DuneFront

Deliverable 7.1

June 2024

Comprehensive investigation of existing designs of the DuneFront Demonstrators

Deliverable 7.1 (D7.1)

Deliverable information

Title	Comprehensive investigation of existing designs of the DuneFront Demonstrators
Deliverable number	D7.1
WP number	7
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Type	Report
Dissemination level	Public
How to cite	Adeli A., Gruwez V., Troch P., Hofland B., Tissier M., Bonte D. (2024). Comprehensive investigation of existing designs of the DuneFront Demonstrators, Version 1.0, DuneFront Project Deliverable 7.1, Ghent University.

Versioning and contribution history

Version	Date	Authors (Institution)	Notes
Version 0.1	25/03/2024	Afshar Adeli (UGent-E), Vincent Gruwez (UGent-E)	Draft
Version 0.2	01/06/2024	Afshar Adeli (UGent-E), Vincent Gruwez (UGent-E), Peter Troch (UGent-E)	Preliminary Report
Version 0.3	07/06/2024	Afshar Adeli (UGent-E), Vincent Gruwez (UGent-E), Peter Troch (UGent-E), Bas Hofland (TU Delft), Marion Tissier (TU Delft)	Version to be checked and approved by DuneFront consortium
Version 1.0	27/06/2024	Afshar Adeli (UGent-E), Vincent Gruwez (UGent-E), Peter Troch (UGent-E), Bas Hofland (TU Delft), Marion Tissier (TU Delft), Dries Bonte (UGent-B)	Final version approved by all Beneficiaries

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Cover page

This report is the first deliverable of work package 7 (D7.1 Demonstrator Design Methodologies) in the DuneFront project. DuneFront focuses on better understanding dune-dike hybrid Nature-based Solutions (DD-hybrid NbS) to create sustainable, inclusive, and visually appealing coastal management infrastructure. These innovative solutions aim to integrate biodiversity while addressing significant socio-economic challenges along Europe's densely populated coasts. By studying existing hybrid NbS, this report lays the groundwork for better understanding the design aspects of these systems.

The primary objective of this report is to evaluate existing Demonstrators of DD-hybrid NbS across four European sea or ocean basins—Mediterranean, Atlantic, North Sea, and Baltic—documenting and comparing their designs. This evaluation involves reviewing, cataloguing, and comparing design methods from selected Demonstrators, aiming to determine the functionality and effectiveness of these hybrid systems in coastal protection.

The DuneFront project considers 12 Demonstrators across six countries—Portugal, France, Belgium, the Netherlands, Germany, and Sweden—with diverse functionalities and environmental conditions. From these 12 Demonstrators, seven Demonstrators were selected (based on the dike contributing to the coastal protection functioning of the DD-hybrid NbS) for detailed analysis: Dunkerque, Sainte-Marie La Mer, Living Lab Raversijde, Middelkerke, Katwijk, Sankt Peter-Ording, and Ystad. This report provides a comprehensive overview of their design methodologies, stability measures, and monitoring and maintenance practices.

The analysis reveals a range of methodologies, from basic, non-specific approaches to highly detailed and adaptive methods. Additionally, the report describes in detail the varied methodologies used for modelling, design, and dike stability. These differences emphasize the importance of selecting appropriate models and methodologies based on local conditions. Monitoring and maintenance methods range from comprehensive plans with advanced technologies like DTMs and LIDAR, to simpler surveys and beach nourishment.

A critical knowledge gap identified is the ad-hoc nature or absence of methodologies for designing dune and dike systems simultaneously. Addressing questions derived from this knowledge gap regarding dune erosion, adaptive measures, probabilistic design aspects, spatial relationships between dunes and dikes, and effects of setup and infragravity waves will transform these gaps into actionable knowledge. These insights will contribute significantly to future development and optimization of DD-Hybrid NbS systems.

In general, this report provides a comprehensive overview of the varied methodologies employed in designing of selected DD-Hybrid NbS, identifying key knowledge gaps and setting a foundation for future research and development.

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List of abbreviations

Abbreviation	Explanation
AMSL	Above Mean Sea Level
BE	Belgium
Brgm	Bureau de Recherche Géologique et Minièreme
CCMA	Communauté de Communes Médoc Atlantic
CUD	Communauté Urbaine de Dunkerque
DD	Dune-Dike
DD-Hybrid	Dune Dike-Hybrid
DE	Germany
DHI	Danish Hydraulic Institute
DHSV	Dike- and main tide gate association
DiD	Dike in Dune
DiFoD	Dune in Front of Dike
DREAL	French National authorities
DTMs	Digital Terrain Models
EVA	Extreme Value Analysis
FORM	First Order Reliability Method
FR	France
GDP	Gross Domestic Produc
GIS	Geographic Information System
GNSS	Global Navigation Satellite system
GPMD	Grand Port Maritime de Dunkerque
HD	Hydrodynamic
Hm0	Significant Wave Height
IG waves	Infragravity Waves
IGN69	Institut Géographique National 1969
LAT	Latitude
LBO1	The lifetime of the dike-in-dune project (in Netherlands)
LIDAR	Light Detection And Ranging
LKN.SH	Ocean Protection of Schleswig-Holstein
LON	Longitude
M7.1	Milestone 7.1
NAP	Normaal Amsterdams Peil (Normal Amsterdam Level), approximately equal to MSL
NbS	Natural-based Solution
NL	The Netherlands
NLPV	Wadden Sea national park of Schleswig-Holstein
NLSWE	nonlinear shallow water equations

OBSCAT	Observatoire de la Côte Catalane
OCNA	regional coastal laboratory
ONF	Office National des Forêts
PMM	Perpignan Mediterranée Métropole
PT	Portugal
RC	Réchauffement Climatique (Global Warming)
RP	Return Period
RSP	Rijkswaterstaat Peil
SARCC	Sustainable And Resilient Coastal Cities
SE	Sweden
SLR	Sea Level Rise
SPO	Sankt Peter Ording
ST	Sand Transport
SW	Sperctal Wave
TAW	Tweede Algemene Waterpassing, approximately equal to a low tide water level
T_{m01}	Mean Wave Period
T_{m02}	Mean Zero-Crossing Period
$T_{m-1,0}$	Spectral Mean Wave Period
T_p	Peak Wave Period
WP7	Work Package 7

1. Introduction

1.1 General

The primary objective of the DuneFront project is to optimize dune-dike hybrid Nature-based Solutions (NbS) as a new generation of sustainable, inclusive, and visually pleasing blue-grey coastal management infrastructure. This approach aims to integrate biodiversity into addressing one of the most significant socio-economic challenges along European coasts. The DuneFront concept is shown in one graphical abstract in Figure 1. These coasts are among the world's most densely populated, with natural sand dune barriers often replaced by traditional hard coastal protection structures.

Without necessary adaptive measures, the number of people exposed to floods is expected to rise dramatically, from 15,000 to 187 million worldwide by the end of the 21st century (Lomborg, 2020). Similarly, total economic costs could increase from 0.008% to 5.3% of GDP. In Europe, substantial flood risks from sea-level rise are anticipated along the coasts of the North Sea, the Baltic Sea, and the Atlantic Ocean, while climate extremes are expected to impact the Mediterranean coasts of southern Europe (Vousdoukas et al., 2017).

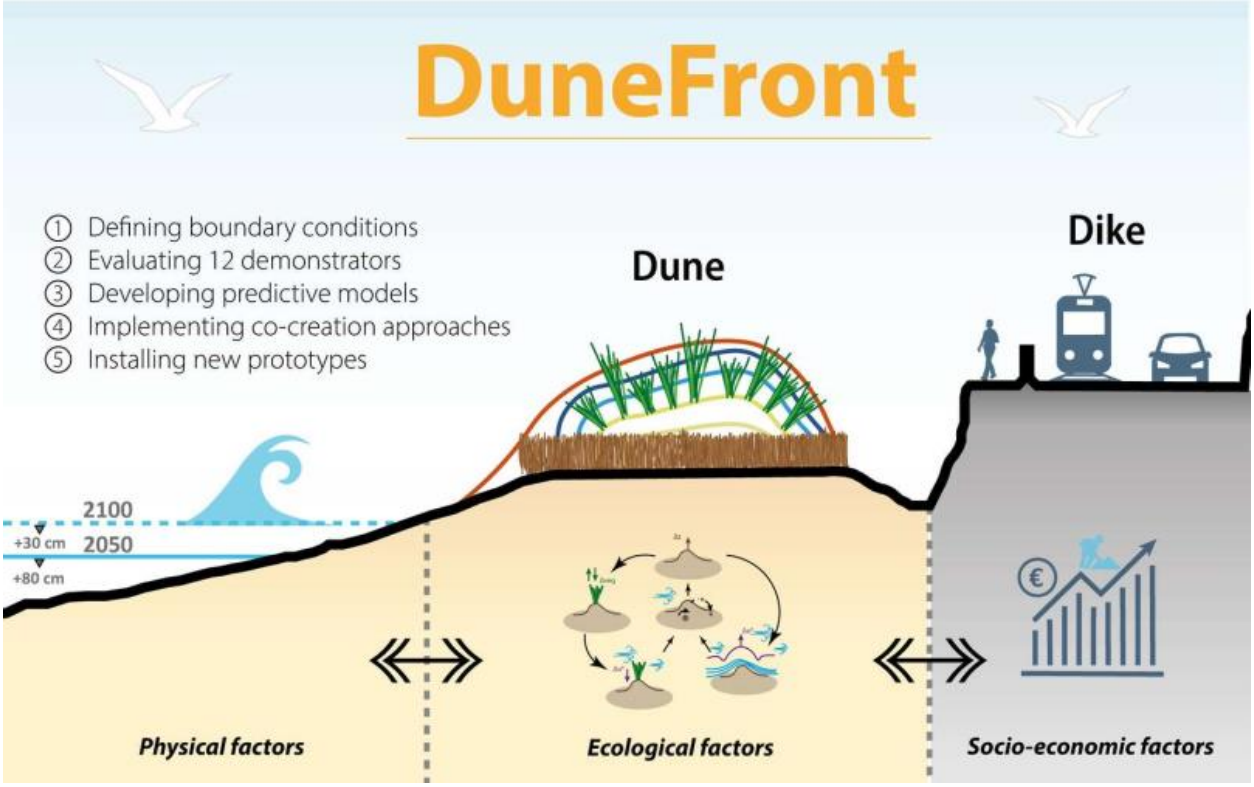


Figure 1 - DuneFront concept in one graphical abstract

Future coastal management must go beyond the current fixed and non-adaptive flood protection setups. Hybrid NbS, which integrate static hard infrastructure with dynamic aeolian and vegetated sediments, are being developed along many urbanized areas of European sandy coasts, though on a small scale. The integration of dikes and dunes for coastal protection, known as dune-dike hybrid Nature-based Solutions (DD-hybrid NbS), exemplifies this approach. Such blue-grey infrastructure offers advantages for coastal safety and protection that neither hard (dikes, seawalls) nor soft (beach nourishments, existing dunes) infrastructure can achieve alone. A key aspect of their adaptability to sea-level rise is the integration of a hard safety line (dikes) with resilient, biodiverse dune systems that function only when both physical and biological conditions are met. This blue-grey infrastructure will provide an integrated, multidisciplinary coastal management system.

1.2 Overview of work package 7 (WP7 –Demonstrator Design)

The primary challenge of the DuneFront project is to identify and understand the biological, physical, and socio-economic boundary conditions and their interactions. This understanding will help tailor specific marine and coastal DD-hybrid NbS to protect human assets, activities, and well-being while enriching coastal biodiversity. This approach surpasses traditional single coastal flood protection methods. DuneFront aims to achieve this by translating evidence from 12 Demonstrators along vulnerable European coasts into new roadmaps for DD-hybrid NbS design and installation.

To achieve optimal designs for biodiversity, coastal safety, and cost-efficiency, DuneFront will evaluate Demonstrators across four sea or ocean basins: the Mediterranean, Atlantic, North Sea, and Baltic. This evaluation involves analyzing both existing and new data for each Demonstrator. Key aspects of this analysis include dimensions and design, sediment dynamics (erosion/accretion dynamics), coastal protection functionality, vegetation development, and the evolution of habitats, invasive species, and ecological integrity. The connection between different work packages of the project is illustrated in Figure 2.

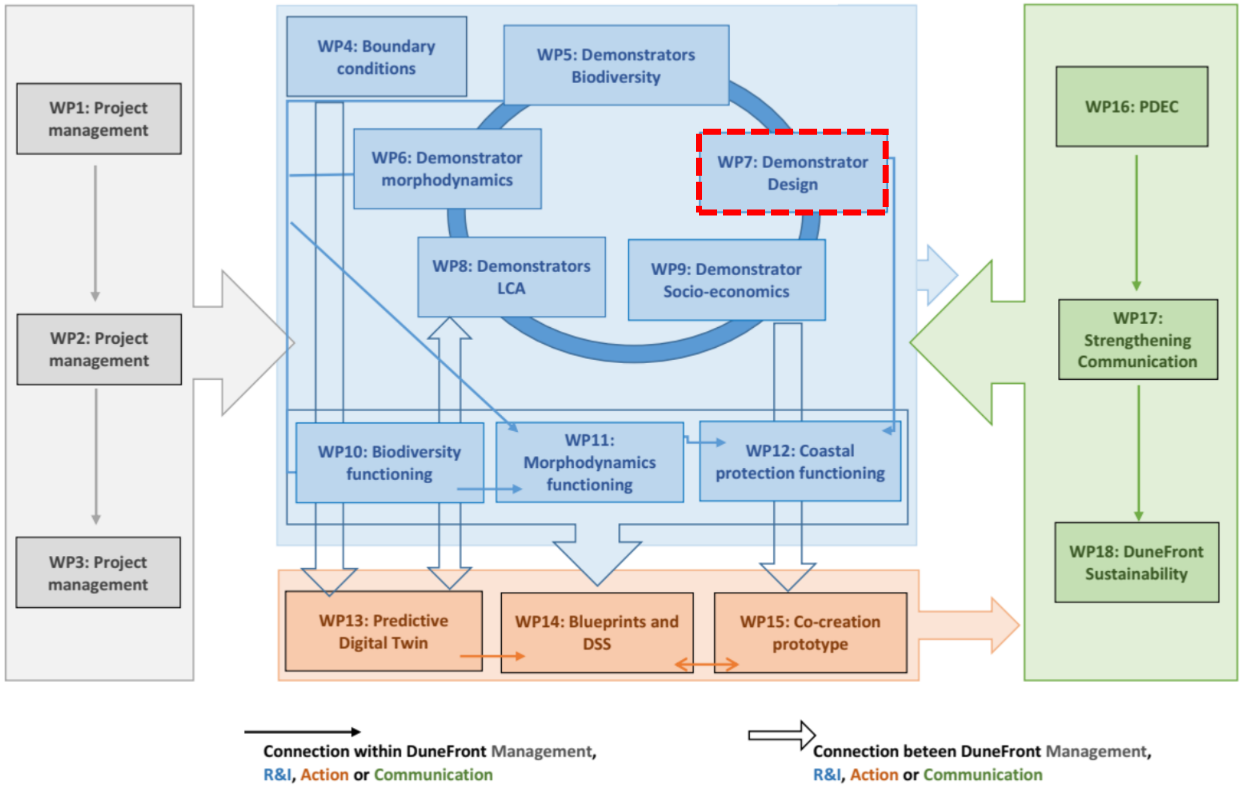


Figure 2 - The structure of the DuneFront project and the interconnection of work package 7 with other work packages in this project.

In the following sections we will discuss the overview of work package 7 (WP7) and its subsections. This report specifically focuses on Task 7.1 of the DuneFront work package 7.

1.2.1 Tasks of work package 7

The objective of the first task (Task 7.1) in this work package, and thus the objective of this report, is to collect and investigate all existing design reports from all Demonstrators as well as making a final selection based of defined selection criteria to determine the functionality of both dunes and dikes for coastal protection. This task involves reviewing, cataloging, and comparing design methods for all selected Demonstrators.

This work package also includes a second task (Task 7.2), which focuses on collecting extreme storm boundary conditions, including various climate change scenarios, for use in physical modelling.

1.2.2 Milestones and Deliverables of work package 7

The key milestone (M7.1) involves the selection and division of design analyses among partners, verified through an agreement report.

The deliverables include:

- **Deliverable D7.1 (this report):** Demonstrator design study and catalogue of design parameters, documenting and comparing the designs of selected Demonstrators.
- **Deliverable D7.2:** Boundary conditions for physical modelling of extreme storms, providing essential data for subsequent modelling.

As we mentioned before, this report primarily focuses on Deliverable D7.1, detailing the comprehensive investigation of existing designs of the DuneFront Demonstrators, setting the stage for subsequent analyses and modelling tasks.

1.3 Aims and objectives of this report

The main objective of this report is to evaluate all existing Demonstrators in four European sea basins (Mediterranean, Atlantic, North Sea, and Baltic) to document and compare the designs of selected Demonstrators. These Demonstrators, located in six different countries, have been chosen based on their diverse functionalities, exposure to various boundary conditions, and governance structures.

At the core of DuneFront are 12 Demonstrators, each representing hybrid Nature-based Solutions (NbS) where dunes and hard infrastructure (such as dikes and groynes) are combined to protect coastal areas. The primary criteria for selecting these Demonstrators include their potential for cost-effectiveness, adaptability to climate and structural changes, and the benefits they provide to both human communities and the environment. Specifically, we targeted systems where both the dune and the dike contribute to the safety of the hinterland, including Dune-in-Front-of-Dike (DiFoD) systems and structural variants like Dike-in-Dune (DiD) systems, as references for alternative designs under various boundary conditions. Aside from the primary criteria, after the initial selection process, which resulted in 12 Demonstrators, we conducted another selection based on the functionality of the dune and dike in terms of coastal safety, the existence of DiFoD or DiD. After this second selection we will focus on the design aspects of the final selected Demonstrators, identifying them as main examples for the DuneFront project.

These hybrid NbS not only aim to enhance coastal protection and biodiversity restoration but also facilitate recreational activities and mitigate aeolian sand nuisance. Additionally, such solutions can form the basis for marine infrastructure, such as artificial islands serving as renewable energy hubs or marine barriers for coastal protection.

The analysis in this report will focus on the general information and characteristics of each Demonstrator along with their design criteria, modeling methodology, dike stability and their monitoring and maintenance methods. This comprehensive investigation will provide a novel overview of well-established NbS along European coasts, offering valuable insights into their design, functionality, and benefits.

1.4 Demonstrator Locations

Table 1 provides a detailed list of the 12 Demonstrators selected for the DuneFront project, each located in different coastal regions across Europe. These Demonstrators are distributed across six countries: Portugal, France, Belgium, the Netherlands, Germany, and Sweden. This diverse selection ensures a comprehensive evaluation of various hybrid NbS under different environmental conditions and governance structures as shown in Figure 3.

Table 1 - Location of 12 selected Demonstrators in DuneFront project

	Demonstrator	Country	Location (LAT-LON coordinates)
1	Douro estuary sand spit	Portugal	41° 8.453'N - 8° 40.055'W
2	Soulac	France	45°31'0.16"N - 1° 7'35.35"W
3	Dunkerque	France	51° 3.014'N - 2° 22.524'E
4	Sainte-Marie La Mer	France	42° 44.094'N - 3° 2.256'E
5	Living Lab Raversijde	Belgium	51° 12.659'N - 2° 51.991'E
6	Middelkerke grass dike	Belgium	51° 10.154'N - 2° 46.145'E
7	Delflandse kust	The Netherlands	52° 2.801'N - 4° 11.097'E
8	Hondsbossche Duinen	The Netherlands	52° 45.925'N - 4° 39.151'E
9	Katwijk	The Netherlands	52° 12.298'N - 4° 23.580'E
10	Texel Prins Hendrikzanddijk	The Netherlands	53° 1.593'N - 4° 49.010'E
11	Sankt Peter-Ording	Germany	54°19'11.8"N - 8°36'23.2"E
12	Ystad	Sweden	55° 25.720'N - 13° 51.546'E

Figure 3 - Overview of the 12 Demonstrators and their location along the European coast (indicated using green pinpoints).

2. Demonstrators overview and selection

2.1 Overview

A comprehensive overview of the 12 coastal Demonstrators across six European countries is shown in Table 2. The columns in the table offer basic design information about each Demonstrator, including its location, configuration of dunes and dikes, the functionality of the dike, availability of design reports and extreme boundary conditions, and the presence of an official local government safety assessment methodology.

Column A "Demonstrator" identifies each project by name and location. Column B "Dune-Dike Configuration", describes the specific arrangement of dunes and dikes. In this column, several Demonstrators featured as "Dune-in-front-of-Dike" setup (the main objective of this study), such as those in Dunkerque (FR) and Living Lab Raversijde (BE), while others, like Katwijk (NL), use a "DiD" configuration or "Breakwater in front of Dune" or "Dune-in-between-Dikes".

Column C "Dike has safety function?" indicates whether the dike in each configuration serves a safety function. Some configurations, such as the Douro estuary sand spit (PT), do not include a dike, whereas others, like Dunkerque (FR) and Katwijk (NL), have dikes that play a crucial role in coastal safety.

In terms of documentation, column D, "Design report available?" shows variability among the Demonstrators. Some, like Living Lab Raversijde (BE) and Texel Prins Hendrikzanddijk (NL), have confirmed design reports, while others, such as Soulac (FR), lack these documents because the dike was built more than a century ago, indicating a gap in formal documentation that could affect the assessment of their effectiveness.

Column E, "Design/extreme boundary conditions available?", reveals that most Demonstrators have the necessary data to evaluate their resilience to extreme weather events. However, some, including Soulac (FR) and Ystad (SE), do not have this critical information readily available.

Finally, column F, "Official (local) government safety assessment methodology available?", shows that while many Demonstrators have an official methodology for safety assessment, others do not. For instance, the Douro estuary sand spit (PT) and Soulac (FR) lack such official assessments, which may impact the formal evaluation of their safety and effectiveness.

Table 2 - The overview table of 12 selected Demonstrators

	A	B	C	D	E	F
	Demonstrator	Dune-Dike configuration	Dike has safety function?	Design report available?	Design/extreme boundary conditions available?	Official (local) government safety assessment methodology available?
1	Douro estuary sand spit (PT)	Rubble-mound breakwater in front of Dune	no dike	yes	yes	no
2	Soulac (FR)	Dune-in-front-of-Dike	no	no	no	no
3	Dunkerque (FR)	Dune-in-front-of-Dike	yes	yes	yes	yes
4	Sainte-Marie La Mer (FR)	Dune-in-front - of-Dike	yes	no	no	yes
5	Living Lab Raversijde (BE)	Dune-in-front-of-Dike	yes	Dune only	yes	yes
6	Middelkerke grass dike (BE)	Dune-in-front-of-Dike/Grass dike	yes	yes	yes	yes
7	Delflandse kust (NL)	Dune	yes, as a longer-term buffer for adjacent coast, but no dike	yes, and 5yr and 10yr evaluations	yes	yes
8	Hondsbossche Duinen (NL)	Dune-in-front-of-Dike	no	yes	yes	yes
9	Katwijk (NL)	Dike-in-Dune	yes	yes	yes	yes
10	Texel Prins Hendrik Zanddijk (NL)	Dune-in-front-of-Dike	no	yes	yes	yes
11	Sankt Peter-Ording (DE)	Dune-in-between-Dikes	yes	yes	yes	yes
12	Ystad (SE)	Dune-in-front-of-Dike	yes	no	no	no

2.2 Description of the coastal protection functioning

Table 2 illustrates the diverse configurations, functionalities, and levels of documentation among the selected Demonstrators. The varying availability of design reports and safety assessments highlights the need for standardized documentation and evaluation methods to ensure the success and scalability of these innovative coastal protection solutions. Table 2 is essential for understanding the overall information and their availability as well as the functionality of each Demonstrator. In the following section, we will investigate the coastal protection functioning of each selected Demonstrator.

2.2.1 Douro estuary sandspit (PT)

The Douro estuary sandspit, located on the left bank of the Douro River in northwest Portugal, plays a crucial role in protecting inland margins and harbours from storm events. Over the past century, the spit has experienced a significant inland shift of approximately 500 meters, influencing the estuary morphodynamics, which are shaped by both natural elements and human interventions. In fact, the sandspit shape is influenced by river discharges and ocean dynamics, with accretion in the past repeatedly causing progression of the spit head towards the north and leading to the obstruction of Douro navigation channel. The estuary, especially its northern bank, was also becoming more exposed to storms, impacting navigation due to rough weather and wave conditions.

The sandspit, rooted on the south bank of the Douro river estuary, is about 300 meters wide (E-W) and 800 meters long (N-S), is stabilized on its eastern part by vegetation and connects to the ecologically significant São Paio Bay marshes. Human efforts to stabilize this dynamic landscape include the construction of a detached rubble-mound breakwater between 2004 and 2008, aimed at improving navigational safety and reducing storm wave impacts, Figure 4. Despite these interventions, the sand spit has shown varying responses to river discharges, ocean waves, and wind conditions, as monitored from 2001 to 2010. While the breakwater has stabilized much of the sandspit, changes in its morphology and the patterns of erosion and accretion have been observed, indicating ongoing challenges in managing this critical natural defence mechanism.

The main objective of Douro estuary sandspit project, led by the Port Authority of Leixões and Viana do Castelo, is to evaluate existing hybrid solutions aimed at stabilizing the nature reserve around the Douro estuary sandspit and São Paio Bay marshes. This involves assessing the effectiveness of an overtopped low-crested detached breakwater in managing the area’s morphodynamics and protecting its natural environments.

This demonstrator does not include a dike, however, the existing breakwater blocks the wave penetration and protects the sand spit from erosion and the combination of sand spit and breakwaters have protective functionality for inland margins and harbours.

Figure 4 – Douro estuary sandspit (PT) Demonstrator, a rubble mound breakwater in front of a Dune

2.2.2 Soulac (FR)

The Soulac Demonstrator, overseen by the Communauté de Communes Médoc Atlantic (CCMA) and managed by the Soulac Council and the Office National des Forêts (ONF), aims to restore the natural state of the Soulac seafront and reduce the transport of windblown sand (aeolian sand transport) into the coastal resort during winter storms. The Demonstrator is situated in the northern part of the coastal resort (Figure 5a). In the early 1900s, when the coast was severely eroding, a large dike was constructed to protect the coastal resort (Figure 5b)

However, due to a nearby large-scale estuarine shoal attaching to the coast, the beach dramatically rose and widened within just a couple of decades (Figure 5b and c), compromising the original safety function of the dike. Today, the beach is nearly 250 meters wide (Figure 5a), and the sand level almost reaches the top of the former dike, which is now essentially buried under the sand. Regarding the safety functioning of the Demonstrator, it is expected that if this area were to experience severe erosion similar to that of the early 20th century, the dune would buffer storm-driven erosion and protect the old dike.

The "DiFoD" Demonstrator aims to manage aeolian sand transport from the wide beach into the coastal resort during winter storms by constructing a dune field through marram grass planting (February 2024, Figure 5e). A similar experiment is planned for a more southern sector of the coastal resort in 2025. Notably, a "DiD" configuration is located adjacent to the "DiFoD" Demonstrator, where a dune field is protected by a series of groynes that were progressively transformed into a continuous seawall between 1853 and 1938. The objective of this configuration was to stabilize the shoreline and protect the dune field, as this was the narrowest section of the peninsula and would have been breached without intervention. This approach has been very successful and remains effective. Although erosion is not as severe as before, storm waves still break against the dike, which continues to protect the dune field. Although not the primary focus of DuneFront, this system will also be monitored during the project. For more details on the long-term changes of this coast related to coastal works and estuarine dynamics, refer to Vandenhove et al. (2024).

This Demonstrator benefits from extensive collaboration with the Office National des Forêts, the leading stakeholder in coastal dune management in France. In partnership with the Université de Bordeaux, they have co-designed experimental approaches to enhance dune mobility in chronically eroding sectors of southwest France and co-developed monitoring strategies for both morphology and vegetation. This collaboration is part of a broader engagement with the regional coastal observatory (OCNA) and the Bureau de Recherche Géologique et Minière (BRGM).

In terms of data resources, the Demonstrator site has a rich archive of shoreline data dating back to the 1940s, derived from aerial photos, satellite imagery, and in-situ surveys (Vandenhove et al., 2024). Recent and ongoing data collection includes yearly topographic Lidar data since 2014 and regular beach and dune surveys at fixed profiles by OCNA. Since February 2024, when marram grass was planted in front of the dike, additional regular (~quarterly) GNSS and/or drone photogrammetry surveys have been performed, along with vegetation studies. These efforts aim to enhance the understanding and management of the coastal environment and address the influence of the new dune on aeolian sand transport into the coastal resort.

Figure 5 - Soulac (FR) Demonstrator, Dune-in-front-of-Dike, wiith (a) aerial view of Soulac coastal resort which is (d) zoomed onto the Demonstrator with (e) a photo of the new dune a few days after marram planting. (b-c) shows how the diked has been burried under the sand after the nearby welding to the coast of a large-scale shoal.

2.2.3 Dunkerque (FR)

At Dunkerque Beach, the focus is on three key locations: Malo les Bains (West and East sections of the dike 'Digue des Alliés') and along the dike 'Digue du Break' (see Figure 6).

Figure 6 - Dunkerque (FR) Demonstrator, at three key locations: Malo les Bains (West and East sections of the Digue des Alliés) and Digue du Break

Coastal dunes were erected at Malo les Bains in 2015 in the eastern part of the digue des Alliés, at the junction with the seawall promenade. Marram grass were planted in April 2016. After the building of an hotel in 2021, this dune was reshaped (lowered) in 2021 in order to preserve sea views (Figure 7 and 8).

Figure 7 - The dune in front of the hotel in November 2021, after "reshaping", the dune was partly destroyed (©Marie-Hélène Ruz)

Figure 8 - Dune erected in 2015 and partly reshaped in 2021 , at Malo les Bains, East Section of the Digue des Alliés (Géodunes)

Additional dunes were established in 2020 in front of the Digue des Alliés. (Figure 9).

Figure 9 - Dune erected in 2020, at Malo les Bains, West Section (Géodunes)

The dune was then stabilised by Marram grass planting, in order to prevent sand transfer from the beach to the canal (Figure 10).

Figure 10 - Marram grass plantation in December 2020 (Ville de Dunkerque)

The dunes erected at Malo les Bains were implemented to mitigate sand invasion on the seawall promenade and on a dike protecting from flooding low-lying Dunkerque districts, but also to enhance flood protection in vulnerable districts of Dunkerque. The efforts were coordinated by the Grand Port Maritime de Dunkerque (GPMD) until 2018 and by the Communauté Urbaine de Dunkerque (CUD) thereafter.

At Malo les Bains these Demonstrators primarily aim to evaluate existing nature-based solutions (NBS) for coastal management. Monitoring and data collection have been extensive since 2014, leveraging technologies like GNSS, LiDAR, and drone photogrammetry.

Further west, coastal dunes naturally started to develop in the early 80's at the toe of Digue du Break, constructed in 1963 and located in the eastern part of the Grand Port Maritime de Dunkerque . Sand patches developed in 1983 and by 2009 accumulation was partly vegetated (Figure 11) and since then, coastal dunes continue to develop (Figure 12).

In this area extensive data has been collected since 1988, including GNSS topographic beach profiles, LiDAR scans from multiple years, aerial photographs, drone-derived digital terrain models (DTMs), and studies on aeolian sand transport, grain size, and oceanic conditions.

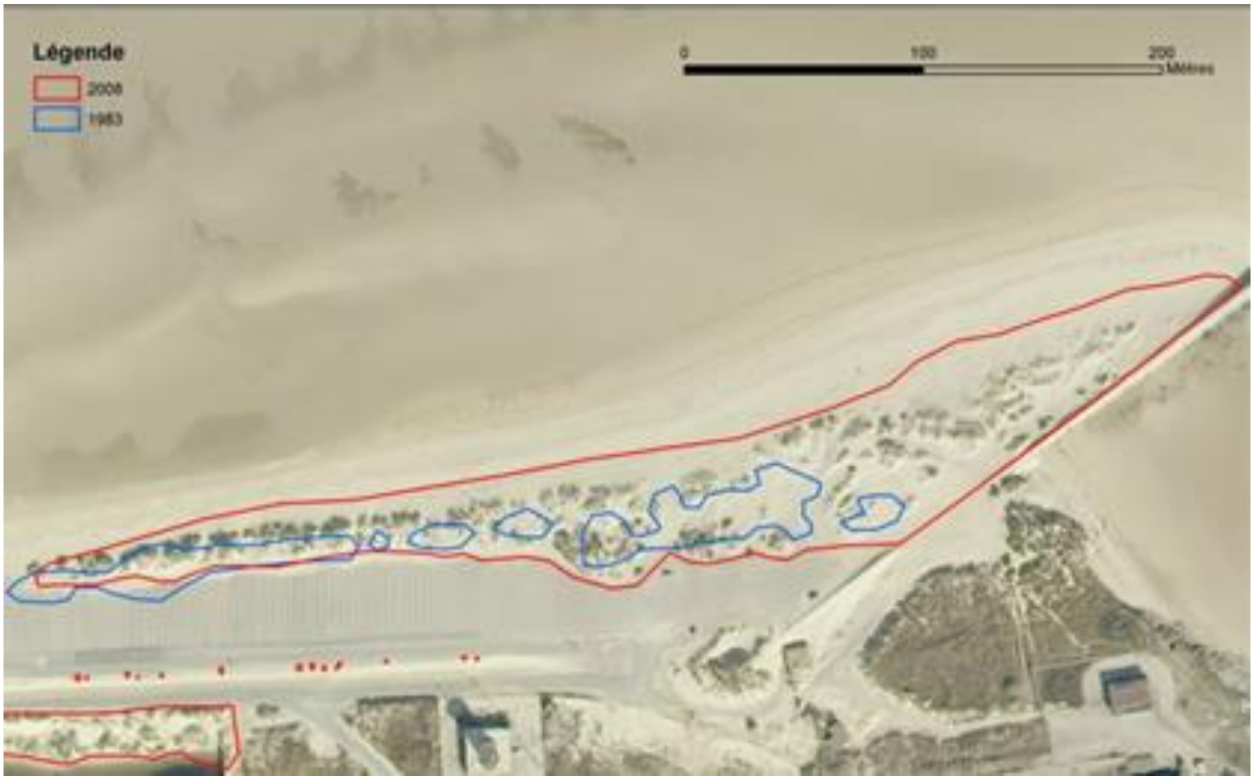


Figure 11 - 1983 and 2009 dune development at the toe of Digue du Break East (Tresca et al., 2014)

Figure 12 - Coastal dunes developed at the toe of Digue du Break in 2021 and 2022 (Géodunes)

Regarding their coastal protection functionality, it is expected that both the hard coastal protection structures (seawall/dike) and the dunes will work together. In the event of design storm conditions, both elements are anticipated to provide coastal protection simultaneously.

2.2.4 Sainte-Marie La Mer (FR)

The Perpignan Mediterranée Métropole (PMM) is the main authority responsible for the Sainte-Marie La Mer Demonstrator project. Covering a length of 1000 meters (Figure 13 A), the Demonstrator was installed in October 2021 downdrift on the last groyn, in an area particularly vulnerable to chronic erosion. Its objective was to reinforce the embryonic dune by installing fences. Positioned in front of a dyke, it serves a dual purpose of protecting the town's economic assets, including coastal resorts, restaurants, and shopping areas, while also functioning as a pedestrian pathway. In response to a severe storm in October 2022, plans are in place for a sediment supply of the beach and nearshore zone of the Demonstrator. Almost every year, a nourishment of approximately 15000 to 20000 m^3 is carried out by the authorities. The environment highly representative of the Mediterranean coast.

Figure 13 - Sainte-Marie La Mer (FR) Demonstrator, Dune-in-front (weld)-of-Dike

The project benefits from extensive stakeholder engagement, particularly with DREAL, Parc Marin du Golfe du Lion, and Office National des Forêts (ONF), focusing on beach-dune interaction, aeolian processes, sediment transport, and coastline dynamics. Collaboration also extends to the Observatoire de la Côte Catalane (OBSCAT), where PMM is a partner. Stakeholder funding primarily sustains the initiative.

Data resources include bi-annual topo-bathymetric surveys since 2013 (upgraded to topographic Lidar since 2019), vegetation identification transects, ground photographs since 2022, and socio-economic information. Aerial photographs dating back to 1945 offer historical perspective and aid in understanding long-term coastal changes.

The southern part of the Sainte-Marie La Mer Demonstrator has recently (April 2024) faced significant damage due to two successive storms, intensifying the chronic erosion issues in the area. The effects have been notable, with part of the dune completely eroded, exposing the “grey” dike beneath (Figure 14).

Figure 14 - The southern part of the "St Marie Demonstrator" after two successive storms in April 2024

Pre- and post-storm topographic surveys have been collected allowing for a detailed assessment of the damage. After this event the beach was closed as stakeholders deliberate on the most appropriate course of action to manage the situation. Sand nourishment is being considered as a probable solution in the coming weeks after event. In response to the situation, authorities have publicly announced their consideration of relocating the "grey" dike landward to mitigate the effect on the dyke of the chronical erosion, in accordance with French regulations. This project will take a few years to be implemented.

Regarding the coastal protection functionality, as discussed in the previous paragraph, in the event of a severe storm, both the dune and the dike provide protection. The dune may be eroded, leaving the dike to act as the final layer of defence for the coastal areas.

2.2.5 Living Lab Raversijde (BE)

The Oostende – Raversijde Demonstrator is primarily overseen by the Flemish government, in collaboration with the city of Ostend as part of the coastal safety plan. The main focus of this initiative is to serve as a pilot site for evaluating DiFoD as a hybrid Nbs, with plans for future extension. DiFoD provides marram planting in various configurations and concentrations, alongside the use of brushwood to manipulate aeolian sand transport dynamics.

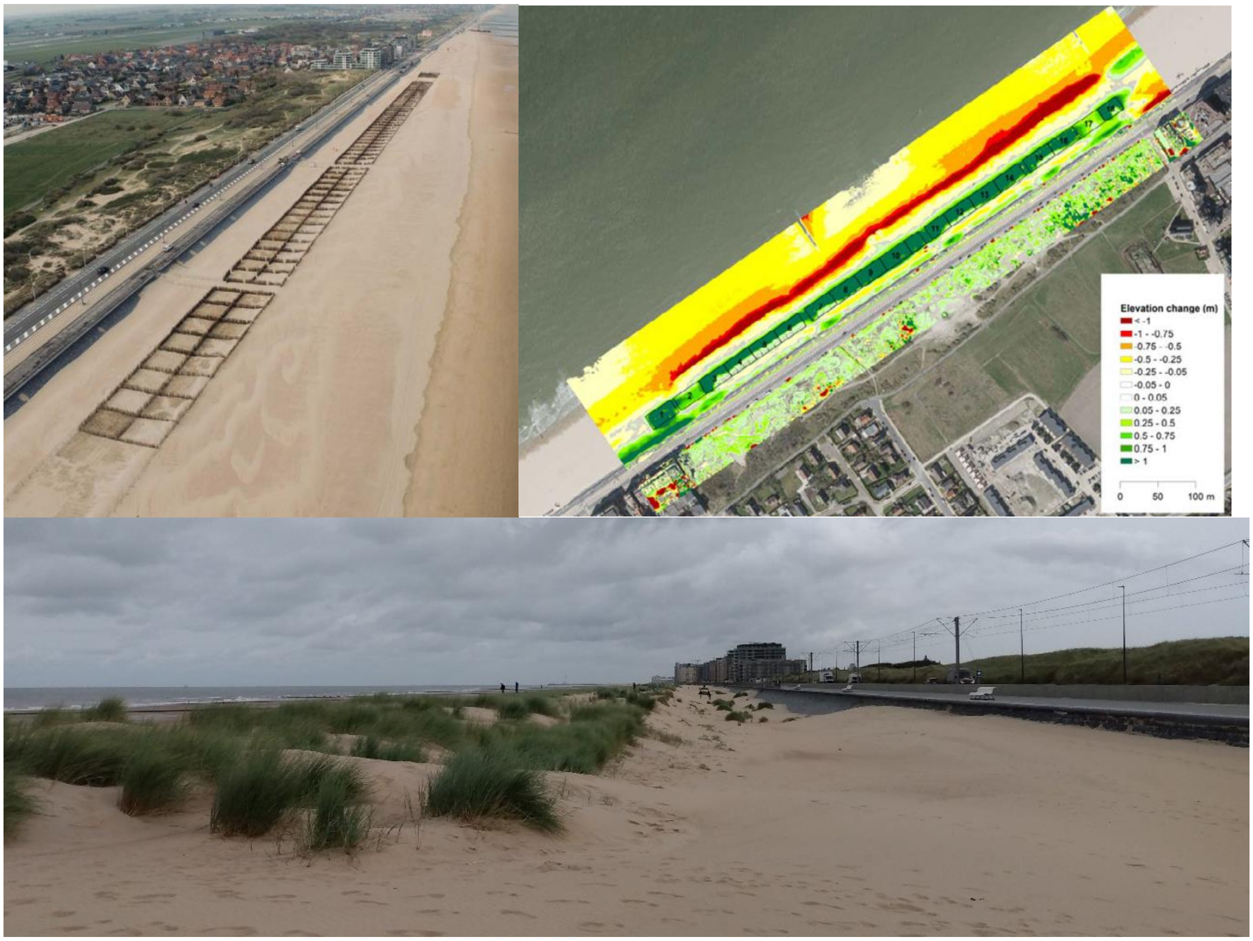


Figure 15 - Living Lab Raversijde (BE) Demonstrator, Dune-in-front-of-Dike

The group associated with the Demonstrator project has extensive experience in engaging with stakeholders. Flemish partners actively collaborate with a diverse range of stakeholders, including local businesses, nature conservation agencies, and dredging entities, among others. This broad engagement ensures comprehensive input and participation from various sectors. Key stakeholders involved in the project include the City of Ostend, encompassing local tourism interests, Natuurpunt vzw, and the Flemish government.

Regarding available data and resources, the project benefits from a range of sources. These include DTMs and RGB drone images, facilitating detailed analysis and monitoring. Additionally, data on drift line vegetation, aeolian dynamics, and meteorology offer insights into environmental processes. Other data such as citizen science data biodiversity, socio-economics & services assessed within the EU Interreg 2 Seas SARCC project (questionnaires and analysis of land an property value increases, amenity and avoided costs for sand cleaning) are also available.

The combination of a DiFoD is expected to provide simultaneous coastal protection. While the dune and its vegetation may be overwashed and removed during severe storms, the dike is designed to continue protecting the area behind it.

2.2.6 Middelkerke – grass dike (BE)

The Middelkerke – grass dike (GRASDIJK) Demonstrator is a collaborative effort between the Flemish government and the city of Middelkerke, forming part of the coastal safety plan. The primary focus of this initiative is coastal defence, aimed at resisting a 1000-year returning storm with a target water level elevation of 10.5 meters above chart datum (Tweede Algemene Waterpassing (TAW), in Dutch). However, there is also a strong emphasis on integrating recreational elements into the design.

The group involved in the project has extensive experience in working with stakeholders across various sectors. Flemish partners actively engage with a wide range of stakeholders, including local businesses, nature conservation agencies, and dredging companies, among others. This inclusive approach ensures that diverse perspectives and expertise are considered throughout the project.

Key stakeholders engaged in the project include the city of Middelkerke, including representatives from the local tourism sector, Natuurpunt vzw, and the Flemish government.

In terms of available data and resources, the project benefits fromlidar and summer/winter images at lower resolution (20cm) from specific remote sensing flights. Socio-economic aspects and ecosystem services are assessed within the SARCC project, utilizing questionnaires and analysis to evaluate factors such as increases in land and property values, amenity benefits, and avoided costs associated with sand cleaning efforts.

Figure 16 - Middelkerke – grass dike (BE) Demonstrator, Dune-in-front-of-Dike

Regarding the coastal protection functionality of this Demonstrator, it consists of a dune constructed in front of an existing seawall. The dune is primarily considered the coastal safety asset since the seawall cannot undergo regular inspections due to the dune's presence. However, in the event of a design storm where the dune is eroded, the seawall is expected to protect the residential areas behind it.

2.2.7 Delflandse kust (NL)

The Sand Motor (Delflandse kust) Demonstrator project, initiated by the Province of South-Holland, represents a collaborative effort involving various stakeholders. Partners such as the Ministry of Infrastructure and Environment – Rijkswaterstaat, the Water Board of Delfland, and multiple municipalities including Westland, The Hague, and Rotterdam, alongside organizations like the Milieufederatie Zuid Holland, the World Wildlife Fund, and EcoShape, have been instrumental in its planning and execution. Contractors Van Oord and Boskalis were tasked with constructing the peninsula.

Figure 17 - The Sand Motor (Delflandse kust) Demonstrator, dune without a dike

The primary focus of the Sand Motor Demonstrator is the evaluation of existing Nbs. Objectives include enhancing long-term coastal flood safety, creating a nature and recreation area, and fostering knowledge development and innovation in coastal management. This initiative serves as an opportunity for stakeholders to gain insights into the effectiveness of alternative strategies while addressing the region's need for recreational and natural spaces.

Throughout the project, stakeholders have been actively engaged through regular management and user meetings. Stakeholders include local municipalities, inhabitants, local recreation businesses, researchers, the Province of South Holland, Rijkswaterstaat, and nature organizations.

Data collection and monitoring have been integral components of the Sand Motor project. Various programs and research projects have been conducted to assess weather patterns, waves and currents, sand distribution, groundwater dynamics, flora and fauna, recreation patterns, and management practices. Monitoring activities utilize technologies such as lidar, JARKUS data, modeling, and sand catching devices to measure erosion and sedimentation, while vegetation, benthos, and bird populations are also monitored. Groundwater dynamics are measured by Dunea, a drinking water company, in the dunes behind the Sand Motor.

Regarding the coastal protection functionality in this Demonstrator, the absence of a dike means that the dune alone is expected to serve as the primary protection structure. The dune is designed to absorb the impact of waves and storm surges, providing a natural barrier against coastal flooding and erosion.

2.2.8 Hondsbossche duinen (NL)

The Hondsbossche Dunes Demonstrator project is a collaborative effort led by the regional water authority Hollands Noorderkwartier and Rijkswaterstaat, with coordination from a consortium comprising Boskalis and Van Oord. Additionally, a three-year research project was conducted by the regional water authority board Hollands Noorderkwartier, Rijkswaterstaat, and an EcoShape consortium.

Figure 18 - Hondsbosch duin (NL) Demonstrator, Dune-in-front-of-Dike

The primary focus of the Demonstrator project is to enhance flood safety, aiming to withstand 1/10,000 year storm conditions. Concurrently, the project seeks to create an area with high spatial quality for recreation and nature.

Stakeholder engagement is a crucial aspect of the project, with active involvement from local inhabitants and businesses, including beach restaurants and holiday housing providers. Concerns regarding sand hindrance were addressed, and opportunities for recreation were integrated into the design in collaboration with the Province of North Holland. Key stakeholders involved in the project include the Province of North Holland, local businesses, inhabitants, municipalities, and nature organizations.

Monitoring and adaptive management practices are carried out by the consortium of Boskalis and Van Oord. A Monitoring and Innovation Research Project conducted from 2015 to 2018 focused on various aspects, including erosion and sedimentation measured with lidar, aerial photographs, and JARKUS. Vegetation development was monitored through permanent plots and species lists, while the chemical soil composition was assessed. Groundwater dynamics were also measured. Subsequent monitoring projects have focused on morphological development and the interaction of marram grass with sand dynamics. However, there is a need for ongoing monitoring to assess ecological development, as no current vegetation development monitoring is in place. New measurements are required to evaluate ecological progress up to the present.

. In this Demonstrator, the coastal protection function is expected to be provided solely by the dune, which shields the inland areas from damage. The dyke behind the dune holds ecological and cultural heritage value but does not contribute to protection.

2.2.9 Katwijk (NL)

The Katwijk Demonstrator project is jointly managed by the Waterboard Rijnland and the Municipality of Katwijk, with a primary focus on evaluating existing Nature-Based Solutions (NBS). One key feature of this project is the hard dike with a formal safety function, embedded within a dune structure. To ensure flood safety despite the narrow (40 m wide and 1.5 km long) vegetated artificial dune, a buried dike slope is incorporated. This narrow vegetated artificial dune serves as a potential ecological connection between larger dune systems to the North and South, although this aspect requires further study. Scenic quality was also a significant consideration in the design.

Figure 19 - Katwijk (NL) Demonstrator, Dike-in-Dune

Stakeholder engagement is an integral part of the project, drawing on the experience gained from other Dutch projects. The Waterboard has expressed willingness to collaborate, indicating a strong commitment to stakeholder involvement. The involved stakeholders encompass a diverse range of entities, including local municipalities, inhabitants, local recreation businesses, researchers, the Province of South Holland, Rijkswaterstaat, nature organizations, as well as contractors and engineering firms involved in the creation of the Demonstrator.

Data resources include detailed documentation of the dune and dike design approach, with maintenance records spanning ten years. Bi-yearly laser scans of the coast, beach, and dune area are conducted by Rijkswaterstaat, supplemented by the use of an XBeach model to study complex three-dimensional areas. Assessments of the main dune body have been carried out using Duros+ and durosTA models, with results readily available. Standard remote sensing images, including satellite and aerial photography, provide valuable insights into vegetation dynamics within the dune area.

Regarding the coastal protection functionality of this Demonstrator, it includes a hard dike embedded within a dune (DiD) to ensure robust flood safety, and provides a strong defence against coastal flooding simultaneously.

2.2.10 Texel, Prins Hendrik Zanddijk (NL)

The Prins Hendrik Zanddijk project, led by the Hoogheemraadschap Hollands Noorderkwartier and executed by Jan De Nul N.V, represents an innovative approach to flood defence, nature development, public services, and recreation on the Dutch island Texel. The primary focus of the project is to integrate flood defence measures with nature conservation efforts, creating a dynamic and resilient coastal landscape.

The project involves upgrading sections of the existing Wadden Sea dike to meet safety standards, while also enhancing ecological value. A key aspect is the creation of a dune landscape as primary coastal protection, complemented by soft protection strategies similar to those employed in the Hondsbossche dunes project. The design aims to upgrade around 200 hectares of the UNESCO World Heritage Site Wadden Sea area, emphasizing interactions between ecology and sediment dynamics.

Regarding the coastal protection functionality, the dune in this Demonstrator serves as the primary protection system. However, the protective role of the dike behind it is not fully clear.

Central to the design is the consideration of trade-offs between safety and ecological value, sediment stability and dynamics, and recreational opportunities and habitat disturbance. Strategies such as using fine sands to stimulate benthos growth and creating salt marshes and seashell patches are employed to enhance habitat diversity while maintaining flood defence functionality.

Figure 20 - Texel, Prins Henrikzanddijk (NL) Demonstrator, Dune-in-front-of-Dike

Stakeholder engagement is a crucial aspect of the project, with outreach efforts including information sessions, newsletters, and a GIS portal providing monitoring data to stakeholders. Residents along the flood defence, farmers, nature organizations, recreational users, fisheries, and port companies are among the stakeholders involved.

Data collection and monitoring are integral to the project, with regular assessments of morphology, aeolian transport, geohydrology, habitat types, marram grass, nesting birds, seals, and benthos. These data inform ongoing management and adaptive strategies to ensure the project's success in meeting its dual objectives of flood protection and ecological enhancement.

2.2.11 Sankt Peter Ording (DE)

The Sankt Peter-Ording (SPO) Demonstrator project is overseen by several key authorities, including the State management agency for coastal protection, national park, and ocean protection of Schleswig-Holstein (LKN.SH), the Wadden Sea national park of Schleswig-Holstein (NLPV), and the Dike- and main tide gate association of Eiderstedt (DHSV

Eiderstedt). The project focuses on assessing the coastal protection potential of coastal dunes, experimenting with reinforcement options, and restructuring habitat zones in the national park area.

Figure 21 - Sankt Peter Ording (DE) Demonstrator, Dune-in-between-Dikes

The involved stakeholders include state authorities for coastal protection and local dike management, the national park authority, the state forest department, local politics, tourist office representatives, and citizens.

Data resources for the project include digital terrain maps spanning from 1949 to 2022, historic maps of the ocean floor, tide gauge data, soil samples, vegetation maps, historic and current photos, atmospheric measurement data, re-analysis data, and information on coastal dune forests. These data sources provide valuable insights into the evolution of the coastal landscape and environmental conditions over time.

Regarding the coastal protection functionality, this Demonstrator features a comprehensive system of multiple dikes and a natural grey dune system. The northern land protection dike, standing at 8 meters above mean sea level (amsl), serves as the first line of defence. South of the dune system, a regional dike with a tar surface layer provides additional protection at 6.4 meters amsl. A middle dike positioned behind both the dune system and the regional dike acts as a secondary defence line. Additionally, a southern land protection dike integrates with the regional and middle dikes to fortify the city vicinity. The natural grey dune system, varying in height from 6 to 16.5 meters amsl, fills the gap between the northern and southern dikes, enhancing the overall coastal protection by offering a resilient, multifunctional barrier against storm surges and flooding.

2.2.12 Ystad (SE)

The Ystad municipality takes the lead as the main authority responsible for the Demonstrator project in Ystad. The primary focus of this initiative is the evaluation of existing Nbs. Specifically, attention is directed towards a bike/walking path equipped with a rubble-mound revetment on its seaward side. Over the years, multiple beach nourishments have been conducted, resulting in the coverage of the revetment with sand and dunes. Topographic/bathymetric and biological surveys have been regularly conducted since the initiation of these nourishments. Additionally, the introduction of sand fences and vegetation on the berm aims to assess their effectiveness in trapping sand.

Figure 22 - Ystad (SE) Demonstrator, Dune-in-front-of-Dike

The group "experiencenvolved experiencen" in this project has extensive experience collaborating with stakeholders. Researchers have previously served as consultants and actively participated in the design and impact assessment of nourishment projects. This engagement reflects a commitment to incorporating diverse perspectives and expertise into the project's development and evaluation process.

Stakeholders engaged in the project include the Ystad municipality, local citizens, a spa hotel, and various municipal functions such as those related to the environment, tourism, business, and education. This broad representation ensures that the project considers the interests and needs of different community sectors.

Data resources for the project include yearly surveyed cross-shore transects of beach topography and bathymetry dating back to 1995, with ongoing measurements as part of the EU project LIFECoastAdapt. Additionally, DTMs derived from LiDAR and multibeam surveys, aerial images since 2016, grain size sampling from 2021 and 2022, and yearly biological surveys of dune areas from 2018 contribute valuable insights into the coastal dynamics and ecosystem health.

Regarding the coastal protection functionality, the existing rock revetment serves as a foundational barrier against coastal erosion and storm surges. The beach nourishment in front of the revetment has led to the formation of new dunes. Additionally, experimental plantations in front of the existing dune row have encouraged the establishment of new dunes. These new dunes are expected to provide extra protection in case of storms, enhancing the overall safety of the coastal area.

2.3 Demonstrator selection for the detailed design comparison

Based on the provided background and descriptions of the 12 selected Demonstrators (Section 2.2), it is essential to narrow them down to those that have the potential to stand out as representatives of DD-Hybrid NbS. The criteria for this second selection step are based on the functionality of both the dune and dike in terms of coastal safety, specifically focusing on the presence of a DiFoD or a DiD. Using these criteria, seven Demonstrators are selected for detailed analysis and investigation of their design methodologies. The list of the finally selected Demonstrators is as follows:

- **France**: Dunkerque and Sainte-Marie La Mer
- **Belgium**: Living Lab Raversijde and Middelkerke
- **The Netherlands**: Katwijk
- **Germany**: Sankt Peter-Ording
- **Sweden**: Ystad

After this selection, we now analyse the design methodologies for the finally selected Demonstrators, aiming to collect detailed information on the design methodologies for DD-Hybrid NbS or separate dune and dike structures. These design methodologies cover several key areas.

We start with general information includes the type of design or assessment (DD-Hybrid NbS or separate dune/dike), whether a deterministic or probabilistic design method is used, design lifetime, design storm duration for morphodynamics and hydrodynamics, reliability methods used (e.g., Monte-Carlo, FORM), design hydrodynamic conditions and parameters, and the accessibility of design reports. Then continue with the design criteria, focusing on safety criteria for the design, the definition and location of safety lines, and other relevant design criteria. The modelling methodology encompasses morphodynamics modelling methods, hydrodynamics modelling methods for overtopping and flooding, models used for overtopping and overwash, and dimensions and physical processes considered in the design.

Dike stability examines the type of dike and the stability methods used from geotechnical and structural perspectives. Additionally, monitoring and maintenance plans included in the design ensure that the infrastructure remains effective over time. By integrating these areas, we aim to provide a comprehensive understanding of the design methodologies employed in the selected Demonstrators, highlighting both the technical aspects and the practical considerations for coastal protection.

3. Design methodologies for the selected Demonstrators

3.1 Dunkerque (France)

3.1.1 General

For Dunkerque Demonstrator in front of the dike des Alliés, a dune was constructed. This hybrid solution, combining a dune with a dike, aims to enhance coastal protection. To protect the dike, a massive beach nourishment of 1.5 million cubic meters was conducted in 2013-2014. Additionally, a beach nourishment of 30,000 cubic meters is scheduled every two years to counteract erosion.

In November 2020, a beach nourishment project included the removal of sand from the seaward side of the dike to prevent weakening of the dike. This operation presented an opportunity to build the dune. The dune, measuring 600 meters in length, 20 to 30 meters in width, and 3 meters in height, was constructed with the sand accumulated on the shoreward side of the dike to enhance its protection. Marram grass was planted on the dune in December 2020.

Figure 23 - Aerial footage of Dunkerque Demonstrator (19/10/2023)

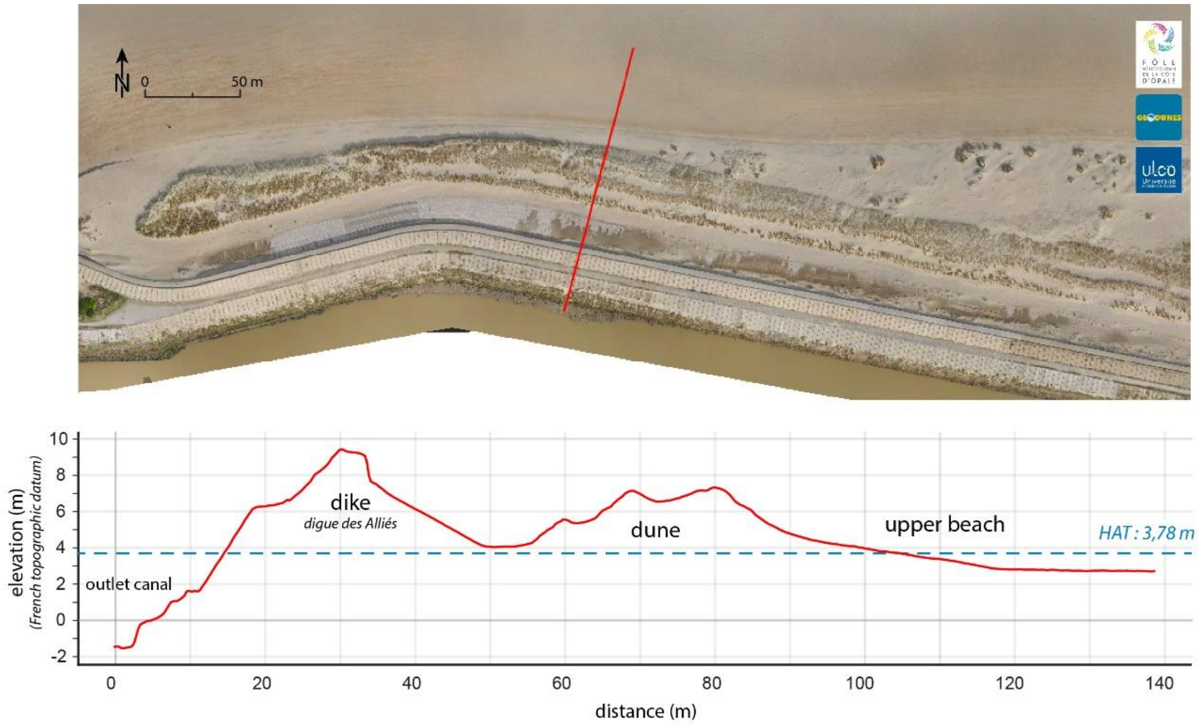


Figure 24 - Cross section profile of Dunkerque Demonstrator, including beach, dune and dike

Regarding the design method, no specific method is known. Calculations of the probability of flooding were performed for the dike before the beach nourishment. The return periods of extreme events calculated by DHI (2011) are provided in Table 3. Based on this table, the wave height at offshore (-10 to -15 meters IGN69) selected for the design of the dike protection, with an annual probability of occurrence of 1/50, is characterized by a significant wave height ($H_{s,50}$) of 3.06 meters.

Table 3 - Significant wave height and return period of extreme swells for different distribution methods

Return Period (Years)	Gumbel H_s(m)	Weibull H_s(m)	Pareto gen. H_s(m)	Exponential H_s(m)
10	2.54	2.82	2.79	2.78
20	2.93	2.91	2.87	2.86
50	**3.06**	3.04	2.98	2.96
100	3.14	3.14	3.06	3.03

The design lifetime of the structure is currently unknown. Further information is being sought from the Port of Dunkerque. The design storm duration for morphodynamics and hydrodynamics/overtopping/flooding is unknown. No specific reliability method is used for this Demonstrator. The design hydrodynamic conditions are also not provided. There is no design report available for the dune.

3.1.2 Design criteria

Safety criteria are not applicable. No safety line, is defined.

Other design criteria include definitions of synthetic storm conditions while considering global warming presented by DHI for the project. These conditions are found in Table 4:

Table 4 - Synthetic storm conditions including global warming

Storm Condition	Water level (m CM)	Wave height H_s (m)
TS1 with RC	+6.97	3.06
TS2 with RC	+7.93	2.08

Note: CM = Cote Marine, below the lowest tide level
RC = Réchauffement Climatique (Global Warming)

3.1.3 Modelling methodology

The starting profile for the evaluation of flooding safety is unknown.

For the dike, the morphodynamic modelling (without the dune) study utilizes a hybrid approach developed by DHI, combining 2DH models with "cross-shore" evolution models of the coastline. This innovative method is further explored in Kristensen et al. (2010). The dimensions considered for the modelling are cross-shore, and the physical processes incorporated into the design process are defined by the Extreme Value Analysis (EVA) tool from the MIKE 21 software suite, which helps determine extreme swells at the dike.

In terms of hydrodynamics modelling, it uses models such as MIKE 21, MIKE 21 SW, and MIKE 21 ST for hydrodynamics, with the LITDRIFT model developed by DHI for sediment transport.

Overtopping, according to DHI, is characterized solely by the water level. The most critical condition for modelling this phenomenon involves a combination of high water levels and low swell. The modelling employs the LITPACK model developed by DHI, which calculates the evolution of swell and surge as it approaches the coast. This is done along a beach profile extending approximately 2 km from the shore (from the bottoms generally between -10 to -15m IGN69), using bathymetric data from the C-Map database and LIDAR topographic data. The model provides sea conditions at the foot of the structure, considering the local bathymetry (Table 5 and Figure 26). The estimation of the overtopping flow is conducted using Eurotop formulations as detailed in the "Wave Overtopping of Sea Defences and Related Structures - Assessment Manual". The dimensions considered for this modelling are cross-shore, and detailed numerical model settings or experimental setups are not available.

3.1.4 Dike stability

The dike, originally built in 1876 and reconstructed twice after the storms of 1949 and 1953, features a concrete core. It is covered with sand, clay gravel, and marl on both the sea and canal sides. The sea-facing slope is protected by masonry, while the canal-facing slope is reinforced with anchored reinforced concrete slabs. Reinforcement works were conducted from June 2017 to July 2018. The specific dike stability method, from geotechnical and structural aspects, is not available.

3.1.1 Monitoring & Maintenance

A monitoring and maintenance plan is included, involving the monitoring of the beach and dune every six months. This monitoring includes DTMs, drone surveys, and surficial grain size analysis.

3.1.2 Other information

Additional relevant information includes a 2D study of wave propagation and currents, along with an almost 3D study of sediment transport, implemented using the SW, HD, and ST modules of DHI's MIKE 21 software suite. This study effectively summarized the hydrosedimentary functioning of the Digue des Alliés site, as detailed in DHI (2012). As shown in Table 5, the water level for the 100-year condition is selected for the study. Therefore, it can be concluded that this return period might unofficially be considered the design or assessment return period.

Table 5 - Estimated total extreme water levels at the foot of the dike (DHI, 2017)

Return Periods (years)		10	20	80	100	100+20 cm	100+60 cm
Level (m NGF)	Static Level	4.40	4.49	4.61	4.7	4.9	5.3
		0	0	0	0.24	0.22	0.18
		nc	nc	0.23	0.02	0.03	0.03
	Total	4.40	4.49	4.84	**4.94***	**5.12***	5.48*
Level (m CM)	Total	7.09	7.18	7.53	7.63	7.81	8.17

Extreme water level at the toe of the dike (before beach nourishment and dune building).
NGF : Mean sea level at Marseille

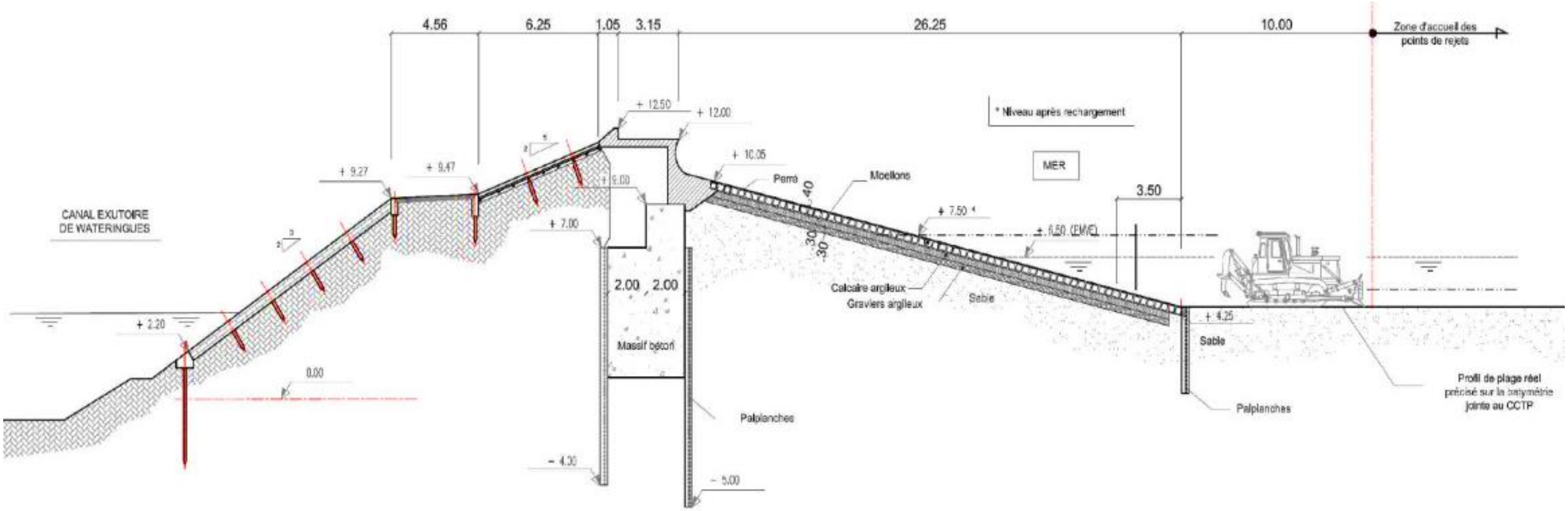


Figure 25 - Existing dike cross section in the Dunkerque Demonstrator (Hamard et al., 2019).

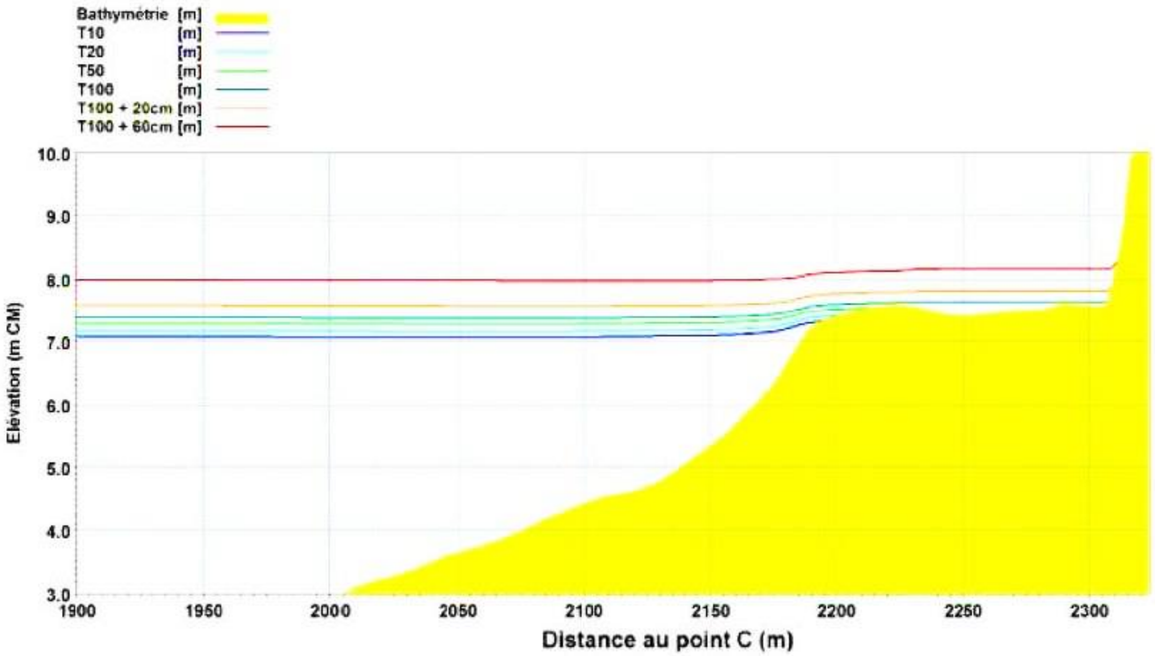


Figure 26 - Evolution of water level for different return periods of extreme water level (DHI, 2017)

3.2 Sainte-Marie La Mer (France)

3.2.1 General

Sainte-Marie La Mer involves a dune on the upper beach against a dike. The dike was built a few decades ago, and a restoration program was completed in December 2021. The design method for the grey dike is not specified as either deterministic or probabilistic, and similar considerations were not taken into account for the dune part. The design lifetime for both the grey dike and the dune was not estimated during the design phase.

The design storm duration is unspecified for the grey dike and was not considered for the dune part. Additionally, no specific reliability method is applied to either the dike or the dune. The design hydrodynamic conditions are not detailed for either the dune or the dike. Although the design report to initiate the restoration program is available, it only includes information about the area, surface, and fence characteristics.

3.2.2 Design criteria

No information on the safety criteria for the design is available for either the dike or the dune although the dyke protects stakes against flooding of part of the city. For the dune restoration, the goal is to mitigate the effects of chronic erosion and damage on the grey dike. However, there is no clearly defined safety line where safety criteria are checked.

3.2.3 Modelling methodology

No information are available regarding modelling methodology of this Demonstrator.

3.2.4 Dike stability

No information are available regarding dike stability.

3.2.5 Monitoring & Maintenance

No monitoring and maintenance plan has been provided for the dike, except for the winter of 2024 following damages in April 2024, although specific details are not yet known. For the dune system, a topographic survey is conducted biannually, and the fence line has been rebuilt following storms. Additionally, an average of 15,000 m^3 of beach nourishment is carried out annually in front of the system.

3.2.6 Other information

In April 2024, strong damage occurred after moderate storms in the area. The southern part of the system experienced complete erosion of the dune and damage to the grey dike. As a result, access to this part of the beach is currently closed (Figure 14).

3.3 Raversijde (Belgium)

3.3.1 General

The design type is a dike on a shallow foreshore, which includes a low embryonic dune and a beach. The safety assessment methodology used is deterministic with a return period of 1000 years. The design aims to ensure safety until at least 2050, as detailed in section 3.3.2 concerning safety criteria. The design storm duration for morphodynamics is 45 hours and the maximum storm surge assumed at the mean spring high water level. The theoretical asymmetric storm surge is defined by:

$$O(t) = O_{max} Cos^2(\frac{\pi . t}{T_s}) \tag{1}$$

In the above formula, $O(t)$ is the storm surge over time, O_{max} is the maximum storm surge, t is the time until O_{max} at t = 18h, and T_s the total duration of the storm surge. The asymmetric storm surge is obtained by assuming T_s = 35h before O_{max} and T_s = 55h after O_{max}.

For hydrodynamics, overtopping, and flooding, the storm duration is 1 hour and 45 minutes, approximately equivalent to 500 waves. The reliability method employed uses safety factors:

- Dune: 2/3 of the height difference between RP = 1000 yrs and RP = 10000 yrs is added to the 1000 year water level.
- Dike: Residual strength of dike after first damage is not taken into account.

The design hydrodynamic conditions are as follows:

Table 6 - The design hydrodynamic conditions for Raversijde Demonstrator

	Water level [mTAW]	SLR	Wave conditions			Location of data	Bottom level at location (non- or breaking conditions)
			Hm0 (m)	Tp / Tm-1,0 / Tm01 / Tm02 / … (s)	Direction (°N) and directional spreading		
Dune	+7.37	Base scenario in 2021	4.85	T_p = 11.61, $T_{m-1,0}$ = 10.2	Omni-directional (s = 24°)	nearshore	-5 m TAW (non-breaking)
Dune	+7.68	SLR scenario +0.3 m	5.00	T_p = 11.61, $T_{m-1,0}$ = 10.2	Omni-directional (s = 24°)	nearshore	-5 m TAW (non-breaking)
Dune	+8.18	SLR scenario +0.8 m	5.25	T_p = 11.63, $T_{m-1,0}$ = 10.27	Omni-directional (s = 24°)	nearshore	-5 m TAW (non-breaking)
Dune	+8.88	SLR scenario +1.5 m	5.58	T_p = 11.64, $T_{m-1,0}$ = 10.36	Omni-directional (s = 24°)	nearshore	-5 m TAW (non-breaking)
Dike	+7.05	Base scenario in 2021	4.66	T_p = 11.21, $T_{m-1,0}$ = 9.9	Omni-directional (s = 24°)	nearshore	-5 m TAW (non-breaking)
Dike	+7.35	SLR scenario +0.3 m	4.80	T_p = 11.21, $T_{m-1,0}$ = 9.92	Omni-directional (s = 24°)	nearshore	-5 m TAW (non-breaking)
Dike	+7.85	SLR scenario +0.8 m	5.04	T_p = 11.21, $T_{m-1,0}$ = 9.99	Omni-directional (s = 24°)	nearshore	-5 m TAW (non-breaking)
Dike	+8.55	SLR scenario +1.5 m	5.36	T_p = 11.24, $T_{m-1,0}$ = 10.05	Omni-directional (s = 24°)	nearshore	-5 m TAW (non-breaking)

The design report by Vuik et al. (2020) is publicly accessible. However, the report by De Roo et al. (2021) is not currently available to the public but will be accessible starting from January 1, 2025.

3.3.2 Design criteria

The design incorporates two safety criteria: the mean overtopping discharge must not exceed 1 l/s/m, and there should be no initial structural damage to the dike. The safety line, which is where these safety criteria are checked, is determined by the areas that need protection against storm surges and related flooding or overtopping. This line is established as the most seaward boundary of habitation, such as buildings, and is provided by the government. There are no other additional design criteria specified.

3.3.3 Modelling methodology

The morphodynamics modelling method for beach and dune erosion over the design storm duration starts with the current cross-shore profile of the beach or dune before the storm event, including the existing height and characteristics of the dunes and beaches. This profile begins at -5 m TAW, or 1500 m offshore from the shoreline, and extends to 100 m landward of the safety line. The real bathymetry is included 250 m on either side of the cross-section. The XBeach numerical model v1.24 [Surfbeat] (Roelvink et al., 2009) is used to simulate morphodynamics such as beach and dune erosion over the design storm duration. The modelling considers 3D with alongshore variable profiles over 500 m. Physical processes considered in XBeach include wave transformation of short-wave motion using the wave action equation, dissipation model, roller model, radiation stress gradients, nonlinear shallow water equations (NLSWE), and sediment transport based on a depth-averaged advection-diffusion equation with a source-sink term derived from the equilibrium sediment concentrations approach formulated by Galappatti and Vreugdenhill (1983)

XBeach Model Parameters are covered in Annex section of this report. The XBeach model settings include several crucial parameters. The bed composition parameters (D50 = 0.000334, D90 = 0.000515) define sediment grain sizes, influencing transport dynamics. The flow boundary conditions are set to absorb incoming waves at both the front and back (front = abs_1d, back = abs_1d). Key physical processes include sediment transport (sedtrans = 1), morphological changes (morphology = 1), and wave modelling using surfbeat for capturing wave group effects. The grid parameters specify a resolution with 417 grid points along the x-axis (nx = 417), and a wave angle range from -90 to 90 degrees. The model time is set for 172800 seconds (48 hours) with a CFL condition of 0.9. The wave boundary condition uses a JONSWAP spectrum (bcfile = jonswap.txt), essential for realistic wave energy distribution.

For hydrodynamics modelling used for overtopping and flooding, a fixed bed assumption is employed, and the eroded bed profile is based on the post-storm XBeach bathymetry. The SWASH version 7.01 numerical model (Zijlema et al., 2011) is used to model wave transformation from deeper water to the dike toe and wave overtopping at the safety line. The modelling is conducted in 3D, considering both 2D horizontal (x and y) and 2 vertical layers (z) for accurate representation of the IG waves (Rijnsdorp et al., 2014), to account for 3D effects such as beach topography, dike geometry, and wave climate. The governing equations in SWASH include the nonlinear shallow water equations with non-hydrostatic pressure and some transport equations, providing a basis for simulating wave transformation in both surf and swash zones due to nonlinear wave-wave interactions, interaction of waves with currents, interaction of waves with structures, wave damping due to vegetation, and wave breaking as well as runup at the shoreline.

SWASH Model Parameters are covered in Annex section of this report. This numerical model operates in 2D non-hydrostatic mode (MODE NONST TWOD), with an initial water level (SET LEVEL 6.93) and water density (SET RHOWAT 1025). Key input grids include the bottom (READINP BOTTOM -1 'SA21_15_172-176_01_zz.bot') and water level (READINP WLEVEL 1 'SA21_15_172-176_01_zz.dwl'), and boundary conditions are specified using a JONSWAP spectrum (BOU SHAP JON 3.3 DSPR DEGR). The friction and wave breaking parameters (FRIC MANN 0.019 and BREAK 0.6 0.3) influence sediment transport and wave dissipation. The model includes non-hydrostatic settings and discretization schemes (NONHYDROSTATIC BOX PREC ILU, DISCRET UPW MOM), and time steps are controlled with TIMEI 0.2 0.5.

The model used for overtopping and overwash is the same SWASH numerical model used for the hydrodynamics modelling. A deterministic value for the mean overtopping discharge (q) is obtained by conducting three SWASH simulations and applying the method of Ottevaere (2011), which represents the upper limit of a 68% error interval. The modelling remains 3D, considering both cross-shore and alongshore variable profiles, with 2D horizontal (x and y) and 2 vertical layers (z). The physical processes considered in the design process are detailed in the SWASH numerical model settings described earlier.

3.3.4 Dike stability

The dike is an impermeable smooth dike. The stability of the dike slopes under storm conditions is a critical criterion, requiring the dike materials and construction to be capable of resisting the hydraulic pressures and dynamic forces of storm-driven waves without failing.

3.3.5 Monitoring & Maintenance

A monitoring and maintenance plan is provided in the design. A safety assessment is required every six years, with beaches and dunes monitored twice per year and the foreshore bathymetry monitored annually. The structural integrity of the dike is also regularly monitored. Maintenance activities, such as beach nourishments and dike renovations or updates (e.g., storm walls), are carried out as needed based on the results of the safety assessments.

3.4 Middelkerke (Belgium)

3.4.1 General

The “Grasdijk” of Middelkerke is a dune constructed in front of the existing sea wall. From a coastal safety perspective, it functions as a dune system. The sea wall’s presence is neglected during safety assessments because it cannot be inspected due to the dune in front of it. The design method used is deterministic, with a return period of 1/1000.

The predesign was assessed at two points in time: in 2020 to determine compliance with current design standards, and in 2070 to evaluate resilience to sea level rise. The design storm duration for morphodynamics is 45 hours, while for hydrodynamics, overtopping, and flooding, it is 40 minutes. Safety margins are included in the design methodology, such as the addition of two-thirds (2/3) of the “decimeringshoogte” (decimating height) to the design water level in XBeach. The design hydrodynamic conditions are detailed in Table 7. The design reports cannot be made publicly accessible.

Table 7 - The design hydrodynamic conditions for Middelkerke Demonstrator

	Water level	SLR	Wave conditions			Location of data	Bottom level at location (non- or breaking conditions)
			Hm0 (m)	Tp	Direction (°N)		
Dune – Xbeach 2020	7.32 m TAW	/	4.95 m	11.4 s		In front of the project location	-5 m TAW
Dune - XBeach 2070	7.74 m TAW	42 cm	5.12 m	11.4 s		In front of the project location	-5 m TAW
Dune-SWash 2020	7.00 m TAW	/	4.82m	11.2 s	90 ° to the local coastline	In front of the project location	-5 m TAW
Dune Swash 2070	7.42 m TAW	42 cm	4.99 m	11.2 s	90 ° to the local coastline	In front of the project location	-5 m TAW

3.4.2 Design criteria

The safety criteria for the design include maintaining a minimum dune volume and ensuring the maximum allowed mean overtopping discharge is not exceeded. A safety line is defined, and it is situated at the seaward side of the buildings on top of the seawall. Other design criteria involve the beach profile meeting requirements related to the exploitation of the beach and the beach slope to avoid cliff formation after summer storms.

3.4.3 Modelling methodology

The morphodynamics modelling method for beach and dune erosion over the design storm duration starts with a profile based on an architectural design and the latest topographic and bathymetric survey. The XBeach model, modified based on the latest knowledge (Kingsday instead of Ground Hog), is applied according to the official safety assessment methodology in Flanders (Suzuki et al., 2015). This model is quasi-2D and considers relevant physical processes as detailed in the design reports.

For hydrodynamics modelling used for overtopping and flooding, a fixed bed assumption is made, using the eroded bed profile at the end of the storm. The SWASH model, in accordance with the official safety assessment methodology in Flanders (Suzuki et al., 2015) and physical model, is applied. The boundary conditions at the toe of the dike are calculated using a 2D SWASH model. Detailed numerical model settings and experimental model setups can be found in the design reports.

For overtopping and overwash, a combination of empirical formulas and the SWASH model is used, according to the official safety assessment methodology in Flanders (Suzuki et al., 2015). The SWASH model in this section is a 1D model, and the physical processes considered in the design process are detailed in the design reports.

3.4.4 Dike stability

The type of the dike and the dike stability method used, are not known.

3.4.5 Monitoring & Maintenance

A monitoring and maintenance plan is included in this project. Monitoring is conducted twice a year using LIDAR, before and after winter, along with some results from drone monitoring. Additionally, a maintenance plan is available to ensure the ongoing integrity of the design.

3.5 Katwijk (The Netherlands)

3.5.1 General

The assessment for the project involves a dike in dune, realized over a total of 1.8 km in 2014 during the KustWerk project in Katwijk. Within this stretch, a 1.0 km segment (RSP 86.40 to RSP 87.40) includes a dike profile buried within the dune. The northern side features an outfall channel, creating a complex 3D situation for which advanced 2D XBeach calculations were made (Arcadis, 2012). However, only the 2D situation of the dike and dune is considered here.

The dike/dune combination consists of a dike profile or revetment with a top layer of placed blocks, situated inside the dune. The general cross-section of this revetment is illustrated in the following figure:

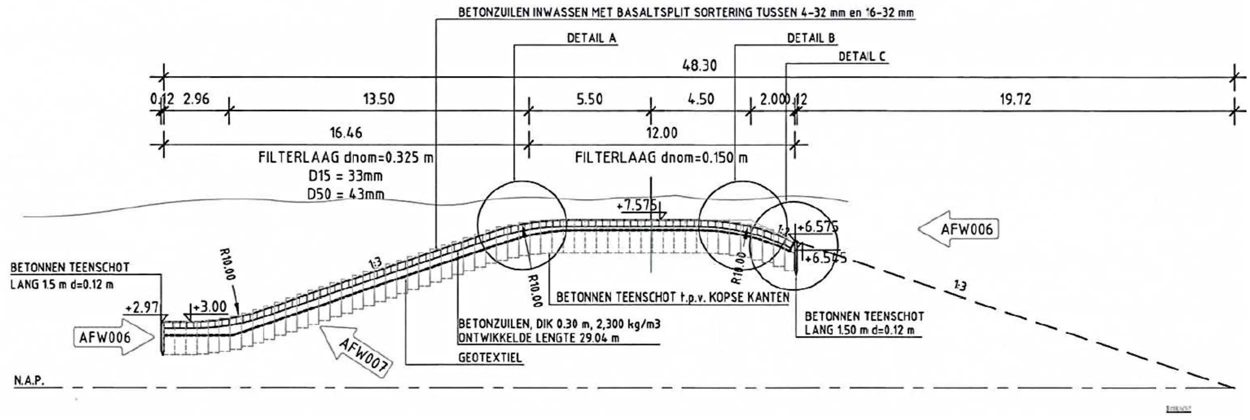


Figure 27 - General cross section of hard construction (Rohde Nielsen & Ballast Nedam, 2014)

The design profile for the beach is provided, as illustrated by Boer and Wouters (2014).

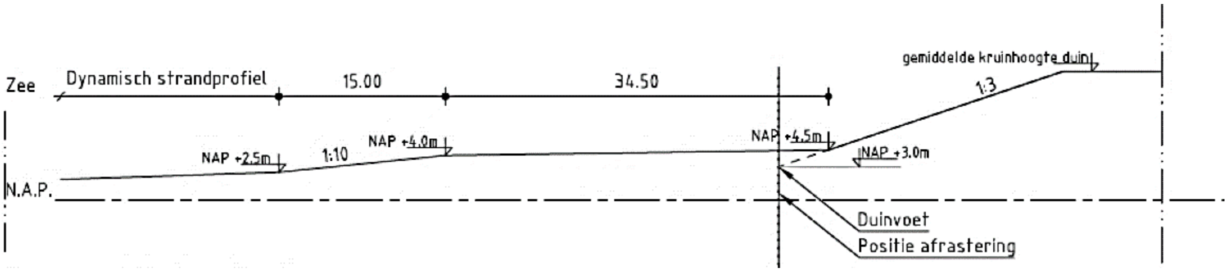


Figure 28 - Design (requirement) of the beach profile to be constructed (Boer & Wouters, 2014).

A calculation using the designed dune profile, dike profile, and eroded dune profile after a design storm is shown in Figure 29.

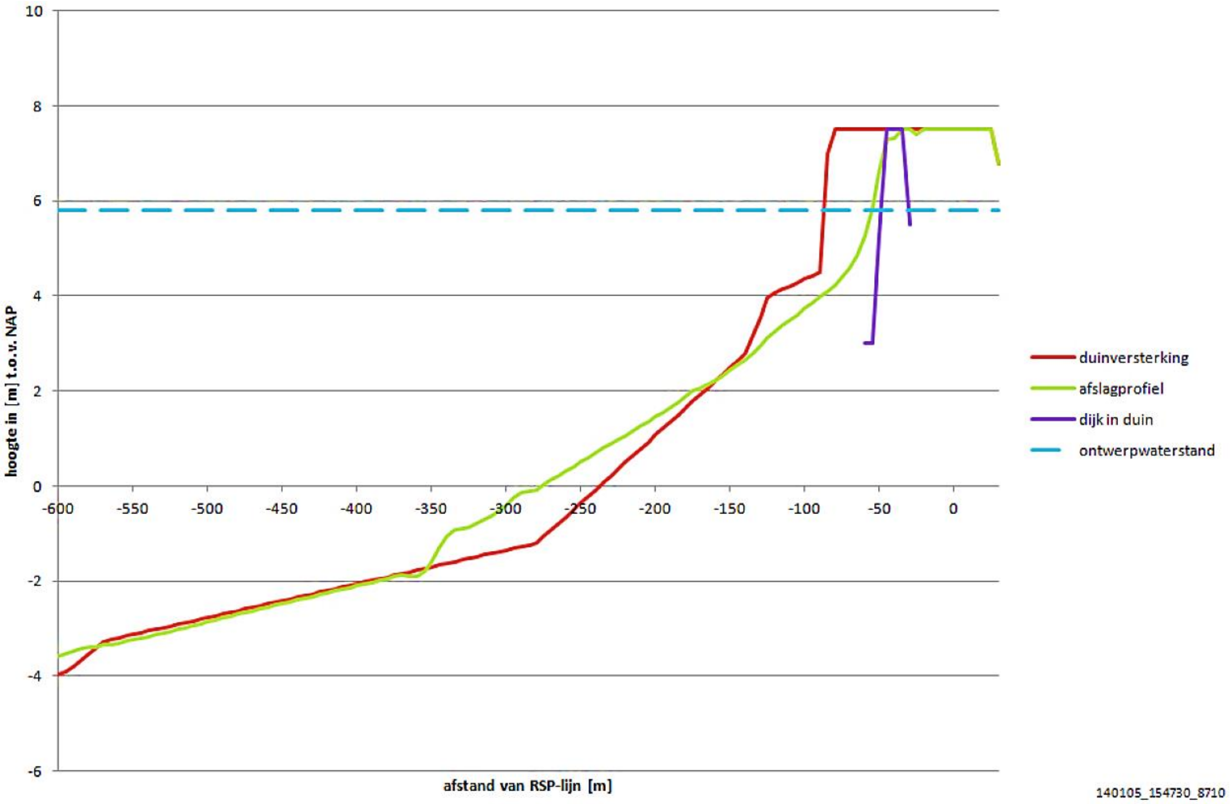


Figure 29 - Cross section of DUROS results of dune erosion at cross section RSP 87.10, where eroded profile (green) reaches the dike slope (purple) (Boer & Wouters, 2014).

The design is based on a minimum sand diameter of 255 microns. At the site, sand with an average diameter of 271 microns and a standard deviation of 30 microns in D_{50} of various samples. The design document discusses the possibility of extra dune erosion immediately adjacent to the hard structure. However, since erosion is not expected to extend much further than the dike, and the dike bends gently towards the land, no additional erosion next to the hard protection was anticipated.

The design method for the project is based on conditions determined by the Dutch probabilistic safety system, HYDRA-NL, which sets an exceedance probability of 1 in 10,000 years.

As the dune is easier to adapt than the buried revetment, different life times have been taken into account (Boer & Wouters, 2014):

- 50 years without adaptations (dune, crest elevation)
- 100 years with adaptations (less adaptable parts of the protection, like slope and toe)

The design reports mention adaptations such as increasing the sand volume and raising the crest height of the dike. The dike slope is designed to meet the requirements for a 100-year lifetime from the outset.

The design storm duration for morphodynamics is 35 hours, with conditions gradually increasing and decreasing, as depicted in the following figure.

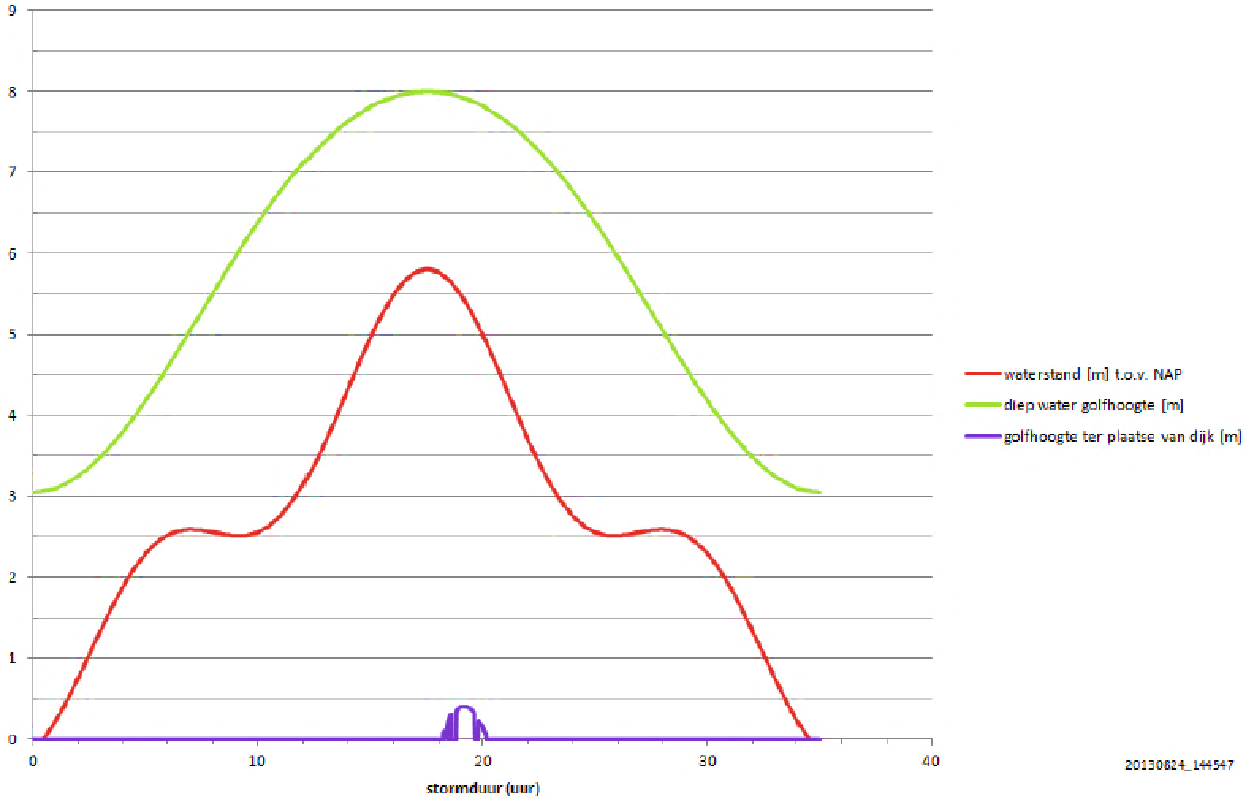


Figure 30 - An example of the hydrodynamic conditions at the site. With the water level (red), deep water wave height (green), and wave height at the dike toe (purple).

Regarding the design storm duration for hydrodynamics/overtopping/flooding, it should be noted that, the hydrodynamics on the dike are considered for the entire duration that the dike slope is uncovered during a storm.

The HYDRA-NL (Slomp, 2016) approach was used to determine the design values of the hydrodynamic variables, following standard Dutch assessment methods. This approach combines simultaneous observations of wind and water levels, WAQUA calculations of extreme water levels, and stationary SWAN calculations for converting offshore extreme wave heights to the coast. This generates a statistical description of the main hydrodynamic parameters, including their correlations. Using a simplified dune erosion model, the exceedance probability and response function (dune erosion) are determined. HYDRA-NL includes various probabilistic methods for calculating failure probability and illustration points, such as direct integration, various forms of Monte Carlo (crude, importance sampling, directional sampling), and First Order Reliability Method (FORM). The specific method used here is unclear, as the report on the derivation of the hydraulic boundary conditions is unavailable.

The design hydrodynamic conditions were taken from the design reports by Boer and Wouters (2014) and Wouters and Boer (2014), as the report describing the derivation of these conditions was not available. These conditions include parameters such as water level, sea level rise (SLR), wave conditions (H_{m0}, period, direction), and specific locations (offshore, dune, or dike toe).

Table 8 - The design hydrodynamic conditions for Katwijk Demonstrator

Condition / scenario	Water level m+NAP for dune / dike	Wave conditions			Location of data	Bottom level at wave output
		Hm0 (m)	Tp / Tm-1,0 (s)	Direction (°N)		
50 years, medium SLR	5.8 / 5.9	8.0	13.9 / 12.6	perp.	deep water	NAP-20 m
100 years, max SLR	6.75 / 6.85	8.4	14.2 / 12.9	perp.	deep water	NAP-20 m

Two design lifetimes were considered: 50 years and 100 years, with the middle and maximum sea level rise scenarios, respectively. The water levels include the formal probabilistically determined assessment level of 5.2 m+NAP, a robustness addition of 0.3 m, expected sea level rise (0.3 m and 0.85 m, respectively), and extra storm surge due to sea level rise (0 m and 0.4 m, respectively). For the dike crest elevation (overtopping), an additional 0.1 m was added to account for rain-shower-induced water level oscillations.

The design reports can be made publicly accessible.

3.5.2 Design criteria

The safety criteria for the design are specified for both the dike crest and the dune. For the dike crest, the overtopping limit under design conditions is set at q = 1 l/m/s. For the dune, the wave height in front of the dike (15 meters seaward from the intersection between the dike slope and the sand profile) should remain under 0.5 meters. The dike was designed using an H_s of 0.6 meters, with the maximum wave height from DUROSTA set at 0.5 meters (a safety margin of 1.2) at 15 meters in front of the dike.

The overtopping safety criterion is defined at the seaward crest line, while the wave height criterion is defined 15 meters seaward of the dike toe. Additionally, the main dune profile, with a 1:3 virtual rear slope intersecting with NAP, should remain away from a predefined line marking the location of houses.

Other design criteria include ensuring that the beach profile and sand diameter are similar to their conditions before the upgrade to avoid altering longshore transport and other morphological effects.

3.5.3 Modelling methodology

The morphodynamics modeling method for beach and dune erosion over the design storm duration begins with the starting point, which is based on the Dutch law (Water Act). The initial profile for the beach was the existing situation, with pre-project coastal profiles shown in Figure 31 as a thick black line which is the averaged profile. The design profile included a 12% safety margin in added volume.

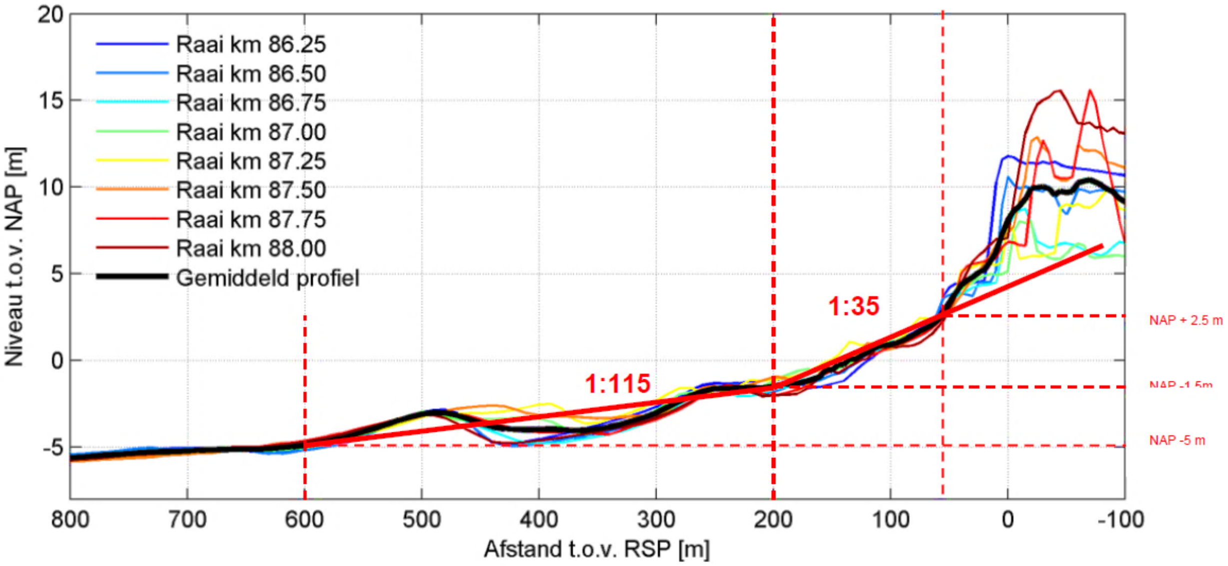


Figure 31 - Transects (yearly JARKUS measurements by Rijkswaterstaat) at the location before the project (Boer & Wouters, 2014)

The DUROSTA model was used for the dune erosion calculations for the transects where the dike was present, considering cross-shore dimensions.

DUROSTA uses the following steps (Baaren, 2007):

- Wave model ENDEC.
- The undertow is calculated from the wave heights.

- The sediment concentration profile is calculated from the preceding hydrodynamic calculations, using a flow profile obtained from turbulence theory.
- The sediment flux is the product of the former two
- The bed changes are calculated from the sediment balance (Exner equation).

A special approach was used for wet and dry dune cliff erosion, with calibration factors derived from large-scale Delta Flume experiments (e.g. for the relative wave height a relative large value of $\gamma = H_s/h = 0.85$ is used).

For hydrodynamics modeling used for overtopping and flooding, the TAW formulae were applied based on an assumed $H_s = 0.5$ m and offshore wave period. The ENDEC wave model, incorporated in DUROSTA, is a one-dimensional wave energy transport and decay (breaking and bottom friction) model, assuming a constant wave period and calculating wave setup from the radiation stress balance. The modeling considered cross-shore dimensions, using a perpendicular wave attack, and did not explicitly account for infragravity waves.

The model used for overtopping and overwash was PC-Overslag, which includes the standard TAW/Eurotop formulas with a user interface and interpolations between different slope shapes and roughnesses. For the Basalton slope, a standard $\gamma_f = 0.9$ was applied. The modeling was cross-shore, using perpendicular wave attack, and did not explicitly consider infragravity waves.

3.5.4 Dike stability

The dike has a 1:3 slope and consists of several layers. From the bottom to the top, these layers include a sand core, a geotextile layer (Geopex NW270 or similar), a 0.3 m thick filter layer of crushed gravel (D_{15} = 33 mm, D_{50} = 43 mm), and a top layer consisting of concrete Basalton columns with D = 30 cm (30 cm height (Figure 27)). The 12% open space between the Basalton columns is filled with basalt split with a D_{50} of 10 mm.

The stability of the dike is calculated using STEENTOETS (v. 1.12), with parameters of $H_s = 0.8$ m, $T_p = 14.2$ s, and perpendicular wave attack. The stability calculations for the Basalton columns employ the leakage length theory. For the wave height an approximately 50% safety margin is added to the $H_s = 0.5$ m that is used to check the erosion, so the slope is designed for $H_s = 0.8$ m.

It is mentioned without reference that sand in the pores will increase the stability of the columns, as long as no sand will come in the filter layer. According to leakage length theory, stability will however decrease with sand in the pores between the columns.

Stability of a placed block revetments as applied in Katwijk can roughly be described by the following equation (Schiereck & Verhagen, 2019):

$$\frac{H_s}{\Delta d} \propto \left(\frac{d}{\Lambda \xi_p}\right)^{0.67} \tag{2}$$

where the leakage length is $\Lambda = \sqrt{\frac{k_F d_F d_T}{k_T}}$, Δ is submerged relative density of the columns, D is concrete column height, ξ_p the Irribarren number based on peak period, H_s the significant wave height k_F and k_T the permeability of filter and top layer, and d_F the thickness of the filter.

By substituting the definition of the leakage length, and assuming all other structural parameters constant we obtain the following proportionality:

$$\frac{H_s}{\Delta d} \propto {k_T}^{0.33} \tag{3}$$

This shows that the critical stability number $H_s/\Delta D$ decreases with decreasing permeability of the top layer (columns) k_T. This in turn would indicate that the stability would be expected to decrease if sand would come between (and not under) the columns, and is not washed out during a storm. It is not sure if this will happen. However, the argument given in the design report that states that decreasing porosity (without specifying where) will increase stability seems questionable.

The elevation down to which the basalton armour layer is extended on the landward side of the dike is quantified based on arguments that, although not explicitly proven, seem plausible. Additionally, the initial 15 cm thick filter layer has been doubled in thickness to mitigate the geotechnical sliding of the subsoil (we infer this pertains to the mechanism where the sand just below the top layer liquifies due to impulsive wave impacts).

3.5.5 Monitoring & Maintenance

No maintenance plan has been provided for the design. However, the dune profiles are measured annually. According to Dutch law (Omgevingswet, Environment and Planning Act, Waterwet, or Water Act), the safety of primary sea defenses in the Netherlands must be assessed every twelve years. In the first assessment round during the lifetime of the dike-in-dune project, known as LBO1, it was observed that the dunes had grown, ensuring that the dike slope would not be reached by a design storm. As a result, the dike-dune part of the protection was approved (Hoogheemraadschap van Rijnland, 2022).

3.5.6 Other information

The dike crest was constructed 0.075 m higher to account for a maximum expected geotechnical settlement of 0.05 m (Grotegoed, 2014). A sensitivity analysis on sand diameter revealed that a 10-micron smaller sand diameter could result in an extra ca. 5 m of landward retreat of the dune cliff (Boer & Wouters, 2014). The vegetation was not considered in the dune erosion calculations in the reviewed design documents. Additionally, in the study for the outfall north of the dike-dune stretch, XBeach was used in 2012. Some calculations compared the XBeach model results with DUROSTA model results, as shown in Figure 32.

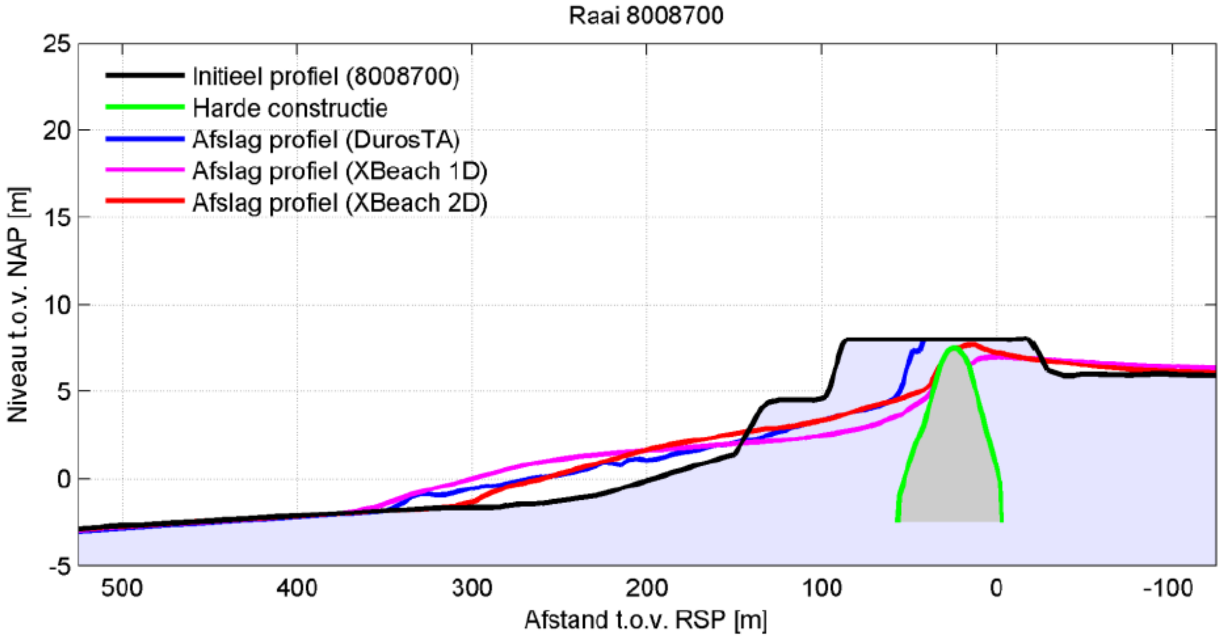


Figure 32 - comparison of erosion profile calculated with DUROSTA, and XBEACH 1D and 2D for chainage 8700 (Arcadis, 2012)

3.6 Sankt Peter-Ording (Germany)

3.6.1 General

The design and assessment of the system encompass several types: a land protection dike north of the dune system at 8 meters above mean sea level (amsl), a regional dike south of the dune system with a tar surface layer at 6.4 meters amsl, and a middle dike behind the dune system and the regional dike serving as a secondary line of defence. Additionally, there is a land protection dike south of the city vicinity where the regional and middle dikes join. This system includes a natural grey dune system ranging between 6 and 16.5 meters amsl, filling a gap between the northern land protection dike and the southern regional dike.

In Schleswig-Holstein (the location of demonstrate), the design method employed is deterministic, utilizing a statistical extreme value approach with a return period of 200 years. This method incorporates safety margins for wave overtopping (0.5 l/s/ m) and sea level rise (0.5 m), resulting in an average land protection dike height of 8.0 meters above mean sea level.

The design lifetime for parts of the system is up to 100 years, but it is revisited whenever sea level rise projections are altered, with changes made if necessary. Schleswig-Holstein has also pioneered the concept of "climate dikes", which were constructed with adaptability, allowing the dike to be raised a few meters if needed without requiring a complete redesign.

The design storm duration varies depending on the aspect being considered. For morphodynamics, there is no federal definition in Germany, but in Schleswig-Holstein, the design storm duration is 5 hours. The state designs sandy or soft structures to withstand two consecutive 5-hour storms without recuperation or nourishment. This design storm is being developed by project partners, filtering storms based on trajectory, duration, wave energy, and wind speeds, to serve as a model for future construction designs by the state agency. For hydrodynamics, overtopping, and flooding, the design water level is based on a 200-year return period, including safety margins of 0.5 meters for sea level rise and up to 0.5 l/s/m of overtopping.

For the Demonstrator's reliability, safety factors are used for the built dikes to account for sea level rise and overtopping. First Order Reliability Methods (FORM) are also applied. Nature-based hybrid solutions are being developed in collaboration with research, utilizing various approaches including physical modelling, numerical modelling, simplified geometric approaches, Duros+, adapted FEMA-540, Dunerule, and the Rational-Design-Concept for sand dikes. The dune system, while natural and not constructed, may require reinforcement in the near future.

The design hydrodynamic conditions for the dune and dike systems incorporate specific parameters and explicit values for water level, sea level rise (SLR), wave conditions, and the location of data collection. The following tables summarize these conditions for both the dune and dike:

Table 9 - The design hydrodynamic conditions for Sankt Peter-Ording Demonstrator

	Water level	SLR	Wave conditions			Location of data	Bottom level at location (non- or breaking conditions)
			Hm0 (m)	Tp / Tm-1,0 / Tm01 / Tm02 / ... (s)	Direction (°N)		
Dune	5.03	0.5	0.499 (1999) 0.425 (2007)	13.6 (1999[1]) 15.25 (2007[2])	272.75 (1999) 282.5 (2007)	N 54.278333 E 8.388420	10 m depth; wave rider buoy
Dike	5.03	0.5	same	same	same	same	same

1) Storm surge Anatol (03.12.1999), data based on 5-hour storm surge median

2) Storm surge Tilo (09.11.2007), data based on 5-hour storm surge median

Table 10 - Derived wave parameters based on the storm surge data from the federal hydrographic office Germany for 1999 and used to obtain input data for design rules to develop dune hybrid concepts

Depth range	h (m)	L (m)	T_P(s)	c_g(m/s)	Ks (-)	H_s(m)
Transition	10.0	146.65	15.25	9.077	1.137	4.25
Transition	20.0	201.20	15.25	11.746	1.007	3.74
Deep water	181.6	363.10	15.25	11.905	-	3.71

Table 11 - Derived wave parameters based on the storm surge data from the federal hydrographic office Germany for 2007 and used to obtain input data for design rules to develop dune hybrid concepts

Depth range	h (m)	L (m)	T_P(s)	c_g(m/s)	Ks (-)	H_s(m)
Transition	10.0	129.80	13.60	8.873	1.125	5.00
Transition	20.0	176.62	13.60	11.221	0.973	4.44
Deep water	144.4	288.78	13.60	10.617	-	4.56

The design reports for the project can be made publicly accessible, at least in part. The general plan for coastal protection can be found online at the following reference (Schleswig-Holstein Coastal Protection General Plan, 2022).

3.6.2 Design criteria

The safety criteria for the design include considerations for both dikes and dunes. For the dikes, the criteria involve accounting for sea level rise and overtopping discharge. In the case of dunes, there are no specific safety criteria defined yet, but ongoing research suggests a minimum dune profile based on a self-developed adoption of the FEMA-540 rule.

A safety line is defined for the dikes, where safety criteria are checked. This involves inspections after every storm surge season by local dike committees known as "Deichschau" which translates to "Dike inspection". These inspections involve checking the dike for damages related to erosion, wave impacts, debris, flotsam, muskrat burrows, drought-related canopy destruction, and crack formation in the clay layer.

Other design criteria include the implementation of climate adaptation dikes in Schleswig-Holstein, as detailed in the referenced sketches and documents as follows:

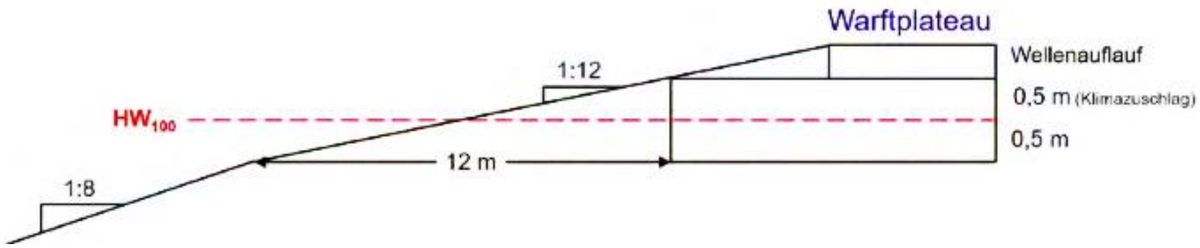


Figure 33 - Blueprint of a climate dike from the Generalplan Küstenschutz (Schleswig-Holstein Coastal Protection General Plan, 2022)

3.6.3 Modelling methodology

The morphodynamics modelling method for beach and dune erosion over the design storm duration includes several key aspects. Although no official design profile exists, a representative cross-profile was chosen during a research project and used for physical and numerical modelling as well as analytical investigations. This profile was simplified for ease of repeated construction in wave flumes at a scale of 1:7. This simplified profile is illustrated in Figure 34.

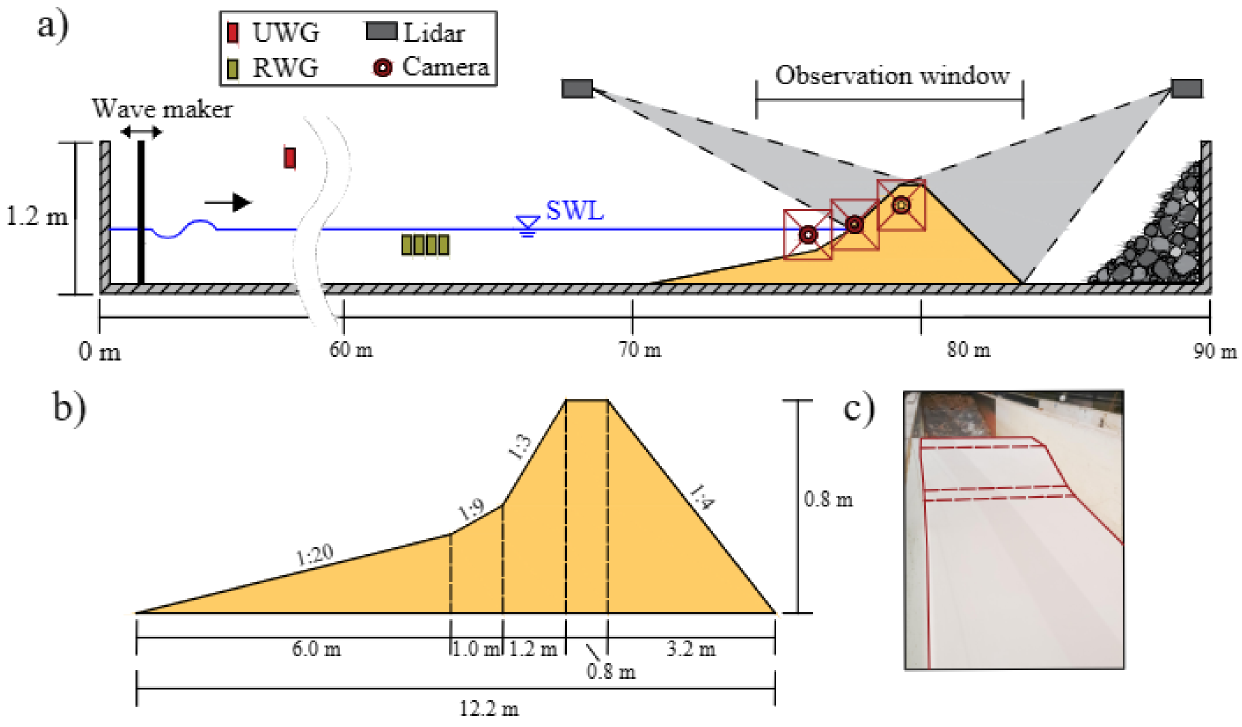


Figure 34 - A chosen simplified representative cross-profile for physical and numerical modelling.

For modelling, the state authority utilizes a hydro-numerical model for water level projections of 1:200 year return period values. This model is run by the Federal Agency for Hydraulic Research (Bundesanstalt für Wasserbau) using a multi-model corridor approach that includes Delft3D, Telemac2D, and Untrim. In research collaborations, physical modelling has been conducted on a 1:7 scale across more than 100 experiments. Additionally, a numerical XBeach model of the simplified dune profile has been calibrated and extensively used, and a numerical Delft3D model of the entire Demonstrator area is currently being calibrated.

The dimensions considered for modelling by the federal agency include a 3D approach with varying grid resolution, using a sigma-layer approach and a sub-model approach. For dike design, hydro-numerics are considered, focusing on tidal water levels and wind-surge but not dedicated wind wave modelling. The research collaboration models also use a physical model at a 1:7 scale to represent the main dune and foredune chain, with lateral extents downscaled. Numerical XBeach models represent both the flume model (1:7) and real-world profiles spanning a cross-shore length of 1.5 to 2.0 km, with multiple profiles available but not fully calibrated. A 3D model of the area is under development using XBeach and Delft3D.

The physical processes considered in the design process by the state agency include wave run-up, overtopping, wind surge, tidal high water, spring tide, sea level rise, and safety margins for amplified wave run-up. In the state research collaboration project on Sankt Peter Ording (SPO), the physical model is driven by a JONSWAP spectrum running an amplified dual storm surge boundary condition for a total of 113 minutes (scaled 1:7). The model is made of sand scaled by the Dean parameter for representative grain sinking velocities. Dune canopy coverage has been omitted for large parts, and experimental lines have approached and mimicked above and below-ground vegetation impacts on overall erosion behaviour. Wave run-up, collision, breaching, and overwash were investigated physically and numerically using XBeach.

For hydrodynamics modelling used for overtopping and flooding, a maximum overtopping volume has been defined based on experiments conducted before 2010, typically based on the Eurotop manual, limiting it to 0.5 l/s/m. The state research collaboration project on SPO conducted erosion experiments under live bed (erodible) conditions, with experiments including a wooden foredune to alter distance and investigate its influence on main dune erosion.

The models applied in the state research collaboration project on SPO include numerical XBeach (scaled and unscaled) and physical flume experiments (1:7 Froude scaled) in a 2m x 1.2m x 90m wave flume, where overtopping volume was captured and measured. The state agency uses a 3D model of the North Sea with variable resolution increasing towards the coast and complex bathymetric areas like estuaries or islands. The state research collaboration project on SPO uses a cross profile of 1.5 to 2.0 km in length, with a resolution of 0.01 to 0.1 meters.

The physical processes considered in the design process by the federal agency for hydraulic engineering include a 3D hydrodynamic model of the North Sea, incorporating salinity, waves, and tides. Detailed model settings and experimental setups are documented in several references, such as (Robert Hagen et al., 2021) and (R. Hagen et al., 2021).

For overtopping and overwash modelling, the state agency follows the Eurotop Manual. The state research collaboration project on SPO utilizes both XBeach and physical models for these processes. The dimensions considered for modelling and the physical processes involved align with the methods described in previous sections.

3.6.4 Dike stability

The type of dike used in the project varies depending on its location and function. The land protection dike north of the dune system consists of a sand core with a clay cover and a grass canopy. The regional dike, which runs south of the dune system until it merges with the southern land protection dike, has a sand core with a tar cover. The middle (secondary) dike is constructed as a sand/earth dike with a clay cover and grass canopy. Additionally, within the town of Sankt Peter-Ording, mobile flood defense walls are deployed in emergencies.

The dike stability method, encompassing geotechnical and structural aspects, is currently unclear and has been forwarded to the state agency for clarification. It is likely that the task is outsourced to a geotechnical engineering office.

3.6.5 Monitoring & Maintenance

A monitoring and maintenance plan is provided in the design, organized at the state level by law. In Schleswig-Holstein, the revision of design water levels is scheduled for 2030. Monitoring is conducted annually after the storm surge season to check for and repair any damages. During the storm surge season, dike boards regularly send out personnel to check the stability of the dikes. Maintenance is performed as needed.

3.6.6 Other information

The regional dike in Sankt Peter-Ording, which spans from the southern side of the dune system to the southern end of the municipality, is currently at 6.4 meters above mean sea level (amsl). The state agency considers this height to be insufficient. A revision and adaptation blueprint is currently in preparation, although the details are not yet available.

3.7 Ystad (Sweden)

3.7.1 General

Ystad Demonstrator involved an existing rock revetment, with a beach nourishment implemented in front of it to stimulate the development of dunes. Experiments with plantation in front of the existing dune row led to the establishment of dunes on the wide beach in front of the original dunes.

The design method did not follow specific criteria; instead, the nourishment was carried out to counteract coastal erosion. The resulting increase in flood safety is a positive but unquantified side effect.

The design lifetime for the nourishment is planned for replenishment every three years. No information is available regarding design storm durations or the design hydrodynamic conditions. Additionally, no reliability methods are applied in this project. However, the design reports can be made publicly accessible.

3.7.2 Design criteria

There are no specific safety criteria for the design.. Additionally, there is no defined safety line where safety criteria are checked. Other design criteria are also not applicable in this context.

3.7.3 Modelling methodology

No information is available regarding the starting profile for the design evaluation of flooding safety. However, model studies have been conducted using tools like LITPACK, though these were not intended for design purposes. The modelling utilized a one-line model, but detailed descriptions of the physical processes considered in the design process, steps taken, and methodologies used are not known.

3.7.4 Dike stability

The type of dike used in the project is a rock revetment. However, information regarding the dike stability method, including geotechnical and structural aspects, is not available.

3.7.5 Monitoring & Maintenance

A monitoring and maintenance plan is provided, which includes regular topographic surveys.

4. Comparison of the design methodologies and discussion

In the following section, we will compare the methodologies employed across the selected Demonstrators, discussing their similarities and differences to offer insights into their effectiveness, adaptability and identify the knowledge gaps to improve the current design methodology for DD-hybrid NbS. To ensure a structured approach, we will follow the same format used in Section 3, focusing on the Design methodologies for the selected Demonstrators. The comparison will begin with general information for each Demonstrator, followed by design criteria, modelling methodology, dike stability, and finally monitoring and maintenance.

4.1 Comparison of general information

Dunkerque employs a hybrid solution combining a dune with a dike, enhanced by substantial beach nourishment. Initial massive nourishment was followed by biennial smaller-scale replenishments to counteract erosion. The design lacks a specific methodology and design storm duration, focusing instead on flood probability calculations based on significant wave heights. According to Table 5, the 100-year return period is considered for the design / assessment of this demonstrator. Therefore, this return period was assumed for the demonstrator. This approach contrasts with the more structured methodologies of other Demonstrators.

Sainte-Marie La Mer features a dune adjacent to an existing grey dike, restored in 2021. The design methods for both structures are unspecified, with no detailed design storm duration or hydrodynamic conditions. The absence of a reliability method and the focus on physical restoration rather than probabilistic safety assessments indicate a simpler, less quantitative approach compared to other Demonstrators.

Raversijde utilizes a deterministic safety assessment with a 1000-year return period and a detailed storm surge model. The design considers morphodynamics and hydrodynamics with specific storm durations, incorporating safety factors for both dune and dike. This methodical approach is detailed, employing safety margins and reliability methods, reflecting a higher level of complexity and precision compared to Dunkerque and Sainte-Marie La Mer.

Middelkerke also adopts a deterministic approach with a 1000-year return period, focusing on compliance with design standards for current and future sea level scenarios. The design includes specific storm durations and incorporates safety margins into the hydrodynamic conditions. This structured approach, similar to Raversijde, emphasizes resilience and adaptability to future conditions, contrasting with the more ad hoc methodologies seen in Dunkerque and Sainte-Marie La Mer.

Katwijk features a combination of dike in dune, assessed using the Dutch probabilistic safety system, HYDRA-NL, with an exceedance probability of 1 in 10,000 years. This comprehensive approach includes detailed hydrodynamic conditions, storm durations, and adaptive measures for different lifetimes. The probabilistic method and extensive design considerations make this one of the most robust and scientifically grounded methodologies.

Sankt Peter-Ording employs a deterministic method with a 200-year return period, incorporating climate adaptation features. The design accounts for sea level rise and wave overtopping, using multiple safety factors and reliability methods. The emphasis on climate resilience and the ability to extend dikes without redesigns highlight its forward-thinking approach, similar in complexity to Katwijk.

Ystad focuses on beach nourishment to combat erosion and promote dune development without specific design criteria or reliability methods regarding the coastal protection functioning. The nourishment is refilled every three years, and while flood safety is enhanced, it is not quantified. This method is simpler and more reactive compared to the structured approaches of Raversijde and Katwijk.

Different return periods can be seen to be applied, ranging from (unofficial) 100 years (France), to 200 years (Germany), to 1000 years (Belgium), to ~10 000 years (Netherlands). These return periods seem to roughly correspond to the local consequences (e.g., casualties, damage to infrastructures,…) of a failure of the flood defence.

For many of the hybrid protections adaptability with sea level rise is taken into account. In many cases the flexibility in the nourished amount of sand is mentioned as a feature. In others also space is allowed to increase the size of the hard structure, like Sankt Ordning and Katwijk (crest height increase).

In general, the methodologies across the selected Demonstrators range from basic, non-specific approaches (Dunkerque, Sainte-Marie La Mer, Ystad) to highly detailed and adaptive designs (Raversijde, Middelkerke, Katwijk, Sankt Peter-Ording). The more complex methodologies involve detailed safety assessments, specific storm durations, and reliability methods, ensuring higher resilience and adaptability to future conditions.

4.2 Comparison of design criteria

For Dunkerque, the design criteria focus on synthetic storm conditions, which incorporate considerations for global warming. No specific safety criteria or safety lines are defined for this Demonstrator. The synthetic storm conditions, specifying water levels and wave heights for different storm scenarios, which emphasising on environmental data and predictive modelling for design rather than strict safety parameters.

In Sainte-Marie La Mer, there is no information available on safety criteria for the dike or dune. The primary goal here is to mitigate chronic erosion and damage to the grey dike. Similar to Dunkerque, there is no clearly defined safety line, suggesting a focus on addressing ongoing erosion issues without specific safety thresholds.

The design methodology in Raversijde is more structured with defined safety criteria. It requires the mean overtopping discharge to not exceed 1 l/s/m and ensures no initial structural damage to the dike. The safety line is clearly established by the government at the most seaward boundary of habitation. This demonstrates a stringent approach to safety, prioritizing overtopping limits and structural integrity.

Middelkerke shares similarities with Raversijde regarding safety criteria. It mandates maintaining a minimum dune volume and limiting the mean overtopping discharge. The safety line is positioned at the seaward side of buildings on the seawall. Additionally, the beach profile must meet specific requirements to prevent cliff formation, indicating a combined focus on safety and functional beach design.

The design at Katwijk is comprehensive, with detailed safety criteria for both the dike crest and the dune. The overtopping limit is set at q = 1 l/m/s for the dike crest, and wave height limits are specified for the area in front of the dike. This limit is specifically valid for Katwijk; however, it can vary depending on the type of rear slope of the dike. For example, the limit might be 0.1 l/m/s for a sandy slope. The safety line is defined at the seaward crest line, and additional criteria ensure the beach profile and sand diameter remain consistent with pre-defined conditions. This approach integrates multiple safety and environmental factors, aiming to preserve both structural integrity and coastal morphology.

In Sankt Peter-Ording, the design criteria for dikes involve considerations for sea level rise and overtopping discharge. Although specific safety criteria for dunes are not defined, ongoing research suggests adopting a minimum dune profile based on the FEMA-540 rule (in that case, it will not be a hybrid solution, but a dune only solution). The safety line for dikes is inspected after storm surge seasons by local committees. Other criteria include the implementation of climate adaptation measures, demonstrating a forward-looking approach that incorporates routine inspections and climate resilience.

For Ystad, no specific safety criteria or safety lines are defined, and other design criteria are not applicable. This lack of detailed criteria indicates a less structured approach compared to the other Demonstrators, potentially due to different project goals or environmental conditions.

In general, the design criteria for the seven selected Demonstrators vary significantly, reflecting their unique environmental conditions and project goals. Across the comparison made, there is a clear variation in the consistency and specificity of design criteria. Dunkerque and Sainte-Marie La Mer focus more on addressing environmental conditions and ongoing erosion without strict safety criteria. Raversijde and Middelkerke prioritize overtopping limits and structural integrity with clearly defined safety lines, reflecting a more stringent safety-oriented methodology. Katwijk combines safety and environmental considerations, with detailed criteria for both dikes and dunes to maintain structural integrity and coastal morphology. Sankt Peter-Ording incorporates climate adaptation and routine inspections, highlighting a proactive approach to safety and resilience. Ystad lacks specific design criteria, suggesting a different set of priorities or conditions that do not necessitate detailed safety guidelines. These differences emphasize the importance of tailoring coastal protection measures to the unique conditions and goals of each location of Demonstrators.

4.3 Comparison of modelling methodology

The modelling methodology in Dunkerque utilizes a hybrid approach combining 2DH models with "one-line" evolution models, particularly for the dike. The innovative method is complemented using the EVA tool from the MIKE 21 software suite for determining extreme swell conditions. MIKE 21 SW, MIKE 21 ST, and LITDRIFT models are used for hydrodynamics and alongshore sediment transport. The LITPACK model calculates swell and surge evolution. Notably, the estimation of overtopping flow is conducted using Eurotop formulations, focusing on cross-shore dimensions without detailed numerical model settings or experimental setups provided.

The Raversijde approach begins with the current cross-shore profile, employing the XBeach model for simulating beach and dune erosion over a design storm duration. The modelling is 3D, considering alongshore variable profiles and includes wave and sediment transport processes. For hydrodynamics, the SWASH model is used, incorporating 3D effects and nonlinear interactions. The SWASH model is also applied for overtopping and overwash, with deterministic values obtained through multiple simulations, maintaining a 3D approach.

Similar to Raversijde, Middelkerke employs the XBeach model for morphodynamics, though it uses a quasi-2D approach. The SWASH model is also utilized for hydrodynamics, holding to the official safety assessment methodology in Flanders. Unlike Raversijde, Middelkerke combines empirical formulas with the SWASH model for overtopping and overwash, primarily using a 1D model instead of 3D.

Katwijk's methodology is grounded in Dutch regulations, utilizing the DUROSTA model for dune erosion. The modelling involves detailed hydrodynamic processes with ENDEC wave models and sediment flux calculations. For overtopping and overwash, the PC-Overslag model with TAW/Eurotop formulas is used, focusing on cross-shore dimensions and perpendicular wave attacks, without considering infragravity waves explicitly.

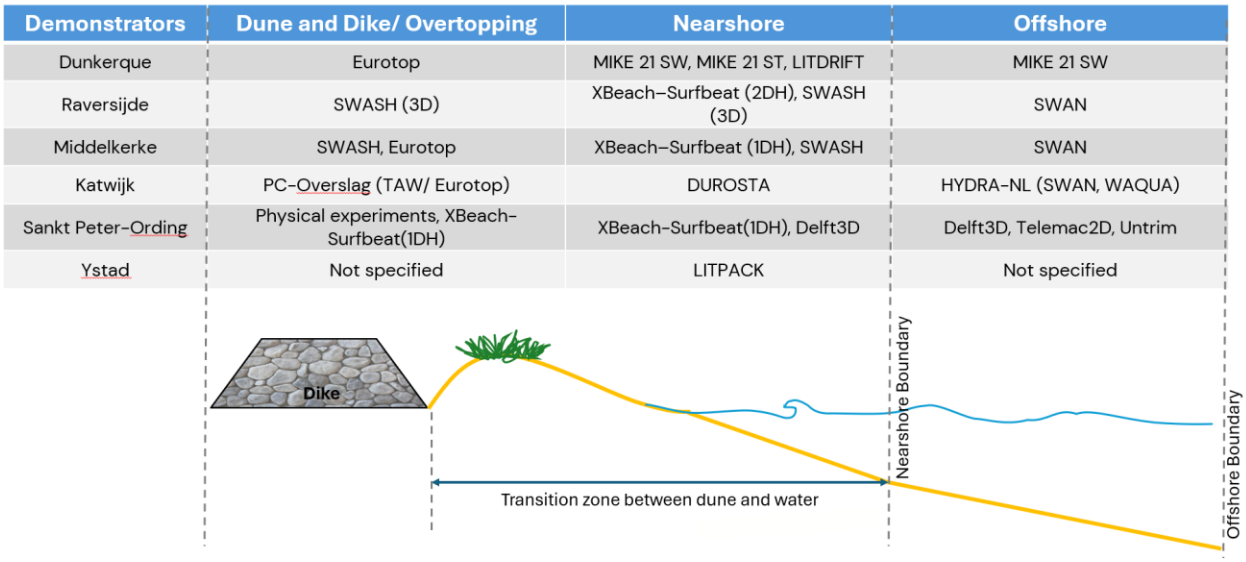
The difference between DUROSTA (used in Katwijk) and LITPACK (used in Dunkerque) lies in their numerical approaches and specific implementations. DUROSTA employs empirical formulations and process-based modelling for dune erosion, focusing on predicting short-term impacts of storm events on dune systems. In contrast, LITPACK uses numerical tools to simulate longshore sediment transport, wave-driven currents, and long-term morphological changes of coastal areas. Both models incorporate fundamental coastal physics, such as wave breaking, sediment transport, and hydrodynamic interactions. However, their numerical techniques and application scopes vary. DUROSTA emphasizes on short-term, event-based simulations, making it particularly suited for assessing the immediate effects of specific storm events on dune erosion. On the other hand, LITPACK employs numerical simulations to analyse long-term coastal dynamics.

In Sankt Peter-Ording, a multi-model corridor approach is adopted, incorporating Delft3D, Telemac2D, and Untrim models for water level projections. Extensive physical and numerical modelling is performed, including XBeach and Delft3D for morphodynamics. Hydrodynamic modelling involves a 3D model of the North Sea to obtain the hydraulic boundary conditions, and physical experiments of the dike (with dune) scaled at 1:7. The methodology emphasizes detailed physical processes like wave run-up and overtopping, incorporating a high-resolution approach and complex bathymetric considerations.

For Ystad, limited information is available. The modelling primarily involved LITPACK and a one-line model, but detailed methodologies, physical processes, and steps taken are not specified.

In general, the methodologies applied to model and design the seven selected Demonstrators exhibit both similarities and differences, reflecting diverse approaches tailored to local conditions and requirements. While Dunkerque and Katwijk primarily utilize cross-shore dimensions, other Demonstrators like Raversijde, Middelkerke, and Sankt Peter-Ording employ more comprehensive 3D modelling approaches. The use of different software tools and models, such as MIKE 21 in Dunkerque, XBeach and SWASH in Raversijde and Middelkerke, and DUROSTA in Katwijk, illustrates the tailored methodologies based on local requirements and conditions.

Raversijde and Middelkerke share similarities in using the XBeach and SWASH models but differ in their dimensional approaches (3D vs. 1D) and reliance on empirical formulas. In contrast, Sankt Peter-Ording's extensive use of physical and numerical modelling, with a focus on high-resolution and multi-model approaches, highlights a more integrated and detailed methodology. Overall, the methodologies reflect a blend of advanced numerical models, empirical formulas, and physical experiments, with varying degrees of complexity and detail tailored to the specific coastal environments and regulatory frameworks of each Demonstrator site. The models used for the selected demonstrators are briefly described in Figure 35.



Demonstrators	Dune and Dike/ Overtopping	Nearshore	Offshore
Dunkerque	Eurotop	MIKE 21 SW, MIKE 21 ST, LITDRIFT	MIKE 21 SW
Raversijde	SWASH (3D)	XBeach–Surfbeat (2DH), SWASH (3D)	SWAN
Middelkerke	SWASH, Eurotop	XBeach–Surfbeat (1DH), SWASH	SWAN
Katwijk	PC-Overslag (TAW/ Eurotop)	DUROSTA	HYDRA-NL (SWAN, WAQUA)
Sankt Peter-Ording	Physical experiments, XBeach-Surfbeat(1DH)	XBeach-Surfbeat(1DH), Delft3D	Delft3D, Telemac2D, Untrim
Ystad	Not specified	LITPACK	Not specified

Figure 35 - A description of the models used for modelling hydro- and/or morphodynamics at the selected demonstrators.

As a general comparison between various numerical models used in coastal engineering we can summarise as follows:

- Mike21 is employing both hydrodynamic and spectral wave modules to model coastal and marine environments. It utilizes finite difference and finite volume methods for numerical computation (DHI Group, 2017b).
- XBeach is specializes in simulating storm impacts on sandy coasts. It uses a non-hydrostatic, depth-averaged approach and can model both short waves and long waves, including infragravity waves, making it effective for assessing coastal erosion and flooding during extreme events (Deltares, n.d.).
- SWASH, is designed for detailed nearshore wave dynamics, using a non-hydrostatic, finite volume method to capture wave transformation processes accurately (Delft University of Technology, 2024b).
- DUROSTA focuses on dune erosion and sediment transport, employing empirical formulations and process-based modelling to predict coastal changes under storm conditions (Van Baaren, 2007).
- SWAN is a widely used wave model designed to simulate wave fields in coastal areas, estuaries, and inland waters. It employs a spectral wave model approach, solving the action balance equation for wave energy spectra, which allows it to account for various physical processes like wave generation by wind, non-linear wave-wave interactions, and wave dissipation due to whitecapping, bottom friction, and depth-induced breaking (Delft University of Technology, 2024a). Unlike XBeach, SWASH, and DUROSTA, SWAN primarily focuses on wave propagation, growth, and decay, without directly

modelling sediment transport or morphological changes, due to this fact, SWAN often integrates with other models like XBeach or SWASH to provide a comprehensive understanding of coastal dynamics
- LITPACK is a comprehensive suite of numerical tools designed to simulate longshore sediment transport, wave-driven currents, and morphological changes over various temporal scales. It integrates wave, current, and sediment transport models to predict changes in coastal morphology accurately (DHI Group, 2017a).

In general, Mik21, SWASH, SWAN focus on hydrodynamic and wave simulations, while XBeach, DUROSTA and LITPACK are specialized in morphodynamic modelling.

4.4 Comparison of dike stability methods

The dike in Dunkerque, originally built in 1876 and reconstructed multiple times, features a concrete core with sand, clay gravel, and marl coverings. The sea-facing slope is protected by masonry, while the canal-facing slope is reinforced with anchored concrete slabs. However, specific details regarding the geotechnical and structural stability methods are not provided.

Regarding Sainte-Marie La Mer, no information is available for the dike stability methods used in this Demonstrator.

In Raversijde, the dike is described as an impermeable smooth dike. The stability under storm conditions is crucial, with the dike materials and construction designed to withstand hydraulic pressures and dynamic forces from storm-driven waves without failure. No extra information is provided for this Demonstrator stability methods.

Details about the type of dike and the specific stability methods used in Middelkerke are not known.

The dike in Katwijk has a 1:3 slope and comprises multiple layers: a sand core, a geotextile layer, a 0.3 m thick filter layer of crushed gravel, and a top layer of concrete Basalton columns with basalt fill. Stability calculations are performed using the STEENTOETS software, incorporating a 50% safety margin for wave height. The leakage length theory is used to ensure the stability of the Basalton columns, and measures are taken to prevent sand from compromising the filter layer.

Sankt Peter-Ording features various types of dikes depending on location and function. The land protection dike north of the dune system has a sand core with a clay cover and grass canopy, while the regional dike south of the dune system has a sand core with a tar cover. The middle dike consists of sand/earth with a clay cover and grass canopy, and mobile flood defence walls are used within the town. The specific geotechnical and structural stability methods are currently unclear, likely managed by a geotechnical engineering office.

The project in Ystad uses a rock revetment dike, but details on the geotechnical and structural stability methods are not available.

The dike parts are made with the different types of armour that are known for dike slope (asphalt, placed blocks, rock, grass), also some of the dikes have hard overtopping-reduction measures, such as recurves (Dunkerque) and storm walls (Belgium). Where for the Katwijk it is claimed (not proven) that the stability of the placed block protection is increased by the sand, in other places the sand is removed – in Dunkerque the sand is actively removed from the dike slope, to prevent a claimed weakening of the dike slope of placed blocks. In e.g. Belgium the dunes are also placed in front of the dike to enable maintenance of the dike slope. No direct weakening of the slopes is claimed. For the rock slopes (Ystad and Sainte-Marie La Mer) no influence is claimed. The Sainte-Marie La Mer slope that was actually uncovered during a storm does not seem to be intact after the storm (Figure 14), but it is not clear if this was intended in the design phase.

In general, the methodologies for dike stability vary significantly among the Demonstrators. Dunkerque and Katwijk have detailed construction descriptions, with Katwijk providing comprehensive stability calculations using specific software and theories. In contrast, Raversijde focuses on the ability of dike materials to withstand storm conditions without detailed methodological descriptions. Sankt Peter-Ording employs different dike types for different regions, reflecting a tailored approach to local conditions, while, the detailed stability methods are not specified. Ystad, with its rock revetment dike, lacks detailed stability information, similar to Sainte-Marie La Mer and Middelkerke, where stability methods are not provided. All Demonstrators employ a range of approaches to dike stability, from specific geotechnical calculations and detailed construction materials to general descriptions of the dike's ability to withstand storm conditions.

4.5 Comparison of monitoring and maintenance methods

Dunkerque has a comprehensive monitoring and maintenance plan that involves biannual monitoring of the beach and dune. This includes the creation of DTMs, drone surveys, and surficial grain size analysis.

In Sainte-Marie La Mer, no specific monitoring and maintenance plan for the dike is provided, except for a temporary plan following storm damage in April 2024. For the dune system, biannual topographic surveys are conducted, and the fence line is rebuilt after storms. Additionally, approximately 15,000 m^3 of beach nourishment is carried out annually, ensuring the dune system's stability and resilience against erosion.

Raversijde's plan is thorough, requiring a safety assessment every six years. The beaches and dunes are monitored twice a year, and foreshore bathymetry is checked annually. Regular monitoring of the dike's structural integrity is also conducted. Maintenance activities, such as beach nourishment and dike renovations, are performed based on safety assessments, ensuring the ongoing stability and functionality of the coastal defences.

Middelkerke includes a detailed monitoring and maintenance plan. Monitoring occurs twice a year using LIDAR before and after winter, complemented by drone monitoring results. This plan ensures the integrity of the coastal defences is maintained and any necessary maintenance is promptly addressed.

Regarding Katwijk, although no specific maintenance plan is provided, annual measurements of dune profiles are conducted. According to Dutch law, the safety of primary sea defences must be assessed every twelve years.

Sankt Peter-Ording features a state-organized monitoring and maintenance plan. Monitoring is conducted annually after the storm surge season to identify and repair any damages. During the storm surge season, regular inspections are performed by dike boards to ensure stability. Maintenance is carried out as necessary, with a revision of design water levels scheduled for 2030.

Ystad's monitoring and maintenance plan includes regular topographic surveys. This straightforward approach ensures that the coastal defences are monitored consistently and maintained as needed to address any changes or damages.

In general, the monitoring and maintenance methods across the Demonstrators show a mix of detailed and basic plans. Dunkerque, Raversijde, Middelkerke, and Sankt Peter-Ording have comprehensive and detailed plans, including regular monitoring, safety assessments, and timely maintenance activities. Dunkerque and Middelkerke utilize advanced technologies like DTMs, drone surveys, and LIDAR, while Raversijde and Sankt Peter-Ording emphasize structured safety assessments and state-organized inspections. In contrast, Sainte-Marie La Mer and Ystad have simpler monitoring plans, focusing on topographic surveys and annual beach nourishment in Sainte-Marie La Mer. Katwijk follows a legal framework for safety assessments, with dune growth monitoring ensuring long-term stability without a specific maintenance plan. Mentioned monitoring and maintenance methods reflect local requirements, regulatory frameworks, and the need to address specific environmental conditions. The comprehensive plans ensure adaptive coastal defence systems, while simpler plans rely on regular surveys and compliance to maintain stability.

5. Knowledge gaps for DD-Hybrid NbS

According to the analyses and comparison of all results, reports, and methodologies presented in this project, none of the Demonstrators have a fully developed methodology for designing the combination of dune and dike simultaneously (only Katwijk applied a first ad-hoc design methodology), which is the main investigation objective of this project.

Aside from the main knowledge gap identified above, other knowledge gaps and questions have been identified based on the results in this report:

- Does the maximum overtopping of the dike occur when the dune is completely, partially, or not at all eroded?
- Is it possible to consider adaptive measures for the future of the DD-Hybrid NbS defence system?
- How can we include probabilistic design aspects in the design procedure of DD-Hybrid NbS coastal defence systems?
- How can we define the distance between the dune and dike systems so that they are not considered as two separate defence systems but work collectively?
- What is the effect of setup and infragravity waves on the dune morphodynamics in combination with the dike (e.g., in the space between the dune and dike, if the space exist)?
- Does the dike slope stability (depending on the type of cover) change in consequence of sand on top of it?

The identified knowledge gaps and the mentioned questions will be utilized in work package 12 to further investigate and enhance our understanding and the design methodology for a DD-Hybrid NbS defence system.

6. Conclusions

The DuneFront project report has highlighted the diverse methodologies used in the design and implementation of dune-dike hybrid NbS across various European coastal regions. This report aimed to better understand these hybrid systems as sustainable, adaptive, and attractive solutions for coastal management, addressing the socio-economic challenges posed by coastal flooding in densely populated areas. The variability in the design approaches stresses the necessity of tailoring solutions to local conditions, an essential aspect of achieving the project's primary goal.

The DuneFront project initially selected 12 Demonstrators across six countries—Portugal, France, Belgium, the Netherlands, Germany, and Sweden—to evaluate various hybrid NbS under different environmental conditions and governance structures. The selection was based on the potential of these sites to combine dune and hard infrastructure to protect coastal areas, with a focus on cost-effectiveness, adaptability, and environmental benefits. From these, seven Demonstrators were further chosen for detailed analysis: Dunkerque, Sainte-Marie La Mer, Living Lab Raversijde, Middelkerke, Katwijk, Sankt Peter-Ording, and Ystad. The criteria for this final selection included the functionality of the dune and dike in terms of coastal safety, specifically looking for systems where dunes and dikes work together, such as Dune-in-Front-of-Dike (DiFoD) or Dike-in-Dune (DiD) configurations. This detailed analysis sets the stage for a comprehensive comparison of their design methodologies, stability measures, and monitoring and maintenance practices, providing valuable insights into understanding hybrid NbS for coastal protection.

The comparison of finally selected Demonstrators reveals a spectrum of methodologies, ranging from basic, non-specific approaches to highly detailed and adaptive designs. For example, Dunkerque and Sainte-Marie La Mer primarily address ongoing erosion and environmental conditions without stringent safety criteria. In contrast, Demonstrators such as Raversijde and Middelkerke integrate detailed safety assessments and reliability methods, probably leading to a better optimized resilience design. This distinction emphasizes the need for adaptable and site-specific design methodologies to enhance coastal protection.

Modelling and design methodologies also vary significantly among the Demonstrators. While Dunkerque employs MIKE 21 for hydrosedimentary analysis, Katwijk utilizes XBeach and DUROSTA for detailed erosion profiles. Raversijde and Middelkerke share the use of XBeach and SWASH models but differ in their dimensional approaches (1D or 3D modelling). Sankt Peter-Ording employs an integrated approach with both physical and numerical modelling. These differences highlight the importance of selecting appropriate models and methodologies based on local environmental conditions and specific project goals, aligning with the project's objective of developing effective hybrid NbS.

The approaches to dike stability further illustrate this diversity. Dunkerque and Katwijk provide detailed stability calculations, while Raversijde focuses on the material's storm resilience. Sankt Peter-Ording adapts its dike types to regional conditions, although detailed stability methods are unspecified. Meanwhile, Ystad, Sainte-Marie La Mer, and Middelkerke offer general descriptions without detailed methodologies. It is possible that we were unable to locate the specific methodologies used. This variation reflects the necessity of integrating local geotechnical and structural perspectives into the design process, enhancing the overall adaptability and effectiveness of the solutions.

Monitoring and maintenance methods across the Demonstrators range from comprehensive plans to more basic approaches. Dunkerque, Raversijde, Middelkerke, and Sankt Peter-Ording feature detailed plans with advanced technologies like DTMs and LIDAR. In contrast, Sainte-Marie La Mer and Ystad rely on simpler surveys and beach nourishment, while Katwijk follows a legal framework without a specific maintenance plan. These differences underscore the importance of ongoing monitoring and maintenance to ensure the long-term functionality and resilience of coastal protection systems, a key component of the DuneFront project's aims.

A critical knowledge gap identified in the project is the ad-hoc nature, or absence of methodologies for designing dune and dike systems simultaneously. This gap is central to the project's objective of investigating and improving DD-Hybrid NbS. Addressing questions about dune erosion, adaptive measures, probabilistic design aspects, the spatial relationship between dunes and dikes, the effects of setup and infragravity waves, and dike slope stability buried under the sands will transform these gaps into actionable knowledge. These insights will contribute significantly to the future development and optimization of DD-Hybrid NbS, ensuring they meet both current and future coastal management challenges.

In conclusion, this report has provided a comprehensive overview of the varied methodologies employed in designing dune-dike hybrid NbS. The report has identified key knowledge gaps and set a foundation for future research and development. The identified knowledge gaps will be utilized in work package 12 to enhance our understanding and design aspects of the DD-Hybrid NbS defence system. By emphasizing the importance of tailored, site-specific solutions and ongoing adaptation, the report aligns with its primary goal of better understand nature based, sustainable, resilient, and adaptive coastal protection systems. This integrated approach will be crucial in addressing the socio-economic and environmental challenges posed by coastal flooding in Europe and beyond.

7. Annex

1. XBeach Model Parameters for Raversijde Demonstrator numerical modelling

```
%%% Bed composition parameters
D50         = 0.000334
D90         = 0.000515

%%% Flow boundary condition parameters
front       = abs_1d
back        = abs_1d

%%% Physical processes
sedtrans        = 1
morphology  = 1
wavemodel  = surfbeat

%%% General
wbctype      = parametric

%%% Grid parameters
depfile      = bed.dep
posdwn       = -1
nx           = 417
ny           = 0
vardx        = 1
xfile        = x.grd
% yfile        = 0
thetamin     = -90
thetamax     = 90
dtheta       = 180

%%% Model time
tstop        = 172800
CFL          = 0.900000

%%% Morphology parameters
morfac       = 1
morstart     = 0

%%% Tide boundary conditions
zs0file      = Tide Ostand 48h-Based on TAW.txt
tideloc      = 1

%%% Wave boundary condition parameters
instat       = 4
taper        = 100

%%% Wave-spectrum boundary condition parameters
bcfile       = jonswap.txt
```

2. SWASH Model Parameters for Raversijde Demonstrator numerical modelling

```
$*************HEADING*****************************************
$
PROJ 'SA21_15' '01'
$ Section 172-176
$
$*************MODEL INPUT*************************************
$
COORDINATES CART
MODE NONST TWOD
SET SEED 12345678
SET LEVEL 6.93
SET DEPMIN 0.010
SET RHOWAT 1025
$
CGRID CURV 815 231 REP Y
READGRID COOR 1 'SA21_15_172-176_01_xy.bot' 1 0 FREE VERT 2
$
INPGRID BOTTOM CURV
READINP BOTTOM -1 'SA21_15_172-176_01_zz.bot' 1 0 FREE
$
INPGRID WLEVEL CURV
READINP WLEVEL 1 'SA21_15_172-176_01_zz.dwl' 1 0 FREE
$
INIT zero
$
BOU SHAP JON 3.3 DSPR DEGR
BOU SEGMENT IJ 1 1 1 25 BTYPE WEAK HYPER SMOO 30 SEC ADDB CON SPECT 4.97 11.23 -61.0 19.0 100 MIN
BOU SEGMENT IJ 1 26 1 78 BTYPE WEAK HYPER SMOO 30 SEC ADDB CON SPECT 4.97 11.23 -61.0 19.0 100 MIN
BOU SEGMENT IJ 1 79 1 120 BTYPE WEAK HYPER SMOO 30 SEC ADDB CON SPECT 4.97 11.23 -61.0 18.8 100 MIN
BOU SEGMENT IJ 1 121 1 146 BTYPE WEAK HYPER SMOO 30 SEC ADDB CON SPECT 4.95 11.23 -61.0 18.6 100 MIN
BOU SEGMENT IJ 1 147 1 176 BTYPE WEAK HYPER SMOO 30 SEC ADDB CON SPECT 4.94 11.23 -61.0 18.5 100 MIN
BOU SEGMENT IJ 1 177 1 205 BTYPE WEAK HYPER SMOO 30 SEC ADDB CON SPECT 4.93 11.23 -61.0 18.3 100 MIN
BOU SEGMENT IJ 1 206 1 231 BTYPE WEAK HYPER SMOO 30 SEC ADDB CON SPECT 4.93 11.23 -61.0 18.3 100 MIN
$
FRIC MANN 0.019
BREAK 0.6 0.3
VISC Horizontal CON
$
NONHYDROSTATIC BOX PREC ILU
DISCRET UPW MOM
DISCRET UPW UMOM HOR MUSCL
DISCRET UPW UMOM VER MUSCL
DISCRET UPW WMOM HOR MUSCL
DISCRET UPW WMOM VER FIRST
BOTCel SHIFT
TIMEI 0.2 0.5
```

8. References

Arcadis. (2012). *Uitwateringsgeul bij keersluis Katwijk. Morfologische ontwikkeling en golfhoogte-verloop tijdens maatgevende stormcondities. 076720579:0.1 – Draft. 26 oktober 2012. In Dutch.*

Baaren, P. (2007). *Influence of the wave period in the dune erosion model DUROSTA* TU Delft. http://resolver.tudelft.nl/uuid:f00be223-01ba-49e6-9fde-88201c870641

Boer, S., & Wouters, J. (2014). *Kustwerk Katwijk; verification dune body. Kustwerk Katwijk, Verificatie duinlichaam. Document number: Kwk-04vo-11100180-001. Revision 3 – final. 8-12-2014. (In Dutch).*

De Roo, S., Trouw, K., Suzuki, T., Thoon, D., & Mostaert, F. (2021). *Toetsing kustveiligheid 2021: Toetsingsmethodologie voor dijken en duinen. Versie 2.0. WL Rapporten, 18_037_3*. W. L. Antwerpen.

Delft University of Technology. (2024a). *SWAN: User manual. Availabel at : https://swanmodel.sourceforge.io/download/zip/swanuse.pdf (Accessed: June 6, 2024).*

Delft University of Technology. (2024b). *SWASH User Manual, Availabel at : https://swash.sourceforge.io/online_doc/online_doc.htm (Accessed: June 6, 2024).*

Deltares. (n.d.). *XBeach Documentation. Availabel at : https://xbeach.readthedocs.io/en/latest/ (Accessed: June 6, 2024).*

DHI. (2011). *Etudes hydrauliques et de conception d'un dispositif de confortement de la digue des Alliés. Rapport, 469 p (In French).*

DHI. (2012). *Etudes hydrauliques et de conception d'un dispositif de confortement de la Digue des Alliés – Partie 1c : Fonctionnement hydrosédimentaire, Rapport Final préparé pour le GPMD, Juillet 2012 (In French).*

DHI. (2017). *Etude de dangers du système d'endiguement constitué par la digue des Alliés et par le barrage Tixier à Dunkerque. Rapport pour la Dreal, 124 p. (In French).*

DHI Group. (2017a). *LITPACK: Littoral processes and coastline kinetics modelling. Available at: https://manuals.mikepoweredbydhi.help/2017/LITPACK.htm (Accessed: June 6, 2024).*

DHI Group. (2017b). *MIKE 21 - Hydrodynamic Modelling User Guide. . Available at: https://manuals.mikepoweredbydhi.help/2017/MIKE_21.htm (Accessed: June 6, 2024).*

Galappatti, R., & Vreugdenhill, C. B. (1983). A depth integrated model for suspended transport. *Journal for Hydraulic Research, 23(4)*, 359–377.

Grotegoed, D. (2014). . *Kustwerk Katwijk, Geotechnisch ontwerp dijkconstructie. Report number 10130007 -30-00-CA-0003, revision E. 30-7-2014.*

Hagen, R., Plüß, A., Ihde, R., Freund, J., Dreier, N., Nehlsen, E., Schrage, N., Fröhle, P., & Kösters, F. (2021). An integrated marine data collection for the German Bight – Part 2: Tides, salinity, and waves (1996–2015). *Earth Syst. Sci. Data, 13*(6), 2573-2594. https://doi.org/10.5194/essd-13-2573-2021

Hagen, R., Plüß, A., Jänicke, L., Freund, J., Jensen, J., & Kösters, F. (2021). A Combined Modeling and Measurement Approach to Assess the Nodal Tide Modulation in the North Sea. *Journal of Geophysical Research: Oceans, 126*(3), e2020JC016364. https://doi.org/https://doi.org/10.1029/2020JC016364

Hamard, X., Nerincx, N., Brassart, G., Doumeng, C., Moubariki, A., & Partouche, S. (2019). Travaux de confortement de la digue des Alliés à Dunkerque. 3ème Colloque sur les digues maritimes et fluviales de protection contre les inondations, Aix-en-Provence, France. https://doi.org/10.5281/zenodo.2533129.

Hoogheemraadschap van Rijnland. (2022). *Beoordeling veiligheid primaire waterkeringen 2017 – 2023. Normtraject 14_8 Katwijk. Novermber 2022, author: Joost Veer*.

Kristensen, S., Deigaard, R., Taaning, M., Fredsoe, J., Droenen, N., & Jensen, J. H. (2010). Long term morphological modelling. *Proceedings of the Coastal Engineering Conference*.

Lomborg, B. (2020). *False alarm: How climate change panic costs us trillions, hurts the poor, and fails to fix the planet*. Hachette UK.

Ottevaere, H. (2011). *Meten en experimenteren. Deel 1: Theorie der meetfouten. 1ste Bachelor in Ingenieurswetenschappen*.

Rijnsdorp, D. P., Smit, P. B., & Zijlema, M. (2014). Non-hydrostatic modelling of infragravity waves under laboratory conditions. *Coastal Engineering*, *85*, 30-42.

Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R., & Lescinski, J. (2009). Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering*, *56*(11), 1133-1152. https://doi.org/https://doi.org/10.1016/j.coastaleng.2009.08.006

Rohde Nielsen, & Ballast Nedam. (2014). *Overzicht Harde Kering. Drawing number 71-00-CD-1103. 19-9-2014*.

Schiereck, G. J., & Verhagen, H. J. (2019). *Introduction to bed, bank and shore protection: Revised edition*. Delft Academic Press. http://resolver.tudelft.nl/uuid:df203dde-6cca-4375-85d2-8b2dbce613cb

Schleswig-Holstein Coastal Protection General Plan. (2022). *Schleswig-Holstein Coastal Protection General Plan*. https://www.schleswig-holstein.de/DE/fachinhalte/K/kuestenschutz/Downloads/Generalplan.pdf?__blob=publicationFile&v=3

Slomp, R. (2016). *Implementing risk based flood defence standards. Rijkswaterstaat report. Version 7, 24 April 2016*.

Suzuki, T., De Roo, S., Altomare, C., Zhao, G., Kolokythas, G., Willems, M., Verwaest, T., & Mostaert, F. (2015). *Toetsing kustveiligheid 2015 - Methodologie: Toetsingsmethodologie voor dijken en duinen. WL Rapporten, 14_014_1. W. L. Antwerpen*. .

Tresca, A., Ruz, M.-H., & Grégoire, P. (2014). Coastal dune development and sand drifting management along an artificial shoreline: the case of Dunkirk harbour, northern France. *Journal of Coastal Conservation*, *18*(5), 495-504. https://doi.org/10.1007/s11852-013-0302-z

Van Baaren, P. F. J. (2007). *Influence of the wave period in the dune erosion model DUROSTA. Master's thesis, TU Delft, Civil Engineering and Geosciences, Hydraulic Engineering. Available at: http://resolver.tudelft.nl/uuid:f00be223-01ba-49e6-9fde-88201c870641*

Vandenhove, M., Castelle, B., Nicolae Lerma, A., Marieu, V., Dalet, E., Hanquiez, V., Mazeiraud, V., Bujan, S., & Mallet, C. (2024). Secular shoreline response to large-scale estuarine shoal migration and welding. *Geomorphology*, *445*, 108972. https://doi.org/https://doi.org/10.1016/j.geomorph.2023.108972

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., & Feyen, L. (2017). Extreme sea levels on the rise along Europe's coasts. *Earth's Future*, *5*(3), 304-323.

Vuik, V., Kuijper, B., Geerse, C. P. M., Strijker, B., Gautier, C., Trouw, K., Vanneste, D., Suzuki, T., Nossent, J., Thoon, D., De Roo, S., & Mostaert, F. (2020). *Het Hydraulisch Randvoorwaardenboek (2020). Rapport. Versie 2.0. WL Rapporten, 18_037_4.*

Wouters, J., & Boer, S. (2014). *Kustwerk Katwijk; verification slope protection. Kustwerk Katwijk; Verificatie taludverdediging dijkconstructie. Project number 12i097. Version 7, final. 13-8-2014. (In Dutch).*

Zijlema, M., Stelling, G., & Smit, P. (2011). SWASH: An operational public domain code for simulating wave fields and rapidly varied flows in coastal waters. *Coastal Engineering*, *58*(10), 992-1012.