



Construction of the crane platforms with the post-storm dune profile at the back (22 April 2022). Photo courtesy of Joosten Group, who provided the geotubes that guaranteed the platform's stability.

2D EFFECTS ON DUNE EROSION AT MAASVLAKTE 2

Dune erosion due to storm surges and severe wave attack is the primary failure mechanism of sandy sea defences. At a curved coastline, dune erosion is greater than at a straight coastline. However, how much higher is often difficult to predict. This article presents a comparison of field observations and model results of the response of the Maasvlakte 2 curved sandy sea defence to storm attack.

The coastline response of the curved coastline of Maasvlakte 2 after the 2022 winter storms is reproduced using a 2D XBeach model. This model was initially set up to support a feasibility study into construction of a wind park at the perimeter of Maasvlakte 2, which is an extension of the Port of Rotterdam, in the Netherlands. At that stage it proved challenging to properly validate the model. Svašek continued to work on the model and was presented with an opportunity: in the period leading up to the construction of the wind park, the Dutch coast endured a heavy storm season in the winter of 2021-2022. Storm Corrie, Dudley, Eunice, and Franklin made landfall just after a regular maintenance survey and before a post-nourishment survey leading to well-observed dune erosion at Maasvlakte 2.

Simultaneously, a new release of XBeach with recommended model settings for 1D dune erosion was prepared to become the mandated tool for evaluating dune safety in the Netherlands (part of the BOI programme 2020-2023). This presented both opportunity and motive to validate the 2D XBeach Maasvlakte 2 model under extreme conditions to: 1) showcase the abilities of this new XBeach release in combination with the 1D BOI model settings at a curved coast; and 2) emphasise the importance of a 2D approach when dealing with strongly curved coasts such as the Maasvlakte 2.

Dune erosion mechanism at a curved coastline

A strongly curved coast behaves fundamentally different than a straight coast when it comes to storm erosion of dunes. On a straight coast, sand eroded from the dunes is deposited on the foreshore, limiting further wave attack and thus, dune erosion. The angle between the incoming waves and the coast varies alongshore on a curved coast. The angle is an important factor in the magnitude of the alongshore transport. Therefore, a gradient in the alongshore transport exists along curved coastlines.

Eroded sediment from the dunes is not deposited locally but transported alongshore

in the direction of the waves (Figure 2). As a result, the curved sea defence is exposed to undiminished wave attacks during the entire storm and erosion volumes can be twice as high as on a straight coast (Den Heijer, 2013). In theory, the location attacked by waves arriving perpendicular to the coastline will not generate longshore transport. In practice, as at the Maasvlakte 2, the effect of increased dune erosion is expected to occur over the entire curved part of the coastline, as the wave angles vary over the course of a storm.

At Maasvlakte 2, not only the curve in the coastline adds complexity to storm erosion processes. A transition between a hard and

sandy sea defence about 1.5 km north of the curved coastline further complicates the matter. For waves incoming from the north, strong southward longshore currents with a high transport capacity (but no sediment to move) arrive over the foreshore of the soft sea defence, leading to high pick up of sediment and consequent erosion at the sandy side of the transition. For waves incoming from the south, sediment eroded from the dunes moves further north, leading to a reduced build-up of the foreshore and additional erosion.

Triplet-storm attack of the Maasvlakte 2 sea defence

At the end of January 2022, storm Corrie swept over the Netherlands. Shortly thereafter

in February, the dunes were tested by a series of powerful and consecutive storms, named Dudley, Eunice and Franklin. This impressive and unique trio of storms resulted in an unprecedented phenomenon: six consecutive days of stormy weather along the coast, setting a record for the Netherlands.

Eunice was the heaviest storm of the three, with peaks up to Beaufort wind scale 11. All Dutch meteorological stations (except Maastricht) observed wind gusts exceeding 100 km/h and coastal areas registered gusts over 160 km/h. The extent and duration of the storm front was exceptional and it was the heaviest storm to hit the Netherlands since 1990. Public life came to a stop and five people lost their lives.

Large waves generated by the storms hit the coast from the north-west (Dudley), south-west (Eunice) and south-west to north-west (Franklin). Coastal defences did their job. Dykes endured the storm and dunes eroded to an extent, as designed, but held. Afterwards, impressive sights of steep cliffs could be observed at many coastal spots as a result of the battering waves.

The Maasvlakte sea defence has been in place since 2012 and the storms of January/February 2022 were among the heaviest in its existence. Waves in these storms reached significant wave heights of up to 6 metres (m), wave periods of over 15 seconds and water levels of up to 2.8 m+NAP. NAP stands for Normaal Amsterdams Peil or the normal water level in Amsterdam, which is slightly lower than sea level, and is used as a base to measure water levels in the Netherlands.

Measurements before and after the storm

PUMA, the project organisation for the extension Maasvlakte 2, was contracted by the Rotterdam Port Authority for designing, constructing and maintaining the Maasvlakte 2 between 2012 and 2022, which included yearly measurements through a combination of multibeam (below water) and laser altimetry (above water). The measurements took place every second quarter of the year to monitor the coastal defence and to direct nourishments where most needed. Before construction of the wind park, the maintenance responsibility of the Maasvlakte 2 sea defence was transferred from the Port Authorities to Rijkswaterstaat. It was the latter who commissioned an additional measurement

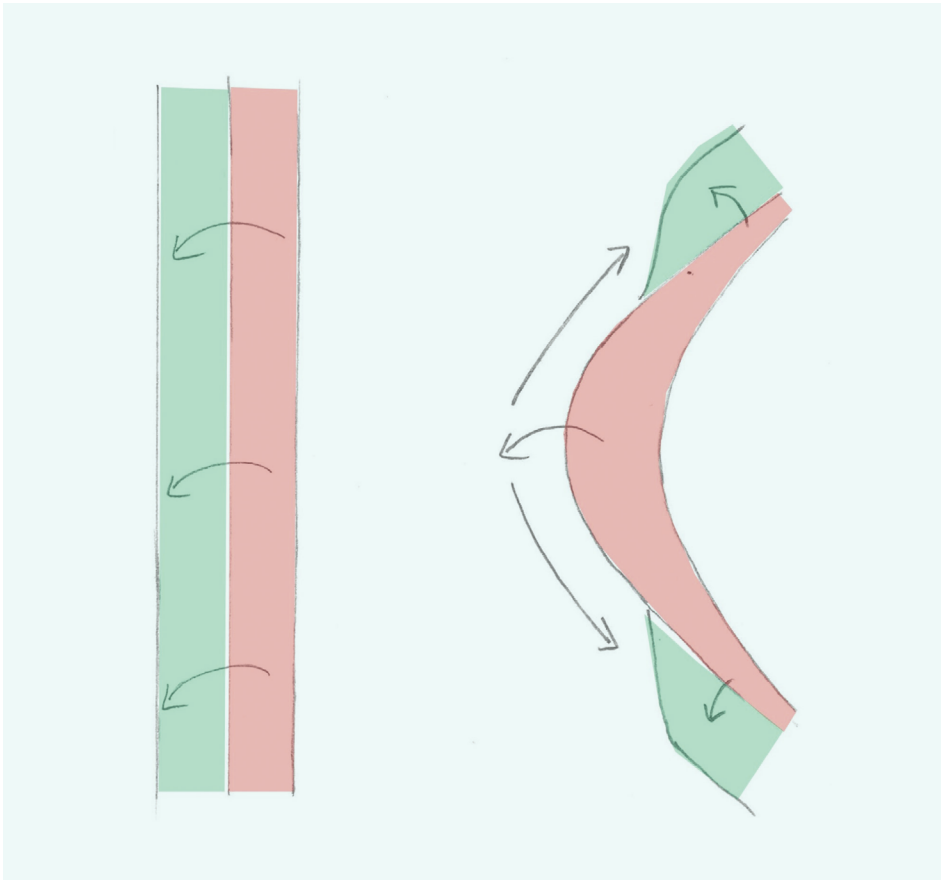


FIGURE 2

Schematised difference in dune erosion and foreshore deposition between straight (left) and curved (right) coasts under directionally varying wave attack.

in Q4 2021 in anticipation of the construction of the wind park by PUMA. This gives a good baseline of the sea defence before the storms.

Together with the survey of Q2 2022 after the completion of the nourishment, the impact of the heavy storm season on the dunes of the Maasvlakte 2 was quantifiable. Unfortunately, the storm-induced bed changes below 3 m+NAP could not be distinguished from the bed changes associated to construction of the platforms and the nourishment. Nonetheless, we processed the Q4 2021 and Q2 2022 measurements to investigate the change in bed level. A transect of this analysis is presented in Figure 4. In this figure, a heightened beach can be observed (see red patch), which is in part due to dune erosion and in part due to the nourishment. In addition, a clear erosion zone is visible at the dune front, which is the result of the storm season (blue patch in Figure 4).

The dune erosion along the complete Maasvlakte 2 is subsequently determined by analysing the volume in the erosion zone (blue patch) for the complete stretch of coastline. This is shown in the top panel of Figure 5. In this figure, we observe two areas with increased dune erosion: 1) at the bend where the material is not deposited on the foreshore and waves hit the dunes unobstructed

The storms of January/February 2022 were among the heaviest in the existence of Maasvlakte 2.



WIND PARK MAASVLAKTE 2

Rijkswaterstaat, responsible for the design, construction, management and maintenance of the Netherlands' primary infrastructure facilities, challenged itself to become climate-neutral before 2030. Wind Park Maasvlakte 2 played an important role in reaching this goal. The park includes wind turbines on the soft (sandy: 3.2-10 km, Figure 1) and the hard (rock and pebbles 0-3.2 km, Figure 1) sea defence of the Maasvlakte. These defences protect the 2 hectares of land reclamation against the North Sea. Rijkswaterstaat asked Svašek Hydraulics to conduct a study into the morphological feasibility of Wind Park Maasvlakte 2, especially concerning the sandy sea defence. In these studies, we investigated the influence of wind turbines on beach and foreshore morphology, and aeolian sediment transport to the dunes.

FIGURE 1

Overview of Maasvlakte 2 including the alongshore referencing.

NOURISHMENTS MAASVLAKTE 2 IN 2022

The Maasvlakte 2 sea defence is an eroding system by design, which needs regular maintenance. This maintenance has been performed every two years via beach and foreshore nourishments. Rijkswaterstaat had scheduled maintenance for 2022 in the summer. However, due to anticipation of the wind park construction, Rijkswaterstaat advanced the nourishment to March. This made it possible to reinforce the storm-eroded volume and simultaneously place sand for constructing the crane platforms. After completion of the nourishment but before platform construction, laser altimetry measurements were performed. The platforms were necessary for the cranes to lift the eleven turbines of the wind park in place. The platforms were made to be resistant to flooding and erosion. To this end, they were constructed to a height of around 3 m+NAP and were lined with geotextile bunds.



FIGURE 3
Wind Park Maasvlakte 2, as seen from the south. Photo© Svašek Hydraulics/Bernard Eikema.

(4.5–6 km); and 2) at the hard to soft transition (around 3.5 km) where the strong longshore transport without supply leads to large pick up and erosion of sediment, in turn leading to a low foreshore and heavy wave attack, and related dune erosion.

Further south (around 6 km), the dune erosion is reduced, even though this is still in the curved section of the Maasvlakte. This is likely

related to the fact that a significant part of the incoming waves arrive perpendicular to the coast at this location (bottom panel in Figure 5) generating less longshore transport, resulting in accumulation of sand on the foreshore, and thus leading to less dune erosion. In addition, the sediment from the highly erosive sections of the coast settles in adjacent sections, causing the heightened foreshore to reduce wave attack and limit

dune erosion. This contrasts with a straight and regular coast where dune erosion would be much more uniform. What is remarkable however, is the reduction of dune erosion right in the middle of the bend (at 5.1 km), but we can only speculate on the cause of this local reduction. It may be related to post-storm recovery (by aeolian processes) or dune reconstruction and nourishment, but we have not been able to verify this.

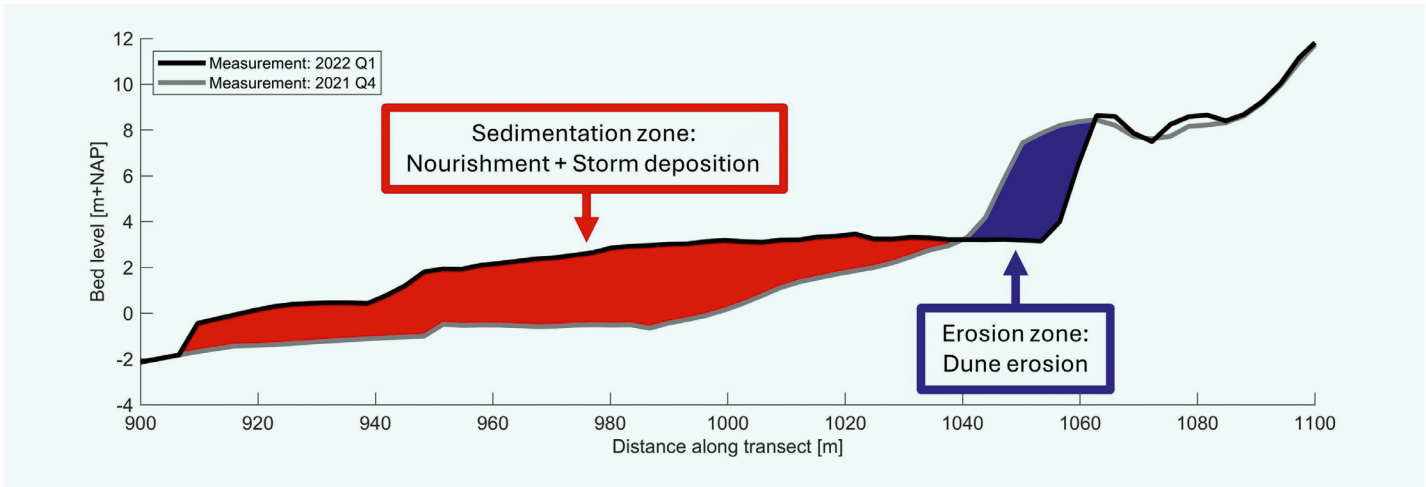


FIGURE 4
Overview of a representative transect at Maasvlakte 2 indicating the dune erosion and the sedimentation.

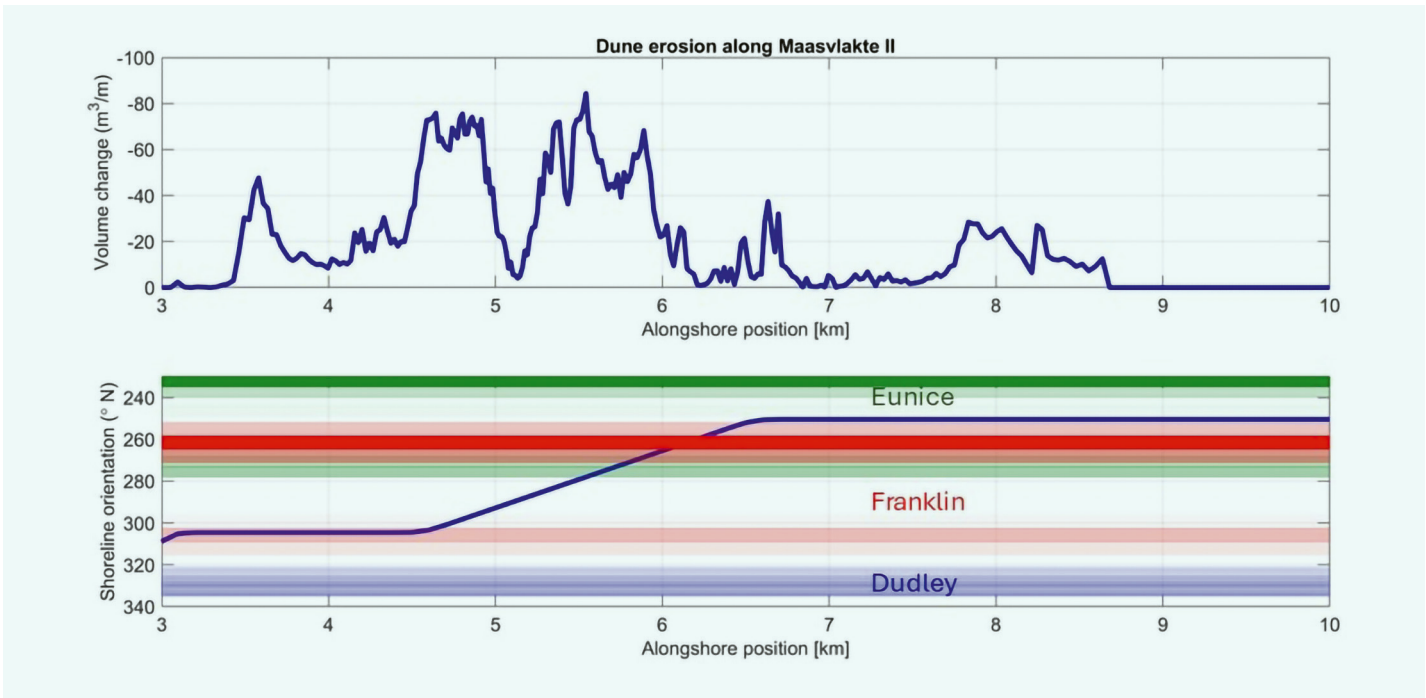


FIGURE 5
Top panel: Dune erosion volume along Maasvlakte 2. Bottom panel: Shoreline orientation of Maasvlakte 2 (blue line) in relation to the incoming wave angles (blue: Dudley, green: Eunice, red: Franklin).

The modelling software

To model the coastal response to storm conditions (i.e. dune erosion) and the complexity at play around the curved coastline of Maasvlakte 2, we chose to apply the two-dimensional XBeach modelling software, as it has been developed especially for modelling dune erosion. The XBeach software is applied in surfbeat mode to simulate the important hydrodynamic and morphodynamic processes in the swash zone that impact sandy coasts. The surfbeat mode resolves the short-wave variations on the wave group scale and the long waves associated with them in combination with a detailed approach to wave-driven sediment transport (Roelvink, 2009). This is the recommended mode since we focus on swash zone processes where long waves are the main driver of dune erosion.

Another reason to apply the XBeach software is that within the national programme BOI (Assessment and Design Instrument for flood

defenses), the new instrument for dune safety assessments is also based on the XBeach modelling software. This development includes a BOI XBeach release (Rijkswaterstaat, 2023) with thoroughly validated model settings for 1D dune erosion applications, tuned especially to the Dutch coastal system (Deltares and Arcadis, 2022). Therefore, the XBeach software is considered very suitable for this case study.

Svašek continued to develop the 2D XBeach model of Maasvlakte 2. When the winter storms in 2022 hit, and pre and poststorm surveys became available, we saw an opportunity to validate the model properly. As the BOI settings had only be validated on 1D cases up to this point.

Modelling approach

We used a curvilinear 2D XBeach computational grid. Applying a curvilinear grid for a curved stretch of coast is very

efficient because gridlines are parallel to the depth contours and grid refinement can be applied from the point of wave breaking until the dune region. This resulted in a grid with a resolution of 2.5 m in the cross-shore direction and a resolution of 25 m in alongshore direction (see Figure 6). These elongated grid cells are justified as the variation in hydrodynamic conditions is gradual in the alongshore direction, while in the cross-shore direction, the hydrodynamic conditions change rapidly. In the end, the computational grid consisted of 70,000 elements.

A crucial next step in the modelling approach is applying adequate wave-forcing conditions on the model boundary since the morphological development of the dunes at the Maasvlakte is primarily governed by wave forcing. The influence of the tidal flow and the river outflow from the Nieuwe Waterweg (new waterway) are found to be of minor importance, as the dune erosion mainly occurs in the upper part of the profile where wave action dominates.

We impose temporarily and spatially varying wave-forcing conditions on the model boundary. The spatial variability in wave-forcing conditions is found to be necessary, as the height and direction of the incoming waves along the model boundary can vary significantly due to the curvature of the coastline. Therefore, spatially and temporarily varying wave-forcing conditions are prescribed at five locations along the model boundary. These wave-forcing conditions are derived with a wave transformation matrix, which was set up during the construction of the Maasvlakte 2 to translate the measured wave conditions at the Europlatform to the -20 m+NAP depth contour along the perimeter of the Maasvlakte.

These wave-forcing conditions have been derived for the complete validation period which is the period between the two bathymetrical surveys. This is a period of 126 days, starting at the end of October 2021 and ending at the beginning of March 2022. However, running this 2D XBeach model for 126 days (or 170 million modelling timesteps) is rather computationally expensive, even though the model is run with parallel computing on our in-house advanced computer cluster.

Therefore, two acceleration techniques have been applied. The first is the application of a morphological acceleration factor

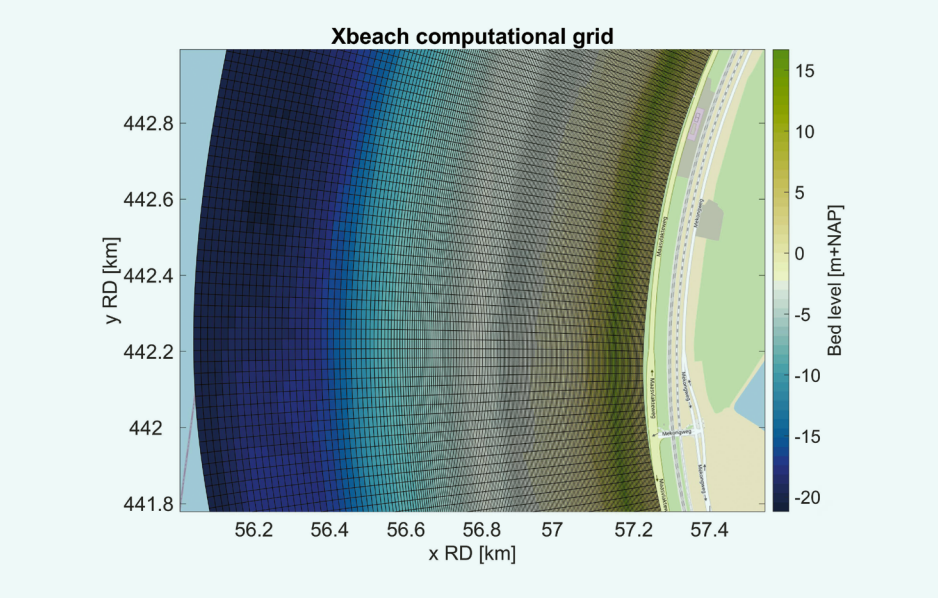


FIGURE 6

Illustration of the applied curvilinear 2D XBeach model grid for Maasvlakte 2.

(or MORFAC, Ranasinghe, 2011) and the second is a model forcing reduction technique (Luijendijk, 2019). The MORFAC technique allows for morphodynamic upscaling and enables the simulation of long-term morphological evolution. The concept is that the MORFAC speeds up the morphological time scale relative to the hydrodynamic timescale. In our modelling approach, a MORFAC of 12 is used. This implies that a simulation for a period of 2 hours with a MORFAC of 12 results in morphological evolution of one day. The assumption behind this concept is that the changes in hydrodynamics are magnitudes bigger than the changes in morphology.

In addition, the model forcing reduction technique allows for a significant decrease in required simulation time by reducing the number of input wave conditions applied and simulated in the XBeach model. This is achievable because this case study focuses solely on dune erosion, necessitating only the forcing conditions leading to such erosion. Since these are only the energetic wave conditions (wave height above 2 m) that attack the dunes during high water conditions (water level above -0.5 m+MSL), a reduction of the applied wave (and water level) time series of 88% is achieved. The combination of these two acceleration techniques allows for very efficient morphological modelling of the dune erosion at Maasvlakte 2, resulting in a simulation

time of only 14 hours to model a period of 126 days.

To investigate the importance of using a two-dimensional approach to predict dune erosion at a curved coastline, we compared

the results of the 2D model with a series of 1D computations. To obtain the erosion volumes for the 1D XBeach simulations, a total of 117 simulations were conducted for 100 m spaced perpendicular transects along Maasvlakte 2. The model settings and boundary conditions for the 1D approach are similar to that of the 2D model. For a fair comparison between the 1D and 2D approach, a surcharge is applied to the 1D results to compensate for the absence of 2D effects. This surcharge depends on the offshore wave height, the erosion volume, the grain size and the coastal curvature.

Modelling results

The validation of the XBeach model involved applying the model to replicate the observed dune erosion at Maasvlakte 2 during the winter storms. To assess the performance of this XBeach model in combination with the 1D BOI model settings and to explore the necessity of employing a 2D modelling approach, we compared the measured dune erosion volumes with the results obtained from both 1D and 2D XBeach simulations. The resulting dune erosion volumes for these simulations are presented in Figure 9.

This figure indicates that the 2D XBeach model is most capable of reproducing the

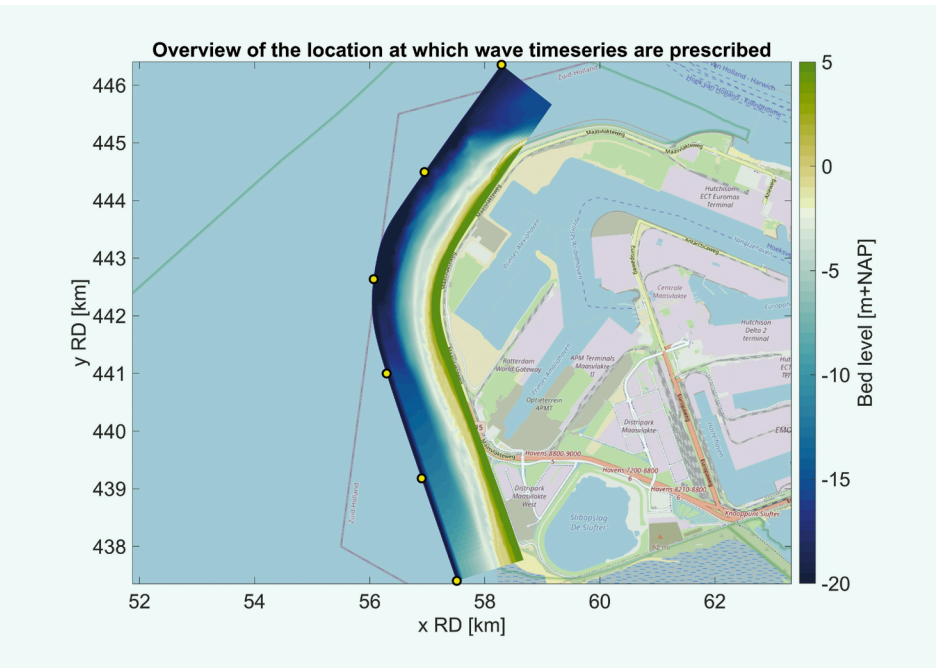


FIGURE 7

Overview of the model bathymetry and the location at which the spatially varying wave-forcing boundary conditions are applied to the XBeach model.

dune erosion volumes accurately, while significant differences in the amount of dune erosion are observable between the 1D and 2D model results. This is especially noticeable in the strongly curved coastal section of Maasvlakte 2 between km 4.5–6.5, where the 1D modelling approach underestimates the amount of dune erosion. The results at straight coastal sections (km 3.5–4.5 and km 7.0–10.0) are more similar between the 1D and 2D approaches. Although the applied surcharge for curved coastlines does increase the predicted dune erosion, it is insufficient to compensate for the high differences between the 1D and 2D predicted erosion at the curved part of the coastline (km 4.5–6.5).

The validation results also show that the 2D XBeach model accurately captures the transition between the highly erosive curved coastal sections and the less erosive sections (km 4.0–4.5 and km 5.5–6.0), indicating that the gradients in the alongshore transport due to variations in incident wave angles are accurately reproduced. The most significant deviation between the measurements and the model results is seen at the remarkable reduction in dune erosion right in the middle of the bend (at km 5.1). However, this reduction is likely to be related to post-storm reconstruction, placement of the nourishment, aeolian dune recovery or displacement of the nourishment.

The difference in performance for the 1D and the 2D model on straight and curved sections is confirmed even more strongly by looking at several relevant transects along the perimeter of the Maasvlakte 2 (Figure 10). The dune erosion predicted by the 1D and 2D model is similar for the transects a) and b) at the straight coastal section. However, the 1D model significantly underestimates the dune erosion at the curved section of Maasvlakte 2 (transect c). When looking at the bed level below 3 m+NAP, significant differences between predicted and modelled bed levels can be observed due to the placement of the nourishment. The accuracy of the model in predicting sedimentation volumes can thus not be assessed directly with these results.

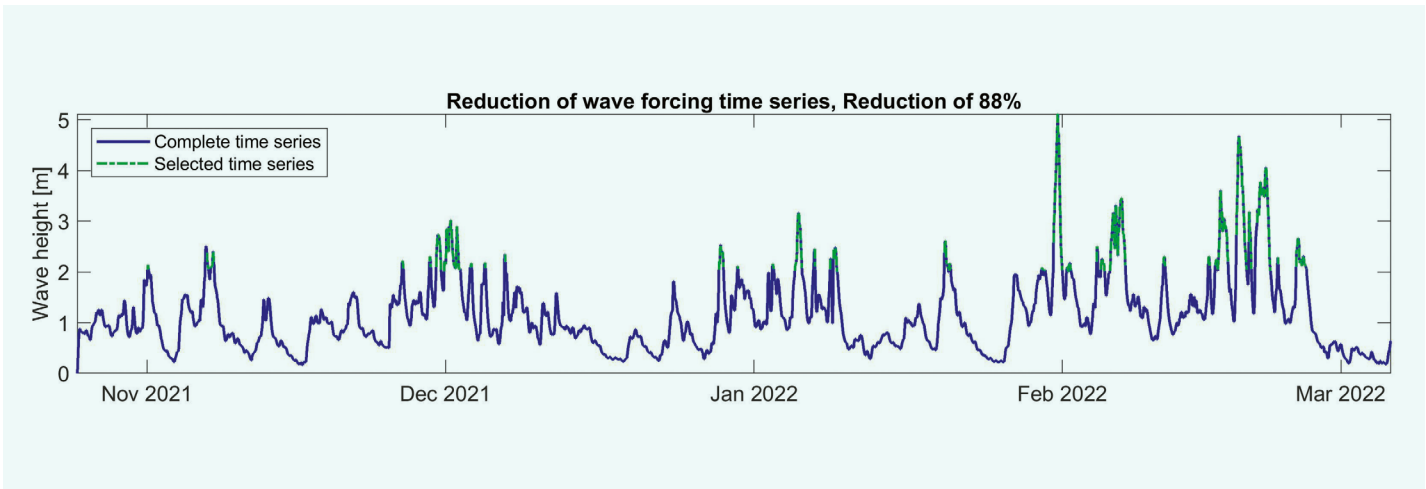


FIGURE 8
Overview of wave time series between the end of November 2021 and the beginning of March 2022 (blue line), together with the reduced wave time series applied in the model (green line).

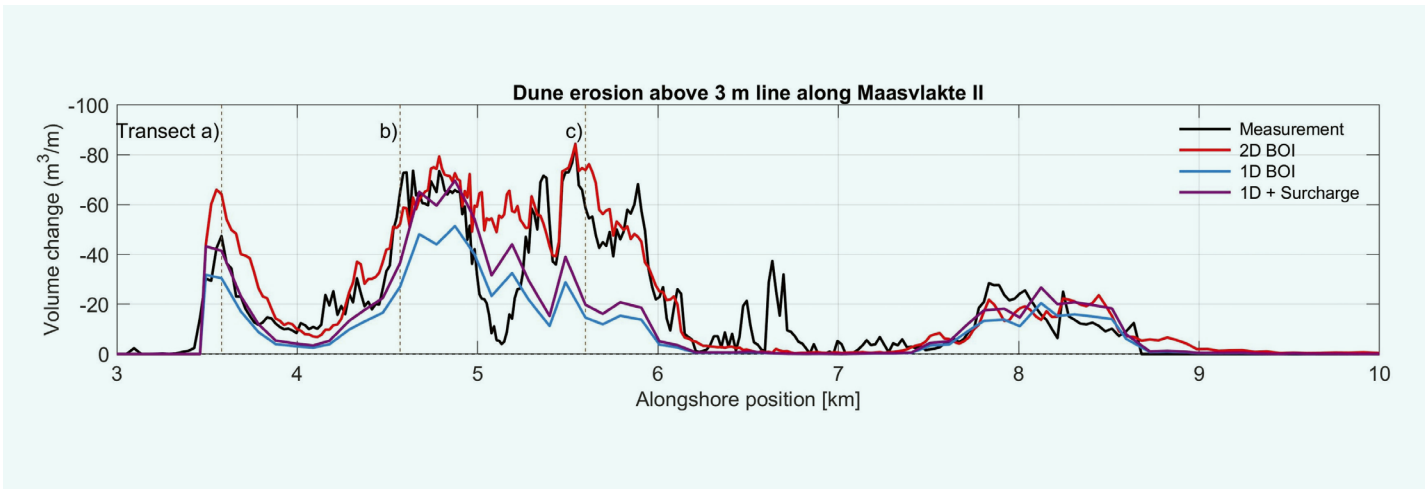


FIGURE 9
Overview of the XBeach model validation showing the measured and modelled dune erosion volumes above the 3 m line.

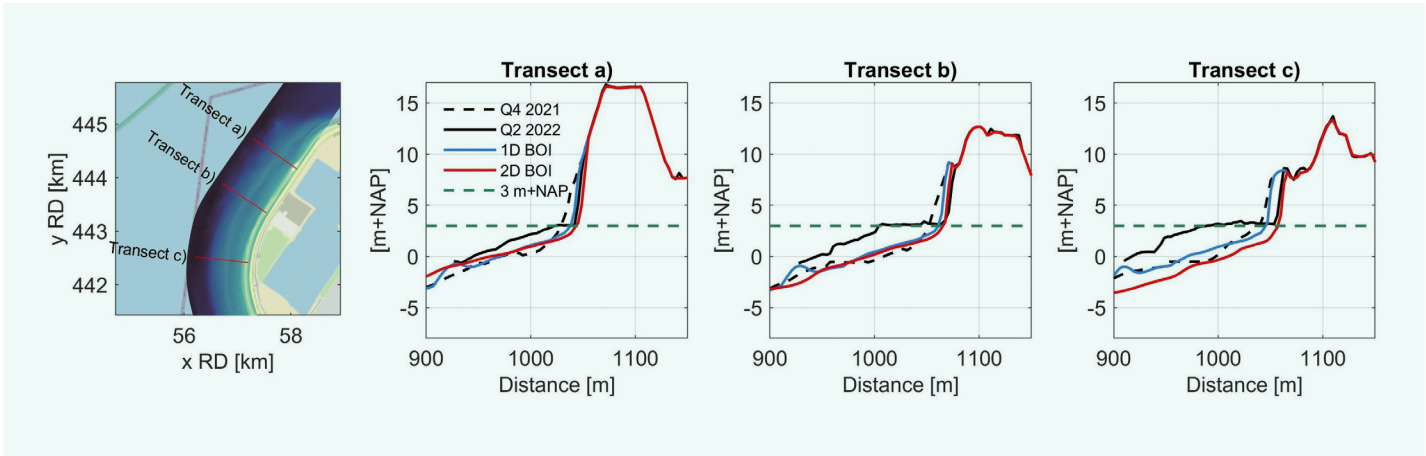


FIGURE 10
Overview of the XBeach model validation showing dune erosion for various transects along Maasvlakte 2. Note that the bed level below 3 m+NAP is heightened by both storm deposition and construction works).

Nonetheless, dune erosion volumes would not be predicted accurately when the pattern of sediment deposition and alongshore transport is not accurate. Moreover, for safety assessments, accurate prediction of erosion volumes is of primary interest.

Based on these validation results, it is concluded that 2D XBeach modelling is required to accurately capture dune erosion at strongly curved coastlines. Furthermore, the validation shows that the 1D BOI settings can accurately model dune erosion at Maasvlakte 2 when applied in a 2D XBeach model.

Discussion

The validation of a two-dimensional XBeach model (BOI2023 version) with 1D BOI model settings to model a curved coastline is a successful first step. However, there are still sufficient challenges before XBeach 2D can be considered a valid model for generic curved coastlines. The profile shape of the Maasvlakte is rather simple, with a steep foreshore and a single dune row. This profile resembles those at the Dutch coast and is close to many cases used to calibrate the model settings. The effects of the tidal current are limited to the deeper foreshore and there are no shoals that induce additional gradients in alongshore transport, as would be the case at the curved coastlines at the heads of the Wadden Islands, which are sheltered by an ebb delta.

Regarding future safety assessment with 2D XBeach models, our results imply that it

will be important to model storms with a non-stationary wave direction and multiple storms with varying peak direction, since a stationary wave angle would significantly underestimate the dune erosion at the point of perpendicular wave incidence.

Conclusion

The dune erosion measurements following the 2022 winter storms at Maasvlakte 2 have been used to validate a 2D XBeach model. This validation event, which is the first proper validation possibility for a dune erosion event at the curved Maasvlakte 2, is successfully utilised to gain insight into the performance of the 1D BOI model settings and the necessity of a 2D modelling approach at a curved coastline.

The XBeach simulations, which have been carried out following both a 1D and 2D modelling approach, revealed that the 2D model with 1D BOI model settings was most capable of reproducing the dune erosion volumes accurately, while a significant underestimation of dune erosion is observable in the 1D model. This underestimation in the 1D model occurred at the strongly curved coastal section of Maasvlakte 2 and could not be compensated for by the prescribed surcharge for 1D modelling approaches at curved coastlines. The underestimation in the 1D modelling approach is likely related to the absence or underestimation of alongshore sediment distribution processes at strongly curved coastlines. This process prevents localised build-up of eroded sediment on the foreshore as it is redistributed alongshore,

leaving the dune vulnerable to undiminished wave attacks throughout the entire storm duration. Therefore, a 2D modelling approach appears to be required for strong curved coasts such as Maasvlakte 2 and is highly advised in similar situations (in the Netherlands).

Results from this study highlight the importance of applying a 2D process-based model such as XBeach on strongly curved coastlines to assess the safety of the dunes under storm conditions. Moreover, the study results suggest that it is important to include non-stationary wave direction when modelling the normative storm conditions to prevent underestimation of the dune erosion. This prompts us to reconsider the schematisation of the normative storm for strongly curved coastal systems, encouraging further research and discussion.

A 2D modelling approach appears to be required for strong curved coasts such as Maasvlakte 2.

Summary

Dune erosion caused by storm surges and severe wave attack is the primary failure mechanism of sandy sea defences. At a strongly curved coast, such as that of Maasvakte 2 (Port of Rotterdam, the Netherlands), dune erosion can be twice as high as at a straight coast.

Following the winter storms of 2022, measurements of dune erosion at Maasvlakte 2 offered a unique opportunity to analyse erosion patterns along this curved coastline. Moreover, it allowed for the validation of dune erosion predictions with a 2D XBeach model, and an investigation into the importance of using a two-dimensional modelling approach to predict dune erosion.

To this end, XBeach simulations have been conducted with both a 1D and 2D modelling approach. Both models use the same model settings, derived for safety assessment at the straight Dutch coast with the 1D model (BOI settings). The study demonstrates that the 2D model was most capable of reproducing the dune erosion volumes accurately, while a significant underestimation of dune erosion is observed in the 1D model. The underestimation of the 1D modelling approach is likely related to the absence of alongshore sediment distribution processes at strongly curved coastlines. This process prevents localised build-up of eroded sediment on the foreshore as it is redistributed alongshore, leaving the dune vulnerable to undiminished wave attack throughout the entire storm duration.

The findings of this study highlight the necessity of utilising a 2D process-based model like XBeach 2D for evaluating dune erosion during storms on highly curved coastlines such as Maasvlakte 2. These results indicate that the 1D BOI settings are also applicable for 2D applications of curved coastlines. Therefore, this approach is strongly recommended for similar scenarios (in the Netherlands) to ensure an accurate assessment of dune safety.



Ype Attema

Ype is the lead expert in morphodynamics at Svašek Hydraulics. He graduated from the Technical University of Delft and started working at Svašek Hydraulics in 2015. Since then, he has been involved in various consultancy and research projects related to morphology. His primary focus within these projects is the modelling of hydrodynamics (flow, waves), morphology and the interplay between these phenomena. Typical projects include channel siltation studies, design and morphological impact studies in the coastal zone, and nature restoration studies in the Eastern and Western Scheldt. In addition, Ype is co-developer of FINEL, a software package developed within Svašek Hydraulics to model hydrodynamic flow and sediment transport.



Anna Kroon

Anna is an experienced consultant in performing hydraulic studies, morphological research, land reclamation projects, cable route studies and port design. Typical projects she's worked on are the port extension of the Port of Rotterdam, Maasvlakte 2, and the reinforcement of the Hondsbossche and Pettemer sea defence. At Maasvlakte 2, Anna was responsible for the derivation of hydraulic boundary conditions, workability and morphological predictions. Within the tender for the reinforcement of Hondsbossche and Pettemer sea defence she was responsible for the design of the maintenance buffer. In June 2024, Anna will defend her PhD research on the propagation of uncertainties in predictions of large-scale sandy interventions in the coastal zone.



Bas van Leeuwen

Bas is senior consultant and deputy director at Svašek Hydraulics. He has worked at Svašek since 2008, after gaining a Master's in Civil Engineering and Management (with honours) at Twente University in the Netherlands. During his career, Bas has focused on a broad range of topics including modelling coastal processes, such as waves, tidal flow and morphology in the Western Scheldt Estuary, along the Dutch beach fronts and worldwide. Typical projects include estimating morphological effects of wind turbines on Maasvlakte 2, setting up new discharge relations for the Dutch Rhine branches and reference design of the Princess Elisabeth Island.

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