Flanders
State of
the Art

21_014_3
FH reports

Monitoring of the dune for dike pilots

Evolution after 3 years

DEPARTMENT
**MOBILITY &
PUBLIC
WORKS**

www.flandershydraulics.be

Monitoring of the dune for dike pilots

Evolution after 3 years

Montreuil, A-L.; Dan, S.; Houthuys, R.; Verwaest, T.

Flanders Hydraulics
Flanders
State of the Art

Legal notice

Flanders Hydraulics is of the opinion that the information and positions in this report are substantiated by the available data and knowledge at the time of writing.
The positions taken in this report are those of Flanders Hydraulics and do not reflect necessarily the opinion of the Government of Flanders or any of its institutions.
Flanders Hydraulics nor any person or company acting on behalf of Flanders Hydraulics is responsible for any loss or damage arising from the use of the information in this report.

Copyright and citation

D/2025/3241/015

This publication should be cited as follows:

Montreuil, A-L.; Dan, S.; Houthuys, R.; Verwaest, T. (2025). Monitoring of the dune for dike pilots: Evolution after 3 years. Version 4.0. FH Reports, 21_014_3. Flanders Hydraulics: Antwerp

Document identification

Customer:	MDK Coastal Division	Ref.:	WL2025R21_014_3
Keywords (3-5):	Dune, morphodynamics, marram grass		
Knowledge domains:	erosion protection coast > dunes > in situ measurements		
Text (p.):	56	Appendices (p.):	/
Confidential:	☒ No	☒ Available online	

Author(s):	Montreuil, A.-L.

Control

	Name	Signature(s)
Reviser(s):	Dan, S. Houthuys, R.	Getekend door:Sebastian Dan (Signature) Getekend op:2025-03-14 09:23:23 +01:00 Reden:Ik keur dit document goed Dan Sebastian Vlaamse overheid Getekend door:Rik Houthuys (Signature) Getekend op:2025-03-14 16:32:34 +01:00 Reden:Ik keur dit document goed Houthuys Rik Vlaamse overheid
Project leader:	Verwaest, T.	Getekend door:Verwaest Toon Getekend op:2025-03-21 13:39:30 +01:0 Reden:Ik keur dit document goed Verwaest Toon Vlaamse overheid

Approval

Head of Division:	Bellafkih, K.	Getekend door:Abdelkarim Bellafkih (Sign Getekend op:2025-03-14 10:05:16 +01:0 Reden:Ik keur dit document goed Bellafkih Abdelkarim Vlaamse overheid

Abstract

At the beginning of 2021, the MDK Coastal Division, and the municipalities of Ostend and Middelkerke built up dunes on the dry beach in front of a sea wall at four locations: Spinoladijk and Raversijde (Ostend), Westende (Middelkerke) and Knokke. Intensive monitoring at these Nature-based-Solution (NbS) sites was carried out from the beginning of 2021 (except in Knokke from 12/2023) to 04/2024 to investigate the development of the built dunes and to follow closely their morphology and planted vegetation. This report documents the evolution of the morphology of the dune for dike pilots until the 3rd year after construction. A progressive evolution of the four pilot sites occurred over the entire monitoring period. A substantial accretion took place in the 1st year in the zones where marram grass and/or brushwood fences were installed. These allowed to capture effectively the aeolian sand transport. Since the 2nd monitoring year , there has been a reduction in sand trapping, which could be related to the saturation of the vegetated boxes as well as a difference of wind conditions over the monitoring periods. At Raversijde, this reduction could be further caused by a diminished sand availability after the nourishment in 2021. Further monitoring surveys will help to understand the observed relationships between accretion in the upper part of the dry beach and erosion dominating its lower part above the low water mark. These would also confirm the temporal behaviour and evolution of the NbS sites.

Contents

List of tables

List of figures

1 Background

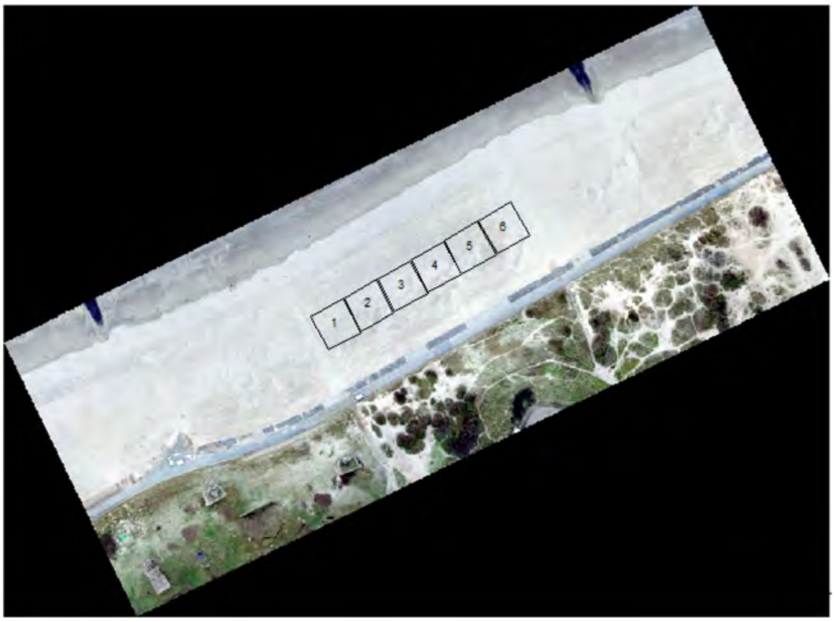
An intensive beach monitoring has been carried out at the NbS sites where dunes were built-up using brushwood fences, fences and/or marram grass was planted to capture aeolian sand transport and prevent blown sand on the seawall and further inland into infrastructures. Another objective is to increase the ecosystem value of the sites and the coastal safety for Westende site. This report presents the morphological changes and evolution since the beginning of the monitoring of each site with a focus on the 3rd monitoring year (except in Knokke). Verwaest et al. (2022) and Montreuil et al. (2023) investigated the morphodynamics of these NbS sites over the 1st and 2nd monitoring year respectively.

1.1 Spinoladijk

A small 120 m long and 20 m wide zone of marram grass was planted on the dry beach in section 120 (near Fort Napoleon in Ostend) in January-February 2021. The marram planting was performed in 6 plots of 20 m x 20 m in the center of the section and at a distance of 20-25 m from the dike. For a more detailed description of the setting, refer to Verwaest et al. (2022).

When the dunes were built up at the start of the project, the dry beach in this section was 50 to 60 m wide (measured from the + 6 m TAW line to the sea dike). The elevation of the planted zone ranged then from 6.5 to 8 m TAW (Figure 1).

A)



B)

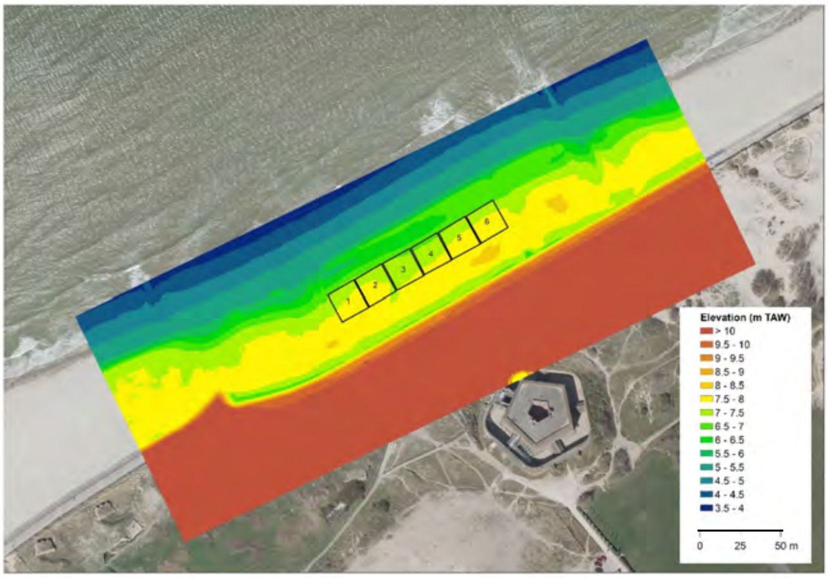


Figure 1 – A) orthophoto, B) digital elevation model on T0 (11/01/2021).

1.2 Raversijde

The pilot site at Raversijde is about 750 m long and 20 m wide and is located in sections 100 to 102. After a beach nourishment in January-February 2021, brushwood fences and marram grass were placed on the dry beach in March and April 2021 (Figure 2). For further description of the setting of brushwood and vegetation planting as well as the nourishment refer to Verwaest et al. (2022).
After the construction of the new dune, the width of the dry beach was 65 to 85 m wide (measured from the + 6 m TAW line to the sea dike). For the placement of the brushwood fences and marram grass plants, the beach was artificially profiled with a berm at level +7.5 m TAW. Then, two years later in February 2023, additional marram grass was planted due to the sand burial of the previous plants.

A)

B)

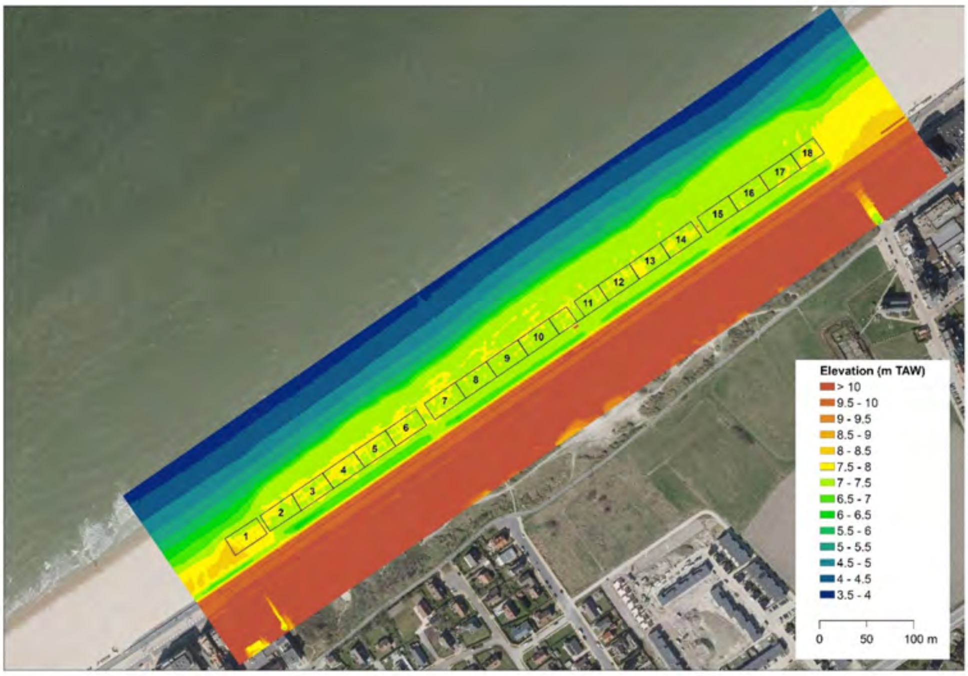


Figure 2 – A) Orthophoto, B) digital elevation model onT0 (31/03/2021) at Raversijde

1.3 Westende

A first phase of a grass dike was planted in Westende (section 74-75) as part of the sea defense project in Middelkerke (Coastal Safety Master Plan) in January-February 2021. The site is 30 m wide and 390 m long (Figure 3) where sand fences and the applied vegetation was marram grass. When this vegetation was planted, the dry beach was approximately 75 m wide (measured from the + 6 m TAW line to the sea dike). The height of the vegetated dune site is approximately equal to the elevation of the sea dike.

A)

B)

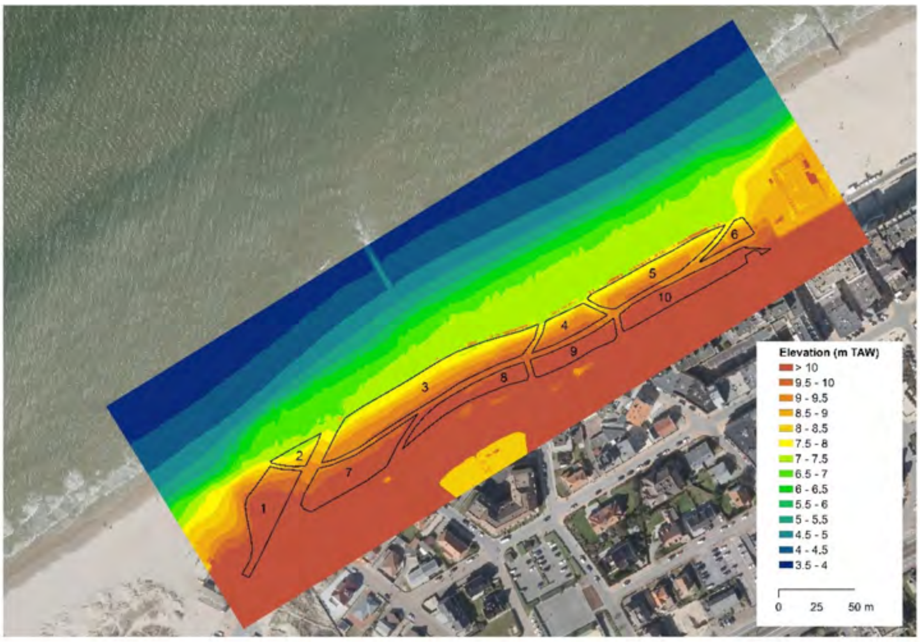


Figure 3 – A) digital elevation model B) orthophoto on T0 (30/03/2021) at Westende.

1.4 Knokke

Wooden poles were installed on 16/10/2023 to demarcate the site in section 233 (Figure 4). This is divided into 2 zones of 90 m by 30 m each with a passage between them. This passage is necessary because otherwise beach cabin users would have to walk around the entire test zone to reach the sea. Then, marram grass was planted on 4 and 15/12/2023 with a variable density of plants. Also, there was no plantation for the last 2 to 3 m on the seaside (Figure 5). Before the NbS deployment, a large beach nourishment was carried out there in February to April 2023.

A)

B)

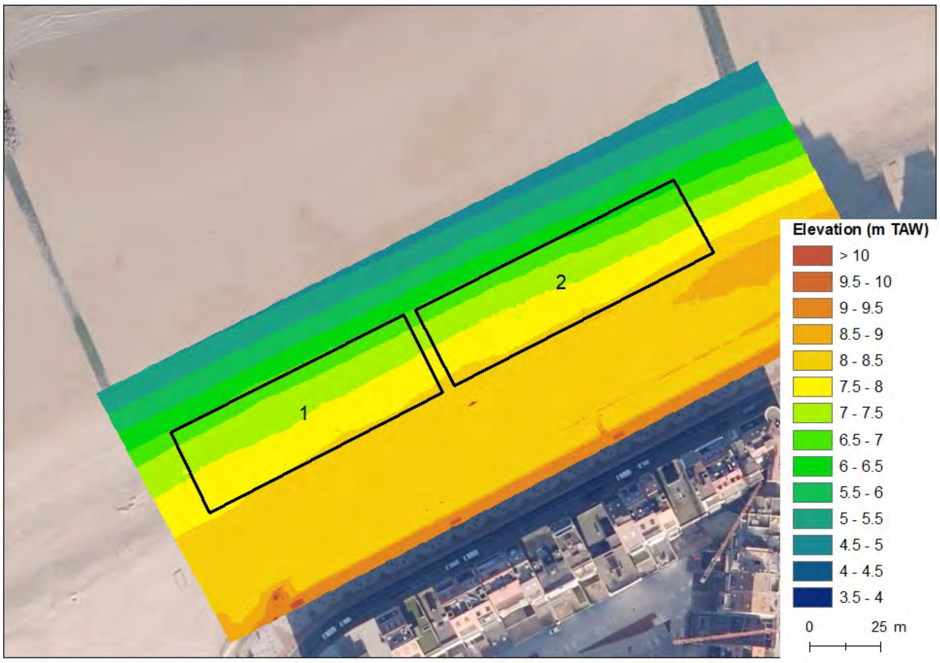


Figure 4 – A) orthophoto, B) digital elevation model on T0 (6/12/2023).

Figure 5 – Ground photograph of the plantation in 12/2023

1.5 Human interferences

1.5.1. Spinoladijk

The surveys and profiles show there are sand bulldozing activities carried out during the monitoring period. However, data on the nature, volume and reason of the activities are at present lacking. The city of Ostend was contacted to inform about this.

1.5.2. Raversijde

In January-February 2021, a large nourishment involving the supply of 498,630 m³ of sea sand was carried out in sections 97 to 105 in Raversijde to Mariakerke. This nourishment preceded the dune plantation pilot in sections 100 to 102. Since then, no nourishment was done at this location.

Excavation works are carried out at Raversijde in the strip between the planted dune and the seawall to prevent aeolian sand transport towards the seawall and further inland (Table 1, Figure 6). This is done by Ostend city near the NbS site and also west and east of it. Along the seawall, the city at times digs a trench along the seawall in order to prevent aeolian sand transport inland. Furthermore, when needed, sand accumulation is removed from the adjacent promenade and tram line. The sand is always brought back to the high waterline by trucks. Such human intervention seaward of the vegetation boxes created a higher plateau at around 6 m TAW as was observed on the UAV orthophoto on 16/2/2024 and also on the field on 14/3/2024.

Table 1 – Description of the human interventions (provided by Ostend city) in Raversijde.

	NbS Raversijde	West zone	East zone	Trench in front of the seawall
4/12/2023- 08/12/2023	x	x	x	
03/01/2024- 05/01/2024	x	x	x	
15/01/2024- 19/01/2024	x	x	x	x
22/01/2024- 26/01/2024	x	x	x	x
29/01/2024- 02/02/2024	x	x	x	x
05/02/2024- 09/02/2024	x	x	x	x
12/02/2024- 16/02/2024	x	x	x	x

A)

B)

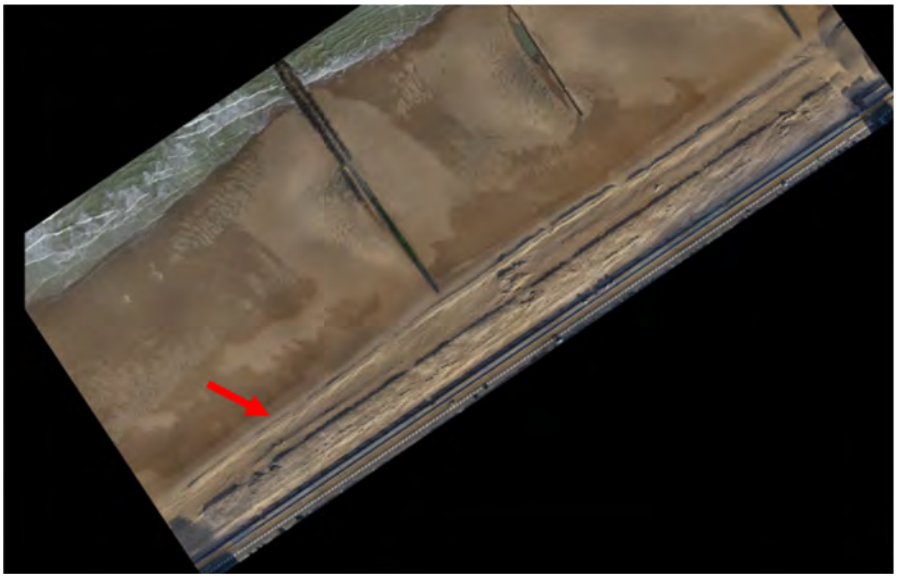


Figure 6 – A) work excavation along the seawall, B) presence of an artifical plateau in Raversijde

1.5.3. Westende

Sand fences are placed in Westende in winter. The city of Middelkerke responsible of the Nature Based Solution was contacted to inform about carried out work. Unfortunately, we did not receive any answer.

1.5.4. Knokke

No human interference is reported on the beach while a large shoreface nourishment was carried out between October 2023 and February 2024. The delivered sand was extracted from the new lock construction site in Terneuzen. Approximately 2.6 million m^3 of sand has been added in Knokke-Heist. More specifically, 1.2 million m^3 was deployed in section 231-244 from October to February 2024. This sand consists of medium to fine grain size with a median of 150 µm as a lower limit (Boerema et al., 2023).

As every year, cabins were deployed in April 2024 for the summer season. They are located between the seawall and the vegetation boxes (Figure 7).

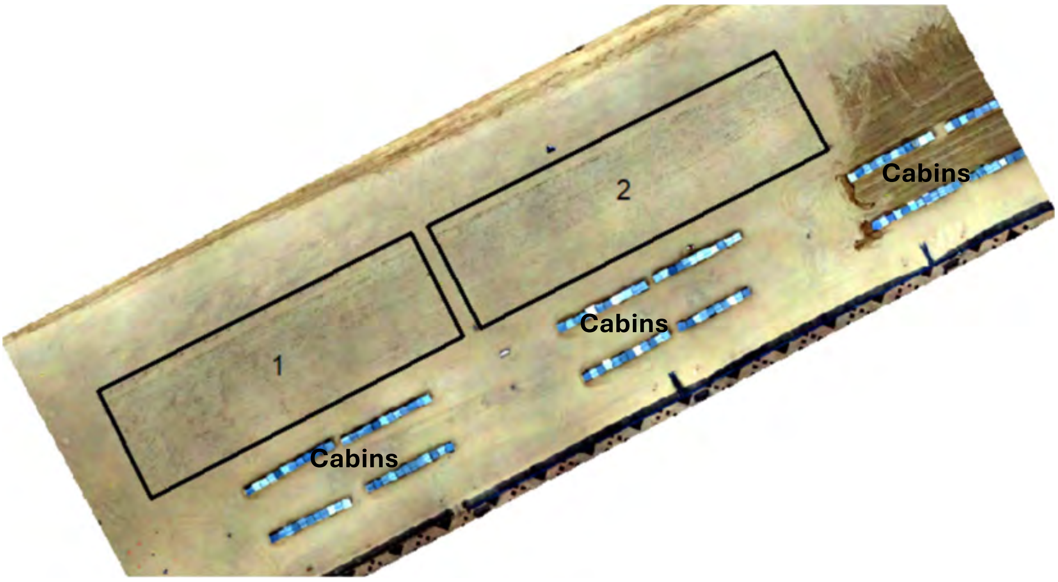


Figure 7 – Summer cabins observed on the UAV orthophoto on 24/5/2024

2 Monitoring method

The monitoring focussed on the morphological evolution of the pilot sites and it was based on the following type of measurements: UAV (Unmanned Aerial Vehicle – UAV) data acquisition and UAV and RTK-GPS beach profiles at Spinoladijk, Raversijde and Knokke. For Westende, the coast-wide LiDAR surveys acquired routinely by MDK Coastal Division were used to monitor the morphological changes.

2.1 Acquisition of UAV surveys

Topographic monitoring was monthly performed with a Phantom 4 RTK UAV by NeXperta-ATO (see Table 2 to Table 5). The flights were typically carried out at a height of 90 m. The survey coverage is about 295 m long and 110 m wide from the dike down to 3.8 m TAW at Spinoladijk (Figure 8). For Raversijde, it was about 845 m long and 165 m wide between the dike and 3.6 m TAW (Figure 9). From 12/09/2022 (T14) on, the survey coverage was extended seaward to the low water line (around 0.7 m TAW) except for 14/03/2024 (survey T27). Thus, the width of survey was extended to 390 m after T14. The survey at Westende covered the area from the sea dike down to 4.5 m TAW and a length of 490 m (Figure 10). For the Knokke site, the coverage is from the seawall to 4 m TAW (Figure 11) and a length of 250 m.

Accuracy is reported to be +/- 5 cm (Verwaest, 2021; Verwaest et al., 2022). The influence of the weather conditions on the UAV survey is described in Verwaest et al. (2022).

Table 2 – Timeline of the surveys at Spinoladijk with UAV error based on check points installed on the field during the survey. The bold boxes correspond to the 3rd monitoring period.

Site	Time	Day	Duration since T0 (m: month)	UAV Z error (cm)	Measurement
Spinoladijk	T0	11/01/2021		1	UAV
	T1	23/02/2021	1.4m	1.1	UAV+hand RTK-GPS profiles
	T1bis	02/03/2021	1.6m	1.7	UAV
	T2	19/03/2021	2.3m	0.7	UAV+hand RTK-GPS profiles
	T3	30/04/2021	3.6m	0.5	UAV+hand RTK-GPS profiles
	T4	28/05/2021	4.5m	0.5	UAV+hand RTK-GPS profiles
	T5	28/06/2021	5.5m	0.4	UAV+hand RTK-GPS profiles
	T6	09/09/2021	8m	0.8	UAV+hand RTK-GPS profiles
	T7	26/10/2021	9.5m	0.6	UAV+hand RTK-GPS profiles
	T8	23/11/2021	10.4m	0.4	UAV+hand RTK-GPS profiles
	T9	07/12/2021	10.9m	0.5	UAV
	T10	17/01/2022	1 y	1	UAV+hand RTK-GPS profiles
	T11	11/02/2022	1 y 1m	0.7	UAV+hand RTK-GPS profiles

	T12	23/02/2022	1y 1.4m	1.7	UAV+hand RTK-GPS profiles
	T13	08/03/2022	1y 1.8m	0.7	UAV+hand RTK-GPS profiles
	T14	23/03/2022	1y 2.4m	1.1	UAV
	T15	19/04/2022	1y 3.3m	1.1	UAV+hand RTK-GPS profiles
	T16	02/05/2022	1y 3.7m	0.9	UAV+hand RTK-GPS profiles
	T17	02/06/2022	1y 4.7m	0.7	UAV+hand RTK-GPS profiles
	T18	12/09/2022	1y 8m	0.7	UAV
	T19	12/10/2022	1y 9m	1.6	UAV
	T20	24/01/2023	2y	0.6	UAV+hand RTK-GPS profiles
	T21	09/02/2023	2y 1m	0.9	UAV+hand RTK-GPS profiles
	T22	29/03/2023	2y 2.6m	0.6	UAV
	T23	08/05/2023	2y4m	0.7	UAV+hand RTK-GPS profiles
	T24	21/06/2023	2y5.3m	0.4	UAV
	T25	14/09/2023	2y8m	0.5	UAV+hand RTK-GPS profiles
	T26	04/10/2023	2y8.8m	1.2	UAV+hand RTK-GPS profiles
	T27	06/12/2023	2y10.8m	1.1	UAV
	T28	27/02/2024	3y1.5m	1	UAV
	T29	23/04/2024	3y3.4m	1	UAV

Table 3 – Timeline of the surveys in Raversijde with UAV error based on check points installed on the field during the survey. The bold boxes correspond to the 3rd monitoring period.

Site	Time	Day	Duration since T0	UAV Z error (cm)	Measurement
Raversijde	T0	31/03/2021		1	UAV+hand RTK-GPS profiles
	T1	28/04/2021	1m	1	UAV+hand RTK-GPS profiles
	T2	27/05/2021	1.9m	1.4	UAV+hand RTK-GPS profiles
	T3	25/06/2021	2.8m	1	UAV+hand RTK-GPS profiles
	T4	08/09/2021	5.3m	1	UAV+hand RTK-GPS profiles
	T5	22/11/2021	7.7m	0.9	UAV+hand RTK-GPS profiles+Quad RTK-GPS profiles
	T6	07/12/2021	8.2m	1.1	UAV
	T7	06/01/2022	9.2m	1.1	UAV+ RTK-GPS Quad profiles
	T8	11/02/2022	10.4m	0.8	UAV+hand RTK-GPS profiles
	T9	23/02/2022	10.8m	1.1	UAV+ RTK-GPS Quad profiles
	T10	21/03/2022	11.7m	0.7	UAV+hand RTK-GPS profiles
	T11	19/04/2022	1y 0.6m	0.7	UAV

	T12	02/05/2022	1y 1m	1	UAV
	T13	01/06/2022	1y 2m	1.1	UAV
	T14	12/09/2022	1y 5.4m	2	UAV+hand RTK-GPS profiles
	T15	12/10/2022	1y 6.4m	1.3	UAV
	T16	24/01/2023	1y 9.8m	1.1	UAV+hand RTK-GPS profiles
	T17	09/02/2023	1y 10.3m	1.2	UAV+hand RTK-GPS profiles
	T18	09/03/2023	1y 11.3m	1.3	UAV+hand RTK-GPS profiles
	T19	29/03/2023	1y12m	1.2	UAV+hand RTK-GPS profiles
	T20	08/05/2023	2y1.3m	1.4	UAV+hand RTK-GPS profiles
	T21	21/06/2023	2y2.7m	1.5	UAV+hand RTK-GPS profiles
	T22	14/09/2023	2y5.5m	1.3	UAV+hand RTK-GPS profiles
	T23	04/10/2023	2y6m	1.7	UAV
	T24	22/11/2023	2y7.7m	1.3	UAV
	T25	06/12/2023	2y8.2m	1.1	UAV
	T26	27/02/2024	2y11m	1.5	UAV
	T27	14/03/2024	2.11.5m	1	UAV
	T28	23/04/2024	3.y0.8m	1.1	UAV

Table 4 – Timeline of the surveys in Westende with UAV error based on check points installed on the field during the survey. The bold boxes correspond to the 3rd monitoring period.

Site	Time	Day	Duration (ref T0)	UAV Z error (cm)	Measurement
Westende	T0	30/03/2021		0.3	UAV
	T1	30/04/2021	1m	0.3	UAV
	T2	31/05/2021	2m	0.3	UAV
	T3	28/06/2021	4m	0.3	UAV
	T4	23/11/2021	7.8m	0.2	UAV
	T5	23/02/2022	10.8m	3	LiDAR
	T6	17/04/2022	12.6m	1	LiDAR
	T7	08/02/2023	1y 10.3m	3	LiDAR
	T8	17/06/2023	2y2.5m	1.4	LiDAR
	T9	17/01/2024	2y9.6m	1	LiDAR

Table 5 – Timeline of the surveys in Knokke with UAV error based on check points installed on the field during the survey.

	Time	Day	Duration since T0	Accuracy (cm)	Measurement
Knokke	T0	06/12/2023		1.1	UAV
	T1	17/01/2024	1.4m	1	LiDAR
	T2	24/05/2024	5.6m	1	UAV

Figure 8 – UAV coverage and profiles location at Spinoladijk

Figure 9 – UAV coverage and profiles location at Raversijde

Figure 10 – UAV coverage and profiles location at Westende

Figure 11 – UAV coverage and profiles location at Knokke

UAV surveys are processed with Agisoft software to generate a digital elevation model (DEM) and an orthophoto with a pixel resolution of 5 and 2.5 cm respectively. This processing procedure took into account the individual reliability of each point of the point cloud. The points with low confidence were not included in the construction of the DEMs. Therefor interpolation was used to fill up the holes caused by the point filtering. Post-processing consisted in generating a DEM of difference (DoD) between the consecutive surveys and taking a fixed reference (T0). The cell size of the DEMs and DoDs is 2 m.

In Westende, UAV surveying was stopped after T4 due to issues with getting a flight permit. Since then, the LiDAR surveys acquired by MDK Coastal Division are used there to assess the morphological evolution.

2.2 Beach profiles - processing and accuracy

In addition to aerial measurements, field topographic measurements with RTK-GPS were carried out along 3 profiles at Spinoladijk (Figure 8), Westende (Figure 10), Knokke (Figure 11) as well as 6 profiles at Raversijde (Figure 6). Generally, the survey profiles extend from the seaward side of the vegetated boxes to the low water line (Table 1 and Figure 3) over a length of ca. 250 m. The distance from the first RTK-GPS survey points (i.e. the most inland measurement) to the dike is approximately 40 m. The interval between profiles is from 110 to 215 m.

Since the measurements are not always located along a straight line, they have been re-projected on planned profiles in ArcGIS using the Linear Referencing tool. Then, they were interpolated using a sampling distance of 1 m. This allows easier comparison of the profiles over time. Finally, the upper-beach was extracted along the profiles from the UAV survey and then it was merged with the reprojected RTK-GPS profiles in order to cover the entire beach. A comparison between RTK-GPS and extracted UAV profiles was carried out indicating a small difference of 0.04 m (Montreuil et al., 2022). Thus, it was decided to stop handheld RTK-GPS profiling after summer 2023. Since then profiles are extracted from UAV data for all the pilot sites.

3 Morphological analysis

3.1 Spinoladijk

The pilot site at Spinoladijk was surveyed from 1/2021 to 04/2024 and the third monitoring period started from 02/2023 (Table 2).

3.1.1 Meteo-marine conditions

3.1.1.1. Spinoladijk

Figure 12 shows time series of water level in Ostend, 10% wave height and wave direction in ‘Ostend Poortjes’ (located 7 km from the coast), wind speed and direction of the weather station in Zeebrugge for the period January 2021 to April 2024. Over the third monitoring period, the water level exceeded 5.5 m TAW four times, namely on 24/11/2023, 21/12/2023, 15/01/2024, and 08/04/2024.

The most severe storm event occurred on 21/12/2023, the water level reached 5.62 m TAW with a surge of 1.36 m, the 10% wave height was approximately 4.1 m coming from WNW, perpendicular to the shoreline, and the wind speed at 10 m was about 13 m/s. While the water level did not reach the threshold of a ‘dangerous coast storm’ of 5.60 m TAW (5.57 m TAW and a surge of 0.97 m) on 24/11/2023, high significant waves of 5.62 m coming from NW were recorded. The two events in 2024 were characterized by a lower magnitude of energy when the water level only reached 5.52 m TAW.

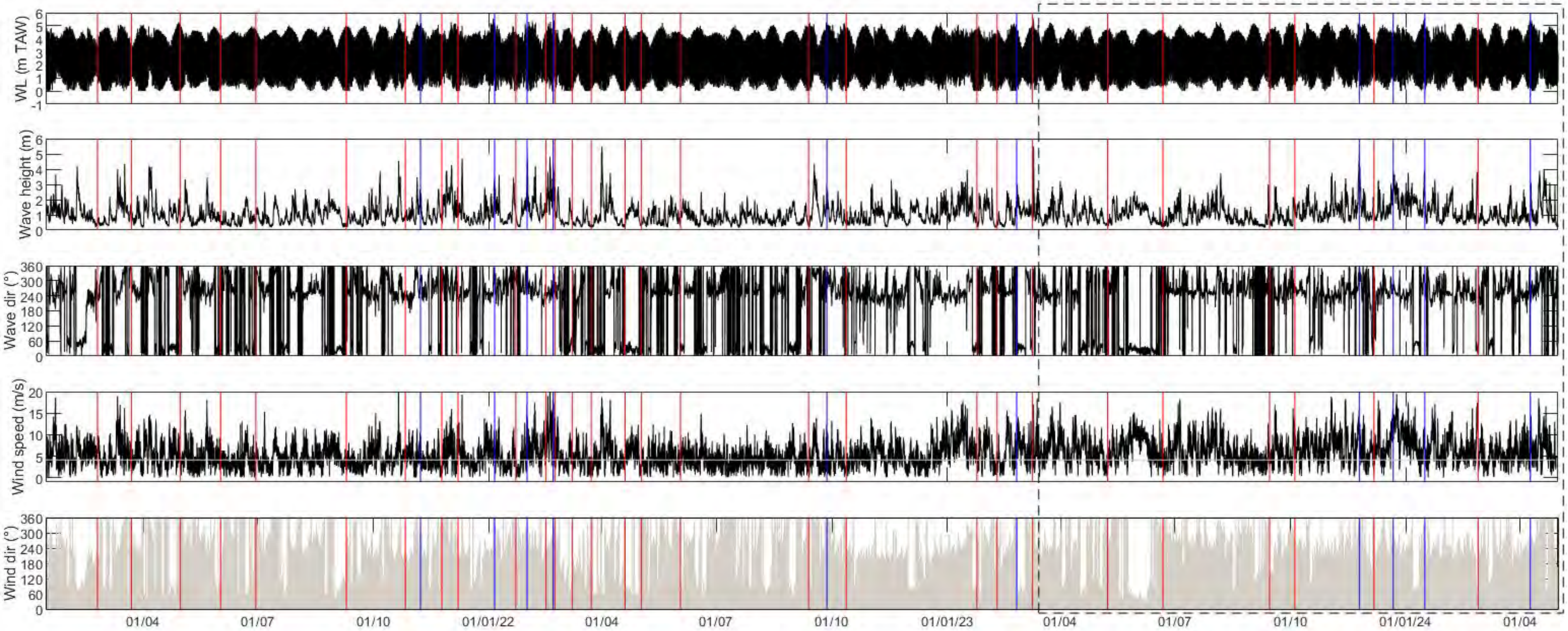


Figure 12 – Time series of the water level in Ostend, 10% wave height and wave direction in Ostend “Poortjes” (buoy located 7 km from the coast), wind speed and direction of weather station Zeebrugge at 10 m high (Meetnet Vlaamse Banken). Vertical red and blue lines correspond to the UAV surveys and energetic events respectively. Horizontal grey line on the wind speed time series is the critical wind speed for aeolian sand transport (7 m/s). The dashed box corresponds to the 3rd year monitoring.

3.1.2 Morphological evolution on the months to 3 years scale

Figure 13 presents the morphological evolution of the entire beach from months to years (refer to Figure 2BB for the elevation across the beach). Note the detailed elevation difference scale. The DoDs clearly indicate the gradual accretion in the vegetated boxes across Box 1 to 6 from 5.5 months to 3 years.

The boxes gradually gained sand material nearly up to 3 m high at the last survey (Figure 13F). The upper part of the dry beach located landward of the boxes shows a large sand accumulation up to 1.6 m high at Boxes 1, 2 and 6. However, this accretion contrasts with the erosion (-0.7 m) of the zone landward from Box 3 to Box 5.

Apart from that, significant negative morphological changes (>- 1 m) occurred on the dry beach located on both sides of the vegetation boxes (e.g. Figure 13B). These are likely due to the surrounding excavation works that were carried out several times by the city of Ostend in this zone as presented in section 1.5. This was also observed on the UAV orthophotos with the presence of truck tires tracks. The lower part of the dry beach (below 6 m TAW), east and in front of the boxes indicates erosion up to -1 m. This could be either natural or due to the interference with the maintenance activities of the city of Ostend. Between the erosion strip and the accreting dunes and the upper part of the beach at 7.5 to 7.7 m TAW there is a line of no morphological change in average of 1 m wide where the changes are below +/- 0.05 m. This ‘no change line’ is relatively stable throughout the entire monitoring period.

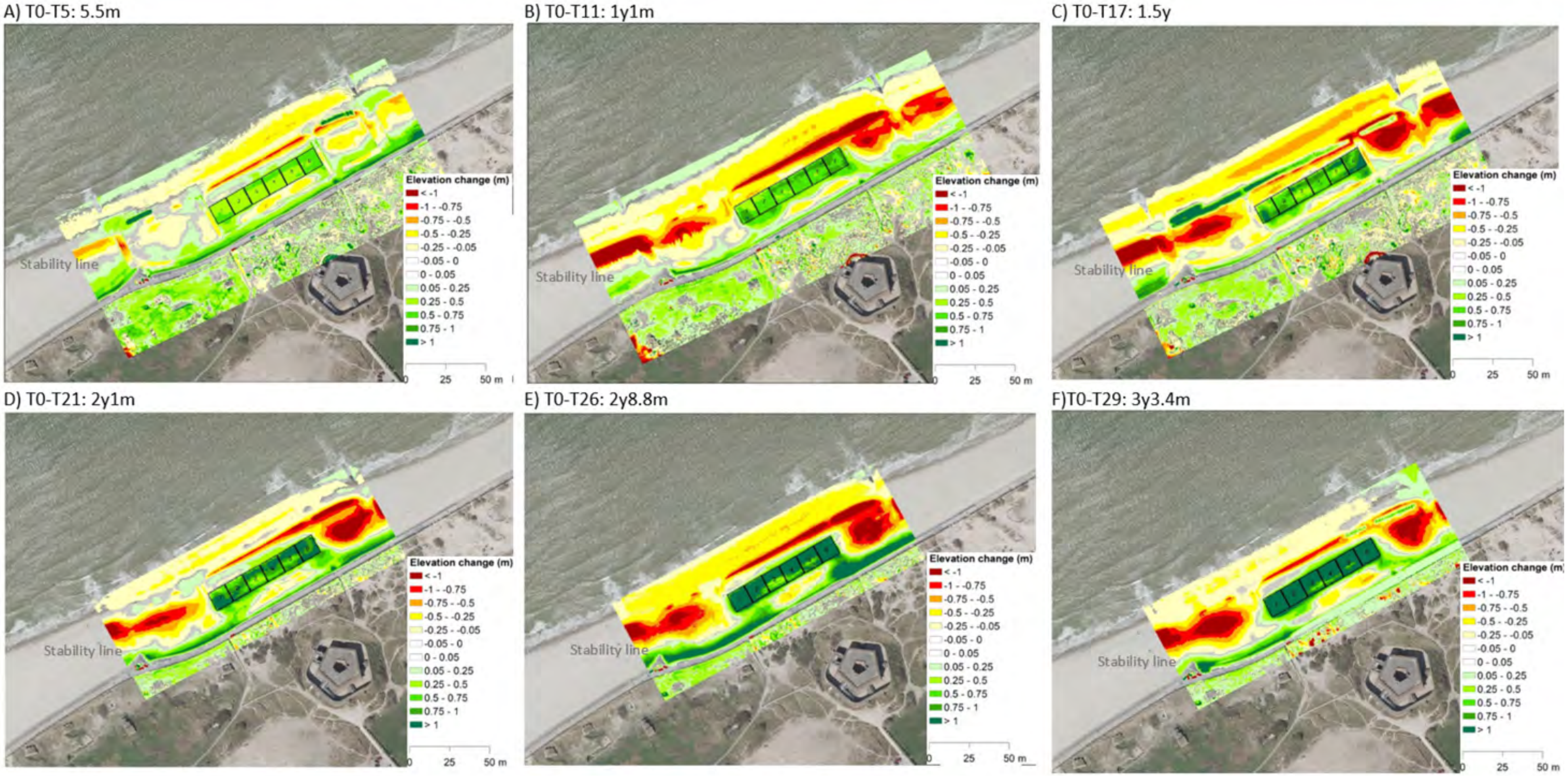
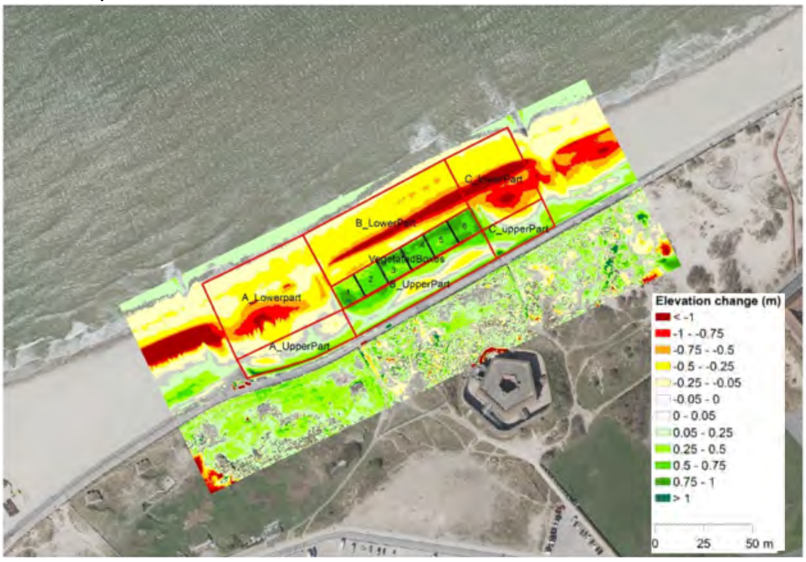


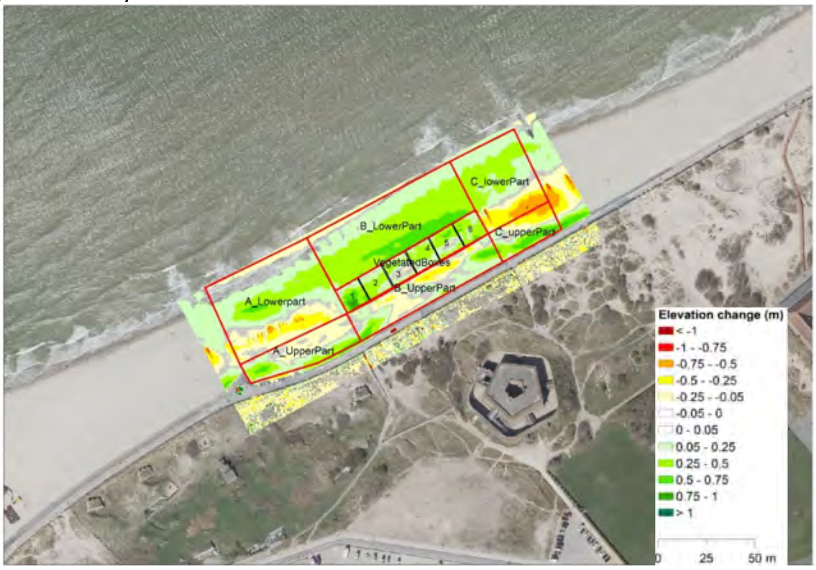
Figure 13 – Global evolution based on Ref DoDs of the UAV surveys at Spinoladijk.

It is clear that the vegetated boxes were subject to more accretion over the 1st monitoring year (T0-T11) than the 2nd one (T11-T21) with a maximum elevation of 1.05 m and 0.9 m respectively (Figure 14). Taking into account that the 3rd year monitoring lasted 3 months longer, accretion in the vegetation boxes was disproportionately larger (1.6 m) than during the previous 2 monitoring years. This was probably related to the more efficient wind regime with oblique onshore wind above 7m/s (i.e. threshold of aeolian sand transport). Slight erosion occurred in the 3rd year on the lower dry beach and seaward of the boxes between 5 and 6 m TAW (except on the east side lower beach: C_lower part). Strong erosion occurred in this area in the 1st year but not in the 2nd year. During the 3rd monitoring period, a gradual decrease in accretion intensity in the boxes is locally observed from Box 1 to Box 6 (from SW to NE) (Figure 14C). This is a contrast with the previous period when the side boxes (Box 1 and 6) gained more sand than the centre ones. This might be related to the dominant oblique wind directions. The boxes at the sides are catching alongshore aeolian sand transport. A common morphological pattern of the 2nd (T11-T21) and 3rd (T21-T29) monitoring year is that the upper-beach area located landward of the boxes was eroding with a line of morphological stability at 7.5 to 7.7 m TAW. This contrasts with the accretion in the first year. This might suggest that sand transport inland was prevented due to higher vegetated dunes after the preceding two years. However trench excavation works by Ostend city cannot be ruled out.

A)T0-T11: 1y1m



B) T11-T21: 1y



C) T21-T29: 1y2.5m

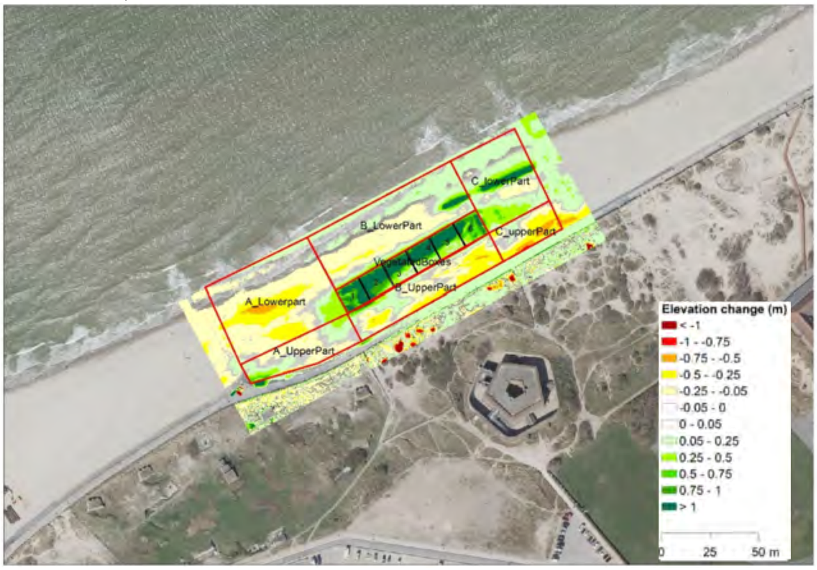
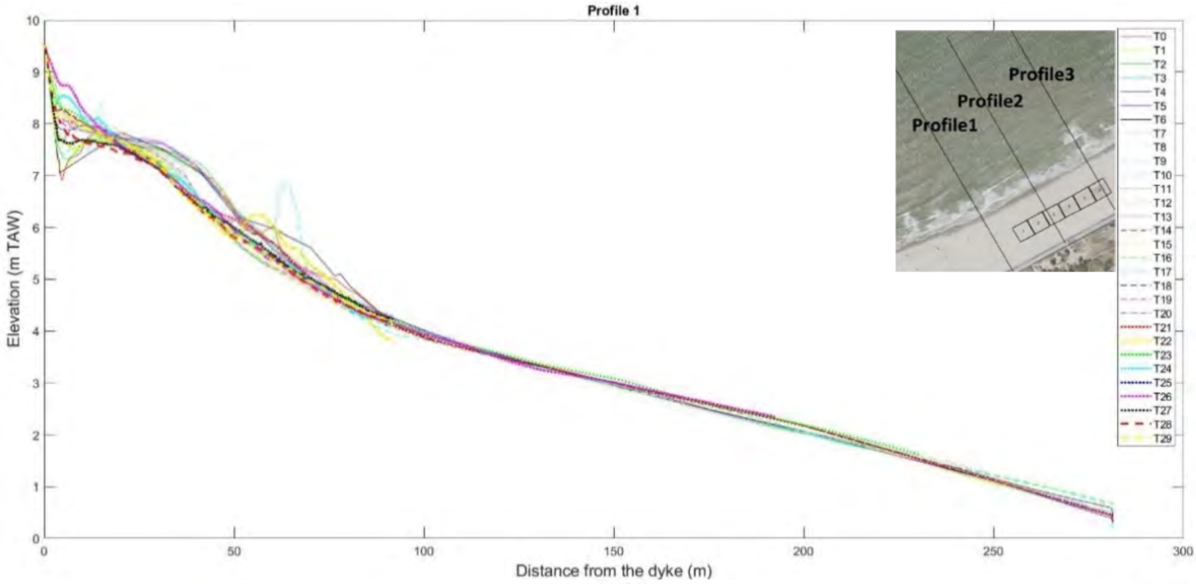
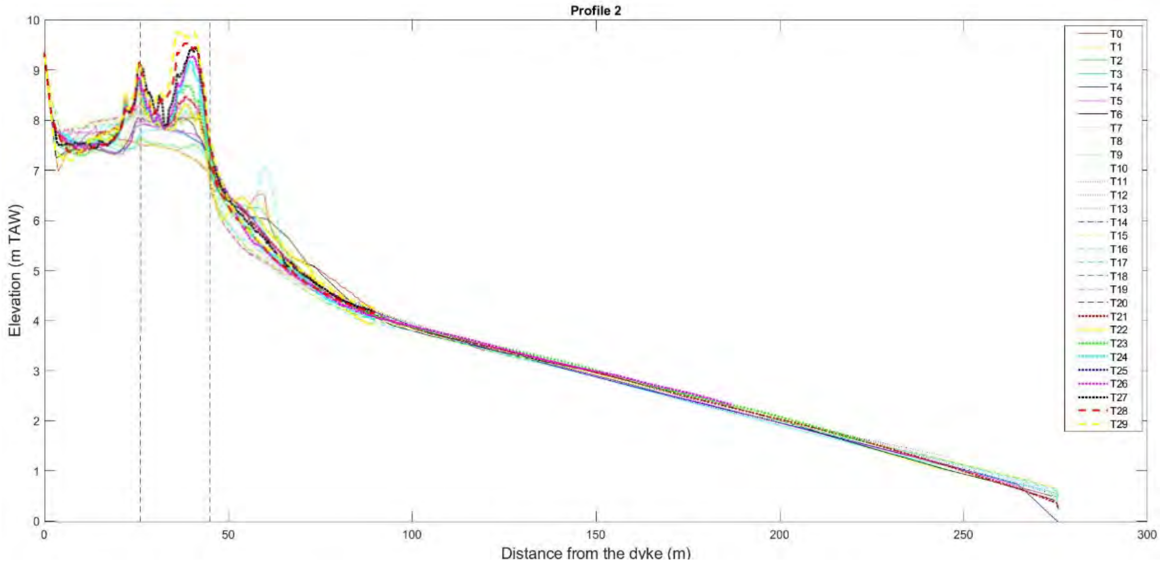


Figure 14 – Annual evolution based on DoDs of the UAV surveys with the locations of the contours of the defined volumetric zones. The UAV survey coverage was smaller in T21 explaining the difference of the DoD size.

Figure 15 displays time series over all surveys of three profiles from the seawall to the low water line. To simplify their visual representations, some selected beach profiles are shown in Figure 16. Profile 1 is located west of the vegetated boxes (i.e. no crossing of any vegetated box) and Profile 2 and 3 intersect Box 3 and 6 respectively. In general, the morphological changes for Profile 1 are limited with a sand loss recorded between T0-T11 but it was then stable for the following periods. Profiles 2 and 3 show a similar pattern with accretion on the upper-beach where the vegetated boxes are located from 20-40 m from the seawall. As already observed on the DoDs in Figure 14, the highest dune crest of 9.7 m TAW m in Profile 2 and Profile 3 is observed in the last survey (T29) when a fast accretion of more than 0.6 m occurred over 6.6 months (T26-T29). Also, a slight erosion dominated along the seaward dry beach slope for the period between T0-T17, and then it was followed by a regain of sand material (T17-T29) characterized by a more gentle slope. In contrast, the intertidal beach was stable (100-260 m from the seawall). Another common trend between Profile 2 and 3 is the bump located at 60 m from the dike on T0 and T17 (Profile 2) and also in T29 (Profile 3) which is likely related to human intervention by dumping material from the removal of sand on the seawall and/or from trench digging in front of it.

A)





B)

C)

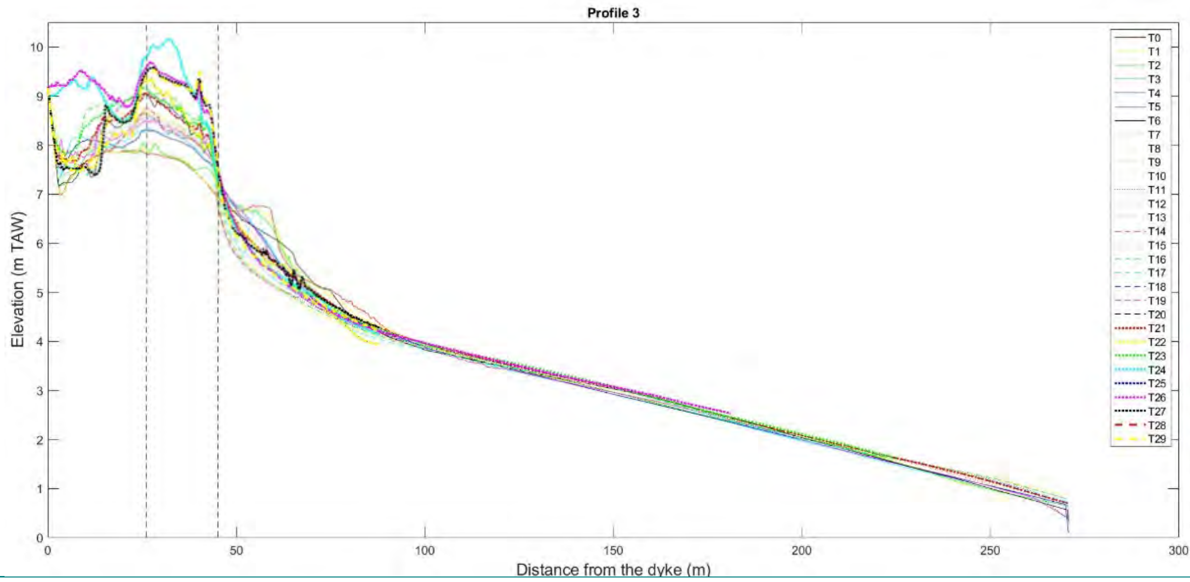
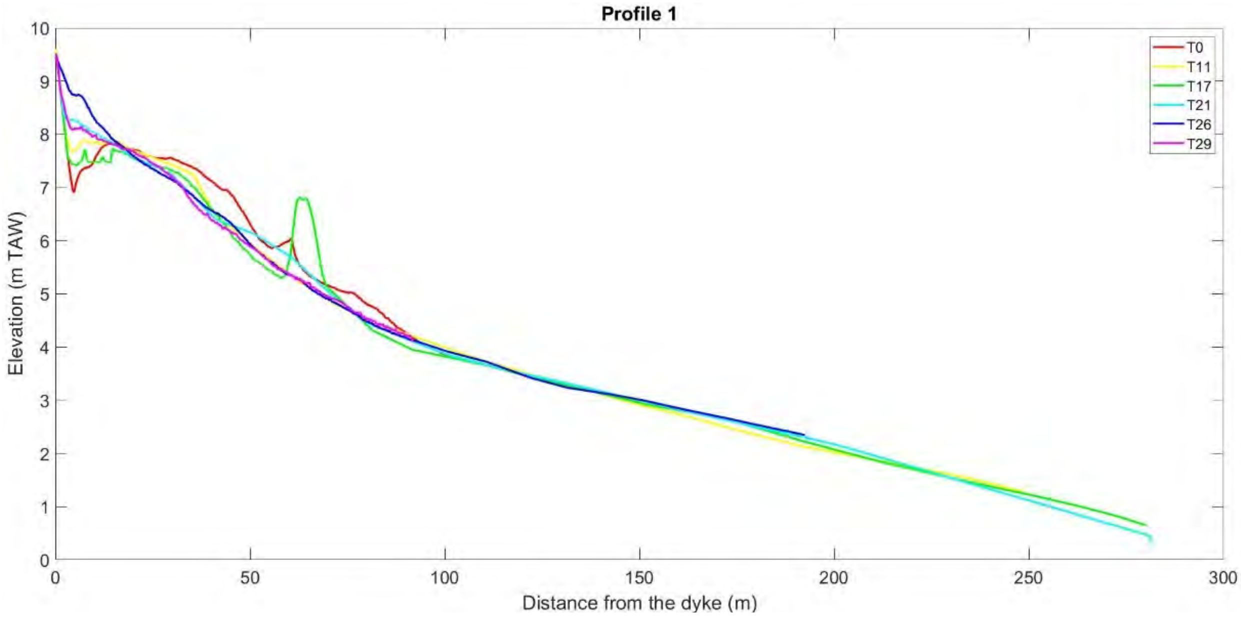
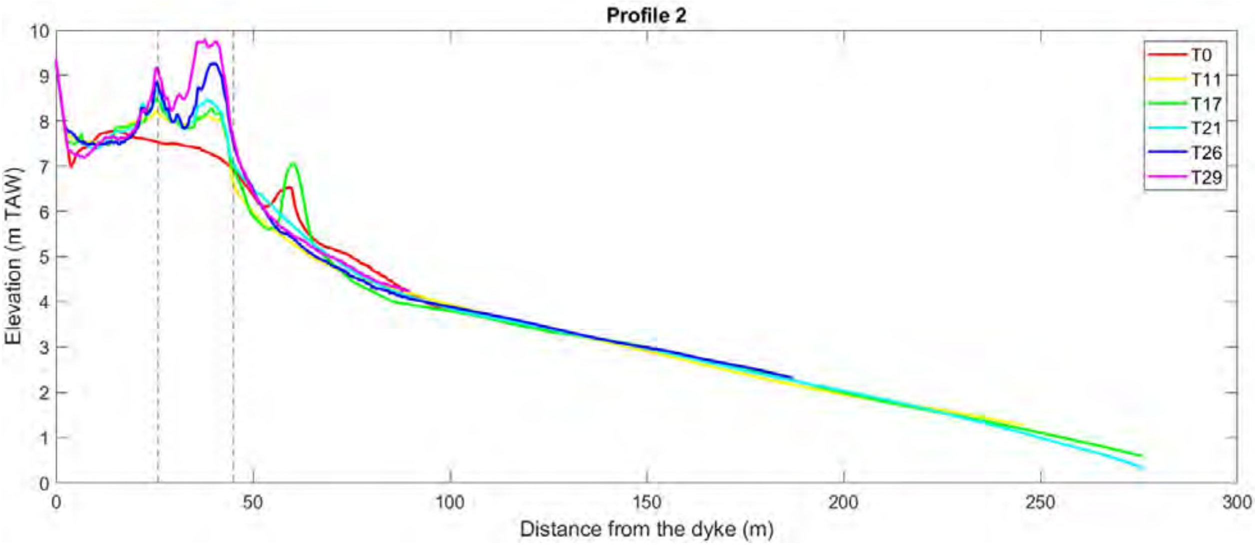


Figure 15 – Time series of all the merged profiles of the UAV and RTK-GPS surveys. The dashed lines correspond to the position of the egetated boxes. Inset indicates the location of the profiles.

A)



B)



C)

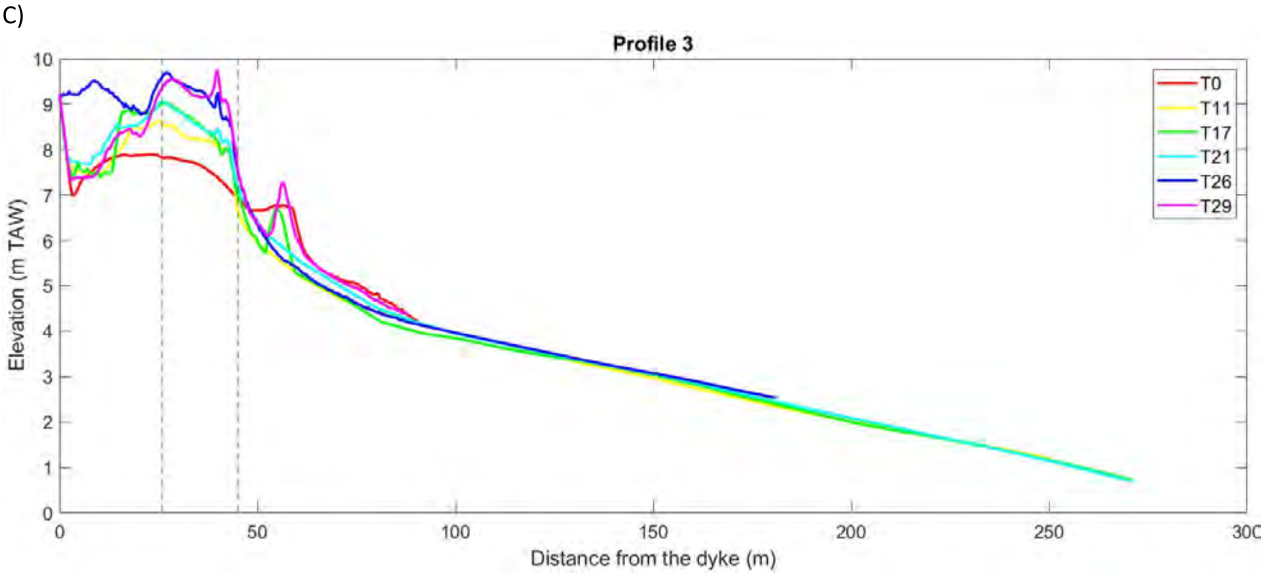


Figure 16 – Time series of evolution of the merged profiles of the UAV and RTK-GPS surveys.
The vertical dashed lines correspond to the location of the wire fences.

3.1.3 Volumetric changes

The study area is divided into a number of zones (Figure 14). The volumetric evolution in these zones was calculated using the UAV DEMs and the results are given in Table 6.

As previously observed on the DoDs, net accretion took place on the landward side of the dry beach (zones defined as upper-part) and the vegetated boxes over the last 3 years, while erosion occurred on the seaward side (zones defined as lower-part). Generally, the volumetric change was lower for the recent year (T21-T29). However, the interpretation of these data is complex because sand works were carried out several times in the period under consideration by the city of Ostend, for which limited quantitative information is available.

In the zone of the vegetated boxes, an average growth of 0.6, 0.28 and 0.74 m^3/m^2/year occurred for the 1st (T0-T11), 2nd (T11-T21) and 3rd (T21-T29) monitoring year respectively. Thus, the accretion was two times lower in the 2nd year but it increased over the last monitoring year. This is likely caused by multiple reasons such as differing wind regime, occurrence of storm events, precipitation and interrelations between morpho-ecology.

Also, the positive and stable volumetric change of the zone landward of the boxes (upper part A, B, C) recorded in the 1st year contrasts with the stability in the 2nd year (T11-T21) and erosion in the 3rd year monitoring (T21-T29). Possibly a yearly decreasing amount of aeolian sand was transported through the vegetated boxes and then locally deposited in the landward zone. But also sand maintenance works by Ostend city might have an important impact. For the zones of the lower part of the dry beach erosion is observed over the 3 years. -

Table 6 – Volumetric changes of the defined zones at Spinoladijk site. Green (accretion), red (erosion), grey (stability:<+/-0.05m).

			VegetatedBoxes	A_UpperPart	A_Lowerpart	B_UpperPart	B_LowerPart	C_upperPart	C_lowerPart
Global	T0-T11	m^3	1500	160	-1730	540	-2470	220	-1770
		$m^3/m^2/y$	0.60	0.08	-0.30	0.19	-0.46	0.18	-0.54
	T0-T21	m^3	2170	290	-5010	690	-4210	300	-2380
		$m^3/m^2/y$	0.45	0.08	-0.46	0.13	-0.41	0.13	-0.38
	T0-T29	m^3	4230	320	-6060	440	-5230	40	-2490
		$m^3/m^2/y$	0.55	0.05	-0.35	0.05	-0.32	0.01	-0.24
Annual	T0-T11	m^3	1500	160	-1730	540	-2470	220	-1770
		$m^3/m^2/y$	0.60	0.08	-0.26	0.19	-0.38	0.18	-0.48
	T11-T21	m^3	660	130	-3270	150	-1740	80	-610
		$m^3/m^2/y$	0.28	0.07	-0.62	0.06	-0.35	0.07	-0.2
	T21-T29	m^3	2060	40	-1060	-250	-1030	-260	-110
		$m^3/m^2/y$	0.74	0.02	-0.17	-0.08	-0.17	-0.19	-0.03

Table 7 displays the volumetric changes in all the vegetated boxes. The average sand deposition in the vegetated boxes ranges from 0.52 to 0.65 $m^3/m^2/y$ over the entire monitoring period (T0-T29). Accretion in the boxes was larger (average 0.75 $m^3/m^2/y$) during the 3rd year than the first year (0.60 $m^3/m^2/y$, T0-T11) following by the 2nd one (0.26 $m^3/m^2/y$, T11-T21) .

As already observed on the DoDs (Figure 14), the westward boxes Box 1 and Box 2 received more sand than the eastward boxes over the 3rd year. For example, the difference between Box 1 and Box 6 is 0.25 $m^3/m^2/y$. This demonstrates that there is a spatial variation in the sand deposition in the vegetated boxes.

Table 7 – Volumetric changes in the vegetated boxes at Spinoladijk site.
Green (accretion), red (erosion), grey (stability: :<+/-0.05m).).

			Box 1	Box 2	Box 3	Box 4	Box 5	Box 6
Global	T0-T11	m^3	210	210	220	230	260	290
		$m^3/m^2/y$	0.56	0.54	0.56	0.61	0.64	0.72
	T0-T21	m^3	370	300	270	320	360	400
		$m^3/m^2/y$	0.50	0.40	0.37	0.44	0.46	0.52
	T0-T29	m^3	710	680	570	650	670	700
		$m^3/m^2/y$	0.65	0.61	0.52	0.60	0.58	0.61
Annual	T0-T11	m^3	210	210	220	230	260	290
		$m^3/m^2/y$	0.56	0.54	0.56	0.61	0.64	0.72
	T11-T21	m^3	160	90	60	90	100	120
		$m^3/m^2/y$	0.40	0.23	0.15	0.24	0.25	0.29
	T21-T29	m^3	340	380	300	330	310	290
		$m^3/m^2/y$	0.80	0.86	0.70	0.77	0.69	0.65

Summary: The planted dunes clearly accumulate sand over the 3-year monitoring period. Sand accumulation is continuous but it shows variation of the accumulation rate through time, probably depending on varying wind conditions. Growth of the dune was higher in the 3rd year compared to the 1st and the 2nd years. The average sand accumulation over the 3-year period is ranging between 1 to 2 m above the initial level. The area between the planted dunes and the seawall starts to lose sand, or it is an effect of trenching works. Accretion at the seawall foot in the area just east and west of the dune experiment is remarkable. Either the protrusion formed by the new dune provides some lateral protection or we see an influence of sand bulldozing works, or a combination of both. The sand accumulation into this dune effectively increases the sand buffer above the 1000 year surge level (ca. +7 m TAW), after 3 years by ca. 4000 m^3. On average this corresponds to ca. +11 $m^3/m/year$.

3.2 Raversijde

The pilot site at Raversijde was surveyed from 03/2021 to 04/2024 and the third monitoring period started from 03/2023 (Table 2).

3.2.1 Meteo marine conditions

Figure 17 shows time series of water level in Ostend, 10% wave height and wave direction in ‘Ostend Poortjes’ (located 7 km from the coast), wind speed and direction of the weather station in Zeebrugge during the whole monitoring period of 3 years. UAV and energetic events are also displayed.

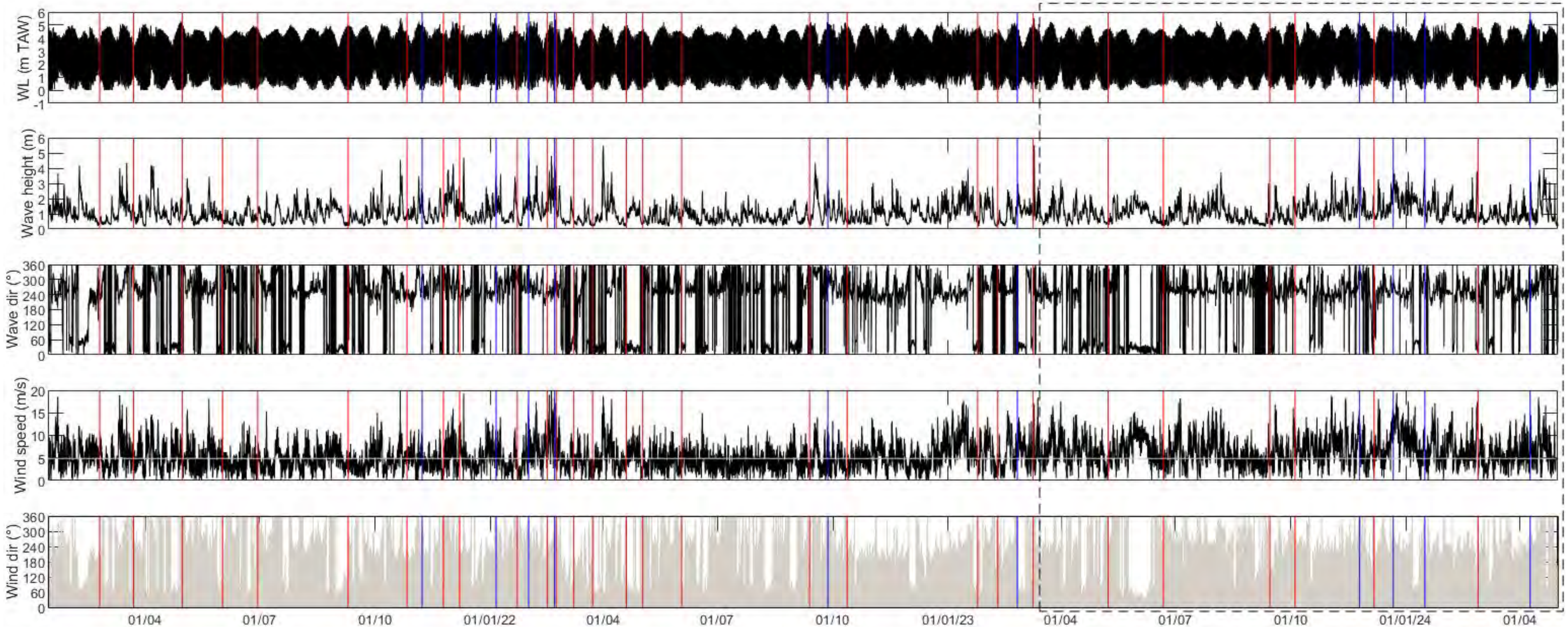


Figure 17 – Time series of the water level in Ostend, 10% wave height and wave direction in Ostend "Poortjes" (buoy located 7 km from the coast), wind speed and direction of weather station Zeebrugge at 10 m high (Meetnet Vlaamse Banken). Vertical red and blue lines correspond to the UAV surveys and energetic events respectively. Horizontal grey line on the wind speed time series is the critical wind speed for aeolian sand transport (7 m/s). The dashed box corresponds to the 3rd year monitoring.

3.2.2 Morphological evolution from months to 3 years

The DoDs indicate a progressive evolution of the pilot site (Figure 18). The net accumulation in the vegetated boxes and at their landward side clearly contrasts with erosion at the seaward side. Sand accretion in the vegetated boxes was above 2 m in the period T0-T28. Figure 19 displays the annual morphological evolution. It seems that the highest sand gain over the 3rd monitoring period occurred at the landward edge of the vegetated boxes. The same trend was observed for the 2nd year monitoring while it was more at the seaward margin and center in the 1st period.

The passages between boxes (Box 1- 2, Box 6-7, Box 10-11, Box 14-15) were filled up over the first monitoring year. However, it did not occur at the same extent over the last 2 years. In addition, a similar pattern of significant erosion in the seaward part of the dry beach (at an elevation below 7.2 m TAW) took place in the 1st and 3rd year monitoring while it was much lower for the 2nd period. Noteworthy, the extent of the UAV survey for T18-T28 allows to observe alternating spatial erosion and accretion on the lower part of the beach between 3 to 0.5 m TAW. A stability boundary at 7.5 m TAW (i.e. morphological change below +/-0.05 m) just located in front of the vegetated boxes divides the morphological pattern between the upper and lower part of the dry beach profile. This feature is observed over the entire monitoring period.

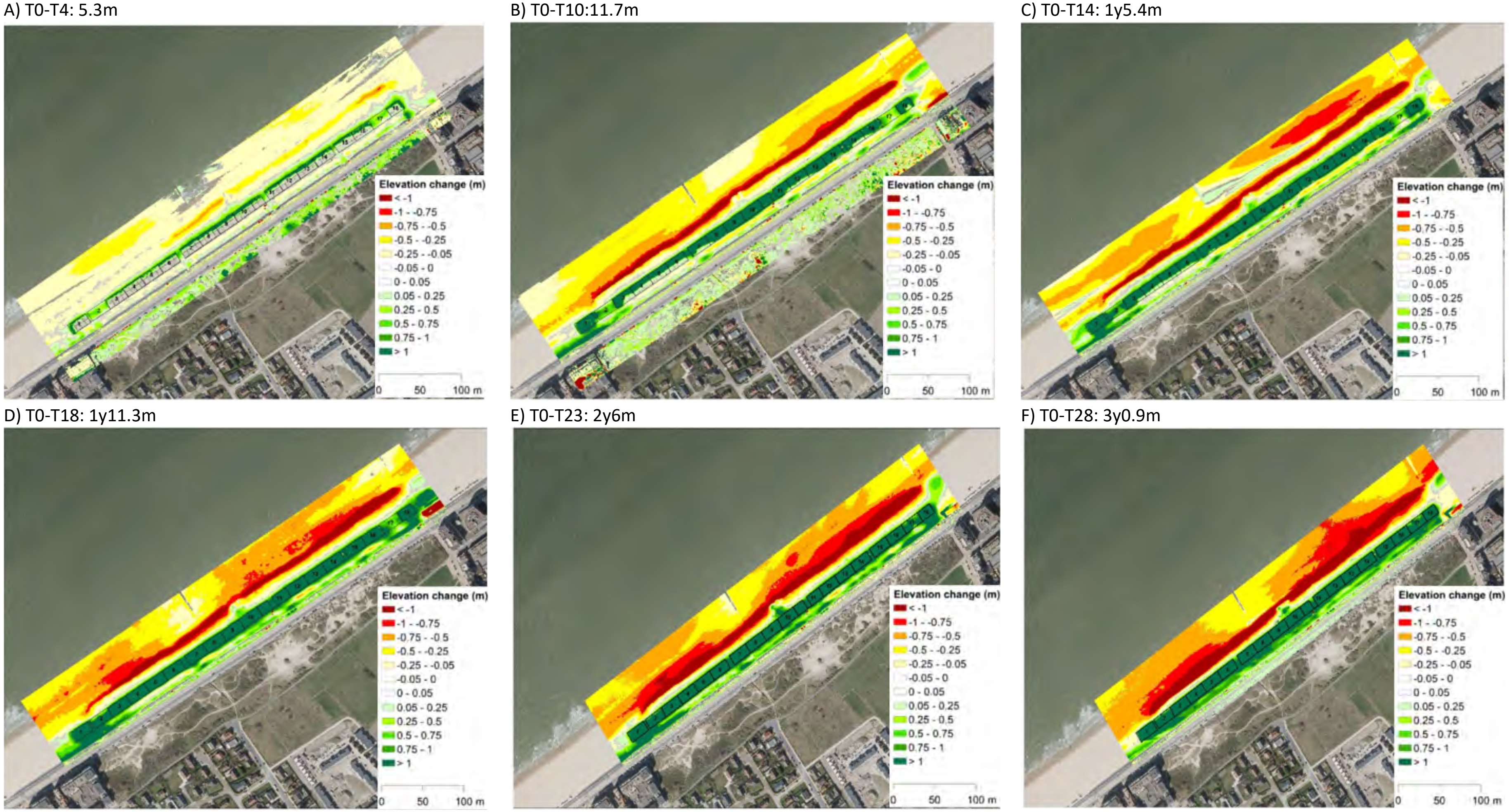
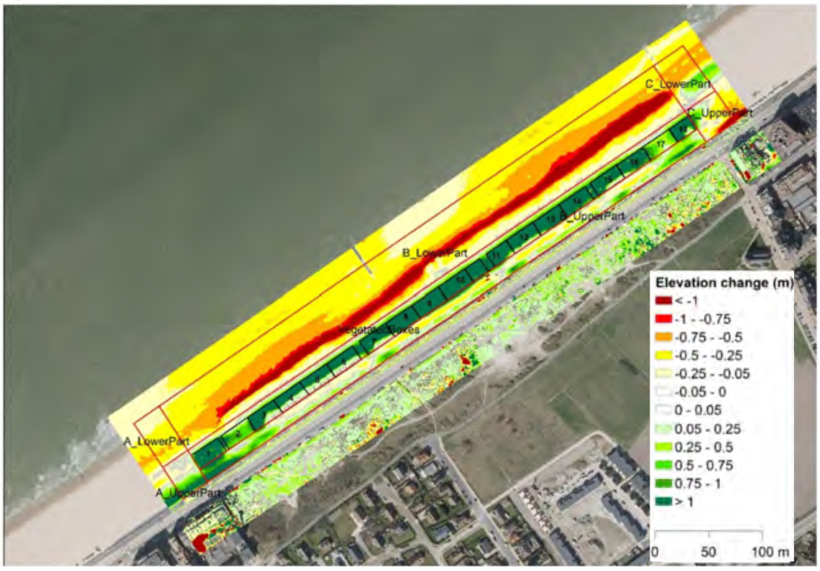
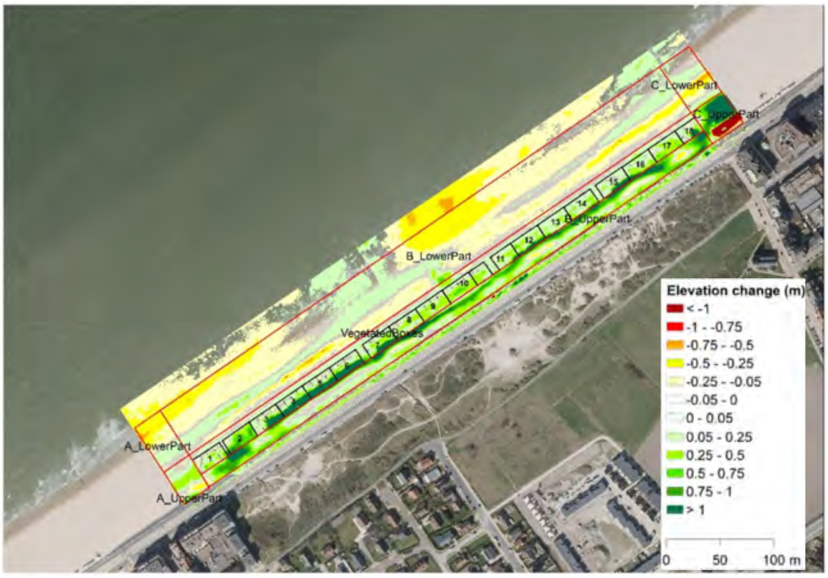


Figure 18 – Global evolution based on Ref DoDs of the UAV surveys

A) T0-T10: 11.7m



B) T10-T18: 11.5m



C) T18-T28: 1y1.5m

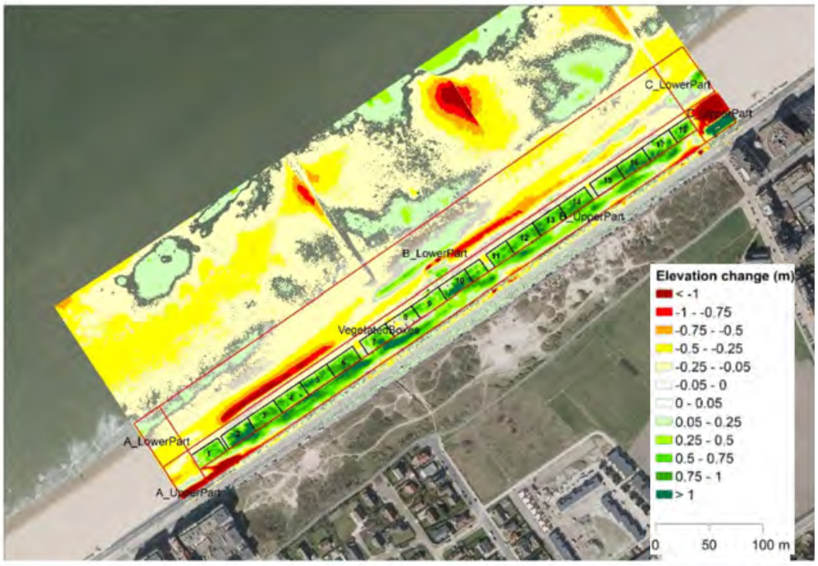
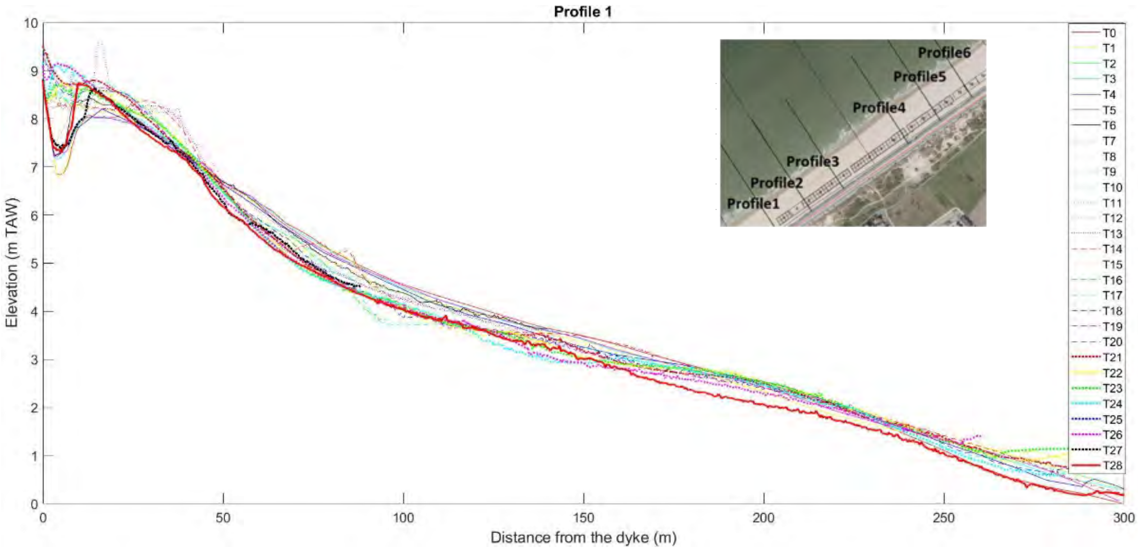


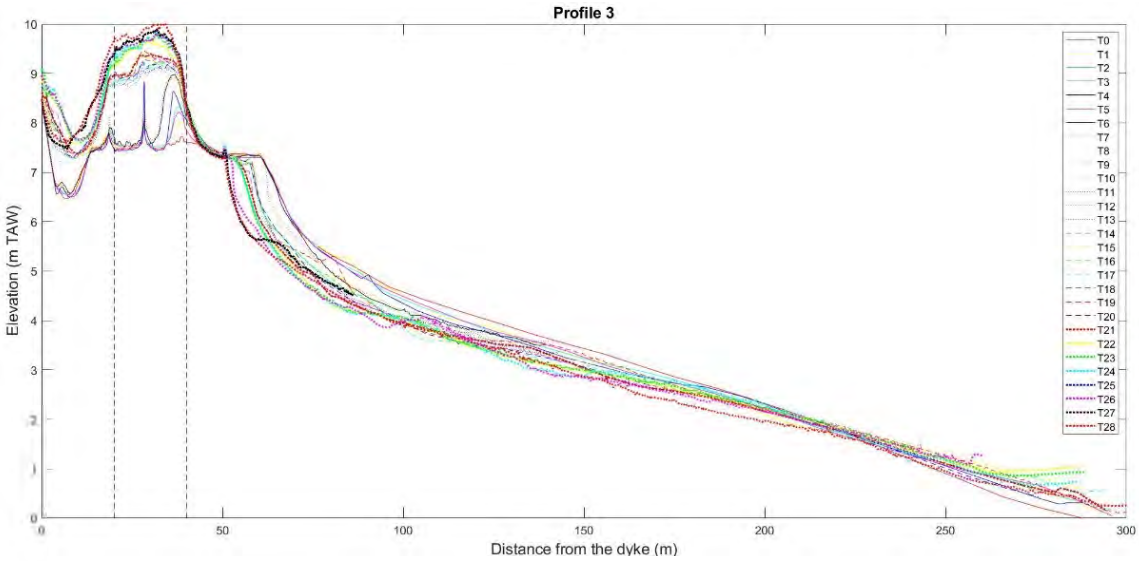
Figure 19 – Annual evolution based on DoDs of the UAV surveys with the Location of the contours of the defined zones

Profile 1, 3 and 6 are presented in Figure 20. Profile 1 is located southwest of the pilot area, and Profiles 1 and 6 cross the vegetated boxes and extend to the low-water mark. Generally, the evolution of the profiles clearly indicates that the upper-dry beach with the vegetated boxes gained a large quantity of sand, vertically up to 2 m, compared to T0 (Figure 21). The accretion is smaller for Profile 1 where no vegetated box is present. Thus, Profile 1 was relatively more stable across the dry beach than in the other profiles. In addition, the seaward slope of the dry beach for the three measured profiles retreated landward with an average of 17 m over the 3 years. Nevertheless, its steepness did not change except in T28 for Profile 6. Erosion dominated the dry beach area seaward of the vegetated boxes. and also in the highest part of the intertidal zone up to 220 m. However, periods of accretion and stability alternated in the lowest part of the intertidal zone.

A)



B)



C)

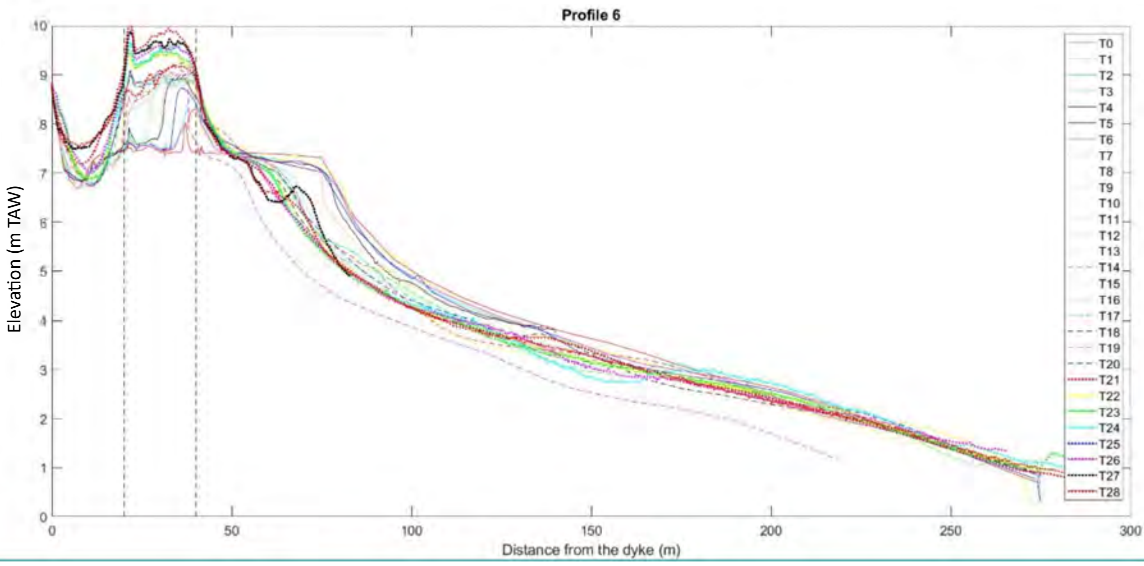
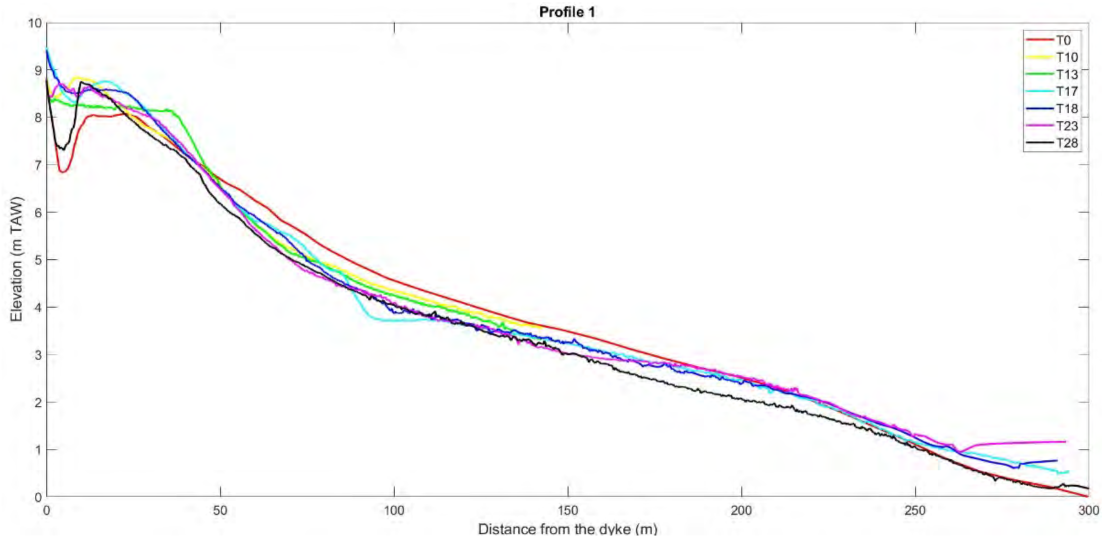
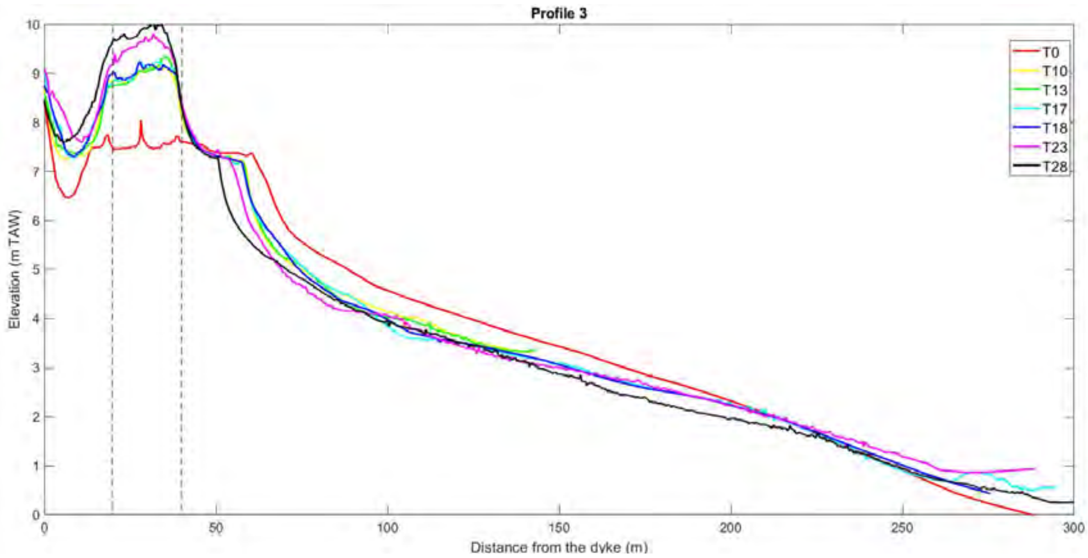


Figure 20 – Time series of all the merged profiles (1, 3, 6) of the UAV and RTK-GPS surveys.
The dashed lines correspond to the position of the vegetated boxes.

A)



B)



C)

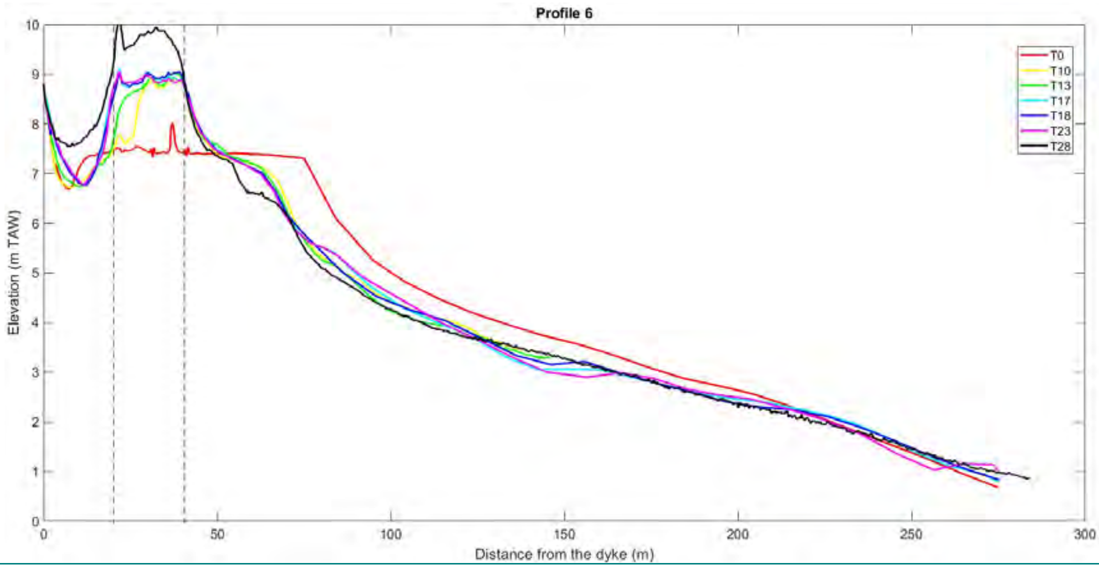


Figure 21 – Time series of evolution of the merged profiles of the UAV and RTK-GPS surveys.
The vertical dashed lines correspond to the location of the vegetated boxes.

3.2.3 Volumetric changes

The pilot study was divided into 7 zones to carry out a volumetric analysis based on the DoD surveys (Figure 19). Table 8 presents the results of the defined zones. The vegetated boxes gained 30400 m^3 equivalent to 0.46 $m^3/m^2/y$ after 3 years. Significant aeolian accretion by 0.30 $m^3/m^2/y$ also occurred landward of the boxes (it is in the upper part of zone B: B_UpperPart) while the sides zones in the upper part (zone A and C) were generally stable. This contrasts with the erosion of all the zones in the lower part of the dry beach. Accretion in the vegetated boxes during the 2nd and 3rd year was 3 times lower than during the first year. However, the accretion rate in the area landward of the boxes in zone B (B_UpperPart) was higher during the last two years. The sand loss in the lower part zones in the 3rd year (B_LowerPart) was slightly larger compared to the 2nd year but much less compared to the 1st year.

Although accretion dominated in the vegetated boxes, there is a small spatial variation between boxes characterized by only marram grass on the one hand and brushwood on the other hand (Table 9). The latter experienced slightly more accumulation by 0.68 to 0.71 $m^3/m^2/y$ after 3 years while it ranged from 0.45 to 0.65 $m^3/m^2/y$ for the marram grass boxes.

Table 8 – Volumetric changes of the defined zones at Raversijde site. Green (accretion), red (erosion), grey (stability: :<+/-0.05m), black (no records due to the limitation of the UAV coverage).

			VegetatedBoxes	A_UpperPart	A_LowerPart	B_UpperPart	B_LowerPart	C_UpperPart	C_LowerPart
Global	T0-T10	m^3	17580	670	-810	2800	-27430	-390	-660
		$m^3/m^2/y$	0.84	0.38	-0.32	0.20	-0.54	-0.18	-0.21
	T0-T18	m^3	23240	910	-11701	8690	-31510	460	-770
		$m^3/m^2/y$	0.55	0.25	-0.23	0.30	-0.31	0.11	-0.12
	T0-T28	m^3	30400	210	-1490	13370	-40980	4	-1090
		$m^3/m^2/y$	0.46	0.04	-0.19	0.30	-0.26	0.00	-0.11
Annual	T0-T10	m^3	17580	670	-810	2800	-27430	-390	-660
		$m^3/m^2/y$	0.84	0.38	-0.32	0.20	-0.54	-0.18	-0.21
	T10-T18	m^3	5660	230	-360	5890	-4080	840	-110
		$m^3/m^2/y$	0.27	0.13	-0.14	0.41	-0.08	0.39	-0.04
	T18-T28	m^3	7160	-700	-310	4690	-9480	-450	-320
		$m^3/m^2/y$	0.34	-0.39	-0.12	0.32	-0.18	-0.21	-0.10

Table 9 – Volumetric change for the boxes with only marram grass (MG), B: brushwood fences with ½ density 'rijshout halve dichtheid'. Green (accretion), red (erosion), grey (stability: :<+/-0.05m).).

			MG	B	B	MG
	Box		2	3	16	17
Global	T0-T10	m^3	530	810	870	430
		$m^3/m^2/y$	0.66	1.00	1.11	0.53
	T0-T18	m^3	950	1140	1110	660
		$m^3/m^2/y$	0.59	0.71	0.71	0.41
	T0-T28	m^3	1550	1650	1660	1080
		$m^3/m^2/y$	0.65	0.68	0.71	0.45
Annual	T0-T10	m^3	530	810	870	430
		$m^3/m^2/y$	0.66	1.00	1.11	0.53
	T10-T18	m^3	430	330	240	230
		$m^3/m^2/y$	0.53	0.41	0.31	0.29
	T18-T28	m^3	600	510	550	4209
		$m^3/m^2/y$	0.75	0.62	0.69	0.52

Table 10 displays the average volumetric change in the west, middle and east boxes. In general, there is no significant spatial difference over the entire monitoring period. As previously observed, the largest accumulation took place in the 1st year and then decreased in the 2nd and 3rd year. The main reason is the effect of the brushwood fences until they were saturated (after 1 year).

Table 10 – Average of volumetric change for the west, middle and east boxes. Green (accretion), red (erosion), grey (stability).

	Box	West (Box1-6)	Middle (Box 7-12)	East (Box13-18)
Global	T0-T10	730	690	780
		0.90	0.86	0.96
	T0-T18	1120	1130	1170
		0.69	0.70	0.73
	T0-T28	1600	1610	1570
		0.63	0.64	0.62
Annual	T0-T10	730	690	780
		0.90	0.86	0.96
	T10-T18	390	440	400
		0.49	0.54	0.49
	T18-T28	480	480	390
		0.53	0.53	0.43

Summary: The NbS dune experiment in Raversijde continues to trap sand in the planted areas after 3 years. The vertical accretion amounts to 2 m in April 2024. Possibly, this will be about a limit as the 3rd monitoring year showed increased accumulation in the strip between the dune and the seawall. Progressive erosion of the area around the high water mark is observed. It is the usual response after a sand nourishment on the beach.

3.3 Westende

Five UAV flights were carried out in the period from 3/2021 to 11/2022 (0.65 years) (Table 4). Then the flight requests were not accepted by the authorities due to the proximity of military domain Lombardsijde. Since then, LiDAR surveys were used to evaluate morphological and volumetric changes. This limits the 3rd monitoring period to 06/2023-01/2024.

3.3.1 Meteo-marine conditions

Figure 22 shows time series of water level in Ostend, wave 10% height and wave direction in 'Ostend Poortjes' (located 7 km from the coast), wind speed and direction of the weather station in Zeebrugge with the indication of the 3rd year monitoring. The surveys and energetic events are also displayed.

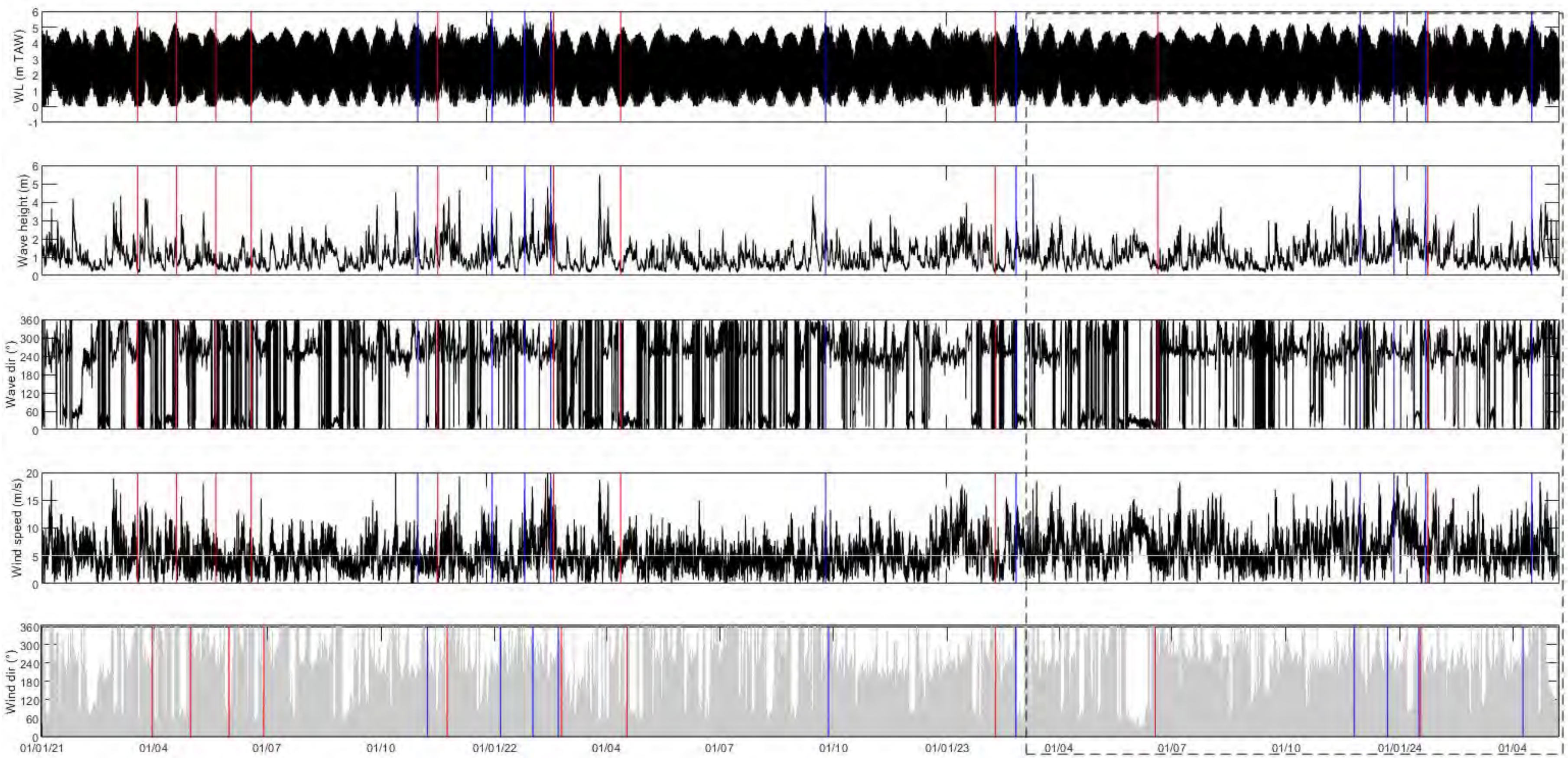


Figure 22 – Time series of the water level in Ostend, wave height 10% and wave direction in Ostend "Poortjes" (buoy located 7 km from the coast), wind speed and direction of weather station Zeebrugge at 10 m high (Meetnet Vlaamse Banken). Vertical red and blue lines correspond to the UAV and LiDAR surveys and energetic events respectively. Horizontal gray line on the wind speed time series is the critical wind speed for aeolian sand transport (7 m/s). The dashed box corresponds to the 3rd part of the monitoring.

3.3.2 Morphological evolution from months to 3 years

Figure 23 presents the DoDs from months to nearly 3 years since T0 (refer to Figure 3B for the elevation across the beach). A clear growth up to 2.3 m is noticeable in the seaward vegetated boxes and mainly in the most westerly ones (Box 1, 2, 3) after 2y 9.6 months (T0-T9). The same trend was already observed one year earlier (T0-T7). This contrasts with the stability in the landward vegetated boxes (Box7, 8, 9, 10). Erosion on the dry beach east of the vegetated boxes is likely related to some interventions such as the setting of summer cabins and dyke expansion from the municipality of Middelkerke which were observed on the UAV orthophotos. Erosion continues on the dry beach seaward of the vegetated boxes. A narrow stability zone around 7 m TAW segments these two opposite morphological trends.

Similar morphological changes are observed between the three monitoring periods with a dominance of erosion for the lower part of the dry beach and relative stability of the landward vegetated boxes (Figure 24). Sand accumulation took place in all the seaward vegetated boxes in the 2nd year monitoring, while it was limited to the westerly boxes in the first and third period (T0-T4, T7-T9). In case of coast-parallel winds from SW, the westernmost boxes are expected to intercept sand and relatively deplete the more eastern boxes. The morphological changes around the fences in the middle part where alternating erosion and accretion occurred in T0-T4 and T4-T7 were not present in the last year (T7-T9) when the fences were removed. Therefore, these fences had only a local and temporary influence on morphology.

The RTK-GPS and LiDAR profile measurements starting seaward of the vegetated boxes in Figure 25. The three profiles display dry beach seaward slope and wet beach, but not the vegetated boxes. Changes observed, such as bumps appearing and disappearing, are probably to a large extent the result of works carried out the municipality of Middelkerke, such as placing and removing fences and beach profiling.

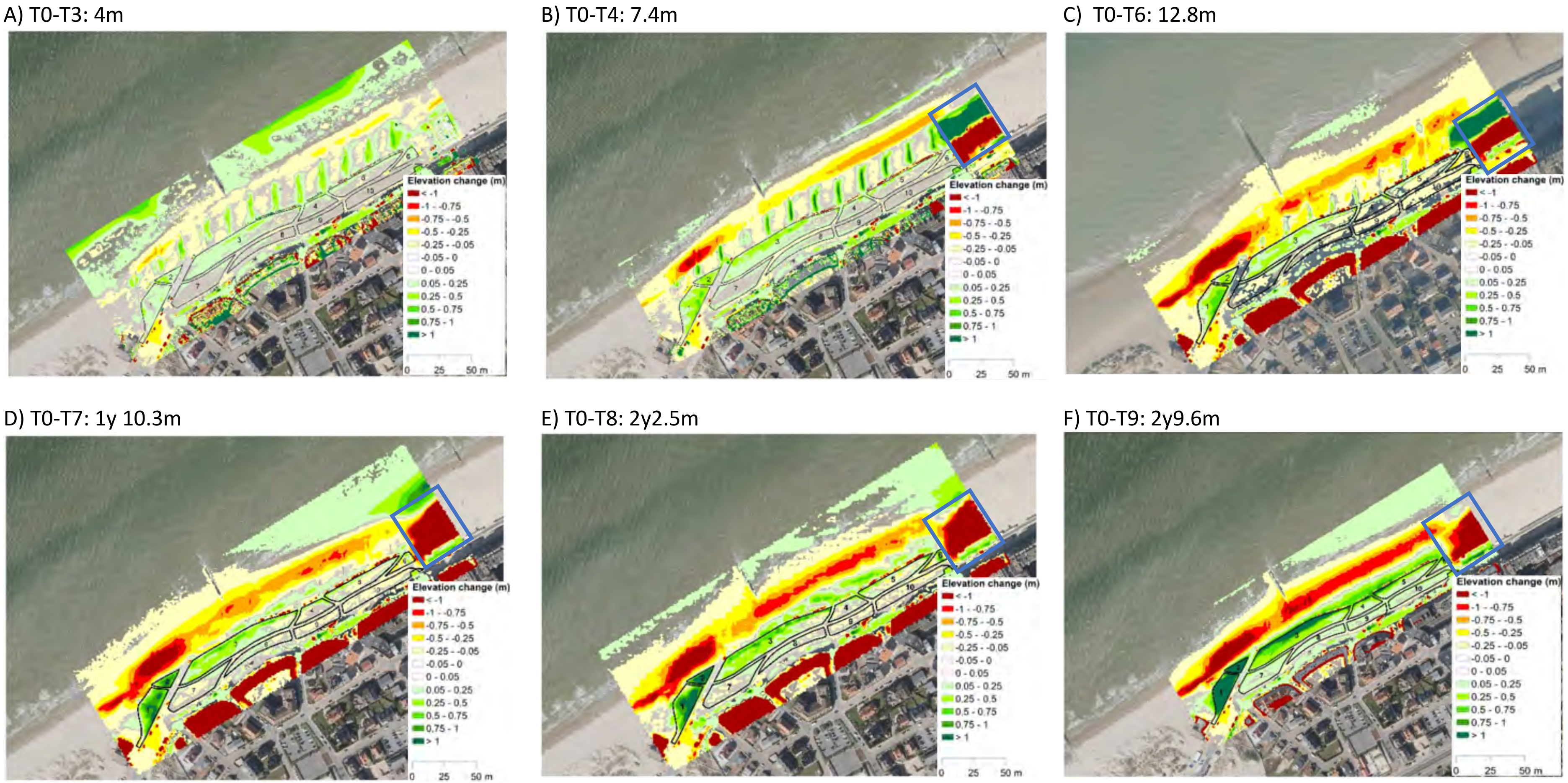


Figure 23 – Global evolution based on DoDs of the UAV and LiDAR surveys at Westende. The changes of the building (landward of the seawall) are artefacts.

A)T0-T4: 7.8m

B)T4-T7: 1y 10.3m

C)T7-T9: 11.3m

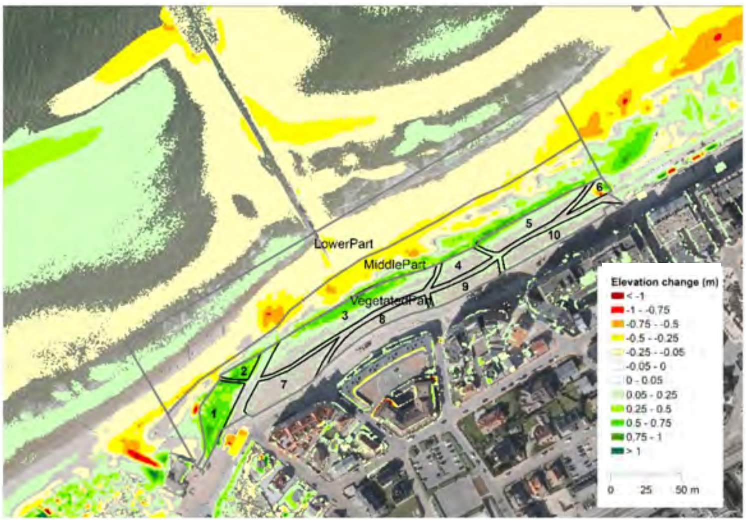
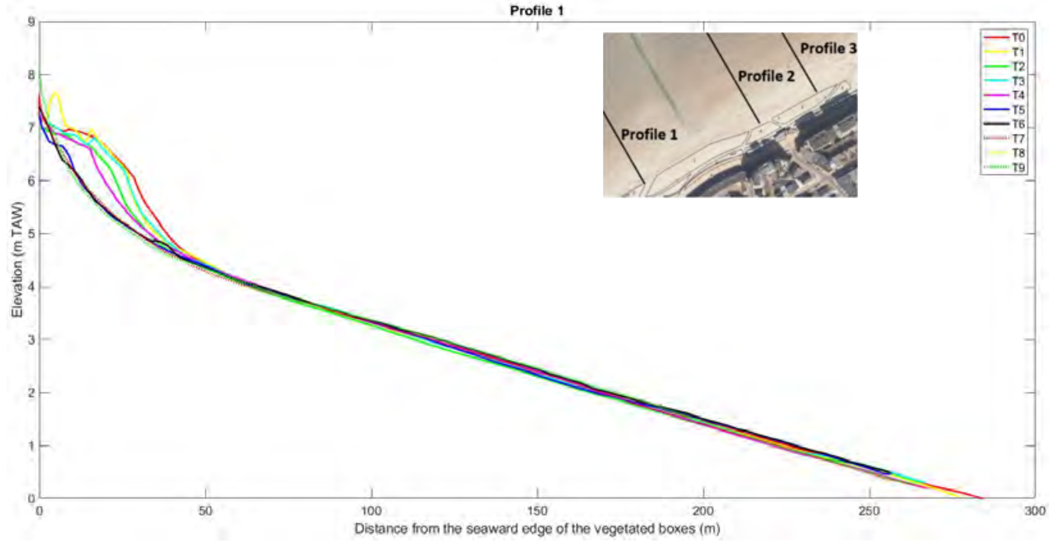
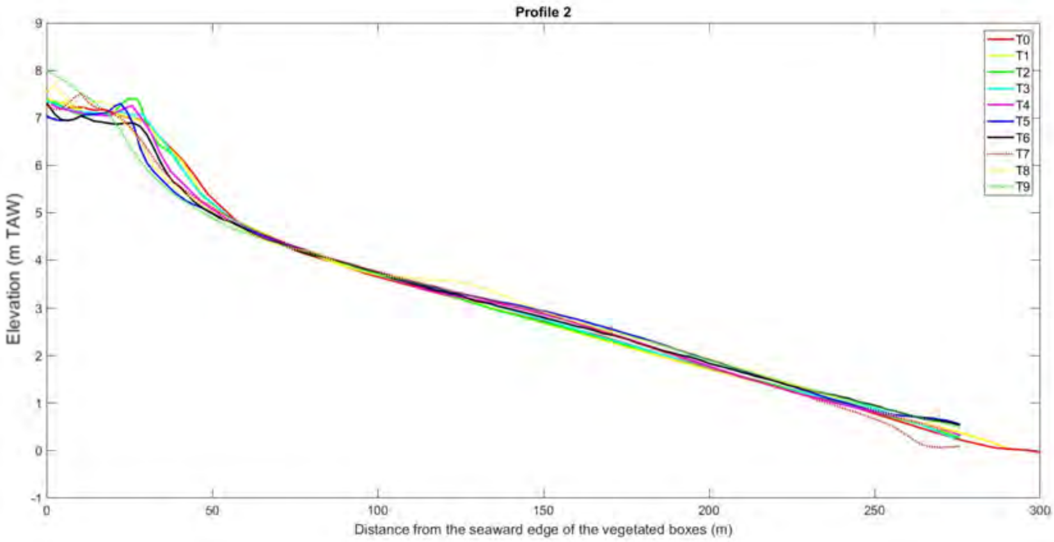


Figure 24 – Annual evolution based on DoDs of the UAV surveys.
The changes of the building (landward of the seawall) are artefacts.

A)



B)



C)

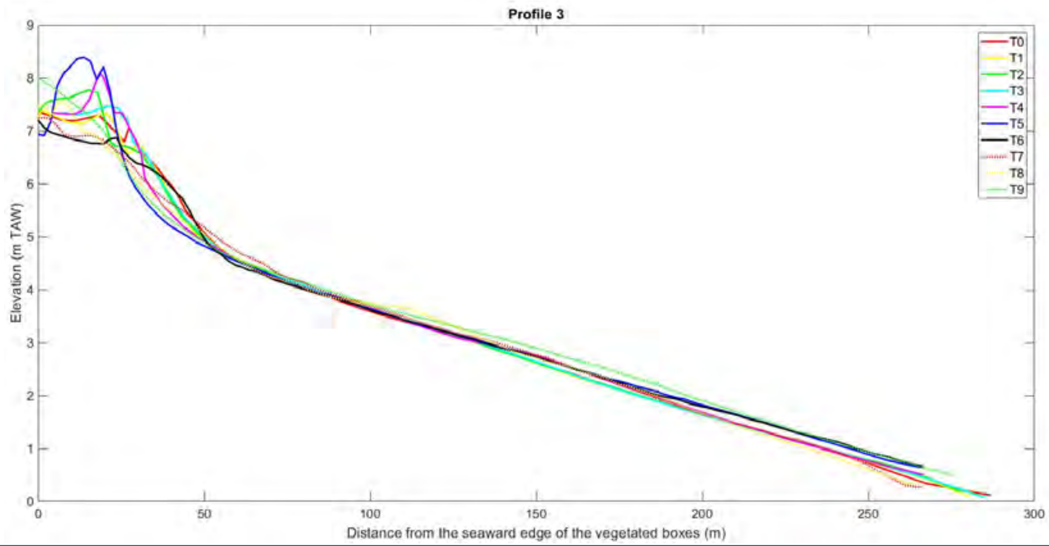


Figure 25 – Time series of the RTK-GPS and LiDAR surveys started seaward of the vegetated boxes. Inset: location of the profiles.

3.3.3 Volumetric changes

For the volumetric calculations, the study area is divided into a number of zones based on the large-scale erosion/sedimentation pattern (Figure 24). The volumetric evolution in these zones was calculated using the UAV and LiDAR surveys and the results are given in Table 11. The vegetated zone experienced a small growth of 0.02-0.05 $m^3/m^2/y$ over the first and second monitoring periods (T0-T4; T4-T7) while a stronger growth of 0.28 $m^3/m^2/y$ is observed over the 3^{rd} period (T7-T9). The winter sand fences 'zandschermen' located in the zone of the middle part might have reduced the sand capture in the inland zone in some periods. The morphological evolution of the middle part was affected by this same winter fences and maybe also cabins installed by Middelkerke municipality. As previously observed on the DoDs, the lower part of the dry beach experienced erosion with a similar rate in the 3^{rd} year as in the previous periods.

Table 11 – Volumetric changes of the defined zones at Westende site. Green (accretion), red (erosion), grey (stability: <+/-0.05m).

			VegetatedPart	MiddlePart	LowerPart
	T0-T4	m^3	1050	590	-3090
		$m^3/m^2/y$	0.05	0.04	-0.10
	T0-T7	m^3	1470	-1940	-6140
		$m^3/m^2/y$	0.06	-0.11	-0.18
	T0-T9	m^3	4960	-630	-8530
Global		$m^3/m^2/y$	0.14	-0.02	-0.16
	T0-T4	m^3	1050	590	-3090
		$m^3/m^2/y$	0.05	0.04	-0.10
	T4-T7	m^3	420	-2530	-3050
		$m^3/m^2/y$	0.02	-0.14	-0.09
	T7-T9	m^3	3490	1310	-2390
Annual		$m^3/m^2/y$	0.28	0.14	-0.14

Summary: The NbS dune pilot at Westende effectively captures sand in front of the seawall. The location of the accretion areas shows an interception of sand supplied mainly from the west. The onshore oblique alongshore transport path remained the same over the three years of the observation period. The dry beach slope in front of the dune pilot at about 40 m from the vegetated boxes is retreating over the 3 year monitoring period which is probably caused by the human intervention from the city.

3.4 Knokke

The pilot site at Knokke was surveyed from 12/2023 to 05/2024 using LiDAR and UAV surveys. Morphological and volumetric analyses were only carried out over a period of maximum 5.6 months due to the recent implementation of the dune scheme.

3.4.1 Meteo marine conditions

Figure 27 shows the time series of water level in Ostend, 10% wave height and wave direction in 'Ostend Poortjes' (located 7 km from the coast), wind speed and direction of the weather station in Zeebrugge. The surveys and occurrence of energetic events are also displayed.

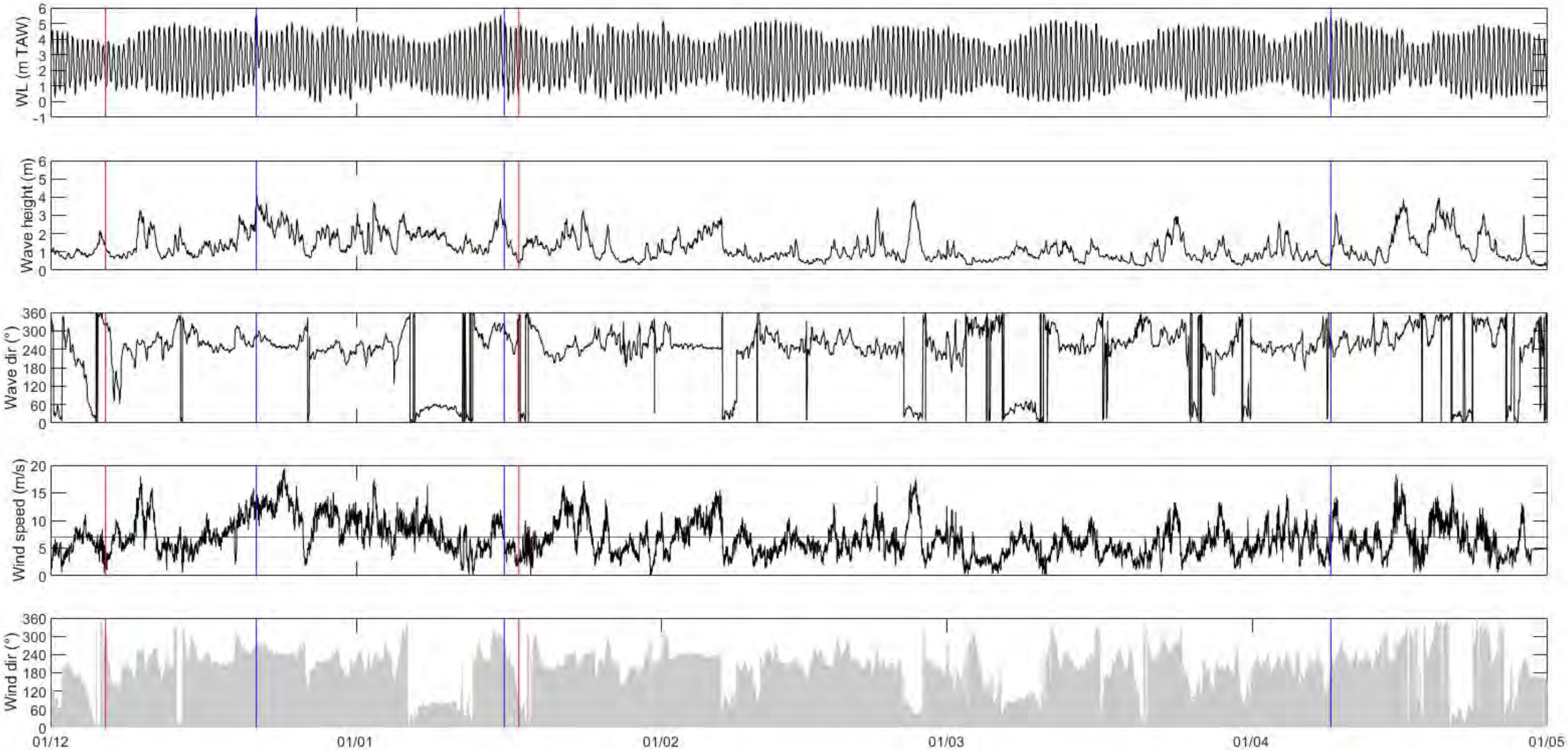


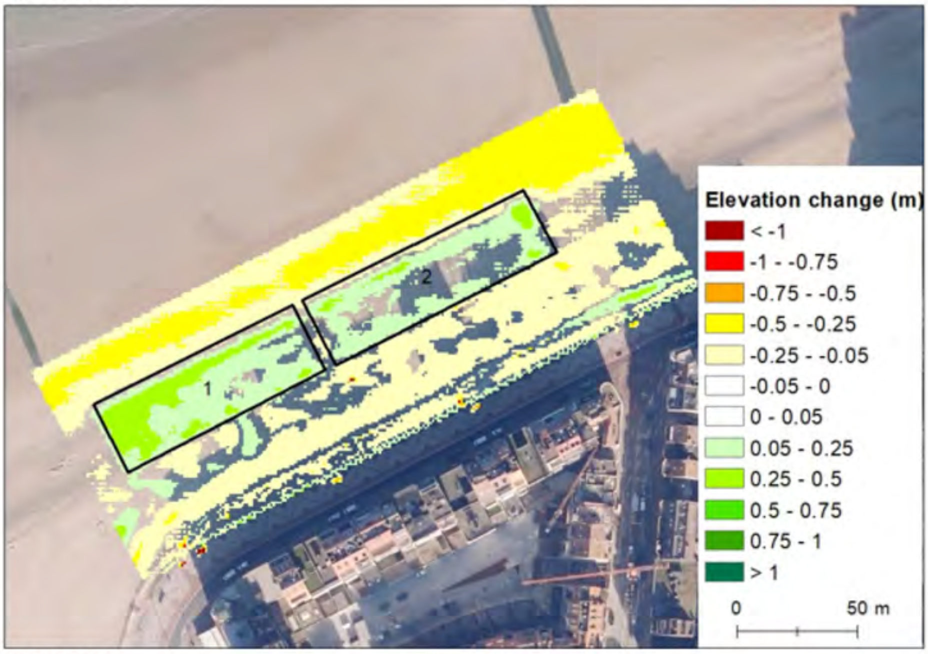
Figure 26 – Time series of the water level in Ostend, 10% wave height and wave direction in Ostend “Poortjes” (buoy located 7 km from the coast), wind speed and direction of weather station Zeebrugge at 10 m high (Meetnet Vlaamse Banken). Vertical red and blue lines correspond to the UAV surveys and energetic events respectively. Horizontal gray line on the wind speed time series is the critical wind speed for aeolian sand transport (7 m/s).

3.4.2 Morphological changes

About 1.4 months after the NbS site installation, accretion ranging from 0.2 to 0.55 m was already observed in the vegetation boxes (Figure 27). No changes occurred in the most 2 m seaward part of the boxes where no vegetation was planted. In contrast, the beach seaward of the boxes experienced erosion and also the area landward of the boxes eroded but at a lower intensity. This pattern persists after 5.6 months but is accompanied with a higher magnitude of elevation changes. Interestingly, more sand deposition took place in Box 1 compared to Box 2. The dark green rectangles on the upper-beach located inland from the vegetated boxes are the cabins set-up during the spring-summer season (Figure 28B, Figure 29B).

Figure 28 presents the seasonal morphological changes. A band of sand deposition of on average 10 m wide and 0.4 m high extending from the middle of Box 1 to the eastward of Box 2 occurred between T1-T2 (01-05/2024). While accumulation was only observed in Box 1 and especially on the westward side during the first period (T0-T1). Also, morphological change of the seaward dry beach slope was limited although the period T1-T2 was longer. Noteworthy, a narrow line of stability at about 6.5-7 m TAW segments the accretion in the vegetated boxes and the erosion dominating the seaward dry beach slope.

A) T0-T1: 1.4m



B) T0-T2: 5.6m

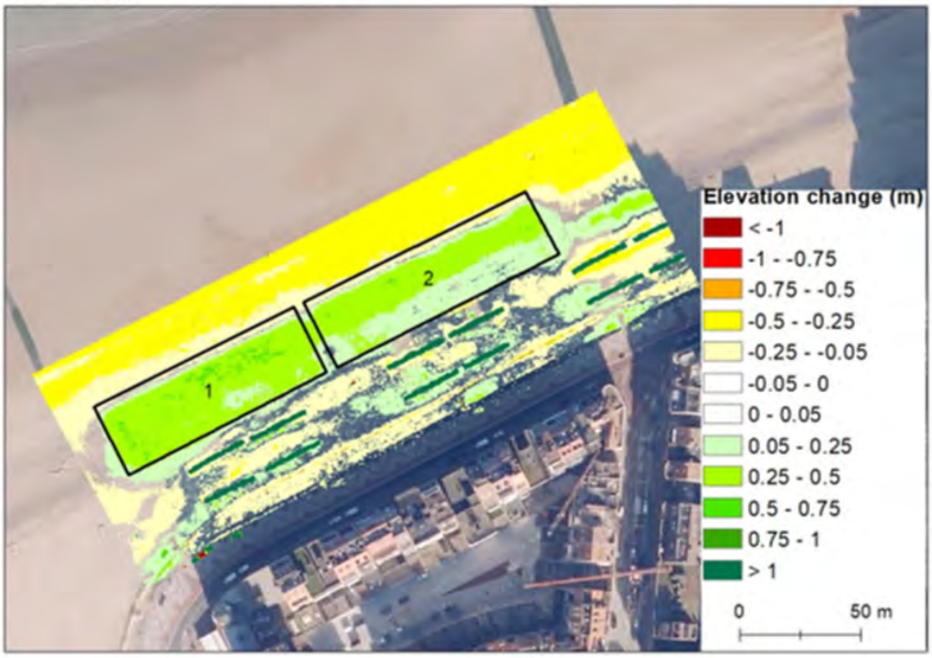
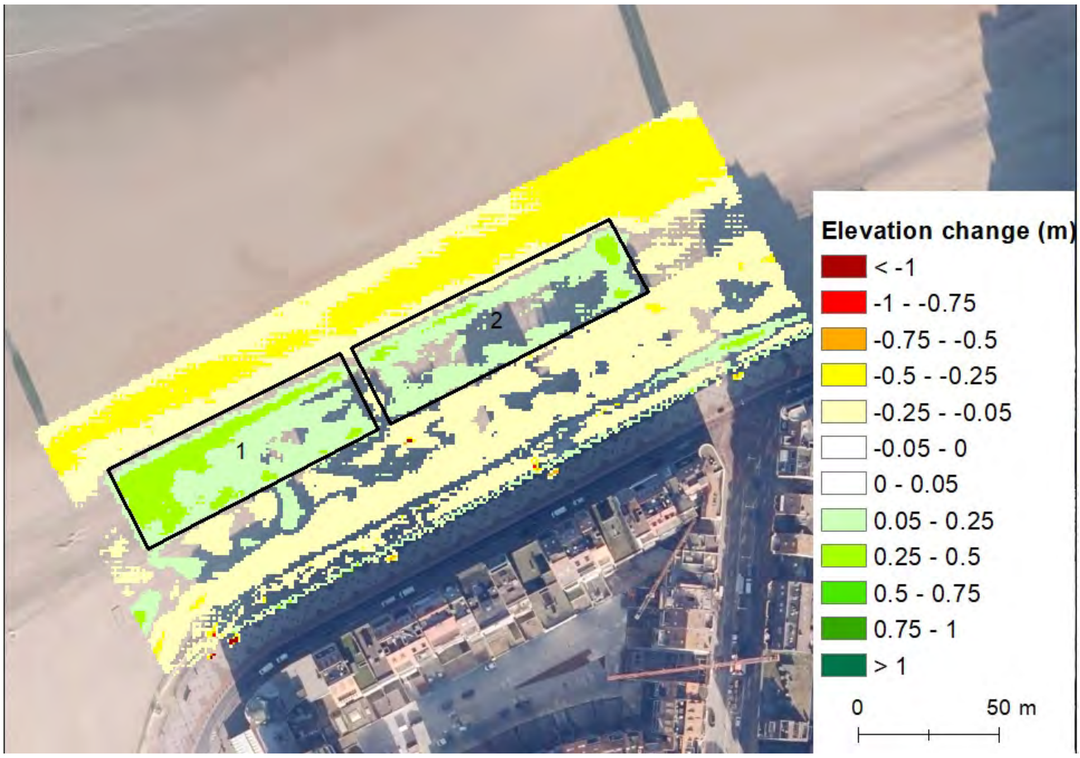


Figure 27 – Global evolution based on Ref DoDs of the UAV and LiDAR surveys

A)T0-T1



B)T1-T2

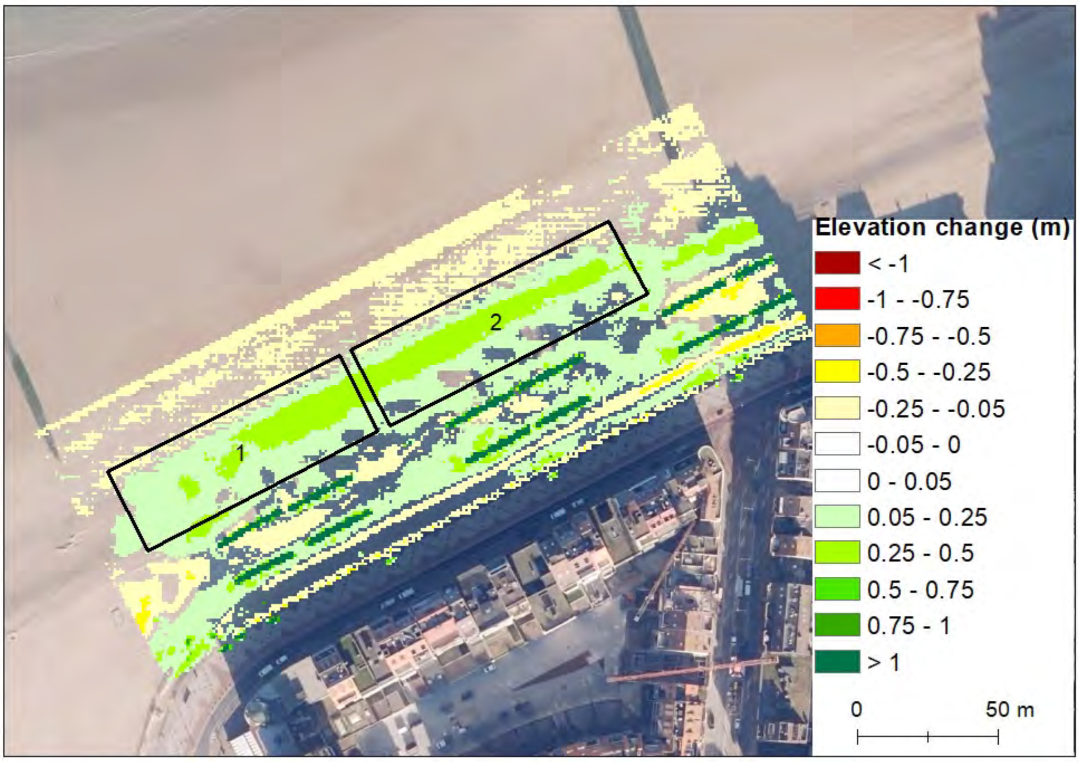


Figure 28 – Seasonal evolution based on UAV and LiDAR surveys with the locations of the contours of the defined volumetric zones. Accretions displayed on the cabins areas are artefacts

Figure 29 presents the time series of extracted profiles from the topographic surveys. The large peaks mark the presence of cabins and smaller ones the presence of fences. In general, the upper beach landward of the vegetation was stable contrasting with the sand accumulation in the vegetated boxes (at a distance of 40-70 m) and the negative morphological changes along the slope of the beach (distance > 70 m).

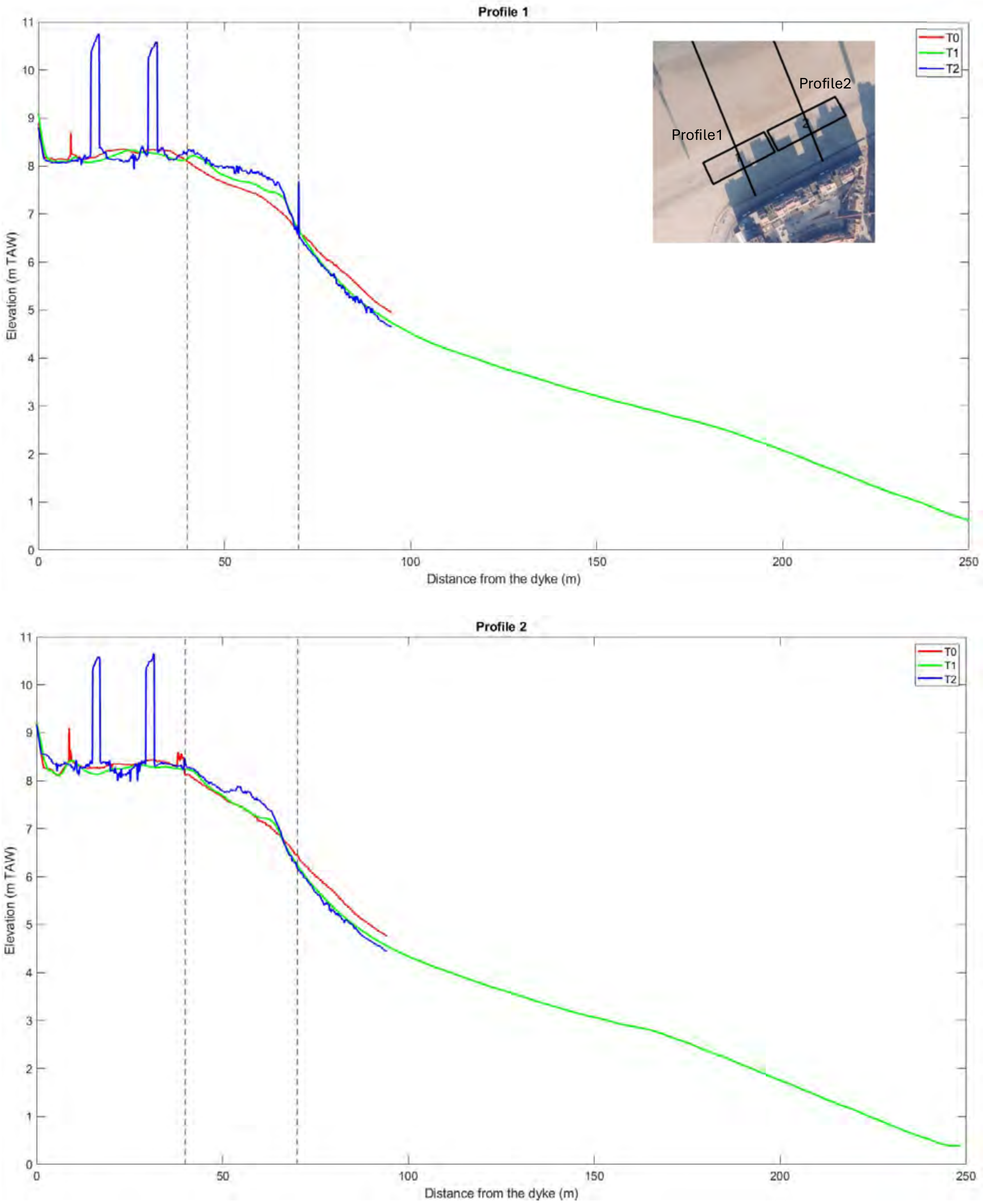


Figure 29 – Time series of the UAV and LiDAR surveys. The dashed lines correspond to the position of the egetated boxes. Inset: location of the profiles.

3.4.3 Volumetric changes

A global accretion of 0.06 and 0.04 m^3/m^2/month occurred in Box 1 and 2 respectively (Table 12). As previously observed, there was a spatial and temporal variation of sand gain. Between T0-T1, the sand gain was nearly two times larger in Box 1 than in Box 2 but it was similar with a gain of 0.03 m^3/m^2/month for the period T1-T2. On average, the sand deposition was for the first period 3 times larger. The coming surveys after the summer will help to confirm the morphological trend of the NbS site.

Table 12 – Volumetric changes of the defined zones at Knokke site. Green (accretion), red (erosion), grey (stability: :<+/-0.05m).)

		Box1	Box2
Global	T0-T2 (m^3)	930	650
	T0-T2 (m^3/m^2/month)	0.06	0.04
Seasonal	T0-T1 (m^3)	530	290
	T0-T1 (m^3/m^2/month)	0.13	0.07
	T1-T2 (m^3)	400	360
	T1-T2 (m^3/m^2/month)	0.03	0.03

Summary: The NbS in Knokke was monitored for nearly 6 months from December 2023. The accretion observed over the first half year after the implementation of the dune pilot indicates a natural trapping of aeolian sand supplied predominantly from the west.

4 Discussion

4.1 Spatial and temporal evolution

The four monitored NbS sites present a different spatial morphological behaviour and trends over the short (season) to medium-term (up to 3 years). Here, we describe them per site and relate them to the long-term coastal trends between the 1980's and 2019. Noteworthy, this latter will be updated next year using LIDAR data from 2020-2024 period. The morphological observations of the vegetated dunes are translated to recommendations in order to guide the continued monitoring of these NbS sites as well as planning future ones.

Spinoladijk: The planted dune clearly accumulates sand over the 3-year monitoring period. Sand accumulation is continuous but it shows variation through time, depending on e.g. varying wind conditions. The average sand accumulation extends now from 1 to 2 m above the initial level. The area between the planted dune and the seawall starts to be depleted and/or influenced by trench digging works. Accretion at the seawall foot in the area just east and west of the dune experiment is remarkable. Either, the protrusion formed by the new dune provides some lateral protection, or we see an influence of sand bulldozing works, or both. The dune created in front of the seawall displays an effectively increased sand buffer in the profile above the storm surge level of the 1000 year safety standard (ca. +7 m TAW), after 3 years by ca. 4000 m^3. The sand gain of the vegetated dune was ca. 11 m^3/m/y over the entire monitoring period. The future progression of dune development will depend on the interaction between vegetation growth and sand burial. It should be realized that the overall morphological evolution of the beach and shoreface will ultimately determine the long-term existence of the new foredune. The large availability of sand material in the shoreface, where sand accumulated due to the sheltered position east of Ostend harbour dams, may constitute a supply of natural beach growth. On the other hand, the barrier formed by Ostend harbour dams may intercept the beach drift from the west and as a result deplete the beach at the location of the NbS. The update of the coastal trend study may clarify this point in 2025.

The vegetated boxes still manage to capture aeolian sand transport from the adjacent beach. A variation in planting density and spatial configuration was introduced during the implementation of the dune scheme but converged into a similar vegetation cover for the entire zone (Strypsteen, et al., 2023). The clustering of the plants evolved into a random pattern during the second growing season. Thus, in this experiment, the variation in the initial planting configuration is not a crucial characteristic for vegetation growth and thus the development of the dune. In contrast, an intermediate level of sand burial and more vegetation stimulates dune growth. It is difficult to interpret the erosion and accretion spots due to the lack of data on the sand works carried out by city of Ostend, such as excavation of a trench along the dike to prevent sand accumulation on the seawall top and supplying sand from the seawall top to the beach. It is recommended to request from the city of Ostend to keep precise records, at least qualitative ones, of these interventions.
Due to the small size of the dune pilot at Spinoladijk boundary effects from the sides are interfering to a large extent its morphological evolution.

Raversijde: The NbS dune experiment continues to trap sand in the planted areas after 3 years. There is no specific morphological behaviour related to the initial marram grass planting scheme. Bonte et al. (2023) observed new and diverse plant communities originating from tidemark species also observed pioneer plants such as Cakile maritima or sea rocket, rush wheatgrass and sand oats at Raversijde after 2 years. These species are very rare along the Belgian coast. The development of tidemark plant communities in and nearby the dune is much higher than on other beaches. This suggest that creating an artificial dune has the potential to shelter and support beach plant communities. The NbS in Raversijde clearly highlights the importance of the biomorphological interactions, relationships between the plants and the morphodynamics, controlling the development of the dune.

The vertical accretion of the vegetated dune amounts to 2 m high after 3 years. Erosion around the high water mark continued as well. The sand gain of the dune was about 13 m^3/m/y on average during the 3 years period. This increase of sand buffer above 1000 year surge level (ca. +7 m TAW) has improved coastal safety, nothwithstanding the lower part of the profile has eroded. The 3rd monitoring year showed an accumulation in the strip between the foredune and the seawall. It is the usual response after a sand nourishment. Depending on the larger-scale evolution of the surrounding beaches and shoreface, the upper part of the beach including the vegetated boxes might switch from an accreting to an eroding stage one of the coming years. The coastal stretch of Raversijde coast has been subject to a long-term erosion of -5.6 m^3/m/y for the beach and -10.82 m^3/m/y for the shoreface. This suggests that sand supply would be limited or even lacking after the depletion of the local material available from the sand nourishment in 2021.

Apart from the ecological and coastal safety benefits, the vegetated dune contributes to nuisance reduction caused by aeolian sand transported over the sea dike and deposited on the tram line as well as on the coastal road. A large amount of aeolian sand transport was captured by the dune during the entire monitoring period. Nevertheless, the efficiency of sand trapping was reduced during the 2nd year monitoring due to a reduced accommodation space. Then it was recommended to replant marram grass in this zone in order to further capture the aeolian transport. Marram grass was replanted in February 2023 which then clearly helped the growth of the dune during the 3rd monitoring year. Additionally, the impact of the sand nuisance on the seawall at Raversijde needs to be tracked and thus it has been recommended to request from the city of Ostend to keep data related to sand works such as cleaning for the tram line and/or coastal path, beach shaping and other interventions.

Westende: The dune pilot effectively captures sand in front of the seawall. The vegetated dune gained an averaged 3 m^3/m/y after 3 years. The location of the accretion areas shows interception of sand supplied from the west. The supply path remained the same over the three years of the observation period. The upper part of the beach in front of the dune pilot is retreating. Depending on the larger-scale morphological developments, this retreat might eventually impact the dune. The section along Westende coast is subject to a long-term erosion for both beach and shoreface with a sand loss of -1.2 and -4.01 m^3/m/y respectively (Table 13).

Since 11/2021, it is no longer possible to carry out monthly UAV surveys at the location of the current pilot site in Westende, because the flight permissions are systematically refused by the military authorities. The monitoring based on the bi-yearly coastal LiDAR surveys (February 2022 to January 2024) has revealed successfully the overall morphological trend of the NbS site.

Knokke: The NbS site was monitored for nearly 6 months from December 2023. The accretion observed over the first half year after the implementation of the dune pilot indicates a natural trapping of aeolian sand supplied from predominantly the west. This was on average nearly 3 m^3/m/y. As well known, Knokke coast suffers from long-term erosion (Table 13). However, it is hoped that the erosion rate may be reduced in the coming years thanks to the recent large shoreface nourishment.

Table 13 – Summary of volume budget for the NbS sites and the long-term coastal trend (extracted from Houthuys et al., 2022).

	NbS average volume trends ($m^3/m/y$)				Corrected coastal trend volume ($m^3/m/y$) [Houthuys et al, 2022]	
	Veg dune	Upper-beach (landward of dune)	Lower dry beach	Sum	Beach (wet + dry) & Dunefoot	Shoreface
Spinoladijk	10.93	0.96	-16.67	-4.78	-16.58	11.29
Raversijde	13.10	5.27	-16.97	1.39	-5.6	1.58
Westende	3.14	-0.41	-5.54	-2.81	-1.2	-4.01
Knokke	2.73				-19.88	-4.64

It is finally also recommended for the four sites that a long-term evolution of the dune volumes at the three pilot sites should be determined using the sand balance on a larger scale than considered in the monitoring program for this project (it is limited to the dry part of the profile). At yearly scale, the part of active zone extending from the upper-dry beach to the foreshore should be taken into account. At decadal scale, the interaction between foreshore and the depth of closure should also be assessed.

4.2 Comparison between NbS sites

A progressive accretion of the vegetated areas characterized the sites during the entire monitoring period, varying per site from 6 months to 3 years. Sand gain in the dune pilot sites, where the vegetated boxes are located, was usually higher during the 3rd monitoring year than during the 2nd year, especially at Spinoladijk and Westende where it was 3 and 10 times greater. For the 3rd year period, averaged sand accretion rates in the vegetated boxes were thus 0.74 $m^3/m^2/y$ at Spinoladijk, 0.34 $m^3/m^2/y$ at Raversijde and 0.28 $m^3/m^2/y$ at Westende. Similar morphological patterns at the three sites were observed over the first three years with accretion dominating the vegetated boxes and the area landward until the dike while erosion characterized the lower part of the dry beach from 7 to 4 m TAW. Noteworthy, the accretion of the vegetated boxes and landward generally more or less counterbalanced the erosion dominating in the lower part of the profile. The limited morphological changes in the upper part (landward of the vegetation) at Spinoladijk and Raversijde over the 3rd monitoring year is probably partly due to human interferences i.e. the sand works by the trucks carried out by the city of Ostend (trench digging). The volumetric estimations divided over the upper and lower part of the sites should be corrected based on the human interventions of sand removal and redistribution after receiving more quantitative or qualitative information about the sand works. Regarding Westende, morphological change across the beach was smaller than at the other two pilot sites. This might be due the presence of winter fences over the first two years located seaward of the vegetated zones which captured sand transport before reaching the planted marram grass. It might also be caused by the larger size of the grass dike compared to all other three NbS sites. Over the recent monitoring period, the accretion in the vegetated boxes was concentrated in the seaward side while no morphological change occurred in their landward side. As is the case for Spinoladijk, Raversijde and also for Westende, works are carried out by the municipality which influence the evolution of the NbS areas, but limited information is available on these works.

A)

B)

C)

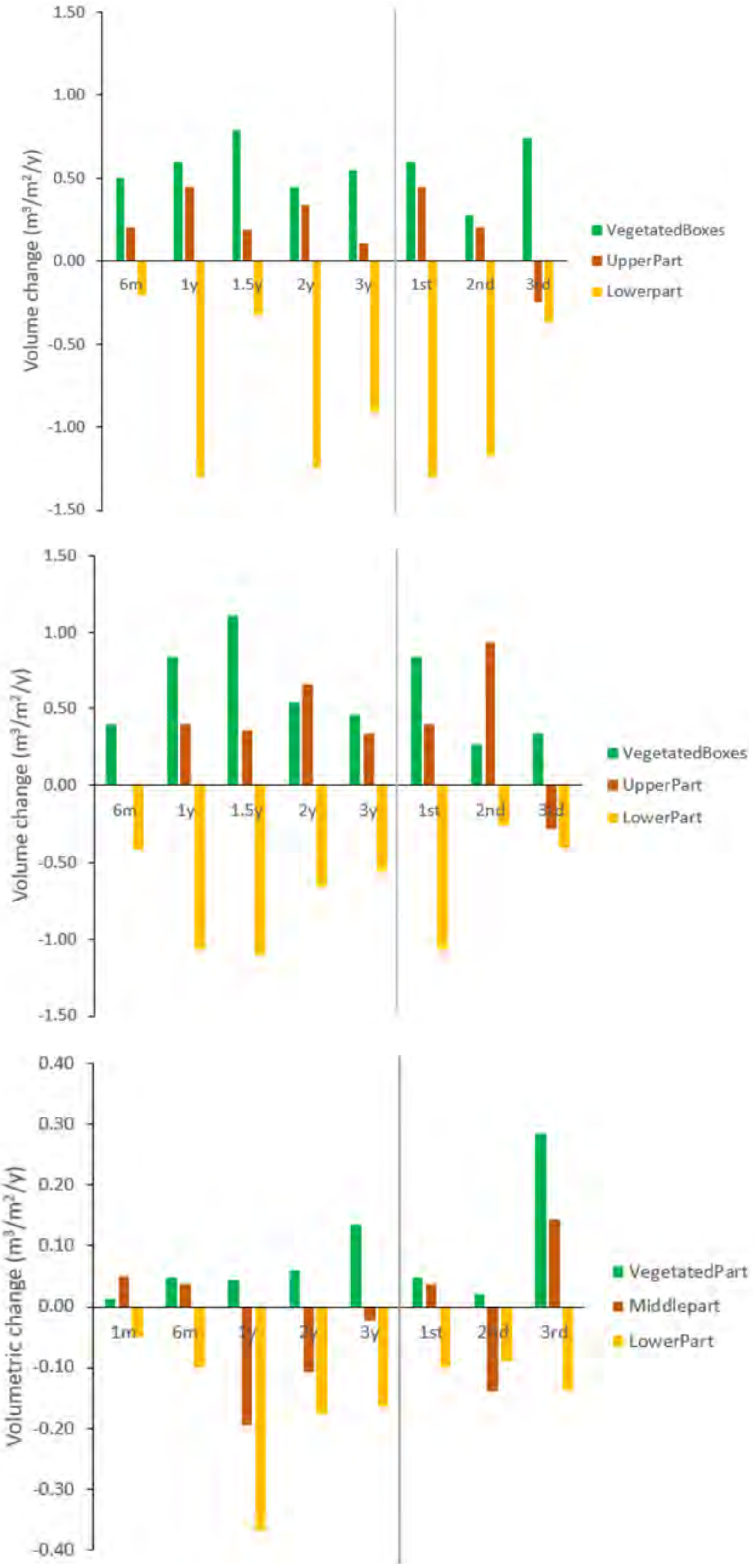


Figure 30 – Evolution of sand budget over observation periods ranging from 6 months to 3 years at the pilot sites: A) Spinoladijk, B) Raversijde and C) Westende. Only part B of the beach is considered here where no human interferences usually occurrs. Note the difference of y-axes. Right of vertical line, bars show evolution per year.

Sand availability, accommodation space to receive deposited sand, vegetation growth and dune topography play important roles too. Another crucial supply factor is the wind regime. The frequency of effective onshore winds (> 7 m/s), capable of transporting sand, was 13% of the time for the 1st year, 10% for the 2nd year and 14% for the 3rd monitoring year. Therefore, the first and most recent periods were slightly more favorable for sand transport. Grain size is also an important controlling factor of sand transport. Unfortunately, no information is available about its change over time. The new experiment site in Knokke where a large shoreface nourishment was recently carried out with small grain size (150 µm) might provide further insights on the influence of this factor on the morphodynamics of the dune development. It would be interesting to investigate the grain size evolution across the beaches in the NbS areas.

The sand balance of the dry beach area after 3 years (from the sea dike to the high water mark) was positive at Raversijde with 0.24 $m^3/m^2/y$, contrasting with the negative one at Spinoladijk and Westende (-0.25 $m^3/m^2/y$ and -0.04 $m^3/m^2/y$ respectively). Maybe the positive sand balance at Raversijde is due to the large availability of sand as a result of the recent nourishment there just before the installation of the dune. However, this sand balance is very sensitive to the choice of seaward boundary and also is depending on the sand works carried out. So one cannot conclude from this about a difference between the NbS sites considered.

Another process which influenced the beach morphology is storm occurrence. Montreuil et al. (2023) reported that the consecutive severe Corrie and Franklin storms in 01 and 02/2022 caused erosion on the seaward side of the dry beach and on the intertidal zone. The eroded material was deposited near and below the low water mark where the fair-weather wave processes carried it back and then was re-transported by aeolian processes to the dune. Similar observations of rapid dune recovery were described by Strypsteen et al. (2023) for more recent storms in April 2022, March 2023 and November 2023.

The lower part of the dry beach is subject to both marine and aeolian processes leading to a deflation of this zone which is important as a supply for the upper zone. At yearly scale, sand accumulation of the entire dune foot zone (above +6.89 m TAW) by aeolian transport processes is therefore stronger than the loss due to erosion caused by storms. This observation coincides with the recent decadal morphological trend of a steady growth of the zone higher than +6.89 m TAW at 'Westende-Bad', 'Raversijde-East' and 'Ostend-East' coastal strips (Houthuys et al, 2022). It is mainly explained by a large availability of sand in the active beach profile, especially in the part above the low water mark. The dune growth of the NbS sites would be maintained in the coming years thanks to the presence of a sand buffer volume on the dry beach ensuring its continuous development. On the longer term, this buffer, however, will probably vanish without any new artificial sand supply, causing the decline of the dune growth and even initiating its decay. However, overall this work highlights the success of the four NbS sites after 3 years, offering insights for sustainable coastal resilience strategies.

5 Conclusions

This report highlights the success of the NbS sites after 3 years and offers insights for this type of sustainable coastal resilience strategies. A significant accretion in the vegetated dunes characterized the four pilot sites during the entire monitoring period. Sand gain during the 3rd year paralleled the high level of sand capture of the first year, while it was lower during the 2nd year. For the last monitoring period, sand budget status for the vegetated boxes was 0.74 $m^3/m^2/y$ at Spinoladijk, 0.34 $m^3/m^2/y$ at Raversijde, 0.28 $m^3/m^2/y$ at Westende and 0.03 $m^3/m^2/y$ at Knokke. Thus, accumulation is the largest at Spinoladijk and Raversijde which is probably due to the high efficiency of marram grass and brushwood fences, the availability of sand as a result of the nourishment as well as the continuous human interventions by the city of Ostende. The main factors controlling the dune growth are sand availability, accommodation space, vegetation and brushwood retention capacity and the wind regime.

The negative morphological trend of the upper-beach area landward of the boxes at Spinoladijk and Raversijde in the 3rd monitoring year contrasts with the observations of the first two years when accretion was recorded. It might suggest that sand could not be transported to and deposited in this upper part because of being trapped by the growing dunes. However, trench excavation works by Ostend city have to be considered as well.

Similar spatial morphological patterns occurred at the four sites over the entire monitoring period. Erosion is observed on the lower part of the dry beach. This erosion and the accretion dominating the vegetated boxes is delimited by a line of morphological stability. The lower part of the dry beach plays an important role since marine and aeolian processes influence this area of deflation to supply sand to the upper zone (including the dunes).

The future evolution of the NbS dune development will be determined by the interaction between vegetation growth, sand burial, wind regime as well as the availability of sand material in the beach-shoreface system. The surveys of the coming years monitoring will support further investigation of the beach morphodynamics over intervals ranging from short (months) to medium-term (years).

Considering largest morphological changes occur in the first years after installation, as well as boundary effects in the smaller pilots, to optimize the efforts of monitoring it is recommended to:

- Spinoladijk site: stop topographic UAV monitoring after 4th year (begin 2025). Continue monitoring as part of coast-wide monitoring using LiDAR and multi-/hyperspectral for vegetation classification
- Raversijde site: carry out 3 more years of intense (4 times/year) topographic UAV monitoring and stop at 7 years after installation (begin 2028). Continue monitoring as part of coast-wide monitoring using LiDAR and multi-/hyperspectral for vegetation classification
- Westende site: continue monitoring as part of coast-wide monitoring using LiDAR and multi-/hyperspectral for vegetation classification
- Knokke site: carry out 2 more years of intense (4 times/year) topographic UAV monitoring but stop after 4th year (begin 2027). Continue monitoring as part of coast-wide monitoring using LiDAR and multi-/hyperspectral for vegetation classification

Finally to be able to better explain morphological changes it is recommended to the responsible authorities to improve documenting the sand maintenance works carried out at the sites and its immediate surroundings.

6 References

Boerema, A. Depaepe, J., Van Holland, G., Pieterse, A., Castro Lara, H. (2023) Hergebruik zandige specie project NST in twee nuttige toepassingen in Knokke Heist en Zeebrugge, pp 48.

Bonte, D., Dhondt, M., Matheve, H., Taelman, C. (2023) Biologische evaluatie van de living labs Oosteroever en Raversijde, 14p.

Houthuys, R.; Verwaest, T.; Dan, S. (2022). Morfologische trends aan de Belgische Kust: Evolutie van de Vlaamse kust tot 2019. Versie 3.0. WL Rapporten, 18_142_1. Waterbouwkundig Laboratorium: Antwerpen.

Montreuil, A-L., Verwaest, T., Dan, S. (2022). Living Lab Raversijde – Monitoring Soft Coastal Defences: Factual data report. 1st working year 2021-2022. Version 2.0. FHR Reports, 21_012_1. Flanders Hydraulics Research: Antwerp.

Montreuil, A-L., Verwaest, T., Dan, S. (2023). Ostend-Middelkerke, Monitoring of the dune for dike pilots: Evolution after 2 years. Version 3.0. FH Reports, 21_014_2. Flanders Hydraulics: Antwerp.

Strypsteen, G., Bonte, D., Taelman, C., Derijckere, J., Rauwoens, P. (2023) Three years of morphological dune development after planting marram grass on a beach, Earth Surface processes and Landforms, 1-18. DOI: 10.1002/esp.5870

Verwaest, T. (2021). duin voor dijk pilot Raversijde-Mariakerke – analyse eerste resultaten. Versie 1.0. WL Memo's, 21_014. Waterbouwkundig Laboratorium: Antwerpen.

Verwaest, T.; Montreuil, A.-L.; Dan, S. (2022). Oostende-Middelkerke, Monitoring duin voor dijk pilots: Evolutie gedurende het 1e jaar. Versie 2.0. WL Rapporten, 21_014_1. Waterbouwkundig Laboratorium: Antwerpen

DEPARTMENT **MOBILITY & PUBLIC WORKS**
Flanders hydraulics

Berchemlei 115, 2140 Antwerp
T +32 (0)3 224 60 35
F +32 (0)3 224 60 36
flanders.hydraulics@vlaanderen.be
www.flandershydraulics.be