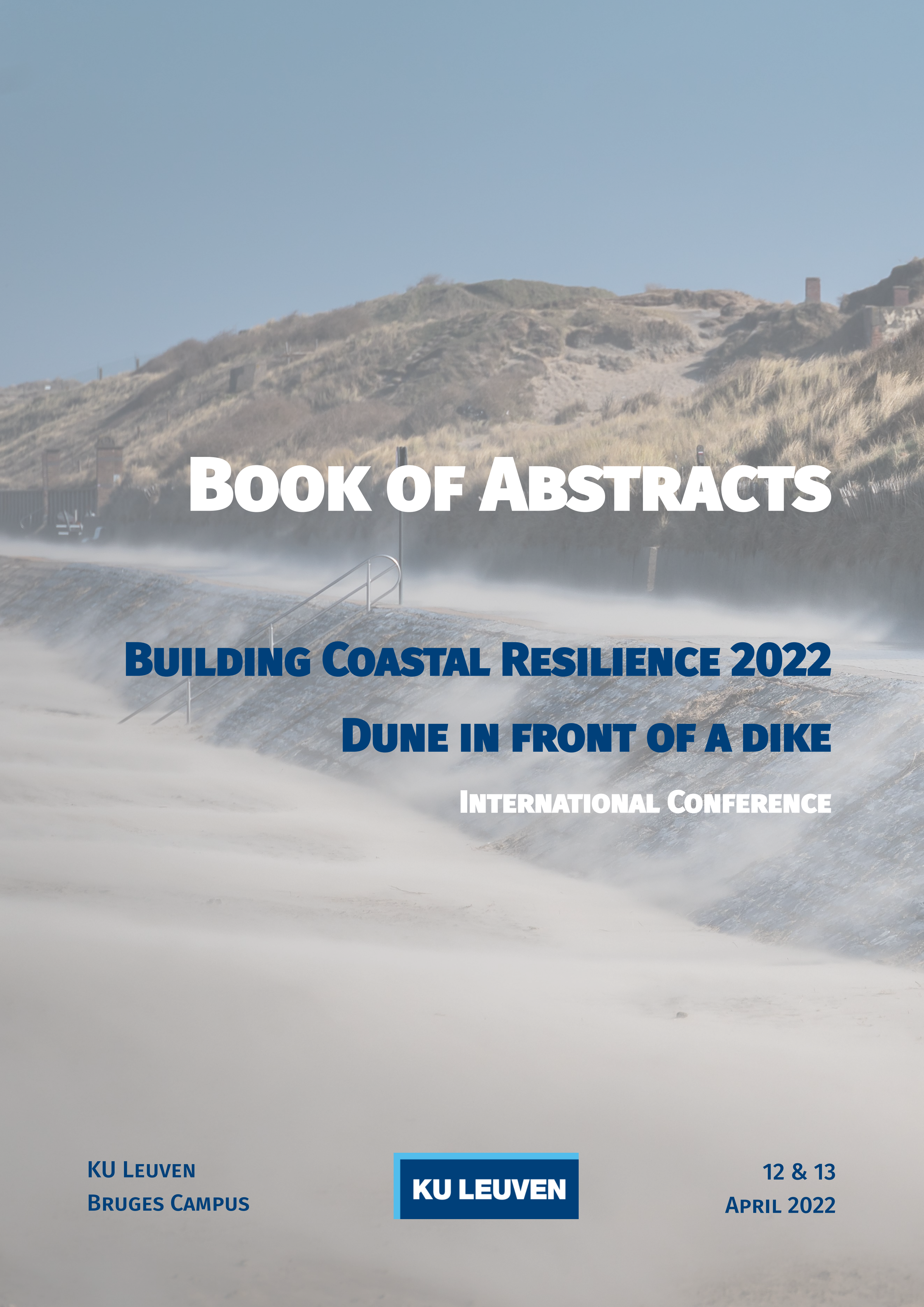

BOOK OF ABSTRACTS

BUILDING COASTAL RESILIENCE 2022

DUNE IN FRONT OF A DIKE

INTERNATIONAL CONFERENCE

KU LEUVEN
BRUGES CAMPUS

12 & 13
APRIL 2022

BOOK OF ABSTRACTS

BUILDING COASTAL RESILIENCE 2022

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EDITORIAL

We are happy to welcome more than 55 delegates from 10 countries at the very first conference on nature-based solutions for coastal protection in Belgium. This conference takes place at KU Leuven Bruges Campus on 12 and 13 April 2022.

The Belgian Dune in front of a Dike pilot was first presented during the Coastal Dynamics 2021 conference in Delft. The paper received a lot of interest, and the question was asked to learn more details of the unique pilot site.

In this conference, we combine technical details on the societal relevance and the scientific monitoring of the pilot sites, a field visit and 32 contributions from academia in the broader topic of coastal resilience and coastal morphodynamics at sandy beaches and dunes.

I want to thank the local organizing committee for keeping track of all practical aspects. Particularly in the last weeks, Bart Roest and Glenn Strypsteen guaranteed smooth preparations. I would also like to acknowledge the support from Post Universitair Centrum (KU Leuven) as a conference secretariat.

I thank the scientific committee for reviewing the submitted abstracts thoroughly and in due time.

Many thanks to prof. Jean Taylor Ellis for accepting our invitation as a keynote lecture. Thanks for the inspiring examples!

Appreciation goes to EU Interreg project SARCC to support the field excursion to the pilot sites.

Finally, I like to thank Flanders Marine Institute (VLIZ) to compile the abstracts in an officially published book of abstracts.

Prof. Pieter Rauwoens
Conference chair

RESILIENT COASTAL PROTECTION: DUNE IN FRONT OF A DIKE

Introduction

The Belgian coastline is 65 km long and mostly consists of sandy beaches. At some locations, it embraces seaward dunes that provide a natural defence against the sea. These dunes are managed by Flanders Coastal Division, with a goal of sustainable use and development. However, the coastline is intensively used including ten coastal towns and cities, protected with sea walls. Besides human activities, the Belgian coast also includes valuable natural areas, such as the tidal inlet at the border with the Netherlands, called the Zwin. Moreover, low-lying polders in the hinterland form a flood prone area where about 400.000 people live.

Why there is a need for dunes in front of a dike?

Initial vulnerable points in the coastal defence had been assessed within a study conducted by the Coastal Division for the preparation of the Master Plan Coastal Safety. The study concluded that about one third of the Belgian coastline was insufficiently protected against severe storm events. Sea level rise and other climate change related effects (such as change in storm and precipitation intensity and frequency) could exacerbate this vulnerability. During the implementation phase of the Master Plan Coastal Safety, the safety level of the entire Flemish coast has been re-assessed through periodical analysis (every 6 years) and after severe storm events, updating flood maps and calculating residual risks after the implementation of measures. The main objective of the Master Plan Coastal Safety, approved in 2011, is to improve Belgian coastal defences to withstand the effects of storms (up to 1,000 years of return period) and sea level rise (+30 cm) by 2050. Improvements should be implemented with a focus on soft engineering measures where possible and hard engineering measures where necessary. These measures are planned considering the dynamic nature of the coast, with an overall objective for sustainable development of the coastal area. Environmental, economic, social, cultural, and recreational objectives are included in the plan to find a balance among all components and with societal participation and stakeholders' involvement.

The calculations in context of the Master Plan Coastal Safety, demonstrated that the required safety level for most vulnerable locations are obtained through sand nourishments. In some seaside resorts, these nourishments are combined with a modification of the seawall by building limited height storm walls on top. After the period 2050-2100, beach nourishments may no longer be the most efficient way to maintain safety levels due to more extreme sea level rise. Other types of solutions, like **dunes in front of dikes**, islands, seagrasses, artificial reefs, are required. It is also essential to keep as much of the sand as possible on the beach. These longer-term objectives, considering the new challenges posed by climate change and updated projections of sea level rise, are now considered within the project "Coastal Vision". It was launched in 2017 and aimed at protecting the coast after 2050.

Due to the sandy nature of the Belgian coast with wide beaches, moderate and high wind events cause the sand to move. Sand moving landward can form dunes, strengthening the coastal protection. At locations without dunes where dikes or seawalls form the protection, sand can cause nuisance during storms. In the area of Ostend, for example, the excessive sand transport towards the sea dike leads to a blockage of adjacent infrastructure, such as the walking promenade, the tramway, and the coastal road. Several times a year, sandy hills are formed forcing the road and tramway to be closed (Figure 1). Cleaning up the sand requires a lot of effort; it is costly and takes time. Furthermore, the sand that is being cleaned up can't be used to nourish the beaches, shoreface or dunes because there is a risk that it has been polluted by the road or the tramway.

Figure 1: Sand nuisance in the coastal area of Ostend, Belgium. Left: Oosteroever. Right: Raversijde.

That is why Coastal Division worked together with several partners to create a natural landscape with planted dunes in front of the traditional seawall. This should lead to an ecosystem that keeps the sand on the beach instead of leading it to the tramway and the road. The natural dynamics due to the action of waves and wind will allow the dune landscape to develop in the accommodation space provided.

How are dunes in front of a dike implemented?

Instead of using concrete elements to catch the sand, we are experimenting with a natural dune landscape. The idea is that vegetation will catch sand, preventing it from reaching the road and tramway, whilst also nourishing the beach for coastal protection.

Nourishments are effective in reducing flood risk at sandy coasts and have the advantage of being flexible with respect to sea level rise: by raising the amount of nourished sand, the beach can cope with the sea level. However, sandy coasts also have some disadvantages due to the very dynamic nature of the North Sea: sand is continuously transported by waves, tidal currents, and wind. This leads to erosion of some parts of the coast whilst other parts are accreting due to sand deposition. Traditionally, sand deposition is beneficial for reducing the flood risk, but it also leads to issues in more urban parts of the coast, as for example in Ostend. The newly installed pilot sites aim to use a nature-based solution to tackle these issues in a sustainable, cost effective and eco-friendly way (Figure 2).

By carefully monitoring these pilot sites, the Flemish Government, together with the universities, are investigating quantitively up to which level marram grass and brushwood fences can prevent beaches from eroding and how it can help in avoiding the nuisance of wind-blown sand. Using the results of this research, advice is given to coastal municipalities and governments to pursue a scientifically underpinned natural approach to coastal protection.

Figure 2: Left: pilot site in Oosteroever. Right: pilot site in Raversijde.

Three pilot sites

Oosteroever, Oostende (installation: January 2021)

Six large patches of marram grass in different patterns and densities of four hundred square meters each without brushwood fences.

Raversijde, Oostende (installation: March 2021)

A seven hundred fifty meters long stretch of coast is planted in plots of hundred square meters each. Variations in plant densities, patterns and brushwood fences offer a unique and large study site.

Westende (installation: March 2021)

A so-called grass dike is installed. Topography change is monitored but no detailed monitoring is taking place there.

Figure 3: Locations of the three dune-in-front-of-a-dike pilot sites at the Belgian coast

Extensive collaboration

The commissioning of the pilots, remote sensing and field monitoring are the results of joint effort and expertise of the following partners:

- Hydraulics and Geotechnics, KU Leuven
- Terrestrial Ecology Unit, UGent
- Flanders Hydraulics Research
- Flanders Marine Institute (VLIZ)
- Research Institute for Nature and Forest
- ATO, Flemish Government
- Coastal Division
- City of Ostend

PROGRAM

Tuesday 12/04/2022

13:00-14:00 Coffee and conference registration

14:00-14:05 Opening and welcome by prof. Pieter Rauwoens

Part 1: Dune in front of a dike: Pilot sites in Belgium – different perspectives

14:05-15:15 Government perspective

- Daphné Thoon (Flanders Coastal Division)
  Dunes: Our natural coastal protection
- Toon Verwaest (Flanders Hydraulics Research)
  Research and monitoring of the dune for dike concept for coastal protection

15:15-15:30 Break

15:30-16:40 Academic perspective

- Glenn Strypsteen (KU Leuven)
  One year monitoring of early-stage dune development
- Dries Bonte (Ghent University)
  Dynamic dunes as self-organizing, living systems

Part 2: Evening Programme

16:40-17:15 Poster pitches

17:15-18:00 Poster session and reception

18:00-20:00 Walking dinner

Wednesday 13/04/2022

08:30-09:00 Coffee

09:00-09:05 Welcome by prof. Pieter Rauwoens

Part 3: International Research on Beach and Dune Dynamics

09:05-09:40 International keynote speaker: Jean Taylor Ellis (University of South-Carolina)
Engineering with nature for coastal protection purposes

Dr. Jean Taylor Ellis is a Professor of Geography at the University South Carolina. With her students, Jean collaboratively approaches coastal research, conducts applied and basic qualitative- and quantitative-based data, and translates this academic research to decision-makers. Current research projects explore response and recovery to storms and king tides, human impacts on the beach-dune system, and wind-blown sand process. Jean is the Director of the Presidential Fellows program at UofSC, one of the only women on the Board of Directors for the Coastal Education and Research Foundation, and a former NOAA Sea Grant John A. Knauss Fellow. For more information about Jean and her students, navigate to the WINDlab website at ellis-coast.com.

09:40-10:40 Research presentations 1

- Francisco Taveira-Pinto (U Porto)
  Building coastal resilience through erosion rates knowledge in the Portuguese Northern Coast
- Caroline Hallin (TU Delft)
  Simulation of medium to long-term dune evolution with interacting marine and aeolian sediment transport processes
- Björn Mehrtens (TU Braunschweig)
  Spatial and temporal growth of coastal dune - field observation of the German Wadden Sea Coast

10:40-11:10	Break
11:10-12:10	Research presentations 2 - Per Sørensen (Danish Coastal Authority) *Aeolian sediment transport management at the central Danish North Sea Coast* - Marien Boers (Deltares) *Reduction of dike revetment fatigue by sand bodies* - Christian Schwarz (KU Leuven) *Sub-millimeter-resolution digital elevation models created by structure-from-motion photogrammetry provide new insights in dune sediment dynamics during storm and calm periods*

Part 4: Afternoon excursion

12:10-13:30	Lunch (take away on bus)
13:30-14:20	Excursion to Oosteroever
14:20-14:40	Towards Raversijde
14:40-15:30	Excursion to Raversijde
15:30-16:00	Back to KU Leuven Bruges campus
16:00	End of conference

The excursion is made possible in collaboration with partners from the SARCC project.

Interreg
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2 Seas Mers Zeeën
SARCC
European Regional Development Fund

VENUE

Welcome at KU Leuven Bruges Campus

As one of the 13 campuses of KU Leuven, spread across Flanders, KU Leuven Bruges campus is a vibrant campus in the heart of West Flanders, Belgium. At a crossroads of students, researchers, and companies on the one hand. In the middle of society and among a broad audience on the other.

However, Bruges Campus also distinguishes itself

- as a warm and committed campus,
- as a growth pole of innovative technological research,
- as an interdisciplinary player with regional anchoring.

Our campus goes for a future-oriented campus concept:

- with a unique educational model and excellent research at the pillars of civil engineering, mechatronics and mechanical engineering, and new materials,
- with great added value for society,
- which we are developing together with our partners in the region.

Engagement is central to each of these pillars.

- Commitment to our students and their living environment in Student City Bruges.
- Commitment to the local industry and professional organizations in the region.
- Commitment to the society of today and the future.

Contact

- KU Leuven Campus Brugge
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- 8200 Brugge
- ✉ campusbrugge@kuleuven.be
- tel. + 32 50 66 48 00

ORAL ABSTRACTS

In order of the program

One year monitoring of early-stage dune development

Glenn Strypsteen

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1. INTRODUCTION

The Belgian coast is a sandy coast, and the beach provides natural protection against flooding. During moderate and high wind events, the wind causes the sand to move. Sand moving landward can form dunes, strengthening the coastal protection. At locations without dunes but where, for example, dikes form the protection, the sand can cause nuisance during severe storms. It is therefore that coastal managers are getting convinced of building with nature concepts, such as engineered dunes in front of traditional dikes, to strengthen coastal protection and as sand mitigation measure. For an optimal design of these marram grass planted dunes, a fundamental knowledge of the morphological changes of dune development is required. Hence, the characterization and prediction of aeolian sediment supply from the beach to the dune is a key component in the development of comprehensive models for beach and dune interactions.

In this study, we investigate dune growth of the 120x20m² dune-in-front-of-a-dike pilot site in Oosteroever, Belgium by exploring a multi-monthly dataset of wind characteristics and high-resolution topographic datasets. This dune field is planted with marram grass (Figure 1B) with three different plant densities (6, 9 and 15 plants/m²) and four spatial configurations (gridded, random, clustered, and staggered) providing a unique experimental setup to study dune growth in the early stage.

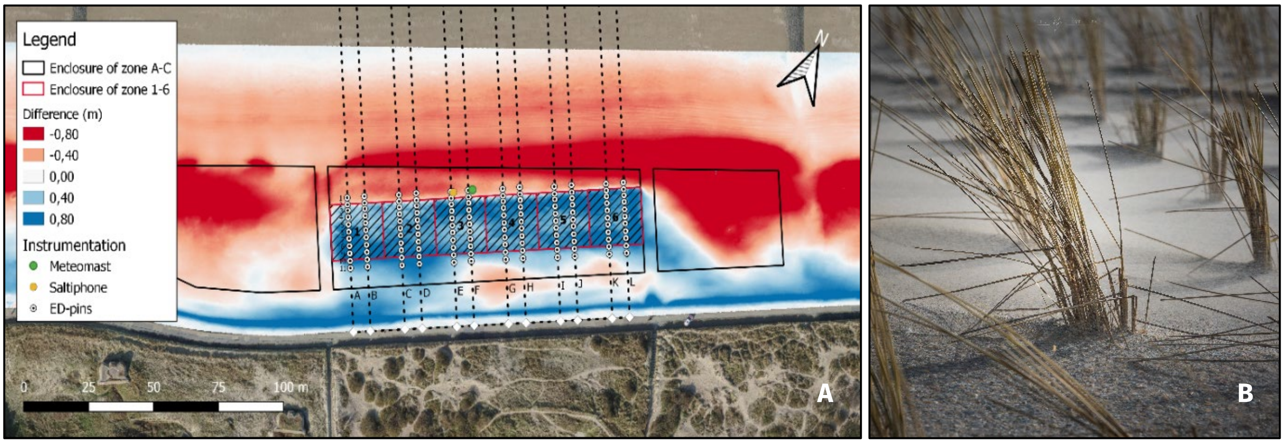

Figure 1: (A) Experimental setup at the dune-in-front-of-a-dike pilot site in Oosteroever. Planted zones are 20x20 m² (6 in total). Blue and red colors show deposition and erosion between the drone surveys of 08/03/2022 and 11/01/2021. (B) Planted marram grass.

2. METHODS

A long-term monitoring station at the study site was erected which permitted the acquisition of continuous records of wind that can be coupled with sand transport measurements over period of months to years. Local wind speed and direction was measured at the seaward side of the dune foot for 9 months with cup anemometers at four logarithmic heights above the surface and a wind vane to extract surface roughness and shear velocities from the vertical wind velocity profiles. Averaged wind data was stored on a Campbell datalogger every 20 seconds. Aeolian transport intensity was measured at a height of 10 cm above the sand surface every one second with a saltiphone. Data on regional wind data, precipitation, and tidal elevations is accessed from Meetnet Vlaamse Banken at Meteopark Oostende located next to the study site. Dune growth is weekly measured by using a combination of erosion-deposition (ED) pins and RTK-GPS measurements along 12 predefined cross-shore profiles (Figure 1A).

Furthermore, topographic elevation changes are measured on a more detailed spatial level with drone flights once every month (except for the summer period) conducted by ATO and Flanders Coastal Division.

3. RESULTS

The total volume of sand in the dune has increased significantly since the plantation of the marram grass (i.e., end of January 2021). In total 14 m³ m-1 of sand has been added due to the aeolian processes translating into a vertical elevation increase of approximately 1 m (Figure 2A). The months March and April 2021 were responsible for half of the annual dune growth (Figure 2B). The other months delivered a comparable amount of net sediment input to the dune (i.e., approximately 1 m³ m-1) but slowly decreased towards the end of the year. From October 2021 onwards the dune volume remained fairly stable due to a combination of supply limitations and a decrease in vegetation trapping efficiency. However, a large amount of sediment is deposited in the landward area of the dune (i.e., 3 m³ m-1). Moreover, the dune suffered from erosion during storm Corrie (i.e., end of January 2022) where cliffs at the dune toe were formed up to 1.5 m exposing the underlying roots of the marram grass. Nearly 1.5 m³ m-1 of sand was eroded in a couple of hours. Initial vegetation patterns in the dune disappeared resulting in a more natural and dynamic dune field. Vegetation growth and density varied throughout the year and thus its sand trapping efficiency.

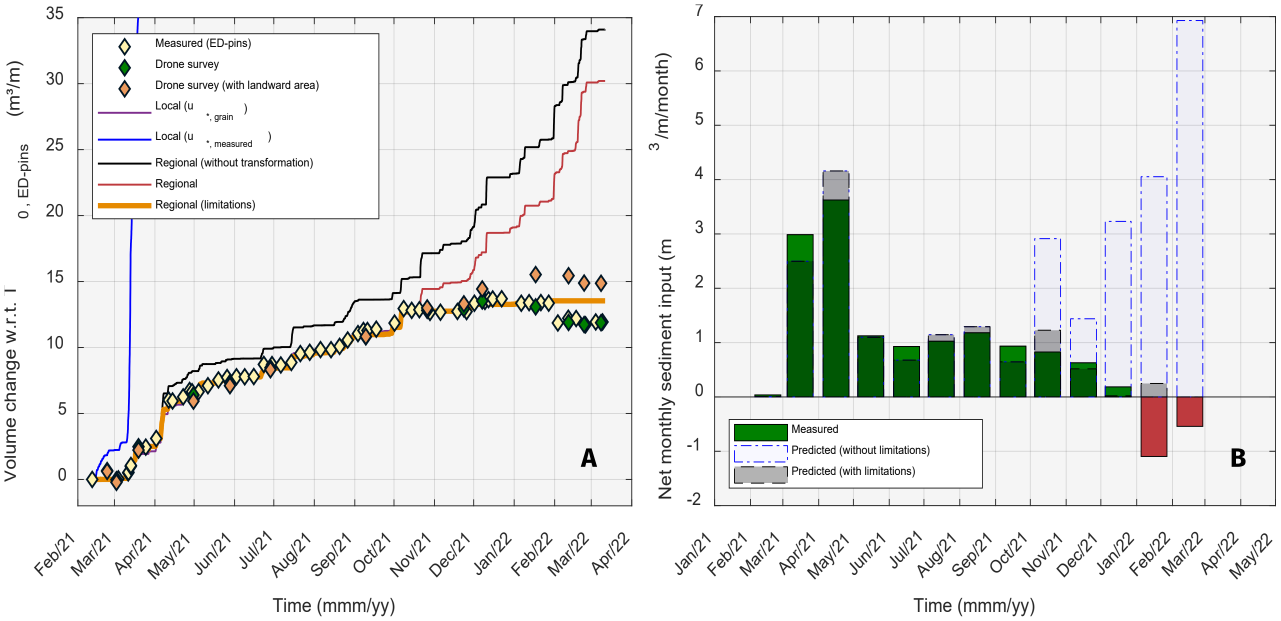

Figure 2: (A) Total sand volume changes in the dune area (120x20m²) with corresponding predictions (with and without supply/vegetation limitations). (B) Monthly net sediment input towards the dune showing measured and predicted values.

The results show a significant dune growth in the dune-in-front-of-a-dike pilot site of Oosteroever which is encouraging for coastal protection. Marram grass proves to be a good mitigation measure to keep the sand on the beach. However, dune growth is influenced by supply limitations, vegetation characteristics, and sediment erosion by wind and storm events.

4. ACKNOWLEDGEMENTS

Thanks to the city of Ostend and Coastal Division to give us the opportunity to work on such a unique pilot site. We thank the support of VLIZ (Flanders Marine Institute) for the use of their research infrastructure. Bart Roest and Jennifer Derijckere, thanks for the help in the field. Thanks to Research Foundation – Flanders for project funding (number: 1243022N).

Dynamic dunes as self-organizing, living systems

Dries Bonte

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As climate change induces sea level rise and possibly heavier storms, coastal protection is in a transition phase from hard structural engineering towards soft measures, that can adapt dynamically to a changing environment. Coastal foredunes represent the most important natural flood barrier for much of the European coastline and thirty percent of all shorelines worldwide. In contrast to urban infrastructure, coastal dunes have the capacity to grow with the rising sea level due to the action of ecosystem engineers . Therefore, they are currently considered as an important nature-based solution for coastal protection. In Europe, the most important dune-building species is marram grass (*Calamagrostis – formerly Ammophila- arenaria*). It is a crucial engineers for the development of coastal dunes, as their growth depends on, and in turn influences aeolian (wind-driven) sand fluxes and hence, dune development.

Marram grass is highly tolerant to burial, with optimal growth depending on sand deposition. At short ranges, positive feedbacks are anticipated to occur when cover is not too high. Then, plants are vital and patchily distributed, since this configuration should enhance sand capture efficiency. However, at longer ranges, cover of marram grass prevent local sand deposition, lowering its vitality and hence competitive strength. The relative contribution of these negative and positive feedbacks is overall conditional to the overall sand input into the system.

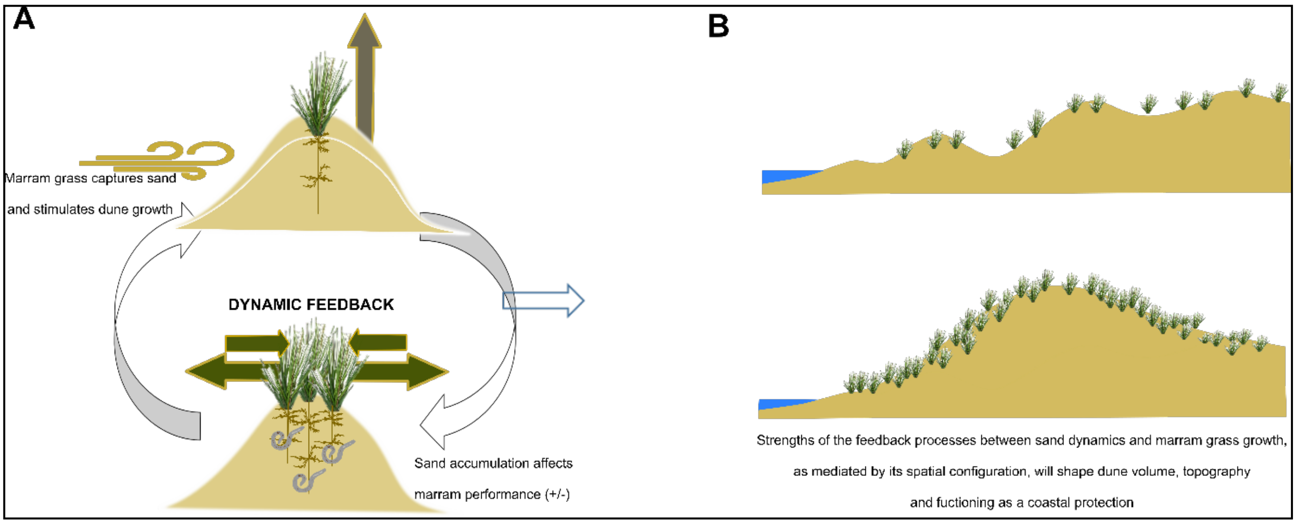

Figure 1: Conceptual figure on the role of marram grass as an engineer in foredune formation. A. Once established, the species' sand capture ability shapes local sand accumulation and make the dune increase in volume. This sand accumulation will promote the species' growth, unless burial is too severe. When sand accumulation ceases, either due to decreased input from the sea, of from shadowing effects from surrounding vegetation, the plant performance will decrease due to pathogen accumulation in the roots, after which marram grass will die off. B. These dynamic feedbacks depend on the species' spatial configuration and external environmental conditions and will eventually shape dune development, its volume and form, and, hence, its stability and resilience against storm surges under climate change. (Adapted from Bonte et al. 2021)

For a dune to be self-healing and optimally recovering after a storm event, it should be dynamic. This requires both patches with open sand and with marram grass. The dynamic coupling of vegetation development and sand fluxes is anticipated to impose a self-organisation of the dune system (Fig. 1). A more in-depth knowledge of the ecological interactions regulating the dynamics of dune-building species is therefore crucial to understand how the dune ecosystem can be used as a nature-based protection against sea level rise and extreme storm events.

During this presentation, I will

- provide a detailed look at the biological mechanisms leading to these dynamic feedbacks;
- demonstrate how West-European coastal dunes converge with respect to the cover of marram grass;
- show that this cover impacts local dune volume changes;
- give an overview on how vegetation is currently integrated in our forecasting models;
- provide an outlook for future biogeomorphological research and modelling efforts

ACKNOWLEDGEMENTS

A big thank you to all colleagues involved into the INTERREG 2-Seas project ENDURE.

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Engineering with nature for coastal protection purposes

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Coastal dunes naturally develop where and when there is an ample supply of sediment, consistent and sufficient wind, vegetation, and adequate fetch. Healthy and natural systems provide the first order of protection against significant wind and wave events and are ecologically and economically important. However, modern coastal dune systems are rarely natural, often sediment-limited, and impacted by an increasing number of climate change- and anthropogenic-related stresses. This keynote talk will highlight significant forcing factors affecting coastal dunes in the United States and assess the methods employed to increase dune resiliency, using the author's research as the foundation.

Storm surge, waves from mid-latitude cyclones, and exceptionally high tides (king tides) consistently erode and scarp the U.S. eastern seaboard foredunes. The magnitude of hurricane-force storm surge is extreme and often results in dune overwash. However, these events occur on an annual time scale. King tides are more concerning, as these can occur more than 50 times per year, using South Carolina as an example.

Sand fences, beach scraping, and dune cores are commonly used engineering techniques to accommodate dune erosion. Sand fencing is an anthropogenic alternative to planting vegetation. Emplacing fences speeds up dune growth, resulting in shorter and wider dunes because of the inhibited sand transport. Other researchers have conceptually identified ideal fence characteristics. Access to material and restrictive laws often prohibit the execution of these configurations in situ. Beach scraping employs heavy machinery to transport foreshore sand to the backshore. It differs from nourishment because no new sediment is added to the system. Scraping is employed before or after significant storms to protect or mitigate storm impacts. More recently, the scraped sand has been placed on the foredune line, thus creating a mechanical dune. The efficacy of these artificial structures is under scrutiny, especially those not vegetated. Dune cores (or geotextile tubes) are hybrid shoreline protection methods. These large cylindrical structures are pressure-filled with sand and installed along the toe of existing dunes or at the core of artificial dunes. Geotextile tube effectiveness varies, and substantial limitations include degradation due to incoming wave and UV energy, and policies limiting deployment. Sand fences, beach scraping, and dune cores are worthy of additional study toward combatting the impacts of dune erosion and building coastal resiliency, especially given the cumulative stresses on this delicate and dynamic system.

Building coastal resilience through erosion rates knowledge in the Portuguese Northern Coast

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1. INTRODUCTION

The Portuguese continental coast is approximately 980 km long facing the Atlantic Ocean to west and to the south. Such coast is mostly sandy, with 60% of dune formations, several estuaries and small river discharges. Several coastal and rocky outcrops provide a degree of natural protection. Since the 1970s, coastal municipalities have experienced a rapid economic growth that has been reflected in significant development of these coastal areas.

About 70% of the Portuguese population lives on the coast and this number is growing due to inland migration to littoral regions, leading to major impacts on estuarine and coastal areas. All these areas are included in various management plans, namely the Coastal Zone Management Plans or the current Coastal Zone Programs, where the coastal line evolution is an important component. These plans have not always been fully effective in controlling the various impacts of different coastal activities and implementing measures to protect, preserve and improve the quality of these coastal areas, namely in relation to coastal erosion. The need for coastal resilience measures is a key issue for the future and for that, a detailed knowledge of the erosion rates is needed.

2. COASTAL ZONES ADAPTATION

A large part of the Portuguese coast is still in a relatively natural state. Some specific areas have today a better management strategy in terms of conservation and development, as there has been an increasing interest from national and local authorities to protect coastal zones from anthropogenic activities, especially near beaches and urban areas, controlling the associated negative impacts and increasing resilience.

In this context, climate change is an important topic for future consideration, especially since extreme events that can be correlated are expected to have significant impacts in coastal zones (Taveira-Pinto *et al.*, 2021a). Some examples of these extreme events include the increase in frequency, variability and intensity of storms, the increase in water depths, the occurrence of greater wave heights and periods, as well as changes in the predominant direction of wave incidence, as in the case of wind, or even the increase in the average mean sea level, among others. Due to these extreme events, the safety of coastal zones is at risk in several sections, namely due to the increased potential for erosion, flooding, and other related phenomena. For these reasons, coastal zone management requires proper adaptation in order to increase its resilience and safety levels (Taveira-Pinto *et al.*, 2021b).

3. RESULTS AND CONCLUSIONS

As part of the work associated with the new Coastal Zone Program of the stretch from Caminha to Espinho (POC-CE), in the northern Portuguese coast, an assessment of erosion rates was carried out taking into account historical data related to the coastline's evolution, as well as areas prone to overtopping and flooding.

For the hazard assessment related to the erosion rates along the 120 km of this stretch, the following subsectors were analyzed:

- Minho River Mouth - Âncora River Mouth;
- Âncora river mouth - Lima river mouth;
- Lima River mouth - Neiva River mouth;
- Neiva River mouth - Cávado River mouth;
- Cávado river mouth - Ave river mouth;
- Rio Ave river mouth - Rio Leça river mouth;
- River Leça mouth - River Douro mouth;
- Douro River mouth - Barrinha de Esmoriz.

This analysis was based on the 1958 coastline and resulted in the definition of areas with low (0.00 - 0.60 m/yr), medium (0.60 - 1.30 m/yr) and high (more than 1.30 m/yr) erosion rates considering the hypothetical evolution between 1958-2012 and 1994-2012.

The areas with higher probability of overtopping for the time horizons of 2050 and 2100 were also defined, considering the mean sea level rise, which was combined with the evolution of the coastline to allow for the identification of 30 critical stretches along the 120 km extension.

In this paper some examples will be presented, as well as some data concerning the general evolution of the coastline in relation to the erosion phenomenon and the future challenges for this coastal area, highlighting the main critical areas of the Caminha-Espinho stretch, showing the need for more resilient measures for the next decades.

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Simulation of medium to long-term dune evoloution with interacting marine and aeolian sediment transport processes

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1. INTRODUCTION

In recent years, dune-in-front-of-dike projects have been carried out at several locations, e.g. at Raversijde and Oosteroever in Belgium and the Hondsbossche dunes in the Netherlands. In the near future, many coastal defence systems require reinforcement to adapt to rising sea levels, and often, natural values along the coasts may also be enhanced. Therefore, it is anticipated that this type of hybrid coastal protection – a mix of grey and green solutions – will become more common in the future. Contrary to grey defence structures, such as earth dikes and rock or concrete structures, dunes are dynamic features. Their level of flood protection depends on their morphological evolution due to aeolian and marine transport processes, vegetation dynamics, and anthropogenic impact.

Numerical models are commonly used tools to assess the safety level of dunes and predict their future evolution. In addition to event timescales (storms), the decadal timescale is typically of interest from a coastal management perspective, especially when considering sea level rise. On this timescale, dune build-up through aeolian transport depends on the wind's transport capacity, and the availability of sediment of the appropriate size exposed to the wind is an important process. Sediment availability for aeolian transport is controlled by other sediment transport processes, such as dune erosion and longshore sediment transport, nourishments, and limiting factors, such as surface moisture and armour layers.

Simulation of dune evolution at the decadal timescale requires an integrated model approach that accounts for the non-linear interactions between marine and aeolian transport processes in the longshore and cross-shore direction. Reduced complexity approaches are required when these models are applied to large temporal (decades) and spatial scales (kilometres).

This study aims to predict medium to long-term dune evolution by developing a new coupled long- term beach and dune evolution model, coDaC (**co**upled **D**unes **a**nd **C**oasts). The new model combines a semi-empirical cross-shore transport model, the CS-model (Hallin *et al.* 2019a), with a longshore transport and coastline evolution model, Unibest CL+ (Figure 1). The coupled model is applied to simulate 22 years of morphological dune evolution along an 8 km-long coastal stretch at the Kennemer Dunes in the Netherlands.

2. THE coDaC MODEL

During simulation, a model coupler exchanges sediment transport rates between the submodels, the CS-model and Unibest CL+. The CS-model is applied to several cross-shore (CS) transects distributed alongshore on the Unibest CL+ coastline grid. The CS-model computes the volume of sediment stored in the dune and a simplified dune morphology based on a triangular or trapezoidal shape. It simulates aeolian transport from the beach towards the dune, q_w [m^3/m/s], dune erosion, q_d, and overwash, and a Bruun-type morphological compensation for sea level rise, q_S. These transports are exchanged with the Unibest CL+ model as sources or sinks that influence the shoreline location. In return, Unibest CL+ exchanges gradients in the longshore transport influenced by beach and shoreface nourishments, dQ/dy.

In the CS-model, changes to sediment availability, dV/dt [m^3/m/s], is computed based on the sediment transport rates at the transects,

$$\frac{dV}{dt} = q_d - q_w - a \cdot (q_s + \frac{dQ}{dy})$$

where a is an empirical coefficient.

The aeolian sediment transport cannot exceed the available volume, V. It becomes supply limited in CS-transects where the potential aeolian transport rates exceed the storage and influx of transportable sediment.

3. CASE STUDY

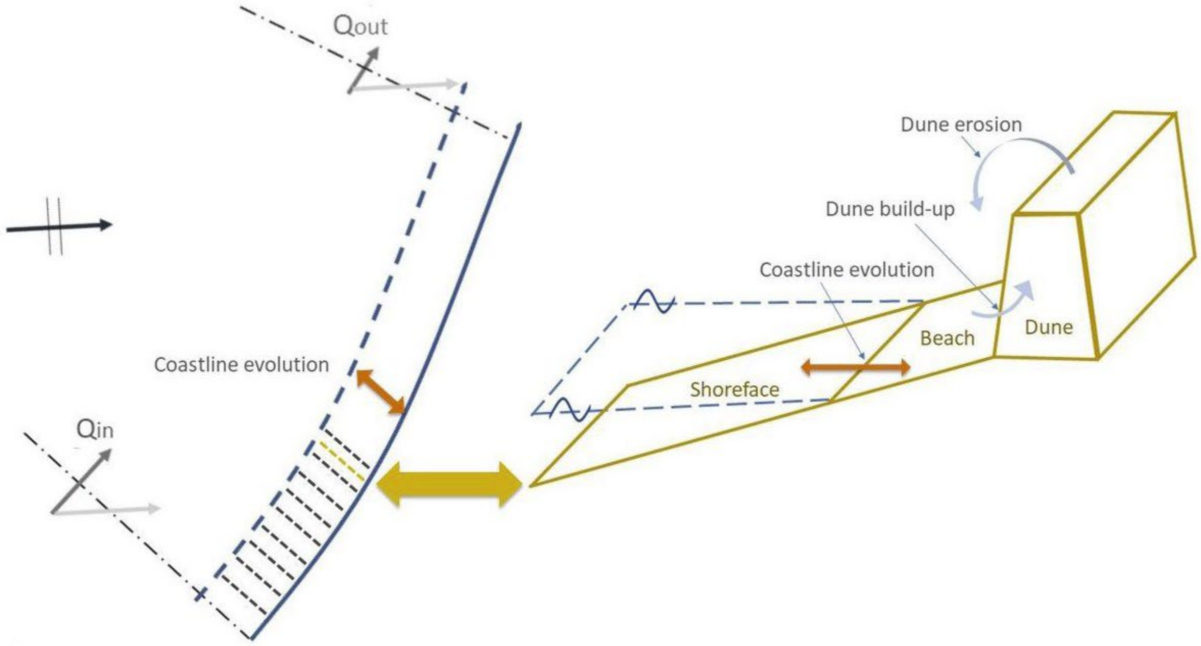

Figure 1: Schematic picture of the coupling between Unibest CL+ and the CS-model in coDaC

The coDaC model was applied to an 8 km-long coastal stretch at the Kennemer dunes with a mix of transport and supply-limited dune evolution. The model was calibrated and validated against yearly observations of topography and bathymetry in 26 transects from the JARKUS data set (Figure 2). The result was compared to a previous application of the CS-model (Hallin *et al.* 2019b). Compared to the application of the non-coupled CS-model, the results improved due to the longshore spreading of nourishments, which previously only were accounted for in the nourished transects (Figure 2). In conclusion, the coupled model requires long data sets for calibration but is a promising tool for predicting long-term dune evolution in areas with abundant data on the historical evolution.

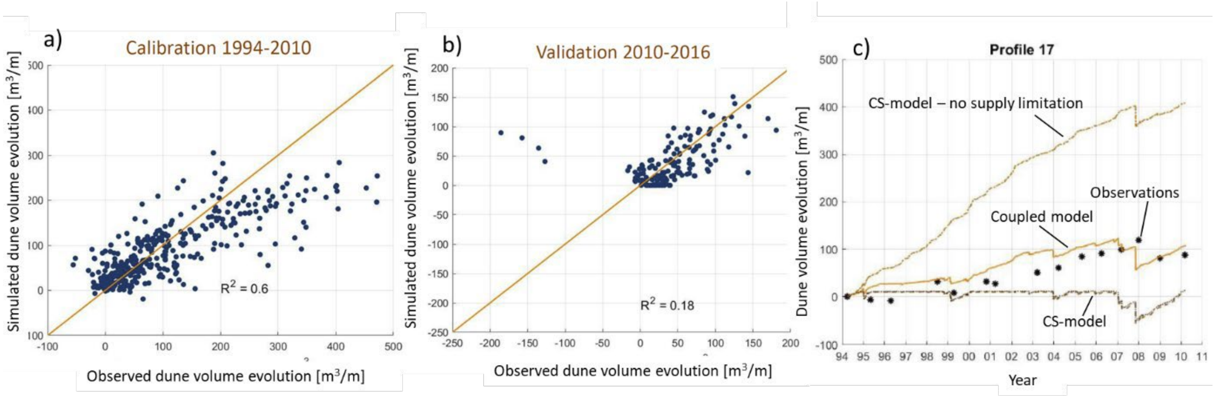

Figure 2: a) Result of calibration coupled model b) Result of validation coupled model c) Result of calibration profile 17 compared to CS-model simulations with and without supply limitation

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Spatial and temporal growth of coastal dune - field observation of the German Wadden Sea Coast

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1. INTRODUCTION

Natural vegetated coastal dunes are an essential component on many sandy, low-sloped coastlines around the world. In addition to their unique ecosystem services, they often provide a first natural barrier of protection against storm surges and protect the adjacent hinterland from flooding. However, sea level rise, changing and widely intensifying coastal wave climates and storm surges are expected to have an impact on dune development and their protection function in the future.

Here, we investigate the development of an incipient elongated coastal dune system on the wide beach of St. Peter-Ording, located at the German North Sea, over a 20-year period. The study is based on digital terrain data with a resolution of 10 m x 10 m for the period from 1996 to 2016, obtained from the EasyGSH-DB portal www.easygsh-db.org (www.doi.org/10.18451/k2_easygsh_1). The goal is to analyze the spatial and temporal variance of the dune in order to understand its evolution velocity, quantify dune dimensions and possibly identify a potentially added natural contribution to coastal protection.

2. METHODS

The changes of relevant dune parameters were evaluated along 144 transects and over a time span of 20 years. In order to reliably record the location of the dune, it is crucial to identify the dune extent. In the past, the location of a dune toe was usually defined by a threshold vertical elevation (e.g. by Hofstede (1997) at St. Peter-Ording, Germany, with +2 m elevation above sea level). However, since this definition does not take into account the individual profile of a dune, it is difficult to draw conclusions about long-term shifting of the dune toe (Diamantidou *et al.* 2020). Therefore, an alternative procedure was developed, that detects the dune toes based on the calculated minimum slopes (Fig. 1). Subsequently, the dune volume results from a numerical integration of the dune cross- section between the two toes.

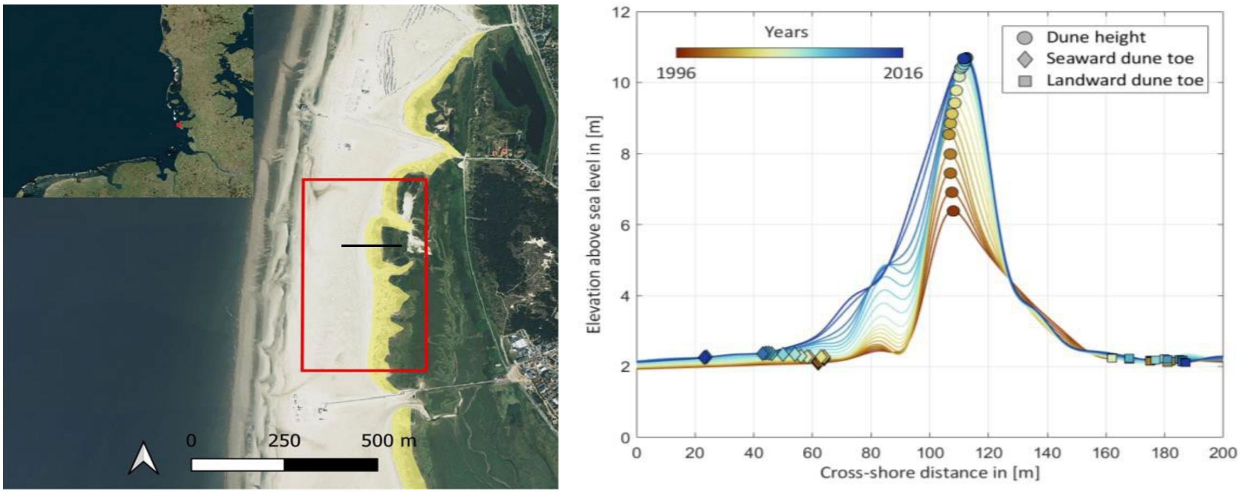

Figure 1: Study area in St. Peter-Ording at the German Bight (©Bing VirtualEarth) and development of the dune along an exemplary transect.

3. RESULTS

Between 1996 and 2016, the lateral position of the seaward dune toe has shifted towards the sea by an average of 2.06 m/year, whereas the landward toe shows no clear direction of movement. Similar to the findings by van IJzendoorn *et al.* (2021) on the Dutch coast, it is also evident that the seaward toe has grown several centimeters in height over the period investigated, accruing faster than the local sea level rise. As shown in Fig. 2, the mean dune height has almost doubled over the years and reached 7.9 m in 2016, with a maximum dune height slightly below 11 m (Fig. 1). The average growth rate was calculated to be approximately 0.2 m/year. Due to the increased dune height as well as the dune width, the mean dune volume has also increased significantly, from 128 m^3/m in 1996 to 345 m^3/m in 2016. Fig. 2 also shows the storm surge classes defined at the German North Sea coast as a function of the local mean high water of 1.65 m above sea level. This shows that the mean dune height is now greater than the level of potential storm surges or storm surges that occurred during this period. However, it should be noted that along the dune system there are several blowouts through which water can flow behind the dune and submerge the adjacent dune troughs.

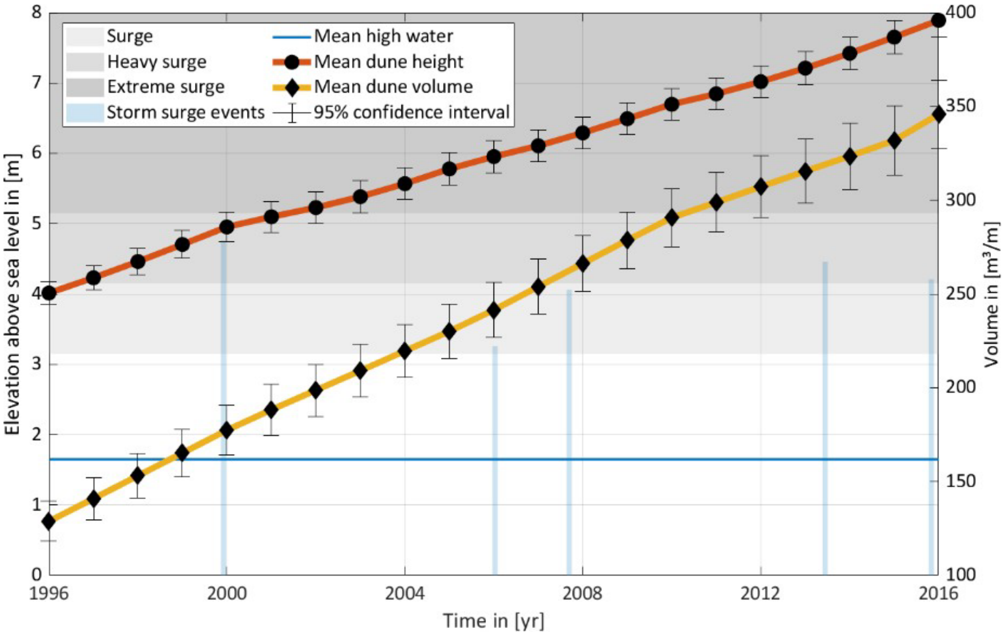

Figure 2: Development of the mean dune height and volume compared to typical storm surge classes and past events

4. DISCUSSION

The results show that an incipient coastal dune system has developed on the beach of St. Peter- Ording over the past decades. The evaluation indicates that this process is not yet complete and that the dune will continue to grow in the near future. For this reason, additional terrain data from the years after 2016 will soon be obtained and processed in order to be able to infer the current development and possible forecasts for the future. In addition, other data sets from before 1996 are currently being analyzed to investigate at what time the initial dune formation process began. This will help to infer possible causes and correlations to sea level, changing wave and wind conditions, certain storm surge events, and other influences. Furthermore, the level of protection provided by the dune will be analyzed in a timely manner to assess its potential contribution as a natural protective barrier.

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Aeolian sediment transport management at the central Danish North Sea Coast

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1. MOTIVATION

The central part of the Danish North Sea coast consists of narrow sandy barriers protecting a low lying hinterland from flooding. The narrow barriers are subject to the forces of the North Sea with prevailing strong westerly winds and corresponding high waves. These forces creates a very dynamic coastal system with high wave and wind driven sediment transport rates. The sediment transport cause a negative sediment budget because of erosion, which cause a retreat of the active profile. The retreat however cannot be accepted in many places because of the safety requirements. So sediment management must be undertaken, but how when there are many other objectives than just providing safety?

2. THE BENEFITS OF A NATURAL AEOLIAN TRANSPORT

At Skodbjerge in the southern part of the central Danish North sea coast the dunes are not managed Figure 1. This is possible because houses and major roads are located quite a distance inland due to the Nature protection Act. The annual profile retreat is 1.0 m/year. Until know the amount of sediment that are transported from the beach to the area behind the dune face has not been accounted in the overall sediment budget due to the lack of long term data.

Figure 1: Natural system at Skodbjerge (left), and managed system at Krogen (right).

Since 2005 annual laserscans with red lidar has been carried out which provides adequate data for analyzing the amount of sediment transport into the hinterland, and the yearly variations. The seasonal variations has lately been done by using drone mounted cameras. The analysis was done by dividing the 3.7 km stretch into 10 cells, 5 seaward cells and 5 landwards cells that includes to the landward boundary of significant Aeolia transport. The volumes in each cell were calculated from the lidar data using ArcMap Zonal statistics tollbox.

The volume analysis showed that accumulation was primarily found on the lee side of the dune crest and in the deflation basin of a blow out. Erosion took place in the seaward boxes. The eroded and accumulated volumes pr. m in the study are both 150 m^3/m in the period from 2006-2019. This means that the safety is generally maintained, despite of the retreat of the dune face. At the same time a natural biodiversity was maintained,

It was found that the windspeed and direction is correlated with the variations in accumulations and accretion, but the R2 value is lower than 0.5

3. THE CHALLENGE OF MANAGING AEOLIAN SEDIMENT TRANSPORT

At Krogen Figure 1 the coast is heavily managed because of the narrow dunes and that houses and major roads are located close to the dune face. The natural profile retreat is 0.8 m/year. Frequent shoreface and beach nourishments are carried out. Marron grass planning, brushwood fences are used to retain the sediment in front of the duneface, Figure 1. Similar volumes analysis are done for the Krogen area as for Skodbjerge area. The analysis showed an volume increase in both the seaward and landward boxes. The increase in the seaward box was 75 m^3/m, and 140 m^3/m for the landward cells which is approximately the same for the unmanaged stretch at Skodbjerge. This shows that the measures implemented to reduce aeolian sediment transport were not sufficient to meet the objective.

4. TEST OF A NEW SEDIMENT MANAGEMENT APPROACH

The above analysis shows that it can be difficult to reduce the Aeolian transport to the hinterland in places where it is needed. Such a place is Northern Torsminde tange 30 km north of Krogen where a road was covered by sand by Aeolian sediment transport. Traditionally the sand is tranpoted back to the beach again by dumpers, but based on the presented analysis test were made with different placement patters of the sediment, Figure 2.

Figure 2: Removed sand for the road and back dune and placed in different patterns on the beach.

3 patters are tested, all of the formed 2 m high, and 20 m wide sand volumes, primarily dictated by the size of the dumpers used. Alongshore to patters were tested. A long continuous sand dike and as two groups of 3 70 m long sand dikes. The sand dikes were established which an angle of ±30 to the dune face. The effect of these new measures have been monitored 20 times during a 2-year period. The analysis of the data are not yet finished.

5. ACKNOWLEDGEMENTS

Most of the work was carried out as a part of the Interreg project Building With Nature, BWN. We are grateful for the support. We would also like to thank University of Twente, TU Delft and University of Copenhagen for fruitful discussions.

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Reduction of dike revetment fatigue by sand bodies

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1. INTRODUCTION

In this abstract, we will emphasize on the relation between the presence of a sand body in front of a sea dike and the failure behavior of dike revetments. The presence of a sand body in front of a dike not only reduces the impact of the incoming waves, but also shortens the duration of the wave load on the revetment of the sea dike. Since failure of a dike revetment, composed of stone, asphalt, concrete or grass, happens by revetment fatigue, the benefits of the presence of the sand body are a combination of the reduction of the magnitude of the wave impacts and the reduction of the number of wave load cycles.

2. OBJECTIVE OF THE STUDY

The reduction of revetment fatigue depends on the volume and the initial shape of the sand body in front of the dike. In our study we investigate the effectiveness of a sand body for the following scenarios (Figure 1):

1. Sea dike only: This reference scenario considers a sea dike without any reduction of the wave load due to the presence of a sand body.
2. Foreshore: A foreshore in front of the sea dike reduces the wave load due to wave breaking. Since the foreshore is always submersed, there is no reduction of the duration of the wave load.
3. Beach: A beach in front of the dike reduces the wave impact on the revetment, and it reduces the duration of the wave load for the lower part of the revetment.
4. Dune: A dune in front of the dike reduces the wave impact on the revetment, and it reduces the duration of the wave load for the entire revetment.

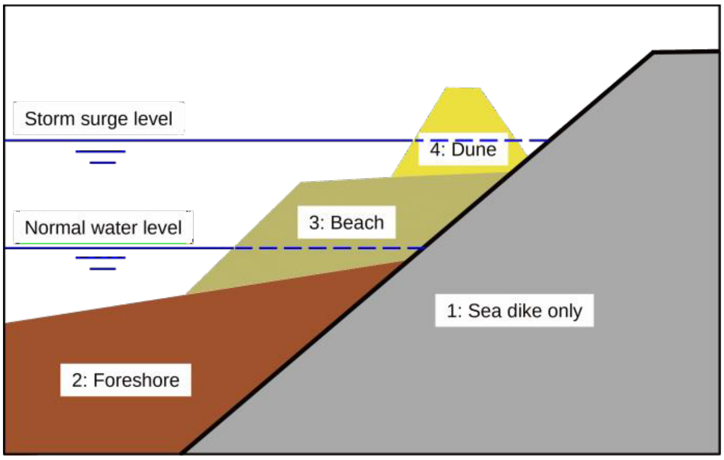

Figure 1: Definition of scenarios

In our study, we consider both stationary and time-varying hydraulic conditions. The stationary conditions give good insight into the protection mechanisms of a sandy body, while time-varying conditions better represent the real conditions during a storm.

3. CALCULATIONS OF REVETMENT FATIGUE REDUCTION BY SAND BODIES

The study involves the following calculations:

- Calculation of the erosion of a sand body during a storm
- Calculation of the wave impact on a revetment during a storm
- Calculation of the damage number of the revetment during a storm

The calculation of the erosion and the wave impact are carried out with the help of Xbeach (Roelvink *et al.* 2009). Figure 2 shows an example for a sea dike protected by a dune.

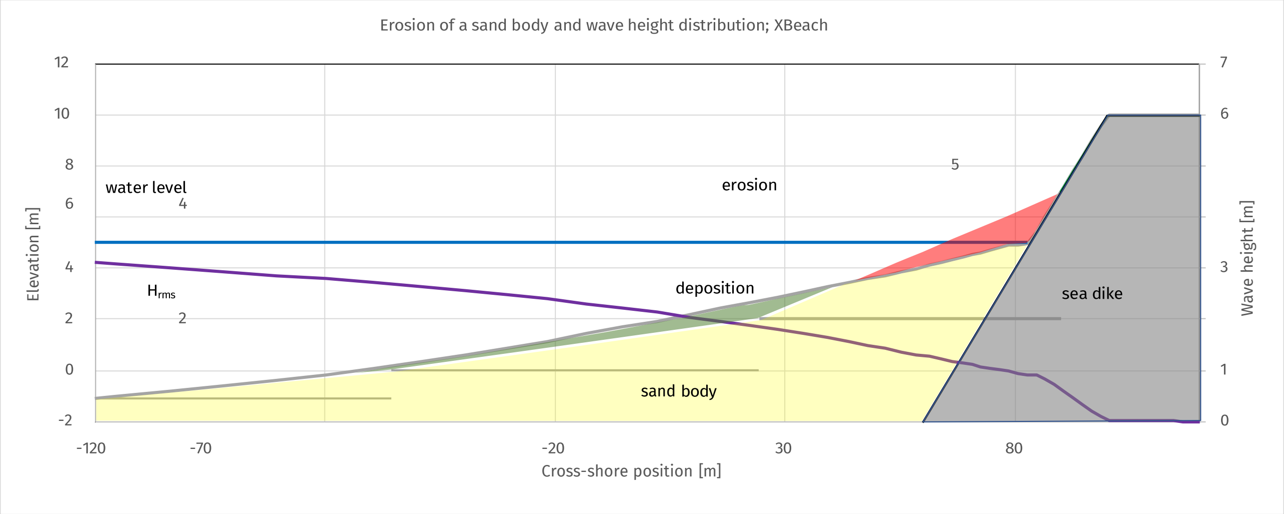

Figure 2: Calculation of erosion and wave impact with XBeach

The damage number of the revetment is defined by Miner's law. In our study we consider a revetment composed of asphalt, although revetment fatigue also happens for the other types of revetment. The calculations are carried out with the help of DiKErnel, the future software application for the assessment and design of revetments for The Netherlands. This model calculates asphalt revetment fatigue according to De Looff *et al.* 2006. Figure 3 shows the calculation of the damage number along an asphalt revetment during a storm surge, without the presence of a sand body.

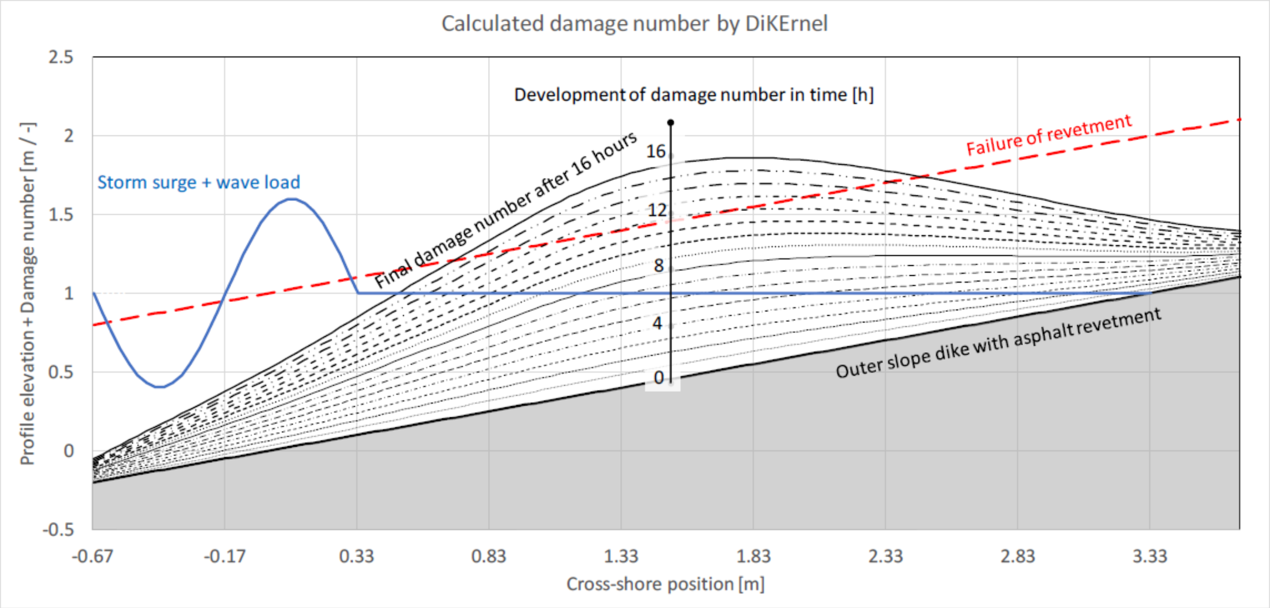

Figure 3: Calculation asphalt revetment fatigue with DiKErnel

4. ACKNOWLEDGEMENTS

This study is carried out within the framework of the Strategic Research program of Deltares. DiKErnel is developed within the framework of the BOI (Assessment and Design Instruments of Water Defenses) of Rijkswaterstaat.

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Sub-millimeter-resolution digital elevation models created by structure-from-motion photogrammetry provide new insights in dune sediment dynamics during storm and calm periods

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1. INTRODUCTION

Coastal dunes are important features located along the land-sea interface, providing an initial barrier against storm surges and other large-waves event that endanger coastal communities. In addition to absorbing incoming wave energy, coastal dunes collect large quantities of sand transported from the beach. The ability of coastal dunes to collect sand, i.e., trapping sand grains entrained by wind, is highly dependent on their vegetation cover. American beach grass (Ammophila breviligulata) is one of the most dominant dune plant species along the Mid-Atlantic US coast and plays a major role in dune recovery during storm-free(calm) periods and dune stabilization during storms (e.g., preventing washovers).

The ability of beach grass to colonize coastal dunes is largely due to its tolerance to salt spray, heat, and sand burial. Aboveground blades trap wind-blown sand and belowground rhizomes expand in both existing dunes and new dunes. The underground rhizome network functions as a complex root system anchoring the plant and keeping the sand in place. American beach grass is prone to grow, vertically and horizontally (Maun 1998), during periods of accretion and can face deterioration during periods of erosion. In the context of dune growth dynamics, dune accretion coincides with inter-storm periods, whereas dune erosion coincides with strong wind and storm events. This study investigates the impact of coastal storms, exemplified by Tropical Storm Elsa hitting the US east coast on July 9th, 2021, on local plant patch-scale sedimentation and erosion. We first validate a structure for motion (SfM) technique creating sub-millimeter-resolution digital elevation models (DEM) with classic sedimentation-erosion bar (SEB) measurements (Verma and Bourke 2019). And subsequently compare sedimentation-erosion patterns during a calm and a storm period between different plant patch organizations of mimics and natural plants.

2. METHODS

Artificial plants (hereafter mimics) were constructed using zip ties simulating various plant densities of Ammophila breviligulata on an expanding foredune in Cape Henlopen, Delaware, US. Two treatments in three replicates each: sparse (interplant distances of 40 cm) and dense (interplant distance of 10 cm) were deployed on the beach during summer 2021. Sedimentation and erosion in the mimics as well as adjacent natural vegetation was monitored. Field monitoring was conducted before and after Tropical Storm Elsa using sediment erosion bar (SEB) and structure-for-motion (SfM) photogrammetry method using a newly established local coordinate reference system (Agisoft). Digital elevation models (DEMs) produced from photogrammetry were exported as GeoTiffs and post- processed using MATLAB.

3. RESULTS – DISCUSSION

Our results show that spatial averaged sedimentation/erosion data collected with the SfM and the sedimentation erosion bar (SEB) technique are well comparable (Fig.1) showing the potential of sub- mm DEMs for dune monitoring (Fig.2).

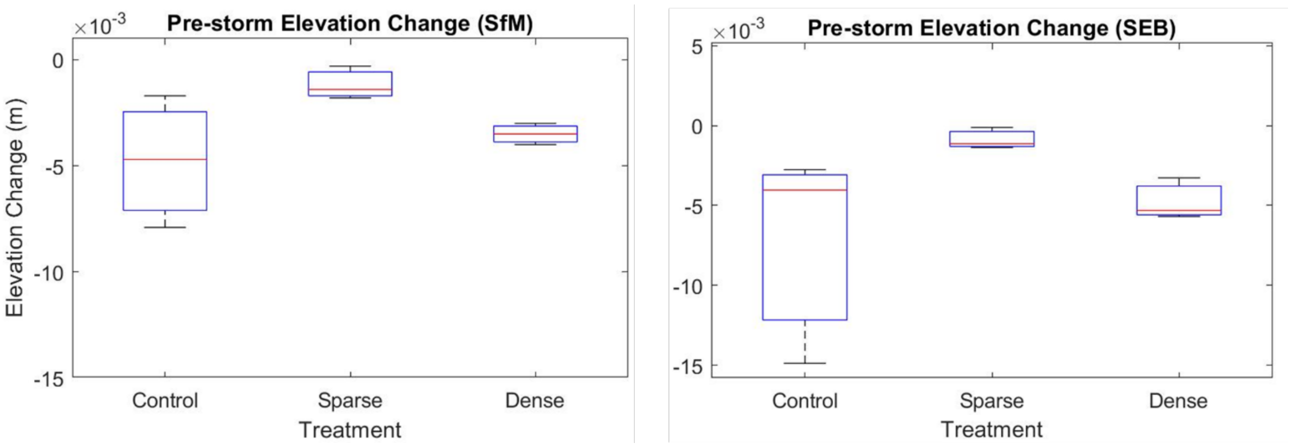

Figure 1: Method validation comparing sub-millimeter structure for motion technique (SfM) with sedimentation erosion bar measurements (SEB). Data was collected at Cape Henlopen state Park, DE, US, measurements were collected from June to August 2021 in a two-wee

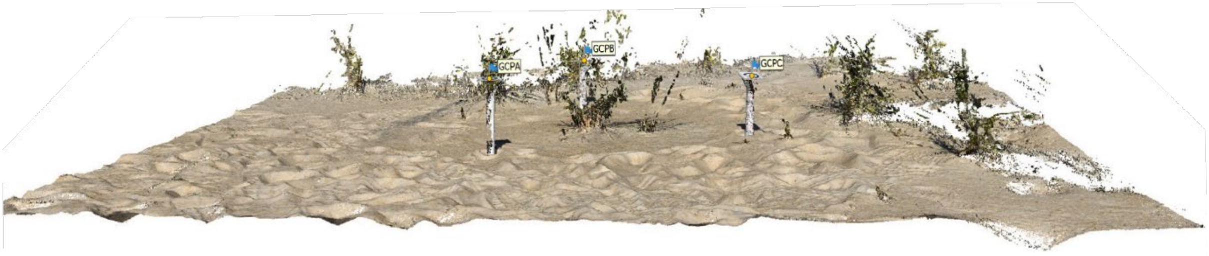

Figure 2: Example of structure for motion data set.

A comparison between the pre-storm and storm observations revealed that sedimentation patterns during calm periods and erosion patterns during storm periods are highly correlated to the spatial organization of the vegetation patches. In turn raising the question of which growth strategies would be optimal to maximize sedimentation during calm periods while minimizing erosion during storms.

4. ACKNOWLEDGEMENTS

We appreciate the cooperation and efforts of Cape Henlopen State Park on allowing and supporting the conducted research. We moreover want to thank MSc students Caldonia Carmello and Pamela Tucker for their support during field work.

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POSTER ABSTRACTS

In alphabetical order

What are ecological and societal benefits of coastal nature-based measures? A quantification of ecosystem services

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1. INTRODUCTION

Mainstreaming nature-based measures into coastal management and policy making requires an in depth understanding of the coastal flood defence contribution of such measures as well as their additional societal benefits. This study investigated which nature-based measures can be used along the Belgian coast to ensure coastal defences and additionally create a multitude of ecosystem services. We investigated six nature-based coastal measures (foreshore/beach/dune nourishments, dune-in- front-of-dike, biogenic reefs and green dikes) compared with a hard reference scenario with a grey dike. The aim was to demonstrate the added value of nature-based measures in the land-sea interaction zone by estimating the coastal defence contribution (part i), quantifying the additional ecosystem services (part ii), and detect local needs (and resistance) for nature-based measures (part iii).

2. METHOD AND RESULTS

i. Coastal defence: Six theoretical scenarios with different nature-based measures where compared to a grey reference scenario (dike heightening/storm wall). The coastal Safety Tool, developed by IMDC, was applied to assess the magnitude of each measure required to protect against a sea level rise of +1.5m. Overall, an important observation is that many of the soft measures do not in themselves provide a fully-fledged coastal defence. In the scenarios those measures were combined with a hard measure (raising the dykes) to meet the coastal safety requirements. The combination of soft and hard solutions can result in a reduction of the required dike height. One specific finding, is that, in order to protect against the same rise in sea level of +1,5m, the required dune height is lower than the required dike height (only +1m above the existing seawall for dunes compared to +2m above the existing seawall for dikes; Figure 1).

Scenario 1.4: dune-i-f-o-dike
Required dune height: 11mTAW
(+1m above existing dike 10mTAW)

Scenario 1.1: reference dike
Required dike height: 12mTAW
(+2m above existing dike 10mTAW)

Figure 1: Estimated height required to protect the coast in the future against a sea level rise of +1.5m: for a dune-in-front-of-dike (left) and for a reference hard dike (right).

ii. Ecosystem services (ES): For each scenario, a series of ecological and cultural services were considered besides coastal safety. The ES of the Flemish coast are described in the report ecosystem vision for the Flemish coast[1]. This is further supplemented with more recent studies for biogenic reefs[2] and dunes[3]. The ES analysis (Table 1) shows the added value of all nature-based measures compared to the hard reference dike, with moderate added benefits for sand measures (nourishments) and the highest gains for measures with plants and animal species (dune vegetation, reef species). However, based on the ES analysis, it is not obvious to say that one measure is better or worse. The purpose of this analysis is therefore primarily to make the multitude of effects specific, rather than to make an overall assessment in favour or against a particular measure.

Category	Ecosystem services Highest values Mid values Lowest values	Unit	S1.1 Ref dike	S1.2 Beach nourishm.	S1.3 Dune nourishm.	S1.4 Dune-ifo-dike	S2.1 Ref dike	S2.2 Reef	S2.3 Foreshore nourishm.	S2.4 Green dike
Provisioning services	Fisheries production	score*ha	6,7	6,4	6,4	6,4	7,7	8,3	7,7	7,7
	Drinking water production	score*ha	0,0	0,0	0,5	0,5	0,0	0,0	0,0	0,0
Regulating services	Air quality regulation	Ton fine dust/ha/y	0,0	0,0	7,4	7,4	0,0	0,0	0,0	2,7
	Sediment retention	Score	3,0	3,0	4,0	4,0	3,0	4,2	3,0	3,8
	Coastal safety, flood prevention	Score	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
	Climate regulation: carbon sequestration	kgC/ha/y	17,2	17,2	206,0	206,0	18,9	-203,5	18,9	111,6
	Water retention	m^3/ha	0,9	1,6	2,3	2,3	1,2	1,2	1,2	1,2
	Water quality regulation: N-retention	kg N/ha/y	8,3	8,3	17,4	17,4	9,2	8,7	9,2	10,6
	Water quality regulation: P-retention	kg P/ha/y	0,6	0,6	3,6	3,6	0,6	0,6	0,6	1,1
	Water quality regulation: denitrification	kg N/ha/y	292,8	281,2	294,2	294,2	336,4	588,3	336,4	339,1
Cultural services	Recreation (ecotourism, outdoor sports activities..)	score*ha	0,6	1,1	1,0	1,0	0,9	0,9	0,9	1,1
	Cultural and natural heritage (archeology, paleontology)	score*ha	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0
	Landscape experience – nature/green/dune	score*ha	0,2	0,5	0,8	0,8	0,4	0,4	0,4	0,6
	Landscape experience – sea view	score*ha	0,6	1,1	0,9	0,9	0,9	0,9	0,9	0,9
	Economic potential, employment	score*ha	0,7	1,2	0,9	0,9	1,0	1,0	1,0	1,0
	Development and transfer of knowledge and research	score*ha	0,0	0,0	0,6	0,6	0,0	1,2	0,0	0,1
Supporting services	Hydrodynamic changes (waves)	score*ha	7,0	7,0	7,2	7,2	8,2	8,4	8,2	8,2
	Habitat biodiversity	score*ha	21,9	21,3	21,8	21,8	25,6	28,4	25,6	25,7

Table 1: Ecosystem services (ES) analysis per scenario, grouped for two different locations with their respective coastal safety assessment (S1.1-S1.4 and S2.1-S2.4).

iii. Reflections from local governments - Our evaluation was presented to local governments to start a discussion about their (practical) considerations or even resistance for implementing nature-based measures. They showed an overall willingness to rethink today's coastline but only if all current user functions are integrated. They raised practical points of attention such as accessibility for elderly/wheelchairs/strollers and necessity for adaptive infrastructure to avoid regular maintenance needs, but also proposed creative solutions such as arranging catering on roof terraces. In addition to the more practical considerations, the local governments also stressed the needs for communication and raising awareness. It is crucial to show equivalent future alternatives (e.g. figure 1) and avoid comparison with today's situation (situations with different coastal safety risk). It was also recommended to focus in public communication on the direct benefits that are of interest to people such as greenery, health and recreation, rather than on policy reasons (safety and risk management) for which there is in general low public attention.

3. DISCUSSION AND CONCLUSIONS

We developed and illustrated a framework to make ecological and social aspects explicit in addition to the technical evaluation (coastal safety requirement). The main purpose was to inform local governments and start a discussion on the practical implementation of nature-based measures. Some remarks; the scenario's and coastal safety assessment were purely theoretical and not intended as a concrete plan of action for a particular location. The ES assessment is not all-embracing and is not giving an exclusive interpretation that one measure is better or worse, but provides the explicit overview of the variety of ecological and societal effects. This provides relevant input for further integrated multi-criteria assessment including investment costs, maintenance costs and other local considerations. This allows for a full economic-ecologic-societal evaluation of nature-based measures.

4. ACKNOWLEDGEMENTS

The authors want to acknowledge the Flemish department of Environment & Spatial Development (Belgium) to finance this study as part of the European Interreg 2 Seas SARCC project (2019-2023). We also thank the University of Antwerp for its support on the ecosystem services quantification part.

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Coastal vision: assessing long term coastal protection strategies for the Belgian Coast

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1. INTRODUCTION

On December 22, 2017, the Flemish government took the initial decision to draw up a long-term 'Coastal Vision' (Vlaamse Regering, 2017). This will be done together with all parties involved in the field. The Coastal Vision project will establish the socially most desirable measures that are necessary to gradually protect our coast and the hinterland against a sea level rise of up to 3 meters in the long term.

The Flemish government is already working on coastal protection via the Coastal Safety Master Plan, which has been implemented in all coastal municipalities since 2011. The objective of the Master Plan is to protect the coastal region against a 1000-year storm until 2050. The Coastal Safety Master Plan takes into account a sea level rise of up to 30 cm by 2050. It is designed on the basis of the climate scenario available at the time. Most projections show that the sea level will rise more strongly and faster after 2050 and that additional efforts will have to be made in addition to the interventions provided for in the Master Plan in order to protect the entire coast against flooding after 2050.

A coastal vision project has therefore been set up to explore the space needed and the best position for various measures and alternatives to protect the Belgian coast against the consequences of higher sea levels and stronger and more powerful waves. The study and comparison of different solutions allows to identify the most desired alternative consisting of a future coast line and associated space.

In this paper the project coastal vision will be presented. A general overview of the study approach will be given with a focus on how alternative solutions, including dune for dyke options, will be assessed in order to identify the most desired future coastal protection strategy highlighting the evaluation aspects related to building a resilient coast.

2. LONG TERM COASTAL PROTECTION STRATEGIES

The central objective is to also ensure the protection of the coast against a 1000-year storm after 2050 against a higher and accelerated sea level rise. The speed and magnitude of sea level rise are uncertain. In order to be sufficiently prepared and to be able to act quickly, an 'adaptive coastal protection' is assumed. 'Adaptive' here means coastal protection that is relatively easy to adapt. So that not only the safety level remains up to standard, but also the lifespan of the infrastructure is extended under increasingly rapidly evolving sea level rises. To give a clearer shape to the adaptive character, we are investigating three scenarios: protecting the coast and the hinterland against a sea level rise of up to 1 meter, up to 2 meter and up to 3 meter. We are also investigating how protection can be scaled up gradually and what the tipping points are at which upscaling is necessary.

In the current research phase, all parties involved work together via 'workbenches' on the basis of the most recent scientific insights, their own research and their own wishes, to develop a strategic plan. This should become a roadmap with the most socially desirable measures to protect our coast against a 1000-year storm in the event of a sea level rise of up to 3 meter.

3. APPROACH

The final goal of the study is to determine the most desired strategy expressed as the position of the future coast line and associated space in which the future coastal defense measures can be implemented. To be able to assess and compare alternatives that cover different spaces, potential measures will therefore be designed, visualized and assessed (see Figure 1).

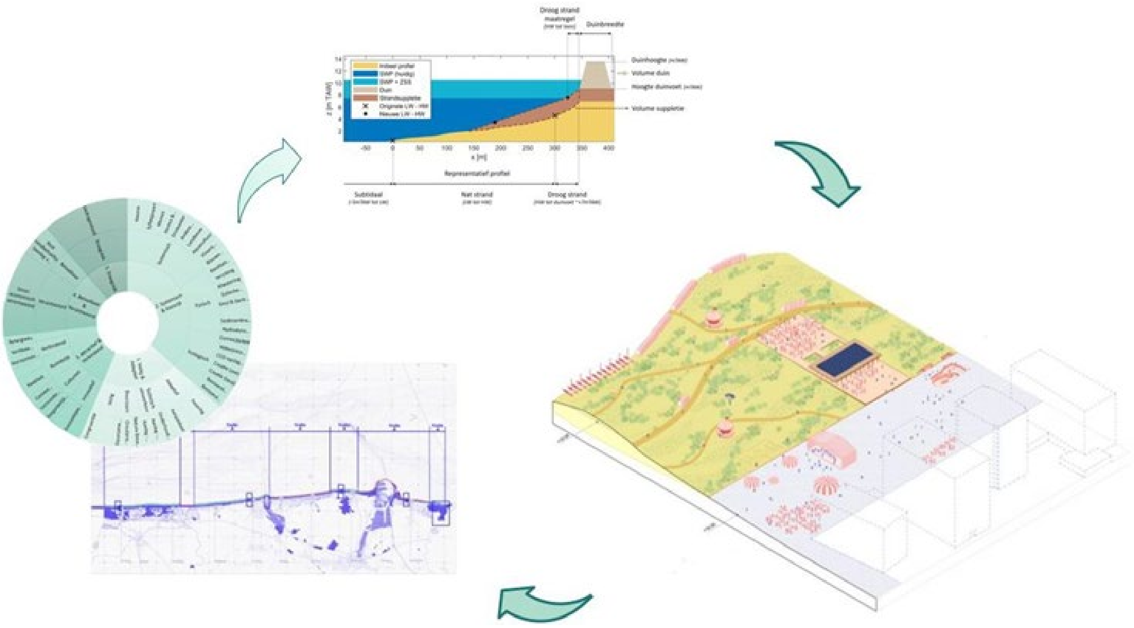

Figure 1: Approach for assessing most suitable coastal protection strategies consisting of the following steps. 1: Designing safe solutions. 2: Spatial design, visualize concepts. 3: Assess the different alternative solutions. Based on the assessment adaptations can be proposed.

As the study is focussing on a strategic level, the design and assessments are focusing on the required amount of detail to allow selecting high-potential alternatives that gradually will be further detailed. The potential measures for ports and along the coast that are considered in this strategic study therefore cover the most important applications in hard solutions (hard measures on dikes and quay walls, storm surge barriers, locks,...), but wherever possible also soft solutions (dune nourishments and dune for dyke solutions), or hybrid cases (Consortium Hoogtij(d) (IMDC, ORG, Arcadis), 2021). Basic design dimensions are determined that give input in the required space and form a starting point for the spatial design. As for the assessment different criteria have been defined that not only allow to investigate effects, but also look for opportunities, taking the interests of the stakeholders into account. Along the process aspects related to building a resilient coast such as potential for nature based solutions, robustness, adaptivity, resiliency and impact on maintenance are taken into account.

4. CONCLUSION

The Coastal Vision project focuses on coastal protection strategies in the long term against a higher and accelerated sea level rise. A wide range of solutions with corresponding space claims are therefore investigated including dune for dike solutions. An assessment frame is applied to investigate in gradual increasing detail the different solutions.

5. ACKNOWLEDGEMENTS

The study team whishes to acknowledge the Flemish government and the department of public works by making these long term strategic studies possible, allowing in view of the changing environment the basis for good stewardship of our surroundings. In addition we appreciate the cooperation and efforts of all stakeholders involved together via 'workbenches'.

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Evolution of the Ostend beach after multiple artificial sand nourishments

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1. INTRODUCTION

Sand nourishments are commonly used at the Belgian coast. Since the early 2000s, Ostend beach has been artificially nourished to improve safety against storm flooding. Expansion of the port of Ostend in the period 2009-2012 caused a blocking of the west-to-east oriented sediment circulation along the coast. Also, it has led to an accumulation of large amounts of sand in front of the city of Ostend (Figure 1). Between 2013 and 2014, a large nourishment was performed in the area Raversijde - Mariakerke (updrift from Ostend) whereby approximately 2 million m^3 was placed both on the beach (dry and intertidal) and on the shoreface, at depths between -1 and -5 m TAW. The nourishment was performed to test the most efficient way to maintain the sandy sea defences on the long term (Dan *et al.* 2021). In early 2018, a new nourishment took place at Ostend beach whereby a volume of approximately 741 000 m^3 was placed both on the beach and on the shoreface. The beach profile was leveled after every nourishment, but as expected local reorganization occurred within the active beach section, creating a complex pattern of sand ridges and channels.

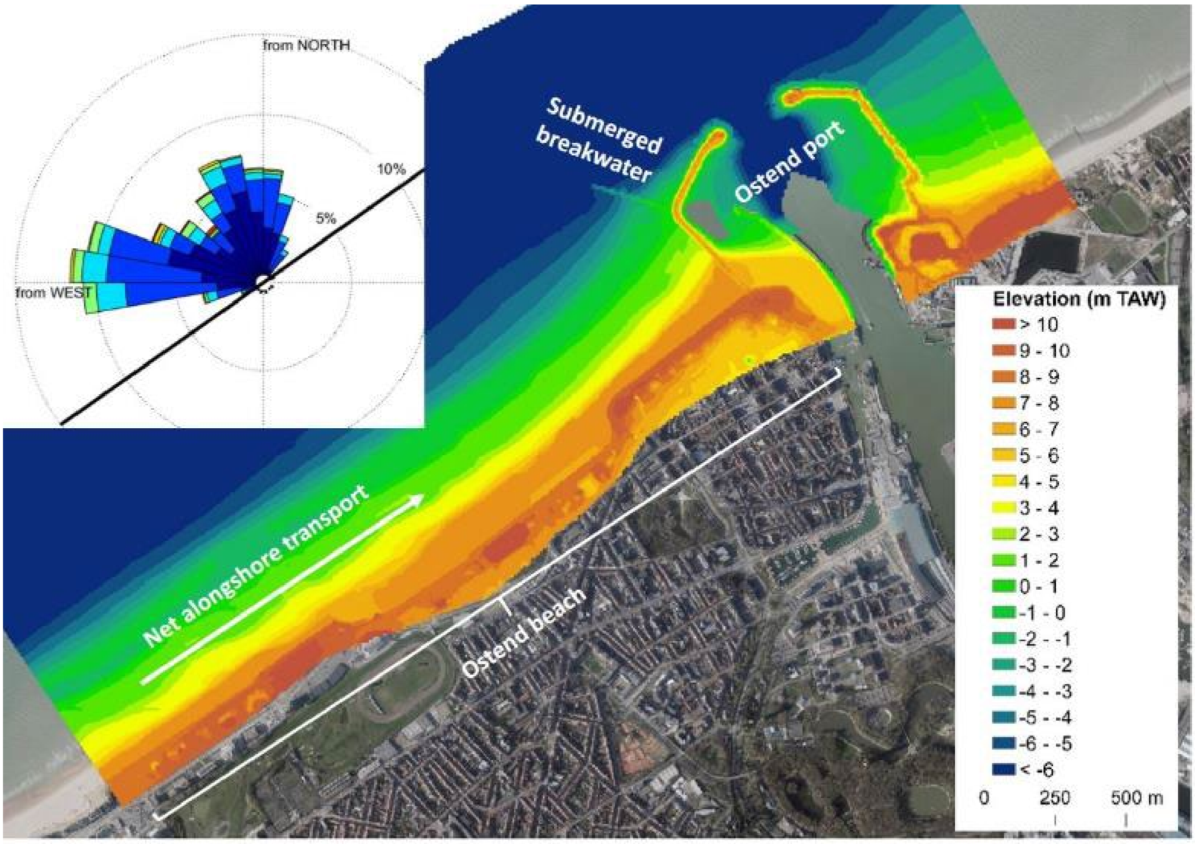

Figure 1: Digital elevation model of Ostend beach (2021)

2. METHOD

The main method for investigation of the beach evolution was building digital elevation models (DEM) based on topographical and bathymetric measurements carried out yearly by Coastal Division. Comparison of successive DEMs, interpretation and sand budgets were also used to understand the local active beach dynamics.

3. EVOLUTION OF THE COAST IN THE LAST YEARS

The evolution of Ostend beach between 2013 and 2021 is dominated by the re-organization of the sand both alongshore and cross-shore under the influence of wave, tides and currents. The erosive trend observed before 2013 was interrupted by the nourishments. The dry beach increased in volume while a decrease in volume was observed for the intertidal beach. The shoreface area retains much of the nourished sand by consolidation of the sand bars. The combination of the net alongshore transport and local configuration (the port and the submerged breakwater) (Figure 1) plays an important role for the sand accumulation at Ostend beach. After the nourishment in 2018, similar re-distribution of sand occurred with loss of sand in the intertidal area but with gains in the shoreface and dry beach areas (Figure 2). This evolution is partially natural due to inherent re-organization of the nourishments mostly for the shoreface area, but also due to human activities related to summer beach activities, especially for intertidal and dry beach. However, much of the sand nourished between 2013 and 2018 is still present in the area. It is expected that the eventual losses are surpassed by the net alongshore transport from southwest to northeast (average magnitude of 200 000 m^3 per year) which will continue to supply Ostend beach with sand. A bypass system to transfer part of the accumulated sand northeast of the port would contribute to restoration of a dynamic equilibrium for Ostend beach and additionally to nourish the downdrift beaches.

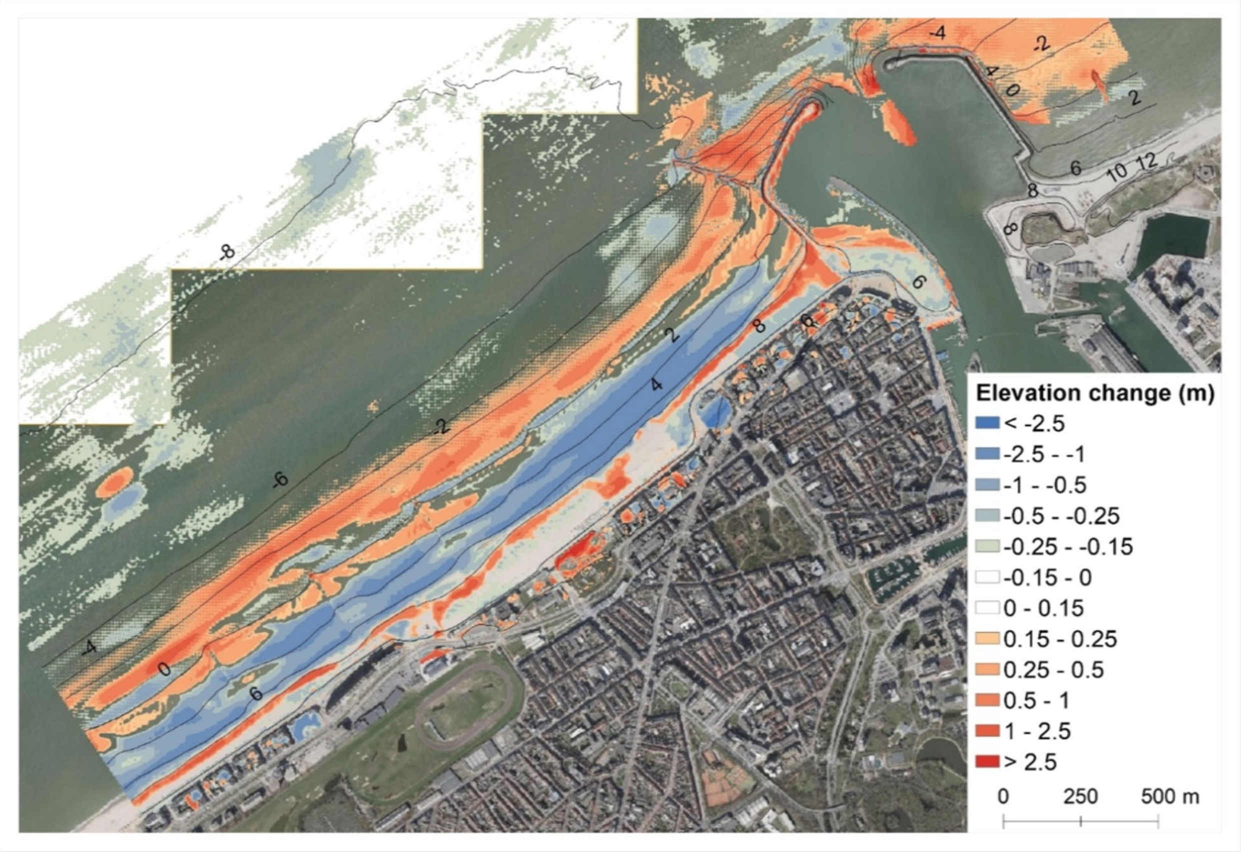

Figure 2: Difference of digital elevation models between 2021 and 2018 at Ostend beach.

4. ACKNOWLEDGEMENTS

The authors acknowledge Agency for Maritime and Coastal Services, Coastal Division and Flanders Hydraulics Research for supporting the present study.

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Initial development of an artificial dune

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1. INTRODUCTION

During strong wind conditions, the local Spinoladijk is blocked due to wind-blown sand. However, this Spinoladijk is an important access road to a leisure beach club and cleaning this dike is a labour-intensive, expensive, and unsustainable work. A dune-in-front-of-a-dike solution was implemented to mitigate this sand nuisance. By creating an artificial dune seawards of the seawall, the traditional sea dike is strengthened with the aid of a nature-based solution. Benefits are a higher level of coastal safety and at the same time a more natural vision and higher ecological and socio-economical values. There are still some knowledge gaps in arranging such solutions (Rizvi and Riel 2020). In this study, we want to identify how these plants must be arranged and especially to define the optimal plant density to protect the dike from sand nuisance.

2. METHODS

A new engineered dune was built at Ostend Oosteroever, Belgium to find out how dunes can be deployed as a coastal protection measurement by using a dune-in-front-of-dike concept. A dune of 2400m² was divided in six zones (1-6) of 20x20m² each with a different planting strategy (regular, clustered and staggered) and density (6, 9 and 15 plants/m²) (Figure 1A). By monthly monitoring the topographical changes with drone surveys combined with weekly measurements on 12 cross-shore profiles (two per zone), conducting aeolian transport measurements and simultaneously measuring wind conditions, the effect of density and planting strategy during the initial months (January-April 2021) of dune development is studied.

3. RESULTS

Results show a clear difference in cross-shore profile development for the different zones (figure 1b), in which the influence of the density is much more prominent than the pattern. Deposition occurs higher and over a shorter distance with increasing density. Sand accumulates on the seawards side of the dune and goes landwards once the vegetation is saturated. At the end of April, zone 4 (9 plants/m² staggered) had the most growing potential (no deposition across the last 2.50m in landward direction). The overall volume of sand accumulated in the dune area is increasing in time and is independent of density and planting strategy, hence completely governed by the aeolian sand supply from the beach. The largest volume change corresponds to the strongest wind conditions (6-8m³/m dune growth at the end of April).

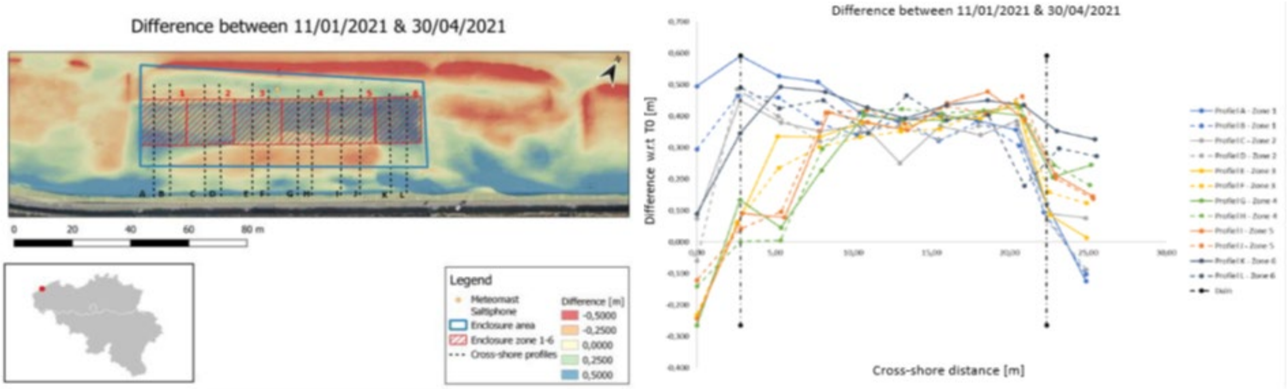

Figure 1: (A) Dune-in-front-of-a-dike pilot site at Ostend Oosteroever, Belgium divided in 6 zones and 12 cross-shore monitoring profiles, (B) cross-shore profile development on 30/04/2021

4. REFERENCE

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A nature-based solution: the Icelandic-type berm breakwater

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1. INTRODUCTION

There is growing interest to use environmentally friendly structures to protect coasts and ports. Nature-Based Solutions (NBS) are used as soft solutions in coastal and port protection projects. Furthermore, hard solutions such as breakwater are commonly practiced. The Icelandic-Type Berm Breakwater (IceBB) constitutes nearly half of the constructed berm breakwaters in the world. This structure is designed and developed for a wide range of wave climates, water depths, and tidal conditions. In this research, the International Union for Conservation of Nature (IUCN) standard is used to assess the characteristics of the IceBB to identify whether this structure can be considered as a NBS.

2. ICELANDIC-TYPE BERM BREAKWATER (IceBB)

The IceBB is designed to be statically stable with only limited stone movement and structural reshaping. To increase the performance of the structure throughout its design life, the void volume of the berm has 35-40% porosity. Furthermore, its narrowly graded armor classes have a higher porosity than wider graded armor classes (i.e., conventional breakwater). This leads to a structure with 1- higher permeability and wave energy absorption, 2- more stability, 3- lower wave penetration into the harbors, and the wave overtopping, and 4- lower wave reflection from the trunk and head of structure (Van der Meer and Sigurdarson 2016). These advantages are highly demanded by ports with narrow entrances that cause high breaking waves and refraction, or coasts that should withstand severe wave conditions and high storm frequency. The preliminary design of the IceBB is based on initial size distribution estimates from potential quarries. The final design is tailored to fit the selected quarry, the design wave load, available construction equipment, transport routes, and required functions. Figure 1 shows the location of some of the IceBB in Iceland for coastal and port protection.

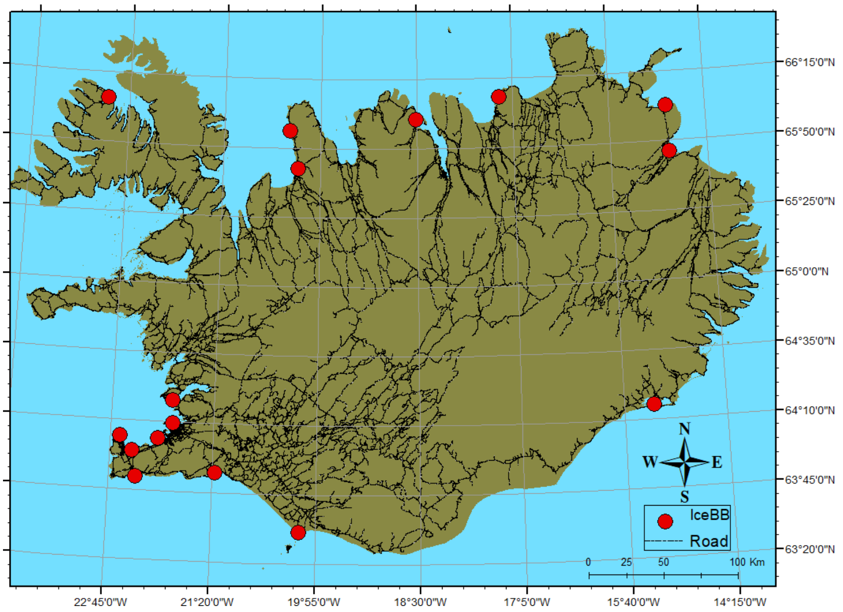

Figure 1: Location of the IceBB for coastal and port protection in Iceland

3. INTERNATIONAL UNION FOR CONSERVATION OF NATURE (IUCN)

NBSs aim to address societal challenges effectively and adaptively (e.g., coastal and port protection) and sustainably add benefits to the ecosystems. IUCN has introduced the global standard (i.e., criteria, indicators) on NBS to ensure the credibility of its implementation. Using this standard, implementation of a NBS can be measured, monitored, and adapted for similar cases (IUCN 2020). The IUCN criteria are 1- NbS effectively address societal challenges, 2- Design of NbS is informed by scale, 3- NbS results in a net gain to biodiversity and ecosystem integrity, 4- NbS are economically viable. 5- NbS is based on inclusive, transparent, and empowering governance processes, 6- NbS equitably balance trade-offs between the achievement of their primary goal(s) and the continued provision of multiple benefits, 7- NbS are managed adaptively, based on evidence, 8- NbS are sustainable and mainstreamed within an appropriate jurisdictional context.

4. DISCUSSION

The IceBB has been constructed by authorities in many countries to protect and develop coasts and ports (criteria #1). The technical quality of the IceBB to protect the ports and coasts has been well documented in the literature which determines its success (criteria #2) (van der Meer and Sigurdarson 2016). The IceBB design and implementation are based on matching the quarry yields which helps to utilize all size grades from the predicted quarry. Thus, its construction limits disturbances in the quarry (criteria #3). The IceBB requires about 25% less volume of rock than the dynamic berm breakwater. Furthermore, its construction cost ranges between 67-86% of the cost for the conventional rubble mound breakwater (criteria #4) (Sigurdarson *et al.* 1998). The design process of the IceBB is through close cooperation with stakeholders including designers, geologists, supervisors, contractors, and local governments (criteria #5). Coastal and port protection provides social and environmental benefits and ensures continued provision of other ecosystem services, such as food supply for sea-dependent coastal communities (criteria #6). The design of the IceBB is relatively easy to be adapted based on the size of rock available from quarry yield (criteria #7). The adaptive development of the IceBB and its durability increases the lifecycle of the structure and its long-term sustainability (criteria #8) (van der Meer and Sigurdarson 2016).

Although IUCN (2020) does not state to what extent the criteria should be fulfilled by a solution (i.e., the IceBB in this research), as discussed, the IceBB can meet the criteria of IUCN for NBS. Therefore, this structure might be considered as a viable NBS for coastal and port protection.

5. ACKNOWLEDGEMENTS

This research was supported in part by the University of Iceland Research Fund (Rannsoknarsjodur Haskola Islands), and the Icelandic Road and Coastal Administration Research Fund (Rannsoknarsjodur Vegagerdarinnar).

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Nature-based beaches and dunes for flood safety and nature; lessons from three large scale nourishment projects

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1. INTRODUCTION

Nature-based (man-made) coastal dunes are being constructed to deliver the diversity of functions that natural dunes provide: flood safety, high natural value, recreation opportunities, and (in some cases) freshwater resources. It is not straightforward, however, to design these dunes since the morphology and sand dynamics, sediment characteristics, vegetation developments, and groundwater dynamics are challenging to reproduce, and a small alteration can have a big effect on the eventual development and functioning of the dune landscape. Therefore, we find it essential to share our lessons on designing such nature-based coastal dunes based upon three case studies in the Netherlands: Spanjaards Duin, the Sand Motor, and the Hondsbossche Dunes. These are all man-made coastal dunes that were realized along the Dutch coast in 2009, 2011 and 2014 (respectively). They had different objectives ranging from high-quality nature development to flood safety and knowledge generation. Based upon these different objectives, the design principles used are also differed. Most importantly, all three locations were monitored for multiple years for their morphological, hydrological, and ecological developments. Not before have the insights from these three cases been combined to feed into design guidelines for nature-based coastal dunes.

	Case studies		
	Spanjaards Duin	Sand Motor	Hondsbossche Dunes
Year of construction	2009	2011	2014
Objective	Nature development (Natura 2000)	Long term coastal defense, nature recreation, knowledge development	Coastal defense
Design	Landscape was constructed including the dunes, which were planted. Interventions were made to steer the development	Peninsula was constructed without dunes, but with a lake and a lagoon. After construction, natural processes could freely shape the Sand Motor	The design was based upon delivering a specific flood risk reduction, creating multiple habitats and trapping sand to reduce dune sand dynamics

Table 1: Description of the case studies

2. APPROACH

In 2021 the International Guidelines on Natural and Nature-Based Features for Flood Risk Management (Bridges *et al.* 2021) were published. We use the key principles addressed in this guideline to analyze the three case studies. We use data and publications from the monitoring programs to compare the performances of the three case studies for flood defense and ecological functioning. Flood risk management objectives are often realized soon after the construction of NNBF, the ecological performance takes more time and is less predictable (Figure 1). We assess to what extent differences in the design and (adaptive) management approach of the case studies may have affected their performance. Based on these results, we can draft lessons for future projects and the mainstreaming of beach and dune Natural and Nature-Based Features (NNBF).

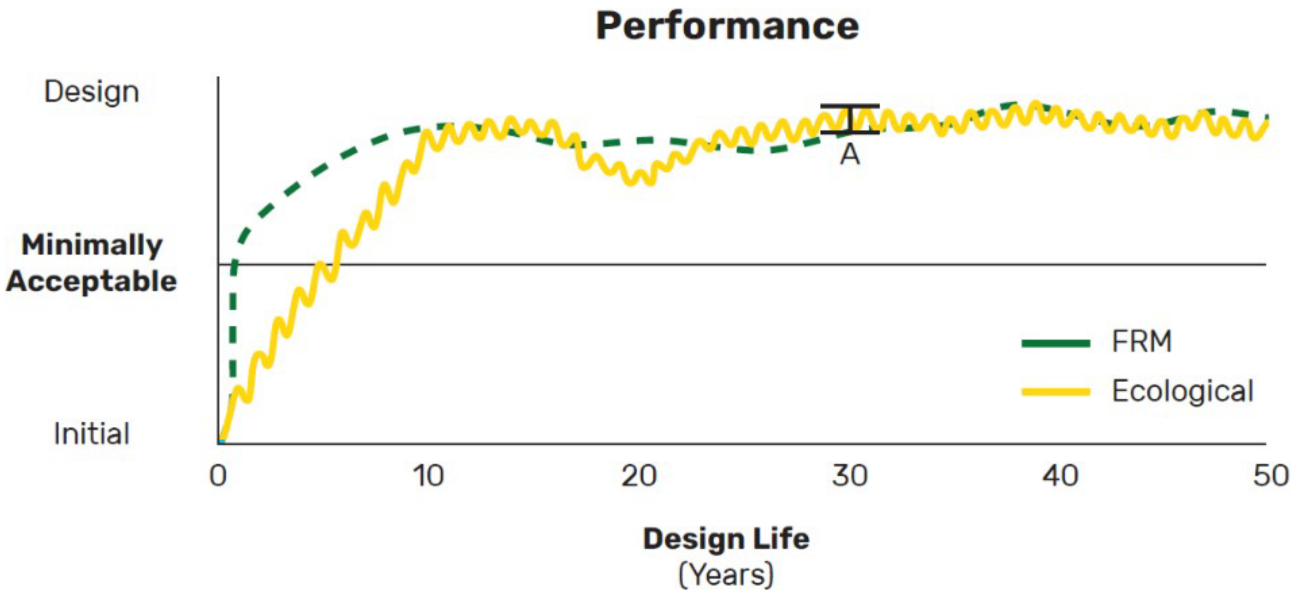

Figure 1: Conceptualized example of performance dynamics of a new NNBF. Green dashed line represents Flood Risk Management (FRM) performance and yellow solid line represents ecological performance. Value A represents typical seasonal variation in ecological performance (Bridges et al., 2021)

3. RESULTS

The results are not available yet and will be presented at the conference.

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Biomechanical parametrization of dune vegetation strengthening nature-based solutions in coastal protection

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1. INTRODUCTION

Nature-based solutions in coastal protection are attracting more attention from research and engineering alike due to their promising potential for biodiversity conservation and climate change adaptation. Especially, coastal dunes offer a high value ecosystem for beach plant and animal species; at the same time, they serve as a natural barrier against flooding due to wave impacts and storm surge. Even though pilot-projects - like the construction of an artificial dune in front of a dike in Ostend (BEL) or in Petten (NL) - show first examples of how an ecosystem-based approach can be integrated in coastal zone management, further research remains crucial; specifically, considerable lack of knowledge exists on the biomechanical characteristics of dune vegetation.

This field study develops a novel acquisition method for the biomechanical parametrization of *Ammophila arenaria* as a typical white dune plant species. As pilot site, a single free-standing dune at the northern coast of the North Frisian island of Spiekeroog, is selected for vegetation sampling. First results include vegetation height and density measurements as well as three-point bending tests to identify the biomechanical properties of aboveground plant parts.

2. METHODS

Spiekeroog offers a variety of dune systems exposed to divergent environmental conditions such as established and incipient dunes as well as artificially-constructed ones. A free-standing dune was chosen for this field study, which is part of the northern white dune system. The select dune offers great potential for investigating dependencies between biomechanical plant traits and local environmental conditions like wind exposure and sand flux, as it features four geographic flanks for erosion and accretion processes to take place. The average wind speed at Spiekeroog is 7.9 m/s with a prevailing wind direction between west and north (source: Deutscher Wetterdienst). The dune covers an area of 3’005 m² and extends approximately 90 m along its north-south axis and reaches a maximum width of 45 m east-west. For sampling, the area is subdivided into ten zones (see Figure 1). Vegetation height and density (in stems per 0.20 x 0.20 m²) are manually assessed using a ruler and aboveground vegetation samples are collected. These vegetation samples are divided into three representing elements, that are separately subjected to three-point bending test, in accordance to Liu et al. (2021), to identify the specific bending modulus.

3. RESULTS

Field data collected between December 2021 and January 2022 indicate that for both measurements, the maximum average vegetation height is about 88 cm and is found in the northern part of the dune (see Table 1). Lowest average values of about 57 and 60 cm, respectively, are achieved in the south-eastern dune zones. Regarding vegetation density, maximum average values of 35 and 23, respectively, are obtained in the north-western dune zones with minimum average values ranging between 8.5 (east) and 9.5 (south-west).

Three-point bending tests were conducted on the aboveground plant parts “stem”, “greenish leaf” and “brownish leaf” sampled in December 2021 and January 2022. The average values of the specific bending modulus are 1700, 2574 and 1866 MPa (December 2021), and 1352, 2459 and 2003 MPa (January 2022), respectively. Depending on the orientation, a correlation between the maximum bending modulus and the north-western dune areas is only observed in January.

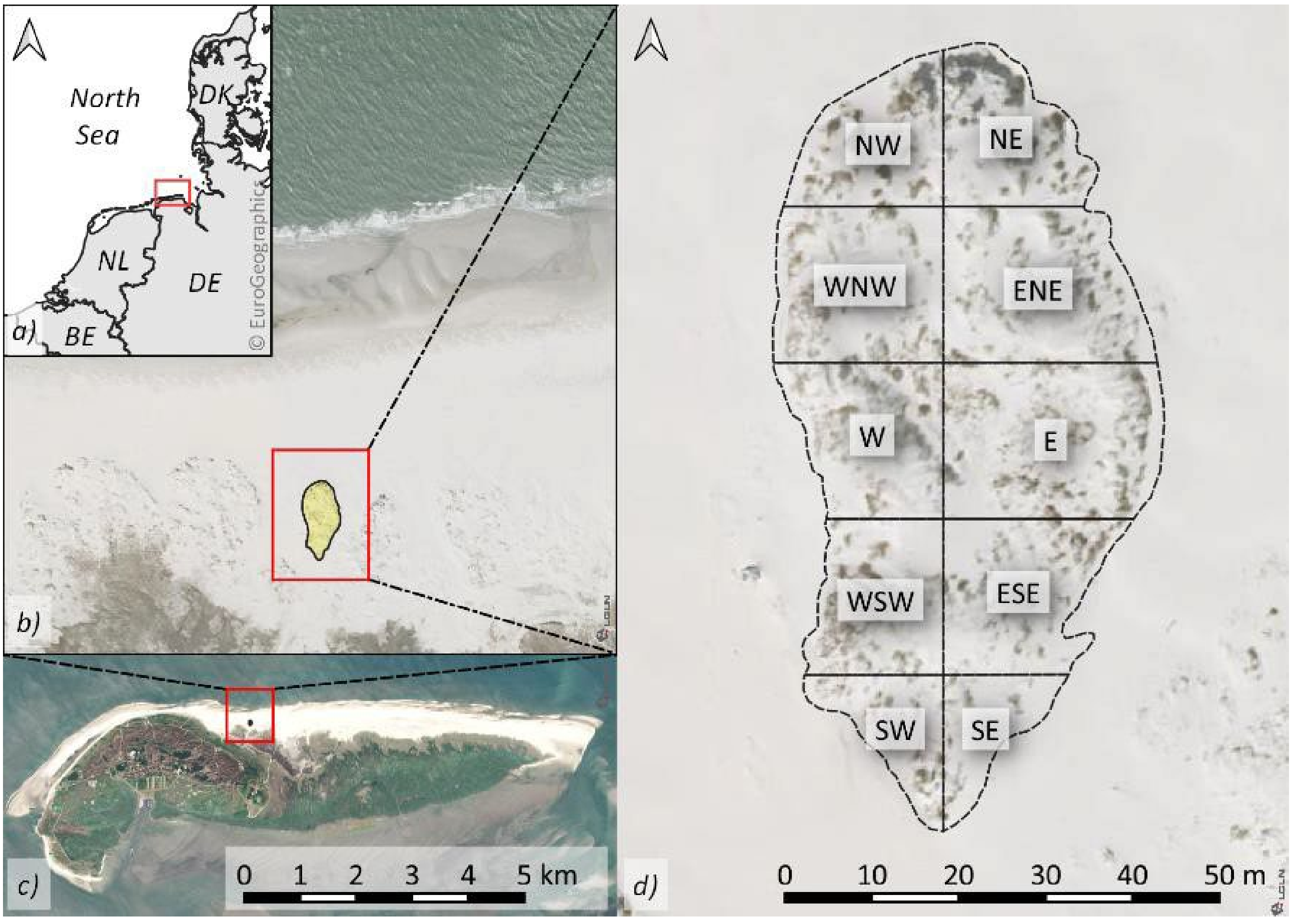

Figure 1: a) Regional map of the North Sea with neighboring coastal countries; b) Birds eye view of the investigated dune c) Overview map image of the tidal barrier island of Spiekeroog with the location of b) marked; d) Detail view of the dune with areal zones delineated. Coordinate Reference System used: EPSG:3034 – ETRS89 – Extended / LLC Europe; ©EuroGeographics for the administrative boundaries. Background image source: TrueDOP – Excerpt from the geodata of the state office for geoformation and survey Lower Saxony, ©2020 1) LGLN

Data	Dune zone									
	NW	NE	ENE	E	ESE	SE	SW	WSW	W	WNW
Zone size (m²)	254.6	268.5	415.8	475.9	327.8	144.5	161.1	276.9	309.4	369.8
December 2021										
V. height (cm)	75.0	88.0	78.5	56.7	73.3	68.3	71.7	72.3	70.0	71.0
V. density	29.0	18.5	34.33	16.0	29.5	11.0	9.5	25.0	35.0	28.5
Sample number	10	10	10	10	10	10	10	10	10	10
January 2022										
V. height (cm)	87.9	68.8	81.1	64.4	83.3	59.4	74.5	75	73.3	72.5
V. density	23.3	13.5	16.0	8.5	15.5	12.5	13.0	17.3	17.0	17.5
Sample number	10	10	10	10	10	10	10	10	10	10

Table 1: Overview of areal size, average vegetation height and density (stems per 0.20 x 0.20 m²)

4. DISCUSSION AND CONCLUSIONS

The data collection will continue monthly (starting from December 2021) as well as complementary parameters serving as a basis for surrogate modelling of dune vegetation for physical and numerical experiments in the light of nature-based solutions for coastal protection.

5. ACKNOWLEDGEMENTS

We are indebted to the National Park authority (Nationalparkverwaltung Niedersächsisches Wattenmeer) for providing site access and permission to use it for scientific research.

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New investigation of coastal dunes evolution along the Belgian coast using ground-penetrating radar

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1. INTRODUCTION

Coastal foredunes are natural features, reflecting interaction among geomorphological and ecological processes. Their formation depends on a wide range of environmental factors, but is associated with strong onshore winds, an ample supply of sediment for aeolian transport and the presence of vegetation to trap sand. Foredune evolution is thus controlled by a broad spectrum of spatial and temporal forcing processes. The advance of geophysical methods such as the ground- penetrating radar (GPR) allows to obtain stratigraphic information on aeolian landforms by reconstructing evolutionary characteristics of the sub-surface. The analysis of GPR data results in the interpretation of radar facies indicating the architectural elements related to depositional environments and allows to extend the more recent 2D database obtained using traditional topographic instruments (Robin et al., 2021). The aim of this study is to investigate coastal foredune evolution at multidecadal scale by combining GPR and airborne LiDAR surveys.

2. STUDY SITE

Groenendijk is a macro-tidal beach located in the western part of the Belgian coast, between Oostduinkerke and Nieuwpoort-Bad (Figure 1). It is typically characterized by well-developed and vegetated foredunes approximately 10m high above TAW. The dune and beach have propagated at a significant rate over the last decades. Onshore high wind speed events (>10 m/s) are associated with SW-W-NW atmospheric circulations which are also associated with the possible occurrence of storm surge (Montreuil et al., 2016).

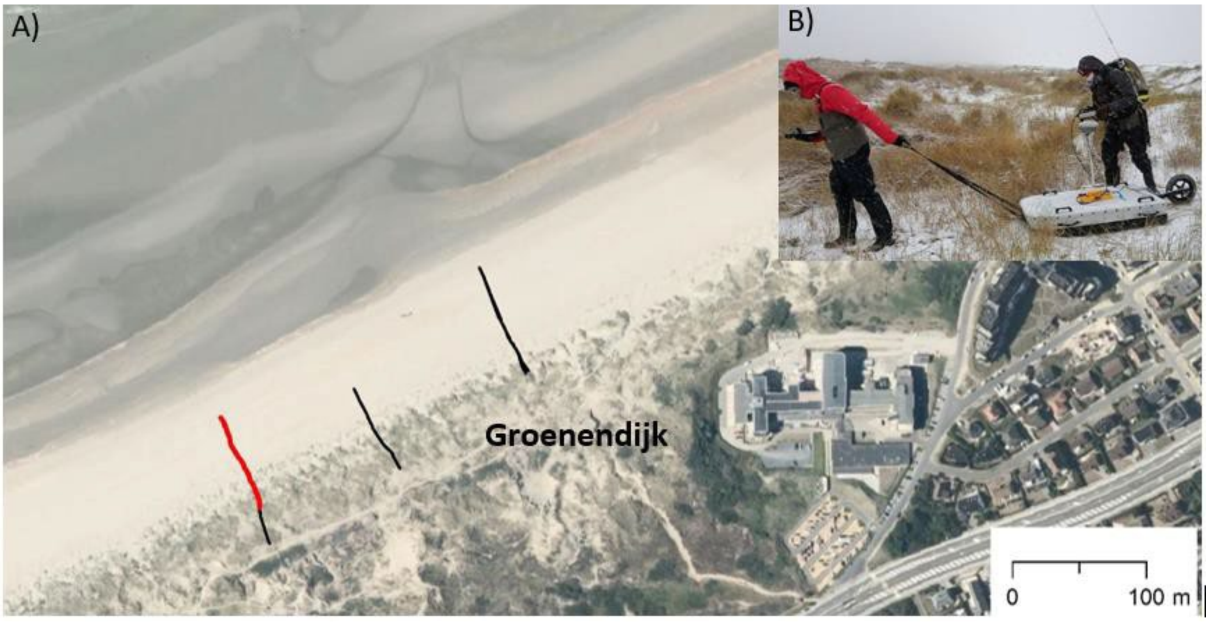

Figure 1: A) Location map of the 6 GPR profiles (profile 601 in red), B) field photograph of the equipment

3. METHODOLOGY

Ground Penetrating Radar (GPR) is a geophysical non-destructive method used to image sedimentary structures and it has been successfully applied in coastal studies (e.g. Robin et al., 2021).

It is based on the propagation and reflection of transmitted electromagnetic pulses. The internal architecture of the foredune at Groenendijk was surveyed in January 2012 using a Mala ProEx system coupled with a RTK-GPS along six cross-shore profiles (Figure 1). The detailed internal architecture of the coastal dune system was imaged using three GPR antennae (100, 250 and 500MHz). Data were processed using ReflexW Software and a constant radar velocity of 0.06 m/ns. After processing, the GPR images were interpreted on the basis of radar facies identified on the profile. The results were then compared with a profile time series extracted from LiDAR surveys provided by Coastal Division.

4. RESULTS

The GPR signal recorded across the profile indicates the upper 3-5m of the internal structure of the dune (Figure 2). It shows two stages of construction and evolution. There was a formation of the foredune at D=70m principally by aggradation until 2010. The position of the dunefoot changed slightly. After 2010, the internal architecture displays a progradational configuration with oblique reflectors towards the NW (seaward), suggesting a rapid development of the foredune and seaward regression of the coastline. During this period, most of the evolution occurred in the center of the profile, while the dune located to the SE of the profile (D = 70m) seems to undergo only a slight change. This study highlights that GPR method combined with chronological topographic data is an efficient tool to understand foredune evolution over the last decades and for management applications.

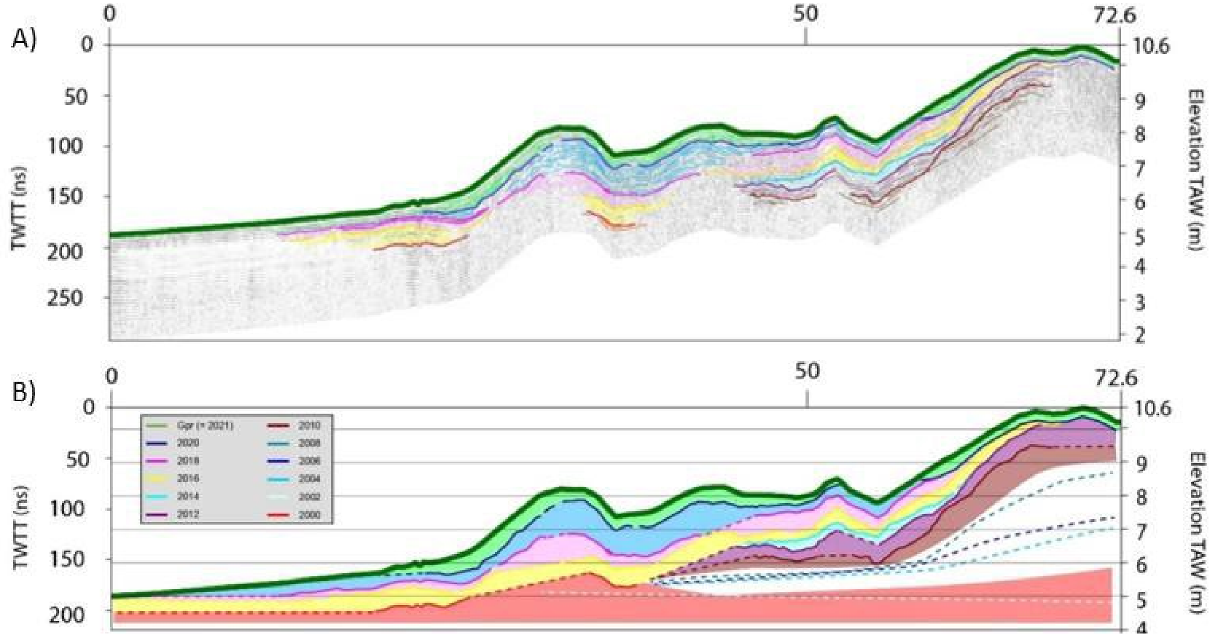

Figure 2: A) reflection-traced versions of the internal architecture of the 601 profile, B) superposed on interpreted GPR and LiDAR profiles.

5. ACKNOWLEDGEMENTS

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Evolution of a beach-dune system after artificial nourishment: The case of São Joao da Caparica (Portugal)

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1. INTRODUCTION

Costa da Caparica seafront margins a low-lying strand-plain where conflicts have coexisted throughout the last seven decades between development and conservation (cf. Veloso-Gomes et al. 2007; Pinto et al. 2007). Development grew exponentially after the 1950's, bringing housing and other infrastructures too close to the shoreline, and this was accompanied by construction of hard coastal defences in the early 1960's including a groin field anchored in a seawall, both having been damaged by the winter 2013/14 Christina storm.

Since the early 2000's the strategy of intervention switched to beach nourishment and dune restoration, adopted as adaption methods to cope with impacts of long- term erosion trend, storm-driven inundation, damages to hard engineering structures and preservation of beach recreational value. Main objectives of this study are the characterization of morphological evolution of São João da Caparica (SJC) of the beach-dune system following artificial nourishment operations and evaluation of hard and soft interventions performance.

2. STUDY AREA

This study focuses on the 1.3 km-long coastal stretch of SJC, in the Atlantic coast of the municipality of Almada (south of Lisbon, mainland Portugal). This beach consists of medium-fine, well to moderately well sorted sand and is limited by two groins; a seawall bounds the southern third of the beach length, whereas to the north it confines with a dune system that has been rehabilitated in 2015 under ReDuna project (http://www.lifebiodiscoveries.pt/sites/default/files/projeto_reduna.pdf). SJC and beaches extending further south along the Caparica seawall and groins for 3.9 km were artificially nourished in the summers of 2007 to 2009 (total ~2.5 M m^3), 2014 and 2019 (1 M m^3 each). Nourishments used dredged sand made available by the Lisbon port authority in the scope of channel maintenance operations (Pinto et al. 2020).

3. METHODS

Topographic data were acquired to characterize seasonal beach changes, as well as to quantify longer-term evolution trends and map volumetric changes over the beach–dune system. Data were acquired by means of repeated RTK-GPS field surveys and photogrammetric processing of imagery captured by unmanned aerial vehicles. These were merged with information obtained under the COSMO monitoring programme (https://cosmo.apambiente.pt/) and unpublished data collected in the scope of projects carried out by Faculdade de Ciências da Universidade de Lisboa, the Portuguese Environmental Agency and the Municipality of Almada (eg., Andrade et al. 2019). Data were processed using Agisoft and ArcGIS Pro to obtain digital elevation models, interpolate selected profiles and obtain beach and dune volumes above mean sea level (MSL) and 2 m (MSL), respectively.

4. RESULTS AND DISCUSSION

Long-term beach erosion in SJC is indicated by consistent decrease of the overall beach volume between successive replenishments: -44,000 m^3/yr. (2009 –2014 and 2014 –2019) and -59,000 m^3/yr. (2019 –2021). Beach responded differently alongshore within the same time window and in distinct periods between nourishments (+0.15 to -0.19 m^3/m day). This is interpreted as resulting from persistently negative sediment budget (cf. Santos et al. 2015) related with longshore processes that is superimposed by shorter-term, cross-shore dominated changes in volume related with seasonal wave regime and beach rotation. Periods of sand loss are separated by abrupt increases in volume determined by artificial sand replenishment of the beach berm. Such operations were conducted in SJC in the summer of 2007 (~29x104 m^3), 2008 (28 x104 m^3), 2009 (28x104 m^3), 2014 (38x104 m^3) and 2019 (17x104 m^3) and increased the berm width (by about 60-70 m) in addition to raising the berm height up to 3-3.5 m MSL. The southern beach sector showed higher susceptibility to erosion and resumed pre-nourishment morphology and volume shortly after post-replenishment storms. This is due to the seawall enhancing reflection of wave energy and precluding temporary profile retreat during storms together with blockage of northward net littoral drift promoted by the groin at the southern beach end and explains the higher performance of nourishments at the northern beach section.

Estimations of total beach volumes and losses over time suggest that the longevity of the nourishments is of 4-5 years, and that a new replenishment should be required not later than 2024 to maintain protection offered by the beach-dune system. Moreover, field monitoring of morphology and of landward reach and impact of wave swash before and after significant storms (observed in the field and reported by media) suggest that a volume bigger than 30x104 m^3 is satisfactory to grant effectiveness in protecting dunes from wave erosion, and to allow for unconstrained beach-foredune aeolian sand transport (cf. Andrade et al. 2019). A critical volume of 16x104 m^3 requires urgent beach refill given the high risk of full beach overwash and dune breaching/overtopping.

Sand fences and vegetation introduced in 2015 under ReDuna restoration, following erosion by Christina storm, led to in situ growth of a small primary dune, shifting the coastline 10-20 m seaward. The new dune grew rapidly in the first year following fence deployment and more slowly in the following two years. Storm erosion and dune overtopping in 2017 and 2018 interrupted the growth pattern at the centre and southern dune sections. Fences were reconstructed after damaging episodes, allowing for aeolian processes to resume increase in dune volume. Following the 2019 replenishment, a second positive pulse in dune growth is noticeable. Field observations indicate that despite erosion and overtopping, the obstacle provided by this dune proved effective in protecting the dune ridges located further landward, which host several beach restaurants.

5. CONCLUSIONS

Hard engineering structures built at, and further south of, SJC beach were effective in halting coastal retreat but this triggered loss of the subaerial beach. In consequence, maintenance of the recreational values of beaches requires regular artificial renourishment of groin field cells. The northern section of SJC has been solely subjected to beach nourishment and dune restoration; altogether this strategy was also quite effective to counteract long term erosive trends with the additional advantage of preserving environmental and recreational values.

6. ACKNOWLEDGEMENTS

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15 years of beach flora monitoring along the Belgian coast

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1. INTRODUCTION

Sandy beaches are a hostile environment for many species, including vascular plants. Ecological stress and disturbance factors include soil mobility, frequent inundation and a high salt concentration. Still, a limited number of plant species is able to grow in these harsh conditions through physiological, morphological and/or phenological adaptations. These species play an important functional part in the sandy coastal ecosystem as their establishment often preludes the initial stage of dune development. Furthermore some are rare in a regional or even international context and deserve special attention in terms of biodiversity conservation. Plenty of reasons to monitor the characteristic beach flora.

2. METHODS

Beach vascular plants are monitored for 15 consecutive years (2007-2021) in 23 transects, regularly distributed over the entire Belgian coast. The transects consist of longshore stretches of 500 m, ranging cross shore from the floodline to the dune foot. Within these transects, individual plants, clones or clusters of plants are mapped using hand held gps. For each gps point location, plant abundance is estimated in classes. Point maps are rasterized to 25x25 m² gridcells for further analysis.

Environmental variables are attributed to both the gps point locations and the grid cells. They include landscape type (urban area, dune or dune with dyke), presence of brushwood fencing and changes in topography. The latter is deduces from the LiDAR based digital elevation maps which are acquired twice a year for the entire beach by the Flemish agency for Maritime and Coastal Services (MDK).

3. RESULTS

About 20 coastal species were found within the transects but only 8 are characteristic for sandy beaches. *Cakile maritima*, *Elymus farctus* and *Ammophila arenaria* are the most common species, with up to hundreds of individuals growing within the transects. Population size, however highly fluctuates in time. *Ammophila* and *Elymus* show a general increase over the 15 years of monitoring, both in total population size as in area (expressed as number of occupied 25x25 m² grid cells). *Cakile* however, shows an overall decline. The others species are rare or very rare and often appear ephemerally. Only *Honckenya peploides* and *Salsola kali* have a stable population. They show no clear trend over time.

Beach plants are far more abundant on beaches adjacent to dunes. This is highly related to a more limited recreational pressure and the absence of mechanical beach cleaning. The presence of brushwood fencing generally has little effect on the distribution of the characteristic beach flora. Only *Atriplex glabriuscula* and *Beta vulgaris* subsp. *maritima* show a clear preference for the shelter of brushwood.

Finally, the beach flora seems well adapted to the dynamics of the beach sand. *Cakile* and *Ammophila*, are found on beaches with up to about 50 cm of beach erosion and 37 cm of accumulation per year. Erosion tolerance for Elymus seems to be smaller. While an optimal beach for *Cakile* is stable, *Elymus* and *Ammophila* are clearly prefer beaches accumulating about 6 cm per year.

4. CONCLUSIONS

The characteristic beach flora consists of a limited number of species adapted to the natural dynamics of this habitat. Populations of the 5 major species show yearly variation in size but remain relatively stable over a longer time. Other species are very rare and often ephemeral. Recreational pressure seems to be a major factor determining local species decline.

Hybrid performance assessment of sand mitigation measures for coastal and desert applications

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1. INTRODUCTION

Windblown sand hazard affects both building environment and human activities (such as transport infrastructures, buildings, urban areas) and ecological system (such as coastal dunes and desert oasis) in sandy coastal and desert environments. On the one hand, ongoing climatic changes have increased the frequency and magnitude of wind storms along coastal regions in extra tropical regions, Europe included. On the other hand, desert regions are increasingly hosting human activities and built structures. In light of this, windblown sand interacts with ground-mounted obstacles of any kind inducing sand erosion and sedimentation around them and detrimental effects, such as transport infrastructure loss of capacity, but also destructive failures (Raffaele and Bruno 2019).

Several Sand Mitigation Measures (SMMs) design solutions to mitigate windblown sand effects have been proposed so far (Bruno et al. 2018). They aim to prevent sand from reaching the protected system. Most of them are located between the sand source and the protected system, and they are intended to trap incoming sand by promoting wind speed lowering and sand sedimentation (Path SMMs). SMMs usually translates into nature-based solutions, such as earthen berms, ditches, porous vegetation belts, or artificial obstacles, such as man-made porous and solid barriers.

However, with some remarkable exceptions, the rigorous design and performance assessment of SMMs remain at their early stage in the engineering literature, while they are mostly based on trial- and-error approaches in the technical practice. According to the authors, this is due to the multidisciplinary and multiphysics/multiscale nature of the phenomenon coupling fluid dynamics and aeolian processes. As a result, on one hand, research should benefit from disciplines adjacent and partially overlapping, e.g. fluid dynamics, wind engineering and aeolian geomorphology. On the other hand, experimental and numerical approaches should be mutually supporting to model multiphase windblown sand processes.

Physical experiments usually translate into full-scale or wind tunnel scale tests. In-situ full scale tests reflects real world environmental conditions but they are expensive, time-consuming, and subject to environmental setup conditions difficult to control. WST testing is almost entirely carried out by scaling the characteristic length L of the surface-mounted obstacle for both economic and practicality reasons. Conversely, sand grain diameter d can hardly be scaled to avoid switching from sand to dust particles and underlying physics. This opens the door to physical similitude theory based on dimensionless numbers (e.g. Re or Fr numbers) referred to the whole multiphase/multiscale flow (Raffaele et al. 2021).

The numerical simulation of windblown sand flow, herein called Erosion-Transport-Deposition (ETD) simulation, is mainly carried out through the resolution of fully Eulerian models coupling wind flow aerodynamics and aeolian processes resulting in in-air sand concentration ϕs and the morphodynamic evolution of the sand bed. Among them, Eulerian ETD simulations adapt well to the engineering needs of modelling large-scale processes and cutting costs with respect to WST and full- scale tests (Lo Giudice and Preziosi, 2020). However, ETD simulations have to be always calibrated and validated on physical measurements.

In this study, the authors take advantage of both WST tests and ETD simulations to assess the performance of a sinusoidal berm SMM. WST tests are carried out in the Wind Tunnel L-1B of von Karman Institute to characterize the sand flux in open-field conditions and around the SMM. The SMM performance is assessed by taking into account the progressive loss of performance of the SMM caused by the gradual accumulation of sand around it. WST measurements are adopted to properly tune and validate ETD simulations carried out with the same scaling of the WST tests. Finally, a full- scale ETD simulation is performed in order to quantify the performance under real-world conditions and quantify the experimental distortion resulting from non-compliance of physical similitude.

The complementary combination of WST and ETD provides deep insight into the scaling effects to SMM performance, lowering the costs with respect to in-situ full scale testing. Furthermore, it constitutes a promising approach to design SMMs and shorten the time required to evaluate in-field efficiency.

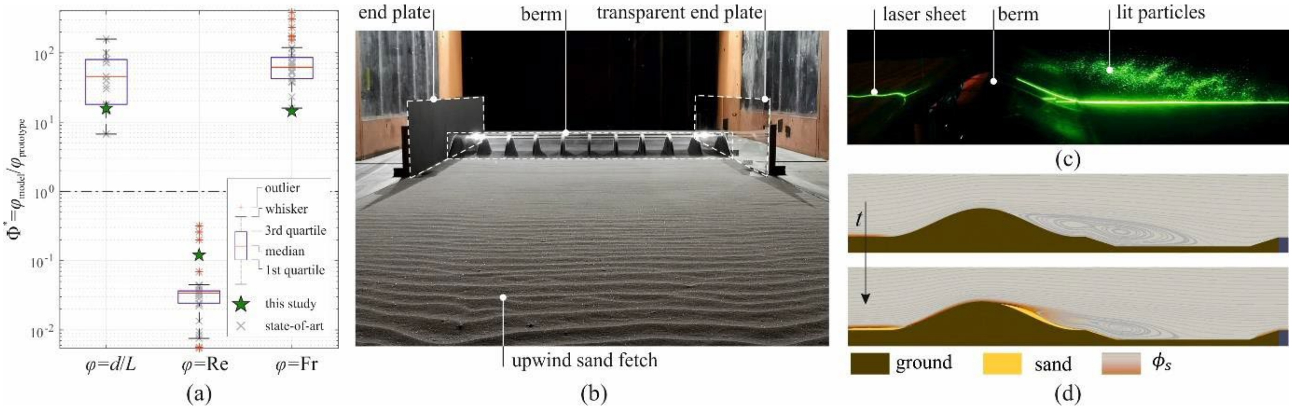

Figure 1: WST setup dimensionless numbers (a), front view of the tested sinusoidal berm SMM (b), laser sheet for PTV grain counting and morphodynamic evolution (c), full-scale ETD simulation for varying time t (d)

2. ACKNOWLEDGEMENTS

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Nourishment efficiency along the Belgian coast

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1. INTRODUCTION

The Belgian sandy coast is a complex and dynamic environment. Several locations suffer from structural or storm-induced erosion, while other locations structurally gain sediment. Coastal management policies are in place to maintain the coastline and keep floodrisk at acceptable levels. Currently the coastline is maintained by sand nourishments, adopting the "soft where possible, hard where needed" philosophy from the Masterplan Coastal Safety (MDK, 2011). Nourishments are mostly applied on the beach and dune foot. Only a few shoreface nourishments were installed along the Belgian coast. Noteworthy is the 'profile' nourishment between Bredene and De Haan, where the whole coastal profile was extended seaward.

As sand nourishments form the core of coastal maintenance in Belgium, their performance or efficiency should be taken into consideration. Verhagen (1996) concluded that independent of nourishment schemes, an increased erosion rate is observed in the first 1-2 years after construction. The decay could be calculated with a combined exponential and linear function. The question is whether it also holds for the Belgian macro-tidal environment.

2. METHODS

Timeseries of coastal volume changes are available for the Belgian coast since the 1980's. Volumes are reported per coastal section and per 'layer' with fixed boundaries (Figure 1). Thus the volumetric development of the dunefoot, beach, shoreface and sea bed can be tracked independently. Furthermore, nourishment and dredging volumes are reported per coastal stretch, administrative units of coast approximately 1.2 km alongshore. These volumes are assumed to be uniformly distributed. Depending on the project type these numbers are assigned to a layer. E.g. shoreface nourishment to the shoreface layer.

The lifetime of a nourishment project is defined as the (extrapolated) time taken to return to the pre-nourishment volume. Coastal safety may however require renourishment before depletion. Given the (bi-)annual monitoring frequency, only larger nourishments (>100 m^3/m) are taken into consideration.

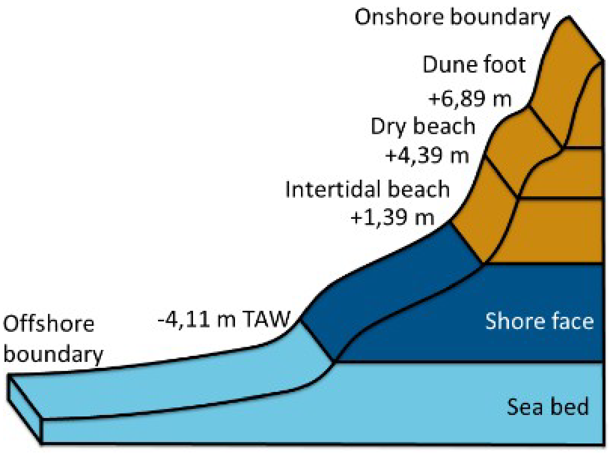

Figure 1: Layers defined for coastal volumes, separated at fixed height. Levels with respect to TAW (Belgian ordnance level), roughly Lowest Astronomical Tide (LAT).

3. RESULTS

Middelkerke's recreational beach was replenished by a large-scale beach nourishment (about 300 m³/m) in 2015 for coastal safety purposes. This nourishment shows the classical behaviour of intensified initial erosion in the first two years after construction as described by Verhagen (1996). The background erosion rate from the beach is 15 m³/m/year, similar as before (Figure 2, left). Previously small-scale recreation oriented nourishments were performed annually. As the beach is backed by a sea dike, there is hardly any accommodation space for wind-blown sediments and only a limited storm buffer can be created.

The large nourishment scheme between Bredene and De Haan in the 1990's has effectively extended the coastal profile seaward. After the nourishment and placement of sand fences in the dunes the beach volume has remained stable. This renders a life time of several decades, making it an enduring project with losses less than 5 m³/m/year. Most likely due to accommodation space in the dunes. Two additional 50 m³/m maintenance nourishments in 2014 and 2017 do however show more rapid decay (Figure 2, right). Both the nourished beach profile and sufficient accommodation space for wind-blown sediments appear to influence the life-time of nourishment at the Belgian coast.

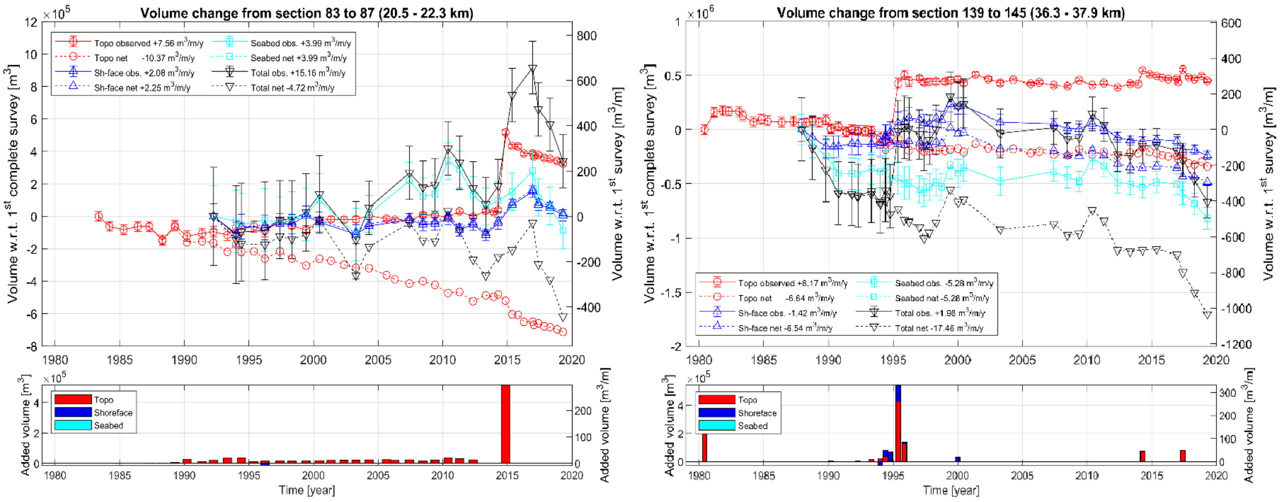

Figure 2: Left: effect of beach nourishment in Middelkerke. The large replenishment in 2015 has increased the beach volume >300 m³/m, while background erosion had remained similar (red lines).

Right: effect of beach nourishment near De Haan. The profile nourishment of 1994-1996 has increased the beach volume >400 m³/m, after which the beach remained stable (red lines).

4. ACKNOWLEDGEMENTS

Flanders Coastal Division is greatly acknowledged for providing coastal volume and nourishment data. Thanks to Rik Houthuys, nourishment and dredging data of the coastal zone are now attributed to coastal stretches.

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The role of gravel pocket beach on stability of urban rocky coastline

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1. INTRODUCTION AND INVESTIGATION SITE

Gravel beaches provide natural coastal protection along other ecosystem services to many coastal areas. By dissipating wave energy, they can contribute to stability of cliffs and coastal structures behind them. This paper investigates the effectiveness of gravel pocket beaches (GPB) for protecting urban coastline in the city of Rijeka, Croatia. Two beach systems were studied, a natural system comprised of a beach and a cliff (Sablićevo) and a man-made system (Ploče) comprised of an artificial beach and a sea wall. The rocky coastline around Rijeka is predominantly formed in carbonates (Benac *et al.*, 2013). A number of pocket gravel beaches can be found at locations of previously weakened carbonates, where a local erosion of coastal cliffs provides the sediment supply (Pikelj and Juračić, 2013). This is a micro-tidal environment with a tidal range between 20 and 50 cm. The coastline is exposed to wind-generated waves from the south-east (SE) to south-west (SW) directions, with the largest significant wave height of 3 m in the Rijeka Bay (Lončar *et al.*, 2014). The highest waves from the SE direction are usually accompanied by storm surges. The heights water elevation of 1.27 m CVD was recorded at the nearby tidal gauge in Bakar Bay, east of Rijeka, on 29th October 2018.

Sablićevo is a natural GPB, subject to moderate beach erosion visible on a 50-year scale (Fig 1). The beach was formed by the erosion of the rock mass. While cliff erosion provides beach sediment supply, it threatens local buildings and infrastructure. Hence, cliff was reinforced with gravity wall, steel netting and ground anchors to prevent further coastal retreat, which reduced sediment supply to the beach. Geotechnical works have been carried out on the beach on several occasions since 1980, but those interventions did not solve the problem and new rock fall would occur each time. Eroded beach in front of the cliff cannot reduce wave attenuation during storm surges and allows high waves to access the cliff face affecting its stability. There is also a negative impact of wave quarrying and abrasion (or corrosion) on rock. As result, the cliff erosion is continuing and the beach is eroding.

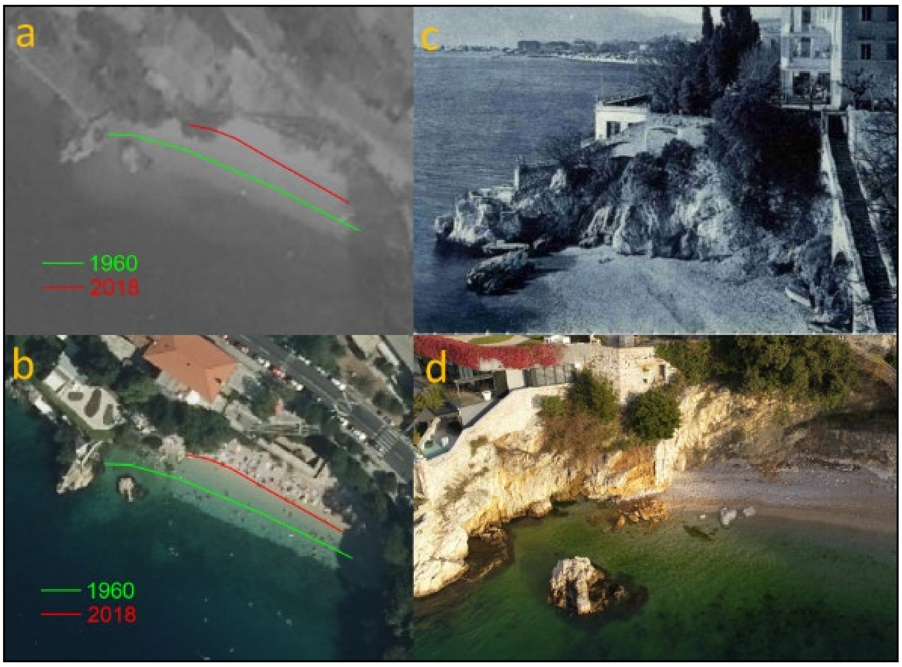

Figure 1: Estimation of beach coastline retreat (a, b). Sablićevo beach around 1930 (c) and 2018 (d)

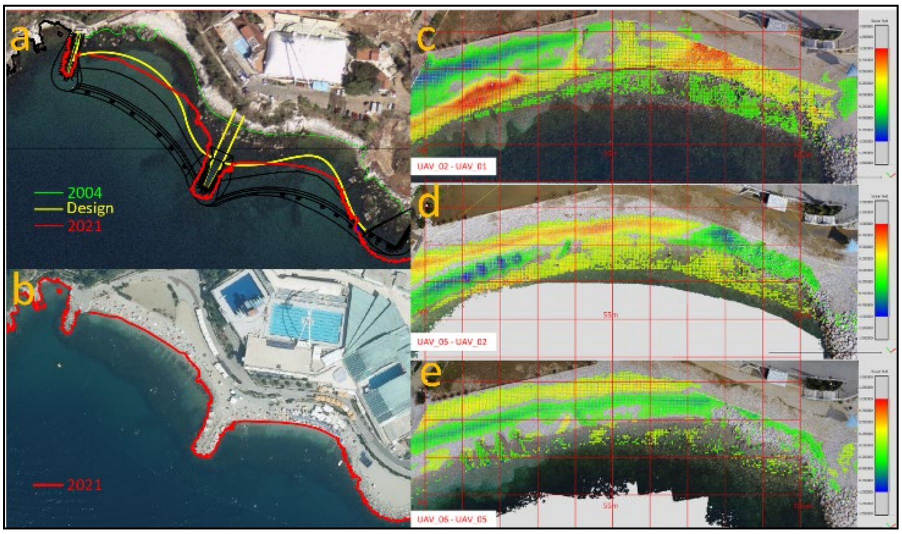

Figure 2: Ploče beach before (a) and after (b) construction. Results of beach monitoring, elevation difference: (c) after and prior of nourishment, (d, e) impact of the first storms

Ploče beach is an artificial GPB built in 2011. The beach consists of two pocket beaches, both about 130 m wide (Fig 2). These beaches are extensions of very narrow gravel beach strips in two small natural embayment, whose headlands have been extended by rock groynes. There is also a submerged sill offshore at a depth of 2 m. Before the Ploče beach was built, sea walls have often been damaged during storms.

3. METHODOLOGY

The beach surveys were conducted on both beaches using UAVs. The images were acquired in JPG format using the UAV DJI Phantom 4 Professional, FC6310 camera with 20-megapixel (4864 x 3648), 1" CMOS sensor, 8.8 mm focal length. The Ploče beach was surveyed 19 times between 17 January 2020 and 26 February 2021, while the Sablićevo was surveyed six times between 2017 and 2021. Point clouds were obtained from the sets of photographs processed using software Agisoft Metashape Professional, v1.7.1. The 3D point clouds were generated using the SfM-MVS photogrammetry technique. Additionally, a terrestrial laser scan (TLS) was deployed on Sablićevo beach in May 2021. The data was processed into 3D point cloud. QGIS was used for GIS analysis and CloudCompare for point cloud data processing. In addition, nearshore waves were simulated using the SWAN numerical model, for the different beach shapes (current, former, hypothetical nourished) and present and predicted sea levels.

4. RESULTS

The estimated retreat of the coastline at Sablićevo beach is between 3 and 7 meters. The estimate is based on the analysis of old images and orthophotos and a 3D point cloud of the beach (limitations: image quality, no tide data). The most recent rock erosion was recorded by monitoring in autumn of 2018. There are two rockfalls in the western part of after SE storm surge (Fig 1).

Figure 2 (c – e) shows the changes observed on the Ploče beach. Comparison of the point clouds shown in figure c shows the influence of beach nourishment. The material was deposited at the eastern end of the cell, and on the opposite side the sediment was pushed closer to the coastline from higher parts. The first waves caused longshore transport of the material from east to west (d). Heavy rain accompanying the storm waves caused local erosion where the fresh water flowed through the beach body. The final image (e) shows cross-shore changes caused by the highest recorded waves. The results suggest that the beach is relatively stable throughout the surveyed period and requires very small amounts of sediment for its maintenance, unlike some other artificial beaches in Croatia. The monitoring has been successful in detecting the locations of beach erosion.

The full paper will include results from further analyses of effectiveness of gravel beach for protection of eroded cliff. Analyses of the interaction between the waves - beach - cliff system are performed on 3D point cloud data. Implications of results for coastal management will be discussed.

4. CONCLUSION

This study shows that geotechnical measures for stabilising cliffs are not effective in protecting cliffs from erosion. On the other hand, carefully designed artificial gravel beaches and their nourishment can reduce impact on sea-walls. This informed the numerical study of beach-cliff interaction. It was found that gravel beaches in front of cliffs can reduce some of impact on cliffs. Hence it is recommended that these beaches are maintained and possibly expanded in line with SLR to keep providing natural protection of cliffs.

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Coastbusters, innovative nature-based solutions for sustainable coastal management

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The use of Nature-based Solutions (NbS) [1] are currently seen as a more sustainable and cost-effective alternative to conventional coastal engineering protection. Additional ecosystems such as dunes, mangroves, seagrass meadows, tidal marshes, coral reefs and shellfish reefs generates a natural resilience to the impact of storms and are able to keep up with sea-level rise through long-term sediment trapping and organic matter accretion [2]. There is thus a growing trend to include regional NbS in estuarine and coastal project development as a way to protect certain areas against natural forces [3]. The implementation of the NbS-concept in the marine environment necessitates in-depth knowledge of the driving parameters and local natural processes. This expertise is needed to integrate the stochastic nature of ecosystem development with the traditional technical engineering of coastal management tools (i.e. design, installation, operational management and maintenance). The result is a ground-breaking new coastal management approach: a Nature-based engineering project which identifies coastal habitats and determines their viability, function and possible contribution to coastal protection [4].

The public-private Coastbusters consortium aims to study and translate desired coastal protection functionality into designs that make use of the capability of ecosystem engineering species. In other words, does ecosystem creation and Nature-based Solutions' technical design provide a more sustainable and cost-effective management approach to conventional coastal engineering? To answer this question, two Coastbusters research projects are executed [5], funded by the Flemish agency for Innovation and entrepreneurship (VLAIO) and co-funded by the industry (Dredging International part of the DEME-group, Jan de Nul group and Sioen industries).

In the first – proof-of-concept – Coastbusters project (2017-2020) three ecosystem engineering species were tested: (1) subtidal seaweeds (*Saccharina latissima*), (2) intertidal tube building sand mason worms (*Lanice conchilega*), and (3) subtidal blue mussels bivalves (*Mytilus edulis*). An initial assessment of the biogenic reef potential of each of the selected species revealed some basic insights on (tidal) boundary conditions, and into the efficiency of their facilitating structures.

The three Coastbusters Nature-based Solutions have been installed successfully in North Sea coastal waters using modified aquaculture techniques. (1) The flora reef deployment shows that not all coastal locations are suitable for every type of ecosystem engineer. Therefore, the consortium will deploy similar setups in a more suitable location. (2) There's a potential for Lanice aggregations at the low tide intertidal fringe, as was demonstrated both in the lab and during small scale field experiments. The next step is a scaled-up field pilot, including new types of materials to ensure a sustainable no- impact NbS. (3) The bivalve reef proved the most promising and became the Coastbusters NbS flagship. The sequel Coastbusters 2.0 project (2020-2023), concentrates on further in-depth investigation and optimization of the setup for one of ecosystem engineering species: the bivalve reef. The project focusses on developing new tunable marine biodegradable & sustainable (bio)materials and optimizing the reef setup design to facilitate the reef development in a more efficient, sustainable and resilient way. Two identical setups have been installed: a sheltered area and one more exposed. These are followed-up with advanced environmental monitoring techniques, researching the effects and boundary conditions of the reef, while developing the optimal sampling techniques and strategy.

Based on diving footage, Van Veen grabs and SPI camera photos, sea floor characterization was performed (figure 1). The video analyses revealed that mussel beds did not develop during the first summer, although some remaining small patches were detected at the sheltered reef site. Moreover, it was clearly observed that the sheltered reef site was dominated by large *L. conchilega* aggregations, along with other organisms such as mud anemones (*Sagartia* spp.), brittle stars (*Ophiura* spp.) and razor clam pits (*E. leyi*). This serves as a baseline for comparisons in the future years of the Coastbusters project.

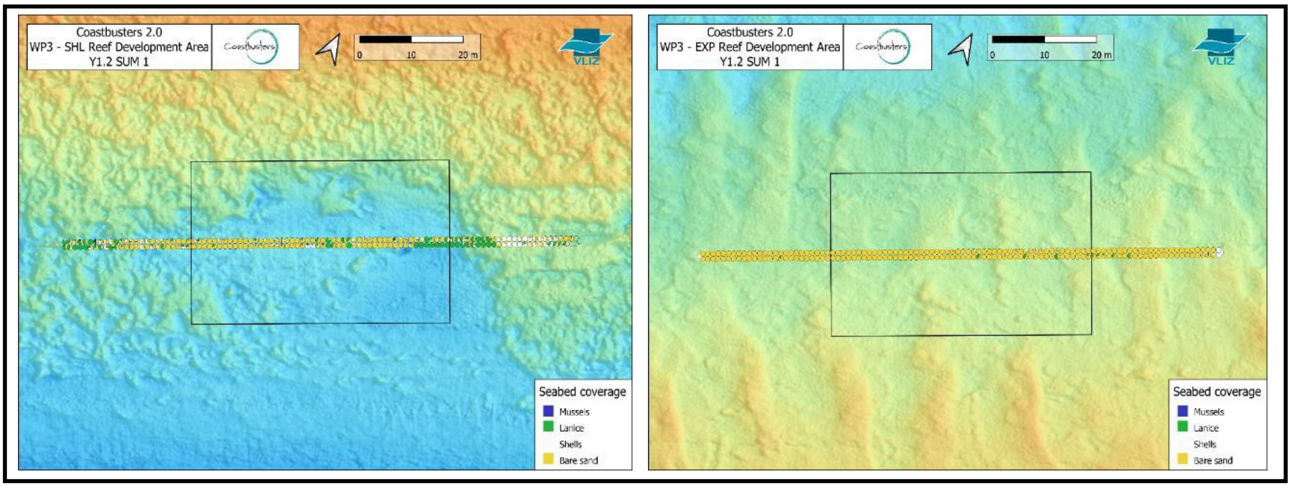

Figure 1: Sea floor characterisation of the Coastbusters site (sheltered (left) and exposed (right) reef development area) in Summer 2020, by video snapshots analysis with QGIS software, based on diving transects.

Furthermore, dynamic resilience and storm survivability are just a few topics to be managed and engineered in the forthcoming years during a further upscaling of the test setup. As a basis for this, innovative monitoring techniques are being developed and deployed (loggers, mooring system with ADCP and sonar, robotics, ...) to get more insight in the highly dynamic behaviour of the installed setups, to reveal the complex natural processes of growing mussels and biogenic reef development and to evaluate the survivability of the mussel reefs under changing conditions.

The pioneering work of Coastbusters clearly demonstrated that each chosen ecosystem engineer and the boundary conditions at deployment location are crucial to the success of NbS projects. Hence, Coastbusters advocates for an Ecosystem-Based Coastal Management solution, with a longer lifetime, higher resilience to changing environmental conditions and reduced maintenance cost compared to conventional coastal protection systems - heading for a more sustainable coastal management.

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Interactions between vegetation and aeolian sediment transport in coastal dune systems, a modelling approach

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1. INTRODUCTION

Coastal beach and dune systems are the most effective natural line of defense against coastal flooding in low elevation coastal zones, such as the Belgian Coast. Maintaining, enlarging and creating dunes have been suggested as one of the effective approaches considering nature based solutions in climate adaption projects (e.g. Vlaamse Regering, (2017)).

Restoration, maintenance or the creation of these systems require understanding of aeolian sediment transport. Understanding this process and estimating the amount of sediment transported by the wind will help in predicting beach and dune evolution on short (storm) and long (decadal) timescales and enable in designing better and more efficient maintenance, adaptation and dune design plans to ensure the resiliency of the dunes (Strypsteen *et al.*, 2019).

In this paper we assess the aeolian transport along the Belgian coast by first comparing two numerical models and thereafter the influence of vegetation.

2. METHODOLOGY AND RESULTS

The first step of this study is to compare the two most commonly used (open-source) numerical models for simulating Aeolian transport: Duna (Roelvink and Costas, 2019) and Aeolis (Hoonhout and Vries, 2016). Both models are designed to simulate aeolian sediment transport and subsequently model the evolution of dunes in situations where supply constraints are important, such as in coastal environment. The models calculate and update the distribution of cross-shore wind speed, velocity thresholds of sand movement, the interaction with vegetation and sediment transport.

In order to compare the models, a test profile that consists of a constant slope with a schematic dune at the top (top panels of Figure 1) was analyzed. For the comparison, the same boundary conditions and dune vegetation characteristics are applied to both models, simulating a constant wind speed of U_{10} = 13 m/s (i.e. 10 m above the refence level) over 3 hours. The vegetation is modelled using a vegetation factor that accounts for the height and density of vegetation, starting at +7 m TAW (i.e. the dune toe) with a low density factor for the pioneering species to a higher value (reaching up to 0.3) on the top and landward side of the dune for the intermediate vegetation species.

As shown in Figure 1 (bottom panels), differences emerge in the modelled sediment transport (mainly) on the seaward slope of the dune. As both models use the same sediment transport model, wind model and supply constraints the difference emerges from the difference in numerical schemes. The implicit upwind scheme in Duna results in a smoothened sediment transport distribution, whereas the implicit Euler backward scheme in Aeolis results in a more oscillating distribution. The analysis shows that both models can be used for calculating aeolian sediment transport, but since Aeolis can eventually be used in 2D situations we have decided to proceed with Aeolis.

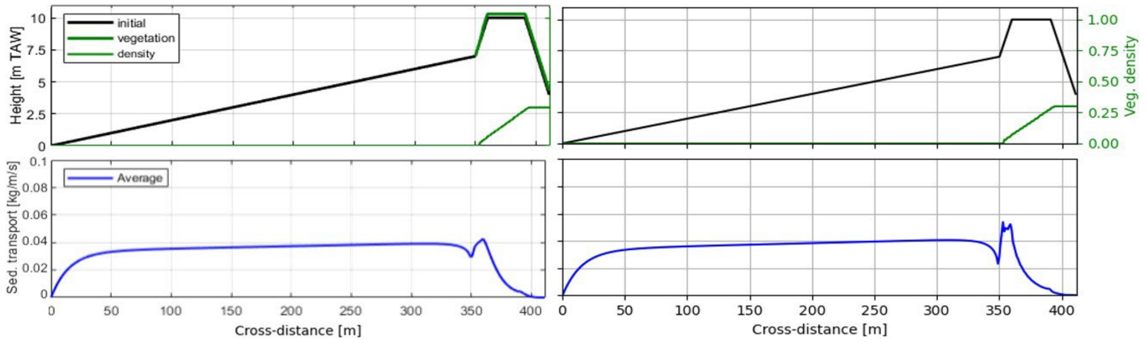

Figure 1: The comparison between Duna (left) and Aeolis (right). Cross-shore profile elevation and vegetation density (upper panels), modelled aeolian sediment transport (bottom panels)

For the second step of this study, we have assessed a representative profile for the Belgian coast and used Aeolis to simulate the effect of dune vegetation on the annual rate of aeolian sediment transport. To have a first estimate of the influence of vegetation on the annual sediment transport, the representative profile with typical vegetation coverage is compared with the same profile without vegetation (Figure 2). The estimated annual rate of aeolian transport is based on the probability of occurrence of different wind conditions (using Oostende wind measurement data from 2012 to 2019) and rainy days for which it is assumed that there is no aeolian sediment transport.

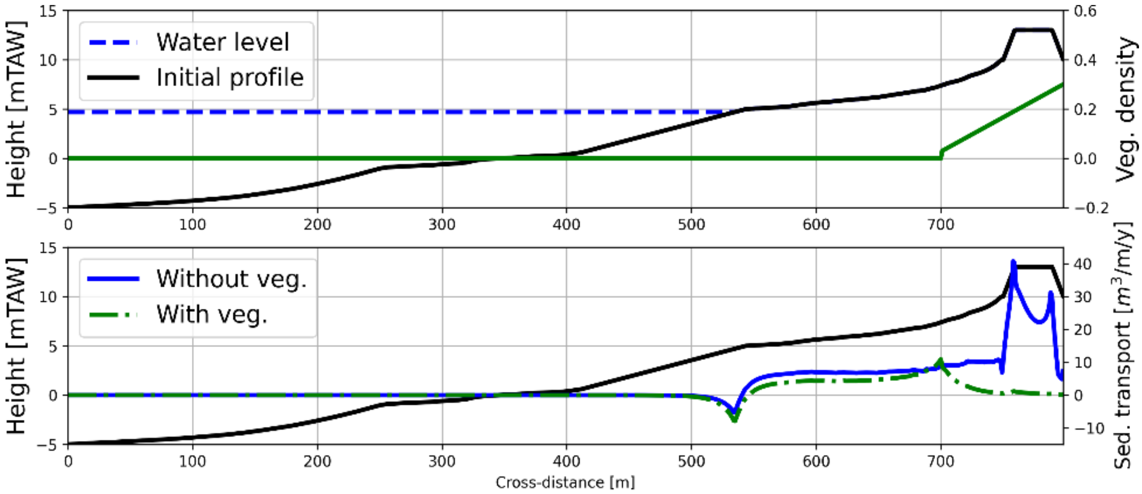

Figure 2: Annual aeolian sediment transport for a typical cross-shore profile along the Belgian coast for a scenario with vegetation and a scenario without vegetation

The most pronounced differences are found around the dune area. In the case of vegetation, transport rates decline rapidly in landward direction, whereas without vegetation transport rates reach their peak at the landward tip of the dune. Hence, it is clear that vegetation has a considerable impact on aeolian transport rates along the profile. The dampening effect and therewith the decline of transport rate towards the dune can imply sedimentation in the dune area. The scenario without vegetation shows on the other hand an increase of transport rates on at seaward slope of the dune, implying that this area is prone to erosion. Eventually it means that vegetation can keep the dunes in place and prevent dunes from migrating landward.

3. CONCLUSION

We observed that two commonly used numerical aeolian sediment transport models (i.e. Aeolis and Duna) are largely similar when looking at sediment transport rates along a schematized profile.

Moreover, when using Aeolis to simulate aeolian sediment transport along a coastal profile it was found that vegetation has a considerable impact on the transport rates. In the case of vegetation we observed a decrease in transport rates, potentially leading to sedimentation in the area of vegetation. For the case without vegetation an increase in aeolian sediment transport at the dune area was found, leading to potential erosion of the dune area.

4. ACKNOWLEDGEMENT

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A field-based model predicting early-stage dune development

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1. INTRODUCTION

An understanding of aeolian sediment transport processes and its interaction with vegetation (i.e., marram grass) is crucial for predicting the development and evolution of coastal sand dunes. More particularly, coastal managers are getting convinced of building with nature concepts, such as dunes in front of dikes, for coastal protection. For an optimal design of these artificial dunes, a fundamental knowledge of morphological changes during the early stages of dune development is required, which heavily relies on the interactions between plant density, distribution, height and morphology and sediment. Despite many decades of research, we remain unable to accurately predict aeolian sediment transport as input for dune growth and the subsequent dune development due to a lack of process knowledge and because of the inherent spatiotemporal complexities of aeolian sediment transport.

With this project, we aim to develop a field-based model predicting dune development in a unique engineered dune field in Oosteroever (Ostend), Belgium by means of dedicated field experiments focusing on sediment transport rates, wind characteristics, vegetation characteristics, and topographic changes (Figure 1). This dune field is planted with different plant densities (6, 9, and 15 plants/m²) and spatial configurations (regular, random, and clustered) providing a unique experimental setup to study dune growth in the early stage. The project offers the necessary link to an integrated coastal zone model describing long-term coastal evolution which can be used to assess the effects of climate change and human disturbance.

Figure 1: Location of the dune-in-front-of-a-dike in Oosteroever, Belgium (image taken on 11 March 2021). Within the engineered dune design marram grass is planted in different spatial distributions with three densities. The dune is surrounded by a fence to prevent beach passage.

2. SCIENTIFIC RESEARCH OBJECTIVES

In this research, the supply-limiting effects of shells, moisture, and vegetation on aeolian sediment transport rates are targeted as well as the improvement of estimating bed roughness, bed shear stress, threshold shear velocity and saturated transport rate. All this information is of fundamental interest to better predict dune development and evolution.

The specific objectives of this research are addressed in three work packages (see Figure 2):

(1) To quantify aeolian sediment transport rates as driving factor for dune development. Here, we obtain a large and high-quality field dataset on aeolian sediment transport processes by quantifying it through dedicated field experiments.
(2) To couple aeolian sediment transport to topographic changes within the dune field. Here, we conduct field experiments focusing on the interaction between aeolian sediment transport rates and vegetation. In this objective we do not focus on the biological processes of the vegetation.
(3) To setup and validate a field-based model predicting early-stage dune development (first 3 years). Here, the objective is to develop a field-based model starting from the process-based aeolian sediment transport model AeoLiS.

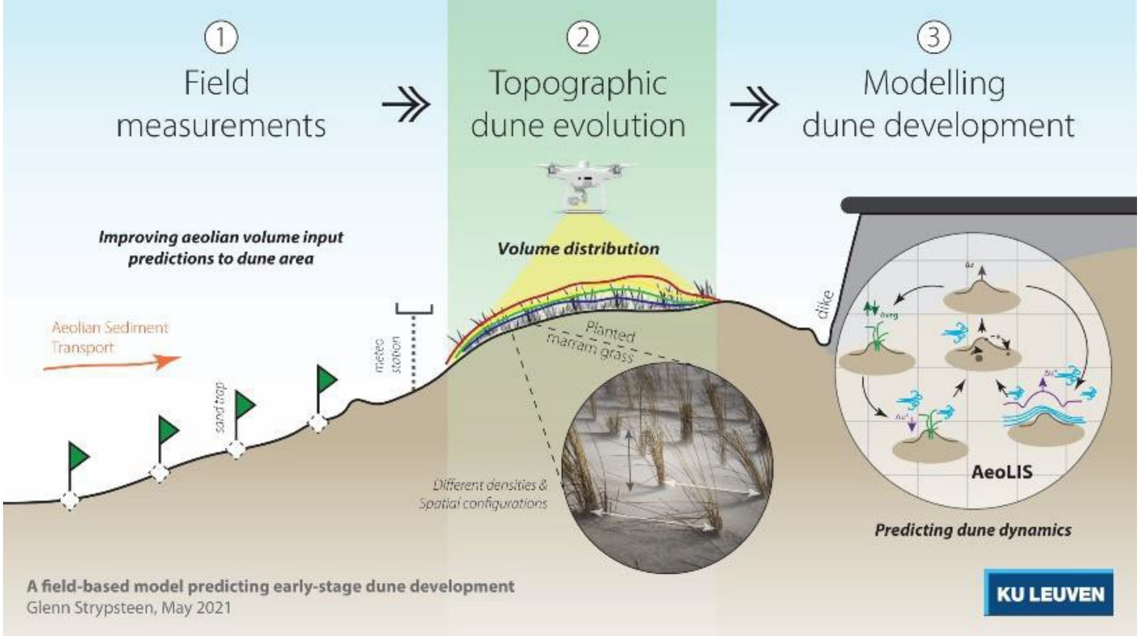

Figure 2: The research methodology consists of three work packages targeting three specific research objectives

3. RESEARCH METHODOLOGY

To reach the objectives of this project, we address the research hypothesis using a combination of field data, analysis and state-of-the-art aeolian models. The results from work package 1 and 2, focusing on aeolian sediment transport processes and its interaction with vegetation respectively, form the basis to setup and validate the field-based model predicting early-stage spatiotemporal dune development developed in work package 3. This project revolves around a unique data-rich study site. This site is a real-life case study of a dune-in-front-of-a-dike coastal defense system and gathered data will form the knowledge base needed for scientific analysis and exploration of new coastal managing strategies.

4. NOVELTY

The focus of this research on aeolian sediment transport and early-stage dune development addresses some unique knowledge gaps. So far, we are unable to predict dune development in an accurate manner and we have not a good understanding on the evolution of engineered dune fields. The high-quality data set on aeolian sediment transport and analytical relationships between vegetation and dune morphologic evolution that will be achieved in this project will encompass a necessary scientific step in the integrated understanding of coastal dune landscapes.

The approach to use a unique dune-in-front-of-a-dike using state-of-the-art measurement equipment and research methodologies is original and extraordinary. Moreover, the use of innovative tools for field measurements and numerical models to quantify dune development is exclusive.

5. ACKNOWLEDGEMENTS

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Coastal engineering benefits of sand nourishments at the shores of Walcheren (SW Netherlands)

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1. INTRODUCTION

Sand nourishments have become an important part of the solution for coastline retreat of sandy shores caused by erosion and sea level rise (Stronkhorst *et al.*, 2017). For decades sand nourishments have been executed throughout the coastline of peninsula Walcheren (SW Netherlands) with the goal of improving coastal safety, widening beaches for recreation and reducing the impact of coastal erosion on dune habitats and the landscape. While the coastal engineering benefits of sand nourishments have become clear, it remains challenging to understand the economic rationale of these nourishments compared to the alternative coastal defense strategy of dike construction and reinforcement. There is demand for direct comparisons between 'soft' *building with nature* methods like sand nourishments and traditional 'hard' coastal engineering methods such as dike construction. This demand is only heightened by the expectation of rising costs due to sea level rise.

2. METHOD

Data on beach and dune development at Walcheren were derived from the JARKUS database (https://publicwiki.deltares.nl/display/OET/Dataset+documentation+JarKus).

The database contains coastal elevations since 1965 for 150 cross sections corresponding with a beach-pole grid spaced 250 m apart. The MorphAn coastal modelling tool (Lodder & van Geer, 2012; Deltares, 2016) was applied to the coastline movement. First, the historical trends were determined in volume and position of individual coastal transects over the pre-sand nourishment period 1965-1978. Second, the estimated erosion or accretion trends were applied to the coastline (MKL) to model a 'what-if' scenario in which the sand nourishments had not occurred over the period 1979-2019. Two models were applied for coastline movement over the last 40 years using these historical trends: a linear trend model and natural log trend model. The modeled MKL was then compared with actual observed coastline MKL in 2019. Third, dune safety was assessed with weak points identified, using Dutch flood risk standards in MorphAn (Figure 1). Finally, a comparison was made between on the one hand the costs of 'hard' coastal defences at these weak points and on the other hand the costs of the conducted sand nourishments. Reference data on cost for the 'hard' coastal defences and sand nourishments originated from regional Waterboard Scheldestromen dike/dune reinforcement project Dishoek in 2008 and national agency Rijkswaterstaat Sand nourishment program in the period 2000-2020, respectively.

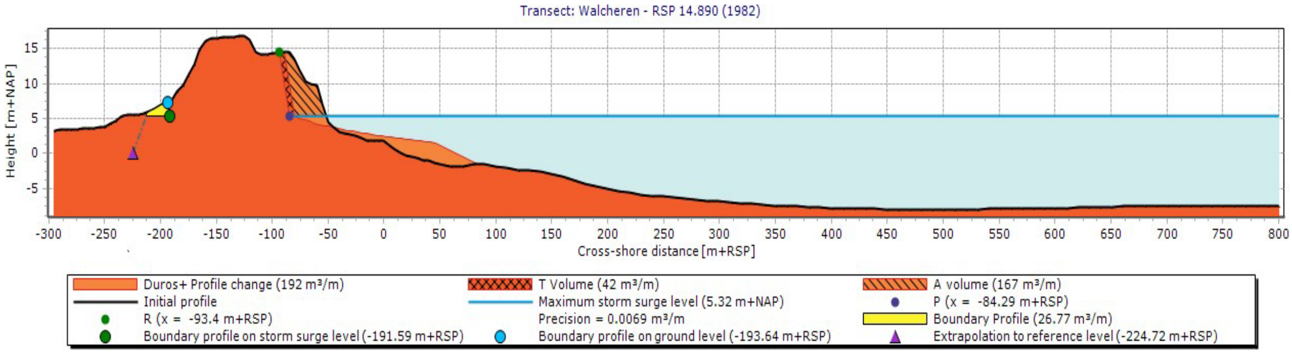

Figure 1: Dune safety assessment module in MorphAn. The hatched area indicates volume loss due to erosion

3. RESULTS AND DISCUSSION

Over the period 1979-2019 some 70 separate nourishments have been executed on the shores of Walcheren at a cumulative estimated cost of €180 million. Table 1 shows a comparison between the observed coastline in 2019 and the modeled coastline (linear and natural log model) in a scenario without sand nourishments. The sand nourishments resulted in coastal advance along 70% of the 33 km long coastline with an average gain of 48-66 m. This indicates that not only are sand nourishments preventing erosion but are meaningfully expanding the dunes and beaches.

Actual MKL (2019) Compared to Modelled Coastline Position (2019)					
Status	Number	Coastline Movement (m)			
		Linear Model		Natural Log Model	
		Average	Standard Dev.	Average	Standard Dev.
Advanced	107	66.2	67.4	47.9	47.2
Retreated	28	-12.2	71.1	-5.4	46.3
Unable to Determine	15	-0.5	N/A	0.6	N/A

Table 1: Comparison of actual coastline position (2019) to modelled position

The model simulations suggest that in the absence of sand nourishments over 40 years, volume trends result in a decrease in dune safety and a growing length of the coastline would require dike reinforcement. Given a unit price of approx. € 13 million per km dike reinforcement, the reinforcement costs are estimated at € 132-155 million (Table 2). The additional cost of coastal maintenance without sand nourishments of € 0.78 million/y was added to the reinforcement costs over the model period. This total compares to an expenditure on sand nourishments.

Total Costs w/o Sand Nourishments by 2019		
	Linear Model (millions)	Natural Log Model (millions)
Reinforcement Costs	€ 155	€ 132
Coastal Maintenance Costs	€ 31	€ 31
Total	€ 186	€ 163

Table 2: Alternative coastal defence costs in a scenario without sand nourishments

In conclusion, the overall value of the sand nourishments looks to be very positive as they advanced most of the coastline substantially, reduced reactive maintenance and increased beach area for recreation.

4. ACKNOWLEDGEMENTS

This study was funded as part of the C-SCAPE project aiming to develop sandy strategies for sustainable coastal climate change adaptation (NWO-SIA project number 17595).

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The importance of the spatial configuration of marram grass (*Calamagrostis arenaria*) on dune functioning and biodiversity

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Dunes are beneficial to humans because they provide ample ecosystem functions such as recreation and flood protection (Van der Biest *et al.* 2017). Marram grass (*Calamagrostis arenaria*) is the keystone-species in dune development because of its effective sand fixation. This enables dunes to grow, counteracting sea-level rise due to climate change, and furthermore regenerate e.g. after a storm. The spatial configuration of marram grass influences its sand fixation capabilities (Reijers *et al.* 2019) and thus also the self-regenerating capabilities of the dune as a whole. Dunes formed by this keystone species are important to biodiversity and are additionally protected by the habitat directive (Bonte *et al.* 2021). Whether the spatial distribution of this grass impact dune development and its functioning, and whether it aligns with optimal biodiversity targets is unknown.

We quantified how (the strength of) the relation between the spatial configuration of marram grass is correlated to its self-regenerating capabilities by modelling, and tested whether biodiversity patterns followed the same direction. Our model includes feedbacks between vegetation development and dune growth and is therefore one of the first that allows testing the joint impact of multiple boundary conditions on the dynamics of dune and vegetation growth. We present the first results from this model analyses. We additionally investigated the link between the spatial configuration of marram grass and the biodiversity by the statistical analyses of biodiversity patterns of invertebrates associated with marram grass tussocks and its spatial configuration along the coast of the Netherlands, Belgium, France.

We show that some, but not all biodiversity components aligns with putative flood protection services and provide an outlook for further research and applications.

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Which ecosystem services can a dune-in-front-of-a-dike deliver?

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1. INTRODUCTION

Ecosystem services (ES) – nature's benefits to people – are produced by biotic and abiotic processes, habitats, species and interactions between them. One of the main arguments for choosing soft coastal defense measures are their perceived benefits in terms of ES. Soft defense measures disturb natural processes much less than hard engineering structures and provide habitat, creating opportunities for ES. Nature-based solutions take one step further by making use of the natural processes to safeguard the supply of ES also on the longer term. Nature-based solutions are usually more expensive to build than hard engineering infrastructure and traditional beach nourishments. Only if the added benefits in comparison to its alternatives can be made explicit, nature-based solutions will be in for the long term. This presentation presents the results of an analysis of different ES of a dune-in-front-of-a-dike in the Netherlands and critically discusses potential benefits of nature-based solutions in relation to natural dynamics.

2. METHOD

The results of an ES quantification of one nature-based solution and one natural system are presented: a dune-in-front-of-a-dike combined with tidal marsh development on the island of Texel in the Netherlands (constructed in 2019) and a dynamic dune system with no obstruction of sand transport in De Panne (hypothetical scenario). Each case is compared to an alternative situation, i.e. restoration of the traditional asphalt and concrete dyke and situation today with presence of a dyke in front of the dune obstructing the natural process of sand transport (respectively).

The approach for quantifying ES was similar for each study and consisted of:

1) Identification of changes in habitat (using NATURA2000 habitat classification and land use);
2) Biophysical quantification of ES for each habitat type (e.g. rates of nutrient cycling). This step is based either on local data or else values found in literature;
3) Each ES was attributed a monetary value using values from literature (local + benefit transfer);
4) The sum of ES (expressed in € per year) was made for each case study and compared to the ES of its alternative.

For the dune-in-front-of-a-dike an additional comparison is made including also the costs for construction and maintenance, allowing for a cost-benefit analysis.

3. RESULTS

The changes in ES of each case compared to its alternative are presented. The results show that the dune-in-front-of-a-dike solution generates more economic benefits in terms of ES than its traditional coastal safety counterpart, and that the initially higher costs for construction and maintenance are compensated by these yearly produced socio-economic benefits. For the comparison between a natural, dynamic dune system and a system with obstruction of sand transport, it was revealed that the dynamic system is capable of providing more ES than the 'fixed' dune system. The additional ES benefits are on account of recreation and coastal safety maintenance on the longer term (growth of dune with sea level rise). Recreational value was higher because people appreciated the typical dynamic dune landscape with patches of marram grass and bare sand and the presence of biodiverse dune slacks more than habitats of older successional stages (e.g. dune scrub) as dominant in the 'fixed' dune system.

4. DISCUSSION

The results show the potential value of nature-based solutions to contribute to human well-being and to provide economic benefits for different stakeholders. However, the study on dune dynamics shows the crucial role of certain ecological processes in the production of ES, and the potential loss of ES if these processes would not be present.

ES assessments are often performed for a given state in which the ecosystem is assumed to evolve with time. This assumes that the essential natural processes that are required to achieve that evolution are actually occurring. Not taking into account these processes may lead to an overestimation of the capacity of the socio-economic value of nature-based solutions. This may have important consequences such as an undermining of the growing support base for nature-based solutions and non-sustainable design of nature-based solutions. A challenge lies in taking these processes into account in ES assessments, and this is especially important in highly dynamic systems such as the coastal zone.

Ecosystem Service	Total Effect
Agricultural production	🟩 +
Fish production	🟩 +
Fresh water production	
Climate regulation	🟩 +
Water quality regulation	🟩 +
Salinization prevention	
Air quality regulation	
Flood protection	🟩 +
Erosion protection	🟩 +
Sedimentation regulation	
Recreation	🟩 +
Heritage	🟥
Cognitive development	🟩 +

Figure 1: Expected ES impacts at the dune-in-front-of-a-dike at Texel (Fordeyn et al. 2019)

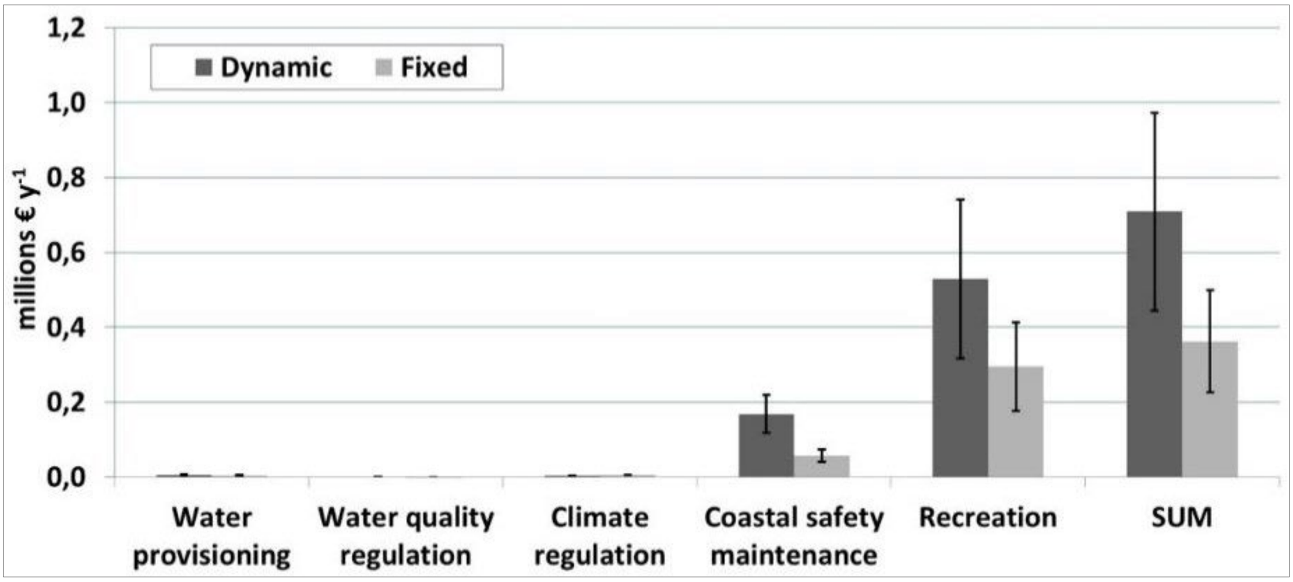

Figure 2: ES in frontal dunes at De Panne, for a dynamic dune system with continuous sand supply and a fixed dune system with obstruction of sand supply (Van der Biest et al. 2017)

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Dune erosion during storm surges: The realdune/reflex experiment at the sand engine

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1. INTRODUCTION

Storm conditions can lead to excessive dune erosion with potential floods as a consequence. Barrier islands and low-lying countries protected by dunes are especially vulnerable to dune erosion. To properly assess the risks these areas face, a clear understanding of the physical processes during dune erosion is required.

An international field experiment was conducted to study dune erosion during storm surges from November 6 2021 until January 6 2022. on the Sand Engine. During the *Realdune/Reflex* experiment, two prototype un-vegetated dunes of 5.5 m high and 150 m long were built just above the high waterline. Due to a different shoreline orientation and nearshore bathymetry, these dunes eroded differently during moderate storm conditions. 3 storms were captured during the campaign.

This abstract presents preliminary results of morphodynamic change during these 3 storms, by means of profile changes and erosion volumes.

Figure 1: Aerial impression of the field site at the Sand Engine, Kijkduin, the Netherlands

2. FIELD LAYOUT AND STORM CHARACTERISTICS

The first storm occurred on November 7 2021, during the deployment phase of the campaign, resulting in fewer instruments measuring on site. The second storm occurred on December 2nd 2021, and the third storm on January 5th 2022. The latter 2 storms were monitored closely with instruments placed along the central cross section of both dunes (Figure 2). Pressure sensors and velocimeters allowed an accurate quantification of the development of the significant wave height, wave period, and wave direction. Regarding surge levels, the storm of January 5th was most significant. The storm of November 7th came second, and December 2nd third (Table 1).

Storm	$\eta\eta$max $HHHHHH$ (mm)	$\eta\eta$max $SSSSHHSS$ (mm)	HH_{ss},max (mm)	TT_{pp},max (ss)	$TTh0$ $(\circ NN)$
07-11-2021 16:20:00	2.36	2.24	3.04	8.3	321
02-12-2021 00:40:00	2.12	2.03	4.27	9.5	335
05-01-2022 16:20:00	2.51	2.28	4.03	9.6	303

Table 1: Storm conditions of the 3 captured storms. The surge level was measured at 2 nearby wave station (HvH - Hoek van Holland station and SCHE – Scheveningen). The water levels are given with respect to NAP. The wave conditions were recorded at the offshore Europlatform station.

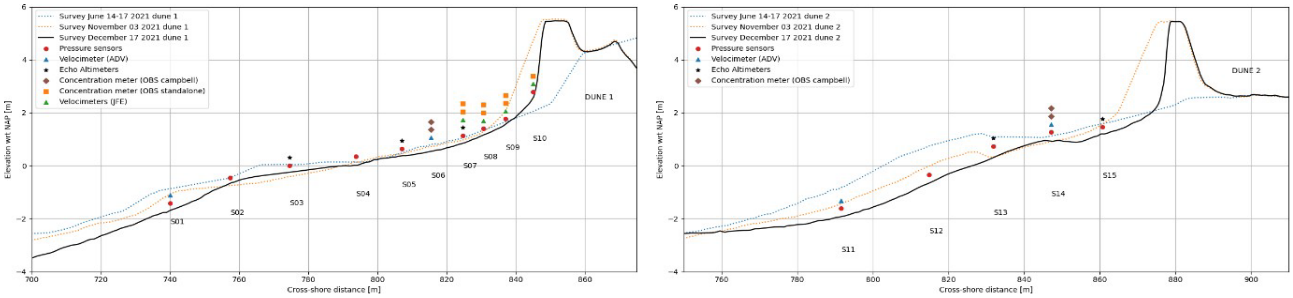

Figure 2: Cross section of both dunes including instruments

3. EROSION QUANTITIES

Before and after each storm, walking surveys were performed for accurate pre- and post- storm profiles (Figure 3). The January storm resulted in significant overwash and, in the end, inundation at dune 2. Using the pre- and post-storm surveys, erosion quantities can be computed for each individual storm (Table 2).

Storm	Erosion dune 1 (m^3 /m)	Erosion dune 2 (m^3 /m)
November 7 2021	7.70	8.52
December 2 2021	6.87	13.35
January 5 2022	8.47	14.09

Table 3: Erosion quantities for dunes 1 and 2 for each of the 3 storms. Erosion was defined as the difference between the pre- and post-storm profile above the 2.0 depth contour.

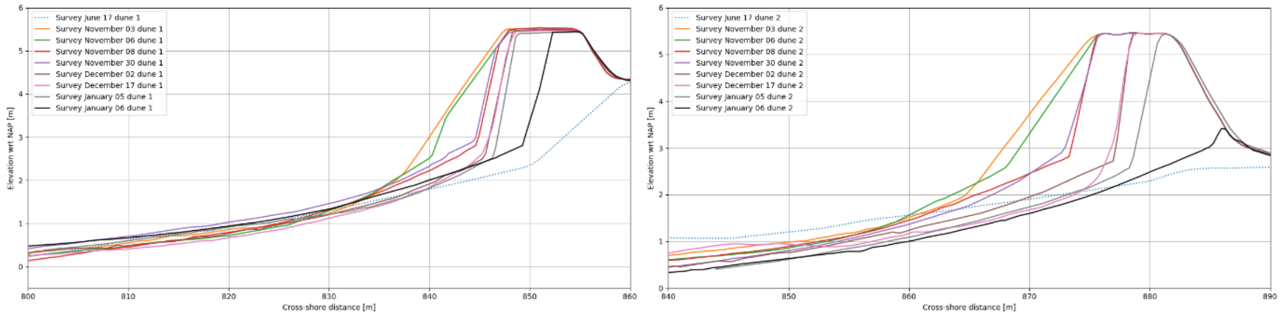

Figure 3: Cross sectional profiles of Dunes 1 and 2 before and after storms

4. CONCLUSION

Initial results show the effect of 3 storms on artificial dunes at the sand engine. Erosion occurred in the collision, overwash, and inundation regime. The storm of 5 January was most significant with respect to surge levels, and also resulted in the greatest amount of erosion at both dunes. Next steps will focus on relating erosion quantities to local wave hydrodynamics.

Shoreface connected ridges as natural sand engines for coastline preservation

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1. INTRODUCTION

A sand engine is usually considered as a large sand nourishment that indirectly feeds the adjacent coastal area on a time scale of decades through the action of waves, currents and winds.

However, sand engines can also be present from natural morphodynamics, namely in the situation where a coastal bank attaches to the shoreline and supplies the neighbouring beaches with sand. In this abstract we explain how morphological research has led us to this hypothesis that shoreface connected ridges are/were natural sand engines for the Belgian coast.

2. SHOREFACE CONNECTED RIDGES AT THE BELGIAN COAST

Shoreface connected ridges are/were present at 3 locations along the Belgian coast (Figure 1).

Figure 1: Correspondance between the location of wide dune areas and the location of (former) shoreface connected ridges along the Belgian coast

2.1 WEST COAST

A natural sand engine is present at Koksijde where the Trapegeer-Broersbank complex attaches to the coastline and feeds part of the Belgian west coast. Empirical evidence is found in the form of the coastline, in particular a local seaward protrusion between Koksijde-Bad and Oostduinkerke-Bad amounting to several hundred metres [Verwaest *et al.*, 2020]. Also modeling with Scaldis Kust numerical model reveals a mechanism of net sand transport via the bank/gully system across the depth of closure towards the active zone [Verwaest *et al.*, 2022]. The size of the young dunes on the west coast can be explained by a continuous feeding from the sea in this area during the last 1000 years. In order of magnitude, 120,000 m^3/year during 1000 year would explain the origin of the dune belt extending 12 km alongshore, 2 km in width and 5 m in height. This process is still active today [Houthuys *et al.*, 2021].

2.2 CENTRAL COAST

Before 1900, the Stroombank in Bredene-De Haan was attached to the coastline (Figure 2). At that time, beaches in that area were fed by a transport of sand along the crest of the Stroombank. This also explains the existence of a relatively wide young dune belt in this zone, because this configuration lasted for several centuries. When a new, dredged channel to the port of Ostend cut through the Stroombank around 1900, the transport path was interrupted and the natural feeding of these beaches was cut off. A rough estimation of the accretion since about 1000 AD is given by an average coastal length of 10 km (Bredene to Wenduine), a young dune width of 500 m with an average terrain rise of 5 m. This results in a natural supply of 25,000,000 m³ during 1000 years, or 25,000 m³ per year [Houthuys *et al.*, 2021].

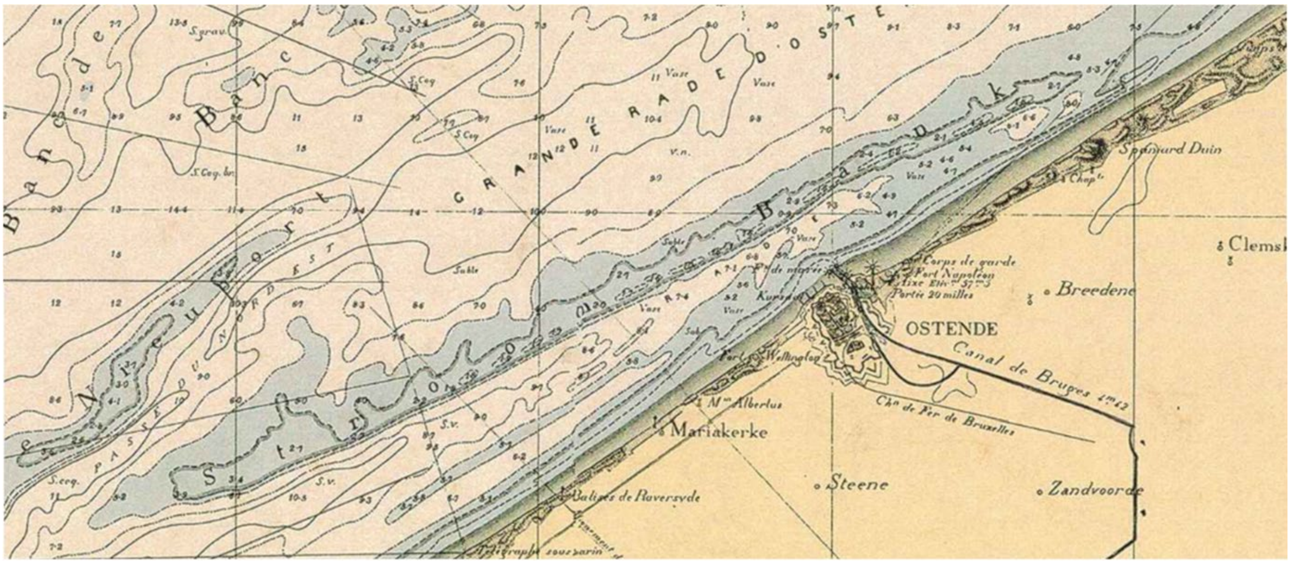

Figure 2: Stroombank attached to the coast in Bredene-De Haan in the 19th century [Stessels, 1866]

Nowadays still a remnant of the attachment of the Stroombank to the coastline is present. It might be possible to restore the mechanism of natural feeding by a large nourishment on the sea bottom in that area. Material available from infrastructure works or maintenance dredging might be used if sediment characteristics allow. The latter might be realized by choosing an optimal dumping location of the sand that is continuously dredged in the fairway to Oostende to maintain this access channel to the port of Oostende.

2.3. EAST COAST

A third shoreface connected ridge was located on the east coast. On old maps this bank is called Hard Zand. On more recent maps, the Wenduinebank-Paardemarkt complex is visible, which attaches to the coastline near Cadzand. The relatively wide strip of young dunes at Knokke-Heist can be explained by the supply of sand via this connection to the sea bed in the period before 1900. Afterwards, the expansion of the port of Zeebrugge into the sea thoroughly changed the sand circulation in this area. A rough estimation of the accretion since about 1000 AD is given by an average coastal length of 5 km (Heist to Het Zoute), an average young dune width of 1250 m with an average terrain rise of 5 m. This results in a natural supply of 31,250,000 m³ during 1000 years, or 31,250 m³ per year [Houthuys *et al.*, 2021].

3. ACKNOWLEDGEMENTS

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The influence of dune pavilions on longer term dune development

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1. INTRODUCTION

The European beach-dune systems are under increasing pressure due to urbanization, beach tourism and the effects of climate change like rising sea level and increased storm intensity. Building with nature solutions (Stive *et al.*, 2013) are advocated as an effective and adaptable approach to protect sandy coasts in the future. This approach however interacts with the increased human use of the beaches-which can have an adverse impact on the efficiency of the building with nature approach. Especially permanent structures influence the natural sand transport dynamics from the beach to the dunes and can have long lasting effects on dune development.

To obtain more insight into the influence of buildings on longer term dune development a 3-months 'Scanex 2020' field campaign was conducted (Poppema *et al.*, 2021) on Noordwijk beach (52.24 °N, 4.42 °E) to monitor the natural sand development around two sea containers (see Figure 1). In addition on a larger scale the dune development around a permanent beach pavilion was monitored for two years (from August 2019 till August 2021) within the CoastScan project (Vos *et al.*, 2017) with a permanent laser scanner.

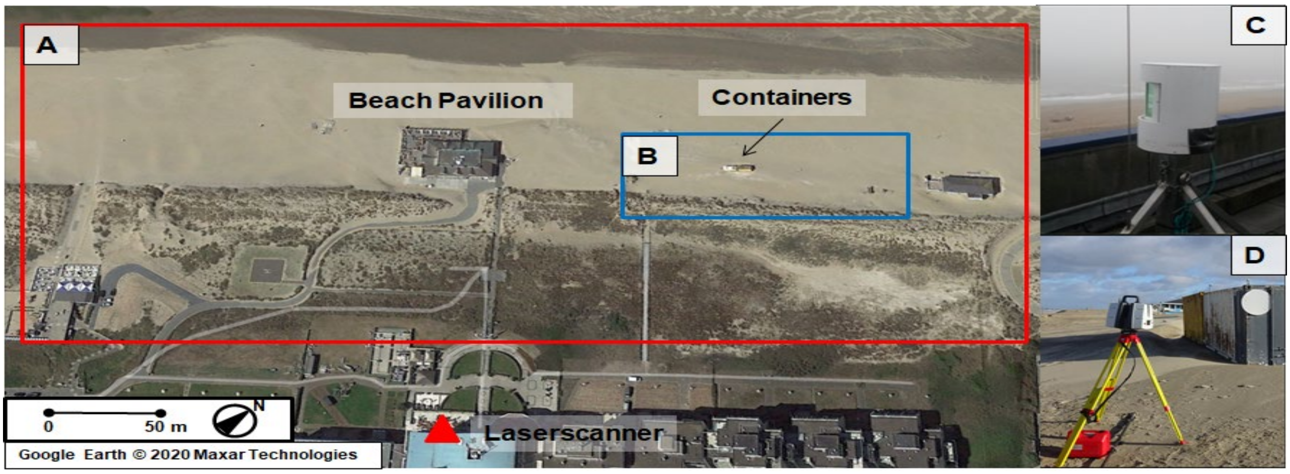

Figure 1: Overview of the Noordwijk study site with (A) area covered by the permanent laser scanner (C and red triangle in A) within the CoastScan project and (B) the study site with containers covered with a mobile laser scanner (D) within the 'Scanex 2020' field campaign.

2. RESULTS

Three winter storms with wind speeds up to 39m/s mostly from the South-West, created a typical horse shoe form (Poppema *et al.*, 2021) in the beach morphology around the containers with height difference up to 50 cm (see black lines in figure 2 with the container indicated with the red square). The longer term effect on the dunes is however more difficult to detect as no clear growth areas (see dashed line in figure 2A) can be distinguished in the three months Scanex 2020 field campaign.

The longer term analysis from the CoastScan data shows a more clear pattern in the dune growth (along the black in figure 2b) due to the beach pavilion (indicated with the red square). Figure 2c shows the dune height in aug 2019 and 2021 and clearly shows a dune top growth south of the beach pavilion with absent growth north of the pavilion.

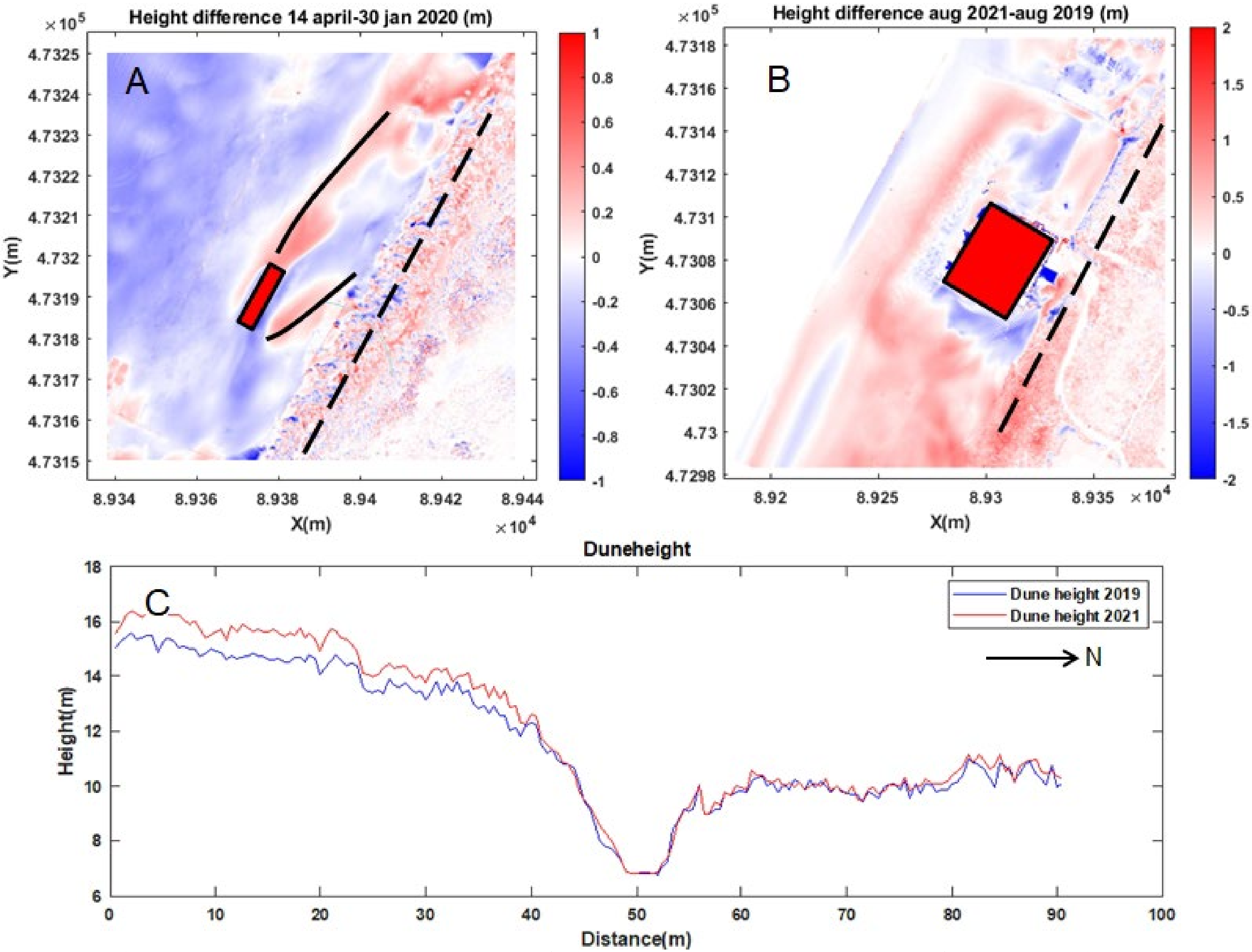

Figure 2: A) Measured beach height difference (m) at the 'Scanex 2020' field site (see Figure 1) between April and January 2020 with the black line indicating the horse shoe effect of the container (red square) on the beach morphology. B) Measured beach height difference between August 2021 and August 2019 (m) around the beach pavilion (red square) with the dune height along the dashed black line displayed in panel C.

3. ACKNOWLEDGEMENTS

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