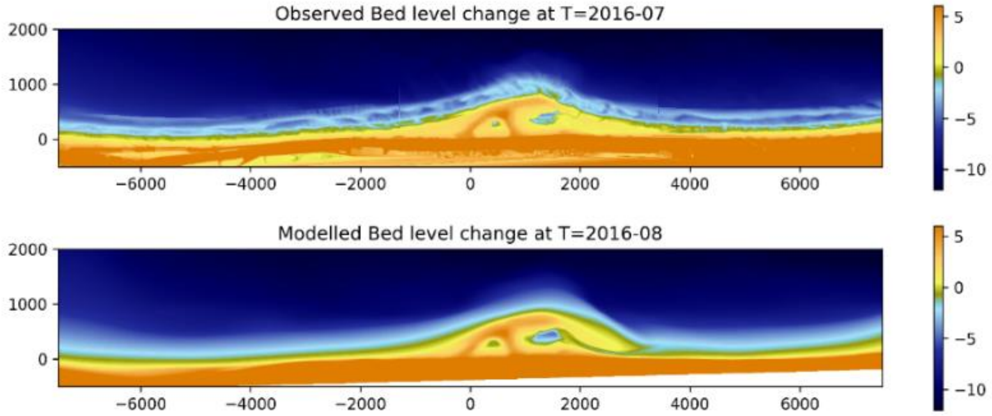

Figure 2 Observed (top) and modelled (bottom) morphological development of the Sand Engine after 5 morphological years.The coastline orientation is rotated for lay-out purposes. Horizontal axes are in meters. Colors represent the bed level with respect to NAP in meters.

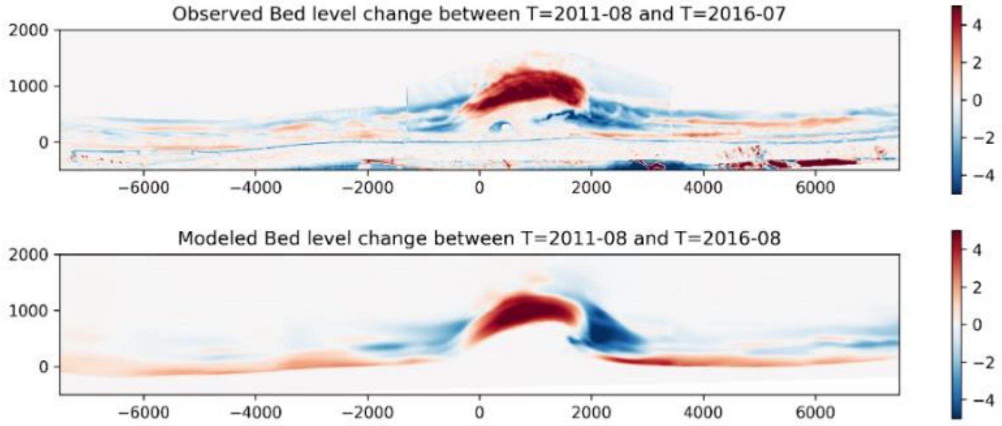

Figure 3 Observed(top) and modelled (bottom) bed level change at the Sand Engine after 5 morphological years. The coastline orientation is rotated for lay-out purposes. Horizontal axes are in meters. Colors represent the bed level change in meters.

3.1 Sediment balance

The volumetric development is computed in pre-defined balance areas to determine whether the Delft3D FM model is capable of reproducing the amount of erosion from the peninsula, the main nourishment body and the deposition at the lateral sections. This approach has been applied repeatedly in previous Sand Engine studies (Luijendijk et al., 2017; Roest et al., 2021; Tonnon et al., 2018).

The dimensions of the balance areas are slightly modified compared to earlier studies by extending the lateral sections further south and north (Figure 4) to make the balance areas suited for 10-year morphological development.

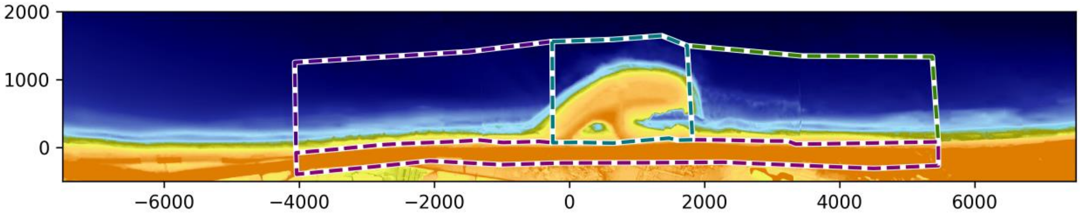

Figure 4 Four sediment balance areas used to compute the volumetric development. The peninsula (blue), southern (purple), northern (green) and dune (pink) areas.

The volumetric analysis is carried out for the observations for the full 10 years and the 5 years of model results. The sediment budget analysis of the balance areas shows that the model reproduces the erosion from the main peninsula reasonably well (Figure 5; blue line) The model predicts an erosion of 3.5 Mm^3 after 5 years compared to 4.0 Mm^3 obtained from observations (13.7 % underestimation). The accumulation of sediment in the northern adjacent balance area is overpredicted, while the volumetric change within the southern area is underpredicted (Figure 5, purple and green lines). Finally, the sediment volume within the dune area has increased over time by about 0.3 Mm^3 in the first five years (Figure 5; purple line). Dune growth and Aeolian processes are not included in the model and consequently the model is not capable of reproducing the response of this zone. This partially explains the opposite rate in the model results.

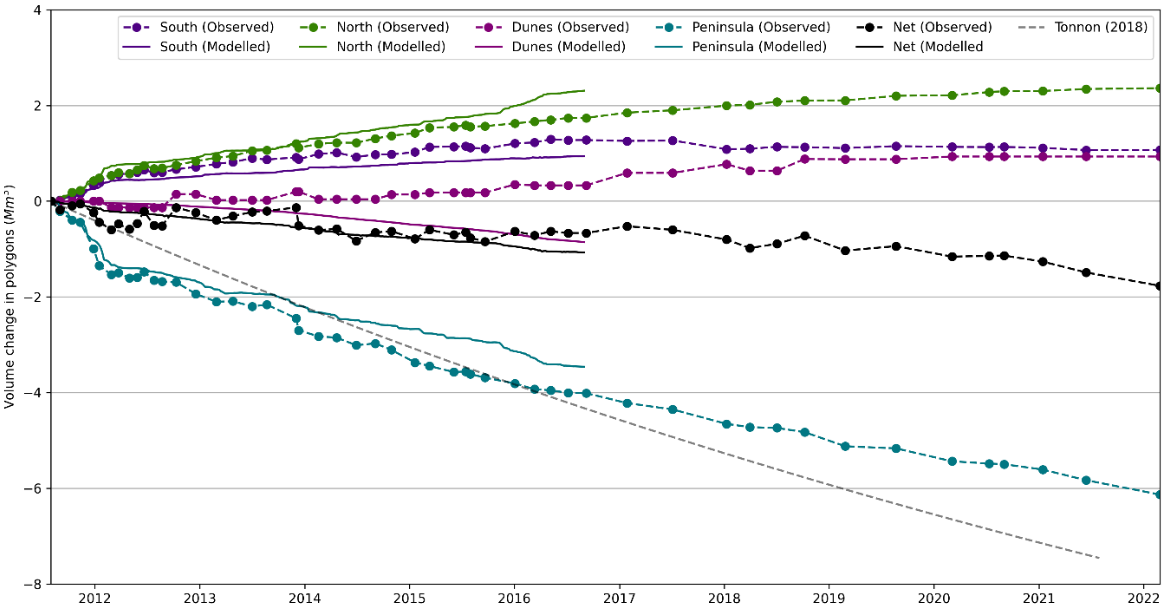

Figure 5 The volumetric development of four sediment balance areas (peninsula, north, south and dunes) and the combined area (net, black line) Measurement data visible in the dots with dashed lines, model outcomes shown in the solid lines. The empirical relation of Tonnon et al 2018 is given in the dashed grey line.

The net sediment balance of all the balance areas combined, shows a significant loss of almost 2 Mm^3 after 10 year (Figure 5; purple line). For the first 5 years where we have model data to compare, we observe a similar loss. These losses could be contributed to offshore losses, further alongshore spreading, onshore losses over the backdunes or compaction of the subsoil or main body.

The empirical relationship of Tonnon et al. 2018 fits well with the observations of the loss of sediment on the peninsula (Figure 5, grey dotted line) especially on first 5 years on which it was calibrated. Our data show that with more recent measurements reaching up to 10 year the two start deviating. On the 10-year timescale we see an overprediction of 1.5 Mm^3 of the eroded volume by the Tonnon et al., (2018) formulation.

3.2 Cross-shore development

State-of-the-art models that compute morphodynamics with a depth-averaged approach tend to have difficulties with predicting cross-shore behaviour. For instance, breaker bar development is often not well captured and subtidal features can be removed. The aim of the DCC FM model is not to predict cross-shore development very accurately, however large errors in cross-shore behaviour could result in inaccuracies in longshore spreading and evaluation of coastal state indicators. Therefore, it is important the cross-shore development is reasonably well reproduced.

First, we evaluate a transect on the intersection between the nourished and unnourished stretch (Figure 6; transect A). At this location with predominantly accretion, the amount and of sedimentation is predicted correctly. The model results show a monotonically decreasing bed level where the observation shows a subtidal bar. This smaller cross-shore feature is not captured by the model. Likewise, part of the sediment is deposited on the subaerial beach (Figure 6; transect A cross shore location 250 m). The model does not deposit the sediment this high up the profile

Second, we examine the cross-shore profile at the most protruding part of the nourishment (Figure 6; transect B). At this location with large erosion, the amount of erosion and depth of closure are well predicted by the model. The retreat of several 100s of meters at this part of the coastline is also well reproduced.

Transects near the entrance of the lagoon (Figure 6; transect C and D) show larger deviations between the model and the data. The amount of sedimentation is overpredicted, resulting in a coastline slightly further offshore. Additionally, the infilling of the lagoon is not well reproduced in the model. Potentially the challenges in replicating the dynamics in around this lagoon entrance influence the skill in this region. Despite the differences in the cross-shore width of the spit, the maximum elevation of the sedimentation is well predicted (Figure 6; transect D cross-shore location 300 m).

Finally, a location which is not (yet) disturbed by the construction of the Sand Engine is analysed (Figure 6; transect E). At this location with limited changes in profile volume over the five years, the profile changes are not well predicted by the model. The model predicts a strong coastline retreat up to the dune foot, which is not similar to the observations.

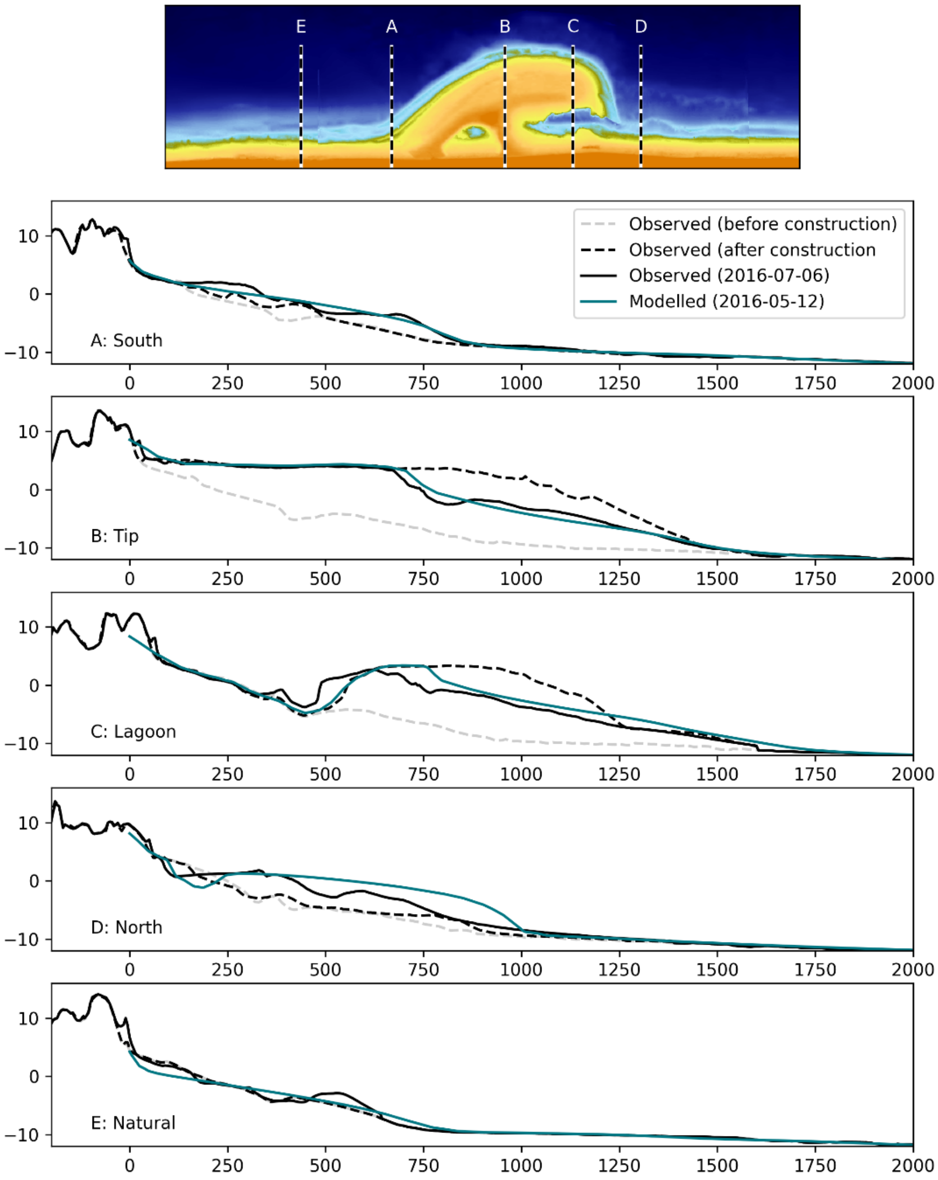

Figure 6 Cross-shore profiles at five locations indicated on the map on top Profile panels (A,B,C,D, E) include a profile before construction (dotted grey), just after construction (dotted black), measured after 5 years (continuous black) and modelled after 5 years (continuous blue).

3.3 Alongshore feeding

The longshore redistribution of sediments in the full profile (cross-shore distance -200 < y < 2000 m) is evaluated. This analysis aims to validate the model's ability to predict the feeding capacity to lateral beach sections and is a key metric to compare various nourishment concepts later in the TKI-DCC project.

The time evolution of the sediment volume from the observations shows a widening of the nourishment by about 2.5 km over the course of the first 5 years (Figure 7; top panel). Little change in volume is observed at the edges of the domain in this period. The modelled response shows a similar redistribution with large accretion at both sides of the peninsula (Figure 7; middle panel).

Comparing the modelled and observed distribution of added sediment volume after 5 year we see a good resemblance at the southern flank of the nourishment (Figure 7; bottom panel alongshore locations -1800 to 1000 m). At large distance from the nourishment on the southern end (alongshore locations -3000 to -1000 m) the model however forecasts erosion up to 500 m3/m, which was not present in the observations. At the northern flank of the nourishment the model over predicts the sediment volume, especially the region with the spit development. Where the observations show minimal change in the shoreline in the last years near the transition zone (Figure 7; top panel, alongshore locations 2000 m), the model shows a persistent trend of seaward expansion even in the later years.

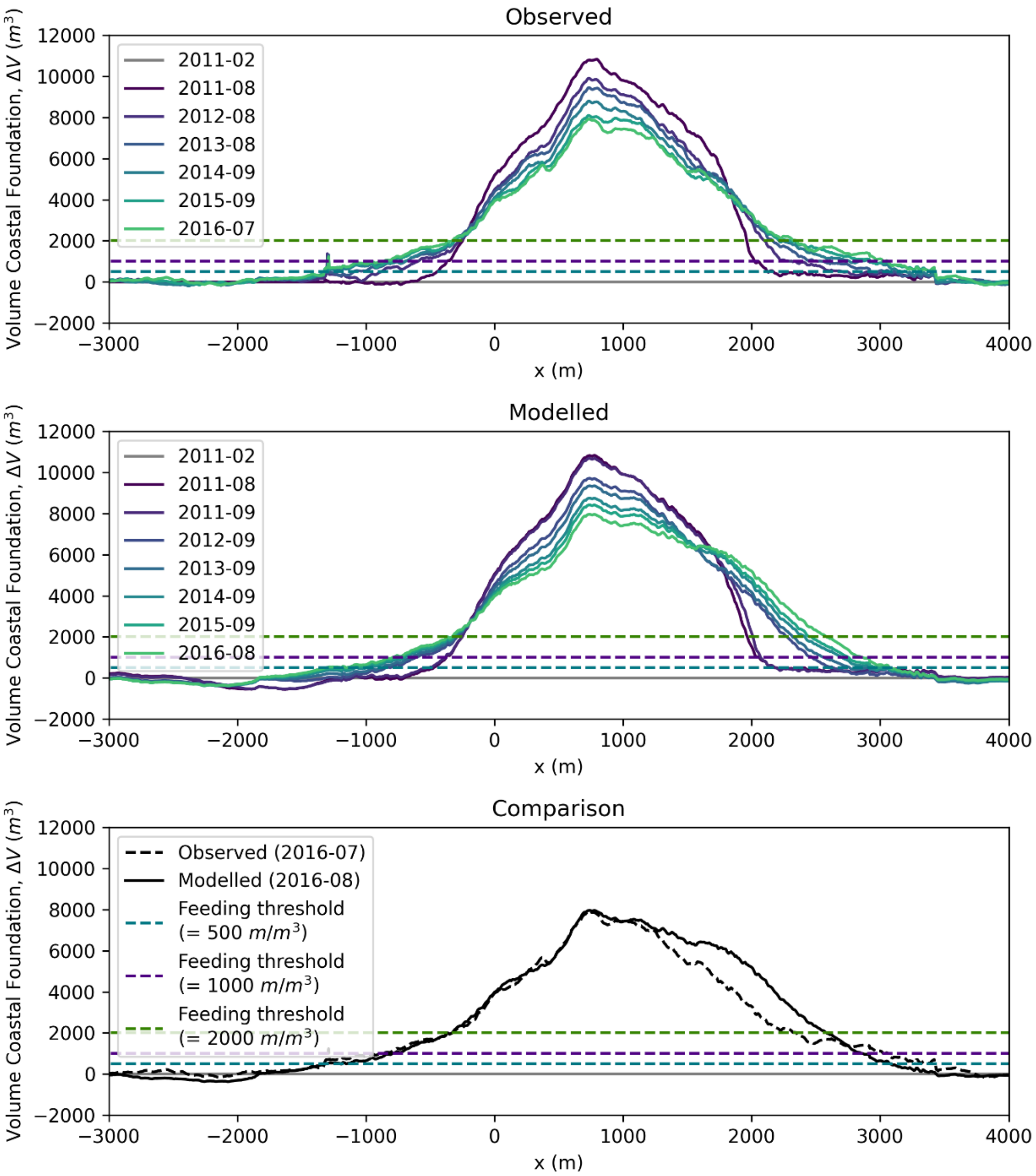

Figure 7 The measured (top) and modelled (centre) difference in sediment volume in the cross-shore profile with respect to the pre Sand Engine survey in 02/2011. (Bottom) Comparison between the model and observations after 5 morphological years. Dashed horizontal lines indicate the thresholds levels of gained volume for 500,1000 and 2000 m3/m.

From this spatial distribution of volume, we compute a "*Zone of influence*", being the alongshore length of the coastal stretch where the accretion exceeds a certain threshold. This metric is a valuable validation parameter since it is used directly in the evaluation of various nourishment concepts. For now, three threshold values are chosen: 500, 1000 and 2000 m^3/m

(Figure 7 blue, purple and green lines). Smaller threshold values are not shown here as these are surpassed by the natural fluctuations in sediment volume.
The development of the zone of influence for three different thresholds is shown in Figure 8. In a qualitative way, spreading occurs most rapidly in the initial phase after construction (<1 year) and decelerates over time, which is also predicted by the model. Quantitatively, the model predictions and measurements show varying differences.
The influence zone for the smallest feeding thresholds are underestimated by the model by about 350 m after 5 years. After these 5 years, the model predicted the length of the coast where the accretion exceeds 500 m^3/m to be 4.38 km (blue line in Figure 8; 1.70 km increase since construction), compared to 4.75 km measured (2.15 km increase since construction). For the largest feeding threshold examined (2000 m^3/m) the length is overestimated by the model by about 150 m, linking to the mismatch at the northern flank of the nourishment (Figure 7; bottom panel, alongshore locations 2000 m).

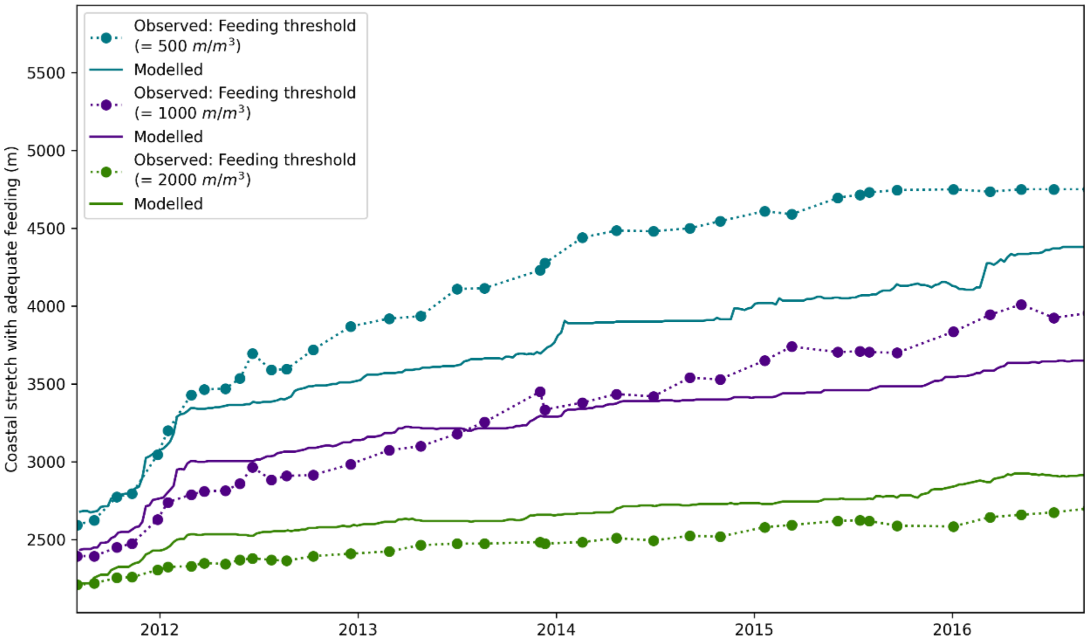

Figure 8 Length of coastal stretch exceeding the accretion threshold of 500, 1000 and 2000 m^3/m.

3.4 Local erosion

The construction of large-scale feeder type nourishments are postulated to introduce local erosive hotspots as a result of longshore transport gradients or eddy formation. At the Sand Engine pilot nourishment this is mitigated by implementing two shoreface nourishments. In this section we evaluate the lateral sections of the nourishment in more detail to focus on potential lee side erosion. For this we computed a volume based shoreline position, the Momentary Coastline Position (or MKL; Van Koningsveld and Mulder, 2004) and change therein.

Model results show local erosion just north and south of the Sand Engine with a coastline retreat of ~50 m (Figure 9; lower panel), but this is not observable from the measurements (Figure 9; top panel).

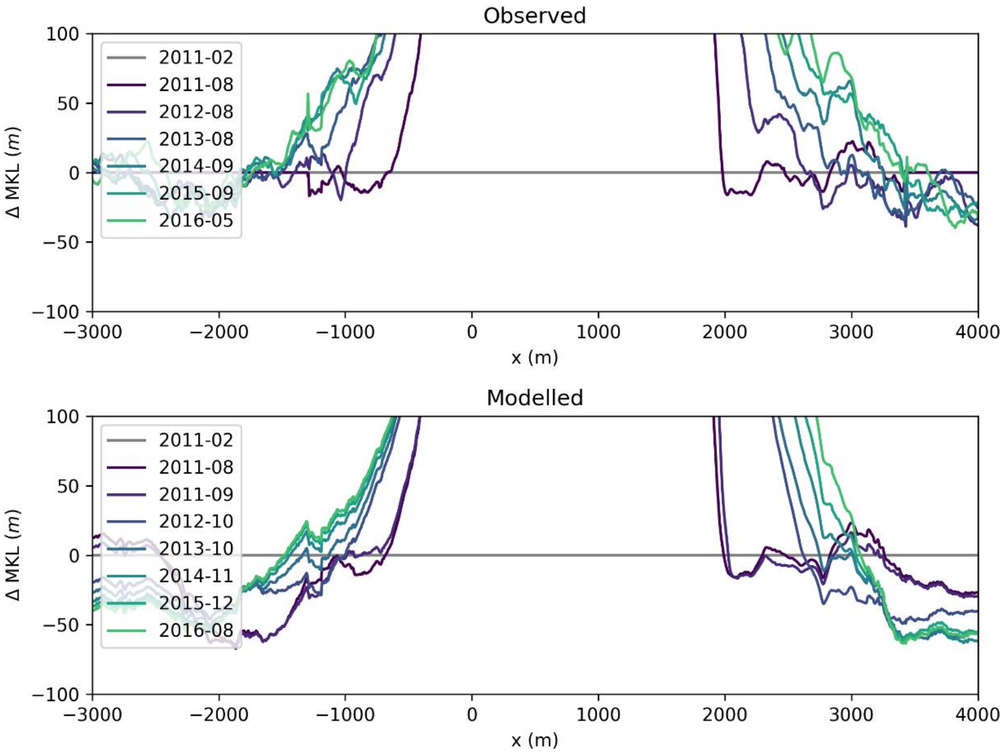

Figure 9 Measured (top) and modelled (bottom) change of coastline position (MKL) with respect to the position in February 2011.

3.5 Sediment balance for a Sand Engine-like nourishment at Egmond.

Previous sections aimed to replicate the behavior of the Sand Engine nourishments located at the Delfland coast. A mega feeder nourishment at Egmond aan Zee (within the DCC region of interest) is examined with the Delft3D model and the relation of Tonnon et al. (2018).

The sediment balance areas for the Egmond are determined similarly to the Sand Engine analysis with a central balance area and two balance areas for the adjacent coastal sections (Figure 10). The longshore transport intensity parameter ($\frac{\delta Q_s}{\delta \theta}$) in the Tonnon (2018) relation (see chapter 2) remains the same as for the Sand Engine model, but the initial nourishment volume, length and width decreased (V_{ini}: 7.5 Mm^3, L_{ini}: 2000 m, W_{ini}: 600 m).

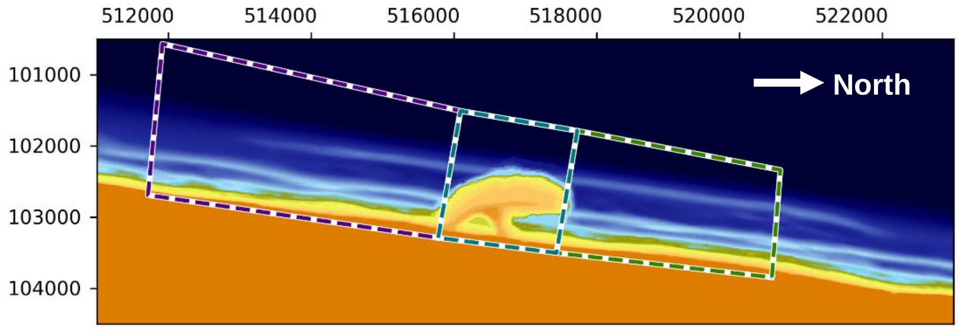

Figure 10 Three sediment balance areas used to compute the volumetric development. The peninsula (blue), southern (purple) and northern (green).

The results of the sediment balance analysis are shown in Figure 11. Sediment volumes in the various areas change rapidly in the first years and in particular during the winter seasons.

The centre region of the nourishment has lost about 3.5 Mm^3 in 5 years. This is similar to the observed and modelled losses at the Sand Engine (Figure 5). The adjacent coastal section at the south side gains the most sediment at the end of the computation, this is in contrast to the observed and forecasted behaviour for the Sand Engine case where the northern beaches gain the most sediment (Figure 5).

It can be seen that the erosion rate from the original nourishment body compares well Tonnon et al., (2018) relation and the model results, especially for the first 5 years after construction. Afterwards, the erosion predicted by Tonnon et al., (2018) is larger compared to the numerical model results. The larger erosion predicted with Tonnon (2018) for longer time periods is in line with the findings at the Sand Engine (see Figure 4).

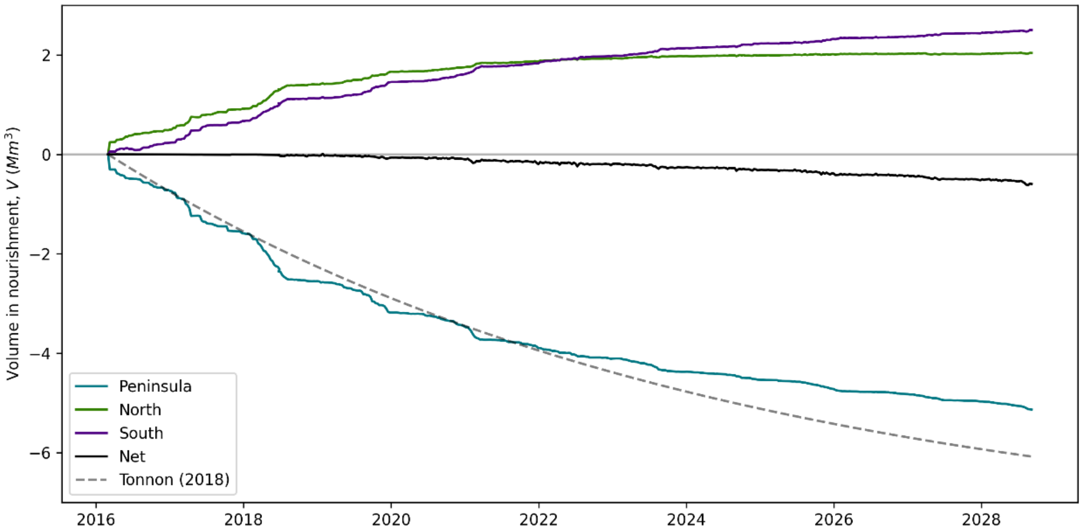

Figure 11 The volumetric development of a Sand Engine like nourishment at Egmond. Lines represent three sediment balance areas (peninsula, north and south) and the combined area (net, black line). The empirical relation of Tonnon et al 2018 is given in the dashed grey line.

4 Discussion and recommendations

In this memo we examined the predictive skills of a FM model setup for the TKI-DCC project. Here we discuss the applicability of the FM model to evaluate nourishment scenarios for the aims of the DCC project and outline several limitations.

4.1 Model applicability

The Delft3D FM model was evaluated on multiple quality metrics in this study, creating a more stringent test than earlier work which focused on the volume change in large sediment budget areas. Across the different metrics we find variations of approximately 20% between the model and the data. For the purposes of the TKI-DCC project, a comparison in between different nourishments, this amount of under- or overestimation is within the acceptable limits.

Although the morphological predictions by the model are accurate enough for the objectives of the DCC project, during the project several model limitations were encountered, affecting the computational costs and workflow (see Appendix 5C). As a result, the scope was revised during the project, reducing the number of possible simulations to test the model skill with recalibrated parameter values or a large range of nourishment schemes (Technische Universiteit Delft, 2023e).

The model's performance was predominantly examined for the alongshore redistribution of sediment. The prediction skill for shoreface nourishments is not adequately tested here, as these rely heavily on cross shore mechanisms. The confidence in the model's performance is therefore mostly for the nourishment concepts that harvest this lateral spreading mechanism (feeder nourishments). For these nourishments the Tonnon et al. 2018 empirical relation was found to give a good first estimate, especially for the first years. With adjusted empirical parameters this relation may be adjusted to suit the 5 to 10 year evolution.

4.2 Cross-shore development

Our findings show good performance for the retreat of the waterline at the most eroding section of the Sand Engine (Figure 6). Transects that are predominantly governed by natural variability rather than a large human intervention are not well reproduced. Improving coastal cross-sectional behavior in depth-averaged modeling has been topic of large interest in the coastal modelling community and several research efforts are currently being carried out to fill this gap. Ongoing in-depth research into these processes through field, lab or numerical experiments could potentially improve the depth-averaged modelling of coastal systems. As long as breaker bars cannot be solved in these models, it will remain difficult to compare nourishment concepts that strongly differ in nature solely on the basis of numerical results (e.g. Sand Motor vs foreshore replenishment). To compensate for potential cross-shore unrealistic behavior it is recommended to use a computation without nourishment. This simulation with the autonomous behavior can be subtracted from the nourished beach results to attain relative shoreline behavior.

4.3 Model assumptions

Current modelling efforts are done using a single, spatially homogeneous grainsize for the full domain. Grain size variations can be present and develop the subaqueous zone through sorting mechanisms (Huisman et al. 2016). This may have a large effect on ecology, but the effect on the large scale sediment spreading patterns may be limited (Huisman et al. 2018). Similarly, Aeolian sediment sorting in combination with coarse particles in the nourished sand can result in armoured layers and impact the evolution of the subaerial beach (Hoonhout and de Vries, 2017).
The subaerial morphological evolution (and sorting effects on it) are currently not included in the model. For a detailed evaluation of safety against flooding, recreation and ecology we

need to asses changes in dunevolume, beach width and ecotopes respectively. For a more complete assessment this it’s recommended to couple state-of-the-art subaerial models with the Delft3D FM model to calculate the aforementioned subaerial parameters.

5 Conclusions

In this memo we evaluated the morphological predictive skill of a Delft3D Flexible Mesh model. The validation was mainly focused on the Sand Engine mega-nourishment located along the Delfland coast. From this validation, the following conclusions can be drawn.

Across the different metrics we find variations of approximately 20% between the model and the data.
The longshore spreading of large scale interventions, that are wave driven forcing, are described well by the model. It must be noted that several key sediment transport parameters have been calibrated prior to this study (*sus*, *bed*, *susw* and *bedw*) to achieve these results. Since the longshore spreading of the sediment is sufficiently well reproduced by the model, the “influence zone” indicator is as well.

The predictive skill of the cross-shore behavior was good in locations where the coastal situation was far off the natural equilibrium state. At the tip of the Sand Engine coastline retreat, erosion volume and depth of closure were all captured well by the model. Predictions of beaches at larger distance of the nourishment were less accurate. Diffusive processes smoothened breaker bars with consequently coastline retreat in some locations.
Comparing the DCC FM model results with a generic relation defined by Tonnon et al., (2018), showed that these morphological predictions can be considered as reasonable outcomes.

For the purposes of the TKI-DCC project, a comparison in between different nourishments, the model skill is within the acceptable limits. The model has reasonable morphological predictive skill for simulating large-scale human interventions that mainly rely on longshore processes. Despite this, practical limitations, such as computational costs, model instabilities and model limitations have been unveiled. These reduced the scope of the scenario testing in the next phase of the DCC project.

References

Hoonhout, B., & de Vries, S. (2017). Field measurements on spatial variations in aeolian sediment availability at the Sand Motor mega nourishment. *Aeolian research*, *24*, 93-104.

Huisman, B. J. A., De Schipper, M. A., & Ruessink, B. G. (2016). Sediment sorting at the Sand Motor at storm and annual time scales. *Marine Geology*, *381*, 209-226.

Huisman, B. J. A., Ruessink, B. G., De Schipper, M. A., Luijendijk, A. P., & Stive, M. J. F. (2018). Modelling of bed sediment composition changes at the lower shoreface of the Sand Motor. *Coastal Engineering*, *132*, 33-49.

Huisman, B. J., Walstra, D. J. R., Radermacher, M., de Schipper, M. A., & Ruessink, B. G. (2019). Observations and modelling of shoreface nourishment behaviour. *Journal of Marine Science and Engineering*, *7*(3), 59.

Luijendijk, A. P., Ranasinghe, R., de Schipper, M. A., Huisman, B. A., Swinkels, C. M., Walstra, D. J. R., & Stive, M. J. F. (2017). The initial morphological response of the Sand Engine: A process-based modelling study. *Coastal Engineering*, *119*, 1–14. https://doi.org/10.1016/j.coastaleng.2016.09.005

Roest, B., de Vries, S., de Schipper, M., & Aarninkhof, S. (2021). Observed changes of a mega feeder nourishment in a coastal cell: Five years of sand engine morphodynamics. *Journal of Marine Science and Engineering*, *9*(1), 1–24. https://doi.org/10.3390/jmse9010037

Stive, M. J. F., de Schipper, M. A., Luijendijk, A. P., Aarninkhof, S. G. J., van Gelder-Maas, C., van Thiel De Vries, J. S. M., de Vries, S., Henriquez, M., Marx, S., & Ranasinghe, R. (2013). A new alternative to saving our beaches from sea-level rise: The sand engine. *Journal of Coastal Research*, *29*(5), 1001–1008. https://doi.org/10.2112/JCOASTRES-D-13-00070.1

Technische Universiteit Delft (2023a). TKI Dutch Coastline Challenge: Description of the inventory of nourishment alternatives. *Memo TU Delft.*

Technische Universiteit Delft (2023b). TKI Dutch Coastline Challenge: Description of the setup of the Delft3D Flexible Mesh model and validation of the hydrodynamics. *Memo TU Delft.*

Technische Universiteit Delft (2023c). TKI Dutch Coastline Challenge: Evaluation of the morphological predictive skills of the Delft3D FM model based on simulations of the Sand Engine*. Memo TU Delft.*

Technische Universiteit Delft (2023d). TKI Dutch Coastline Challenge: Morphological and ecological indicators for the Dutch Coastline Challenge nourishment evaluation. *Memo TU Delft.*

Technische Universiteit Delft (2023e). TKI Dutch Coastline Challenge: Morphological and ecological evaluation of nourishment concepts. *Memo TU Delft.*

Tonnon, P. K., Huisman, B. J. A., Stam, G. N., & van Rijn, L. C. (2018). Numerical modelling of erosion rates, life span and maintenance volumes of mega nourishments. *Coastal Engineering*, *131*, 51–69. https://doi.org/10.1016/j.coastaleng.2017.10.001

Van Koningsveld, M., & Mulder, J. P. M. (2004). Sustainable coastal policy developments in the Netherlands. A systematic approach revealed. *Journal of Coastal Research*, *20*(2), 375-385.

Appendices

A Model input bathymetry

Sand Engine model was initiated with a bathymetry consisting of several sources. For the Sand Engine peninsula the post construction survey was used. For the adjacent beaches the JarKus survey from 2011 was used. The bathymetry is translated to a local coordinate system aligned with the cross- and alongshore direction (Figure 12). The origin of the local coordinate system is near the Schelpenpad beach entrance (x: 72421 m, y: 451326) and rotated with 48 degrees with respect to North.

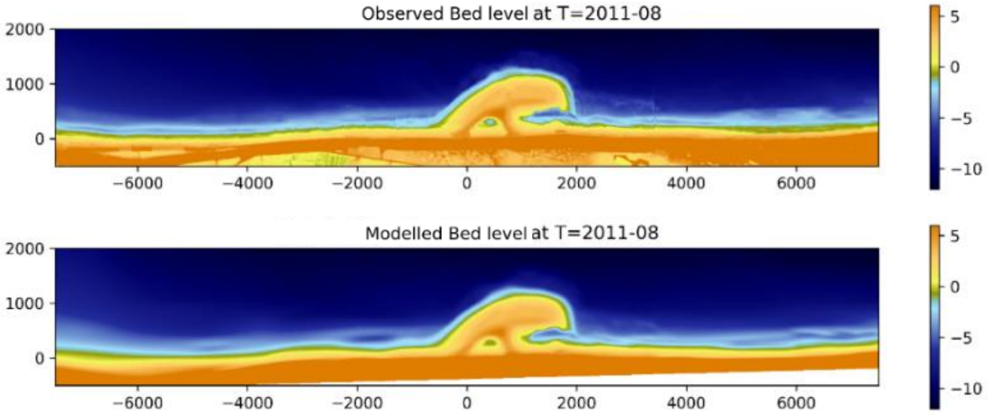

Figure 12 Post construction survey (top) and initial bathymetry for the Sand Engine model computations (bottom). Axes are in the local coordinate system centered around the Schelpenpad entrance. Colors are bed elevation with respect to NAP.

The Egmond Sand Engine case used in section 3.5 is initialized with the grid and bathymetry elaborated upon in Technische Universiteit Delft (2023c). A peninsula type mega nourishment is implemented in the Egmond 2019 bathymetry (Figure 10) by copying the Sand Engine. The size of 7.5 Mm^3 for the nourishment was obtained by scaling the horizontal dimensions of this Sand Engine.

B Model parameter settings

Full details of the model settings and the underlying motivation can be obtained from the author. The table below gives the main model parameter settings for the sediment transport and morphology in the D-Flow model.

Key sediment transport and morphology parameters in the D-Flow model

Model option	**Selected approach/ parameter value**	**comments**
Medium sand diameter (D50)	250 µm	
Morphological scale factor (morfac)	3	Different from the DCC model (= 4)
Multiplication factors for suspended and bedload concentrations (sus, bed)	2	Calibrated based on longshore transport

Wave-related suspended and bedload transport factors (susw, bedw)	0.2	Lowered to stabilize cross-shore behaviour
Transport formula	Van Rijn (2007)	Resulted in more realistic longshore transport in deeper water, compared to Van Rijn (1993)

For completeness a copy of model parameter files (*.mdu, *.mdw, *.mor, *.sed) are included in Technische Universiteit Delft (2023b).

C Model developments, practical use and recommendations

The diverse scope of the project in terms of nourishment concepts, study area, and potentially driving forces, required an unprecedented high resolution model covering a large domain with brute force time series. The support of unstructured grids enabled a refinement of local areas of interest, resulting in multiple mesh configurations varying from 100.000 (local refinement around Egmond) to 350.000 (entire North Holland and Texel coast refined) cells. The scale of this Delft3D FM model from Texel to Ijmuiden for nourishment evaluation proved challenging throughout the project, as computational costs increased, and stability issues arose. Several notes are made below on the use of the model.

Computational costs and acceleration techniques

Originally, the aim was to apply acceleration techniques to reduce the computational time, but unfortunately this model feature was not available for this study yet. During the project, we found that the MorMerge approach was not compatible with MPI D-Flow yet. Eventually, running on the Deltares-h6 computational cluster on 4 nodes (4x4 processors), simulating one morphological year approximately took 7 days. Considering these computational speeds, the original scope of the project (multiple nourishment concepts for various longshore locations on decadal scale) became out of reach.

Wave modelling

A large percentage of computational time in the current simulations is contributed to the wave modelling in D-Waves (up to 30-50%, besides the time it takes D-Flow to read and write the communication files). These percentages are with a cross-shore resolution set to 40 m, which is increased with the initially intended 20 m. Since parallel computing with MPI D-Waves resulted in instabilities, it was not possible to use domain partitioning for the wave model. A solution to reduce the computational time consumed by wave modelling could be the application of faster wave models, supporting an “online” coupling approach (not file-based), preferably BMI-compatible.

Model stabilities

Although computational costs restricted the project scope, model stability issues were possibly more problematic for the lead time and amount of labor needed to keep the model in the air. Many model crashes occurred during the project, on a regular and irregular basis, and not directly traceable to physical processes. This required many model restarts, resulting in a loss of computational time, lots of manual effort and additional post-processing work. Due to the randomness of these events, and impending project deadlines, it was complicated to “automate” this process.

We failed to identify the cause behind these instabilities during the project. It is very likely that the size of the model, with both the number of cells of the computational grid and the size of the input files (~10GB) for forcing, are related to the stability issues. Guidelines for model size, file size, use of shared files, etc. would be very useful to increase the applicability of the model for future projects.

User / beginner experience

Many other bugs or lacking functionalities caused an increased lead time and need for manual labor. Some examples:

- The dumping functionality conflicted with domain partitioning when the border between two domains crosses the dumping polygon. Manually adjusting these partitions is time consuming and did not provide a proper generic solution, due to the large variation of nourishment shapes and locations.
- In an earlier used FM version, the sediment transport through cross-sections was only stored for one partition domain.
- The nesting functionality in D-Waves cannot handle partial cut-outs from one of the wave grids. This issue was found after some non-realistic wave conditions were found on the offshore boundary of the inner grid, but these weren’t immediately discovered.