DuneFront

Deliverable 11.2

June 2026

DuneFront

Morphodynamic hindcast Deliverable 11.2 (D11.2)

Deliverable information

	Numerical demonstrators
	D11.2
	11
	Oliver Lojek(TUBS), Constantin Schweiger (TUBS), Pieter Rauwoens (KU Leuven), Jianghua Guo (KU Leuven), Mahmoud Abouhalima (UPORTO), Paulo Rosa Santos (UPORTO)
	TUBS
	UPORTO, KU Leuven
	Report
	Public
	Lojek O., Schweiger C., Rauwoens P., Guo J., Abouhalima, M., Rosa-Santos P. (2024). Morphodynamic hindcast modeling of dune growth and erosion for select demonstrators, Version 1.0, DuneFront Project Deliverable 11.2, Technische Universität Braunschweig.

Versioning and contribution history

Version 0.1	09/06/2026	Oliver Lojek (TUBS), Constantin Schweiger (TUBS), Pieter Rauwoens (KU Leuven), Jianghua Guo (KU Leuven), Paulo Rosa Santos (UPORTO), Mahmoud Abouhalima (UPORTO)	Version to be checked and approved by DuneFront consortium
Version 0.2	31/06/2026	Oliver Lojek (TUBS), Constantin Schweiger (TUBS), Pieter Rauwoens (KU Leuven), Jianghua Guo (KU Leuven), Paulo Rosa Santos (UPORTO), Mahmoud Abouhalima (UPORTO)	Draft
Version 1.0	27/07/2026	Oliver Lojek (TUBS), Constantin Schweiger (TUBS), Pieter Rauwoens (KU Leuven), Jianghua Guo (KU Leuven), Paulo Rosa Santos (UPORTO), Mahmoud Abouhalima (UPORTO)	Final version approved by all Beneficiaries

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

DuneFront

Cover page

This report is the first deliverable of work package 11 Morphodynamic functioning (D11.2 Numerical demonstrators) 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 gather relevant information and data to set up and calibrate numerical XBeach and AeoLiS models for selected demonstrators as a basis for the investigation of their morphodynamic functioning.

The DuneFront project considers 12 Demonstrators across six countries - Portugal, France, Belgium, the Netherlands, Germany, and Sweden – given the complexity of numerical models a selection of demonstrator sites will be modelled with the two open-source software packages

This compilation presents results obtained regarding morphodynamic functioning of select demonstrators using the open-source software packages XBeach and AeoLiS investigating wave driven and wind driven sediment transport volumes, patterns and pathways. This report will be complemented by deliverables D11.1 contributing the initial status and performance of numerical models of select demonstrator sites.

In general, this report provides an overview of model setups and initial results. Complimentary reports D11.2 and D11.3 will advance the morphodynamic understanding of the simulated demonstrator sites by incorporating more details and simulating historic periods (D11.2) as well as project potential future developments (D11.3).

Table of Content

DuneFront

List of Figures

List of Tables

List of abbreviations

	Explanation
DD	Dune-Dike
DD-Hybrid	Dune Dike-Hybrid
NbS	Nature based Solution
GIS	Geo-Information-System
WP	Work Package
RBMPs	River Basin Management Plans
WFD	Water Framework Directive
PoM	Programs of Management
KTM	key types of measures
NUTS	nomenclature of territorial units for statistics
APSFRs	Assessment of potential significant flood risk
RBD	river basin districts
PRFA	preliminary flood risk assessment
EFAS	European Flood Awareness System
EMODnet	European Marine Observation and Data Network
TWL	total water level
ECFAS	European Coastal Flood Awareness System
RI	Return interval
BSS	Brier-Skill-Score

1. Introduction

1.1 Overview of work package 11 (WP11 – Morphodynamic functioning)

The overarching goal of work package 11 "Morphodynamic functioning" consists of using spatial data researched in other work packages, mainly WP1-4 and WP6, for Europe pertaining to physical, biological and socio-economic boundary conditions and derived morphological signals to setup numerical computer models of select demonstrator sites using XBeach and AeoLiS. These models in a first step must be calibrated in a meaningful way.

1.1.1 Tasks of work package 11

The objective of the first task (Task 11.1) in this work package, is to obtain and compile the necessary source code of the two open-source models XBeach and AeoLiS, which are to be used for setting up demonstrator models. For the demonstrators, the input data must be aggregated and implemented with meaningful boundary conditions to achieve running and physically sound results. This is necessary for further improvement and ongoing research for following tasks (Task 11.2 & Task 11.3).

The objectives for the second task (Task 11.2) within the work package focus on using the setup demonstrator models of Task 11.1 to simulate past periods. This hindcasting will allow for comparisons to observation data and evaluation of model accuracy.

The objectives of the third task (Task 11.3) aims to project potential morphodynamic trends and developments within the demonstrator models. For this, IPCC RCP scenarios will guide literature research on projected developments of implemented boundary conditions (e.g., changes in wind speed and direction or sea level rise and wave climate). Findings will be used by altering prescribed boundary conditions within the demonstrator models to project potential impacts on morphodynamic functioning.

1.1.2 Milestones and Deliverables of work package 11

The key milestone (M11.1) involves the setup of working numerical demonstrator models with AeoLiS and XBeach. This milestone has been met.

The deliverables include:

- **Deliverable D11.1**: Setup of numerical models of select demonstrator sites using open-source software packages XBeach and AeoLiS. Deliverables D6.1, D6.2 and D10.2 are used as data source for setting up the models. A prototype root resistance module for XBeach has been used.
- **Deliverable D11.2** (this report)**:** The numerical models developed in D11.1 are used to hindcast past periods or events to test model performance against available

observation data. Vegetation coverage is implemented based on available digital orthophotos (DOP) and identified vegetation coverage.
- **Deliverable D11.3:** The numerical models are used to project potential impacts on morphodynamic functioning stemming from IPCC developed RCP scenarios.

1.2 Aims and objectives of this report

The main objective of this report is to present methods used and results achieved using numerical demonstrator models in XBeach, AeoLiS and Delft3D.

2. Numerical modelling

In this work package, numerical models (XBeach, AeoLiS and Delft3D) are to be established for the purpose of representative demonstrators. To this end, numerical models of the German demonstrator St. Peter-Ording (SPO), the Douro estuary sand spit in Portugal, and the Living Lab Raversijde in Belgium stemming from WP11.1 are used to investigate the possibilities to investigate recent and/or historic morphological developments at these respective demonstrators.

2.1 Methods

Based on the initially introduced AeoLiS and XBeach models, the functional possibility of linking the two fundamentally different process-oriented models was investigated. AeoLiS, a model to simulate wind driven dune building and XBeach, a model to simulate wave dominated beach and dune erosion, were coupled in segmented approach for the German demonstrator SPO under the working hypothesis that directly coupled accretion and subsequent erosion could yield improved overall results.

This was achieved scripting a coupling routine between the IO interfaces of AeoLiS and XBeach using Python. The script was developed in such a way that a manually defined peak over threshold (PoT) for the model inherent tidal water level activates it. The PoT was oriented at federal storm surge water level definitions for Germany as an indicator/switch between aeolian transport regime for dune build-up and wave driven beach and dune erosion during storm surge events:

- AeoLiS for fair weather conditions during dune growth
- XBeach for storm surge conditions during dune and beach erosion

The scripted coupling is activated once the water level surpasses or falls below the defined PoT. This method follows the general concept that aeolian transport regimes occur on longer time scales throughout the year if the conditions, dry surface area and sufficient windshear, are met. Once the PoT is surpassed and a storm surge event is identified in the water level time series, the model bathymetry is being inundated and the aeolian transport is interrupted.

With receding water levels following the passing of a storm surge event, the script is activated again and the processes switch from a wave dominated erosion regime to an aeolian transport accretion regime.

Accordingly, the running AeoLiS model is stopped once the PoT is surpassed by rising water levels, a storm surge is detected and model geometry is exported into XBeach as starting conditions. XBeach is initiated drawing on available boundary conditions using water level, wave conditions, wind and pressure as driving forces. The storm surge event is simulated using XBeach surfbeat mode with a higher temporal resolution compared to AeoLiS to account and correctly map the hydrodynamic boundary conditions. The model domain grid is kept consistent across both models.

The scripted segmented coupling is called XBAeoLink and facilitates the coupling of the two models to investigate focus sites using longer time series and ensuring both accretion and erosion are simulated for a given coastal dune area. Figure 1 shows the general workflow of XBAaoLink:

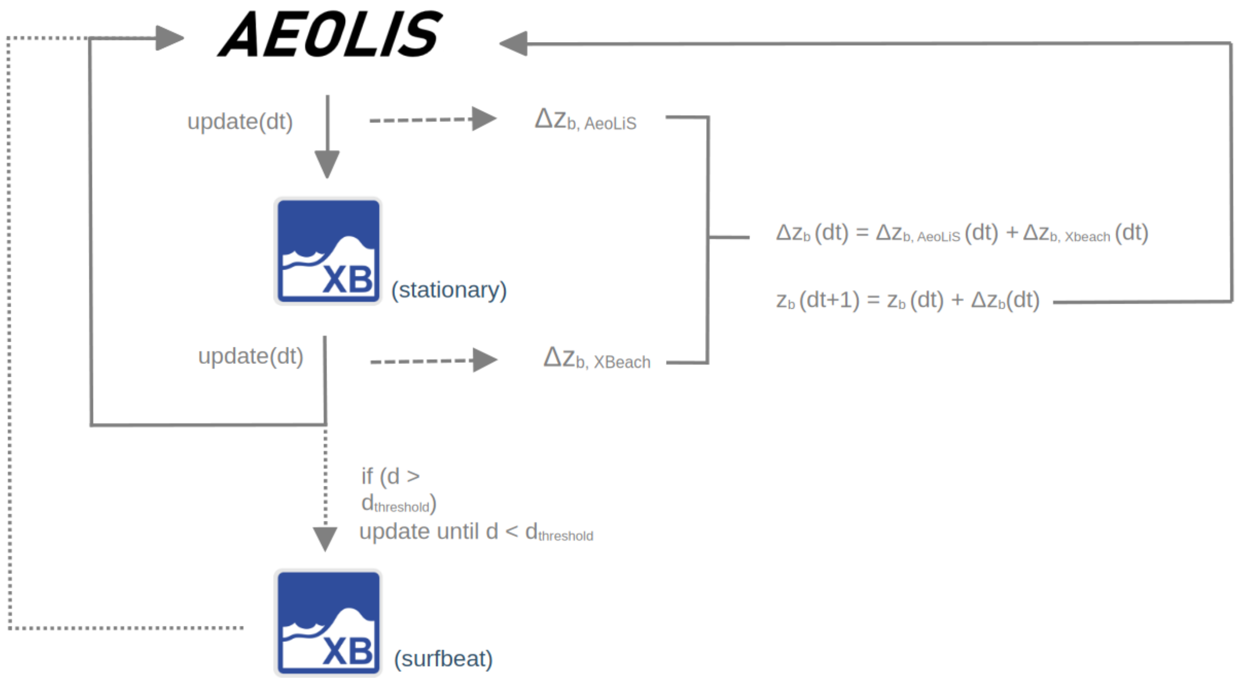

Figure 1: XBAeoLink flow chart outlining the general concept of the segmented coupling script between XBeach and AeoLiS.

For this report and D11.1, an annual hindcast was conducted using data from the year 2010 drawing on federal data basis of annual digital elevation models (DEM) with a resolution of 10 m by 10 m, which were re-sampled onto a 5 m by 5 m and a 1 m by 1 m domain grids, yielding model variants with 10 m, 5 m, and 1 m spatial resolution. Results detailed in this report pertain to the 5 m variant. Boundary data entails tidal water level time series obtained from tide gauge stations, as well as a federal hydraulic hindcast model developed and maintained by the federal hydraulic research agency (Bundesanstalt für Wasserbau, BAW) available for the years 1996-2016 (Easy-GSH) and 2016-2022 and ongoing (TriLaWatt) with an expansion into the Dutch and Danish coastal waters of the North Sea. The model is calibrated and tested against federal data ensuring a robust continuous data base to draw upon and compare results against, obtained within WP11.

Results presented in this report for the German Demonstrator entail absolute elevation changes under the influence of wind driven and wave driven sediment fluxes – these are readily compared to federal data. Volume fluxes obtained are viewed as quality based given the model configurations and simulated processes. Additional Brier Skill Score values are computed to present an established performance metric.

One distinction between the XBeach and AeoLiS model setup consists in that the AeoLiS model entails surface vegetation coverage, germination and die-off processes, which are not readily transferred to XBeach. Literature presents contrasting findings on the potential impact of above-ground and below-ground vegetation on coastal dunes during storm surge erosion (Feagin et al. 2023; Kosmalla et al. 2024; Kosmalla et al. 2021) .

2.2 German demonstrator – St. Peter-Ording

The model area extends 800 m in cross-shore and 500 m in long-shore direction and is visualized in Figure 2 A). The North Sea coast lines the left domain boundary. The dune crest is oriented North-South on the right-hand side of the plot and reaches a maximum crest height of 7.2 m above sea level. In between the coastline and the dune toe a roughly 500 m wide, flat beach extends at 2.0 m above sea level. Grid resolution was set to 5 m by 5 m resulting in 16.000 cells, the 1 m resolution yielded 400.000 cells and is computationally very expensive.

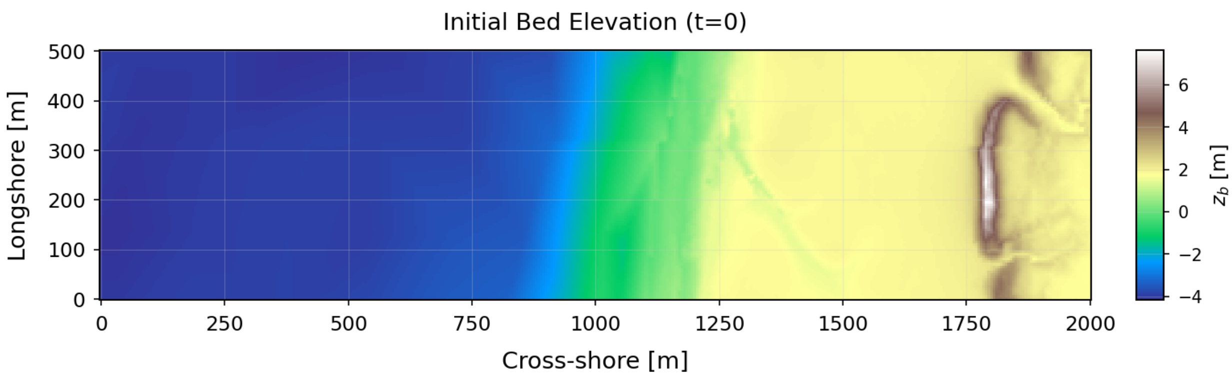

Figure 2: A) Topographic plot of the model domain with color coded elevation values. North Sea coastline is on the left hand side, coastal dune is located on the right hand side and has a North-South oriented ridge. B) Vegetation density for the AeoLiS domain.

2.2.1 Model setup

In Figure 3, the vegetation coverage and density are displayed, initially defined for the AeoLiS model. The green patches represent the initial coverage of the dune in SPO, with marram gras (*Ammophilia* Arenaria) being the dominant species here. The foredune area exhibits a vegetation density of 0.3, while the landward located salt marsh area is initially covered with a vegetation density coefficient of 1.0 (full coverage).

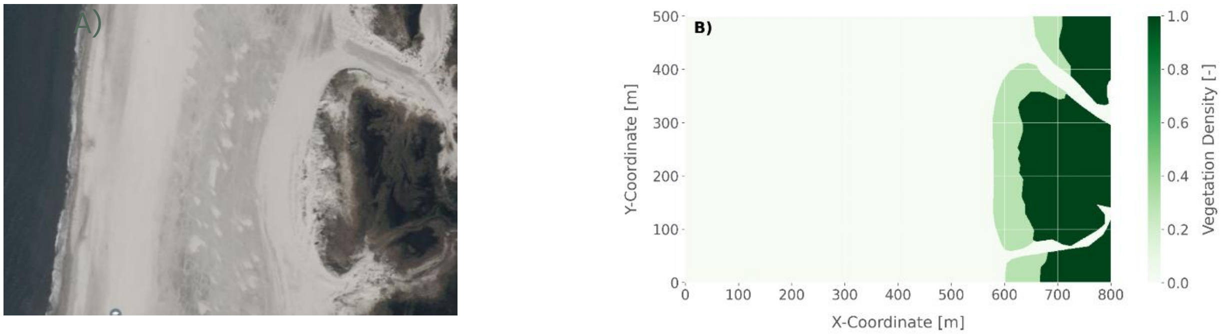

Figure 3: A) Satellite image of the demonstrator site model domain from 2024; B) Initial vegetation density coverage in AeoLiS for the coupled simulation 2010-07-01.

These values are based on satellite imagery (compare Figure 3A) displaying heterogenous vegetation coverage atop the foredune, while the ensuing salt marsh shows a continuous blanketed coverage. Assigned vegetation values are compiled in Table 1:

Table 1: Vegetation parameters assigned to the initial model setup and variants for sensitivity analysis

Parameter	Symbol	Values	Unit
Mean grain size diameter	d_{50}	0.15, 0.20, **0.25**, 0.30	mm
Vegetation roughness	Γ	4, 8, **16**, 32, 64	-
Vegetation density	$p_{veg}(t=0)$	0.2, **0.3**, 0.4, 0.6	-
Vertical growth rate	$v_{vertical}$	0.5, **1.0**, 2.0, 4.0	m/yr

* **bold** values indicate default settings

Boundary forcing was compiled from various data bases, using COSMO-REA6 meteorological re-analysis data for wind and pressure fields, tidal and wave climate data from UnTRIM2 and DEM data from EasyGSH (Plüß 2020; Sievers et al. 2020; Bollmeyer et al. 2015). Data was curated and processed into boundary file conform formatting for usage by AeoLiS and XBeach. Boundary conditions for the conducted simulation time period are given in Figure 4:

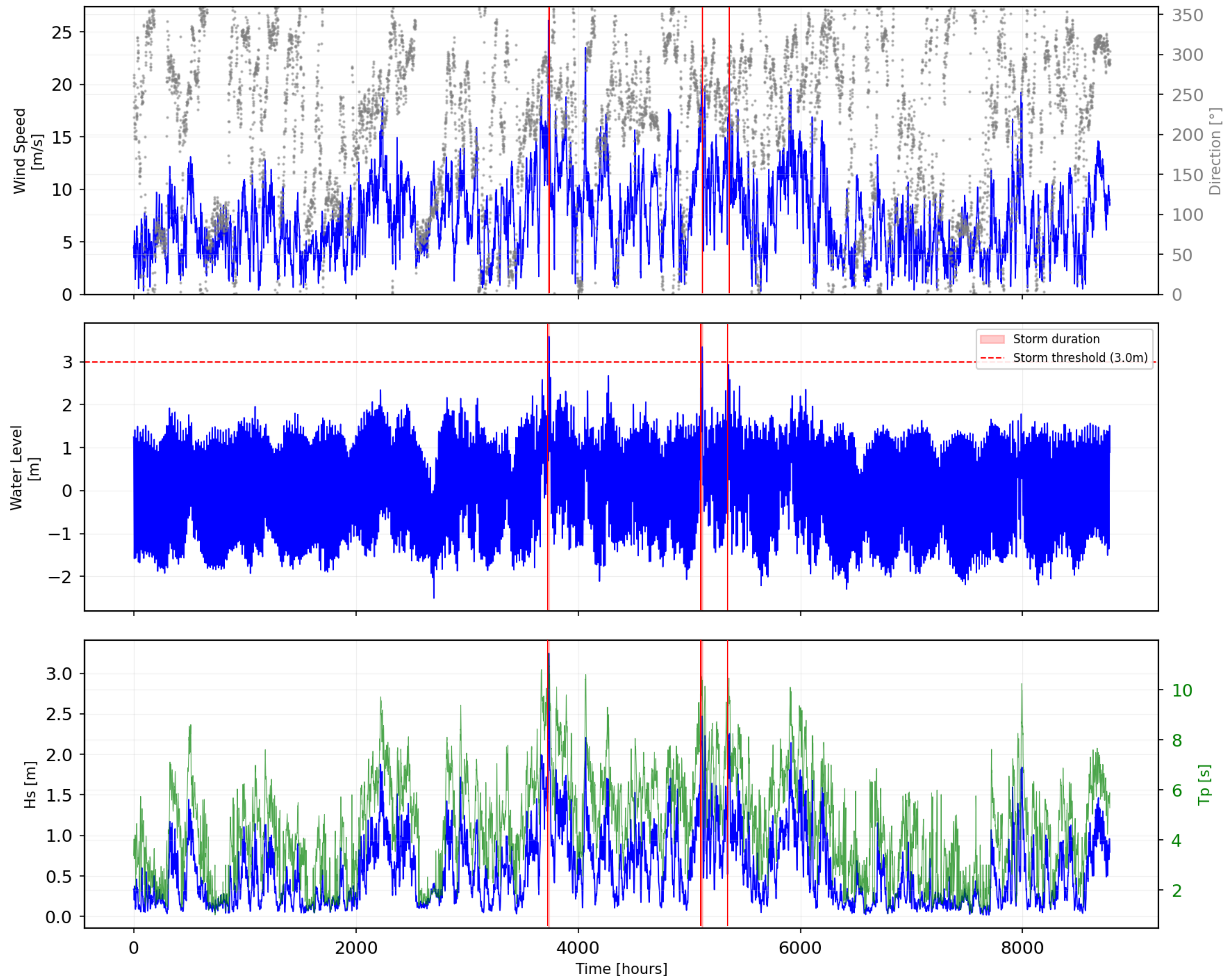

Figure 4: Boundary forcing data for wind speed and direction, water level, significant wave height and period 2010-2011.

2.2.2 Model results

The segmented XBAeoLink coupling for 2010-2011 resulted in the following output summary for the simulation, indicating a detection of two storm surge events surpassing a tidal water level of 2.87 m above mean tidal high water for the demonstrator site. Consequently, the coupling segmented the model run into five consecutive simulations starting with 001_AeoLiS, followed by the first storm surge event 002_Surfbeat, succeeding 003_AeoLiS, second storm surge 004_Surfbeat and panning out into 005_AeoLiS covering 365 days from summer 2010 to summer 2011:

Simulation: 2026_06_24_5x5_350

Mode: SEGMENTED (2D)

```
Start:   2010-07-01 00:00:00
End:     2011-07-01 00:00:00
Duration_s: 31536000
Grid source: /home/user/01_xbaeolink-aeolis-surfbeat/input_data/Shared/SPO_Grid_2010_uniform_1_350
XBeach grid cells: nx=2000, ny=500
XBeach spacing:      dx=0.984808, dy=0.984808

Storm Detection:
  Threshold: 3.00 m
  Events detected: 3

Segments: 7
  1. aeolis_only: segment_001_aeolis
  2. surfbeat_only: segment_002_surfbeat
  3. aeolis_only: segment_003_aeolis
  4. surfbeat_only: segment_004_surfbeat
  5. aeolis_only: segment_005_aeolis
  6. surfbeat_only: segment_006_surfbeat
  7. aeolis_only: segment_007_aeolis
```

Accordingly, there are four (4) simulation segments run with AeoLiS and three (3) run with XBeach:

Segment	1	2	3	4	5	6	7
AeoLiS	■		■		■		■
XBeach		■		■		■	

AeoLiS | Segments 1, 3, 5, 7

The vegetation density coverage is displayed in Figure 5, lasting 155 days until the first storm surge event is detected. From the simulation it becomes apparent that the vegetation density is diminishing over time. Initially, the foredune was covered with 0.3 and the saltmarsh area with 1.0 – at the end of the first segment, the foredune density coverage exhibits values ranging between 0.2 – 0.25 and the salt marsh ranges density coverage varies between 0.6 – 0.8.

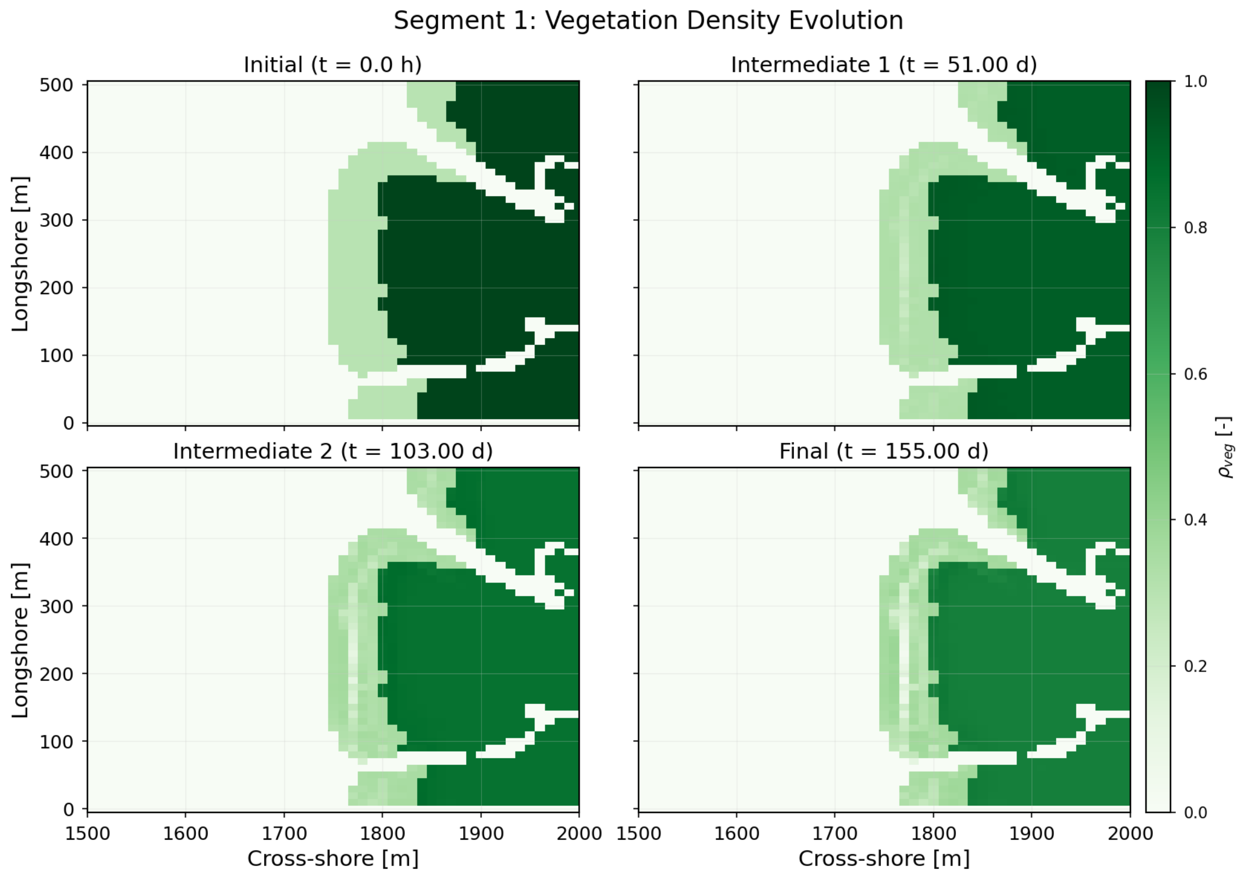

Figure 5: Segment 1 - AeoLiS simulation results for vegetation density evolution.

After day 155, the first storm surge was detected by the XBAeoLink coupling exceeding the defined PoT. Segment 2 corresponds to the surfbeat simulation and is given in Figure 9.

The ensuing AeoLiS simulation covering segment 3 ran for 55 days and shows similar vegetation density evolution values given in Figure 6 compared to segment 1 in Figure 5. Values range around 0.3 for the foredune with the crest or ridge being less covered and the sheltered salt marsh remains around 0.7.

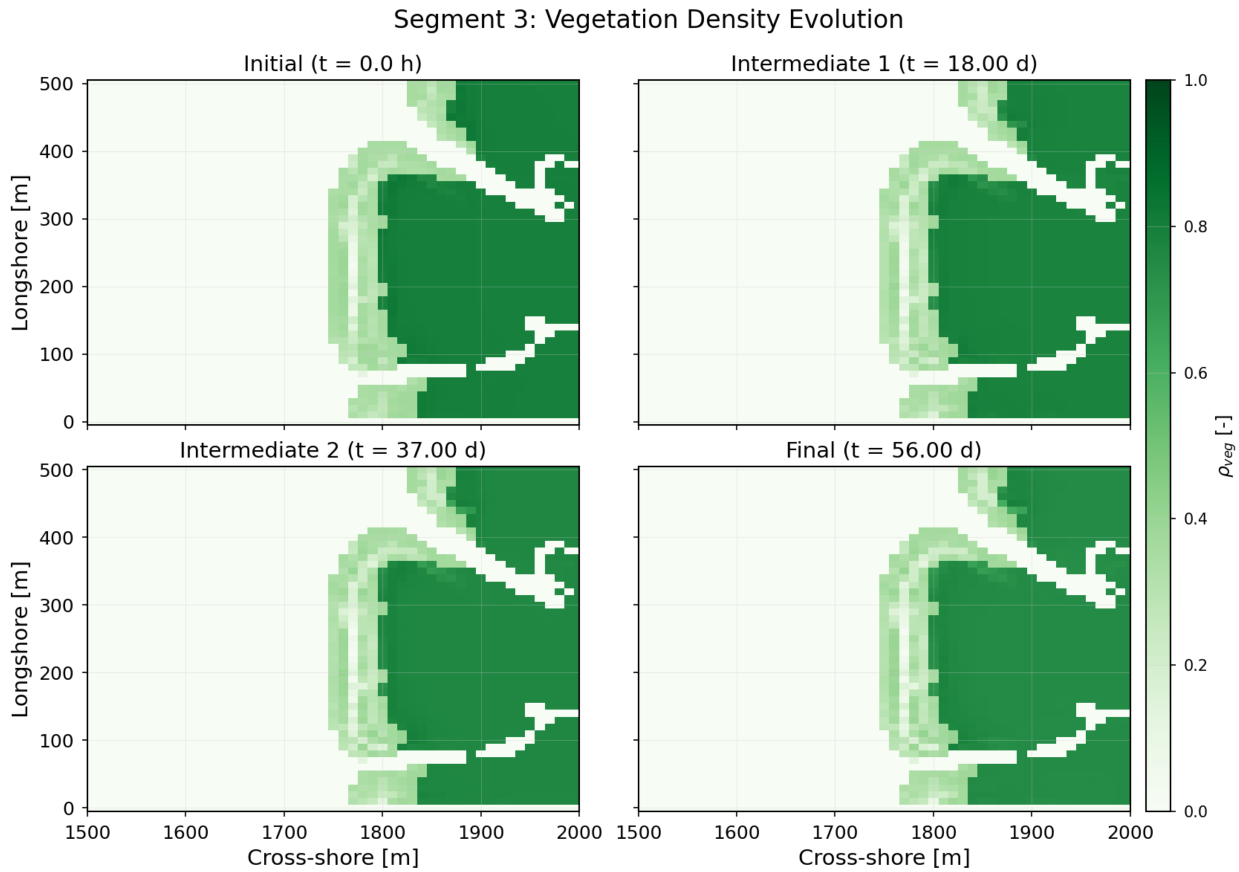

Figure 6: Segment 3 – AeoLiS simulation results for vegetation density evolution.

Segment 4 displays the surfbeat simulation results and is given in Figure 10. The Following AeoLiS simulation is detailed in segment 5 shown in Figure 7 – the segment spans a relatively short simulation period of 9 days real-time between two consecutive storm events. Naturally, the values for the vegetation density evolution show no observable changes in pattern or intensity.

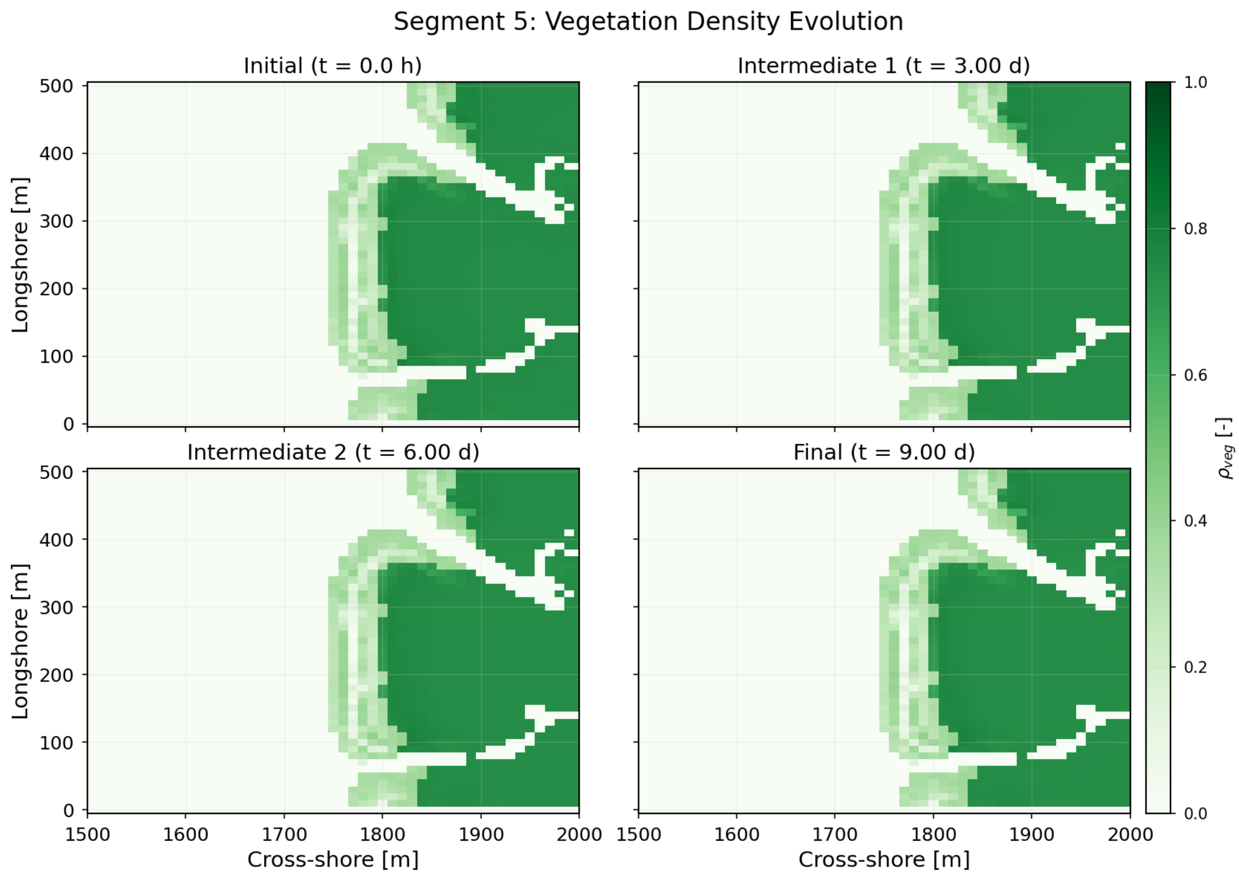

Figure 7: Segment 5 - AeoLiS simulation results for vegetation density evolution.

The final simulation period for AeoLiS is segment 7 spanning 142 days – results for the vegetation density evolution are given in Figure 8. A slight further reduction of the overall density values is observable, with the foredune thinning out and developing a ridge-parallel oriented pattern of reduced density and values around 0.18. The salt marsh area exhibits further reduction down to 0.5.

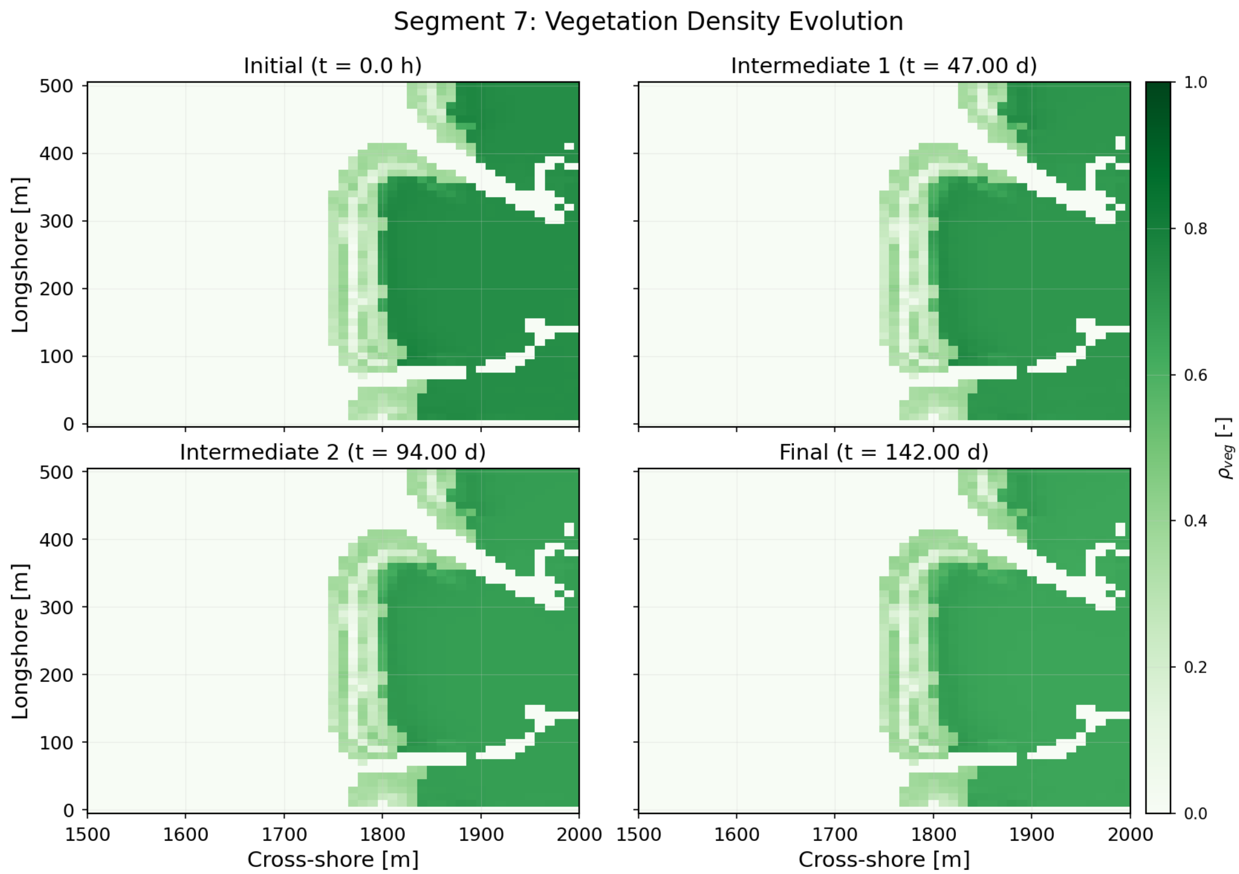

Figure 8: Segment 7 - AeoLiS simulation results for vegetation density evolution.

Surfbeat | Segments 2, 4, 6

The surfbeat simulations span the three detected storm surge events, with the first one being covered by segment 2 shown in Figure 9

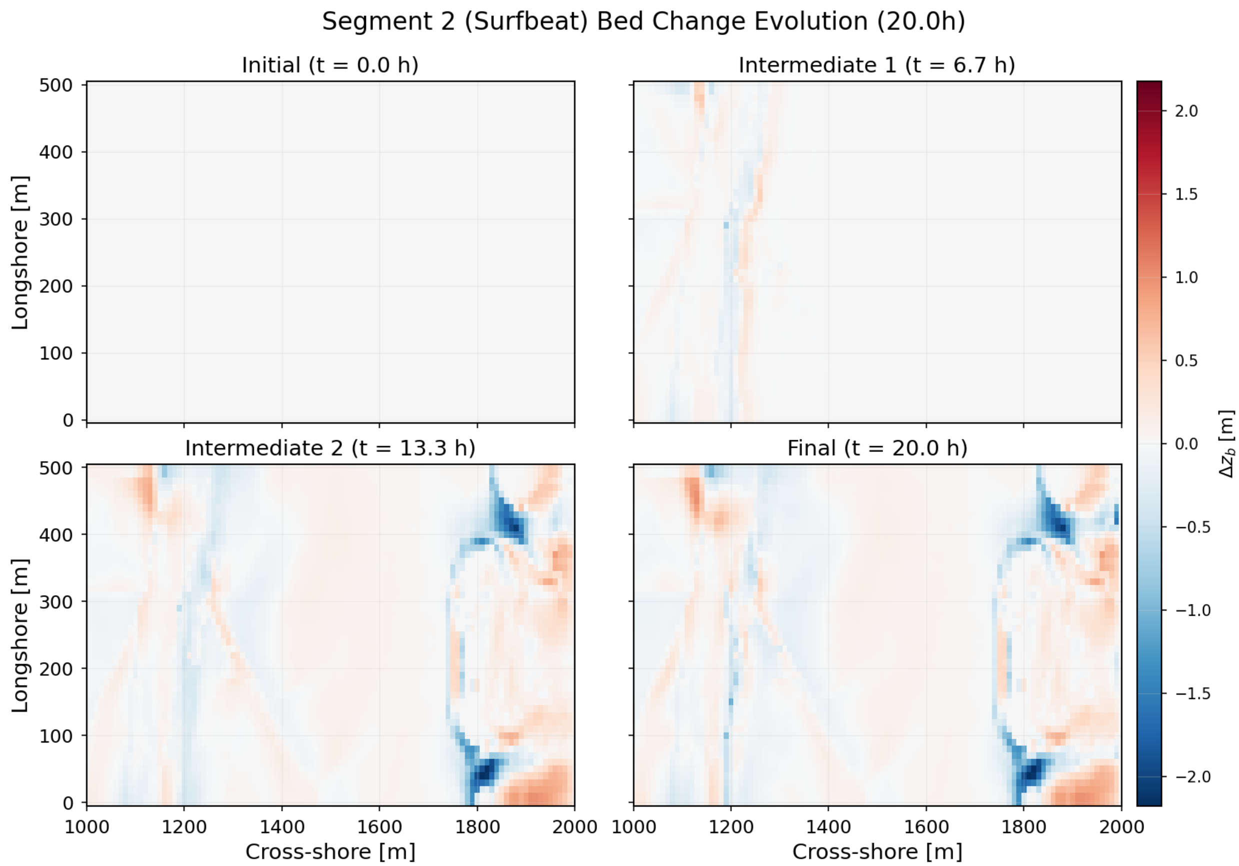

Figure 9: Segment 2 – XBeach surfbeat simulation results for cumulative surface elevation changes.

Surface elevation changes range within +/- 1.7 m and show erosion at the seaward dune toe and the adjacent breaches deepening them (blue shades), while the beach shows slight accumulation (slight red shades) and a development of flood related delta fans behind the dune breaches accumulating material in the lee side of the dune.

The adjacent AeoLiS simulation is given in segment 3 shown in Figure 6.

Subsequently, the AeoLiS simulation is stopped, as the tidal water level rises above the defined PoT. Bathymetric/Topographic domain information is passed onto XBeach surfbeat and corresponding boundary conditions are generated from the available time series for the second storm event. Elevation changes are shown in Figure 10. The surfbeat simulation resolves the highly energetic storm event and its induced hydrodynamics on much smaller time steps (constrained by CFL = 0.7) and computes a beach and dune erosion.

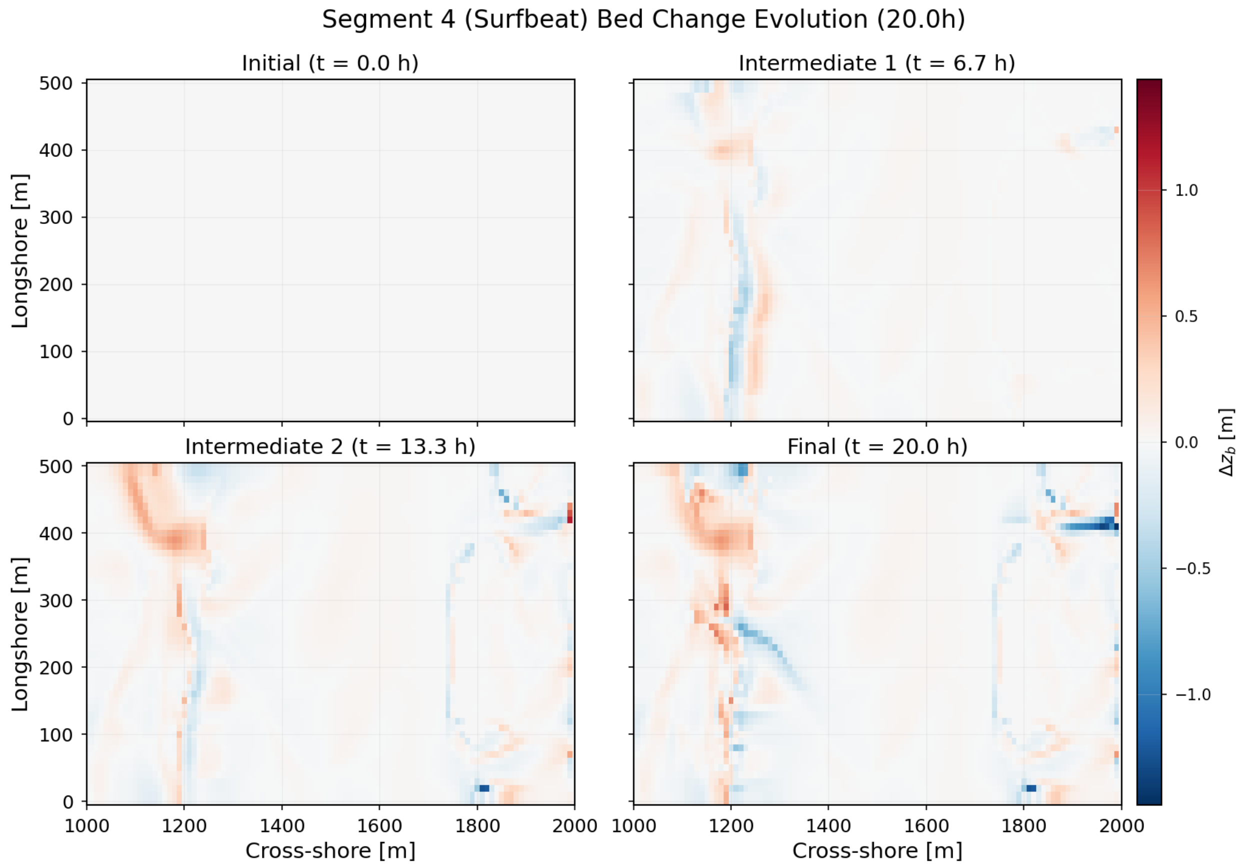

Figure 10: Segment 4 – XBeach surfbeat simulation results for cumulative surface elevation changes.

Within a total duration of 20 h, the second storm surge event of 2010 develops a different impact on the bathymetric/topographic domain grid compared to the first one. The coastline shows erosion (red shade) with material being eroded by the waves and transported and deposited in offshore direction (blue shaded parallel ridge). With rising water levels (t = 13.3 h), the waves start reaching the dune toe area and induce erosion. After the storm surge event recedes (t = 20 h) the coastline shows erosion and accumulation from the wave action, the dune toe area is eroded and the breaches show less erosion compared to the first storm surge event. Slight accumulation is seen at the spit areas on the back side of the foredune lining the two breaches.

Segment 5 shown in Figure 7 details the vegetation density evolution corresponding to the AeoLiS simulation. Given the short duration of this simulation, changes are negligible. Segment 6 captures the third storm surge event simulated with XBeach surfbeat. The resulting bed elevation changes are plotted in Figure 11.

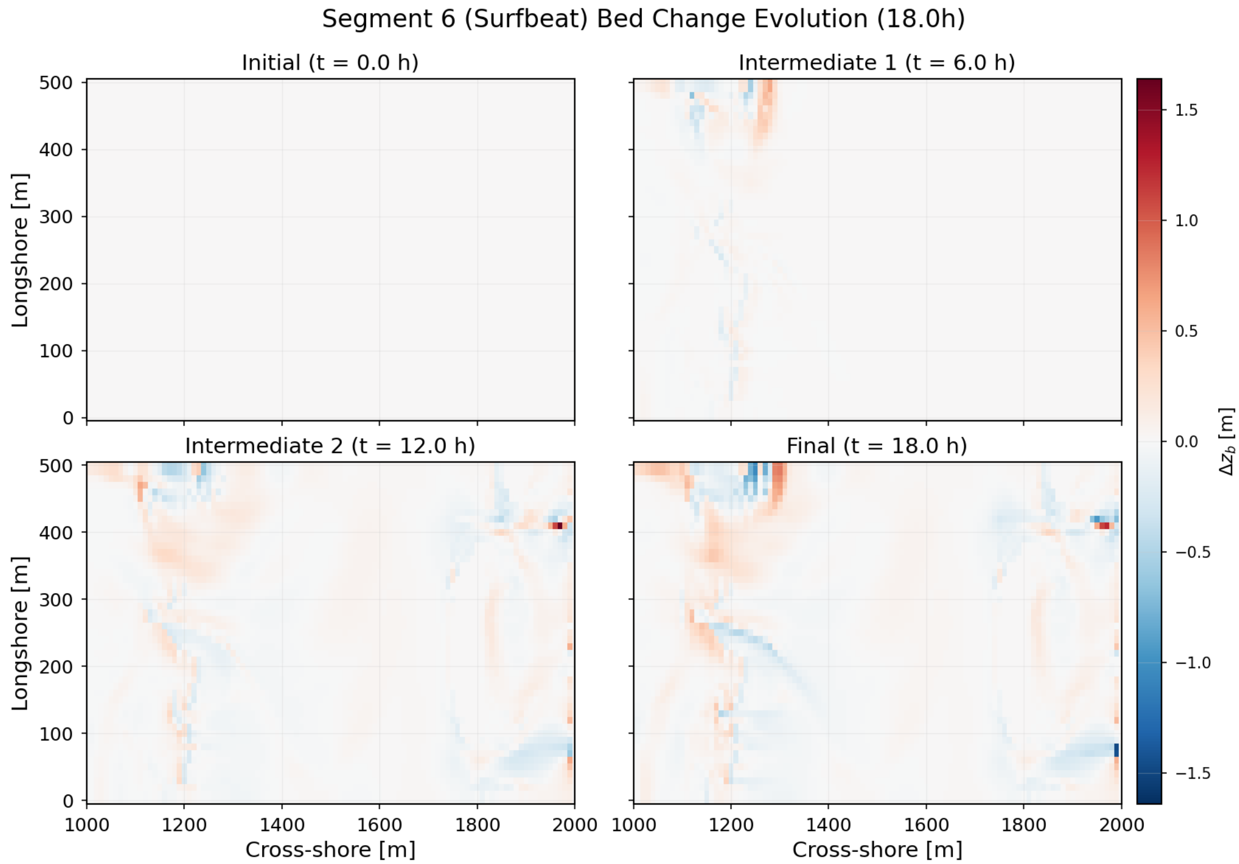

Figure 11: Segment 6 - Xbeach surfbeat simulation results for cumulative surface elevation changes.

The third storm surge event shows similar characteristics compared to the previous two events in segments 2 and 4 (cf. Figure 9 and Figure 10) in that the coastline shows an erosion and offshore transport and deposition of material by wave action. With rising water levels, the dune toe area is eroded and material is transported behind the dune area. The natural breaches are slightly eroded by the wave action through wave run-up.

Combined

The resulting elevation changes are given in Figure 12 for the AeoLiS impact only (**top panel**), the combined impact with XBAeoLink in the middle panel and the corresponding reference data from the federal hindcast model.

The AeoLiS results show an erosion of the dune toe area, with a subsequent deposition on the crest and an overall foredune height increase through the simulation of 0.3-0.5 m/yr. The beach section shows no elevation changes.

The inclusion of XBeach in the **middle panel** shows the impact of hydrodynamics on the beach and dune system with erosion of the coastline, accretion of the frontal beach area. The dune toe area and adjacent breaches show erosion due to wave action and funneling of wave-run up. Material is transported through the breaches and deposited behind the foredune forming a flood-delta. The dune exhibits a height increase through aeolian transport.

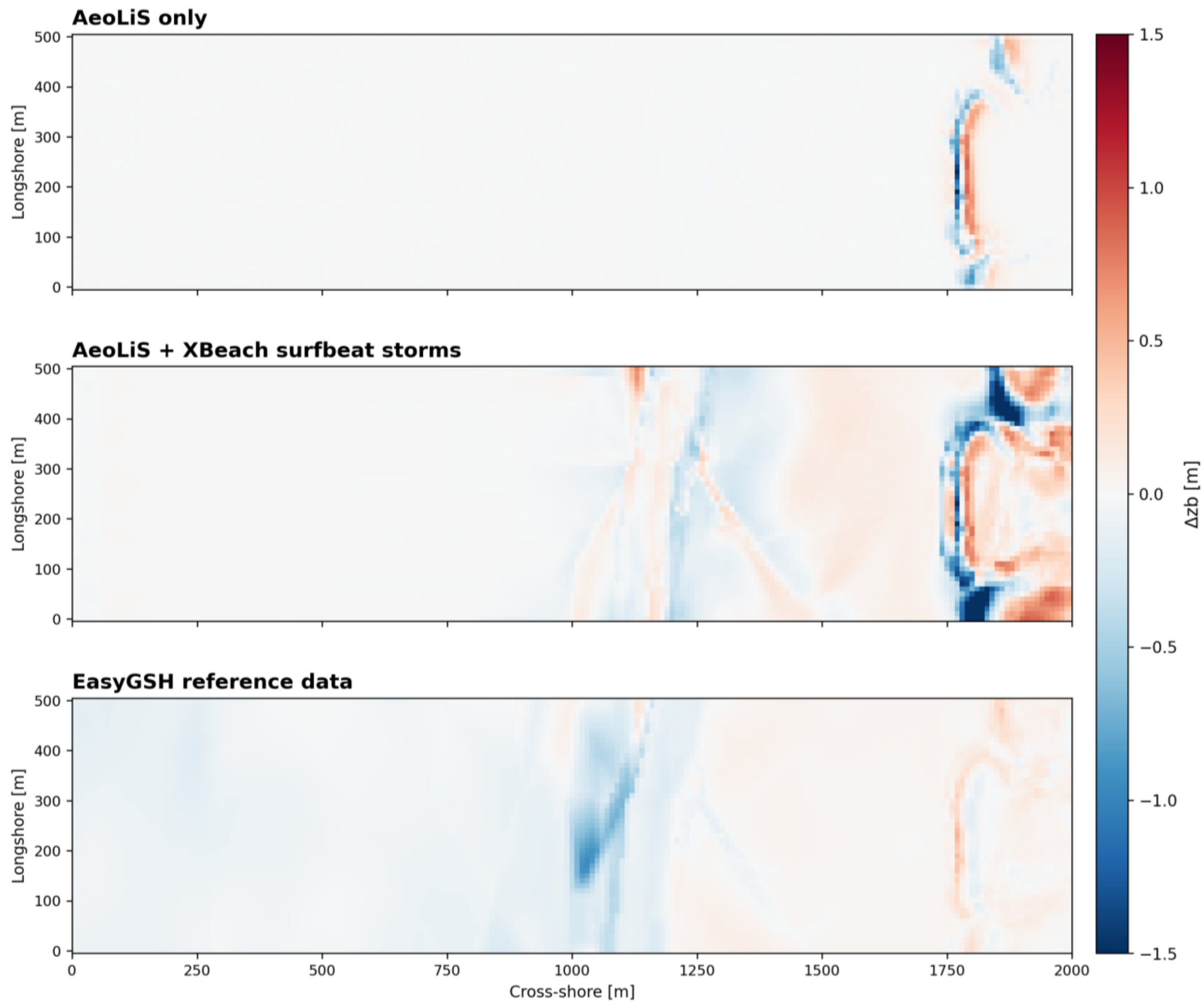

Figure 12: Final cumulative elevation changes after 7 segments and 365 days of XBAeoLink simulation. Top panel AeoLiS only, middle panel XBAeoLink, bottom panel reference data.

The **bottom panel** shows reference data obtained for the model domain from the federal hindcast model EasyGSH (REF). The overall pattern matches, yet the dune related processes are not fully resolved and show less pronounced erosion around the dune toe area and the adjacent breaches. EasyGSH and the successor TriLaWatt do not simulate aeolian transport or the impact of coastal vegetation – the model is a hydro-morphodynamic one, which is driven with partial tides and meteorological boundary conditions, making the comparison difficult. Survey data is unfortunately scarce for the period.

A direct quantitative comparison between the simulated and reference elevation changes is inherently challenging because comprehensive observational data describing storm-induced dune erosion and subsequent post-storm recovery are generally limited. While the federal hindcast model provides a valuable regional-scale reference, it is itself a numerical representation rather than a direct measurement of morphological change. Furthermore, differences in the underlying process descriptions, spatial resolution, and forcing conditions between the models complicate a one-to-one comparison of individual erosion and deposition patterns. In particular, the omission of aeolian sediment transport and vegetation effects in the hydro-morphodynamic reference model results in a fundamentally different representation of foredune evolution, especially during the recovery phase following storm events.

The availability of field observations for validating storm-induced dune erosion remains limited, as high-resolution topographic surveys immediately before and after storm events are rarely available. In addition, the rapid temporal evolution of coastal dunes, combined with logistical constraints during extreme events, makes the acquisition of suitable validation datasets particularly difficult. Consequently, model evaluation often relies on comparisons with other numerical models or on qualitative assessments of the reproduced geomorphic patterns rather than on comprehensive field measurements. Despite these limitations, the agreement in the large-scale erosion and deposition patterns provides confidence that the coupled model captures the dominant coastal processes governing the evolution of the beach-dune system.

2.3 Belgian Demonstrator – Oostende/ Raversijde-Mariakerke

Model settings

To check the numerical model performance and the parameter settings. XBeach was used to hindcast Storm Corrie, which occurred on 31 January to 1 February 2022, with a peak significant wave height of around 3.68 m (2022-01-31 13:30) and a peak water level of 5.73 m TAW (2022-01-31 11:50). The wave information and water level time series during the storm event are shown in Figure 13.

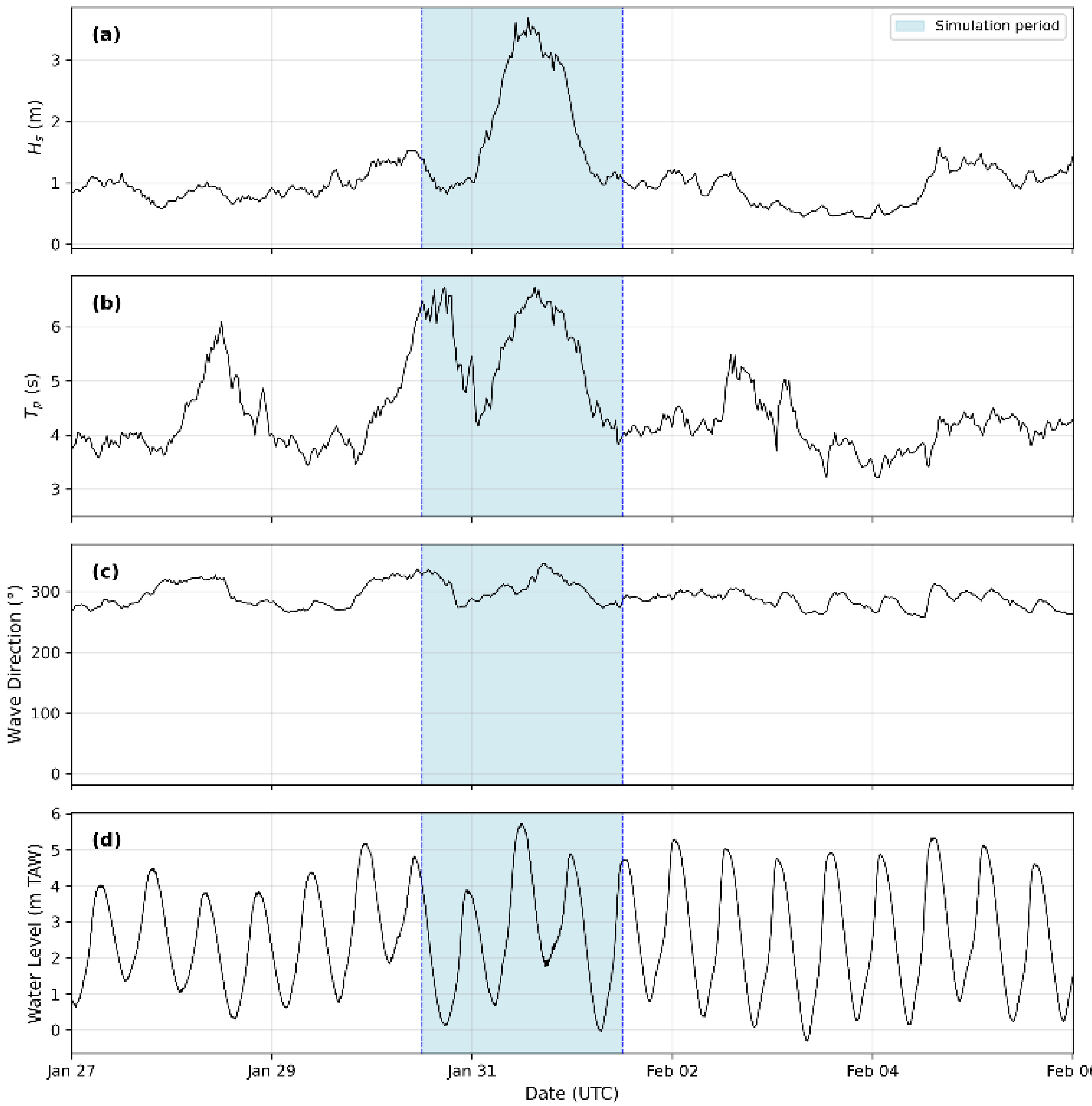

Figure 13: Wave and water level information during storm event for the Belgian demonstrator

In this study, the parameter setting is based on the parameters which was re-determined by WTI2017 (Wettelijk Toets Instrumentarium) project (van Geer et al. 2015).The particle size D50 = 250 μm is used to for the whole computational domain, which is a typical value for this site. The duration of the simulation is 48 hours (172800 seconds), which covers the storm event.

For the Aeolis model, approximately 1 year --- from 22 November to 12 October --- a hindcast was conducted. The initial topography is derived from airborne LiDAR survey data collected on 22 November 2021. Topographic data from 12 October 2022 are used for model validation. The shore-norma direction has an azimuth of 30° (counterclockwise from north). The initial topography used in the simulation is shown in Figure 14. The simulation covers the period 22-11-2021 to 12-10-2022 with a time step of dt = 7200s. Wind, tide, and wave data were obtained from the Meetnet Vlaamse Banken monitoring network operated by the Agency for Maritime Services and Coast. Wind data were measured at the Ostend weather station, tide data at the Ostend Harbour tide gauge, and wave data at the Raversijde 1 buoy, respectively (Figure 15).

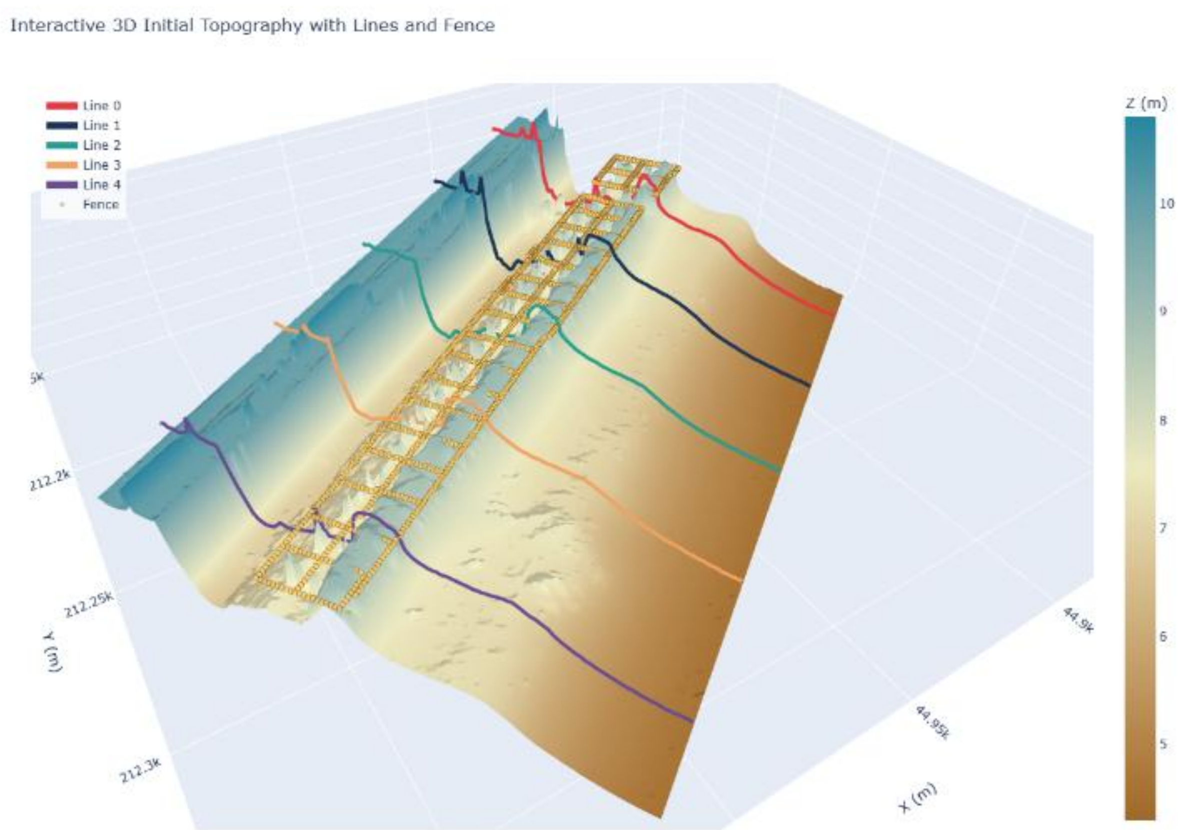

Figure 14: Initial topography with six reference profiles at Raversijde, Belgium.

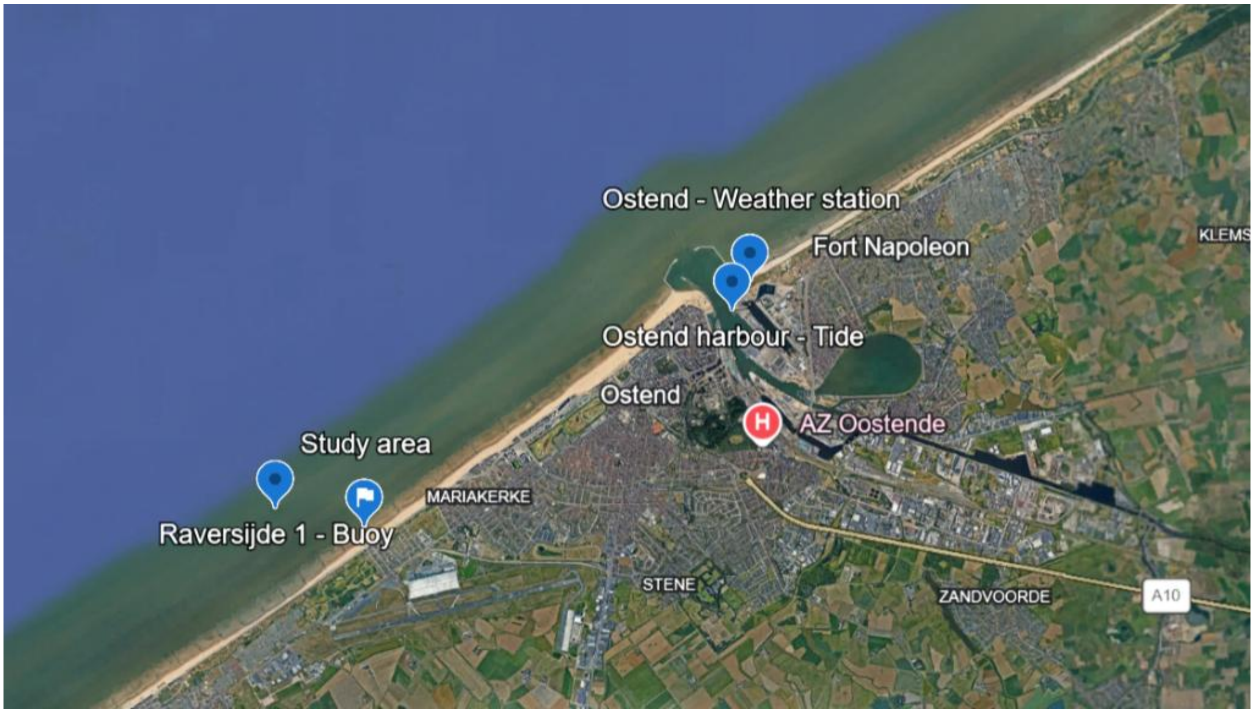

Figure 15: Study area at Raversijde, Belgium.

The wind speed measurements were calibrated using field observations to better represent the local wind conditions at the study site. The wind rose in Figure 16illustrates the distribution of wind direction and wind speed at the study site. The dominant wind directions are from the South (S) and the south – southwest (SSW), with secondary contributions from the northeast (NE). Most wind speeds range between 3–9 m/s, while stronger winds (>9 m/s) occur less frequently.

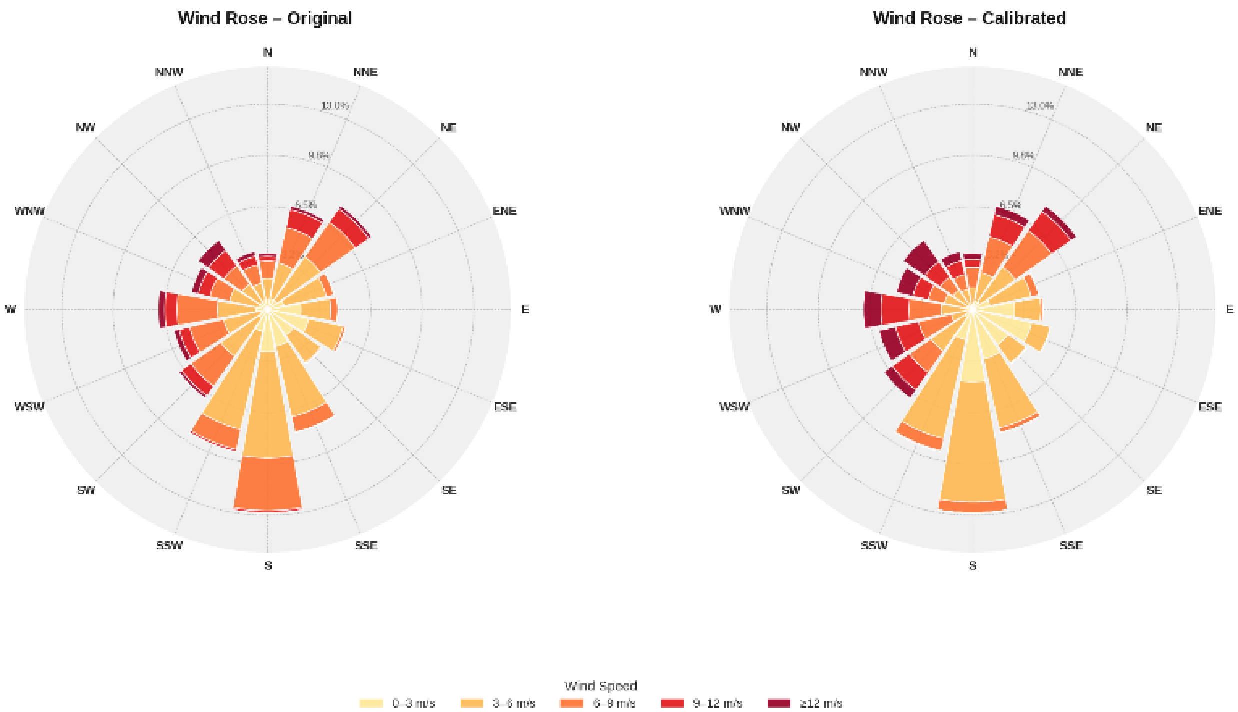

Figure 16: Wind rose showing the distribution of wind directions and speeds at Raversijde, Belgium.

The main parameter settings are shown in Table 2: Parameter settings for Raversjide, Belgium.

Table 2: Parameter settings for Raversjide, Belgium.

Parameters	Value	Unit
Simulation period	Nov 22, 2021 – Oct 12, 2022	-
Model time step (dt)	7200	s
Output interval	86400	s
Grid resolution (dx = dy)	1	m
Grain size (d)	2.3×10^{-4}	m
Bed roughness(k)	0.005	m
Transport method	van Rijn–Strypsteen	-
Base angle of repose	33	degrees
Spatial reduction factor	0.48	-
Initial shear reduction factor	0.10	-

Model results

XBeach

Error! Reference source not found. shows the final terrain and elevation change. The main erosion area is located at around (43000, 211000). The eroded sediment was transported offshore flattens the dune. Each cross-section has varying degrees of erosion, as illustrated in Figure 18.

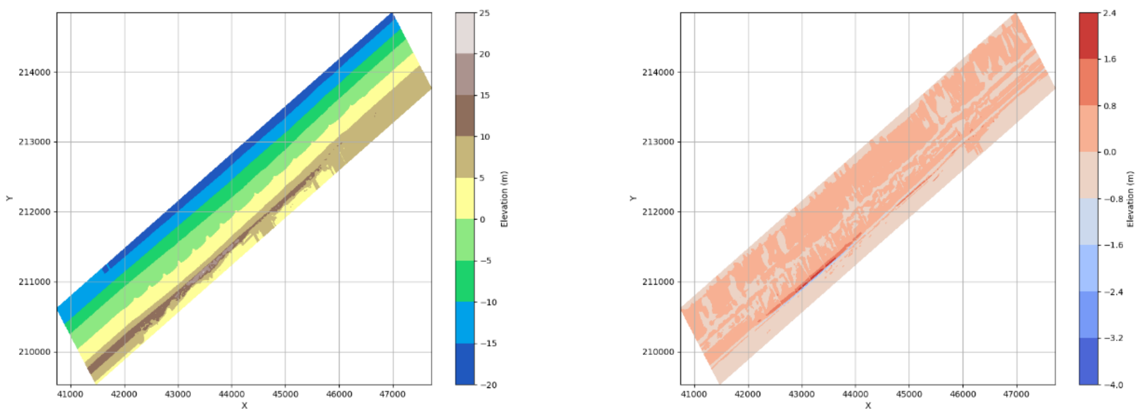

Figure 17: Final terrain(left) and Elevation Change (Δz m) (right)

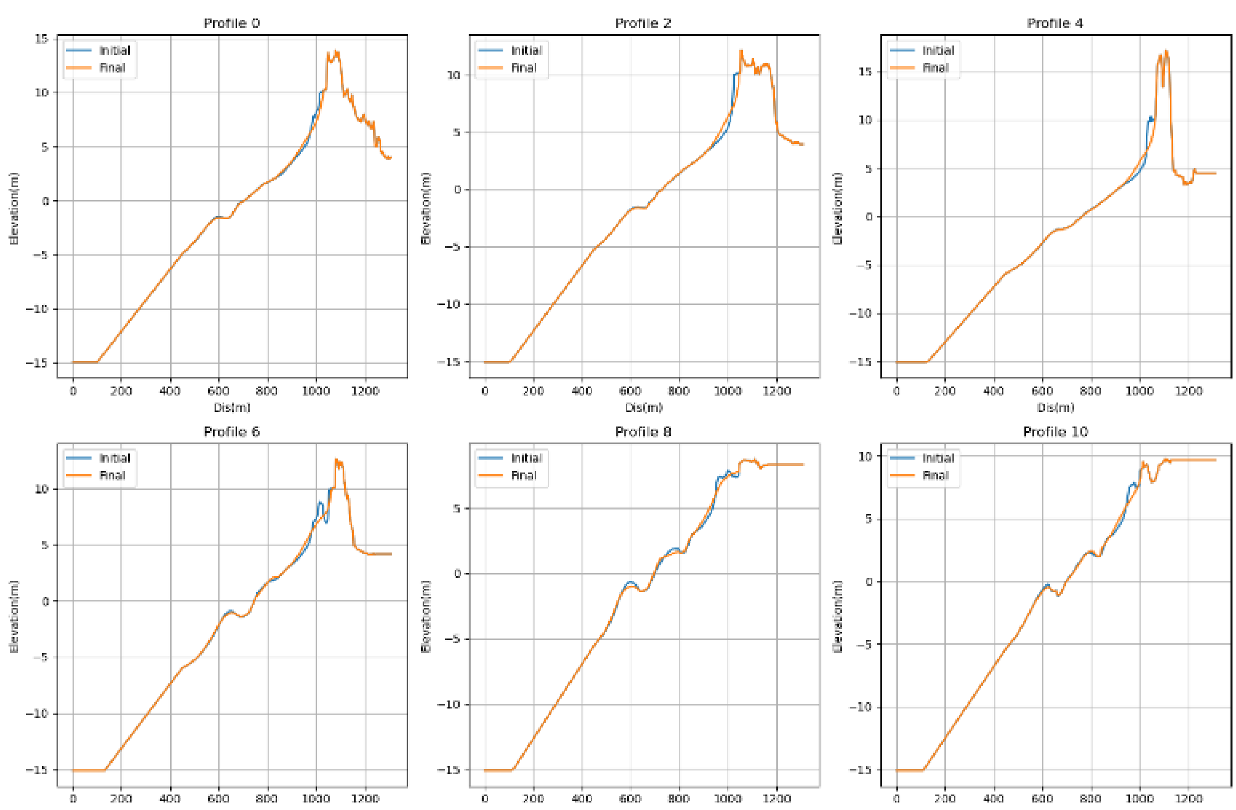

Figure 18: Comparison of the Initial and Final Cross-sections

AeoLis

Error! Reference source not found.shows the terrain change, with a significant increase in elevation observed in areas covered by vegetation. However, on the seaward side, the elevation increase is more pronounced, while on the landward side, wind erosion occurs instead. This can also be observed from the cross-section at y = 190 m (Figure 19).

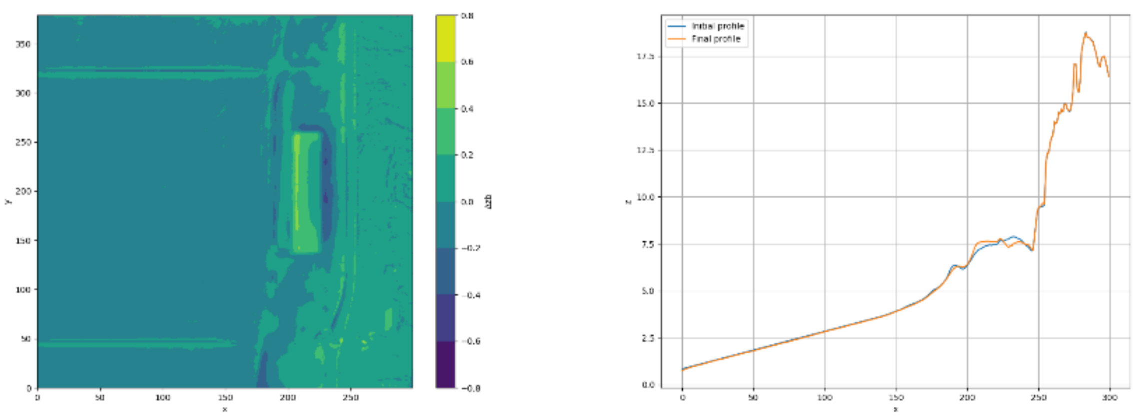

Figure 19: Top view of terrain change (left) and cross-sectional view (right)

Dune volume changes are well predicted. However, vegetation dynamics proved to be crucial for good model results.

2.4 Portuguese Demonstrator - Douro

The Douro sandspit is situated at the mouth of Douro River, between the cities of Porto and Vila Nova de Gaia, Figure 20, and exposed to the Atlantic Ocean. The Douro River has the largest watershed in the Iberian Peninsula, with a total area of nearly 100.000 km^2. The sandspit protects inland margins and the natural reserve of São Paio Bay from storms. In 2004, a detached rubble-mound breakwater was constructed in front of the sandspit to stabilise the estuary's bank and inlet and to improve navigation safety. Since then, the sandspit has been growing in area and volume, with the exception of some eroding events related to heavy storms. On average, the sandspit has grown by 68.000 m^3 per year since the construction of the breakwater has finished, in 2008. The dune reaches a maximum height of around 8 m above the mean sea level.

The Douro sandspit is a complex morphological case considering the different drivers that affect it. This location is influenced by an interaction of wave action, fluvial discharge, and aeolian processes, in addition, to the effects that the breakwaters have on the hydrodynamics. This makes numerical modelling particularly challenging.

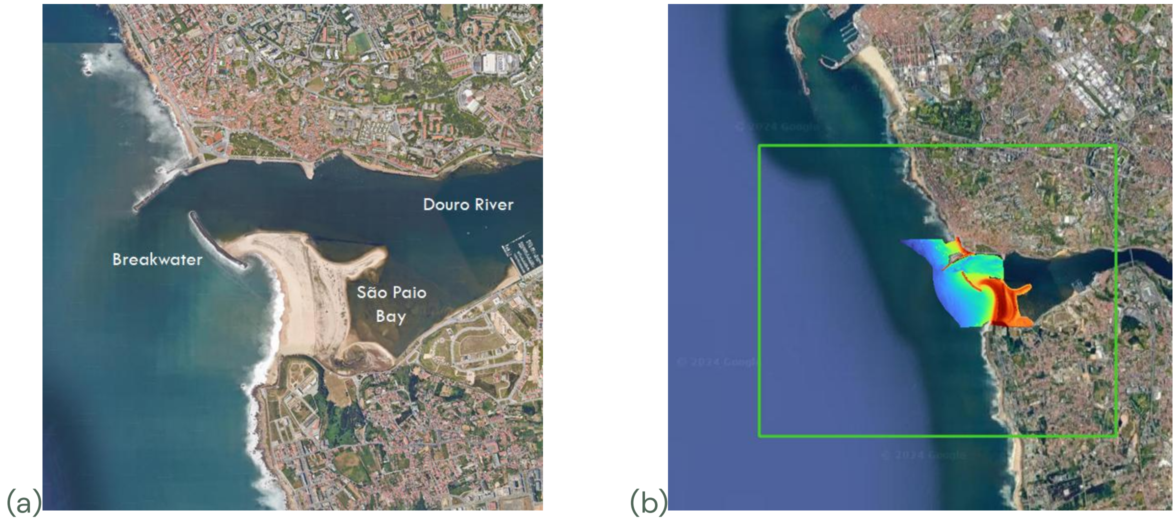

Figure 20. (a) Douro sandspit showing the breakwaters and the São Paio Bay. (b) Domain area along with the demonstrator's high-resolution DEM.

The numerical work presented in this report is for the period from September 2017 to April 2018, Figure 21. This period is chosen since there are available topographic surveys for the dunes at the beginning and end of this 7 months period. The models will attempt to hindcast the changes that happen to the topography status of Oct. 2017 till April 2018.

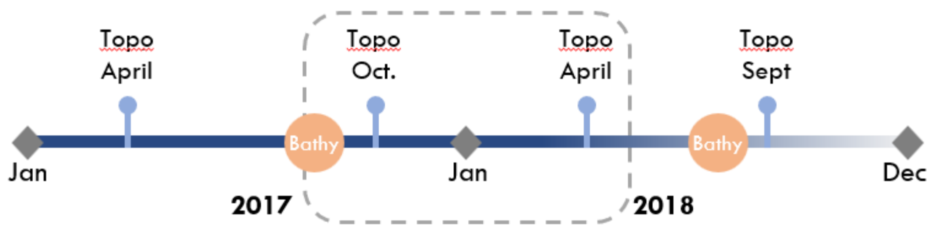

Figure 21. Timeline showing available bathymetric surveys at September 2017 and August 2018 in addition to topographic surveys in April 2017, October 2017, April 2018, and September 2018.

2.4.1 Coupling Strategy

Calm periods are simulated by Delft3D, for marine related growth, while stormy periods are simulated by XBeach using the surfbeat module. Sequences of storms and calm periods are determined by a static wave height threshold, with its value determined through several trials for calibration.

The storm sequencing transforms a long-term environmental forcing data into a structured timeline of hydrodynamic events based on its tranquility. Datasets of waves, wind, tide, and river discharge are loaded and aligned over a selected time window. Storm events are identified using a peak over threshold approach applied to the significant wave heights. The algorithm scans the timeseries and identifies periods where the threshold is exceeded, allowing for short gabs or interruptions to exist within the same storm event. Each storm is then characterized by its duration and forcing parameters of waves, wind, tide, and river discharges.

After the storm identification, a chronological sequence of alternating storms and calm periods is constructed. Storms are then assigned to XBeach and the relatively longer calm periods are assigned to Delft3D ensuring continuity.

A key component of the framework is the two-way exchange of bathymetric information between the models. At the end of each simulation, the final bed file is loaded and interpolated to the subsequent model. Nonetheless, the interpolation is only performed on a predefined region of interest, the vicinity of the sand spit, with filtering of invalid points. Figure 22 presents a flowchart of the coupling. The sequence is simulated in series to ensure realism and continuity between the models. Boundary conditions are dynamically assigned based on the event type and timing. Aeolis model is not considered in this coupling strategy because existing information shows that aeolian transport is of secondary importance in this case study.

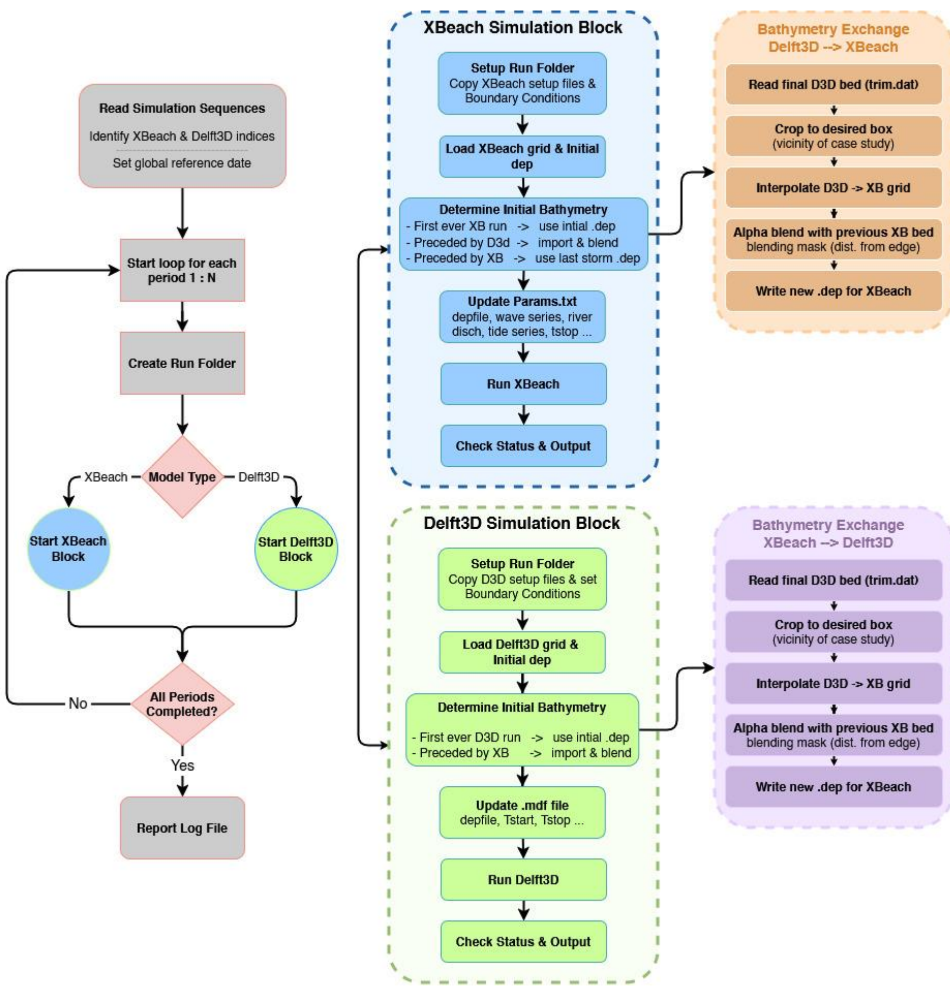

Figure 22 Coupling framework between XBeach and Delft3D with bed update.

2.4.2 Model setup

XBeach

The preparation of the XBeach surfbeat model is based on a bathymetric survey of the area of interest conducted in 2017 with a DEM of resolution 30 cm, Figure 20 (b). The computational domain covers an area of 5100 m (cross-shore) by 6250 m (along shore). The remainder of the area was assimilated from other lower-resolution bathymetries.

To stabilize the propagation of waves at the offshore boundaries, a constant depth of −25 m was assumed for nearly 160 m Figure 23 (a). Also, to prevent having significant wave shadow areas, the domain was oriented towards the global X-direction, instead of being perpendicular to the shoreline as is typically favored. This was chosen since orienting the grid slightly to the south would cause many North-Western waves to exit the domain from the bottom lateral before reaching the shoreline, resulting in a larger shadow area at the upper lateral boundary. Then, a varying grid resolution was chosen to decrease the computational effort. A grid size of 5x5 m was chosen to the area of interest and gradually increased towards the boundaries. In the cross-shore direction, dx varied from 5 m to 10 m Figure 23 (b). While in the along-shore direction, dy varied from 5 m to 20 m. The total grid consists of 841 x 553 mesh cells. Several cells were marked as non-erodible to correspond to the real case as closely as possible, Figure 23(c). These cells represent the breakwaters, the riverbanks, and several rocky patches along the coastline.

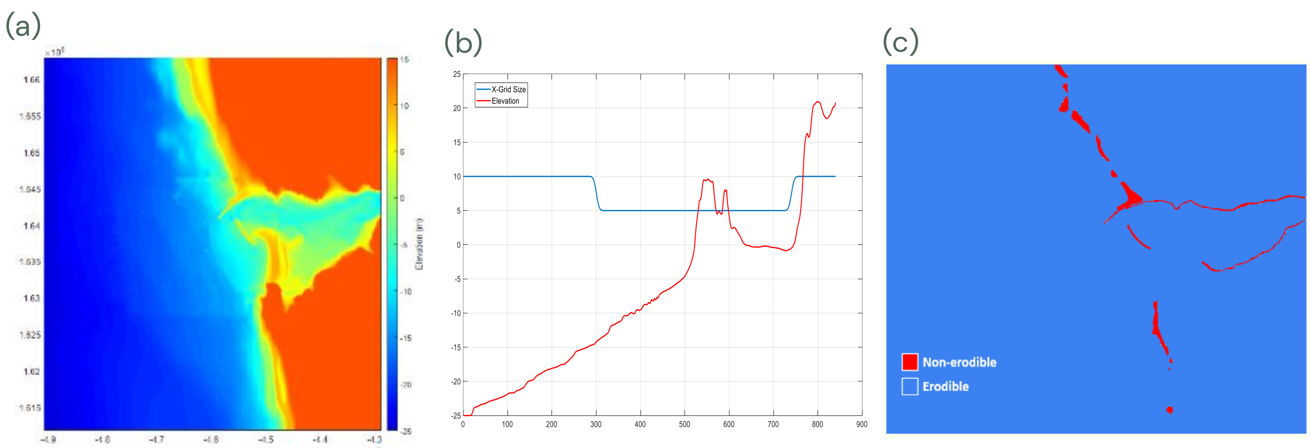

Figure 23. (a) XBeach model bathymetry with artificial offshore depth of -25m. (b) Grid size in cross-shore direction, dx, along with the bed profile. (c) Non-erodible regions (red) covering the river banks, breakwaters, and rocky spots along the coast.

The lateral boundaries of the domain were assumed to be Neumann for the hydrodynamics and wavecrest for the waves. Front and back boundaries were set to abs_2d. Implementing a cyclic boundary condition resulted in an erroneous behaviour because the bathymetries at either end of the domain are completely different, which does not allow a smooth reentering of the waves from one side to the other. For the offshore boundary, a time-varying spectral wave condition was defined along with a wind time series, which had a one-hour temporal resolution. Additionally, a daily averaged timeseries of river discharge was applied from the onshore direction. Sea level variations were implemented using astronomical tide components with a temporal resolution of half an hour and a tidal range of 3.75 m. The sediment transport module was set to the VanThiel_VanRijn equations, and the D_{50} was set to 0.5 mm. Other parameters were kept as simple as possible, and many coefficients remained as XBeach's recommended default values.

Delft3D

The Delft3D model is constructed to simulate the long-term morphological evolution of the case study area, with a particular focus on its growth and accretion potential. The model is used within the coupled framework to simulate low-energy (calm) periods between storm events, providing the baseline morphological evolution that complements the high-resolution storm simulations to be performed using XBeach.

The computational domain covers a spatial extent of approximately 16 km in the alongshore direction and 8 km offshore. To achieve a balance between the required spatial resolution and computational efficiency, a decomposed grid approach was adopted, Figure 24. This allows for local refinement in the region of interest while maintaining a coarser resolution in offshore areas. The grid resolution varies from approximately 5 × 5 m in the area of interest to about 70 m offshore.

Figure 24. Delft3D decomposed domain showing subdomains for the coastal area, estuary area, and the river area.

The model is implemented in depth-averaged (2DH) mode, solving the shallow water equations with online coupling between hydrodynamics and wave processes. Wave boundary conditions are derived from a SWAN model for the region of North Portugal and calibrated using buoy measurements (Ramos et al., 2022). Tidal forcing is prescribed using harmonic boundary conditions based on 14 tidal constituents, ensuring accurate representation of the local tidal dynamics. River discharge is imposed at the upstream boundary using time series obtained from publicly available data provided by SNIRH (SNIRH, n.d.).

2.4.3 Model results

The classification of the events is based on the exceedance of a predefined threshold value of significant wave height equal to 4 m. After the storm's detection, the complete time series is divided into alternating storm and calm periods. Storm events are assigned to XBeach surfbeat model to resolve infragravity wave dynamics and storm induced erosion. The calm periods are assigned to Delft3D to simulate a longer time period with low energy conditions and sediment input from the river.

To avoid splitting single storm into multiple ones due to temporary reductions in wave heights, consecutive events that are separated by less than six hours are counted as a single continuous storm. Furthermore, only events that last than six hours are chosen in order to exclude isolated energetic waves that are unlikely to produce significant morphological response. For every detected storm, the algorithm extracts the corresponding parameters such as wave height, period, direction, wind velocities, tide levels, and river discharge. These parameters serve as the boundary conditions for the numerical models. An illustrative example for the classification of the wave timeseries is shown in Figure 25.

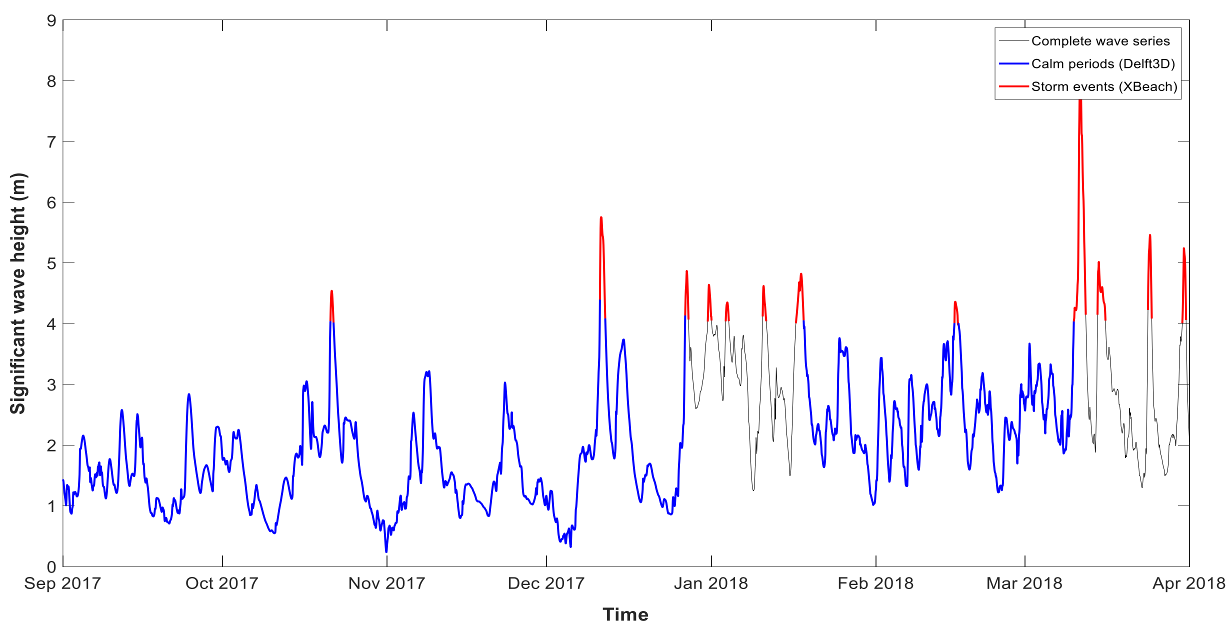

Figure 25 Significant wave height classification in either calm periods for Delft3D simulation (blue) or stormy conditions for XBeach simulations (red) for the period from September 2017 to April 2018.

A filter was implemented on the calm periods to only keep them if a consecutive interval exceeded two weeks. This was twofold. First it ensures that only morphological significant recovery periods are simulated. Second it decreases the number of exchanges between models and the spin up periods, thus reducing the overall simulations time. Table 3 presents the alternating sequence detected for the hindcast period.

Table 3 Modelling sequence of chronological Delft3D - XBeach simulations for the period between September 2017 to April 2018.

Event_ID	Model_Type	Start_Time	End_Time	Duration (Days)
1	Delft3D	01/09/2017 00:00	21/10/2017 08:00	50.3
2	XBeach	21/10/2017 08:00	21/10/2017 22:00	0.6
3	Delft3D	21/10/2017 22:00	11/12/2017 01:00	50.1
4	XBeach	11/12/2017 01:00	12/12/2017 01:00	1.0
5	Delft3D	12/12/2017 01:00	27/12/2017 02:00	15.0
6	XBeach	27/12/2017 02:00	27/12/2017 17:00	0.6
7	XBeach	31/12/2017 08:00	01/01/2018 01:00	0.7
8	XBeach	03/01/2018 17:00	04/01/2018 07:00	0.6
9	XBeach	10/01/2018 16:00	11/01/2018 08:00	0.7
10	XBeach	16/01/2018 22:00	18/01/2018 09:00	1.5
11	Delft3D	18/01/2018 09:00	15/02/2018 18:00	28.4
12	XBeach	15/02/2018 18:00	16/02/2018 12:00	0.8
13	Delft3D	16/02/2018 12:00	10/03/2018 05:00	21.7
14	XBeach	10/03/2018 05:00	12/03/2018 11:00	2.3
15	XBeach	14/03/2018 16:00	16/03/2018 04:00	1.5
16	XBeach	24/03/2018 04:00	24/03/2018 21:00	0.7
17	XBeach	30/03/2018 15:00	31/03/2018 08:00	0.7

The simulations are still ongoing, with additional parameter tuning and testing of the coupling framework currently underway. Nevertheless, the preliminary results indicate that the proposed Delft3D–XBeach framework is capable of reproducing the main morphological changes observed during the hindcast period with encouraging accuracy.

Figure 26 compares the simulated and observed elevation changes over the Douro sand spit. The spatial comparison yields an overall RMSE of 0.48 m, demonstrating reasonable agreement between model predictions and field observations considering the highly dynamic nature of the study area. The simulation successfully reproduces the primary zones of erosion and accretion along the seaward margin of the sand spit, particularly along the exposed western shoreline where the most significant morphological adjustments occurred during the study period.

A visual comparison of the two maps reveals that the model captures the dominant large-scale sediment redistribution patterns. The strongest accretion signal along the northern curved section of the spit and the pronounced erosion along the western shoreline are reproduced in both magnitude and spatial extent. This indicates that the coupled framework is adequately representing the key hydrodynamic and sediment transport processes governing shoreline evolution within the active coastal zone.

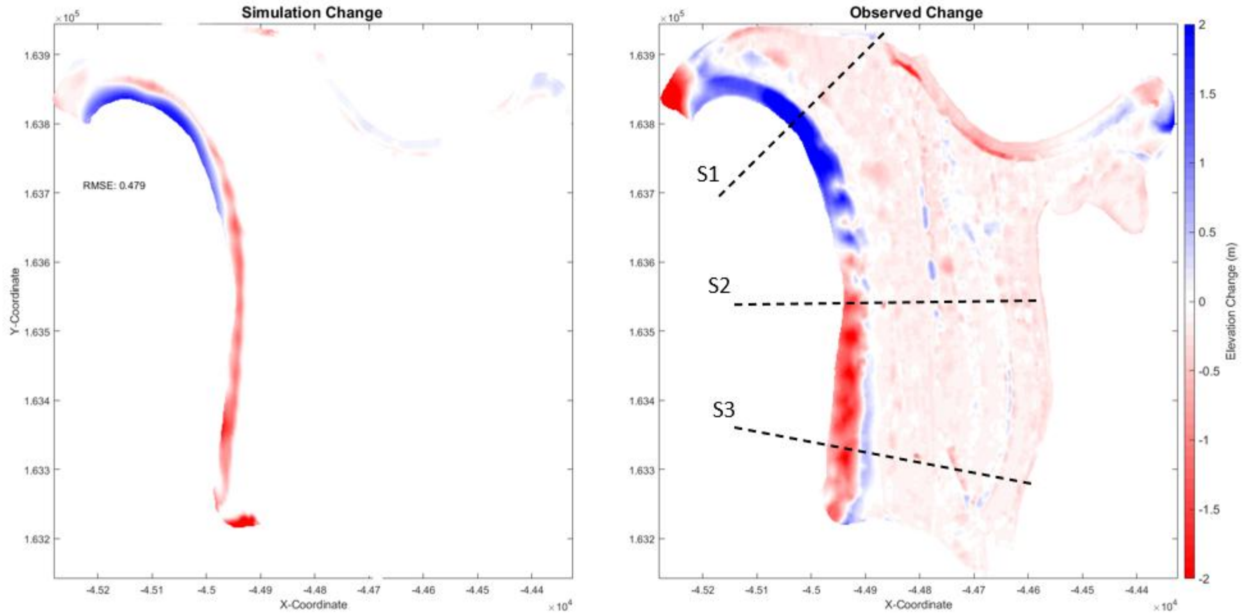

Figure 26 Preliminary results for hindcast period from Sept 2017 to Apr 2018. Left shows numerical simulation changes. Right shows observed changes

The cross-shore profile comparisons further demonstrate the framework's ability to reproduce observed morphological evolution (Figure 27). Profiles S1, S2, and S3, located in the northern, central, and southern portions of the sand spit, respectively, show generally good agreement between simulated and observed shoreline positions and profile shapes. The error metrics presented in Table 4 are calculated for dune part only of the cross-shore profile, i.e., the overlapping portion of the simulated vs the observed.

Overall, good agreement is achieved between the simulated and observed profile geometries, with the model successfully capturing the main erosional and accretional features across all three transects. Profile S1 exhibits the highest skill, with a BSS of 0.49 and an MAE of 0.42 m, accurately reproducing the steep accretional transition, crest position, and overall profile shape, although the landward extent is slightly underestimated. Profile S2 yields a BSS of 0.42 and the lowest MAE of 0.19 m, showing particularly strong agreement throughout the central section of the profile, where crest elevations and trough locations are closely matched. Profile S3 records a BSS of 0.33 and an MAE of 0.25 m. Despite the lower skill score, the model still reproduces the general profile morphology and principal topographic features. Nevertheless, the results indicate that the coupled framework is capable of reproducing the dominant morphological response of the sand spit, with BSS values ranging from 0.33 to 0.49, corresponding to fair-to-good predictive skill for coastal morphodynamic modelling applications. Further calibration and sensitivity analyses are expected to improve these results and reduce the remaining discrepancies between simulated and observed changes.

Table 4 Profile error metrics

Profile	Mean Average Error (MAE)	Brier Skill Score (BSS)
S1 (North)	0.424	0.486
S2 (Middle)	0.185	0.415
S3 (South)	0.255	0.311

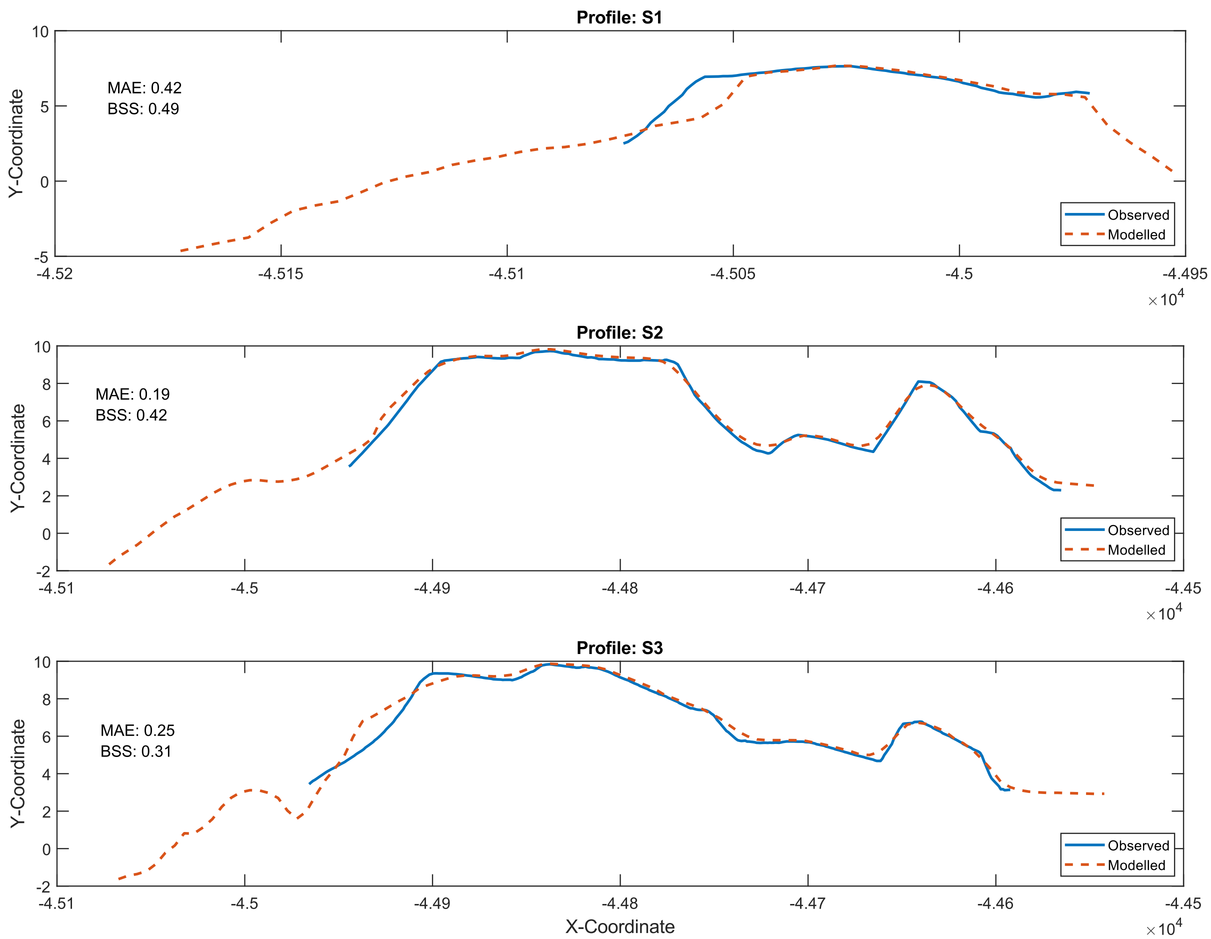

Figure 27 Profile results for hindcast period. From top to bottom shows Profiles S1 (north), S2 (middle), and S3 (south), respectively.

3. Conclusions

This report details hindcast simulations conducted with numerical demonstrator models developed and outlined in Report of D11.1 covering the German, Belgian and Portuguese demonstrators.

For the German Demonstrator Sankt Peter-Ording, the previously developed and setup AeoLiS and XBeach models have been coupled in a segmented approach called XBAeoLink. This developed scripted environment allows the semi-automatic simulation of extended periods of time with both models for a defined model domain – here the German demonstrator. The script switches between long term aeolian transport mode for dune buildup and wave dominated erosion during short-lived storm surge events. This is implemented through a simple peak over threshold value for the occurring water level. If the PoT is exceeded through rising water levels indicating storm surge levels, the AeoLiS model is stopped, computed surface elevation values are transferred into the XBeach framework, boundary conditions are obtained from a data base and the surfbeat mode is started. The surfbeat simulation lasts for the duration of the storm surge and is stopped, once the water level recedes again below storm surge levels. Then the computed surface elevation level is transferred back into AeoLiS and the aeolian transport regime is continued.

This approach was developed to include the short-lived hydrodynamic impacts of individual storm surge events upon beach and dune morphology. AeoLiS covers the aeolian transport, vegetation coverage and development and dune build-up but does not account for wave-induced transport, which supplies the beach with sediments, that are transported into the adjacent dune system by the wind transport mechanics. Xbeach is designed to capture storm driven beach and dune erosion on short time scales.

Results obtained with AeoLiS only show the clear absence of bed modulation at the coastline and the beach. Results obtained with XBeach only are limited to short duration events and supply limited as the beach and dune system would be eroded without a recuperation phase. The exemplary run for 2010-2011 shows that the concept is working and can be extended to include longer time series.

The comparison with federal model data obtained from the EasyGSH data base details that the overall patterns obtained with the XBAeoLink approach match. However, the XBAeoLink results show more pronounced details around the foredune within the domain. This is attributed to the fact that the EasyGSH model approach does not entail specific aeolian transport mechanisms but focuses on hydro-morphodynamic impacts through wind and tidal wave impacts. The XBAeoLink approach represents a promising concept and is further investigated to investigate system-sensitivities through parameter studies and grid convergence studies investigating the impact of different spatial resolutions on the results.

For the Portuguese demonstrator, a preliminary implementation of a coupled Delft3D-XBeach framework was chosen for the simulation of the Douro sandspit under alternating calm and storm conditions. Combining the strengths of Delft3D in representing longer term conditions mainly related to the growth of the sand spit and XBeach in representing short episodes of eroding storms, the framework provides a process based approach to modelling the sand spit evolution across multiple temporal scales.

Although calibration and parameter optimization are still ongoing, the initial hindcast simulations demonstrate encouraging performance. The coupled framework successfully reproduces the dominant patterns of erosion and accretion observed during the study period, particularly along the exposed seaward margin of the sand spit. Spatial comparisons yielded an overall RMSE of 0.48 m, while profile-based assessments produced Brier Skill Scores ranging from 0.33 to 0.49, indicating fair to good predictive skill. Ongoing calibration, sensitivity analysis, and refinement of the coupling procedures are expected to further improve model performance and robustness.

4. Publication bibliography

Bollmeyer, C.; Keller, J. D.; Ohlwein, C.; Wahl, S.; Crewell, S.; Friederichs, P. et al. (2015): Towards a high-resolution regional reanalysis for the European CORDEX domain. In *Quart J Royal Meteoro Soc* 141 (686), pp. 1–15. DOI: 10.1002/qj.2486.

Feagin, Rusty A.; Innocenti, Rachel A.; Bond, Hailey; Wengrove, Meagan; Huff, Thomas P.; Lomonaco, Pedro et al. (2023): Does vegetation accelerate coastal dune erosion during extreme events? In *Science advances* 9 (24), eadg7135. DOI: 10.1126/sciadv.adg7135.

Kosmalla, Viktoria; Lojek, Oliver; Ahrenbeck, Lukas; Mehrtens, Björn; Schürenkamp, David; Goseberg, Nils (2024): Towards Accurate Modeling Of Aboveground Vegetation In White Dunes: Biomechanics Of Marram Grass (Ammophila Arenaria). In *CoastLab*. DOI: 10.59490/coastlab.2024.798.

Kosmalla, Viktoria; Schönebeck, Jan-Michael; Mehrtens, Björn; Keimer, Kara; Paul, Maike; Lojek, Oliver et al. (2021): Soil-vegetation interactions in coastal landscapes - erosion reduction as ecosystem service in the context of integrated coastal zone management.

Plüß, A. (2020): EasyGSH Abschlussbericht - Erstellung anwendungsorientierter synoptischer Referenzdaten zur Geomorphologie, Sedimentologie und Hydrodynamik in der Deutschen Bucht (EasyGSH-DB). Edited by Bundesanstalt für Wasserbau (BAW).

Ramos, V.; Giannini, G.; Calheiros-Cabral, T.; Rosa-Santos, P.; Taveira-Pinto, F. (2022): An Integrated Approach to Assessing the Wave Potential for the Energy Supply of Ports: A Case Study. Journal of Marine Science and Engineering, 10(12). https://doi.org/10.3390/jmse10121989

Sievers, Julian; Malte, Rubel; Milbradt, Peter (2020): EasyGSH-DB: Bathymetrie (1996-2016). With assistance of Smile Consult GmbH.

SNIRH. (n.d.). Sistema Nacional de Informação de Recursos Hídricos—SNIRH. Retrieved 27 July 2026, from https://snirh.apambiente.pt/index.php?idMain=

van Geer, P.; den Bieman, J.; Hoonhout, B.; Boers, M. (2015): Deltares Technical Report 1209436-002-HYE-0001. XBeach 1D Probabilistic Model, focusing on the ADIS module, configuration Settings, model uncertainties, and its Graphical User Interface (GUI) designed for dune safety assessments. 1st ed. Deltares. Delft, Netherlands.