REDUCING INUNDATION RISK AT BARRIER ISLANDS UNDER A RISING SEA LEVEL

Anna Kroon[1], Ype Attema[1], Lennard Spaans[1], Tom Pak[1], Bas van Leeuwen[1], Kevin van der Giessen[2], and Dano Roelvink[3]

At the Dutch Barrier Island Schiermonnikoog, the inundation risk is higher than allowed according to Dutch standards. The drafting of reinforcement plans, which aim to enhance both the present safety level and the long-term resilience of the island, started in 2022. As part of these plans, the (partial) removal of the first dune row (by creating blowouts) is under consideration in combination with a simultaneous reinforcement of the most landward dune arc with the removed sediments. The feasibility of constructing active blowouts is investigated considering the ambient morphological trends. This analysis leads to the conclusion that blowouts are most viable in the Stuifdijk, the most eastern and seaward dune row. A two-dimensional XBeach model setup is used to investigate the inundation risks of the island when constructing multiple blowouts and using the excavated sediments to reinforce the most landward dune arc (the Kooiduinen). The computations show that the system is significantly strengthened by relocating the sand from the Stuifdijk to the most landward dune arc. In this way, the short-term inundation risk is reduced without using external materials, while simultaneous construction of blowouts possibly increases the islands' resilience regarding sea level rise on the long-term. As such, these results show that (partial) removal of the first dune row by constructing blowouts can be effective at more vulnerable coastal sections if the right precautions against inundation are included in the plans.

Keywords: barrier island;dune reinforcement; blowout; XBeach 2D

INTRODUCTION

Barrier Island Flood Resilience

Developed barrier islands are more likely to drown due to anthropogenic activities that reduce overwash delivery and the landward extent of overwash (Rogers et al., 2015). An example of such activities is the sand-drift dike development that has been common practice in the last decades on the Dutch barrier islands. As a result, sediment mobility and overwash delivery are significantly reduced (Oost et. al, 2012). This leads to accelerated succession of vegetation in the salt-marsh on the back-barrier side of the island, which in turn prevents the supply of fines from the back-barrier basin and consequent relative deepening of the barrier island (Bakker et al., 2023).

Coastal management

While sediment at the beach is usually calcium-rich, the calcium content of inland dunes reduces over time. This calcareous sand from the beach offers several benefits for dune ecosystems. It contributes to higher soil pH levels, which can influence vegetation succession and nutrient availability in dune environments (Grootjans et al., 2013) and supports a rich flora, including lime-loving plants that are otherwise rare in certain regions.

Awareness of coastal managers towards the ecological benefits of increasing sediment mobility in foredunes is growing rapidly (Arens et al., 2013), and (partial) removal of these sand-drift dikes is under consideration at multiple locations (de Groot et al., 2016). Mainly in the form of notching of the most seaward dune row to create blowouts that can bring large amounts of sediments over a distance in the order of 100 m landward (Ruessink, 2018) and suspended sediments over distances in the order of 1000 m (Van Hateren, 2020).

So far, removal locations are constrained to wide dune systems with low inundation risks for the polders lying behind them. However, reversing the adverse effects of sand-drift dike construction might increase a barrier island's resilience in the long term as a natural barrier island is more likely to keep up with sea level rise (Rogers et al., 2015).

Schiermonnikoog

The inundation risk at the Dutch Barrier Island Schiermonnikoog is higher than allowed according to Dutch standards (the island is marked red in Fig. 1b and schematically drafted in Fig. 1a). The drafting of reinforcement plans that aim at both enhancing the present safety level and the long-term resilience of the island, started in 2022. As part of these plans, the (partial) removal of the sand-drift dike (named the Stuifdijk) is being considered, combined with the simultaneous reinforcement of the most landward dune arc (named the Kooiduinen) using the sediments made available from the sand-drift dike. To this end, this paper investigates the feasibility of creating more dune dynamics at the seaward dune row while reducing the short-term inundation risk by placing the sediments that are made available at the landward dune arc.

---

[1] Svašek Hydraulics, kroon@svasek.com.
[2] Wetterskip Fryslân
[3] IHE Delft, Deltares.

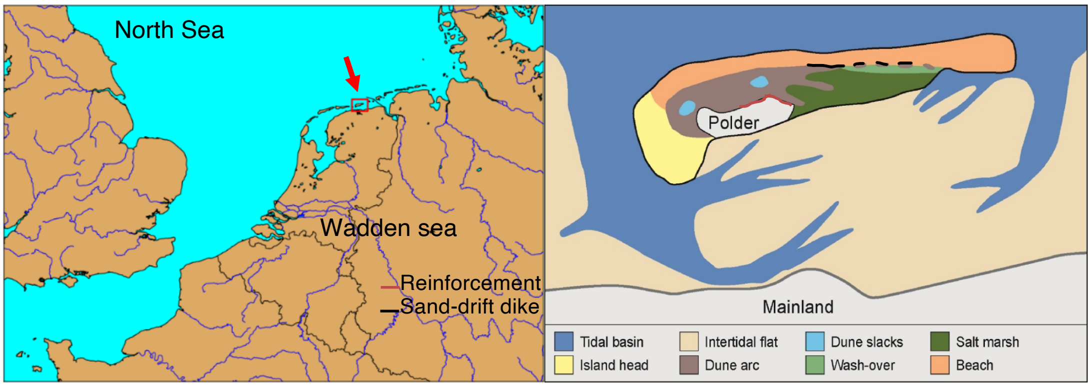

Figure 1 – Location of the Dutch Barrier Island Schiermonnikoog (a) and biogeomorphological units (adapted from Bakker, 2023) and position of sand-drift dike at Schiermonnikoog (b).

METHODS

The feasibility of increasing dune dynamics relies heavily on the background trends in morphology. Therefore, this paper presents a two-step approach. The first step consists of a data analysis of the island's morphological trends to investigate whether partial removal of the sand-drift dike could lead to increased deposition of calcareous sediments in the hinter-lying area. The next step is to show that the safety level in the short term can be increased by placing the sediments retrieved from the sand-drift dike. This is done with a modelling approach using a 2D XBeach model (Roelvink, 2009).

Kooiduinen Schiermonnikoog case study

The relatively low-lying polder of the Wadden Sea island of Schiermonnikoog is protected against high water levels by a primary flood defence consisting of a 9-kilometre dune system located along its northern, eastern, and western sides. On the Wadden Sea side (south), the polder is protected by a sea-dike. In the 1960s, the dune system on the island's northeast side was artificially extended by the construction of a sand-drift dike; the Stuifdijk. This intervention aimed to capture sediments actively and create a more sheltered environment for the salt-marsh.

An assessment of the island's flood defences revealed that parts of the dune system do not comply with national safety standards, as illustrated in figure 2 (Wetterskip Fryslân, 2023). With sea level rise, normative conditions will lead to breaching of the Stuifdijk and waves from the North Sea will be able to reach the inland-located dune row called the Kooiduinen. As a result, this dune row does not meet the safety standards and needs reinforcement. This paper only focuses on this specific part of the dune reinforcement.

In the coming years, efforts will focus on designing and implementing the necessary measures to ensure that the primary flood defence complies with legal safety requirements. The design process incorporates several objectives, such as utilizing locally sourced materials and creating a flood-resilient landscape that contributes holistically to high-water safety.

Aligned with this vision, resilience-enhancing components such as blowouts and washovers have been identified within the context of an integrated, environment-focused project approach. These components offer opportunities to achieve the outlined goals. Firstly, sand excavated during the creation of one or multiple blowouts (e.g., in the Stuifdijk) can be used to reinforce other areas (e.g., the Kooiduinen). Secondly, both forms of dynamic interventions can enhance ecological values and promote a landscape that can adapt more naturally to rising sea levels.

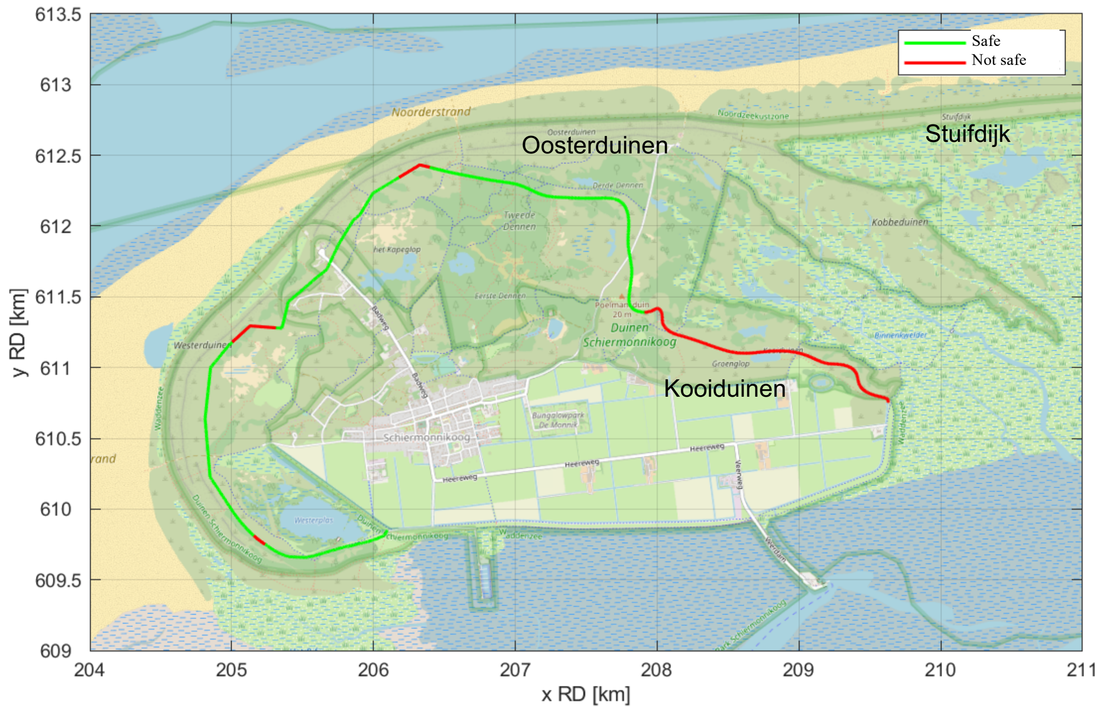

Figure 2: Formal sea defence location and indication whether the defence meets the safety standards (green) or not (red).

Background morphological trends

Natural dynamic blowouts are most common on retreating coastlines as the cycle of erosion and recovery prevents embryonic dune growth and guarantees the supply of aeolian transport through the blowout. Which in turn prevents the establishment of vegetation in the blowout and guarantees the transport of sediment inland. Therefore man-made blowout construction is considered most feasible for landward-moving shores. To this end, the island's morphological trends over the last decades are investigated.

The developments on the island are analyzed using the JARKUS Analysis Toolbox (Van IJzendoorn, 2021). The Jarkus consists of bathymetry data of cross-shore transects with a spacing of approximately 200 m measured yearly since 1965.

The dune volume and beach width are derived from these measurements. The dune volume is defined as the volume landward of the intersection of the profile with the 3 m+NAP[4] contour and a landward boundary. This landward boundary is chosen such that beyond this limit, dune dynamics are negligible (bed level variance < 0.1 m). Beach width is defined as the distance between the 0 m+NAP and 3 m+NAP positions. For the analysis, the study area was divided into four sections: (1) the island head, between reference profile (rsp) 2 and 4, (2) the Oosterduinen, between rsp 4 and 7, and (3) the Stuifdijk; between rsp 7 and 10.

[4] Nieuw Amsterdams Peil (NAP) is the Dutch reference level which is roughly equal to mean sea level.

Figure 3: JARKUS coordinate system and sections of analysis. Island head (blue), Oosterduinen (orange) and the Stuifdijk (Yellow).

Two-dimensional XBeach model

A two-dimensional XBeach model is set up to investigate the inundation risk of Schiermonnikoog after (partial) removal of the sand-drift dike. The dune erosion is modelled for a storm with an exceedance frequency of once in 1,200 years, with 66 cm of sea level rise assumed for the year 2078. The model settings are based on both scale tests and field observations of overwash and dune erosion (Coumou et al., 2022). The most important XBeach model settings that were used based on this calibration are presented in Table 1. The median grain size diameter (D50) is set to 164 µm. As a conservative assumption the island is assumed to be free of vegetation.

Table 1: Overview of XBeach model settings

Model parameter	Description	Value
morfac	Morphological acceleration factor	4
CFL	Value of Courant-Friedrichs-Lewy numerical stability criterion	0.95
alfaD50	Coefficient of grain size sensitivity in sediment transport	0.4
wetslp	Critical avalanching slope under water	0.15
facAs	Coefficient contribution wave asymmetry to sediment transport	0.20
facUa	Coefficient for wave skewness and asymmetry	0.15

The boundary conditions for a 1/1,200 year storm event in 2078 are prescribed by the Dutch safety standards (Deltares, 2017). Storm conditions are schematized by a parabolic surge level, a storm duration of 44 hours and conditions at the peak of the storm as shown in Table 2.

Table 2: Boundary conditions for wind, waves and water levels at the peak of a 1/1,200 year storm event in 2078.

Peak storm condition	Value
SLR scenario	50yrs (66cm)
Frequency [1/y]	1/1,200
Direction [°N]	330
Hs [m]	11.2
Tp [s]	19.7
Water Level [m+NAP]	5.01
Wind Speed [m/s]	33

The boundary conditions during the 44-hour storm period are presented in Figure 4. The peak value of the wave conditions is reached after 22 hours. The phase shift between high astronomical tide and the peak of the storm is 3.5 hours. Under storm conditions with a northwest direction, a water level gradient between the North Sea and the Wadden Sea is expected and confirmed by measurement data; this gradient is assumed to be 40 cm under normative conditions.

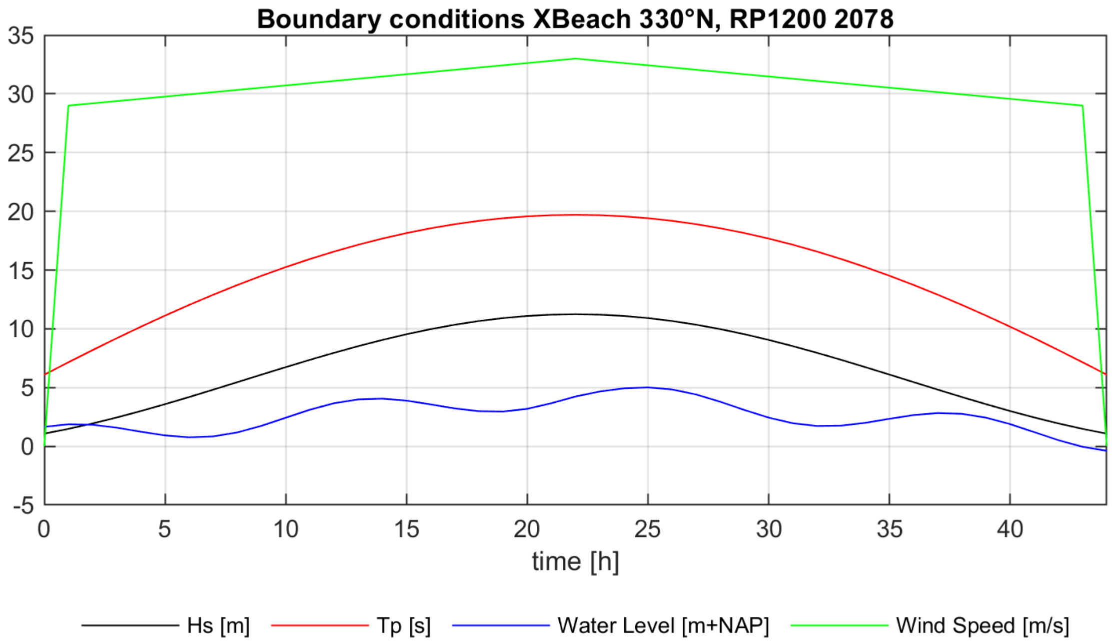

Figure 4: Boundary conditions for wind, waves and water levels during a 1/1,200 year event in 2078.

The computational grid of the two-dimensional XBeach model is shown in Figure 5. The model's horizontal resolution in the area of interest is 4 m. Further offshore, the resolution is based on the local water depth. The bathymetry of the model is based on of measured data from AHN4 (Algemene Hoogte Kaart Nederland, 2023), supplemented by Vaklodingen (Rijkswaterstaat, 2023) up to a depth of NAP-13m, corresponding to a wave celerity ratio of 0.95. From there, the profile is extended to NAP-30m with a 1:50 slope. This is necessary, as the seaward boundary of the model must have a wave celerity ratio ($n=c_g/c$) not larger than 0.90 (Coumou et al., 2022), which is reached at NAP-30m for the conditions specified in Table 2. The bed level in the area of interest is shown in Figure 6.

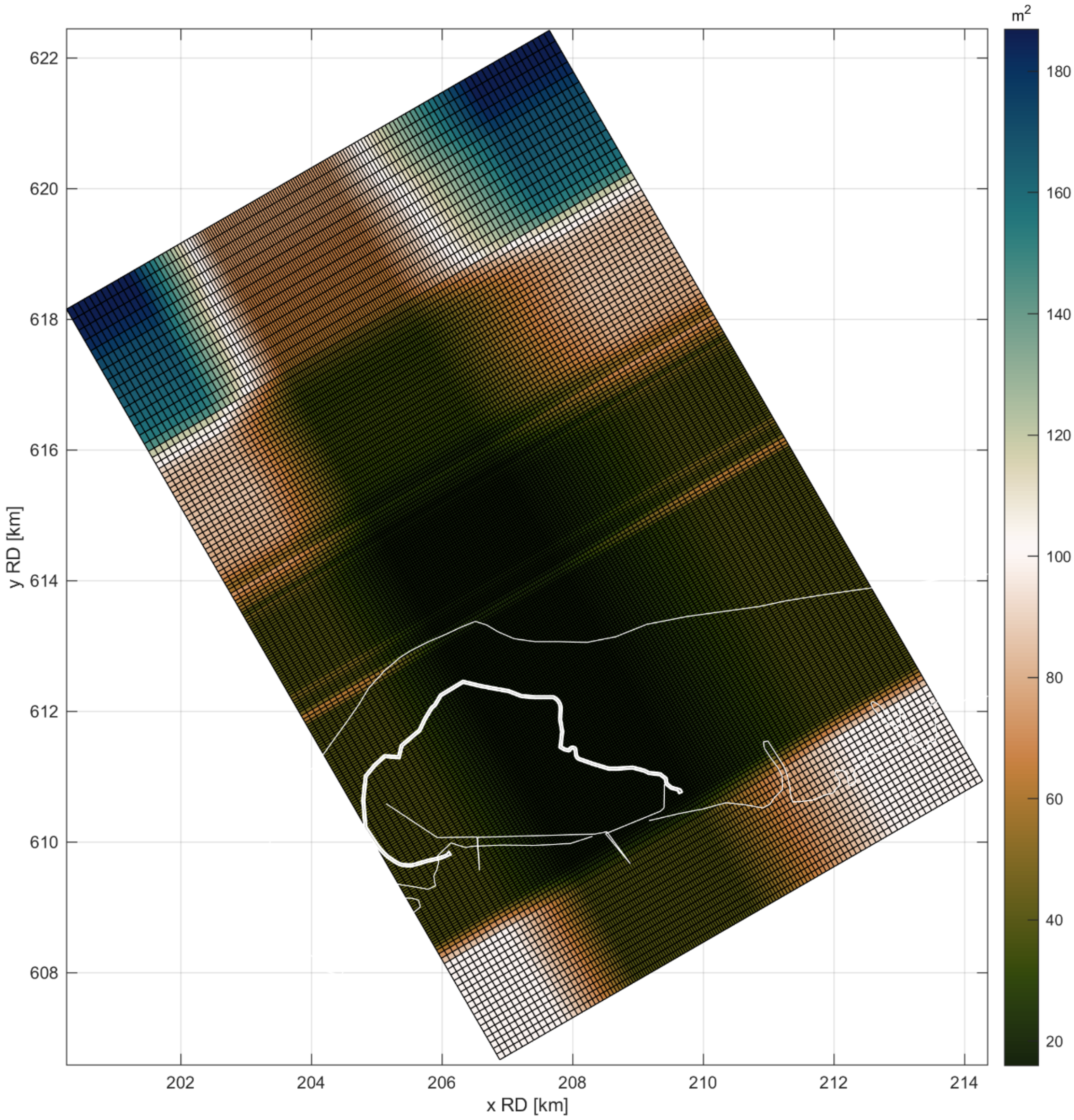

Figure 5 – Computational grid of the two-dimensional XBeach model. Every 10th grid cell is shown for readability. i.e. the actual grid has ten time more resolution in both directions. The colors indicate the area of each actual grid cell.

To investigate the effect of partial removal of the sand-drift dike for water safety, a relatively extreme scenario is considered for this study in which five blowouts are constructed in the Stuifdijk. The blowouts have a width of 50m and are gently sloping up. The bed level differences of the Stuifdijk with and without blowouts is shown in Fig 6b. A total volume of sand of 150.000 m3 becomes available. This sand is placed on top and in front of the most landward dune arc, in the Kooiduinen.

Note that plans for the reinforcement of the dunes are still being drafted, and the number, location, and dimensions of any sand removal measures have not yet been determined. The planned approach involves initiating with small-scale measures, closely monitoring their outcomes, and expanding the scope (only) as feasibility and success are demonstrated. The considered geometry in this study is purely used as a proof of concept.

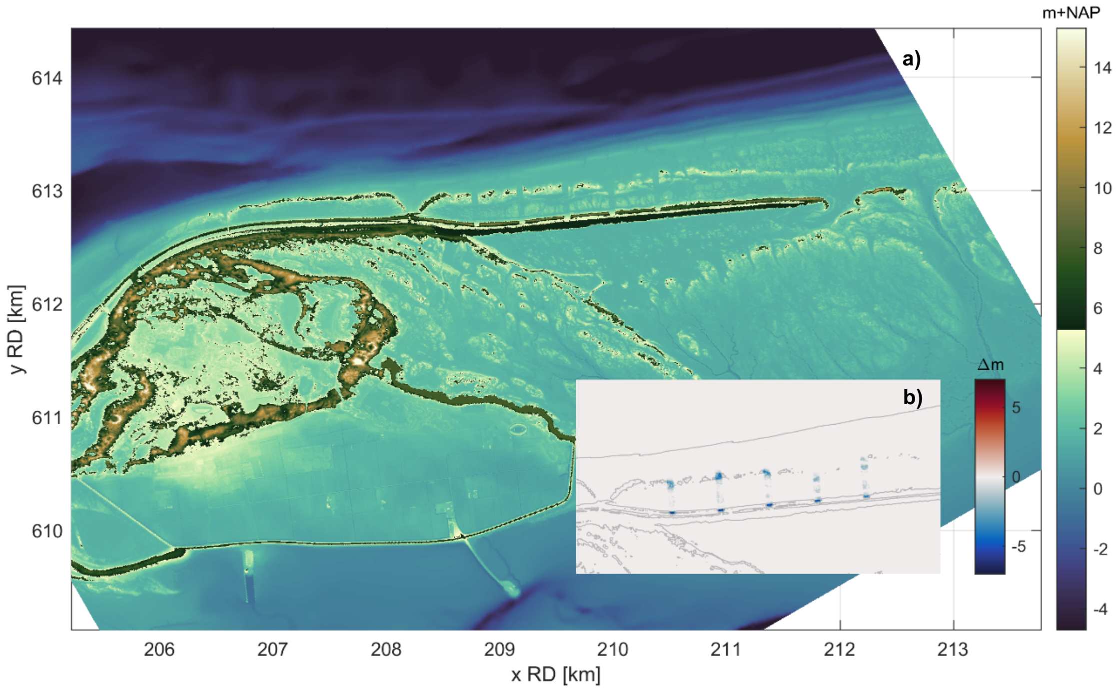

Figure 6 – Bed level in area of interest (a) and the difference in bed level with and without blowouts in the sand-drift dike (b).

RESULTS

Background morphological trends of the island

The morphological development of Schiermonnikoog is primarily driven by the periodic arrival and distribution of large sand volumes from the outer delta. The most recent sandbank attachment from the outer delta in 1997 was especially large in response to the closure of part of the back-barrier basin in 1969 (Elias & Oost, 2021). As a result, the beach width increased significantly in the decade leading up to that event (Fig. 7a).

The average beach width along the island reached its maximum around the year 2000 (black line Fig. 7a) and has been steadily decreasing since. Especially at the Oosterduinen and Stuifdijk, the beach width is getting into a range that allows for marine influence in the dunes. At the island’s head the beach width reached its maximum approximately five years later when the sandbank and the island had fully merged. Although since that time, the beach width is also decreasing at the island's head the absolute width is still very large. The next sandbank attachment from the outer delta is already approaching, expected to increase the beach width for both the island's head and the Oosterduinen.

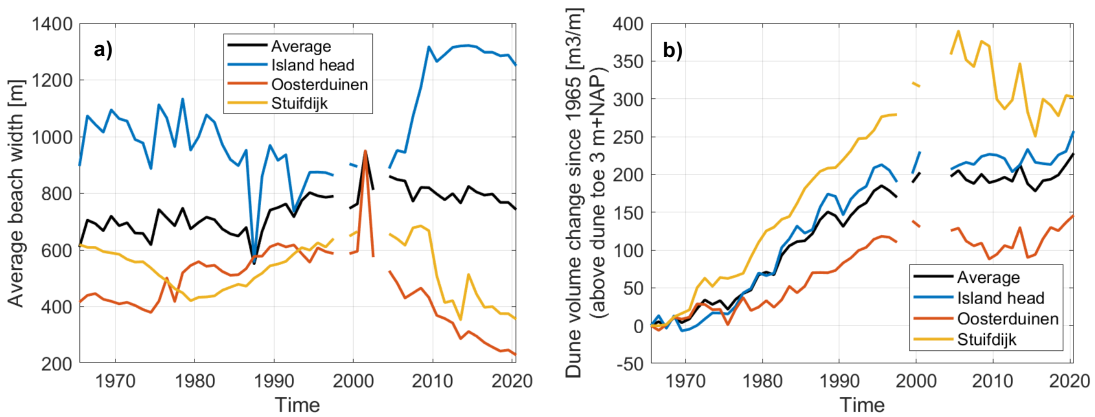

Figure 7 – Average beach width (a) and Dune volume change since 1965 (b) at different sections of Schiermonnikoog.

As a result of the wide beach, marine influence on the upper beach and dunes is minimal. This limited marine influence led to the formation of a "green beach" around the year 2000 (Fig. 8). Vegetation on the green beach traps sediment and prevents aeolian transport to the adjacent foredunes. Particularly at the island's head (in the west), the beach remains so wide that dune dynamics have reduced significantly. This leads to a significant change in dune volume trend, which was linearly increasing before 2000 and remains approximately constant after (Fig. 7b).

Figure 8 – Satellite image of Schiermonnikoog in 1998 without a green beach (a) and in 2002 with a green beach (b).

Opportunities to increase dynamics on Schiermonnikoog seem most promising in the Stuifdijk area. For the Stuifdijk, an erosive trend is evident in both volume and beach width, and the arrival of a new sandbank from the outer delta will be the least influential in this area (on the short term). Moreover, portions of the embryonic dunes and the green beach, which have trapped sand and suppressed aeolian transport since 2000, have been partially eroded recently. A larger portion of the green beach and embryonic dunes may naturally erode in the coming years, creating opportunities for increased dynamics in the Stuifdijk. Other sections are less promising due to the upcoming sandbank landing, which could lead to wide beaches for which aeolian transport is trapped in embryonic dunes instead of blown trough the blowouts.

XBeach model results

With the two-dimensional XBeach model two computations have been performed. The first is a computation with the system in the present state for the storm event in the year 2078 with the expected sea level rise of 66 cm. The second is a computation in which the sand-drift dike is partially removed by constructing five blowouts for which the reclaimed volume is placed in front and on top of the Kooiduinen.

In the simulation with the system in the present state, the sand-drift dike will overwash, and overwash delivery will be deposited at the salt-marsh in between the Stuifdijk and the Kooiduinen (Fig. 9a). No overwash of the most landward dune (the Kooiduinen) is expected, but waves from the North Sea in combination with currents from the back-barrier side, are predicted to cause erosion at the Kooiduinen. The extent of erosion is such that the remaining sand bodies will likely fail due to short wave overwash or geotechnical instability, e.g. processes not included in the model. Consequently, the safety standards are not met.

The sand-drift dike will erode hours earlier if it is (partially) removed, e.g. by constructing blowouts according to the simulation with interventions. In the direct lee of the blowout, significant erosion is predicted (Fig. 9b). However, this additional erosion is local and does not lead to a large-scale increase of erosion in the salt marsh area. On the contrary, overwash deposits are thicker and extend approximately 100 m further inland and westward (Fig 9c). Dune erosion of the Kooiduinen does increase due to the construction of the blowouts. Despite this increased dune erosion, the reinforcement with the sand of the blowouts is sufficient and the remaining sand bodies meet the safety standards.

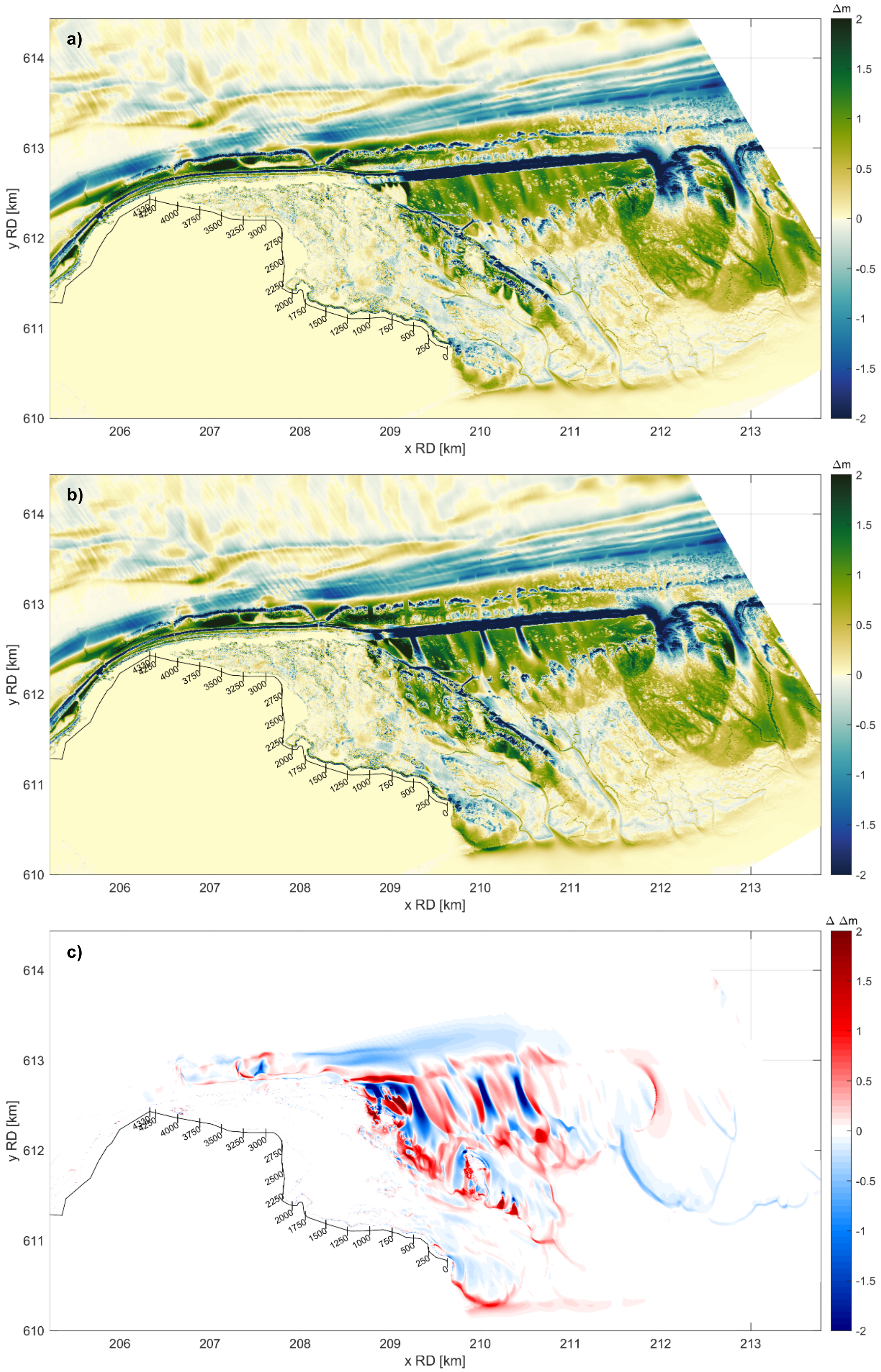

Figure 9 – Bed level changes after 1/1.200-year storm at the Barrier island of Schiermonnikoog, (a) without interventions, (b) with 5 blowouts in the Stuifdijk and reinforcement of the Kooiduinen, and (c) difference between the two simulations. The black line denotes the distance along the most landward dune arc.

DISCUSSION

With no alterations to the system, the overwash deposition will benefit only the eastern side of the island. This would only lead to strengthening part of the island that is irrelevant for protection of the inhabited regions. The deposition pattern is not significantly altered by the partial removal of the sand-drift dike, yet the overwash deposits are thicker and further inland and westward. This does heighten the island closer to the sea defence. In addition, the mechanical relocation of sediments to the most landward dune arc (the Kooiduinen) reduces the inundation risk of the western part of the island. Furthermore, the influx of sediment from the beach through the blowouts can strengthen the system further but this is not even considered here as the deposition magnitude and pattern are difficult to predict.

It remains uncertain whether the investigated blowouts will generate the considered increased dynamics as it might be challenging to maintain active blowouts. In addition to the ambient morphological trends, the activity of blowouts depends on many factors such as the presence of vegetation roots and the orientation of the blowout to the dominant wind direction. As such, uncertainty remains regarding the suspended transport of calcareous sand further inland.

CONCLUSIONS

There are plans to reduce the inundation risk at the barrier island of Schiermonnikoog by constructing one or multiple blowouts in the most seaward dune row (the Stuifdijk) and using the excavated sediments to strengthen the most landward dune row (the Kooiduinen). On the long-term the bowouts have the potence to increase the barrier islands resilience while the strengthening of the Kooiduinen increases the inundation risk at the short term.

The island had a very wide beach since the last landing of a large sand bank from the outer delta. These wide beaches have reduced marine influences and therewith dynamics in the dunes in the past decades. Recently, beach widths at the island's north side (Oosterduinen and the Stuifdijk) have reduced sufficiently such that erosion of the embryonic dunes and green beach occurs occasionally. Without further erosion, aeolian transport will not reach beyond the vegetated beach and blowouts have a high chance of revegetation. However, a new sand bank is expected to land on the island which will increase the beach width at the island head and the Oosterduinen in the short term. Therefore, the Stuifdijk appears to be the most viable location for the construction of blowouts as it is expected that here the erosive trend will persist. Which will allow for marine influences and the reintroduction of dynamics in the dunes and thus for the wanted aeolian transport towards the hinterland.

Effects for inundation risks are investigated with a two-dimensional XBeach model. To illustrate the impacts, a hypothetical case of five blowouts in the Stuifdijk is investigated. The computations show that the system is significantly strengthened by relocating the sand from the Stuifdijk to the most landward dune arc. In this way, the short-term inundation risk is reduced without using external materials, while simultaneous construction of blowouts possibly increases the islands' resilience regarding sea level rise on the long-term. As such, these results show that (partial) removal of the first dune row by constructing blowouts can be effective at more vulnerable coastal sections if the right precautions against inundation are included in the plans.

REFERENCES

Algemene Hoogte Kaart Nederland (2023). Arcgis, Mapviewer. Consulted on March 8, 2023, from https://www.arcgis.com/apps/mapviewer

Arens, S.M., J.P.M. Mulder, Q.L. Slings, L.H.W.T. Geelen, P. Damsma (2013). Dynamic dune management, integrating objectives of nature development and coastal safety: Examples from the Netherlands. *Geomorphology*. 199, 205–213.

Bakker, Berg, Grootjans, Olff, Schrama, Reijers, Van der Heide, (2023). Biogeomorphological aspects of a model barrier island and its surroundings - Interactions between abiotic conditions and biota shaping the tidal and terrestrial landscape: A synthesis, *Ocean & Coastal Management*, 239, 106624.

Deltares. (2017). Achtergrondrapport Hydraulische Belastingen - Wettelijk Beoordelingsinstrumentarium 2017. Report with reference 1230087.008.HYE-0001, version 4, september 2017. Authors: Chbab, H. en de Waal, H.

Elias, E. & Oost, A.P. (2021). Morfologische processen van het Friesche Zeegat. Een conceptueel model. Deltares rapport: 11205236-003-ZKS-0005.

Grootjans, A.P., Dullo, B.S., Kooijman, A.M., Bekker, R.M., Aggenbach, C. (2013). Restoration of Dune Vegetation in the Netherlands. In: Martínez, M., Gallego-Fernández, J., Hesp, P. (eds) *Restoration of Coastal Dunes*. Springer Series on Environmental Management. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-33445-0_15

Hateren, J.A. van, van Buuren, U., Arens, S.M., van Balen, R.T. & M.A. Prins (2020). Identifying sediment transport mechanisms from grain size-shape distributions. *Earth Surface Dynamics*, 8, 527–553.

IJzendoorn, C. van (2021): Characteristic parameters extracted from the Jarkus dataset using the Jarkus Analysis Toolbox. Version 1. 4TU.ResearchData. dataset. https://doi.org/10.4121/14514213.v1

Oost, Hoekstra, Wiersma, Flemming, Lammerts, Pejrup, Hofstede, van der Valk, Kiden, Bartholdy, van der Berg, Vos, de Vries, Wang, (2012). Barrier island management: Lessons from the past and directions for the future, *Ocean & Coastal Management*, 68, 2012, 18-38.

Rijkswaterstaat (2023). Vaklodingen, Deltares OPeNDAP. Consulted on March 8, 2023, from https://opendap.deltares.nl/thredds/catalog/opendap/rijkswaterstaat/vaklodingen_new/catalog.html

Roelvink, D., Reniers, A., van Dongeren, A. van Thiel de Vries, J., McCall, R. en Lescinski, J. (2009). Modelling storm impacts on beaches, dunes and barrier islands. Journal of Coastal Engineering. Vol. 56, pp. 1133-1152.https://doi.org/10.1016/j.coastaleng.2009.08.006

Rogers, Moore, Goldstein, Hein, Lorenzo-Trueba, and Ashton (2015). Anthropogenic controls on overwash deposition: Evidence and consequences, *J. Geophys. Res. Earth Surf.*, 120, 2609–2624.

Ruessink B.G., S.M. Arens, M. Kuipers, J.J.A. Donker (2018). Coastal dune dynamics in response to excavated foredune notches. Aeolian Research. 31, 3–17, http://dx.doi.org/10.1016/j.aeolia.2017.07.002.

Coumou, L., Santen, R. van, Baan, J. van der, McCall, R., de Bakker, A., Quataert, E., and Goede, R. de (2022) *Validation of dune erosion model XBbeach. Development of 'BOI Sandy Coasts'*. March 21, 2022

Wetterskip Fryslân, (2023). *Nota kansrijke alternatieven*. Dijk- en duinversterking Schiermonnikoog Verkenningsfase. Rapport S0041, 22 november 2023.