Netherlands Centre
for Coastal Research

Book of Abstracts

NCK Days 2025

‘Get Ready for Coastal Innovation’

March 19-21

Rijkswaterstaat

Preface

Coastal protection and maintenance has always been important to the Netherlands. By extension, coastal science is one of the pillars of this work. Connecting science with practice is a large part of the NCK and we hoped you all enjoyed this interchange at the NCK Days we organised in March 2025!

And what better place to connect coastal science with practice than the Eastern Scheldt Barrier? The NCK Days 2025 started with a boat excursion on the Eastern Scheldt and a visit inside the Eastern Scheldt Barrier. Thursday and Friday were both packed with presentations, both oral and poster. PhD’s had their chance to practice their pitch and learn from the community, while seniors could inspire participants with their latest work. All of these presentations were very well received. In total, 96% of the audience submitted that the presentations were excellent (scored a 4 or 5 on a scale of one to five). We would like to congratulate everyone who presented for their great contribution!

Willy Dekker provided a keynote and each day concluded with an awards ceremony recognizing outstanding contributions. Floris van Rees wowed everyone with his presentation on Thursday, earning the best presentation award, while Pauline Overes took home the prize on Friday. Kamiel Röell took home the best poster award on Thursday, and Bart van Westen wrapped up the event with his award-winning poster on Friday.

We hope you have shared your findings and connected with the community during the NCK Days 2025. And most of all we hoped you enjoyed it. See you next year!

Kind regards,

Laura Brakenhoff & Freek Brils
The organising committee

About NCK

The Netherlands Centre for Coastal Research is a cooperative network of private, governmental and independent research institutes and universities, all working in the field of coastal research. The NCK links the strongest expertise of its partners, forming a true centre of excellence in coastal research in The Netherlands.

Objectives

The NCK was established with the objectives:

- To increase the quality and continuity of the coastal research in the Netherlands. The NCK stimulates the cooperation between various research themes and institutes. This cooperation leads to the exchange of expertise, methods and theories between the participating institutes.
- To maintain fundamental coastal research in The Netherlands at a sufficient high level and enhance the exchange of this fundamental knowledge to the applied research community.
- To reinforce coastal research and education capacities at Dutch universities;
- To strengthen the position of Dutch coastal research in a United Europe and beyond.

For more than 30 years, the NCK collaboration continues to stimulate the interaction between coastal research groups, which in the past had often worked more isolated. It facilitates a strong embedding of coastal research in the academic programmes and courses, attracting young and enthusiastic scientists to the field of coastal dynamics. Several times a year, the NCK organises workshops and/or seminars, aimed at promoting cooperation and mutual exchange of knowledge. NCK is open to researchers from abroad and exchanges of young researchers are encouraged. Among the active participants we often find people from a lot of different institutes and companies.

NCK Partners

TU Delft – Delft University of Technology

Universiteit Utrecht

UNESCO – United Nations Educational, Scientific and Cultural Organization; IHE DELFT – Institute for Water Education in partnership with UNESCO

NIOZ – Royal Netherlands Institute for Sea Research

WAGENINGEN UNIVERSITY & RESEARCH

UNIVERSITY OF TWENTE.

Rijkswaterstaat – Ministerie van Infrastructuur en Waterstaat

Deltares

TNO innovation for life

Every partner has a representative in the Programme Committee, the Directory Board and Young-NCK.

Organisation
The NCK Programme Committee establishes the framework for the activities to be organised by NCK. These include for instance the theme for the annual coastal symposium ("The NCK Days") and the topics for the seminars ("Theme days"). The Programme Committee gathers twice a year. Since 1998 a part-time Programme Secretary has been appointed. The Programme Secretary is also the main contact person for the NCK.

As of September 2024, the NCK Programme Committee consists of:
- T. Gerkema PhD. (Royal Netherlands Institute for Sea Research, NIOZ, Chairman)
- N.P. Vermeer MSc. (Programme Secretary NCK, c/o Deltares)
- L. Brakenhoff PhD. (Rijkswaterstaat)
- B. Huisman PhD. (Deltares)
- D.S. van Maren PhD. (Deltares)
- P.C. Roos PhD. (University of Twente)
- M. van der Wegen PhD. (IHE Delft)
- M.J. Baptist PhD. (Wageningen Marine Research)
- M. Tissier PhD. (Delft University of Technology)
- S. van Heteren PhD. (TNO Geological Survey of the Netherlands)
- V.C. Reijers PhD. (Utrecht University - IMAU)

The NCK Programme Committee and the Programme Secretary are supervised by the NCK Directory Board. As of March 2024, the Directory Board consists of:

- D.J.R. Walstra PhD. (Deltares, Chairman)
- N.P. Vermeer MSc. (Programme Secretary NCK, c/o Deltares)
- M.E. Busnach-Blankers MSc. (Rijkswaterstaat)
- B.C. van Prooijen PhD. (Delft University of Technology)
- prof. B.G. Ruessink PhD. (Utrecht University - IMAU)
- prof. K.M. Wijnberg PhD. (University of Twente)
- prof. H. Dolman PhD. (Royal Netherlands Institute of Sea Research NIOZ)
- prof. D. Roelvink PhD. (IHE Delft)
- T. Bult PhD. (Wageningen Marine Research)
- D. Maljers MSc. (TNO Geological Survey of the Netherlands)

Young NCK (YNCK) was created in 2023 with the aim to strengthen the NCK for young/early career professionals within the field of coastal studies in the Netherlands. As of March 2025, the YNCK board consists of:

- J. Beemster MSc. (Wageningen University & Research, Chairman)
- L. Portos-Amill MSc. (University of Twente, Secretary)
- T. de Wilde MSc. (Deltares, Treasurer)
- W.J. Gerats MSc. (Utrecht University)
- M. Klein Obbink MSc. (Rijkswaterstaat)
- K. Nawarat MSc. (IHE Delft)
- F.F. van Rees MSc (Royal Netherlands Institute of Sea Research NIOZ)
- M.A. Wassink (Delft University of Technology)

Program

Wednesday 19 March 2025	
10:30 - 16:30	**Excursion Oosterscheldekering**
10:30 - 11:00	Registration at Topshuis
11:00 - 12:15	Opening & walk towards Neeltje Jans
12:15 - 13:30	Boat tour of the Oosterschelde (bring your binoculars to watch seals!). Experience the 1953 storm surge disaster simulator. Walk back to Topshuis
13:30 - 14:30	Lunch
14:30 - 16:30	Movie and tour through Topshuis and Oosterscheldekering
20:00 - 22:00	**Icebreaker** at Grand Hotel Ter Duin (Burgh-Haamstede)

Thursday 20 March 2025	
08:45 - 09:15	**Registration**
09:30 - 09:45	**Opening Ceremony**
09:45 - 10:15	**Session 1: Coastal Management & Nearshore**
09:45 - 09:57	de Vet An unbridgeable sediment deficit (“zandhonger”) in the Oosterschelde?
09:57 - 10:09	van der Grinten Wave runup extraction on dissipative beaches: new video-based methods
10:09 - 10:21	Larsen A novel type equilibrium slope model for swash zone sediment transport rates
10:21 - 10:33	Ridderinkhof Effect of alternative nourishment strategies on the morphologic evolution of the Texel SW coast
10:33 - 10:45	Geukes Evaluating the coastal multifunctionality of sand nourishment strategies at decadal timescales
10:45 - 11:45	**Coffee break and poster session**
	Leijnse Developing fast tools for assessing wave-driven flooding at large scales
	de Winter An Integrated Perspective on the Uncertainties of Sea-Level Rise, Hazards and Impacts, and Adaptation
	Rutten Sandy strategies for multiple functions under accelerated sea-level rise
	de Vries Are coastal dunes affected by shoreface nourishments?
	Poppema The Hybrid-Dune experiment: hybrid flood defences tested in the field

van der Neut Creating Olympic fairness: measuring and modelling waves on rowing courses

Timmer Satellite Derived Bathymetry as a tool for Coastal Erosion Management in The Gambia

Wang A numerical study of the particle-bed collision process during aeolian transport on moist sand surfaces

de Bruijn Acoustic Measurements of Stratification and Internal Seiching in an Enclosed Former Estuary

Galiforni-Silva Developing a Predictive Digital Twin for a Hybrid Dune-Dike System: First Insights

Florentina How to uncover the long-term impact of mechanical beach reshaping on the foredune development

van de Lageweg HydroFest – wave and current dynamics of lake Veere revisited

Groeneboer Modelling of the morphodynamic change of an artificial washover on The Boschplaat (Terschelling)

Siemerink Obtaining high-resolution flow velocities from fast, accurate, coarse resolution model simulations for estuarine environments

klein Obbink Refining the conceptual morphological models of the Vlie tidal basin for management and maintenance practices

Lodder Research for Coastal Policy and Practice – a case study on the policy process and the role of conceptual models

Hulskemper Skeletonization as Means to Track Geomorphic Changes in Point Cloud Time Series: The Case of Sandy Coastal Embryo Dunes

Haakman Evolution of Tidal Asymmetry at Tide Gauges Along the Dutch Coast

Shafiei Exploring the network structure of coastal sediment pathways at the initial stage of rip-channel formation

Bootsma Impact of restored intertidal area on salt intrusion in estuaries

Taal Knowledge development programme Sandy Coast: System knowledge and coastline management connected for the Netherlands

González-Fernández Nearshore sandbar morphodynamics of a nourished barrier island coast, Ameland

Raaghav Reducing saltwater intrusion through shipping locks using bubble curtains - bridging laboratory and reality

Piedelobo Building Learning Communities for Long-Term Delta Management: Insights from the Delta Wealth Project

Basnayake A country-level comparison of present-day coastal vulnerability to coastal flooding and erosion

11:45 - 12:45	**Session 2: Dunes and Flood Risk Safety**
11:45 - 11:57	Berghuis Biogeomorphic feedbacks in coastal dunes: How the initial spatial distribution of dune grass patches shapes future dune morphology
11:57 - 12:09	van Rees Biotic and Abiotic Drivers of Coastal Dune Height on the U.S. East Coast: A Multi-Scale Approach Using Remote Sensing, Field Surveys, and Stable Isotopes
12:09 - 12:21	Quataert Forecasting Hurricane Impacts on the US coast
12:21 - 12:33	de Bruijn Integrating Thermal and Coastal Dynamics in Modelling Permafrost Erosion: A Case Study at Barter Island
12:33 - 12:45	Rosman Measured Storm Erosion at a Hybrid Dune Compared with a Sandy Dune
12:45 - 13:45	**Lunch**
13:45 - 14:45	**Session 3: Estuaries and Tidal Inlets**
13:45 - 13:57	van Keulen Channel-harbour exchange and its influence on salinity dispersion in a partially stratified branch of the Rhine-Meuse estuary
13:57 - 14:09	Traas Cutting the tail: will the tidal channel Eilanderbalg reduce the length of Schiermonnikoog?
14:09 - 14:21	Alvila Ruiz Studying structural solutions for salt intrusion in multi-channel estuaries
14:21 - 14:33	Vermeer The Roggenplaat intertidal flat nourishment: morphological evaluation after 5 years of monitoring
14:33 - 14:45	Mi Tidal amplification induced by the historical evolution of estuarine landscapes
14:45 - 15:30	**Coffee break and poster session (continued)**
15:30 - 16:20	**Session 4: Sediment Transport**
15:30 - 15:42	-
15:42 - 15:54	van Weerdenburg Variations in suspended sediment concentrations at multiple timescales in the Dutch Wadden Sea
15:54 - 16:06	van der Lugt Cross-shore bed load transport around a storm event in the surf zone of a low-energy beach
16:06 - 16:18	Huisman Unravelling transports along the Wadden island of Ameland
16:20 - 16:40	**Keynote Willy Dekker (HID RWS ZD)**
16:40 - 17:00	**Awards ceremony Thursday and closing**
17:00 - 18:00	**Drinks**
18:00 - 21:00	**Dinner & Young NCK activity**

Friday 21 March 2025	
08:30 - 09:00	**Registration**
09:00 - 10:15	**Session 5: Nature-based Solutions**
09:00 - 09:12	Verhage Ten years of spatiotemporal suspended aeolian sand flux across a remobilized coastal dune system, Zuid-Kennemerland, The Netherlands
09:12 - 09:24	Minns Yes to NbS? Supporting balanced decision-making in the Gambia
09:24 - 09:36	Smits Mangrove recovery by habitat restoration using nature-based solutions
09:36 - 09:48	Baltussen Natural sedimentation in the Nieuwe Waterweg: an experimental study of a potential NbS
09:48 - 10:00	Wu Upscaling nature-based coastal protection: Effects on estuarine biodiversity
10:00 - 10:12	Barciela-Rial Desalination of marine dredged cohesive sediment for beneficial use: lessons learnt from three pilot projects
10:15 - 11:15	**Coffee break and poster session**
	van IJzendoorn How to design coastal dunes as a nature-based solution?
	van Westen Innovative Tools for Nature-based Solutions: Enhancing Dune Mobilization through Nourishment Design
	Hulskamp Analysing dune development and sedimentation-vegetation interactions at the Zandmotor landscape: advancing climate resilient landscapes through engineering
	Bard Cyclical Dynamics of Tidal Flats and Saltmarshes: Implications for Sustainable Management Practices
	Pleij The tidal dynamics in the North Sea derived from SWOT satellite data
	Dutta Delta-ENIGMA: an update from its first year of operation
	Leenders Towards developing guidelines for mega nourishments with a positive effect on habitat development
	Beemster Beyond the highs and lows: capturing the full tidal story from high-low data
	Willemsen Salt marshes: where climate change adaptation meets climate change mitigation
	van der Meer Simulation of the influence of transitional polders on flooding risks
	Tas 2D chenier dynamics and their impact on mangrove-mud shoreline evolution
	Walles Are our nourished tidal flats becoming climate traps for benthic species?

Bhoobun Automated Characterisation of Tidal Course Morphology for Intertidal Mudflat Study

Luo Comparing the effects of mangroves versus salt marshes on delta morphodynamics

Kindermann Evaluating clustering techniques for predicting extreme sea level probabilities at the Dutch coast

Jonathans Evaluating Vegetation Recovery Time in Tidal Marshes

van de Vijsel Impacts of Storm Characteristics on Accretion Rates in Back-Barrier Salt Marshes

Bruil Lateral edge retreat at the Wierum salt marsh: finding a relationship between erosion rate and hydrodynamic forcing

Gijsman Mangrove Restoration in Lac Bay Lagoon, Caribbean Netherlands

Bond Prediction of Alongshore Cobble Transport on a Nature-Based Solution for High-Energy Coastlines

Wijnberg SALTGARDEN - enabling resilient salt marshes in the Wadden Sea

Portos-Amill Linear stability analysis on a sloping shelf: effects on tidal sand wave formation

Nnafie Morphodynamics of sand ridges on the shelf: modelling effects of waves, wind and tide

van Puijenbroek Salt marsh resilience for sea level rise depends on management

Muller Saltmarsh erosion near toe of a sea dike under extreme storm conditions

Bénit How the Ebb Tidal Delta Affects Wave Loads on the Eastern Scheldt Storm Surge Barrier

de Maat Storm Surge Events and the Link With Serial Cyclone Clustering: A Study of the Dutch Coastline

Steenman Predicting salinity in the Haringvliet Outer Delta for operational and long-term applications using Machine Learning

11:15 - 12:15	**Session 6: Ecology and Salt Marshes**
11:15 - 11:27	Feng How Geomorphic Shifts and Climate Variability Reshape Saltmarsh Ecosystems in the Western Scheldt Estuary
11:27 - 11:39	-
11:39 - 11:51	Tobal Cupul Adapting an ecomorphodynamic 1-D model to estimate the presence of macrozoobenthos species in Venice Lagoon
11:51 - 12:03	van Belzen Priming nourishments with local sediment to accelerate recovery: A large-scale In Situ Experiment
12:03 - 12:15	Antonini Quantifying the Performance of Salt Marshes Under Extreme Hydrodynamic Conditions: Insights from a Large-Scale Experiment

12:15 - 13:00	**Lunch**
13:00 - 13:45	**Poster session (continued)**
13:45 - 14:45	**Session 7: Subtidal and Offshore**
13:45 - 13:57	van Dijk Sand Extraction within a demanded North Sea
13:57 - 14:09	van de Pas The influence of river discharge, tides and monsoon forcing on seasonal water level variations in the eastern Bengal Delta
14:09 - 14:21	de Wit Scour Protection for an Energy Island - A Comparison between Numerical and Laboratory Stability Predictions
14:21 - 14:33	Overes Understanding the role of 3D processes for the infilling of cable trenches in offshore sand wave fields
14:33 - 14:45	**Awards ceremony Friday & Closing ceremony**

Conference locations

Icebreaker
Grand Hotel Ter Duin
Hogeweg 55
4328 PB Burgh-Haamstede

Conference venue
Topshuis
Dijkgraaf A.M. Gelukweg 1
4354 RA Vrouwenpolder

Conference dinner
Topshuis
Dijkgraaf A.M. Gelukweg 1
4354 RA Vrouwenpolder

Netherlands Centre for Coastal Research

Book of Abstracts 2025 - Complete

An unbridgeable sediment deficit (“zandhonger”) in the Oosterschelde?

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[1] Deltares; [2] TU Delft; [3] NIOZ & Utrecht University; [4] HZ University of Applied Science; [5] University of Groningen; [6] University of Twente; [7] Wageningen Marine Research; [8] Rijkswaterstaat.

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Introduction

The Oosterschelde (Eastern Scheldt) tidal basin, located in the Southwest of the Netherlands, contains extensive (100 km^2) intertidal flats serving as vital foraging grounds for migrating birds. The 8 km long storm surge barrier (1986) and closure dams (Figure) ensure flood safety while maintaining the open tidal connection with the North Sea. Nevertheless, the storm surge barrier and closure dams reduced the tidal prism – the amount of water flowing through the estuary – by 30% (Vroon, 1994). As a result, the equilibrium volume of the Oosterschelde’s channels (a function of the tidal prism) reduced. The channels have been facing a sediment deficit of 400-600 million m^3 after the construction of the storm surge barrier (Mulder and Louters, 1994), known as “Zandhonger” in Dutch. Consequentially, the tidal flats in the Oosterschelde have been eroding ever since. As the total volume of sediment in the tidal flats is only a fraction of the channels’ sediment deficit and with sea levels rising, the future fate of the tidal flats is in question.

Objective and Methods

This study unravelled the adaptation of the tidal flat morphology and channels’ sediment deficit after constructing the storm surge barrier from extensive field measurements. By combining the strengths of independent morphology datasets, we ensured a cross-validation of observations and complementary insights. For example, triennial Vaklodingen elevation maps captured the whole Oosterschelde, whereas annual RTK-dGPS transects provided more precise bed elevation time series at specific locations. Further details are documented in De Vet et al. (2024).

These measurements revealed the morphological state of the system (e.g., tidal flat volume and elevation evolution) and allowed for an assessment of the evolution of the channels’ sediment deficit. We considered changes in both (1) channel volume and (2) equilibrium channel volume (through changes in tidal prism) resulting from (a) tidal flat erosion and (b) sea level rise. In this way, we could pinpoint whether the channels’ sediment deficit changed over time and by which mechanisms.

Results

The intertidal flats of the Oosterschelde have been eroding and flattening since the completion of the storm surge barrier. Despite the major channels’ sediment deficit, the datasets indicate a ~30% decay in erosion over the past decades. Apart from tidal flats adapting to post-barrier hydrodynamics and storm impacts, we identified contrary to previous perceptions a ~35% reduction in the channels’ sediment deficit (i.e., a reduced demand for sediment from the flats). The volume of the channels barely changed so far. Instead, the channels’ sediment deficit reduction resulted almost solely from changes in the channels’ equilibrium volume, demonstrating the relevance of post-barrier gains in tidal prism. Tidal flat erosion caused most of these tidal prism gains (more water enters the estuary with lower flats). However, the influence of sea level rise on the tidal prism is increasing with the reduction of the tidal flat erosion. While the reducing channels’ sediment deficit is good news regarding reducing tidal flat erosion, sea level rise remains increasing tidal flat submergence and pressuring the existence of these vital foraging grounds.

Overview of The Oosterschelde with its storm surge barrier and closure dams (indicated with the red lines, including years of completion). Satellite picture, credit: Copernicus Sentinel data (2020), processed by ESA, CC BY-SA 3.0 IGO.

References

De Vet, P.L.M., Van Prooijen, B.C., Herman, P.M.J., Bouma, T.J., Van Maren, D.S., Walles, B., Van der Werf, J.J., Ysebaert, T., Van Zanten, E., Wang, Z.B. (2024). Response of estuarine morphology to storm surge barriers, closure dams and sea level rise, Geomorphology. https://doi.org/10.1016/j.geomorph.2024.109462 (https://doi.org/10.1016/j.geomorph.2024.109462)

Mulder, J.P.M., Louters, T. (1994). Changes in basin geomorphology after implementation of the Oosterschelde Estuary project. Hydrobiologia. https://doi.org/10.1007/BF00024619 (https://doi.org/10.1007/BF00024619)

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Wave runup extraction on dissipative beaches: new video-based methods

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2 Texas A&M University, USA

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Introduction

Wave runup observations are crucial for enhancing our understanding of nearshore processes and play a key role in coastal management. They provide valuable data that helps validate predictive models of inundation frequencies and erosion rates, both of which are essential for assessing the vulnerability of coastal ecosystems and infrastructure. However, automated algorithms used to extract the instantaneous water line from video imagery face significant challenges under dissipative conditions. In particular, the presence of a seepage face and the lack of contrast between the sand and the swash make accurate extraction difficult, often requiring time-intensive data quality control or manual digitization. This research aims to develop automated frameworks for accurate wave runup extraction from video imagery, addressing challenges posed by highly dissipative coastal conditions.

Objective and Methods

This study focuses on improving wave runup detection using video imagery collected from Galveston Island, Texas, along the Gulf of Mexico, where timestack images were extracted for analysis. Two novel methods were developed to address challenges associated with dissipative conditions: one based on color contrast (CC) and the other employing machine learning (ML). The CC method enhances waterline detection by combining texture roughness, measured as local entropy, with saturation. In this approach, images are first binarized using entropy values and then refined through noise reduction applied to the saturation channel. The ML method uses a convolutional neural network (CNN) informed by five preprocessed timestack images as input channels, including grayscale intensity, its time gradient, the saturation channel, and entropy with its time gradient. Both methods were validated using nine manually labeled, 80-minute timestack images.

Results

The CC method demonstrated strong agreement with manually digitized water lines (RMSE = 0.12 m, r = 0.94 for vertical runup; RMSE = 0.08 m, r = 0.97 for 2% runup exceedance ($R_2\%$); RMSE = 3.88 s, r = 0.70 for mean period ($T_{m-1,0}$)). The ML model also showed good performance (RMSE = 0.10 m, r = 0.96 for vertical runup; RMSE = 0.09 m, r = 0.97 for $R_2\%$; RMSE = 3.51 s, r = 0.79 for $T_{m-1,0}$). See Figure 1 for comparing the two methods with the manual results. Both methods showed strong agreement with the empirical formula by Stockdon et al. (2006), with RMSE values below 0.13 m and correlations exceeding 0.70, demonstrating their reliability for runup prediction. The ML method holds promise for long-term analysis but faces challenges with unseen data. Future work could focus on improving the CNN architecture, incorporating additional data, and testing across diverse environments to enhance robustness. The CC method remains robust for extreme value and wave-by-wave analysis under dissipative conditions. Together, these methods reduce the need for manual processing and support real-time coastal monitoring and predictive modeling.

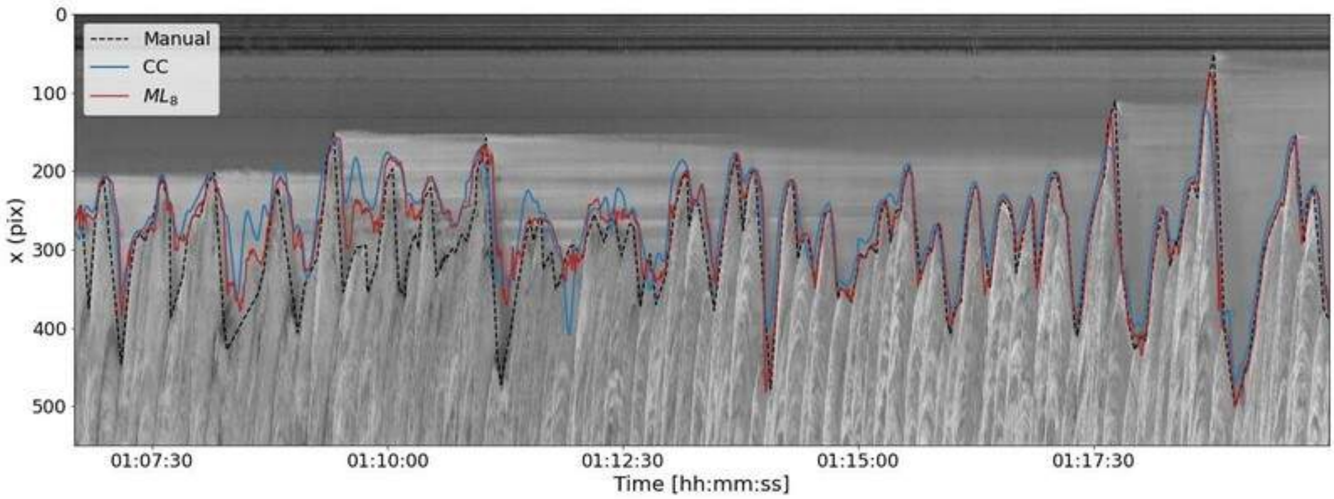

Figure 1: Section timestack from November 14th (video ID: GX050084), with the manually digitized water line (back dashed), and the CC (blue solid) and ML results (red solid).

A novel type equilibrium slope model for swash zone sediment transport rates

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Introduction

Cross-shore sediment transport remains difficult to predict for practical engineering models. One of the challenging regions for such models is the swash zone, where many models use so-called distribution methods to predict the sediment transport rates from the last point of the hydrodynamic and sediment transport models to the point of maximum run-up (van Rijn, 2009). Other types of models for swash zone transport rates have been developed, and many of these are build on a so-called equilibrium slope (see e.g. Chen et al., 2024). Both the distribution type models, and the equilibrium slope type models have, however, only been tested on a limited range of scenarios, and it is not known how well they perform across a wide range of wave conditions with a wide range of initial cross-shore profile shapes and sediment characteristics.

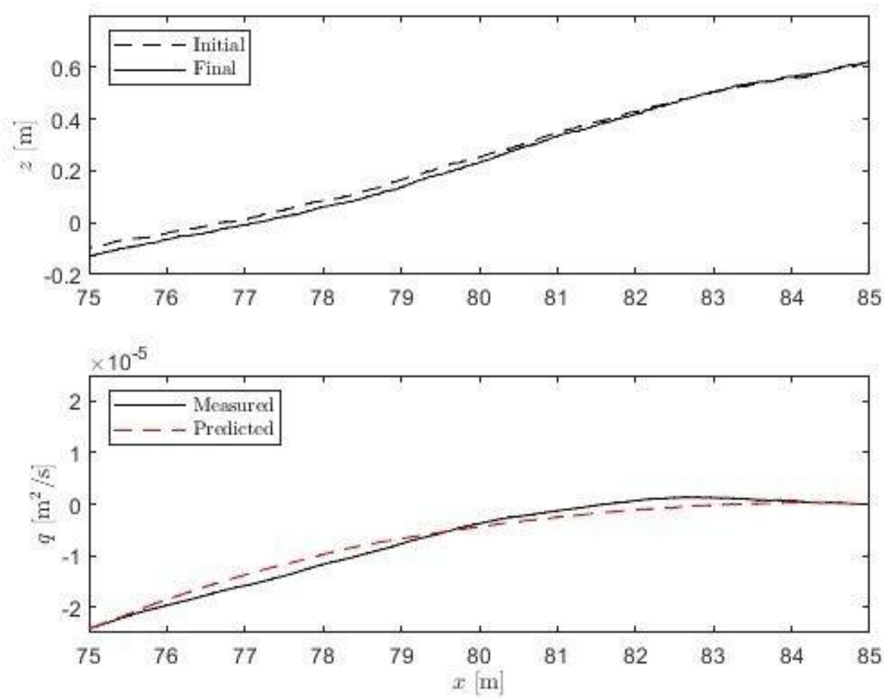
Objective and Methods

This work is an extension of Öz (2025) and aims at evaluating existing types of swash zone sediment transport models for a wide range of conditions as well as formulating a new type of model (as a result of the evaluation). This will be achieved by assembling a large experimental database for testing, formal mathematical analysis and idealized scenarios. A new model will be suggested which avoids some of the identified issues with the existing models and the experimental database will be used to tune model parameters.

Results

In many of the equilibrium slope type models the sediment transport is offshore directed if the slope is steeper than the given equilibrium and onshore directed if it is milder. While this appears intuitive, there are many examples where a constant slope has been reached for part of the swash zone, but the transport rate in this region is not zero (Larsen et al., 2023). The beach is in other words eroding or accreeding, but maintaining its slope. The reason for this is that erosion/accretion is governed by the gradients of the transport rates rather than the transport rates. Secondly, by means of mathematical analysis and idealized scenarios it is proved that some models will not tend towards the equilibrium slope as the second derivative of the transport rates have the wrong sign. It is demonstrated that convergence towards equilibrium can be achieved with a model for the gradients of the transport rates rather than the sediment transport rates themselves. Using optimal coefficients, the new model is demonstrated to match experimental results well as demonstrated in the accompanying figure.

Financial support is acknowledged from the European Research Council, Horizon 2020 Research and Innovation Program (Grant Agreement No. 101163534).



Measured and predicted sediment transport rates from the erosive condition of van Rijn et al. (2011)

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Effect of alternative nourishment strategies on the morphologic evolution of the Texel SW coast

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Introduction

The southwestern coast of Texel is influenced by sediment bypassing that leads to the formation of shoals on the ebb-tidal delta. These shoals migrate towards the coast, acting as a natural supply of sediments. Both subtidal and supratidal shoals attach to the coast with different intervals. Periods between the large supratidal shoals exceed centuries. The repetitive attachment of shoals and associated channel migration results in a varying beach width, and thereby to a dynamic dune evolution.

Human interventions have also impacted the natural dynamics of this area. The closure of the Zuiderzee led to large-scale reshaping of channels and shoals on the ebb-tidal delta. Along the coastline, the construction of a groin field (1959-1987) reduced the coastal retreat. The nourishment program that has maintained the coastline since 1993 resulted in an additional sediment supply of 180,000 m³/year.

Current beach management presents several challenges. The nourishment program is demanding, requiring interventions every 3-4 years. The nourishments result in higher, more uniform primary dunes that hinder sand flux to the landward nature area, causing unnatural aging of vegetation and reduced biodiversity. Additionally, the beach width is sometimes too narrow for recreational and military use. Finally, sea level rise places pressure on the flood safety.

Objective and Methods

Six alternative coastal management strategies were investigated on behalf of Province Noord Holland, Municipality Texel, Hoogheemraadschap Hollands Noorderwartier, Rijkswaterstaat, Staatsbosbeheer and the Ministry of Defense to resolve the present-day and future challanges. The coastal management alternatives were evaluated on the themes: Nature, Water, Use, Landscape, Sustainability, and Costs.

This evaluation was performed for the present-state coastal system and for future conditions. Evaluation of future conditions was made using morphological projections have been made for the expected state of the alternatives and reference situation in 2050 and in 2100. The following components were considered: beach width, the surface area of various natural habitats (e.g. dune valleys, embryonic dunes, white dunes, grey dunes), the sand flux towards the nature area, the required nourishment volumes to maintain the coastline. This was done based on literature, conceptual reasoning, and available observations.

Results

Morphologic projections for 2050 and 2100 have been elaborated to such a level of detail that it became possible to carry out the impact assessment and identify relevant differences in the effects of the various alternatives. For this, a sea level rise of 0.38 m in 2050 and 1.24 m in 2100 is assumed (the upper boundary of the high CO_2 emissions climate scenario obtained from the KNMI '23 climate scenarios).

For all variants, the morphological expectations have been elaborated to such a level of detail that it became possible to carry out the impact assessment and identify relevant differences in the effects of the various variants. Specifically, we have developed projections for (1) the effect of migration shoals on the morphological developments in the coming decades; (2) the effect of sea level rise on the required nourishment volumes at a beach that is protected by groins; (3) the effect of blowouts and dune notches on dune volume and sand fluxes to the nature areas.

Project area southwest Texel

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Evaluating the coastal multifunctionality of sand nourishment strategies at decadal timescales

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Introduction

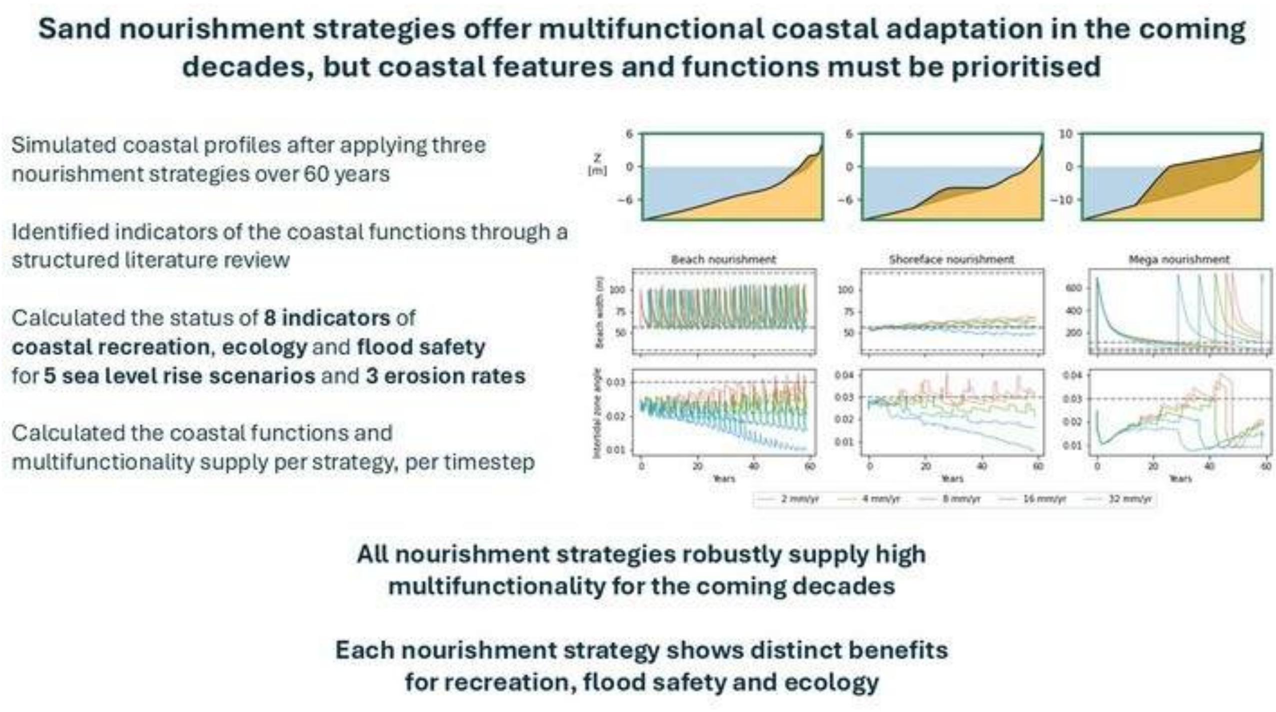
Coastal climate change impacts such as sea level rise, extreme weather events and erosion rates increase and threaten the multiple functions that coastal areas offer. Therefore, there is a global, growing need for multifunctional coastal climate adaptation of sandy shores. Coastal engineering worldwide is increasingly embracing nature-based approaches for such adaptation. Especially sand nourishment strategies are increasingly regarded as promising and innovative multifunctional adaptation tools, as they may increase flood prevention and mitigate erosion while enhancing recreational and ecological functioning. However, their multifunctional potential has not yet been assessed under diverse climate impacts at decadal scales.

Objective and Methods

Using a systems-based approach, this study aimed to identify the effects of beach, shoreface and mega-nourishment strategies on coastal multifunctionality. We identified indicators for recreational, ecological and flood safety functions through a structured literature review. We integrated these indicators into a diffusion-based cross-shore sand distribution model for dissipative coastal profiles that was developed by Kettler et al. (2024). Thereby, we simulated indicator states as the coastal profile responded to the nourishment strategies under five sea level rise scenarios and three erosion rates, and calculated the extent to which coastal functions and multifunctionality were supplied over six decades.

Results

We found that all three nourishment strategies could supply coastal multifunctionality to a high extent over the coming six decades, although the drivers of this potential differed per strategy. These findings imply that sand nourishment strategies are viable approaches for multifunctional coastal climate adaptation in the coming decades. However, these strategies require prioritising ecological, flood safety and recreational benefits and the diverse physical aspects of these coastal functions. Further research could therefore investigate the future societal and ecological demands for these coastal functions. While sand nourishment strategies remain high-impact interventions, they also allow for creating coastal landscapes that may not only prevent floods but also enhance the environmental and societal functions and features we desire of sandy shores worldwide.



Graphical summary

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Developing fast tools for assessing wave-driven flooding at large scales

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Introduction

Coastal communities worldwide are under threat of flooding due to a combination of tide, surge, rivers, rain and waves. However, for coastal flooding assessments at regional to continental scales, waves are often not or only by approximation accounted for due to the high computational expense needed of numerical models. While the physics of wave-driven flooding is already included in the fast flood model SFINCS (Leijnse et al., 2021), boundary conditions to drive SFINCS were in the past still needed from a computationally expensive numerical model like XBeach (Roelvink et al., 2009), or from 1D based (meta) models (McCall et al., 2024). To truly make use of SFINCS' computational speed, we therefore need to derive nearshore infragravity (IG) wave conditions in a computationally efficient way. These we consequently need to force in a 2D fast flooding model, to resolve wave runup and overtopping dynamically with a low computational expense.

Objective and Methods

This study aims to validate and demonstrate how recent innovations in the fast numerical models of SFINCS and SnapWave can be combined to model wave-driven flooding for large coastal areas. We use the method by Leijnse et al. (2024) to efficiently estimate nearshore IG wave boundary conditions at large spatial scales using a wave spectral model (SnapWave, Roelvink et al. 2025). These nearshore IG conditions can subsequently be used to force dynamic IG waves in SFINCS using a nearshore wave generating boundary condition, in an integrated way.

In this work, we apply this approach for one laboratory case test A3 of the GLOBEX experiments (Ruessink et al., 2013), for validation of a sandy beach profile with a mildly sloping beach setting. Also, an application and comparison to an XBeach model is performed for the barrier island of Wrightsville Beach, North Carolina, USA. The large-scale potential is highlighted by modelling 1000 km of the full Carolinas coastline during Hurricane Florence (2018). Besides wave-driven forcing, other compound flood drivers like the tide, storm surge, rainfall and river inflow are included as well.

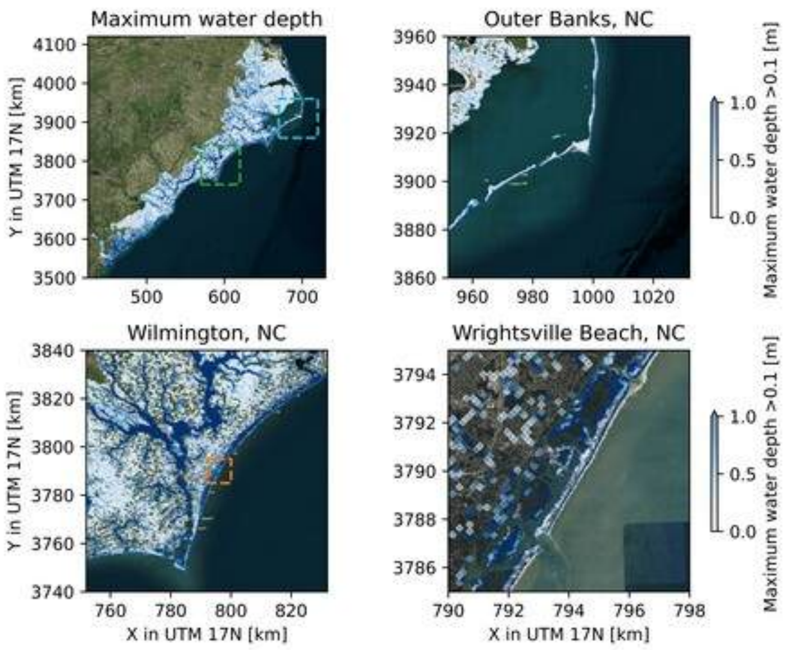
Results

Results for the laboratory validation indicate that the incident and IG wave heights as well as the wave-induced setup as modeled by SFINCS+SnapWave have a similar accuracy as XBeach. As results are sensitive to the exact balance of radiation stress gradients of the incident wave heights and resulting IG wave growth, this is an indication that the physics is implemented correctly.

Applying the model in a real world setting of a barrier island, results in modelled incident and IG wave heights generally match the results of a 2D XBeach-SurfBeat model. The maximum runup at the beach is slightly underestimated by SFINCS, but this comes at a computational gain from 27 hours for XBeach to only 90 seconds for SFINCS.

Finally, the large-scale application highlights that the model can resolve wave-induced flooding with dynamic IG waves on a 1000 km scale, with a higher accuracy in matching observed high water marks compared to simpler methods to include parametrized wave setup.

The large computational gain of the SFINCS model with integrated SnapWave solver shows the potential of utilizing reduced-complexity approaches for large-scale modelling. This could for instance be applied to modelling the Dutch coast in 1 single model for flood risk assessments and early warning systems.



Modeled maximum water depths during Hurricane Florence (2018) for entire domain (A), with zoom at the North Carolina' Outer Banks (B), Wilmington (C) and Wrightsville Beach (D), for minimum flood depths of 0.1 m and for areas above 0 m+NAVD88 only.

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An Integrated Perspective on the Uncertainties of Sea-Level Rise, Hazards and Impacts, and Adaptation

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Introduction

Adapting to future sea-level rise (SLR) is an interdisciplinary challenge (Oppenheimer et al., 2019). However, the interaction between scientists studying different aspects of this challenge is often limited. For instance, studies on SLR projections are typically presented at NAC, but studies on hazards and impact at the NCK Days. Additionally, academic research activities are not always connected to the needs of policy makers and vice versa, expectations of policymakers on which uncertainties will be reduced in the (near) future do not necessarily line up with what researchers consider to be feasible.

Objective and Methods

To address these concerns, we organized a workshop in June 2024 that gathered 22 scientists and policymakers. The goals of the workshop were to stimulate collaboration between communities in the Netherlands, develop a common research agenda, and harmonize research activities across related researched fields. In preparation for the workshop, a questionnaire was sent out to participants to obtain their perspectives on which uncertainties in sea-level research are most important and what is needed to reduce them. During the workshop participants were asked to discuss the interacting uncertainties across three different disciplines: sea-level projections, hazards and impacts, and adaptation. After the workshop, a literature-based overview was made of the most important uncertainties in each of these disciplines. Next to that, we explored how and to what extent these uncertainties can be reduced and which aspects require more certainty in order to better prepare the Netherlands for future sea-level conditions. Insights obtained from this literature assessment and discussions during the workshop were collected in an integrated perspective paper (Hermans et al., under review).

Results

Based on the workshop, we developed a perspective on the most important uncertainties in each discipline and the feasibility of managing and reducing those uncertainties. We find that enhanced interdisciplinary collaboration is urgently needed to prioritize uncertainty reductions and increase the relevance of science to adaptation planning.

In the coming decades we expect that significant uncertainties will remain or newly arise in each discipline and rapidly accelerating SLR will remain a possibility (see Figure 1). Therefore, we recommend investigating how early warning systems for adaptation can help policymakers to make timely decisions under remaining uncertainties. Given the importance of interdisciplinary collaboration, we will share our perspective at both the NAC (20-21 March 2025), NCK-days (19-21 March 2025) and potentially other conferences attended by communities dealing with sea-level rise.

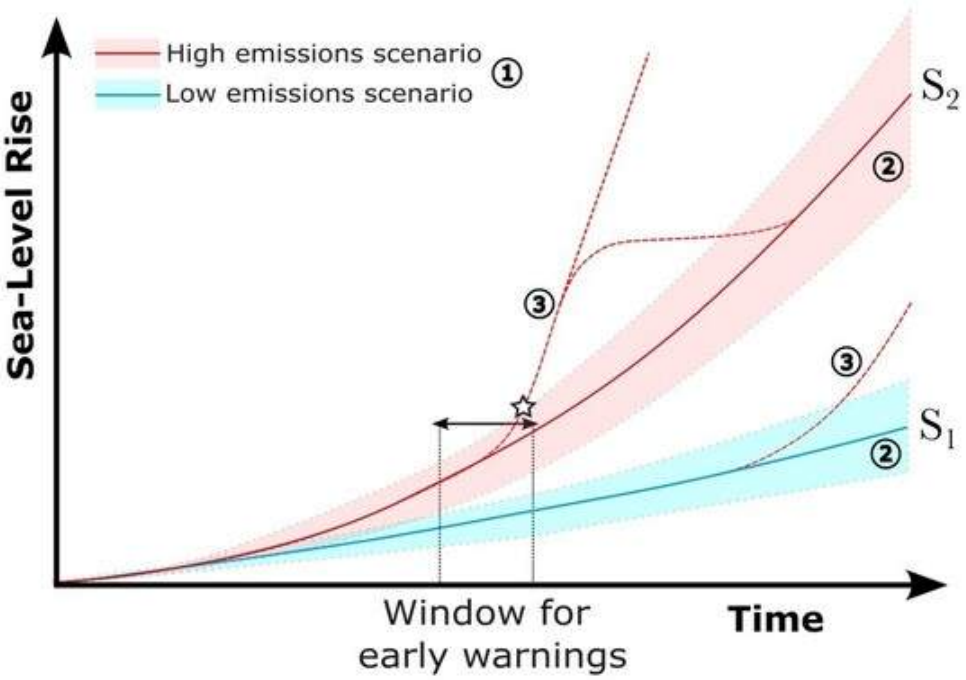

Figure 1: Schematic projections of mean SLR for a low (S1, blue) and high (S2, red) emissions scenario (Category 1). The shading around S1 and S2 depict quantifiable uncertainty (Category 2). The red dashed lines represent deep uncertainty (Category 3) related to tipping behaviour that may lead to a (temporary) departure of mean SLR from S1 or S2. The star indicates when such a departure may emerge from the quantifiable uncertainty of the projections, and the black arrow the time window in which early warnings of this departure may be received.

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Sandy strategies for multiple functions under accelerated sea-level rise

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Introduction

A large part of the Dutch beaches suffers from erosional losses that will result in shoreline retreat without the compensating sand nourishments that are now currently placed on a regular basis. Currently, the total annual nourishment volume is linked to observed sea-level rise rate (Lodder and Slinger, 2022). Projected increase in sea-level rise rate is thus expected to demand larger nourishment volume (Haasnoot et al., 2018; Van Alphen et al., 2022). Different strategies exist to upscale nourishment volume, including more frequent placement of nourishments with regular volume and infrequent placement of large nourishments (e.g. Zandmotor, Hondbossche Duinen).

The coastal zone provides a multitude of ecosystem services. Nourishment strategy can differently affect these services. Therefore, integrated assessment of the key functions is demanded to highlight under which conditions these functions can be guaranteed and how they evolve with time.

Objective and Methods

Our aim is to demonstrate how three key functions (flood safety, a functional ecosystem, recreation) of the Dutch coast are affected by different nourishment strategies under increasing rates of SLR, and explore the potential multi-objective adaptation pathways.

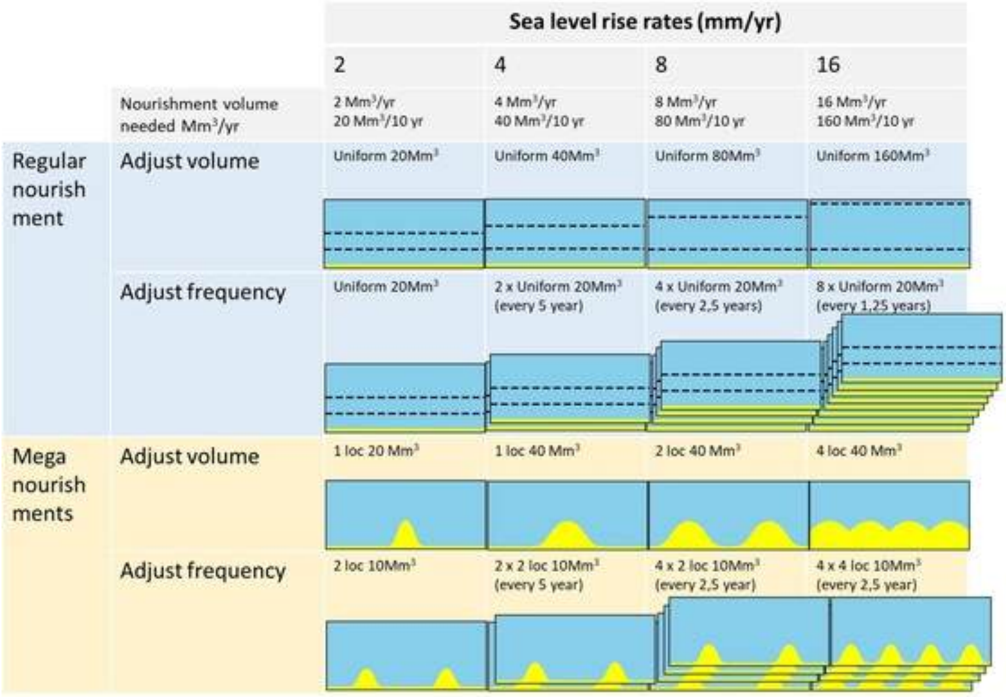
Following the Dynamic Adaptive Policy Pathways (DAPP) approach (Haasnoot et al., 2013), we linked indicators to the objectives and define a solution space of adaptive measures and changing conditions. Here, we applied the DAPP approach three times, providing pathways for each objective. Based on scientific literature, technical reports, expert judgement and stakeholder input, indicators were evaluated over a 10 year timeframe for each adaptive measure.

The following indicators were selected: (i) dune volume for flood safety, (ii) benthic species richness and diversity for a functional coastal ecosystem, and (iii) beach width and swimmer safety for recreation.

The solution space, wherein the nourishment volume budget scales with the rate of SLR in 2100, contained two shoreface nourishment and two mega-nourishment strategies for four SLR scenarios (16 strategies in total; Fig. 1). Strategies were designed for a 20-km long straight coast, uninterrupted by harbour jetties and with wind-blown dunes, inspired by the Delfland coast.

Results

Evaluation of the indicators reveals that many strategies score adequate for most objectives, and thus several strategies remain an option for increasing rates of SLR. Dune volume is not assumed to decrease given that dune erosion volumes were predicted to not notably increase under SLR if nourishments were placed with volumes that scale with SLR (De Winter and Ruessink, 2017). Note that specific mega-nourishment strategies remain difficult to evaluate as currently no future projections exist on dune growth at beaches far but under influence of the mega-nourishment. Benthic species richness and diversity directly after nourishment are assumed to be inadequate due to the thick layer of nourished sand leading to suffocation. Full recovery of benthic fauna was observed to take several years (Van Dalfsen and Essink, 1997), and thus strategies with frequent intervention are not preferred for the functional ecosystem objective. Beach width and swimmer safety are not largely affected by shoreface nourishments, and thus recreation is evaluated as adequate up to 10 years after the first intervention. Local 500-1000m increase in beach width due to mega-nourishments can hamper the recreation objective. Corresponding adaptive pathways will be shown at the conference, revealing which strategies support multiple objectives.



Solution space of sandy strategies in 2100 with schematics showing top view of coast wherein shoreface nourishments (dashed lines) and mega-nourishments (yellow areas) are indicated.

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Are coastal dunes affected by shoreface nourishments?

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Introduction

The morphology of coastal dunes changes with time. Long term sediment supply and aeolian wind forcing may cause dunes to grow gradually and storms may cause dunes to erode. Yearly measurements of dune morphology collected over several decades have revealed linear development of dune volumes at different locations (e.g. de Vries et. al., 2012; Strypsteen et. al., 2019). However, the spatially varying magnitude of these growth rates on decadal scales cannot be explained yet.

Sustained shoreface nourishments in the marine part of the coastal profile may stimulate the growth of coastal dunes indirectly by reducing storm erosion and/or increase the sediment supply to the aeolian system. It could therefore be expected that decadal trends in dune growth rates increase at locations that are affected by nourishments.

In this paper the decadal development of dynamic coastal dunes affected by shoreface nourishments is investigated. The extensive measurements along the Dutch coastal zone (since 1965 to date) and the sustained national nourishment program, in the order of 10 million cubic meters of sediment added to the coastal system on a yearly basis (since 1990 to date, Brand et. al., 2022), provides a unique opportunity to unravel the effects of shoreface nourishments and storms on decadal scale dune dynamics.

Objective and Methods

For this study the Dutch JARKUS dataset (JAaRlijkse KUStmeting) is employed. The JARKUS dataset consists of topographic measurements that include foreshore, beach and dune area along approximately 350km coastline collected yearly since 1965. All yearly data are interpolated to fixed transects that are spaced 200-250m alongshore. The JARKUS Analysis Toolbox ('JAT' as described in van IJzendoorn et. al., 2021) is used to analyze the measured topographic profiles and derive yearly dune volumes at 1033 transect locations (where only transect locations that contain more than 40 years of data are considered).

Dune volumes are extracted for every year at every transect location following the procedure described in De Vries et. al. (2012). For every transect location a piecewise linear relationship is fitted where it is hypothesized that the start of the nourishment program causes a break in trend of dune volume development. The year of the break in trend and the magnitude of the trends before and after the 'break point year' are the free fitting parameters that are optimized by minimizing the root mean square error.

Results

The extracted timeseries of the development of dune volumes indeed show a break in trend at many transect locations along the Dutch coast (see Figure 1 left panel for a clear example). Applying the piecewise linear fit to the extracted dune volume timeseries at all 1033 transect locations leads to a general increase in fitting quality. The 'break point year' seems to occur mostly around 1995 when considering all transect locations (Figure 1, right panel).

The current bulk-analysis of the dune volume development and the piecewise linear fits suggests that the nourishment program along the Dutch coast may have caused a break in trend of dune volume development. This break in trend seems to occur mostly around 1990-1995 at many locations. The break in trend may be explained due to the start of the national nourishment program in 1990. The nourishment program may have resulted in a shallower foreshore that could limit storm erosion and accretion of the beach which could have increased the sediment supply for aeolian sediment transport. As the nourishment program may have influenced dune growth, the results of this study have important implications for the integral management of dynamic coastal dunes as part of the sediment sharing coastal profile (foreshore-beach-dune).

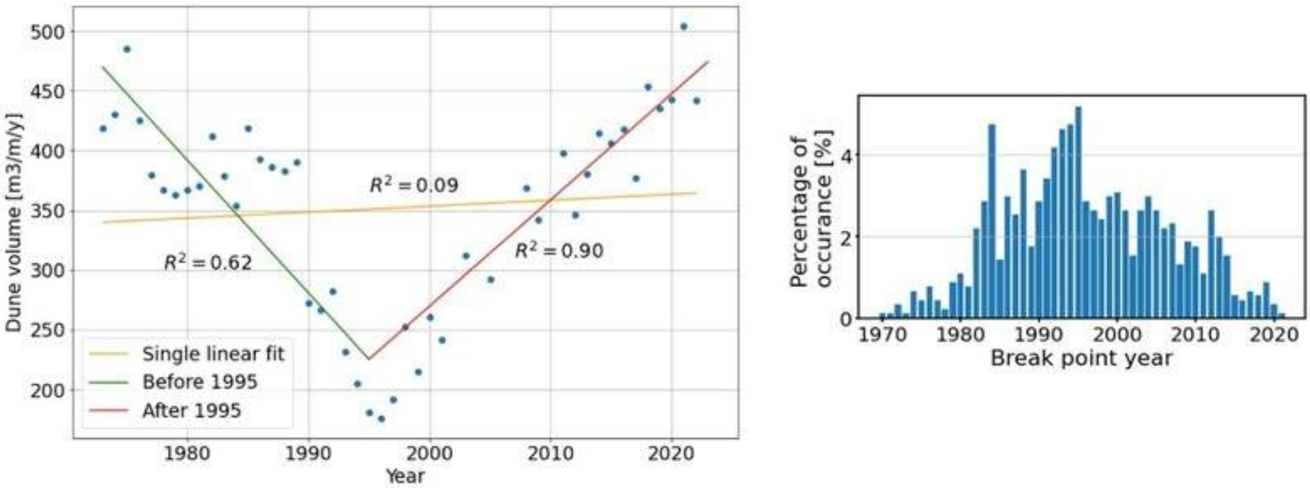

Figure 1. Left panel shows an example of a piecewise linear fit of dune volume development in time with a break in trend at 1995. Before 1995 the dune volume decreased by about 10m3/yr and after 1995 the volume increased by about 10m3/yr (transect ID-7002965). Right panel shows the percentage of occurrence of the break point year when applying the piecewise linear fit to the 1033 considered transect locations. Most occurring break point years seem to be are around 1990-1995.

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The Hybrid-Dune experiment: hybrid flood defences tested in the field

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Introduction

Hybrid flood defences, which combine sandy dunes with hard structures, are increasingly used in coastal flood protection. This combination allows to harness the opportunities sandy dunes offer in terms of nature, recreation and their potential to grow with sea level rise, while simultaneously benefitting from the reliable erosion resistance provided by traditional hard structures (stones, concrete elements, etc). By combining hard and soft elements, the stability of these hybrid flood defences becomes a function of the complex interplay between hard and soft, i.e. between dune morphology, wave action and structural stability. These interactions, though poorly understood, are essential to properly design new hybrid dunes or evaluate the safety of existing ones. We conducted the Hybrid Dune field experiment to measure the hydrodynamics and dune erosion at hybrid flood defences during storms. This work forms part of the NWO project Future FRMtech, with the experiment largely funded by Rijkswaterstaat. In this contribution, we will present the experimental setup, instrumentation and first results.

Objective and Methods

The Hybrid Dune experiment aims to better understand the erosion of hybrid dunes during storms, caused by the interplay between sandy dunes and hard structures. In a large field experiment, an artificial life-size hybrid dune was constructed just above the highwater line, to observe its response during storms. Methodologically, this resembles the RealDune experiment of Van Wiechen et al. (2024). The experiment took place at the Sand Motor in the winter of 2024/2025. The test dune contained four cross sections: 1) a classical sand dune section as baseline; 2) a dike section with a concrete revetment; 3) a hybrid dike-in-dune section, with the hard revetment covered by sand and 4) a dune with a vertical sea wall under the dune.

An extensive measurement array recorded water levels, waves, current velocities, sediment concentration, wave pressure at the hard structure and morphological evolution of the dune and foreshore. Hereto, the setup included 2 offshore ADCP's; 5 ADV's with each 2 OBS sensors in front of the cross sections, 12 pressure transducers in the intertidal zone and 30 on the hard-soft interface, 4 lidar scanners and 6 GoPro's. In addition, topography was surveyed using a handheld GPS and a lidar drone.

Results

The experiment has resulted in a unique dataset with simultaneous high-resolution observations of hydrodynamics, sediment transport, dune- and foreshore morphology, wave runup and wave load on the structures. This will enable quantitative analysis of the morphological response to hydrodynamic drivers and hybrid dune configuration. Moreover, these observations can be used to include hybrid dunes in numerical dune erosion models.

Strong erosion occurred at the tested hybrid dune, caused by five storms during the measurement period, with peak water levels up to +2.1 m NAP. At the dike-in-dune, the initially-covered revetment (concrete tiles) was already uncovered by the first storm. The subsequent storms exposed more of the revetment, allowing the revetment to interact with the waves and sand transport. Sand eroded from underneath the revetment of section 1 and 3, causing them to gradually collapse from the sides. Nonetheless, no scour occurred in front of the concrete revetment. Likewise, scour remained absent in front of the wall-in-dune. Moreover, morphological differences between the different cross sections appeared to be limited. Seemingly, the beach response in front of the hybrid dune was principally governed by the large-scale sediment supply, beach elevation and hydrodynamic conditions, rather than the hard-soft interactions at the hybrid dune.

The test setup at the Sand Motor. Just after construction, with the concrete tiles of the dike section visible and the hard elements of the dike-in-dune and wall-in-dune still hidden under the sand.

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Creating Olympic fairness: measuring and modelling waves on rowing courses

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Introduction

Weather conditions play a crucial role in rowing competitions, significantly impacting athlete performance. Wind and wind-generated waves, in particular, result in unfair conditions when these forcings vary across different lanes of a rowing course. Such discrepancies arise due to spatial variations in wind and wave characteristics, influenced by topography, buildings, and vegetation surrounding the course.

To enhance fairness in rowing competitions, the World Rowing Federation aimed to assess and mitigate these variations. For the Paris 2024 Olympics, wind and wave conditions at the Vaires-sur-Marne rowing course were measured, modelled, and implemented into the event planning process. By analysing temporal and spatial variability, the federation sought to ensure equal conditions across all lanes, ultimately improving race fairness.

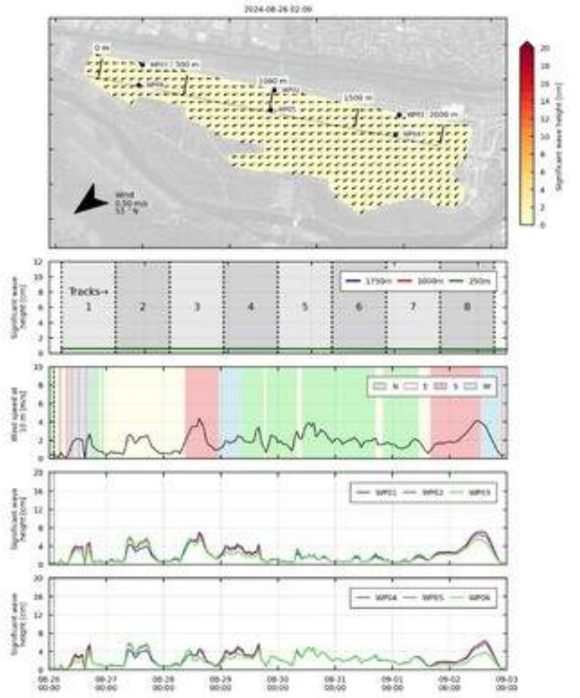
Objective and Methods

The objective of this study was to analyse and mitigate the effects of wind and waves on rowing fairness at the Vaires-sur-Marne course. The study focused on assessing spatial and temporal variations in wind-generated waves and their impact on different rowing lanes at cm level.

To do so, 6 specialised in-house built weather buoys, measuring wind speed, direction and wave heights were placed for a period of 6 weeks in an array surrounding the rowing tracks prior to the Olympics. Spatial wave variations were measured under different wind conditions. These measurements were used to develop and calibrate a SWAN wave model. Ultimately, the SWAN model was coupled to the ICON meteorological forecast model to predict the spatial and temporal variations in the wave conditions during the upcoming rowing competitions.

Results

The real-time measurements revealed significant spatial variability in wind and wave conditions across the Vaires-sur-Marne rowing course. Certain lanes experienced consistently higher wave exposure due to prevailing wind directions and surrounding topography. The numerical modelling successfully replicated the observed conditions, providing accurate wave heights for locally predicted wind speeds. The model and real-time measurements where fully integrated during the Olympics 2024 event, allowing the fairness committee to anticipate and mitigate any potential unfair conditions. Extending the successful application, the model will be further developed and applied to other rowing tracks across the world. Amongst these developments is the integration of tidal and wind-driven currents for the designated track of the Los Angeles Olympics in 2028.



Modelled waves per track

Satellite Derived Bathymetry as Input for Hydrodynamic Models in Coastal Erosion Management in The Gambia

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Introduction

Coastal regions are one of the most densely populated areas on the world, which are under threat of climate change-induced coastal erosion. This risk is particularly pronounced in less developed countries, which lack the resources to manage such risks, leaving poor communities disproportionally affected.

To deal with coastal erosion, hydro- and morphodynamic models have become an indispensable tool for gaining insights into nearshore hydro- and morphodynamics. However, these models rely heavily on expensive in-situ bathymetry data. This data is often unavailable in less developed countries, such as in data-poor regions like West-Africa, limiting effective coastal erosion management in these regions. To address this data scarcity, Satellite Derived Bathymetry (SDB) offers an innovative solution by using satellites to collect bathymetry data. High resolution, open-access satellites (Sentinel-2 and ICESat-2) offer unprecedented spatio-temporal data coverage. This could transform coastal sciences from a data-poor field into a data-rich field.

One of the West-African nations that can profit from SDB is The Gambia. Coastal erosion poses a direct threat to its vital tourism sector, which is situated predominantly along a fast-eroding coast. SDB has the potential to fill bathymetry data gaps, which in turn can help reduce the impact of coastal erosion in The Gambia.

Objective and Methods

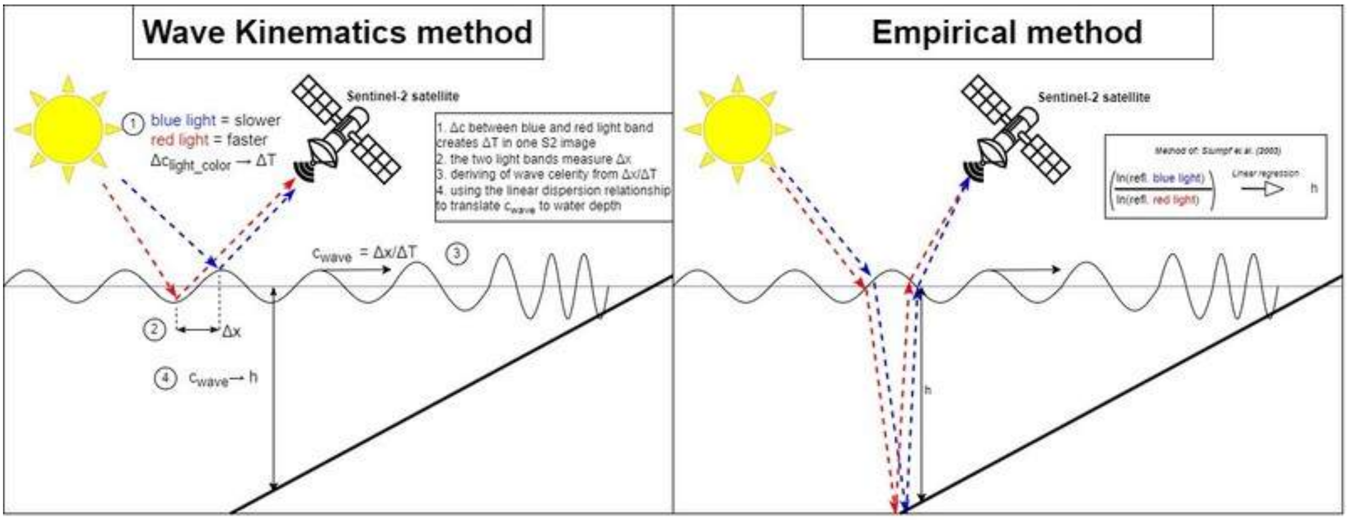
The objective of this study is to determine the applicability of open-access SDB in hydro- and morphodynamic modelling in data-scarce regions. To reach this goal, two SDB methods will be used: the wave kinematics method4, and the empirical method. The wave kinematics relies on deriving wave celerity from satellite images, and translating this to water depth, using the linear dispersion relationship of waves. The empirical method builds on the principle that light intensities are scattered and absorbed by water, establishing a relationship between the depth of the water column, and the measured reflected light.

The first step of the study is to compare the two SDBs with in-situ bathymetry. This will include a sensitivity analysis into the effect of important factors such as turbidity and wave action intensity. The second step is implementing these SDBs into an existing Delft3D model of The Gambia's coast. The model output of both nearshore currents, and bed shear stresses, will be compared with the original model (based on in-situ bathymetry measurements), to assess the applicability of SDB for nearshore hydro- and morphodynamic computations.

Results

Although this study has just started, it is expected to provide valuable insights into the performance of SDB methods in shallow coastal environments. During literature research, two state-of-art methods, that offer large spatial coverage, were identified. The wave kinematics method shows worse RMSE values (compared to in-situ bathy), but its computation times are much shorter. The empirical method must deal with light attenuation, of which turbidity poses the most significant problem, increasing computation time and limiting the water depth it can be applied to. However, it does show better statistical performance, with lower RMSE values.

There is little research on implementing SDB in hydro- and morphodynamic modelling. Therefore, the applicability of doing so is largely unknown. This study's findings could pave the way for broader SDB applications in coastal management projects.



Schema of the two main SDB method: the sea surface sensing Wave Kinematics method, and the sea bed sensing Empirical method

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A country-level comparison of present-day coastal vulnerability to coastal flooding and erosion

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Introduction

The vulnerability of coastal environments can be understood by evaluating the susceptibility of coastlines to coastal hazards such as erosion and flooding, and their capacity to resist and recover from the impacts of hazards. Coastal vulnerability assessments can be used to identify the level of vulnerability at different locations along coastlines. A widely used method to express coastal vulnerability is the Coastal Vulnerability Index (CVI), because of its straightforwardness and ease of application. Several methods are suggested in the literature for estimating the CVI using different indicators and these methods have been applied to different locations in various countries. Often these CVI studies are being carried out at the local scale or regional scale. However, at the global scale, a consistent coastal vulnerability assessment is still lacking. Global scale coastal vulnerability assessments will be important for informing macro-scale decisions. In this context, this study calculates global CVIs, aggregated at country level, for the present-day condition by using four different CVI methods, and compares these CVIs to understand how the CVIs vary depending on the method of calculation.

Objective and Methods

In this study, the four different CVI calculation methods suggested by respectively López et al. (2016), Thieler & Hammar-Klose (2000), Shaw et al. (1998) and Gornitz (1991), were adopted to compute and compare the country median CVI for the global coastline. All four methods use geophysical and coastal forcing indicators to determine the vulnerability of coastal environments. Openly available global coastal datasets were used for each indicator at the sampling locations spread over the global coastline. The selected indicators and the method of assigning the vulnerability rankings differ from one method to another (for more details refer to (Koroglu et al., 2019). The overall CVI value at a sampling location was calculated by taking the square root of the product mean of vulnerability ranks given for each indicator at that location.
In each method, calculated vunerability index values were classified into five equal-sized vulnerability classes from Very Low to Very High vulnerability. Value ranges for each vulnerability class were decided based on the percentile ranges (i.e., the Lowest 20% of the locations were classified as 'Very Low' etc.). Further, CVI classes derived in this study were validated with those from the previous local and regional studies conducted at different locations worldwide. The pointwise CVI values were then aggregated to the country level by taking the median CVI value for each country and classified them into the CVI classes.

Results

Figure 1 shows the variation of median CVI classes calculated at the country level for the four CVI methods. For many countries, median vulnerability classes change according to the method used in calculating the CVI. These differences in CVI classes can be due to the different approaches followed in each method, particularly in assigning the vulnerability ranks to individual indicators. Among the 146 countries analyzed in the study, 26 countries (i.e., Australia, Bahrain, India, Lithuania, Namibia, Sierra Leone, United States, Yemen, China, Djibouti, Ecuador, Georgia, Madagascar, Malaysia, Thailand, Costa Rica, Japan, Singapore, South Korea, Bosnia and Herzegovina, Croatia, Greece, Malta, Montenegro, Norway, Slovenia) exhibit the same median vulnerability class across all four CVI methods. Also, all four methods indicate that the majority of Very High/ High vulnerability countries are located in the tropics or subtropics.

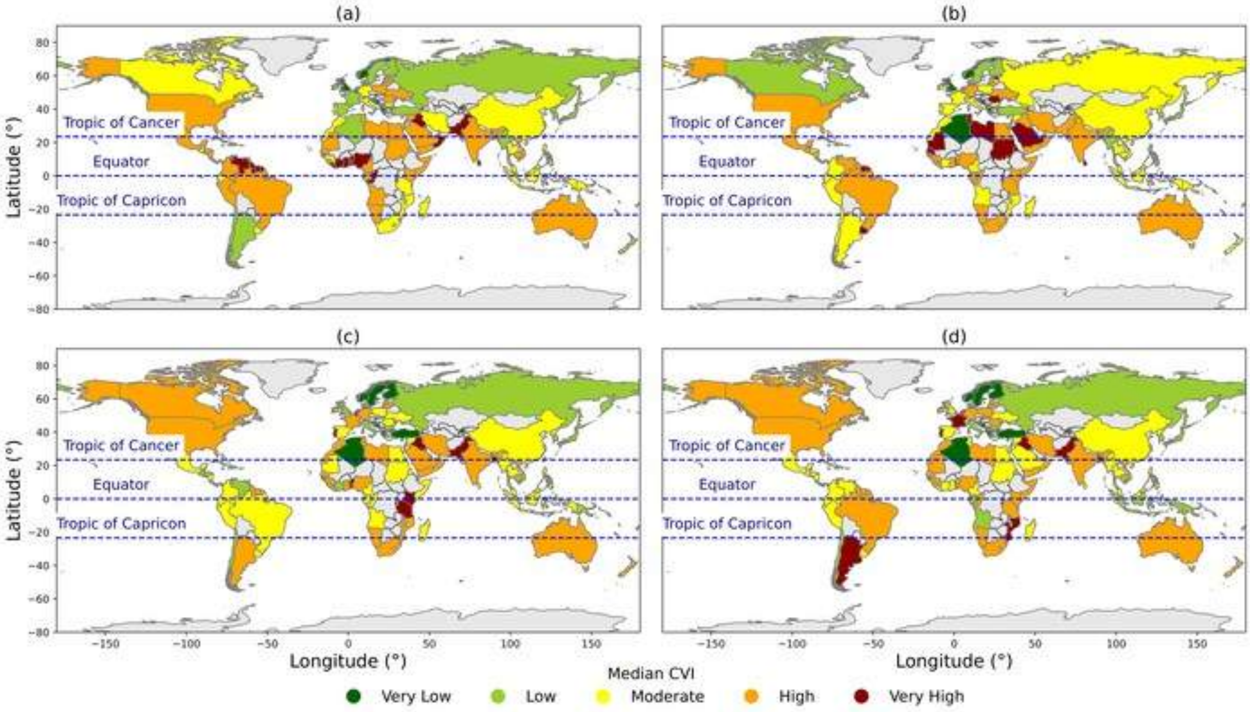

Figure 1: Median CVI classes calculated at the country level for the four CVI methods suggested by (a) López et al., (2016), (b) (Thieler & Hammar-Klose, 2000), (c) (Shaw et al., 1998) and (d) (Gornitz, 1991)

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A numerical study of the particle-bed collision process during aeolian transport on moist sand surfaces

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Introduction

The collision between saltating particles and the sand bed is widely recognized as the primary mechanism driving particle entrainment in aeolian transport. Sand moisture, a critical factor in natural environments, significantly alters particle dynamics during these collisions, thereby influencing transport patterns. The commonly used laws to describe this process, known as splash functions, are extensively employed in the numerical modeling of aeolian sediment transport as a bridge between the particle scale and subsequent larger scales (Anderson & Haff, 1988; Kok & Renno, 2009). However, these splash functions are primarily derived from experiments involving single-particle impacts on static, dry or moist sediment beds in the absence of wind (Beladjine et al., 2007; Ralaiarisoa et al., 2022). Recent studies, however, highlight substantial deviations in the ejection processes observed during saltation events with the presence of wind compared to controlled single-particle impact experiments without wind (Jia & Wang, 2022; Tholen et al., 2023; Jiang et al., 2024). Despite these findings, the influence of moisture on ejection dynamics during full saltation events remains poorly understood, creating a critical gap in our understanding of moisture-modified aeolian processes.

Objective and Methods

This study aims to investigate the influence of sand moisture on rebound and ejection dynamics during particle-bed collisions in aeolian transport using discrete particle simulations. Moist sand particles are represented by an advanced particle model incorporating evolving liquid bridges. A wind flow model is two-way coupled to the particle model, accounting for fluid-particle interactions. By simulating the transport evolution from initially a few mobile particles and driven by wind towards steady-state transport, extensive particle statistics are obtained. A detailed analysis identifies the moments of particle collisions with the bed and subsequent ejections. The coefficient of restitution for saltating particles and the properties of ejected particles are then evaluated as functions of impact velocity and moisture content, providing the basis for a new moisture-dependent splash function during saltation.

Results

The statistical analysis reveals that in the steady state of aeolian transport, rebound and ejection properties exhibit minimal sensitivity to moisture content. However, during the transient phase, the coefficient of restitution for saltating particles increases with moisture content. Additionally, moisture reduces the average number of ejected particles per impact while simultaneously increasing the mean ejection velocity. Based on these findings, a new splash function was developed from the simulation data, offering a promising improvement for predicting aeolian transport dynamics on moist surfaces.

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Acoustic Measurements of Stratification and Internal Seiching in an Enclosed Former Estuary

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Introduction

Many enclosed former estuaries experience water quality problems. The problems are related to stratification, which inhibits the downward mixing of dissolved oxygen to the deep former estuarine channels and pits, leading to hypoxia. Former estuaries like Lake Veere and Grevelingenmeer have also seen events of massive fish mortality, presumably related to the wind-driven upwelling of deep water. To unravel these dynamics, we require more insight into the spatiotemporal behaviour of the stratification.

Stratification is currently measured through fortnightly temperature-salinity-oxygen transects with measurement points every few kilometres. These often do not capture all relevant dynamics, such as mixing and internal oscillations of isopycnals (e.g., tilting, seiching). Echosounding, which overcomes these issues, has been used extensively in the ocean to monitor stratification (Brenner et al., 2023; Shibley et al., 2020), but has seen limited use in lakes, where scatterers are often scarce. Potential scatterers include impedance gradients (i.e., stratification, air bubbles), biota, and turbulence (Bassett et al., 2023). The current generation of acoustic Doppler current profilers (ADCPs) allows for multi-frequency echosounding in combination with the usual velocity, providing new opportunities to acoustically monitor stratification.

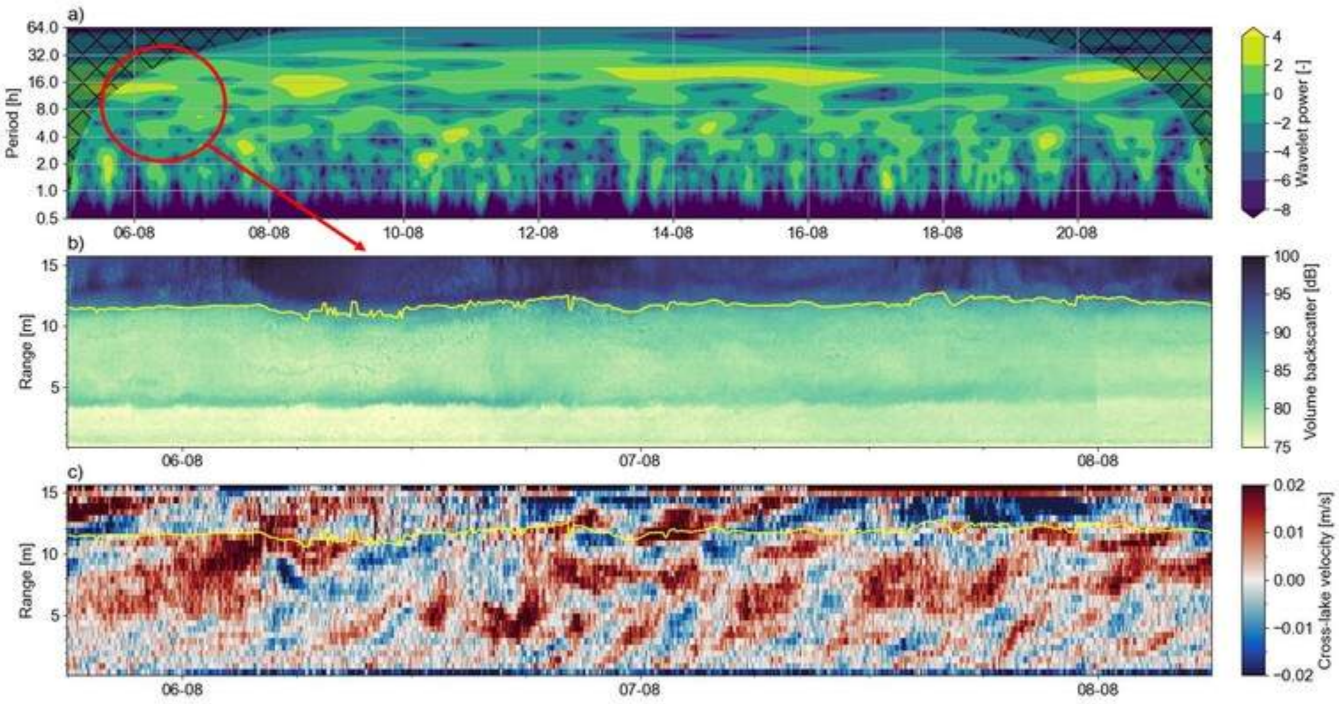
Objective and Methods

This study aimed to integrate acoustic and mooring data to develop a method to monitor stratification at a high spatiotemporal resolution. Subsequently, we used this method to characterize internal oscillations of the thermocline. In the summer of 2024, measurements were collected with two up-looking ADCPs, three underwater moorings equipped with thermistorchains, and a high-resolution conductivity-temperature-depth (CTD) casting instrument. The ADCP measured backscatter at three narrowband frequencies: 1000, 500, and 250 kHz, a wide bandwidth that we expected to facilitate the distinction between backscatter mechanisms at a high spatial resolution.

We compared direct temperature measurements by moorings, CTD casts, and acoustic backscatter at multiple frequencies to characterize backscatter mechanisms in Lake Veere. We used the acoustic backscatter to monitor stratification by tracking (gradient) maxima. We compared acoustically derived thermocline heights to the thermocline heights inferred from the temperature moorings. Finally, we used the monitored stratification to characterize internal seiching by combining data from several locations. To that end, we analysed the time series of thermocline heights using the continuous wavelet and wavelet coherence transforms to identify periods of internal seiching. We validated the latter using the current profiles measured by the ADCPs.

Results

We only observed stratification of the upper water column in the acoustic data during extended warm periods. The upper and lower layers were separated by a gradient in backscatter, with increased backscatter in the upper water column. This gradient coincided with the directly measured main thermocline, demonstrating the potential of monitoring the thermocline height through acoustic backscatter. We hypothesize that the large gradient (as opposed to a local maximum) was caused by a difference in phytoplankton concentration (Warren et al., 2003), which remained above the thermocline due to buoyancy effects and bloomed during extended warm periods. We did not observe impedance gradients; instead, we attribute backscatter maxima to suspended matter aggregating on isopycnals (Haught et al., 2024). We found periods of both cross-lake and along-lake internal seiching in thermocline heights through increased coherence and out-of-phase behaviour between measurement locations. Additionally, vertical shear in the internal seiching frequency band was a sporadic indicator of thermocline height, but not as consistent as for basins of a more regular shape (Simpson et al, 2021). Our results demonstrate the potential of characterizing stratification in former estuaries using acoustic backscatter.



a) Wavelet spectrum of the thermocline height inferred from one of the ADCPs. The marked area represents a spell of internal seiching, with a forced oscillation followed by a free oscillation. We zoom in on b) the measured volume backscatter during this spell and on the c) cross-lake velocities. The thermocline height, derived from the volume backscatter in (b), is shown in yellow.

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Building Learning Communities for Long-Term Delta Management: Insights from the Delta Wealth Project

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Introduction

In delta management, a key bottleneck in enabling large-scale transitions is the need for a common knowledge base among actors with diverse backgrounds and interests. Addressing climate adaptation requires integrating scientific expertise with local knowledge and stakeholder priorities. The Southwest Delta (SW-Delta) in the Netherlands has been continuously reshaped by both natural processes and human interventions. Historically, this dynamic system of tidal flats, estuaries and saltmarshes was altered by centuries of land reclamation and, more recently, by the Delta Works, which transformed the region's tidal character to enhance flood protection. However, with accelerating sea-level rise and changing climate conditions, the long-term viability of these infrastructures is uncertain. The Delta Wealth project seeks to develop integral adaptation strategies that ensure a safe, ecologically sustainable and economically resilient SW-Delta. This abstract focuses on the project's innovative transdisciplinary approach, emphasizing the formation of a Learning Community, and the integration of five knowledge domains, to co-create viable adaptation strategies.

Objective and Methods

The Delta Wealth project has established a Learning Community as a dynamic science-policy-society interface that integrates knowledge and expertise from research institutions, governmental bodies, private sector actors, NGOs and local stakeholders. The Learning Community is supported by PhD researchers from TU Delft, Utrecht University, NIOZ, Wageningen University & Research, and HZ University of Applied Sciences, working across five knowledge domains: (i) flood risk management, (ii) freshwater availability and salinization, (iii) ecology, (iv) social welfare, and (v) societal support.

Interviews, workshops, one-on-one PhD meetings, biweekly meetings, expert consultations, lectures and co-creation sessions are used to inform the three investigated adaptation strategies: Protect-Open (increased tidal exchange and ecosystem restoration), Protect-Closed (enhanced flood defenses and compartmentalization) and Seaward Defense (land reclamation and offshore protection). Each strategy is visualized using ArcGIS StoryMaps, combining scientific data with accessible narratives and visuals to engage both expert and non-expert audiences.

Results

The Learning Community fosters collaboration and trust among scientists, policymakers, businesses and local stakeholders, enabling collective knowledge creation and joint decision-making in the SW-Delta. ArcGIS StoryMaps enable clear communication of complex adaptation strategies, making research accessible to diverse audiences. This is an essential step towards enabling the necessary large-scale transitions.

The Protect-Open StoryMap, synthesizing research across the five knowledge domains, explores reopening estuarine connections, restoring natural sediment transport and integrating nature-based solutions to enhance resilience. Stakeholder feedback has raised key concerns regarding feasibility and public acceptance. Many asked "Is this realistic?" Others questioned whether communities would accept relocation due to shifts in flood protection measures. At the NCK Days, we will present the Protect-Open StoryMap in an interactive poster session to gather input from the NCK community and refine the strategy further. Beyond this, the project will continue expanding stakeholder engagement, assessing the Protect-Closed and Seaward Defense Strategies, and ultimately comparing all strategies to inform regional coastal management (i.e., beheerplannen, PAGW) and climate adaptation plans (i.e., herijking voorkeurstrategie DP), offering valuable lessons for delta regions worldwide.

Delta Wealth Learning Community

Developing a Predictive Digital Twin for a Hybrid Dune-Dike System: First Insights

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Introduction

Nature-based solutions are increasingly being adopted for coastal protection worldwide, balancing effective hazard mitigation with reduced environmental impact compared to conventional approaches. While several benefits exist, nature-based solutions are complex and, consequently, hard to forecast given their associated natural dynamics. Digital Twins (DT) emerged as a potential tool integrating process-based and data-driven models to predict system behavior and provide stakeholders with insights into the system's potential use and reliability. A DT is defined as a digital copy of a physical system based on models and data-driven methods, where continuously updated information from its real counterpart is used as boundary condition for testing and forecasting. Although the concept has been used in different fields (Dal Zilio et al., 2023; Pregnolato et. al, 2022), its use in coastal applications and nature-based solutions is still in its preliminary stages (Jiang et al, 2021).

Objective and Methods

Here, we present and test a first conceptualization of the planned framework to be used for the development of a DT for a hybrid dune-dike system, aiming to be applied for planning and decision-making on coastal management projects. For a hybrid dune-dike system, the virtual twin needs to reproduce not only immediate changes but also the decadal evolution of the system. Thus, we use a coupled shoreline model (ShorelineS, Roelvink, et al., 2020) and beach-dune model (CS model, Hallin et al., 2019) as the base of our DT. We apply the proof-of-concept in several schematic and simplified scenarios and one real case (Hondsbossche Duinen, NL). Schematic scenarios aim to test specific situations, such as increased beach width and dune supply, whereas the real case serves as a general applicability test. For the real case, we simulate the year 2020-2021. Topographic maps made available by Rijkswaterstaat are used to calculate the initial shoreline position and dune characteristics. Wave and wind data made available by Rijkswaterstaat and KNMI, respectively, are used as boundary conditions.

Results

Results show that the proof of concept can simulate most of the overall trends regarding the alongshore spread of sediment and the sediment supply to the dunes. Patterns such as deposition/erosion due to alongshore transport gradients, changes in supply due to beach width variability, and dune erosion due to storm conditions were successfully simulated within the proof-of-concept. For Hondsbossche Duinen, the predictive DT was able to qualitatively simulate the overall beach-dune patterns in terms of volume change. However, even though the overall beach-dune volume trends match the measured data, certain parameters, such as shoreline position, did not perform well for certain coastal stretches, suggesting that better parametrizations for cross-shore sediment redistribution may need to be incorporated into the DT. Further steps include the development of the data assimilation layer and the incorporation of detailed parametrizations from specific process-based models. Nonetheless, the current setup can capture the overall dynamics found in the study area while leaving direct connection points for further development into a DT.

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How to uncover the long-term impact of mechanical beach reshaping on the foredune development

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Introduction

Coastal dunes provide not only a natural barrier against storm surges and waves[1)] but also provide value for tourism, recreation, and habitat for diverse plant and wildlife species[2,3)]. Amid the growing population, the anthropogenic influences in the beach-dune system will also increase. One example is the mechanical beach reshaping (usually using bulldozers) with various purposes, such as for the placement of seasonal beach buildings[4)] and the maintenance of recreational beach infrastructures[3,5)].

While affecting the beach-dune's morphological processes[5)], the interactions of bulldozer activity with the beach-dune moprhodynamics are still rarely taken into account, and are thus not understood yet. The sediment flux caused by this bulldozing activity is rarely quantified, nor its long-term effects on foredune development. The available numerical models for beach-dune development do not include bulldozing activity, although in reality their contribution can be critically important in certain conditions[6)].

In this paper we present an approach for obtaining insights in the long-term effects of mechanical beach reshaping on foredune development.

Objective and Methods

The objectives of our pioneering study on long-term impacts of mechanical beach reshaping are:

1. Identifying the various purposes of mechanical reshaping, their interaction with the natural sand dynamics, and their related spatio-temporal characteristics
2. Extending a biomorphological model to include the mechanical reshaping as an anthropogenic process dynamically interacting with the natural sand dynamics
3. Understanding the long-term effects of mechanical reshaping on foredune development through the extended morphological model.

The developed methodology is summarized in Figure 1a). Data collection for objective 1 will be conducted through interviews and topography measurement which serves as initial basis for the model extension. For objective 2, we will expand the rule-based cellular automata (CA) model DuBeVeG (Dune Beach Vegetation)[7)]. The extension will add the mechanical reshaping activity as a process interacting with natural sand dynamics, i.e. moment and location will depend on various actors' motivations, that can also be related to the natural sand dynamics. The model will be validated by comparing the topography and vegetation change between the model and various datasets. For objective 3, a range of scenarios will be simulated, to explore the impact of different beach reshaping strategies and different beach-dune lay-outs (e.g. morphology, beach buildings).

Results

A first, exploratory model exercise considered a beach with a box-shaped beach building in front of the dune, with and without some simplified form of mechanical reshaping. Effects on simulated foredune topography (Figure 1b, top panel) and vegetation (bottom panel) development were compared after 20 years. The DuBeVeg version including effects of buildings[8)] was used as the basis. The reshaping activity was implemented as a yearly bulldozing activity creating a flat area around the building to maintain the building's accessibility by removing hindering effects of aeolian morphodynamics. The reshaped area was defined as a rectangle with its sides 10 meter from each of the building's faces.

The simulations showed for both cases the development of a new foredune interrupted by the building's presence. Without mechanical reshaping, aeolian deposition concentrated upwind of the building while with the reshaping included, the sand accumulated more on the downwind side, accompanied with more dense vegetation in the deposition areas. Impacts of bulldozing activity on topography and vegetation thus clearly extend beyond the bulldozed area itself. For further work, first the implementation of bulldozing activity will be adapted based on outcomes of objective 1.

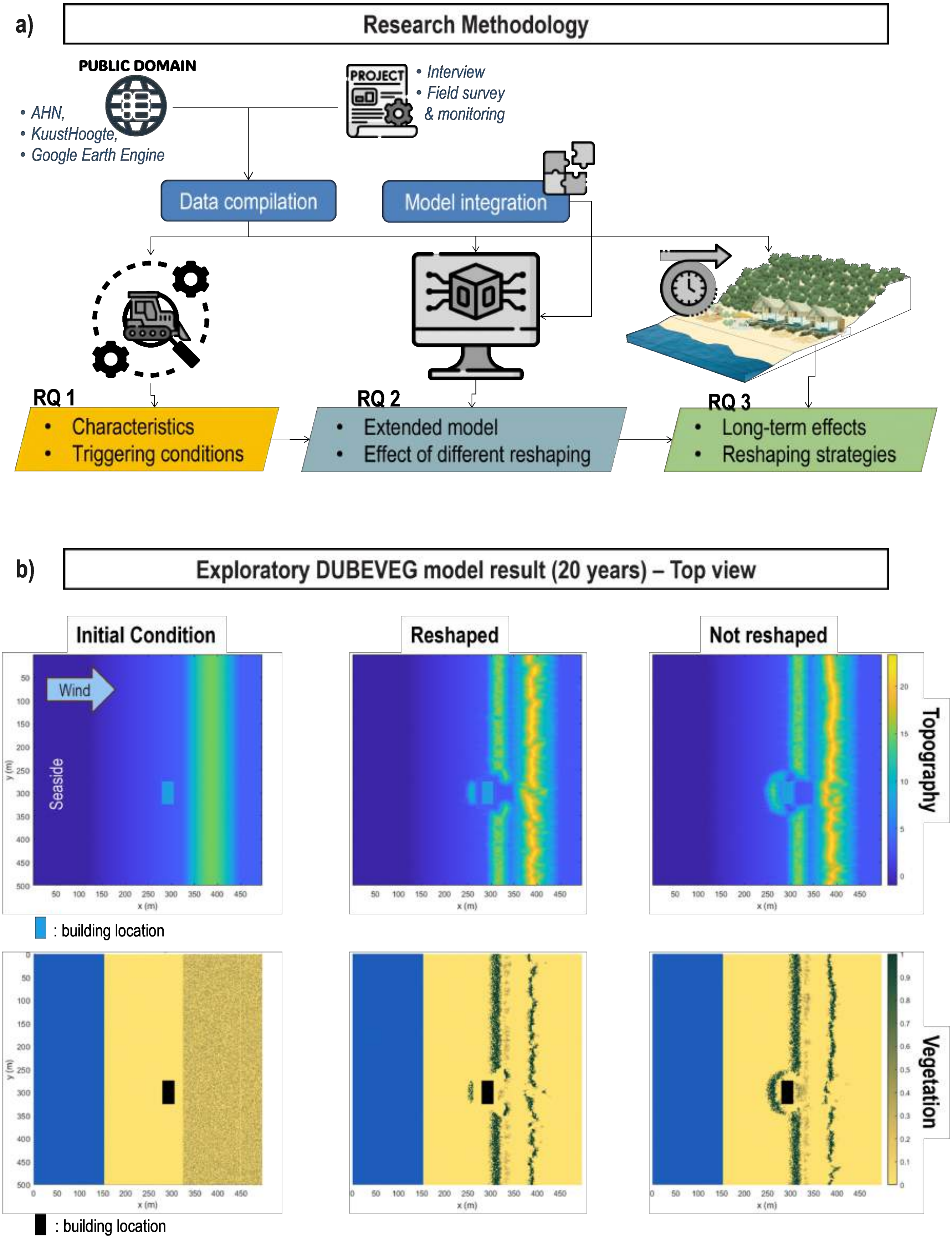

Figure 1. a) Research methodology for uncovering long-term impact of mechanical reshaping on foredune development b) Results of exploratory modelling of simplified reshaping activity around a beach building simulated for 20 years showing: topography (top) and vegetation (bottom) change for reshaped (middle) and not reshaped (right) compared to the initial conditions (left).

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HydroFest – wave and current dynamics of lake Veere revisited

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Introduction

A water-level rise of lake Veere is inevitable in the longer term (>25 years) due to a rise of the water level in the Eastern Scheldt. Currently, the shallow lakeshore zone is predominantly (~90%) protected by hard shore protection with no natural ability to adapt to a higher water level. Indeed, topographical analyses indicate that multiple outer dike will be flooded immediately if a higher water level of only 10 cm would be set with serious implications for (holiday) homes, recreational activities and ecological functioning.

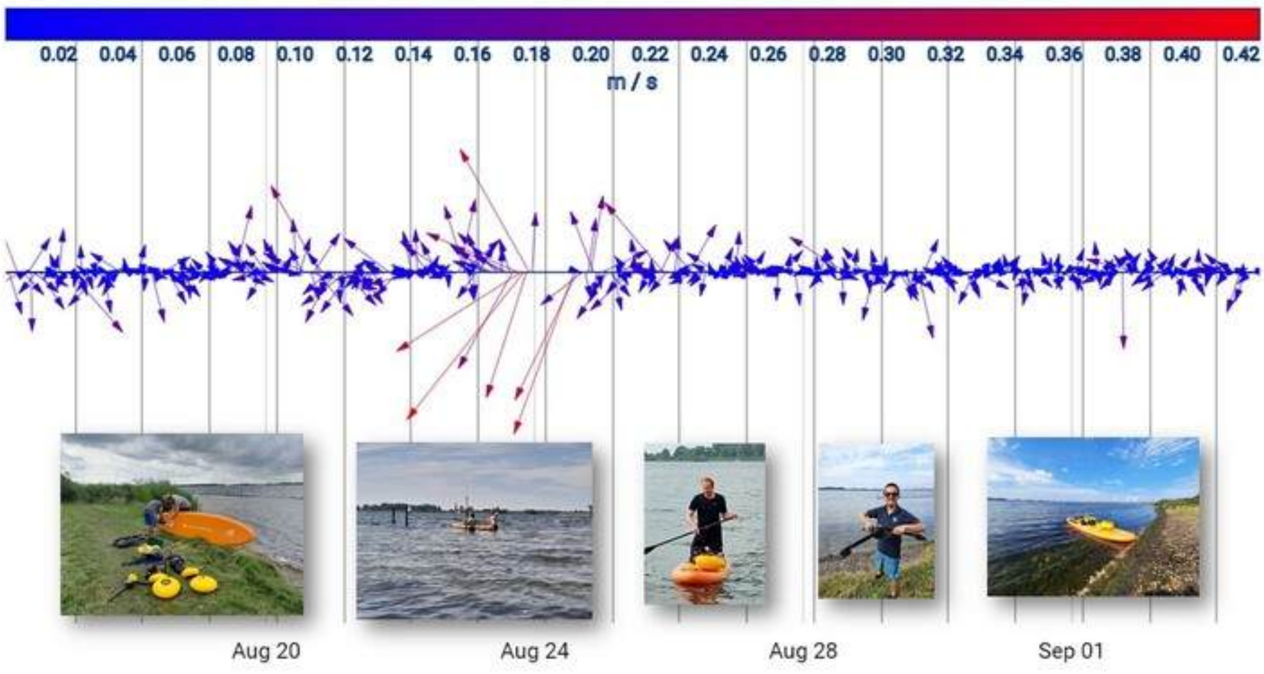
Nature-based measures provide a promising path towards the future shores of lake Veere to strengthen its natural functioning as well as providing a more flexible management tool. Softer and natural shores already exist in a limited number of more sheltered locations, including Goudplaat (i.e. undefended where erosion is prevented by a breakwater in the foreshore), Haringvreter (pioneer salt marsh and mudflats where waves break and erosion is limited) and Schelphoek (artificial sandy beach with a gentle foreshore to dampen wave attack). Yet, to assess the feasibility of upscaling these softer natural shores to other location a good understanding of the hydrodynamics of the shallow zone of the lake is required to inform decisions about the future shore management.

Objective and Methods

A monitoring campaign was carried out from July-December 2024 to measure currents and waves in the lake. Applied sensors include three Nortek ECO ADCPs (see https://eco.nortekgroup.com/) and three Ocean Sensor Systems (OSSI-010-003B/C) wave gauges positioned at the various depths on the shallow shores of Schotsman and Oostwatering in the western part of lake Veere. The monitoring campaign was aligned with ADCP measurements in the deeper parts of lake Veere in the context of the StratiFest project aimed at unravelling stratification patterns.

Results

Preliminary analyses suggest a strong wind-driven wave and current climate with wind-direction representing the strongest link with wave/current speeds and directions. At 10 m depth, peak flow velocities reached 0.19 m/s whereas closer to the shore a velocity of 0.5 m/s was reached during the strongest wind event. A maximum significant wave height of 0.4 m was recorded at the exposed Schotsman shores. The collected wave and current data provides new insights into wind-driven larger-scale circulation patterns from deeper to shallower shores that may hold important clues to better understand the ongoing stratification issues as well as the feasibility of more nature-based future lake shores.



Deployment of Eco-ADCPs in lake Veere to monitor current dynamics from deeper to shallower shores.

Modelling of the morphodynamic change of an artificial washover on The Boschplaat (Terschelling)

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Introduction

Barrier islands are dynamic systems with active morphodynamics. On The Boschplaat, the tail of the island Terschelling, these dynamics disappeared since the creation of a sand drift dike in the 1930s and 1980s (OBN Deskundigenteam Duin- en Kustlandschap, 2018). This dike prevents sediments from the North Sea to deposit on parts of the tail, resulting in a stagnant salt marsh with low biodiversity and a high risk of drowning with sea level rise (OBN, 2018 and SBB, 2018). To address this, a plan has been developed to create an artificial overwash by making a gap in the dike and reintroduce sediment dynamics. However, no studies have yet been conducted on the long-term developments of such a washover complex. Will the gap expand or silt in? And how long will this process take? This study aims to resolve this knowledge gap by simulating the washover development over the next 25 years.

Objective and Methods

We set up a Delft3D FLOW + SWAN model to simulate washover morphodynamics during storms (see also Tavill, 2024). We couple this model with a Matlab-routine that simulates dune development in the intermediate (non-stormy) parts of the year. The initial bathymetry is based on AHN4 (lidar) and Vaklodingen (jarkus) data, and adjusted to create a 500-meter-wide overwash between beach poles 24.20 and 24.80. The hydrodynamic boundary conditions for 6 storm scenarios were selected based on the model output of Lenstra et al (2019). Each of these 6 storms are simulated every 5 years, then morpodynamically corrected for their recurrence time, and finally summed linearly to obtain a representative 5-yearly effect of storms. During quiet periods in between storms, a simple dune model is implemented to grow dunes from the yearly aeolian sediment input, as defined by Keijsers et al. (2014), across the washover area.

This cycle is repeated every 5 years to simulate 25-year morphologic development.

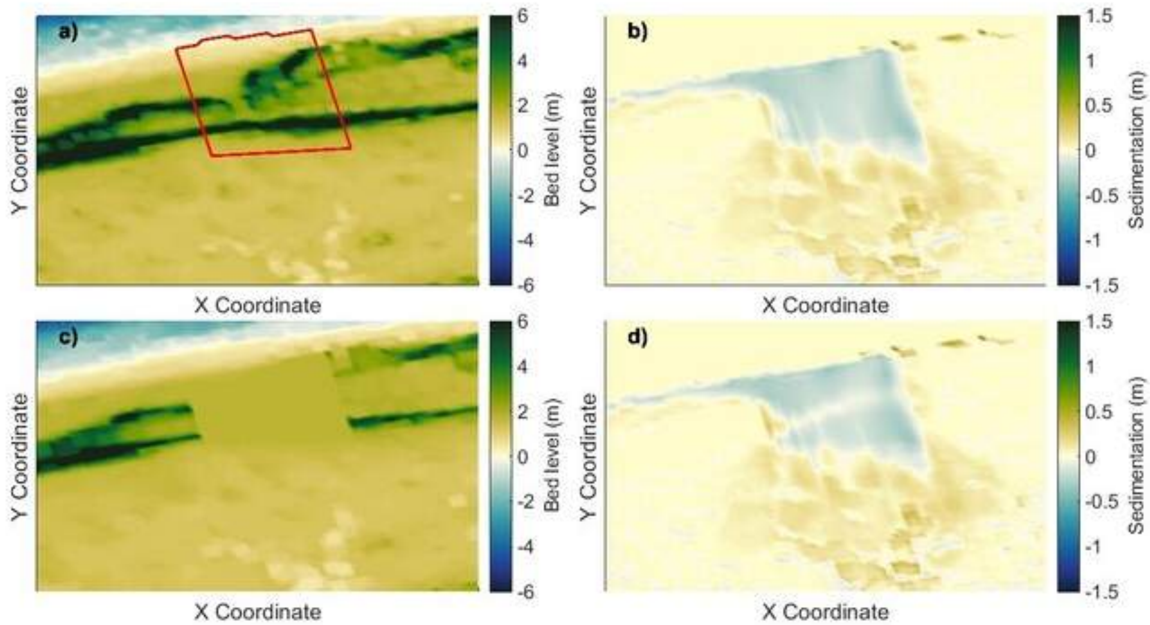
Results

We find that the resulting morphology is a balance between aeolian sand input and storm erosion. Sand available for dune building is approximately 13 /m/yr, whereas storm erosion equals 67 /m/yr for an overwash with an initially constructed gap height of +1.7m NAP (Fig. 1).

We also find that most erosion occurs within the washover gap created in the dike (Fig. 1b). Landward of this gap, deposited sediments form a washover complex. The spatial erosion pattern inside the washover gap likely indicates the onset of channel formation. Channels were observed to form in wide washovers by Tavill (2024). Similarities in erosive patterns are observed across different washover heights.

The morphologic effect did not vary significantly between the 6 storm classes: smaller waves seem to be as important as higher waves for yearly erosive patterns when their frequency is considered. This is consistent with findings of Wesselman (2020) on washover dynamics.

Finally, we wish to highlight the importance of evaluating the long-term accretionary processes, such as dune building, alongside long-term erosional processes caused by storms and, if the washover gets eroded to lower elevations, potentially tides. These processes must be in balance to maximize the lifespan of this constructed overwash gap.



Original bed level of the overwash area (a); bed level after digging out an overwash extending down to + 1.7m NAP (c); bed level change after one year of storm erosion (b), bed level change after one year of storm erosion and dune growth (d).

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Obtaining high-resolution flow velocities from fast, accurate, coarse resolution model simulations for estuarine environments

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Introduction

Management and conservation of estuarine environments is often supported by hydrodynamic models to help assess impacts of management interventions. In such models, the simulation of detailed flow patterns is important for predicting future morphological and ecological developments. However, due to the spatial scales of estuaries, detailed hydrodynamic simulations are very time consuming. Subgrid-based hydrodynamic models reduce the computational cost for such large-scale hydrodynamic simulations. The subgrid-based method computes water levels and flow velocities at a coarse resolution grid, whereas high resolution input data is used to guarantee an accurate computation of wetting and drying, and effects of friction and advection. (Casulli, 2009; Volp et al., 2013). To obtain detailed flow patterns from the coarse grid results, a velocity reconstruction must be performed. In previous studies, an accurate flow velocity reconstruction has been achieved for uniform structured grids (Volp et al., 2016), but has never been applied to real-life estuaries with spatially varying computational grid sizes. This study aims to create a flow velocity field at high resolution for a non-uniform, structured computational grid that is applied to real-life estuarine environments.

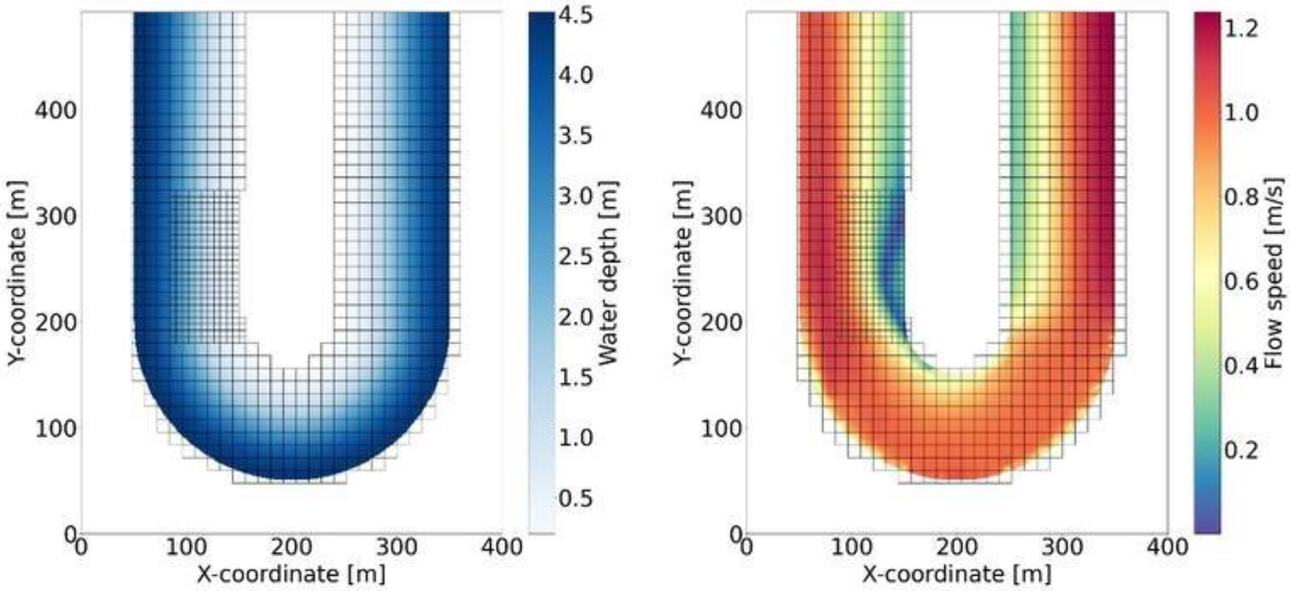
Objective and Methods

Real-life applications of subgrid-based hydrodynamic models can benefit from a non-uniform, structured computational grid. For example, increasing the grid resolution in areas with high flow variability and in regions of interest. The presented flow velocity reconstruction uses the results of a subgrid-based hydrodynamic model. The computations are based on square computational cells, where a quadtree structure allows for different computational grid resolutions across the model domain. The quadtree structure allows for transitions between grid cell widths of a factor two (Stelling, 2012). The quadtree structure and square grid cells allow for an independent evaluation of flow velocity components in x- and y-direction. The flow velocity reconstruction consists of two stages: i) interpolating water levels from the computational grid to the subgrid, and ii) reconstructing flow velocity components in the x- and y-direction on the subgrid. To capture the basic physics the reconstruction is based on the continuity principle in streamwise direction and a simplified momentum balance in cross-stream direction (Volp et al., 2016).

Results

The presented flow velocity reconstruction method is applied to both theoretical testcases, and real-life examples. It will be shown that the method is accurate and applicable under real-life estuarine conditions. Consequently, we can demonstrate the potential it has for dealing with wetting and drying, and for allowing sediment transport computations with limited computational costs. This creates the possibility for more efficient long-term simulations suited to forecast morphological and ecological developments.

The theoretical testcase shows the detailed flow pattern in a bend with a crossflow gradient in the bathymetry. This testcase demonstrates the ability and accuracy of this new method to capture the distribution of flow velocities across the depth profile within a coarse grid cell. For a real-life example the method is applied to the Elbe estuary. The model will be set up using different computational grid resolutions with the quadtree structure across the domain (Korporaal, 2024). We expect the model results for this real-life situation to show a good ability to efficiently compute flow patterns at the fine grid resolution for a complex system such as the Elbe and to give insight in reducing computational cost with respect to traditional methods.



Results of the reconstruction steps for a simulation of a schematised bend with varying bathymetry (deep outer bend and shallow inner bend). Computations are based on a high resolution grid (subgrid) of 1m x 1m and a computational grid of 12m x 12m with a refined area of 6m x 6m. Left: Water depth based on the water level interpolation. Right: Reconstructed flow speed.

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Refining the conceptual morphological models of the Vlie tidal basin for management and maintenance practices

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Introduction

The Wadden Sea is highly valued for its complex dynamic nature and rich ecosystems, yet the morphological processes and interaction on different temporal and spatial scales are not yet fully understood (Oost et al., 2017). This presents challenges regarding management and maintenance practices. A better understanding of the Wadden Sea's natural dynamics can reduce anthropogenic pressures by minimizing dredging impacts, regulating salt and gas extraction, and informing policies for sustainable fishing practices. Additionally, ecological management plans, such as the Natura2000 plans, benefit from a morphological system understanding.

A way to improve decision-making in management and maintenance is through the use of conceptual models (Lodder, 2022). Conceptual models are crucial in translating detailed scientific knowledge into a comprehensive overview, thereby increasing system understanding and facilitating informed decision-making. These models also support the development of adaptive management strategies for climate change and sea-level rise. Ongoing research is essential to continuously update and refine our understanding of the Wadden Sea's natural dynamics. Our results show an update of the conceptual morphological model for the Vlie basin based on recent studies. We reflect on the relevance for Rijkswaterstaat, the organization responsible for maintenance dredging and nature conservation in the Wadden Sea.

Objective and Methods

Our case looks in more detail at the Vlie basin and refines the existing conceptual models of the Vlie inlet in the Wadden Sea. Recently, several studies have been conducted for the Vlie basin within the management and maintenance research program of Rijkswaterstaat, which together contributed to an improved system understanding on a larger scale.

We will highlight several applications of the conceptual model, focusing on areas relevant for management questions. For instance, a morphological analysis between Harlingen and the North Sea fairways identifies different causes for current increased dredging volumes. Combined with another study that investigates the abiotic effects of dredging it provides a clearer understanding of how these activities impact the ecosystem. Furthermore, studying the morphology of inlets sheds light on sediment transport and tidal dynamics. The area of channels and tidal flats in the basin, and its development over time, gives insight on trends in the tidal prism. Methods used within the studies range from analyzing bathymetric data over a decadal timescale, bathymetric data of channels with a higher spatial and temporal resolution, to the application of numerical models that analyze flow velocities and patterns.

Results

The resulting conceptual model provides insights on three temporal and spatial scales: the western Wadden Sea (large scale), the basin, and a detailed scale zooming in on areas of interest. The large scale provides boundary conditions for developments on a smaller scale, while local processes can influence large scale trends as well. The visual representation helps connect the interaction of different hydrodynamic and morphological processes. Various aspects on different spatial scales are relevant for different management questions. It is therefore essential to align the conceptual model with the questions that it should address.

Figure 1 shows the morphological changes in the Vlie basin on a decadal timescale. It gives insight into the hydrodynamic and morphological development of the channels and intertidal flats in the basin. These show processes like the migration of sandbanks in the inlet and the interaction of ebb and flood channels at local bottlenecks for channel maintenance. Our work shows that different management questions need to build on different (connected) conceptual models to identify the relevant trends and development to come up with the best management practices.

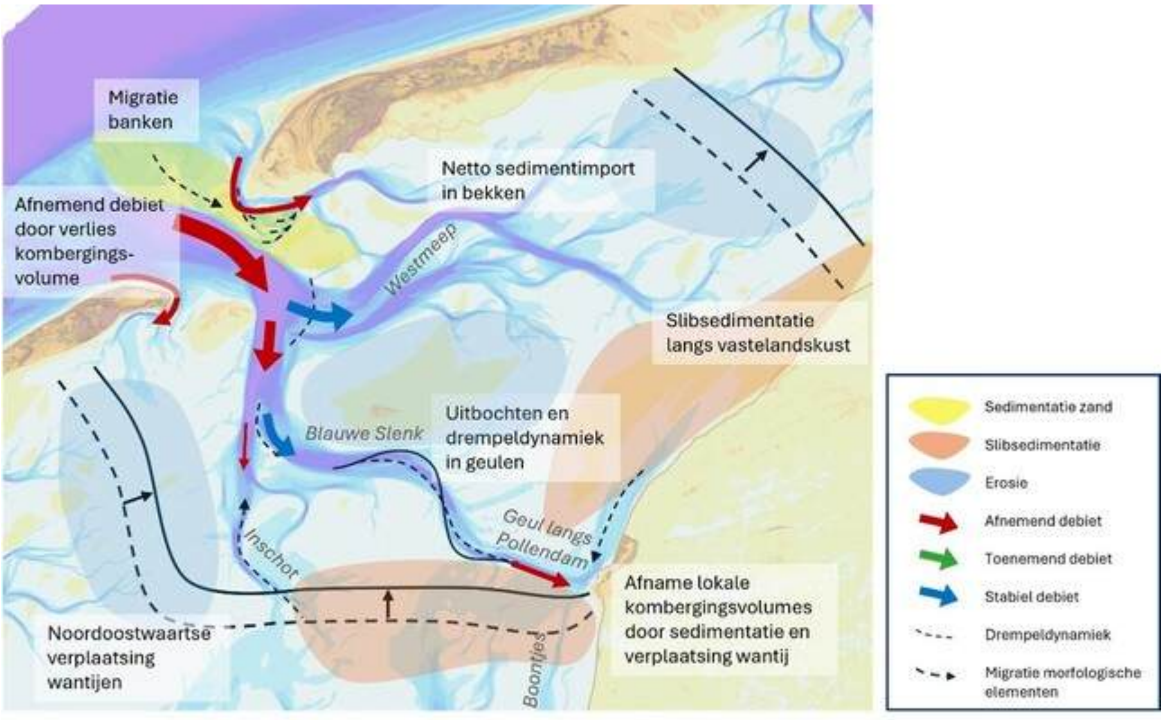

Figure 1: Development of the Vlie inlet on a timescale of decades.

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Research for Coastal Policy and Practice – a case study on the policy process and the role of conceptual models

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Introduction

Many of us work on our coast on a daily basis. We draft research proposals, do research, write papers and reports, and teach new generations of coastal scientists, practitioners and policy makers. Often our aim is to advance on all aspects: deliver great science, robust policy, and innovative practice. However achieving this is difficult, especially achieving impact on policy and practice from science. Achieving impact on policy and practice requires bringing together science and policy in a meaningful and effective way. Connecting science to policy is seen, not without reason, as one of the top challenges for sustainability in the 21th century (UNEP, 2012). In the Dutch situation, however, there is a long history within Coastal Flood and Erosion Risk Management of an established link between science and policy. This makes the Dutch policy-driven research approach an intriguing object of study.

Objective and Methods

Case Study Coastal Genesis 2. At present the Dutch coast is maintained using a dynamic conservation strategy (also referred to as dynamic preservation), developed using the results from the Coastal Genesis (Kustgenese) research programme from the nineteen eighties and –nineties. With accelerating sea level rise this management strategy could require a significant increase in nourishment volumes in the future, raising questions regarding the sustainability of the strategy. Accordingly, Rijkswaterstaat initiated the Coastal Genesis 2 (Kustgenese 2) research programme in 2015 aimed at developing a robust and sustainable long-term coastal management strategy. We analyse the policy-driven Coastal Genesis 2 research programme, identifying the process that was followed in its initiation, in determining the research agenda and in synthesizing and communicating the results. We assess the role that conceptual models play in achieving impact on policy and practice (Figure 1).

Results

Our analysis highlights that synthesising new scientific insights into shared conceptual models is critical to achieving impact in policy and practice. In the context of Coastal Genesis 2, a new shared conceptual model of the long-term sediment demand of the Dutch coast enabled the development of potential nourishment strategies. In 2021, the Minister of Infrastructure and Water Management officially articulated her intention to adopt the advised nourishment strategy from 2024 onwards in a letter to parliament.

Figure 1: The ‘Research for Policy’ cycle to support coastal policy development in the Netherlands (Lodder and Slinger 2022) CC 4.0

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Skeletonization as Means to Track Geomorphic Changes in Point Cloud Time Series: The Case of Sandy Coastal Embryo Dunes

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Introduction

The morphology of sandy coastal systems is extremely dynamic with separate constituents like dunes, bars, and berms shifting in shape, position, and volume. Apart from these larger entities, smaller morphologies, like embryo dunes can exist, which can be transient, persistent, or show spatiotemporal variations in orientation, size, and shape (Montreuil et al., 2013, Van Puijenbroek et al., 2017). Understanding their three-dimensional dynamics requires tracking their movement and morphological evolution over time.

The topography of embryonic dune fields can be captured in high detail using Unoccupied Aerial Vehicle (UAV) based LiDAR measurements. Through comparison of repeated measurements at different epochs, their dynamics can then be studied. However, with a larger number of epochs, manual investigation becomes impractical, necessitating automated methods.

Current automated methods for extracting morphological changes often assume a Eulerian approach (e.g., Kuschnerus et al., 2024), meaning change is defined as displacement of the surface at one point in space. While appropriate for mass balance assessments, specific landform dynamics escape these methods as the captured feature is time series of elevation change rather than geomorphic characteristics evolution.

Objective and Methods

The objective of this study is to develop a method for extracting the extent and characteristics of individual embryo dunes from point clouds and tracking their evolution over time using a Lagrangian approach. This allows for the identification of transport direction and morphological changes.

To achieve this, we apply the Medial Axis Transform (MAT; Ma et al., 2012; Peters & Ledoux, 2016) to extract “skeletons” of dunes, i.e., their mathematical internal and external surfaces. Several properties can be derived from these MAT surfaces, including ridge lines, dune feet, and overall dune extents. To obtain the extent of each dune, we first cluster the internal MAT points using DBSCAN, ensuring that each cluster represents a single embryo dune. Next, we delineate the outline of each cluster by fitting an alpha shape around the points used to construct the MAT.

The MAT is applied to a dataset of five consecutive UAV LiDAR point clouds acquired between February and October 2024 as part of an ongoing measurement campaign. The area under consideration in this study is an embryo dune field at the Zandmotor, The Netherlands (52°02'40"N 4°10'50"E).

Results

Figure 1A shows the derived outlines and projected internal MAT surface of part of the embryo dune field. Over time, dune outlines change from elongated to compact and rounded, while their number increases. Figure 1B presents a zoomed-in view of the black-boxed area in Figure 1A. The ridge line of the orange dune changes shape after the first epoch and later bifurcates. Figure 1C shows the orientation distribution of the MAT surfaces. In the first epoch, most dunes are orientated northeast. Over time, their orientations become more evenly distributed between 315° and 135°, reflecting the observations in Figure 1A. This suggests a shift in dominant transport directions, potentially influenced by external environmental forces.

The results demonstrate that the MAT can effectively extract representative dune extents and track their morphological evolution. Future research will explore how these changes correlate with environmental conditions like predominant wind direction, intensity, and vegetation characteristics. Further steps in the research also includes the temporal matching of identified dune extents, considering their potential merging, splitting and movement.

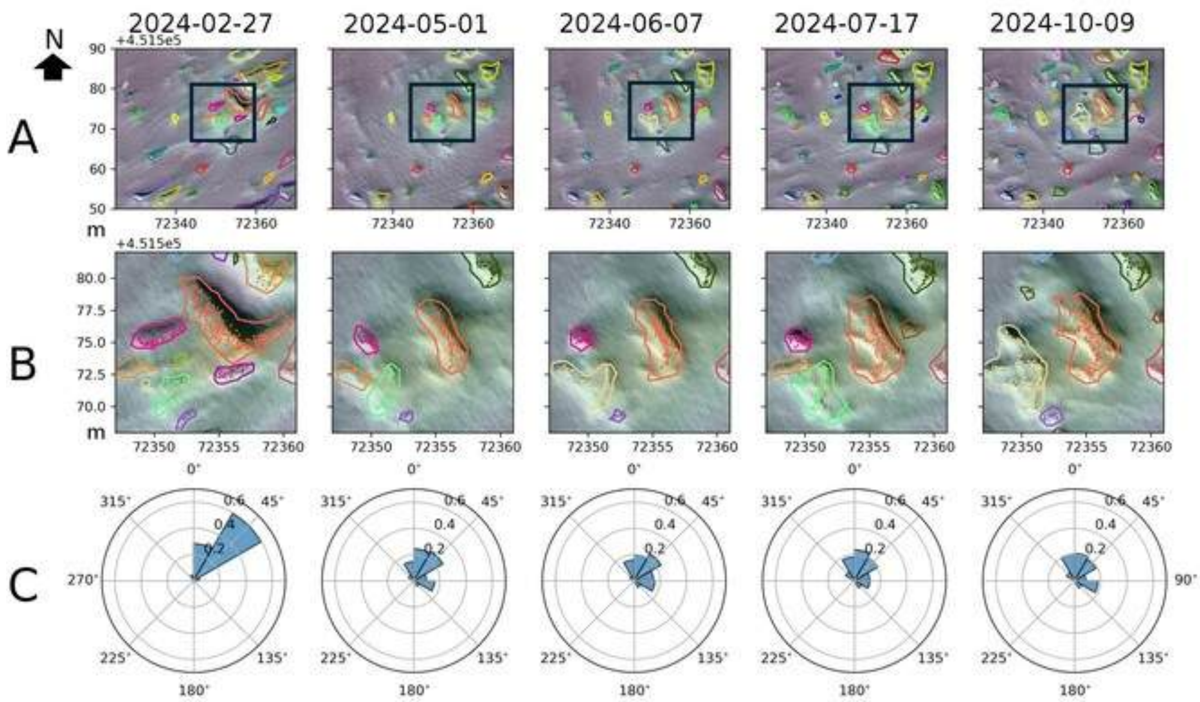

Figure 1: A) Spatial extent of different dunes, automatically extracted through the Medial Axis Transform (MAT). B) Zoom on black box of A. Here the planar projection of the internal MAT is shown for each extracted dune. C) Distribution of orientation of the internal MAT of the dunes.

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Evolution of Tidal Asymmetry at Tide Gauges Along the Dutch Coast

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Introduction

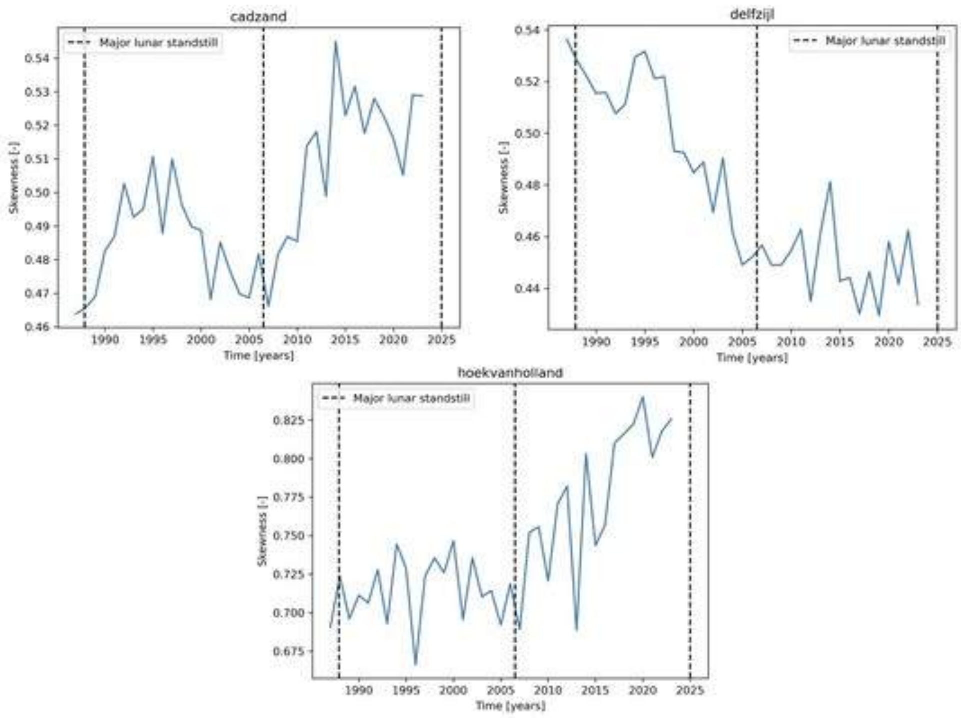
Tidal asymmetry plays a crucial role in sediment transport and morphological evolution in coastal systems. Temporal variations in tidal dynamics due to e.g. coastal engineering, sea-level rise or increasing ocean stratification can also cause changes in tidal asymmetry. Along the Dutch coast, these factors have contributed to decadal variations in tidal characteristics.

Objective and Methods

This study aims to quantify the evolution of tidal asymmetry along the Dutch coast over the past decades. We analyze surface elevation measurements from tide gauges spanning 1987 to 2024, computing the skewness of the time derivative of water level time series for each year. This metric provides insight into the relative duration and intensity of rising versus falling tides, which affects net sediment transport. Further, the contribution of different combinations of tidal constituents to the skewness is computed which could aid in the attribution process.

Results

Our findings reveal spatially variable trends in tidal asymmetry along the Dutch coastline. In the southwest Netherlands, a coherent increase of approximately 15% in tidal skewness is observed at the Cadzand, Westkapelle, Vlissingen, and Hoek van Holland tide gauges. This increase suggests an increasing flood dominance, which may enhance landward sediment transport. Conversely, at Delfzijl, tidal skewness has decreased by about 20%, indicating a reduction in flood dominance. Understanding these trends is important for anticipating changes in sediment transport and informing sustainable coastal management strategies.



Time series of water level derivative skewness at selected Dutch tide gauges.

Exploring the network structure of coastal sediment pathways at the initial stage of rip-channel formation

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Introduction

Sandy coasts are highly dynamic environments where hydrodynamic forcings drive sediments in varied directions through time and space. Therefore, analysing the resultant large number of particle trajectories is challenging. Coastal sediment connectivity is a newly-developed framework which takes advantage of techniques from network science to systematically investigate the dynamics of sediment pathways [1,2]. One of the main initial steps to analyse sediment connectivity is to establish the structure of its complex network. This step enables us not only to illustrate the sediment pathways in a quantifiable manner but also to calculate the relevant local and global network metrics.

Objective and Methods

The sediment pathways are obtained using the particle-tracking model SedTRAILS (Sediment TRAnsport vIsualization & Lagrangian Simulator) which is the core of the coastal connectivity framework. Particles in SedTRAILS are transported using hydrodynamics derived from an Eulerian model (here, the Delft3D model of Reniers et al. [3]). To mitigate the effects of lateral boundaries, only the central part of the surf zone is seeded with particles. The equations of Soulsby et al. [4] are then used to convert flow velocities and bed shear stresses to effective particle velocities. These particle velocities are then used to propagate the sediments along a fixed bed. The initial spatial configuration of the seeded particles is used to create polygons centered around each particle. These polygons are connected according to the trajectory and residence time of the particles passing through them. Consequently, it is possible to obtain the structure of the sediment connectivity network by considering the number, strength, and direction of the connections between the polygons. Furthermore, morphodynamic simulations of Delft3D can be used to define new input bathymetries for SedTRAILS at regular intervals. In this way, the temporal evolution of the network structure can be investigated.

Results

The strongest velocity is offshore directed and occurs on the sea side of the bar at around $800<y<1000$ m (Figure 1(a)). This is the location where the main channel is eventually excavated in the morphodynamic model (not shown in this abstract). Figure 1(b) shows the movement of the seeded particles in the first 30 minutes of SedTRAILS simulation. The color of each particle gets lighter as they age during the simulation. It is observed that the particles over the bar travel the longest path, and the convergence of particles emerges around the downstream of the strongest undertow. Furthermore, the resultant network of sediment pathways is structured as in Figure 1(c). The network shows spatially coherent patterns corresponding to rip currents and eddies. Once in this format, the network can be further analyzed to quantify the interconnected sediment pathways. For example, we will be able to identify the spatial distribution of main sediment sinks and sources; furthermore, patterns of sediment collection and spreading will be explored.

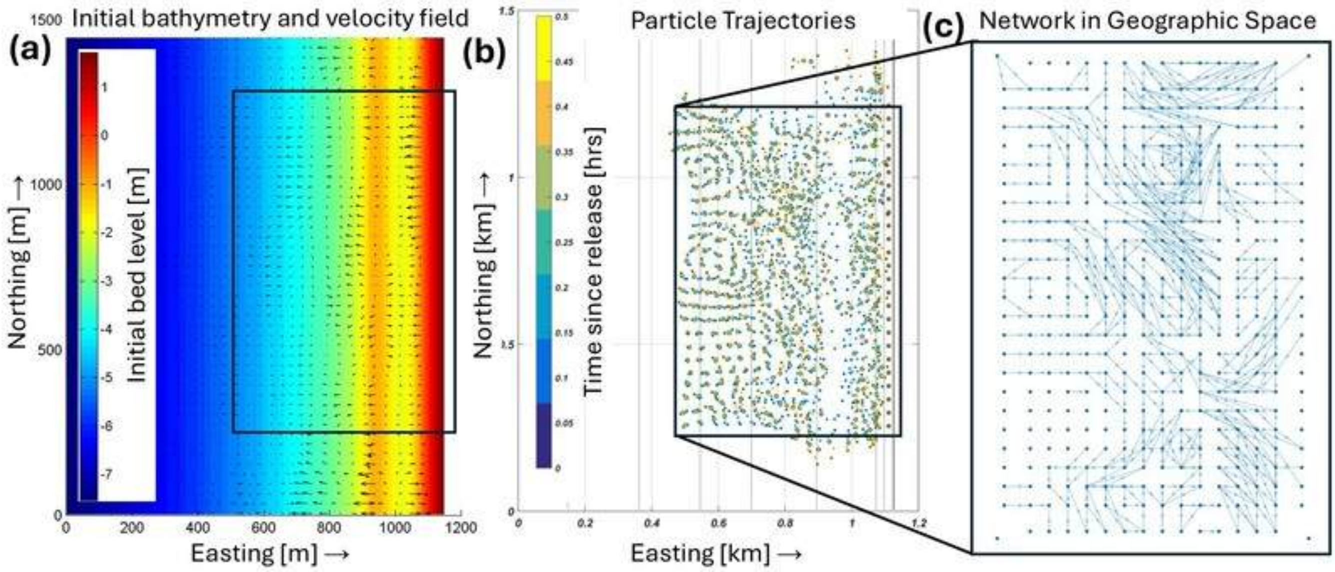

Figure (1). Simulation results (The black solid rectangle highlights the section chosen to be the SedTRAILS domain). (a) morphostatic Delft3D results - initial bathymetry and velocity field used as inputs of SedTRAILS. (b) SedTRAILS results – evolution of the positions of the particles from their initial configuration (blue) to final state (after 30 minutes; yellow). (c) SedTRAILS results - the resultant sediment connectivity network in geographic space with uniform resolution of 40 meters.

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Impact of restored intertidal area on salt intrusion in estuaries

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Introduction

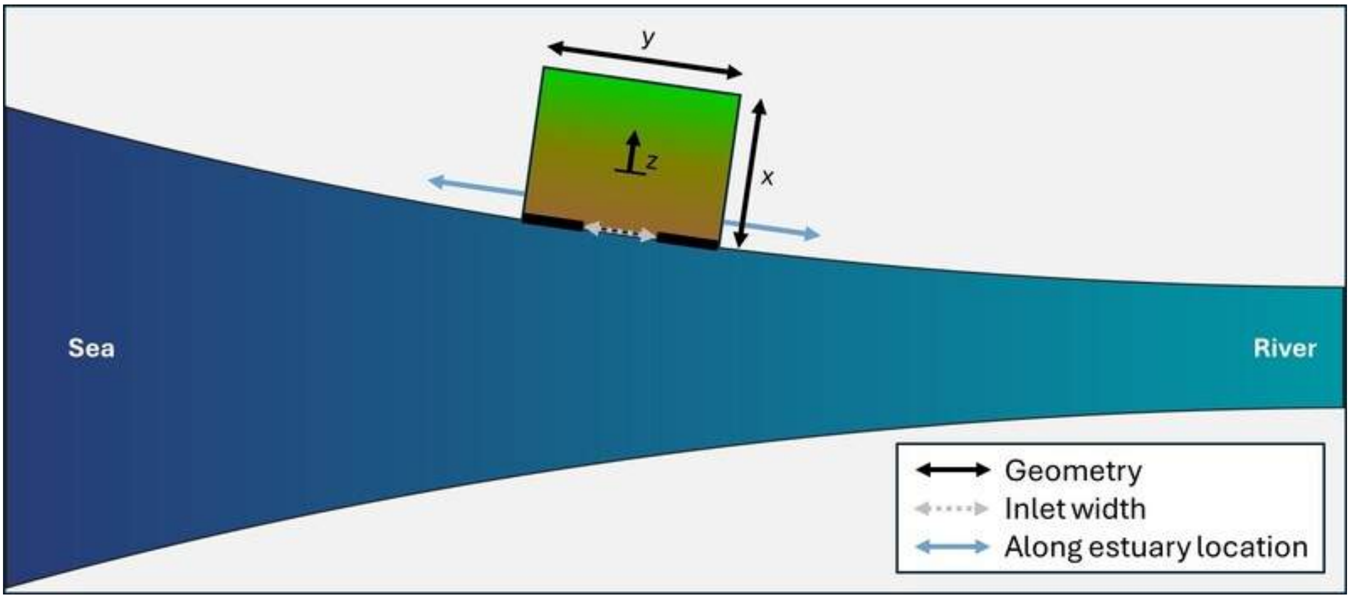
Restoring intertidal area through managed realignment is gaining attention to enhance biodiversity and flood resilience in estuaries. However, these restoration projects can also influence estuarine salt dynamics. Previous research has shown that the impact of intertidal area on salt intrusion varies depending on estuary classification (stratified vs. well-mixed) (Hendrickx & Pearson, 2024; Siemes, 2024). Furthermore, a case study in the Scheldt estuary demonstrated that managed realignment sites can either increase or decrease salt intrusion length depending on their location (Riepen, 2024). In such a well-mixed estuary, intertidal restoration near the estuary mouth tends to reduce the salt intrusion length, whereas sites further upstream may have the opposite effect. Building on these insights, this study aims to assess how restoration of intertidal areas influences salt intrusion across different estuarine types, with a specific focus on geometry and location of the restored intertidal area.

Objective and Methods

We utilize a 3D hydrodynamic model with an idealized estuary geometry using Delft3D-FM (Hendrickx & Pearson, 2024). By varying river discharge and tidal range, we were able to study a range of estuary types (salt wedge, partially mixed and well-mixed). This study focuses on short estuaries where the salt intrusion length is comparable to the tidal excursion length, making tidal dispersion the dominant salt transport mechanism. In these systems, restoring intertidal areas is expected to have a significant impact on salt intrusion dynamics due to the higher ratio of intertidal area to total estuary area. Additionally, we investigate the effect of open versus constrained inlets of restoration projects, analyzing their influence on water level-flow velocity phase differences causing tidal trapping, which is known to significantly affect salt intrusion in short estuaries.

Results

Initial model results show that substantial intertidal area is required to affect salt dynamics at the estuary scale. By focusing on short estuaries, a higher ratio of connected intertidal area to estuary area is achieved, increasing the potential for significant changes in salt intrusion. Further analysis will aid in our understanding how different realignment configurations modify estuarine salt dynamics across varying estuary types.



Schematic overview of the scenarios. For a typical funnel-shaped estuary, a managed realignment site is connected in *which the geometry, inlet width and along estuary location is varied*

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Knowledge development programme Sandy Coast: System knowledge and coastline management connected for the Netherlands

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Introduction

Dutch coastal policy aims to sustainably maintain flood protection and other functions of the coastal zone and dune areas. This is elaborated into a tactical approach and operational objectives. These have key components like ‘maintaining the coastline at its 1990 position’, ‘conserve sediments in the coastal system’ and ‘preference for soft solutions’ (see e.g. Rijkswaterstaat, 2020 and Lodder, 2024). For this it is pivotal to have insight in the needs for sand, both for the coming 15 years as well as for the longer term, with accelerated sea level rise. The knowledge development programme ‘Zandige Kust’ (Sandy Coast) was set up to improve such insights.

In the first year of the programme Deltares and Rijkswaterstaat collaborated to evaluate how much sand should be nourished, under the assumption of continuation of the present policy, should the sea level have risen with 0.5 up to 5 metres in the next one or two centuries.

Objective and Methods

For the work in the first year it was necessary to define the area that determines the position of the coastline on the long term. In other words: which parts participate in the spreading of nourished sand and should grow with the sea level. This is called the ‘active zone’ and this area needs to receive enough sediments to ‘keep up with sea level rise’ (Figure 1). The amount of sediment needed was calculated as the sum of net transports out of the area plus the product of surface area and rate of sea level rise (Taal et al., 2023).

In the next two years of the programme, much new knowledge was derived (i) on the sediment balance of the Dutch coastal system, especially since the start of the present policy (1990), (ii) on the behaviour of the deeper shoreface (bordering the coastal zone) and (iii) on the net alongshore transports in the active zone (Figure 1). This new knowledge was combined with information on nourishments since 1990 for each coastal section and all existing knowledge on the morphological behaviour.

Results

In this way the need for sediments and/or nourishments for the coming 15 years was assessed using three different calculations for each coastal section: (i) using the concept of the active zone, (ii) using the method of Rijkswaterstaat (2020) and (iii) using historical nourishment volumes. This was done for four levels in the morphological scale cascade: the individual active zone, a coastal cell, a coastal subsystem (Delta coast, Holland coast, Wadden coast) and for all coastal zones of the Netherlands together. As a whole the results were close to the calculations of Rijkswaterstaat (2020), but with reduced uncertainty and more elaboration on smaller spatial scales. This also serves other purposes, like better planning of nourishments that are not immediately needed for coastal maintenance (but serve the aim of conserving sediments in the coastal system, on each spatial scale).

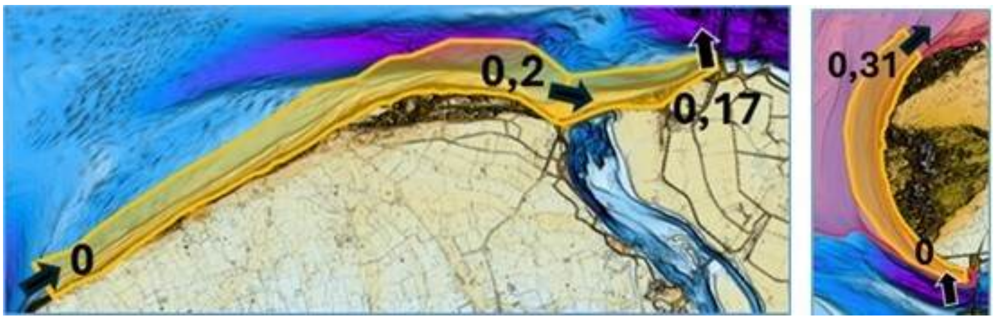

Figure 1: Transports and surface area of active zones of the coasts in the coastal cell: 'mouth of the Eastern Scheldt'

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Nearshore sandbar morphodynamics of a nourished barrier island coast, Ameland

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Introduction

The implementation of shoreface nourishments induces significant morphological perturbations in the nearshore zone, impacting natural morphological features such as alongshore sandbars (Grunnet & Ruessink, 2005). These sandbars play a crucial role in coastal protection by acting as natural barriers that dissipate wave energy during storm events, thereby mitigating beach and dune erosion (Shand et al., 2001). Moreover, sandbars play a role in the redistribution of (nourished) sand in the nearshore. Therefore, understanding their post-nourishment response is essential for assessing coastal safety and ensuring the long-term stability of the nearshore environment.

Objective and Methods

The dynamics of nearshore sandbars along the barrier island of Ameland, The Netherlands, is influenced by both natural and artificial sand inputs. Cyclical shoal attachments (natural inputs) from the outer delta occur at the island's western tip, while multiple sand nourishments (artificial inputs) have been implemented in the central region since 1998. These complex interactions make it difficult to assess the long-term impact of foreshore nourishments on sandbar dynamics and to separate their effect from natural processes. This study uses JarKus annual bathymetry data of Ameland's northern coast to identify sandbars and analyze the evolution of their parameters from 1965 to 2023, focusing on their variability in both cross-shore and alongshore directions, while examining the influence of natural and artificial sand inputs.

Results

The results show that foreshore nourishments along Ameland's northern coast have significantly impacted the nearshore dynamics, particularly the growth and migration of sandbars. Shoal attachments increased the profile volume of the western section and temporarily paused the offshore migration of sandbars. In contrast, nourishments led to an increase in profile volume through increased sandbar volumes in the central and eastern sections, at times doubling the total sandbar volume (e.g., from 400 m3/m to above 800 m3/m after the 1998 nourishment; see Figure 1). Nourishments were also found to pause the offshore migration and promote the development of crescentic patterns, bar switching, and the formation of additional sandbars. The pause in offshore migration has been observed to last longer due to shoal attachments. Nourishments of greater length (e.g., 1998 and 2010) coincided with larger increases in sandbar volume (see Figure 1), although such instances partly coincided with natural sand inputs. In our contribution to the meeting, the key forcing mechanisms responsible for these changes in sandbar characteristics are identified and discussed.

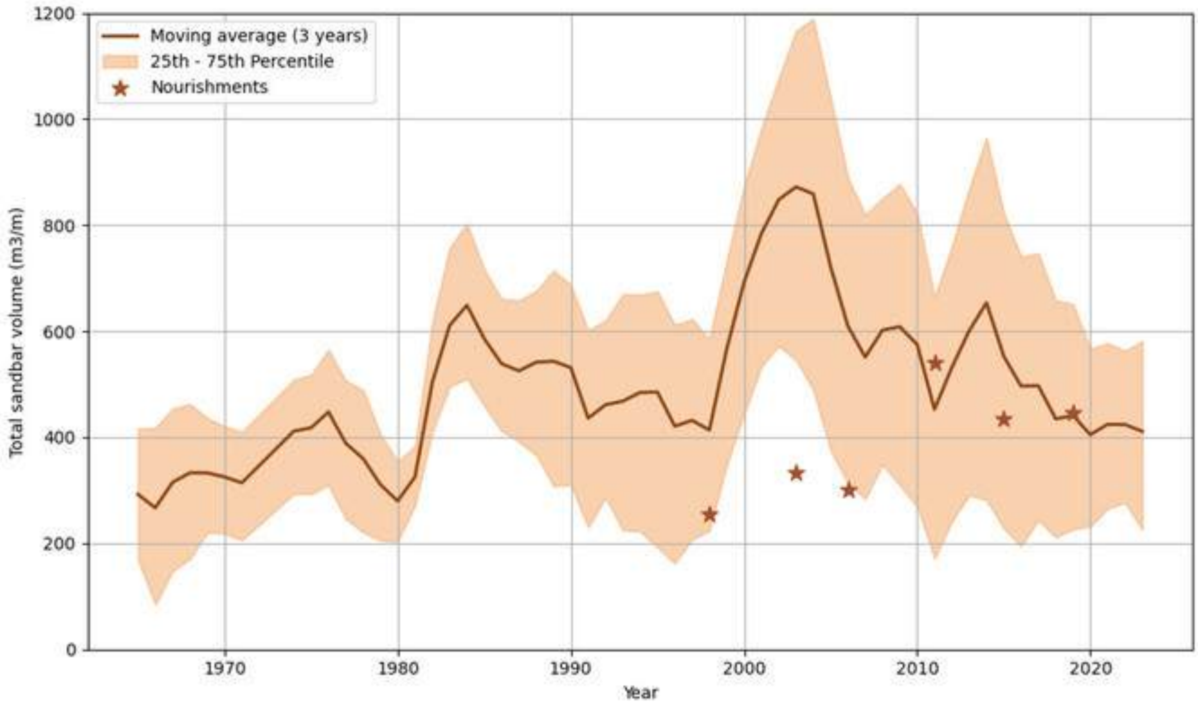

Figure 1. Average total sandbar volume (in m³/m) using a 3-year moving average for the entire study area. Total sandbar volume represents the cumulative sandbar's volume within each transect. Stars indicate nourishment events and their corresponding volume.

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Reducing saltwater intrusion through shipping locks using bubble curtains - bridging laboratory and reality

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Introduction

Increasing occurrence of seasonal droughts and rising sea water levels due to climate change result in enhanced saltwater intrusion in rivers and shipping locks. This poses a threat to the freshwater sources and enhances harbour siltation and maintenance due to changes in salinity. In a shipping lock, the opening of the lock gate results in an undesirable saltwater intrusion where the denser salty water flows underneath the lighter freshwater in the form of a gravity current. A common and reliable choice for mitigating saltwater intrusion is the use of bubble curtains. The vertical momentum of the water entrained by the bubble curtain disrupts the horizontal flow of the intruding gravity current. To ensure better design and robust field installation, it is imperative to further our understanding of the physics and operation of the bubble curtains. We performed computational fluid dynamics (CFD) simulations of bubble curtains in a lock-exchange configuration. Numerical simulations help overcome several limitations associated with experiments and field measurements such as access to 3D volumetric time-resolved velocity and salinity data, and flexibility to simulate a wide range of domain sizes.

Objective and Methods

This work aims to characterize and explain the flow resulting from the interaction between the bubble curtain and the gravity current for different values of the governing parameters. The overarching goal is to translate laboratory-scale results of bubble curtain effectiveness to field-scale locks.

We employ Euler-Euler large-eddy simulations to model the air-water bubbly upward flow, and we consider the Boussinesq approximation for the density differences due to salt concentration in the momentum equations. We use a prototypical lock-exchange setup, where the bubble curtain initially separates the fresh and salty side of a lock. The simulations cover a wide parameter range (lock depth – H , density difference – $\Delta\rho$ and air flow rate – q_{air}) covering a wide range of Froude air number $Fr_{air} = (gq_{air})^{1/3}/(g'H)^{1/2}$ values, with g the gravitational acceleration and g' the reduced gravity. Fr_{air} represents the air flow inertia required to counteract the inertia of the gravity current. We additionally vary the aspect ratio of the lock $AR = H/W$ (with W the width of the lock) for a broad range of lock sizes covering laboratory setups with $AR \sim 1$ and real shipping locks with $AR \sim 0.25$. Cases with $AR \sim 1$ were validated using experimental data [1].

Results

The physical quantity of interest for evaluating the bubble curtain's performance is the effectiveness, which characterizes the amount of salt water that is blocked by the curtain in comparison with the case without the curtain. We consider as a reference locks with $AR \sim 1$. In this case, for $Fr_{air} < 0.91$, the inertia of the curtain is not enough to stop the gravity current in what is known as the breakthrough regime (see Figure 1a). For $Fr_{air} > 0.91$, the curtain-driven regime emerges, where the curtain's inertia is strong enough to stop the gravity current, and the strong entrainment of water into the bubble curtain drives recirculation cells on each side of the curtain (see Figure 1b). We determined the typical velocity, length and time scales of these recirculation cells as a function of Fr_{air}. For the cases with field-scale AR, intriguing secondary flow patterns are observed in the curtain-driven regime. This result points to a difference between the flow in field-scale and laboratory-scale locks. We quantify the influence of these secondary flow patterns on the effectiveness and the scales of motion thereby shedding light on the applicability of laboratory-scale results to field-scale scenarios.

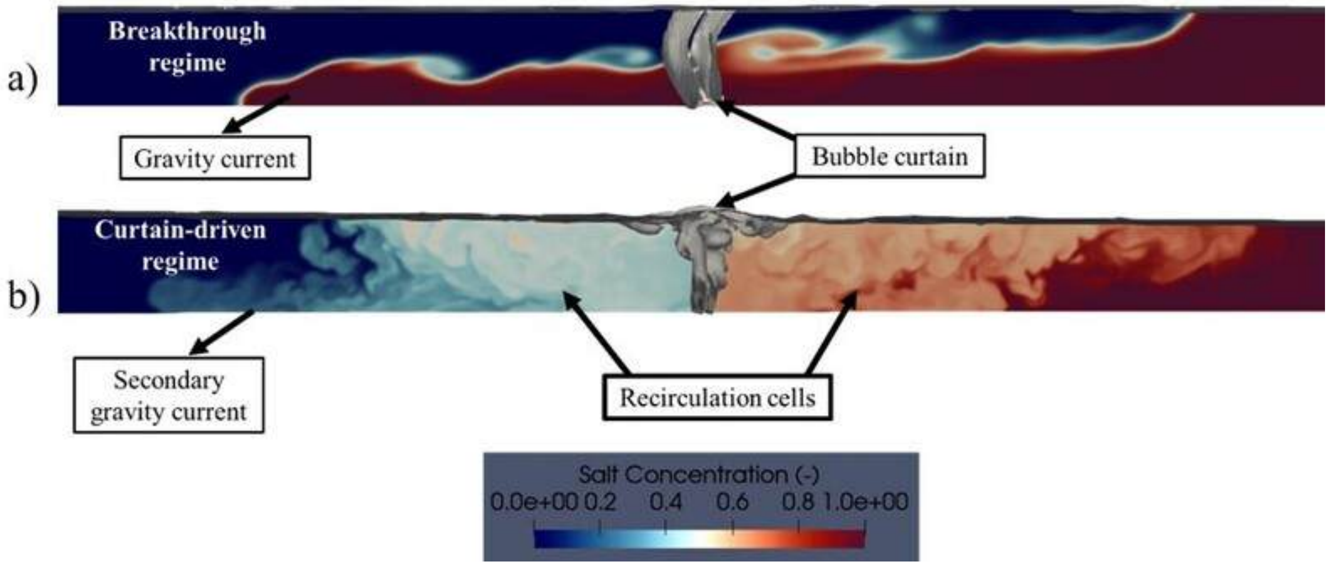

Figure 1: Contours of salt concentration fields obtained from simulations for a) breakthrough regime and b) curtain-driven regime

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Biogeomorphic feedbacks in coastal dunes: How the initial spatial distribution of dune grass patches shapes future dune morphology

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Introduction

Biogeomorphic systems are formed by the dynamic interplay between living organisms and geomorphological processes (Viles, 1988). In coastal ecosystems, these interactions are particularly pronounced, as engineering organisms - from marsh vegetation to reef-building corals - actively shape the shoreline. Because of the ecosystem services they provide, including biodiversity, freshwater provision, carbon storage, and flood defense, biogeomorphic coastal landscapes are of great value (Barbier et al., 2011).

In many biogeomorphic systems, a positive feedback is present between the engineering species and its environment. An archetypical example of such a feedback is found in coastal dune systems. Pioneer dune grasses initiate dune formation by trapping airborne sediment. This sediment buries the grasses, which stimulates plant growth, thereby increasing their sand-trapping capacity (Bonte et al., 2021; Nolet et al., 2018). The strength of this feedback is species-specific and is influenced by the spatial organization of aboveground plant biomass Lammers et al., 2023; Reijers et al., 2021). Although we have a solid understanding of how individual plants can build dunes, the interactions between these plants, and the embryonic dune bodies they create, are less well understood. The initial spatial organization of individual dune grass patches could play a crucial role in shaping the biogeomorphic landscape (Schwarz et al., 2018).

Objective and Methods

In this work we will look beyond individual dune formation, and investigate the role of the initial spatial organization of vegetation patches on subsequent dune build-up. We hypothesize that, much like the shoot organization within an individual patch (Reijers et al., 2019), the spatial distribution of dune grass patches can steer local sand trapping efficiency at the landscape scale. Using high-resolution aerial imagery and elevation models, we tracked the development of a large natural dune system in the Netherlands over a 10-year period. We extracted the spatial characteristics of the initial embryonic dune field and assessed its effect on subsequent dune build-up and landscape formation.

Results

Our results indicate that, rather than the initial size of embryonic dunes, the proximity to neighboring embryo dunes strongly influences dune build-up on a landscape scale. We observed a clear relationship between the local density of dune grass patches and subsequent dune height. Following a S-shaped curve, patches in areas of low density exhibit only limited height accumulation, while increasing density leads to a rapid rise in future dune height that eventually flattens of at the highest densities. In our study system, the strength of this S-shape relationship intensifies over time and displayed a dominant spatial scale of 3–13 meters. Our findings demonstrate the persistence of dune grass patches, and highlight how the initial spatial distribution of embryonic dunes can serve as a blueprint for future dune formation. Moreover, they illustrate the importance of biogeomorphic feedbacks that extend beyond the scale of individual plants, and their role in shaping coastal landscapes.

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Biotic and Abiotic Drivers of Coastal Dune Height on the U.S. East Coast: A Multi-Scale Approach Using Remote Sensing, Field Surveys, and Stable Isotopes

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Introduction

Coastal dunes play a crucial role in protecting shorelines from erosion and flooding, yet their resilience is increasingly challenged by climate change and rising sea levels (Haigh et al., 2016). While abiotic processes such as wind, waves, and sediment availability shape dune morphology (Edelman, 1972), vegetation also plays a key role in stabilizing dunes through plant-sediment interactions. Species-specific plant traits influence dune height and slope, with *Uniola paniculata* forming narrower dunes with lower sand accretion than *Ammophila breviligulata* due to differences in growth form (Hacker et al., 2019).

Beyond inherent plant traits, allochthonous nutrient inputs, such as seabird guano, further influence vegetation dynamics, modifying plant productivity and sand capture efficiency (Anderson et al., 2008; Buelow et al., 2018). Therefore, guano-driven changes in vegetation cover effects morphology on sandy coastal ecosystems (Reijers et al., 2024). Along the U.S. East Coast, *Ammophila breviligulata* and *Uniola paniculata* are expanding their ranges due to climate change, raising questions about how shifting species distributions and nutrient dynamics will alter dune morphology and resilience.

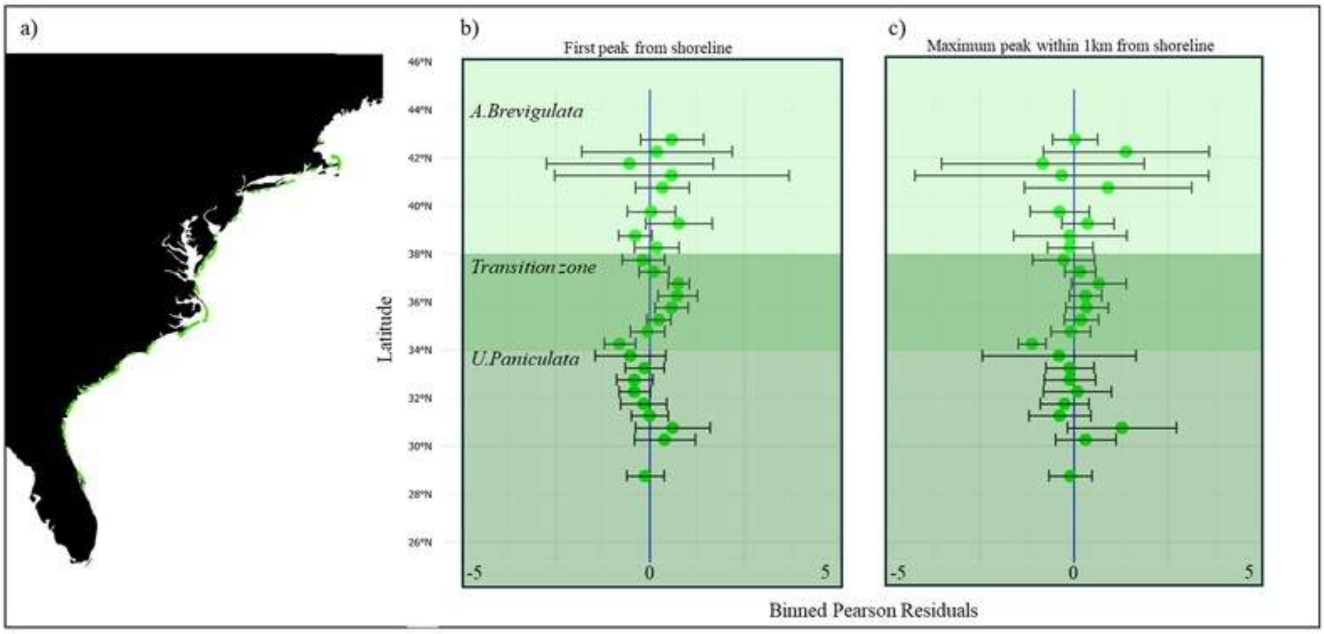
Objective and Methods

This study quantifies how biotic factors influence dune height and morphology along the U.S. East Coast. We assess deviations from abiotic-based dune height predictions and link them to the distribution of *Ammophila brevigulata* and *Uniola paniculata*. We examine species differences in sand-trapping traits, their impact on dune morphology, and how allochthonous nutrients influence trait variability.

To achieve this, we use remote sensing, field surveys, and stable isotope analysis. Dune heights are derived from DEMs and predicted using PCA of abiotic variables, with residuals analyzed across the species' latitudinal ranges. A field survey quantifies key plant traits, while drone-derived DEMs and orthomosaics reveal how these traits shape dunes. Stable isotope analysis links nutrient subsidies to plant traits, clarifying their effect on sand-trapping capacity.

Results

GLM models for dune height, based on abiotic predictors, explained 75.9% and 73.6% of the deviance in dune elevation. Model residuals were positive in the *Ammophila brevigulata* range and negative in the *Uniola paniculata* range, particularly in the 34°–38° latitude transition zone, where increasing Ammophila brevigulata presence coincides with a gradual rise in dune height. Post-hoc emmeans tests revealed that the species differ most in the degree of inhomogenous shoot orientation, particularly between embryo dunes and foredune crests. Drone imagery shows that *Ammophila brevigulata* exhibits a distinct lateral growth strategy, aligning at ~45° to the dune slope. In contrast, Uniola paniculata lacks this clear orientation. Allochthonous nutrient assimilation increases the spatial inhomogeneity of *Ammophila brevigulata* on both embryo dunes and foredune crests. However, for *Uniola paniculata*, this effect is weaker on embryo dunes and slightly negative on foredune crests. This suggests that nutrient-driven trait changes in *Ammophila brevigulata* may enhance its ability to modify dune morphology, while *Uniola paniculata* exhibits greater resistance to allochthonous nutrient influences.



Panel a) shows the outline of the USA, in which green points depict natural coastal dune systems included in the analysis, the y-axis expresses latitude. Pearson residuals based on GLMs for the prediction of dune height are averaged over 0.5° latitude intervals and are plotted versus latitude mid-point of the bin. Panel b)shows the residuals based on the GLM to predict the first elevation peak from the shoreline (proxy for dune height). Panel c) shows the maximum elevation peak within 1 km from the shoreline (proxy for dune height). The error bar displays the standard deviation in Pearson residuals per latitude bin. The latitudinal range of A. Brevigulata and U. Paniculata is depicted in light green and dark green respectively.

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Forecasting Hurricane Impacts on the US coast

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Introduction

Coastal zones are areas of high economic and ecological value which are under threat of natural hazards such as flooding and erosion. Extreme weather events like hurricanes cause loss of life, property damage, harm to the environment and disruption of local economies. Moreover, accelerated sea level rise will potentially increase intensities of extreme water levels, which will aggravate the impact of natural hazards.

It is therefore important to understand and predict the impact of these events so that authorities are able to prepare and evacuate the population. This necessitates an approach to assess flooding and damages using a forecasting system. While a number of forecasting systems are available, these usually focus on a relatively small area and a small number of hazards, mostly total water level, and rarely impacts.

The NOPP Hurricane Coastal Impacts (NHCI) project's goal is to improve our understanding of the physical processes of flood and erosion hazards and their impacts. Through ongoing research and model development, it contributes to the goal of enhancing coastal resilience against the increasing threat of extreme weather events. This presentation focusses on coastal impact forecasts, by upscaling our models to larger regions, including more physics and more impacts.

Objective and Methods

The COSMOS2 (COastal Storm MOdelling System) forecasting system covers both a large area of the US East Coast and Gulf of Mexico, and is an innovation of Barnard et al. (2014) who assessed hazards on the US West Coast. The new forecasting system is able to provide real time predictions of water levels, wave heights, flooding and morphological impact along the US coast. We use a modelling train that includes fast wave, surge and flooding models (SFINCS (Leijnse et al., 2021) and HurryWave), using forecasted COAMPS-TC wind and pressure fields. For the morphological impact prediction use more complete 2D XBeach models (Roelvink et al., 2009), with 700+ XBeach domains all along the sandy coastal areas. Computational expense of the computationally intensive 2D Xbeach models was reduced by optimizing the domain size, grid resolutions and settings as much as possible.

The forecasting system was applied, tested and continuously improved during hurricane seasons of 2022, 2023 and 2024 on the US East and Gulf of Mexico Coasts. It provided predictions of the impact of impactful Hurricanes Ian, Idalia, Lee, Ophelia, Helene and Milton.

Results

Validation of the modelled water levels and wave heights were validated by comparing with the observations at NOAA stations and deployed (drifter) wave buoys. The system was able to make an accurate forecast of the water levels and wave heights, both in terms of timing and maximum value of the high water.

Using the hydrodynamic surge and wave forcing, local 2D XBeach models are activated to predict dune erosion, overwash and breaching. To make a quick assessment of the morphological impact, the XBeach output was classified according to the Sallenger (2000) regimes of increased severity of coastal change. Figure 1 shows an example of a morphological prediction around Midnight Pass, south of Siesta Key. This former inlet has been closed for decades and re-opened during Hurricane Helene and Milton where a small shallow breach was formed, as observed in the post Milton imagery by NOAA.

In the presentation we will focus on the performance of the modelling system for the 2024 hurricanes Helene and Milton, as well as discuss the importance of taking uncertainties into account.

Figure 1: Pre-Helene/Milton imagery (left) and Post-Milton imagery (mid, source: NOAA) showing a small shallow breach and overwash deposits at Midnight Pass. The Xbeach model predicted breaching (right).

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Integrating Thermal and Coastal Dynamics in Modelling Permafrost Erosion: A Case Study at Barter Island

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Introduction

Permafrost affects over 30% of the world’s coastline. These coasts are susceptible to rapid erosion rates of up to 2 – 10 meters per year (Lantuit, 2012). In the Arctic, erosion mechanisms differ from conventional low-latitude coastlines like the Netherlands due to the importance of thermal processes (Ravens, 2017). First, the seasonal presence of sea ice attenuates waves for a large part of the year. Second, sediment can only be eroded when thawed due to one of the two dominant erosion processes, which are called thermal abrasion (Figure 1a) and thermal denudation (Figure 1b). Models are being developed for these environments but are in their pioneering stages.

The Arctic region is undergoing transformative environmental shifts due to global warming. For example, the number of days the Arctic sea remains open has been rising. This enables the creation of larger waves due to longer fetches. Moreover, warmer air temperatures and increased permafrost temperatures are all linked to increased coastal erosion. This study delves deeper into the mechanisms at play, particularly thermal denudation, to enhance our ability to simulate and predict erosion for permafrost-affected coastlines.

Objective and Methods

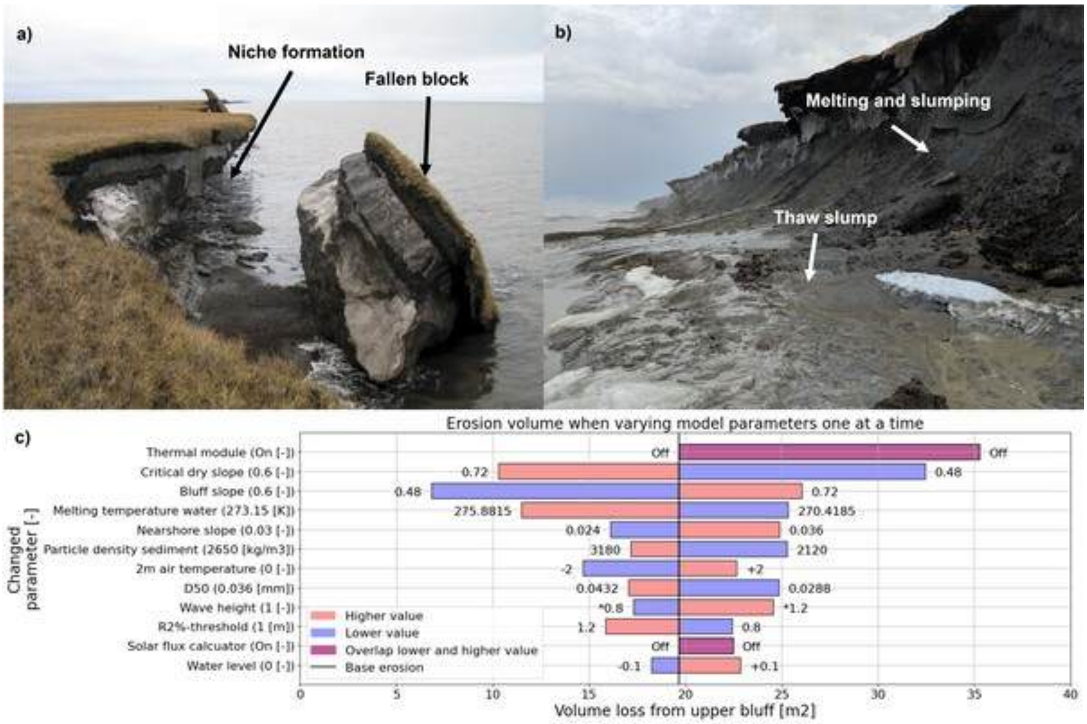
To research the effect of climate change on thermal denudation-affected coastlines, we required a process-based model with the ability to simulate extended periods of time. Ravens et al. (2017) provided a starting point. They present a method for modeling Arctic erosion, referred to as ‘Arctic XBeach’. Their model integrates a thermal model directly into XBeach. To facilitate the simulation of climate change time scales, we developed a Python wrapper that decouples the thermal model from XBeach. The thermal model simulates the ground temperature to determine an erodible layer. It is relatively fast and can run continuously, while the wrapper only activates XBeach during periods with expected morphological change, i.e., during storms. This change allowed us to simulate decades instead of just single storms.

Including the thermal model led to better predictions of Arctic coastal retreat and a better understanding of thermal denudation (Figure 1b). Validation against observed data at Barter Island (AK) confirmed the model's reliability, with skill scores showing accuracy in predicting ground temperature and coastal retreat. Moreover, our findings highlight the critical need to include thermal processes when modelling Arctic erosion, which requires the integration of thermo-, hydro-, and morphodynamics to accurately hindcast erosion in the Arctic.

Results

Our sensitivity analyses indicated that the environmental drivers affected by climate change (i.e., air and sea temperatures, water level) will accelerate the erosion of permafrost-affected coastlines under the effects of climate change, confirming the findings of previous work. For example, an increase in air temperature of 2 degrees resulted in >10% more erosion. Additionally, an increase in sea level of 0.1 meters resulted in over 15% more erosion (Figure 1c). Moreover, rising temperatures will compound with diminishing sea ice to widen the annual window during which erosion can occur, which will increase the number of storm events that lead to erosion. We showed that lower bluffs composed of finer sands are especially vulnerable, with a 20% smaller mean sediment diameter resulting in 25% more erosion (Figure 1c).

The low computation cost means that the model can be applied to predict coastal erosion for larger regions, potentially benefiting strategic coastal management and policymaking. The developed model can be used as a tool to research the quantitative effects of climate change on the erosion of Arctic coastlines and gain a deeper understanding of how climate change affects the processes that ultimately lead to the erosion of permafrost bluffs.



Example of thermal abrasion (Figure 1a, Drewpoint, AK. Photo by Benjamin Jones, 2017), example of thermal denudation (Figure 1b, Barter Island, AK. Photo by Shawn Harrison, 2018), and most sensitive parameters found during sensitivity analysis with the developed model (Figure 1c).

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Measured Storm Erosion at a Hybrid Dune Compared with a Sandy Dune

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Introduction

Rising sea levels and intensifying storm events are increasing the risks of coastal erosion and flooding. This underscores the need for innovative and sustainable coastal defense strategies, such as hybrid dunes ("dike-in-dune"), in addition to traditional sandy dunes (Almarshed et al., 2019). Hybrid dune structures combine the natural buffering capacity of sandy dunes with the structural stability of a dike, potentially offering a more resilient approach to coastal protection. This study compares the erosion response of hybrid and sandy dune systems during a high-energy storm surge in a field experiment on the Sand Engine near The Hague, Netherlands.

Objective and Methods

As part of the Hybrid Dune project, four different dike/dune sections were constructed at an erosive location to assess their erodibility. This study focuses on Section 1 (Hybrid Dune) and Section 2 (Sandy Dune) during the period of December 21–23, 2024, when the dunes were exposed to multiple high-water events with two largest peak levels of 2.1 and 1.7 m NAP.

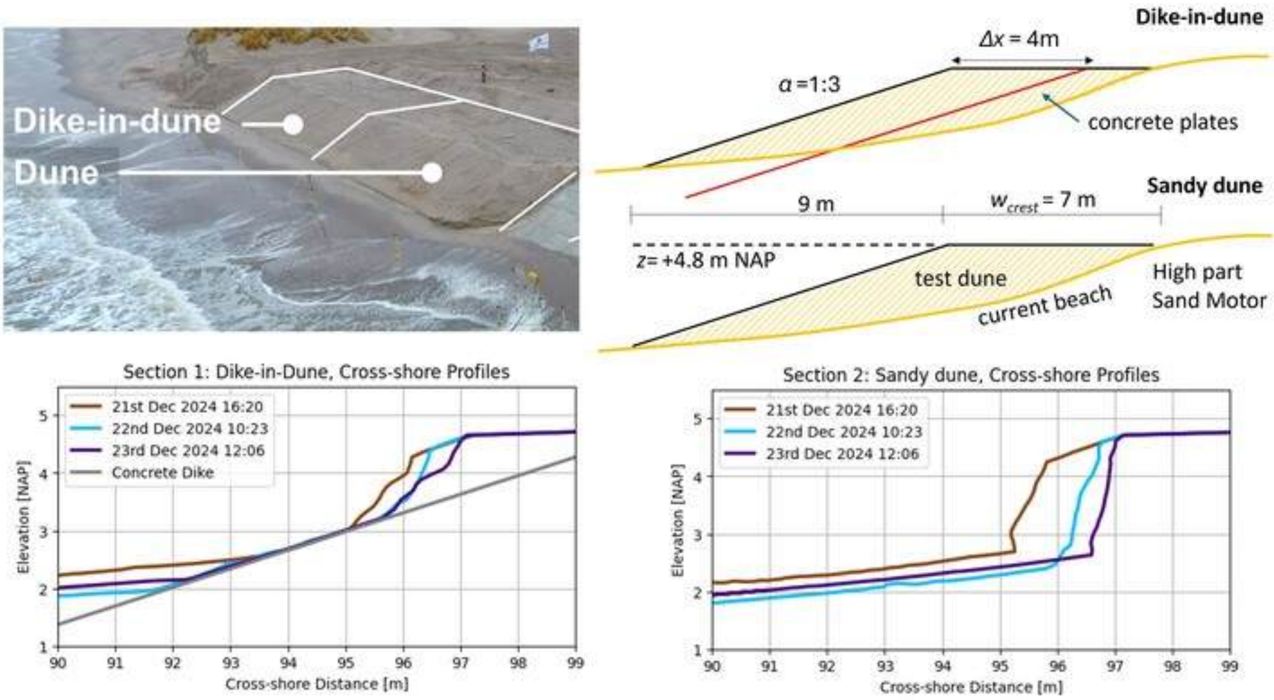
To measure morphological changes, high-frequency 3D laser scanners were installed in front of the dune sections. These scanners recorded cross-shore profiles, enabling high-resolution detection of erosion and sediment redistribution patterns. While LiDAR technology has been rarely applied in coastal studies to capture fine-scale morphological changes, it has been successfully demonstrated in previous work (Van Wiechen et al., 2024)

Results

The bottom-left panel of the figure presents the cross-shore profiles of Section 1 (Hybrid Dune), showing a 30–50 cm retreat of the dune face following high water on December 22. During the subsequent high-water event (1.8 m NAP), the dune crest retreated an additional 30 cm, while the beach profile increased by 2–8 cm, indicating sediment accumulation.

The bottom-right panel illustrates Section 2 (Sandy Dune), where the dune face retreated by 1.0 m after the first high-water event. The second high tide caused a further 30 cm retreat, with sediment transported offshore. However, the beach profile increased by 10 cm, suggesting sediment redistribution and partial recovery.

Despite differences in structure, both dune sections exhibited a similar pattern of initial dune face erosion followed by beach elevation, indicating comparable sediment redistribution. While the hybrid dune reduced landward erosion, sediment dynamics in front of the dune remained similar to those in a fully sandy system. This suggests that hybrid dunes can enhance coastal safety by providing structural protection while still facilitating natural sediment transport, supporting long-term resilience to storm-induced erosion.



Overview of the Hybrid-Dune project, focusing on Sections 1 and 2. The bottom-left panel illustrates the cross-shore profile of Section 1 (Hybrid Dune), while the bottom-right panel presents the cross-shore profile of Section 2 (Sandy Dune), both recorded between December 21–23, 2024.

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Channel-harbour exchange and its influence on salinity dispersion in a partially stratified branch of the Rhine-Meuse estuary

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Introduction

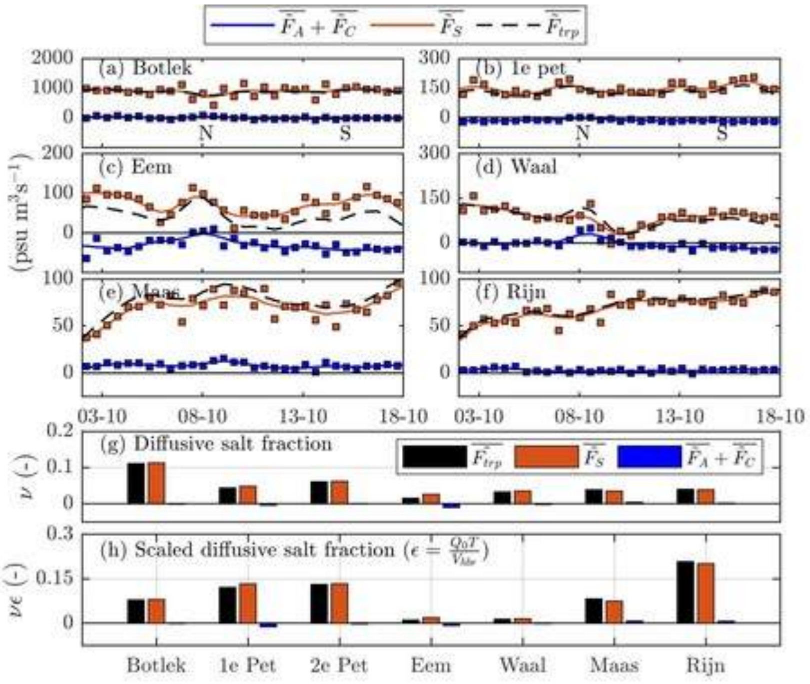
Salt intrusion is known to be influenced by harbours and side channels. These features may enhance salt dispersion by temporarily trapping incoming salt water and releasing it later in the tidal cycle (Okubo, 1973; Dronkers,1978; MacVean and Stacey, 2011). While the contribution of these features to tidal dispersion is well-established for well-mixed estuaries, the governing processes in deeper (partially stratified) systems have remained less studied. In this study, we investigate the channel-harbour exchange in the New Meuse, a partially stratified branch of the Rhine-Meuse estuary.

Objective and Methods

We aim to determine the mechanisms of channel-harbour exchange in a partially stratified situation, explain where these mechanisms depend on and quantify the degree in which they contribute to salinity dispersion. For this, we study harbour basins in the New Meuse located just upstream of the junction with the Old Meuse and the New Waterway, a region characterized by large salinity gradients over short distances. During a field campaign, four shipboard surveys were conducted at two harbour basins under both spring and neap tide conditions, and the contribution of different exchange mechanisms was quantified using a decomposition of the instantaneous salt flux through the harbour entrance. Next, a numerical model of the Rhine-Meuse estuary was used to verify the field observations and assess the net salt flux resulting from channel-harbour exchange on an intertidal timescale (tidal trapping).

Results

The decomposition of the instantaneous fluxes through the harbour entrance revealed significant differences in the relative contributions of a vertically sheared exchange flow. A weak exchange flow was observed in the harbour, where the salinity range in the main channel was limited. Analysis of the exchange flow and salinity range suggests that the exchange flow is proportional to the salinity range raised to the power 3/2, which explains the observed differences. The harbour-induced additional up-estuary salt flux (tidal trapping) was found to be primarily driven by the dispersive effect of this exchange flow (Fig. 1). Given the sensitivity of exchange flow to the salinity range, harbours located in regions with a smaller salinity range contributed significantly less to the net up-estuary salt flux. This also explained why the largest harbours contributed the least to the up-estuary salt flux, which is contrary to expectations, as the storage/release flux typically scales with harbour size. The contribution of tidal filling and emptying of the harbour basins was found to be small and to dampen the additional up-estuary salt flux. Overall, the results indicate that in deeper systems, tidal trapping is governed by diffusive exchange, and the contribution of classical tidal trapping is negligible.



Overview of additional salt flux resulting from channel-harbour exchange. (a-f) Excursion-averaged additional salt flux ((F ̃_trp) ̅), contribution of the diffusive channel-harbour exchange (F ̃_S) ̅ (mainly vertical exchange) and contribution of cross-sectional averaged exchange ((F ̃_A) ̅+(F ̃_C) ̅), shown for different harbours in the New Meuse. (g) Excursion-averaged and time-averaged additional salt flux, shown as a fraction of the total up-estuary transport to balance flushing by river discharge (diffusive salt fraction) for different harbours. (h) Same as (g), but with scaled diffusive salt fraction to eliminate size differences.

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Cutting the tail: will the tidal channel Eilanderbalg reduce the length of Schiermonnikoog?

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Introduction

The Dutch Wadden Sea consists of several tidal inlet systems that typically feature one or several channel-shoal complexes. An example is the channel/shoal-system of the Wadden Sea located in between Schiermonnikoog and the mainland. West of Schiermonnikoog, water can enter or leave the Wadden Sea through the channels Westgat, Zoutkamperlaag and Gat van Schiermonnikoog, whilst east of Schiermonnikoog, water typically enters through the Lauwers channel with the Eilanderbalg as one of its branches near the southern shore of Schiermonnikoog. The border where the tidal currents from both sides meet is the tidal divide, which in this case separates the tidal basin of the Zoutkamperlaag in the west and the tidal basin of the Lauwers in the east.

Historic bathymetric surveys indicate a highly dynamic morphology of the tidal basins consisting of migrating channels and shoals, whilst also the tidal divide migrates through time. Schiermonnikoog expands towards the east, while the Eilanderbalg channel erodes the southern shore of the island tail. The question raises: can the eastward expansion of Schiermonnikoog continue or will the Eilanderbalg cut off the island tail? As a result, in-depth knowledge regarding the historic morphological evolution is vital for predicting the future morphologic evolution of Schiermonnikoog.

Objective and Methods

In this work, the historic morphological evolution of Schiermonnikoog and the channel-shoal system between Schiermonnikoog and the mainland has been analysed. The resulting findings have been used to provide an outlook for the expected developments in the near future. For this work, large-scale bathymetric surveys with a resolution of 20 m (availability every 1 to 4 years) were obtained from Rijkswaterstaat for the period 1970-2022. These surveys were examined through establishing morphological trends in transects and erosion-sedimentation maps through time. Based on the findings of these analyses, a prediction was made regarding the expected future trends in bed level evolution.

Results

The analyses of the historic bathymetric surveys indicate that the bed level in the study area varies between +2 m LAT and -15 m LAT. After the closure of the Lauwerszee in 1969, the channel-shoal system between Schiermonnikoog and the mainland evolved towards a new morphological equilibrium. This caused significant (eastward) migration of the tidal divide and the associated channels and shoals until the year 2000. Since 2000, the position of the tidal divide is relatively stable, whilst the channels and shoals remain dynamic.

Due to the alongshore east-west sediment transport in the North Sea, Schiermonnikoog is expanding towards the east. The Eilanderbalg has migrated eastward since 1970 due to the eastward expansion of Schiermonnikoog and its tidal divide. Depending on the location of the outer bend, the Eilanderbalg experiences northward or southward migration, see Figure 1. The northward migration of the Eilanderbalg causes erosion of the southeastern shore of Schiermonnikoog (Figure 1, transect A). Within the upcoming decades, it is expected that the Eilanderbalg will cut through the eastern island tail reducing the length of Schiermonnikoog and creating a more direct route to the North Sea. As a result, the tidal divide will likely experience westward migration.

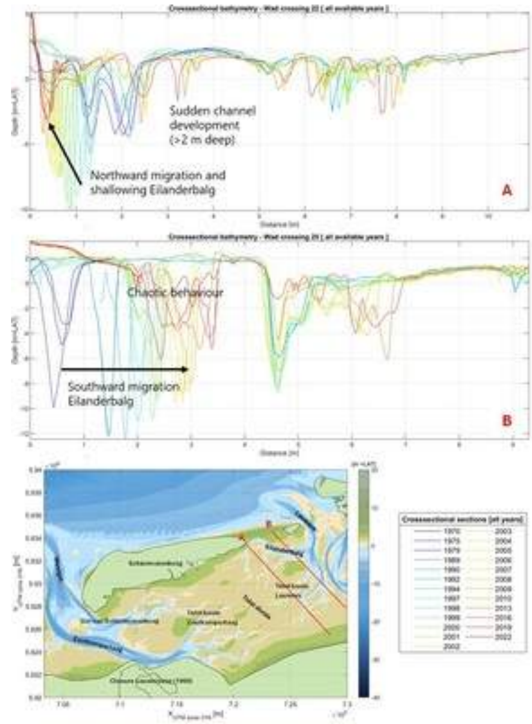

Figure 1: Historic seabed levels in the Wadden Sea area along two transsects showing the morphological evolution. Cross-sections are plotted from Schiermonnikoog (0 km) to the mainland.

Studying structural solutions for salt intrusion in multi-channel estuaries

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Introduction

In the face of climate change, deltas worldwide also face grave challenges in elevation loss, fluvial sediment decline and erosion, salt intrusion, and flooding (Vorosmarty et al., 2003) (Best, 2018). Salt intrusion is a natural process in deltas, but the increasing trends can significantly alter freshwater supply, food and job security and livelihoods, as it affects the freshwater supply by diminishing the availability and quality of source water for drinking and agricultural purposes. This is the case for the Mekong Delta, which has experienced a significant increase in salinity in the last two decades, mainly associated with riverbed erosion due to fluvial sediment decline and sand mining (Eslami et al., 2021). This heightens the necessity for mitigation measures to address the saltwater intrusion in deltas. With the Mekong River dividing into many distributary channels before draining into the sea, the Mekong Delta transforms into a multi-channel estuarine system. Studies into the potential effectiveness of mitigation measures in deltas that can be considered multi-channel estuaries is scarce, emphasizing the importance of this study.

Objective and Methods

This study examines the effect of a potential estuarine channel closure, its effectiveness and potential hydrodynamic impacts on the multi-channel estuarine system, while reducing and mitigating excessive saline water intrusion. The study utilizes a state-of-the-art Delft3D-FM numerical model of the Vietnamese Mekong delta (VMD) and the coastal region, with a network made up of both 2DV (widthintegrated but depth-varying) and 3D (three-dimensional) unstructured grids to model the flow (Eslami et al., 2021). To mitigate the salt intrusion in the VMD, the model incorporates dams along the Ham Luong channel, which is a single branch in a multi-channel system dealing with a rapid increase in salinity (Eslami, Hoekstra, Nam, et al., 2019). The incorporated structures are high enough, such that no flow exchange occurs within the branch of placement. The salt intrusion in the delta is determined by calculating the distance that saltwater is able to penetrate in each branch forming the VMD. At the same time, the flow division in the delta is determined using the subtidal cumulative discharge and averaging it over the running period (Eslami, Hoekstra, Kernkamp, et al., 2019).

Results

The results showed an intriguing impact of a closure in the multi-channel estuarine system. While it can block salt intrusion in the closed channel, its impact on the overall intrusion in the delta is sensitive to the location of the closure. The flow division in the delta also changes as a result of this structural solution, since more river discharge is re-directed towards the other non-closed branches, which in turn affect the vertical salinity distribution in the other branches, in some instances leading to more stratification. This means that the salinity response to the integration of the closure is more complex as the alongshore salinity is also influenced by the closure location. All in all, the complex interaction of the multi-channel estuarine system with the coastal sea suggests that studying these kind of structural solutions does demand complex modeling approaches that do integrate interaction between upstream, downstream and coastal seas in sufficient detail and in 3D to represent various salt transport mechanisms.

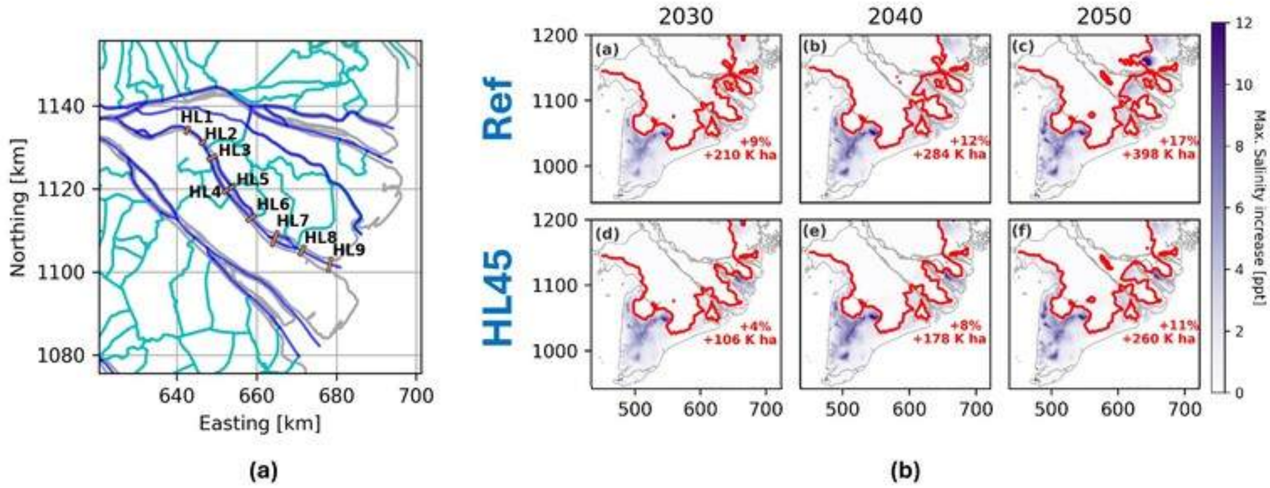

Figure 1a: Closures placed along the Ham Luong branch. Figure 1b: Future projections of the VMD under moderate anthropogenic stresses with closure (HL4 and HL5) and without closure (Ref) for which the increase in salinity-affected areas with respect to the reference case is determined by giving the increase in percentages and the increase in thousand hectares (K ha).

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The Roggenplaat intertidal flat nourishment: morphological evaluation after 5 years of monitoring

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Introduction

The construction of the Eastern Scheldt storm surge barrier (1986) resulted in intertidal flat erosion. This has negative effects on the natural as well as other values of the Eastern Scheldt. Primarily because the intertidal areas serve as a resting and foraging area for birds, marine mammals, and fish.

In the autumn of 2019, a large-scale nourishment (1.13 Mm^3) was accomplished on the Roggenplaat (Eastern Scheldt), to mitigate the losses of bird foraging area. This Roggenplaat nourishment consists of seven elements, with each element being unique in terms of their location, elevation, and thickness of the sediment layer. Rijkswaterstaat, together with WMR, Deltares, NIOZ and Deltamilieu Projecten, have been extensively monitoring the Roggenplaat since 2015 to evaluate the eco-morphological evolution of this nourishment and to gather understanding on the mechanisms involved. These insights enable eco-morphological optimization of future nourishments in the Eastern Scheldt.

Objective and Methods

The monitoring of the Roggenplaat was focused on assessing the effects of the nourishments on hydrodynamics, morphodynamics, and ecology. In addition to evaluating the nourishments, we focussed on understanding the underlying processes such that differences in evolution of the nourishment elements could be explained.

The morphological monitoring employed a range of techniques to collect comprehensive data. These included LiDAR for high-resolution terrain mapping and RTK for precise topographic survey location data. SED sensors tracked sediment dynamics and transport, while sediment sampling provided insights on sediment composition (e.g., mud fraction). Additionally, multibeam SONAR was utilized to produce detailed bathymetric maps of the two major tidal creeks through the Roggenplaat. These monitoring data have been used to evaluate the morphological development of the Roggenplaat and the nourishments over the first five years after construction (2020-2024).

Results

The morphological data indicate that the area with an exposure time exceeding 50% (especially beneficial for the birds) increased by 16% due to the nourishments aligned with the nourishment design (Van der Werf et al., 2016). Post-nourishment, the area with an exposure time of 50-80% decreased, while the area with an exposure time of more than 80% completely disappeared. The largest changes occurred within the first year. Location played a crucial role, with southern nourishments (more exposed to waves) experiencing more erosion than the more sheltered northern nourishments. The nourishments migrated predominantly towards the north/northeast along the direction of the prevailing winds, and there was a tendency for the initially steep bed slopes to flatten. Additionally, creeks developed between the nourishments. The nourishments were constructed with relatively coarse sand, which showed some refining over past years. Still, the grain size on the nourishments remained coarser than in the pre-nourishment situation. This evolution is generally in line with the expectations during the design phase. However, further morphological optimizations (e.g., regarding grain size) remain important in ensuring maximal ecological potential of future nourishments.

Satellite image from April/May 2020 depicting the Roggenplaat in the Eastern Scheldt, the Netherlands. The (former) Island of Schouwen is located to the north, while the Eastern Scheldt Storm Surge Barrier lies to the west. The contours of the Roggenplaat and the nourishments are highlighted in yellow.

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Tidal amplification induced by the historical evolution of estuarine landscapes

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Introduction

Like many estuaries, the Western Scheldt has undergone significant morphodynamic changes due to both natural evolution and human interventions since the Middle Ages, heightening its vulnerability to sea-level rise and storm surges (Leuven et al., 2019). This study investigates how historical morphological evolution has changed tides in the Western and Eastern Scheldt.

Objective and Methods

We used old maps combined with modern measurements and tools to reconstruct bathymetries starting from the year 1200. Applying the General Estuarine Transport Model (GETM; Burchard and Bolding, 2002) on these bathymetries revealed how tidal dynamics respond to historic morphological changes.

Results

Our bathymetric reconstructions involve major transformations of the estuary, particularly in tidal basin connectivity and hypsometry, which can be classified in three distinct stages: 1) Expansion stage (13th–15th century): The Honte was not yet fully connected to the Scheldt, and characterized by shallow waterways and abundant intertidal zones. 2) Transition stage (16th–18th century): The Western Scheldt gradually replaced the Eastern Scheldt as the dominant tidal channel. 3) Closure stage (19th century–present): The connectivity between two Scheldt basins was gradually blocked and dredging substantially deepened the Western Scheldt.

The model results illustrate how tidal dynamics evolved in response to these morphological changes, showing that the Western Scheldt estuary transitioned from a tidal range absorber to an amplifier. We found that the empirical relationship between tidal prism and morphological parameters has remained robust on a long-time scale, tidal amplification is a trend in tide-dominated estuaries. This trend has significantly intensified since the 19th century. We will further explore the distinct impact of dredging and land reclamation on tidal amplification. These historical reconstructions provide valuable insights for current and future estuarine management.

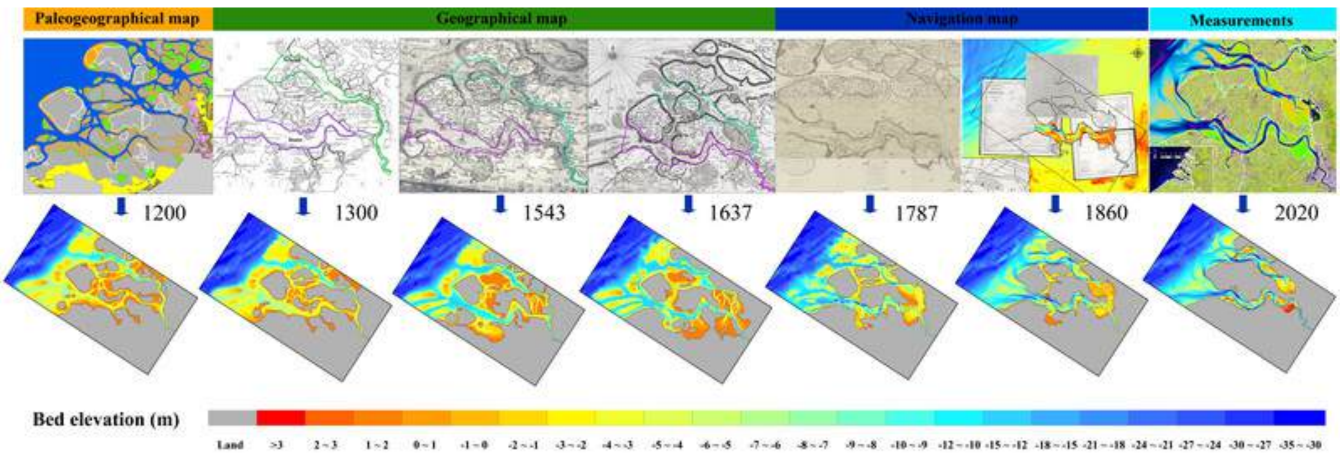

Fig 1. Historical bathymetrical reconstruction

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Variations in suspended sediment concentrations at multiple timescales in the Dutch Wadden Sea

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Introduction

Channel-shoal systems in the central part of the Dutch Wadden Sea typically become muddier with increasing distance from the tidal inlet, towards both the mainland coast and tidal divides. The resulting increase in mud availability leads to higher turbidity, reducing light availability at the seabed, and necessitates dredging to maintain the fairway. For example, the fairway to the Holwerd ferry terminal, located just west of Ameland's tidal divide, is maintained by dredging of approximately 0.8-1.2 million cubic meters of sediment annually. This volume is roughly four times the yearly net mud supply to the Ameland Basin (Colina Alonso et al., 2024), suggesting that most of the channel deposition results from mud dynamics within the basin, including local resuspension and channel-shoal exchange. Optimizing sediment management strategies in the Dutch Wadden Sea thus demands a quantitative understanding of the sediment dynamics in the system.

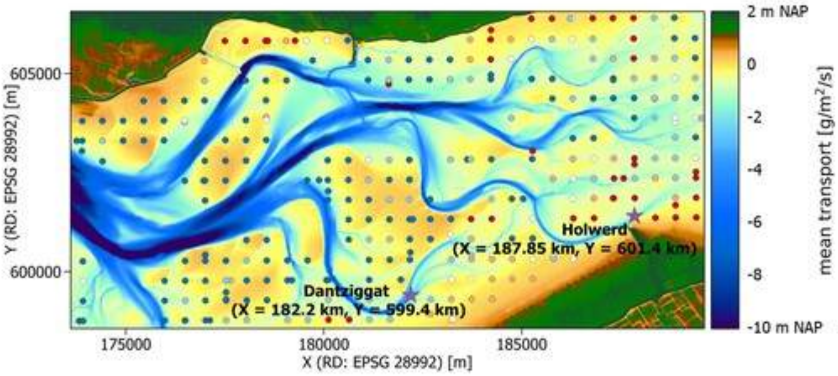
Objective and Methods

We aim to better understand the mechanisms driving variations in suspended sediment concentrations (SSC) and associated dredging volumes in the Ameland Basin across timescales ranging from hours to years. We use a set of field observations at measurement stations Holwerd and Dantziggat, collected by Rijkswaterstaat since July 2022. This dataset contains local hydrodynamics (i.e., water levels, flow velocities, and wave conditions) and water quality parameters, with turbidity being most relevant to our analysis. In addition, we use the SIBES dataset (Bijleveld et al., 2012) to estimate mud availability in the seabed, MWTL measurements to assess SSC variations over multiple years, records of dredging and disposal activities, and KNMI meteorological observations.

Results

At short (intra-tidal) timescales, peaks in SSC are observed during peak ebb and flood velocities. The largest wave heights occur during periods of significant water level set-up. However, this set-up reduces the wave impact on the seabed (i.e., the penetration of orbital velocities down the water column), meaning SSC is often higher during moderate rather than extreme wave heights. At longer timescales, the largest (residual) transport rates are associated with strong winds from the west-southwest, which enhance flow and transport in the flood direction, and with mild to strong winds from the east, which enhance flow and transport in the ebb direction. Superimposed on a seasonal variation, with higher SSC in fall and winter, SSC were particularly high from October 2023 to April 2024. We hypothesize that a sequence of wind conditions caused an increase in mud availability in October 2023, which remained in suspension throughout the winter months, until calmer spring conditions in May 2024.

In this presentation, we will explore the long-lasting impact of specific events on mud availability and SSC. Quantitatively understanding these dynamics helps evaluate fluctuations in for example dredging volumes and saltmarsh growth, as well as their implications for sediment management strategies.



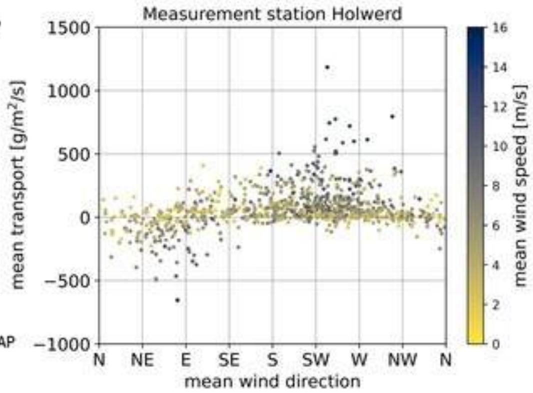


Figure 1: Left: Bathymetry map of the Wadden Sea south of Ameland, with the locations of measurement stations Dantziggat and Holwerd indicated by purple stars. Blue dots indicate sandy (pmud 0.3-0.4) areas, according to SIBES data (Bijleveld et al., 2012). Right: Residual transport in flood (positive) and ebb (negative) direction with varying wind conditions.

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Cross-shore bed load transport around a storm event in the surf zone of a low-energy beach

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Introduction

Low-energy, fetch limited sites can have different cross shore profiles than commonly reported on the open coast. Observations of the Prins Hendrik Zanddijk (PHZD), a nourished back-barrier beach on Texel in the Netherlands, showed three persistent sections in the profile: a nearly horizontal Submerged platform, a distinct beach step and a steep beach face around the msl of a steepness varying between 1:8 and 1:10 (van der Lugt et al. 2024). At this low-energy site, sediment mobility is intermittent, and the dominant transport regime is the vortex ripple regime, possibly even during storm. The presence of ripples complicates the mechanisms of cross-shore sediment transport. However, changes in ripple geometry and migration, when closely monitored, can provide estimates of bed load transport under field conditions and thereby aid the understanding of the driving profile-shaping processes at the PHZD.

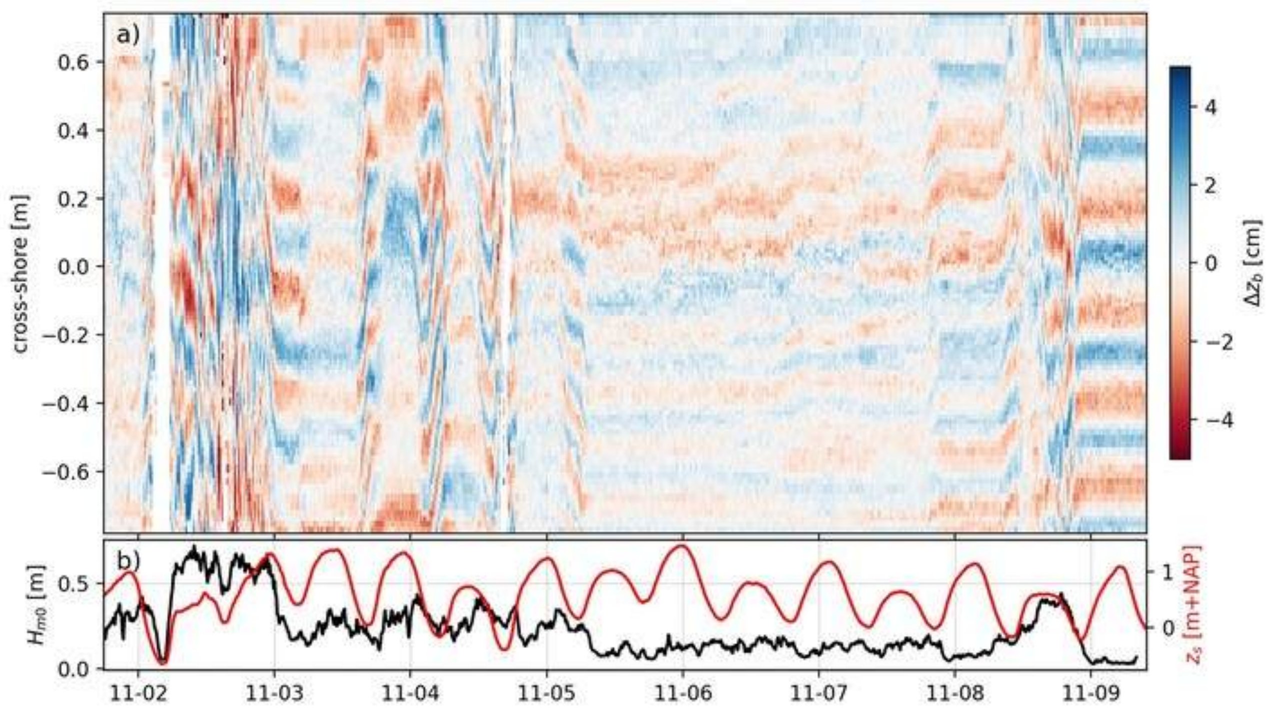
This research therefore describes the findings on cross shore sediment transport processes at a low energy beach around a storm event, by analysing unique collocated data of hydrodynamics and bedform change as well as topography.

Objective and Methods

We gathered in-situ measurements of ripples and near-bed velocity data from November 1-8 2023 during around storm Ciaràn (November 2nd 2023). A frame was placed just offshore of the beach step, at NAP-1.4 m, containing a Marine Electronics Sand Ripple Profile Scanner and a Nortek Acoustic Doppler Velocimeter. From these observations the bed ripples are classified according to the scheme of Clifton and Dingler (1984), and their predictability through a mobility number is investigated. Migration of the ripples is estimated from 1D and 2D cross-correlation of the reconstructed footprints. The hydrodynamics is used to characterize the changing ripple geometry and drivers for ripple migration. Using the hypothesis that cross-shore ripple migration is a proxy for cross-shore bed load transport under sub-critical flow conditions, the observed intra-wave hydrodynamics are then used in a bed load transport predictor along the lines of Ribberink (1998) and Nielsen (2006). With this predictor we aim to quantitatively capture the drivers of on- and offshore cross-shore bed load transport at this low-energy beach.

Results

Our observations show that both during and in the aftermath of the storm, the bed was rippled with average ripple height of 5 cm and ripple length varying from 10-40 cm, which classify as orbital ripples given the short wave period's (<5 seconds) at this site. Migration rates were highly varying, both in rate as well as direction. In the week post-storm ripples were observed to both migrate onshore as well as offshore with a rate up to approximately 6 cm/hr. This shows that that moments of migration clearly hold relation with the mobility number as well as moments of enhanced wave nonlinearity. Moments of offshore transport were seen to correlate weakly with undertow, but much less than expected. The comparison of our observations to sediment transport predictors using the intrawave velocity signal quantitatively confirms that cross-shore ripple migration, and therefore bedload, responds strongly to the wave nonlinearity, but does not respond to the mean flow components.



Ripples captured at the PHZD around storm Ciaràn (fall 2023). a) Time stack of the cross-shore swath of the sea-bed (positive y-axis is onshore directed). b) Time series of significant wave height (black) and water level (red).

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Unravelling transports along the Wadden island of Ameland

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Introduction

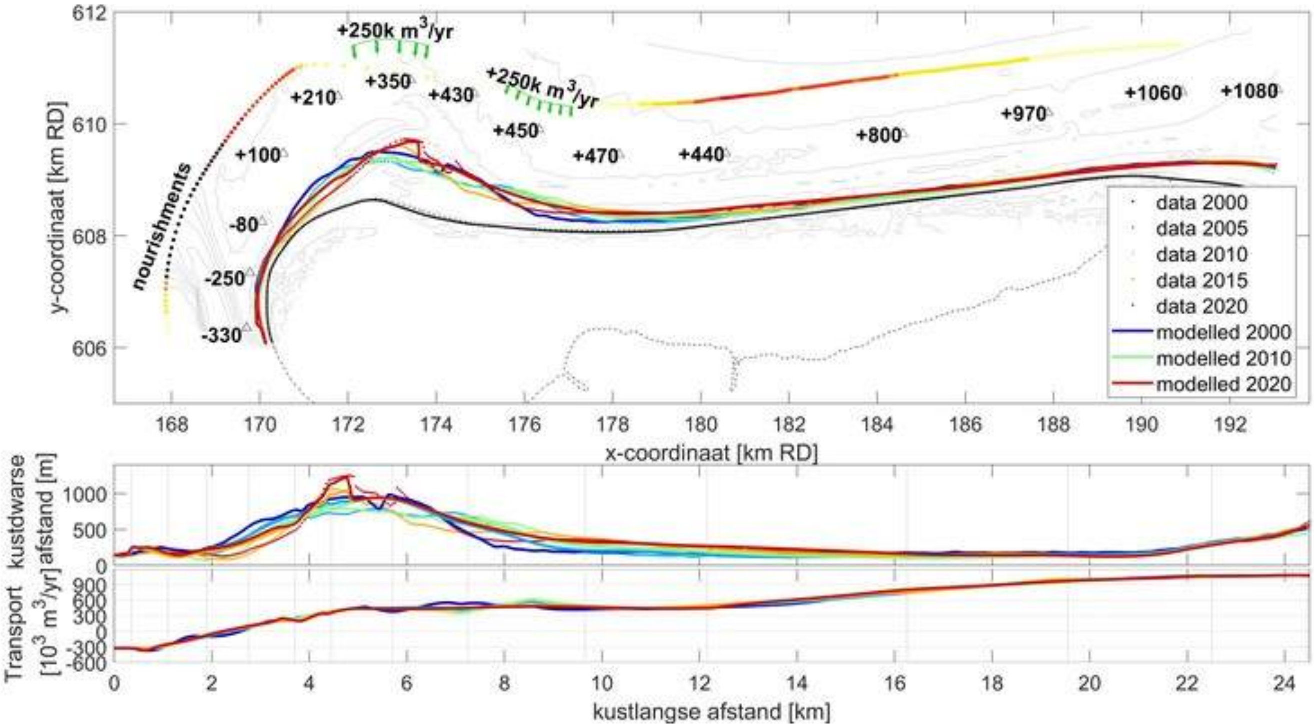
The Dutch Wadden coasts is characterized by a sequence of sandy barrier islands and tidal inlets with eb-deltas. It is known that these islands cannot be considered separate entities, as they are connected through bypassing over the delta's. Intermittent shoal landings take place at the western headlands of the islands at intervals of a few decades. Furthermore, continuous exchange of sediment takes place between the coasts and the (eb-deltas of the) tidal inlets, while island tails export sediment to the eastward located inlets. However, studies that can quantify the behaviour of the island coasts at decadal scales and the exchanges of the eb-deltas with the coast are lacking. Such quantitave information will be necessary though, as we need to be able to explore future sedimant demand of Wadden island coasts to mitigate impacts of future sea level rise scenarios. This research aims at making reliable quantitative hindcasts for all Dutch sandy coastal sections in the framework of the Knowledge program Sea Level Rise of Rijkswaterstaat. The Ameland case is highlighted here as it contains interesting new findings.

Objective and Methods

A 1D coastline model (Unibest-CL+) is used to track the development of the island coast of Ameland over a two-decade period (from 2000 to 2020). Coastlines were derived from the yearly coastal measurements (Jarkus) as a starting-coastline. Also, fourteen cross-shore profiles were derived, which extended from 6m depth to the first dune and were spaced 1 to 4 km apart along the Ameland coast. The model uses wave conditions at 6m water depth that were transformed from offshore stations for all 14 profiles (Booij et al, 1999). And also average tidal currents were deerived at this depth from a tide-model. The Van Rijn (2007) formulation was used to compute longshore transport rates, using a D50 of 250 micrometer and default settings. All 18 historic sand nourishments were added, with a total of 26 million m3. And in addition to that also a source at the norhtwestern head of Ameland, which acted as a proxy for the bypass rate of the eb-delta. Calibration of the wave conditions was performed based on the observed coastlines from 2001 to 2020, which consisted of few degree adjustments of the incoming wave angles. Besides the hindcast, the goal was then make simulations with enhanced rates of sea level rise, with and without the bypass of the eb-delta.

Results

A shoal landing led to strong accretion of up to 400 meter at the island head between 2000 and 2010 (km 6 and 10), while the beach straightened along the Amelander sea inlet (km 2 to 6). The middle of the island (km 10 to 18) experienced coastal accretion of up to 100 meter, while the island tail was stable. Computed longshore transport ranged from -300,000 at the western head to about 1 million m3/yr at the tail of the island, resulting in large erosion gradients. More than 10 million m3 was therefore eroded between 2000 and 2010. This trend was reversed by nourishments from 2010 onwards. An important finding in this study was that coastline changes at the head of Ameland could not be achieved unless an artificial bypass of the eb-delta of 500,000 m3/yr was added. Even doubling transport rates or adjusting angles by over 10 degrees could not make up for this bypass transport, which indicates it is a real feature. Any reduction in this bypass can enhance island erosion in the future. Still, solutions to maintain the island could be found even for 25 mm/yr of sea level rise, but this will require a large effort.



Observed and calculated coastal changes with the transports, cross-coastal losses and intensity of nourishments for Ameland (top panel), long-coastal representation of the coastal position (middle panel) and calculated transports along the coast by waves and tides (bottom panel).

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Ten years of spatiotemporal suspended aeolian sand flux across a remobilized coastal dune system, Zuid-Kennemerland, The Netherlands

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Introduction

As an integral part of the sandy coastal system, aeolian dunes provide protection against rising sea levels, freshwater storage, diverse ecosystems and recreational areas. Traditional Dutch dune management focused on *stabilizing* dunes by planting marram grass, increasing height and steepness of foredunes, thereby reducing aeolian sand transport towards the hinterland, resulting in biodiversity loss. Modern dune management focuses on *remobilizing* dunes to restore natural dynamics.

This study focuses on Zuid-Kennemerland, where artificial notches and blowouts were created in 2013 to promote aeolian transport. The effectiveness of notches is demonstrated through measurable elevation changes and observable sand bodies (Ruessink et al., 2018; Van Kuik et al., 2022). However, suspended sand deposition in the hinterland is typically to low to be detected, leading to underestimates of the total sand flux and their influence on soil composition in the Grey Dune habitat.

Here we present data from 15 sand traps to provide insights into spatial and temporal transport variability of suspended aeolian sand flux for over a decade. Findings will help refine models for dune remobilization and sand transport, improving management strategies. Understanding these processes is crucial for predicting long-term impacts on dune systems in response to climate change and human interventions.

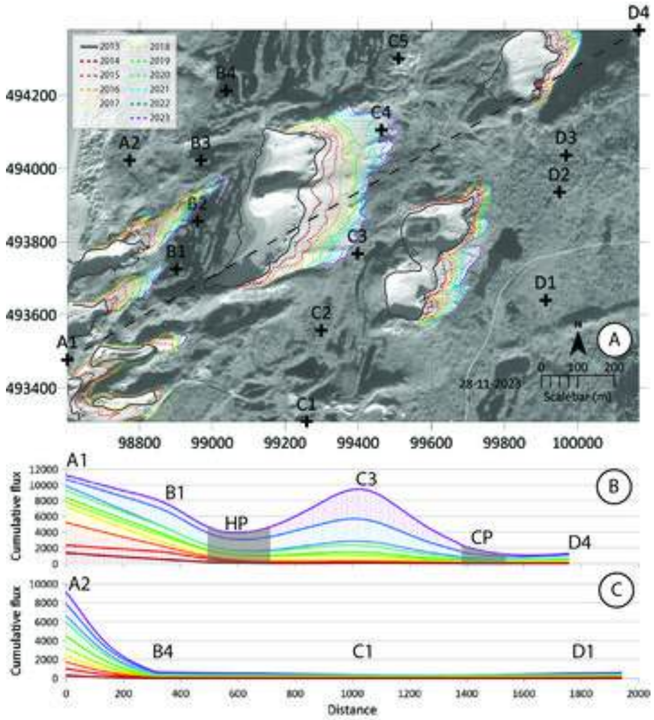
Objective and Methods

The research aim is twofold: to study the spatiotemporal variability of aeolian sediment flux in relation to meteorological conditions and to improve understanding of suspended sand transport in a remobilised coastal dune system. Using a grid of 15 sand traps (see figure) placed in four rows with increasing distances from the foredune, the sand was captured. The traps are designed from a 80 cm PVC pipe standing 1.5 m above ground level. The 180° opening faces the dominant southwestern wind direction. A 106 µm mesh allows air and smaller particles to flow through while trapping larger particles. The traps were emptied biweekly and weight measurements were used to calculate flux. Data have been collected from October 2013 to December 2023.

Meteorological data from KNMI weatherstation 225 (IJmuiden) provides 10 minute-resolution wind speed and direction data. This data was recalculated into daily values and were used to correlate the sand flux with the wind events during each sampling interval. Satellite imagery from 2014 to 2023 was analysed to monitor morphological changes in relation to sediment flux trends. The spatiotemporal data is plotted in contour maps of the cumulative flux.

Results

The sand traps collected approximately 60 kg of sand in total. The results show that storms (average hourly windspeed >20.8 m/s) have a major impact on suspended aeolian sand flux in the study area. Suspended aeolian sand reaches distances of at least 700 meters from the foredune crest. Storms are responsible for up to 88 % of the total decadal suspended sand flux, with the highest fluxes during severe storm events (average hourly windspeed >24.4 m/s), highlighting their importance for the sand suspension transport. The spatial distribution of sand traps, relative to the notches and the blowouts, influences the recorded sand flux trend over time. Traps downwind of notches (e.g. A1) show a declining flux over time, as a function of reduced transport capacity through the widening of notches. In contrast, the traps downwind of blowouts (e.g. C4) show an increasing flux trend, related to the progradation of depositional lobes towards the sand traps. Sand traps not influenced by notches or blowouts (e.g. A2) show a linear trend over time. We demonstrate that these trends are not influenced by increases or decreases in windiness during the sampling period.



A) satellite imagery of the research area where the depositional sand lobes behind the notches and blowouts have been traced each year. On the map the original shape of the blowouts in 2013 is indicated by the black line. The location and name of the sand traps is indicated by the crosses. B) profile A1-D4 shown as a cross section showing the interpolated cumulative sample weight data of the sand traps. HP and CP indicate the extent of the Houtglop and Cremermeer Parabole blowouts. C) profile A2-D1 is a reconstruction of flux in an unnotched system, based on data from sand traps A2, B4 C1 and D1.

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Yes to NbS? Supporting balanced decision-making in the Gambia

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Introduction

The coastline of The Gambia is essential to its tourism sector, attracting thousands of visitors annually to the pristine beaches of the Smiling Coast of Africa. However, rising sea levels and coastal erosion threaten these attractions, which are vital to The Gambia's economy and local communities' livelihoods. To address these challenges, the Ministry of Tourism of the Gambia has initiated the Tourism Diversification and Resilience in the Gambia Project (TDRGP). As part of this program, Royal HaskoningDHV has been contracted to aid in the development of a sustainable and long-term management strategy to enhance the tourism sector's resilience and ensure sustainable coastal management.

Objective and Methods

During the project, in-depth technical analyses were integrated with social, economic, financial and environmental analyses. Using a funnel design approach, a long list of solutions was narrowed down to three alternatives that would be effective to solve the identified risks in the coastal system. The shortlisted solutions were graded in a Multi-Criteria Analysis (MCA). This approach encompasses 25 aspects across six themes: Technical, Social, Environmental, Economic, Tourism, and Institutional. By systematically scoring and weighting these criteria, MCA provides a comprehensive framework to assess and prioritize different resilience strategies, ensuring balanced and informed decision-making.

Results

This project is an engineering example of the complexities that are encountered while comparing alternatives involving Nature-based Solutions (e.g. sand nourishments) and traditional “grey” solutions (e.g. rockworks). Addressing the maintenance and financial aspects of these solutions is crucial for their long-term success. Additionally, the MCA is shown to be effective in incorporating more subjective criteria related to Nature-based Solutions including perceived societal and environmental benefits together with proof of their long-term effectiveness.

Gambia: The Smiling Coast of Africa

Mangrove recovery by habitat restoration using nature-based solutions

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Introduction

This abstract presents four examples of Nature-based Solutions (NbS) to restore degraded mangroves and mangrove-mud coasts. These examples are from Guyana and Suriname, and are meant to provide inspiration for the restoration of other such coasts.

This work was published as part of the article 'Mangrove recovery by habitat restoration using nature-based solutions' in Ecological Engineering 212: 107520 (Winterwerp et al., 2025). It can be regarded as a supplement to the Engineering with Nature Atlas issued by ERDC (2024), which focuses on temperate climate environments though.

Objective and Methods

The designs are based on a qualitative/conceptual understanding of the bio-physical system. The restoration measures utilise the natural system dynamics caused by large-scale mudbanks that migrating along the shore of the Guyana Shield (Allison and Lee, 2004; Anthony et al., 2011), and their interactions with cheniers during interbank phases (Augustinus, 1989; Anthony et al., 2014). This system understanding from literature review is supplemented by an in-depth analysis of historic satellite images and historic maps, while quantitative data are scarce, as is generally the case in these environments.

Results

Though all sites are part of the greater Guiana coastal zone and driven by the same physical processes, local conditions are so different that different NbS measures were required to catch and arrest sufficient sediments to recreate mangrove habitat. The examples in this paper show how improved drainage, coast-perpendicular groins, coast-parallel structures (breakwaters, cheniers) and (temporary) setbacks do initiate mangrove
bilitation, though have their own specific niche of deployment. When the restored mangrove forest is large enough, it may become self- maintaining. These examples are used to gain insights into why and how one solution works at one location, while elsewhere another approach was successful.

Development of green-grey coastal defence infrastructure around Anna Regina, Guyana (Google Earth satellite images).

From Deltares and Conservation International (2022).

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Natural sedimentation in the Nieuwe Waterweg: an experimental study of a potential NbS

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Introduction

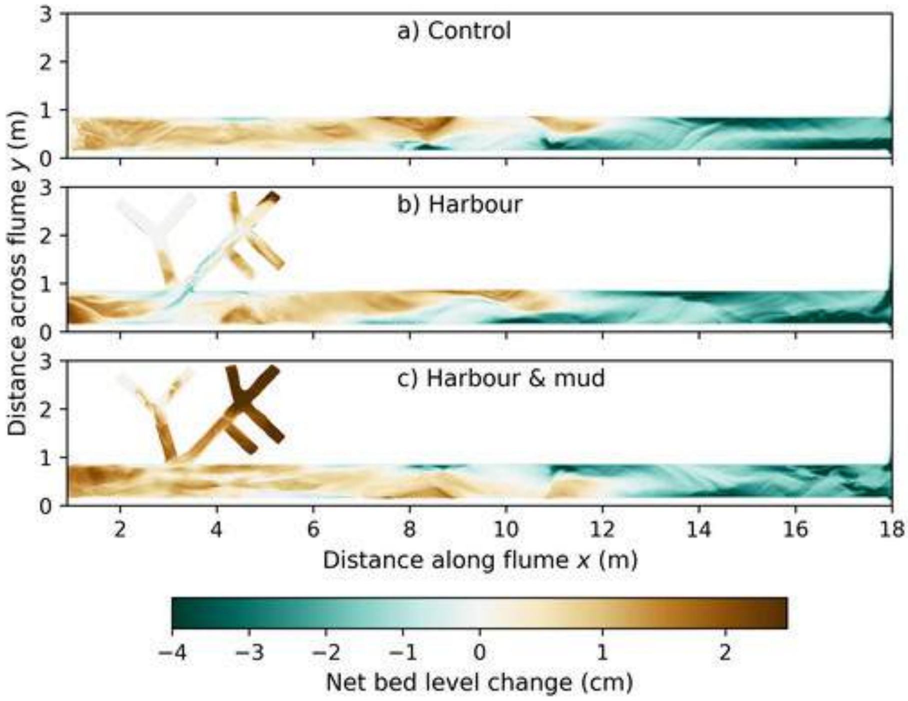
The Nieuwe Waterweg is a heavily engineered estuary that forms the mouth of the Rhine and Meuse rivers and the entrance to the Port of Rotterdam. To accommodate increasingly larger ships to the harbours, the Nieuwe Waterweg has been narrowed, straightened and embanked, and the bed is continuously dredged to an unnaturally deep water depth (currently -16m NAP) (Cox et al., 2022). This has led to increased flood risks, salinity intrusion and ecosystem degradation in the area and these issues are expected to worsen with climate change-induced sea-level rise and more frequent storms and low river discharges. Historically, flood safety has been ensured with hard engineering solutions, such as dikes and the Maeslantkering storm surge barrier. However, salinity intrusion and ecological loss are no longer acceptable as trade-offs for the economic benefits of harbour development. An alternative, nature-based solution to counteract these issues was proposed by Meyer et al. (2021): stop dredging and allow natural sedimentation processes to make the channel shallower again. However, the morphological responses under these natural sedimentation conditions are unknown due to the unnatural planform shape of the estuary. This knowledge gap is addressed here by scale experimentation (graduation research project of Baltussen, 2025).

Objective and Methods

Our objective is to provide an imaginary of a future where natural sedimentation processes are given free range and gain insight into the ensuing sedimentation-erosion patterns. The morphological development of the Nieuwe Waterweg without dredging was simulated in physical scale experiments in the Metronome tidal facility at Utrecht University (www.uu.nl/metronome). The Metronome is a 20 by 3 m flume, that periodically tilts on its short axis to generate reversing tidal flows capable of sediment transport, which leads to the formation of dynamic estuarine morphology (Kleinhans et al., 2017). The tilting was asymmetrical to create initial flood dominant conditions as present in reality, and has a period of 40 s and amplitude <0.1 m. Three experiments were conducted: a control experiment with a straight channel with fixed banks, representing the Nieuwe Waterweg, and sand only, an experiment with the addition of a harbour complex, representing the Botlek and Third Petroleum Harbour, and an experiment with the same set-up plus mud supply (crushed nutshell) at the river boundary. The development of the sedimentation-erosion patterns over 10,000 tidal cycles was captured by overhead photography and measured with laser scans of the dry bed.

Results

Due to the fixed planform shape, the morphology in the experiments developed a converging shape in the vertical instead of the horizontal as in natural estuaries. This resulted in a pattern of increasing landward shallowing by net sedimentation and seaward deepening by net erosion in all experiments (see the figure). In the experiments with the harbour complex, the larger tidal prism resulted in more landward sedimentation, especially with mud supply. The harbour complex itself acted as a sediment trap in both experiments, also with most sedimentation with mud supply. In general, the mud deposited mostly in inactive areas, on top of bars and in the landward end of the estuary. For the Nieuwe Waterweg, the same general pattern of landward shallowing and seaward deepening is expected to develop. However, due to the large water depth in the Nieuwe Waterweg, this is expected to develop by increasing amounts of landward sedimentation only. This development would have large consequences for the accessibility for ships and thus the harbour industry. However, shallowing would also counteract saline intrusion, decrease flood risks and provide new areas for nature restoration which could turn the harbour areas into new attractive living and working spaces.



Total bed level change after 6000 tidal cycles, relative to the initial bed level elevation (0 cycles) for the a) control, b) harbour and c) harbour & mud experiment. Positive values correspond to sedimentation, negative values to erosion.

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Upscaling nature-based coastal protection: Effects on estuarine biodiversity

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Introduction

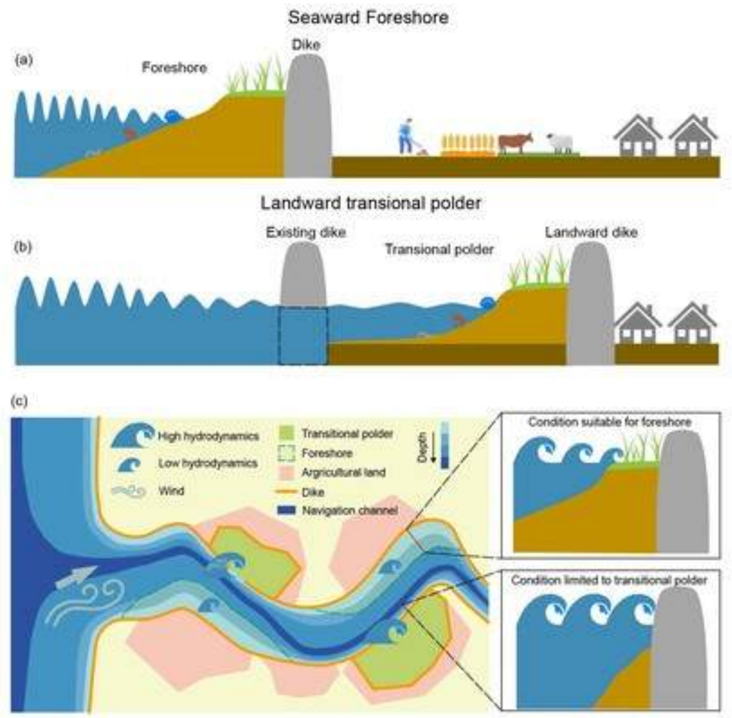
Nature-based Solutions (NbS), integrating ecosystems and natural processes, offer a promising approach to deliver benefits to both ecosystems and human society. In estuarine and coastal regions, highly vulnerable to storm surges and large waves exposures, NbS schemes are often primarily evaluated for flood risks (Duarte et al., 2013; Möller et al., 2014; Zhu et al., 2020). Comprehensive assessments of their broader impacts on biodiversity are frequently overlooked.

Objective and Methods

This study presents an integrated modelling approach to compare the long-term estuarine biodiversity outcomes of two nature-based coastal protection schemes: (i) a seaward foreshore and (ii) a landward transitional polder (i.e., a temporary de-embankment aimed at raising the land before returning it to agriculture). These schemes involve the creation of coastal wetlands, each subjected to different environmental and landscape settings.

Results

Our findings demonstrate that the two NbS schemes initially offer different benefits for biodiversity and ecosystem functions. However, the biodiversity effects converge over time due to accretion, making both solutions largely comparable in terms of long-term biodiversity outcomes. As the long-term biodiversity development is strongly influenced by the rate of sea level rise and available suspended sediment, these drivers may ultimately determine the NbS-selection and their objectives. Given practical constraints on implementing seaward foreshores due to hydrodynamic forces and societal constraints to land use changes for implementing transitional polders, the choice between alternative NbS often depends on factors beyond biodiversity alone. Yet, the rotational strategy of transitional polders offers a broader nature-based solution to the problem of salinization, which threatens the long-term viability of agriculture due to land subsidence. Scaling up implementation of transitional polders across estuaries using spatial planning and phased tidal exposure need to be aligned across regional agricultural and ecological objectives to optimize trade-offs and ensure social acceptance. Here we provide an essential toolset, offering ecological insights to optimize design of future NbS, thereby aiding policymakers and conservation planners in decision making.



A conceptual illustration of two nature-based coastal protection schemes. (a) The seaward foreshore involves developing a saltmarsh in front of existing dikes to enhance coastal protection. (b) The landward transitional polder scheme involves creating a transitional polder between double dikes, which can act as a buffer and contribute to flood defense. (c) Feasibility of foreshore and transitional polder. In areas with gentle slope gradients and low hydrodynamic forces, seaward schemes such as foreshores are more feasible as these conditions allow marshes to develop naturally and thrive (top right). Conversely, in regions near deep navigation channels with steep gradients and strong hydrodynamic forces which may further intensified by wind-induced waves (as depicted in the left high hydrodynamics area), seaward marsh establishment is considerably more challenging or impossible (bottom right). In such high-energy environments, landward schemes, like transitional polders, are the only option for reliable nature-based coastal protection. Here, dikes can be (temporarily) breached by constructing a tidal inlet, to convert agricultural land (temporarily) into tidal wetlands, offering a viable alternative for marsh creation in areas where direct seaward approaches are less/not effective.

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Desalination of marine dredged cohesive sediment for beneficial use: lessons learnt from three pilot projects

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Introduction

Substantial quantities of sand are utilized in industrial applications and infrastructure projects. As a result, sandy sediments are becoming increasingly scarce, while billions of cubic meters of fine cohesive sediments are dredged globally to maintain navigation channels. This necessitates the increasing use of these fine sediments in infrastructure development. However, compared to sand, the use of dredged cohesive sediments is more complex due to their heterogeneous composition, which includes water, fines, sand, organic matter, gas, and other components. Marine sediments also contain salt, which influences the physical and (bio)chemical behavior of the mixture.

Objective and Methods

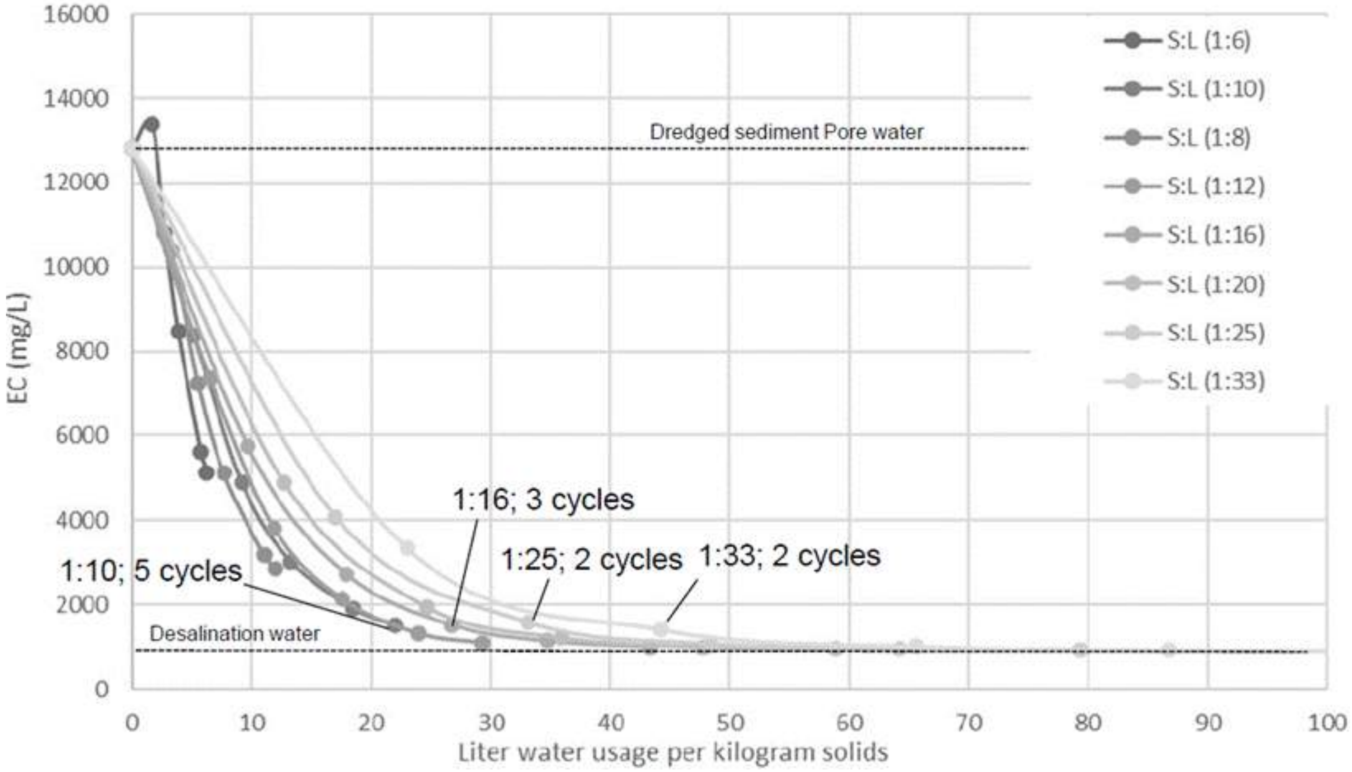
This paper presents the lessons learned from desalination in three pilot projects with different beneficial use objectives (agriculture, flood defense, ceramic industry): Raising Agricultural Lands, Growing Dike, and Sea Silt Ceramics.

Desalination experiments were conducted using dredged sediments from three locations. For the Raising Agricultural Land Pilot, sediment from Eems Haven was mixed with fresh water at a 1:6 ratio and allowed to settle in glass columns. In the Growing Dike Pilot, Lauwersoog Harbour sediment was mixed using a rotating cement mixer. Finally, in the Sea Silt Ceramics Pilot, Delfzijl Zeehavenkanaal sediment was mixed at various solid-to-liquid ratios in test beakers. Salinity and ion concentration were measured at different stages and dilutions to assess desalination effectiveness.

Results

The experimental outcomes demonstrate that an immediate reduction in salt content is achieved through rinsing with fresh water. It is also observed that the decrease in salinity is directly proportional to the water ratio. While the desalination process begins immediately, the removal of nutrient ions with larger valence is a more gradual process. The larger the water ratio (dilution), the greater the decrease in salinity, although there is an optimum point. Moreover, the same reduction in salinity can be achieved with different combinations of dilutions and rinsing cycles, but each combination requires a different amount of fresh water per kilogram of solids.

This study demonstrated that desalination of dredged sediment has a lot of potential.To economize the desalination process, mechanical dredging is preferred over hydraulic dredging. However, it is crucial to understand the optimal soil parameters. The method should be customized to meet specific objectives, which may sometimes conflict. For instance, in agriculture, it is essential to maintain suitable nutrient levels and organic matter while reducing salt content to prevent groundwater salinization, thereby making the soil suitable for a wider variety of crops.



Liters of water used per kg of solids and electrical conductivity

How to design coastal dunes as a nature-based solution?

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Introduction

Coastal dunes provide coastal protection and ecosystem services like recreation, habitat, and drinking water. Coastal dunes are under increased pressure due to urbanization and sea level rise. The value of coastal dunes as a Nature-Based Solution (NBS) is becoming increasingly recognized, so measures are being taken to maintain, restore or create coastal dune areas (Lodder, et al. 2021).

Coastal engineers and managers traditionally assess the performance of coastal dunes based on their capacity to provide coastal protection (Figlus, 2022). For example, the strength of coastal dunes can be calculated based on a set volume of sand that needs to remain after a design storm. This provides valuable information about the short-term, protective capacity of coastal dunes. However, it does not provide information on future coastal dune development or the state of the ecosystem.

For future adaptation, it would be valuable for management and engineering projects to include quantitative assessment of objectives such as coastal resilience and ecological restoration. By including quantitative assessments ecosystem services can become an integral part of design. We present a framework (Figure 1) that can be used by researchers, engineers and planners to work towards quantitatively incorporating dune growth and ecological processes in the coastal dune NBS design.

Objective and Methods

The implementation of coastal dunes as an NBS can be prompted by social, engineering and ecological problems, such as coastal erosion, habitat loss, and sand nuisance. Measures to ‘enhance’ coastal dunes include dune preservation, artificial blowout construction, vegetation planting, sand fencing, and artificial and hybrid dune construction. The applicability of these measures depends on the project objectives and environmental setting.

A range of models is available to simulate coastal dune development processes such as dune erosion (DUROS, X-Beach), dune building (AeoLiS, CDM), ecological development (GenVeg), and shoreline change (ShorelineS, CoSMoS COAST). Geometric models (CS-model, DRT) offer a simplified way to simulate both dune erosion and growth. All these models are continuously being developed, and they are increasingly combined and applied.

The suitability of different models to assess coastal dune NBS depends on project objectives. When assessing coastal protection objectives, a dune erosion model may suffice. However, assessing sand nuisance reduction may require an aeolian transport model, while the success of ecosystem restoration may only be replicated with an ecological model. More generically, it is expected that exploratory modeling using simplified models is suitable for (long-term) policy decisions, whereas detailed modeling using process-based models is more suitable for engineering design decisions.

Results

The proposed framework emphasizes that different models are required to assess different project objectives during the iterative design of coastal dune NBS. The future assessment of objectives will depend on determining which quantitative criteria are best used to measure success for each objective. Additionally, knowledge about the physical system will be needed that is currently relatively unknown compared to knowledge applied in designing/managing dunes for coastal protection. For example, dune growth and ecological processes will require knowledge about accommodation space, sediment supply, and characteristics of plant species needed for coastal dunes to develop. In future work, we aim to improve knowledge of unknown factors within the framework (bolded, Figure 1) and improve the applicability of various models for assessing the objectives of projects that use coastal dunes as an NBS.

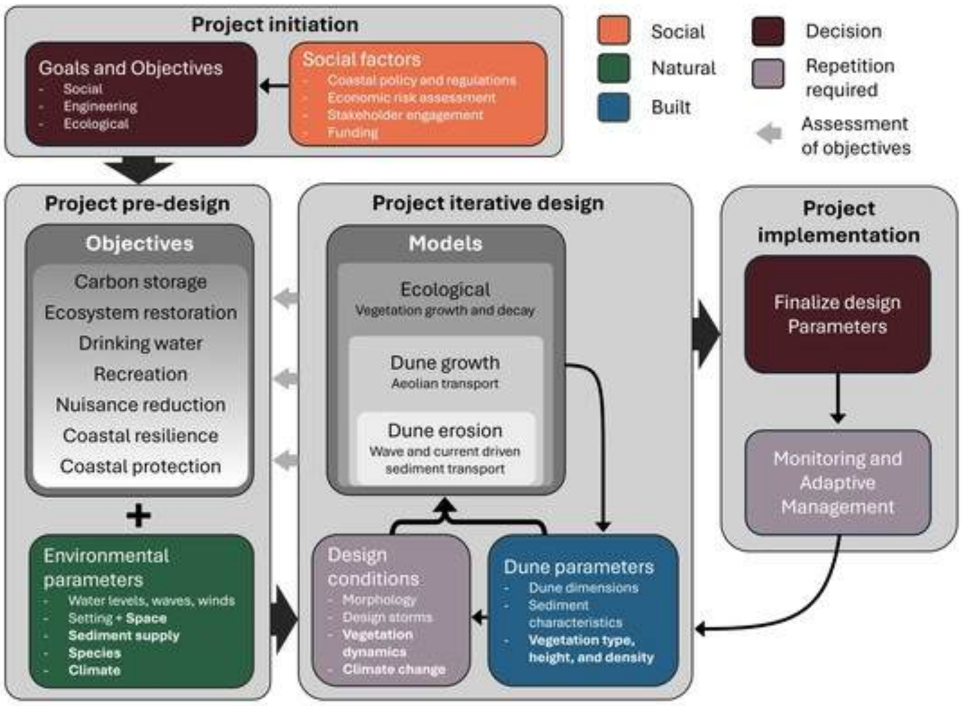

Figure 1. Framework for the implementation of coastal dunes as a nature-based solution (adapted from Ostrow et al. 2022). Parameters in bold are relatively unknown.

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Innovative Tools for Nature-based Solutions: Enhancing Dune Mobilization through Nourishment Design

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Introduction

Coastal dune dynamics can support adaptive responses to sea-level rise by widening the transition zone between beach and dunes, enhancing inland sand transport. Maintaining aeolian dynamics sustains sediment supply deeper into the dune system, which is crucial for preserving biodiversity while allowing dunes to grow with the sea. Since the 1990s, Dutch coastal policy has focused on maintaining the coastline position through nourishments. This has reduced the need for dune stabilization and created opportunities to reintroduce dynamics into the system. However, efforts to restore these dynamics (e.g., through artificial notches) have not always been successful. Excess sediment supply can stimulate marram grass growth, leading rapid blowout closure, limiting fresh sediment influx into the inner dunes.

This raises the question: can nourishments be designed to enhance dune mobility and sustain sediment connectivity? Existing tools primarily focus on single domains, lacking the capacity to assess cross-domain interactions. Understanding these interactions is essential for simulating how sediment supply from nourishments influences dynamic dune development. Addressing this challenge requires interdisciplinary tools (Figure 1) that integrate (i) subaerial landform evolution under supply-limited conditions and (ii) marine-driven processes influencing sediment supply.

Objective and Methods

This study aims to demonstrate how recently developed numerical tools can be useful in designing nourishments to enhance dune mobility, ultimately showcasing their potential in designing interdisciplinary Nature-based Solutions. We use a combination of three numerical tools to examine a case study located along the Delfland coast (Figure 1).

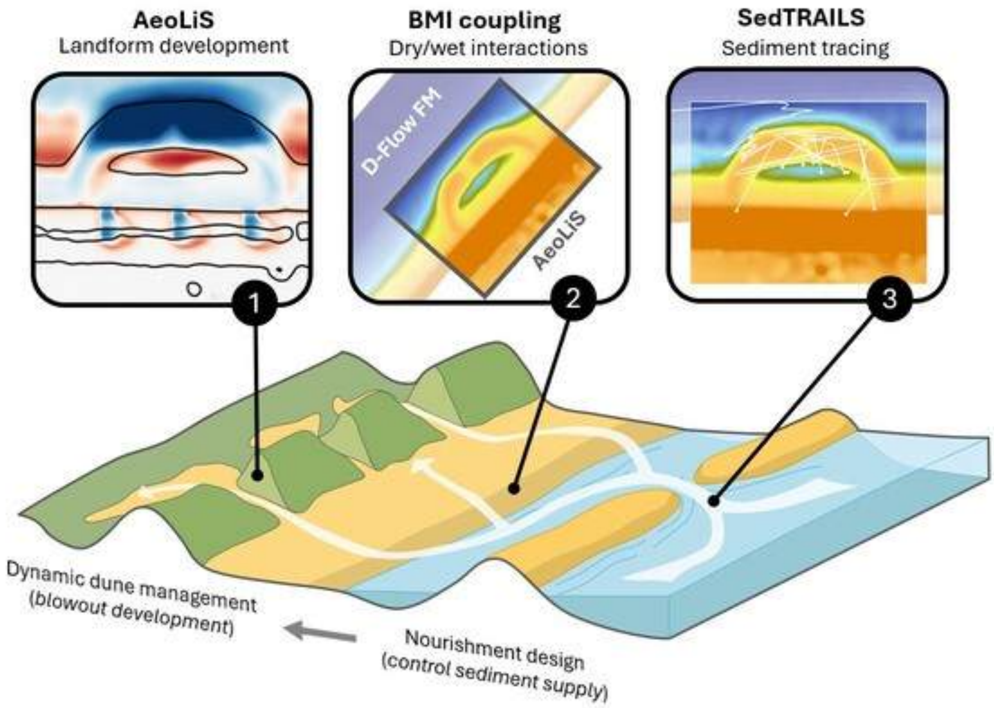
Subaerial landform evolution is simulated using a recent version of AeoLiS (van Westen et al., 2024b), which incorporates supply-limited conditions and models landform evolution. This is coupled with Delft3D Flexible Mesh using a BMI-based framework (van Westen et al., 2024a) to represent marine-driven sediment transport and nearshore morphodynamics.

In our simulations, we evaluate two contrasting nourishment designs: (1) a conventional beach nourishment, where sediment moves freely from the waterline to the foredune, and (2) a lagoon-based nourishment, which initially restricts sediment supply, potentially extending the period of blowout development. The model results are analysed to quantify spatiotemporal variations in aeolian sediment supply at the dune foot, which are then correlated with blowout evolution. Finally, we employ SedTRAILS (van Westen et al., under review) to track sediment pathways and quantify the fraction of nourished material reaching the inner dunes, providing insight into how nourishment design influences sediment connectivity between the beach and inner dunes.

Results

Results from the simulated scenarios show that nourishment design can influence dune mobilization, as reflected in the simulated differences in blowout evolution. In the conventional beach nourishment case, high sediment supply accelerates embryonal dune formation, leading to rapid stabilization and closure of blowouts, which ultimately blocks sediment fluxes to the inner dunes. In contrast, the lagoon-based nourishment initially restricts sediment supply, allowing blowouts to remain active for a longer period before the lagoon fills. This extended phase of sediment limitation enables blowouts to develop further, establishing a more persistent pathway for aeolian transport into the hinterland.

While the scenarios are idealized, these findings suggest that controlling sediment supply constraints through nourishment design can enhance blowout longevity and connectivity between the beach and inner dunes. Additionally, these results demonstrate how the integration of AeoLiS, BMI coupling, and SedTRAILS can provide valuable insights for designing interventions across the dry-wet interface. This innovative approach underscores new opportunities for coastal engineers and scientists to incorporate ecomorphological interactions in the design and evaluation of Nature-based Solutions.



Conceptual overview of sediment pathways from a lagoon-based nourishment into the backdune, assessed using an interdisciplinary modelling approach: (1) AeoLiS for subaerial landform development, (2) BMI coupling for wet–dry interactions, and (3) SedTRAILS for sediment tracing.

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Analysing dune development and sedimentation-vegetation interactions at the Zandmotor landscape: advancing climate resilient landscapes through engineering

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Introduction

Coastal dunes are dynamic ecosystems that provide critical services such as flood protection, habitat provision, and recreational opportunities, while contributing to climate resilience. However, these systems are increasingly threatened by climate change, sea-level rise, and intensifying human activities, leading to coastal squeeze [1, 2]. Coastal squeeze restricts the natural adaptation of dunes and hinders coastal ecosystems from fulfilling their critical services. An option to mitigate the effects of coastal squeeze can be by creating seaward space through artificial beach widening.

This study focuses on the Zandmotor [3], a mega-nourishment project initiated in 2011 near The Hague, The Netherlands, as a case study for creating new coastal space and as a model for sustainable coastal management. The Zandmotor has expanded beaches, fostered biodiversity, and provided valuable recreational space. Despite these successes, the long-term evolution of its landscape, particularly the interaction between sedimentation and vegetation dynamics and dune development, remains underexplored. This study investigates the processes driving dune development at the Zandmotor, focusing on the interplay of sediment accretion and vegetation establishment. By using remote sensing data, this research aims to deepen understanding of how engineered landscapes can stimulate dune growth, offering insights into sustainable coastal management and adaptation strategies for mitigating climate-driven threats.

Objective and Methods

This study investigates how new dunes develop at the Zandmotor through interactions between vegetation establishment and sedimentation dynamics. We focus on the evolution of a flat, barren sandy surface into significant dune structures.

To achieve these objectives, cross-shore transects spaced 100 meters apart were created over the Zandmotor area. Elevation data was analysed and extracted along these transects using bi-annually collected digital terrain models (DTMs) that are publicly available. Bi-annual dune volumes were calculated by integrating the elevation profiles and a linear trend was fitted through the volumes over time, that represents the volume change per alongshore meter per year of the transect. Vegetation presence was assessed using publicly available RGB aerial photographs converted to greyscale and classified, while distinguishing vegetated areas from sandy surfaces (with Otsu's method [5]). By combining dune elevation and volume changes with vegetation distribution data, this study identifies key interactions between sediment and vegetation, offering a detailed understanding of the processes driving dune formation and the role of engineered landscapes in enhancing coastal resilience.

Results

The study highlights significant dune growth at the Zandmotor, driven by sediment dynamics and vegetation development. Initially, sedimentation was concentrated near the existing dune (x = 40 m), with a new foredune forming during the project's early years (see Fig. 1). From 2017 onward, sediment deposition expanded seaward (x = 150–300 m). Analysis of cross-shore transects revealed predominantly accretive processes.

Dune volume increased (surprisingly) linearly, with an initial growth rate of 15 m^3/m/year (R^2 = 0.90) prior to vegetation establishment. After vegetation began developing in 2016, the growth rate accelerated to 53 m^3/m/year (R^2 = 0.99). Vegetation thrived around elevation peaks (see Fig. 1), playing a crucial role in sediment trapping and amplifying dune volume increases. Although vegetation generally persisted and expanded, occasional losses were observed.

These findings underscore the vegetation's critical role in enhancing dune volume and coastal resilience [6, 7, 8], aligning with broader coastal trends [4]. The Zandmotor demonstrates how engineered landscapes may foster resilient ecosystems, support biodiversity, and promote sustainable coastal management. This research is a first step of integrating ecosystems and biodiversity to build adaptive landscapes, mitigate climate-related disasters, and address challenges such as sea-level rise and coastal squeeze, offering insights into nature-based solutions for climate adaptation.

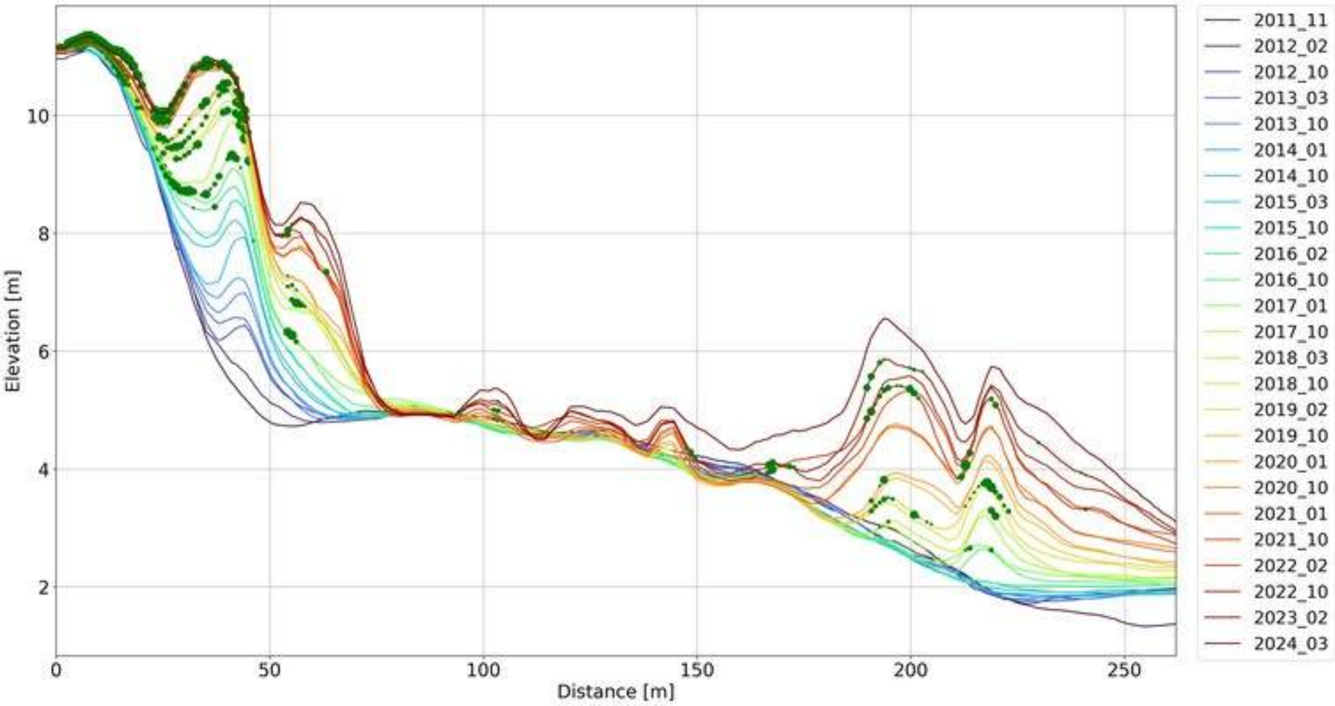

Fig. 1. Transect profile: cross-shore distance on the x-axis (0 m is bicycle lane, right is the seaward side), elevation in meters on the y-axis. Coloured lines represent profiles of different years. Green dots represent the presence of vegetation, extracted from RGB images. The larger the dot the higher percentage of vegetation per m2. Note that vegetation data is only present for the following timestamps (year_month): 2016_02, 2017_01, 2018_03, 2019_02, 2020_01, 2022_02, 2023_02.

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Cyclical Dynamics of Tidal Flats and Saltmarshes: Implications for Sustainable Management Practices

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Introduction

Intertidal estuarine environments, including tidal flats and saltmarshes are dynamic systems with wide ranging benefits from flood resilience to habitat biodiversity. Saltmarshes and tidal flats are eroding globally with an estimated saltmarsh loss of 0.28% per year between 2000 to 2019 [1]. This is expected to continue with rising sea levels, increased storm intensity, and human interventions that are reducing sediment supply. The protection of saltmarshes and tidal flats from erosion is therefore key to enable continued benefit realisation.

Despite many long term erosive trends, in the short term, the same saltmarsh may retreat and expand and the same tidal flat may erode and accrete indicating they are naturally rebuilding systems. This poses an opportunity to manage these natural processes to minimise the erosion whilst maximising the expansion.

Objective and Methods

We aim to provide conceptual models to explain the processes that drive tidal flats and saltmarsh biomorphodynamics globally. For tidal flats we focus on the vertical changes in sediment, whereas at the saltmarsh edge we focus on the horizontal movement. These conceptual models are based on global literature, including management and recommendation manuals. This aims to provide an understanding of the similarities and differences in the processes occurring and the management strategies to optimise resilience.

Results

Conceptual models have been designed for the processes occurring on tidal flats and saltmarshes globally.

In the short term (days), tidal flats experience fluctuations in the bed shear stress due to the hydrodynamics, which can trigger either erosion or accretion. Over the long term, the tendency towards erosion or accretion depends on the sediment supply into the system as more energy is required to keep more sediment in suspension. Once a tidal flat enters a long term state of erosion or accretion, the shape reinforces this process, creating a self-sustaining morphological cycle.

Saltmarshes experience an expansion-retreat cycle, influenced by the sediment dynamics at the tidal flat- saltmarsh interface. The retreat stage is triggered when a height difference forms, leading to marsh cliff formation. However, short term retreat does not always indicate long term trends, as accretion on the tidal flat or a toppled marsh platform may reduce the height difference, fostering seed settlement.

Since saltmarshes and tidal flats are highly interrelated, management approaches must consider the system as a whole. During the meeting I will discuss how these processes can be used to improve management of intertidal estuary environments.

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The tidal dynamics in the North Sea derived from SWOT satellite data

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Introduction

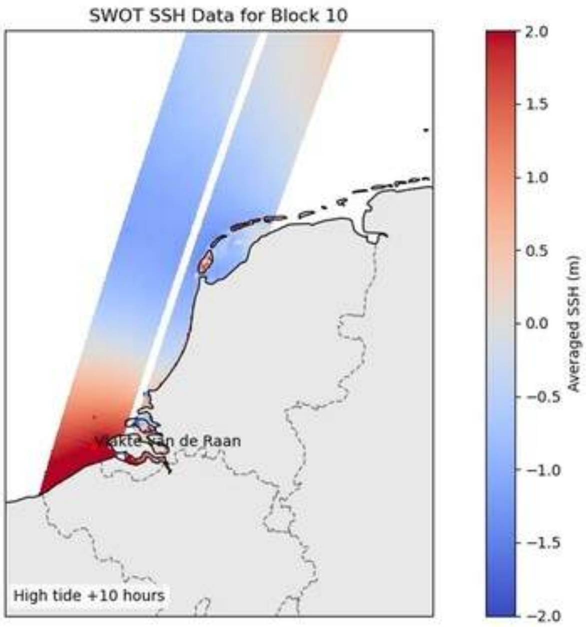
Tidal dynamics have traditionally been studied using fixed tide gauges, which provide high temporal resolution but are limited in spatial coverage. To understand tidal dynamics across larger regions, numerical models have been used. With the launch of the SWOT (Surface Water and Ocean Topography) satellite in 2022, it is now possible to study water levels with high spatial resolution (2 km x 2 km resolution) over large areas (swath of 120 km wide, with a nadir gap of 20 km). However, a major drawback is that SWOT has low temporal resolution, the satellite will have a 21-day repeat orbit (Morrow et al., 2019).

Objective and Methods

This study utilizes the newly available SWOT data to map the tidal dynamics of the North Sea at a high spatial resolution of 2 km. First, the quality of the SWOT data was assessed through comparison with in-situ measurements from 38 tide gauges from Rijkswaterstaat (Rijkswaterstaat Waterinfo). Second, the SWOT satellite data and data from a tide gauge were integrated to create a representative tidal signal with high spatial and temporal resolution. A harmonic analysis was performed on this data set enhance our understanding of tidal behaviour in the North Sea.

Results

The comparison between SWOT and Rijkswaterstaat data demonstrates a strong 1:1 correlation and small bias for North Sea stations, confirming the reliability of the satellite observations. The average RMSE is 13 cm, and the average bias is 7 cm, with SWOT values consistently higher than Rijkswaterstaat data. However, in the Wadden Sea, the quality of SWOT data is reduced, likely due to noise originating from exposed land areas. By relating all SWOT images to local time of high water at Vlakte van de Raan and by scaling the data with the observed tidal range at moment of the SWOT image, a comprehensive data set was created that condenses the sparse temporal data into one representative tidal cycle. For the first time, we show the large-scale tidal dynamics solely based on data. The data reveals the propagation patterns and the changes in the tidal amplitude. We will compare the observed tidal patterns with model results and discuss similarities and differences.



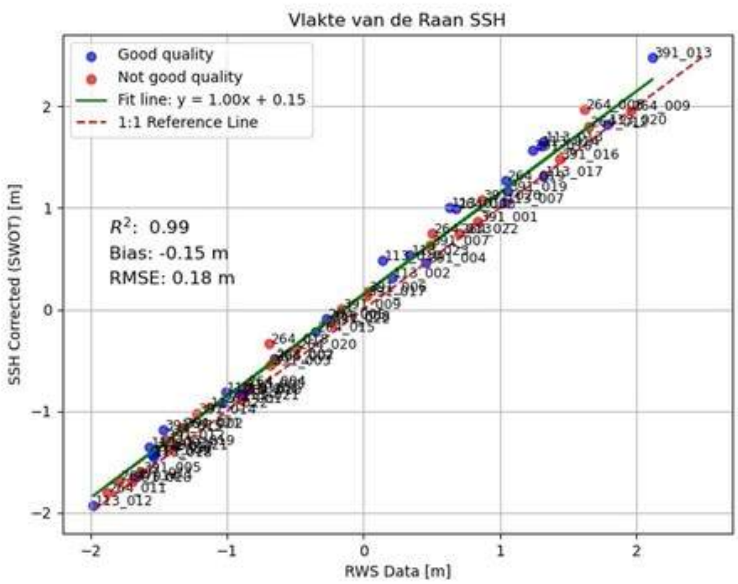


Fig 1 SWOT data shown for 10 hours after high water at Vlakte van de Raan (image from 6 Dec 2024) - Fig 2 Comparison of SWOT and Rijkswaterstaat data

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Delta-ENIGMA: an update from its first year of operation

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Introduction

Deltas and coastal plains are facing growing risks from the adverse effects of human activities and climate change, including sea-level rise. Deltas are shaped by physical forces, human interventions and physical-ecological relations. Understanding biogeomorphology — how natural forces and organisms shape these landscapes — is key to predicting the future of deltas. The Delta-ENIGMA project aims at bringing biogeomorphology research in the Netherlands to the next level, by providing a unique research infrastructure to understand how organisms, currents, waves, wind and sediment load together shape the delta landscape, including during extreme events.

Delta-ENIGMA is a 10-year NWO-funded Large Scale Research Infrastructure (LSRI) project, in which a consortium of seven Dutch institutions of NCK and NCR closely collaborate. The Delta-ENIGMA project develops a delta-scale observation network of bio-morphological processes, using state-of-the art equipment (e.g. 3D laser scanners, submerged flow and sediment monitoring, multibeam echosounders), over a 10-year period at fixed number of key-site transects across rivers, estuaries and beach-dune systems. Doing so, Delta-ENIGMA will establish the Dutch delta as a Super Site for bio-geomorphological field measurements focusing on data collection during extreme events to capture slow trends and sudden disruptions.

Objective and Methods

Delta-ENIGMA comprises 8 Work Packages that will establish the following (Figure 1):

- A long-term observation network measuring the slow and cumulative processes during normal conditions in rivers (WP1), estuaries (WP2), beaches and dunes (WP3), as well as during extreme events (WP4).
- Upgraded and new laboratory facilities to study events and conditions that are presently unobservable in the field (WP5), but may become realistic under climate change.
- A productive knowledge interaction facility (PROD) boosting interactions between experts, policymakers and delta managers (WP6).
- A coherent open database by bringing all produced sensor data into one infrastructure supporting researchers with a wealth of data for own or shared needs (WP7). Project governance (WP8).

To maximize societal impact, scientists and stakeholders will collaborate to identify strategies for implementing adaptative measures. Over the 10-year period, a comprehensive open database will accumulate results, serving as the foundation for conceptualizing delta processes, developing novel models, and validating them. The institute retrieves and processes data from sensors, adds documentation and metadata, then transfers it to Yoda platform for sharing. Yoda is Utrecht University's institutional repository for storing, publishing, and sharing research data. Effective data management is crucial, to ensure data is structured, accessible, and reusable.

Results

In 2024-the first year of the project, Delta-ENIGMA successfully achieved several keys tasks and objectives. Effective collaboration among partners and open communication facilitated the integration of expert knowledge.

WP1-WP3 identified the following field monitoring stations:

- WP1-river: Dodewaard, Vuren, Rotterdam and Hoek van Holland
- WP2-estuary: Zuidgors and Waarden, both in the Western Scheldt
- WP3-beaches and dunes: Sand Motor (nourishment), Egmond aan Zee (recreational beach) and Castricum (dynamic dune management)

Besides that, WP4-events acquired the appropriate equipment for storm events and extreme conditions, e.g. AQUADOPP, turbidity logger, ADCP’s, wave recorders, multispectral drone etc.. Various teams, involving MSc students, are being set-up to go out into the field when an extreme event is imminent.

WP5-laboratory facilities made progress with equipment procurement and with the designing of wind tunnel, mesocosm lab and the complex BioLiveFlumes lab.

WP6- PROD facility successfully designed the roadmap for 4 labs (IDlab-Deltares, Wanderlab-WUR, Serious Gaming Lab- TUD and the Design Lab- UT).

WP7-ICT designed a roadmap for the data management infrastructure. iRODS in combination with Yoda is chosen for the federated data environment.

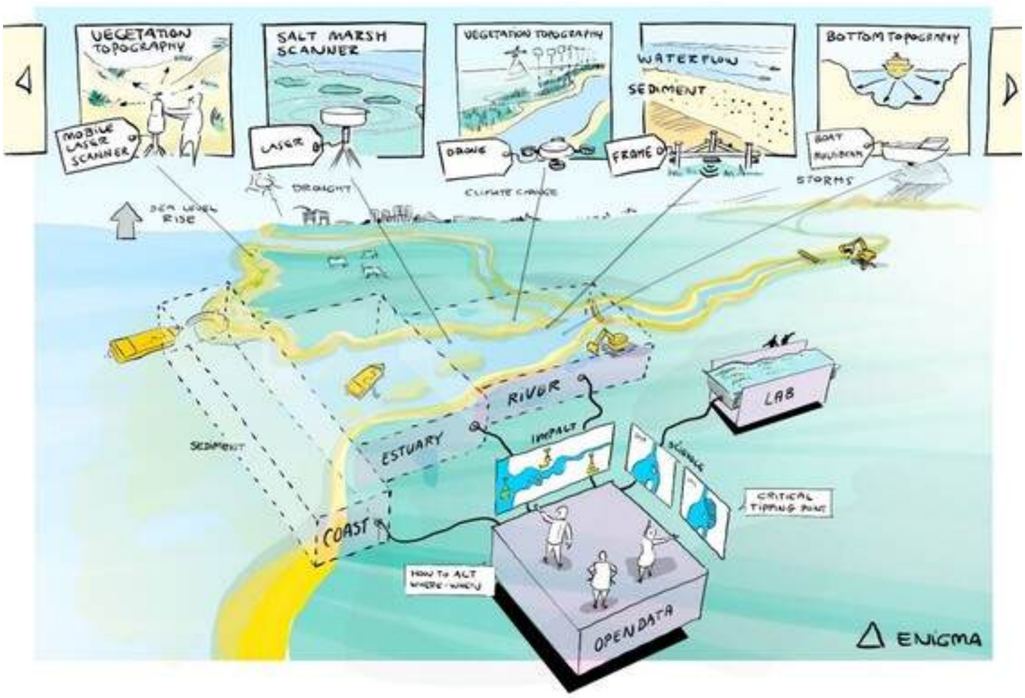

Figure 1.

Towards developing guidelines for mega nourishments with a positive effect on habitat development

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Introduction

Dune nature is under pressure. Coastal erosion, rising sea levels, nitrogen deposition, acidification, overgrowth, increasing recreation and land use by other functions are placing increasing pressure on the dune landscape. Due to sea level rise, dune areas will be under even more pressure in the future. . This is especially the case in relatively narrow dune areas. Where dunes are narrow, large-scale dynamics are not an option, due to risks for coastal defense and functions in the area close to the sea.

Can seaward strategies provide solutions? A seaward extension provides safety for the area behind it. In addition, space is created for new dune nature. It may also contribute to increasing the freshwater supply.

In this OBN-project (Ontwikkeling+Beheer Natuurkwaliteit) insight is provided to assess the effects of options for seaward coastal expansion on the ecology of the dune nature.

Objective and Methods

The objective of the project is to develop guidelines for seaward coastal defence solutions that can be used to optimally develop dune nature and/or to halt the decline of dune nature in the current dune area. The methods that are used to meet this objective consist of a mix of review of literature, analysis of existing spatial data, field research and discussion of the findings with stakeholders and colleagues.

Time and spatial scales are important for strengthening coastal dunes, dune nature and the freshwater supply. Aeolian structures larger than embryo dunes can only form with a coastal extension of some size and the process of dune formation takes time (decades).

The existing seaward extensions in the Netherlands are mostly young, usually less than 20 years old.

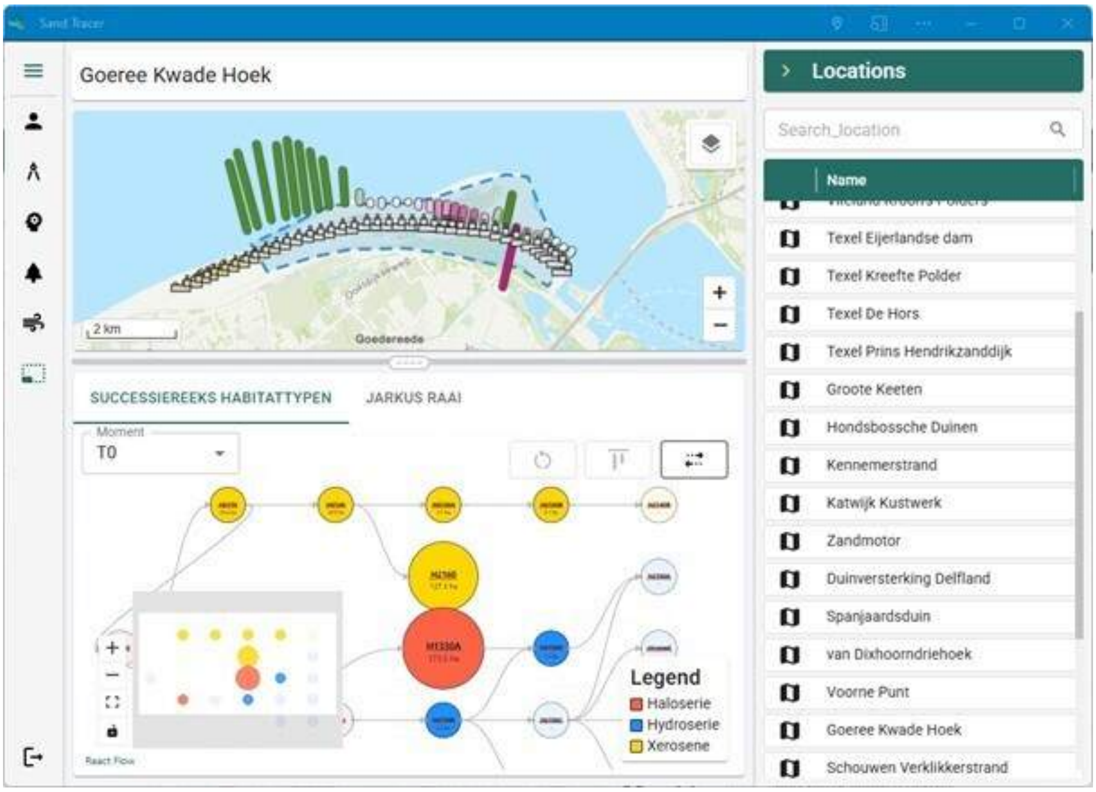
Several examples have already been implemented in the Netherlands of both permanent solutions, which vary from small to large-scale, and temporary solutions. In some cases, these examples do not, strictly speaking, concern expansion of the coast, but they do contribute to the expansion of the dune area. In our approach we assume these systems develop in a similar manner as meganourishments.

Results

Developing dune ecosystems requires sufficient space and time. Pioneer communities can emerge quickly (0 years to the first decades), but the development of later successional stages that are also important for biodiverse dunes require more time (> four decades) due to the time required for soil succession and establishment of plant and animal species. This means that seaward expansions only contribute to high-quality dune nature if they have a certain spatial scale and have a sufficiently long survival time. As the formation of a freshwater bubble in a new dune area and the enlargement of the freshwater bubble in the existing dunes requires a minimum extent and a long development time (approximately 1 century).

This research will be finalisedmid-2025 and will result in:

- An overview of existing seaward solutions and natural references with their current natural values and development over time;
- Guidelines for new mega nourishments and other seaward solutions for optimal development of new and existing nature;
- Insight into which goals can be achieved with mega nourishments and which goals are difficult to achieve
- a viewer in which the data that was gathered for each study area is clearly presented (Figure)



Screenhot of viewer in which data on geomorphological development and habitatdevelopment is presented interactively.

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Beyond the highs and lows: capturing the full tidal story from high-low data

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Introduction

Water-level measurements, some spanning centuries, provide a valuable historical perspective on estuarine and coastal dynamics. While modern tide gauges record high-frequency water level data, many historical records are limited to high- and low-water observations. Recognizing the significance of these low-resolution records, recent data rescue efforts have focused on digitization and preservation. However, existing tidal analysis methods, optimized for high-frequency time series, fail to fully leverage the information embedded in high- and low-water records.

To address this gap, we develop a methodology tailored specifically to high- and low-water records, enhancing harmonic analysis and reconstructing full-resolution water level datasets. This approach improves our ability to analyze long-term tidal changes, interactions with storm surges and river discharge, and the role of sea-level rise. Moreover, it enables a better understanding of human-driven hydrodynamic modifications in estuarine systems.

Objective and Methods

We introduce and test specialized tidal analysis techniques designed for high- and low-water observations. By integrating a derivative constraint, a robust regression method (iteratively reweighted least squares – IRLS), and insights from recent high-resolution observations, we refine the estimation of tidal constituents and enhance the extraction of the tidal component from historical water level time series. Additionally, we explore interpolation techniques to reconstruct full water level time series from high-low data.

To evaluate our methodology, we apply it to high-low observations derived from modern high-resolution tide gauge data and synthetic datasets containing realistic measurement errors. This controlled approach allows us to assess the sensitivity of different methods to varying tidal regimes, error structures, and noise levels.

Results

Customizing tidal analysis techniques for high-low water data significantly improves the reliability of harmonic analysis. Introducing a derivative constraint yields substantial improvements over traditional least-squares harmonic analysis. The implementation of IRLS, combined with seeding the dataset with low-weight, best-guess intermediate points, further enhances performance. By incorporating insights from recent observations—either as priors or for better-informed interpolation—the method achieves accuracy comparable to traditional harmonic analysis applied to high-frequency data.

A major improvement stems from reduced sensitivity to background noise and measurement errors, enabling a more accurate reconstruction of full water level records. This, in turn, allows us to detect storm surges and refine long-term sea-level rise estimates. Our findings highlight the potential of rescued high-low tidal records to reconstruct past water level variability and advance our understanding of long-term estuarine and coastal hydrodynamics.

Salt marshes: where climate change adaptation meets climate change mitigation

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Introduction

Global society is facing the intertwined crises of climate change and biodiversity loss[1]. Over the last decade, Nature-based Solutions (NbS) with salt marshes have globally been recognized as a solution to adapt to and mitigate climate change by providing regulating ecosystem services (ES), while preserving biodiversity. However, constructed or supported salt marshes in NbS develop differently than natural marshes. NbS pilot projects only appeared in the last decade, so there is limited knowledge about the fundamental long-term development and functioning. So, comprehensive assessments quantifying ES in NbS with salt marshes are sparse and field-based evidence is missing. Furthermore, while there are synergies and trade-offs between ES[2,3]. ES for adaptation and mitigation are generally not integrated in a multi-service approach. These combined knowledge gaps impede the effective design and management of NbS with salt marshes. To address these contemporary knowledge gaps, this research project aims to:

Understand and quantify the fundamental relation between marsh development and ES to define guidelines for NbS with salt marshes that enable climate change adaptation and mitigation, by:

1. quantifying (in)organic aboveground and belowground development of salt marshes; and

2. assessing the magnitude, synergies and trade-offs of combined ES and biodiversity.

Objective and Methods

Quantitative field-evidence on the long-term development and functioning of salt marshes (WP1; *Figure*) will be used to inform a multidisciplinary approach to ES and biodiversity synergies and trade-offs (WP2). This knowledge will be combined in a surrogate model to explore the larger-scale application of NbS with salt marshes for climate change adaptation and mitigation (WP3).

To quantify the long-term (in)organic development of historical NbS over a decadal timescale, data of the past 50 years will be used (WP1). A database will be built based on existing long-term biophysical data of the marshes including elevation maps, marsh zonation and extent and sedimentation/erosion data[4]. This database will be extended with field measurements from study sites covering the landscape gradient from the seaward to the landward side of the dike.

Individual ES will be quantified based on the WP1 database, focusing on: storm protection, erosion control, climate regulation and biodiversity. A cultural biography5 (i.e. timeline) will be reconstructed for the development of historical NbS. This information enables the identification of changes in NbS construction and adaptive management and associated (in)organic development of historical NbS.

Results

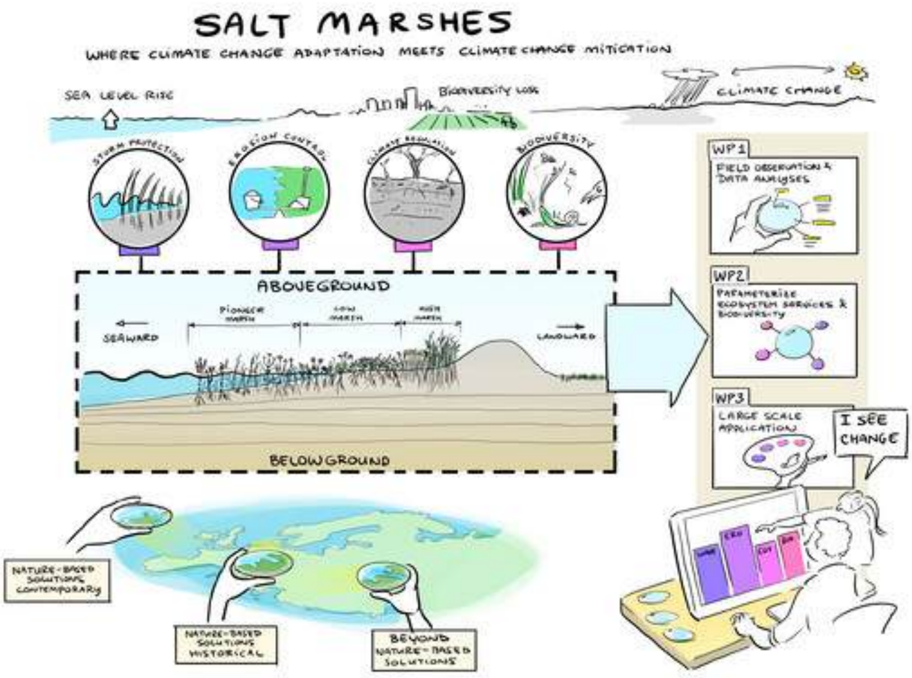
The impact of future climate change scenarios on NbS development and its associated ES will be simulated using the numerical model Delft3D Flexible Mesh[6]. Using process-based model predictions and parameterizations from WP1 and WP2, a surrogate model will be used to show salt marsh development, related ES, biodiversity and their trade-offs and synergies.

The model results will be used to quantify long-term ES of NbS. This enables the quantification of NbS guidelines from a biophysical and cultural-historical perspective enabling application of NbS for combined climate change adaptation and mitigation, while preserving biodiversity.

The research plan will be presented during the NCK-Days 2025 to receive feedback and better integrate the study in the NCK community.

This research is funded by NWO Talent Programme, VENI-AES 2023 (21063). Collaboration partners are Deltares,

Ecoshape, Wageningen Environmental research, State Agency for Coastal Protection - National Park and Marine Conservation Schleswig-Holstein, Wageningen Marine Research, University of Groningen, University of Twente, Leibniz University Hannover, DEME, US Army Corps of Engineers, Sun Yat-Sen University.



Graphical abstract of the research project

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Simulation of the influence of transitional polders on flooding risks

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Introduction

Sea level rise requires adaptation measures to prevent the land from flooding and mitigate the damage once a flood occurs. The traditional approach of raising the primary dyke structures comes with serious disadvantages. Apart from the increasing costs this will bring, a higher dyke reduces only the probability of a flood, but not the consequences. Simulations show that for 1 meter SLR in the Western Scheldt, flood damage will be much wider spread, and also the mortality rate increases at least tenfold compared to the current situation. This poses a serious challenge in maintaining regulatory safety standards.

Adaptation measures should therefore aim at reducing both flood risk and flood consequences. And example of such a measure is promoting foreland establishment e.g. via the establishment of a double dyke system (van Belzen et al., 2021, Figure 1). In the Western Scheldt, due to it's high suspended sediment concentration, this will cause the land to increase rapidly in height by sedimentation and vegetation, leading to a salt marsh with natural channels and mudflats (Weisscher et al. 2022). For the implementation of a transitional polder as part of coastal defence, we need to know 1) how such a system will develop, and 2) how it affects dyke breach scenario's.

Objective and Methods

In order to model the flooding risk for different sea-level rise scenarios we use the newest flooding models in Delft3D FM Suite 1D2D in combination with a 2D model for tidal flat & salt marsh dynamics (SFERE, van de Vijsel et al., 2023), for which we adapt the sediment and vegetation term to describe the development of the new marsh under varying SLR rates and suspended sediment concentrations. The second model is based on the shallow water equations and can quickly model the gully formation patterns and sedimentation height in the coming decades, under influence of vegetation. The model is applied specifically to the 30-3 dyke trajectory in Zak van Zuid-Beveland. We will validate this model by comparing the result to existing salt marshes and channels in the Western Scheldt. The novelty of the described method lies in the combination of flooding models with the modelling of growing salt marshes.

Results

Preliminary results show that transitional polders significantly reduce the damage of flooding under sea level rise, due to a shallower dyke break and less water intruding the land.

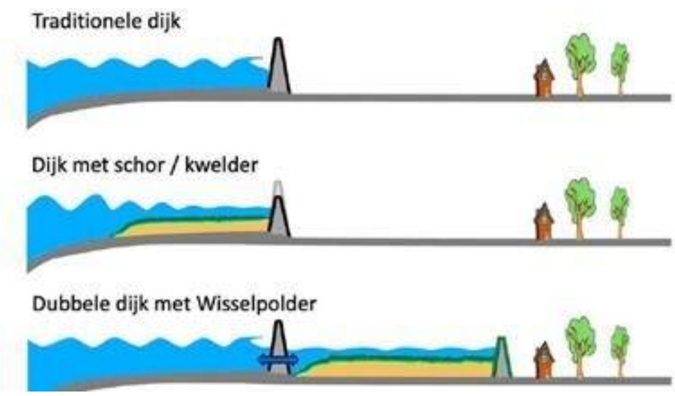

Figure 1, cross-sections comparing a dyke, dyke with foreland, and transitional polder (van Belzen et al., 2021).

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2D chenier dynamics and their impact on mangrove-mud shoreline evolution

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Introduction

Cheniers are ridges or bars composed of wave-reworked coarse-grained sediments, resting on and surrounded by muddy sediment (Otvos and Price, 1979; Augustinus 1989). Although cheniers require a specific balance between sediment availability and wave action, they occur in diverse locations worldwide ranging from micro- to macrotidal environments across all latitudes. Chenier coastlines, characterized by fine sediments with a minor fraction of coarse particles, exhibit mildly sloping foreshores and low to moderate wave energy. These coastlines are particularly vulnerable to coastal erosion, and cheniers often form through the reworking of eroded sediments by waves. In turn, cheniers can act as natural buffers against wave attack, stabilizing eroding coastlines (Anthony et al., 2019; Tas et al., 2022a).

Objective and Methods

Unlike bars and beach ridges on sandy shores, which consist of material similar to the adjacent beach and shoreface, the volume of a chenier is limited by the availability of coarser particles in the otherwise muddy shoreface. Consequently, when subject to wave action, cheniers typically migrate (in cross-shore and/or longshore directions) rather than building out, due to the lack of additional coarse sediment. Understanding these chenier dynamics is crucial for improving predictions of vulnerable muddy coastline evolution.

This study aims to enhance our understanding of 2D chenier dynamics (cross-shore and longshore) under daily wave and tidal influences to evaluate their impact on shoreline evolution over decadal timescales. As a first step, a process-based numerical model (Delft3D) is developed to simulate 2D chenier dynamics, expanding upon the 1D model setup by Tas et al. (2022b). This model is calibrated using measured bathymetric transects.

Results

A morphodynamic monitoring campaign conducted between August 2021 and September 2022 in Demak, Indonesia (Fig. 1a), observed a chenier migrating diagonally across shore-normal transects (Fig. 1b) (Gijón Mancheño et al., under review). A bathymetry representative of August 2021 is approximated based on older bathymetry, monitored transects and Google Earth satellite images, and used as the initial condition for the Delft3D model. The 2D chenier dynamics are then simulated over the course of the year. However, process-based models are computationally expensive for long-term predictions (beyond seasonal timescales). Therefore, a reduced-complexity approach, building upon the idealized chenier model of Tas et al. (2022a) is explored to simulate 2D chenier dynamics on decadal timescales.

Acknowledgements

The data used in this study was collected as part of a project funded by NWO, under project number 18473.

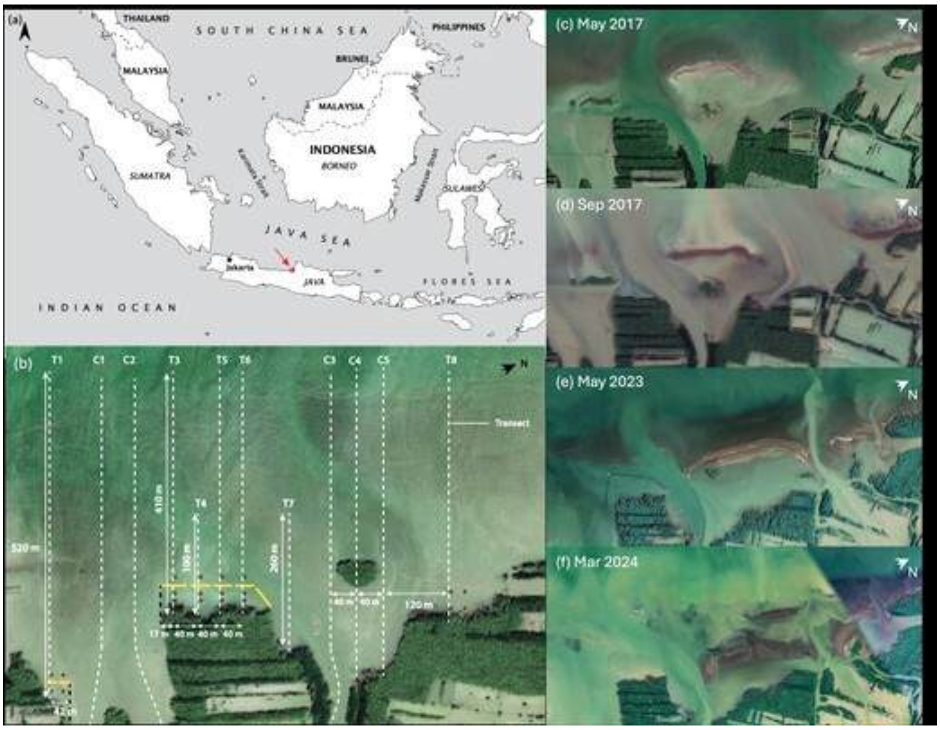

Figure 1. (a) Location of Demak, Indonesia. (b) Location of the morphodynamic monitoring transects. (c-f) 2D chenier evolution between May 2017 and March 2024 (Google Earth)

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Are our nourished tidal flats becoming climate traps for benthic species?

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Introduction

Grain size and water content of sediments influence thermal dynamics. Coarse sands drain quickly, dry out faster, and absorb more heat under direct sunlight, potentially creating thermal stress for burrowing benthic species. Shallow-burrowing organisms, such as bivalves, are particularly vulnerable to extreme surface heating, as they cannot escape rising temperatures. Prolonged heat stress can disrupt their survival, alter burrowing behavior, and reduce their availability as prey for higher trophic levels, such as oystercatchers.

The decline of estuarine ecosystems due to reduced sediment supply is a growing global concern, as these habitats are vital for biodiversity, coastal protection, and ecosystem services. To mitigate this loss, nature-based solutions like tidal flat nourishments are increasingly implemented. In the Oosterschelde, nourishments have been carried out since 2008, starting with Galgeplaat (0.13 million m^3), followed by Schelphoek in 2011 (0.09 million m^3), Oesterdam in 2013 (0.35 million m^3), and Roggenplaat in 2019 (1.13 million m^3), with the next large-scale nourishment planned for Galgeplaat-Dortsman in 2026 (3 million m^3).

These engineered habitats are typically composed of coarser sediments than natural tidal flats. With climate change pushing temperatures in natural tidal flats toward lethal levels, could coarser sediment in nourishments unintentionally amplify heat stress in these man-made environments?

Objective and Methods

We investigated how sediment characteristics and inundation regimes influence thermal dynamics in tidal flat ecosystems. We deployed temperature sensors in 2024 at three contrasting sites: a muddy tidal flat (Paulinapolder, Westerschelde), a sandy tidal flat (Dortsman, Oosterschelde), and a sandy nourishment area (Roggenplaat, Oosterschelde). Sensors were placed at multiple sediment depths (0, -3, -5, -10, -20, and -40 cm) to monitor temperature fluctuations across varying inundation times (20%, 33%, 50%, 66% and 80%). The goal was to assess how sediment properties, particularly grain size and water content, contribute to temperature buildup and how this varies with different inundation regimes. Initial field observations suggest that nourished sediments dry out quickly, potentially enhancing heat accumulation, which could exacerbate thermal stress for benthic species.

Results

The data collected from various tidal flats revealed significant temperature fluctuations across sites and depths. At several points, temperatures exceeded 30°C for hours at a depth of -3 cm, the depth typically occupied by cockles.

An advanced sediment temperature simulation model developed at NIOZ (Liu et al., in prep) accurately replicates temperature dynamics but struggles to capture peak temperatures during warm days. Adjusting water content in the model improved predictions, suggesting that drying of the sediment alters thermal properties, leading to higher-than-expected temperatures during heatwaves.

In nourishment areas with low water content and coarse grain sizes, the potential for extreme temperatures is further amplified, potentially exceeding lethal thresholds for benthic organisms. Shallow-burrowing species like cockles are particularly vulnerable, as they cannot escape these elevated temperatures.

These findings emphasize the need to better understand thermal dynamics in these habitats, particularly how sediment properties influence temperature extremes. This knowledge is crucial for designing sustainable intertidal nourishments that mitigate the losses of bird foraging area. Without careful consideration of sediment properties, we risk creating unintended climate traps for benthic infauna undermining restoration efforts meant to protect foraging habitat for birds.

Automated Characterisation of Tidal Course Morphology for Intertidal Mudflat Study

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Introduction

In the context of climate change and increasing anthropogenic pressures, coastal systems are experiencing shifts in the frequency and intensity of hazards. These areas are often densely populated and economically important, making them more vulnerable to environmental changes. Intertidal mudflats, which are vital but fragile coastal habitats, play an essential role in both ecological functionalities and geomorphological processes. Tidal courses within these mudflats, including channels and creeks, are crucial for water and sediment exchange, contributing to mudflat stability. Due to their dynamic nature, understanding how the morphology of these tidal courses relates to physical mudflat characteristics is essential.

Objective and Methods

The objective of our study is to quantify key morphological features of tidal courses, such as width, depth, and rhythmicity, and correlate these features with mudflat characteristics to better understand the relationship between tidal courses and mudflat dynamics.

To achieve this, we developed an automated toolbox for quantifying tidal course morphology using LiDAR-based Digital Elevation Models (DEMs). This toolbox automatically detects and measures key features, such as the depth and width of the tidal courses. It starts by extracting cross-sectional profiles along both the x-axis and y-axis from the DEMs and identifying changes in elevation to determine the edges and calculate the width and depth of the tidal courses. The data from both directions are then integrated to provide a comprehensive distribution of the courses' morphological features.

Results

The toolbox provided results on the tidal course locations, depths and widths associated with the mudflat slope (e.g., for a Seine Estuary mudflat in Figure 1). Further application to other intertidal areas revealed significant variability in tidal course distributions. Tidal course depths were notably lower within constrained intertidal areas (e.g., elevated mudflats with embankments), whereas the tidal courses were deeper in wider mudflats (e.g., at the mouth of the Seine Estuary, France). Moreover, tidal course dimensions were related to the mudflat morphology, with the largest courses (i.e., deeper and wider) occurring near the tidal flat slope break. Hence, the developed toolbox provides a generic method to investigate the interaction between tidal courses and mudflat morphologies.

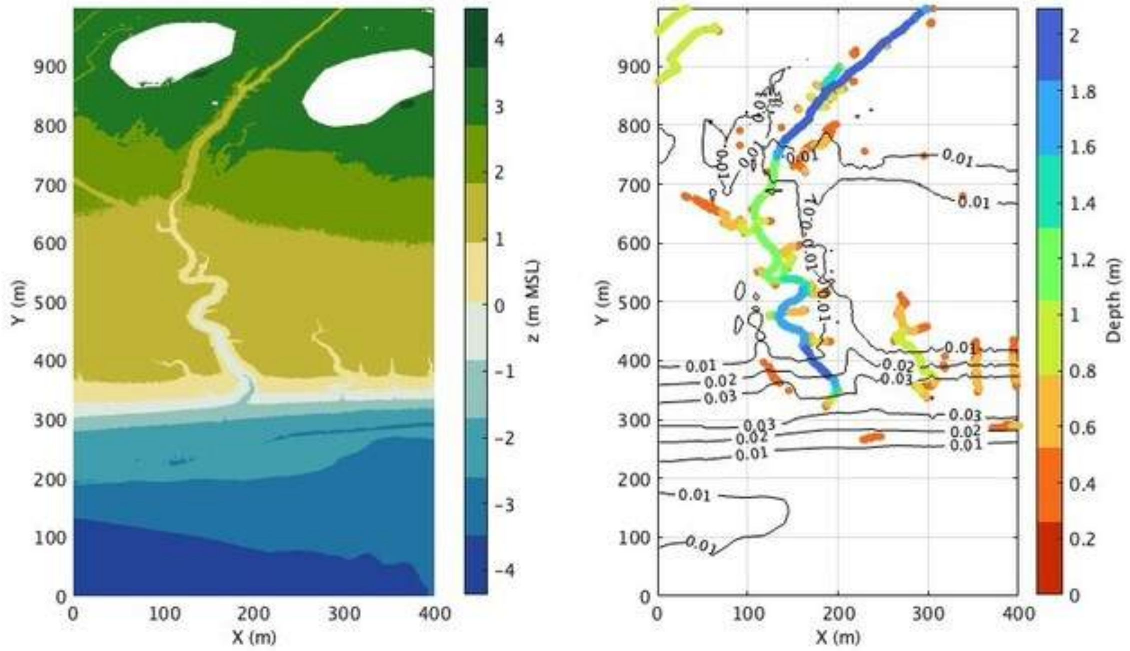

Figure 1: Mudflat elevation z, relative to mean sea level MSL (left), and tidal course depth (> 0.4 m, colour dots) and mudflat slope (black iso-lines) (right), at the mouth of the Seine Estuary, France.

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Comparing the effects of mangroves versus salt marshes on delta morphodynamics

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Introduction

Salt marshes and mangrove wetlands provide crucial ecosystem services to deltaic areas. They also significantly modulate hydrological conditions (e.g., currents, tides, and waves), thereby altering sediment dynamics and morphology. However, quantified comparison between these vegetation types and their effect on morphology remains a largely unresolved question.

Here we compare the hydro-morphodynamic development of a salt marsh versus a mangrove restoration site.

Objective and Methods

We have conducted fieldwork in the Changjiang (Yangtze) River Estuary (salt marshes) and in the Beibu Gulf (mangroves) in China. The fieldwork encompasses measurements of flow velocities, waves, tides, turbidity levels, sediment grain sizes, bed level changes, and vegetation characteristics. Additionally, the numerical model Delft3D is utilized to investigate the interactions between vegetation and hydro-sedimentary processes.

Results

Preliminary results from fieldwork reveal that both salt marshes and mangroves effectively attenuate waves and currents, promoting sediment deposition, particularly at the interface between bare flats and vegetated zones. In calm weather, salt marshes tend to accumulate sediment more readily than mangroves. However, during storm events, salt marshes are more susceptible to erosion, resulting in greater variability in sediment dynamics. There are also seasonal differences. In salt marshes, wave and current attenuation is more pronounced during summer than winter, whereas such seasonal variation is less significant in mangroves. Multi-year variability, on the other hand, may be greater in mangroves.

In ongoing numerical simulations, we find a strong nonlinear sedimentation effect as mangroves transition from small saplings to mature individuals (Figure 1). Future work will include modeling the role of salt marshes, with comparisons across different temporal scales (e.g., tidal cycles, seasons, years, and decades) and in direct competition with mangroves. Broadly, these findings will help us to explore potential river delta change as mangroves encroach on salt marshes in our warming planet.

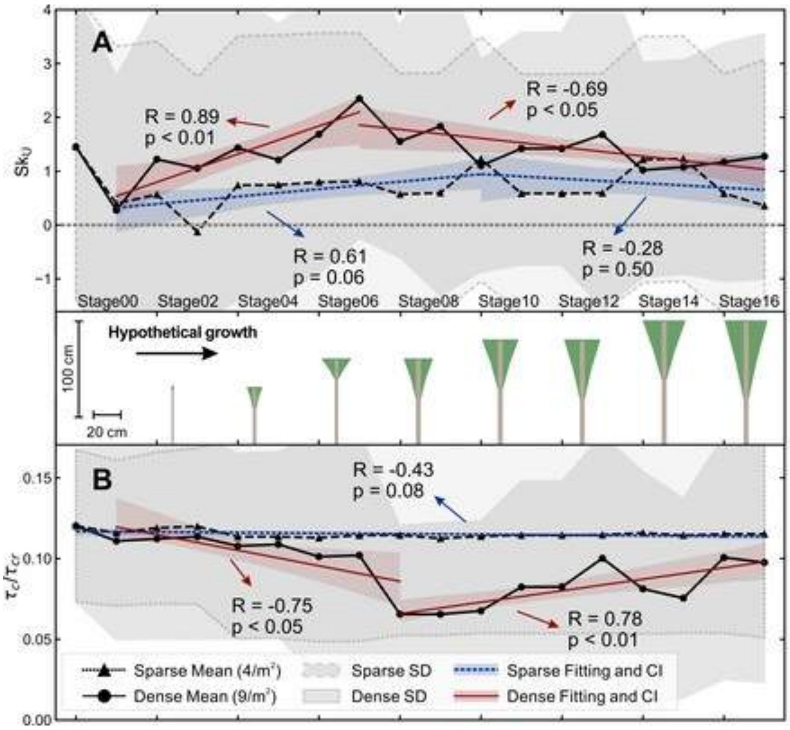

Figure 1. Simulated progressive alteration of hypothetical vegetation morphological growth on hydrodynamics at the early growth stage within a restored estuarine pond. Impact of plant growth on (A) tidal asymmetry denoted by velocity skewness Sk_U; and (B) normalized bed shear stress \tau_c/\tau_{cd}. SD in the figure denotes standard deviation, and CI denotes confidence interval. Red blocks represent the dense planting scenarios and blue blocks represent the sparse planting scenarios. (Figure from Luo et al., in review.)

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Evaluating clustering techniques for predicting extreme sea level probabilities at the Dutch coast

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Introduction

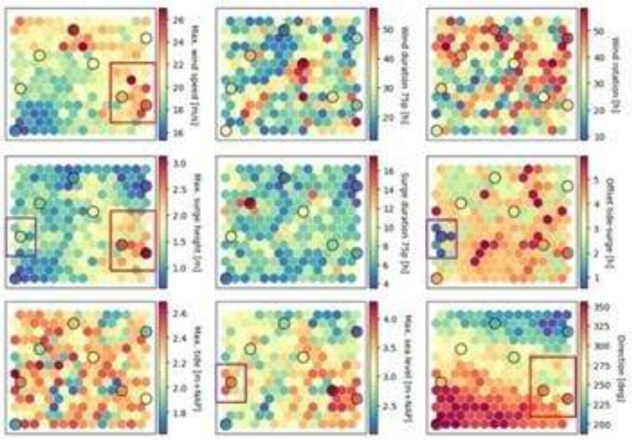
The Dutch coast is characterized by dikes, dunes, and structural barriers with low-lying, densely populated hinterland, which makes the area vulnerable to coastal flooding. Extreme storms above the North Sea are the main driver of coastal flood risk in the Netherlands, resulting in high waves and extreme sea levels due to storm surge. Therefore, the reliability of coastal flood forecasting models is of great importance: accurate short-term forecasts (up to 10 days lead time) are necessary for operational decision-making processes (e.g. closing the storm surge barriers on time), while mid-term forecasting (more than 10 days lead time) is useful for the planning of maintenance, for example. Traditionally, storm forecasting relies on numerical weather prediction and hydrodynamic models, but for long lead times computational demands increase significantly. In such cases, machine learning offers a promising alternative. With recent advances in short-, mid-, and long-range forecasting, extensive datasets of simulated weather and hydrodynamic conditions are now available (e.g. Hersbach et al. (2020)). These datasets can be used to train machine learning models for predicting extreme sea levels and to enhance our understanding of the driving mechanisms of extreme sea levels.

Objective and Methods

This study aims to investigate the potential of various clustering techniques for predicting extreme sea level probabilities and unraveling their driving mechanisms. Recently, the Royal Dutch Meteorological Institute (KNMI) generated an extensive dataset of simulated sea levels, using the WAQUA-DCSMv5-model with wind data from SEAS5 (van den Brink & de Valk, 2024). This dataset effectively represents approximately 9,000 years of simulated wind fields and sea level time series, which were used as training dataset. From this dataset, extreme storm events were identified, in terms of associated mean sea level pressure fields over the North Sea and time series of wind speed, wind direction, sea levels, and astronomical tide at six locations along the Dutch coast. Two clustering algorithms—Self-Organizing Maps (SOM) and K-Means—were applied and several clustering approaches were explored: (1) based on the parametrization of storm events into nine storm features, (2) using the full storm time series at point locations, and (3) clustering mean sea level pressure fields over the entire North Sea. These approaches were compared in terms of their ability to estimate sea level probabilities. Besides, the results provided insights into driving mechanisms and interactions between storm characteristics.

Results

As an example, results are presented for the SOM algorithm applied to clustering based on storm features. Figure 1 presents the mean feature values for each node from the trained SOM algorithm for location Vlissingen, with each plot corresponding to one of the nine storm features used for clustering. The nodes (hexagons) represent clusters of storms, and the colors indicate the mean feature values for each node. It can be observed that the SOM algorithm effectively captures several physical relationships. For instance, the plots show that southern (180–270°N) wind directions (lower right plot) are generally associated with higher wind speeds (upper left plot) compared to northern wind directions. However, these high wind speeds only result in significant surge heights for western to northern wind directions, as highlighted by the red square. Notably, a few nodes exhibit relatively high sea levels despite low surge heights as indicated by the purple square in the lower center plot. This can be explained by the minimal time offset between the surge peak and astronomical high tide (right center plot), meaning that the maximum surge (almost) coincides with high tide, which results in high sea levels even if the surge is only moderate.



Feature plots resulting from the trained SOM algorithm for location Vlissingen.

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Evaluating Vegetation Recovery Time in Tidal Marshes

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Introduction

Tidal marshes have a crucial role in coastal protection, habitat provision and carbon sequestration. The ability to recover after a large disturbance, the ecosystem's resilience, is key for maintaining a healthy marsh ecosystem. However, accelerating sea-level rise and subsidence reduce resilience, potentially causing the marsh to collapse. To prevent marshes from collapsing, understanding marsh resilience and its recovery process after a large disturbance is essential. Recovery time is defined as the duration required for vegetation to regrow after a disturbance. A large recovery time may indicate reduced resilience, making it a potential early warning indicator for marsh degradation.

Objective and Methods

This study aims to quantify the recovery time of tidal marshes after Hurricane Katrina in the Mississippi Delta in 2005, using remote sensing data. This is done by using NDVI time series acquired from Landsat 5 images to estimate the recovery time of marshes with approximately 400 m resolution covering an area of 1260 km^2. These recovery times are then analysed and compared with bed elevation data from LIDAR data (OCM Partners, 2025). The quality of our analyses is assessed by comparing areas with estimated large recovery times with areas of observed marsh loss, as provided by Murray et al. (2022).

Results

Preliminary results show large spatial variability in recovery time across the marsh (Figure 1). No clear correlation with bed elevation is found, suggesting that other environmental factors are important in determining marsh resilience. Ongoing analyses explore such additional factors and evaluate their applicability as early warning indicators of marsh loss. These indicators can serve as a guideline to inform landscape managers to most effectively apply marsh protection strategies.

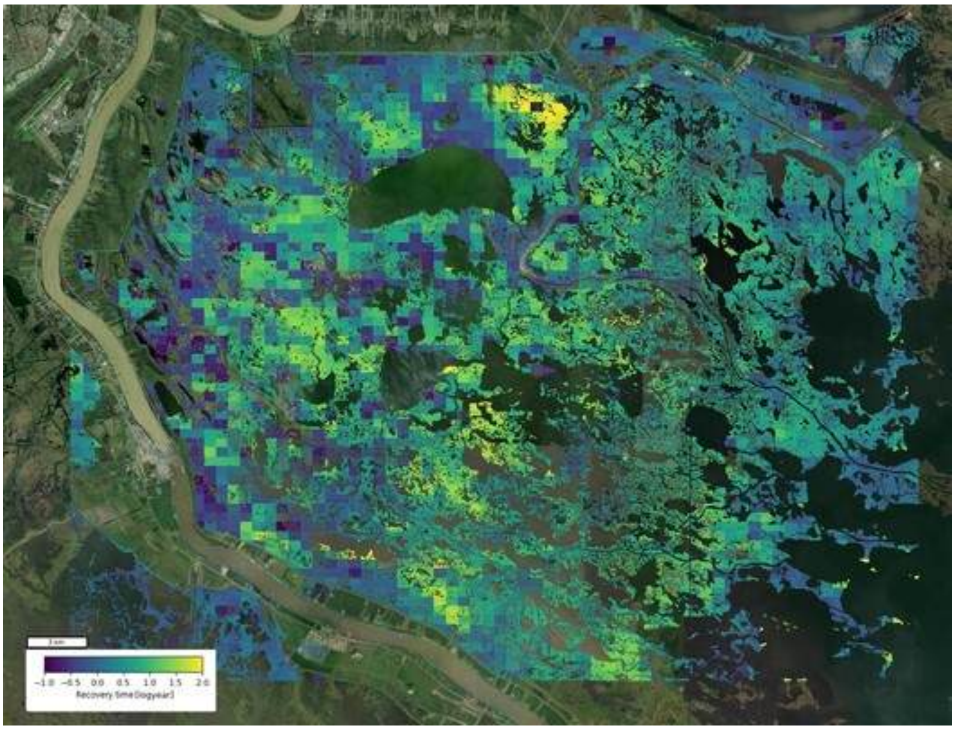

Figure 1. Recovery time of tidal marshes after Hurricane Katrina. Recovery time is derived from NDVI time series (Landsat 5). The represented recovery time shows large spatial variability within the area of interest.

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Impacts of Storm Characteristics on Accretion Rates in Back-Barrier Salt Marshes

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Introduction

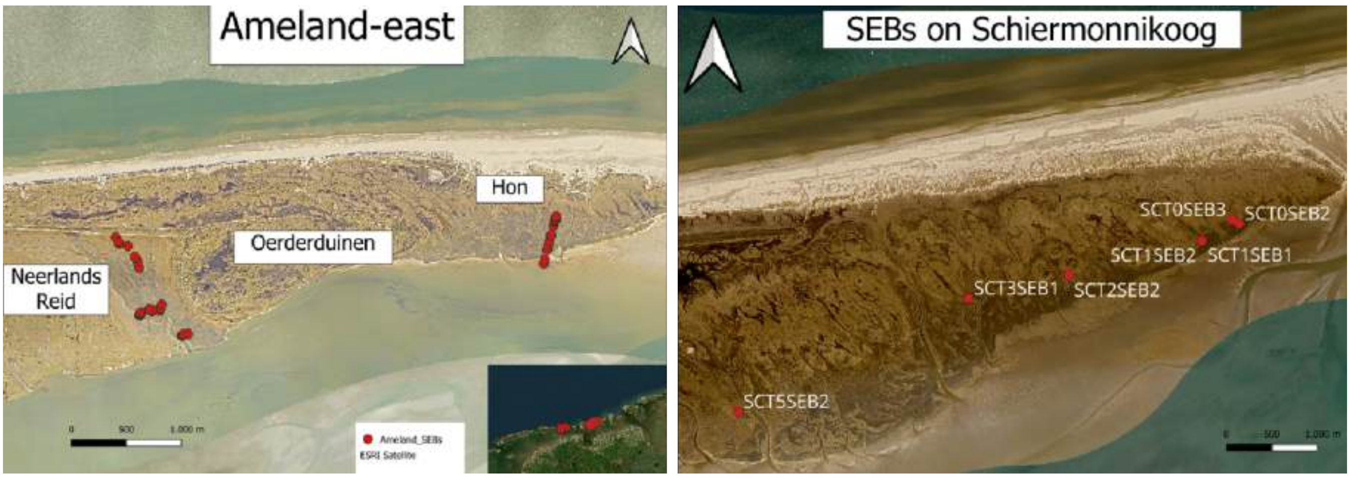
Salt marshes provide key ecosystem functions, including flood protection, biodiversity, and carbon storage. Marsh resilience is, however, increasingly compromised by sea-level rise and land subsidence. While these coastal wetlands can keep up with relative sea-level rise through vertical accretion, the impact of storm-induced sediment dynamics on marsh accretion remains underexplored.

Objective and Methods

Here, we assess how vertical marsh accretion depends on storm characteristics, distinguishing the impact of flood regime variables (inundation frequency, depth and duration), and variables that drive suspended sediment concentrations (e.g., wave height, wind speed, and direction). Our study focusses on marshes along the back-barrier islands of Ameland and Schiermonnikoog in the Dutch Wadden Sea. Accretion time series are derived from long-term sedimentation-erosion bar measurements, and compared to storm characteristics using multiple linear regression analyses.

Results

Although previous studies suggest that the dynamics of suspended sediment concentration and inundation depth are largely independent from each other, we find a strong correlation between these two variables. This finding implies that inundation depth is not only indicative of storm intensity, but also is a better proxy for suspended sediment concentrations than previously suggested. This stronger correlation than expected is likely due to the longer timescales (annual averages) considered here. Our work thus shows that inundation depth effectively predicts vertical marsh accretion on longer timescales. This insight helps in advancing our understanding of marsh development under increasingly energetic storm events.



Locations of sedimentation-erosion bars (SEBs) used in this study. SEBs are located along the back-barrier islands of Ameland and Schiermonnikoog, Dutch Wadden Sea.

Lateral edge retreat at the Wierum salt marsh: finding a relationship between erosion rate and hydrodynamic forcing

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Introduction

Salt marshes are critical coastal ecosystems, valued for their ability to attenuate wave energy (Dzimballa et al., 2025) and reduce hydraulic loads on engineered defences (Schoonees et al., 2019). However, global trends reveal increasing lateral erosion of marsh edges, driven by the tide and waves (Bendoni et al., 2021). Existing literature often describes a positive, linear relationship between erosion rates and hydrodynamic forcing (Leonardi et al., 2016), but also a power law relationship was found (Houttuijn Bloemendaal et al., 2023).

Formed as a result of historical semi-natural land reclamations, the Wierum salt marsh in the Wadden Sea experiences erosion at the seaward edge. The marsh edge at this marsh is characterized by near-vertical cliffs with an average height of 0.5 m (Figure 1b). However, there are also parts where there is a gentle or stair-shaped slope towards the mudflat.

Objective and Methods

The Wierum salt marsh is used as a case study to investigate whether there is a relationship between cliff retreat and hydrodynamic forcing. The influence of edge complexity and vegetation on local erosion rates is also tested.

Aerial imagery and hydrodynamic data spanning from 2016 until 2024 is included. The marsh edge retreat is quantified using aerial photographs and digital elevation models (DEM's) (Figure 1a). Hydrodynamic forcing was analysed using the wave power (P in W/m) and wave thrust (T in N/m) calculated from wave height and water depth, assuming shallow water conditions. Dimensionless wave power and wave thrust are obtained by dividing by the average over the whole time period. Additionally, the inundation frequency was determined as percentage of hours per year that there is water at the cliff. The hydrodynamic parameters calculated are plotted against the dimensionless retreat rate per year and a linear and power law model are fitted against the data to find a possible relationship.

The spatial differences in erosion rate are examined and compared to vegetation density and marsh boundary complexity. These are quantified respectively through Normalized Difference Vegetation Index (*NDVI*) determined from satellite data and fractal dimensions of the edge shape using the box-counting method.

Results

The average marsh edge retreat rate between 2016 and 2023 is 1.8 m/year. The findings indicate a positive relationship between wave power and average marsh edge erosion rate (Figure 1c). The linear results are well in line with existing literature (Leonardi et al., 2016; McLoughlin et al., 2015). A positive relationship between wave thrust and erosion rate was found using a linear fit ($E^* = 0.90\ T^*$, $R2 = 0.34$) and a power law fit ($E^* = 1.00\ T^{*} \wedge 0.50$, R2 = 0.28). A negative relation was found between the frequency of inundation and erosion rate. This could indicate that the wave force at the time of inundation rather than the total period of inundation influences lateral cliff retreat.

The marsh edge complexity was found to correlate negatively with erosion rate, indicating that a marsh with a more smooth marsh edge erodes faster than a marsh with a more complex marsh edge. This is also observed in literature, even though methods and scales vary greatly (Leonardi et al., 2016). No convincing relationship was found between vegetation density and erosion rate.

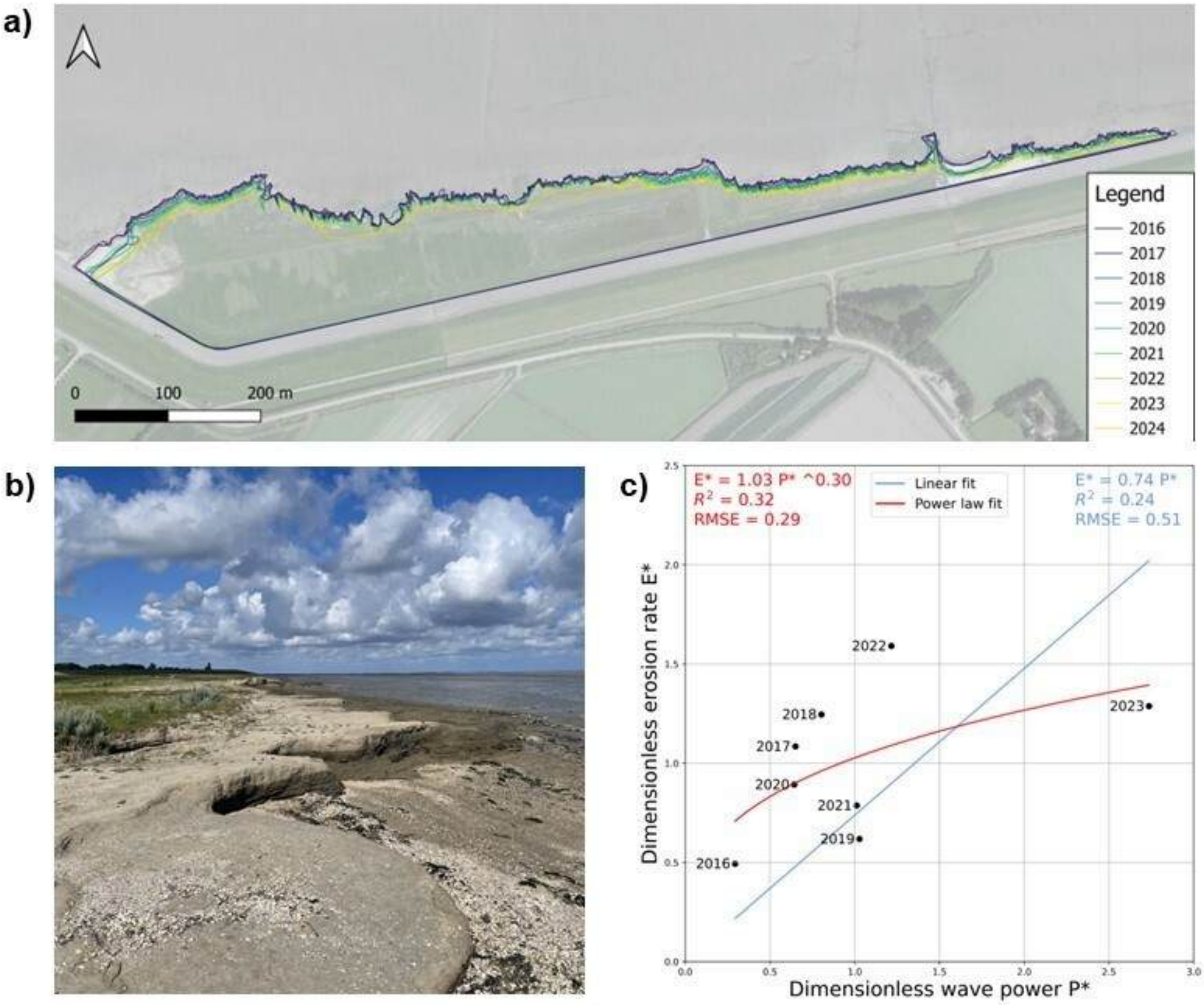

Figure1: a) The Wierum marsh edge location from 2016 until 2024, showing a lateral retreat. A background the aerial image of 2016 is used.; b) Picture of the cliffs at the Wierum marsh; c) Relation between dimensionless wave power (P) and dimensionless erosion rate (E*) including a linear fit (blue) and a power law fit (red).*

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Mangrove Restoration in Lac Bay Lagoon, Caribbean Netherlands

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Introduction

Mangrove forests are increasingly recognized for their environmental and societal values. Over the past century, however, the global mangrove forest cover has drastically declined due to their conversion to other land-use purposes and coastal erosion (Goldberg et al., 2020). In response to the increased awareness of mangroves' value, the mangrove cover decline rates have reduced and several initiatives to restore previously lost mangroves have been initiated. To restore mangroves, it is paramount that knowledge of the geomorphological settings of the to-be-restored mangrove forests is considered, since mangrove forest dynamics vary substantially between settings (Balke and Friess, 2016).

This study considers the restoration of a mangrove forest in Lac Bay lagoon in Bonaire, Caribbean Netherlands. Lac Bay is characterized by a microtidal regime and a carbonate mangrove forest of multiple species. The mangrove forest in Lac Bay has been suffering from an excess of terrestrial sediment, causing that tidal creeks have been filling in over the past decades. The resulting clogging of tidal creeks has caused a reduction in tidal flushing and the degradation and mortality of mangrove trees in the most landward area. Mangrove restoration efforts in response to the degradation included the reopening of tidal creeks.

Objective and Methods

The objective of this study is to obtain quantitative understanding of the hydrodynamic and morphological processes in Lac Bay on a spring-neap tidal timescale. The focus is specifically on the flow velocities and sediment transport through the natural and restored tidal creeks. For this purpose, field measurements were conducted in Lac Bay lagoon between January and May 2022 (Gijsman et al., 2024). Flow velocities in the tidal creeks were measured with Lowell Instruments LLC Tilt Current Meters (TCM's). Turbidity was measured with optical backscatter sensors (RBRsolo^{3}Tu) and converted to suspended sediment concentrations through a lab calibration. The water flow and sediment transport through the tidal creeks were related to water level and wave fluctuations throughout Lac Bay.

Results

The field measurements revealed a substantial attenuation of water levels across the mangrove forest in Lac Bay. In addition to a daily reduction in tidal amplitude, a spring-neap tidal variation in water levels was measured in the landward degraded mangrove area, where water levels step-wise increased towards spring tides, to then step-wise decrease towards neap tide. The daily and spring-neap tidal variation in water levels forced the water flow through the tidal creeks. The suspended sediment concentration in the tidal creeks was also found to vary on a daily timescale as well as to increase gradually on a spring-neap tidal timescale. Consequently, flows were primarily lagoon directed during neap tide conditions, when suspended sediment concentrations were high. This combination caused the export of sediment to the lagoon on a spring-neap tidal timescale.

Hence, while the reopening of tidal creeks enhanced the tidal flushing in the degraded mangrove area, it also increased the export of sediment to the lagoon, where the mangrove forest can replace other pristine ecosystems such as seagrasses. The example of Lac Bay lagoon thus showcase the importance of local knowledge about the geomorhological settings and dynamics for informed restoration of mangroves.

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Prediction of Alongshore Cobble Transport on a Nature-Based Solution for High-Energy Coastlines

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Introduction

Composite beaches are composed of a gently sloping sandy foreshore backed by a steep cobble berm that evolves over time under wave impact. Composite beaches are common in locations including the United Kingdom, New Zealand, Canada, and the Pacific Northwest of the United States (PNW). Composite beaches have been noted to be a relatively stable beach type (Allan et al. 2005), and are a natural analog to dynamic cobble berm revetments. Dynamic cobble berm revetments can be a suitable alternative to hard structures such as riprap revetments when a nature-based solution is desired in an energetic wave environment, but beach nourishment is not practical. The cobbles that make up a dynamic cobble berm revetment move and roll during wave impact and dissipate wave energy. The shape of a dynamic cobble berm revetment is expected to change over time, and some alongshore transport of the cobbles is expected. Understanding the controlling factors of the alongshore transport rate of cobble is important for determining the resilience of composite beaches and for developing maintenance requirements for dynamic cobble berm revetments. However, the relative importance of the different drivers of alongshore transport of cobbles on composite beaches is not well understood.

Objective and Methods

The objective of this study is to collect field observations of alongshore cobble transport on two natural composite beaches in Oregon (Arch Cape and Falcon Cove) and a dynamic cobble berm revetment in Washington (Westport) to elucidate potential relationships that may be viable as predictors of alongshore cobble transport rates. We adopted the procedures of Allan et al. (2006), who used Radio Frequency Identification technology (RFID) to track the transport of cobbles. We collected and tagged ~100 cobbles from each beach with RFID tags. The cobbles ranged in size, and represented the grain size distribution measured at the sites. We replaced half of the cobbles collected from each site in Fall 2023 and the remaining cobbles in January 2024. Throughout the 2023-2024 winter season, the cobble berm was searched 1-2 times per month with a handheld RFID antenna and cobble locations were recorded with an RTK-GPS system. For analysis, the alongshore displacement for each cobble was calculated between each survey. Wave data from offshore buoys and tide data from nearby tide stations were used to calculate the cumulative number of hours that runup exceeded the toe elevation of the cobble berm (Stockdon et al. 2006).

Results

The dominant transport direction of cobbles for the two natural composite beach sites was northward. On average (and maximum), cobbles traveled 22 m (130 m) at Arch Cape and 45 m (150 m) at Falcon Cove over the 6-month experiment. The runup hours and transport distance appeared to be related. Over the first 2 months at both Oregon sites, the runup hours above the cobble toe were 125 and 300 hrs, respectively, and the average cobble displacement was negligible. However, high spring tides, increasing wave heights, and the erosion of sand in the third month caused the increase of runup hours to 677 and 685 hrs and the increase of the average cobble displacement to 6.5 m and 24 m. Observations at Westport showed negligible cobble movement, likely due to the relatively few hours of runup interaction related to the higher elevation of the cobble toe. (Figure 1). This result indicates that the runup elevation is an important predictor of cobble transport, a result which is not currently captured in any coarse-grained alongshore transport equations. Future work will investigate variables such as cobble elevation, cobble mass, and wave direction to quantify their influence on the alongshore transport rate.

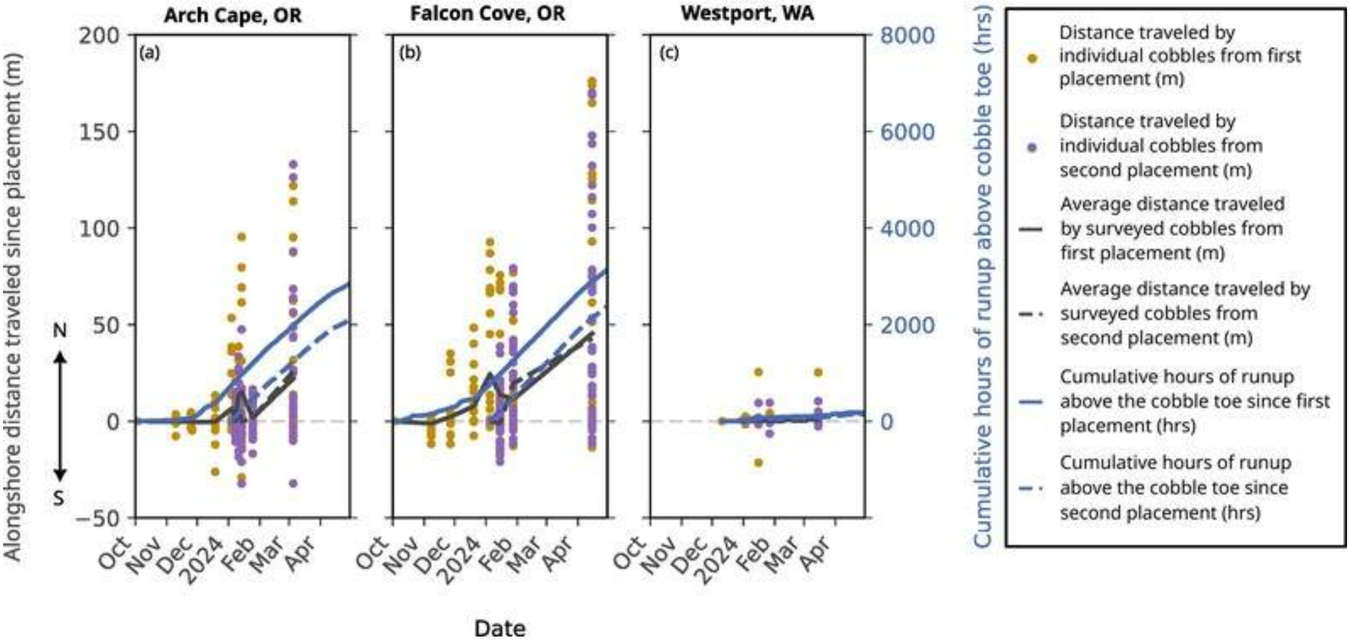

Figure 1: Total alongshore displacement of each cobble from its starting position on each survey date (dots) and average total alongshore displacement (grey solid/dashed line). Cumulative hours of runup above the cobble toe since cobble placement are displayed on the right y-axis (blue solid/dashed line).

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SALTGARDEN - enabling resilient salt marshes in the Wadden Sea

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Introduction

The Wadden Sea is the world's largest continuous natural habitat shaped by tidal forces. This unique configuration of coastal and marine ecosystems is of Outstanding Universal Value and was recognised as a UNESCO World Heritage Site in 2009. However, this valuable yet vulnerable ecosystem is increasingly threatened by the impacts of the triple ecological crisis: climate change, biodiversity loss, and pollution. In principle, the natural dynamics of the salt marshes in the Wadden Sea can contribute to the mitigation of and adaptation to the impacts of the triple ecological crisis. Their ability to trap suspended sediments and stabilise soils strengthens their role as natural coastal protection and facilitates adaptation to sea level rise due to climate change. At the same time, salt marshes serve as important pollutant and carbon sinks, whilst delivering outstanding biodiversity. However, most Wadden Sea salt marshes have undergone anthropogenic use for centuries, with a strong focus on coastal protection and agriculture. With SALTGARDEN we aim to move away from managed and static salt marshes, towards diverse and dynamic salt marshes of different successional stages -referred to as 'SALTGARDENS'- in order to improve the functioning and resilience of the vegetated coastal ecosystems in the Wadden Sea.

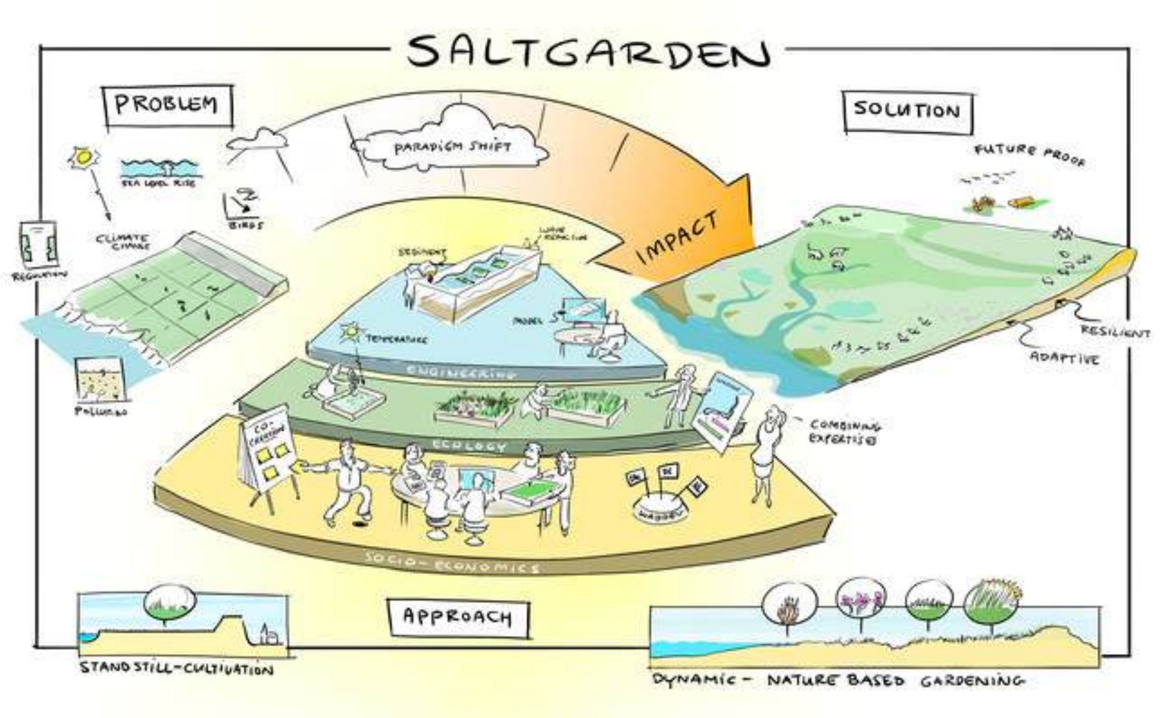
Objective and Methods

The SALTGARDEN project explores new restoration concepts that aim to maintain the ecological integrity of salt marsh systems and strengthen their associated ecosystem services. Our desired societal impact is a paradigm shift in the management of salt marshes towards new ecological guiding principles that we name **Nature-based Gardening** (NbG). This shift requires social and political acceptance. SALTGARDEN therefore aims to co-create socially and politically accepted NbG strategies to establish adaptive and resilient salt marshes through sustainable management, thereby enabling and enhancing their natural dynamics. For this, it needs to be widely understood that coastal spatial design should not only consider the current state of salt marshes, but also their possible future states. In the project, different plant communities and successional stages will be tested in mesocosms for their vulnerability, resilience and the functioning of their ecosystem services under the influence of different stressors. Numerical model predictions and remote sensing observations will be coupled with socio-economic assessments to predict future changes in the functionality and persistence of dynamic coastal landscapes. Lastly, NbG strategies to promote dynamic salt marshes will be co-created together with stakeholders, to enable adaptive coastal landscapes and to consolidate this new paradigm at the policy level.

Results

The intended results of the SALTGARDEN project will provide quantitative insights in the dynamics and resilience of managed and static salt marshes in comparison to the functioning of biodiverse and dynamic salt marshes. The NbG strategies will enable such biodiverse and dynamics salt marshes, creating landscapes that deliver the highest ecological value and ecosystem services, whilst being adaptive and resilient in the long term. These salt marsh landscapes will also enhance the aesthetics and natural beauty of the Wadden Sea ecosystem, contributing to the Outstanding Universal Value of this World Heritage site.

By promoting the establishment of biodiverse and dynamic salt marshes, we consider the NbG approach to be a progression of the established paradigms of 'REstoration', 'REcreation' or 'REbuilding'. The project thus questions whether these RE-created past ecosystems are sufficiently adaptive and resilient in the face of the present triple ecological crisis, and at the same time introduces the biodiverse SALTGARDENS as future-proof salt marshes with a solid contribution to the Outstanding Universal Value of the Wadden Sea. We believe that NbG can strengthen the ecological status and ecosystem services of the Wadden Sea salt marshes for future generations.



Planned impact and approach of the SALTGARDEN project (illustration by Joost Fluitsma).

Linear stability analysis on a sloping shelf: effects on tidal sand wave formation

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Introduction

Tidal sand waves are rhythmic bed features often found in tidally-dominated shelf seas. They have wavelengths of 100 - 1000m, heights of 1 - 10 m, and migration rates of 1 - 10 m/yr (van Dijk and Kleinhans, 2005).

Hulscher (1996) explained sand wave formation as a free instability of a flat seabed subject to tidal motion using a linear stability analysis. Recently, observations have indicated that the underlying topography affects the shape of a sand wave field, by yielding, e.g., more two-dimensional sand wave fields on top of sand banks than on the sandbank slopes (Krabbendam et al., 2023). However, the effects of a sloping shelf on sand wave formation have not been studied in detail.

We aim to systematically study the effects of a sloping background topography on the initial stage of sand wave growth. Similarly to the shoreface-connected sand ridges study of Calvete et al. (2001), we make use of a linear stability analysis.

Objective and Methods

Consider an offshore region of a shallow shelf sea with an alongshore-uniform background topography that is sloping in the cross-shore direction y, $H(\gamma y)$. We assume a weak cross-shore dependence, hence γ is small. The background topography is in morphodynamic equilibrium, on top of which sand waves may develop (Figure 1).

We build a model based on the 3D shallow water equations, where bed evolution is modelled with the Exner equation, considering bedload sediment transport. The model is forced with an M2 tidal signal in the alongshore direction. We assume periodicity in the alongshore direction.

We then perform a linear stability analysis on the model equations, which allows us to study the growth or decay of seabed perturbations on the basic state topography (the shelf without sand waves).

The weak dependence on y of the shelf topography allows for solving the basic state semi-analytically, by expanding the equations in terms of the small parameter γ. The first-order solution is characterised by a sinusoidal dependence on the alongshore coordinate, with wavenumber k. For each k-value, the stability analysis yields the mode (flow and bathymetry) with the highest growth rate, which is often considered to characterise the system.

Results

The basic flow shows tide-topography interactions leading to upslope residual currents at the seabed similar to those over sandbanks. These effects depend on both the local depth and slope.

Our first-order model reproduces the flow over an imposed hypothetical sand wave topography. It is also able to compute the fastest growing mode for the flatbed case, with $\gamma = 0$, reproducing the results of Hulscher (1996). Results on the stability analysis for a non-zero shelf slope ($\gamma > 0$) will be presented at the conference.

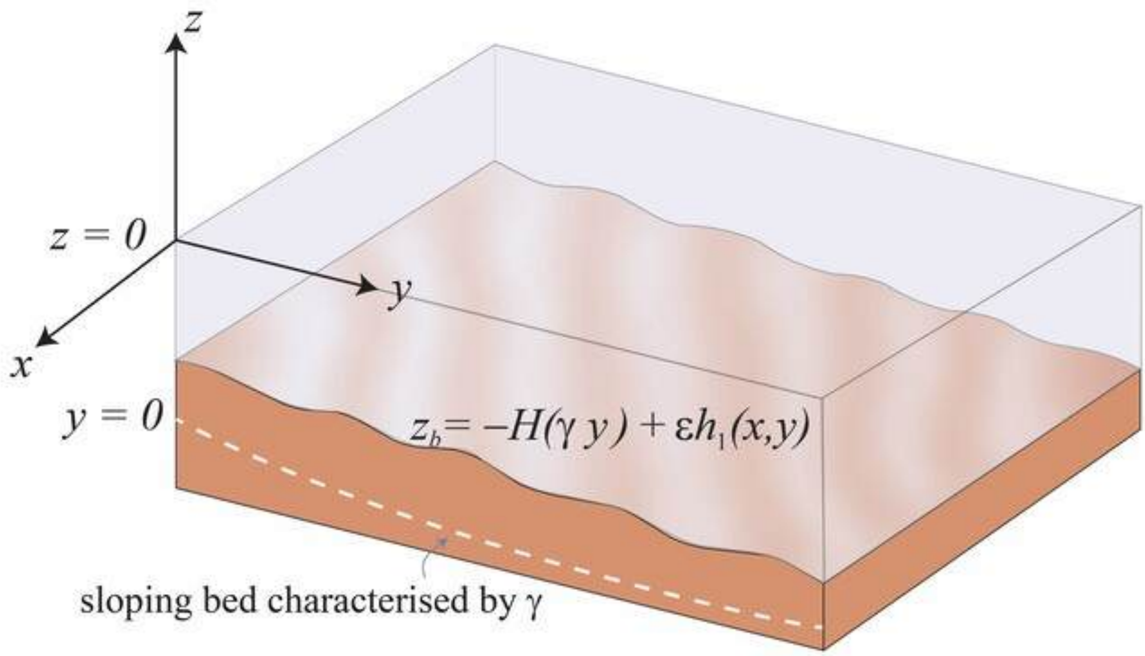

Figure 1: Sketch of the model geometry, with alongshore coordinate x, cross-shore coordinate y and vertical coordinate z.

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Morphodynamics of sand ridges on the shelf: modelling effects of waves, wind and tide

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Introduction

Sandy continental shelves often feature the presence of large-scale rhythmic bedforms, known as shoreface-connected sand ridges (sfcr) and tidal sand ridges (tsr). These ridges typically evolve on centennial time scales, with spacings of 2-15 km between successive ridge crests, lengths of 10-50 km, widths of 1-10 km, and heights of 5-25 m (Dyer and Huntley, 1999). Typically, sfcr are found on inner shelves frequently exposed to storms, whereas tsr form on outer shelves under strong tidal conditions (tidal range > 3 m). On shelves subject to both frequent storms and strong tides, such as the Belgian shelf, both sfcr and tsr develop.

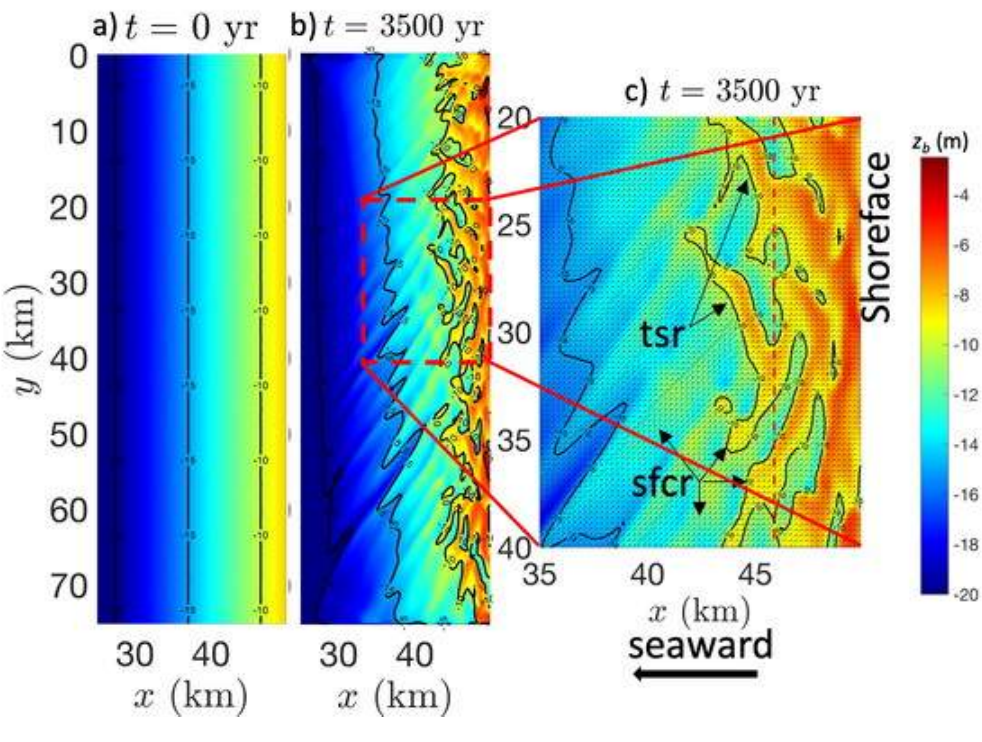
Studies so far (see the reviews by Ribas et al., 2015; de Swart and Yuan, 2019) have focused either on sfcr, thereby assuming weak tidal conditions (tidal range < 1 m), or on tsr, disregarding wave and wind effects. The objective of this study is to investigate the impact of the combined waves, wind and tide on the long-term evolution of shelf ridges.

Objective and Methods

The coupled Delft3D+SWAN numerical model (Lesser et al., 2004; Holthuijsen, 2007) is applied in a setting representative of the Belgian shelf. An experiment is carried out for a duration of 3500 years, in which the model is forced with waves, wind and tide. This experiment starts from small-scale random bottom perturbations (with root-mean square height of 10 cm) superimposed on the initial bathymetry (panel a in the figure).

Results

Model results (panels b and c in the figure) show that a mix of two type of ridges emerges on the shelf, which resemble the sfcr and tsr observed on the Belgian shelf. However, a notable difference is that observed tsr are located further offshore than modelled ridges. A potential explanation for this difference is the neglectance of sea level rise, which can significantly influence ridge evolution. Effects of sea level rise will be investigated in the coming months, and if succcessful, the results will be presented at the conference.



Snapshots of the simulated bed level zb at times t = 0 yr (a) and t = 3500 yr (b). A zoom-in at t = 3500 yr is displayed in panel c.

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Salt marsh resilience for sea level rise depends on management

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Introduction

Saltmarshes are vital ecosystems that provide multiple ecosystem services such as habitat for specific plants and birds, coastal protection and carbon storage. However, they are vulnerable to rising sea levels. Salt marshes may gradually drown if sedimentation cannot keep pace with rising sea levels. The response of salt marsh vegetation to such drowning remains uncertain, yet is crucial for understanding salt marsh resilience.

Objective and Methods

We compared the vegetation development of two back-barrier salt marshes: Oost-Ameland en Schiermonnikoog. On Oost-Ameland, deep soil subsidence due to gas extraction has occurred, and sedimentation has partly been insufficient to compensate for it. Both study sites have areas that are grazed by cattle and areas that remain ungrazed, allowing us to compare their vegetation development. Vegetation changes were assessed using Rijkswaterstaat vegetation maps over a 25-year period.

Results

The island experiencing deep soil subsidence had more vegetation regression to an earlier succession stage than the island without subsidence. The high salt marsh vegetation transitioned to a lower salt marsh vegetation and bare patches increased. Additionally, vegetation regression occurred more in grazed areas with soil subsidence, suggesting that grazing reduces salt marsh resilience to sea level rise.

Aerial image of the two study sites: Ameland and Schiermonnikoog. Top: Ameland with grazed marsh Neerlands Reid (1) and ungrazed marsh De Hon (2). Bottom: Schiermonnikoog with the grazed marsh (3) and the ungrazed marsh with an similar age to the De Hon (4). The red lined areas are our study sites. The dotted black lines indicate the deep soil subsidence in cm (NAM, 2022).

Saltmarsh erosion near toe of a sea dike under extreme storm conditions

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Introduction

Nature-based flood defences receive increasing interest as a viable option for improving flood safety worldwide. A contemporary case is using the ability of saltmarshes to attenuate waves during storm conditions for strengthening coastal flood defences (Vuik et al., 2016). Contrary to conventional coastal protection solutions, a saltmarsh is dynamic as it can erode. Although many research and observations has been done on saltmarsh dynamics, the erosion mechanics under extreme storm conditions are not well understood. Particularly at the transition between the saltmarsh and the coastal structure such as a sea dike, wave forcing and potential scouring at the toe of the dike pose a serious threat for the overall flood safety. Detailed observations on the near-bed velocities, the interaction with vegetation and erosion of a saltmarsh in front of a dike during storm conditions are missing.

Objective and Methods

In this work, we quantify the wave-driven near-bed velocities at the toe of a dike fronted by a saltmarsh with specific attention to the role of degrading vegetation and focusing on the erosion at the toe during extreme storm conditions.

The experiment was performed in the Deltaflume at Deltares. A real-life saltmarsh (70 m long) was created by harvesting blocks at a field site at the Dutch Wadden sea during Autumn. At the end of the model, a non-erodible dike was built with a slope of 1:3.6, typical for a Dutch coastal sea dike.

Irregular wave scenarios ranged from intermediate to extreme storm conditions, with significant wave heights (Hs,0) between 0.75 to 2.0 m at an offshore water depth between 4.4 to 6.9 m, corresponding to 1.5 to 4.0 m water depth on the marsh respectively. The wave scenarios were repeated as the vegetation (*Elymus athericus*) gradually got damaged and was finally removed by mowing. In total, the experiment covers 40 hours of exposure.

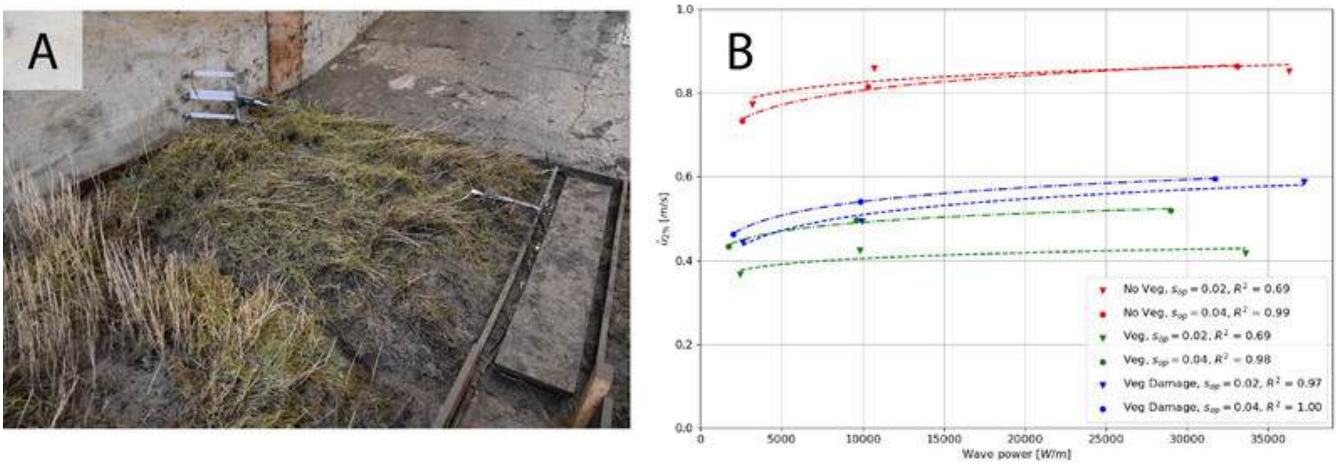
Near-bed velocities at the dike toe were measured by Acoustic Doppler Velocimeter (ADV) (Fig. 1a). Wave characteristics were measured with wave gauges. Erosion at the toe was monitored in between wave scenarios when the flume was drained.

Results

After approximately 40 hours of exposure, minimal erosion was observed at the toe of the dike. Even under extreme wave conditions ($H_{s,0}$ = 2.0 m), where heavy wave breaking occurred on the dike slope, scouring at the toe remained negligible (see Figure, Panel A).

Stronger wave conditions increased maximum near-bed velocities at the dike toe ($\hat{u}_{2\%}$), ranging from 0.4 to 0.5 m/s for wave heights ($H_{s,0}$) between 0.75 m and 2.0 m for fully intact vegetation. The presence of vegetation effectively reduced these near-bed velocities (see Figure, Panel B). As the vegetation was gradually damaged, stems and leaves still provided wave attenuation. After full vegetation removal, $\hat{u}_{2\%}$ increased to 0.7 to 0.9 m/s, indicating a 50% reduction in near-bed velocities at the toe due to the vegetation presence. Attenuation of the velocities was higher for longer waves scenarios (s_{op} = 0.04) compared to shorter waves (s_{op} = 0.02).

Our findings extend previous research on maximum near-bed velocities (Spencer et al., 2016). Even under extreme storm conditions for an extensive period of exposure, these velocities did not exceed the critical threshold required for significant erosion at the toe. These results demonstrate the stability of the transition between a saltmarsh in front of a sloped coastal structure even during extreme conditions.



State of the saltmarsh at the toe of the dike after ca. 20 hours of wave exposure with the ADV deployed at the right side of the block (panel A) and maximum near-bed velocities for different states of the vegetation (panel B)

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How the Ebb Tidal Delta Affects Wave Loads on the Eastern Scheldt Storm Surge Barrier

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Introduction

The Eastern Scheldt storm surge barrier (OSK) plays a critical role in coastal protection, mitigating extreme wave impacts and water levels, while maintaining tidal exchange with the estuary. The wave conditions at the OSK are derived in a series of steps, summarized as:

1. Modelling of the wave transformation from the North Sea to the barrier using the spectral wave model SWAN for various stationary, uniform wind and water level conditions and in absence of flow,
2. Correction of the model outcomes (significant wave height, Hm0 and mean wave period, Tm-1,0) for bias with nearby wave measurements,
3. Derivation of a maximum individual wave height, Hmax, and corresponding wave period THmax, based on a wave height distribution function.
4. Translation of wave conditions into wave pressures on the gate and stresses in the gates and pillars (not considered in this study).

The ebb tidal delta of the Eastern Scheldt affects the wave conditions (Hm0, Tm-1,0, Hmax, THmax) through (spectrally varying) attenuation of wave conditions (step 1), changing the Hmax/Hm0 ratio at shallow areas (step 3).

Objective and Methods

Our objective is to analyze how the failure probability of the OSK changes with alternate assumptions regarding the effect of the delta on the wave loads.

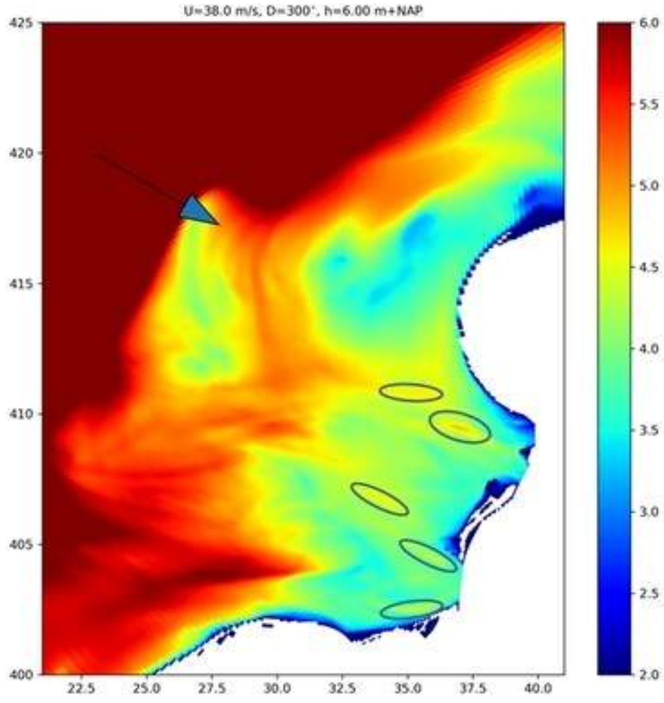
The ratio between Hmax and Hm0. Previous assessments used a Rayleigh distribution to establish the ratio of Hmax/Hm0, which does not account for bathymetric effects and non-gaussian wave shape in non-linear waves. A closer inspection of the SWAN model results, contrastingly indicated that local bathymetric effects may play a role. We have applied the Battjes-Groenendijk, which accounts for depth-induced wave breaking effects, using various assumptions. The presence of a sill at the crossing of the ebb and flood channels was a factor of particular interest.

The representation of refraction in SWAN. A limitation of the wave model SWAN is its poor representation of long-wave refraction over steep channel slopes. SWASH better captures this phenomenon, although at increased computational costs and without the local effects of wind. We conduct SWASH simulations to assess the impact of long-wave refraction on the wave loads at the OSK. We simulate conditions closely matching SWAN calculations at the design point of the OSK to facilitate a direct comparison of short and long wave propagation.

Results

The ratio between Hmax and Hm0. The SWAN model indicates that various bathymetric variations (channel slopes and sills (-10 m+NAP) in front of the ebb channels (~ -15 m+NAP)) alter the wave conditions significantly. Modifying our assumptions on the representative water depths, bottom slopes and storm duration, the calculated Hmax/Hm0-ratio varied between values of 1.94 (deep water), 1.73 (sill depth) and 1.53 (nearby flats). Analysis of wave measurements showed that deviation from the Rayleigh distribution varies with Hm0, in part explained by an associated increase in wave period and in part by increase depth induced breaking. The scatter in the data is very large and substantial maximum individual wave heights above the Rayleigh estimate were found. Ultimately we demonstrated that applying Hmax/Hm0=1.73 results in a reduction factor of structural failure probabilities of individual gates between 2.5 and 5.5. We recommended a cautious reduction of 5% to the Hmax based on the Rayleigh distribution, and further analysis into individual wave propagation and explicitly representing the uncertainty.

The representation of refraction in SWAN. Building onto the previous, a SWASH model simulation is conducted to study the refraction of longer and shorter waves on channel slopes and subsequent reduction of the maximum wave heights. The results will be presented at the conference.



SWAN model output of significant wave height Hm0 (m) for a wind speed of 38 m/s with direction 300°N (arrow) and a uniform water level of NAP+6 m. Circles: shallow flats with an increased significant wave height along the channels leading to the OSK.

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Storm Surge Events and the Link With Serial Cyclone Clustering: A Study of the Dutch Coastline

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Introduction

Extreme weather events, particularly storm surges, pose an increasing risk to coastal communities worldwide due to climate change. In the Netherlands, storm surges, characterized by sudden sea level rise, are primarily caused by extratropical cyclones (ETCs). Research has shown that storm surges are complex natural hazards influenced by a combination of meteorological, oceanographic, and geographic factors. One key meteorological driver is the clustering of serial cyclones (SCC), a phenomenon in which multiple ETCs pass over the same area within a short timeframe. Recent findings by Rantanen et al. (2024) indicate that nearly 50% of extreme sea level events in the Baltic Sea are linked to periods of SCC. Despite the significant threat storm surges pose to the Dutch coastline, most existing research has focused on single storm surge events. This knowledge gap introduces critical uncertainties in coastal defence planning and flood risk management. Specifically, the extent to which SCC amplifies storm surges and influences extreme water level statistics, such as return periods, remains unclear. These uncertainties are crucial for designing robust coastal protections.

Objective and Methods

This study assesses whether storm surges amplify along the Dutch coastline during clustered events and aims to identify the factors driving this amplification across regions. It addresses a key knowledge gap on storm surge amplification linked to SCC, investigating how these factors heighten the severity and frequency of major events, particularly in low-lying areas like the Netherlands. To quantify storm surge amplification, its regional variations, impacts on flood metrics, and the role of SCC, we analyse hourly water level data from 10 Dutch tide gauge stations alongside ERA5 meteorological reanalysis data. Storm surge events are extracted from the low-pass filtered residual water levels using the 95th percentile as threshold. Peak water levels are considered clustered if they occur within a three-day window. ETC tracks are derived and six-hourly MSLP fields are analysed while excluding ETCs lasting 24 hours or traveling 500 km to focus on larger systems. Clustering is identified when ETCs pass within two to three days of each other. A statistical model is then applied to assess impacts on flood metrics, incorporating extreme value statistics and mixture models to evaluate how clustering influences return periods and storm surge heights.

Results

Preliminary results indicate that clustered storm surges lead to higher peak water levels across all tidal stations. Return period analysis suggests that in some areas, conventional methods may underestimate the impact of clustering, as clustered storm surges result in higher water levels for given return periods compared to non-clustered events. For example, a return period of 10 years at the Bath (near Belgian border) for clustered storm surges show an increase of 12 cm compared to single storm surge events. Additionally, in southern regions like the Western Scheldt, this signal appears to be stronger than in northern regions like the Wadden Sea. Further analysis is underway to refine these findings, assess regional variations in storm surge amplification, and identifying factors driving the amplification of clustered storm surges.

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Predicting salinity in the Haringvliet Outer Delta for operational and long-term applications using Machine Learning.

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Introduction

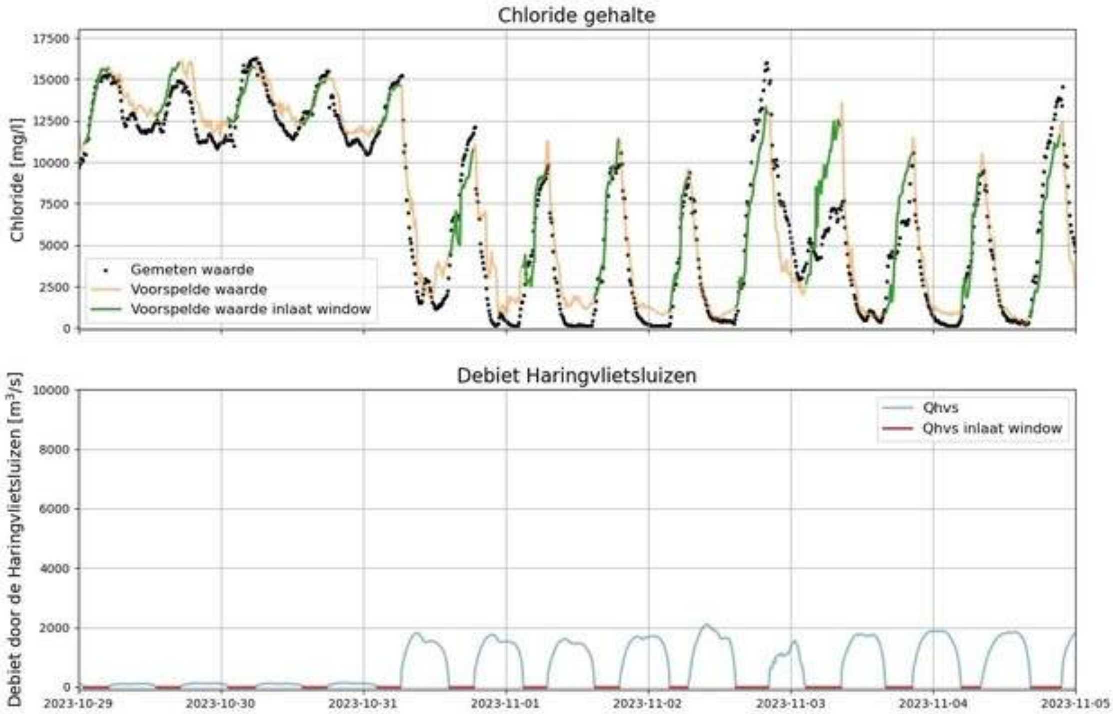
As part of the research program Onderzoeksprogramma Verzilting van Lerend Implementeren Kierbesluit Haringvlietsluizen, fish migration into the Haringvliet must be stimulated while maintaining feasible boundary conditions for inland salinity penetration. To support this, simulations and field studies are conducted to investigate salt dispersion in the Haringvliet estuary. A key parameter in this research is the salinity in the Haringvliet Outer Delta ('Voordelta'), located on the sea side of the Haringvliet barrier. This barrier contains sluices that regulate inland water levels by periodically discharging freshwater into the Outer Delta, creating a stratified system. Additionally, these sluices will allow limited saltwater inflow to facilitate fish migration. The salinity at Stellendam-Buiten at -5m depth is particularly indicative of the water intake quality. Despite abundant measurement data, predicting salinity levels remains challenging, with existing methods such as 3D modeling being highly resource-intensive and costly.

Objective and Methods

The extensive dataset on salinity levels in the Outer Delta offers the potential for leveraging Machine Learning (ML) models to improve predictive accuracy at a lower cost. This study investigates the feasibility of ML models in predicting complex estuarine salinity dynamics with minimal investment. Two ML models of varying complexity were developed. First, the predictive potential of the dataset was assessed using a simple decision tree model (Random Forest Regression), which demonstrated reasonable accuracy and was developed in just two days. Building on this, a more advanced decision tree-based model (Extreme Gradient Boosting) was implemented. The five-year dataset was divided into a training set (48 months), a calibration set (2.5 months), and a test set (3.5 months). Input parameters were selected through exploratory data analysis and Recursive Feature Elimination with Cross-Validation (RFECV).

Results

The advanced model accurately predicted salinity levels in the Outer Delta with low computational cost, achieving a Mean Absolute Error (MAE) of 390 mg/L across the test dataset. Model performance depended primarily on the discharge rate of the Haringvliet sluices, identified as the most critical input parameter. The model showed the highest accuracy at low discharge rates (3000 m³/s), predicting slightly higher salinity peaks during non-discharge periods. However, under moderate discharge conditions (>1000 m³/s & 3000 m³/s), the model occasionally underestimated salinity peaks, which could pose safety risks. This research highlights the potential of ML applications for cost-effective and accurate prediction of salinity dynamics in estuarine environments. The model can be used in long-term predictions for the salinity levels in the Haringvliet Outer Delta and, under consideration, support decision support for sluice operators. The model can be improved significantly by considering the latest measurements of the salinity concentration as one of the input parameters. Furthermore, more complex ML models, such as deep learning models, might perform better at the expense of higher computational costs.



Predictive capability of the ML model with respect to the measurement data for the transition between a low sluice discharge regime to a high sluice discharge regime.

How Geomorphic Shifts and Climate Variability Reshape Saltmarsh Ecosystems in the Western Scheldt Estuary

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Introduction

Saltmarsh ecosystems are dynamic landscapes where geomorphic change and climate variability converge to shape vegetation patterns and ecosystem functions. This study integrates two complementary investigations in the Western Scheldt estuary, Netherlands, to unravel how these dual forces interact to drive long-term ecological changes.

Objective and Methods

Firstly, we explored the bio-geomorphic interplay between tidal emergence and vegetation dynamics through pixel-based geospatial analysis by using emersion duration maps and vegetation maps of the Dutch Western Scheldt estuary over a period of decades (1993-2016) (Feng et al., 2025).

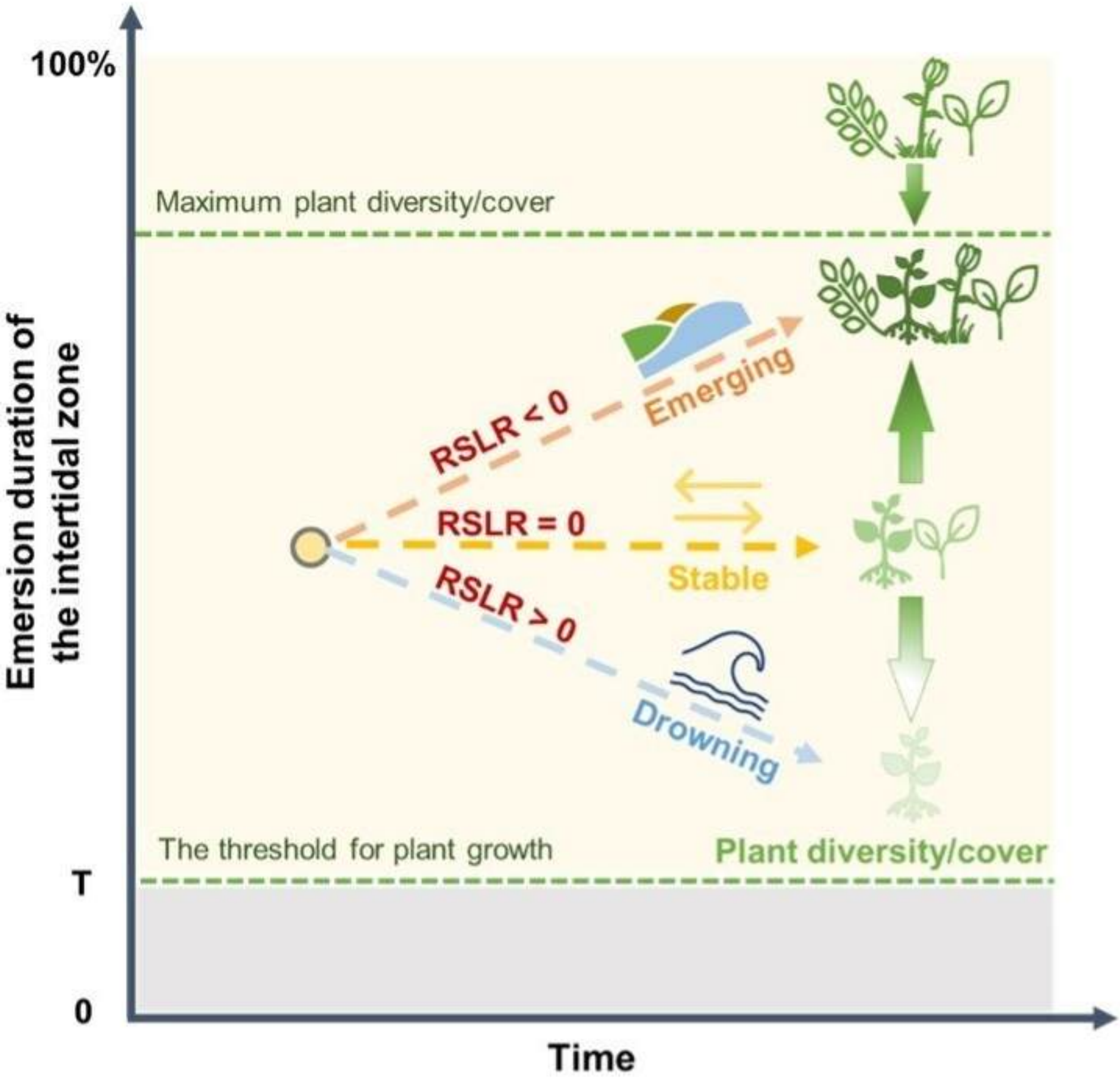
Secondly, we investigated long-term vegetation phenology from 1993 to 2022, using Landsat satellite-derived 2-band enhanced vegetation index (EVI2) and climate data, coupled to existing sequential maps of vegetation communities.

Results

We uncovered how elevation and emersion duration influence plant diversity and species distribution. Higher intertidal areas, experiencing increased elevation and emersion duration have greater plant diversity and cover, while lower intertidal zones show declines in elevation and emersion duration. Responses were species-specific: pioneer species like *Spartina spec.* and *Salicornia spec.* dominate lower elevations, whereas high marsh species such as *P. australis* thrive in elevated areas. These findings highlight the tight links between geomorphic processes and vegetation dynamics and underscore the need to integrate localized relative sea level changes into ecosystem management.

We also identified phenological shifts, including earlier green-up, accelerated peak growth, and extended growing seasons, driven by seasonal climate variability. Higher intertidal areas exhibit earlier growth onset than lower intertidal areas. In addition, there was phenological asynchrony—pioneer species green up earlier than high marsh species. Seasonal climate variables, such as spring warming and winter precipitation, (cor)relate with these phenology patterns, with warmer springs advancing growth onset and higher winter precipitation extending the growing season.

By decoding the dual forces of geomorphic shifts and climate variability, this research provides a novel framework for understanding and predicting saltmarsh ecosystem responses to environmental change.



Conceptual diagram of main drivers to change the emergence of the local area of the intertidal zone and its ecological consequences (Feng et al., 2025).

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Adapting an ecomorphodynamic 1-D model to estimate the presence of macrozoobenthos species in Venice Lagoon

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Introduction

Salt marsh ecosystems are highly dynamic environments that offer a range of ecosystem services, including coastal protection, climate regulation, and biodiversity support. Nevertheless, these ecosystems are increasingly vulnerable to both natural and anthropogenic pressures. To effectively restore and manage salt marshes, it is crucial to understand the complex interplay between ecological and morphodynamic processes.

Globally, there has been an interest in macrozoobenthos (invertebrates that inhabit seabed environments as the intertidal zone), because they are used as key indicators of environmental health in salt marshes due to their sensitivity to changes in water quality, sediment conditions, habitat structure and their played role in the functioning of salt marsh ecosystems.

In the case of Venice Lagoon (VL), various 1-D and 2-D models have been developed to simulate the ecological and morphodynamic processes of salt marshes. However, they have specially focused on only the interaction between salt marsh vegetation and its hydro-morphodynamics.

Objective and Methods

The aim was to determine macrozoobenthos species presence in a salt marsh in the VL by analyzing key ecomorphodynamic processes driving long-term marsh evolution through a one-dimensional mode. We built on Tambroni and Seminara (2012) idealized 1-D model for VL to incorporate Total Organic Carbon (TOC), and macrozoobenthos presence.

The model consists of different parts, the hydrodynamic submodule calculates flow field due to a tidal forcing, the morphodynamic module assesses sediment flux and deposition (inorganic and organic), while the vegetation module models plant growth/decay based on local hydrodynamic conditions. Finally, TOC content is calculated as a function of vegetation, and the macrozoobenthos submodule evaluates species presence based on local water depth and TOC thresholds.

We consider four vegetation species (*Spartina, Sarcocornia, Limonium,* and *Juncus)* and five macrozoobenthos species (*Abra alba, Capitella capitata, Cerastoderma glaucum, Hediste diversicolor*, and *Heteromorfos filiformis*). Historical data from 94 stations were used to determine macrozoobenthos dominance over TOC thresholds using Indicator Species Analysis.

Simulations over 140 years explored sea level rise (SLR) impacts under IPCC scenarios SSP3-7.0 and SSP5-8.5, compared to a no-rise scenario, providing insights into marsh evolution and species dynamics.

Results

The enhanced 1-D model predicted the marsh evolution and the presence of macrozoobenthos in VL, particularly Capitella *capitata, Cerastoderma glaucum,* and *Hediste diversicolor*, considering their dominance for different TOC levels.

Vegetation is found to mitigate the impact of SLR, even when elevated sea levels inhibited vegetation growth. At the end of the 140-year simulations under the SSP5-8.5 SLR scenario the salt marsh retreated and drowned for different vegetation species. However, early growth during the first 30-40 years helped marshes withstand SLR, particularly in the multi-vegetation scenario. Similar results were found for SSP3-7.0 scenario.

Figure 1 shows the presence of *Hediste diversicolor* which reaches peak after the first 30 years of simulation but disappears after 140 years in the SSP5-8.5 scenario due to the vegetation-dependent nature of TOC. Further research for TOC sources is required to refine the macrozoobenthos presence.

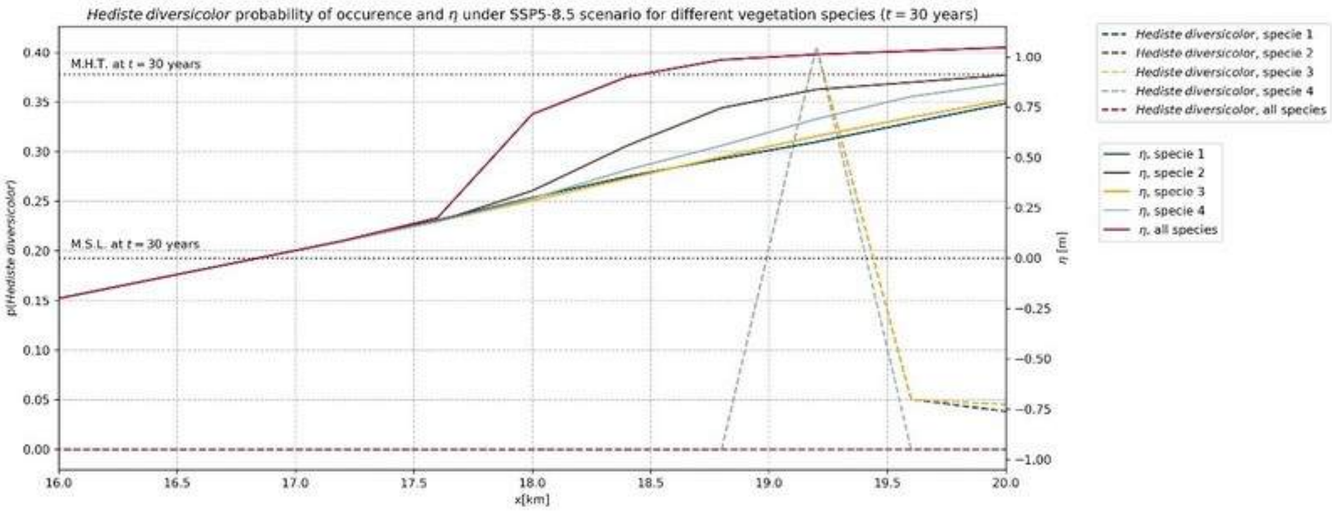

Figure 3. Probability of occurrence of Hediste diversicolor along the marsh at the end of 30-years simulation (SSP5-8.5) using bed elevation (η) of different vegetation scenarios as reference.

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Priming nourishments with local sediment to accelerate recovery: A large-scale In Situ Experiment

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Introduction

Estuaries worldwide are under pressure from climate change and human activities. To protect coastal communities from flooding, many estuaries have been (semi-)closed by storm surge barriers. However, these structures disrupt hydrodynamic processes, leading to estuarine "drowning"—a phenomenon often exacerbated by sea-level rise. The Oosterschelde (Netherlands) is one such drowning former estuary, undergoing system-wide erosion since the construction of a storm surge barrier and compartmentalization dams in the 1980s. This erosion results in the loss of intertidal areas, which are critical foraging grounds for shorebirds. Since removing barriers is not a short-term management option, mitigation measures are needed. To counteract intertidal loss, sand nourishments have been implemented since 2008—starting with small-scale pilot projects and gradually increasing in scale and ambition.

Objective and Methods

Despite the necessity of tidal flat nourishments to restore and maintain foraging habitats for shorebirds, these interventions can be highly disruptive to their food source, the benthic communities. Investigating methods to reduce this impact is therefore crucial.

In this study, we tested whether priming nourishments with local sediment can enhance recovery of the benthic community during a large-scale nourishment operation. In autumn 2019, a 1.13 Mm^3 nourishment was carried out on the Roggenplaat (Oosterschelde) to compensate for bird foraging habitat loss. This nourishment consisted of seven distinct elements, varying in location, elevation, and sediment thickness.

On one nourishment element, we tested a priming approach by relocating local sediment rich in benthic fauna by piling it up before embedding it within a standard nourishment with nonlocal sediment (sourced from the channel). We also applied cockle-seeding: i.e., cockles were seeded on top of the nourishment whereafter the animals had to burry themselves in. The experiment consisted of 12 plots divided into four treatments: (1) 3 pots with standard (non-primed) nourishment; (2) 3 plots with sediment priming; (3) 3 plots with cockles seeding; and (4) 3 control plots were established in the surrounding undisturbed tidal flat.

Results

We found that nourished areas primed with local sediment recovered significantly faster than plots seeded with cockles or standard (non-primed) nourishment plots. Immediately after nourishment, primed plots exhibited higher biomass, suggesting that this approach partly preserves the benthic community. One year after nourishment, the primed plots were nearly fully recovered. This accelerated recovery is likely due to the retention of key soil properties (e.g., grain size and organic matter content) that remained closer to pre-nourishment conditions. Additionally, benthic community development in primed plots progressed faster than expected based on nourishment thickness alone. This faster initial recovery is particularly beneficial for shorebirds, as (non-primed) nourishments recover slowly, especially thicker nourishments are taking years before they become valuable foraging grounds again. Our findings suggest that sediment priming could be a valuable strategy to enhance the ecological quality of nourishments. Our results underscore the need for further testing this technique to improve the recovery and ecological function of tidal flat nourishments e.g. by priming local sediment on top of thicker less quickly recovering nourishments.

Supplementation element 2 from the northeast (dashed white outlined polygon) and the embedded priming plots (black outlined polygons).

Quantifying the Performance of Salt Marshes Under Extreme Hydrodynamic Conditions: Insights from a Large-Scale Experiment

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Introduction

Coastal areas worldwide rely on hard engineering structures for flood protection, but concerns over their static nature and long-term efficacy under climate change have prompted interest in nature-based solutions. Salt marshes, known for their wave attenuation properties, have been proposed as sustainable alternatives. Although their role in coastal defence has been acknowledged, a lack of quantitative data on their performance under extreme hydrodynamic conditions has limited their integration into flood protection frameworks. Previous research has focused primarily on mild wave conditions, leaving a gap in understanding their resilience during storms. This study presents a large-scale experiment aimed at assessing the response and survivability of salt marshes when exposed to extreme hydrodynamic loads. The results will contribute to the development of risk-based coastal defence strategies that incorporate natural elements.

Objective and Methods

This study aimed to quantitatively evaluate wave attenuation and the morphodynamic response of salt marshes under storm-like conditions. A month-long experimental campaign was conducted in the Delta Flume at Deltares, featuring a 71-meter-long salt marsh model built from vegetated clay blocks. These blocks were harvested from a real salt marsh in the Peazemerlannen Nature Reserve, Netherlands, ensuring realistic soil composition and vegetation characteristics. A range of wave conditions (HS between 0.8–2.0 m) was tested under varying water depths (4.4–6.9 m) and offshore wave steepness (s_{op} between 2.8–5%). Measurements included water surface elevation, velocity profiles, pore pressure, wave loading on a dike, and biomass degradation.

Additionally, the study focused on morphological changes such as sediment erosion, vertical deformation of the marsh platform, and cliff retreat at the seaward edge. The experiment was structured into three vegetation conditions, healthy, intermediate, and degraded, to assess the progressive effects of the vegetation on the hydrodynamic forcing. Data collection methods included wave gauges, pressure sensors, accelerometers, and laser scanning for erosion and topographic assessment.

Results

The study provides the first large-scale quantitative insights into salt marsh performance under extreme wave conditions. Initial findings focus on wave attenuation capacity, sediment erosion patterns, and vegetation resilience. Results indicate that **wave attenuation increases for lower wave heights when vegetation quality is high**, demonstrating the effectiveness of well-developed salt marshes in dissipating wave energy under moderate conditions. However, **under extreme wave conditions, the attenuation effect of the vegetation remains nearly the same regardless of vegetation quality**, suggesting that storm waves largely overpower the influence of vegetation structure.

These findings provide critical insights into the role of salt marshes in coastal protection, highlighting their potential effectiveness under normal conditions but also their limitations during extreme events. This study offers a valuable dataset for improving the integration of nature-based solutions into coastal flood risk management and informs future designs that balance ecological function with engineering reliability.

Morning activities along a vegetated Delta flume

Sand Extraction within a demanded North Sea

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Introduction

The North Sea is a vital marine area, supporting rich biodiversity and various human activities. Sand extraction is one of them and is essential for coastal protection of the Dutch coast; however, its predicted to increase in intensity as sea-levels continues to rise, raising sustainability concerns. Sand is a finite resource, limited by the geological characteristics of extraction sites. This limitation necessitates strategic planning to manage sand reserves sustainably and minimize damage to marine habitats, particularly in ecologically sensitive areas, such as Natura 2000 sites.

Maritime Spatial Planning (MSP) aims to optimize the allocation of marine space, balancing economic needs with environmental sustainability. These plans ensure compatibility between sand extraction and other activities, such as shipping, fishing, and renewable energy development. Rijkswaterstaat, as the manager of the Dutch North Sea, prioritizes coastal resilience as well as ecological integrity. High-quality sand is selected for nourishment projects to support natural coastal processes, while avoiding or minimizing harm for the environment. By integrating ecological considerations with sustainable resource management, the aim is to balance the increasing pressures on the North Sea with the preservation of biodiversity and long-term ecosystem health.

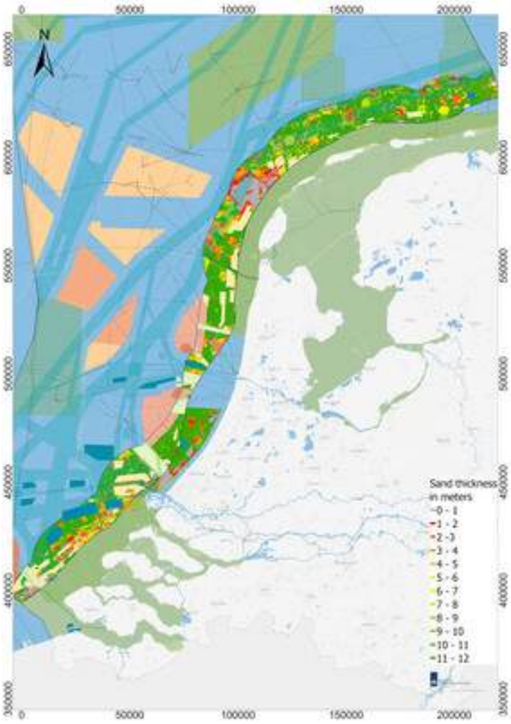
Objective and Methods

One of our objectives is to map sand availability through a detailed geological model (build by Deltares and TNO) of the reserved area for sand (Delfstoffen Informatie Systeem, DIS). This model provides insights into sand distribution, quality, and accessibility, guiding future extraction strategies. The geological model provides first insights in the quantity of sand for the long-term, whereas it also identifies location of interest for sand extraction in the near future. For example, preparations of the Environmental Impact Assessment (EIA) 2028–2037 include identifying extraction sites that balance geological, ecological and spatial considerations. The MSP plays a crucial role in reconciling ideal theoretical scenarios with practical constraints, such as competing uses of marine space, ecological sensitivities, and logistical challenges. This presentation emphasizes the importance of integrating geology, ecological objectives into sand extraction planning to ensure practices remain sustainable for now and in the future, while addressing the growing spatial pressures in the North Sea.

Results

DIS has identified significant sand reserves within the designated reservation area, considering a depth of 12 meters. However, variations in extractable depth due to old channel remnants and heterogeneous geological deposits highlight the complexity of efficient resource utilization. Where the sand availability sometimes is high, but the need for nourishments are low. Preliminary ecological assessments, done within the Monitoring and Evaluation Program 'Zand uit Zee' (www.zanduitzee.nl), indicate potential impacts on marine habitats, sediment transport, and biodiversity, necessitating mitigation measures. Additional factors, such as new cable routes for offshore wind farms and expanding marine protected areas, e.g., Borkumse Stenen, further complicate spatial planning.

Critical extraction zones are identified near the southern coast of Zeeland, the port of IJmuiden, and the Wadden Islands Texel and Vlieland. Approximately 50% or even more of the reserved area overlap with competing activities, such as shipping routes, (future) energy infrastructure, and protected ecosystems. These findings underscore the need for adaptive strategies to balance sand extraction with ecological and spatial constraints. Future efforts will focus on refining extraction plans and strategies, integrating up-to-date ecological data, and ensuring alignment with evolving Maritime Spatial Plans to support sustainable resource use in the North Sea.



Sand thickness map overlain by other activities for the Dutch North Sea

The influence of river discharge, tides and monsoon forcing on seasonal water level variations in the eastern Bengal Delta

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Introduction

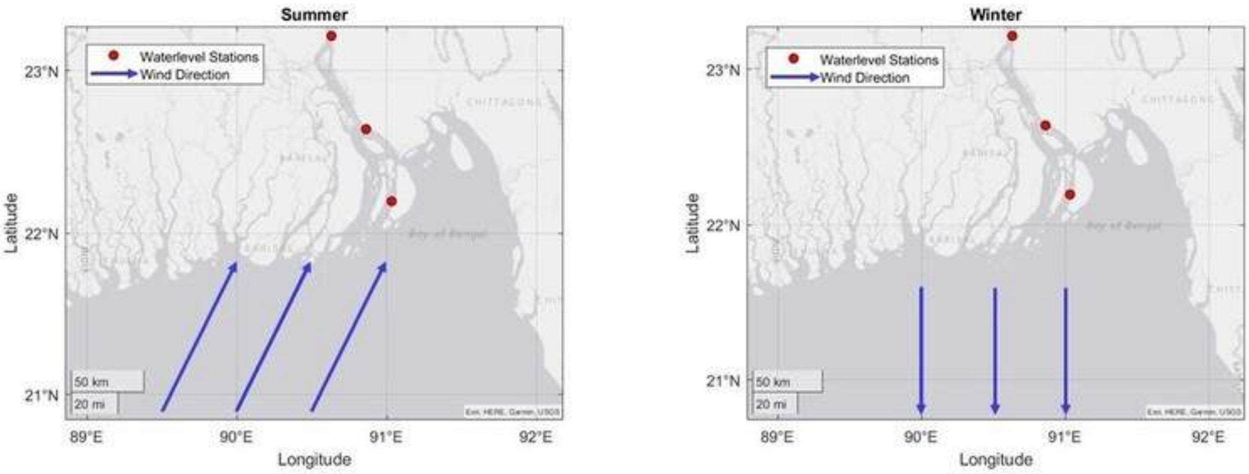
Water levels near the equator are often influenced by monsoonal winds. These winds have a strong seasonality as they blow in opposite directions during Summer and Winter. This can create a seasonal wind setup of up to 30 cm. The Bay of Bengal has an ideal geometry for a high wind setup due to its funnel shape. This wind setup is often overlooked when modelling this area, which potentially underestimates the actual water levels, which is especially dangerous when flood risks are investigated. However, this wind setup is not the only factor influencing the water levels near the Bengal coast: tidal dynamics and river discharge also have a substantial effect. This interaction between wind setup, tides and discharge is complex and has only been investigated on shorter time scales, typically in relation to storm surges, but on a seasonal timescale these interactions have not been investigated in detail yet.

Objective and Methods

The aim of this study is to gain a better understanding of wind-tide-discharge interactions on a seasonal timescale through data analysis of wind and water level datasets in the Bay of Bengal. This is achieved by comparing different wind and water level timeseries and through non-stationary harmonic analysis (Matte et al. 2012). This approach identifies non-linear interactions between discharge, tides and wind, such as the modulating effects of discharge and wind on tidal amplitudes. For instance, when discharge increases, tidal amplitudes generally decrease due to an increase in friction of river flow acting on the tides, while amplitudes increase as the water level increases, due to reduced friction.

Results

Altimetry data reveal a clear yearly water level cycle up to 350 km from the coast with a coastward increasing amplitude to a maximum of 0.25 meter. This pattern coincides with a clear seasonal cycle in the wind data, showing strong southerly winds from April to September and lower northerly wind speeds from November to March, indicating that this seasonal cycle in sea level is caused by wind-setup. In the Lower Meghna, tidal amplitudes decrease with increasing discharge for the most upstream stations, indicating a strong influence of discharge. On the contrary, tidal amplitudes increase with increasing discharge at the coast, suggesting that the river flow effects are not dominant and wind setup may play a role. Overall, there was convincing evidence supporting the influence of wind setup, although separating discharge and wind-induced signals in the river proved to be challenging.



Waterlevel stations in the Lower Meghna and the wind direction in the summer and winter season

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Scour Protection for an Energy Island - A Comparison between Numerical and Laboratory Stability Predictions

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Introduction

The production of wind energy necessitates the transportation of energy to the mainland via cables. The power generated by the wind turbines is commonly converted at nearby offshore platforms before being transported ashore. However, due to the recent growth of wind farms, the construction of an energy island serves an economically viable alternative, providing a much larger capacity. In 2024, the construction of the world's first energy island commenced: the Princess Elisabeth Island in the Belgian coastal zone.

Even though 40 kilometers offshore, wave and current conditions can be classified as coastal, given the strong tidal currents and water depth of 20 meters. One of the challenges is the large structure being fully exposed to waves and currents. To ensure the island's stability, proper scour protection is required. Because of the novelty of this project, no standard formula for scour protection rock is available. Therefore, a combination of numerical models, a stability formula and laboratory testing is applied.

Objective and Methods

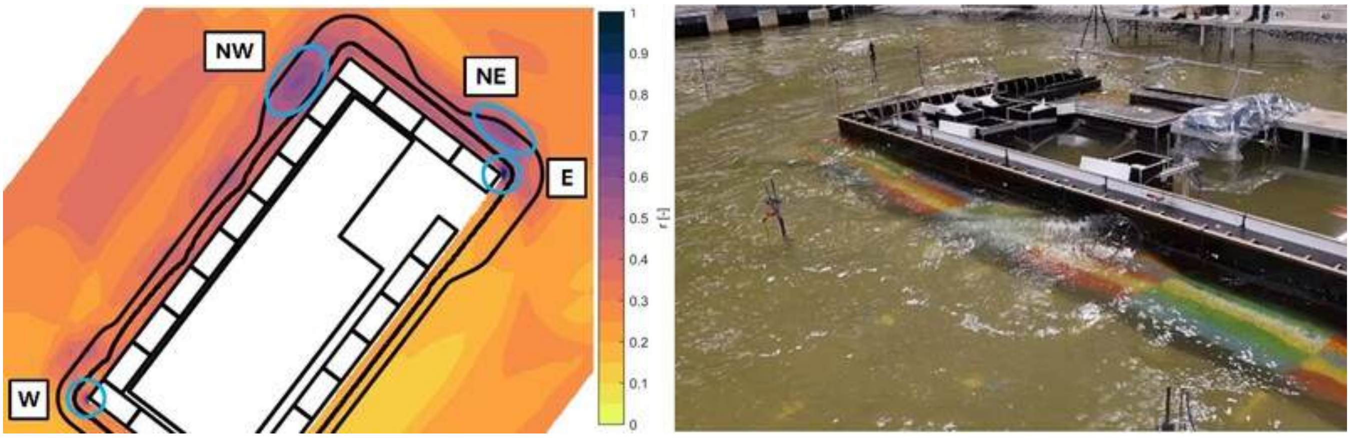
This study aims to spatially predict the required rock diameter and stability of the scour protection. This is done by applying a rock stability formula (van Rijn, 2019) in which wave- and current-induced bed-shear stresses are provided by two state-of-the-art numerical models.

Near-bed wave-induced bed shear stresses are predicted using the nonhydrostatic wave model SWASH (Zijlema et al,. 2011). This model is capable of simulating highly nonlinear storm waves, standing wave patterns and diffraction around the sharp island edges. The flow induced bed shear stresses are predicted using the fully 3D CFD model TUDflow3d (de Wit, 2015). This model resolves the turbulent eddies and wake zones that arise when the undisturbed tidal flow is obstructed by the energy island. A range of flow and wave conditions are considered to obtain governing bed shear stresses around the island.

In addition, the stability of the rock scour protection has been tested with 3D laboratory wave and current experiments. These have been conducted by TM Edison, a joint venture from the Belgian marine contractors DEME and Jan De Nul, at the laboratory facilities of DHI in Denmark (van Doorslaer et al., 2024).

Results

The rock stability formula with substitution of model results is applied in two stages. In the first stage, an estimate of the required rock size diameter is determined. In the second stage, the formula is applied inversely which gives the dimensionless movement factor r as a function of the rock size diameter for a certain rock class (r = 0.4 for occasional movement at some locations and r = 1.0 for frequent movement at nearly all locations). For conditions with a return period of 100 years, the left panel of the figure visualizes the movement factor r. The right panel of the figure shows a picture of the laboratory experiments. For a range of return periods and storm directions, the laboratory experiments were conducted. After each of these tests, the movement was quantified. At the NCK days the numerically predicted movement will be compared against the observations from the laboratory experiments. It should be noted that both numerical and laboratory results are from a preliminary phase of the project.



Numerically predicted movement factor r under combined wave and current loads (left). Picture of the 3D laboratory experiments used to validate the numerical predictions (right).

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Understanding the role of 3D processes for the infilling of cable trenches in offshore sand wave fields.

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Introduction

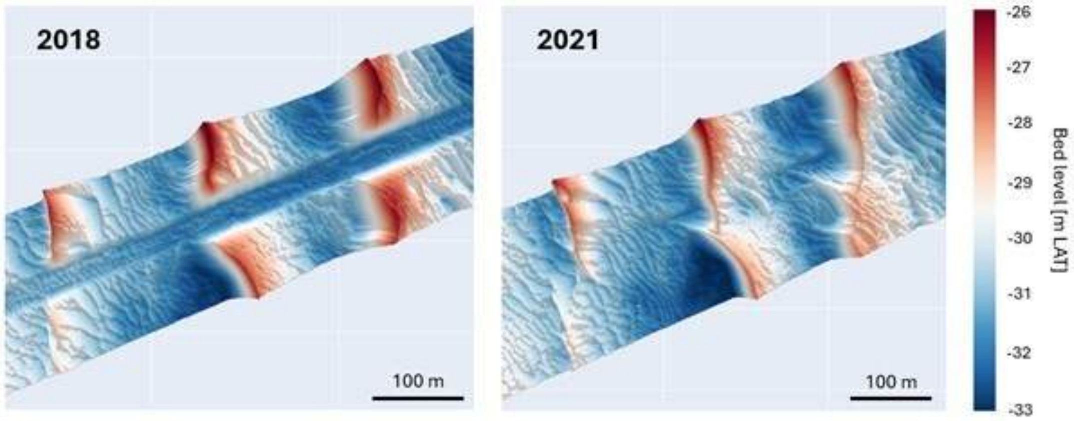
The interest in the offshore area is increasing at a rapid pace. This area supplies the key to realizing the energy transition, especially in densely populated regions like the Netherlands. Seabed level changes caused by dynamic bed forms, such as sand waves, may pose a threat for the offshore structures needed for producing and transporting green energy. To reduce risks, often dredging interventions are carried out before installation. However, it is generally unknown how the seabed will develop after these interventions. The data-driven analysis, which is usually applied for predicting future bed levels, is unsuitable for dealing with changes in the system caused by human interventions. To understand and predict the morphological development after human interventions, we need other tools, like numerical modelling. Numerical models have been applied to predict sand wave regrowth after dredging in a 2DV model setting (e.g. Campmans et al. 2021). However, when partially dredged sand waves are considered, data suggest that interactions occur between the dredged area and the surrounding sand waves, which cannot be included in 2DV sand wave models. Using 3D models insights can be gained into the processes leading to sand wave regeneration and related recovery timescales of trenched sand waves.

Objective and Methods

The goal of this study is to identify the processes which play a role in the hydrodynamics and sediment transport and their contributions to the long-term trench infill and sand wave regeneration after dredging. We setup a high-resolution 3D Delft3D Flexible Mesh model, based on field measurements of a cable trench situated offshore of Belgium. The bathymetry data shows recovery of the trenched sand waves over three years after dredging, see Figure. During this period the surrounding sand wave crests have lowered, indicating interactions between the sand waves and the trench. For these type of systems, we thus require a 2D horizontal analysis and, as sand waves generation needs vertical flows, this means 3D models. The three year period between measurements is hindcasted to allow for comparison of the morphological results with the measurements. The hydrodynamic conditions are extracted from the Dutch Continental Shelf Model and include both tidal and non-tidal forcing, such as meteorological conditions, following Overes et al. (2024). No morphodynamic upscaling is used and default bed-slope parameters are applied. Next to the long-term morphodynamics we focus on specific periods to investigate the influence of storm-induced currents and to see how the influence of processes changes over time.

Results

The results show that the infilling of the trench is mainly caused by slope induced transport at the trench slopes. This process is most prominently present at the crest location of the surrounding sand waves, where the side-slopes are steepest, thereby directly contributing to regrowth of the sand waves. Furthermore, the net sediment transport within the trench is directed from the trough to the crest location due to vertical, tide-averaged current circulation. The strength of these circulation cells, which is usually related to the sand wave height and steepness, is remarkably amplified within the flattened trench due to the influence of the surrounding, non-dredged sand waves. Lastly, the influence of storm-induced currents on infill volumes was found to be surprisingly limited, although the resulting asymmetry in infill location may drive sideways migration of the trench. Comparison with the measurement data shows that the model is well able to reproduce the lateral redistribution of sediment over the trench. This shows that 3D simulations can be used to reproduce multiyear morphological development of a trenched sand wave. Moreover, the gained insights into the driving mechanisms allow for better assessments of trench design and more accurate estimations of infill timescales.



Bathymetry measurements showing cable trench through a sand wave field right after dredging (left) and infilled trench three years later (right).

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