

Flanders
State of
the Art

21_014_4
FH reports

Monitoring of the dune for dike pilots

Evolution after 5 years

DEPARTMENT
MOBILITY &
PUBLIC
WORKS

www.flandershydraulics.be

Monitoring of the dune for dike pilots

Evolution after 5 years

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

Flanders Hydraulics
Flanders State of the Art

Cover figure © The Government of Flanders, Department of Mobility and Public Works, Flanders Hydraulics

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

© The Government of Flanders, Department of Mobility and Public Works, Flanders Hydraulics 2026
D/2026/3241/246

This publication should be cited as follows:

Montreuil, A-L.; Dan, S.; Verwaest, T. (2026). Monitoring of the dune for dike pilots: Evolution after 5 years. Version 4.0. FH Reports, 21_014_4. Flanders Hydraulics: Antwerp

Reproduction of and reference to this publication is authorised provided the source is acknowledged correctly.

Document identification

Customer:	MDK Coastal Division	Ref.:	WL2026R21_014_4
Keywords (3-5):	Dune, morphodynamics, marram grass		
Knowledge domains:	erosion protection coast > dunes > in situ measurements		
Text (p.):	54	Appendices (p.):	18
Confidential:	☒ No	☒ Available online	

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

Control

	Name	Signature
Reviser(s):	Dan, S.	Signed by:Sebastian Dan (Signature) Signed at:2026-11-19 09:57:03 +01:00 Reason:I approve this document Dan Sebastian Vlaamse overheid
Project leader:	Montreuil, A-L.	Signed by:Montreuil Anne-Lise Clémence M Signed at:2026-11-19 12:47:04 +01:00 Reason:I approve this document Anne-Lise Montreuil

Approval

Head of Division:	Bellafkih, K.	Signed by:Bellafkih Abdelkarim Signed at:2026-11-19 14:16:29 +01:00 Reason:Ik keur dit document goed Bellafkih Abdelkarim Vlaamse overheid

Abstract

At the beginning of 2021, the MDK Coastal Division, Ostend and Middelkerke municipality built-up dunes on the dry beach in front of a sea dike at four locations: Spinoladijk (Ostend), Raversijde, Westende 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 03/2026 to investigate the morphological development and evolution of the built dunes. This report documents evolution of the morphology of the dune for dike pilots until the 5th year after construction. A progressive evolution of the four pilot sites occurred over the entire monitoring period.

A substantial accretion took typically 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. Over time, 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 condition over the monitoring periods. At Raversijde, this reduction could be further caused by a diminution of sand availability after the nourishment in 2021. A combination of natural and human factors might have caused this in Spinoladijk and Westende. 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. These would also confirm the temporal behaviour and evolution of the NbS sites.

Contents

Abstract III
Contents IV
List of tables VI
List of figures VII
1 Monitoring NbS sites 1
1.1 Spinoladijk 1
1.2 Raversijde 4
1.3 Westende 7
1.4 Knokke 9
2 Methodology 12
2.1 UAV surveys acquisition 12
2.2 LiDAR acquisition 12
2.3 RTK-GPS profiles and beach indicators 12
3 Meteo-marine conditions 13
3.1 Storm occurrence 13
3.2 Wind regime 13
4 Results of morphological analysis 15
4.1 Spinoladijk 15
4.1.1 Annual morphological evolution 15
4.1.2 Volumetric changes 20
4.2 Raversijde 22
4.2.1 Annual morphological evolution 22
4.2.2 Volumetric changes 27
4.2.3 Nourishment performance and lifetime 29
4.2.4 Recent development of embryo dunes 35
4.3 Westende 38
4.3.1 Annual morphological evolution 38
4.3.2 Volumetric changes 42
4.4 Knokke 43
4.4.1 Annual morphological evolution 43
4.4.2 Volumetric changes 46
4.4.3 Cliff formation 47

5 Discussion 48
5.1 Morphological comparison between NbS sites 48
5.2 Recommendations 51
6 Conclusions 53
7 References 54
Appendix A A1
Appendix B A17

List of tables

Table 1 - Timeline of the interventions and surveys at Spinoladijk with UAV error based on check points installed on the field during the survey. The thick borders indicate distinct monitoring periods. 3

Table 2 - Timeline of the interventions and surveys in Raversijde with UAV error based on check points installed on the field during the survey. The thick borders indicate distinct monitoring periods. 6

Table 3 - Timeline of the interventions and surveys in Westende with UAV error based on check points installed on the field during the survey. The thick borders indicate distinct monitoring periods. 9

Table 4 - Timeline of the interventions and surveys in Knokke with UAV error based on check points installed on the field during the survey. The thick borders indicate distinct monitoring periods..... 11

Table 5 - Summary of storm occurrence from 2021-2025 with description of water level recorded in Ostende tide gauge, significnat wave height (Hs) and direction (Dir) recorded in Ostende Poortjes buoy..... 13

Table 6 - Summary of beach indicators extracted from the profiles..... 20

Table 7 - Volumetric changes of the defined zones at Spinoladijk site. Green (accretion), red (erosion), grey (stability:<+/-0.05m)..... 21

Table 8 - Volumetric changes in the vegetated boxes at Spinoladijk site. Green (accretion), red (erosion), grey (stability: :<+/-0.05m)..... 21

Table 9 - Summary of beach indicators extracted from the profiles. T33 and T36 were carried out in 03/2025 and 12/2025 respectively..... 27

Table 10 - 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). 28

Table 11 - Average of volumetric change for the west, middle and east boxes. Green (accretion), red (erosion), grey (stability). 28

Table 12 - Timeline of merged beach and shorface data 29

Table 13 - Summary of the total volumetric budgets from 2020 to 2025. 35

Table 14 - Summary of beach indicators extracted fom the profiles. T11 and T13 were carried out 04/2025 and 10/2025 respectively..... 42

Table 15 - Volumetric changes of the defined zones at Westende site. Green (accretion), red (erosion), grey (stability: <+/-0.05m)..... 42

Table 16 - Summary of beach indicators extracted from the profiles. The surveys in Tbefore and T0 were carried out in 10/2023 and 12/2023 respectively..... 46

Table 17 - Volumetric changes of the defined zones at Knokke site. Green (accretion), red (erosion), grey (stability: :<+/-0.05m).)..... 46

Table 18 - Summary of volume budget for the NbS sites over the entire monitoring period and the long-term coastal trend (extracted from Houthuys et al., 2022). To compare the rates, the volumetric trend was converted to $m^3/m/y$..... 49

Table 19 - Design comparison between the NbS sites. Dunefoot is defined here to be at 5.8 m TAW..... 51

List of figures

Figure 1 - A) orthophoto, B) digital elevation model on T0 (11/01/2021) at Spinoladijk. 2

Figure 2 - A) Orthophoto, B) digital elevation model onT0 (31/03/2021) at Raversijde..... 5

Figure 3 - A) digital elevation model B) orthophoto on T0 (30/03/2021) at Westende. 8

Figure 4 - A) orthophoto, B) digital elevation model on T0 (6/12/2023). 10

Figure 5 - Annual wind roses. Data recorded by the Zeebrugge Leopold weather station. 14

Figure 6 - Global evolution based on Ref DoDs of the UAV and LiDAR surveys at Spinoladijk. 16

Figure 7 - Annual evolution based on DoDs of the UAV surveys with the locations of the contours of the defined volumetric zones. 18

Figure 8 - Time series of beach profiles evolution. The vertical dashed lines correspond to the location of the wire fences. 20

Figure 9 - Global evolution based on reference DoDs of the UAV surveys in Raversijde. 23

Figure 10 - Annual evolution based on DoDs of the UAV surveys with the Location of the contours of the defined zones in Raversijde. 24

Figure 11 - 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. 26

Figure 12 - Delimitation of the zones 30

Figure 13 - Consecutive DoDs from 2020 (pre-nourishment) to 2025 33

Figure 14 - Time series of extacted beach (UAV) -shoreface (MB) profile 1, 3 and 6 from 2020 to 2025. Location presented in Figure 13. 34

Figure 15 - Aerial images collected during the UVA flight in 2025. 36

Figure 16- Topography of the embryo dunes observed during the UAV survey on T36 (Dec 2025) 37

Figure 17 - Global evolution based on DoDs of the UAV and LiDAR surveys at Westende. The changes of the building (landward of the seawall) are artefacts due to human interventions. 39

Figure 18 - Annual evolution based on DoDs of the UAV surveys. The changes of the building (landward of the seawall) are artefacts. Blue polygons indicate observed human interventions. 40

Figure 19 - Time series of the RTK-GPS and LiDAR surveys. Distance from the seaaward edge of the vegetated boxes start at 0 m. Inset: location of the profiles. 41

Figure 20 - Global evolution based on Ref DoDs of the UAV and LiDAR surveys 44

Figure 21 - Annual evolution based on UAV and LiDAR surveys with the locations of the contours of the defined volumetric zones. 44

Figure 22 - Time series of the UAV and LiDAR surveys profiles. The dashed lines correspond to the position of the vegetated boxes. Inset: location of the profiles. 45

Figure 23 - Ground photograph after Benjamin storm on 24/10/2025. Photo from Knokke-Hesit municipality. 47

Figure 24 - Evolution of sand budget over observation periods ranging from 1year to 5 years at the pilot sites: A) Spinoladijk, B) Raversijde, C) Westende and D) Knokke. 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 after 5th year..... 50

1 Monitoring NbS sites

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. Verwaest et al. (2022), Montreuil et al. (2023), Montreuil et al. (2024) investigated the morphodynamics of these NbS sites over the first three years monitoring.

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 (Figure 1). 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. Barbed wires wet set-up to limit access to the NbS. The orientation of the site is about 59° related to North. 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). Since April 2025, the access inside the NbS is open to the public. Additional boxes delimited by fences were installed on the west and east sides of the pilot site where marram grass were partly planted.

The survey monitoring reveals that sand bulldozing activities were undertaken during the monitoring period. These interventions have an impact on the interpretation of the dune site evolution. At present, however, details regarding the nature, volume, and purpose of these activities are lacking. The City of Ostend has been contacted to obtain additional information.

A)

B)

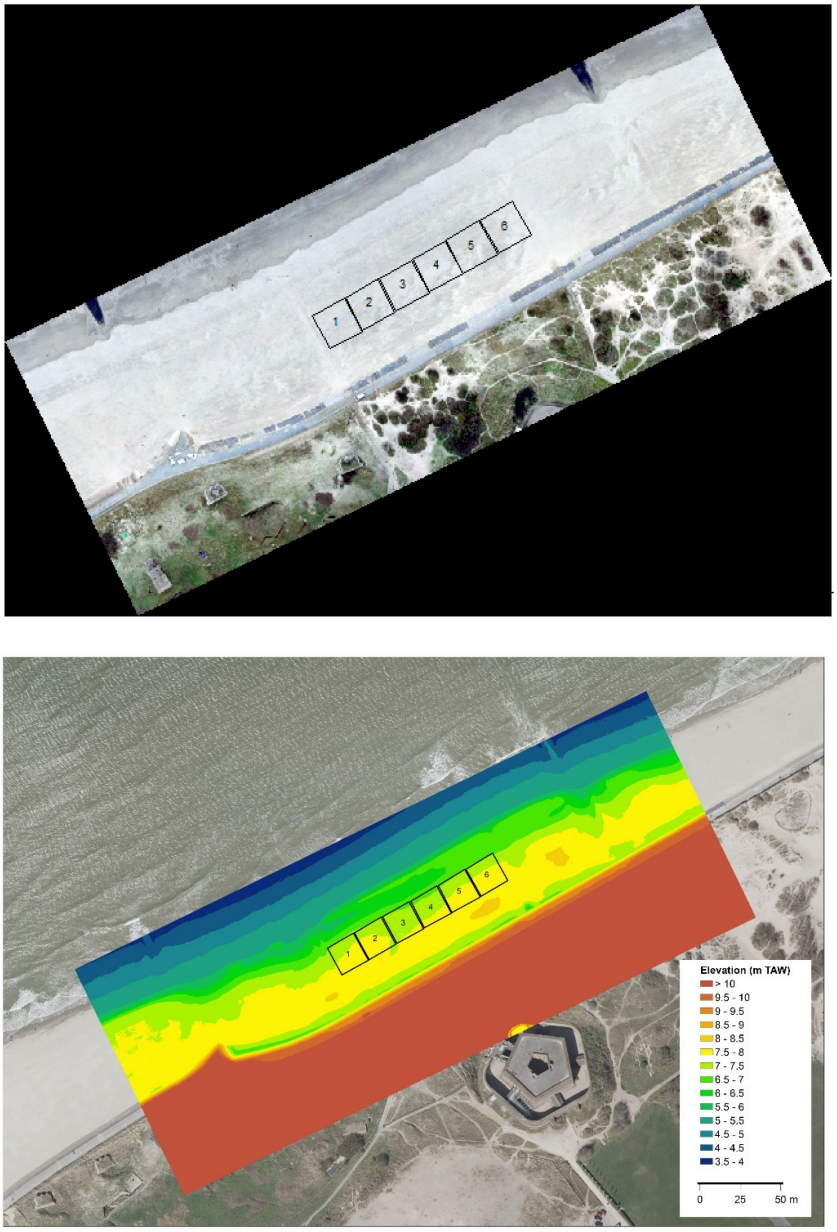


Figure 1 - A) orthophoto, B) digital elevation model on T0 (11/01/2021) at Spinoladijk.

Table 1 presents the timeline of the NbS interventions and the monitoring surveys at Spinoladijk.

Table 1 - Timeline of the interventions and surveys at Spinoladijk with UAV error based on check points installed on the field during the survey. The thick borders indicate distinct monitoring periods.

Time	Day	Duration since T0 (m: month)	Measurement
01-02/2021		Plantation of marram grass	
T0	11/01/2021		UAV
T1	23/02/2021	1.4m	UAV+hand RTK-GPS profiles
T1bis	02/03/2021	1.6m	UAV
T2	19/03/2021	2.3m	UAV+hand RTK-GPS profiles
T3	30/04/2021	3.6m	UAV+hand RTK-GPS profiles
T4	28/05/2021	4.5m	UAV+hand RTK-GPS profiles
T5	28/06/2021	5.5m	UAV+hand RTK-GPS profiles
T6	09/09/2021	8m	UAV+hand RTK-GPS profiles
T7	26/10/2021	9.5m	UAV+hand RTK-GPS profiles
T8	23/11/2021	10.4m	UAV+hand RTK-GPS profiles
T9	07/12/2021	10.9m	UAV
T10	17/01/2022	1 y	UAV+hand RTK-GPS profiles
T11	11/02/2022	1 y 1m	UAV+hand RTK-GPS profiles
T12	23/02/2022	1y 1.4m	UAV+hand RTK-GPS profiles
T13	08/03/2022	1y 1.8m	UAV+hand RTK-GPS profiles
T14	23/03/2022	1y 2.4m	UAV
T15	19/04/2022	1y 3.3m	UAV+hand RTK-GPS profiles
T16	02/05/2022	1y 3.7m	UAV+hand RTK-GPS profiles
T17	02/06/2022	1y 4.7m	UAV+hand RTK-GPS profiles
T18	12/09/2022	1y 8m	UAV
T19	12/10/2022	1y 9m	UAV
T20	24/01/2023	2y	UAV+hand RTK-GPS profiles
T21	09/02/2023	2y 1m	UAV+hand RTK-GPS profiles
T22	29/03/2023	2y 2.6m	UAV
T23	08/05/2023	2y4m	UAV+hand RTK-GPS profiles
T24	21/06/2023	2y5.3m	UAV
T25	14/09/2023	2y8m	UAV+hand RTK-GPS profiles
T26	04/10/2023	2y8.8m	UAV+hand RTK-GPS profiles
T27	06/12/2023	2y10.8m	UAV
T28	27/02/2024	3y1.5m	UAV
T29	23/04/2024	3y3.4m	UAV

T30	24/05/2024	3y4.5m	UAV
T31	04/10/2024	3y8.8m	UAV
T32	12/04/2025	4y3m	LiDAR
T33	05/11/2025	5y	LiDAR

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 of 498 630 m³ 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). The orientation of the site is about 56° related to North. 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.

At Raversijde, excavation works are regularly conducted in the zone between the planted dune and the seawall to limit aeolian sand transport toward the seawall and further inland (described for the period from December 2023 to February 2024 in Montreuil et al., 2024). These works are carried out by the city of Ostend near the NbS site as well as in adjacent areas to the west and east. In addition, the city periodically excavates a trench along the seawall to further prevent wind-blown sand from moving inland. When necessary, accumulated sand is also removed from the nearby promenade and tram line. The excavated sand is consistently transported by truck and redeposited at the high-water line. The last intervention of digging trench along the dyke was observed on the field in December 2025. The city of Ostende has been contacted to provide in more details about their work. Unfortunately, we did not receive any answer.

A)



B)

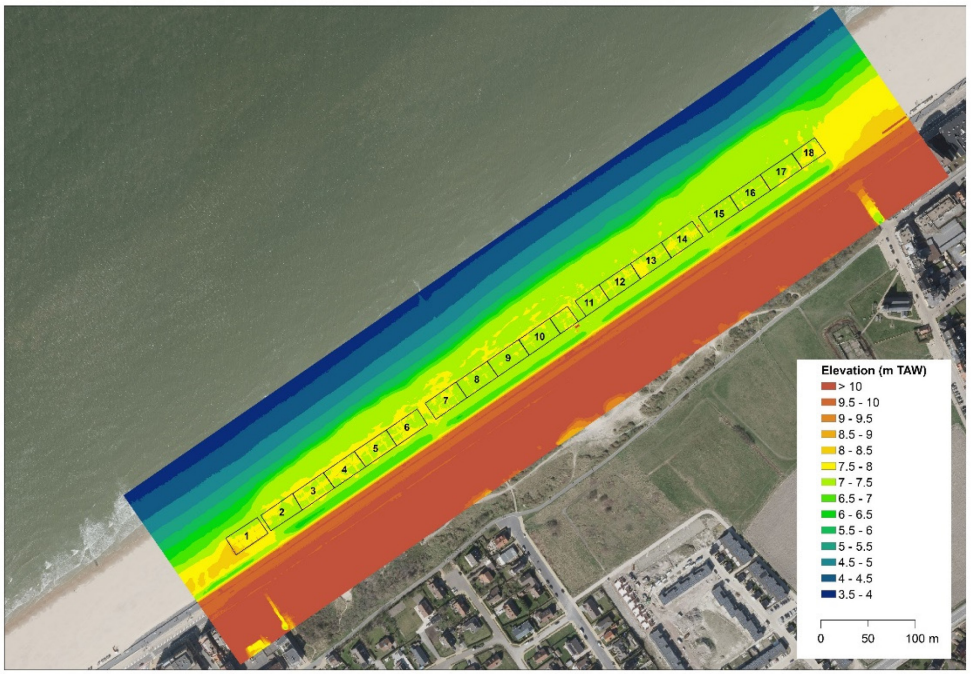


Figure 2 - A) Orthophoto, B) digital elevation model onT0 (31/03/2021) at Raversijde.

Table 2 presents the timeline of the NbS interventions and the monitoring surveys at Raversijde.

Table 2 - Timeline of the interventions and surveys in Raversijde with UAV error based on check points installed on the field during the survey. The thick borders indicate distinct monitoring periods.

Time	Day	Duration since T0	Measurement
18/01-18/02/2021		Beach nourishment+beach reprofiling	
03-04/2021		Plantation of marram grass	
T0	31/03/2021		UAV+hand RTK-GPS profiles
T1	28/04/2021	1m	UAV+hand RTK-GPS profiles
T2	27/05/2021	1.9m	UAV+hand RTK-GPS profiles
T3	25/06/2021	2.8m	UAV+hand RTK-GPS profiles
T4	08/09/2021	5.3m	UAV+hand RTK-GPS profiles
T5	22/11/2021	7.7m	UAV+hand RTK-GPS profiles+Quad RTK-GPS profiles
T6	07/12/2021	8.2m	UAV
T7	06/01/2022	9.2m	UAV+ RTK-GPS Quad profiles
T8	11/02/2022	10.4m	UAV+hand RTK-GPS profiles
T9	23/02/2022	10.8m	UAV+ RTK-GPS Quad profiles
T10	21/03/2022	11.7m	UAV+hand RTK-GPS profiles
T11	19/04/2022	1y 0.6m	UAV
T12	02/05/2022	1y 1m	UAV
T13	01/06/2022	1y 2m	UAV
T14	12/09/2022	1y 5.4m	UAV+hand RTK-GPS profiles
T15	12/10/2022	1y 6.4m	UAV
T16	24/01/2023	1y 9.8m	UAV+hand RTK-GPS profiles
T17	09/02/2023	1y 10.3m	UAV+hand RTK-GPS profiles
14-17/02/2023		Plantation marram grass	
T18	09/03/2023	1y 11.3m	UAV+hand RTK-GPS profiles
T19	29/03/2023	1y12m	UAV+hand RTK-GPS profiles
T20	08/05/2023	2y1.3m	UAV+hand RTK-GPS profiles
T21	21/06/2023	2y2.7m	UAV+hand RTK-GPS profiles
T22	14/09/2023	2y5.5m	UAV+hand RTK-GPS profiles
T23	04/10/2023	2y6m	UAV+hand RTK-GPS profiles
T24	22/11/2023	2y7.7m	UAV
T25	06/12/2023	2y8.2m	UAV
T26	27/02/2024	2y11m	UAV
T27	14/03/2024	2.11.5m	UAV
T28	23/04/2024	3.y0.8m	UAV

T29	24/05/2024	3y1.8m	UAV
T30	07/06/2024	3y2.3m	UAV
T31	22/10/2024	3y6.73m	UAV
T32	20/12/2024	3y8.7m	UAV
T33	17/03/2025	3y11.5m	UAV
T34	13/06/2025	4y2.5m	UAV
T35	10/09/2025	4y5.5m	UAV
T36	08/12/2025	4y8.3m	UAV
T37	06/03/2026	4y11.2m	UAV

1.3 Westende

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. The orientation of the site is about 59° related to North.

Typically, 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.

A)



B)

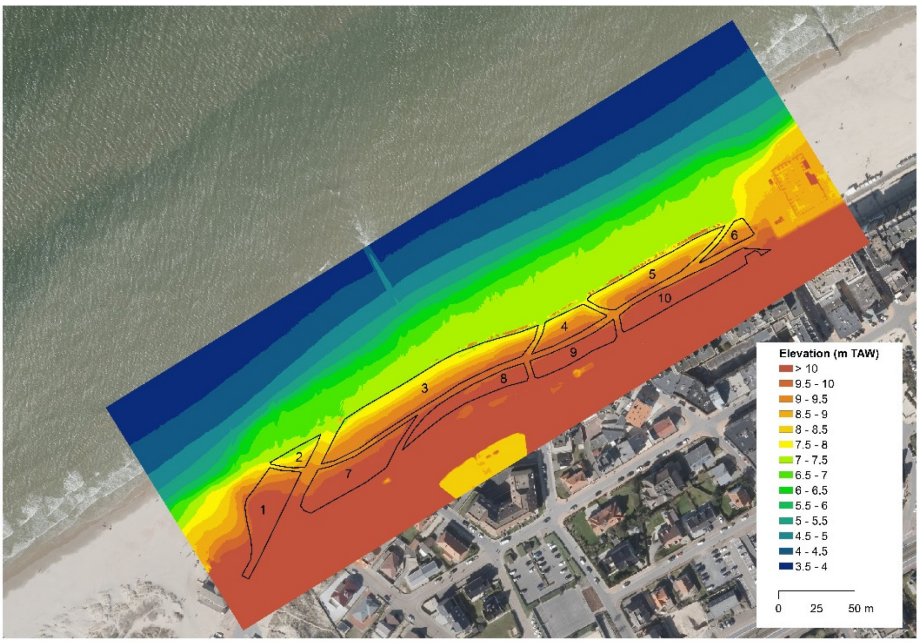


Figure 3 - A) digital elevation model B) orthophoto on T0 (30/03/2021) at Westende.

Table 3 presents the timeline of the NbS interventions and the monitoring surveys at Westende.

Table 3 - Timeline of the interventions and surveys in Westende with UAV error based on check points installed on the field during the survey. The thick borders indicate distinct monitoring periods.

Time	Day	Duration (ref T0)	Measurement
01-02/2021		Construction of grass dyke	
T0	30/03/2021		UAV
T1	30/04/2021	1m	UAV
T2	31/05/2021	2m	UAV
T3	28/06/2021	4m	UAV
T4	23/11/2021	7.8m	UAV
T5	23/02/2022	10.8m	LiDAR
T6	17/04/2022	12.6m	LiDAR
T7	08/02/2023	1y 10.3m	LiDAR
T8	17/06/2023	2y2.5m	LiDAR
T9	17/01/2024	2y9.6m	LiDAR
T10	29/11/2024	3y8m	LiDAR
T11	12/04/2025	4y0.5m	LiDAR
T12	05/11/2025	4y7.2m	LiDAR

1.4 Knokke

Wooden poles were installed on 16/10/2023 to demarcate the site in Rubensplein, 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. Also, this passage is often cleaned mechanically by the municipality. Marram grass was planted on 4 and 15/12/2023 with a variable density of plants (Figure 4), but there was no plantation for the last 2 to 3 m on the seaside. Before the NbS deployment, a large beach nourishment was carried out there in February to April 2023. The orientation of the site is about 71° related to North.

A large nearshore nourishment of 1.2 million m^3 was carried out in section 231-244 between October 2023 and February 2024. The delivered sand was extracted from the new lock construction site in Terneuzen. This sand consists of medium to fine grain size with a median of 187 µm (Montreuil et al., 2025, 2023). In addition, beach was supplied with about 510 574 m^3 of sand in section 230-241 from February to April 2023. Finally, cabins are deployed every year from April to the end of the summer season. They are located between the seawall and the vegetation boxes.

The interventions carried out by the city of Knokke-Heist was reported for the period from end 2025 to 2026 (Appendix B).

A)

B)

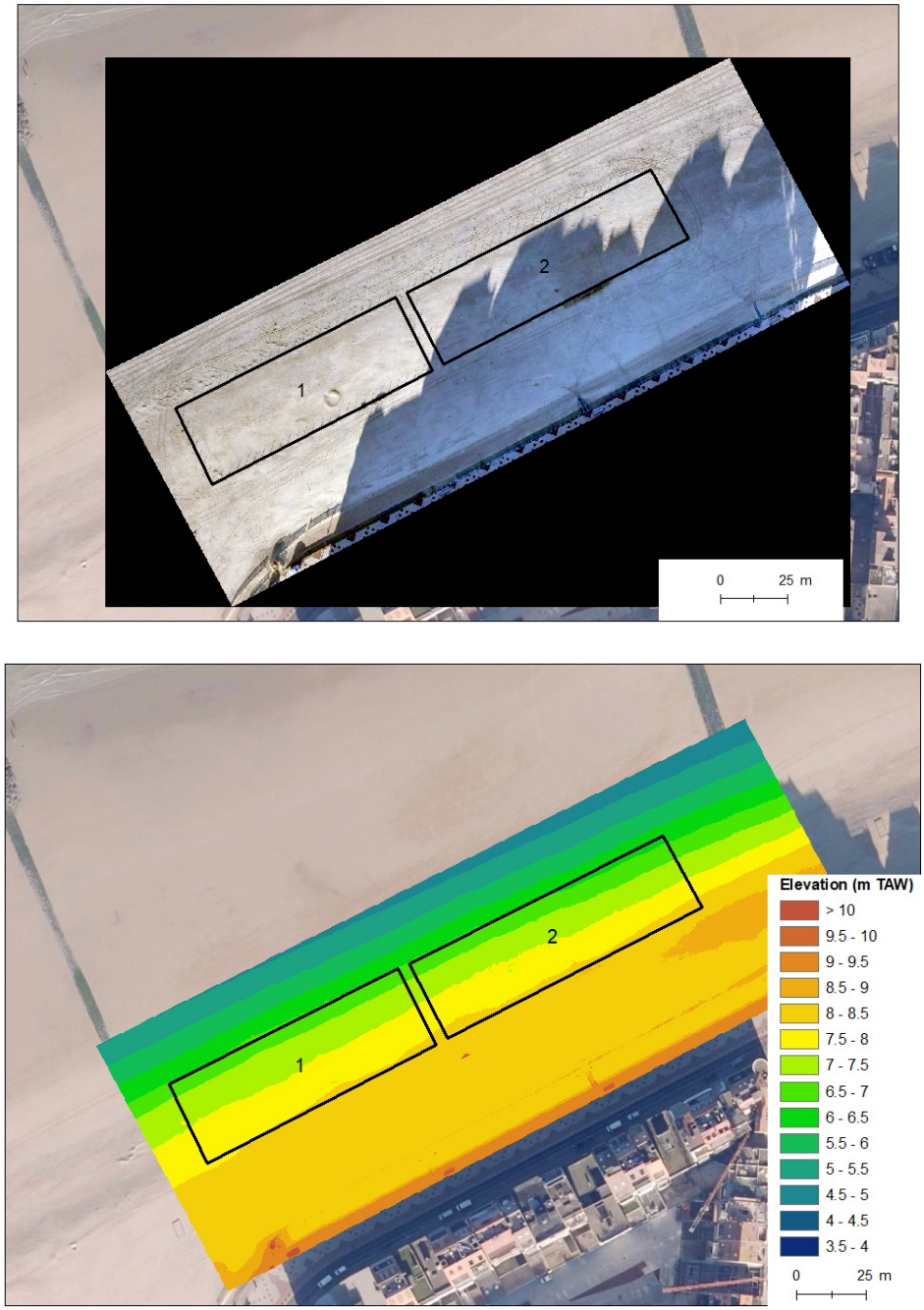


Figure 4 - A) orthophoto, B) digital elevation model on T0 (6/12/2023).

Table 4 presents the timeline of the NbS interventions and the monitoring surveys at Knokke.

Table 4 - Timeline of the interventions and surveys in Knokke with UAV error based on check points installed on the field during the survey. The thick borders indicate distinct monitoring periods.

Time	Day	Duration since T0	Measurement
	16/10/2023	Fixation of brushwoods	
	4-15/12/2023	Plantation of marram grass	
T0	06/12/2023		UAV
T1	17/01/2024	1.4m	LiDAR
T2	24/05/2024	5.6m	UAV
T3	29/11/2024	11.8m	LiDAR
T4	12/04/2025	1y4.2m	LiDAR
T5	05/11/2025	1y11m	LiDAR

2 Methodology

The monitoring focussed on the morphological evolution of the 4 pilot sites based on the UAV (Unmanned Aerial Vehicle) and airborne LiDAR data acquisition.

2.1 UAV surveys acquisition

Topographic monitoring was performed with a Phantom 4 RTK and M350 (from T31 October 2024) UAV by NeXperta-ATO (see Table 1 to Table 5). The flights were typically carried out at a height of 90 m. Montreuil et al. (2024) describes in detail the survey coverage per sites. Accuracy is reported to be below 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).

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. Therefore, interpolation was used to fill up the gaps 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 DoDs is 5 cm.

2.2 LiDAR acquisition

No more UAV surveys are carried out in Spinoladijk, Westende and Knokke over the recent period due to a budget reduction. Instead, the bi-annual LiDAR surveys commissioned by Coastal Division is used for morphological analysis. DEM of 1 m cell size is delivered and further processed to fill data gaps. 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 DoDs is 5 cm. The accuracy for the LiDAR surveys over the last years ranged from 2 to 3 cm.

2.3 RTK-GPS profiles and beach indicators

Profile surveys with RTK-GPS were carried out along 6 profiles at Raversijde, 3 profiles at Spinoladijk, Westende as well as 2 profiles at Knokke. For more description refers to Montreuil et al., 2024. Since summer 2023, profiles are extracted from UAV data for all the pilot sites.

The assessment of the indicators from the cross-shore profiles was made following the definitions of the morphological levels for the dune crest (+6.89 m), MHWL (+4.39 m) and MLWL (+1.39 m) TAW. The upper-beach width corresponds to the distance between dune crest and MHWL and the upper-beach slope to the slope between these two levels. The width and slope of the intertidal beach was also estimated from the profiles. It corresponds to the distance between the MHWL and MLWL.

3 Meteo-marine conditions

3.1 Storm occurrence

Table 5 indicates the timeline of storm occurrence between 2021-03/2026. A storm is defined as an event with a water level exceeding 5.5 m TAW combined with a surge above 0.5 m. Since the NbS sites are relatively close to each other, we can assume that the marine parameters are the same. Nine storms were recorded during the period from 2021 to 2025 but none in 2026. The winter 2021-2022 was energetic with 4 recorded events while the following periods were calmer with only 2 events per winter.

Table 5 - Summary of storm occurrence from 2021-2025 with description of water level recorded in Ostende tide gauge, significnat wave height (Hs) and direction (Dir) recorded in Ostende Poortjes buoy

Time	WL (m)	Surge (m)	Hs (m)	Dir (°)
07/11/2021	5.65	0.81	245	290
05/01/2022	5.60	0.77	389	288
31/01/2022	5.73	1.49	450	293
21/02/2022	5.57	0.82	431	255
24/11/2023	5.57	0.97	562	315
21/12/2023	5.62	1.36	410	280
15/01/2024	5.52	0.75	390	300
08/04/2024	5.52	0.63	136	290
23/10/2025	5.66	0.9	475	290

3.2 Wind regime

Figure 5 presents the annual wind roses from 2021-2026. The most efficient wind regimes took place in 2021 and 2023 when nearly 31% of the wind recorded was efficient to transport sand to the vegetated dunes (i.e. wind above 6m/s coming from 240°-60°). This was followed by the year in 2024 and 2022 with an efficient wind above 26%. In contrast, the year in 2025 was calm with an efficient wind just below 21%.

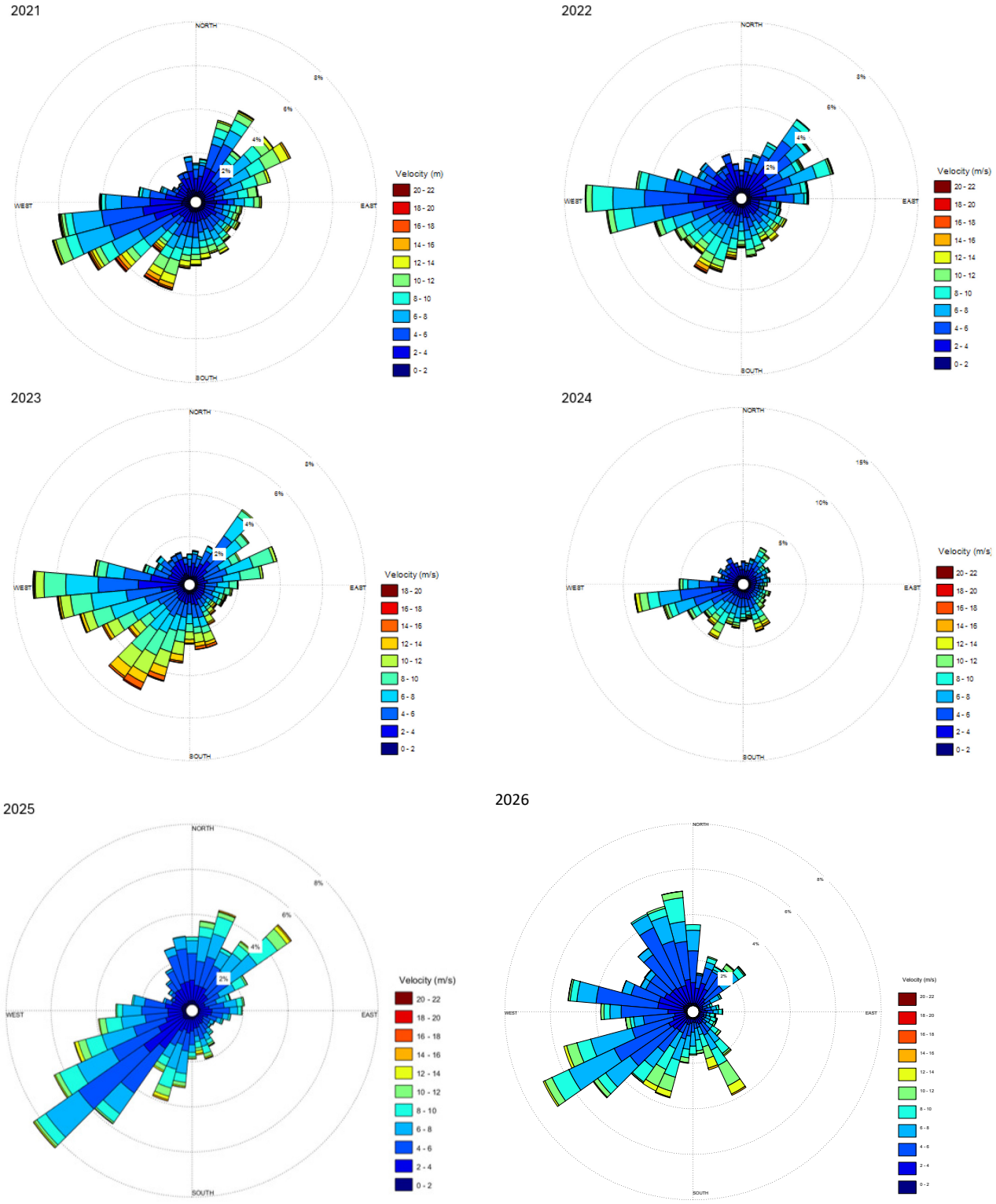


Figure 5 - Annual wind roses. Data recorded by the Zeebrugge Leopold weather station.

4 Results of morphological analysis

4.1 Spinoladijk

The pilot site at Spinoladijk was surveyed with UAV from 1/2021 to 04/2024 and from 4/2025 with LiDAR (Table 1).

4.1.1 Annual morphological evolution

Figure 6 illustrates the morphological evolution of the entire beach over a 1-5 year period. The DoDs show progressive accretion within the vegetated boxes over the monitoring period, with sand accumulation reaching 3.2 m by the final survey (Figure 6D). The upper dry beach landward of the boxes exhibits substantial accretion up to 2 m at Boxes 1, 2, and 6, contrasting with erosion of up to -0.55 m between Boxes 3 and 5. Significant erosion up to -1.4 m also occurred on both sides of the vegetation boxes, likely related to repeated excavation works by the city of Ostend, as supported by several UAV orthophotos showing truck tire tracks. Additionally, the lower dry beach below 5 m TAW experienced erosion ranging from 0.1 to 0.3 m. The significant elongated erosion strip of 170 m long and around 6 m TAW could be caused by natural processes or maintenance activities. Between this erosion zone and the accreting dunes and upper beach (7.5-7.7 m TAW), a relatively stable ‘no-change line’ about 1 m wide persisted throughout the monitoring period, with elevation changes within ±0.05 m.

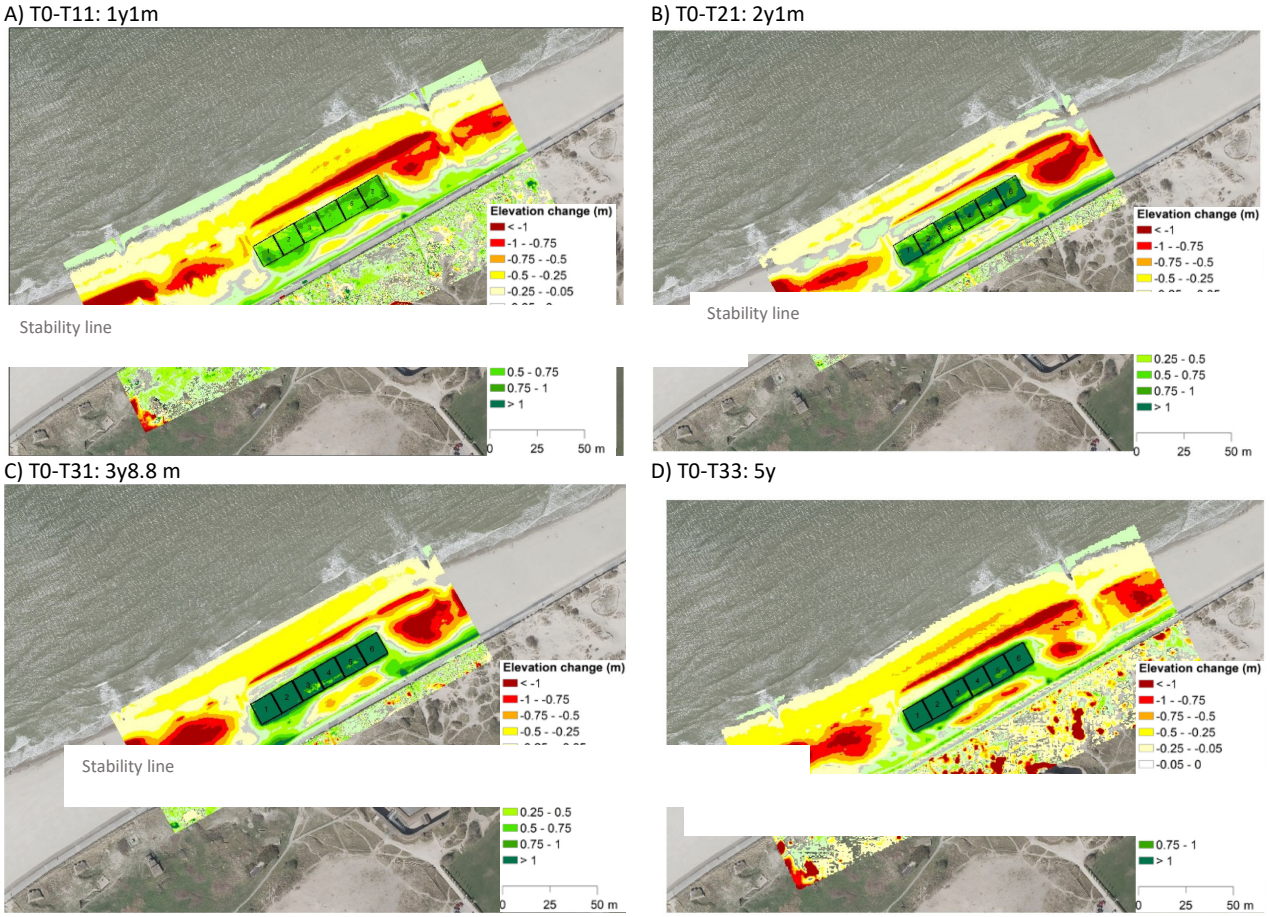


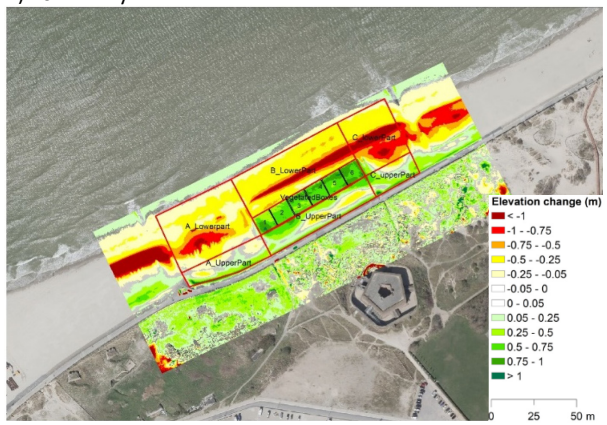
Figure 6 - Global evolution based on Ref DoDs of the UAV and LiDAR surveys at Spinoladijk.

The vegetated boxes experienced a larger accretion during the 1st year (T0–T11) and 3rd year (T21-T28) with maximum elevations of 1.05 m and 1.4 m respectively (Figure 7). While it was less for the 2nd (T11–T21) and 4th year (T28-T32) and 5th monitoring year (T32-T33). Noteworthy, the last interval T32-T33 lasted only 7 months and not a full year. The observed morphological pattern is in agreement with the recorded efficient wind transport regimes (section 3.2).

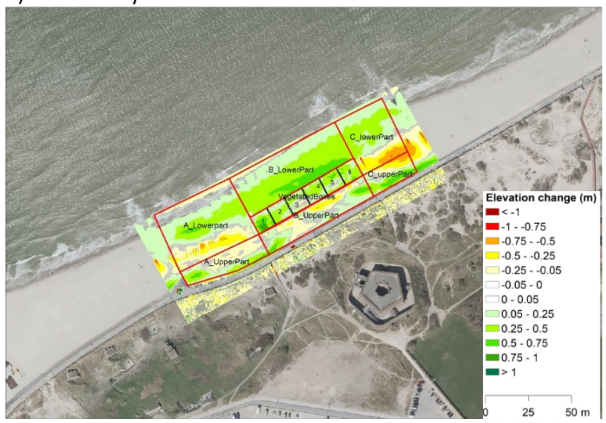
During the 5th year, a slight erosion occurred on the lower dry beach between 5 and 6 m TAW in front of the vegetated boxes and also on the east side, whereas strong erosion in the entire lower dry beach took place in the 1st year. Accretion within the boxes during the 5th year was confined to the seaward side (Figure 7E), contrasting with the previous years when sand gain occurred inside the boxes. This might be due to the trapping efficiency of the marram grass and also the frequent wind coming to W-NW while the wind was more blowing from W-SW for the first 3 years.

For both the 4th and 5th year, the upper beach landward of the boxes alternated between accretion and erosion. Sand accumulation along the dykes is connected to Box 1 and 6. This contrasts with the erosion back to Boxes from 2 to 5. This may indicate a reduced inland sand transport due to the development of higher vegetated dunes, although the influence of trench excavation works by the city of Ostend cannot be excluded.

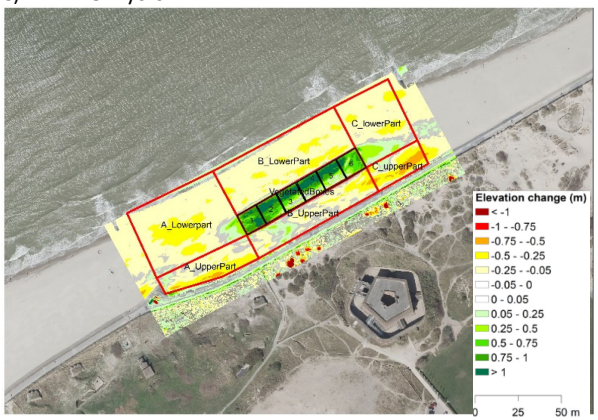
A) T0-T11: 1y1m



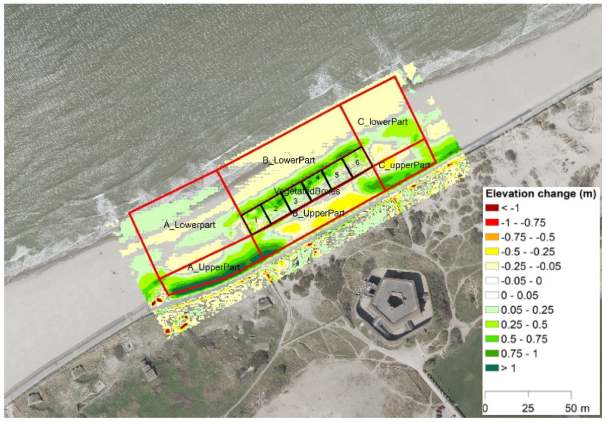
B) T11-T21: 1y



C) T21-T28: 1y0.6



D) T28-T32 LiDAR: 1y1m



E) T32-T33 LiDAR: 7m

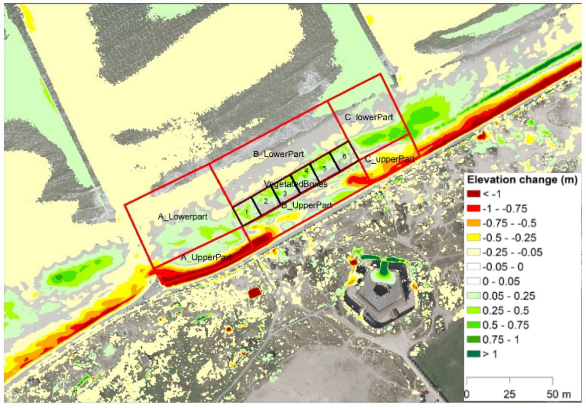
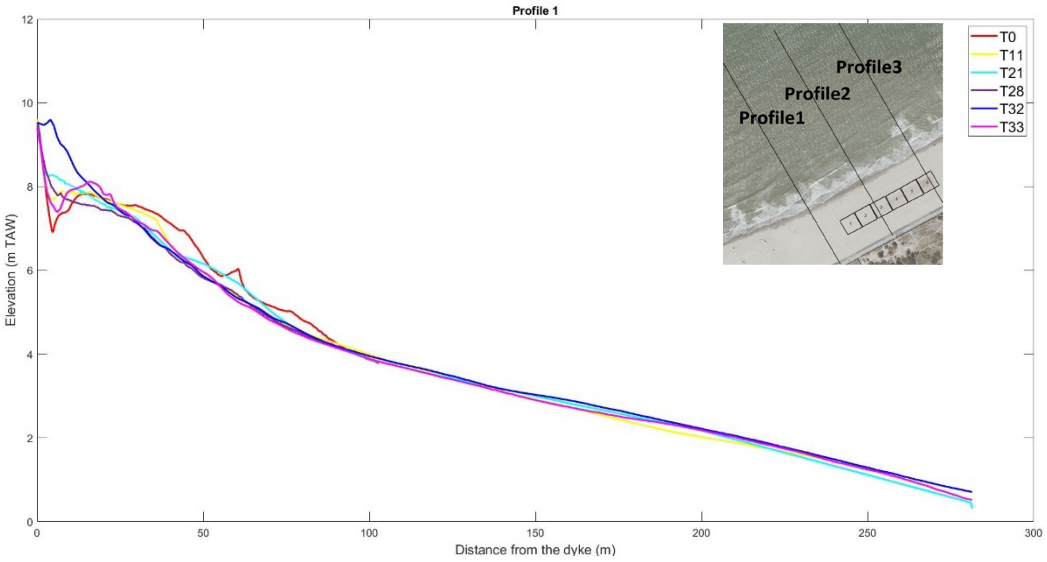


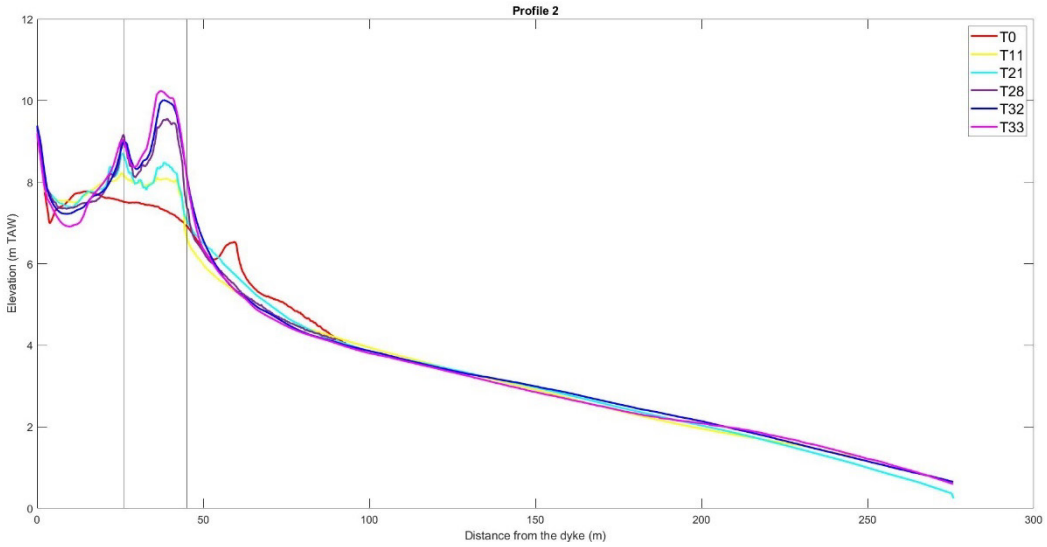
Figure 7 - Annual evolution based on DoDs of the UAV surveys with the locations of the contours of the defined volumetric zones.

Figure 8 presents time series of three beach profiles extending from the seawall to the low water line across all surveys for selected periods for clarity. Profile 1, located west of the vegetated boxes, shows limited morphological change, with sand loss between T0 and T11 followed by overall stability. The steep upper-part of the profile above 8 m TAW is likely caused by beach reprofiling carried out by the municipality. In contrast, Profiles 2 and 3 intersect Boxes 3 and 6, respectively, and exhibit similar behaviour, with upper-beach accretion (at a distance from 20-40 m from the seawall) where the vegetated boxes are located. Consistent with the DoDs in Figure 6, the highest dune crest located at 50 m in Profile 2 and 3 progressively grown to reach 10 m high after 5 years. The second crest (i.e. landward) located at 30 m was already observed in T11 and was also gradually grown at a lower rate than the 1st crest. This was expected since the first crest trapped most of the sand. Accretion dominated the seaward dry beach between T11 and T21, followed by a slightly lost in T28 and finally a stability till T33. The data covering the intertidal beach is limited but it suggests a general morphological stability.

A)



B)



C)

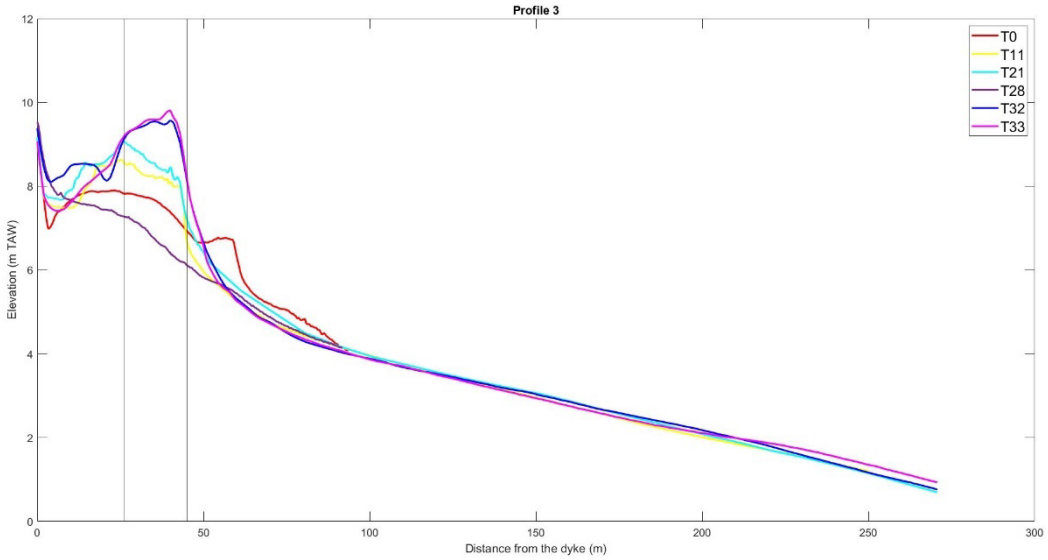


Figure 8 - Time series of beach profiles evolution.
The vertical dashed lines correspond to the location of the wire fences.

The morphological indicators for the reference Profile 1 indicate that the upper-beach became less steep over the monitoring period. In contrast, an increase of the slope for the upper-beach at Profile 3 is observed which might be related to the gain in height of the dune. Interestingly, the width of the intertidal beach increased a bit after T0 for Profile 1 and Profile 3.

Table 6 - Summary of beach indicators extracted from the profiles.

	Profile1							Profile 3						
	Before T0	T0	T11	T21	T28	T32	T33	Before T0	T0	T11	T21	T28	T32	T33
Time	2020	2021	2022	2023	2024	Begin 2025	End 2025	2020	2021	2022	2023	2024	Begin 2025	End 2025
Beach width (m)	32	44	45	44	48	51	45	35	29	32	34	30	29	30
Beach slope (-)	0.08	0.06	0.06	0.06	0.05	0.05	0.05	0.07	0.08	0.08	0.07	0.08	0.09	0.08
Intertidal zone width (m)	156	150	160	160	163	161	161	152	152	163	158	167	161	169
Intertidal slope (-)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

4.1.2 Volumetric changes

The study area is divided into a number of zones (Figure 7). The yearly volumetric evolution in these zones was calculated using the DEMs and the results are given in Table 7.

As shown by the DoDs, a net accretion occurred on the landward side of the dry beach (upper zones) and within the vegetated boxes over the entire monitoring period, while erosion dominated the seaward side (lower zones). However, the latter gained significant sand in the most recent year (T32-T33) due the repeated sand deposition carried out by the city of Ostend aiming to bring back the inland blown sand.

In the vegetated boxes, the maximum sand accumulation occurred in the 1st (T0-T11) and 3rd year (T21-T28) when the most efficient years of wind sand transport were recorded (Table 7). For the last year, the mean growth rate was still high with 0.28 m³/m²/yr (T32-T33) which was slightly higher than the previous period (T28-T33). In general, positive and stable accretion occurred in the area landward of the boxes (upper zones A–C) over the entire monitoring except for the period T21-T28 and T32-T33 due the works from the city.

Table 7 - 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-T33	m^3	4814	54	1589	357	2483	-135	27
		$m^3/m^2/y$	0.41	0.00	0.14	0.03	0.21	-0.01	0.00
Annual	T0-T11	m^3	1504	163	-1782	543	-2453	217	-1759
		$m^3/m^2/y$	0.70	0.10	-0.37	0.22	-0.54	0.21	-0.63
	T11-T21	m^3	662	125	249	151	1504	83	185
		$m^3/m^2/y$	0.28	0.07	0.05	0.06	0.30	0.07	0.06
	T21-T28	m^3	1385	-311	-715	-171	-740	-310	-242
		$m^3/m^2/y$	0.55	-0.16	-0.13	-0.06	-0.14	-0.26	-0.08
	T28-T32	m^3	577	781	2	214	-72	265	-55
		$m^3/m^2/y$	0.22	0.38	0.00	0.07	-0.01	0.21	-0.02
	T32-T33	m^3	386	-703	3835	-379	4244	-390	1898
		$m^3/m^2/y$	0.28	-0.67	1.06	-0.25	1.21	-0.59	0.96

Table 8 displays the yearly volumetric changes in all the vegetated boxes. The average sand deposition rate in the vegetated boxes ranges from 0.38 to 0.45 $m^3/m^2/y$ over the 5 years. Accretion in the boxes was the largest during the 1st and 3rd year with an average 0.6 $m^3/m^2/y$ while it was lower over the last two recent years with 0.13 $m^3/m^2/y$ recent year. As already observed on the DoDs (Figure 7), the westward boxes Box 1 and Box 2 received more sand than the eastward boxes over the 3rd year. This demonstrates that there is a spatial variation in the sand deposition in the vegetated boxes. For the 4th and 5th year, the accretion was lower than the 3 previous years. The average accretion was about 0.30 $m^3/m^2/y$ over these two last years.

Table 8 - Volumetric changes in the vegetated boxes at Spinoladijk site. Green (accretion), red (erosion), grey (stability: :<+/-0.05m).

			1	2	3	4	5	6
Global	T0-T33	m^3	808	789	672	736	716	746
		$m^3/m^2/y$	0.45	0.44	0.38	0.41	0.40	0.42
Annual	T0-T11	m^3	213	212	215	232	258	287
		$m^3/m^2/y$	0.65	0.63	0.65	0.71	0.74	0.84
	T11-T21	m^3	155	92	59	90	102	117
		$m^3/m^2/y$	0.44	0.25	0.17	0.25	0.27	0.31
	T21-T28	m^3	249	248	188	204	191	178
		$m^3/m^2/y$	0.67	0.65	0.50	0.55	0.48	0.46
	T28-T32	m^3	141	195	154	146	102	125
		$m^3/m^2/y$	0.35	0.47	0.38	0.36	0.24	0.30
	T32-T33	m^3	49	42	56	64	64	40
		$m^3/m^2/y$	0.24	0.20	0.27	0.31	0.31	0.19

Summary: The NbS dunes show clear and continuous sand accumulation over the 5-year monitoring period, with varying rates likely driven by changing wind conditions, sand availability, vegetation development and human interventions. The strongest dune growth rate was in the 1st and 3rd year while it was 1.5 lower times lower for the 5th period due to several possible reasons (e.g. wind climate, less sand available from dry beach, less sand storage capacity in the boxes caused by the infilling during the previous years). Overall, sand levels increased up to 3 m above the initial surface. Meanwhile, the lower part of the dry beach experienced erosion due to both natural and human processes. Also, the area between the dunes and the seawall is losing sand, probably due to trenching activities. A notable sand accumulation occurred on the landward sides of the western and eastern dune boxes, likely due to the development of the root systems of the marram grass. In total, the dunes increased the sand buffer above the 1000-year surge level (approx. +7 m TAW) by about 40 m³/m (i.e. length of the pilot site) over 5 years.

4.2 Raversijde

The pilot site at Raversijde was surveyed from 03/2021 to 03/2026 (Table 2).

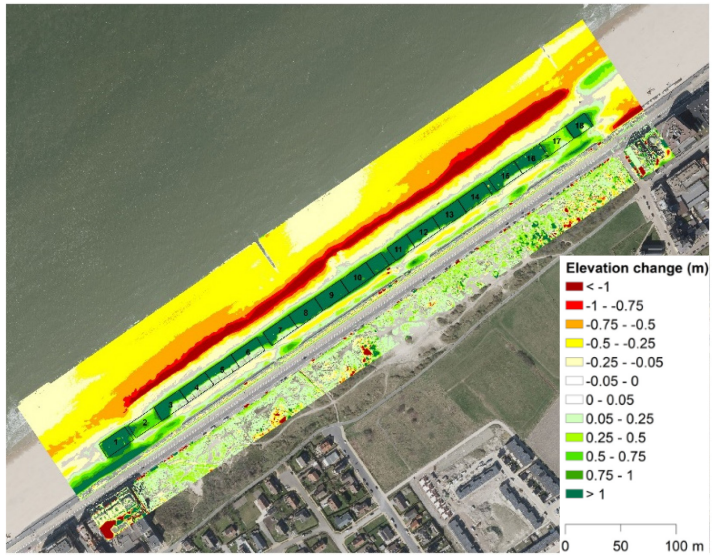
4.2.1 Annual morphological evolution

The DoDs show a progressive morphological evolution of the site (Figure 9), with clear net accretion within the vegetated boxes exceeding 3.5 m during T0-T37 (5 years) and also at a lower magnitude in the landward of the vegetated boxes. This contrasts with erosion on the seaward side Also, a significant sand gain occurred in the area between the landward edge of the boxes and the dyke (distance of 19 m) after nearly 4 years (Figure 9D). Interestingly, a local accretion took place just in front of the seaward side of Box 10 after 2 years (Figure 9B). These are embryo dunes observed in the field (see section 4.2.4).

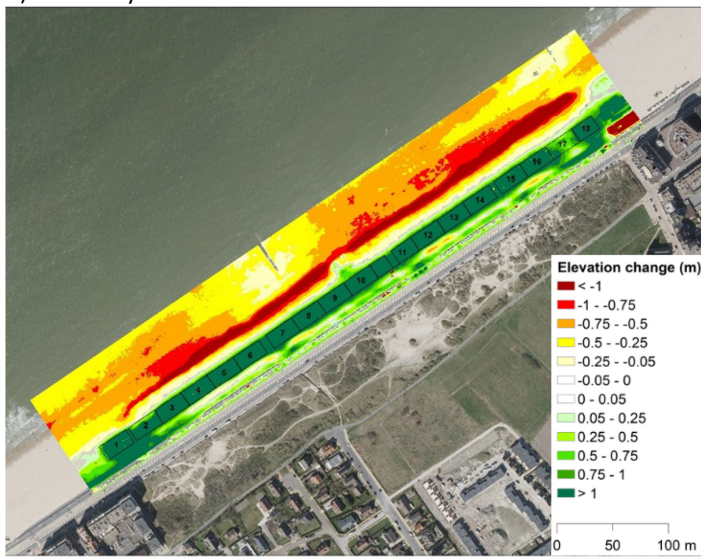
Figure 10 displays the annual morphological evolution. It seems that the highest sand gain over the 5th monitoring period (T33-T37) is relatively well-spread in the vegetated boxes, while it was more at the landward edge of the boxes for the 2nd (T10-T18) and 3rd (T18-T26) year monitoring. For the 1st year and 4th year (T26-T33), the highest sand gain took place at the seaward margin and center. These were controlled by both the eco-morphological interactions and the dominated wind regime during the period. The passages between boxes (Boxes 1-2, 6-7, 10-11, and 14-15) were largely infilled during the 1st monitoring year and to a further extent after 5 years. In addition, erosion dominated the seaward dry beach (in the B_lowerpart below 7.2 m TAW) during the entire monitoring period. From the 2nd period, a spatial pattern with alternating erosion-accretion in the area seaward of the vegetated boxes (lower part zones) is observed which is accentuated in the last 2 monitoring periods (T26-T33, T33-T37). This observation is expanded to the zone below the B_lowerpart at 3.3m TAW. This pattern reflects the presence of an intertidal bar-through system (Figure 11).

Finally, a persistent stability boundary at 7.5 m TAW, characterized by elevation changes within ±0.05 m and located just in front of the vegetated boxes, separates the upper and lower dry beach morphodynamics throughout the monitoring period. The upper-part zones (landward of the vegetated boxes) experienced a stability with local high erosion spots in the most recent period (T33-T73). These spots were clearly related to the human interventions from the city of Ostend since an opposite trend with accretion was recorded for the previous period (T26-T33) when extra sand was brought along the dyke. This was probably naturally blown by the wind over time. However, it was local since the sand was not spread to the upper-beach from the seaward side of the boxes where stability was recorded.

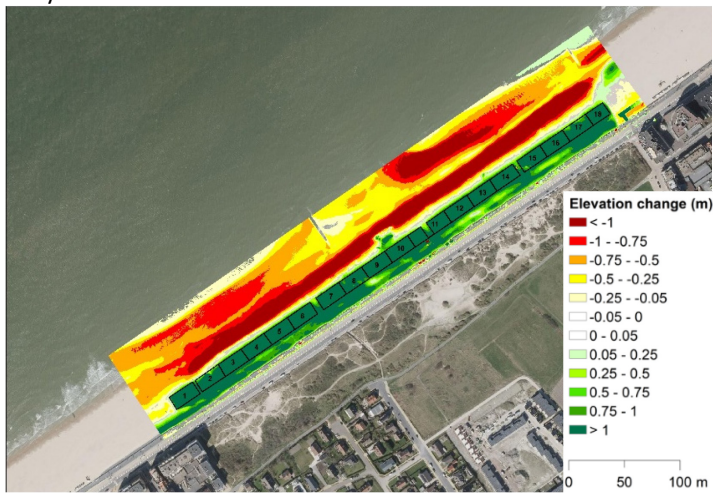
A) T0-T10: 11.7m



B) T0-T18:1y11.3m



D) T0-T33: 3y11.5m



E) T0-T37: 5y

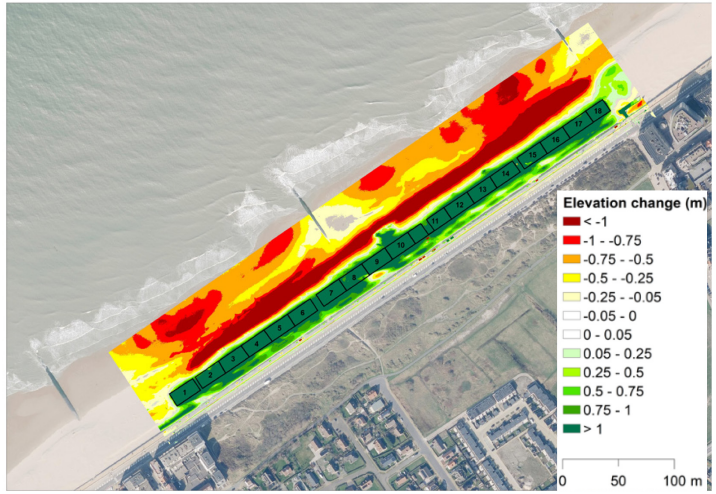
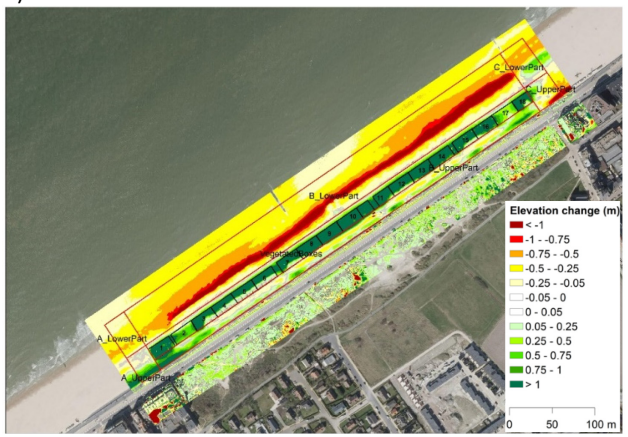
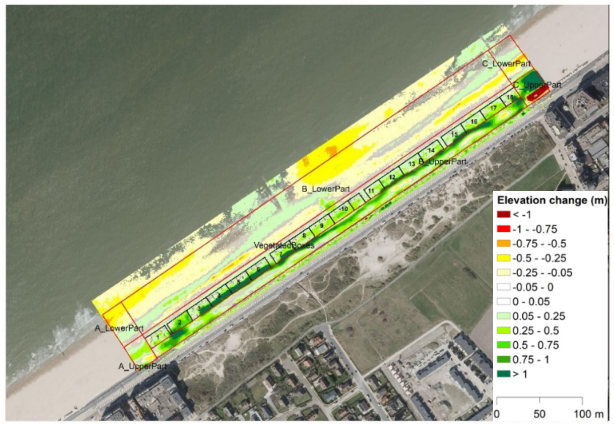


Figure 9 - Global evolution based on reference DoDs of the UAV surveys in Raversijde.

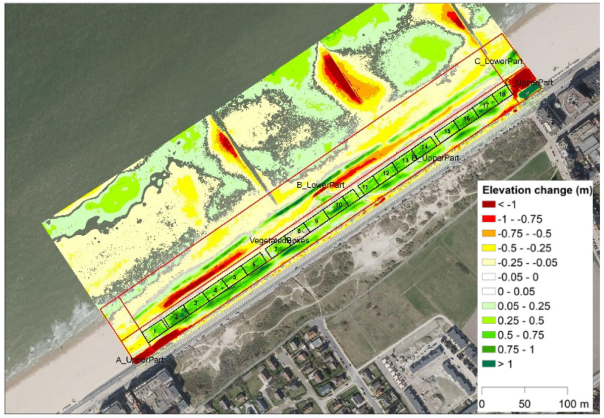
A) T0-T10: 11.7m



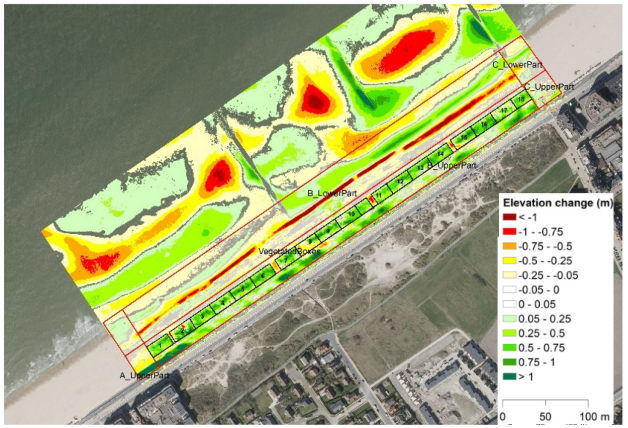
B) T10-T18: 11.5m



C) T18-T26: 1y0.6m



D) T26-T33: 1y0.6m



E) T33-T37: 1y

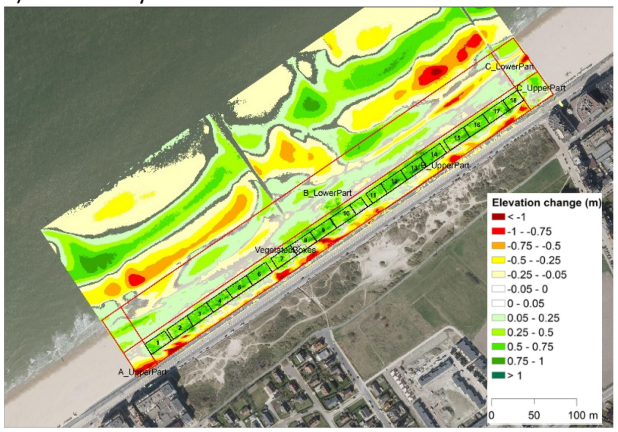
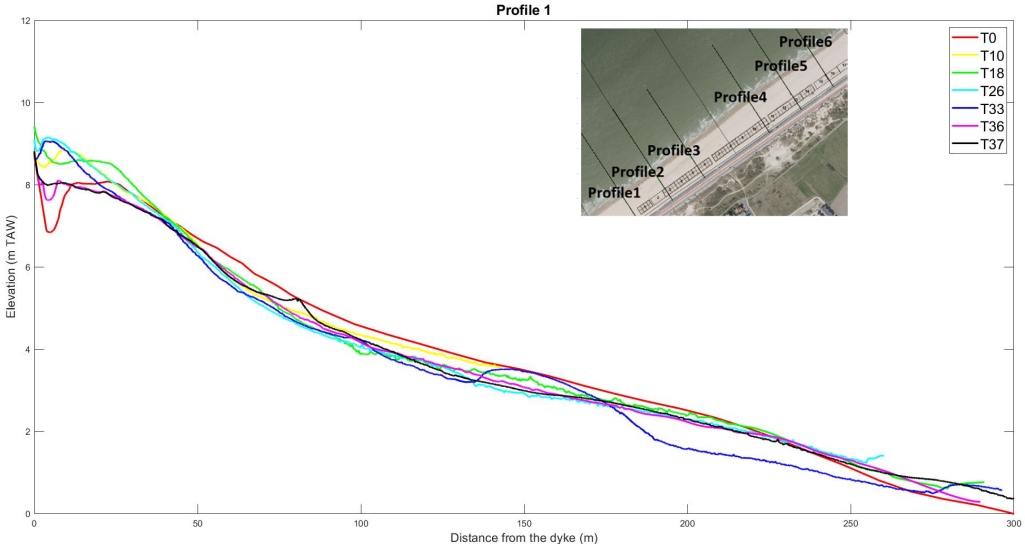


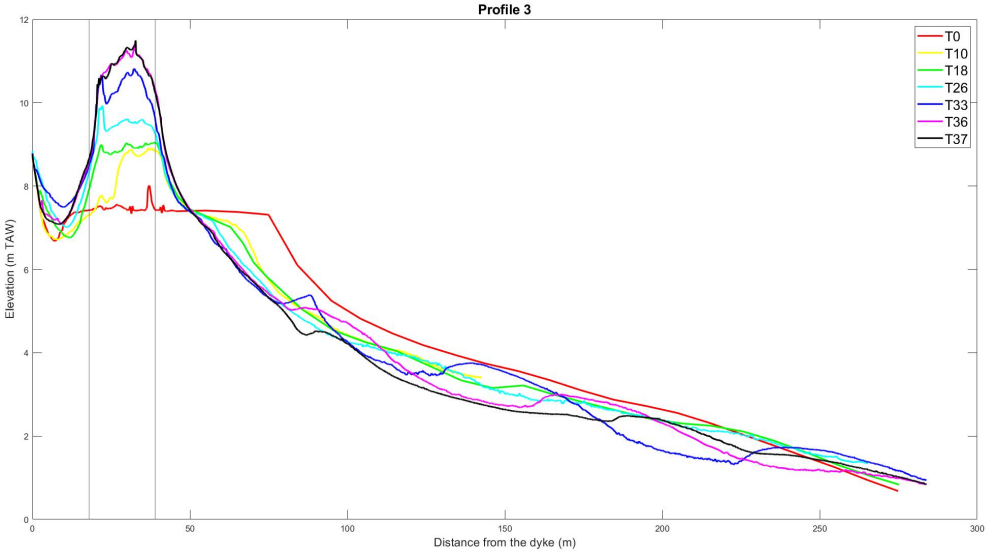
Figure 10 - Annual evolution based on DoDs of the UAV surveys with the Location of the contours of the defined zones in Raversijde.

Profiles 1, 3, and 6 are shown in Figure 11. Profile 1 is located southwest of the pilot area, while Profiles 3 and 6 cross the vegetated boxes and extend to the low-water mark. In the first years, a common bedform of the profiles crossing the vegetated boxes such as a berm was located at 7.3 m TAW and 65 m from the dyke. It can be suggested that this bedform protected the dune during energetic high tide conditions. Moreover, Profile 3 and 6 show a substantial sand accretion on the upper dry beach within the vegetated boxes, reaching up to 4 m relative to T0. Accumulation is smaller along Profile 1, where no vegetated box is present, making this profile more stable across the dry beach. Over the 5-years period, the seaward slope of the dry beach retreated landward with a distance from 11 to 21 m. Erosion dominated the dry beach seaward of the vegetated boxes and the upper intertidal zone up to 220 m, while the lower intertidal zone alternated between accretion and stability. The T0 moment was recorded just after the nourishment deployed on the beach to stimulate the dune growth, therefore the amplitude of this erosion is lower when compared with the situation pre-nourishment. Interestingly, two new intertidal bars along Profile 3 and 6 were observed in T33 which were further present in T36 when they moved landward. In T37, the most upper-part bar seems to have merged with the dry beach and a new bar at 200 m is formed. This is interesting, as it highlights a possible mechanism for landward sand transport on the intertidal beach. Further surveys will help to monitor these bars and their relationship with the growth of the vegetated dunes.

A)



B)



C)

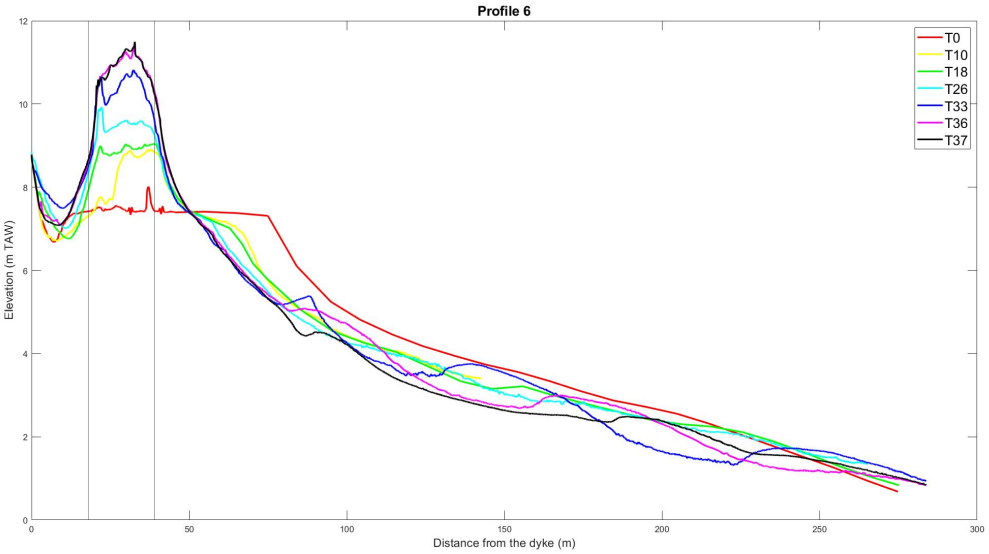


Figure 11 - Time series of evolution of the merged profiles of the UAV and RTK-GPS surveys.
The vertical dashed lines correspond to the location of the vegetated boxes.

The trends of the morphological indicators are presented in Table 9. In general, the upper-beach width in the reference Profile 1 (no vegetated dune) was large with a slope ranging from 0.04 to 0.06. The width of the upper-beach in Profile 6 decreased after the set-up of the NbS (39 m). This caused a slight increase of the slope (>0.06). A restraint temporal variability of the intertidal beach width of both profiles occurred but the slope was always gentle (0.02). The retreat of the upper-beach width in T37 is likely due to the presence of a small trough after the bar merging with the beach.

Table 9 - Summary of beach indicators extracted from the profiles.
T33 and T36 were carried out in 03/2025 and 12/2025 respectively.

	Profile 1								Profile 6							
	Before T0	T0	T10	T18	T26	T33	T36	T37	Before T0	T0	T10	T18	T26	T33	T36	T37
Time	2020	2021	2022	2023	2024	2025	2025	2026	2020	2021	2022	2023	2024	2025	2025	2026
Beach width (m)	34	57	47	40	40	50	49	52	41	48	40	39	40	42	49	39
Beach slope (-)	0.07	0.04	0.05	0.06	0.06	0.05	0.05	0.05	0.06	0.05	0.06	0.06	0.06	0.06	0.05	0.06
Intertidal zone width (m)	152	142	158	163	163	120	153	147	155	141	158	155	145	112	122	157
Intertidal slope (-)	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02

4.2.2 Volumetric changes

The pilot area was divided into seven zones for volumetric analysis based on the DoD surveys (Figure 10), with results summarized in Table 8. Over 5 years, the vegetated boxes gained 44,000 m³, equivalent to 0.42 m³/m²/yr. In general, significant aeolian accretion up to 0.18 m³/m²/yr also occurred landward of the boxes (UpperPart zones). For several periods, significant volume of sand was artificially removed or deposited in the zones A_upperPart and C_upperPart as observed on the DoDs. In contrast, all lower dry beach zones (LowerPart zones) experienced erosion.

Accretion in the vegetated boxes during the 5th year was 1.5 higher than the previous periods (from T10-T33). The largest accumulation took place in the 1st year due to the saturation of the effect of the brushwood fences and due to the nourishment allowing a large availability of sand on the dry beach initially. The volumetric changes of the defined zones were usually significant but decreased from T26. For the most recent period (T33-T37), only the zone A_lowerpart and C_upperpart experienced significant changes.

Table 10 - 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
		m^3	44053	6	-821	12928	-39494	394	-666
Global	T0-T37	$m^3/m^2/y$	0.42	0.00	-0.07	0.18	-0.16	0.04	-0.04
		m^3	17580	670	-810	2800	-27430	-390	-660
	T0-T10	$m^3/m^2/y$	0.84	0.38	-0.32	0.20	-0.54	-0.18	-0.21
		m^3	5660	230	-360	5890	-4080	840	-110
	T10-T18	$m^3/m^2/y$	0.27	0.13	-0.14	0.41	-0.08	0.39	-0.04
		m^3	6415	-755	-200	2745	-6388	-450	-20
	T18-T26	$m^3/m^2/y$	0.29	-0.40	-0.08	0.18	-0.12	-0.20	-0.01
		m^3	5514	326	3	4634	-4068	41	-17
	T26-T33	$m^3/m^2/y$	0.25	0.17	0.00	0.31	-0.08	0.02	-0.01
		m^3	8883	-469	548	-3136	2988	348	139
Annual	T33-T37	$m^3/m^2/y$	0.42	-0.26	0.22	-0.22	0.06	0.16	0.04

Table 11 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. The vegetated zones extended to 8 m seaward (i.e. coverage of the extension of the vegetation). This explains the slight difference of the dune growth rate between Table 10 and Table 11.

Table 11 - 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)
		m^3	13775	13321	12421
Global	T0-T37	$m^3/m^2/y$	0.58	0.54	0.56
		m^3	730	690	780
	T0-T10	$m^3/m^2/y$	0.90	0.86	0.96
		m^3	390	440	400
	T10-T18	$m^3/m^2/y$	0.49	0.54	0.49
		m^3	2460	1820	2278
Annual	T18-T26	$m^3/m^2/y$	0.48	0.34	0.48
		m^3	2177	1714	1915
	T26-T33	$m^3/m^2/y$	0.43	0.32	0.40
		m^3	2406	2214	2323
	T33-T37	$m^3/m^2/y$	0.50	0.44	0.52

Summary: Over 5 years, vegetated boxes in Raversijde gained significant sediment of 0.42 $m^3/m/y$, while landward areas also experienced aeolian accretion and lower beach zones were dominated by erosion. Accretion rates decreased substantially after the first year, with much smaller gains observed in years 2, 3, 4, and 5. Morphological profiles indicate that vegetated areas promoted sand build-up and dune protection, while non-vegetated areas remained more stable but showed less accretion.

The volumetric analysis shows no major spatial differences across the west, middle, and east zones. The highest sand accumulation occurred in the first year due to the effectiveness of brushwood fences before saturation and due to the nourishment allowing a large availability of sand on the dry beach initially. The beach evolved with landward retreat of the dry beach slope, formation and migration of intertidal sandbars, and alternating erosion–accretion patterns linked to bar-trough dynamics. Overall, the site shows progressive morphological development, with strong sediment accumulation within and behind vegetated zones, contrasted by erosion on the seaward side and localized effects from human interventions. In total, the NbS dunes including vertical extension and the nourishment in 2021 increased the sand buffer above the 1000-year surge level (approx. +7 m TAW) by about 59 m^3/m over 5 years.

4.2.3 Nourishment performance and lifetime

The objective of this section is to assess the efficiency of the beach nourishment in Raversijde just after the intervention and also its lifetime.

4.2.3.1. Methodology

The methodology is primary based on merged UAV and multibeam (MB) surveys carried out at the same period for the morphometric analysis. However, the MB bathymetric coverage is typically limited to the section 100-102 so that the combined LiDAR and single beam surveys were used to determine the morphological trend and to carry out volumetric analysis.

Table 12 - Timeline of merged beach and shorface data

Time	Description	Resolution (m)
2020 (pre-nourishment)	18/11/2020 LiDAR+26/05/2020 Annual SB	2
18/01-18/02/2021	Beach nourishment	
2021	28/04/2021 LiDAR+28/04/2021 Annual SB	2
04_06/2021	28/04/2021 LiDAR+24/06/2021 MB	1
2022	17/04/2022 LiDAR+15/05/2022 Annual SB	2
09/2022	12/09/2022 UAV+13/09/2022 MB	1
10/2022	12/10/2022 UAV+10/10/2022 MB	1
01/2023	24/01/2023 UAV+24/01/2023 MB	1
02/2023	09/02/2023 UAV+09/02/2023 MB	1
03_04/2023	29/03/2023 UAV+05/04/2023 MB	1
2023	17/06/2023 LiDAR+01/07/2023 Annual SB	2
06/2023	21/06/2023 UAV+19/06/2023 MB	1
09/2023	14/09/2023 UAV+23/09/2023 MB	1
11_12/2023	22/11/2023 UAV+07/12/2023 MB	1
2024	29/11/2024 LiDAR+02/07/2024 Annual SB	2
10/2024	22/10/2024 UAV + 04/10/2024 MB	1
2025	2/04/2025 LiDAR+01/04/2025 Annual SB	2
09/2025	10/09/2025 UAV+10/09/2025 MB	1

For further investigation, the dune-beach-shoreface was delimited into 5 zones along the sections 97- 105 (Figure 12). The delimitation of the zone is based on the morphological evolution of the nourishment.

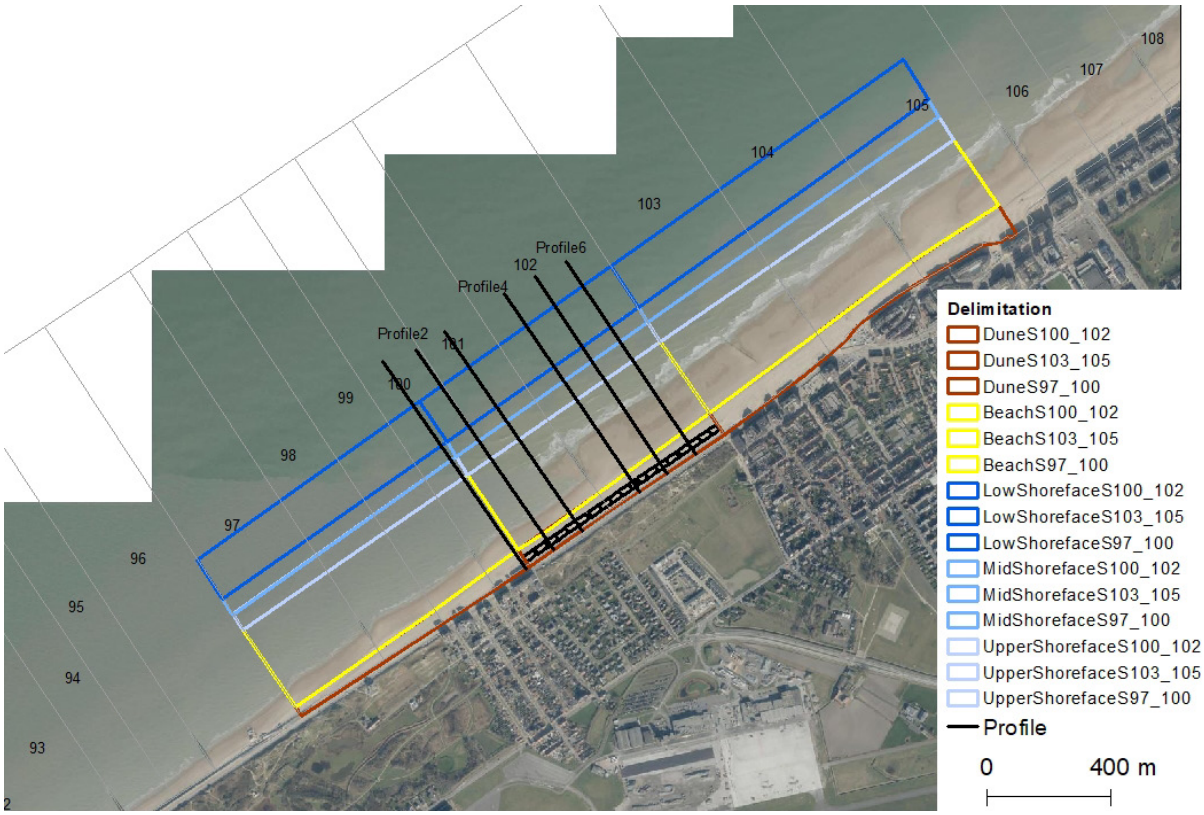


Figure 12 - Delimitation of the zones

Note: Dune zone: dyke to -5m TAW includes most of the dry part of the beach; Beach zone: 5m TAW to LW (note: mostly wet part of the beach); UpperShoreface zone: LW- -2m TAW; MidShoreface zone: -2m TAW to -4m TAW; LowShoreface: -4m TAW- -6.5m TAW.

4.2.3.2. Results

The placement efficiency of the beach nourishment of reported 498 630 m^3 was assessed using the merged LiDAR and single beam bathymetric survey between 18/11/2020 (pre-nourishment, 2 months before the intervention) and 28/4/2021 (post-nourishment, 2.3 months after the intervention).

On the pre- to post-nourishment DoD (Figure 13A), accretion can be observed across the beach zone up to the low water line from section 98-104. For section 97, the sand was only deposited on the upper-part of the beach till 3 m TAW. Also, the deposition in section 105 was limited only to the area close to the water line. Regarding the shoreface, an immediate response of the trough took place around -1 m TAW where it was filled up with sand from the nourished zone by seaward cross-shore transport.

The observed sand budget of the beach nourishment was about 420,940 m^3 (Table 12). Compared to the reported nourished sand, the placement efficiency of the nourishment was of 84%. This corresponds to what is a typically estimated volume loss of 15% during execution of a beach nourishment (Houthuys et al, 2026). However, it is important to note that this assessment of placement efficiency is based on surveys conducted 2 months before and after the nourishment when natural coastal processes may have interacted with the artificially placed sand.

As expected, in the first year after the nourishment erosion concentrated on the upper-beach and along the groynes and occurred rapidly after the nourishment as observed in Figure 13B, DoD 2021-2022. Nevertheless, the sand lost from the entire zone (97-105) was small about -18,200 m^3 (i.e. just above the uncertainty value). Thus, this suggests that the sand was not lost from the active system but was internally spread. Mainly a transfer from the nourished berm towards the lower part of the beach occurred. In addition, the DoD shows clearly an alongshore spreading of sand toward section 105 which was the only section gaining sand in the beach zone between 2021-2022. An opposite pattern of the bar-through system occurred in the shoreface, indicating a landward movement of the breaker bar with an erosion of its seaward side (Figure 14). The sand budget in the total shoreface zone was about -16,900 m^3 so that the sand lost was limited there 1 year after the nourishment.

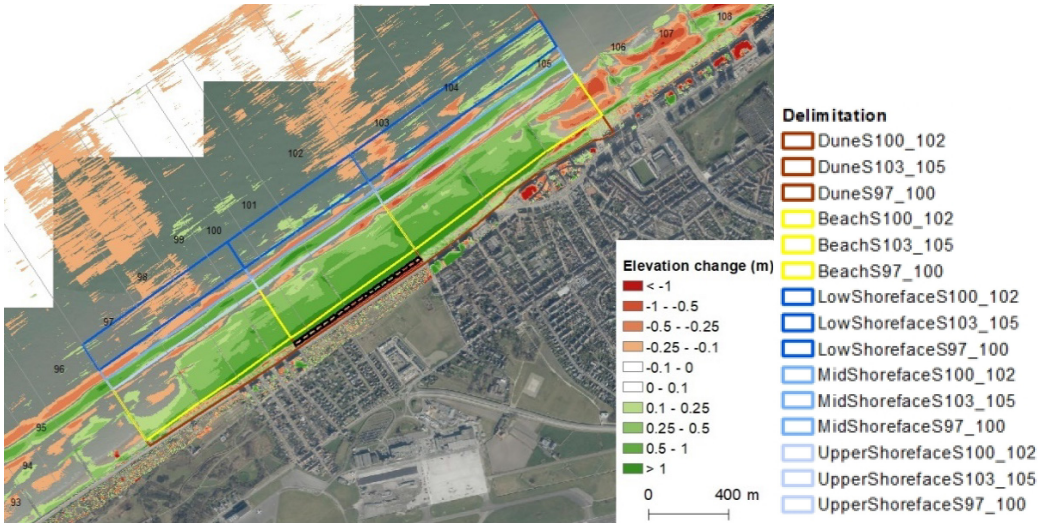
For the period 2022-2023, the clear pattern of accretion vs erosion on the beach disappeared. The sand lost seems to be localized on the lower part of the beach from section 101 to 105. The total sand budget of the beach was about -36,260 m^3 which corresponds to a small loss of 0.05 m. The bar-through system still grew and continued to migrate landward (Figure 14).

In the period 2023-2024 we observed more morphological changes on the beach from section 103 to 105 where an internal redistribution of sand occurred with a footprint of alternating erosion/accretion across the beach. The total sand budget was about -18,800 m^3 for the beach and -42,200 m^3 for the shoreface which are below the uncertainty. Thus, the sand lost from the beach nourishment was relatively limited.

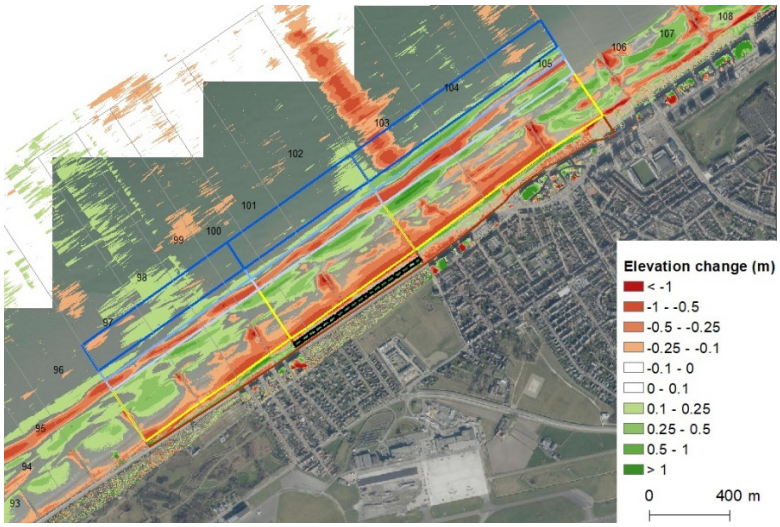
For the following period 2024-2025, a similar pattern on the beach took place at a higher magnitude and also extending from section 101 to 105. The total beach sand budget was very negligeable (-6550 m^3) which was opposite to the sand gain of the entire shoreface with 64,000m^3. Possibly a cross-shore sand transfer took place from the nourished beach to the shoreface. The longitudinal sand strip indicates a merging of the bar with the beach (Figure 14).

Over the monitoring, the volume at the beach decreased progressively. After 4 years, there is still 80% of the nourished sand in the beach zone. The remaining sand was partly lost from the active system or it was used to develop the vegetated dunes.

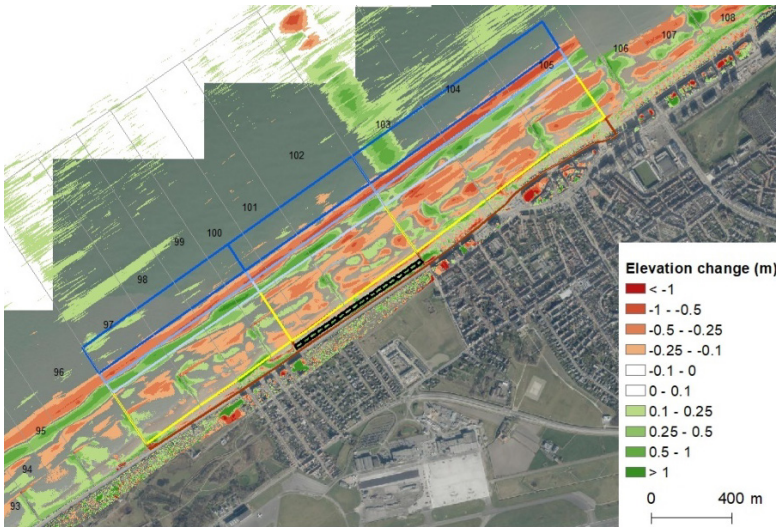
A) 2020 (pre-nourishment)-2021



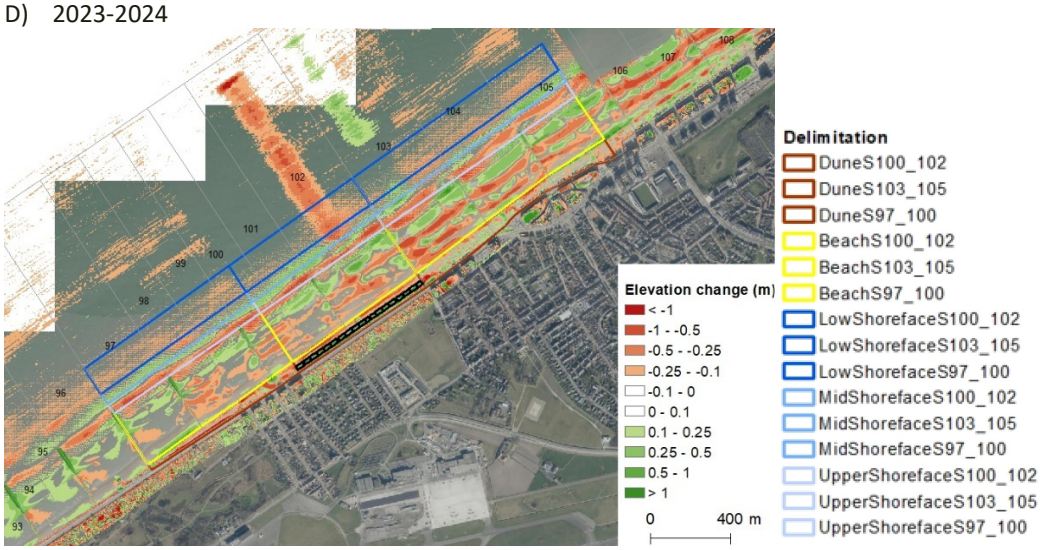
B) 2021-2022



C) 2022-2023



D) 2023-2024



E) 2024-2025

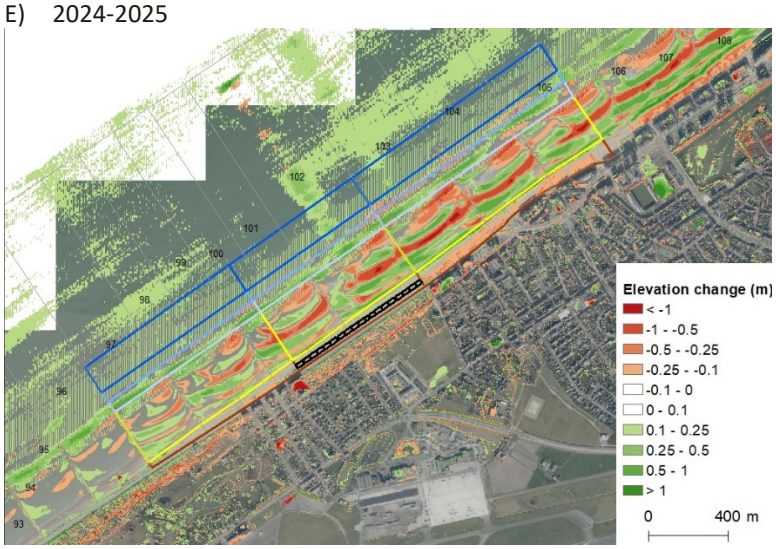
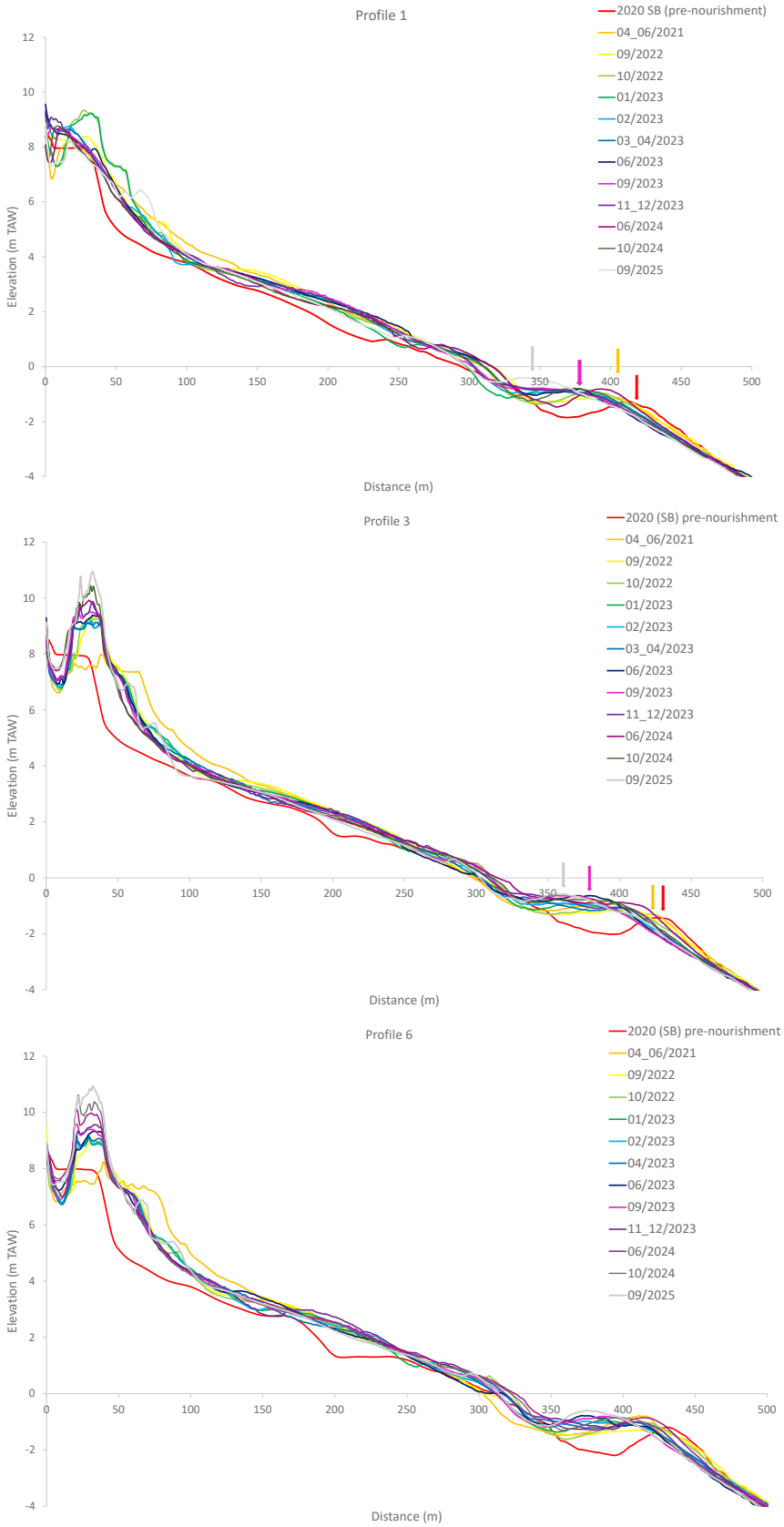


Figure 13 - Consecutive DoDs from 2020 (pre-nourishment) to 2025



Note: the vertical arrows indicate the positions of the bar.

Figure 14 - Time series of extacted beach (UAV) -shoreface (MB) profile 1, 3 and 6 from 2020 to 2025. Location presented in Figure 13.

Table 13 - Summary of the total volumetric budgets from 2020 to 2025.

		Total				%
		Dune	Beach	Shoreface	All	% nourished sand volume remaining at the beach (between 5 m TAW and LW) after the nourishment
2020-2021 (nourishment)	m^3	134549	286393	72630	493572	100 (by definition)
	m^3/m^2	0.72	0.37	0.09	0.28	
2021-2022	m^3	3837	-22038	-16895	-35096	92
	m^3/m^2	0.02	-0.03	-0.02	-0.02	
2022-2023	m^3	23622	-36258	-442	-13078	80
	m^3/m^2	0.13	-0.05	0.00	-0.01	
2023-2024	m^3	-2508	-18816	-42239	-63563	73
	m^3/m^2	-0.01	-0.02	-0.05	-0.04	
2024-2025	m^3	4558	-6547	64022	62033	71
	m^3/m^2	0.02	-0.01	0.08	0.04	
Uncertainty	m^3	9346	38787	168796	216930	**

Summary:

The beach nourishment initially showed strong placement performance, with about 84% efficiency (rising to ~99% when accounting for dumping losses), indicating that most of the placed sand remained within the system shortly after intervention. Early changes revealed redistribution of sand in the active system rather than loss, as sand moved from the upper beach toward lower and alongshore, with only minor net losses from the active system in 97-105 observed. Over the following years, gradual morphological adjustments occurred, including landward migration of the breaker bar and cross-shore sediment exchanges between the beach and shoreface. After almost five years, around 70% of the nourished sand remained in the beach zone, with the rest contributing partly to dune development and partly being lost from the active system of the area.

4.2.4 Recent development of embryo dunes

As previously observed in 4.2.1., relatively large embryo dunes (also called nebkha) have been developed seaward from the vegetated Box 10 after summer 2021 (i.e. first time observed on the UAV orthophoto in September 2021). Appendix A presents in detail the morphological and granulometric characteristics of these new embryo dunes. In December 2025 (T36), their height reached up to 9.8 m TAW and covered an area of 590 m^2 (Figure 16). These embryo dunes are special since they are colonized by Leymus arenarius (in Dutch zandhaver) grass which is ecologically iconic plant since it is endemic (Ecopedia, 2025). It is a dune-building bio-engineer plant because of its capacity of sand stabilization for a better erosion control (Verwaest et al., 2025a).

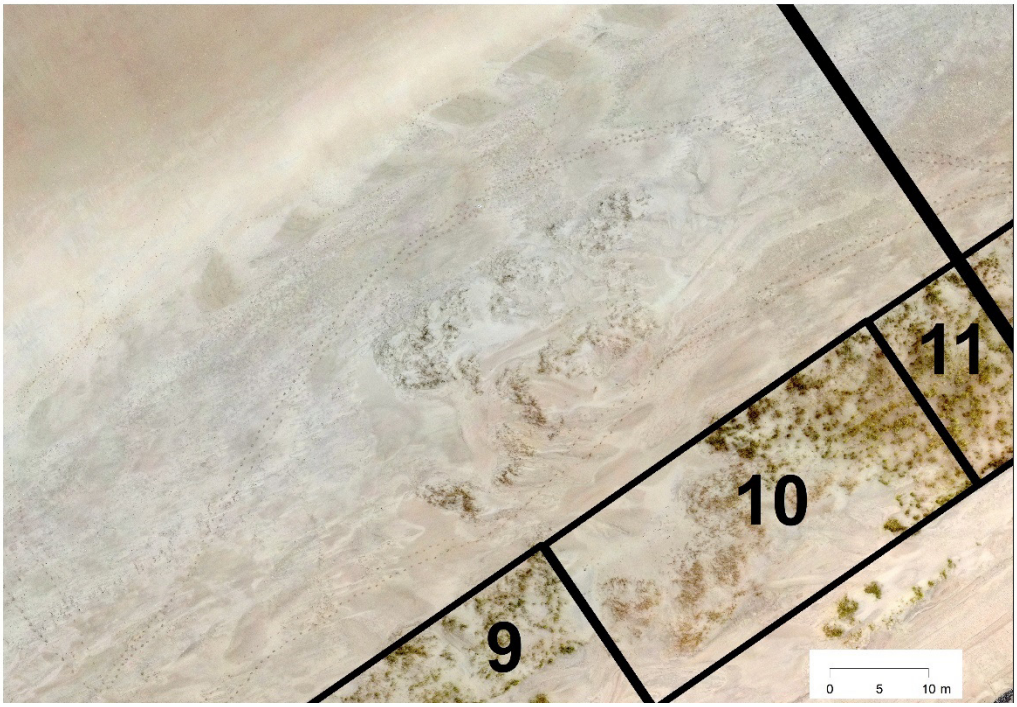
Strong eco-morphological interactions of the embryo dunes in Raversijde have been observed in September 2025. The plants form a spatial pattern described as ‘islands’ where plants occur in large, isolated patches and capture large volumes of sand, forming a heap. The morphology of the embryo dunes is more hummocky also called nebkha, and not very well connected to each other, in contrast to Ammophila dunes which usually form a ‘ridge’ (personal communication Charlotte Taelman and Dries Bonte). Also, Leymus arenarius grass has a fast expansion in the surroundings since their settlement in summer 2021.

Verwaest (2025) investigated the granulometry of these embryo dunes and found that they were characterized by a D50 of 320 µm which is close to the grain size of the sediment artificially supplied during the beach nourishment in 2021.



Figure 15 - Aerial images collected during the UVA flight in 2025.

A)



B)

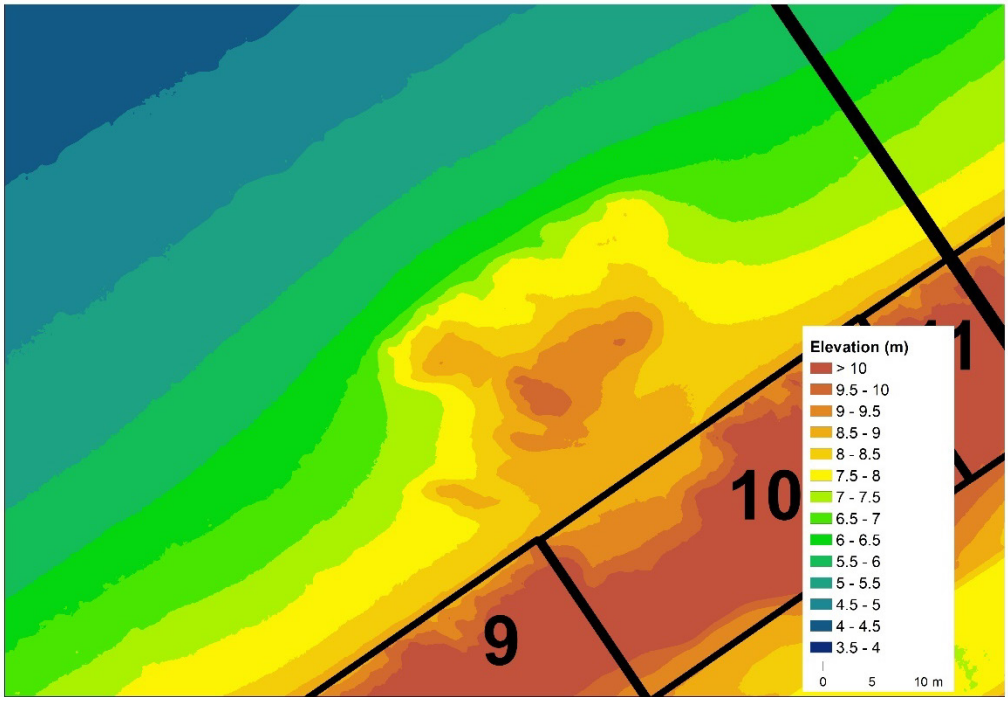


Figure 16- Topography of the embryo dunes observed during the UAV survey on T36 (Dec 2025)

4.3 Westende

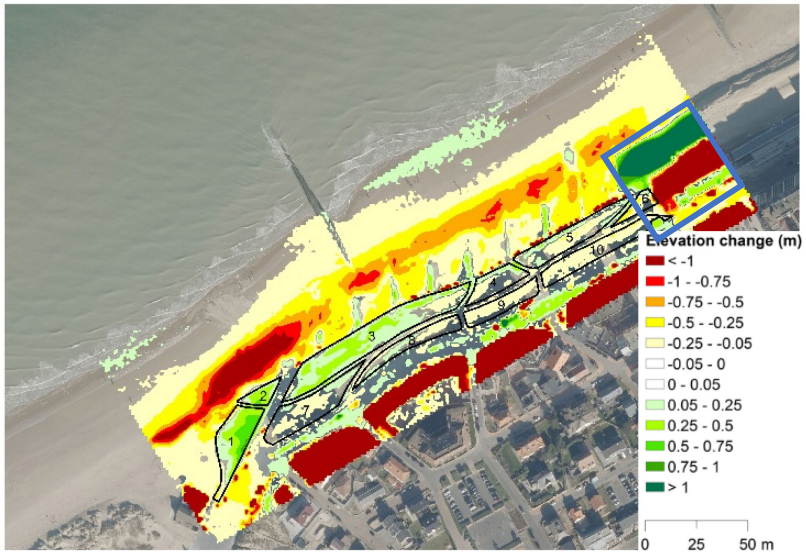
Five UAV flights were carried out in the period from 3/2021 to 11/2022 (0.65 years) (Table 3). Then the flight requests were not accepted by the authorities due to the proximity of military domain Lombardsijde. Since then, LiDAR surveys were used to evaluate the morphological and volumetric changes.

4.3.1 Annual morphological evolution

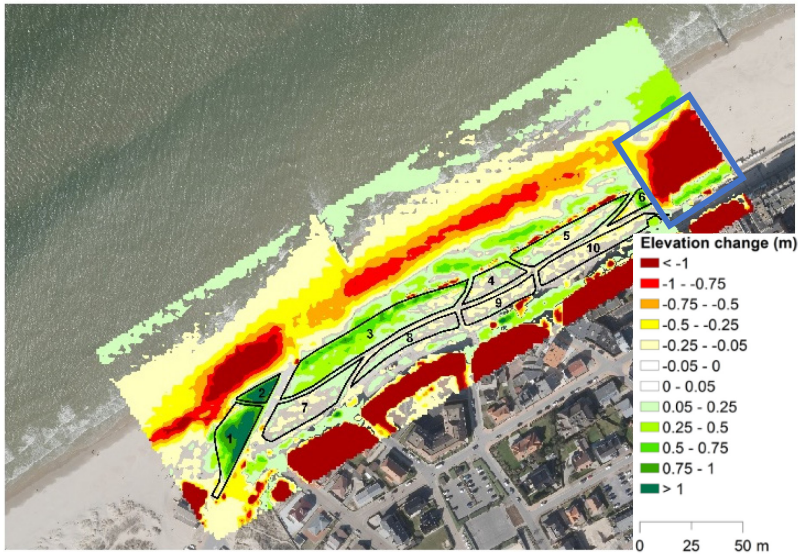
Figure 17 shows the DoDs from 1 year to 5 years after the implementation of the grass dyke (T0). Pronounced sand gain of up to 2.4 m is evident in the seaward vegetated boxes, particularly in the Boxes 2 and 3. This accretive trend of the most west boxes including Box 1 was already observed after 1 year (T0-T6). This further increased over the monitoring period which was consistent with coast-parallel SW winds trapping sand. It startles that this evolution of Box 1 was altered during 2025 (Figure 17D and Figure 18D). This is probably due to human interventions of the municipality of Middelkerke which is supported by a talus of sand reaching 2.1 m in front of Box 1 (Figure 18D). Regarding the landward vegetated boxes (Boxes 7–10), a sand accumulation with an average of 0.2 m occurred after 5 years. Seaward of the boxes, a continued erosion up to 1.4 m occurred on the dry beach below 6.3 m TAW. A narrow stability zone around 7 m TAW separated opposing morphological trends (erosion in the seaward vs accretion in the landward). Also, erosion on the dry beach east of the vegetated boxes is likely linked to municipal interventions, such as summer cabin installation and dyke expansion by the municipality, as observed in several UAV orthophotos.

Similar morphological trends were observed over the annual monitoring periods, with dominant erosion on the lower dry beach and with a relative stability of the landward vegetated boxes (Figure 18). A common pattern between the last annual periods (starting from T6) is the sand deposition in front of the parallel vegetated boxes (3-5). This suggests that accumulation was facilitated by structures such as fences. Alternation between erosion and accretion in this area is only observed in the first year. Fences were probably installed each year contributing to the overall morphological impact.

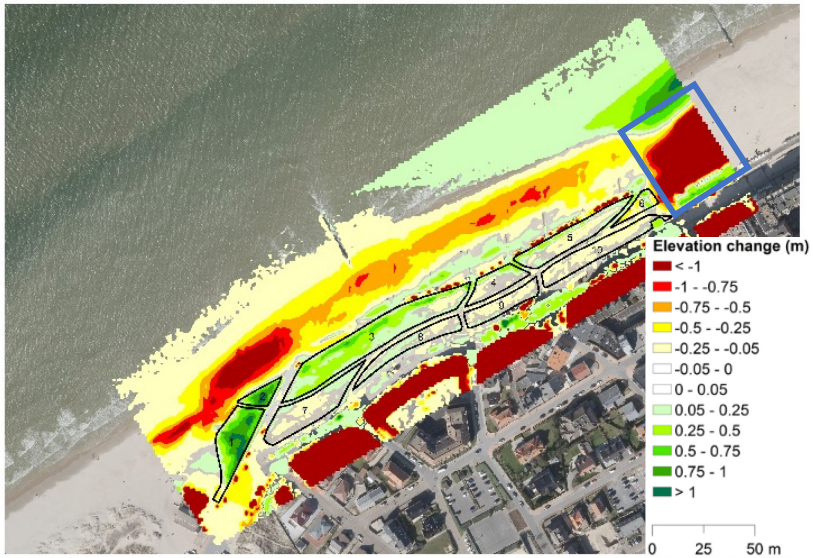
A) T0-T6: 12.8m



B) T0-T8: 2y2.5m



D) T0-T10: 3y8m



E) T0-T12LiDAR: 4y7.2m

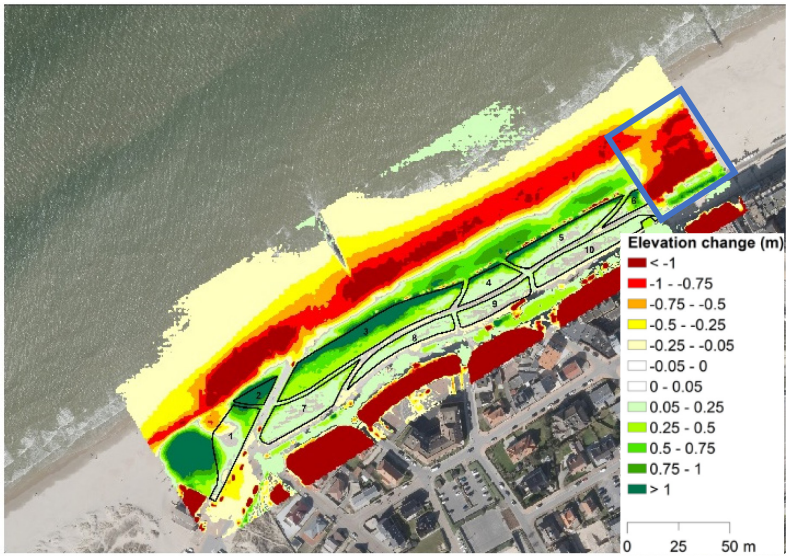
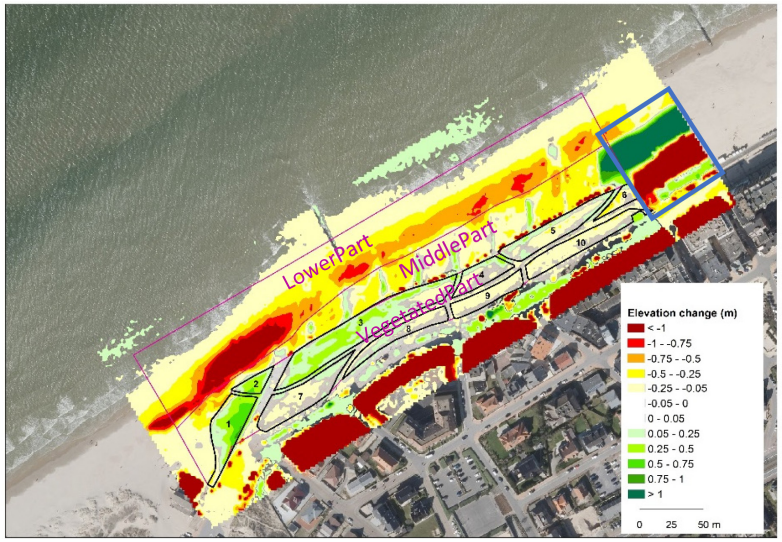
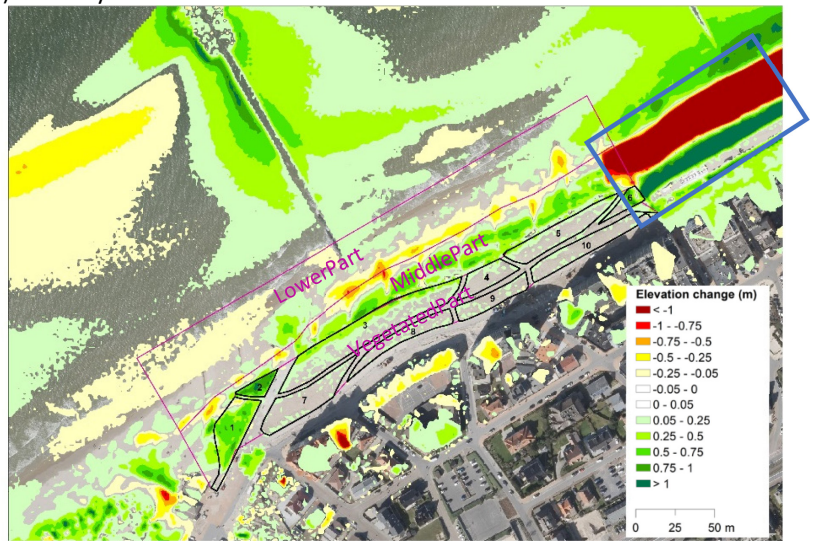


Figure 17 - Global evolution based on DoDs of the UAV and LiDAR surveys at Westende. The changes of the building (landward of the seawall) are artefacts due to human interventions.

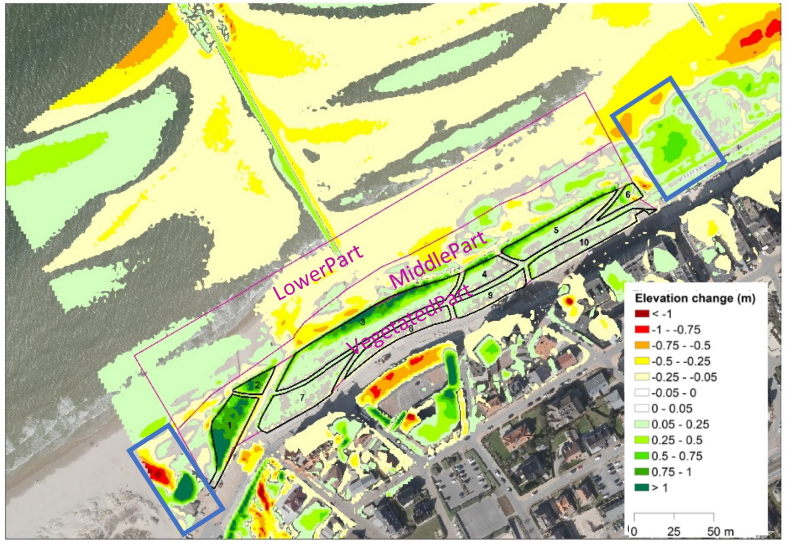
A)T0-T6: 12.8m



B)T6-T8: 1y 2m



C)T8-T11:1y9.8m



D)T11-T12: 7m

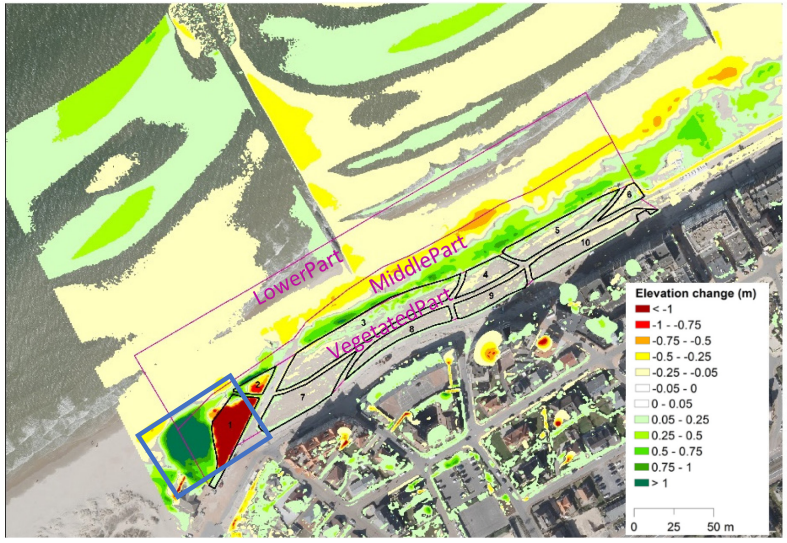
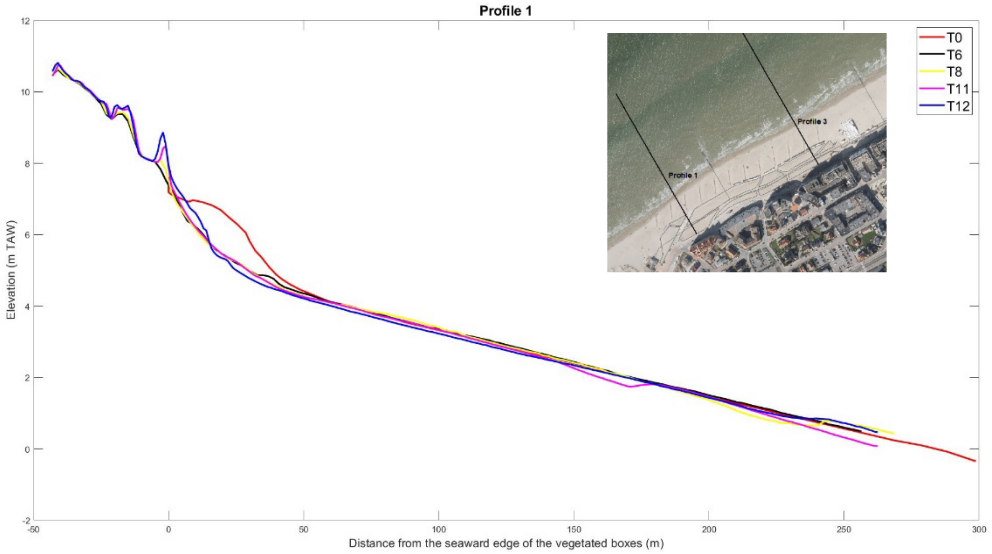


Figure 18 - Annual evolution based on DoDs of the UAV surveys. The changes of the building (landward of the seawall) are artefacts. Blue polygons indicate observed human interventions.

The beach profile measurements are displayed in Figure 19. Profile 1 located westward shows a morphological stability after T6 (17/04/2022). In contrast, Profile 3 was more dynamic with a landward migration of a bump located around 10 m on the upper-beach which progressively gained in height and migrated landward over time. The height was approximately 9.5 m TAW at T12 (05/11/2025). However, this bump disappeared on Profile 3 at T11. 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.

A)



B)

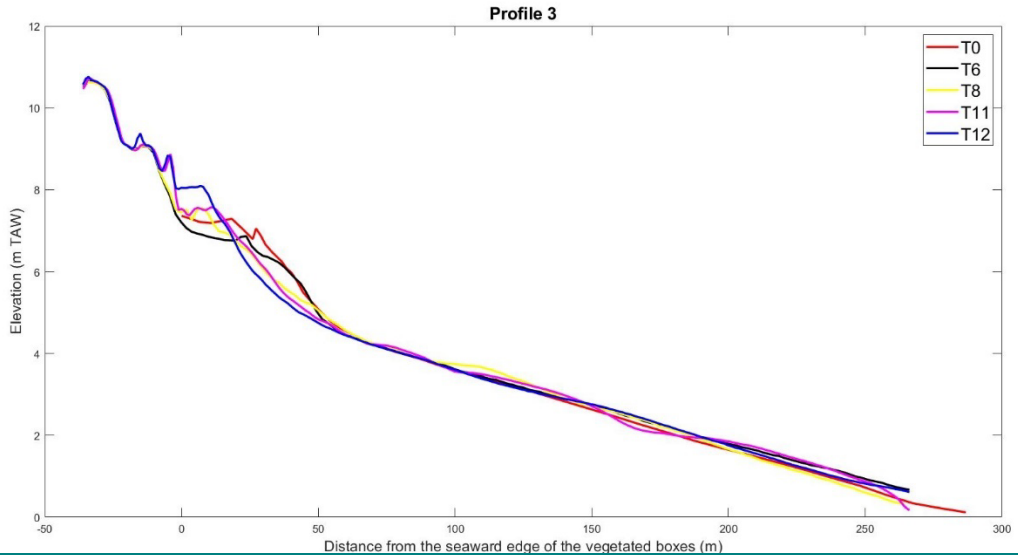


Figure 19 - Time series of the RTK-GPS and LiDAR surveys. Distance from the seaaward edge of the vegetated boxes start at 0 m. Inset: location of the profiles.

Same morphological pattern of the upper-beach took place for Profile 1 and Profile 3. The average width was about 44 m and no obvious difference between pre- and post-NbS set-up was observed. The slope of the upper-beach was about 0.06. In contrast, temporal variability of the intertidal beach width occurred. The slope was gentle (0.02) for the entire monitoring period.

Table 14 - Summary of beach indicators extracted fom the profiles. T11 and T13 were carried out 04/2025 and 10/2025 respectively.

	Profile 1						Profile 3					
	Tbefore	T0	T6	T8	T11	T13	Tbefore	T0	T6	T8	T11	T13
Time	2020	2021	2022	2023	2025	2025	2020	2021	2022	2023	2025	2025
Beach width (m)	41	39	45	43	43	36	42	41	50	48	45	45
Beach slope (-)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.06	0.06
Intertidal zone width (m)	162	154	158	152	155	159	158	148	161	146	160	156
Intertidal zone slope (-)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

4.3.2 Volumetric changes

For the volumetric analysis, the study area was divided into zones based on large-scale erosion and accretion patterns (Figure 18). Volumetric changes derived from UAV and LiDAR surveys are presented in Table 15.

The VegetatedPart showed limited growth during the first period (0.04/m²/yr in T0-T6), followed by a stronger increase in the 2nd and 3rd period to 0.15 m³/m²/yr (T6–T8, T8-T11). This contrasts with the negative volumetric change in T11-T12 when human intervention was carried out in box 1. The volume of the MiddlePart was first dominated by erosion in T0-T6 but then accretion took place. In the most recent year (T11-T12), the sand gain reached up to 1779 m^3 equivalent to 0.31 m^3/m/y. Unfortunately, there is no information whether the municipality carried out some works in this zone such as where fences are typically present in the summer period. As also indicated by the DoDs, the lower dry beach (LowerPart) consistently experienced erosion, with a maximum sand loss during the 1st year but it was lower during the following years.

Table 15 - Volumetric changes of the defined zones at Westende site. Green (accretion), red (erosion), grey (stability: <+/-0.05m).

			VegetatedPart	MiddlePart	LowerPart
Global	T0-T12	m^3	4442	962	-10013
		$m^3/m^2/y$	0.07	0.02	-0.12
Annual	T0-T6	m^3	519	-1984	-7265
		$m^3/m^2/y$	0.04	-0.19	-0.37
	T6-T8	m^3	2337	1431	801
		$m^3/m^2/y$	0.15	0.13	0.04
	T8-T11	m^3	2870	-265	-1603
		$m^3/m^2/y$	0.12	-0.01	-0.05
	T11-T12	m^3	-1284	1779	-1946
		$m^3/m^2/y$	-0.17	0.31	-0.18

Summary: Over a 5-year monitoring period, strong sand accretion (up to 2.4 m) was observed in the seaward side of the vegetated boxes, especially Boxes 2 and 3, likely driven by coast-parallel southwest winds trapping sand. The westernmost area (Box 1) initially followed this trend but showed reduced accretion

later, probably due to human interventions such as sand reprofiling by the municipality of Middelkerke.

Landward vegetated zones (Boxes 7–10) experienced only minor sand accumulation, indicating relative stability compared to the dynamic seaward zones. Meanwhile, the lower dry beach consistently underwent erosion (up to 1.4 m), with a clear boundary between erosion and accretion zones around 7 m TAW. Overall, natural processes and human activities together shaped the beach morphology, with ongoing changes influenced by the interventions from the municipality of Middelkerke. In total, the NbS dunes increased the sand buffer above the 1000-year surge level (approx. +7 m TAW) by about 12 m^3/m over 5 years.

4.4 Knokke

The pilot site at Knokke was surveyed from 12/2023 to 11/2025 using LiDAR and UAV surveys. Morphological and volumetric analyses were only carried out over a period of maximum 1 year and 11 months after the implementation of the dune scheme. Appendix B reports the human interventions carried out nearby the pilot site from end 2025 to 2026.

4.4.1 Annual morphological evolution

About 1y11 months after the NbS site installation, accretion of 0.1-1.7 m was already observed in the vegetated boxes (Figure 20). This mainly occurred in the seaward side of the boxes and on the westward side of Box 1. Thus, the first seaward row of marram grass trapped the sand. Also, the alongshore SW blown sand was captured by the plants of Box 1. Thus, the westside of this box experienced the highest accumulation which was probably related to the efficient alongshore wind transport from SW over the period of 1 year from T3-T5 (Figure 21B). In contrast, erosion affected the beach below 6.2 m TAW and also the area landward of the boxes between 8 m and 8.2 m TAW with lower intensity. This pattern persisted for the entire monitoring period, though with larger elevation changes when one refers to the last survey(T0-T5).

A progressive accretion occurred in the vegetated boxes during the annual periods of T0-T3 and T3-T5 (Figure 21). This was also observed in the passage between the boxes. Another common trend between the annual periods is the erosion experienced by the beach at the seaward side (Lower part zone). 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 sand gain in the landward zone back to the vegetated boxes (elevation from 8.2 m TAW to the dyke) is recorded between T3-T5 which is related to a natural trapping of aeolian sand transport. The dark green rectangles on the upper beach landward of the vegetated boxes represent seasonal cabins installed during the spring-summer period (Figure 21A, Figure 22, Appendix B).

A) T0- T3: 11.8m



B) T0-T5: 1y11m

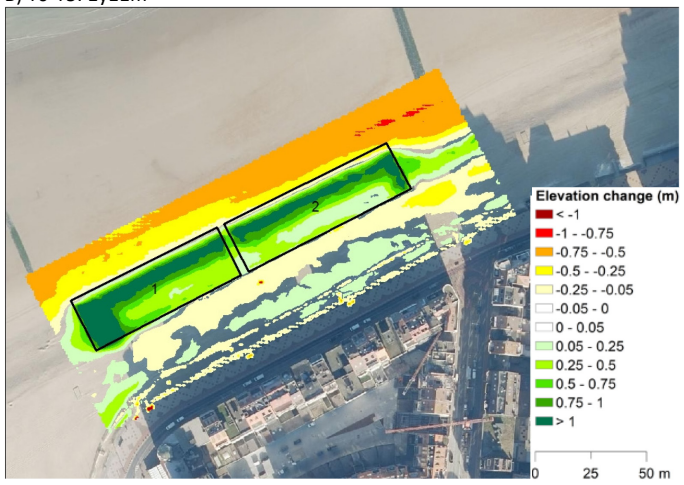
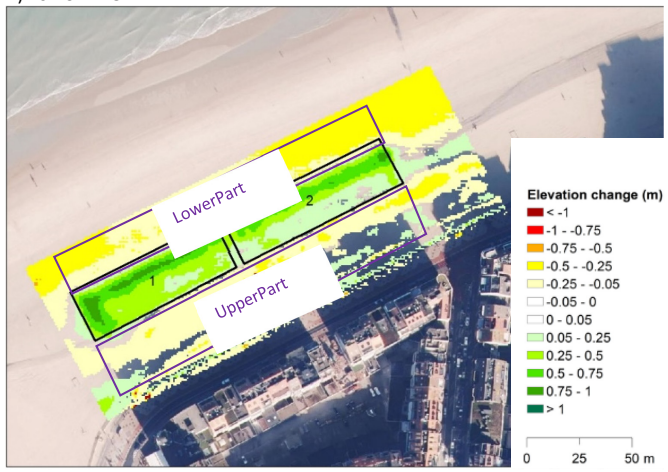


Figure 20 - Global evolution based on Ref DoDs of the UAV and LiDAR surveys

A) T0-T3: 11.8m



B) T3-T5: 11.2m

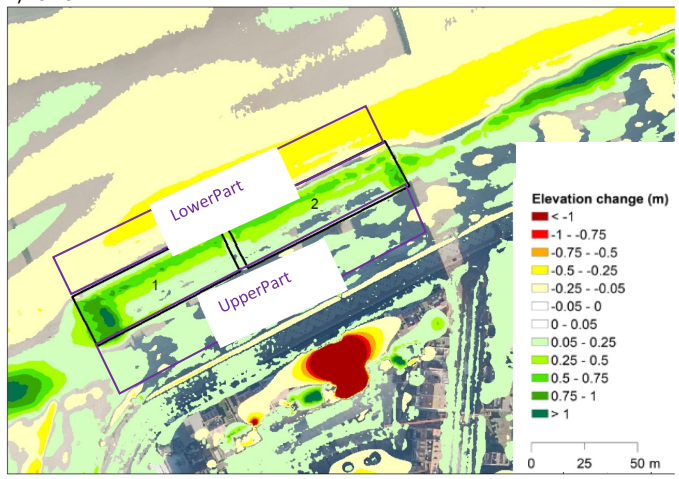


Figure 21 - Annual evolution based on UAV and LiDAR surveys with the locations of the contours of the defined volumetric zones.

Figure 22 presents the time series of the beach 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 vegetated boxes was stable. This contrasted with the significant sand accumulation in the vegetated boxes at a distance of 40-70 m developing rapidly after the marram grass plantation. The height of the new dunes in T5 (11/2025) reached up to 8.7 m TAW which corresponded to a gain of 1.4 m since the marram grass plantation in 12/2023. The second dune located landward gained only around 0.5 m since all the aeolian sand is trapped by the more seaward dune. Finally, negative morphological changes in T1 just after the plantation of marram grass are observed along the slope of the dry beach (distance > 70 m) but it was then stable between T2 and T4. Finally, the beach slope experienced again negative changes in T5. The bars present in the intertidal zone in T4 were related to the nearshore nourishments carried out in 10/2023-02/2024 (Houthuys et al., 2026). In the most recent survey (T5), the beach became again flat due to the reprofiling of the beach from the municipality.

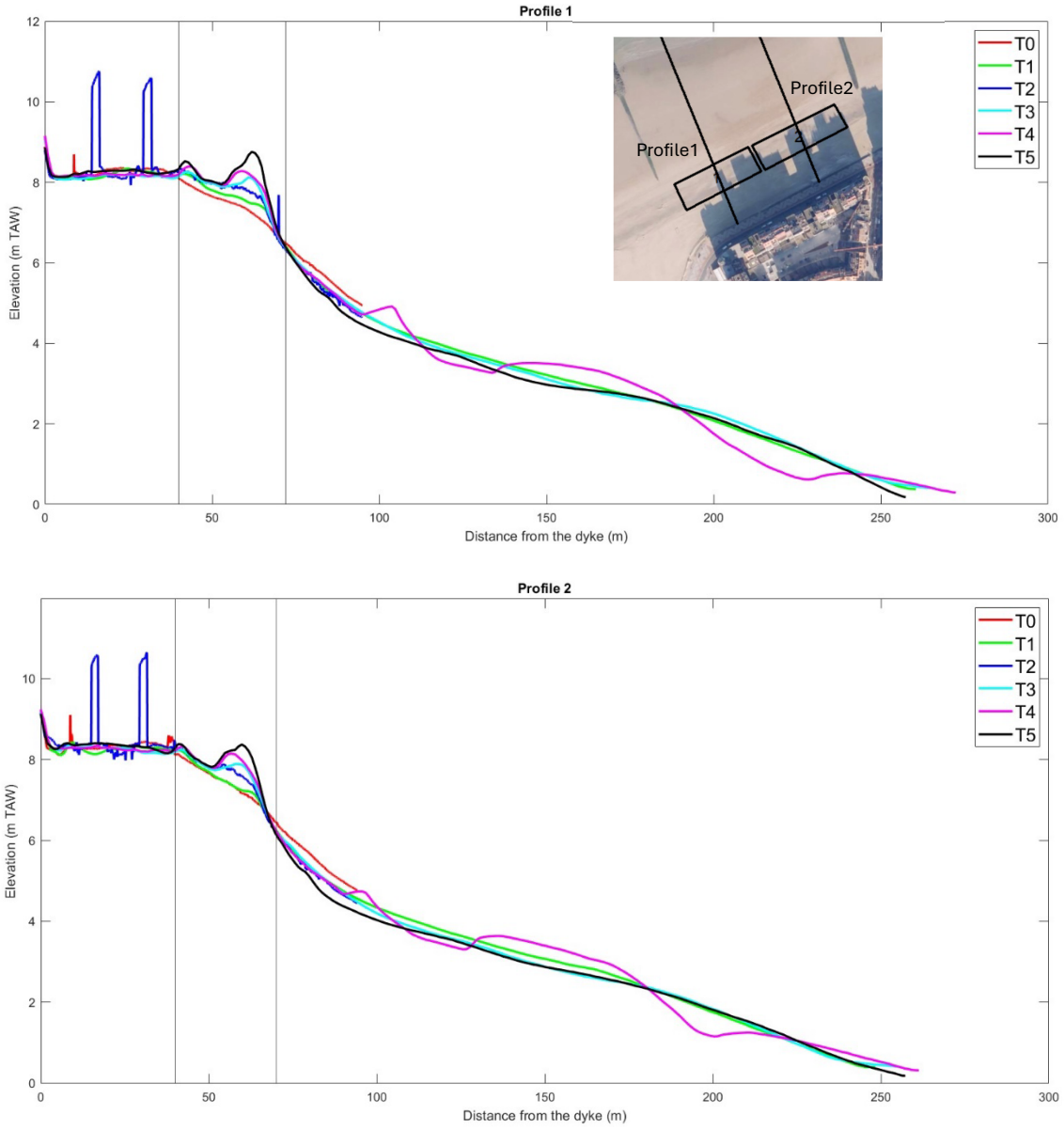


Figure 22 - Time series of the UAV and LiDAR surveys profiles. The dashed lines correspond to the position of the vegetated boxes. Inset: location of the profiles.

Profile 1 and Profile 2 follow the same pattern for the indicators. The upper-beach width was larger before the set-up of the NbS. The beach profiling leaded to a steep slope of 0.05 before the installation of the NbS. This slope has steepened in the two years period of NbS evolution. Regarding the intertidal beach, the width increased slightly but the slope remained relatively stable over the entire monitoring period after the plantation (0.02).

Table 16 - Summary of beach indicators extracted from the profiles.
The surveys in Tbefore and T0 were carried out in 10/2023 and 12/2023 respectively.

	Profile 1				Profile 2			
	Tbefore	T0	T3	T5	Tbefore	T0	T3	T5
Time	2023	2023	2024	2025	2023	2024	2024	2025
Upper-beach width (m)	49	35	35	28	53	35	35	23
Upper-beach slope (-)	0.05	0.07	0.07	0.09	0.05	0.07	0.07	0.1
Intertidal zone width (m)	107	119	125	128	109	119	125	125
Intertidal slope (-)	0.03	0.03	0.02	0.02	0.03	0.03	0.02	0.02

4.4.2 Volumetric changes

Overall accretion rates of 0.4 and 0.58 $m^3/m^2/y$ were recorded in Box 1 and Box 2 respectively (Table 17). As observed previously, sand gain varied in both space and time. During the first phase T0-T3, a larger accretion in Box 1 was observed compared to Box 2, which was also the case in T3-T5. The sand gain for the most recent year was lower than for the first year. As observed on the DoDs, the dry beach (LowerPart zone) experienced erosion which was much higher than the volumetric changes observed in the UpperPart zone located at the back of the vegetated boxes. Interestingly, accretion of 0.06 $m^3/m^2/y$ was recorded there during the recent period (T3-T5). Future surveys will help confirm the morphological trends at the NbS site as well as the effect of the large shoreface nourishment with fine sand.

Table 17 - Volumetric changes of the defined zones at Knokke site. Green (accretion), red (erosion), grey (stability: :<+/-0.05m).)

		Box1	Box2	UpperPart	LowerPart
Global	T0-T5 (m^3)	2273	1680	-118	-2289
	T0-T5 ($m^3/m^2/y$)	0.58	0.40	-0.01	-0.37
Annual	T0-T3 (m^3)	3348	1728	-378	-1674
	T0-T3 ($m^3/m^2/y$)	0.62	0.32	-0.07	-0.31
	T3-T5 (m^3)	2862	1296	324	-1188
	T3-T5 ($m^3/m^2/y$)	0.53	0.24	0.06	-0.22

Summary: The vegetated boxes in Knokke showed rapid sand accretion (0.1–1.7 m) within nearly two years, especially on the seaward side and the west side of Box 1 due to effective trapping of wind-blown sand. Marram grass played a key role in capturing both onshore and alongshore sediment, while erosion mainly affected the lower part of the dry beach. Areas landward of the boxes were also affected by erosion in the 1st year of the NbS set-up. Over time, a consistent pattern emerged with accretion in the vegetated zones and erosion on the seaward beach, separated by a stable elevation band around 6.5–7 m TAW.

Dune growth was significant, with the seaward dune increasing by up to 1.4 m, while inland dunes grew less due to sediment being trapped more seaward. Sand accumulation rates were lower in the 2nd year compared to the 1st year. Continued monitoring is needed to follow-up on this evolution. In total, the NbS dunes increased the sand buffer above the 1000-year surge level (approx. +7 m TAW) by about 13 m³/mover nearly two years.

4.4.3 Cliff formation

Beach cliffs are typically formed after a storm along Knokke-Heist coast. This was the case during Benjamin storm on 24/10/2025 when a cliff of several decimetres was formed. However, no cliff was observed along the NbS thanks to the presence of the roots of marram grass (Figure 23). Unfortunately, there is no pre- and post-storm topographic surveys and information about beach reprofiling to further investigate this process.



Figure 23 - Ground photograph after Benjamin storm on 24/10/2025. Photo from Knokke-Hesit municipality.

5 Discussion

The four monitored NbS sites present different spatial morphological behaviors and trends both on yearly evolution as well as for the entire monitoring period of 5 years. Here, we describe them per site and relate them to the long-term coastal trends between the 1980's and 2025 (Houthuys et al., 2026). 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.

5.1 Morphological comparison between NbS sites

Although the design of the four NbS is different (Table 19), similar morphological patterns were observed (Figure 24). Accretion dominated within the vegetated boxes and landward areas up to the dike, while erosion prevailed on the lower dry beach (7 to 4 m TAW). Notably, the accretion in the upper zones generally is lower than the erosion occurring on the lower beach profile. Also, the past storm events did not affect any of the NbS dunes since the surge levels were lower than 6 m TAW. 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 morphological characteristics of the NbS sites are:

Spinoladijk: The vegetated dune experienced an increase of 2.9 m high with an average sand gain of approximately 0.41 m^3/m^2/year over the 5 years monitoring period (Table 18). Its future development will depend on the balance between vegetation growth and sand burial, while the long-term stability of the foredune is ultimately controlled by the broader morphological evolution of the beach and shoreface. The sheltered position east of Ostend harbour dams promotes sand accumulation on the shoreface, potentially supporting natural beach growth; however, the dams also interrupt west-to-east sediment transport along the coastline, leading to local sediment deficits.

The vegetated boxes continue to effectively trap aeolian sand. Although different planting densities and configurations were initially applied, vegetation cover became relatively uniform, with plant clusters evolving into a random pattern. This suggests that initial planting design is less critical for dune growth than factors such as moderate sand burial and vegetation development, as well as sand availability from offshore.

Interpretation of local erosion and accretion patterns remains challenging due to insufficient data on municipal sand works, including trench excavation and sand redistribution along the dike. Improved documentation of these interventions is therefore recommended. Additionally, the relatively small size of the Spinoladijk pilot site makes it particularly susceptible to boundary effects, which significantly influence its morphological evolution.

Interestingly, the new delimited areas in 2025 at the west and east side of the NbS site have grown over the last 5 years when an accretion up to 0.6 m was observed. This will be further investigated in the next monitoring report.

Raversijde: The vegetated dune has reached approximately 4.1 m high, with an average sand gain of about 0.42 m^3/m^2/year over the monitoring period. After 5 years, the NbS dune experiment continues to effectively trap sand within the planted areas, with no clear link to the initial marram grass planting configuration.

New and diverse plant communities have developed, including tidemark species and rare pioneers such as Cakile maritima (sea rocket), rush wheatgrass, and sand oats observed at Raversijde. In addition to the Leymus arenarius grass in the observed new embryo dunes, the presence of these species, rare along the Belgian coast indicates that artificial dunes can provide valuable habitats and support the establishment of beach plant communities. This case also highlights the importance of bio-morphological interactions between vegetation and sediment dynamics in driving dune development.

Erosion persists near the high-water mark. During the 5th year, additional accumulation occurred between the dune and the seawall. Given the long-term erosive trend at Raversijde, future sediment supply towards the dune may become limited once the effects on sand availability of the 2021 nourishment are faded out.

Beyond ecological and coastal protection benefits, the vegetated dune also reduces nuisance from windblown sand affecting the seawall, tram line, and coastal road. Although sand trapping efficiency temporarily declined during the second year due to limited accommodation space, replanting marram grass in early 2023 improved dune growth and sand capture in the following year. Continued monitoring of sand nuisance and better documentation of municipal interventions such as cleaning, beach reshaping, and other sand works are recommended to better understand and manage these dynamics.

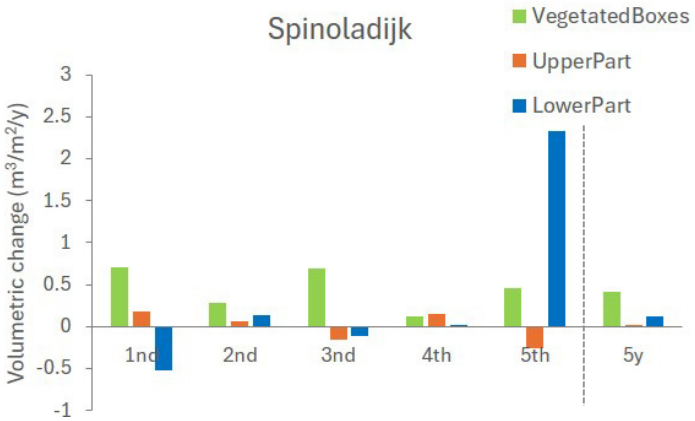
Westende: The dune pilot effectively captures sand in front of the seawall, with the vegetated dune gaining an average of 0.07 m^3/m^2/year and a height of 1.1 m high over 5 years. The spatial pattern of accretion indicates interception of sand transported from the west, with this supply pathway remaining consistent throughout the monitoring period. The Westende coastal section is characterized by long-term erosion in particular in the shoreface zone (Table 18). The NbS set-up helps the upper-beach beach to gain stability by reducing erosion processes.

Knokke: The NbS site was monitored for nearly 2 years from December 2023. The accretion observed after the implementation of the dune pilot indicates an efficient trapping of aeolian sand supplied with an average nearly 0.58 m^3/m^2/y with an increase of height of 1.2 m from the planted marram grass. As already reported, this high efficiency also occurred for the other NbS sites in the beginning of the 1st year monitoring. As it is well known, this coast is subject to long-term beach erosion. However, the recently implemented large-scale shoreface nourishment is expected to help reduce beach erosion rates in the coming years. This could provide a source of sand transported by aeolian processes to the NbS site resulting in continued dune growth.

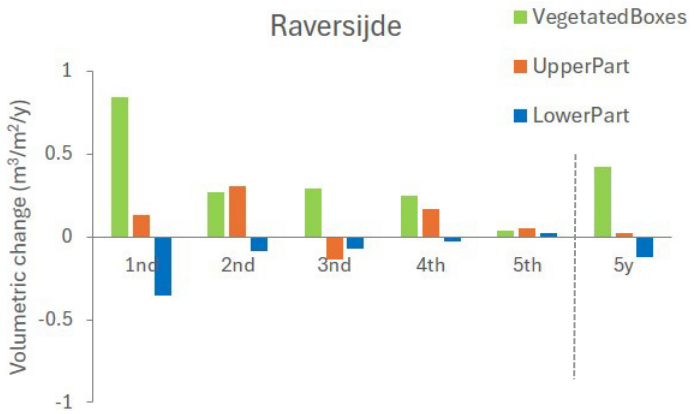
Table 18 - Summary of volume budget for the NbS sites over the entire monitoring period and the long-term coastal trend (extracted from Houthuys et al., 2022). To compare the rates, the volumetric trend was converted to $m^3/m/y$

	NbS average volumetric trends ($m^3/m/y$)				Corrected coastal trend volume in the active profile ($m^3/m/y$) [Houthuys et al, 2026]	
	Veg dune	Upper-beach (landward of dune)	Lower dry beach	Sum	Beach (wet + dry) & Dunefoot	Shoreface
Spinoladijk	8.02	0.15	2.28	10.45	-6.52	20.42
Raversijde	11.75	0.74	-4.55	7.94	-6.54	4.14
Westende	2.28	0.49	-5.14	-2.36	-1.31	-2.09
Knokke	7.21	-0.43	-8.35	-1.57	-26.46	5.59

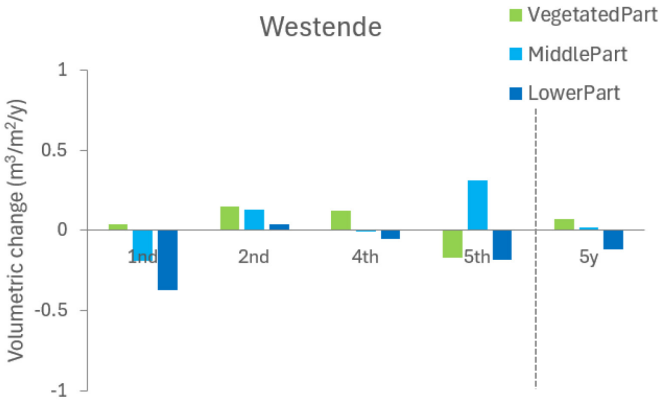
A)



B)



C)



D)

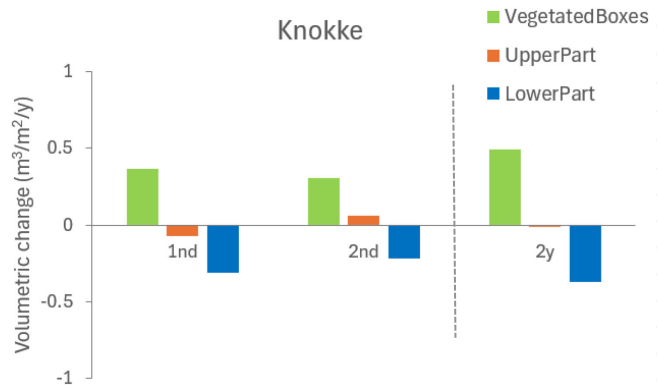


Figure 24 - Evolution of sand budget over observation periods ranging from 1year to 5 years at the pilot sites: A) Spinoladijk, B) Raversijde, C) Westende and D) Knokke. Only part B of the beach is considered here where no human interferences usually occurrs. Note the difference of y-axes. Right of vertical line, bars show evolution after 5th year.

5.2 Recommendations

A progressive vertical expansion of vegetated areas was observed across all sites throughout the monitoring period of 5 years (except in Knokke for nearly 2 years).

Nowadays, average sand gain rates within the vegetated boxes reached 8.02 $m^3/m/y$ (equivalent to 0.41 $m^3/m^2/y$) at Spinoladijk, 11.75 $m^3/m/y$ (0.42 $m^3/m^2/y$) at Raversijde, 2.28 $m^3/m/y$ (0.07 $m^3/m^2/y$) at Westende and 7.2 $m^3/m/y$ (0.58 $m^3/m^2/y$) at Knokke (Table 18). In general, the sand gain is greater than the dune accretion rates of 6 $m^3/m/y$ recorded along the Belgian coast in previous decades (Strypsteen et al., 2019). At Westende, the magnitude of the morphological changes was smaller in the vegetated boxes but also in the middle and low part of the beach, likely due to winter fences installed that trapped sand before reaching the vegetated zones and beach profiling.

Significant accretion that took place in Spinoladijk site in the most recent year is linked to human interventions with sand work carried out by the city of Ostend. Also, in Westende and around the vegetated dunes, beach profiling and fences were applied. Similar to the other sites, human interventions were caried out in Knokke on the upper-part. At Raversijde, sand management works were undertaken on the beach, including the construction of sand-capture trenches and the redistribution of sand removed from the dyke during cleaning operations. Except at Knokke-Heist, these human activities are not very well documented and introduce uncertainty in volumetric estimates, which should be refined when more detailed information becomes available.

Table 19 - Design comparison between the NbS sites. Dunefoot is defined here to be at 5.8 m TAW

	Spinoladijk	Raversijde	Westende	Knokke
Design	120*20	750*20	390*30	180*30
Distance from dyke (m)	22	13	0	35
Distance from dunefoot*(m)	18	42	30-48	10
Distance from low water line(m)	263	257-269	276-287	175

In addition to human interventions, factors such as sand availability, accommodation space, vegetation growth, dune topography, and wind regime play key roles. Grain size is also an important control, though no temporal data are available; the new site in Knokke, where fine sand (187 µm) was used for shoreface nourishment, may provide further insights.

Over a period of 5 years, the sand balance of the dry part of the profile (from the sea dike to the high water line including the upper-part zone and NbS vegetated boxes) was positive for all the NbS sites: 0.43 m^3/m^2/year at Spinoladijk, 0.64 m^3/m^2/year at Raversijde, 0.09 m^3/m^2/year at Westende, 0.97 m^3/m^2/year at Knokke (Figure 24). This contrast of magnitude may reflect differences in sand availability, particularly due to the recent shoreface nourishment at Knokke and the beach nourishment in Raversijde in 2021, although such estimates remain sensitive to boundary definitions and human interventions. Case by case detailed sand balance studies are needed to improve and maintain the understanding of the morphological evolution in all sites.

The lower dry beach acts as a key sediment source, where combined marine and aeolian processes drive sand transport toward the dune foot. On an annual scale, aeolian accumulation above +6.89 m TAW exceeds storm-driven erosion, consistent with long-term trends of dune growth along nearby coastal stretches. This growth is supported by a substantial sand buffer on the dry beach, which is expected to sustain dune development in the short term but may diminish over time without additional nourishment.

Provided coastline maintenance is realised, sustained dune growth with values around 5 $m^3/m/y$ are expected on decadal time scale, such as is observed in the past decades in many areas along the Belgian coast (Brackx et al., 2025).

Overall, the results demonstrate the effectiveness of the NbS sites over 5 years and provide valuable insights for enhancing long-term coastal resilience strategies. The NbS dunes 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 5 years by ca. 4780 m^3 in Spinoladijk, 44,160 m^3 in Raversijde, 4560 m^3 in Westende and 6860 m^3 in Knokke after nearly 2 years. It can be assumed that the increased sand buffer above the +7 m TAW level has enhanced the coastal protection level in all pilot areas. To quantify this effect simulations with XBeach dune erosion modelling is recommended.

A new numerical dune model DUNA has been coupled with ShorelineS model aiming to simulate at short-term scale (weeks-1 year) vegetated dune development (i.e. release during the TKI ShorelineS 2 workshop on 23/6/2026). Continuous interaction between aeolian sand transport, vegetation growth and morphological changes have been implemented for forecasting dune growth for NbS sites. Continuous monitoring will support analysis of beach morphodynamics over both seasonal and annual timescales. Regarding the monitoring in Raversijde for 2026, four drone flights (seasonal) and one ad hoc flight (storm) will be conducted by ATO on behalf of the WL as part of the MANABAS COAST project. The plan for drone monitoring from 2027 to 2030 in Raversijde is to continue at a frequency of 4 times +1 ad-hoc per year. This has been submitted to Coastal Division in order to cover the NbS study site. For the other NbS locations, the bi-annual LiDAR flight surveys will be used for monitoring until 2030.

6 Conclusions

This report highlights the success of the NbS sites after five years and provides insights into sustainable coastal resilience strategies. Significant accretion in the vegetated dunes was observed across all four pilot sites throughout the monitoring period. After 5 years, the sand budget for the vegetated boxes reached 0.41 $m^3/m^2/y$ at Spinoladijk, 0.42 $m^3/m^2/y$ at Raversijde, 0.07 $m^3/m^2/y$ at Westende, and 0.58 $m^3/m^2/y$ at Knokke. Thus, the highest sand gain in Knokke was related to the high efficiency of the marram grass after being planted to trap blowing sand. Also, the accumulation was relatively similar at Spinoladijk and Raversijde. This is likely due to the effectiveness of marram grass and brushwood fences, increased sand availability from nourishment, and continuous human interventions by the city of Ostend providing sand availability on the lower beach (cleaning sand from tram tracks and coastal path and then bringing it beach to the beach). Key factors influencing dune growth include sand supply, available space, vegetation and brushwood retention capacity, and wind conditions.

Across all sites, similar spatial patterns were observed, with erosion occurring on the lower dry beach and accretion within the vegetated zones, separated by a stable morphological boundary. The lower dry beach remains important as it supplies sand to the upper areas through marine and wind-driven processes.

In general, the upper-beach area landward of the boxes gained sand at a lower magnitude than the vegetated boxes. Also, temporal variation was observed at each site except Westende (i.e. no upper-beach is defined) which may indicate that sand transport to this zone can be restricted due to trapping by the vertical expansion of the dunes, although trench excavation works by the city of Ostend may also have contributed. The future development of NbS dunes will depend on the interaction between vegetation growth, sand burial, wind dynamics, and sediment availability within the beach-shoreface system.

Overall, the results demonstrate the effectiveness of the NbS sites over 5 years and confirms the potential of these solutions to became standard measure for protection and development of the sandy coasts. The planned continuous monitoring with the bi-annual LiDAR surveys and 4 drone surveys/period in Raversijde for the period 2026-2030 would undoubtedly help to gain further knowledge about the coastal dynamics within the NbS dune-beach system. Finally, improved documentation of sand maintenance activities by responsible authorities is recommended to better understand observed morphological changes.

7 References

Brackx, M.; Verwaest, T.; Dan, S (2025). Groei van de zeereep op schaal decennia: Ontwikkeling van een conceptueel model. Versie 4.0. WL Rapporten, 22_006_4. Waterbouwkundig Laboratorium: Antwerpen.

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., Montreuil, A-L., Dan, S., Brackx, M., Verwaest, T. (2026). Morfologische trends aan de Belgische Kust: Evolutie van de Vlaamse kust tot 2025. Versie 2.0. WL Rapporten, 24_015_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.

Montreuil, A-L., Dan, S., Houthuys, R., Verwaest, T. (2024). Monitoring of the dune for dike pilots: Evolution after 3 years. Version 3.0. FH Reports, 21_014_3. Flanders Hydraulics: Antwerp.

Strypsteen, G., Houthuys, R., Rauwoens, P. (2019) Dune volume changes at decadal timescales and its relation with potential aeolian transport, Journal of marine Science and Engineering, 7. DOI:org/10.3390/jmse7100357

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., Provoost, S., Montreuil, A.-L., Taelman, C., Rauwoens, R., Dahirel, M., Bonte, D., Brackx, M., Dan, S. (2022). Nebkha @Raversijde due to Leymus arenarius, VLIZ Marine Dag 2025

Verwaest, T. (2025). Monitoring of the dune for dike pilots. WL Memo's, 21_014_4. 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

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

Ecopedia (2025). Zandhaver. https://www.ecopedia.be/planten/zandhaver

Appendix A

Meetcampagne korrelgrootte zandmonsters thv Nebkha zandhaver profiel d.d. 21/12/2024

Inleiding

Ikv de opmaak van een poster “Nebkha @Raversijde due to Leymus arenarius” voor de VLIZ Marine Science Day 5/3’25 (Brugge) dag verzamelde ik in het droge gedeelte van het dwarsprofiel t.h.v. deze locatie 17 zandmonsters (vanaf de duinen landwaarts van de kustbaan) plus één monster nabij de laagwaterlijn[1].

Eenvoudige positiebepaling met smartphone Google Maps app.

Korrelverdeling met de Bettersize3000 in het sedimentlabo van het WL op 31/1/’25.

Overzicht locaties

De nummering gaat van land naar zee in een (min of meer recht) profiel door de nebkha.

Nr	Locatie	Nr	Locatie	Nr	Locatie
1	duin landwaarts van de kustbaan	7	landwaarts duinvak	13	top nebkha
2	op de tramsporen	8	landwaarts duinvak bis	14	zeewaartse kant nebkha
3	op de zeedijk; tegen het muurtje	9	midden in duinvakken	15	embryonaal duintje zeewaarts van nebkha
4	op de zeedijkglooiing	10	zeewaarts duinvak	16	iets hoger dan de hoogwaterlijn
5	in strook tussen zeedijk en duin	11	zeewaartse rand duinvakken	17	Hoogwaterlijn
6	landwaartse rand duinvakken	12	tussen nebkha en duinvakken	18	laagwaterlijn

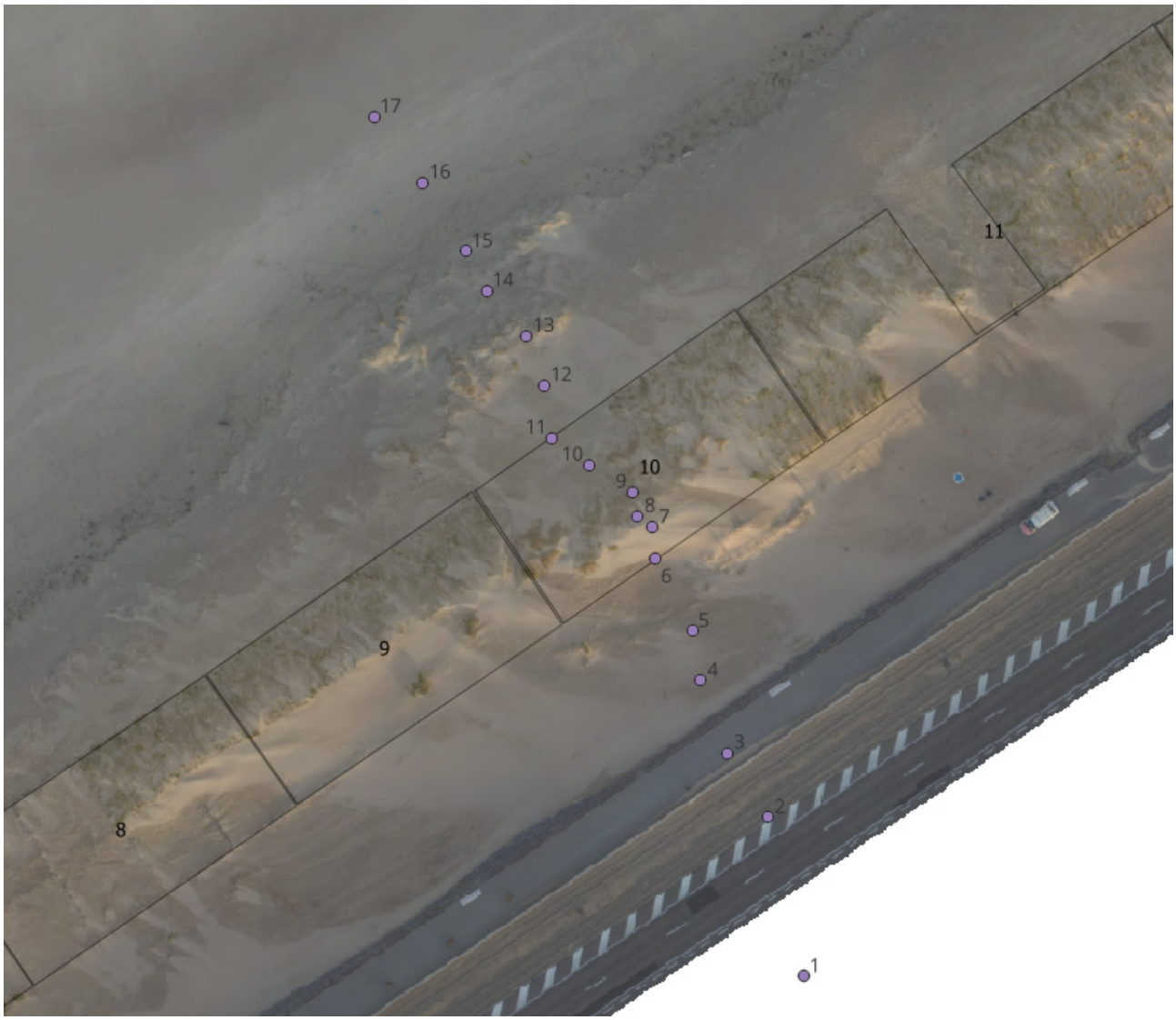
De nrs. 1,2,3 situeren zich op de zeedijk of landwaarts ervan (zeereep duinenrij).

De nrs. 4,5 bevinden zich in de zone tussen de zeedijk en de duin voor dijk.

De nrs. 6,7,8,9,10,11 bevinden zich in de zone van de duin voor dijk.

De nrs. 13,14,15 zijn op de nebkha.

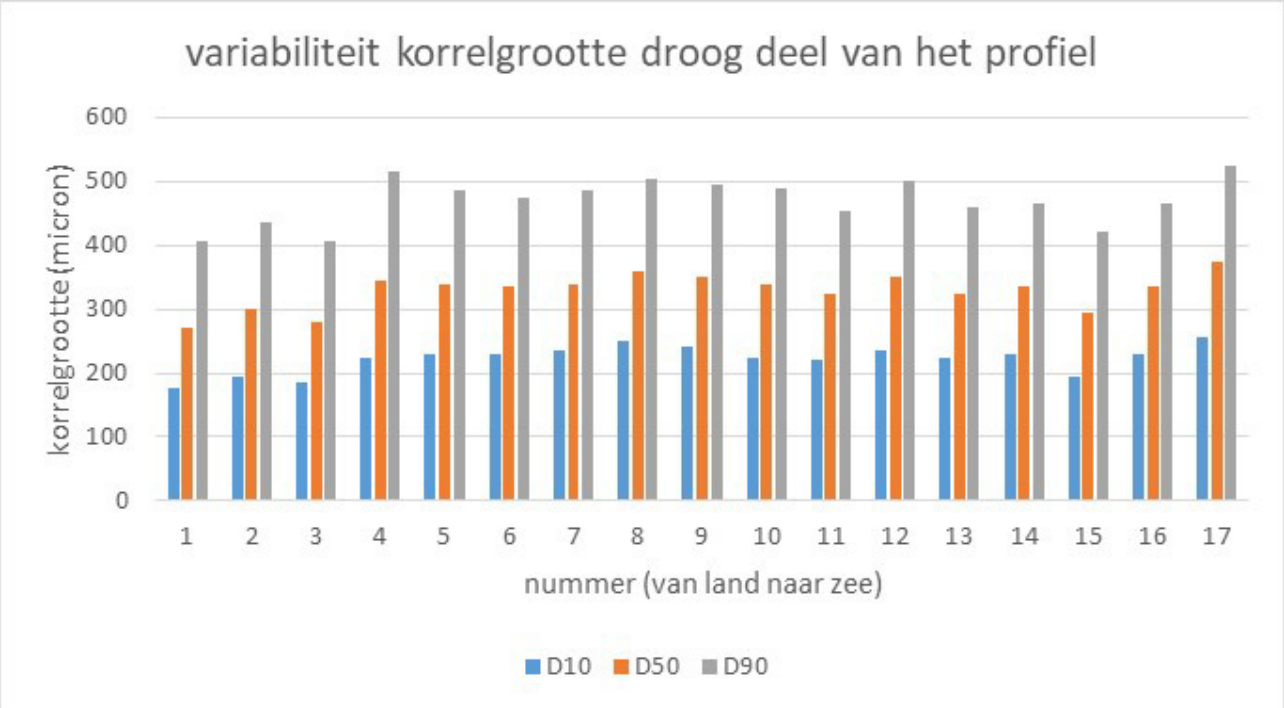
[1] deze monsters hebben ook als doel om referentiemateriaal te verzamelen voor de zoektocht naar surrogaatzand voor het schaalmodel van de strandzone in de grote golfgoot, via verschaling van de valsnelheid (24_075).



Achtergrond: orthofoto op basis van de drone-opname d.d. 20/12/2024.

Resultaten korrelverdeling

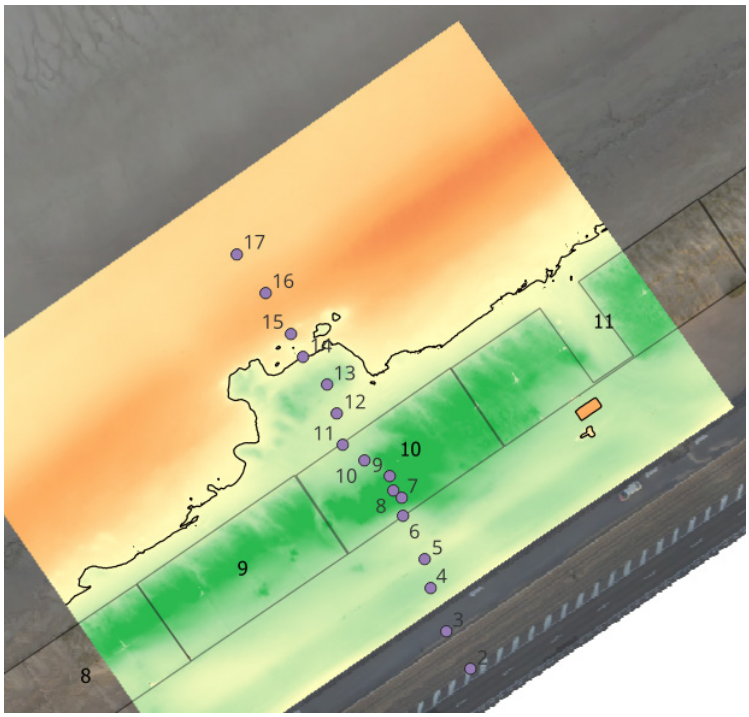
Nr	D10-D50-D90 (micron)	Nr	D10-D50-D90 (micron)	Nr	D10-D50-D90 (micron)
1	175-270-405	7	235-340-485	13	225-325-460
2	195-300-435	8	250-360-505	14	230-335-465
3	185-280-405	9	240-350-495	15	195-295-420
4	225-345-515	10	225-340-490	16	230-335-465
5	230-340-485	11	220-325-455	17	255-375-525
6	230-335-475	12	235-350-500	18	210-315-460



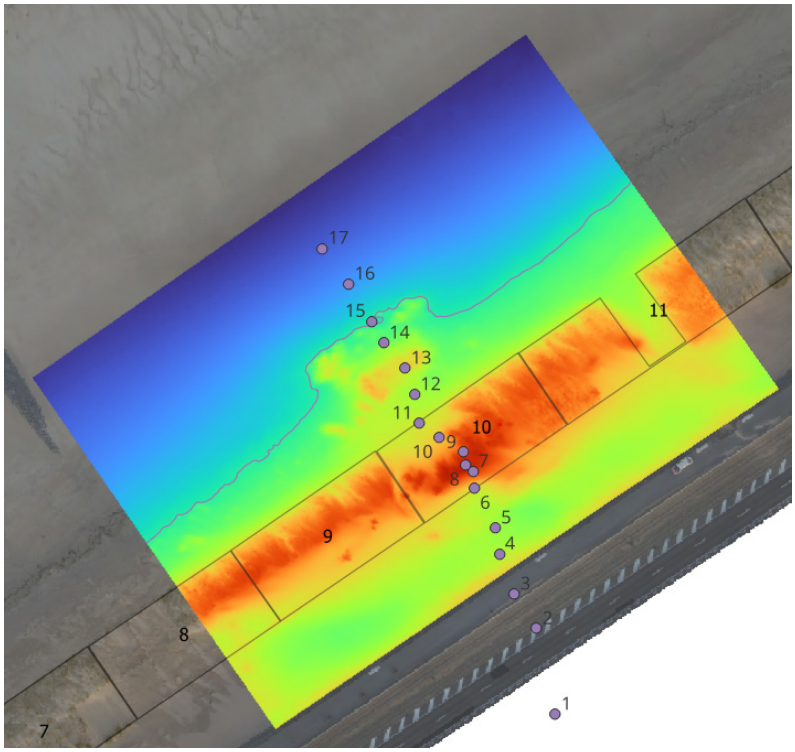
De variabiliteit van de korrelgrootte in het droog deel van het profiel is wellicht niet door één proces te verklaren want relatief complex. Eolisch transport -mede beïnvloed door de vegetatiedynamiek- is dominant op de meeste locaties, behalve op de meest zeewaartse locaties waar afslag door golven optreedt. Men ziet in de data een niet-monotoon verloop van zowel D10, D50 als D90. Op en voorbij de zeedijk (nrs. 1-3) is de korrelgrootte kleiner (D50 gemiddeld 280 micron versus 340 micron op het droog strand en in het duin), en is tegelijk de sortering iets minder (D90/D10 is er 2,2 versus 2,1 op het droog strand en in het duin). Op de hoogwaterlijn (nr. 17) is de korrelverdeling gelijk aan de korrelverdeling van het suppletiemateriaal dat in 2021 gebruikt is om het strand te verbreden. Op basis van beunmonsters had dat materiaal D10-D50-D90 van 260-370-525 micron.

Link met morfologie

Op een morfologische verschilkaart tussen 20/12/'24 (T32) en net na de aanleg van de pilot 31/3/'21 (T0) zijn een zone van netto aangroei in het hogere deel van het profiel en een zone van netto erosie in het lagere deel van het profiel te zien. De scheidingslijn tussen netto aangroei en netto erosie bevindt zich t.h.v. de nebkha ongeveer 20 m meer zeewaarts dan in de naburige zones. Het punt nr. 14 op de nebkha ligt precies op deze scheidingslijn (zwarte lijn op onderstaande figuur).



De duinvoet (6,89 m TAW contourlijn) bevindt zich ongeveer 10 m meer zeewaarts t.h.v. de nebkha. Punt nr. 15 ligt op deze lijn. In het verloop van de korrelverdeling over het profiel is deze locatie een lokaal minimum qua korreldiameters.



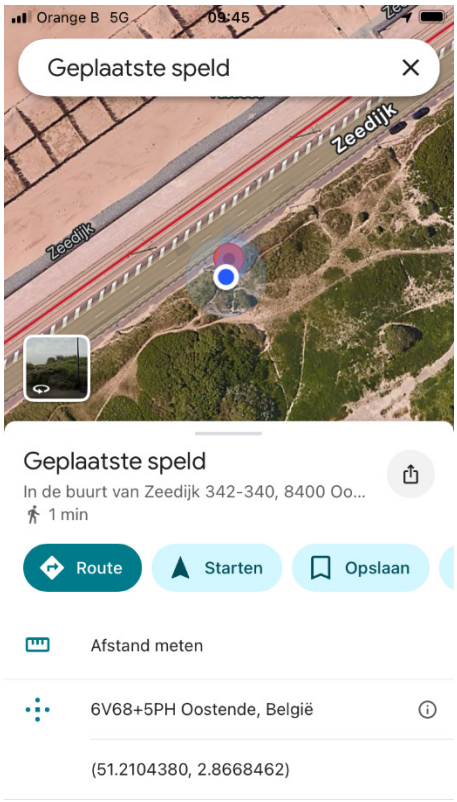
Detailresultaten korrelverdeling

Sample Name	Test Date	D10(um)	D35(um)	D50(um)	D65(um)	D90(um)	D[3,2](um)	D[4,3](um)
nr1-Average	31/01/2025	174	235,9	269,3	306,6	403,7	251	279,8
nr2-Average	31/01/2025	194,3	262,2	297,3	335,6	433,5	277,2	306
nr3-Average	31/01/2025	186,4	248,2	279,8	314,6	404,8	263,2	288,5
nr4-Average	31/01/2025	223,9	303,7	345,9	392,7	514,4	322,7	358,4
nr5-Average	31/01/2025	228,9	301,7	338,3	378	483,2	319	347,7
nr6-Average	31/01/2025	229,7	299,8	335	373	472,6	317,3	344,3
nr7-Average	31/01/2025	233,7	306	342,1	381,5	485,5	323,7	351,4
nr8-Average	31/01/2025	248,8	321,6	357,8	398,2	505,1	340,1	367,5
nr9-Average	31/01/2025	238,5	312	348,6	388,9	495,6	329,9	358,1
nr10-Average	31/01/2025	227,5	301,6	339,4	380,9	492	319,6	349,9
nr11-Average	31/01/2025	219,9	288,9	323	360	456,3	305,1	331,5
nr12-Average	31/01/2025	233,7	309,3	347,6	389,8	501,6	327,8	358
nr13-Average	31/01/2025	223,7	292,1	326,2	362,6	459,3	308,5	334,8
nr14-Average	31/01/2025	229,9	298,1	331,6	366,8	459,9	314,3	339,2
nr14-Average	31/01/2025	230,3	299,3	333,7	370,4	465,6	316,4	342,3
nr15-Average	31/01/2025	196,9	260,2	293,1	328,7	417,7	275,6	300,9
nr16-Average	31/01/2025	229,3	299,2	334	371,2	467	316,2	342,7
nr17-Average	31/01/2025	255,1	334,3	374,2	416,8	525,4	352,7	383,1
nr18-Average	31/01/2025	209,9	280,2	316,4	356,1	459,8	297,6	327,1

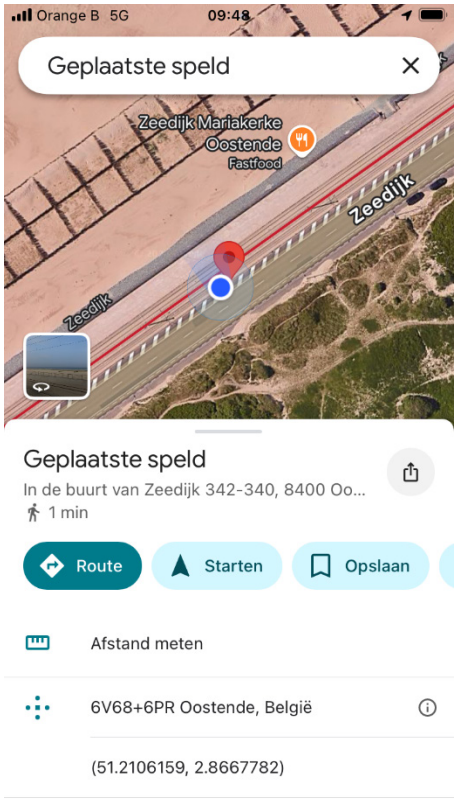
Sample Name	less than 2um content(%)	2um to 63um content(%)	63um to 2000um content(%)
nr1-Average	0	0,01	99,99
nr2-Average	0	0	100
nr3-Average	0	0	100
nr4-Average	0	0	100
nr5-Average	0	0	100
nr6-Average	0	0	100
nr7-Average	0	0	100
nr8-Average	0	0	100
nr9-Average	0	0	100
nr10-Average	0	0	100
nr11-Average	0	0	100
nr12-Average	0	0	100
nr13-Average	0	0	100
nr14-Average	0	0	100
nr14-Average	0	0	100
nr15-Average	0	0	100
nr16-Average	0	0	100
nr17-Average	0	0	100
nr18-Average	0	0	100

Details ligging 18 meetpunten

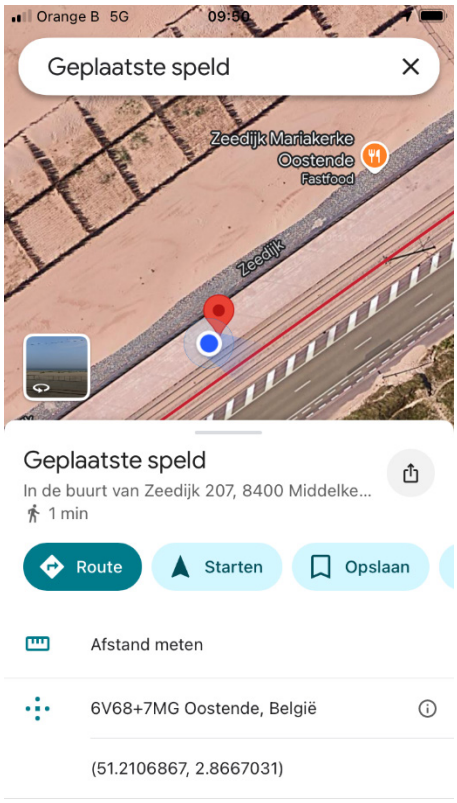
Monster NR 1 (duin landwaarts van de kustbaan):



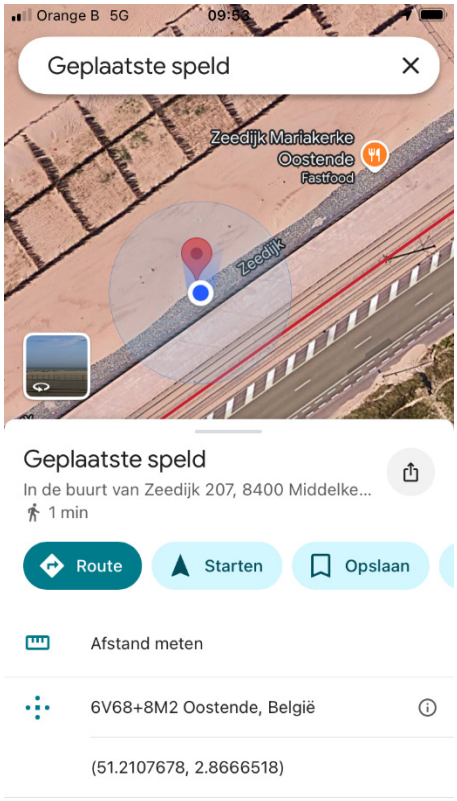
Monster NR 2 (op de tramsporen):



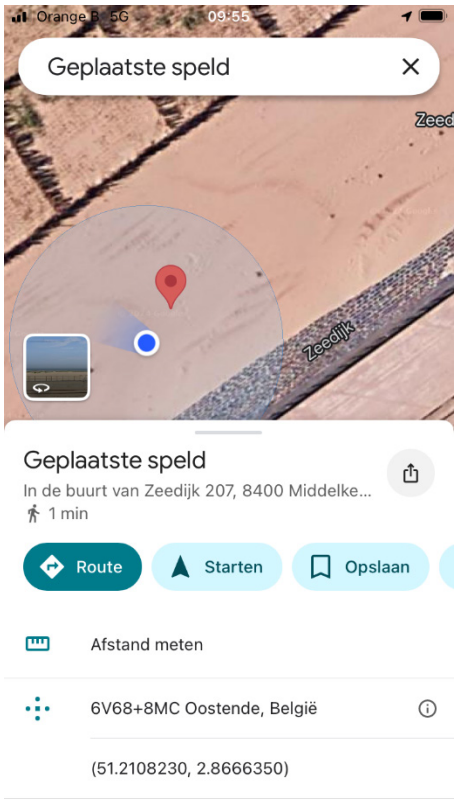
Monster NR 3 (op de zeedijk; tegen het muurtje):



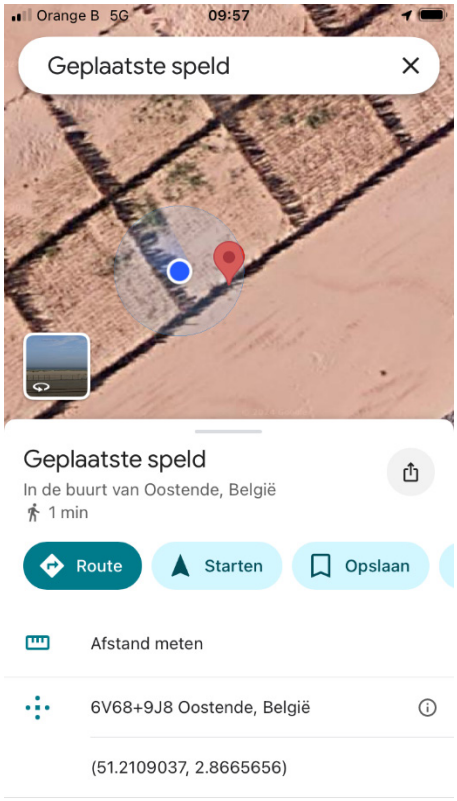
Monster NR 4 (op de zeedijkglooiing):



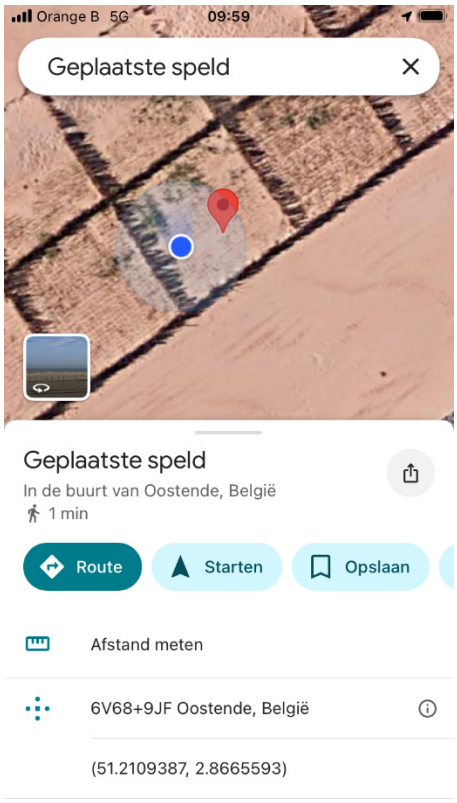
Monster NR 5 (in strook tussen zeedijk en duin):



Monster NR 6 (landwaartse rand duinvakken):

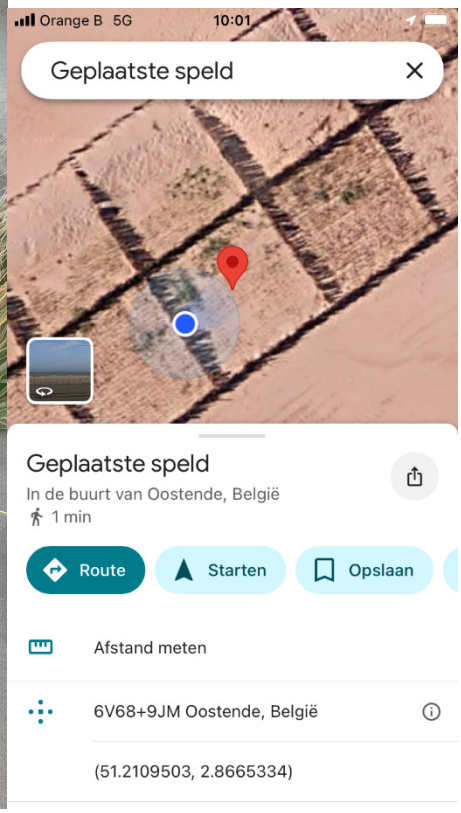


Monster NR 7 (landwaarts duinvak):



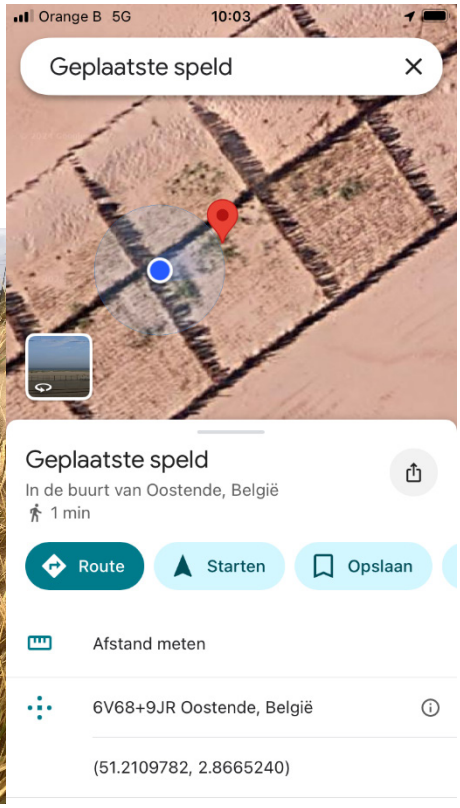
Monster NR 8 (landwaarts duinvak bis):





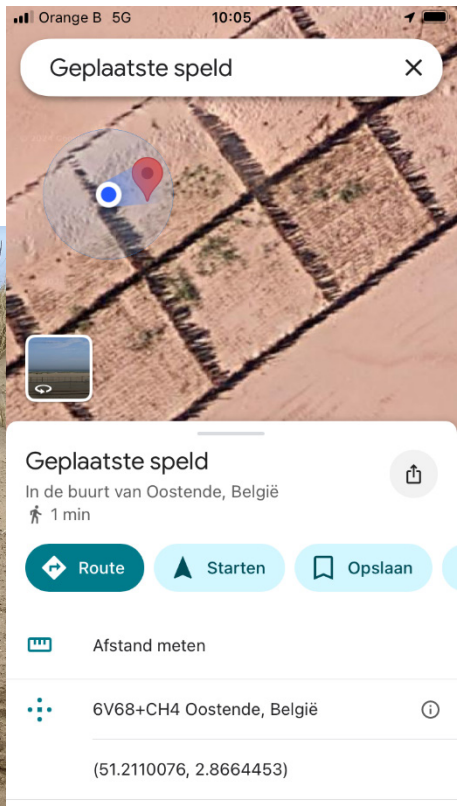
Monster NR 9 (midden in duinvakken):





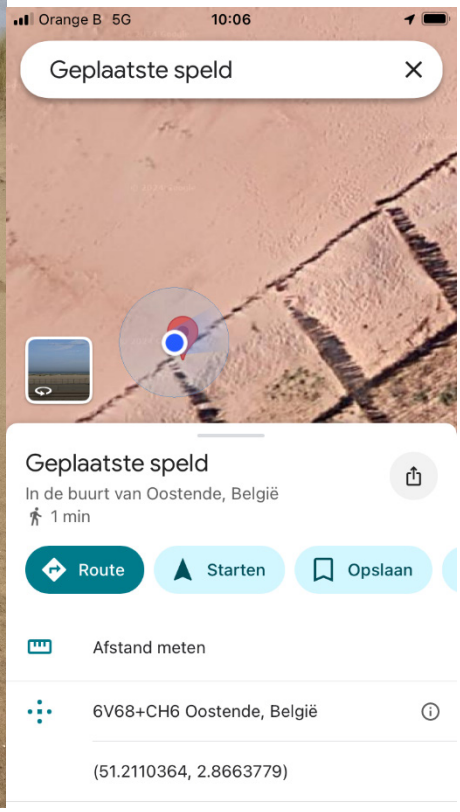
Monster NR 10 (zeewaarts duinvak):





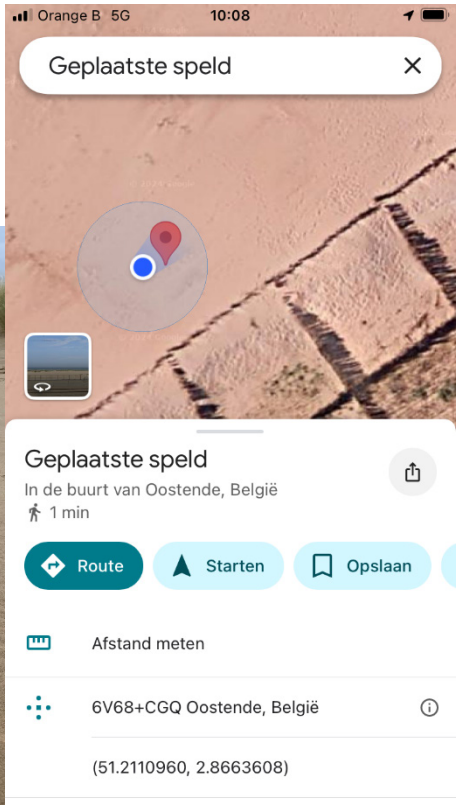
Monster NR 11 (zeewaartse rand duinvakken):





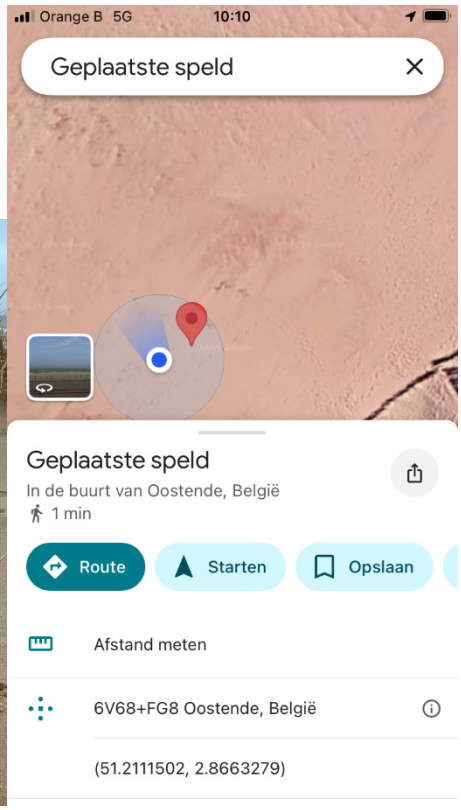
Monster NR 12 (tussen nebkha en duinvakken):



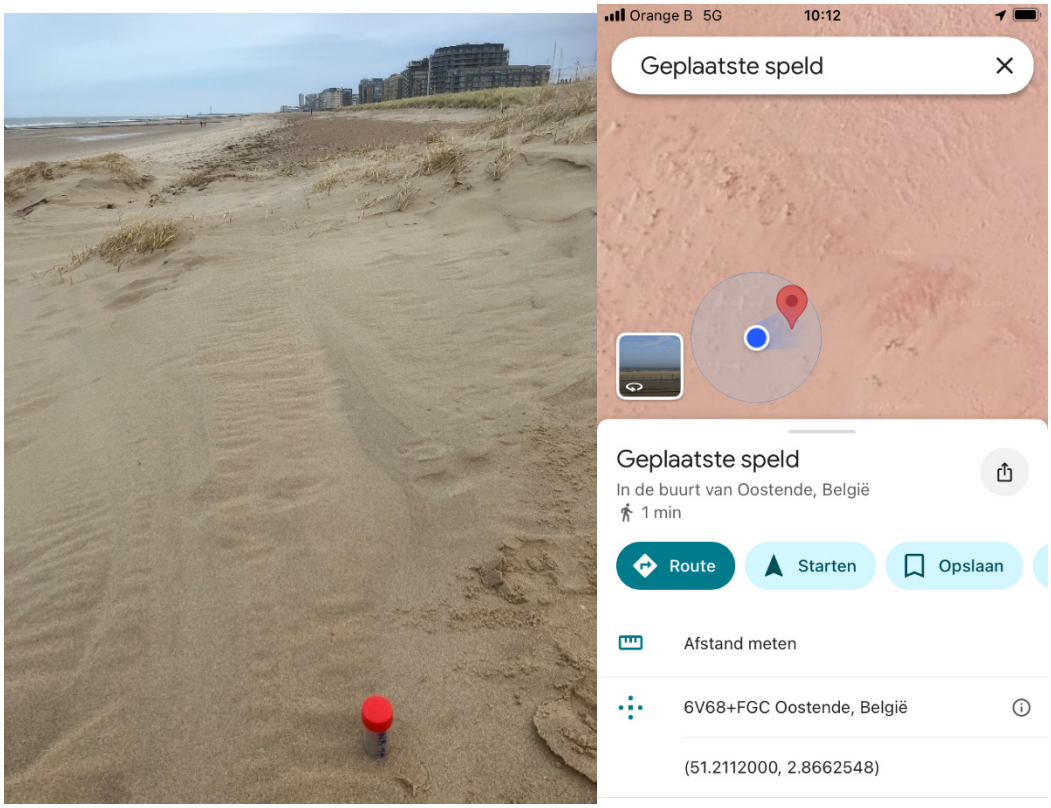


Monster NR 13 (top nebkha):

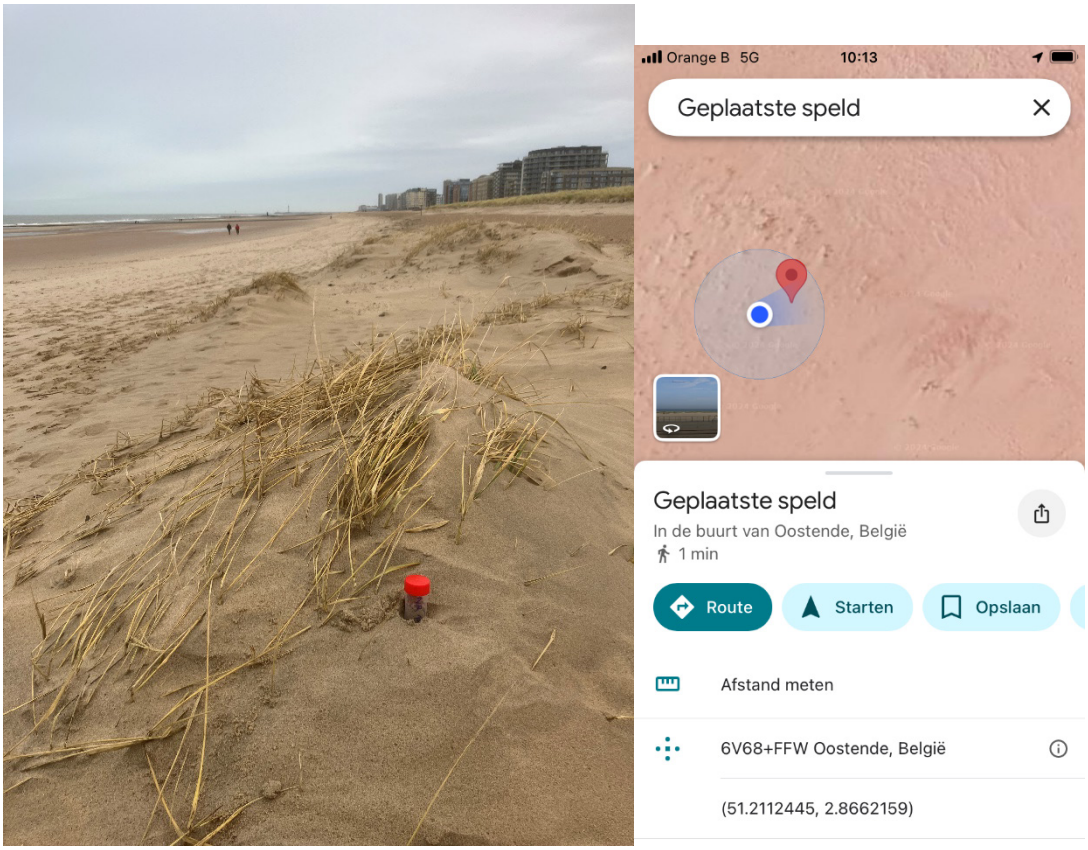




Monster NR 14 (zeewaartse kant nebkha):

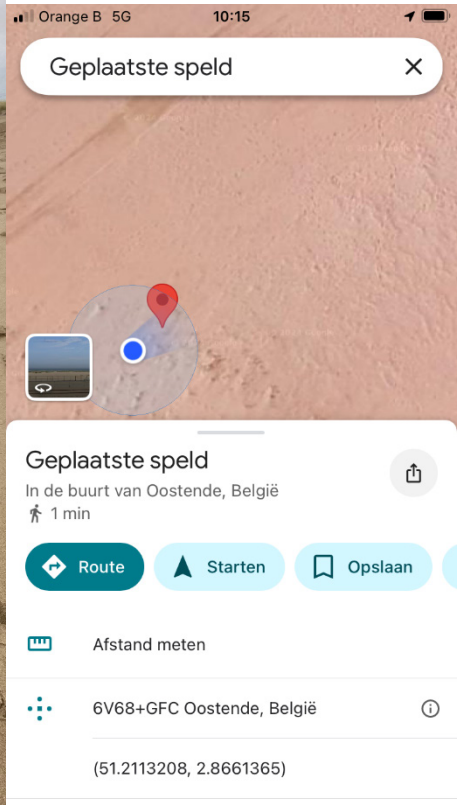


Monster NR 15 (embryonaal duintje zeewaarts van nebkha):



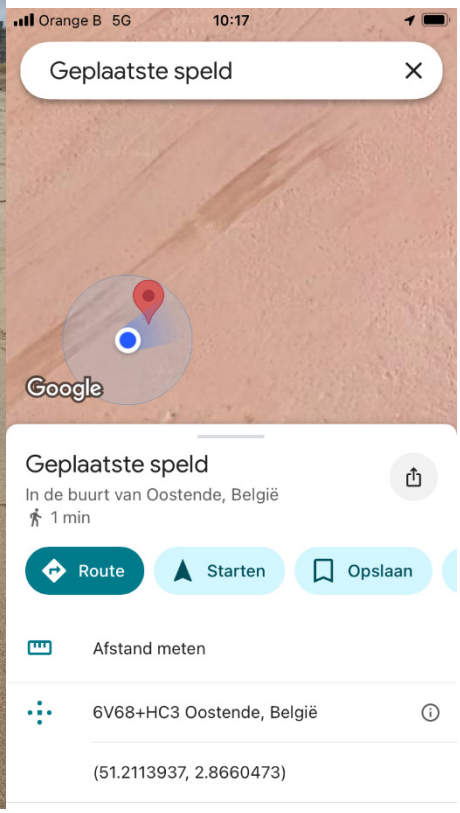
Monster NR 16 (iets hoger dan de hoogwaterlijn):





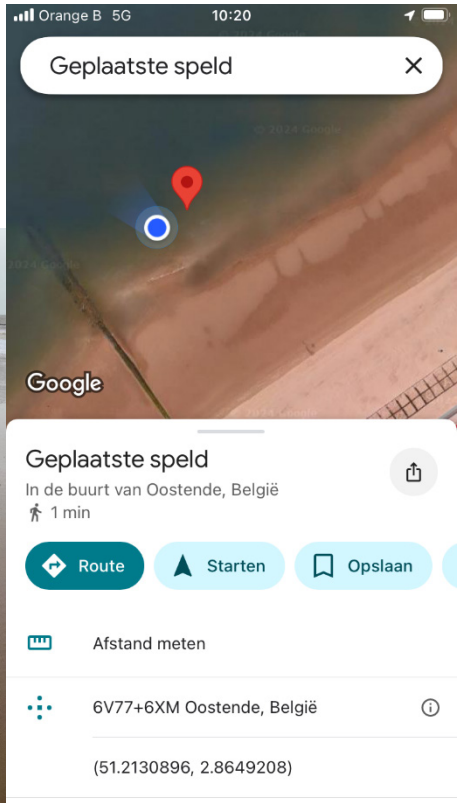
Monster NR 17 (hoogwaterlijn):





Monster NR 18 (laagwaterlijn):





Appendix B

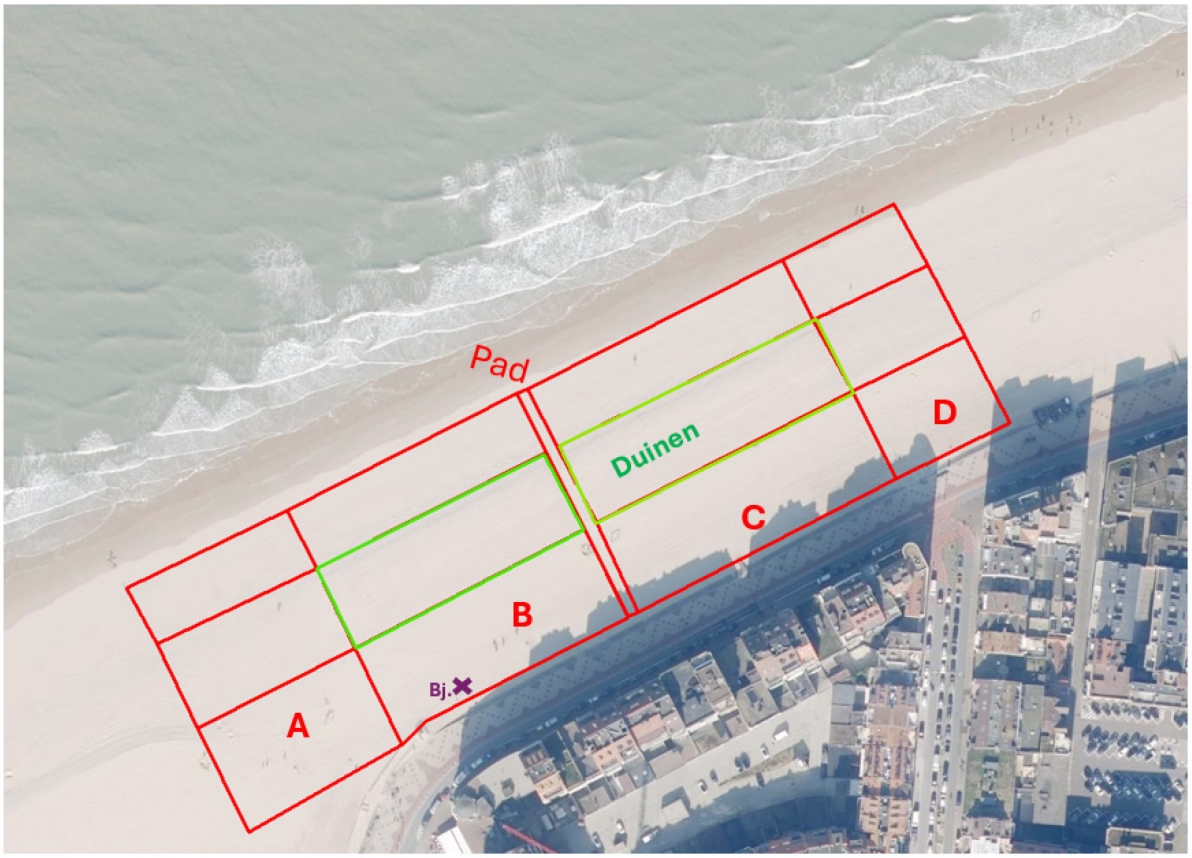
Informatie over het werk in Knokke from end 2025-2026 received

Received from Barbara Geschier from Knokke-Heist municipality

Contact:

anne-lise.montreuil@mow.vlaanderen.be

toon.verwaest@mow.vlaanderen.be



	Tijd (bij. van tem)	Locatie met tekening (bij. op de dijk, op het strand, graven van een geul tussen de nieuwe duinen en de dijk; aanwezigheig van cabines; nivelling van het strand…)	Beschrijving met overzicht van het volume (bij. kwantiteit in een vrachtwagen)
Bj.	*10/10/2025*	*Op het strand langs de dijk*	*Graven van een geul tussen de nieuwe duinen en de dijk*

1 A B C D	3/11/2025 tot 7/11/2025	Wielladers op het strand	Plaatsen strandhagen winteropstelling + wegnemen vuilnisbakken
2 A B C D	19/01/2026 tot 23/01/2026	Wielladers op het strand	Wegnemen strandhagen voor zomeropstelling
3 A B C D	09/03/2026 tot 13/02/2026	Kettingbulls + wielladers op het strand	Nivelleren volgens niveauhoogte zomerstrand
4 A B C D	11/03/2026	Jeep+ tractor+ unimog wiellader	Plaatsen palen voor strandcabines
5 B C D	15/03/2026 tot 15/05/2026	Jeeps + werktuigdragers particulieren	Plaatsen strandcabines particulieren
6 A B C D	13/04/2026 tot 17/04/2026	Unimog + graafkraan en tractor	Plaatsen vuilnisbakken
7 A	8/06/2026 tot 12/06/2026	Wiellader + unimog	Plaatsen sportstrand
8 A B C D	17/04/2026 tot 31/08/2026	Unimog+ tractor + wiellader+ strandveegmachine + Jeep	Ledigen vuilnisbakken en opkuis strand volgens noodzaak

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