DuneFront

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Morphodynamics patterns

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Version 1.0	14/12/2024	Nicolas Robin (UPVD), Marie-Hélène Ruz (ULCO), Bruno Castelle (UBx-B), Emmanuel Blaise (ULCO)	Final version approved by all Beneficiaries

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Cover page

The overall objective of WP6 is to quantify a range of physical processes, including sediment dynamics, vegetation coverage, and metocean conditions, across 12 hybrid dune-dike demonstrator sites distributed throughout Europe. These 12 demonstrator sites, located in six different countries (Fig.1), encompass a range of functionalities and are subject to diverse boundary conditions and governance structures. Nine demonstrators are dune-in-front-of-dike, two are dune only and one is a dike-in-dune. Each of the demonstrators represents a hybrid natural and structural solution, combining dunes and hard infrastructure (such as dikes) with the primary objective of coastal protection and natural adaptation and resilience through biodiversity restoration. Additionally, these solutions can facilitate recreation and mitigate aeolian sand nuisance.

The aim of this report is, for each Demonstrator, to collect the available topographic data and to carry out a first analysis of the dune and upper beach topographic evolution since the demonstrators' construction (D6.1). Our results show that most of the dunes gained sand after construction. Erected above highest astronomical tide (HAT), the dunes usually were in accretion during the first year, just after beach nourishment. Depending on their "age", local hydrodynamics and sediment availability, most of them remained stable or slowly accreted after its initial stage. The evolution of the area above HAT was, however, more diverse. In five demonstrators the surface area increased, while in seven demonstrators a surface area decrease was recorded, although some of these demonstrators were constructed only 2 or 3 years ago. This evolution could be related to storm events, inducing erosion on the upper beach or management practices. However, despite reduction of the upper beach surface, most of the dunes remained stable or accreted, illustrating their key function in coastal protection.

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List of abbreviations

Abbreviation	Explanation
NbS	Nature-based Solutions
DiFoD	dune-in-front-of-dike
DiD	dike-in-dune
DD–NbS	Dune-Dike hybrid Nature-Based Solutions
HAT	Highest Astronomical Tides
MSL	Mean Sea Level
NNH	Northern North-Holland
DEM	Digital Elevation Model
aMSL	Above Mean Sea Level

1 Introduction

The aim of the DuneFront project is to enhance the efficacy of dune-dike hybrid Nature-based Solutions (NbS) as a new generation of blue-grey coastal infrastructure in developing innovative strategies for the sustainable protection of European coastlines that are vulnerable to the impacts of climate change. The objective of this project is to enhance coastal protection and biodiversity conservation at both local and regional scales, by considering the geographic, climatic and socio-economic boundary conditions.

In Europe, the 'dune-in-front-of-dike' (DiFoD) or 'dike-in-dune' (DiD) are being developed as Dune-Dike hybrid Nature-Based Solutions (DD-NBS) with the objective of improving the resistance of coastlines to erosion while simultaneously providing sufficient coastal protection from flooding during storms and delivering multiple other services to the public. Both DiFoD and DiD are hybrid solutions that involve the deposition of a body of sand in front or on top of existing or newly constructed hard infrastructures. This sand body is then typically planted with vegetation to further promote its development and enhance its resistance against erosion and resilience to sea level rise. The construction of sand bodies in front of hard structures, or covering hard structures, has been demonstrated to reduce the impact of waves, mitigate sand losses from the system, and enhance recreational values. The objective of this project will be achieved by utilizing a series of demonstrator sites along the European coastlines.

Twelve DuneFront demonstrator sites, located in six different countries (Figure 1), encompass a range of functionalities and are subject to diverse boundary conditions and governance structures. Each of the demonstrators represents a hybrid NbS, combining dunes and hard infrastructure (such as dikes) with the primary objectives of coastal protection and biodiversity restoration. Additionally, these solutions can facilitate recreation and mitigate aeolian sand nuisance.

The demonstrators have been selected based on their potential for cost-effectiveness, climate and structural adaptability, as well as the ecosystem services they provide to both human communities and the environment. The demonstrator research targeted DiFoD systems but also included structural variants (DiD) as a reference for alternative designs under anticipated different boundary conditions. Such hybrid NbS also form the basis of marine infrastructure, including the construction of artificial islands that serve as renewable energy hubs or as marine barriers for coastal protection. An analysis of the physical, morphodynamical, ecological and socio-economic data available from these demonstrators will lead to the first comprehensive and novel overview of well-known NbS available along the European coastline.

Figure 1 – Location of the 12 selected Demonstrators

Table 1 – Coordinates of the 12 selected Demonstrators

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

1.1 Overview of work package 6 (WP6 Demonstrator morphodynamics)

The overall objective of WP6 is to quantify a range of physical processes, including sediment dynamics, vegetation coverage, and metocean conditions, across 12 hybrid dune-dike demonstrator sites distributed throughout Europe. This effort will compile a valuable spatio-temporal database that captures the variations in these processes across space and time, enabling a deeper understanding of how hybrid coastal defense structures function and integrate across diverse European contexts.

The analysis of existing data from the demonstrators, with available data on dunes and dikes individually, will serve as the primary foundation for designing DiD or DiFoD systems. This analysis will include studies of erosion and accretion dynamics, vegetation development, and their interactions with various governance-related factors, such as recreation and beach nourishment. Quantifying sediment dynamics across all demonstrators is essential, linking these dynamics to local boundary conditions and assessing the subsequent maintenance actions required. This analysis will also address how sediment dynamics are influenced by recreational pressures and vegetation development, recognizing vegetation as a key driver of aeolian dynamics, which will vary across the sites. Finally, it will be necessary to quantify both the average responses of these systems and their behavior under extreme conditions.

1.1.1 Tasks of work package 6

Firstly, sediment dynamics will be derived from a spatiotemporal analysis of high-resolution digital elevation models (DEMs) for all demonstrator sites (**this report**). This analysis will be supplemented with meteorological data sourced from on-site or nearby weather stations. The resulting dataset will be compared against a reference site that lacks dikes or dunes in proximity to the DD-hybrid NbS infrastructure. This comparison will facilitate the evaluation of the relative effectiveness of the DD-hybrid NbS system at the demonstrator sites. Validation will be carried out by hindcasting sedimentary evolution within the demonstrators. To enhance accuracy, a recently developed root mapping function will be further refined for integration into the XBeach dune erosion model. This adaptation will enable the modeling of erosion dynamics and resistance even in cases where site and plant-specific root trait data are unavailable. Considering the significant spatiotemporal variability of sand and vegetation drivers, the objective is to quantify the average impacts and estimate associated uncertainties using sensitivity analysis. The DEM data will also be utilized to calibrate numerical process-based models XBeach (for dune erosion) and AeoLiS (for dune growth) for conducting kilometer-scale morphodynamic predictions that extend beyond the DuneFront project's lifetime. Projections of potential future changes in sedimentation and erosion within the demonstrator sites will be generated using Representative Concentration Pathway (RCP) scenarios 3, 4.5, 6, and 8.5, according to the IPCC reports.

1.1.2 Milestones and deliverables of work package 6

Task 6.1 (this report) Morphodynamic patterns (Lead: TUB-E; Involved partners KULEUVEN, UPORTO, UPVD, ULOC, M1-M12) - Analysis and quantification of sediment dynamics deduced from collected DTM data for multiple years per Demonstrator (D6.1).

Task 6.2 Vegetation-sediment interactions (Lead: KULEUVEN; Involved partners TUB-E: M6-M15) - TUB-E and UGENT-B will use data from D5.2 and D6.1 to conduct spatiotemporal regression analyses on sedimentation/erosion budgets and vegetation cover data under various physical boundary conditions to assess vegetation cover impact and improve an existing root mapping function for XBeach to consider dune erosion resistance impacts of vegetation (D6.2).

Task 6.3 Environmental influences (Lead: TUB-E; involved partners KULEUVEN, UGENT-B, M1-18) - KULEUVEN and TUB-E assess boundary conditions from WP5 and correlate these boundary conditions with quantified morphodynamic patterns (D6.1) as well as vegetation coverage (D6.2) to deduce potential influences from abiotic as well as anthropogenic conditions at each site on observed sediment and vegetation dynamics (D6.3).

2 Morphological change analysis

The aim of this report is to provide, for each Demonstrator, an analysis of high-resolution DEMs.

2.1 Methodology

To conduct a consistent and comparable analysis of morphological changes across all sites, a methodological approach has been proposed. This approach relies on topographic surveys, typically using LiDaR or photogrammetry, the delineation of the demonstrator dune, and astronomical tide data. These combined data have enabled the automated calculation of volumes, surfaces, and elevations for different compartments, distinguishing between the demonstrator dune area and the overall beach-dune system. Data has been stored in a digital repository [https://ugentbe.sharepoint.com/sites/PR202201795/WPs/Forms/AllItems.aspx?id=%2Fsites%2FPR202201795%2FWPs%2FWP06&viewid=cc8e0215%2D736e%2D478c%2D89a6%2Dee78882d00d6]. For each site, two directories have been created: (1) DEM, which contains all the digital elevation models in GeoTIFF format, named as yyyymmdd-SiteName.tif; and (2) a Boundary directory, which gathers shapefiles defining the boundaries of the demonstrator dune (Boundary_dune.shp) and the overall beach-dune system (Boundary_system.shp). At the root directory of each demonstrator site, a MATLAB program is available to generate site maps, calculate changes in various indicators, and compute topographic differences. This program requires as input: the offset between the vertical reference and mean sea level; the longitude/latitude of the corresponding demonstrator (from which the highest astronomical tide level (HAT) is collected from D4.1 (Castelle & Dahirel, 2024), the date of the demonstrator's implementation t0 and EPSG code. An example of code is given in Annex 7.

For each site, the domain was divided into several compartments to calculate the temporal evolution of four morphological proxies for the demonstrator: two for the dune alone and two for the entire beach-dune system (Fig. 2). The proxies for the dune (subscript “d”) are: (1) the dune volume Vd with Sd, given that this surface Sd is constant over time and defined by the file Boundary_dune.shp; and (2) Zdmax, the maximum elevation of the dune crest within the same surface area. These two proxies make it possible to assess the sand volume flux and elevation of the system in the planted sector area. The two proxies for the entire beach-dune system (subscript “a”) are: (1) the dry beach surface Sa which corresponds to the surface area of the beach-dune system above the highest astronomical tide (HAT); and (2) the volume Va of the beach-dune system above mean sea level (MSL). These two proxies provide insights into the evolution of the entire beach-dune system in terms of dry surface area (Sa) and volume (Va) gains.

These different proxies are illustrated in Figure 2a for an idealized profile, which enables an understanding of the time series of proxies before and after the demonstrator's implementation (Figure 2b). Since most demonstrators are not uniform, Figure 2c provides a top-down view showing the predefined surfaces Sd and S as defined in the files Boundary_dune.shp and Boundary_global.shp, respectively, within which the described proxies are calculated.

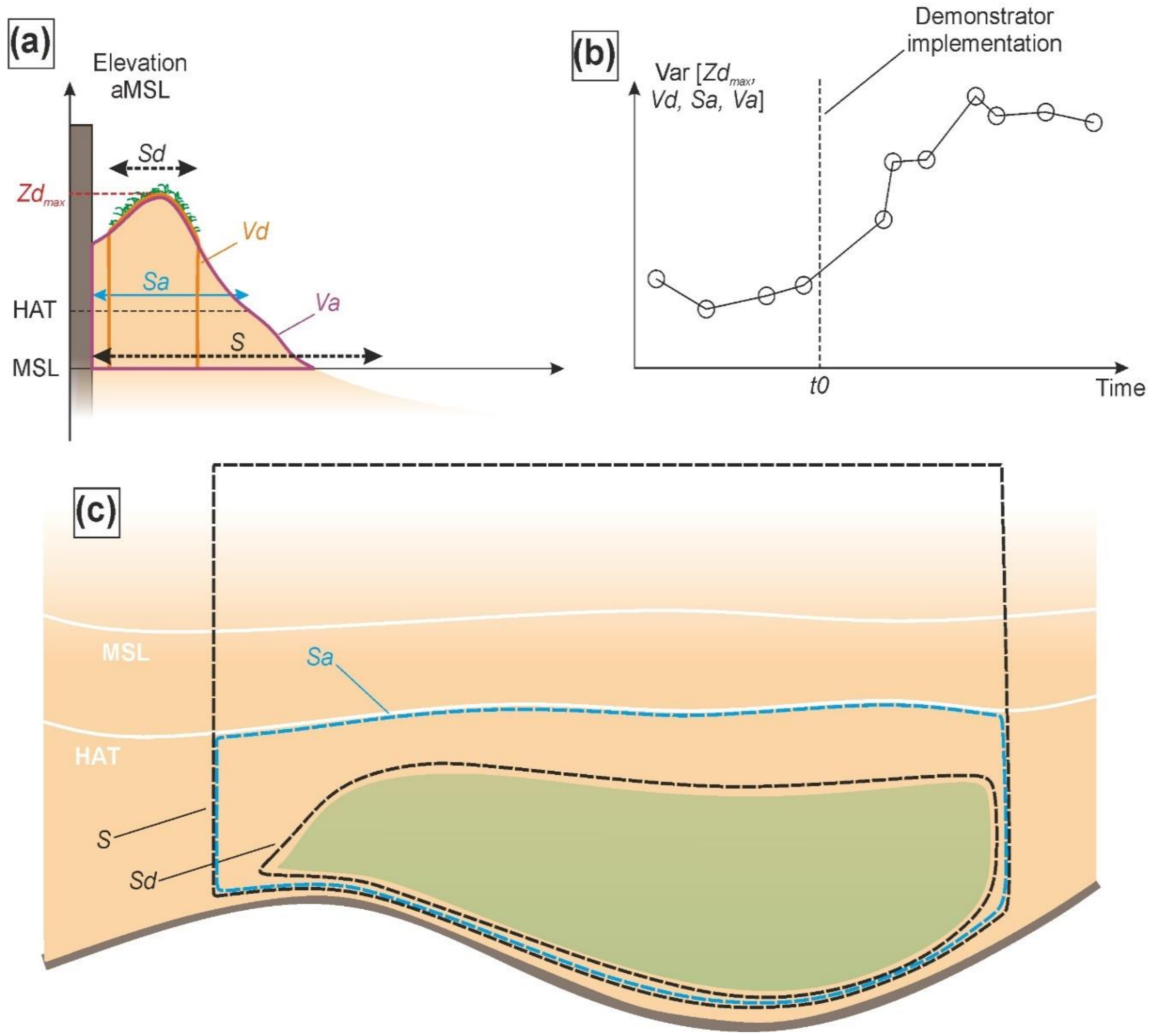


Figure 2. (a) Diagram of an idealized profile of a beach-dune demonstrator system, with the morphological proxies, which vary over time, highlighted in color. These are used to assess (b) the morphological evolution associated with the implementation of the demonstrator. A top-down view is shown for non-uniform demonstrators along the coast (c), highlighting the predefined surfaces Sd and S used for proxy calculations.

2.2 Results

2.2.1 Douro estuary sandspit (Portugal)

The Douro estuary sandspit, is located on the left bank of the Douro River in northwest Portugal (Fig. 3). The sandspit is about 300 meters wide (E-W) and 800 meters long (N-S) and is stabilized on its eastern part by vegetation. A breakwater was constructed from mid 2004 to 2008. This demonstrator does not include a dike; however, the existing breakwater protects the sandspit from erosion and the combination of sandspit and breakwaters have protective functionality for inland margins and harbor.

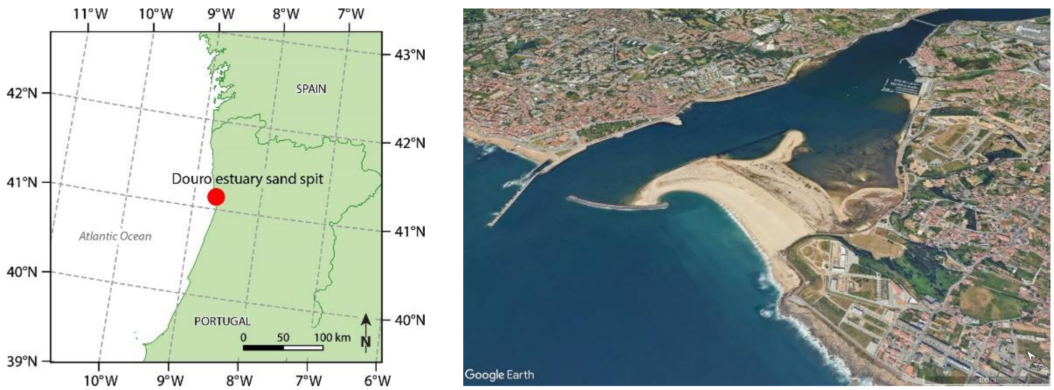


Figure 3. Location map (left) and satellite view (right) of the estuary mouth partially closed by the sandspit (photo: Google Earth)

The north-western Portuguese coast is highly energetic, with offshore mean significant wave heights of 2–3 m, and mean wave periods of 8–12 s. In winter, storms generated in the North Atlantic are frequent and can persist for up to five days, with significant wave heights reaching 8 m (Costa et al., 2001). Tides are semi-diurnal, with tidal ranges from 2 m to 4 m during neap and spring tides, respectively. Waves usually come from the NW, inducing a drift current from North to South. The coastal wind regime is characterized by a high seasonal variability. From April to August there are predominant WNW and NW winds, while in other periods of the year the E–SSE wind is more frequent. W–SW winds are not frequent, although very important during storm events (Bastos et al., 2021).

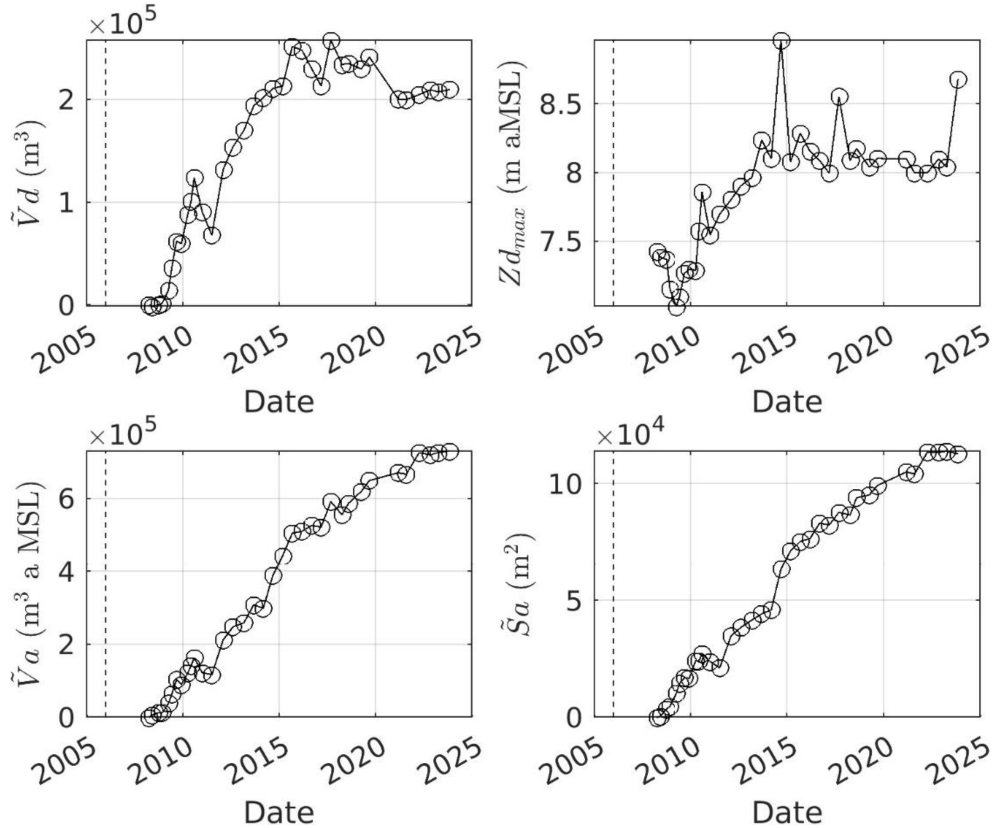


Figure 4. Time series of (top left) dune volume difference, (top right) maximum dune elevation aMSL (bottom left) zone volume aMSL and (bottom right) zone area aHAT for the Douro demonstrator. In all panels the vertical dashed line indicates the implementation date of the demonstrator

After the construction of the breakwater, the dune increased in volume (Fig.4), especially between 2015 and 2019. The maximum dune crest elevation was variable, reaching up to 8,9 m in September 2014, and 8,7 m in November 2023 (Fig. 4), with mean dune elevation gaining 0,6 m over the surveyed period. For the entire zone (Annex 1), accumulation prevailed, with an accumulation of almost 740000 m^3 aMSL between 2008 and 2023, inducing a seaward widening of the dune area (Fig. 5 middle). However, the change in elevation in the upper part of the dune area (Fig. 5 bottom) shows limited accumulation during the surveyed period, contrary to the seaward side of the dune.

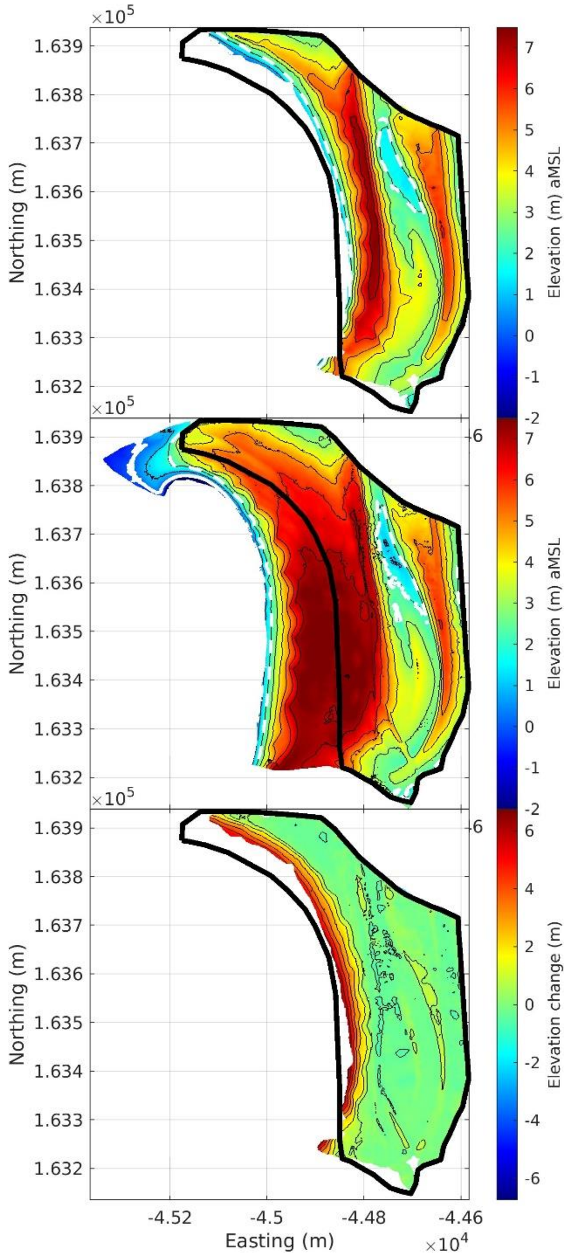


Figure 5. DTM in April 2008 (top), and in November 2023 (middle). Change in elevation (m) between 2008-2023 (bottom).

2.2.2 Soulac-sur-Mer (France)

This demonstrator is located in southwestern France, south of the Gironde estuary, in the northern part of the coastal resort of Soulac along the North-Médoc coast. Over the centuries, the North-Médoc coastline has experienced periods of severe erosion, which has threatened coastal infrastructure and led to the progressive implementation of coastal protection structures. More recently, localized beach nourishment and, as part of the DuneFront initiative, the use of DD-hybrid techniques has been introduced.

A distinctive feature of shoreline evolution along the North-Médoc coast (see Vandenhove et al., 2024) is the alternating pattern of rapid erosion (< −5 m/yr) and substantial accretion (> 20 m/yr), occurring over relatively short time frames (≈ 10 years) and across limited alongshore distances (e.g., a few kilometers). In the early 1900s, a dike was built to protect the Soulac resort from severe localized coastal erosion. Today, due to a combination of natural and anthropogenic factors (Vandenhove et al., 2024), the beach has significantly risen and widened, now stretching nearly 250 meters in width. The sand level has almost reached the top of the former dike, which is now largely buried beneath the sand (Fig. 6). The objective of this demonstrator is to manage the aeolian transport of sand from the wide beach into the resort during winter storms. This is being achieved through the establishment of a dune field, with marram grass planting carried out in February 2024.

Figure 6. Location map (left) and aerial views (right) of the Soulac demonstrator (dashed area) (Photos: Google Earth and B. Castelle)

The North-Médoc coast is macro-tidal, with a maximum tidal range of 5.4 meters recorded at Pointe de Grave (SHOM, 2013). The wave climate is energetic, with dominant wave incidence from the W to NW (Butel et al., 2002). High-energy winter swells and storm waves typically come from the W-NW, with significant wave heights sometimes exceeding 8 m offshore. In contrast, smaller and shorter summer waves generally approach from the NW (Castelle et al., 2014; 2015). However, near-breaking wave heights are significantly reduced at the demonstrator site, as waves undergo complex transformations across the inner shelf (due to tide- and depth-induced refraction and breaking) because of the proximity to the Gironde estuary and the complex morphology of offshore channels and rocky outcrops (Vandenhove et al., in revision). Tide-driven currents can be intense, exceeding 1 m/s offshore.

Prevailing winds on the Médoc Peninsula are from the WNW to WSW, accounting for 50% of the total wind direction (Michel & Howa, 1999). The strongest winds, which can reach speeds of up to 26 m/s, are typically recorded in winter, with an average direction between SW and NW. Sand trapping measurements by Favennec et al. (2002) show that approximately 70% of aeolian sand transport occurs in autumn and early spring along the Aquitaine coast. Additionally, during the strongest wind events, sands with grain sizes up to 300 µm can be transported to the inner part of the dune ridge.

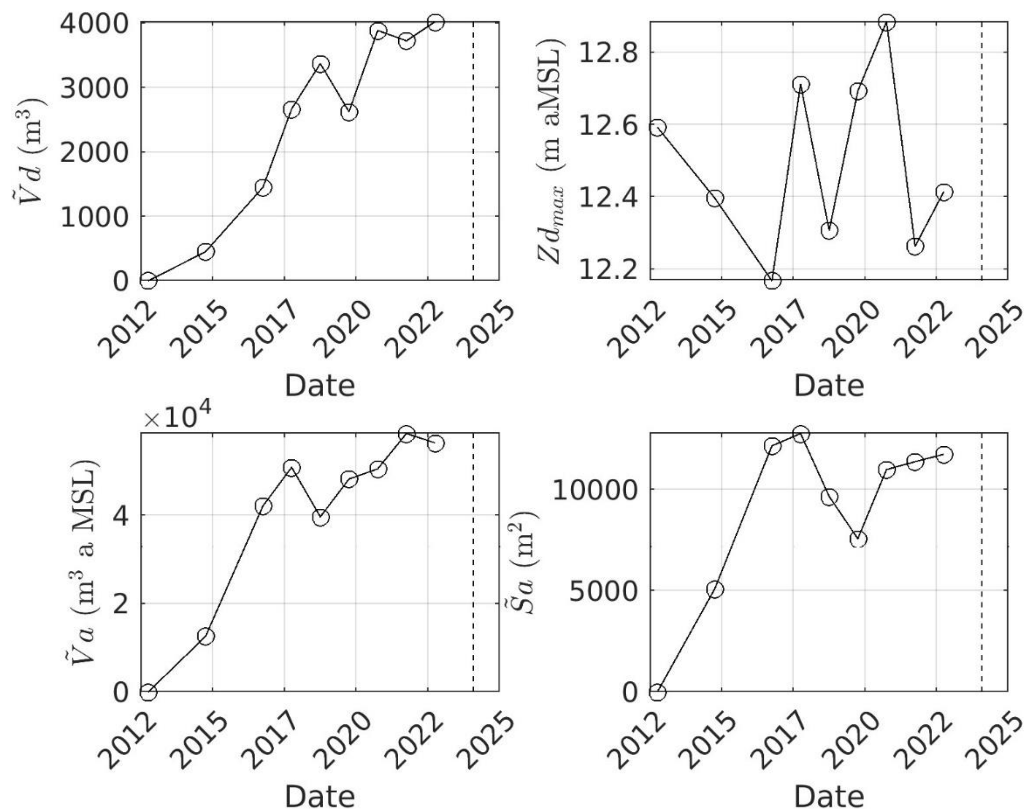


Figure 7. Time series of (top left) dune volume difference, (top right) maximum dune elevation aMSL (bottom left) zone volume aMSL and (bottom right) zone area aHAT for the Soulac demonstrator. In all panels the vertical dashed line indicates the implementation date of the demonstrator

Before the dune was planted with marram grass in February 2024, the dune gained 4000 m^3 (bare sand) and the maximum dune crest elevation ranged from 12,2 m to 12,8 m (Fig. 7), with slight variations. Between 2012 and 2022 an accretion of almost 1 m was recorded for the mean dune elevation (Fig. 8, bottom). During the surveyed period, accumulation prevailed above HAT (Fig. 8, middle), with a net volume increase between 2012 and 2022. Change in elevation (Fig. 8

bottom) show a net tendency to accumulation for the entire zone, especially on the upper beach. Contrastingly, the dune slowly accreted and nearly remained stable at its landward limit.

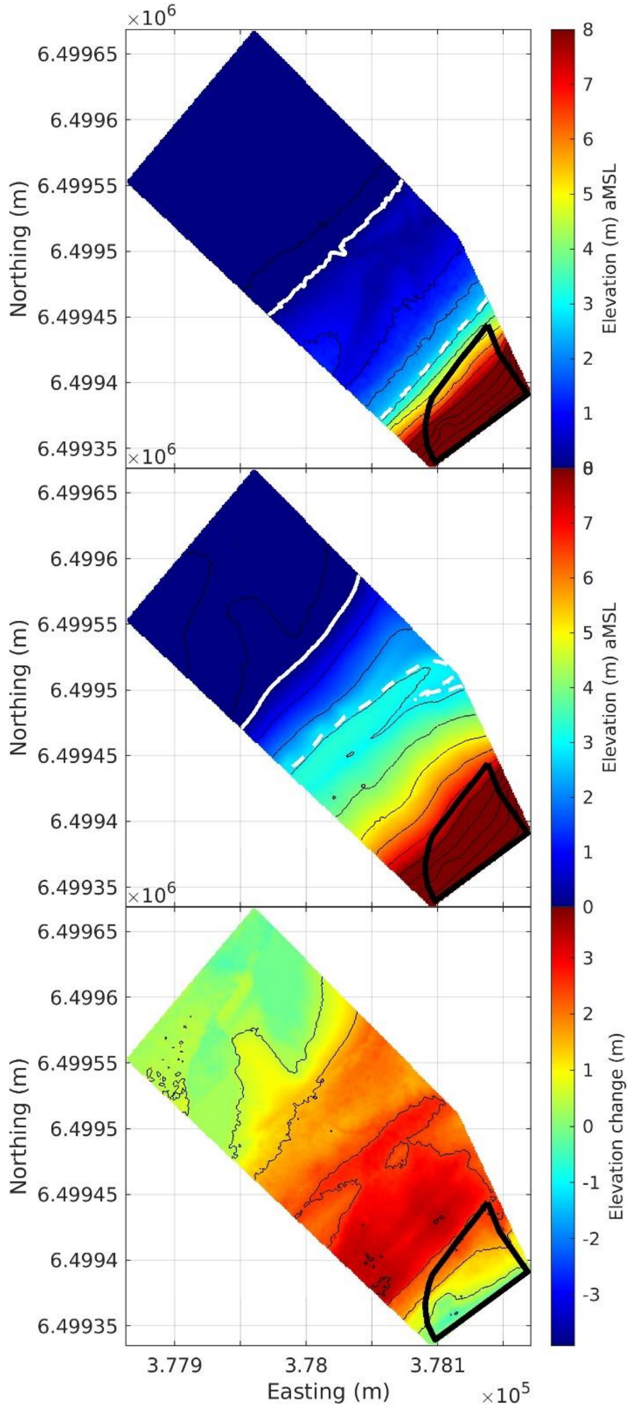
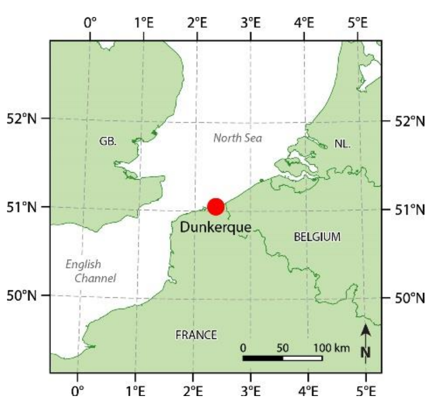


Figure 8. DTM in October 2012 (top), and in October 2022 (middle). Change in elevation between 2012-2022 (bottom). White line is MSL and dashed white line is HAT level.

2.2.3 Dunkerque (France)

Dunkerque is in northern France, along the southern North Sea coastline. This dike, built in 1876, is 900 m long and is a limit between Malo-les-Bains beach and the main outlet of the polder. It is also a major protective structure against marine flooding. Built in 1876, the dike was breached during the storms of March 1 and 2, 1949, and January 31 and February 2, 1953, resulting in the flooding of several districts of Dunkirk City, affecting almost 40 000 people. In 2013 and 2014 a beach nourishment (1,5 million m^3) was carried out to protect the dike from wave attack. In 2020, to enhance coastal protection and avoid sand invasion on the dike, a dune, 600 m long, was built in front of the dike and stabilized by marram grass.

The coast essentially consists of wide and gently sloping sandy beaches with multiple intertidal bars (Anthony et al., 2005) backed by coastal dunes. The tidal regime in the region is semi-diurnal and is macrotidal, the tidal range reaching 5, 6 m at Dunkirk during spring tides. Except for episodic storm events, the coast is exposed to low-energy waves. The dominant winds are from west to southwest, with a secondary wind direction from north to northeast. Winds are usually moderate, with a mean wind velocity of 5,8 m/s. Median significant wave height is less than 1 m with wave periods typically ranging from 4 to 8 s, but maximum wave height may episodically exceed 4 m with periods of 9 to 10 s during major storms (Ruz et al., 2009). Wave heights are significantly lower at the coast, due to significant breaking and energy dissipation over the offshore sand banks, resulting in wave heights that hardly exceed 1 m in the intertidal zone even during storms (Héquette and Cartier, 2016).



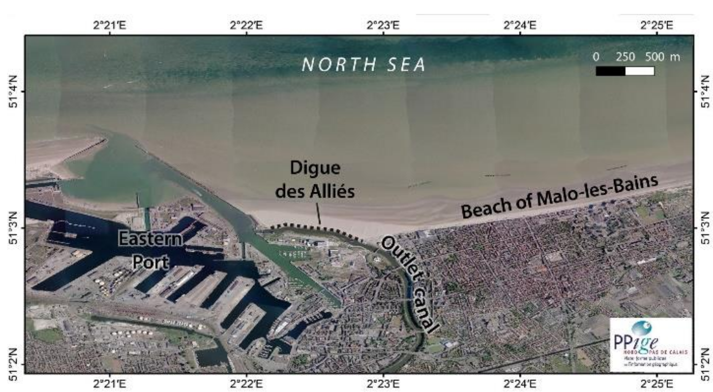


Figure 9. Location maps (top left), aerial view (top right) and location of the Digue des Alliés (bottom) of the Dunkerque demonstrator (photo: Géodunes)

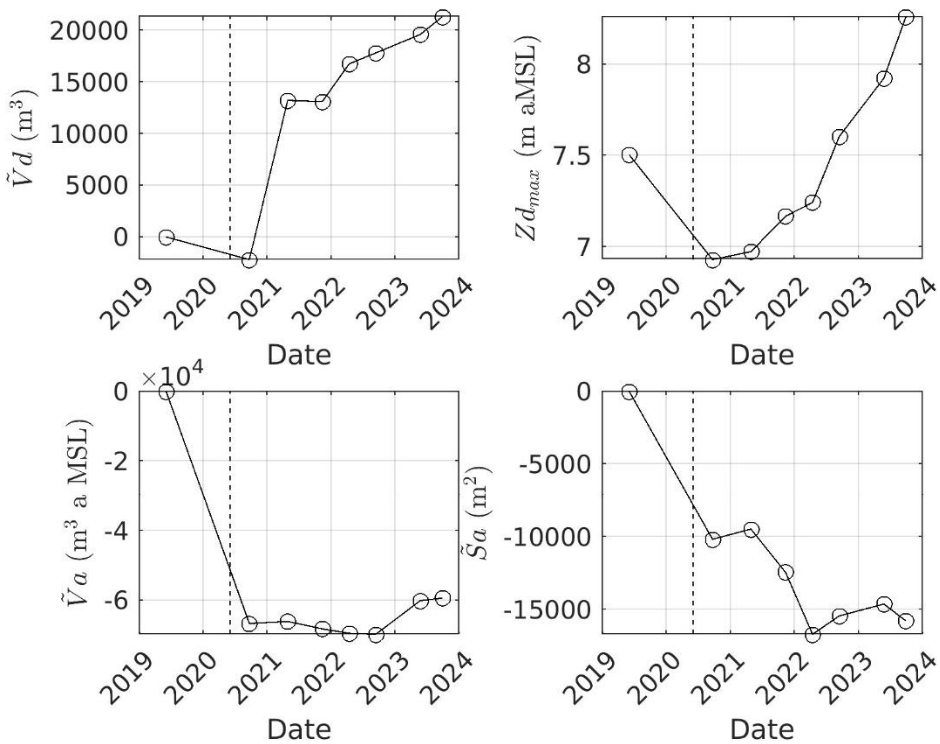


Figure 10. Time series of (top left) dune volume difference, (top right) maximum dune elevation aMSL (bottom left) zone volume aMSL and (bottom right) zone area aHAT for the Dunkerque demonstrator. In all panels the vertical dashed line indicates the implementation date of the demonstrator

The dune was built in November/December 2020, on a sand platform, above HAT, created in 2014 by a massive sand nourishment (Spodar et al., 2018). In 2020, the sand accumulating on the seaward face of the dike (Fig. 11 top) was removed and partly used to build the dune. Accumulation prevailed on the dune (more than 8000 m^3 between 2021 and 2023), enhancing dune crest growth, with an accumulation of 1,2 m (Fig. 10). Meanwhile, embryonic dunes naturally developed on the sand platform (Fig.11). On the total area erosion occurred in the western part of the site (Fig. 11), related to dominant southwest/ northeast littoral drift. Minor (30 000 m^3) sand nourishments were carried out in 2020, 2022 and 2023 in the western part of the site to compensate for the sand deficit.

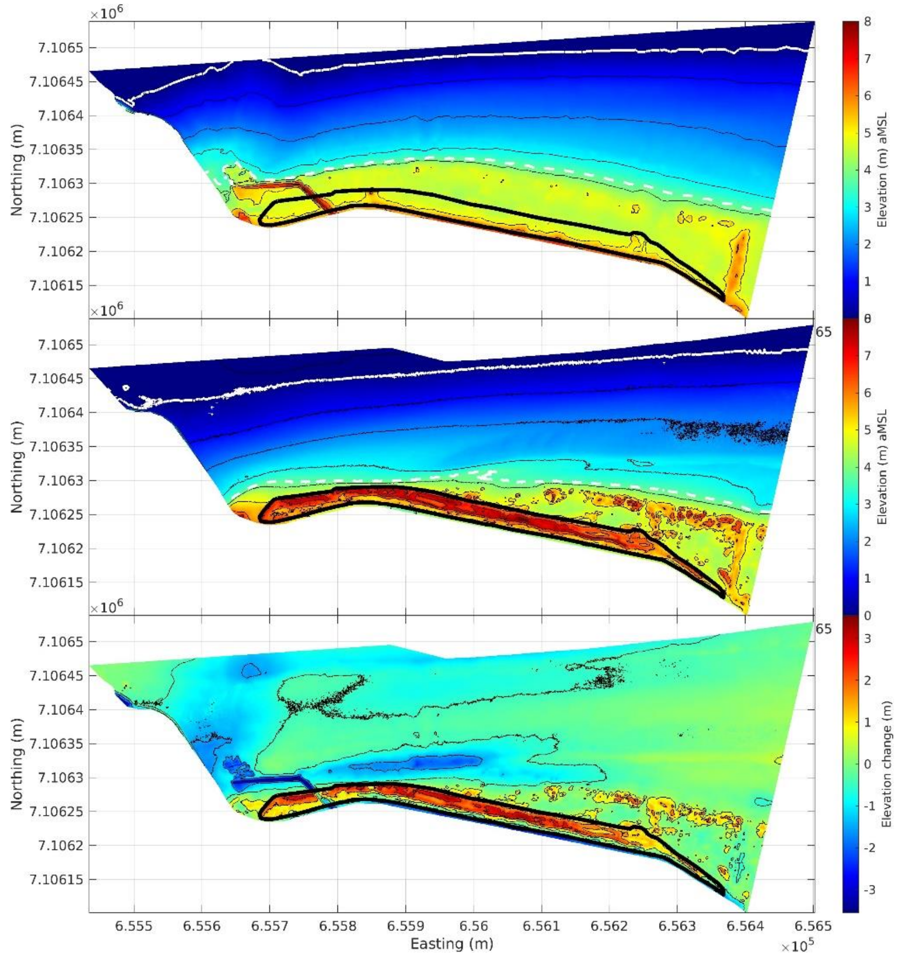


Figure 11. DTM in June 2019, before the dune building (top), and in September 2023 (middle). Change in elevation between 2019-2023 (bottom). Note the erosion in the western part of the site.

2.2.4 Sainte-Marie-la-Mer

Sainte-Marie-la-Mer is located along the Mediterranean coastline, in the south of the Gulf of Lions (Fig. 12). This site is experiencing chronic erosion since 1940's and is located downdrift of 6 hard structures (2 detached breakwaters and 4 groins) and facing a dyke. An ecological restoration program took place in November 2021 involving the installation of wooden fences (one or three lines) along this 2300 m long coastline. This project did not include sand nourishment in the box nor vegetation planting, but sand nourishments are carried out each year (around 10 000 m^3/yr) in the south part of the beach (Robin et al., 2024).

Positioned in front of a dike, the demonstrator was installed in 2021 in an area particularly vulnerable to chronic erosion. Its objective was to reinforce the embryonic dune by installing sand fences. The demonstrator is part of the full ecological restoration area.

The Gulf of Lions is a microtidal, wave-dominated environment with an average tidal range <0.3 m at mean spring tides. The prevailing winds are offshore winds (NW) and can exceed 30 m s^{-1} for a few hours (Lamy et al., 2024. Onshore winds (SE) are less frequent and are accompanied by swell (mean annual Hs = 0.66 m) or winter storms. In this area, coarse-grained sand (D50= 0.75 mm) barrier beaches are backed by small vegetated coastal dunes, mostly artificial and stabilized (with fencing and vegetation).

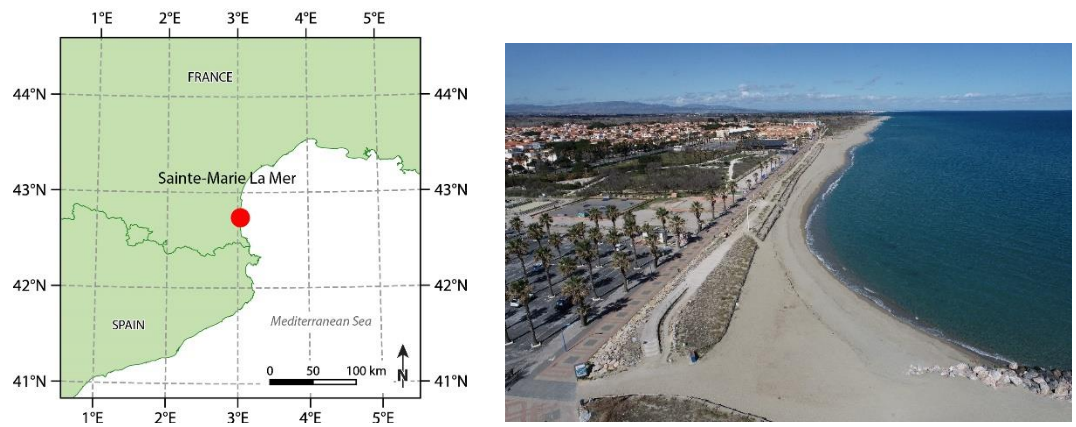


Figure 12. Location map (left) and aerial view of Sainte-Marie la Mer demonstrator (Photo: N. Robin)

After sand fences erection in November 2021, the dune volume increased (Fig. 13), however the maximum dune crest elevation remained stable, with changes in the order of 0,10 m, except in September 2023, with a 0,20 m lowering of the dune crest. For the whole area (see Annex 4), accumulation of about 4000 m^3 was recorded a few months after sand fences installation (Fig. 13), followed by a volume loss of the same order, despite sand nourishments.

Change in elevation (Fig. 14 right) reveal spatial variations along this stretch of coastline, with accumulation above HAT in the central part of the site, stability to the south and slight erosion to the north, although the beach is wider in this area.

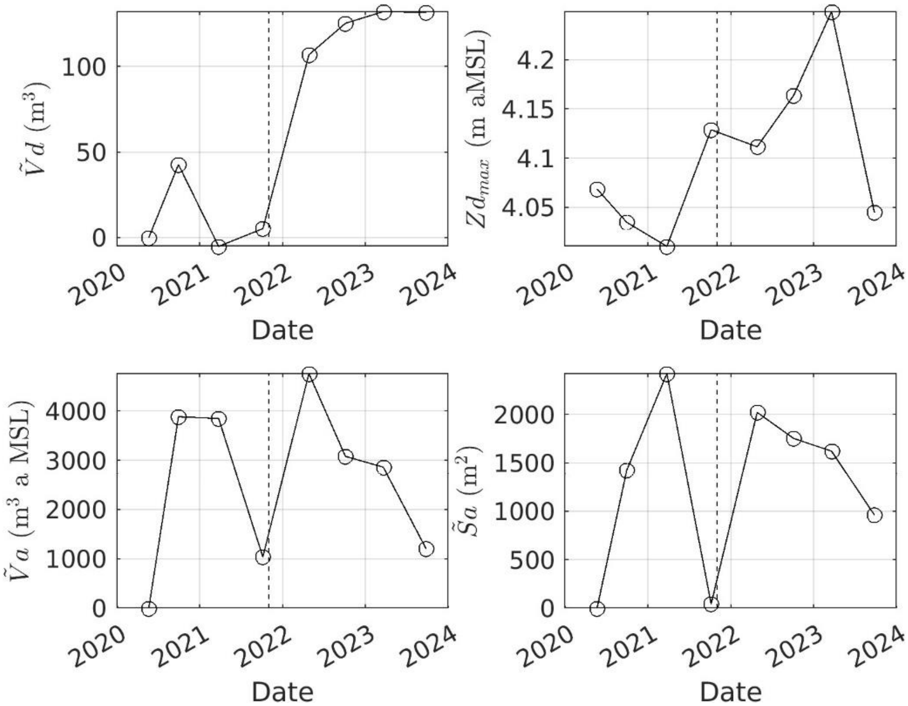


Figure 13. Time series of (top left) dune volume difference, (top right) maximum dune elevation aMSL (bottom left) zone volume aMSL and (bottom right) zone area aHAT for the Sainte-Marie-la-Mer demonstrator. In all panels the vertical dashed line indicates the implementation date of the demonstrator

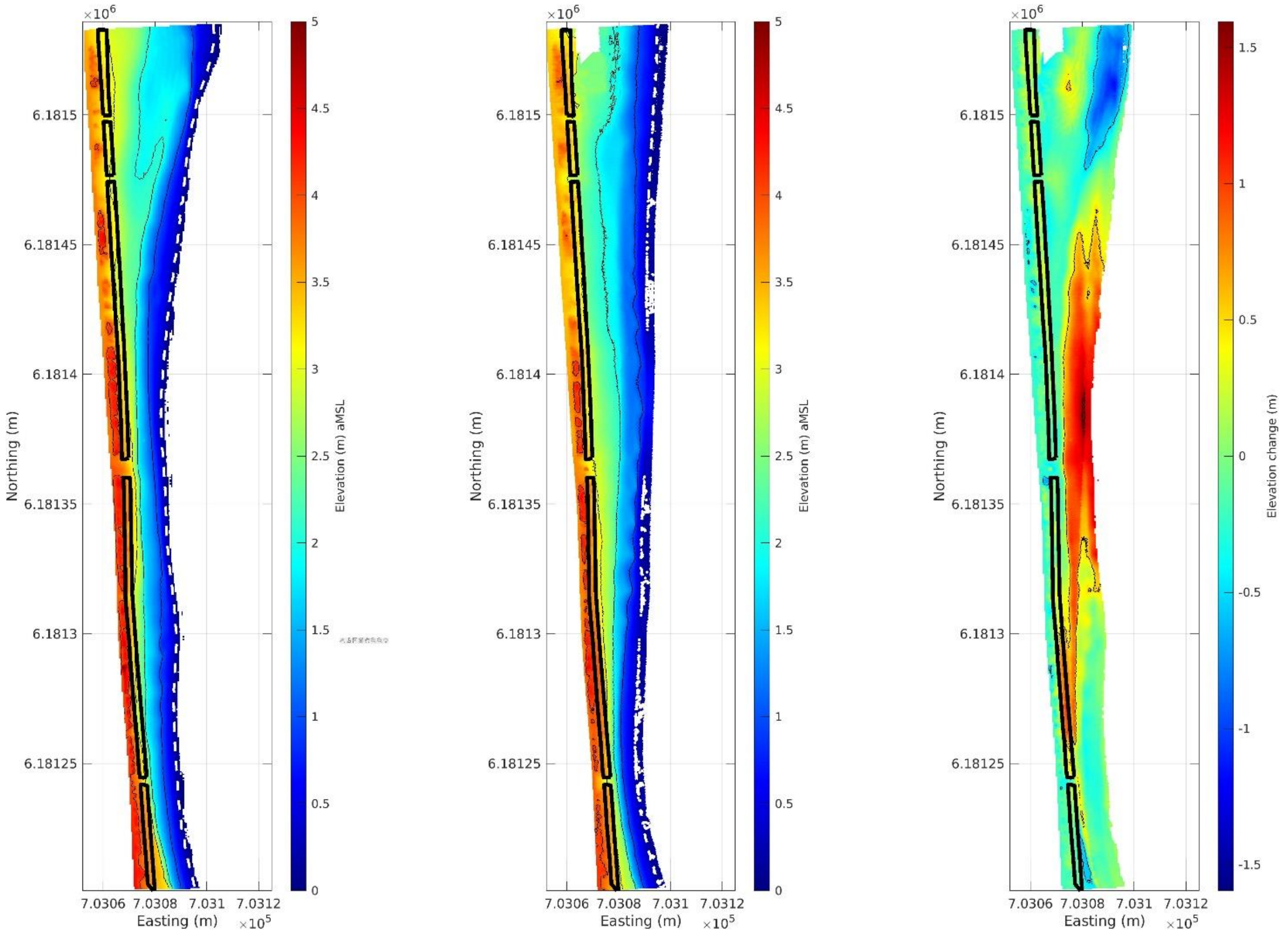


Figure 14. DTM in May 2020, before the dune building (left), and in September 2023 (middle). Change in elevation between 2020-2023 (right).

2.2.5 Living Lab Raversijde (Belgium)

This demonstrator is located West of Ostend, a municipality in Belgium along the North Sea coast (Fig. 15). It is a pilot site for evaluating DiFoD as a hybrid NbS. Brushwood fences were placed on the dry beach (from 10/03/2021 to 02/04/2021) and marram grass was planted with different densities (from 15/03/2021 to 02/04/2021) after beach nourishment and beach reshaping in early 2021 (Montreuil et al.,2023). In February 2023, part of the dune area was replanted with new vegetation to cover the bare sand at elevated level. The main aim of this intervention is to limit nuisance caused by aeolian sand on the coastal road/tram line/sea dike.

The beach is around 320 m wide and is composed of medium to fine sand, with a median grain size of 0.25 mm (Strypsteen, 2023). Tidal ranges fluctuate between 3,5 m during neap tides and 5 m during spring tides and consequently, the offshore tidal currents are notably high, ranging between 1 and 1,2 m/s (Haerens et al., 2012). The combined effects of the coastal orientation from northeast to southwest, residual northeast tidal currents and prevailing southwest winds and waves lead to a predominant sediment transport directed north-eastward.

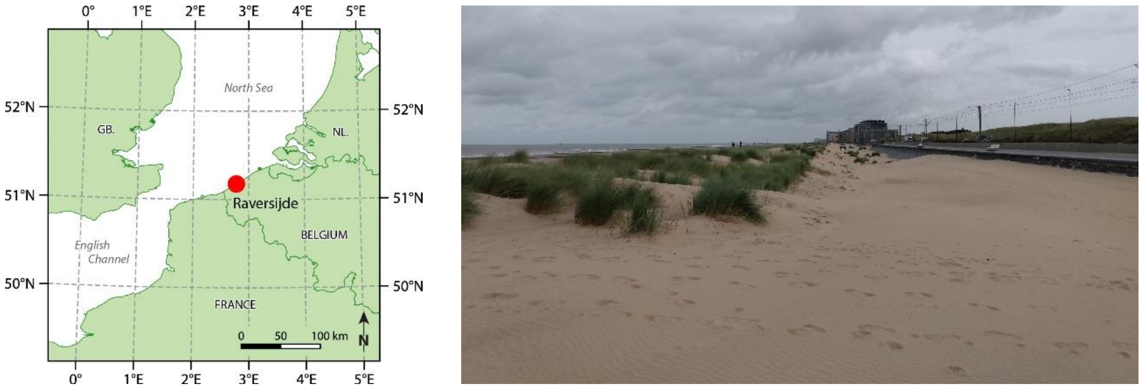


Figure 15. Location map (left) and terrestrial view of the Raversijde demonstrator (right) (Photo: D. Bonte)

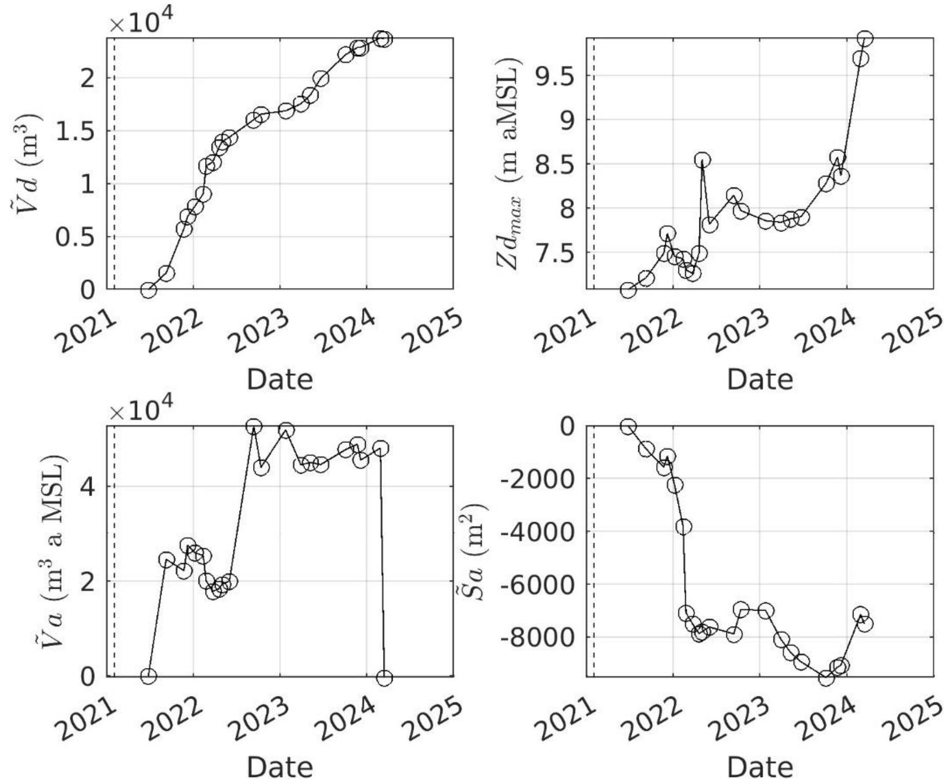


Figure 16. Time series of (top left) dune volume difference, (top right) maximum dune elevation aMSL (bottom left) zone volume aMSL and (bottom right) zone area aHAT for the Raversijde demonstrator. *In all panels the vertical dashed line indicates the implementation date of the demonstrator*

After brushwood fence erection and marram grass planting, the dune volume increased, with a gain of about 23 700 m^3. The maximum dune crest reached an elevation of 9,9 m in March 2023 with an accumulation of 2,2 m since 2021 (Fig. 16). For the entire area (see Annex 3), a slight reduction in sand volume above MSL occurred in 2022 and an erosion of about 48 400 m^3 was recorded between February and March 2024, annihilating the previous accumulation. The surface above HAT was also reduced in 2022 and in 2024, in response to storm events. The dune, however, was not impacted, and accumulation prevailed. Change in elevation (Fig. 17 bottom) illustrate this evolution, with erosion on the beach and accumulation in the dune, illustrating the safety role the dune provided.

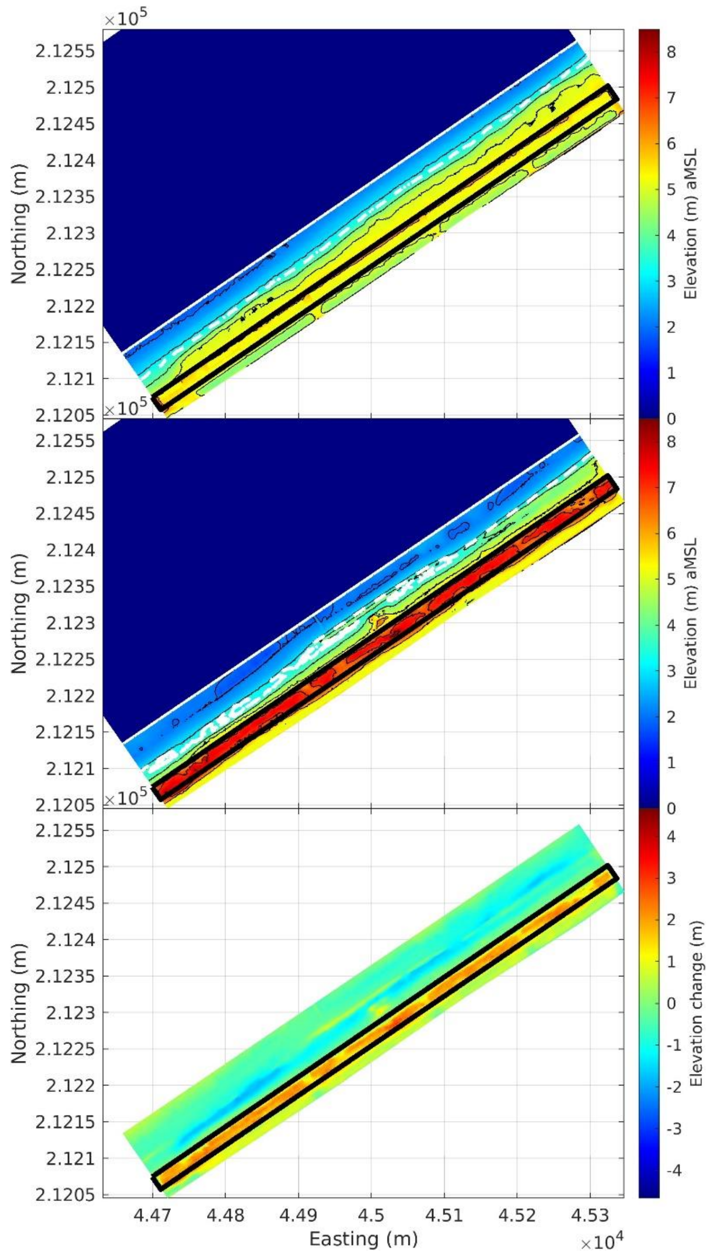


Figure 17. DTM in 2021, before the dune building (top), and in 2024 (middle). Change in elevation between 2021-2024 (bottom).

2.2.6 Middelkerke – grass dike (Belgium)

At the beginning of 2021, MDK - Coastal Division built-up dunes on the dry beach at Middelkerke. Located few kilometers West of Ostend this Demonstrator consists of a dune constructed in front of an existing seawall. In the event of a storm where the dune is eroded, the seawall is expected to protect the residential areas behind it. The site is 30 m wide and 390 m long (Montreuil et al., 2023). Sand fences were erected on the upper beach and marram grass planting was carried out in the dune.

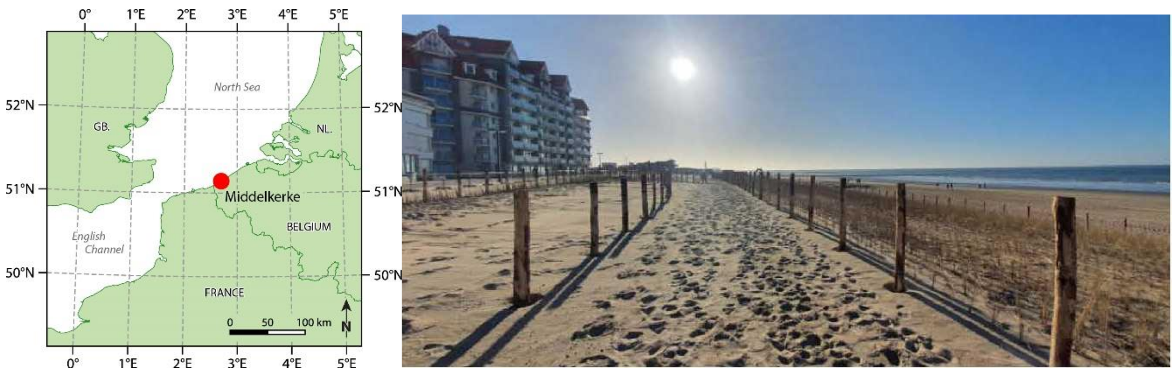


Figure 18. Location map (left) and terrestrial view of the Middelkerke demonstrator (right).

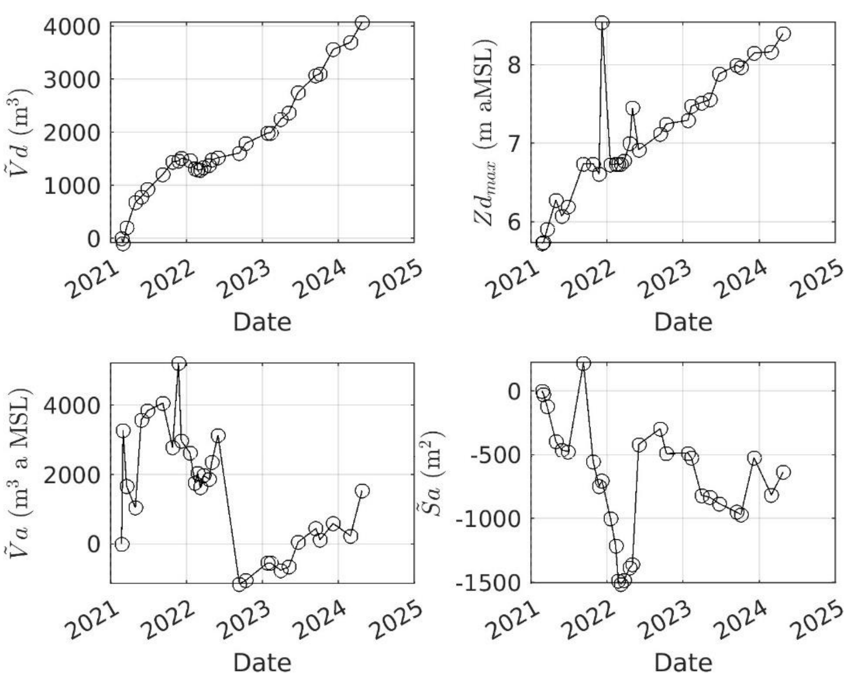


Figure 19. Time series of (top left) dune volume difference, (top right) maximum dune elevation aMSL (bottom left) zone volume aMSL and (bottom right) zone area aHAT for the Middelkerke

demonstrator. In all panels the vertical dashed line indicates the implementation date of the demonstrator

The dune volume, as well as the dune crest elevation rapidly increased the first year after the works carried out in this area. In the entire zone considered in this report (see Annex 3), a net decrease in sand volume above MSL occurred in early 2022, then, accumulation prevailed between 2022 and 2024, however the sand volume remained well below the initial volume (2021-2022), with a net loss of more than 2500 m^3. The surface above HAT was also reduced in 2022 (Fig. 20 middle). After Montreuil et al. (2023), this loss of sand was probably caused by both natural processes and human interventions. Montreuil et al. (2023), mention that the consecutive severe storms in 01-02/2022 caused erosion on the seaward side of the dry beach and on the intertidal zone and that an energetic event, of lower magnitude occurred in 09/2022. Changes in elevation during the surveyed period show accumulation in the dune area, and stability of the upper beach to slight erosion below HAT level (Fig. 20 bottom).

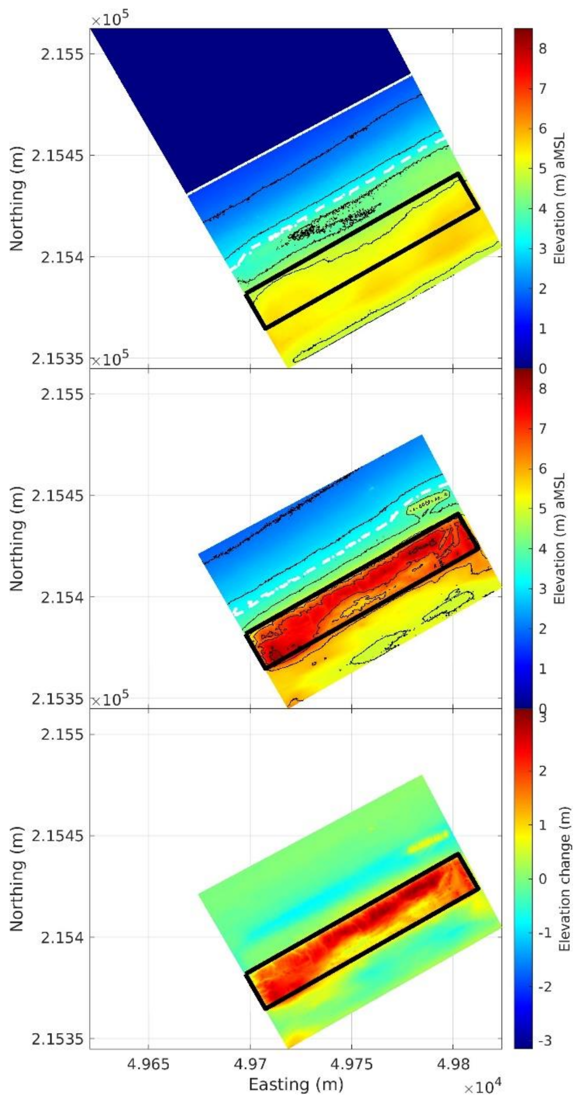


Figure 20. DTM in 2021, before the dune building (top), and in 2024 (middle). Change in elevation between 2021-2024 (bottom).

2.2.7 Delflandse kust (Netherlands)

The Sand Motor (Delflandse kust) Demonstrator is located along the Dutch coastline, it is a dune, without a dike. 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.

The Sand Motor is located just south of the city of The Hague, along the Delfland coast, and has a hook-shaped design. Just after its construction in summer 2011 the Sand Motor had a surface area of about 28 ha, extending 2,5 km along the coastline and protruding 1 km into the sea.

This coastline is wave-dominated with a semi-diurnal tide and is microtidal, with a mean tidal range of about 1,7 m. Waves are wind driven and mainly come from the southwest and north-northwest, with an average significant wave height of 1 m in summer and 1,7 m in winter (Wijnberg, 2002). Sediment grainsize along the Holland coast is variable, both in space and time. Beach and dune sediments are fine sands (100–200 µm) and the sand used for construction of the Sand Motor had an average median grain size of 278 µm.

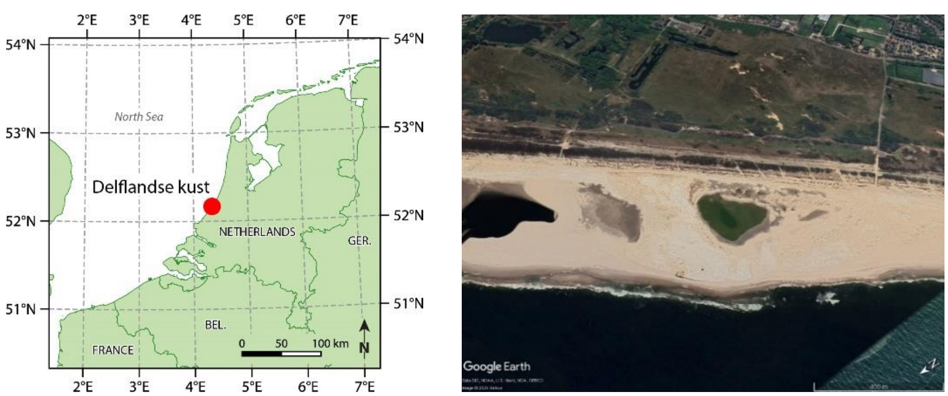


Figure 21. Location map (left) and aerial view of the Delflandse kust demonstrator (right) (Photo: Google Earth)

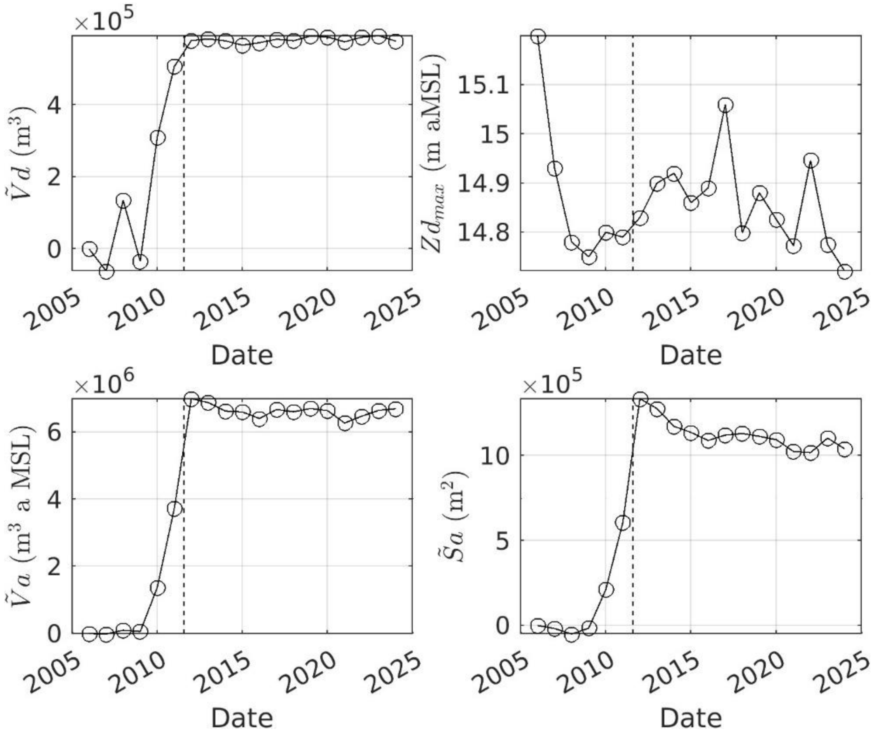


Figure 22. Time series of (top left) dune volume difference, (top right) maximum dune elevation aMSL (bottom left) zone volume aMSL and (bottom right) zone area aHAT for the Sand Motor demonstrator. In all panels the vertical dashed line indicates the implementation date of the demonstrator.

From 2011 (construction of the Sand Motor) to 2024, the volume of the dune remained stable (Fig. 22). The maximum dune crest elevation decreased before the Sand Motor building and after its construction variations in elevation were less than 0,3 m. For the entire area (Annex 4), massive beach and nearshore nourishment induced a net increase of the sand volume above MSL (Fig. 22 and Fig. 23 middle), the surface above HAT however was rapidly reduced after the sand nourishment. Changes in elevation (Fig. 23) before and after massive nourishment show a net accumulation along this stretch of coastline, especially on the very upper beach.

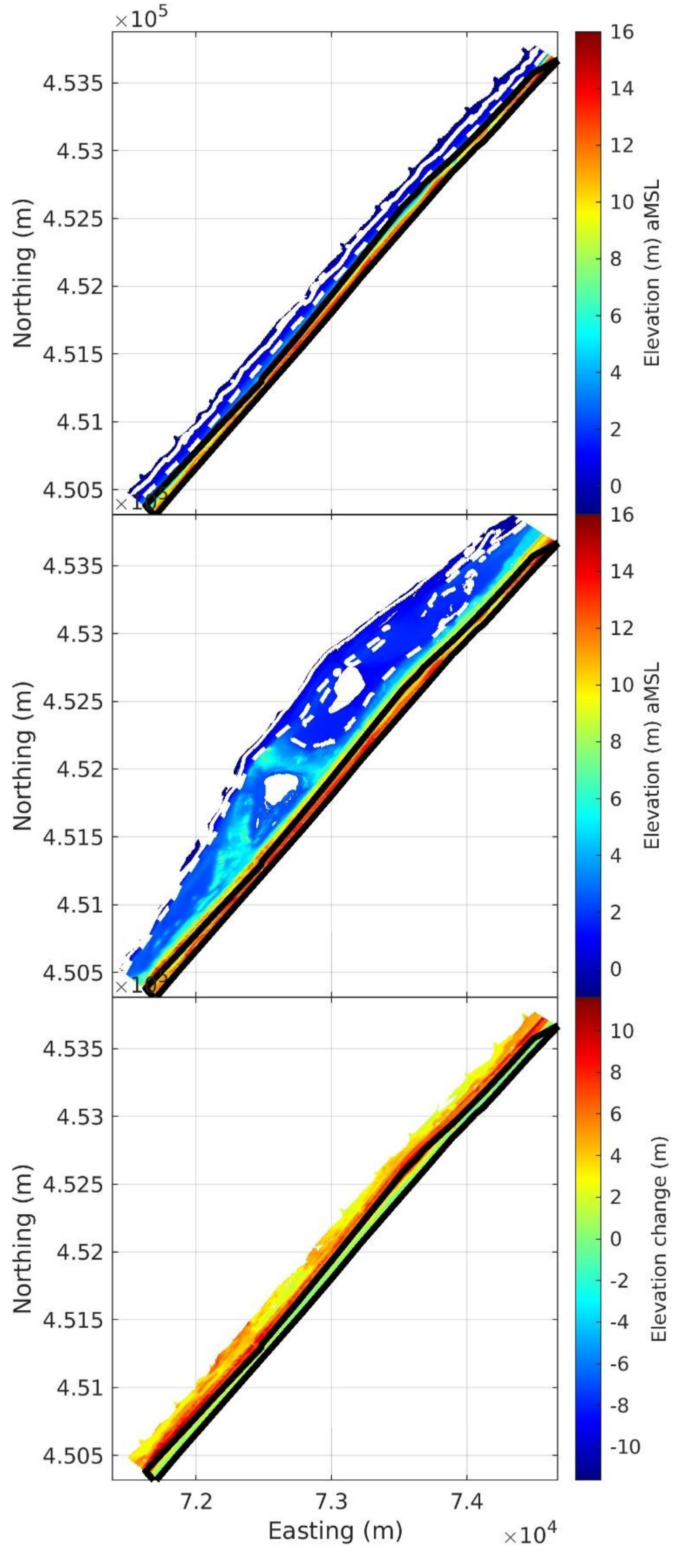


Figure 23. DTM in 2006, before the dune building (top), and in 2024 (middle). Change in elevation between 2006-2024 (bottom) for the dune and the upper beach.

2.2.8 Hondsbossche duinen (Netherlands)

The Hondsbossche Demonstrator is a dune built in front of a dike. The Hondsbossche duinen is situated at the Northern North-Holland (NNH) coast in the Netherlands. This dune-dike system stretches along 9 km between the villages of Petten and Camperduin. Instead of raising a dike, a nourishment of 30 million m^3 was carried out in 2015. This mega-nourishment was placed in front of a sea dike that was considered a weak link in the Dutch sea defence. This new sandy coastal defence consists of a shoreface, beach, and dune, aimed to increase safety against flooding while creating space for nature and recreation. After placement, the newly created beach was on average 1,5–2 times wider, the subaqueous slope 1,5–2,5 times steeper, and the coastline curvature about 4 times larger than the adjacent coastal sections (Kroon et al., 2022).

The NNH coast is a sandy, wave-dominated coast bounded by the Marsdiep tidal inlet in the north and the breakwaters of IJmuiden harbour in the south. The NNH coast is exposed to a semidiurnal tide with a range of about 1,6 m. The spatial variation in the offshore wave climate along the Holland coast is small. Wind waves are mainly approaching from a southwesterly and northwesterly direction with longer period waves arriving mostly from the north. The annual mean wave height Hs is 1,0 m, coinciding with wave periods typically of 4.3 s, at a depth of −10 m + NAP (Kroon et al., 2022).

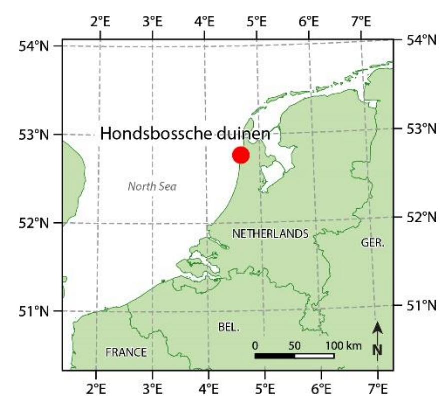


Figure 24. Location map (left) and aerial view of the Hondsbossche duinen demonstrator (right) (Photo: Waternetwerk)

After this mega-nourishment, the dune volume increased about 800 000 m^3 between 2016 and 2024. After Kroon et al., (2022), dune growth was observed along the entire nourished site, either in the form of embryo dune establishment on the nourished beach, or dune progradation and heightening of the first dune row. Kroon et al., (2022) showed that the average dune volume increase over 5 years at the nourished beach is about 30m^3/m/y and almost 60m^3/m/y at the centre of the nourished section, illustrating a significant alongshore variation of deposition in the dune.

The maximum dune crest elevation decreased after the first year (Fig. 25), with a lowering of about 2 m. For the entire area considered in this report (see Annex 4), maximum volume variations above MSL were in the order of 480 000 m^3. Change in elevation between 2010 (before nourishment) and 2024 show a net accumulation in the dune area (Fig. 26).

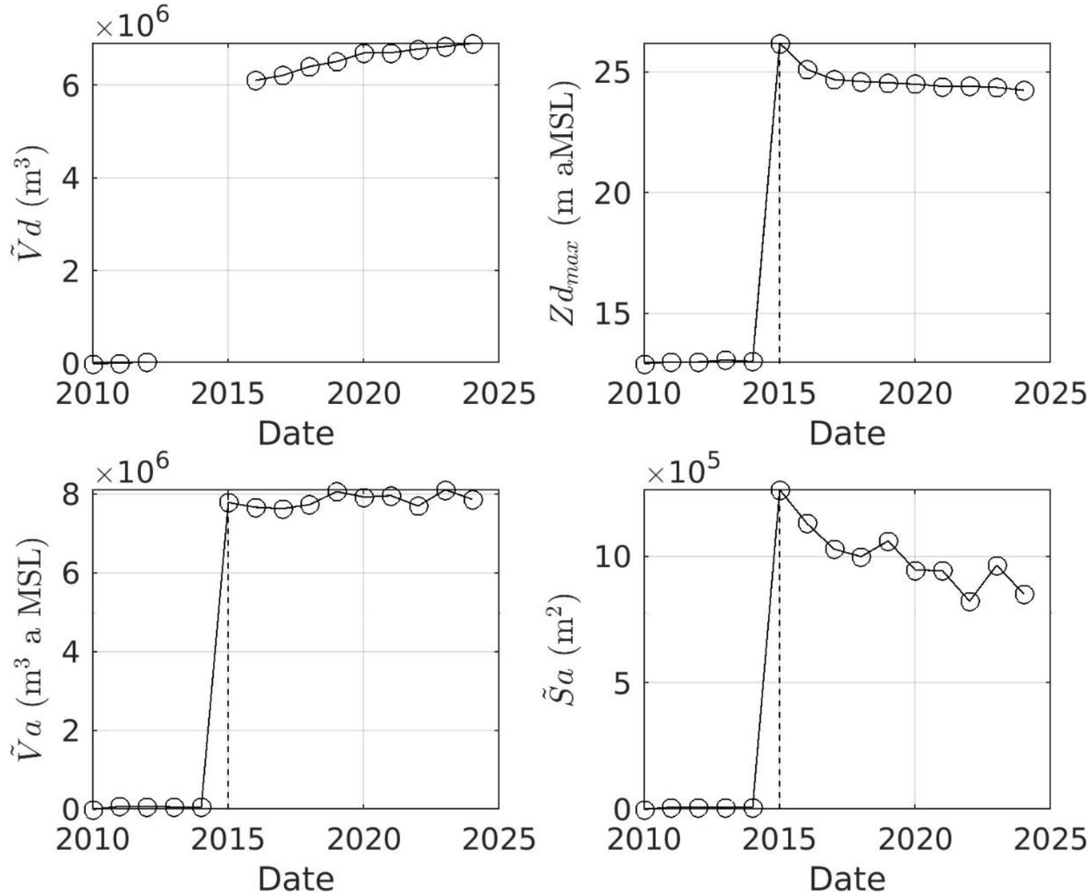


Figure 25. Time series of (top left) dune volume difference, (top right) maximum dune elevation aMSL (bottom left) zone volume aMSL and (bottom right) zone area aHAT for the Hondsbossche demonstrator. In all panels the vertical dashed line indicates the implementation date of the demonstrator.

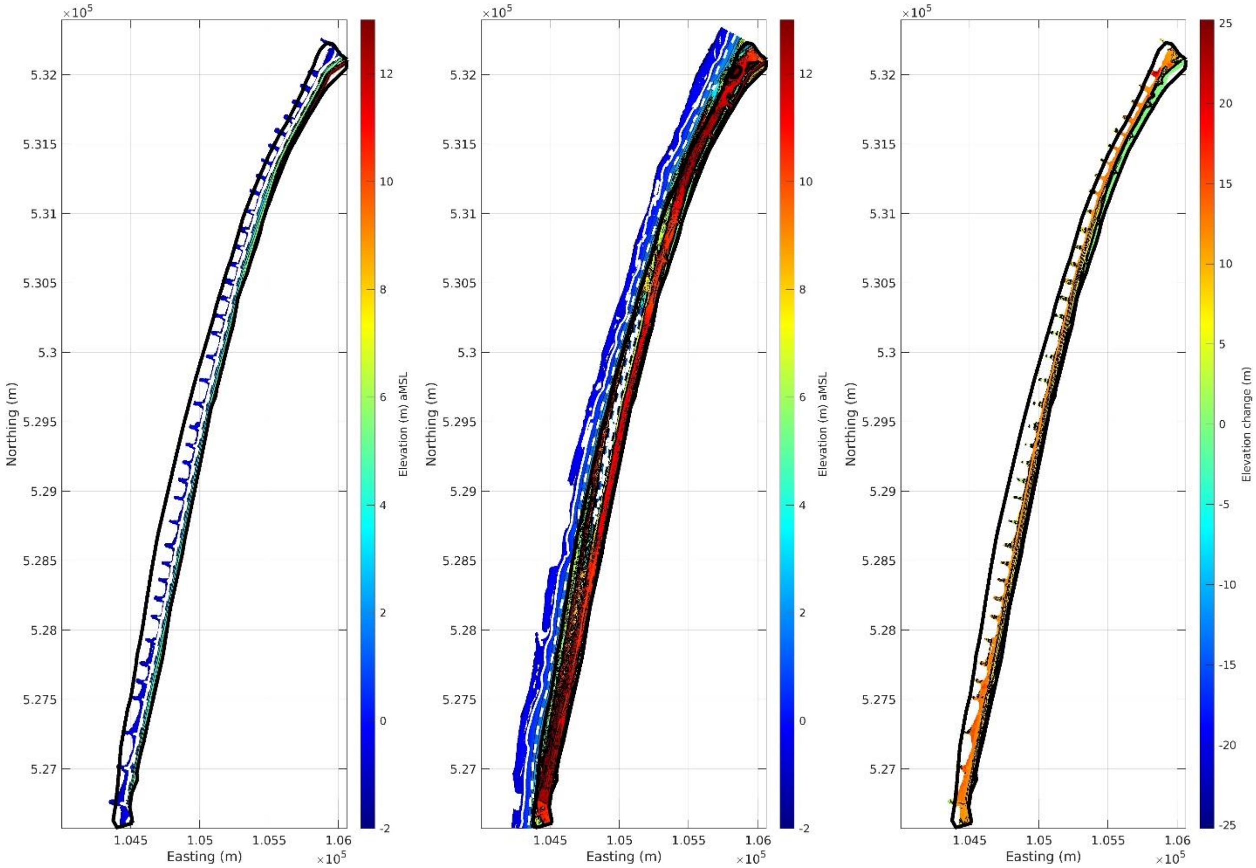


Figure 26. DTM in 2010, before the beach nourishment and the dune building (left), and in 2024 (middle). Change in elevation between 2010 and 2024 (right), showing only the dune and the upper beach.

2.2.9 Katwijk (Netherlands)

Located along the South Holland coast, this Demonstrator includes a hard dike embedded within a dune (DiD). Despite the narrow (40 m wide and 1.5 km long) vegetated artificial dune, a buried dike slope is incorporated, to provide strong protection against coastal flooding.

Between October 2013 and February 2015, the coastal defenses at Katwijk were reinforced. A 1200 m long beach restoration (including a dike) was realized at Katwijk. The dike is covered with sand for protection purposes, but also to maintain the natural look of the dunes and the beach. Around 2,4 million cubic meters of sand were used to build the dunes. To accommodate the need for parking places, the Municipality of Katwijk decided on an underground parking garage at the same location. The Dike-in-Dune solution thus offers security and parking space, while improving the spatial quality.

Figure 27. Location map (left) and aerial view of the Katwijk demonstrator (right)

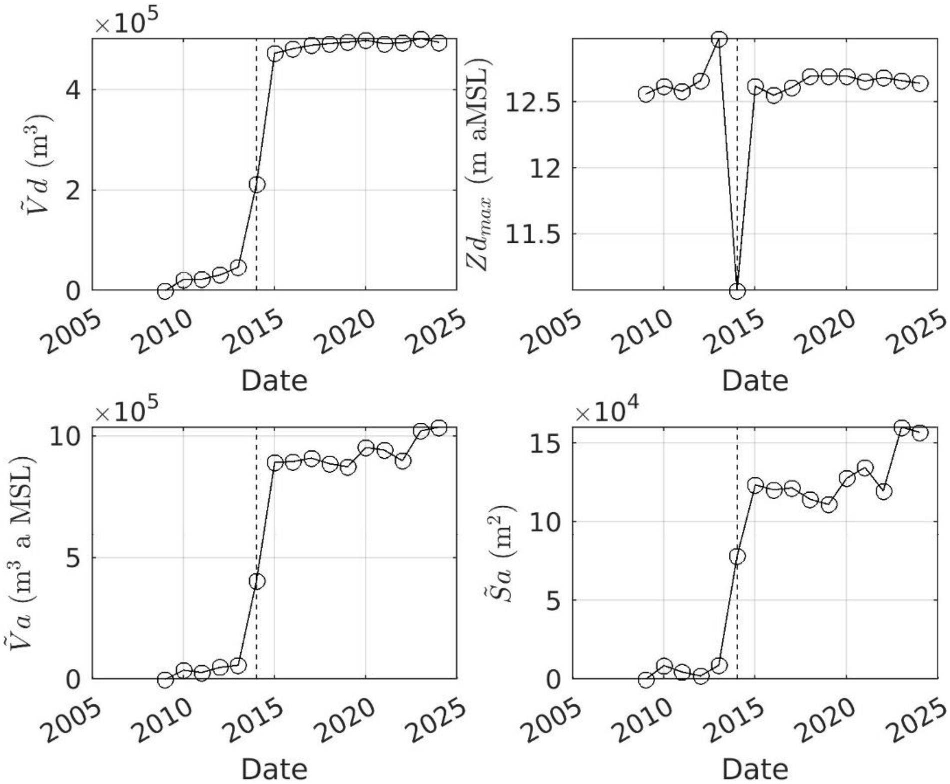


Figure 28. Time series of (top left) dune volume difference, (top right) maximum dune elevation aMSL (bottom left) zone volume aMSL and (bottom right) zone area aHAT for the Katwijk *demonstrator. In all panels the vertical dashed line indicates the implementation date of the demonstrator.*

After sand nourishment and construction of the dune on the dike, the dune volume was almost constant, with a variation of less than 22000 m^3 between 2015 and 2024. The maximum elevation of the dune, before beach nourishment, decreased between 2013 and 2014, with a crest lowering of almost 2 m, due to the construction of the DiD. The maximum crest elevation as well as the mean dune elevation of the “new” dune, erected above the dike, was almost stable since the dune building. An increase in beach and dune volume above MSL (Fig. 28 and 29) as well as a widening of the surface above HAT was recorded, especially in 2024 and 2025.

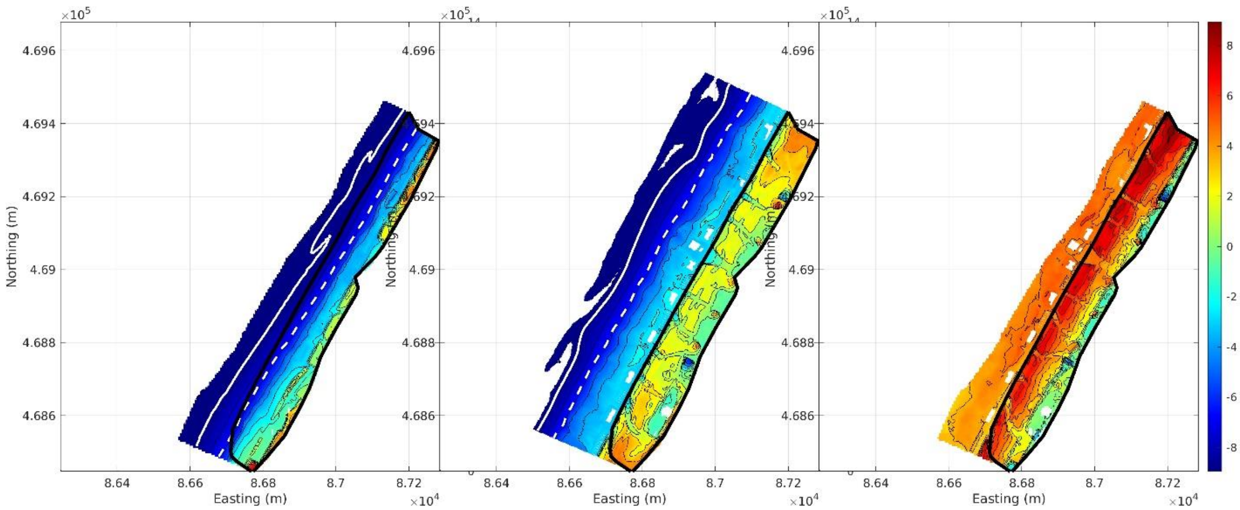


Figure 29. DTM in 2009, before the dune building (left), and in 2024 (middle). Change in elevation 2009-2024 (right).

2.2.10 Texel, Prins Hendrik Zanddijk (Netherlands)

The Prins Hendrik Zanddike is located on Texel Island, in a sheltered area in the Wadden sea. The mean tidal range of nearly 1.4 m increases to 2.0 m during spring tide. Wind measurements taken at the nearby Texel-Hors station show a mean wind velocity of 7.1 m s^{-1} from a south-southwesterly direction. Nearshore, the most frequent wave directions lie between southwest and north, with mean significant wave heights of 1,44 and 1,48 m respectively (Elias and Van der Spek, 2017).

The dike no longer met the legal safety requirements and the dike, which is 3 km long, has been reinforced in a unique way: sand in combination with nature development. During the second half of 2017, 5.5 million m³ of marine sand was dredged and reclaimed in front of the dike to build the dune. In 2018 and 2019, additional elements were installed, such as a bicycle path, an observation point and marram grass on top of the dunes. Now there is a new sand dune on the seaside of the former hard dike.

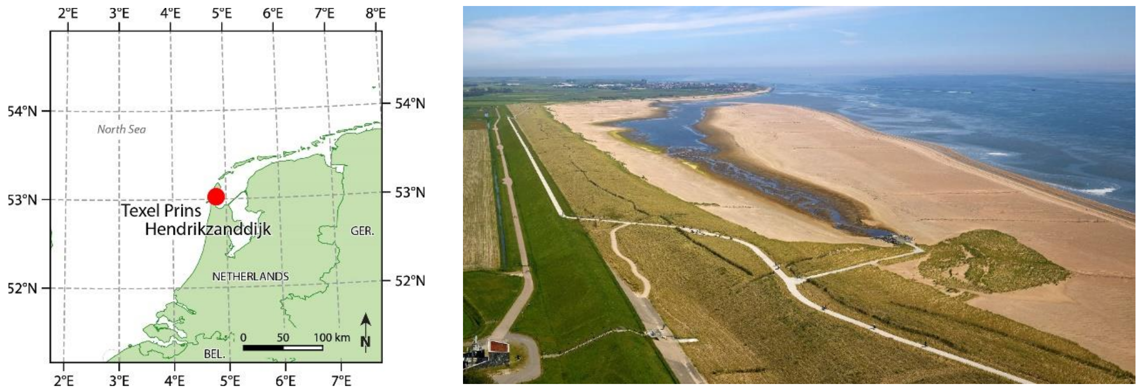


Figure 30. Location map (left) and aerial view of the Texel demonstrator (right) (Photo: Vicky Stratigaki)

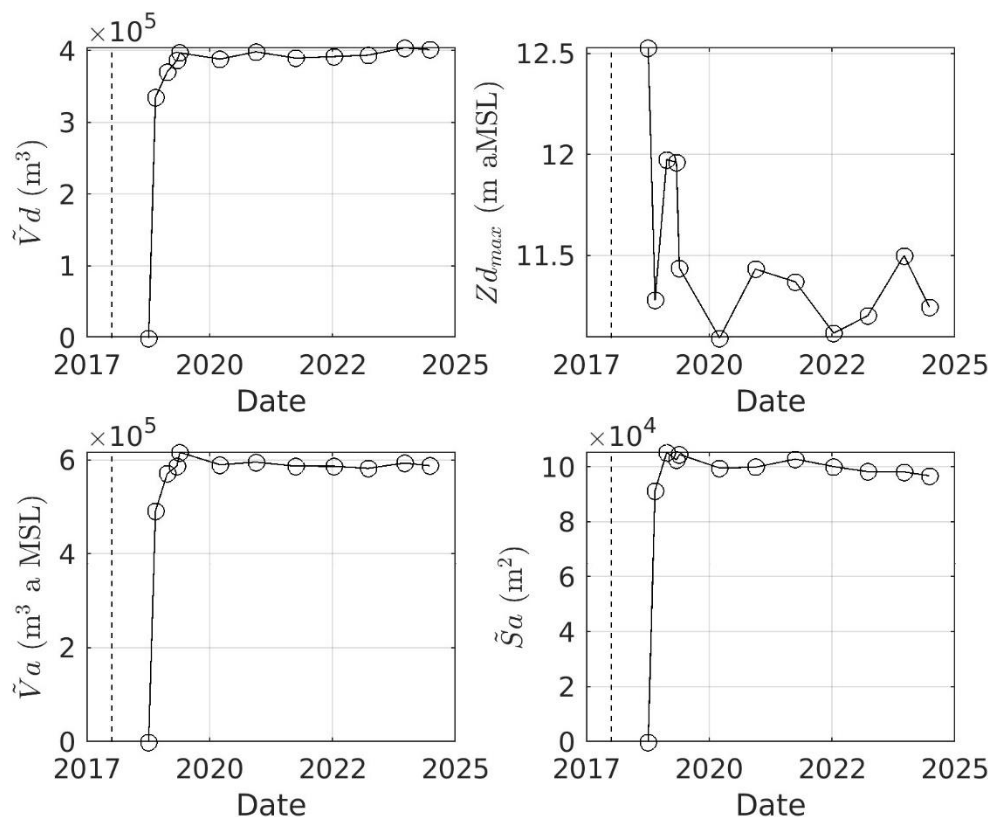


Figure 31. Time series of (top left) dune volume difference, (top right) maximum dune elevation aMSL (bottom left) zone volume aMSL and (bottom right) zone area aHAT for the Texel *demonstrator. In all panels the vertical dashed line indicates the implementation date of the demonstrator.*

After sand nourishment, the dune volume was about 820 000 m^3 and increased to up to 888 900 m^3 in 2023. The maximum dune crest elevation decreased (-1,25 m) between October and November 2018, and about -0,9 m between February 2019 and March 2020 (Fig. 31). The mean dune elevation however remained almost stable, with an accumulation of 0,6 m between 2018 and 2024 (not shown). The sand volume above MSL as well as the surface above HAT did not show substantial variations. For the whole area (see Annex 6), after sand nourishment, accumulation prevailed on the northeastern part of the dune in 2018 (Fig. 32 top), then in 2024, the entire dune area was in accumulation, especially in the southwestern part, with a widening of the upper beach (above HAT). The elevation change between 2018 and 2024 shows preferential accumulation in the western part of the Demonstrator, probably in relation to sand input during sand nourishment process.

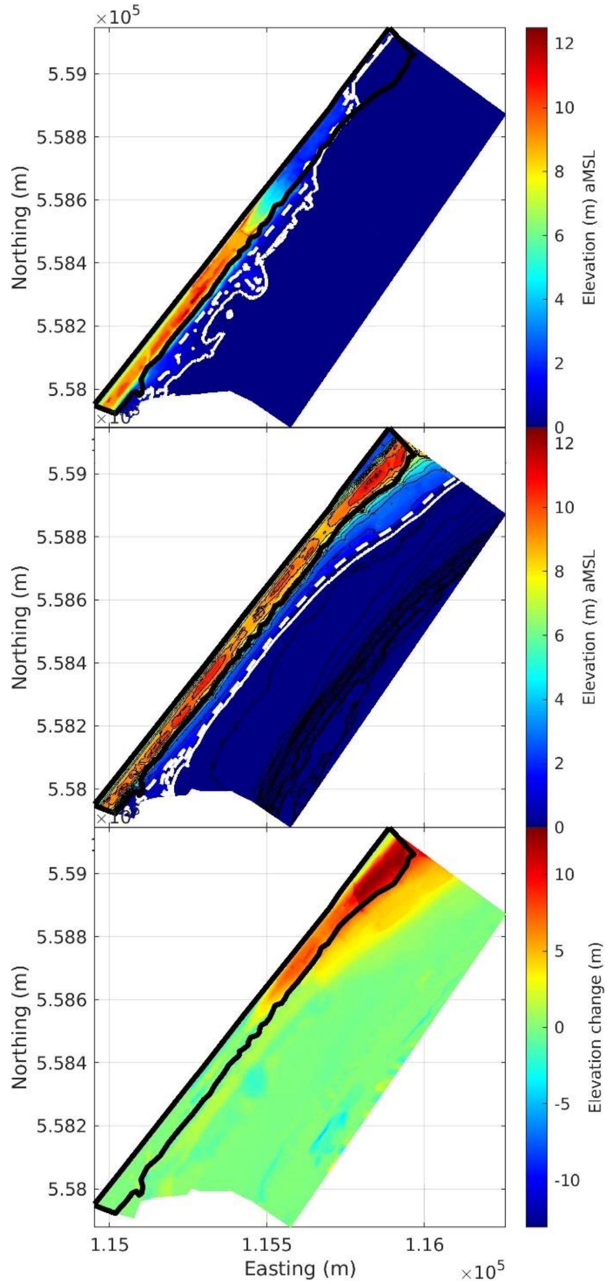


Figure 32. DTM in 2018 (top), and in 2024 (middle).
Change in elevation 2018-2024 (Bottom).

2.2.11 Sankt Peter Ording (Germany)

This demonstrator is situated along the west coast of the Eiderstedt peninsula, in the North Frisian Wadden Sea in Germany (Fig. 33). This is a barrier beach system, in which foredunes have been formed since the 1970s (Soares et al., 2022).

The region is situated in the mid-latitudes of Northern Europe, where the North Sea forms a continental shelf sea with the German Bight in the south-eastern area. The tidal regime is diurnal mesotidal, with an average tidal range of approximately 3,0 m near the coast (Mehrtens et al., 2022).

The demonstrator is characterized by a broad system of multiple dikes and a natural grey dune system. The northern land protection dike, situated at an elevation of 8 m above mean sea level (amsl), serves as the primary line of defense. To the south of the dune system, a regional dike with a tar surface layer provides supplementary protection at an elevation of 6,4 m above mean sea level (amsl). A middle dike, situated behind both the dune system and the regional dike, serves as a secondary line of defense. The natural grey dune system, which varies in height from 6 to 16,5 m, occupies the space between the northern and southern dikes, thereby enhancing the overall coastal protection by providing a resilient, multifunctional barrier against storm surges and flooding.

Figure 33. Location map (left) and aerial view of the Sankt Peter Ording demonstrator (right)

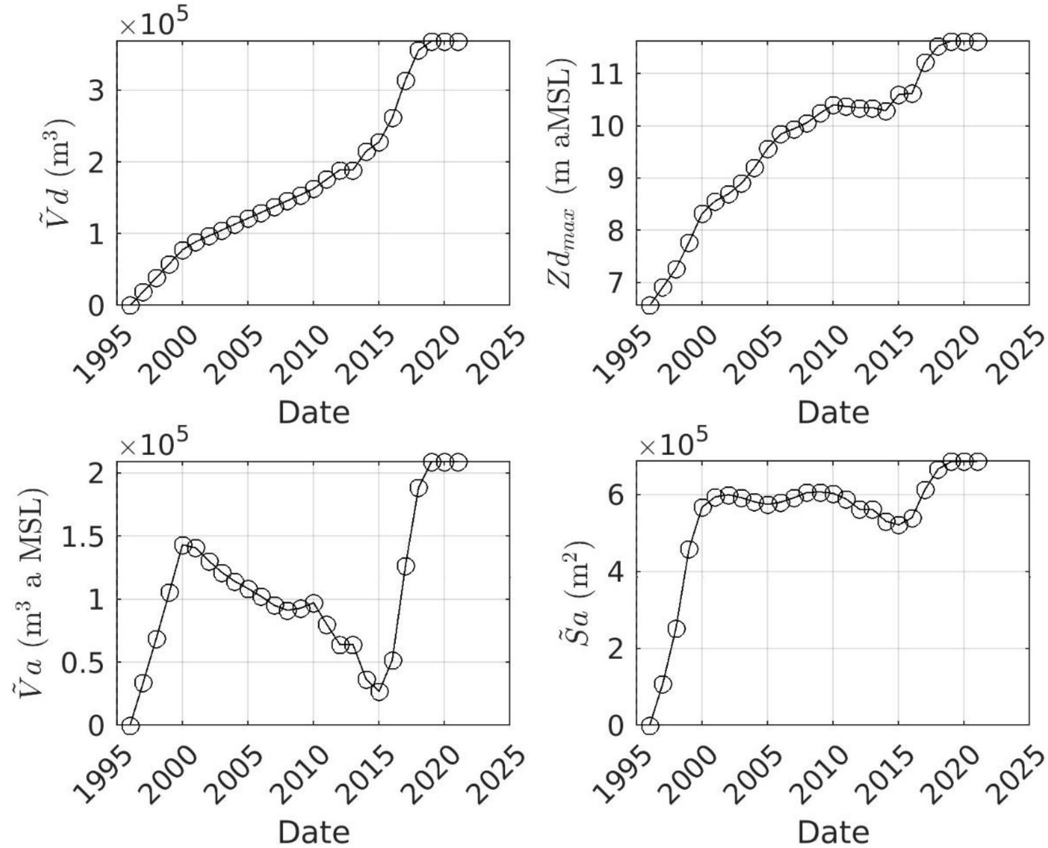


Figure 34. Time series of (top left) dune volume difference, (top right) maximum dune elevation aMSL (bottom left) zone volume aMSL and (bottom right) zone area aHAT for the Sankt Peter Ording demonstrator.

In the area selected in this report (see Annex 6), the dune volume increased (Fig. 34) from 1996 to 2018, then remained stable from 2018 to 2021. After 2018, no change in maximum dune crest elevation was recorded (Fig. 34). The sand volume above MSL increased till 2000, then sand accumulation was strongly reduced from 2000 to 2015. After 2015 accretion prevailed again. The surface above HAT also decreased in 2015, maybe in response to a storm event. The elevation change (Fig. 35 bottom) shows accumulation (Fig. 35 bottom) at the dune toe, stability on the upper beach and erosion below.

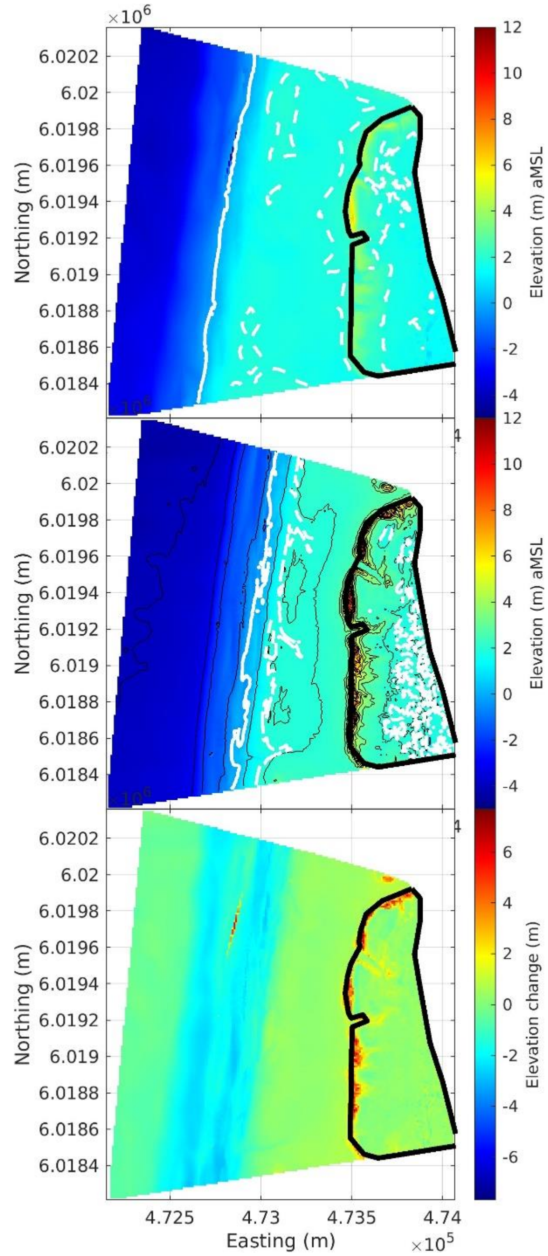


Figure 35. *DTM in 1996 (top), and in 2021 (middle). Change in elevation between 1996 and 2021 (bottom).*

2.2.12 Ystad (Sweden)

Ystad Demonstrator, located along the south Baltic Sea coastline, involved an existing rock revetment, with a beach nourishment implemented in 2011, with re-nourishments in 2013, 2017 and 2020. 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.

The wave climate in the Baltic Sea is dominated by short-period wind-generated waves. Normal tidal ranges in the adjacent Baltic Sea are less than 0,25 m. At Ystad the predominant wave direction is predominantly from SSW followed by E/ESE. Hs between 0 and 1,5 m are the most frequent and the highest waves approach from S and SSW. The longshore current is mainly wave-induced.

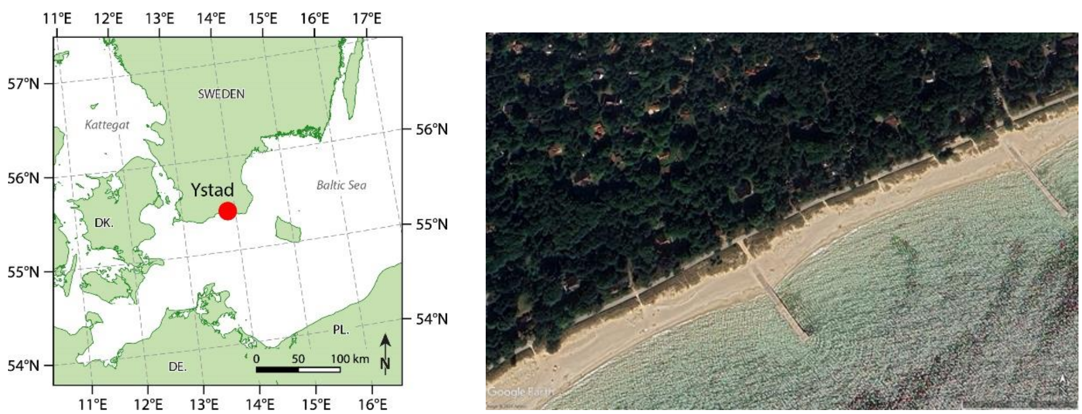


Figure 36. Location map (left) and aerial view of the Ystad demonstrator (right) (Photo: Google Earth)

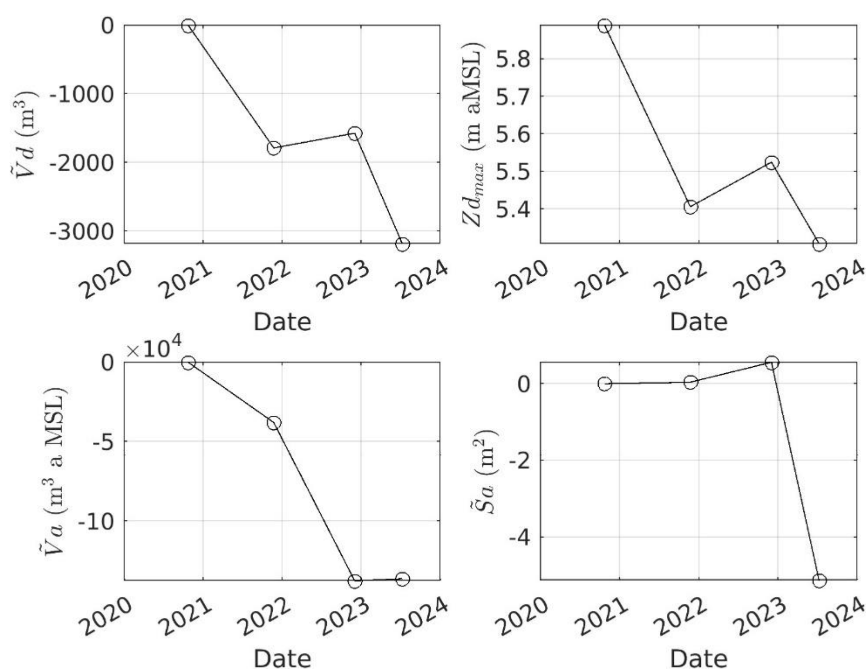


Figure 37. Time series of (top left) dune volume difference, (top right) maximum dune elevation aMSL (bottom left) zone volume aMSL and (bottom right) zone area aHAT for the Ystad demonstrator. In all panels the vertical dashed line indicates the implementation date of the demonstrator.

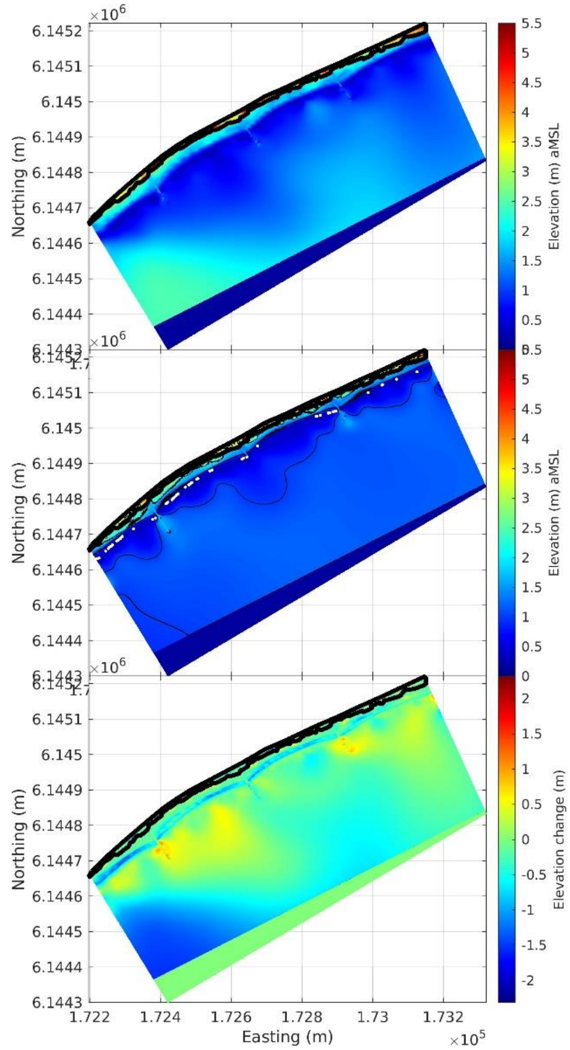


Figure 38. DTM in 2020, before the dune building (top), and in 2023 (middle). Change in elevation between 2020-2023 (bottom).

The dune, from 2020 to 2022, lost more than 3000 m^3, and the dune crest elevation decreased about 40 cm. For the entire area (see Annex 6), changes in elevation, between 2020 and 2022 (Fig. 38) show a slight erosion. The dune line is very narrow and was stable over the surveyed period. However, the foreshore was lowered in 2022. This Demonstrator is the only one in erosion since the dune building.

3 Conclusion

The aim of this report was, for each Demonstrator, to collect available topographic data and to carry out a first analysis of dune and upper beach topographic evolution since the demonstrators' construction. The datasets will be then used in Task 6.2 to conduct spatiotemporal analyses of sedimentation/erosion budgets and vegetation cover evolution under various physical boundary conditions, and in Task 6.3 to correlate boundary conditions with quantified morphodynamic patterns.

Table 2. Overview of main characteristics and of data available for the 12 Demonstrator

	Demonstrator name	Type	Year of instal lation	Data available	Frequency	Sand Nourishment	Sand Fences	Marram grass planting
1	Douro Estuary Sandspit	Dune without a dike	2004-2008	2008 to 2023	Twice a year	No	No	No
2	Soulac	Dune-in-front-of-dike	2024	2012 to 2022	Yearly	No	No	Yes
3	Dunkerque	Dune-in-front-of-dike	2020	2019 to 2023	Twice a year	Yes	No	Yes
4	Sainte-Marie-la-Mer	Dune-in-front-of-dike	2021	2020 to 2023	Twice a year	Yes	Yes	No
5	Living Lab Raversijde	Dune-in-front-of-dike	2021	2021-2024	Monthly	Yes	Yes	Yes
6	Middelkerke grass dike	Dune-in-front-of-dike (seawall)	2021	2021-2024	Monthly	Yes	No	Yes
7	Delflandse kust (sand motor)	Dune alone	2011	2006 to 2024	Yearly	Yes	No	No
8	Hondsbossche	Dune-in-front-of-dike	2015	2010 to 2024	Yearly	Yes	No	Yes
9	Katwijk	Dune-on-dike	2013-2015	2009 to 2024	Yearly	Yes	No	Yes
10	Texel Prins Hendrikzanddijk	Dune-in-front-of-dike, dike-in-dune	2019	2018 to 2024	Yearly to twice a year	Yes	No	Yes
11	Sankt Peter Ording	Dune-in-front-of-old dike	1985	1996 to 2022	Yearly	No	No	?
12	Ystad	Dune-in-front-of-dike (revetment)	2011-2021	2020 to 2023	Yearly	Yes	Yes	Yes

Most dune constructions in front of a dike or a seawall are recent (less than 5 years), outlining the increasing interest for such a practice. Nine demonstrators are dune-in-front-of-dike, 2 are dune only and 1 is a dune on a dike (Table 2). Most of them are associated with sand nourishments, involving variable volumes, ranging from mega-nourishments (several million cubic meters) as for the Delflandse kust and Hondsbossche to smaller ones (10 000 to 30 000 m^3). Sand volumes of the dunes are therefore variable, depending on the dune size (lenght, width, height), varying from 2800 m^3 at Sainte-Marie-la-Mer to 7 792 460 m^3 at Hondsbossche.

The frequency of surveys for available data (delivered by Demonstrator leads) is variable, from yearly to monthly. Moreover, the temporal database varies between each demonstrator, with some sites where monitoring begins only at the time of the demonstrator's installation, limiting the understanding of the study site's functioning. Furthermore, there is also a disparity in the age of the demonstrators, ranging from those that have existed for one or several decades (Porto, Delflandse kust..) to others, such as Soulac, which has only recently been implemented. This disparity complicates a comprehensive comparison of the data, leading the project at this stage to adopt a site-specific approach. Nevertheless, a more detailed analysis of the morphodynamics of these hybrid solutions—considering both biotic and abiotic parameters of each site, as well as the objectives that guided the implementation of these solutions—is the aim of deliverable D6.3.

Most of the dunes gained sand after construction, except at Ystad and Delflandse kust demonstrators (Table 3). Stability prevailed at Sainte-Marie-la-Mer and no data is available yet for the Soulac demonstrator. Erected above HAT, the dunes usually were in accretion, especially during the first year, just after beach nourishment. Depending on their “age” and on local hydrodynamics conditions, most of them remained stable or slowly accreted. However, some demonstrators lost beach dune volume as Sainte-Marie-la-Mer, Delflandse kust and Ystad. Mean dune elevation increased or was stable for all demonstrators, excepted Ystad (Table 3).

The Evolution of the area above HAT was more contrasted. In 5 demonstrators the surface increases, while in 7 demonstrators a surface diminution was recorded (Table 3), although some demonstrators were constructed only 2 or 3 years ago. This evolution could be related to storm events, inducing erosion on the upper beach or management practices. There is no direct relationship between surface area above HAT gained or lost and dune volume and elevation evolution. Although in some areas the upper beach was eroded, the dune was stable or accreting.

To conclude, a more comprehensive and in-depth analysis of the morphodynamics associated with these hybrid solutions is required. This involves carefully examining both the biotic and abiotic factors specific to each site, as these elements play a crucial role in understanding the overall performance and impact of the solutions. Additionally, it is essential to consider the initial objectives and motivations that guided the implementation of these systems at each location, as these contextual factors provide valuable insights into their intended functionality and effectiveness. This detailed investigation constitutes the core objective of deliverable D6.3, which aims to establish a clearer understanding of these hybrid solutions within their diverse environmental and operational contexts.

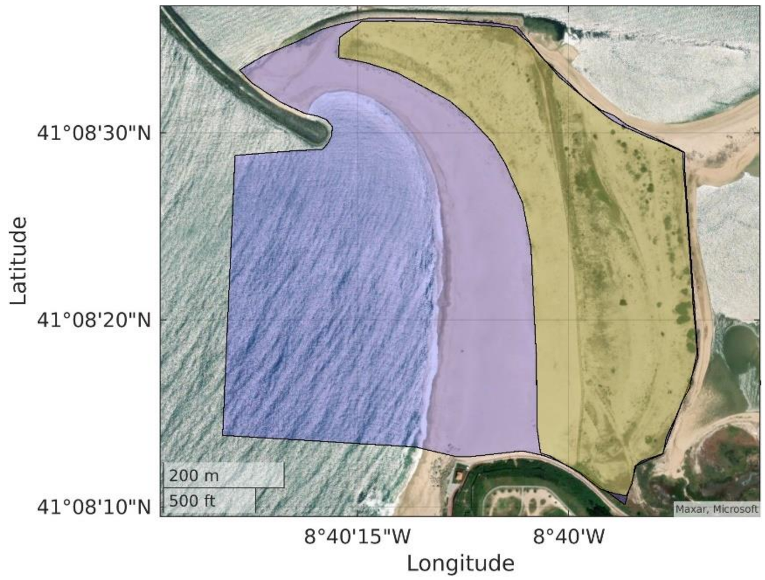
Table 3. Overview of Demonstrator evolution since their construction

	Demonstrator name	Type	Year of installation	Survey duration after installation	Evolution of Dune Volume	Evolution of Mean dune elevation	Evolution of surface area aHAT
1	Douro Estuary Sandspit	Dune without a dike	2004-2008	15,5 y	Increase	Growth	Increase
2	Soulac	Dune-in-front-of-dike	2024	0	No data	No data	Increase
3	Dunkerque	Dune-in-front-of-dike	2020	3 y	Increase	Growth	Decrease
4	Sainte-Marie-la-Mer	Dune-in-front-of-dike	2021	3 y	Stable	Stable	Decrease
5	Living Lab Raversijde	Dune-in-front-of-dike	2021	3 y	Increase	Growth	Decrease
6	Middelkerke grass dike	Dune-in-front-of-dike (seawall)	2021	3 y	Increase	Growth	Decrease
7	Delflandse kust (sand motor)	Dune alone	2011	12 y	Stable to decrease	Stable	Decrease
8	Hondsbossche	Dune-in-front-of-dike	2015	9 y	Increase	Growth	Decrease
9	Katwijk	Dune-on-dike	2013-2015	10 y	Increase	Growth	Increase
10	Texel Prins Hendrikzanddijk	Dune-in-front-of-dike, dike-in-dune	2019	6 y	Increase	Growth	Increase
11	Sankt Peter Ording	Dune-in-front-of-old dike	1996	25 y	Increase	Growth	Increase
12	Ystad	Dune-in-front-of-dike (revetment)	2011-2021	3 y	Decrease	Loss	Decrease

4 Annex

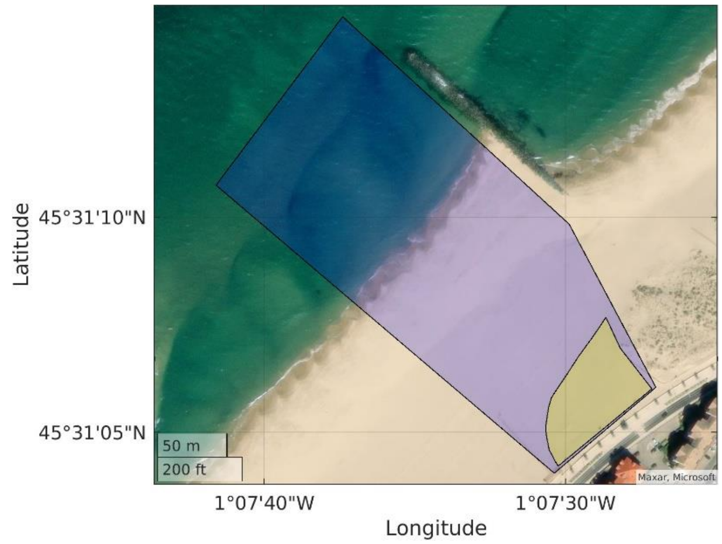
Annex 1

Douro Demonstrator



Satellite view of the Douro estuary demonstrator with the area of interest (blue) and planted dune area (yellow)

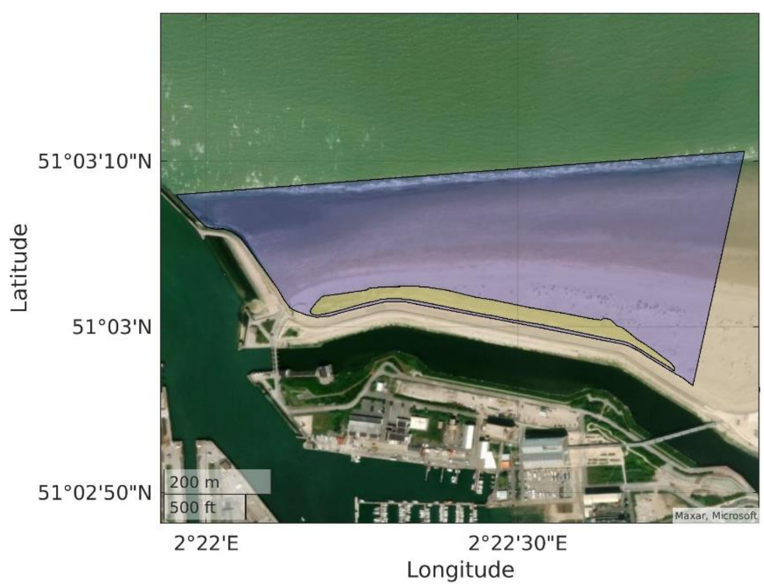
Soulac Demonstrator



Satellite view of the Soulac demonstrator with the area of interest (blue) and planted dune area (yellow)

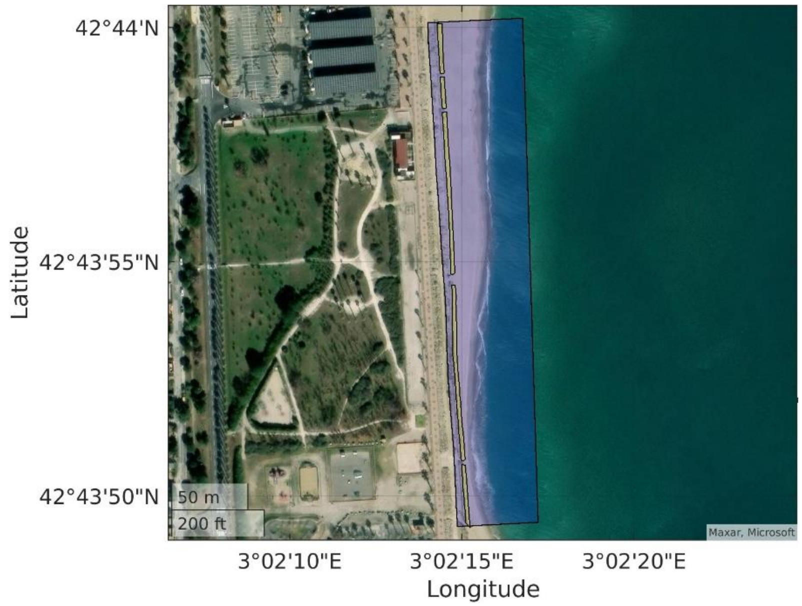
Annex 2

Dunkerque Demonstrator



Satellite view of the Dunkerque demonstrator with the area of interest (blue) and planted dune area (yellow)

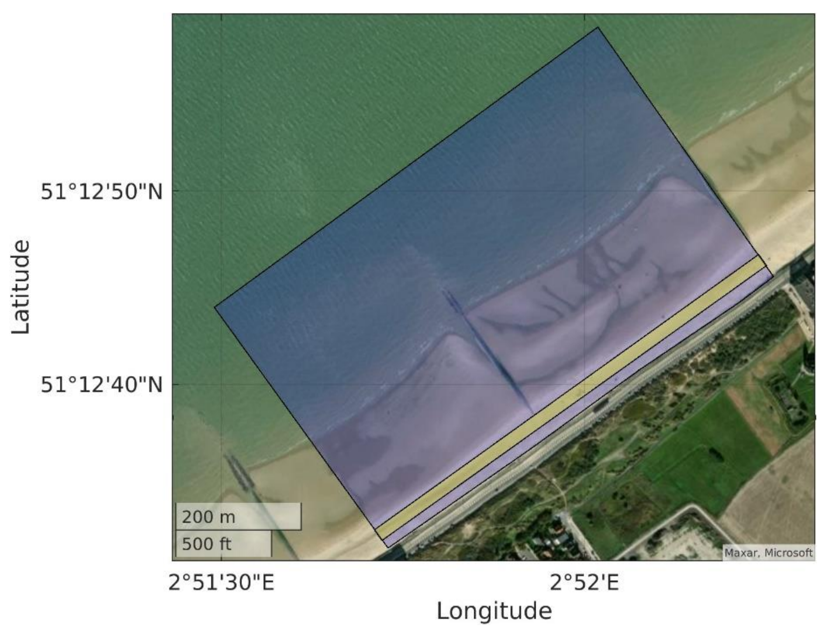
Sainte-Marie-la-Mer Demonstrator



Satellite view of the Sainte-Marie-la-Mer demonstrator with the area of interest (blue) and planted dune area (yellow)

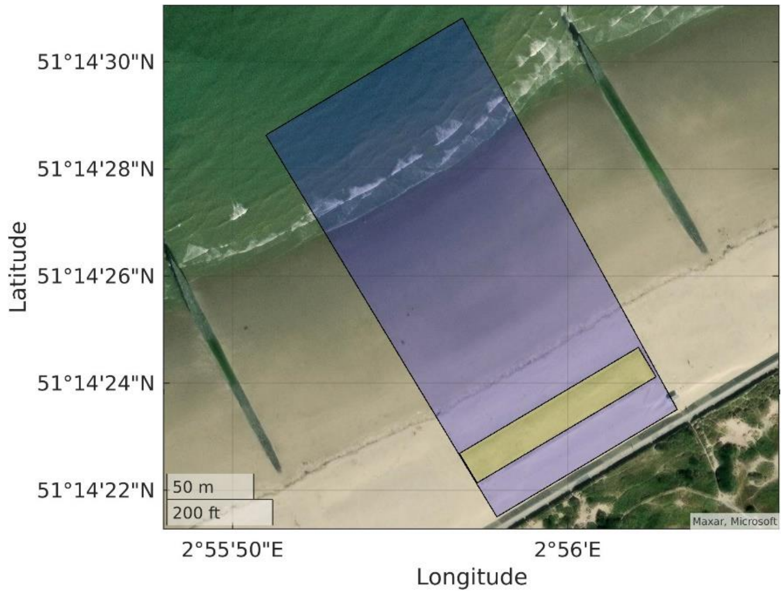
Annex 3

Living Lab Raversijde Demonstrator



Satellite view of the Raversijde demonstrator with the area of interest (blue) and planted dune area (yellow)

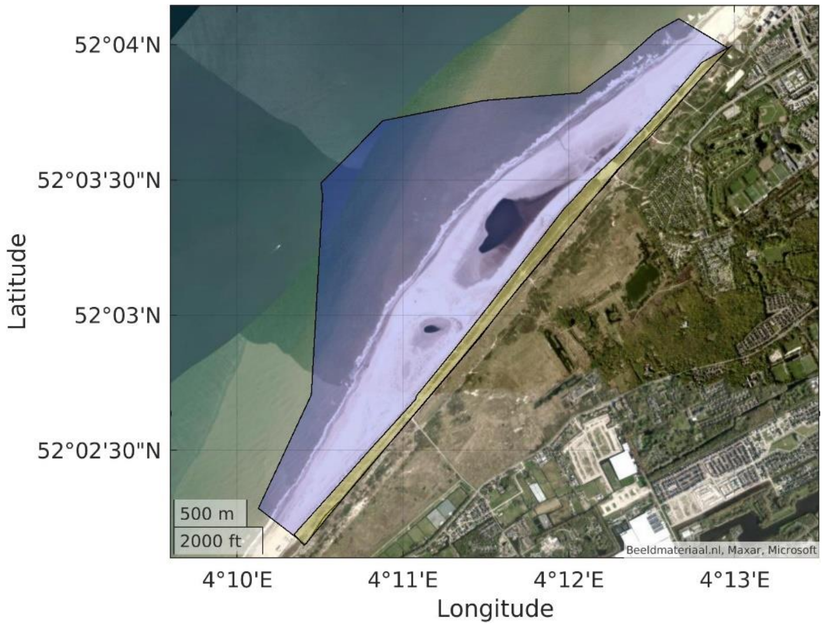
Middelkerke grass dike Demonstrator



Satellite view of the Middlekerke grass dike demonstrator with the area of interest (blue) and dune area (yellow)

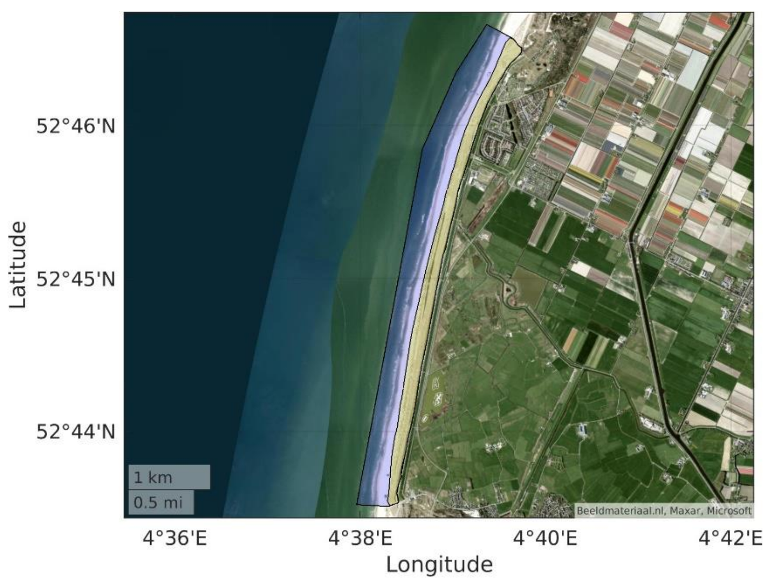
Annex 4

Delflandse kust (Sand Motor) Demonstrator



Satellite view of the Sand Motor demonstrator with the area of interest (blue) and dune area (yellow)

Hondsbossche Duinen Demonstrator

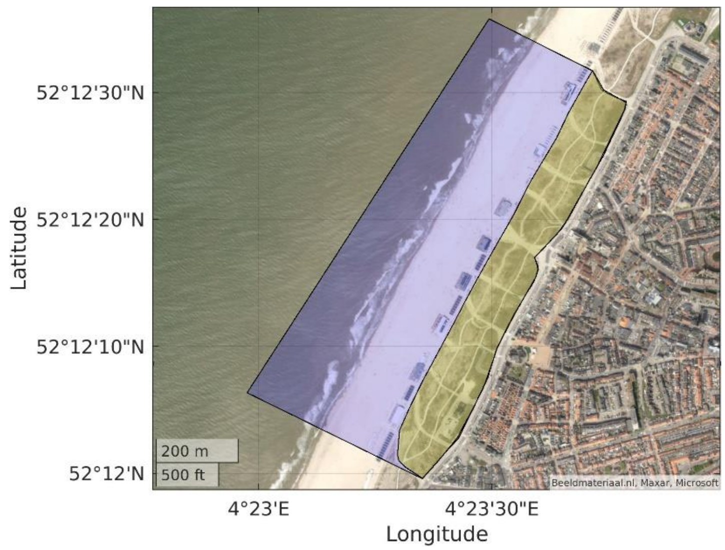


Satellite view of the Hondsbossche *demonstrator with the area of interest (blue) and planted dune area (yellow)*

Annex 5

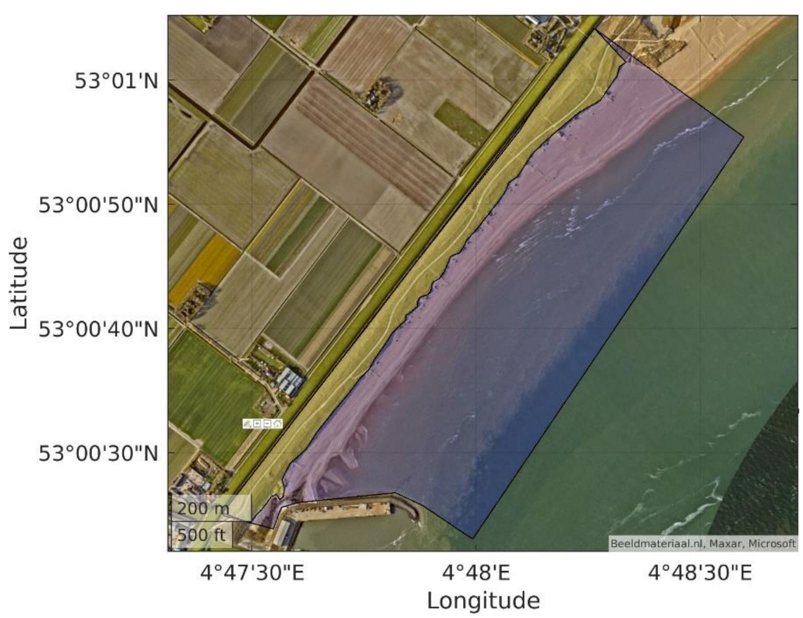
DuneFront

Katwijk Demonstrator



Satellite view of the Katwijk *demonstrator with the area of interest (blue) and planted dune area (yellow)*

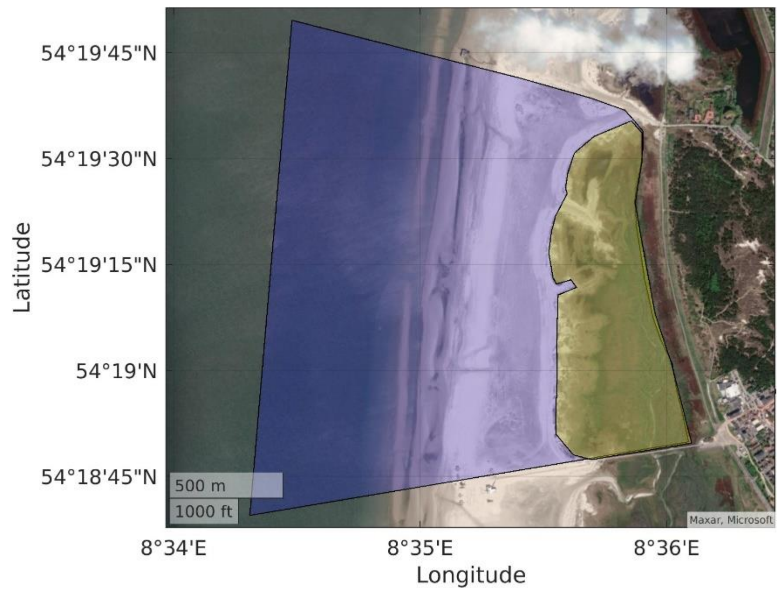
Texel Prins Hendrik zand dijk Demonstrator



Satellite view of the Texel demonstrator with the area of interest (blue) and planted dune area (yellow)

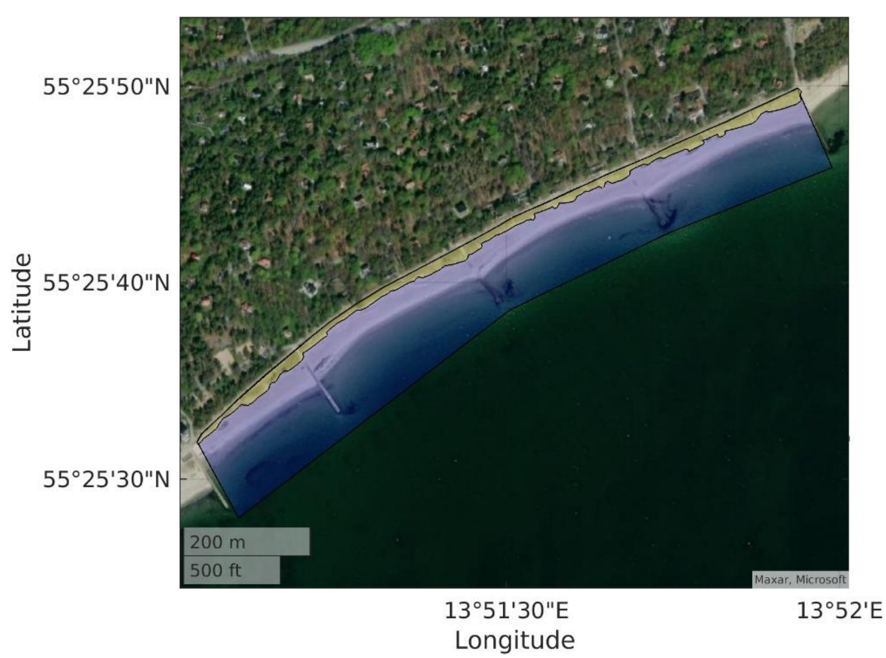
Annex 6

Sankt-Peter-Ording Demonstrator



Satellite view of the Sank-Peter-Ording demonstrator with the area of interest (blue) and dune area (yellow)

Ystad Demonstrator



Satellite view of the Ystad demonstrator with the area of interest (blue) and planted dune area (yellow)

Annex 7

Exemple of source code: Soulac

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% CODE TO READ DEMONSTRATOR DEM AND GENERATE FIGUES (.jpg) / DATASETS
% (.txt) of different morphological proxies - See D6.1 Report for details
%
% DuneFront-EU Project WP6.1
%
% Created Nov. 2024
% Bruno Castelle - EPOC/CNRS/Univ. Bordeaux
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all
close all

%% Site-specific inputs to be provided
Name='Ystad'
limZh=1000; % above the value elevation is NaN (useless for most sites)
Lat_d=55.425; % longitude of the demonstrator
Lon_d=13.85; % longitude of the demonstrator
dz_MSL=-0.16; % z elevation in meter at MSL
demo=datenum(2011,1,1); % start date of the demonstrator
EPSG=3008; %

%% Compute highest astronomical tide level from DuneFront WP physical boundary conditions outputs (see D4.1 and Castelle & Dahirel, 2024)
load('../HAT_Coast.mat'); % Mat file containing the modelled D4.1 highest astronomical tide across the entire coast of Europe and beyond
distances = sqrt((Lat - Lat_d).^2 + (Lon - Lon_d).^2);
[~, index] = min(distances);
HAT=HAT_(index); % highest astronomical tide collected at the closest shoreline point
```

```
%% Dealing with files and folders ...
Folder=pwd;
Folder_tiff=[Folder '/DEM/'];
Folder_shp=[Folder '/Boundary_demonstrator/'];
Folder_outputs=[Folder '/Outputs_' Name '/'];
mkdir(Folder_outputs);
Files_tif=dir([Folder_tiff '*.tif']);
file_dune='Boundary_dune.shp'
file_global='Boundary_global.shp'

%% Read the delimitations of the demonstrator
S_dune=readgeotable([Folder_shp file_dune])
S_dune_=shaperead([Folder_shp file_dune]);
x_dune=S_dune_.X;
y_dune=S_dune_.Y;

S_global=readgeotable([Folder_shp file_global])
S_global_=shaperead([Folder_shp file_global]);
lon_global=S_global_.X;
lat_global=S_global_.Y;

%% Plot location map with dune & global areas
figure
geoplot(S_global,'FaceAlpha', 0.2,'FaceColor','b');hold on;
geoplot(S_dune,'FaceAlpha', 0.3,'FaceColor','y')
geobasemap("satellite")
exportgraphics(gcf, [Folder_outputs '/Zones_DuneDemonstrator.jpg'], 'Resolution', 300, 'ContentType', 'image',
'BackgroundColor', 'none');



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Raster reading and post-processing
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Create file where different proxy data will be store (mostly for D6.1 report drafting i.e.
adding numbers in the text)
fid = fopen([Name '_Outputs.txt'],'w');
fprintf(fid,'%s',['Date , Dune Volume Vd (m3), Mean dune elevation (m), Maximum dune elevation Zdmax
(m), ...' ...
'Zone volume aMSL Va (m3), Zone area aMSL (m2), Zone volume aHAT (m3), Zone area aHAT Sa (m2) ']);
fprintf(fid,'\n');
```

```
% Some projection required
Projto = projcrs(EPSG);
%[x_dune, y_dune] = projfwd(Projto, lat_dune,lon_dune);
[lat_dune, lon_dune] = projinv(Projto, x_dune,y_dune);
x_dune_closed = [x_dune, x_dune(1)]; % Append the first x value
y_dune_closed = [y_dune, y_dune(1)]; % Append the first y value

for i=1:length(Files_tif) % Let's go, for all tiff files

[Files_tif(i).folder '/' Files_tif(i).name]
namef=Files_tif(i).name;
Date(i)=datenum(str2num(namef(1:4)),str2num(namef(5:6)),str2num(namef(7:8))); % Get matlab date from
geotiff file name
aa=datestr(Date(i),'yyyy-mm-dd HH:MM');
fprintf(fid,'%s',aa);
fprintf(fid,'%s',',')



[A,R]=geotiffread([Files_tif(i).folder '/' Files_tif(i).name]);
A=A-dz_MSL;
geotiffinfo([Files_tif(i).folder '/' Files_tif(i).name]);
[x,y] = worldGrid(R);
rasterSize = size(A);
[rowGrid, colGrid] = meshgrid(1:rasterSize(1), 1:rasterSize(2));
[xZ, yZ] = pix2map(R, rowGrid, colGrid);
x_Z=xZ(:,1);y_Z=yZ(1,:);
dx=abs(xZ(2,1)-xZ(1,1));dy=abs(yZ(1,2)-yZ(1,1));

Proj = projcrs(EPSG);
[latZ, lonZ] = projinv(Proj, x, y);



% Dune part only
Cont=-20:20;
clear IN_dune ind xMask yMask
IN_dune=inpolygon(lonZ,latZ,lon_dune,lat_dune);
Z_dune=A;
Z_dune(find(IN_dune==0 | Z_dune>limZh))=NaN;
Z_dune=Z_dune';
% Step 1: Find the indices where x and y meet the conditions
xMask = (x_Z>min(min(xZ(find(IN_dune'==1))))) & (x_Z<max(max(xZ(find(IN_dune'==1)))));
```

```
yMask = (y_Z>min(min(yZ(find(IN_dune'==1))))) & (y_Z<max(max(yZ(find(IN_dune'==1)))));
% Step 2: Use the indices to subset X, Y, and Z
X_d = xZ(xMask, yMask); % Submatrix of X
Y_d = yZ(xMask, yMask); % Submatrix of Y
Z_d = Z_dune(xMask, yMask); % Submatrix of Z=

figure;
pcolor(X_d,Y_d,Z_d);shading flat;caxis([-2 7.5]);c=colorbar;title(c, 'Elevation (m) aMSL');
hold on;
[contourMatrix, h] =contour(X_d,Y_d,Z_d,Cont,'k');
clabel(contourMatrix, h);
hold on;
contour(X_d,Y_d,Z_d,[0. 0.0001],'w','Linewidth',2);
hold on;
contour(X_d,Y_d,Z_d,[HAT HAT+0.0001],'--w','Linewidth',2);
axis equal
xlim([min(min(xZ(find(IN_dune'==1)))) max(max(xZ(find(IN_dune'==1)))) ])
ylim([min(min(yZ(find(IN_dune'==1)))) max(max(yZ(find(IN_dune'==1)))) ])
grid on;
xlabel('Easting (m)');ylabel('Northing (m)');
print('-djpeg', [Folder_outputs '/' datestr(Date(i),'yyyy-mm-dd') '_Dune.jpg']);
pause(5)

VDune(i)=nansum(Z_dune(isnan(Z_dune)==0))*dx*dy
ZDune(i)=nanmean(Z_dune(isnan(Z_dune)==0))
ZDune_max(i)=nanmax(nanmax(Z_dune(isnan(Z_dune)==0)));
fprintf(fid,'%10.1f %s',VDune(i),',');
fprintf(fid,'%2.2f %s',ZDune(i),',');
fprintf(fid,'%2.2f %s',ZDune_max(i),',');

if i==1 %First DEM
X_d_ini=X_d;
Y_d_ini=Y_d;
Z_d_ini=Z_d;
end
if i==length(Files_tif) %Last DEM
X_d_end=X_d;
Y_d_end=Y_d;
Z_d_end=Z_d;
end



% Demonstrator area above HAT only
```

```
clear IN_zone ind xMask yMask
IN_zone=inpolygon(lonZ,latZ,lon_global,lat_global);
Z_zone=A;
Z_zone(find(IN_zone==0 | Z_zone>limZh))=NaN;
Z_zone=Z_zone';
% Step 1: Find the indices where x and y meet the conditions
xMask = (x_Z>min(min(xZ(find(IN_zone'==1))))) & (x_Z<max(max(xZ(find(IN_zone'==1)))));
yMask = (y_Z>min(min(yZ(find(IN_zone'==1))))) & (y_Z<max(max(yZ(find(IN_zone'==1)))));
% Step 2: Use the indices to subset X, Y, and Z
X_z = xZ(xMask, yMask); % Submatrix of X
Y_z = yZ(xMask, yMask); % Submatrix of Y
Z_z = Z_zone(xMask, yMask); % Submatrix of Z

figure;
pcolor(X_z,Y_z,Z_z);shading flat;caxis([-2 7.5]);c=colorbar;title(c, 'Elevation (m) aMSL');
hold on;
[contourMatrix, h] =contour(X_z,Y_z,Z_z,Cont,'k');
clabel(contourMatrix, h);
hold on;
contour(X_z,Y_z,Z_z,[0. 0.0001],'w','Linewidth',2);
hold on;
contour(X_z,Y_z,Z_z,[HAT HAT+0.0001],'--w','Linewidth',2);
hold on;plot(x_dune_closed,y_dune_closed,'k','Linewidth',3);
axis equal
xlim([min(min(xZ(find(IN_zone'==1)))) max(max(xZ(find(IN_zone'==1)))) ])
ylim([min(min(yZ(find(IN_zone'==1)))) max(max(yZ(find(IN_zone'==1)))) ])
grid on;
xlabel('Easting (m)');ylabel('Northing (m)');
print('-djpeg', [Folder_outputs '/' datestr(Date(i),'yyyy-mm-dd') '_Zone.jpg']);
pause(5)



VZone_MSL(i)=nansum(Z_zone(find(isnan(Z_zone)==0 & Z_zone>0)))*dx*dy
AZone_MSL(i)=length(find(isnan(Z_zone)==0 & Z_zone>0))*dx*dy
fprintf(fid,'%10.1f %s',VZone_MSL(i),',');
fprintf(fid,'%8.1f %s',AZone_MSL(i),',');
VZone_HAT(i)=nansum(Z_zone(find(isnan(Z_zone)==0 & Z_zone>HAT)))*dx*dy
AZone_HAT(i)=length(find(isnan(Z_zone)==0 & Z_zone>HAT))*dx*dy
fprintf(fid,'%10.1f %s',VZone_HAT(i),',');
fprintf(fid,'%8.1f %s',AZone_HAT(i),',');

if i==1 %First DEM
X_z_ini=X_z;
```

```
Y_z_ini=Y_z;
Z_z_ini=Z_z;
end
if i==length(Files_tif) %Last DEM
X_z_end=X_z;
Y_z_end=Y_z;
Z_z_end=Z_z;
end

fprintf(fid,'\n');
end


fclose(fid);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Now we're done with computations (can take time with large DEM like e.g. Ystad)
% Let's plot synthetic output figures
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Time series 4-panel figure
figure
set(gcf,'PaperPosition', [0.5 0.5 20 14]);
subplot(2,2,1)
plot(Date,VDune-VDune(1),'-ok');datetick('x');grid on;
hold on;
plot([demo demo],[min(VDune-VDune(1)) max(VDune-VDune(1))],'--k');ylim([min(VDune-VDune(1))
max(VDune-VDune(1))]);
xlabel('Date');ylabel('$\tilde{V}d$ (m$^3$)', 'Interpreter', 'latex')
subplot(2,2,2)
plot(Date,ZDune_max,'-ok');datetick('x');grid on;
hold on;
plot([demo demo],[min(ZDune_max) max(ZDune_max)],'--k');ylim([min(ZDune_max) max(ZDune_max)]);
xlabel('Date');ylabel('$Zd_{max}$ (m aMSL)','Interpreter', 'latex')
subplot(2,2,3)
plot(Date,VZone_MSL-VZone_MSL(1),'-ok');datetick('x');grid on;
hold on;
plot([demo demo],[min(VZone_MSL-VZone_MSL(1)) max(VZone_MSL-VZone_MSL(1))],'--
k');ylim([min(VZone_MSL-VZone_MSL(1)) max(VZone_MSL-VZone_MSL(1))]);
xlabel('Date');ylabel('$\tilde{V}a$ (m$^3$ a MSL)','Interpreter', 'latex')
subplot(2,2,4)
```

```
plot(Date,AZone_HAT-AZone_HAT(1),'-ok');datetick('x');grid on;
hold on;
plot([demo demo],[min(AZone_HAT-AZone_HAT(1)) max(AZone_HAT-AZone_HAT(1))],'--
k');ylim([min(AZone_HAT-AZone_HAT(1)) max(AZone_HAT-AZone_HAT(1))]);
xlabel('Date');ylabel('$\tilde{S}a$ (m$^2$)','Interpreter', 'latex')
exportgraphics(gcf, [Folder_outputs '/TimeSeries.jpg'], 'Resolution', 300, 'ContentType', 'image',
'BackgroundColor', 'none');




%% IMap initial and final DEM and resultinf different plot
% not that caxis should be adjusted depending on the site considered
Cont2=-10.5:10.5;
figure;

t = tiledlayout(3, 1, 'Padding', 'compact', 'TileSpacing', 'compact'); % 2 rows, 1 column

nexttile
title(['Initial - ' num2str(datestr(Date(1),'yyyy'))])
pcolor(X_z_ini,Y_z_ini,Z_z_ini);colormap(jet);shading flat;caxis([0 5.5]);c=colorbar;c.Label.String =
'Elevation (m) aMSL';
%hold on;
%[contourMatrix, h] =contour(X_z_ini,Y_z_ini,Z_z_ini,Cont,'k');
%clabel(contourMatrix, h);
hold on;
contour(X_z_ini,Y_z_ini,Z_z_ini,[0. 0.0001],'w','Linewidth',2);
hold on;
contour(X_z_ini,Y_z_ini,Z_z_ini,[HAT HAT+0.0001],'--w','Linewidth',2);
hold on;plot(x_dune_closed,y_dune_closed,'k','Linewidth',3);
axis equal
xlim([min(min(xZ(find(IN_zone'==1)))) max(max(xZ(find(IN_zone'==1)))) ])
ylim([min(min(yZ(find(IN_zone'==1)))) max(max(yZ(find(IN_zone'==1)))) ])
grid on;
xlabel('Easting (m)');ylabel('Northing (m)');

nexttile
title(['Final - ' num2str(datestr(Date(end),'yyyy'))])
pcolor(X_z_end,Y_z_end,Z_z_end);colormap(jet);shading flat;caxis([0 5.5]);c=colorbar;c.Label.String =
'Elevation (m) aMSL';
hold on;
[contourMatrix, h] =contour(X_z_end,Y_z_end,Z_z_end,Cont,'k');
%clabel(contourMatrix, h);
```

```
hold on;
contour(X_z_end,Y_z_end,Z_z_end,[0. 0.0001],'w','Linewidth',2);
hold on;
contour(X_z_end,Y_z_end,Z_z_end,[HAT HAT+0.0001],'--w','Linewidth',2);
hold on;plot(x_dune_closed,y_dune_closed,'k','Linewidth',3);
axis equal
xlim([min(min(xZ(find(IN_zone'==1)))) max(max(xZ(find(IN_zone'==1)))) ])
ylim([min(min(yZ(find(IN_zone'==1)))) max(max(yZ(find(IN_zone'==1)))) ])
grid on;
xlabel('Easting (m)');ylabel('Northing (m)');

% If ini and end grids are different for the difference plot

[X_z_ini_,Y_z_ini_]=meshgrid(X_z_ini(:,1),Y_z_ini(1,:));
Z_z_ini_interp=interp2(X_z_ini_,Y_z_ini_,Z_z_ini',X_z,Y_z);

nexttile
title(['Difference plot ' num2str(datestr(Date(1),'yyyy')) '-' num2str(datestr(Date(end),'yyyy'))])
pcolor(X_z,Y_z,Z_z_end-Z_z_ini_interp);colormap(jet);shading flat;caxis([-max(max(abs(Z_z_end-
Z_z_ini_interp))) max(max(abs(Z_z_end-Z_z_ini_interp)))]);c=colorbar;c.Label.String = 'Elevation change
(m)';
%hold on;
%[contourMatrix, h]=contour(X_z,Y_z,Z_z_end-Z_z_ini_interp,Cont2,'k');
%clabel(contourMatrix, h);
hold on;plot(x_dune_closed,y_dune_closed,'k','Linewidth',3);
axis equal
xlim([min(min(xZ(find(IN_zone'==1)))) max(max(xZ(find(IN_zone'==1)))) ])
ylim([min(min(yZ(find(IN_zone'==1)))) max(max(yZ(find(IN_zone'==1)))) ])
grid on;
xlabel('Easting (m)');ylabel('Northing (m)');

% Adjust figure and layout properties to reduce whitespace
set(gcf, 'Units', 'inches', 'Position', [0, 0, 15, 10]); % Adjust dimensions as needed
set(t, 'Padding', 'none', 'TileSpacing', 'none');

% Save with exportgraphics (without 'Bounds')
exportgraphics(gcf, [Folder_outputs '/Dune_DiffPlot_' datestr(Date(end),'yyyy-mm-dd') ' - '
datestr(Date(1),'yyyy-mm-dd') '.jpg'], 'Resolution', 300, 'ContentType', 'image', 'BackgroundColor', 'none');
```

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