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Evolution after 2 years

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Evolution after 2 years

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D/2023/3241/190

This publication should be cited as follows:

Montreuil, A-L.; Dan, S.; Verwaest, T. (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

Document identification

Customer:	MDK afdeling kust	Ref.:	WL2023R21_014_2
Keywords (3-5):	Dune, morphodynamics, marram grass		
Knowledge domains:	erosion protection coast > dunes > in situ measurements		
Text (p.):	58	Appendices (p.):	1
Confidential:	☒ No	☒ Available online	

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

Control

	Name	Signature
Reviser(s):	Dan, S.	Getekend door:Sebastian Dan (Signature Getekend op:2023-07-31 10:44:12 +02:0 Reden:Ik keur dit document goed Sebastian Dan Vlaanderen
Project leader:	Verwaest, T.	Getekend door:Toon Verwaest (Signature Getekend op:2023-08-25 12:45:46 +02:0 Reden:Ik keur dit document goed Toon Verwaest

Approval

Head of Division:	Bellafkih, K.	Getekend door:Abdelkarim Bellafkih (Sign Getekend op:2023-07-26 12:19:08 +02:0 Reden:Ik keur dit document goed Abdelkarim Bellafkih

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Abstract

At the beginning of 2021, the MDK Coastal Division, Ostend and Middelkerke built-up dunes on the dry beach in front of a sea dike at three locations: Spinoladijk (Ostend), Raversijde and Westende. Intensive monitoring at these sites was carried out from the beginning of 2021 to 03/2023 to investigate the development of the built dunes and to follow closely their morphology and planted vegetation. This report documents the 2nd year evolution of the morphology of the dune for dike pilots. A progressive evolution of the three pilot sites occurred over the entire monitoring period. A substantial accretion took place in the 1st year in the zones where marram, fences were installed. Aeolian sand transport was captured to an extent thanks to them. However, sand gain was strongly reduced there over the 2nd year at the three sites. This was probably due to an obstruction by the formed dunes, higher marram grass plants, and a lower wind regime over this period. Also, there was a reduction of sand availability at Raversijde. Storm impact of 01/2022 and 09/2022 was relatively limited. Further monitoring surveys would help to understand the observed relationship between accretion in the upper-part of the dry beach and erosion dominating its lower part above the low water mark.

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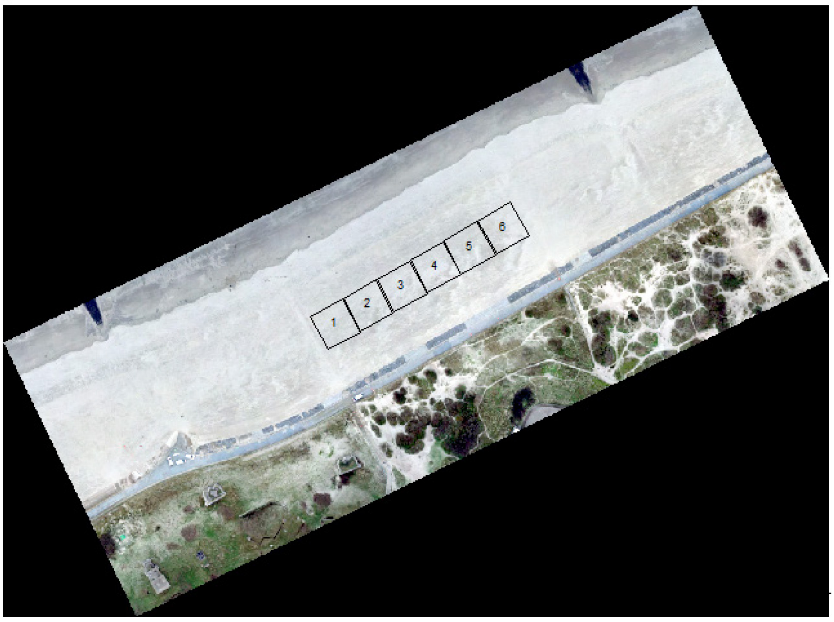
1 Background

An intensive beach monitoring has been carried out by MDK Coastal Division at the pilot study sites where dunes were built-up using brushwood fences, fences and/or marram grass was planted to capture aeolian sand transport.

1.1 Spinoladijk

A small zone of marram of 120 m long 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 (Figure 1). For protection, the zone was demarcated by wire fences to prevent entry which might cause the deterioration of the vegetation. The density of the marram plantation is different in each plot. For more description of the setting, refer to Verwaest et al., 2022. The implemented interventions are intended to promote dune formation and ecology. In addition, the planted zone is a pilot site for dune construction on the dry beach in front of a sea dike. When the dunes were constructed for the dike pilot, 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 with an elevation ranging from 6.5 to 8 m TAW (Figure 1).

A)



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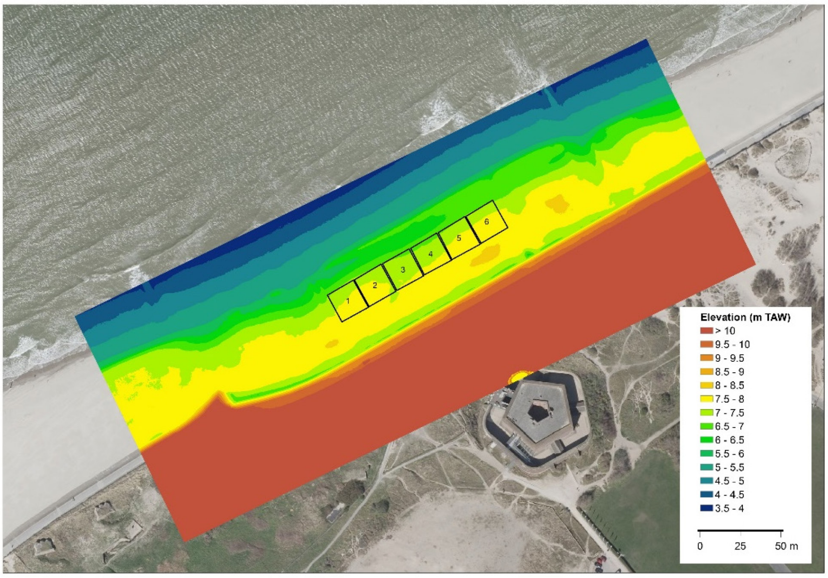


C)

Figure 1 - A) orthophoto, B) digital elevation model in T0 (11/01/2021), C) ground photograph at Spinoladijk

1.2 Raversijde

The pilot site at Raversijde is about 750 m long and is located in sections from 100 to 102. Brushwood fences were placed on the dry beach (from 10/03/2021 to 02/04/2021) and, similar to Spinoladijk area, marram grass was planted with different densities (from 15/03/2021 to 02/04/2021) after a beach nourishment and beach reshaping in early 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). The main aim of this intervention is to limit nuisance caused by aeolian sand on the coastal road/tram line/sea dike. In addition, it is a pilot for dune construction on the dry beach in front of a sea dike.

A)

B)

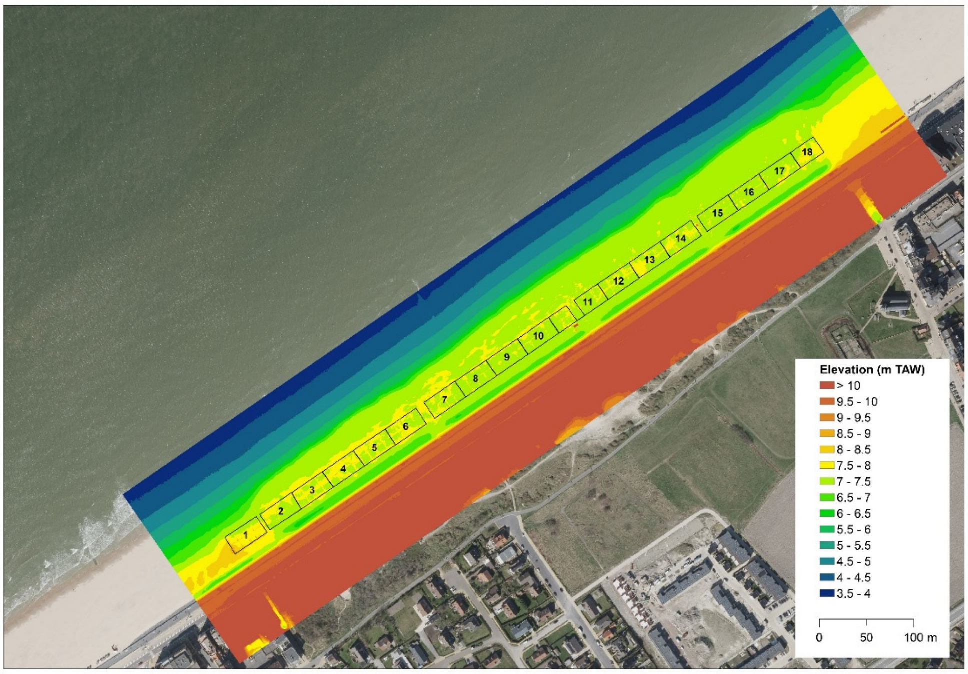


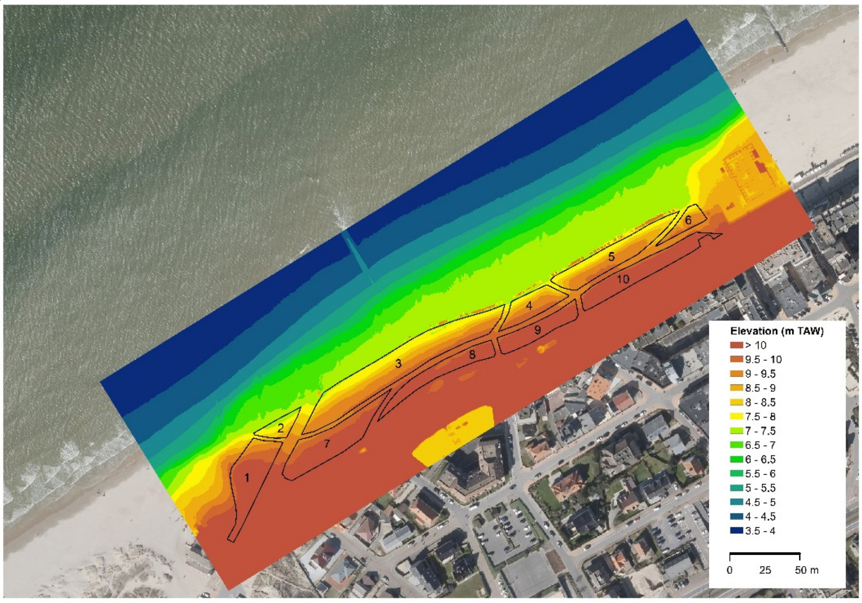
Figure 2 - A) Orthophoto, B) digital elevation model on T0 (31/03/2021) at Raversijde

The width of the dry beach was 65 to 85 m wide (measured from the + 6 m TAW line to the sea dike) when the dune was constructed for the dike pilot. In the area, this width gradually increases from southwest to northeast. 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. Additional marram grass was planted between 14 and 17/02/2023 when 93 zones were set-up with 6 plants/m^2 in a staggered pattern (see Appendix A). In total, 55 800 plants were planted in 2023.

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 01-02/2021. The study site was designed with a high elevation (+10.5 m TAW) in order to comply with the coastal safety standard for a 1000-year storm. Also, the site is 30 m wide and 390 m long (Figure 3). The most southwestern part of the grass dike, in sections 74-75, was selected as the 3rd dune for dike pilot. Sand fences 'zandschermen' and marram grass planting was carried out before the start of the monitoring. 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)

C)

Figure 3 - A) orthophoto, B) digital elevation model in T0 (30/03/2021), C) ground photograph at Westende

2 Monitoring method

The monitoring focussed on the morphological evolution of the pilot sites and was based on two main types of measurements: UAV (Unmanned Aerial Vehicle – drone) data acquisition and RTK-GPS beach profiles.

2.1 Acquisition of UAV surveys

Topographic monitoring at the two dune for dike sites was monthly acquired with a Phantom 4 RTK drone by Xperta-ATO (Table 1). The flight was carried out at a height of 90 m. The survey coverage was about 295 m long and 110 m wide from the dike to 3.8 m TAW at Spinoladijk (Figure 4A). For Raversijde, it was about 845 m long and 165 m wide (between the dike and 3.6 m) (Figure 4B). From 12/09/2022 (T14), the survey coverage was extended seaward to the low water line (around 0.7 m TAW). Thus, the width of survey was of 390 m. The survey coverage generally extended from the sea dike to 3.5 m TAW which was about 125 m wide (except for T4 with 90 m wide) and 485 m long. The survey at Westende covered from the sea dike to 4.5 m TAW and 490 m (Figure 4C). 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).

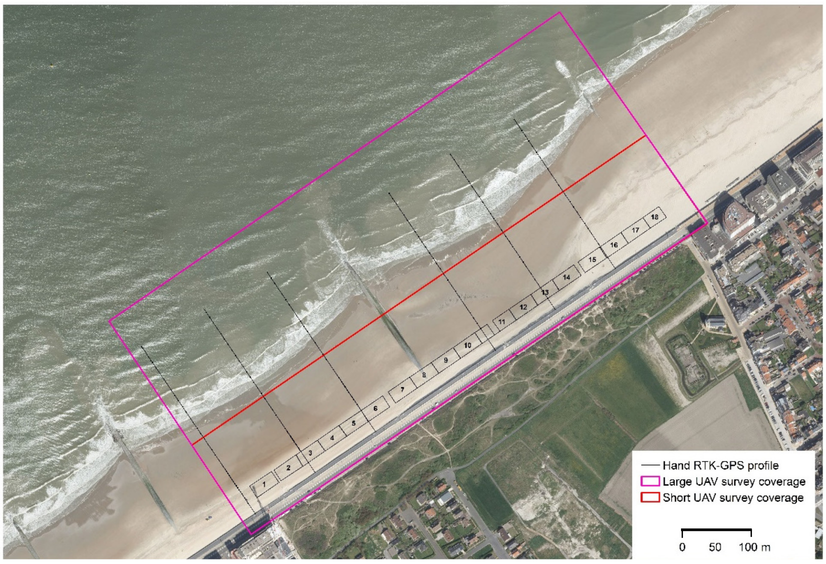
Table 1 - Timeline of the surveys with UAV error based on check points installed on the field during the survey. The bold boxes corresponds to the 2nd monitoring period.

Site	Time	Day	Duration (ref T0)	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
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
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

A)

B)



C)

Figure 4 - Pilot sites with location of the profiles: A) Spinoladijk, B) Raversijde and C) Westende

UAV surveys are processed with Agisoft software to generate digital elevation model (DEM) and 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 a DEM. Therefore interpolation was used to fill up the holes caused by the point filtering. Post-processing consisted in generating DEM of difference (DoD) between consecutive surveys and based to a reference (T0).

Unfortunately, UAV monitoring of the pilot in Westende was stopped after T4 due to issue of getting flight permit. Since then, the LiDAR survey acquired by Coastal Division is used there to assess morphological evolution. The cell size of the DEM and DoD was of 2 m.

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 and Westende as well as 6 profiles at Raversijde (Figure 4). Generally , the survey profiles extended from the seaward side of the vegetated boxes to the low water line (Table 1 and Figure 3). Each profile extends from the seaward vegetation boxes to the low water line 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 reference tool. Then, they were interpolated at a 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.

3 Morphological analysis

3.1 Spinoladijk

The pilot site at Spinoladijk was surveyed from 1/2021 to 02/2023 and the second monitoring period started from 02/2022 (Table 1).

3.1.1 Meteo-marine conditions during the second monitoring period

3.1.1.1. Spinoladijk

Figure 5 shows time series of water level in Ostend, wave height 10% and wave direction in 'Oostende Poortjes' (located 7 km from the coast), wind speed and direction of the weather station in Zeebrugge. The water level exceeded 5.5 m TAW four times, namely on 07/11/2021, 05/01/2022, 31/01/2022 (Corrie storm), and 21/02/2022 (Franklin storm). While for the period between Franklin storm and the last UAV survey, it only reached 5.3 m TAW only two times on 27/09/2022 and 25/02/2023 when the wind speed was below 10 m/s coming from NW. During the Corrie storm on 31/01/2022 at 12:00, the water level reached 5.73 m TAW (a surge of 1.49 m), the 10% wave height was approximately 5.24 m coming from NW (perpendicular to the shoreline) (Table 2) and the wind speed was about 15 m/ blowing from NW. During the Franklin storm on 21/02/2022 at 3:00 am, the meteo-marine conditions were lower than the Corrie storm with a water level of 5.57 m TAW (a surge of 0.82 m), the 10% wave height was approximately 4.31 m from W (diagonal to the coastline) and with a wind speed about 14 m/s blowing from W. The first year monitoring was characterized by more peaks of wind events than the most recent period starting from 05/2022.

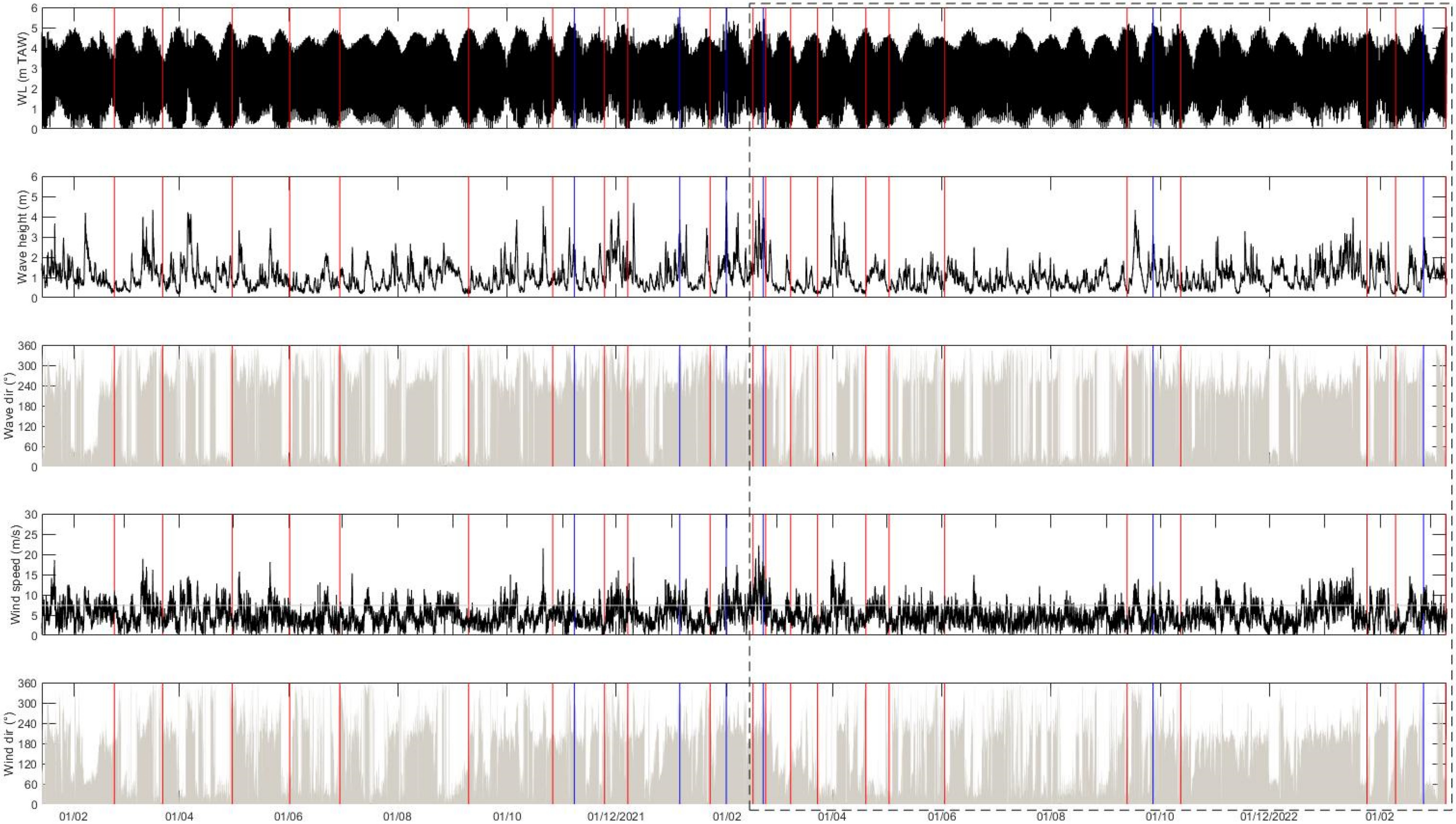


Figure 5 - Time series of the water level in Ostend, wave height 10% and wave direction in Ostend "Poortjes" (buoy located 7 km from the coast), wind speed and direction of weather station Zeebrugge (Meetnet Vlaamse Banken). Vertical red and blue lines correspond to the drone surveys and energetic events 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 2nd year monitoring.

3.1.2 Morphological evolution from months to 2.5 years

Figure 6 presents the morphological evolution of the entire beach DoDs from months to years. Refer to Figure 1B for the elevation across the beach. DoD clearly indicates the gradual accretion in the vegetated boxes between Box 1 and 6 from 2.3 month to 2.08 year. The boxes have gained sand material nearly up to 2 m high till the last survey (Figure 6F). The upper part of the dry beach located landward of the boxes shows a large sand accumulation up to 1 m high along the dike, which contrast with negative morphological changes on the beach located just east and west of the vegetated boxes. These are likely due to the surroundings of the excavation works were carried out several times by the city of Ostend in this zone as part of the policy to reduce the nuisance caused by sand transport over the dike (i.e. observation of the truck tires tracks on the UAV orthophotos). The lower part of the dry beach and seaward of the boxes and below 5 m TAW indicates erosion up to 0.4 m, but here too it should be mentioned that there were interferences from the activities of the city of Ostend. Noteworthy, there is a line of morphological stability where the changes was below +/- 0.05 m at 7.5 to 7.7 m TAW and also at 6 and 5 m TAW delimiting the different spatial morphological trend across the beach.

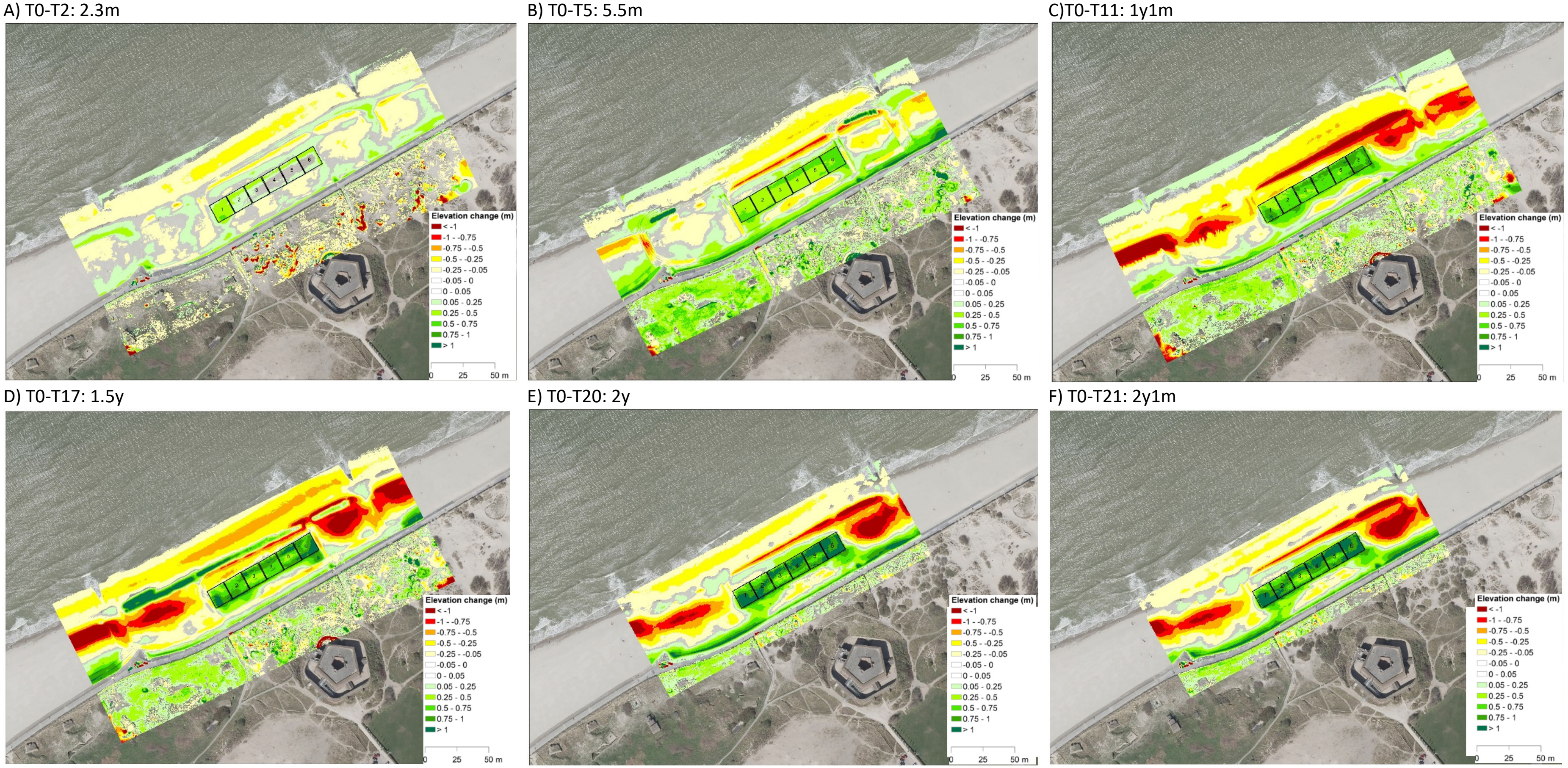
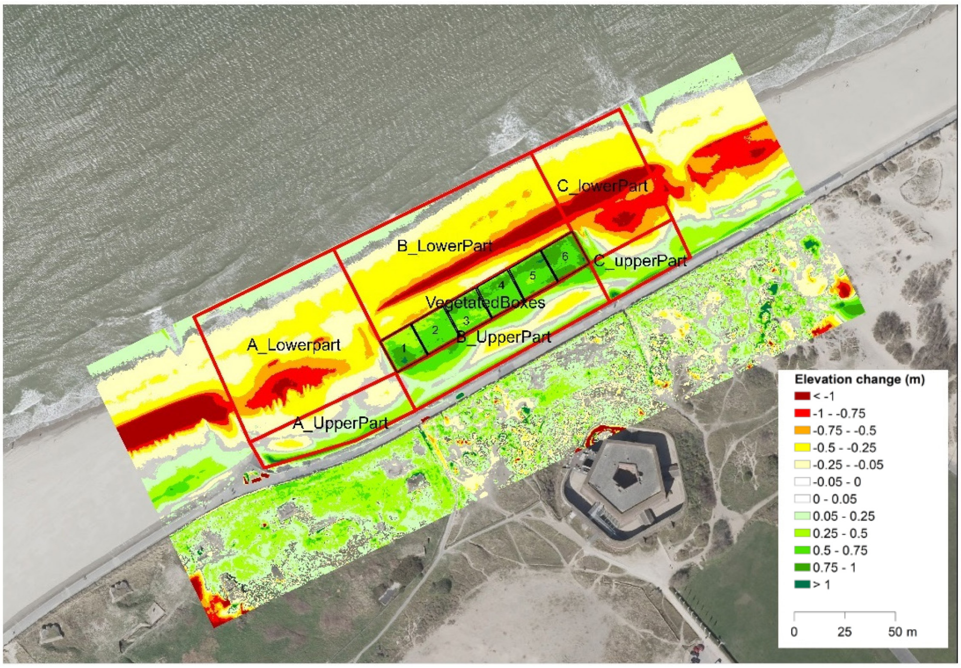


Figure 6 - Global evolution based on Ref DoDs of the UAV surveys at Spinoladijk

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 7). Interestingly, the side boxes (Box 1 and 6) seems to gain more sand than the centre ones and in particular Box 1 for the most recent period. It is probably related to their position at the side which is favourable to catch alongshore aeolian sand transport. As previously mentioned, human interferences might have caused the large erosion observed on the lower part of the dry beach (i.e. seaward of the vegetated boxes) over the 1st year but this erosion was limited for the recent period. A common morphological pattern between the two periods is that the upper-beach located landward of the boxes was in accretion with a line of morphological stability at 7.5 to 7.7 m TAW. However, the lower part of the dry beach located seaward of the boxes was subject to opposite trend with erosion between T0-T11 and accretion between T11-T21.

Figure 8 displays time series of all the merged UAV and RTK-GPS profile surveys. To simplify their visual representations, evolution of some selected beach profiles is shown in Figure 9. Profile 1 is located west of the vegetated boxes and Profile 2 and 3 intersect Box 3 and 6 respectively. Profiles 2 and 3 show a similar pattern with accretion on the upper-beach where are located the vegetated boxes, while erosion dominates along the seaward dry beach slope compared to T0. However, this area gained sand during the period T11-T21. The bump located at 60 m from the dike on T17 disappeared in the recent period. Noteworthy, the net accretion in the vegetated boxes horizontally expanded to their landward side up to 18 m as displayed in Profile 3. Regarding Profile 1 located west of the vegetated box, the upper-beach close to the dike gained height (filling of the trench excavated by city of Ostend) but the rest of the profile seems to have lost sand. Same observations as Profile 2 and 3, the bump present in T17 vanished in the recent period and accretion on the seaward dry beach slope dominated the period between T11-T21 .

A)T0-T11: 1y1m



B) T11-T21: 1y

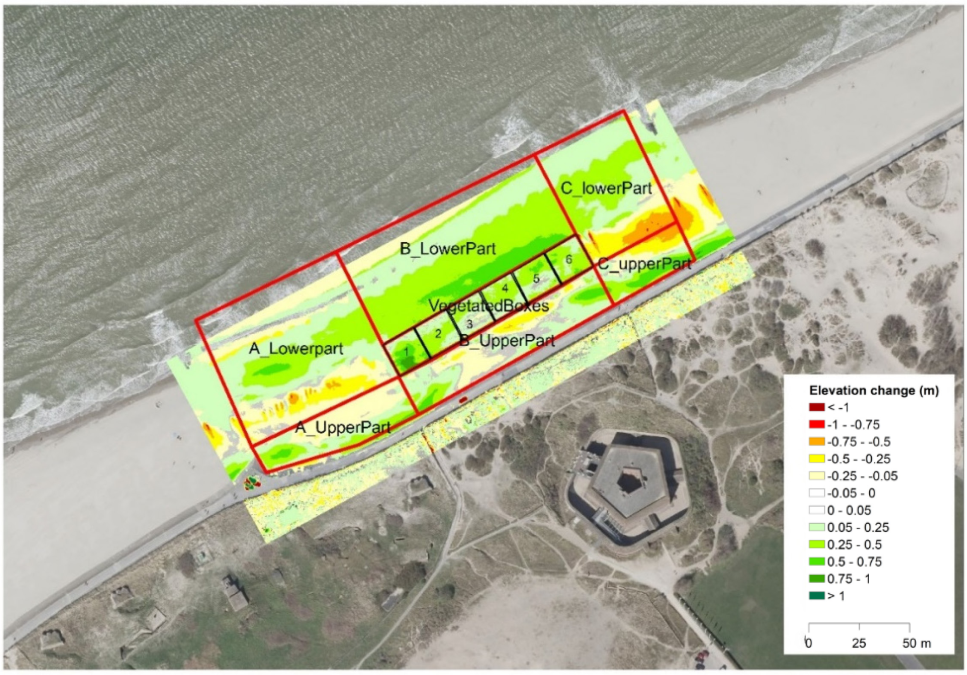


Figure 7 - Annual evolution based on DoDs of the UAV surveys.
The UAV survey coverage was smaller in T21 explaining the difference of the DoD size.

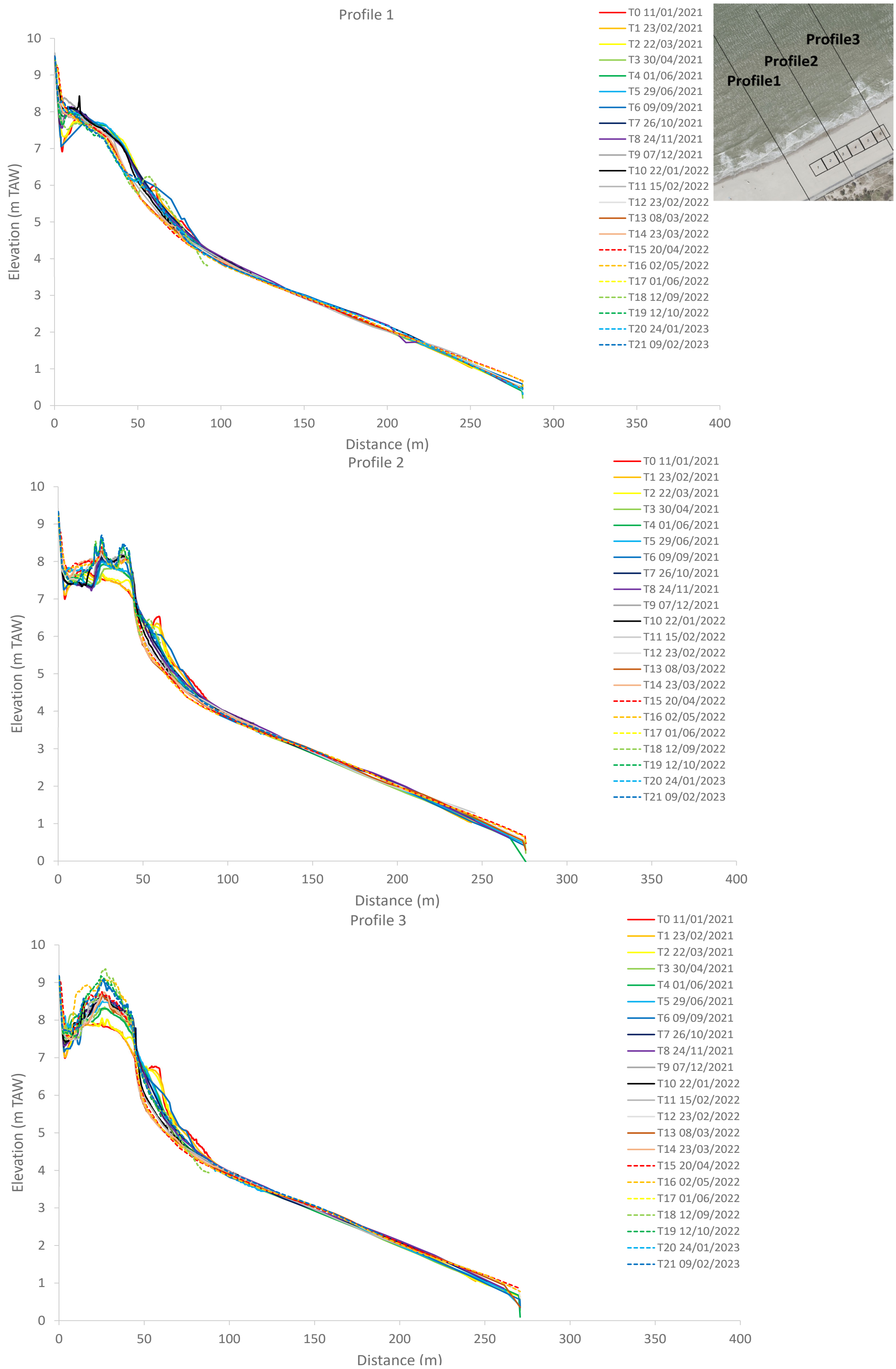


Figure 8 - Time series of all the merged profiles of the UAV and RTK-GPS surveys. Inset indicates the location of the profiles.

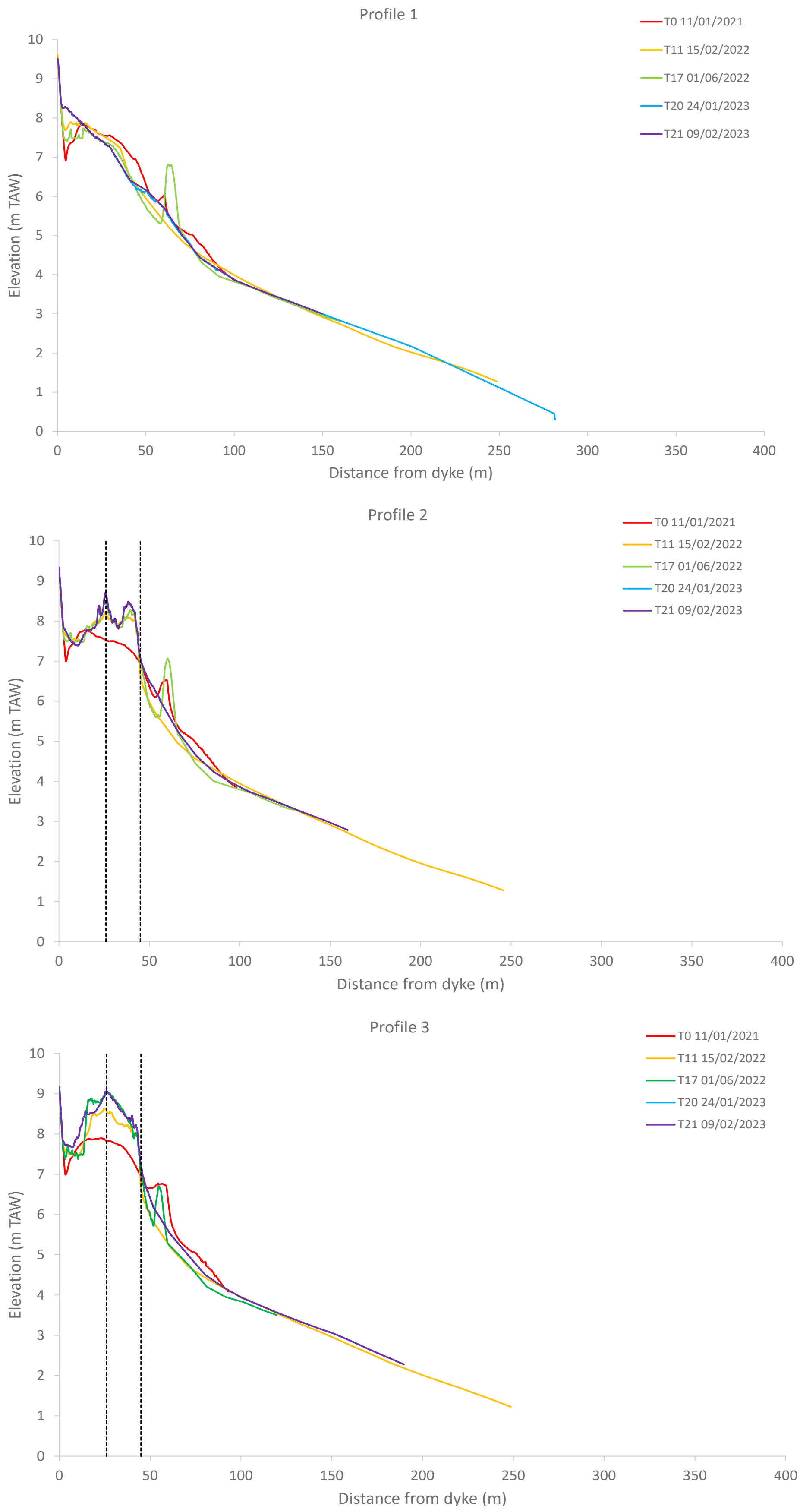


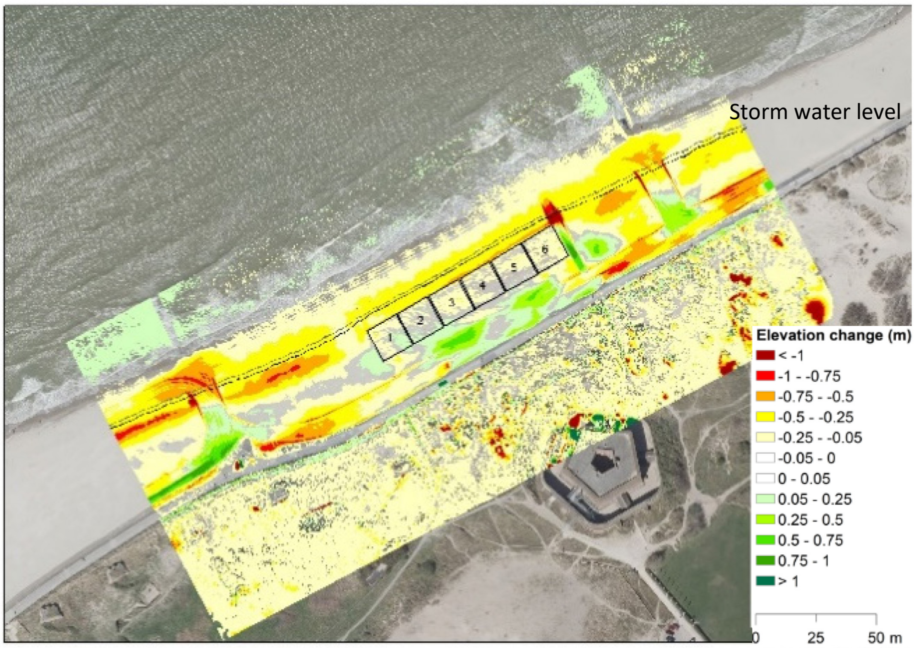
Figure 9 - Time series of evolution of the merged profiles of the UAV and RTK-GPS surveys.
The vertical dashed lines correspond to the location of the wire fences.

3.1.3 Comparison of impacts from energetic events

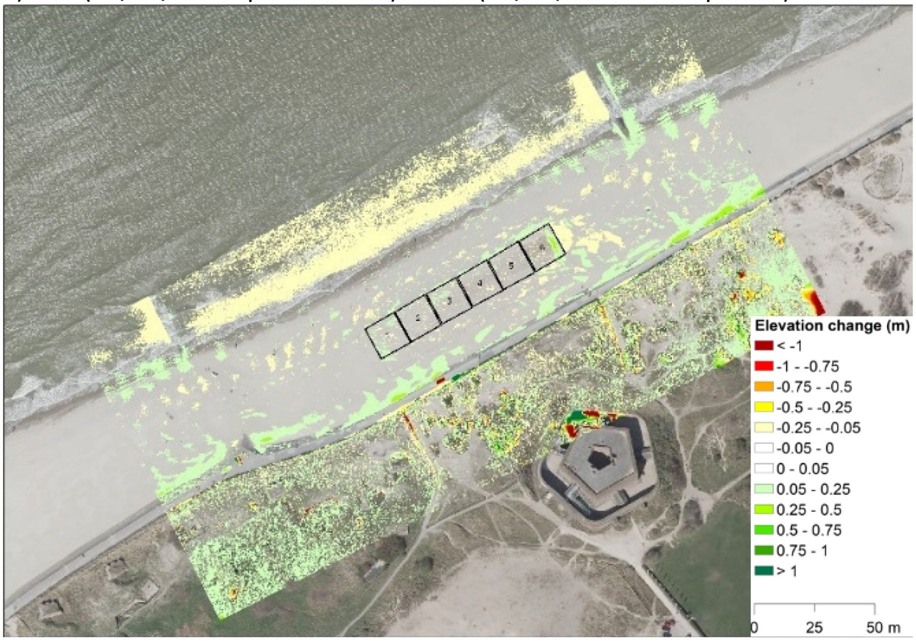
DoDs of the dry beach (above 3.5 m TAW) for the pre and post-energetic events are displayed in Figure 10. Generally, morphological change in the vegetated boxes was limited over these periods. Storms in 01-02/2022 reached a maximum water level of 5.73 m and 5.57 m TAW. Erosion up to 1 m occurred in front of the vegetated boxes, while no significant changes occurred within and landward of the boxes (Figure 10A). In the area aside the boxes erosion is also visible along the dike. There was a limited presence of a small cliff. The question arises whether this is a natural phenomenon or the result of sand works carried out by the city of Ostend. However, no data is available on the sand works carried out by the city of Ostend. The post-storm period T12-T13 indicates no significant changes in height occurred on the dry beach (height difference < 5 cm), while the lower part suggests slight erosion (Figure 10B). The water level for the recent energetic event on 09/2022 reached 5.36 m TAW. Generally, the beach between 6.2 and 4.5 m TAW was in erosion, while the lowest part of the dry beach gained sand (Figure 10C). It is likely that sand was deposited there from the eroded zone by aeolian processes. Clear accretion spots are observed in front of the vegetated boxes, however no erosion occurred in front of them (in contrast to what was observed for 01-02/2022 storm). These accretive spots are still present for the post-storm period T19-T20 considered as calm since no energetic event occurred. Compared to the pre-post storm period, an opposite trend in the lower part of the dry beach is observed with a sand gain during the recovery period. Thus, the common observation between the two energetic events is this opposite morphological change named reversal morphological trend between pre- and post-storm, as well as the stability in the vegetated boxes.

Time series of the pre-, post and recovery period of the merged profiles of the UAV and RTK-GPS surveys are presented in Figure 11. Generally, the dry beach slope was eroded during 01-02/2022 while it was relatively stable during 09/2022 storm. As previously observed in the DoDs, the consecutive 01-02/2022 storm events impacted at a higher magnitude the beach than the energetic event in 09/2022.

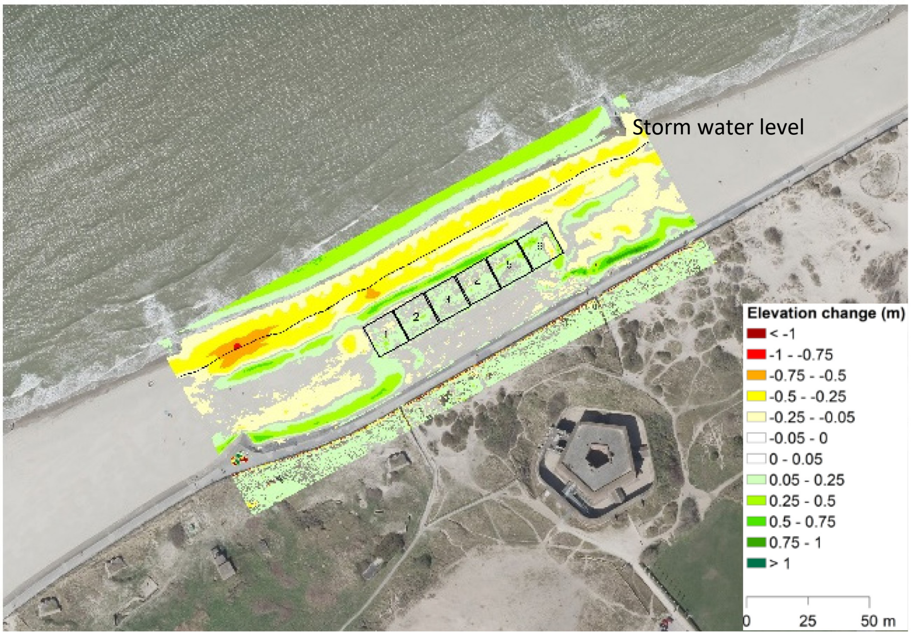
A) T10 (17/01/2022) - T12 (23/02/2022: post-storms)



B) T12 (23/02/2022: post-storms) – T13 (08/03/2022: calm period)



C) T18 (12/09/2022) - T19 (12/10/2022: post-storm)



D) T19 (12/10/2022: post-storms) – T20 (24/01/2023: calm period)

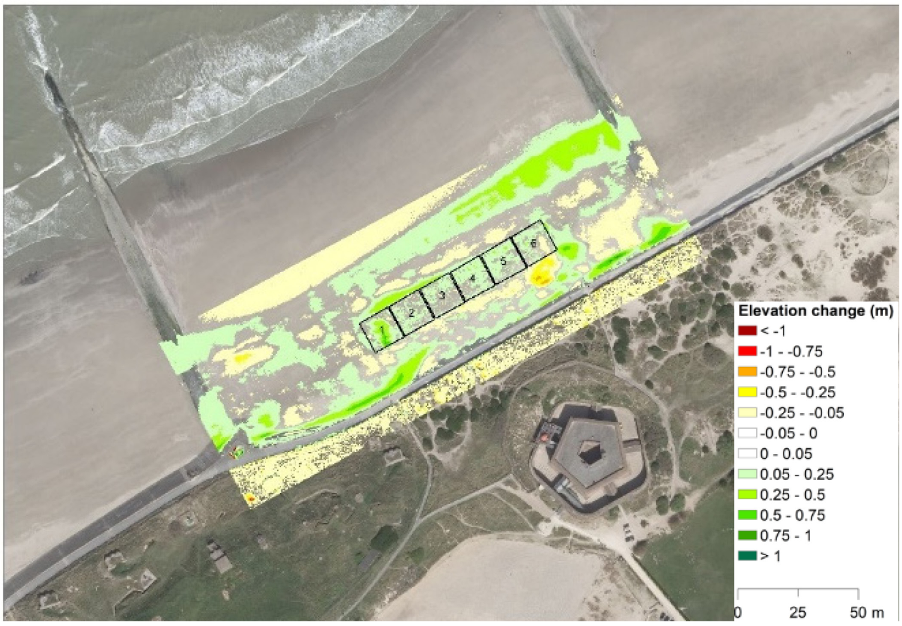
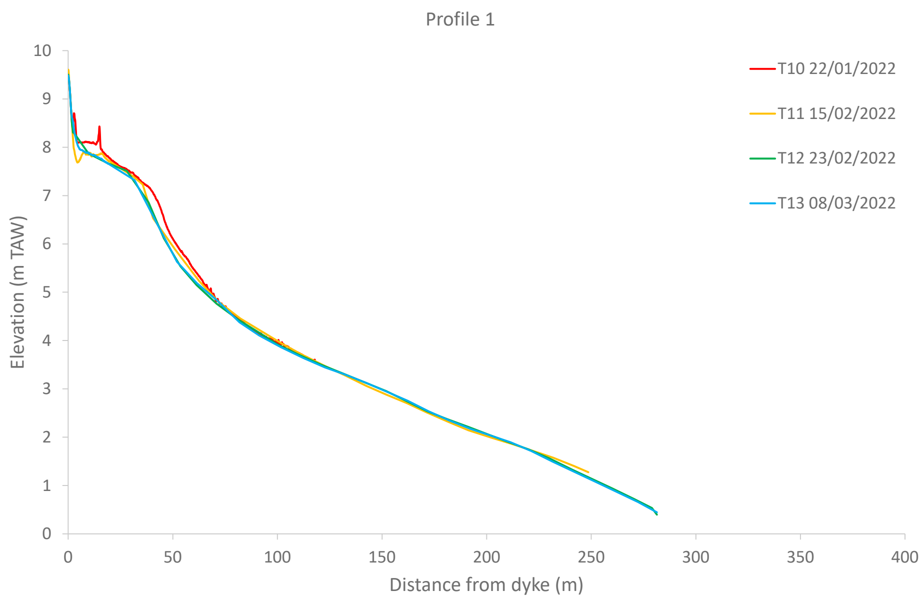
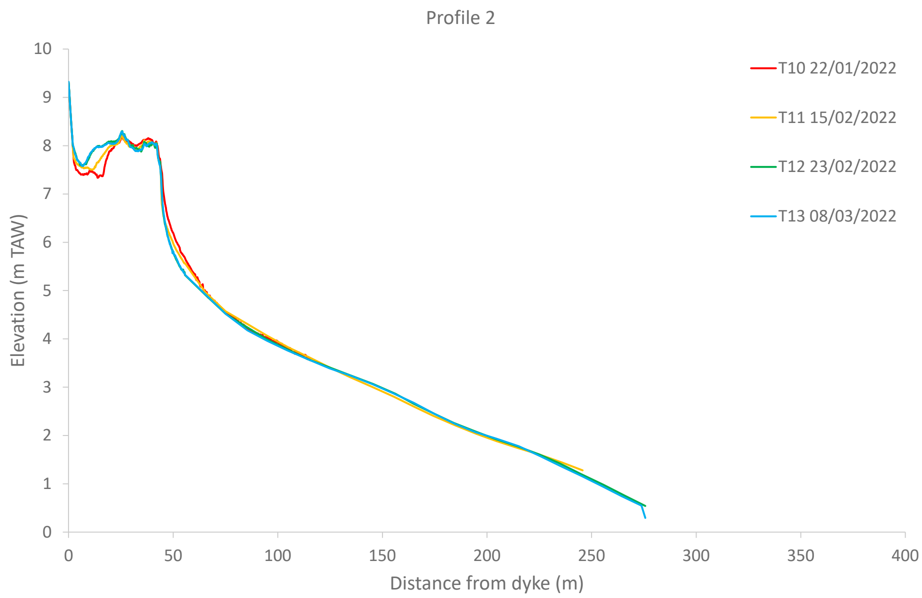
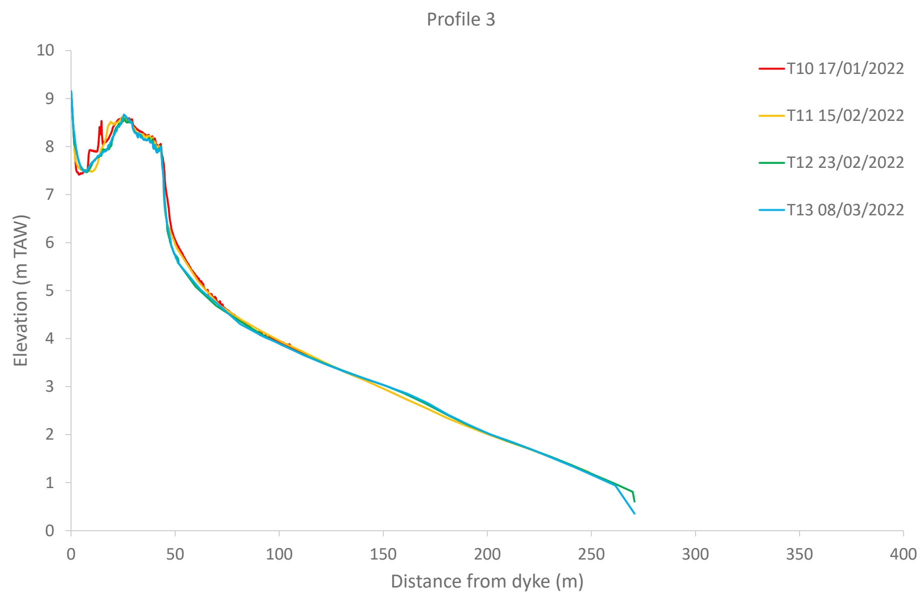


Figure 10 - DoD of pre and post-energetic events and calm period: T10-T12 (17/01/2022-23/02/2022); T12-T13 (23/02/2022-08/03/2022); T18-T19 (12/09/2022-12/10/2022); T19-T20 (12/10/2022-24/01/2023).
The dashed lines correspond to the water level reached during the energetic events.


Profile 1
Elevation (m TAW)
Distance from dyke (m)
T10 22/01/2022
T11 15/02/2022
T12 23/02/2022
T13 08/03/2022


Profile 2
Elevation (m TAW)
Distance from dyke (m)
T10 22/01/2022
T11 15/02/2022
T12 23/02/2022
T13 08/03/2022


Profile 3
Elevation (m TAW)
Distance from dyke (m)
T10 17/01/2022
T11 15/02/2022
T12 23/02/2022
T13 08/03/2022

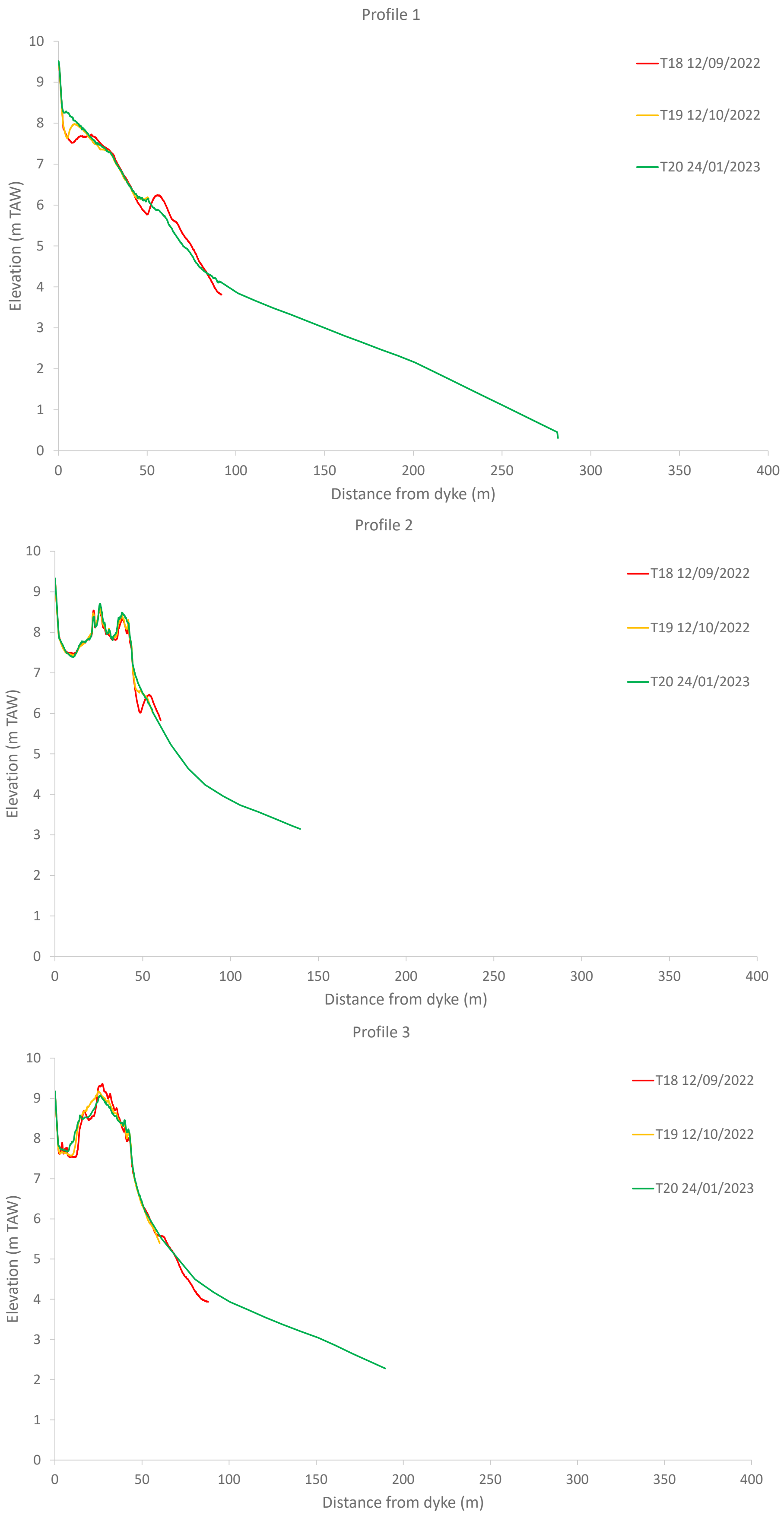


Figure 11 - Time series of the pre-, post and recovery period of the merged profiles of the UAV and RTK-GPS surveys.

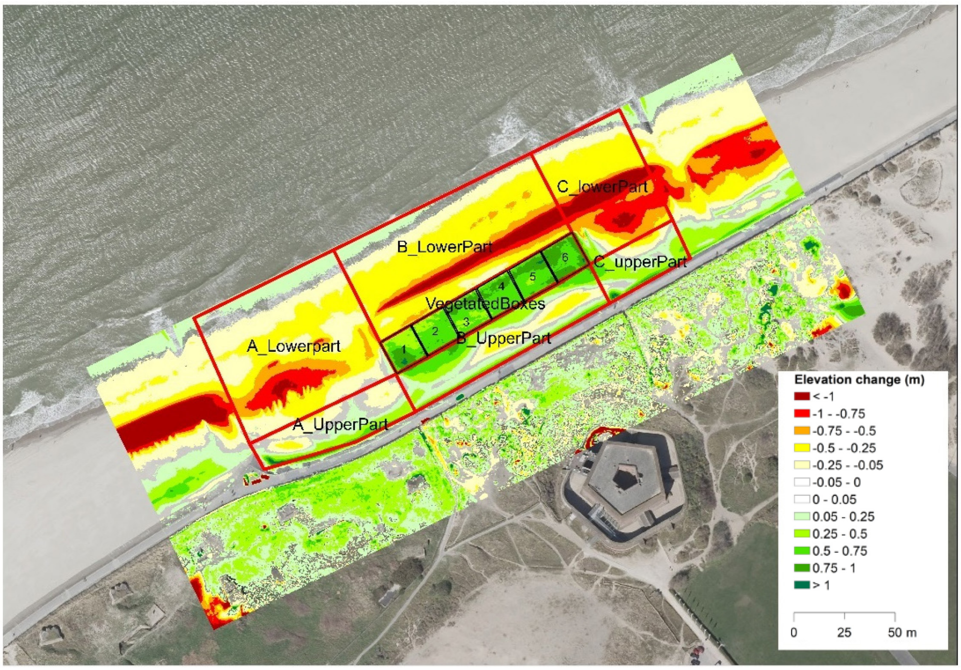
3.1.4 Volumetric changes

The study area is divided into a number of zones (Figure 12). The volumetric evolution in these zones was calculated using the UAV DEMs and the results are given in Table 2.

As previously observed on the DoD, a net accretion took place on the landward side of the dry beach (zones defined as upper-part) on the 1st (T0-T11) and 2nd (T11-T21) monitoring year, while erosion occurred on the seaward side (zones defined as lower-part). Generally, the volumetric change was lower for the recent year. However, the interpretation of these data is made more difficult because sand works were carried out several times in the period under consideration by the city of Ostend, for which no data are available. In the zone of the vegetated boxes, an average growth of 0.6 m^3/m^2/year and 0.28 m^3/m^2/year occurred for the 1^{st} (T0-T11) and 2^{nd} (T11-T21) monitoring year respectively. Thus the accretion was two times lower for the recent period. Also, a positive volumetric change of the landward zone (upper part A, B, C) generally occurred for the 2^{nd} year monitoring. Despite it is lower for the 2nd year monitoring than the first period, the sand gain is still significant, both behind the boxes as well as aside the boxes. In the 2^{nd} year less aeolian sand was transported through the vegetated boxes and then locally deposited in the landward zone behind Box 1 and 6 (upper part B). Surprisingly, a slight and spreaded erosion was also observed there for the landward side of Box from 2 to 5. For the zones of the lower part accretion is observed during the 2^{nd} year, in contract to erosion during the 1^{st} year; the overall sand balance in the area is not conclusive (net loss of -0.19 m^3/m^2/year). It is probably partly due to the sand works carried out in the surrounding of the study site by the city of Ostend, and partly to natural erosion.

Generally, the morphological impact on the beach zones caused by the storm in Jan-Feb 2022 is larger than the one in 09/2022. In general, no significant changes occurred in the vegetated boxes, except a slight sand gain for the period T18-T20. As expected, a storm with a water level reaching a high elevation erodes the most. In the case of the consecutive storms in 01-02/2022, the impact was greater due to a restricted time of 22 days for the beach to recover between the events. The lower part of the beach and in particular zone A upper-part lost sand just after the occurrence of both storms (T10-T11, T18-T19), whereas accretion or stability took place in the other zones. The post-storm periods (T12-T13, T19-T20) with calm conditions is usually characterized by a slightly positive or stable sand budget.

A)T0-T11: 1y1m



B) T11-T21: 1y

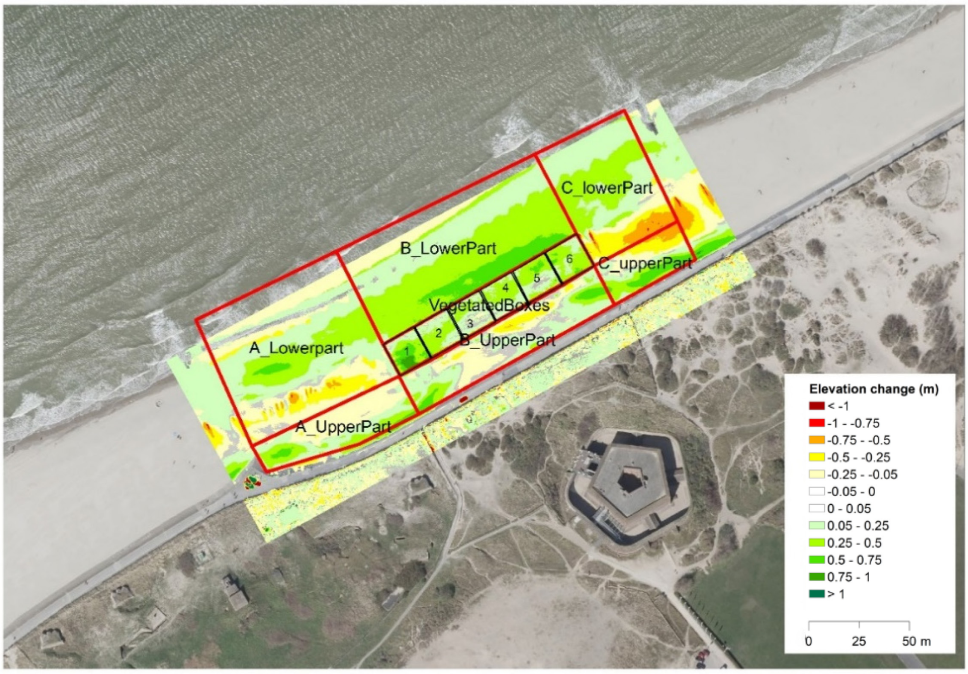


Figure 12 - Location of the contours of the defined zones on the DoD: A) T0-T11, B) T11-T21.
Note: the drone coverage of the lower part of the beach was reduced from T18.

Table 2 - Volumetric changes of the defined zones. Green (accretion), red (erosion), grey (stability).

		Diff Volume (m^3/m^2)						
	Time	VegetatedBoxes	A_UpperPart	A_Lowerpart	B_UpperPart	B_LowerPart	C_upperPart	C_lowerPart
Global (Ref T0)	T0-T2	0.16	0.01	-0.05	0.01	-0.11	0.06	-0.10
	T0-T5	0.46	0.18	0.00	0.19	-0.19	0.32	-0.14
	T0-T17	0.73	-0.07	-0.21	0.18	-0.30	-0.05	-0.56
	T0-T21	0.93	0.16	-0.02	0.26	-0.01	0.26	-0.38
	T0-T21 ($m^3/m^2/y$)	0.45	0.08	-0.01	0.13	0.00	0.13	-0.18
Annual	T0-T11	0.65	0.09	-0.28	0.20	-0.41	0.19	-0.52
	T0-T11 ($m^3/m^2/y$)	0.60	0.08	-0.26	0.19	-0.38	0.18	-0.48
	T11-T21	0.28	0.07	0.26	0.06	0.40	0.07	0.14
	T11-T21 ($m^3/m^2/y$)	0.28	0.07	0.26	0.06	0.40	0.07	0.14
Consecutive surveys for storm event	T10 -T11 (post-Corrie storm)	-0.05	-0.20	-0.09	0.00	-0.06	-0.26	-0.12
	T11 (post-Corrie storm)-T12 (post-Franklin storm)	-0.01	-0.02	-0.07	0.08	-0.07	-0.08	-0.08
	T12 (post-Franklin storm)-T13 (calm period)	0.00	0.03	-0.02	0.02	-0.03	0.01	-0.02
	T10-T12 (post-storms)	-0.06	-0.22	-0.16	0.08	-0.12	-0.21	-0.20
	T18 -T19 (post-Sept storm)	0.08	0.08	-0.09	0.02	-0.03	0.10	-0.03
	T19 (post-Sept storm)- T20 (calm period)	0.08	0.08	-0.01	0.02	0.05	0.06	0.10

3.2 Raversijde

The pilot site at Raversijde was surveyed from 03/2021 to 03/2023 and the second monitoring period started from 03/2022 (Table 1).

3.2.1 Meteo marine conditions during the second monitoring period

Figure 13 shows time series of water level in Ostend, wave height 10% and wave direction in 'Oostende Poortjes' (located 7 km from the coast), wind speed and direction of the weather station in Zeebrugge.

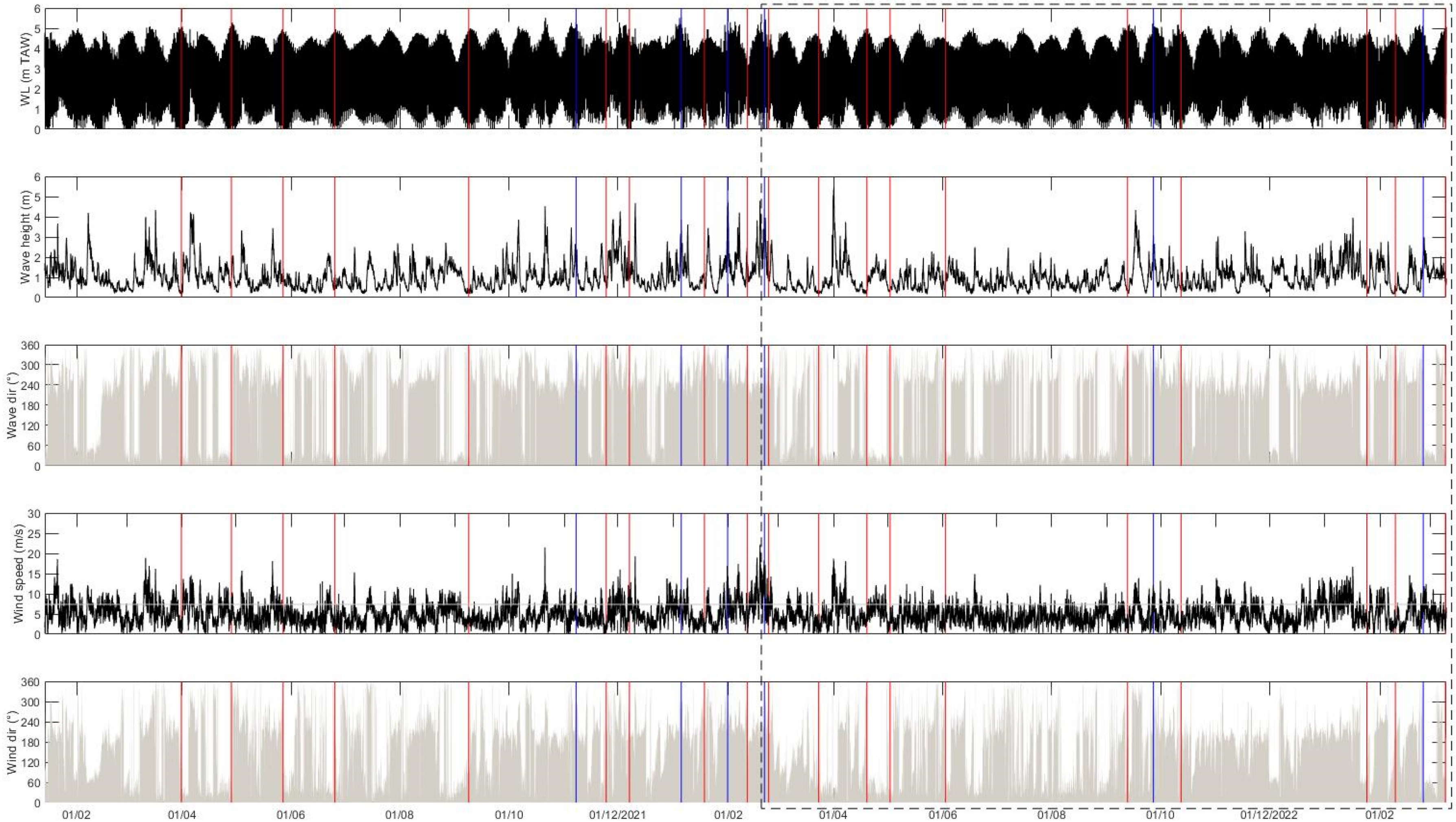


Figure 13 - Time series of the water level in Ostend, wave height 10% and wave direction in Ostend "Poortjes" (buoy located 7 km from the coast), wind speed and direction of weather station Zeebrugge (Meetnet Vlaamse Banken). Vertical red and blue lines correspond to the drone surveys and energetic events 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 2nd year monitoring.

3.2.2 Morphological evolution from months to 2 years

The DoDs indicate a progressive evolution of the pilot site (Figure 14). Refer to Figure 2B for the elevation across the beach. The net accumulation in the vegetated boxes and in their landward side clearly contrasts with erosion in the seaward side. Sand accreted in the vegetated boxes from 1.5 m to 1.2 m for the period between T0 -T10 and T10-T18 (Figure 15). It seems that the highest sand gain over the 2nd monitoring period occurred at the landward edge of the vegetated boxes while it was more in the seaward and center in the 1st period. The passages between boxes and especially Box 1 located southwest were more filled up in T0-T10 than in T10-T18. Another difference is that a significant erosion clearly dominated the beach at an elevation below 7.2 m TAW while it was much lower for the second period. Noteworthy, the extend of the UAV survey for T10-T18 makes possible to observe the accretion of 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 upper and lower part of the beach profile.

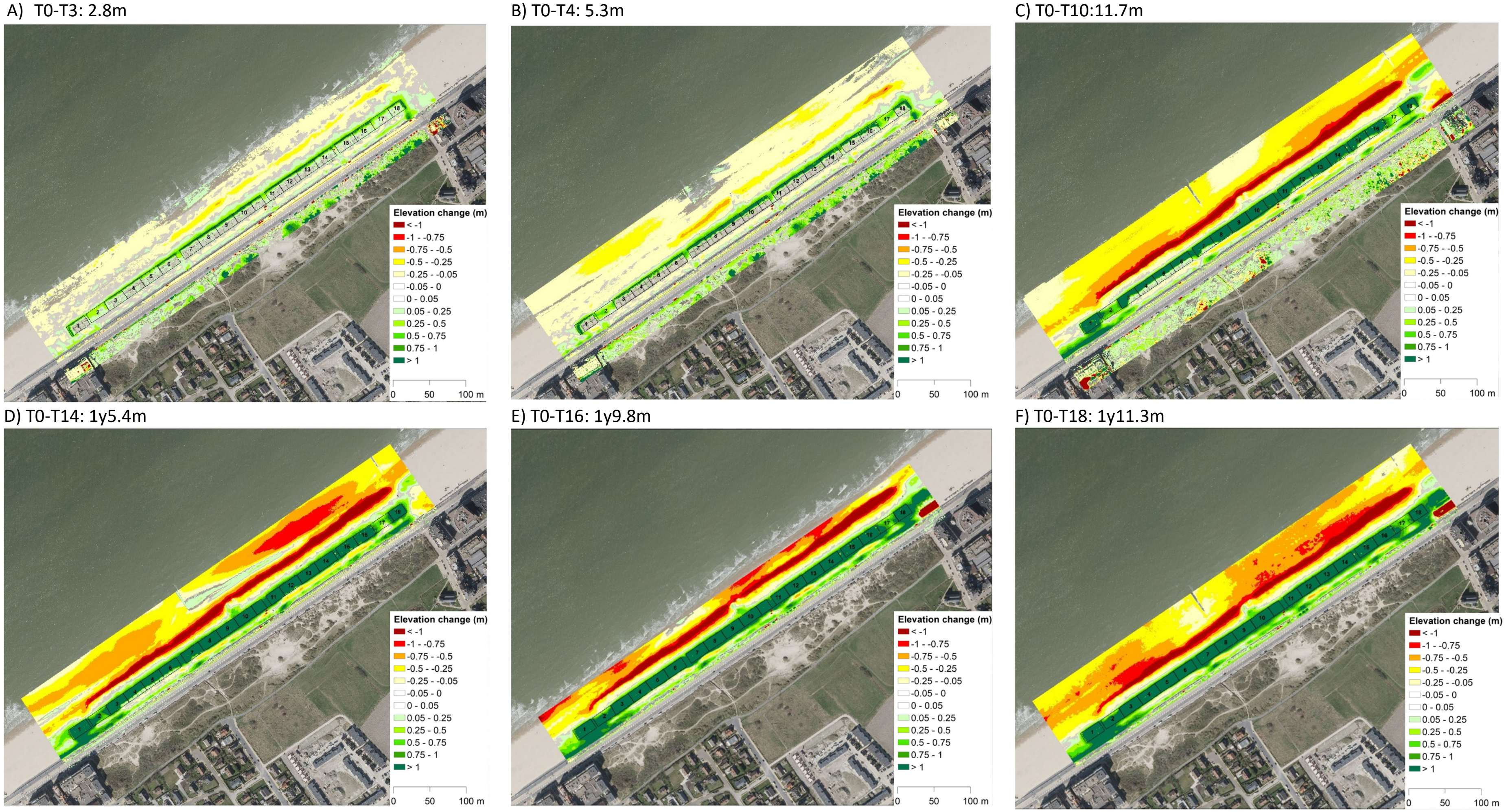
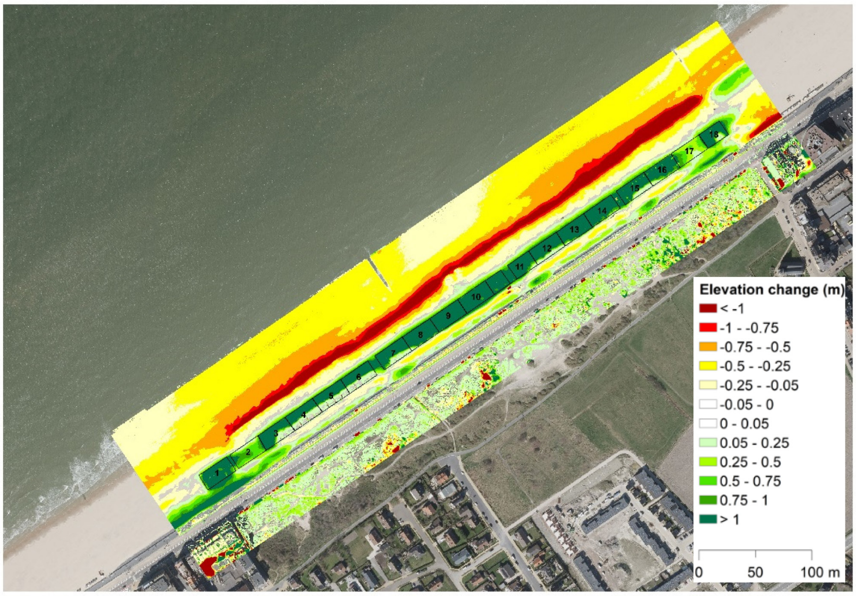


Figure 14 - Global evolution based on Ref DoDs of the UAV surveys

All the 6 merged profiles of the UAV and RTK-GPS surveys are presented in Figure 16. Profile 1 is located southwest of the pilot area, and Profiles 2 to 6 cross the vegetated boxes and extent to the low-water mark. Generally, the evolution of the profiles clearly indicate that the upper-dry beach where are the vegetated boxes gained a large quantity of sand up to 2 m high compared to T0 (Figure 17). This was lower for Profile 1 where no vegetated box was present. Thus, Profile 1 was relatively more stable across the dry beach than in the other profiles. This can probably be linked to the plateau that was created during the construction of the pilot, which is not present at Profile 1. The absence of brushwood fences in this area might have prevented sand capture but instead it was blown towards the hinterland. In addition, the slope of the upper-beach for the three measured profiles retreated landward with an average of 13 m over the time. Nevertheless, it seems that its steepness did not change. Erosion dominated the dry beach located seaward of the vegetated boxes and also partly in the intertidal zone. However, accretion occurred in the lowest part of the intertidal zone at a distance of > 200 m as observed by the green band located the most seaward (Figure 15B). This can be explained by the deposited sand that was eroded in the higher part of the profile during stormy conditions.

A) T0-T10: 11.7m



B) T10-T18: 11.5m

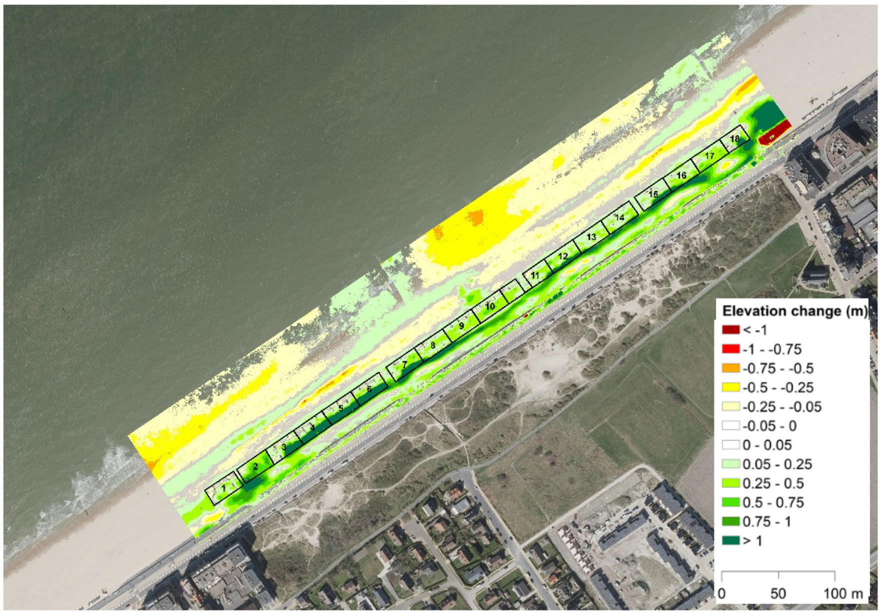
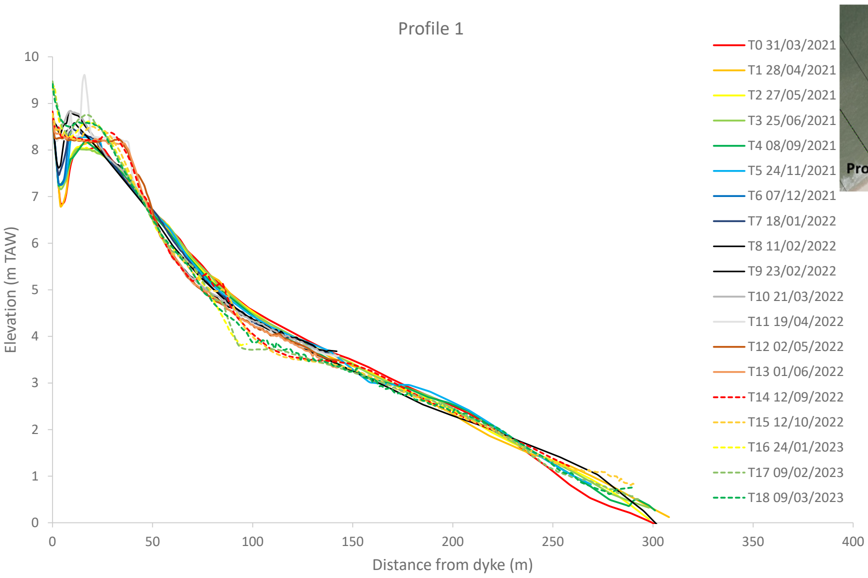
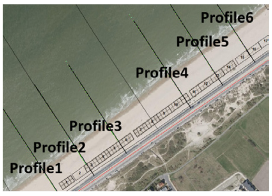
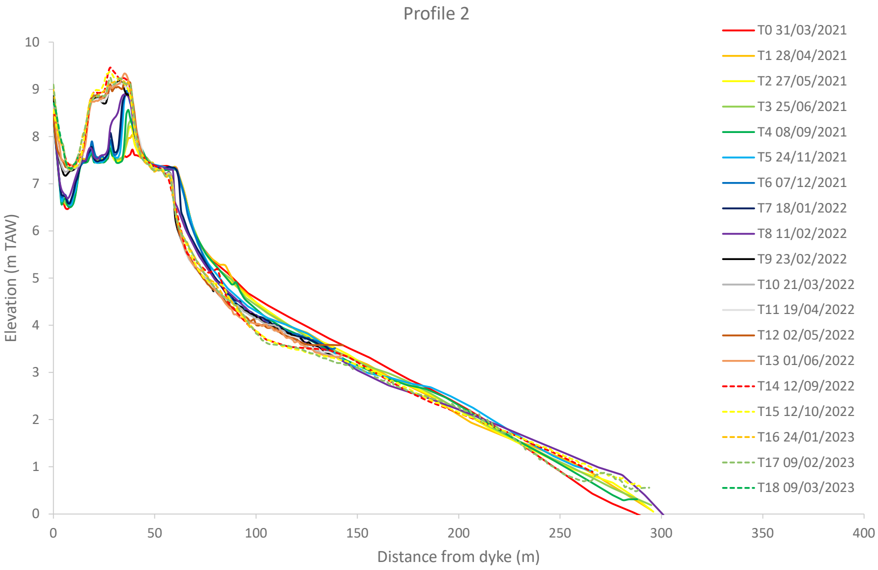
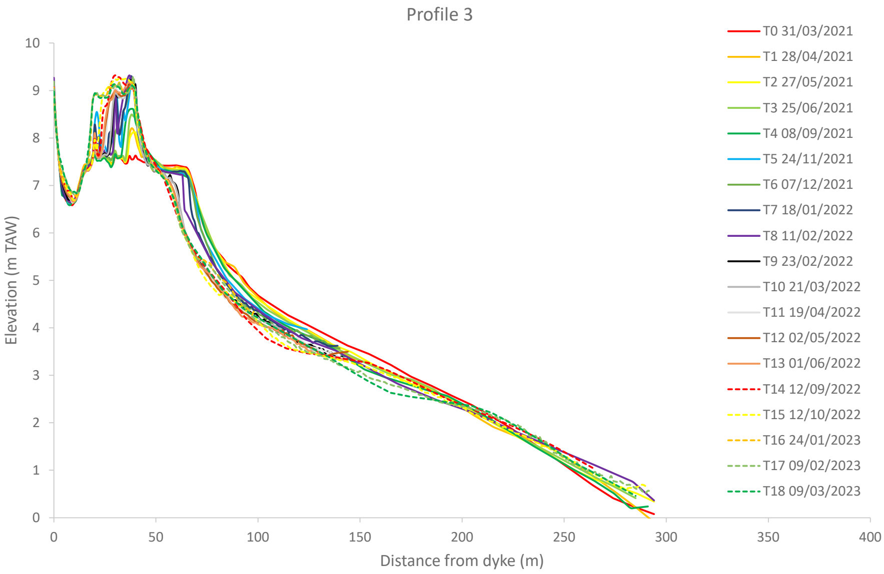


Figure 15 - Annual evolution based on DoDs of the UAV surveys


Profile 1
Elevation (m TAW)
Distance from dyke (m)
T0 31/03/2021
T1 28/04/2021
T2 27/05/2021
T3 25/06/2021
T4 08/09/2021
T5 24/11/2021
T6 07/12/2021
T7 18/01/2022
T8 11/02/2022
T9 23/02/2022
T10 21/03/2022
T11 19/04/2022
T12 02/05/2022
T13 01/06/2022
T14 12/09/2022
T15 12/10/2022
T16 24/01/2023
T17 09/02/2023
T18 09/03/2023


Profile6
Profile5
Profile4
Profile3
Profile2
Profile1


Profile 2
Elevation (m TAW)
Distance from dyke (m)
T0 31/03/2021
T1 28/04/2021
T2 27/05/2021
T3 25/06/2021
T4 08/09/2021
T5 24/11/2021
T6 07/12/2021
T7 18/01/2022
T8 11/02/2022
T9 23/02/2022
T10 21/03/2022
T11 19/04/2022
T12 02/05/2022
T13 01/06/2022
T14 12/09/2022
T15 12/10/2022
T16 24/01/2023
T17 09/02/2023
T18 09/03/2023


Profile 3
Elevation (m TAW)
Distance from dyke (m)
T0 31/03/2021
T1 28/04/2021
T2 27/05/2021
T3 25/06/2021
T4 08/09/2021
T5 24/11/2021
T6 07/12/2021
T7 18/01/2022
T8 11/02/2022
T9 23/02/2022
T10 21/03/2022
T11 19/04/2022
T12 02/05/2022
T13 01/06/2022
T14 12/09/2022
T15 12/10/2022
T16 24/01/2023
T17 09/02/2023
T18 09/03/2023

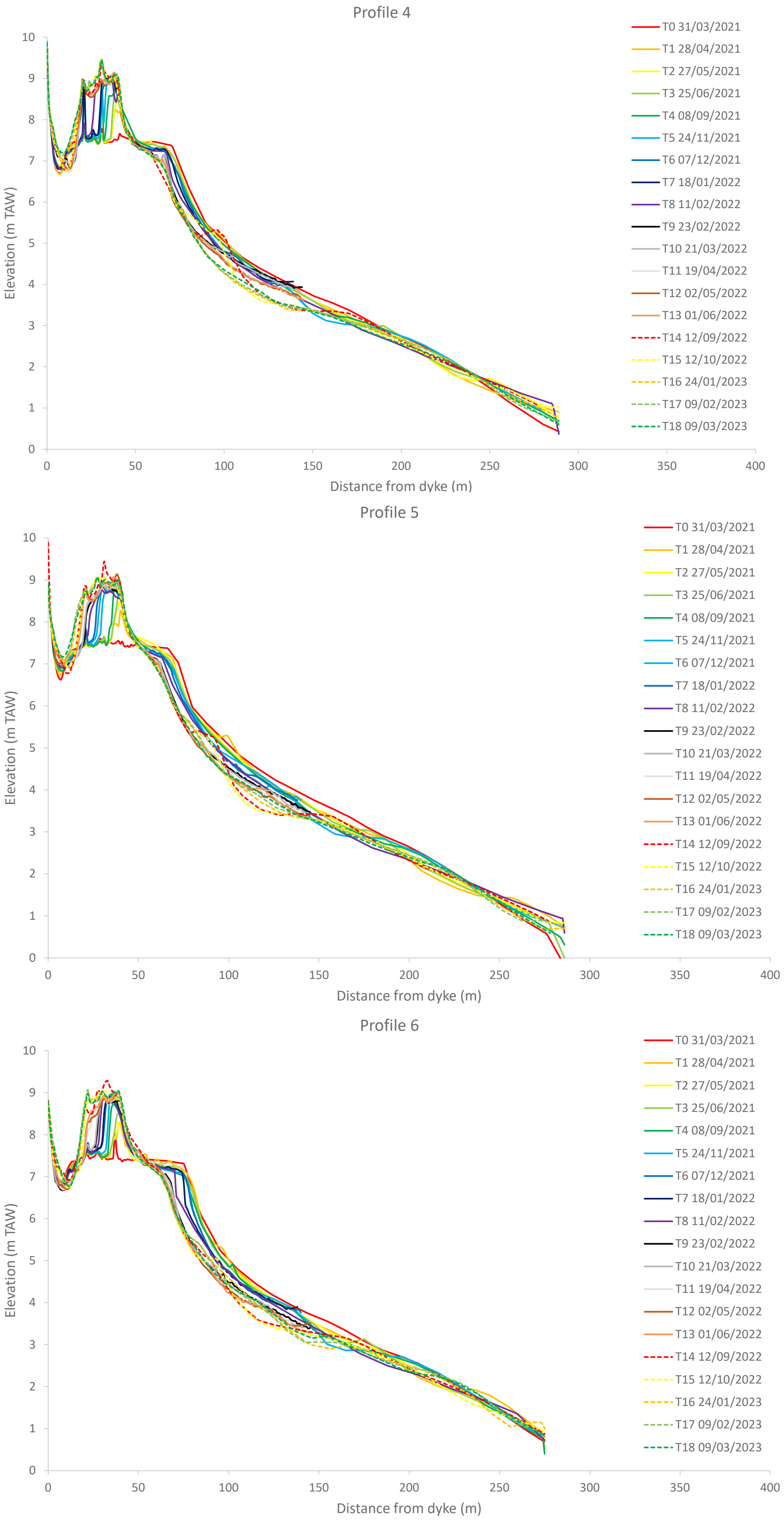
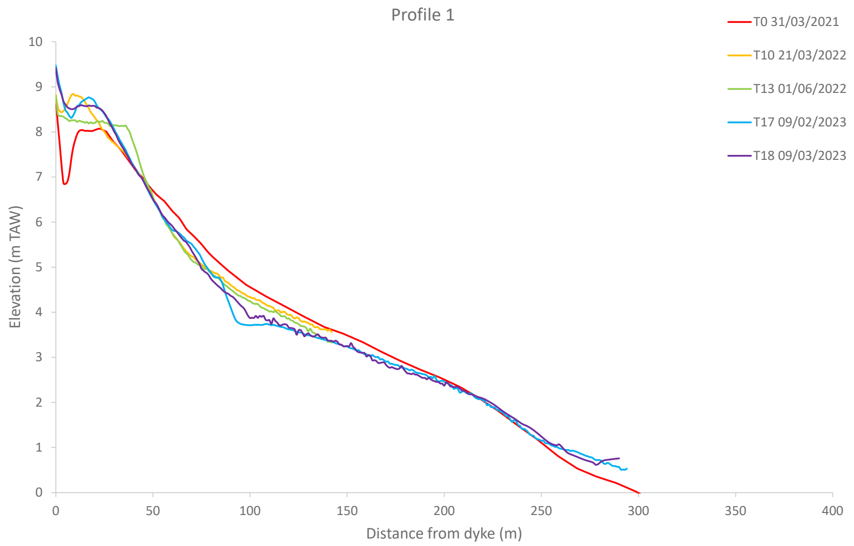
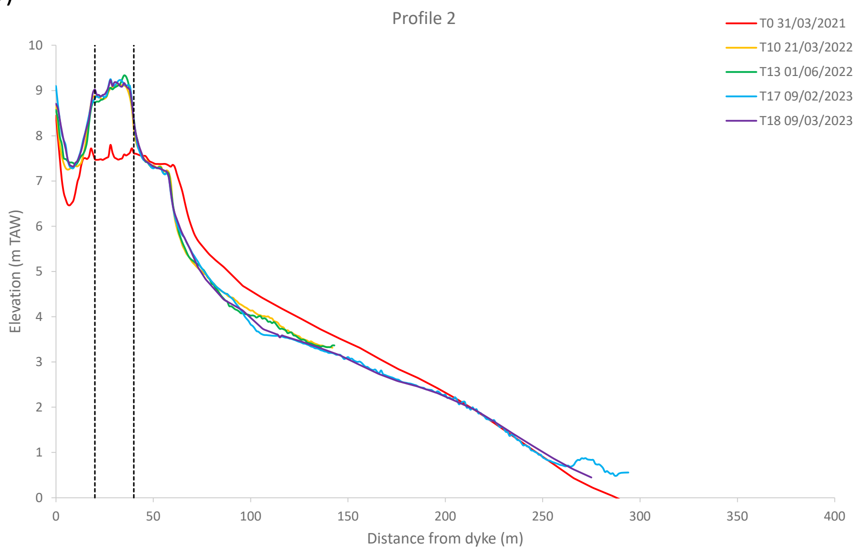


Figure 16 - Time series of all the merged profiles of the UAV and RTK-GPS surveys.

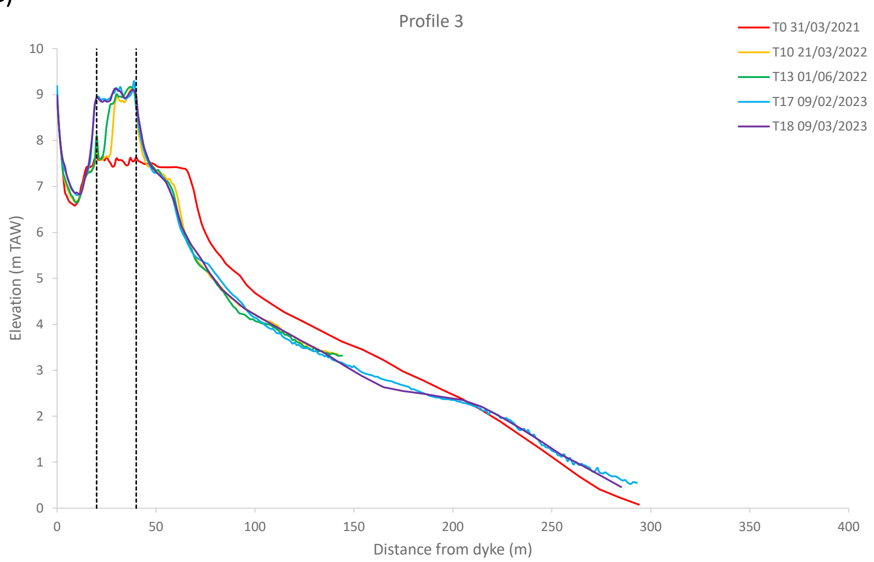
A)


Profile 1
T0 31/03/2021
T10 21/03/2022
T13 01/06/2022
T17 09/02/2023
T18 09/03/2023
Elevation (m TAW)
Distance from dyke (m)

B)


Profile 2
T0 31/03/2021
T10 21/03/2022
T13 01/06/2022
T17 09/02/2023
T18 09/03/2023
Elevation (m TAW)
Distance from dyke (m)

C)


Profile 3
T0 31/03/2021
T10 21/03/2022
T13 01/06/2022
T17 09/02/2023
T18 09/03/2023
Elevation (m TAW)
Distance from dyke (m)

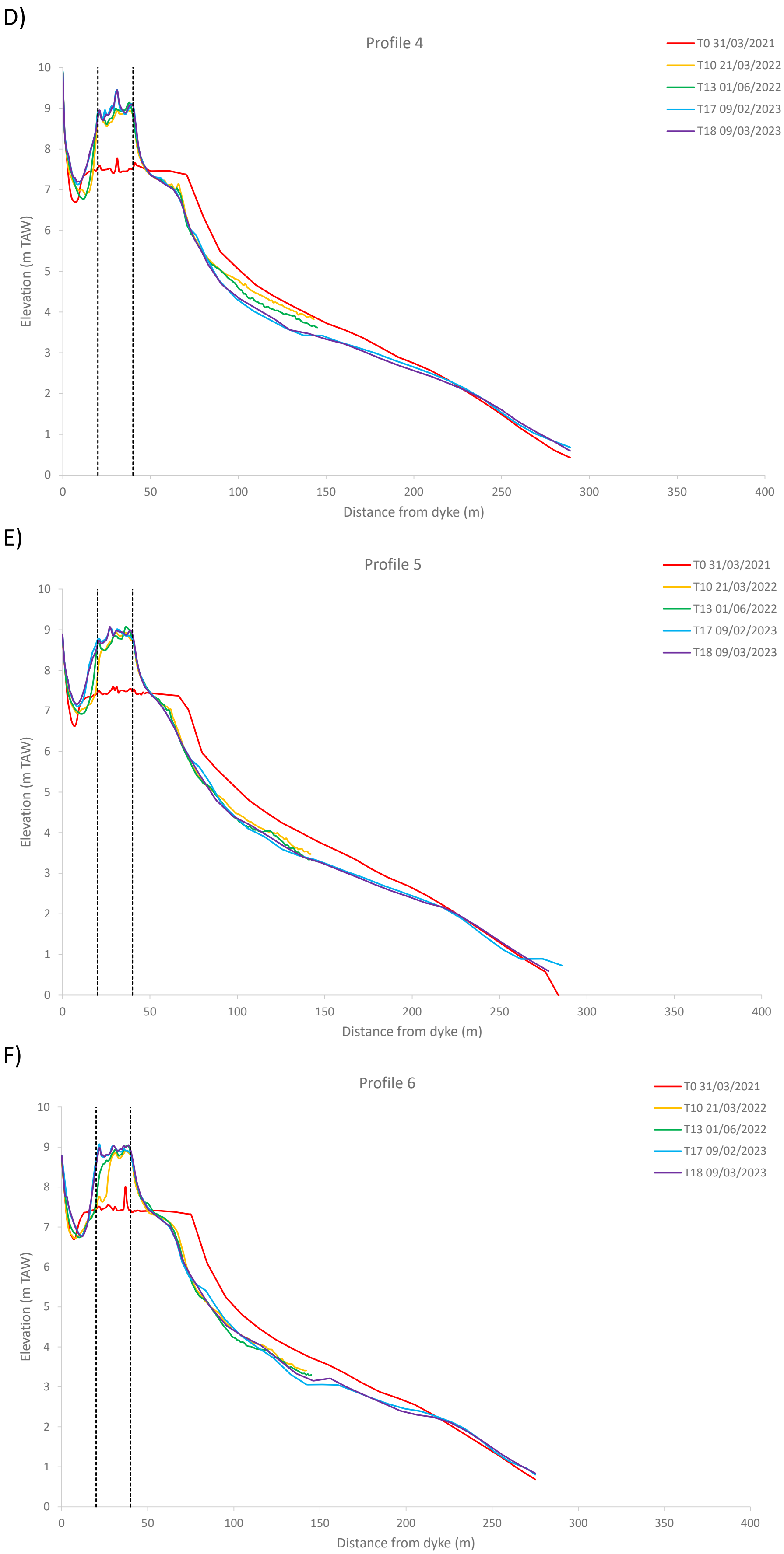
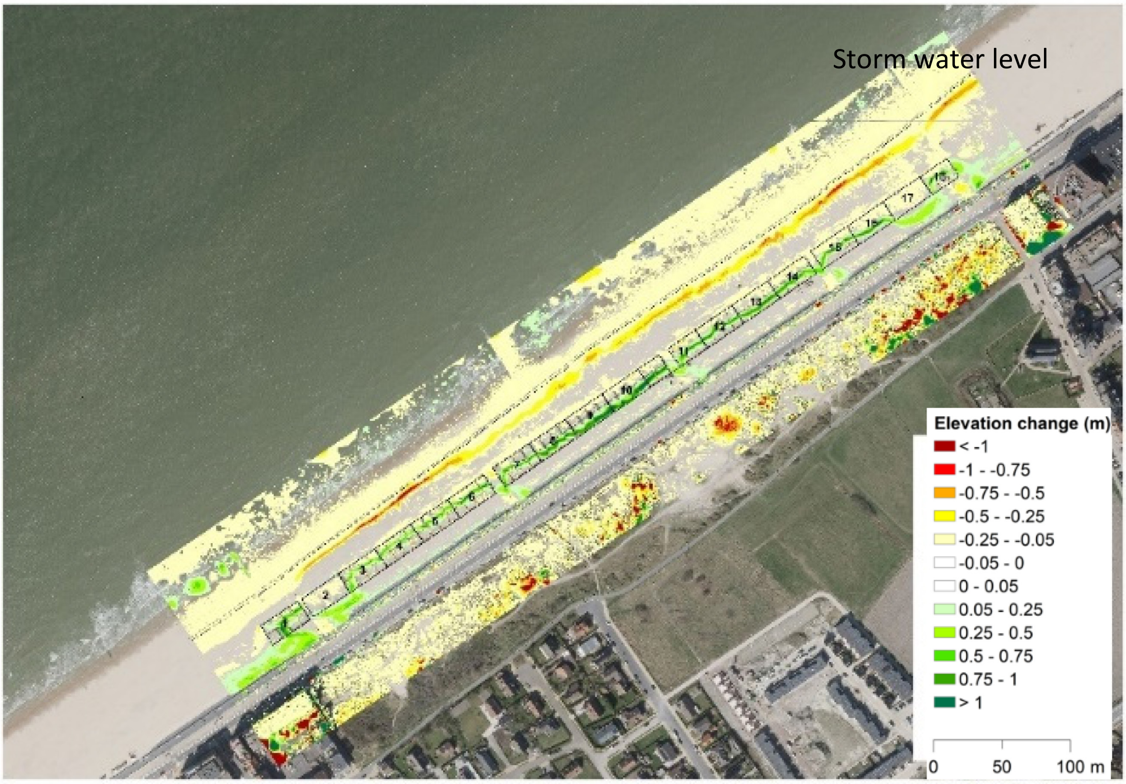


Figure 17 - Time series of evolution of the merged profiles of the UAV and RTK-GPS surveys.
The vertical dashed lines correspond to the location of the vegetated boxes.

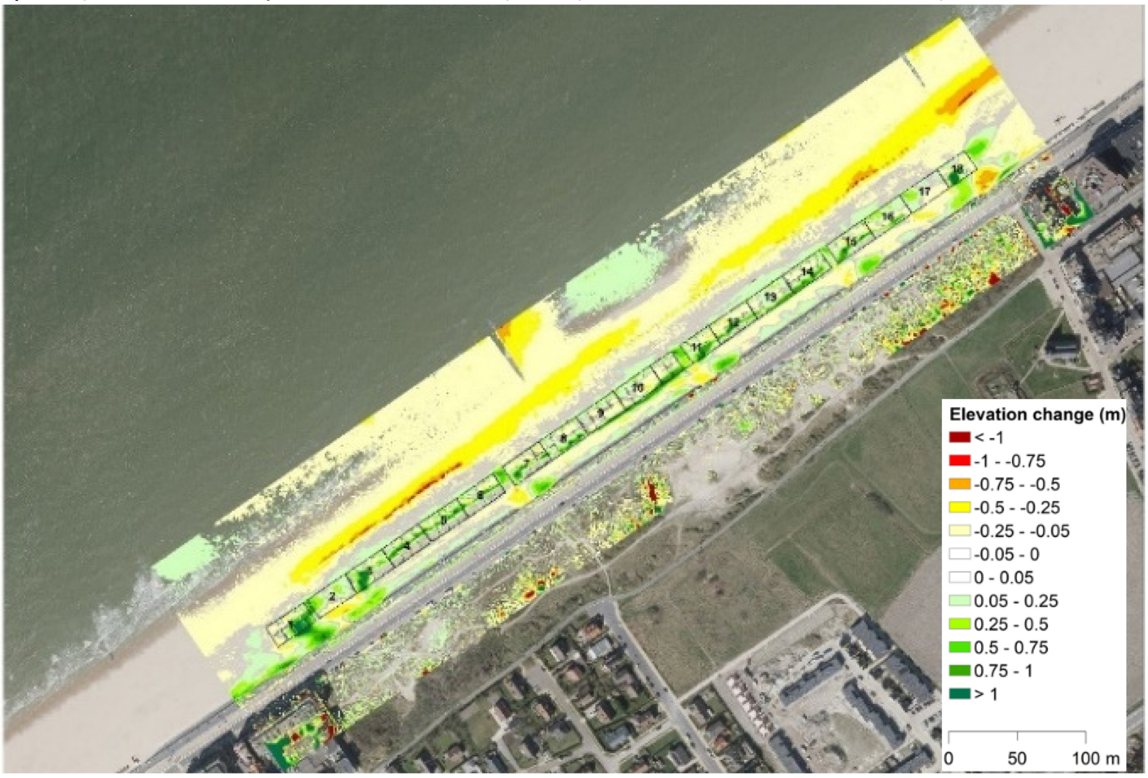
3.2.3 Comparison of impacts from energetic events

DoDs of the pre, post and recovery period of the storm events in 01-02/2022 and 09/2022 are displayed in Figure 18. Corrie and Franklin storm reached a maximum water level of 5.73 m and 5.57 m TAW respectively in the period 01-02/2022. Cliffs were formed with a top at about 6.4 m TAW and they were located 25 to 35 m seaward from the vegetated boxes (T7-T8). The effect of these consecutive storms is also illustrated in some profiles with the retreat of the seaward slope, while the beach below 5 m TAW was stable (Figure 19). Erosion of the beach slope was amplified by Franklin storm. For the recovery period (T8-T9), sand was only gained in the vegetated boxes while the beach still suffered from erosion. The energetic event of lower magnitude in 09/2022 attained a maximum water level of 5.36 m TAW. Erosion ranging from -0.2 to -0.6 m dominated the beach below the maximum water level, while positive morphological change as well as stability was observed above it. The area seaward of the vegetated boxes experienced erosion contrasting with the sand accumulation on their landward side. Generally, the profiles indicate a sand loss along the landward beach slope caused by the energetic events. A stability of the beach between the vegetated boxes and the elevation of 5.4 m TAW occurred during the calm period (T15-T16 of 3.4 months). However, the lower part of the beach spatially alternated with positive and negative morphological changes. As observed in the DoD, the beach profiles confirm that the upper-part of the dry beach located landward of the vegetated box was not affected by the storm events. In contrast, erosion took place along the beach slope at their seaward side and in particular during the consecutive storm events in 01-02/2022.

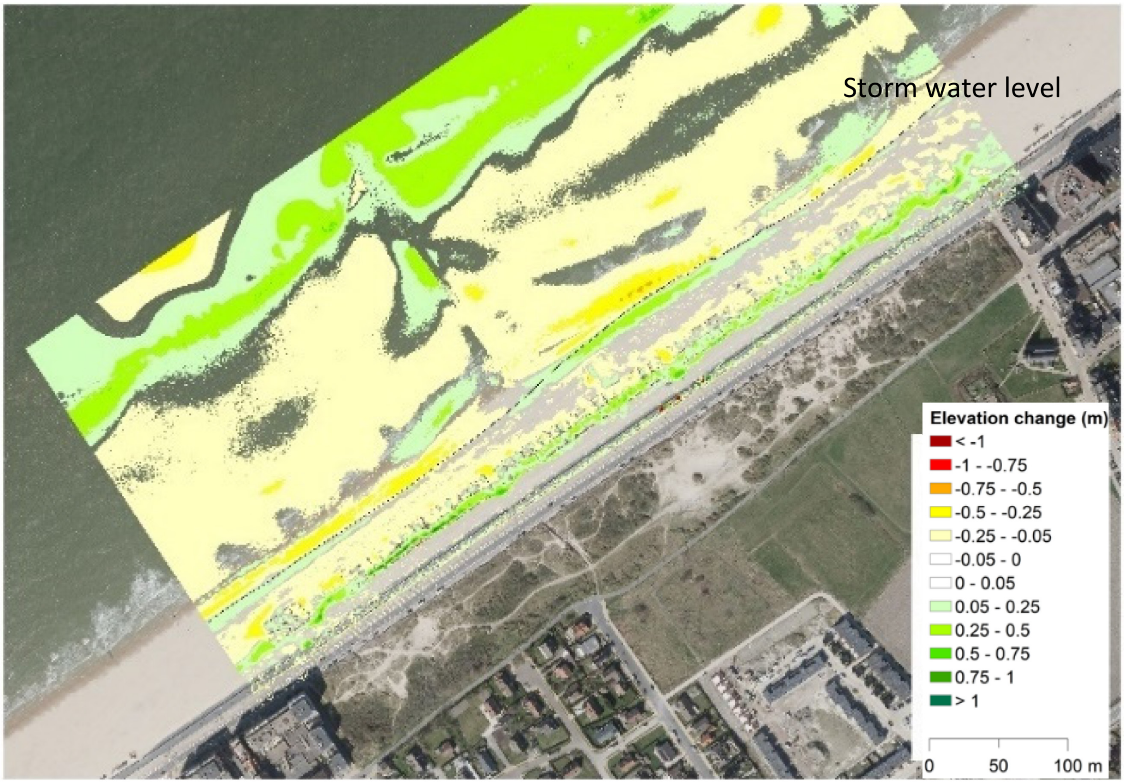
A) T7 (06/01/2022) - T8 (11/02/2022: post-Corrie storm)



B) T8 (11/02/2022: post-Corrie storm) -T9 (23/02/2022: Post-Franklin)

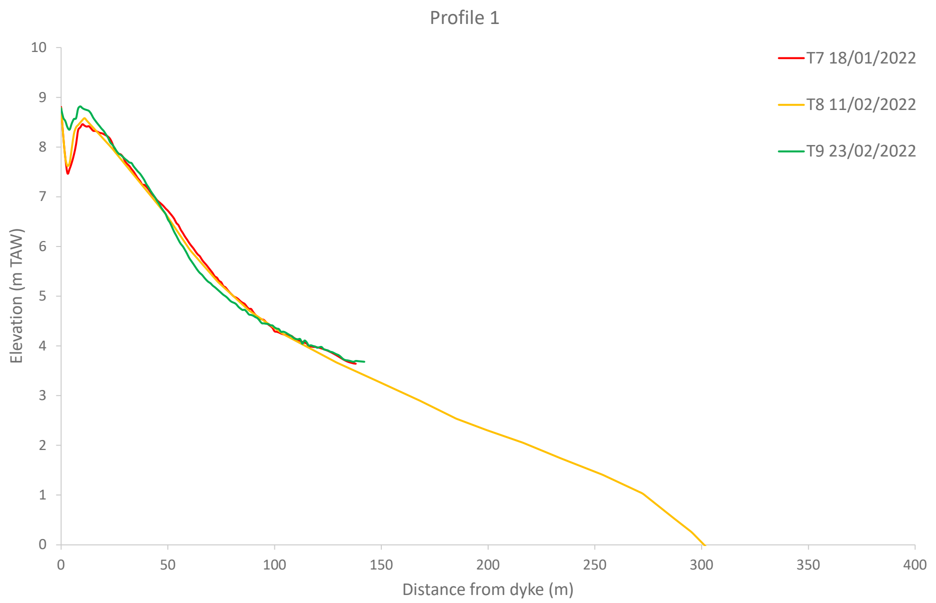


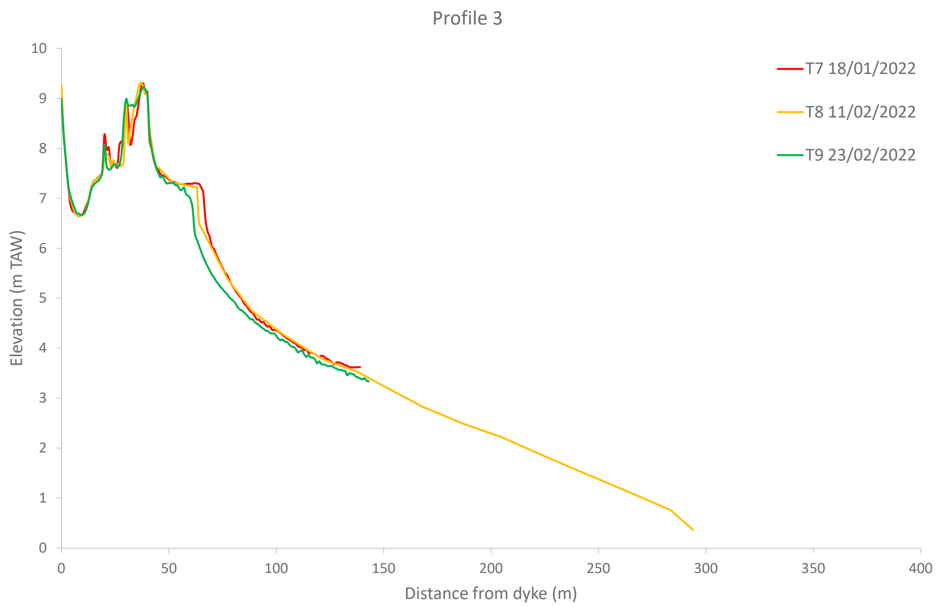
C) T14 (12/09/2022) – T15 (12/10/2022: post-Sept storm)

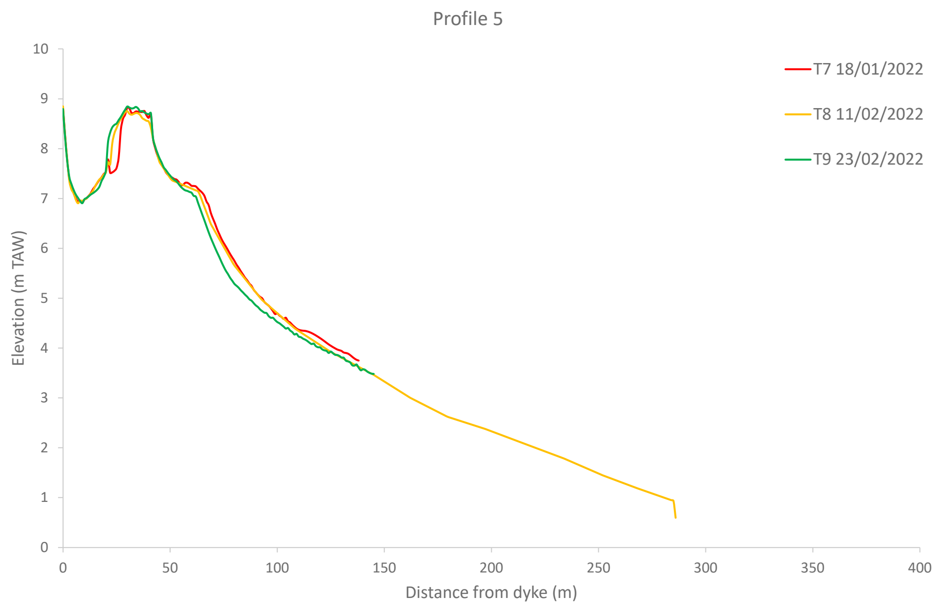


D) T15 (12/10/2022: post-Sept storm) -T16 (24/01/2023: calm period)

Figure 18 - DoD of pre and post-energetic events and calm period: T7-T8 (06/01/2022-11/02/2022); T8-T9 (11/02/2022-23/02/2022); T14-T15 (12/09/2022-12/10/2022); T15-T16 (12/10/2022-24/01/2023).
The dashed lines correspond to the water level reached during the energetic events.


Profile 1
T7 18/01/2022
T8 11/02/2022
T9 23/02/2022
Elevation (m TAW)
Distance from dyke (m)


Profile 3
T7 18/01/2022
T8 11/02/2022
T9 23/02/2022
Elevation (m TAW)
Distance from dyke (m)


Profile 5
T7 18/01/2022
T8 11/02/2022
T9 23/02/2022
Elevation (m TAW)
Distance from dyke (m)

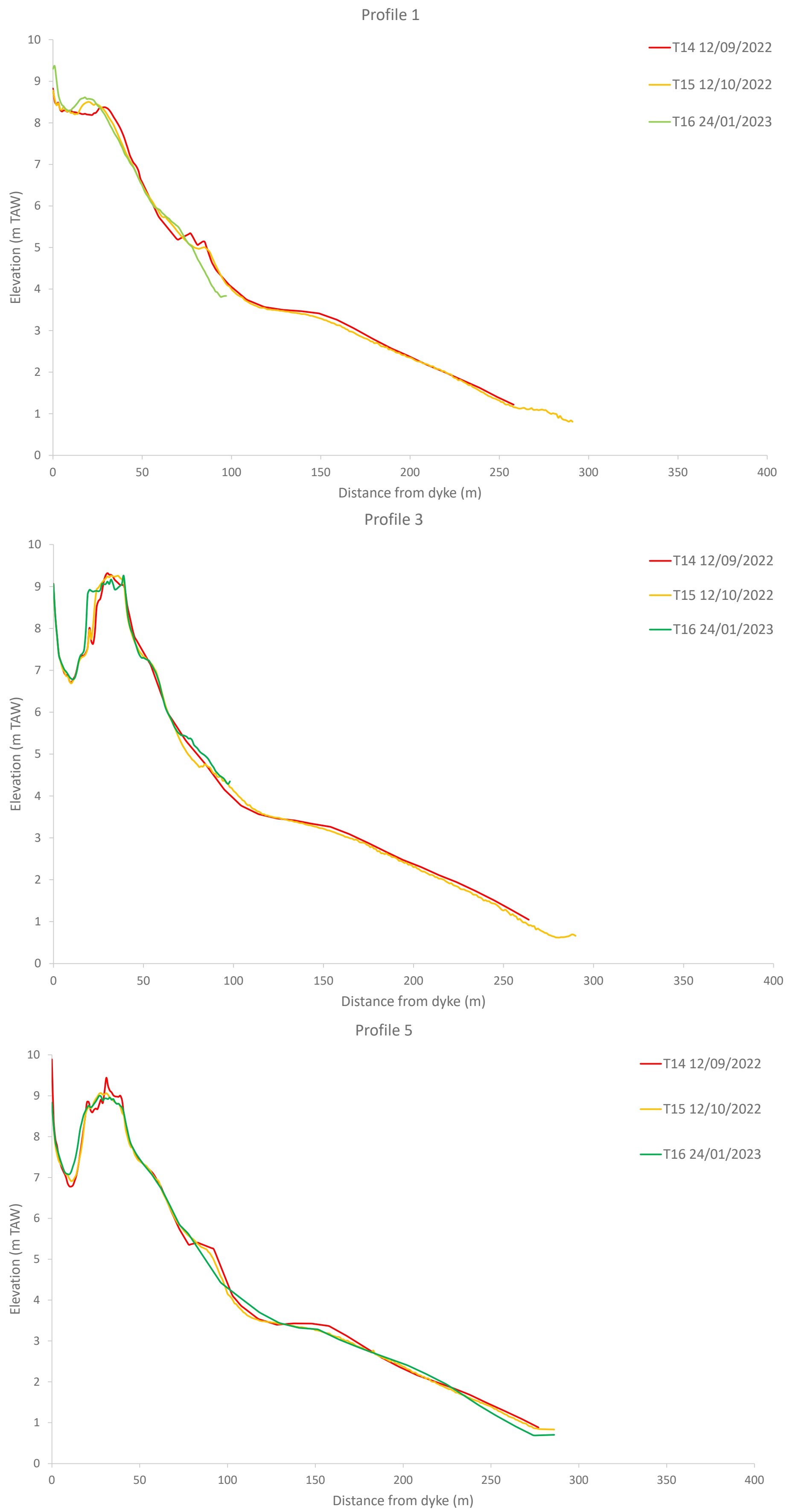


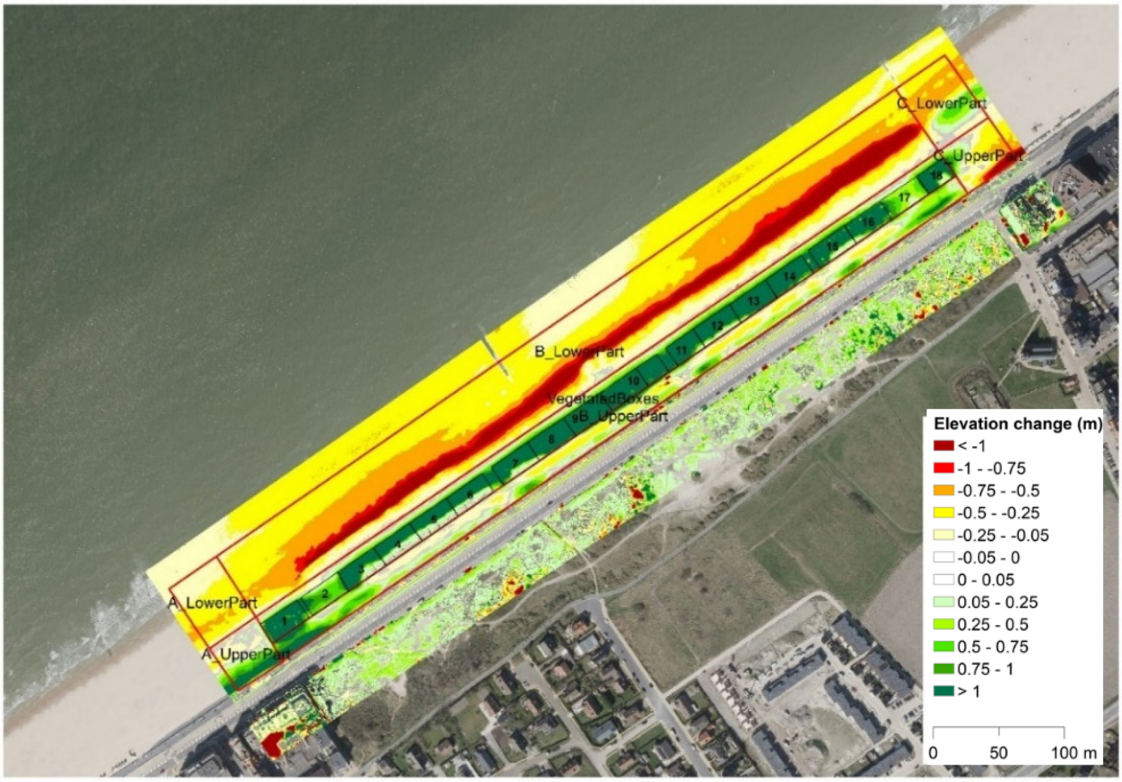
Figure 19 - Time series of the pre-, post and recovery period of the merged profiles of the UAV and RTK-GPS surveys

3.2.4 Volumetric changes

The pilot study was divided into zones to carry out volumetric analysis based on the UAV DEM surveys (Figure 19). Table 3 presents the results of the defined zones. The vegetated boxes gained 0.57 $m^3/m^2/y$ over the two monitoring years. Significant aeolian accretion 0.31 $m^3/m^2/y$ also occurred in area landward of the boxes. Accretion in the boxes during the 2nd year was 3 times lower than during the first year, but in the area landward of the boxes the accretion rate was 3 times higher during the 2nd year compared to the 1st year.
The same spatial trend of accretion of the upper part and erosion of the lower part of zone A and C is observed over the two years. The loss in the highest part of zone C (C_UpperPart) may be explained by excavation works by the city of Ostend. Sand budget was relatively stable in the vegetated and upper part zones after the storm events. However, the lower part experienced a sand loss of -0.26 m^3/m^2 in 01/2022 and -0.07 m^3/m^2 in 09/2022. Interestingly, different trends occurred during the calm period after the two storms. As observed, the beach was still losing sandy material 12 days after the consecutive storm events, whereas the beach fully recovered in 3.4 months after 09/2022 storm. This winter period was relatively calm without energetic events recorded. Hence, it suggests that the pilot site needs a few months to recover from an energetic event. Further investigation of the future storms will confirm this.

Although accretion dominated in the vegetated boxes, there is a spatial variability (Figure 21). Sand gain ranged from 0.55 to 1.33 m3/m2/y in the 1st monitoring year and from 0.21 to 0.59 in the 2nd monitoring year. In addition, a clear difference of morphological change between the zones with brushwood fences (Box 3 and 16) and the zones with only planted marram grass (Box 2 and 17) occurred. In average, the boxes with brushwood fences and marram grass gained respectively 1.09 m^3/m^2 and 0.61 m^3/m^2 in the 1st year monitoring. While there was barely a difference between both in the 2nd monitoring year when the gain was around 0.3 m^3/m^2. Further investigations will be carried out on the spatio-temporal variability between the boxes.

A) T0-T10: 11.7m



B) T10-T18: 11.5m

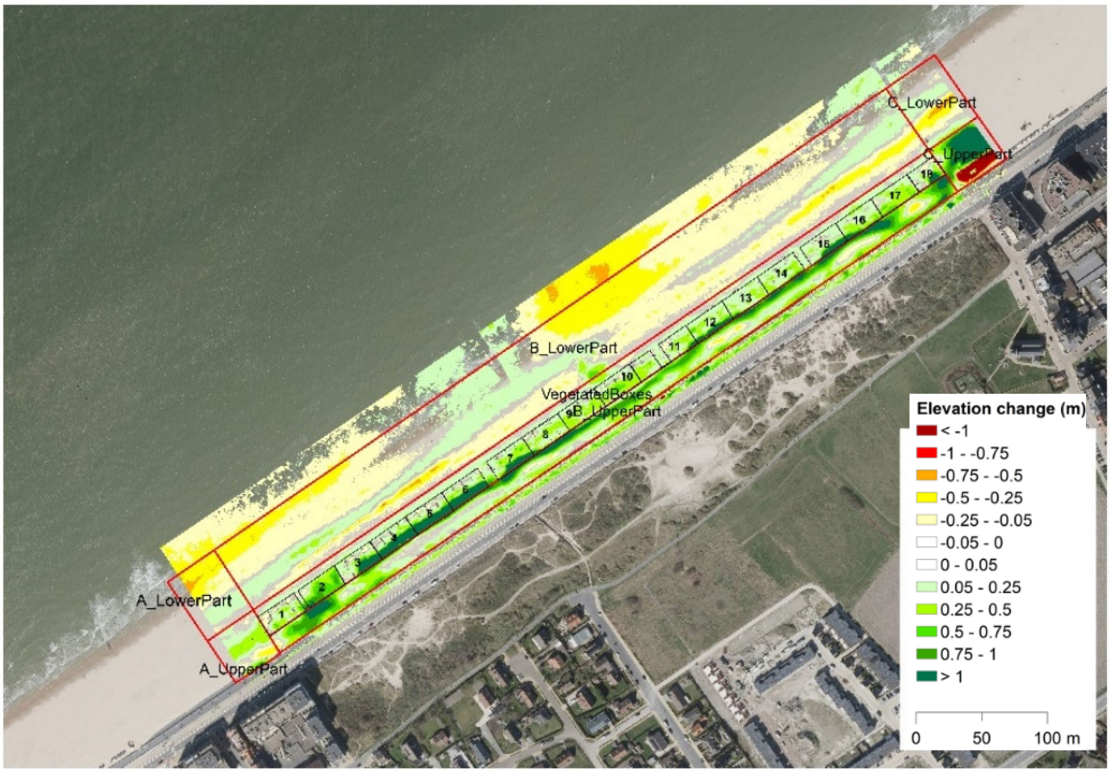


Figure 20 - Location of the contours of the defined zones overlapped on the DoD for the 1st and 2nd year monitoring (duration in month). Note: the UAV coverage of the lower part of the beach was reduced from T18 to optimize the survey.

Table 3 - Volumetric changes of the defined zones at Raversijde. Green (accretion), red (erosion), grey (stability), black (no records due to the limitation of the UAV coverage)

		Diff Volume (m^3/m^2)						
	Time	Vegetated Boxes	A_Upper Part	A_Lower Part	B_Upper Part	B_Lower Part	C_Upper Part	C_Lower Part
Global (Ref T0)	T0-T4	0.35	0.06	-0.10	0.01	-0.16	0.09	-0.11
	T0-T14	1.07	0.50	-0.31	0.35	-0.54	-0.13	-0.22
	T0-T16	1.09	0.52		0.57		0.14	
	T0-T18	1.10	0.52	-0.47	0.61	-0.62	0.18	-0.25
	T0-T18 ($m^3/m^2/y$)	0.57	0.27	-0.24	0.31	-0.32	0.09	-0.13
Annual	T0-T10	0.84	0.38	-0.32	0.20	-0.54	-0.25	-0.20
	T0-T10 ($m^3/m^2/y$)	0.86	0.39	-0.33	0.20	-0.56	-0.26	-0.21
	T10-T18	0.27	0.52	-0.47	0.61	-0.62	0.18	-0.25
	T10-T18 ($m^3/m^2/y$)	0.26	0.49	-0.45	0.58	-0.59	0.17	-0.24
Storm	T7-T8 (post-Corrie storm)	0.04	0.06	-0.04	0.03	-0.11	0.04	-0.15
	T8 (post-Corrie storm) -T9 (Post-Franklin)	0.13	0.09	-0.07	0.04	-0.15	-0.03	-0.25
	T14-T15 (post-storm)	0.00	-0.03	-0.07	0.04	-0.06	0.06	-0.05
	T15 (post-storm) -T16 (calm period)	0.02	0.05		0.18		0.21	

Table 4 - Volumetric change for the boxes located in the middle of the vegetation sections (Box 4, 9, 13, 17). Green (accretion), red (erosion), grey (stability). MG: only marram grass, B: brushwood fences with ½ density 'rijshout halve dichtheid', Mid: located in the middle of the section with a mix of marram grass and brushwood fences,

		Diff Volume (m^3/m^2)						
		MG	B	Mid	Mid	Mid	B	MG
	Time	Box2	Box3	Box4	Box9	Box13	Box16	Box17
Global (Ref T0)	T0-T4	0.35	0.22	0.20	0.42	0.42	0.45	0.38
	T0-T14	0.99	1.37	1.18	1.41	1.40	1.33	0.68
	T0-T16	1.15	1.39	1.38	1.52	1.43	1.37	0.86
	T0-T18	1.19	1.41	1.39	1.53	1.45	1.42	0.83
	T0-T18 ($m^3/m^{2/}y$)	0.61	0.73	0.72	0.79	0.75	0.73	0.43
Annual	T0-T10	0.66	1.00	0.77	1.29	1.22	1.11	0.53
	T0-T10 ($m^3/m^{2/}y$)	0.68	1.04	0.79	1.33	1.26	1.15	0.55
	T10-T18	0.53	0.41	0.62	0.24	0.23	0.31	0.29
	T10-T18 ($m^3/m^{2/}y$)	0.51	0.39	0.59	0.23	0.21	0.30	0.28
Storm	T7-T8 (post-Corrie storm)	-0.05	0.07	0.04	0.21	0.12	0.08	-0.08
	T8 (post-Corrie storm) -T9 (Post-Franklin)	0.12	0.30	0.18	0.05	0.16	0.13	0.05
	T14-T15 (post-storm)	0.02	0.01	0.08	0.06	0.05	0.03	0.06
	T15 (post-storm) -T16 (calm period)	0.15	0.00	0.12	0.05	-0.02	0.02	0.12

3.3 Westende

Five UAV flights were carried out in the period from 3/2021 to 11/2022 (0.65 years). Then the flight requests were not accepted by the authorities due to the proximity of military domain Lombardsijde. For the recent monitoring period, LiDAR surveys were used to evaluate morphological and volumetric changes. The storm impact assessment could not be realized due to the lack of survey close to the moment when the storms occurred.

3.3.1 Meteo-marine conditions during the second monitoring period

Figure 21 shows time series of water level in Ostend, wave height 10% and wave direction in 'Oostende Poortjes' (located 7 km from the coast), wind speed and direction of the weather station in Zeebrugge with the indication of the 2nd year monitoring.

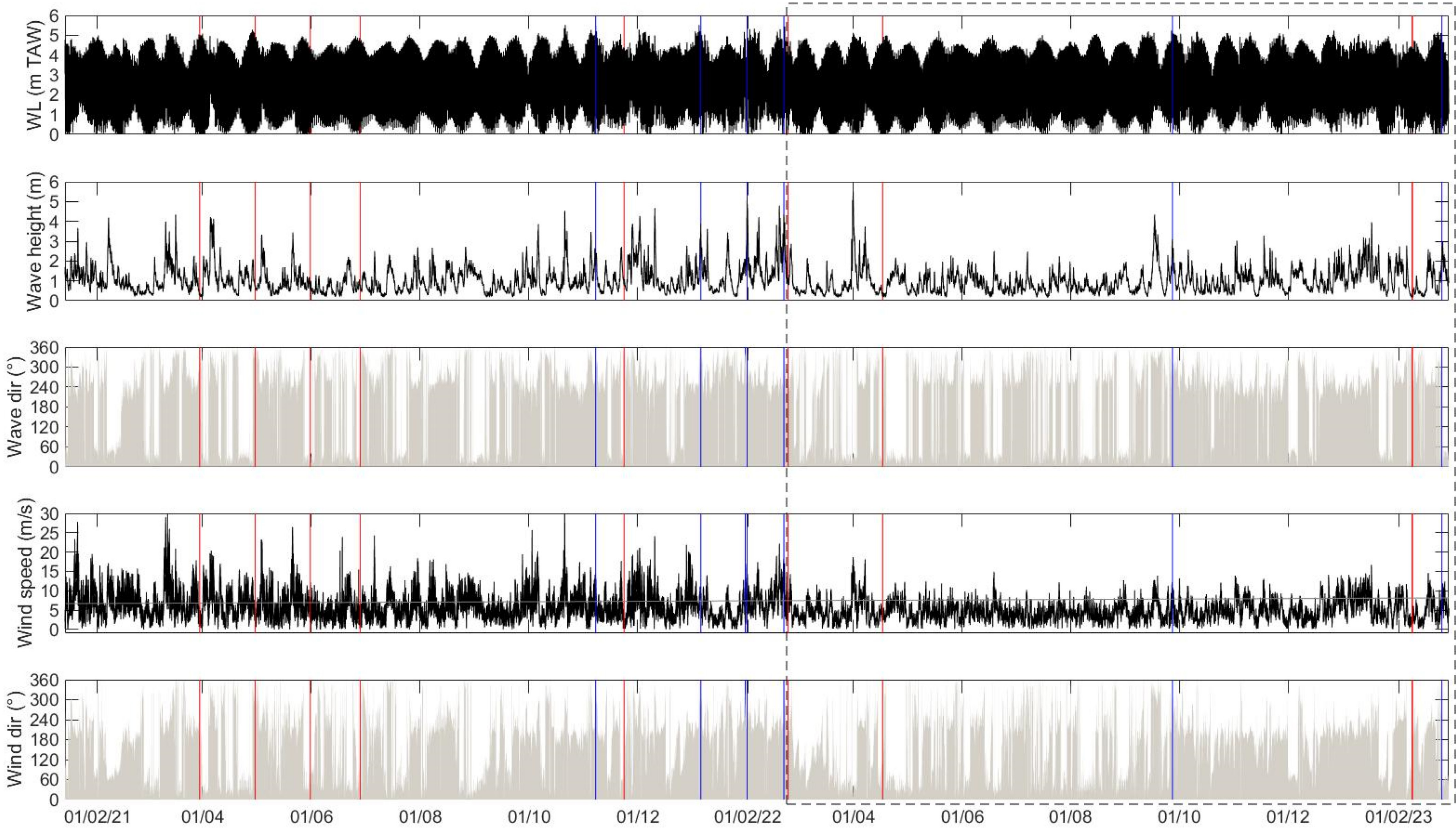


Figure 21 - Time series of the water level in Ostend, wave height 10% and wave direction in Ostend "Poortjes" (buoy located 7 km from the coast), wind speed and direction of weather station Zeebrugge (Meetnet Vlaamse Banken). Vertical red and blue lines correspond to the drone surveys and energetic events 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 2nd part of the monitoring.

3.3.2 Morphological evolution

Figure 22 presents the DoDs from months to years. Refer to Figure 3B for the elevation across the beach. A clear growth ranging from 0.1 to 0.8 m is noticeable in the seaward vegetated boxes and mainly in the most westerly ones (Box 1, 2, 3) after 1y 10.3months (Figure 22). Additionally, an accretion is noticeable around the fences in front of the vegetated boxes and obliquely orientated whereas a stability occurred in the landward vegetated boxes. Positive morphological change of the higher part of the dry beach is accompanied by erosion on its lower part. Similar trend is observed between the two monitoring periods (T0-T4 and T4-T7) with a dominance of erosion for the lower part of the beach and relative stability of the landward boxes (Figure 24). In addition, sand accumulation took place in all the seaward vegetated boxes over this period, while it was limited to the westerly boxes in the first period. It is probably related to the wind regimes between monitoring surveys, as reported in Verwaest et al. (2022). The observed high erosion in the eastward of the site is due to the work of the new seawall.

The RTK-GPS and LiDAR profile measurements starting seaward of the vegetated boxes due to the obstruction from the structure are shown in Figure 24. The three profiles display similar trends with an increase of the seaward slope accompanied by a landward retreat as well as a gain in high with a bump at a distance around 20-40 m from the sea dike and located in the seaward vegetated boxes except for the last survey T6. For this last period, it seems that the sand gain from the previous bump was reduced in high and moved seaward to soften the slope. It might be caused by sand works carried out by Middelkerke coastal community. Also, a slight accretion of the intertidal beach below 140 m is observed for the three profiles.

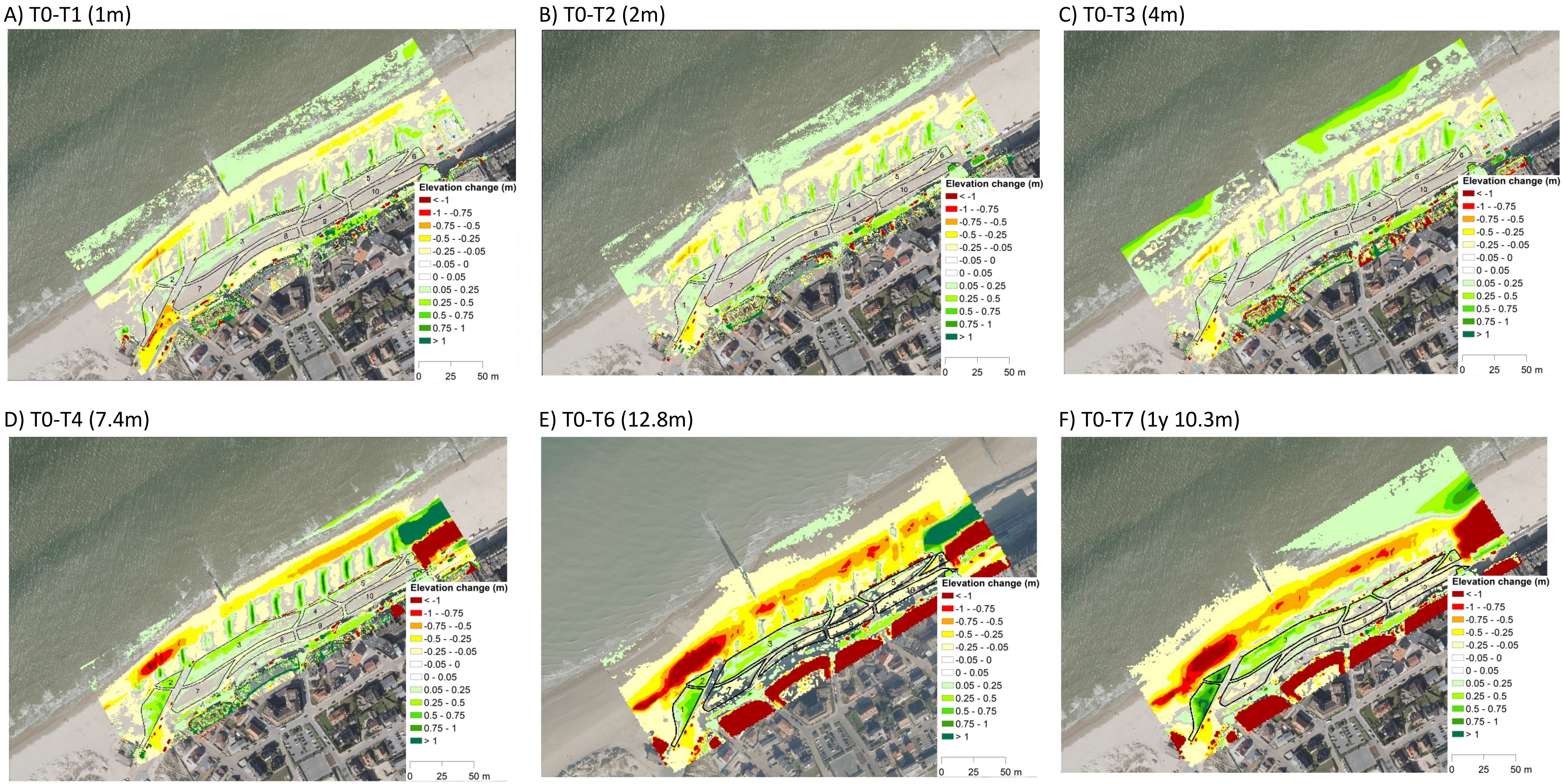
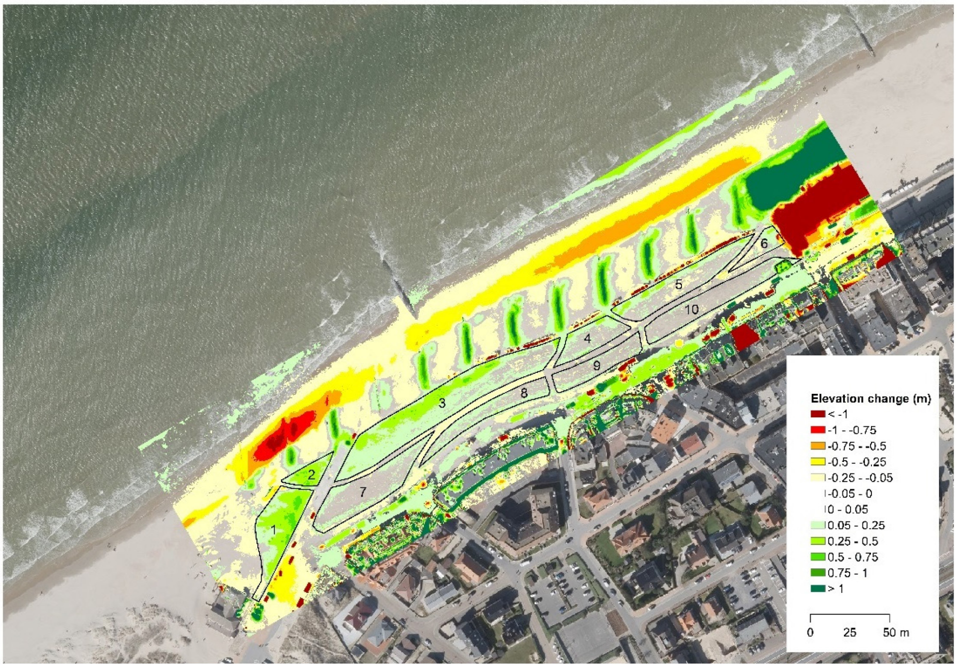


Figure 22 - Global evolution based on DoDs of the UAV and LiDAR surveys at Westende

A)T0-T4: 7.8m



B)T4-T7: 1y 10.3m

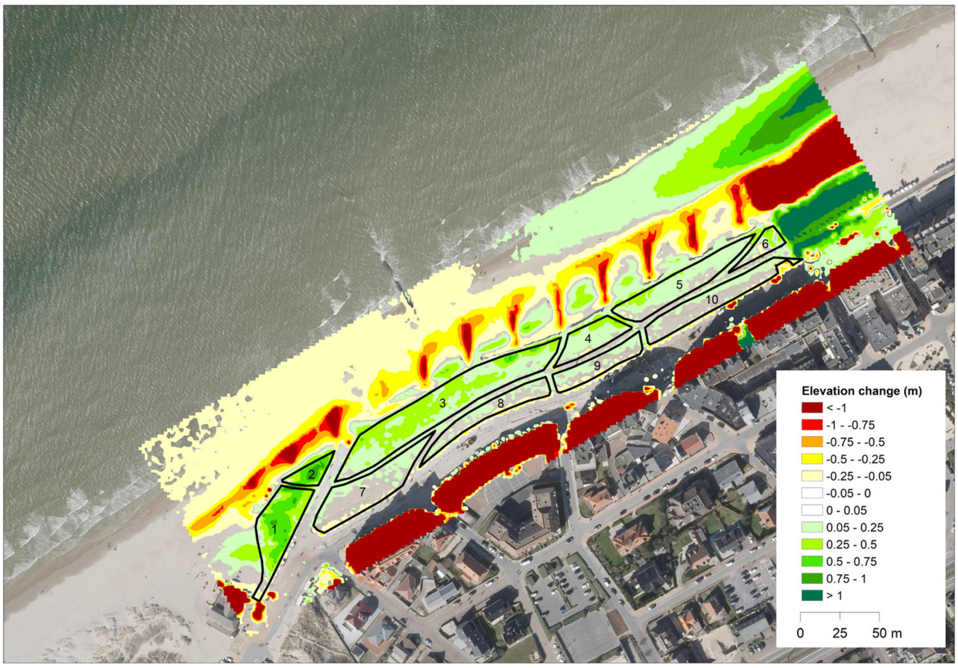


Figure 23 - Seasonal evolution based on DoDs of the UAV surveys

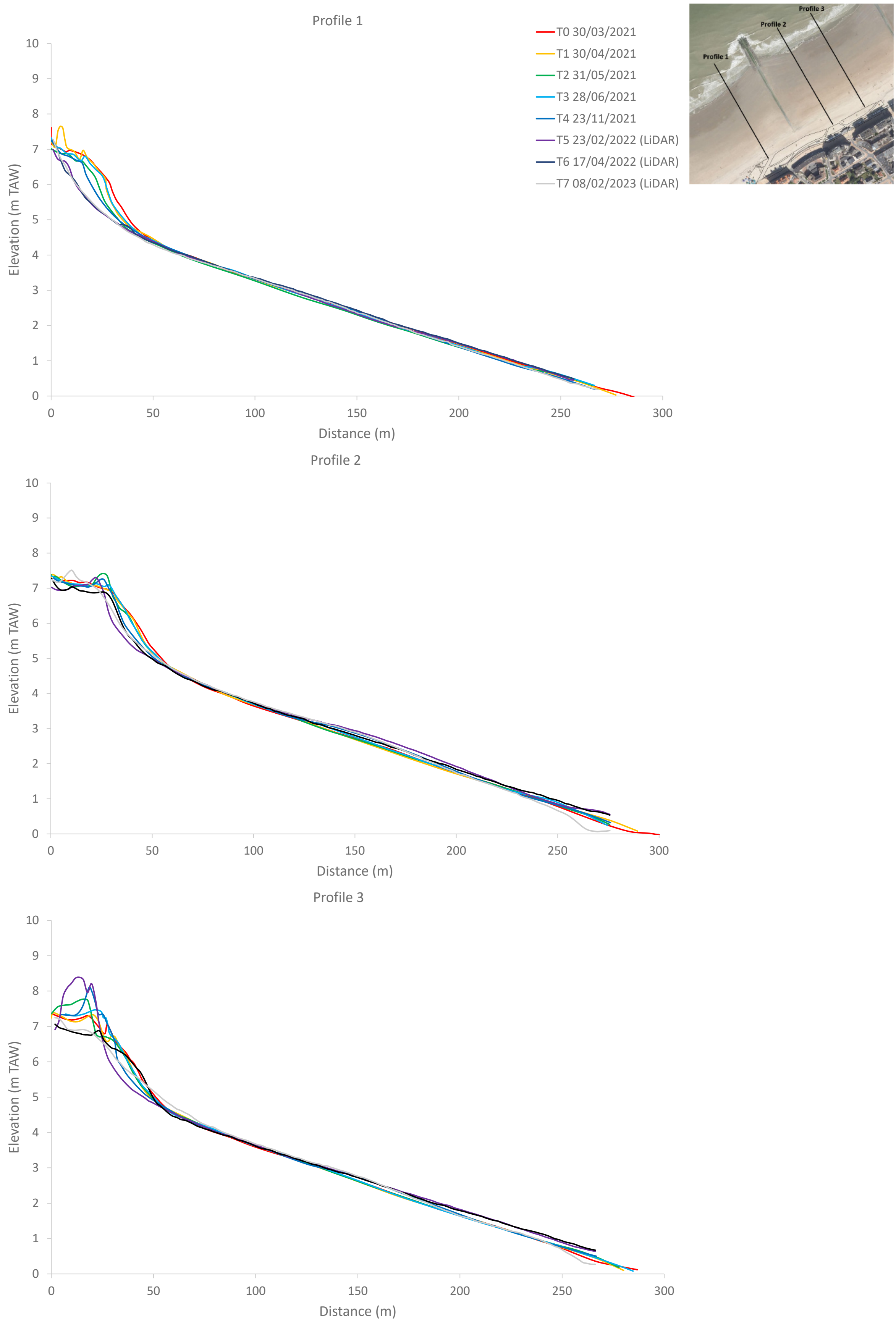
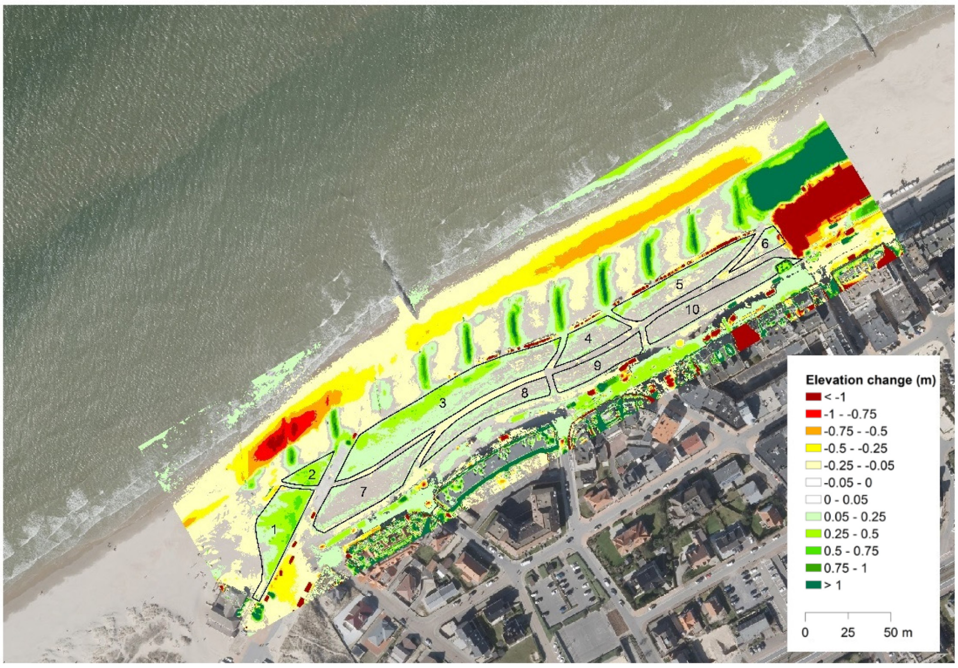


Figure 24 - Time series of the RTK-GPS and LiDAR surveys started seaward of the vegetated boxes. Inset: location of the profiles

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 25). The volumetric evolution in these zones was calculated using the UAV and LiDAR surveys and the results are given in Table 5. The vegetated zone experienced an average growth of 0.11 $m^3/m^2/y$ over the first monitoring period (T0-T4) while a stability dominated the second period (T4-T7). It suggests that the marram grass plants were very efficient to capture sand in the first period. The winter sand fences ‘zandschermen’ located in the zone of the middle part might have reduced the sand capture in the inland zone. Also, another difference between these two monitoring periods occurred for the middle part namely stability in the first period followed by erosion in the second period. This area could was affected by the winter fences and the cabins installed by the city. As previously observed of the DoD, the lower part experienced erosion with a similar order between the 2nd year period.

A)T0-T4: 7.8m



B)T4-T7: 1y 10.3m

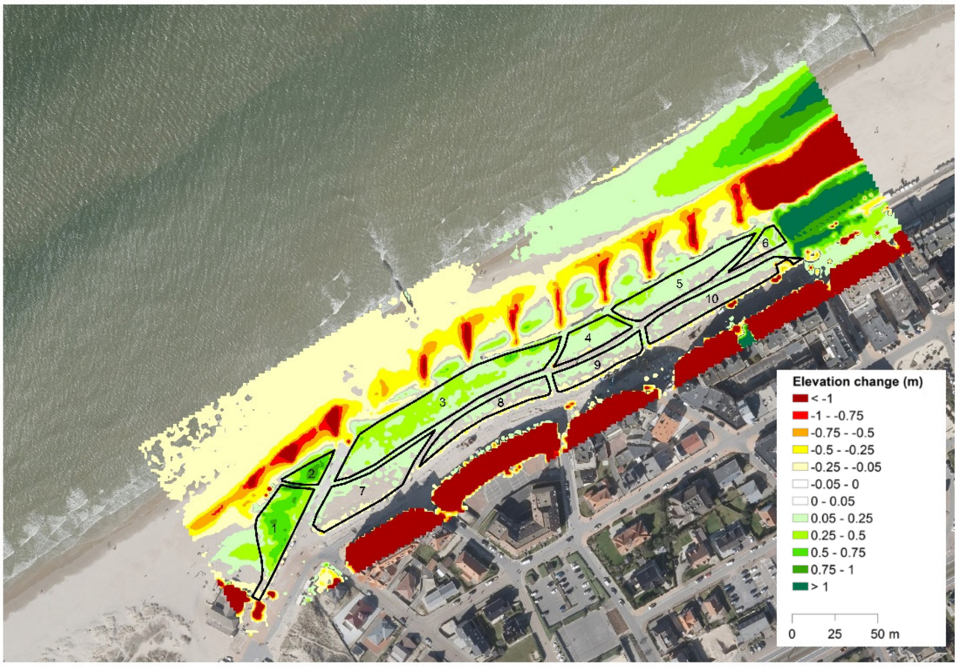


Figure 25 - Location of the contours of the defined zones at Westende

Table 5 - Volumetric changes of the defined zones at Westende. Green (accretion), red (erosion), grey (stability)

	Diff Volume (m^3/m^2)		
Time	VegetatedPart	Middlepart	LowerPart
T0-T1	0.01	0.05	-0.05
T0-T4	0.07	0.06	-0.12
T0-T4 ($m^3/m^2/y$)	0.11	0.09	-0.17
T4-T7 LiDAR	0.04	-0.26	-0.16
T4-T7 LiDAR ($m^3/m^2/y$)	0.03	-0.22	-0.13

4 Discussion

4.1 Spatial and temporal evolution

A progressive accretion of the dry beach characterized the three pilot sites during the entire monitoring period from 6 months to 2 years (Figure 26 A, B, C). Sand gain of the vegetated boxes considering only the part B where no human interferences occurred (Figure 12, Figure 20, Figure 25) was usually lower for the 2nd year of monitoring than for the 1st year, especially at Spinoladijk and Raversijde where it was 2 and 3 times lower, respectively. For the recent period, sand budget of the vegetated boxes was of 0.28 $m^3/m^2/y$ at Spinoladijk and Raversijde and 0.03 $m^3/m^2/y$ at Westende. Similar morphological patterns at the three sites occurred over the 1st year of monitoring with accretion dominating the vegetated boxes and the upper-part while erosion characterized the lower part of the dry beach. For the 2nd period, the same spatial pattern is only observed at Raversijde contrasting with the positive morphological change at Spinoladijk. Noteworthy, the accretion of the beach including the upper zone and vegetated boxes counterbalanced and the erosion dominating in the lower part of the beach in the 1st year and 2nd monitoring year for Spinoladijk and Raversijde. Interestingly, the upper part gained 4.5 times more sand than the vegetated boxes in the last year of the monitoring when sand was trapped between the dunes and the dyke. Over the same period, positive and stable morphological change of the lower part of the beach took place at Spinoladijk. This was probably due to less human interferences with the sand works by the trucks carried out by the city of Ostend. In Spinoladijk, the evolution is probably underestimated due to the excavation works on the dry beach close to the dike. The volumes of sand would have been larger in absence of excavation works. The 3rd year monitoring will clarify the observed morphological patterns across the beach. Regarding Westende, morphological change across the beach was much lower than at the other two pilot sites. It might be due the presence of winter fences located seaward of the vegetated zones which captured sand transport before reaching the planted marram grass. Over the 2nd year monitoring, the accretion in the vegetated boxes was diffused along the site contrasting with the concentrated growth in the most southwestern part. The middle part of the dry beach, where winter fences and cabins are present, and also its lower part lost slightly sand material (< -0.22 m^3/m^2), which were probably caused by both natural processes and human interventions. Similarly, future surveys would help to assess in more details this site.

The pilot sites are influenced by multiple factors including the presence of marram grass, brushwood fences that can capture either onshore or alongshore aeolian sand transport. Typically, accretion occurred at locations where the sand transport capacity of the wind is lower due to the presence of these obstacles. Their height, density and width controls the amount of accretion.

Marram grass only captured ~50 % of the aeolian supply, while 90% is accounted for the brushwood fences in the 1st year monitoring as occurred in Raversijde (Verwaest et al., 2022). It should be emphasized that these are average values observed. For 2nd year monitoring, the sand capture efficiency of the marram grass was relatively similar (35-40%). In contrast, it was more spatially variable for the brushwood fences. High efficiency occurred for Box 16 while it was much lower for Box 3. Hence, local variability of sand trapping of the brushwood might be controlled by the local factors of the brushwood fences such as their sand fulfillment or saturation, geometry and density and also their surroundings. Detailed analysis should be performed to further investigate the spatio-temporal variation of the capture efficiency.

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 of 13% for the 1st year and 10% for the 2nd monitoring year. Therefore, the most recent period was less favorable for sand transport. Grain size is also important controlling factor of sand transport. Unfortunately, no information is available about its change over time.

It would be thus interesting to investigate monthly the grain size across the beach collected at the time of the UAV surveys.

All these factors change over time and space which explain the morphodynamic from months to years. Generally, the greater sand budget values recorded across the beach at Raversijde are probably due to the large availability of sand as a result of the nourishment and partly from the beach reshaping with a plateau that was carried out just before the monitoring favoring sand transport processes. However, the decrease of the sand gain in the zone of the vegetated boxes may be caused by the reduction of sand available on the seaward beach and less favorable beach shape for aeolian sand supply. Also, the saturation of the brushwood fences as well as a less effective onshore wind regime might be other reasons of the reduction of sand accretion in the vegetated boxes.

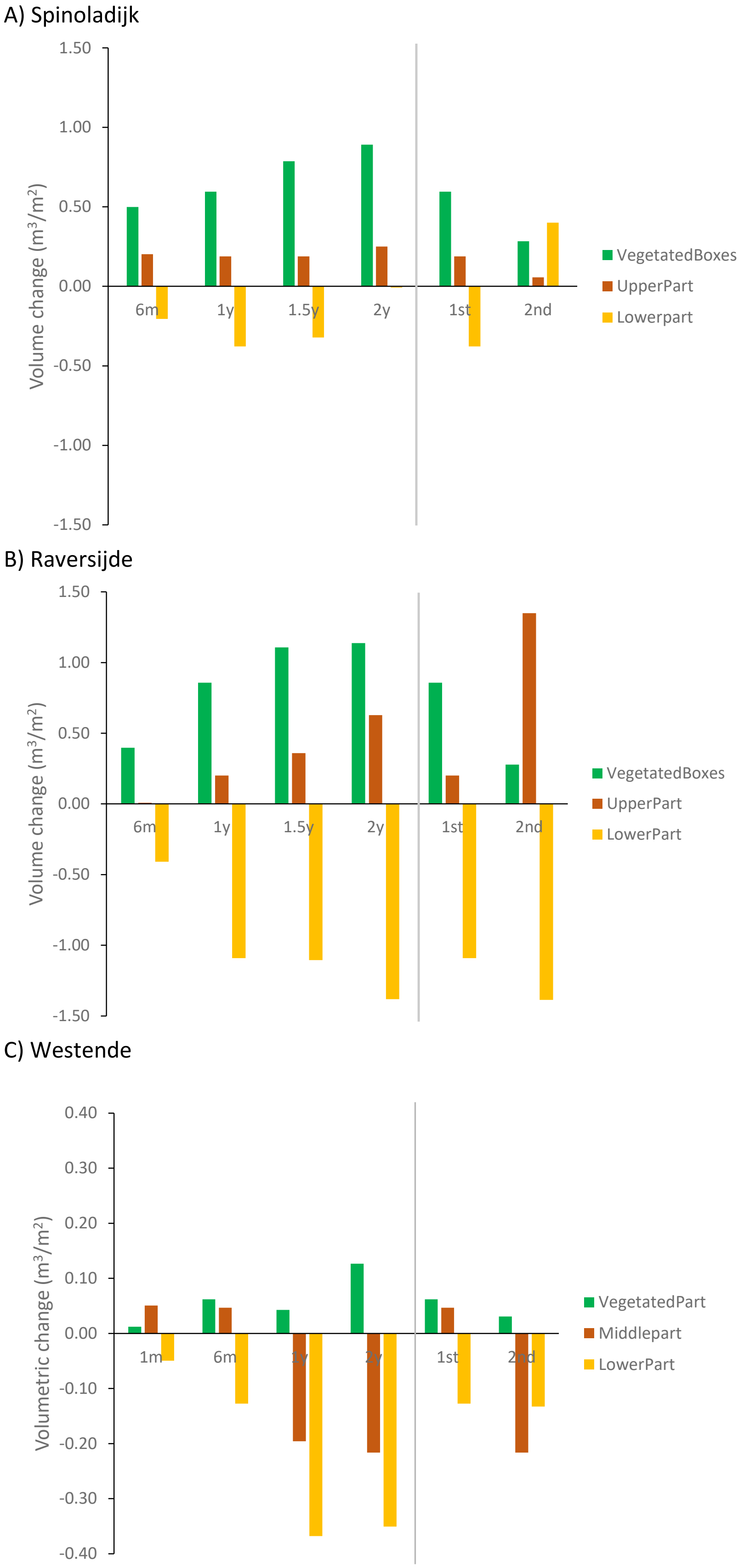


Figure 26 - Evolution of sand budget from 6 months to 2 years at the pilot sites: A) Spinoladijk, B) Raversijde and C) Westende. Only part B of the beach is considered here where no human interferences usually occurrs. Note: the difference of y-axes

Another process which influenced the beach morphology is the storm occurrence. The consecutive severe storms in 01-02/2022 caused erosion on the seaward side of the dry beach and on the intertidal zone. This material was deposited near and below the low water mark. For the energetic event of lower magnitude in 09/2022, the impact across the beach was limited. Generally, the lower part of the dry beach was subject to both marine and aeolian processes leading to a deflation of this zone which important to supply the upper zone. At yearly scale, sand accumulation of the entire beach system by aeolian transport processes was 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 'Oostende-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 pilot 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, would be probably vanished without any artificial sand supply causing the decline of the dune growth and further its decay.

4.2 Recommendations

Although, dune growth in Spinoladijk was reduced during the 2nd year monitoring, the vegetated boxes are still efficient to capture aeolian sand transport. As observed on the UAV orthophotos, there was less human interferences carried out on the beach by the city of Ostend (i.e. digging trench along the dike, cleaning up sand on the Spinoladijk beach, returning it further on the beach, and other activities) during the 2nd year monitoring period. However it is difficult to interpret the erosion and accretion spots due to the lack of data on the sand works. It is recommended to request to the city of Ostend to keep precise records on these interventions such as excavation a trench along the dike and cleaning up sand on the dike.

At Raversijde pilot site, the dune for dike contribute to nuisances reduction from aeolian sand transported over the sea dike and deposited on the tram line as well as on the coastal path. A large amount of aeolian sand transport was captured by the placed brushwood fences, and locally by the planted marram grass during the entire monitoring (Figure 14). Nevertheless, the efficiency of trapping sand was reduced during the 2nd year monitoring due to a limited accommodation space and less effective wind regime. This was already noticed at the end of the 1st monitoring period (Verwaest et al., 2022). Then it was recommended to replant marram grass in this zone in order to further capture the aeolian transport and thus to help the dune growth. Marram grass was replanted in 02/2023 as presented in Appendix A. Its effect could not be yet observed in the UAV survey on 09/03/2023 (T18) since the plants need time to grow and then to trap sand. The changes in the morphological pattern will be revealed in the coming months. Additionally, the impact of the sand nuisance on the dike at Raversijde needs to be estimated. Thus, it is recommended to request 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.

Since 11/2021, it is not anymore possible to carry out monthly UAV survey at the location of the current pilot site in Westende, because the flight permissions are systematically refused by the military authorities. Monitoring of this site can be continued using the (bi-)yearly coastal LIDAR surveys.

Furthermore, a long-term evolution of the dune volumes at the three pilot sites should be determined by the sand balance on a larger scale than considered in the monitoring program for this project. At yearly scale, the 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 must also assessed.

5 Conclusions

A progressive accretion of the dry beach characterized the three pilot sites during the entire monitoring period. Sand gain was generally lower for the 2nd year monitoring than for the 1st year and especially at Spinoladijk and Raversijde. For the recent period, sand budget status for the vegetated boxes was 0.14 m^3/m^2 at Spinoladijk, 0.28 m^3/m^2 at Raversijde and 0.03 m^3/m^2 at Westende. Thus, accumulation is the largest at Raversijde which is probably due to the high efficiency of brushwood fences, the availability of sand as a result of the nourishment and partly by the beach reshaping with a plateau that was carried out just before the monitoring. The sand accumulation on the upper-part zone of the beach at Raversijde was larger than for the vegetated boxes. It suggests that sand was transported and deposited in the upper part despite the dune growth and saturation of the brushwood fences in the boxes. The main factors controlling the dune growth are the sand availability, accommodation space, vegetation and brushwood retention capacity and the wind regime, all reduced over the second year when compared to the first year.

Similar morphological pattern at the three sites occurred over the 1st year of monitoring with accretion dominating the vegetated boxes and the upper-part of the dry beach and erosion characterizing the lower part of the dry beach, delimited by a line of morphological stability. For the 2nd period, the same spatial pattern is only observed at Raversijde contrasting with the positive morphological change at Spinoladijk. For the latter, positive and stable morphological change of the lower part of the beach took place at Spinoladijk which was probably due to less human interferences. Additionally, a sand balance between the dry beach (including the dry zone and vegetated boxes) gaining material and its lower part with erosion occurred in the 1st year monitoring for Spinoladijk and Raversijde. For the lower part of the dry beach, marine and aeolian processes influence this area of deflation which is important for the sand supply of the upper zone. Another process which influenced the beach morphology is the magnitude and frequency of storm occurrence. The consecutive severe storms in 01-02/2022 caused erosion on the seaward side of the dry beach and on the intertidal beach. This material was deposited near and below the low water mark. For the lower energetic event in 09/2022, impact across the beach was limited. Nevertheless, a common and interesting observation between the two events is this reversal morphological pattern of the lower part of the beach characterized by erosion just after storm versus accretion during calm period. It suggests that the beach has a rapid and strong resilience against energetic wave event. The surveys of the coming years monitoring will support further investigation of the beach morphodynamics from short (months) to long-term (3 years).

6 References

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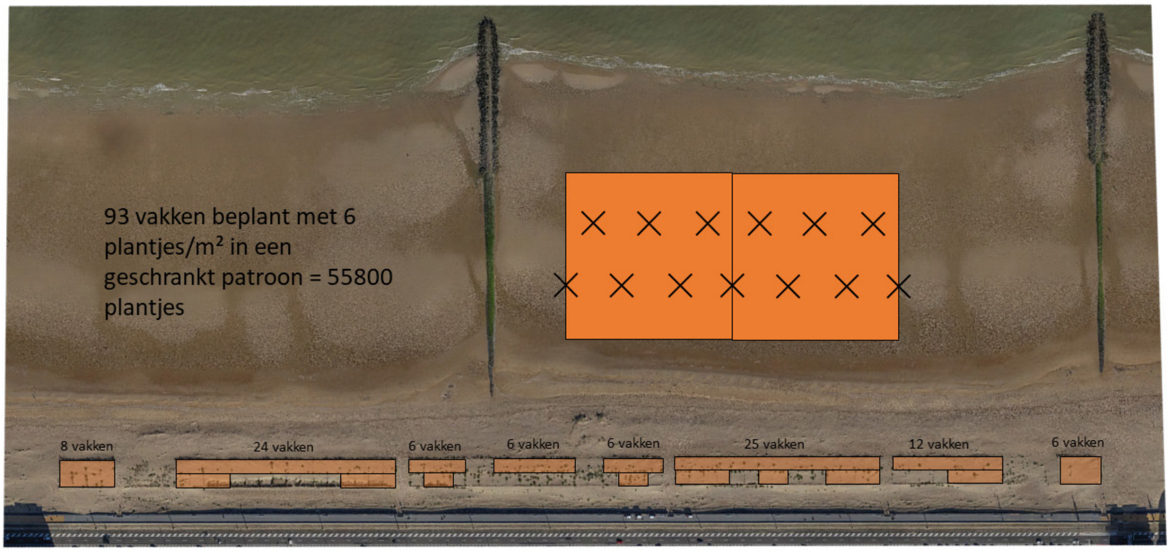
Appendix A


93 vakken beplant met 6 plantjes/m² in een geschrankt patroon = 55800 plantjes
8 vakken
24 vakken
6 vakken
6 vakken
6 vakken
25 vakken
12 vakken
6 vakken

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