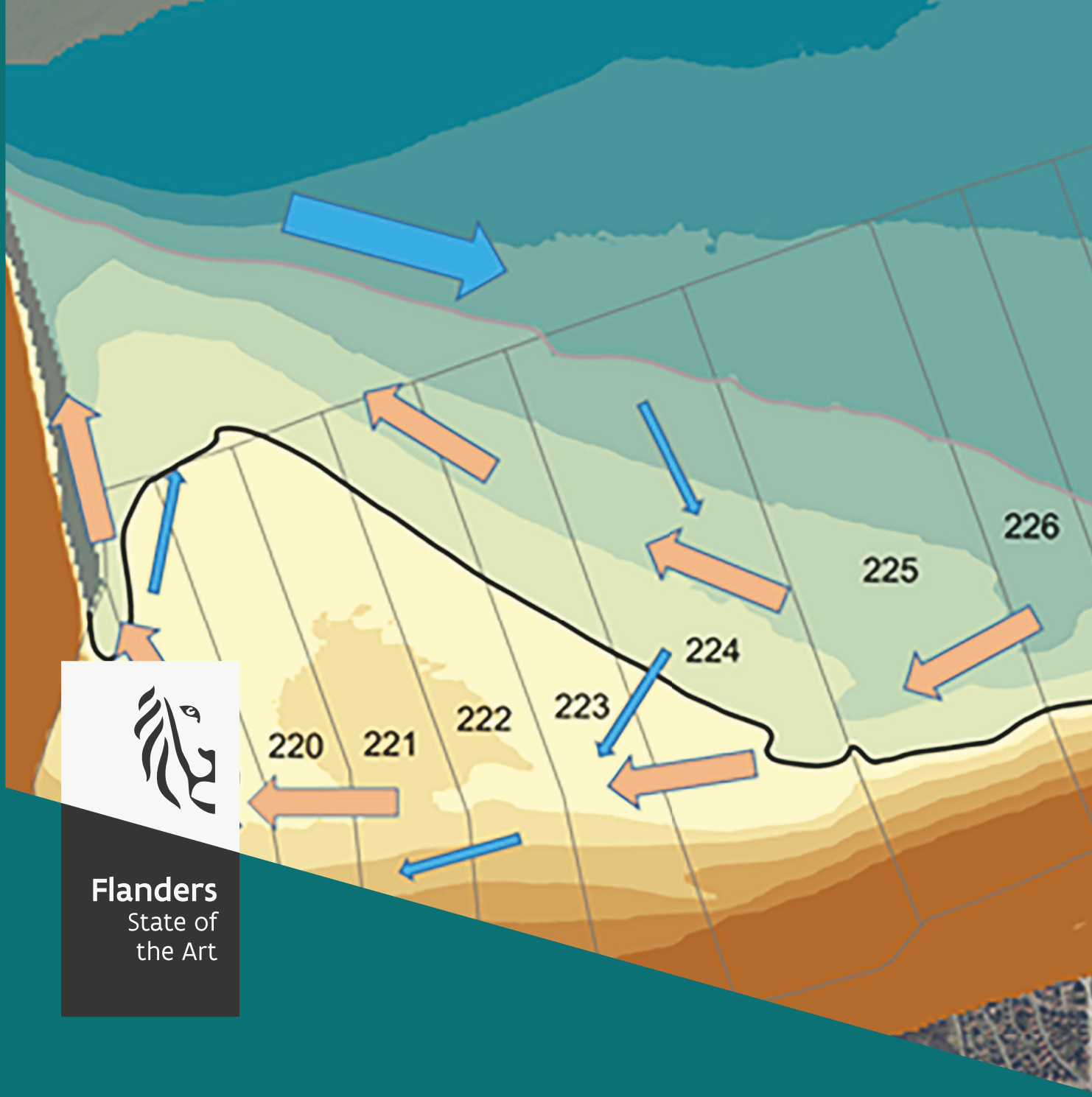

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Evolution of a large coastal nourishment at Knokke

Final report

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Evolution of a large coastal nourishment at Knokke

Final report

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

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Abstract

Beach erosion occurs along a large part of the Belgian coast but is often more intense at Knokke coastal zone. Artificial nourishment of the active beach system is one of the most applied and successful measures to prevent and to cope with erosion. After repeated beach nourishments over the past decades, a major scheme is now being implemented: a combined large beach and nearshore nourishment of a total of 3.4 million m^3 of sand for the Knokke area in the period 2020 – 2024. The aim of this study is to understand the hydrodynamics and morphodynamics of the Knokke area and to evaluate the effect of the beach and nearshore nourishments. This 5^{th} year and final report focuses on coastal morphological changes along the east Belgian coast from Zeebrugge to east of the Zwin between 2018 and 2024. The results clearly indicate the significant effect of the nourishments on the beach and shoreface morphology as well as the spatial spreading of sand over time driven by tidal and wave currents. The continued topo-bathymetric surveys in the coming years will allow to monitor the further evolution of the large nearshore nourishment.

Contents

Abstract III
Contents IV
List of tables V
List of figures VI
1 Introduction 1
2 Study site 3
3 Methodology 6
3.1 Definition of the coastal zones 6
3.2 Topographic survey acquisition and processing 7
3.3 Volumetric calculation 8
4 Sand nourishments 9
5 Results 12
5.1 Long-term morphological changes 12
5.2 Annual morphological changes 13
5.3 Monthly morphological changes of the large nearshore nourishment 34
6 Discussion 41
6.1 Volume increase at Duinbergen 2021 beach nourishment 41
6.2 Volume increase at Knokke-Zoute 2021 to 2023 beach nourishment 42
6.3 Volume increase at Knokke-Zoute 2020 and 2021 nearshore nourishment 42
6.4 Volume increase at Knokke-Zoute - nearshore nourishment in 2023-2024 44
6.5 Morphological evolution of the beaches after the beach nourishments 46
6.6 Morphological evolution of the shoreface after the nearshore nourishments 47
6.7 Implications on the morphological processes 53
6.8 Local morphological impacts 56
7 Conclusions 58
8 Recommendations 59
9 Highlights 60
10 References 61

List of tables

Table 1 – Description of the defined coastal zones..... 6

Table 2 – Timeline of topographic and bathymetric measurements, as well as the nourishments between 2018 and spring 2024. 7

Table 3 – Volume and grain size of the sand supplies from Terneuzen lock. 11

Table 4 – Sediment budgets of the delimited zones of the beach-shoreface system between 2018 and 2024. Beach is the sum of the sediment budgets over the backshore and foreshore. Red and green colour indicates significant negative or positive differences respectively while no colour values are not significant. 13

Table 5 – Consecutive sediment budgets of the delimited zones of the backshore and beach from 2018 to 2024. Red and green colour indicates significant negative or positive differences respectively while no colour values are not significant..... 31

Table 6 – Consecutive sediment budgets of the delimited zones of the foreshore and shoreface from 2018 to 2024. Red and green colour indicates significant negative or positive differences respectively while no colour values are not significant..... 32

Table 7 – Sediment budgets of the beach nourished aeras from 2018 to 2024. Values in bracket correspond to the volume in $m^3/m^2/y$. Red and green colours indicate significant negative or positive trends respectively and no colour values are not significant. 34

Table 8 – Corrected sediment budget based on the long-term coastal trend from 1980's to 2019 (Houthuys et al., 2022)..... 41

Table 9- Sediment budget in the area of the nearshore nourishment in 2018-2022. Values in 4^{th} column correspond to the volume in $m^3/m^2/y$. Green colour for the volume indicates significant positive trends differences and no colour values are not significant. 44

Table 10 – Sediment budget in the area of the nearshore nourishment in 2023-2024. Values in bracket correspond to the volume in $m^3/m^2/y$. Red and green colours for the volume indicate significant negative or positive trends respectively, while no colour values are not significant..... 45

Table 11 – Sediment budgets from 2018 to 2024 of the entire offshore area and the offshore area excluding the large shoreface nourished zone in 2023-2024. Values in bracket correspond to the volume in $m^3/m^2/y$. Red and green colour indicates significant negative or positive trends respectively and no colour values are not significant..... 53

List of figures

Figure 1 – A) The design of the Knokke nourishment project between 2019-2024. The solid lines with points approximately parallel with the present shoreline describe the nourishment; B) Design of the nearshore nourishment (Sassevaart vof, 2020a). 2

Figure 2 – A) Nautical map with distinct geomorphological marine bedforms; B) topography of the east coat with contour lines. 3

Figure 3 – Time series of volume changes between Zeebrugge and The Netherlands (stretches 44-51) (from Montreuil et al., 2019). 4

Figure 4 – D50 (µm) of sediment collected on the beach along the project site in winter 2021 5

Figure 5 – Defined coastal zones. Beach includes backshore and foreshore. 6

Figure 6 – Definition of the sediment layers in cross-shore and alongshore direction. 8

Figure 7 – Locations of the nourishments from 2019 to 2024. 9

Figure 8 – Study area of the shoreface/foreshore nourishment execution in Knokke-Heist in 2023-2024; B) Volume distribution as a function of the distance from Zeebrugge harbour (extracted from Boerema et al., 2023). 10

Figure 9 – DoD of the merged beach and shoreface between 2018 and 2024 with indications of the nourishment locations. Black, dark grey and light grey contour lines correspond to +5, 1.39 and -5 m TAW in 2018. 12

Figure 10 – Generated DEMs of the merged beach and shoreface surveys. Grey lines represent contour lines of +5, +1.39 m and -5 m TAW. 17

Figure 11 – Cross-shore profiles (Profile 1 in section 225, Profile 2 in section 230 and Profile 3 in section 235) extracted from the LiDAR surveys at Duinbergen. 20

Figure 12 – Consecutive DoDs of difference of the merged beach and shoreface with indications of the nourishment locations. Black, dark grey and light grey correspond to +5, 1.39 and -5 m TAW in 2018. 24

Figure 13 – DoDs of the merged beach and shoreface from the reference survey in 2018 with indications of the nourishment locations. Black, dark grey and light grey correspond to +5, 1.39 and -5 m TAW in 2018. 27

Figure 14 – Delimitation of the observed beach nourished areas of Duinbergen and Knokke on the DoD 2018-2024. The black contour lines correspond to 1.39 m and -5 m TAW respectively in 2024. 33

Figure 15 – A) UAV and MB DEM, B) example of extracted profiles 35

Figure 16 – DEM of the pre and post nourishment surveys in the area of the large nearshore nourishment in October 2023-February 2024. The black, dark grey and light grey lines correspond to 5 m, 1.39 m and -5 m TAW respectively. The pink grid corresponds to the location of the dump area. MB and SB stands for multibeam and single beam bathymetric surveys 38

Figure 17 – DoD of the pre and post nourishment surveys in the area of the large nearshore nourishment in October 2023-February 2024. 39

Figure 18 – Extracted profiles in the large nearshore nourishment zone. Inset: locations of the profiles. 40

Figure 19 – DoD between 2019 and 2022 i.e. the period including the 2020 and 2021 Knokke-Zoute nearshore nourishments, with the nourishment area shown in blue. The pink polygons correspond to the investigate offshore area (section 6.6). Contour lines correspond to -5 m, 1.39 m TAW in 2018. 43

Figure 20 – DoD between 2023-2024 pre- and post-large nearshore nourishment MB and drone surveys, with the area of the nourishment (purple rectangle). 45

Figure 21 – Conceptual model for the evolution of a nourishment in the coastal are of Knokke. 47

Figure 22 – DoD between 2018 and 2024 delimiting A) the entire offshore area (pink polygon), B) the offshore area excluding the large nearshore nourishment zone in Knokke in 2023-2024 (blue polygon). The black contour lines correspond to 1.39 m and -5 m TAW respectively in 2024. 49

Figure 23 – Annual DoDs between 2018 and 2024 delimiting the offshore area excluding the large nearshore nourishment zone in Knokke in 2023-2024 (blue polygon). The black contour lines correspond to 1.39 m and -5 m TAW respectively in 2024. 52

Figure 24 – Conceptual model of the hydrodynamic flow patterns derived from the configuration with the harbour dam, and the morphological development of the seabed and foreshore, near Heist. Blue arrows show flow at high tide, orange arrows at low tide. (Houthuys et al., 2023) 54

Figure 25 – Contour lines evolution between 2000-2019 (Houthuys et al., 2022). 55

Figure 26 – DEM in 2024 with contour lines evolution between 2018 (bold line) and 2024 (dashed line). 56

Figure 27 – Interpretation of sediment transport based on sediment transport processes in section from 240-247 superimposing on the pre-post nourishment DoD. The thick blue arrows show the sediment transport derived from the morphological development over the period. Purple values are the height difference at some selected points. Green is accretion and red erosion. The area of the nearshore nourishment is indicated by the rectangles in sections 239 to 244. (Houthuys et al., 2024) 57

1 Introduction

A long-term erosive trend has been observed in the area of Knokke-Heist in the last decades. Risk of flooding during extreme storms is significant with possible impact on the economic and ecological potential of the beach area. One of the most used and successful measures to cope with erosion is the artificial nourishment of the active beach and shoreface system. This measure was widely applied in the last decades along Knokke-Heist coast. After repeated beach nourishments over that period, a major scheme is now being implemented, as communicated by Coastal Division: a mega-nourishment of the beach and shoreface was performed at the Knokke area during the period 2019 - 2024 (Figure 1). In the period 2019 -2024, a total of approximately 3.4 million m^3 of sand was nourished. Part of the nourished sand originates from the new lock construction site in Terneuzen (NL). The nourishment took place in several steps spread over several years and adapted according to circumstances, such as the supply of sand.

The updated calendar of the nourishment is detailed below:

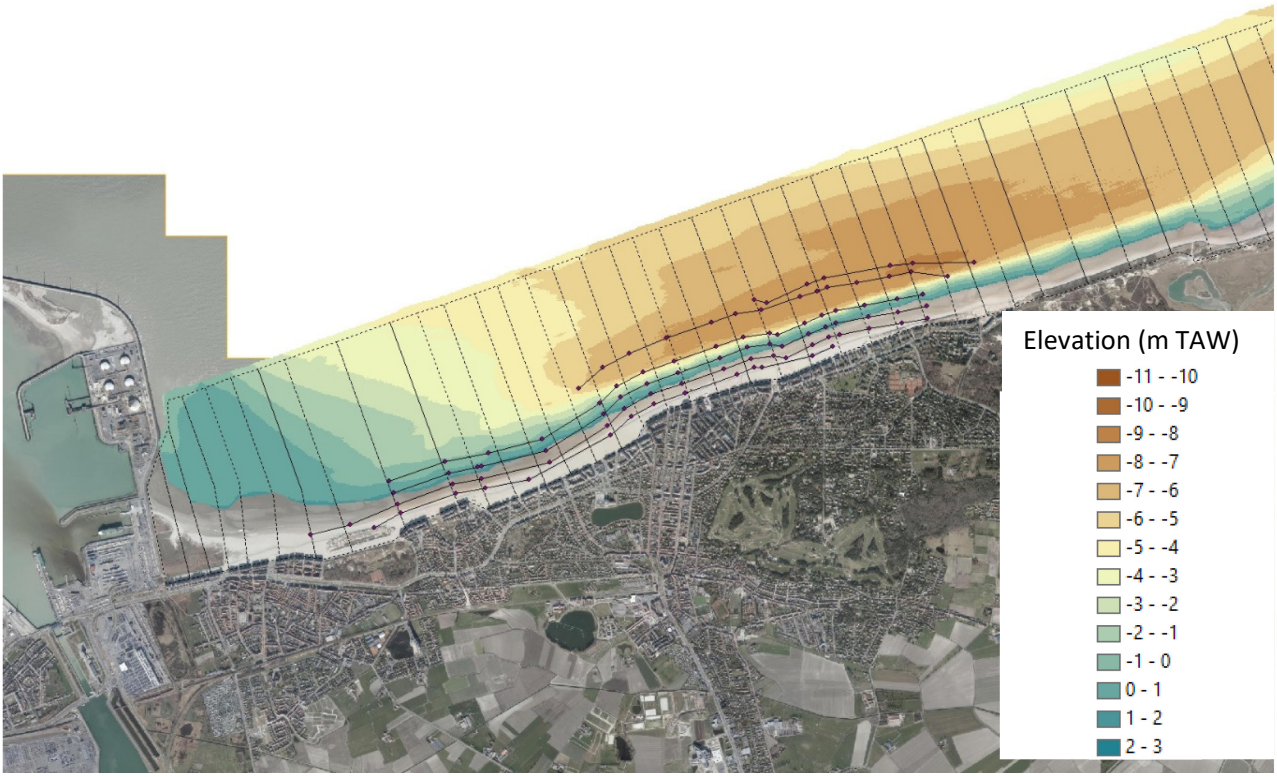
- 2019: beach nourishment of 292 802 m^3 in section 234-243
- 2020: nearshore nourishment: first phase in May and June, second phase November and December with a total of 145 767 m^3 covering sections 235-240;
- 2021: nourishment from February to March of 981 821 m^3 on the shoreface of sections 223-230, beach supply of 33 500 m^3 in Knokke Zoute (section 242-246) from March to May, nearshore nourishment in Knokke (section 232-240) of 161 708 m^3 supplied from the new lock in Terneuzen.
- 2022: dry nourishment of 33 000 m^3 spread over the dry beach.
- 2023: beach nourishment of 510 574 m^3 in Knokke-Heist from February to March (section 230-241).
- End 2023-2024: nearshore nourishment of +/- 1.2 million m^3 from October 2023 to February 2024 in Knokke (section 231-244).

The aim of this project is to better understand the hydrodynamics and morphodynamics of the Knokke area and its surroundings under the influence of sand nourishments. The effect of the nourishments on the morphological behaviour and evolution is also investigated. Four work packages were designed to structure the investigation of the nourishment at Knokke according to the project proposal:

- WP1 Literature review
- WP2 Measurements at the study zone and the general hydrodynamic conditions
- WP3 Morphological evolution of the study area
- WP4 Nourishment efficiency and recommendations

This final report documents the coastal morphodynamics and processes along the east Belgian coast from Zeebrugge to the Zwin between 2018 (pre-nourishment) and 2024.

A)



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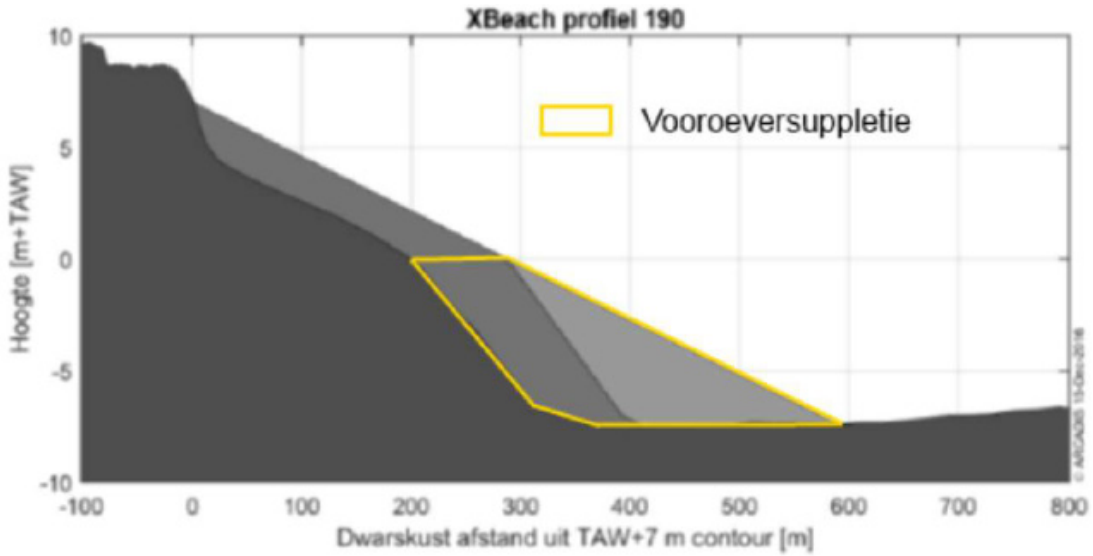
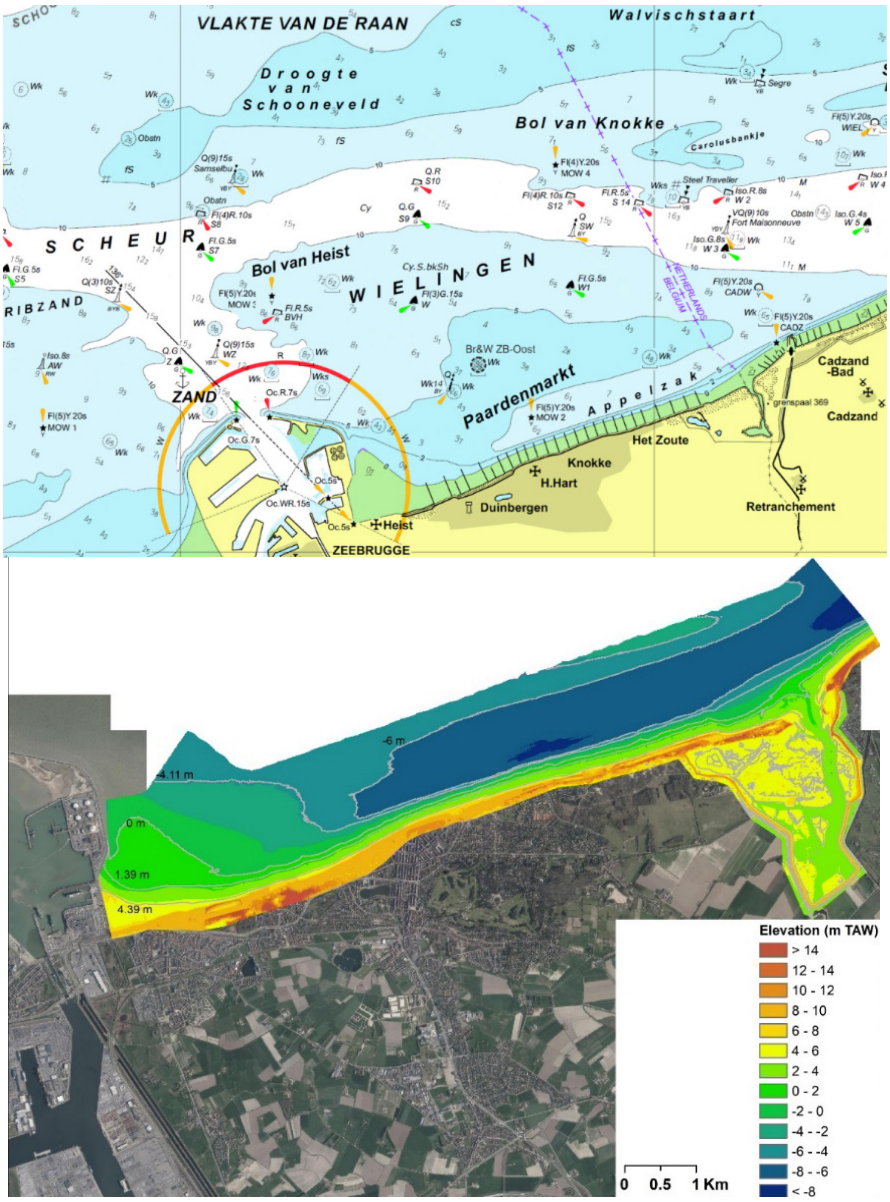


Figure 1 – A) The design of the Knokke nourishment project between 2019-2024. The solid lines with points approximately parallel with the present shoreline describe the nourishment; B) Design of the nearshore nourishment (Sassevaart vof, 2020a).

2 Study site

The eastern part of the Belgian coast, stretching from the outer port of Zeebrugge to the Zwin inlet has a complex morphology due to the presence of the harbour of Zeebrugge, a complex bathymetry with shoals and channels, frequent artificial sand supplies and the undulating trace of the coastline/sea dikes (Figure 2). The coast experiences two large opposing sediment fluxes alongshore that sum to approximately zero, leading to large spatial gradients and morphological variability (Montreuil et al., 2019). On average, the recent sediment budget shows a stability, yet locally erosion is problematic (Figure 3). Further details about past and contemporary morphology, human interventions as well as regional hydrodynamics are presented in the previous progress reports of this project (Montreuil et al., 2021, 2022, 2023, 2024).

Figure 2 – A) Nautical map with distinct geomorphological marine bedforms; B) topography of the east coat with contour lines.



Up to 2 km from Zeebrugge port's eastern breakwater to Duinbergen (stretches 44-46), a large accretional trend occurs in the Baai van Heist mainly caused by natural processes (Montreuil et al., 2019, Houthuys et al., 2022). However, the rate of accretion there has decreased in recent years. Towards east, the long-term evolution of the coast from Duinbergen-centrum to Zwin (stretch 47-51) is erosional. The largest erosional trend occurs at Knokke-Zoute with a rate of -42.16 $m^3/m/y$ over the period from 1986 to 2019. This is probably related to the gradient in longshore transport as well as the natural deepening of the Appelzak tidal channel. The channel is fed with beach-derived sand during storm erosion but the temporary deposited sediments are cleared away by marine currents induced by the tidal asymmetry. Locally stronger tidal currents may also be related to the protrusion of the coastline/sea dike in this stretch. An expression of flow current erosion is the trend of the channel to extend eastward. The tidal currents appear to create two parallel flow axis traces inside the Appelzak channel, named Branch 1 (close to the shore) and Branch 2 (close to Paardenmarkt sandbank) (Figure 2). It has also been suggested that natural accretion and landward migration of the Paardenmarkt sand bank, coupled with the stationary shoreline position due to repeated nourishments, prevent the Appelzak channel from shifting landward, thereby forcing it to deepen its bed.

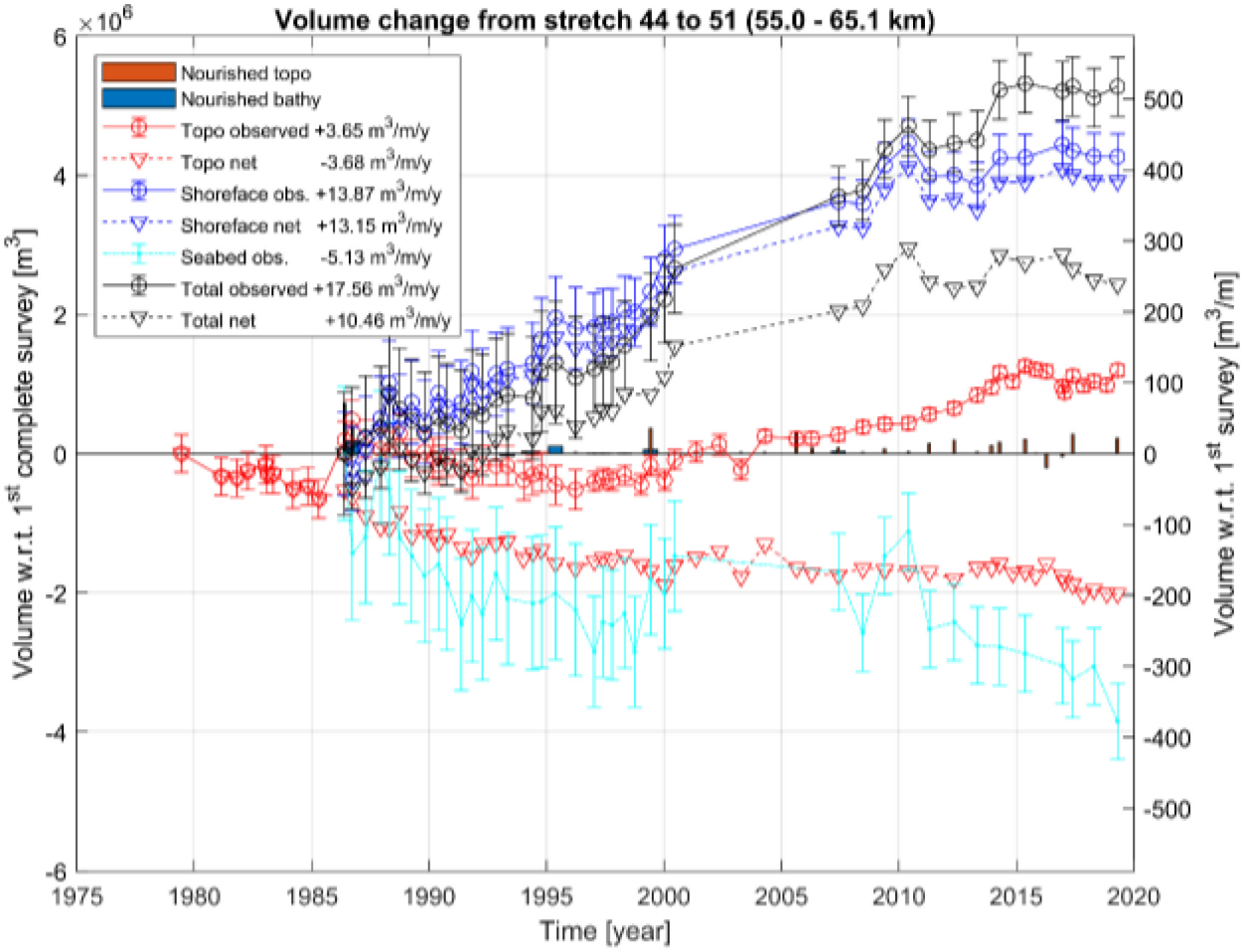


Figure 3 – Time series of volume changes between Zeebrugge and The Netherlands (stretches 44-51) (from Montreuil et al., 2019).

Beach sediment material varies along the study coast ranging from 88 µm to 1200 µm and with an average of 330 µm (Figure 4). The grain size ranges from 300 to 500 µm in the regular nourishments carried out before 2024 in the Knokke area. Thus, coarse sand is mainly associated with the carried-out sand nourishments. Also, a cross-shore sediment variability characterizes the beach. Noteworthy, the grain size in the shoreface along the entire study coast is not yet precisely determined.

Figure 4 – D50 (µm) of sediment collected on the beach along the project site in winter 2021

3 Methodology

3.1 Definition of the coastal zones

The east coast is about 12 km long and is divided into sections from 217 to 266. These elementary morphological monitoring units cover the cross-shore domain from the foredunes or the sea dike up to 1500 m offshore and span approximately 200-300 m alongshore. Their boundaries are determined by the position of 24 groynes and the port of Zeebrugge, while a more uniform spacing is adopted in the case of absence of engineering structures. For this project, these sections are merged to 9 coastal zones labelled from A to I from west to east (Figure 5) (Table 1).

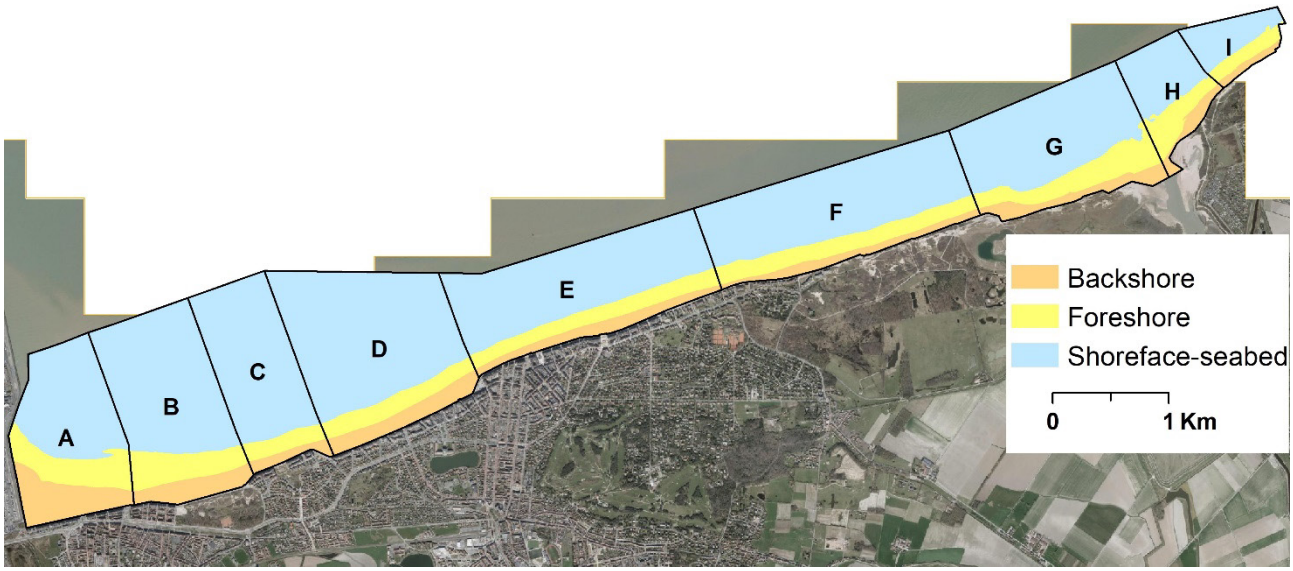


Figure 5 – Defined coastal zones. Beach includes backshore and foreshore.

Table 1 – Description of the defined coastal zones.

Zone	Sections	Stretches	Location	Length (m)	Area (m^2)
A	217-221	44-45	Heist-west	950	933 868
B	222-224	46	Heist-east	1 100	1 534 340
C	225-226	47	Duinbergen	755	1 129 990
D	227-232	48	Albertstrand	1 455	2 304 730
E	233-241	49	Knokke-Zoute	2 240	3 265 450
F	242-249	50	Lekkerbek	2 325	3 528 140
G	250-255	51	Zwin	1 750	2 638 630
H	256-260	52	Zwin geul	1 070	935 345
I	261-266	53	Cadzand-west	685	1 207 360
Total	217-266	44-53	Heist-west to	2 390	17 477 853

3.2 Topographic survey acquisition and processing

Airborne LiDAR (Light Detection And Ranging) surveys are yearly conducted to measure the emerged beach above the low water line. This dataset is owned and kept at MDK Coastal Division which is made available in ASCII format (X, Y in Lambert 72 and Z in TAW). The morphological evolution between 2018 and 2024 is here analysed for the surveys presented in Table 2. The spatial resolution of the surveys is always at least 1, and often over 5 points/m². These data were used to generate Digital Elevation Models (DEM) with 2m-grid size. They extend from the dyke or dune foot to the low water line. The nearshore bathymetry of the east coast is also part of the routine monitoring. It is surveyed annually with a single beam bathymetric system (Table 2). These data are owned and stored at MDK Coastal Division and it is made available in ASCII format (X, Y in Lambert 72 and Z in TAW). These data were used to generate a Triangulated Irregular Network (TIN), per survey. The TINs were then converted to 10 m cell size DEMs covering the shoreface at least up to 1.5 km from the coastline. Finally, beach and shoreface DEMs were merged to new rasters of 5 m-grid size. DEMs of difference (DoD) were generated between the pre-nourishment situation (2018) and the years 2019 to 2024 in order to assess the morphodynamics of the study zone and the evolution of the nourishment. The differences between consecutive years were also constructed to detect possible sudden changes in the erosion/deposition pattern.

Table 2 – Timeline of topographic and bathymetric measurements, as well as the nourishments between 2018 and spring 2024.

Date	Description
17/04/2018 (pre-nourishment)	LiDAR survey
28, 30/05 and 06/07/2018	Bathy survey
02-03/2019	Beach Nourishment (Zone E-F, section 234-243) 292 802 m^3
20/04/2019	LiDAR survey
23/05/2019	Bathy survey
10/04/2020	LiDAR survey
05-06/2020	Nearshore Nourishment (Zone E, section 235-240) 14 839 m^3
23/06/2020	Bathy survey
11-12/2020	Nearshore nourishment (Zone E, section 235-240) 130 930 m^3
02-03/2021	Beach Nourishment (Zone B-D, section 223-230) 981 821 m^3
28/04/2021	LiDAR survey
3-5/2021	Beach Nourishment (Zone F, section 242-246) 33 500 m^3
31/05/2021	Bathy survey
05-06/2021	Nearshore nourishment (Zone E, 232-240) 161 708 m^3
17/04/2022	LiDAR survey
12/05/2022	Bathy survey
02-03/2022	Beach Nourishment* (Zone D, section 231-232) 30 000 m^3
05/2022	Beach Nourishment* (Zone A-B, section 217-222) 3 000 m^3
08/02/2023	LiDAR survey
28/02/2023 to 04/04/2023	Beach Nourishment (Zone D and E, 230-241) 510 574 m^3

17/06/2023	LiDAR survey
11/08/2023	Bathy survey
17/01/2024	LiDAR survey
02/10/2023**	Limited bathy survey multibeam and UAV (Zone E-F, 231-244)
10/2023-02/2024	Large Nearshore nourishment (Zone E-F, 231-244) 1.2 million m^3
10/01/2024***	Limited bathy survey multibeam (Zone D-F, 229-248)
11/03/2024**	Limited bathy survey multibeam and UAV (Zone E-F, 231-244)
29/04/2024	Bathy survey singlebeam
26/06/2024***	Limited bathy survey multibeam (Zone E-F, 241-247)

Note:
*Sand supply in 2022 was from a construction site at Boereboomplein delivered by trucks.
** Multibeam survey combined with beach UAV topography carried out by DEME
***Multibeam survey carried out under the nearshore nourishment monitoring campaign carried out by hydrography department

3.3 Volumetric calculation

To assess the volumetric changes, the coastal system was divided into 3 layers: "backshore" extending from the dyke/dunes to the level of 5 m TAW, "foreshore" from 5 m TAW to 1.39 m TAW; and "shoreface" from 1.39 to -5 m (Figure 6). "Beach" is a sum-up of the backshore and foreshore. The elevations of the divisions are conventional boundaries and are not defined on the basis of tidal datums. The level of +5 m TAW more or less corresponds to the highest tide at equinoctial spring tide. The level of +1.39 m TAW corresponds roughly to low water level at neap tide. It is also used as a separation level in the routine coastal volume monitoring. The shoreface-seabed zone is considered as the area above the depth of closure which is estimated to be –5 m TAW (i.e. not the fixed 1500 m boundary). The latter is defined as the seaward limit of the shoreface-seabed below which morphodynamics is less influenced by waves. The layer definition was applied on the 2018 survey, after which the boundaries shown in Figure 6 were kept constant for all later volume calculations. Volumetric changes per unit surface per time were then computed, enabling comparison of volumetric results despite differences of spatial coverage and the duration between surveys.

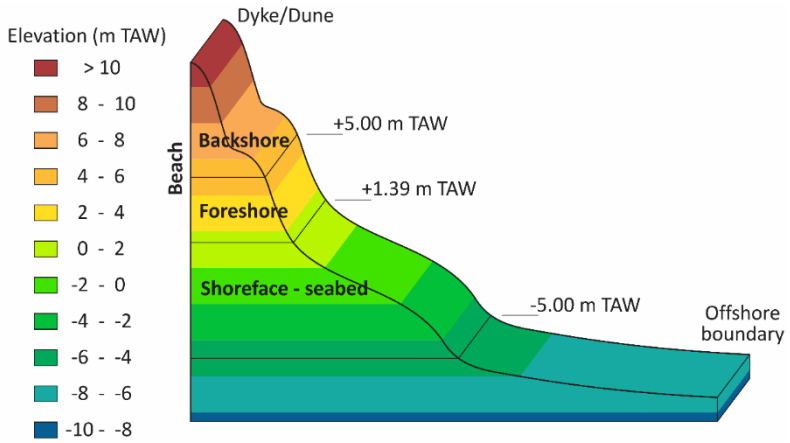


Figure 6 – Definition of the sediment layers in cross-shore and alongshore direction.

4 Sand nourishments

In the framework of this project, sand supplies of the shoreface and the beach were carried out in numerous phases between 2019 and 2024 (Figure 7, Table 2). Figure 7 indicates nearshore nourishment design and supply areas between October 2023-February 2024.

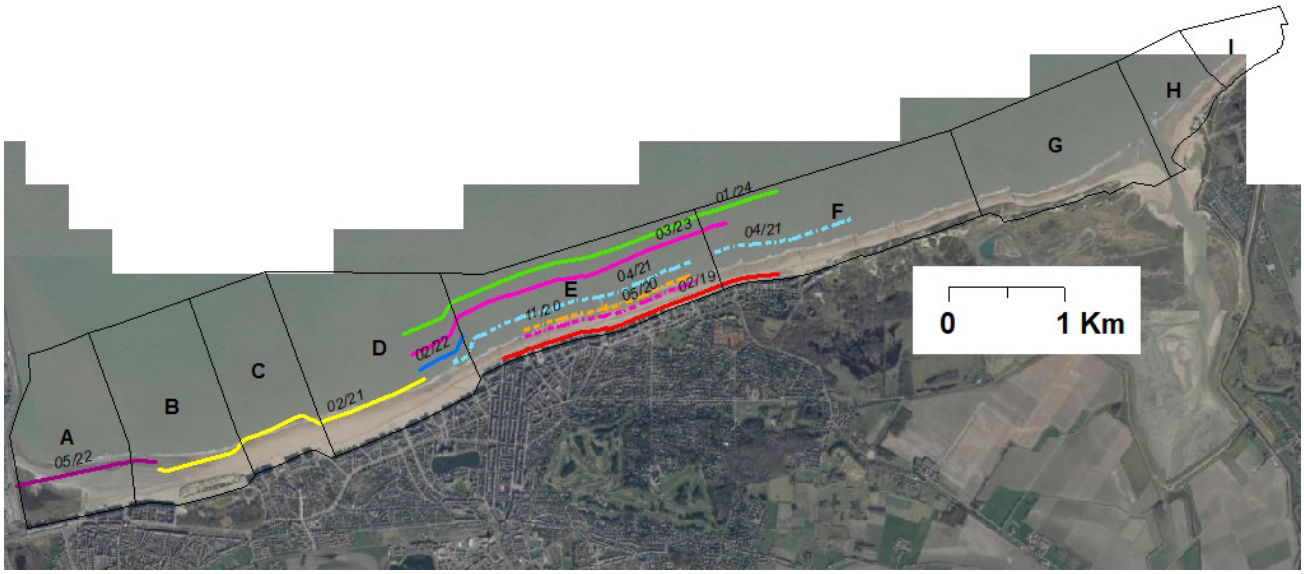
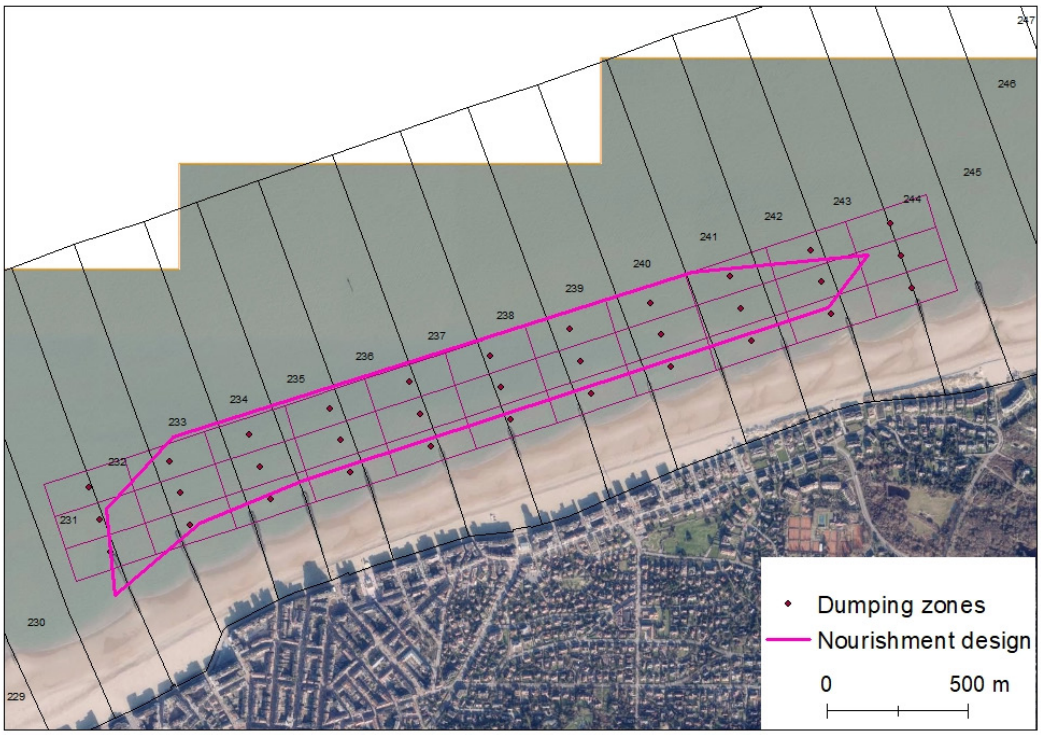


Figure 7 – Locations of the nourishments from 2019 to 2024.

The nourishment phase carried out in 02-03/2021 increased the protrusion of the beach in section 225-226 (Duinbergen). In the most protruding sections, the low-water mark was moved 90 m seawards by the nourishment and the high-water mark by 120 m. The vertical accretion amounted to 3 m in the most heavily nourished sections. The nourishment affected the profile from TAW +7 m down till -1 m, so it includes a part of the upper shoreface.

The extracted sand from the new lock in Terneuzen project provided enough sand to carry out a large nearshore nourishment of 1.2 million m^3 for the part below 0 m TAW. Table 3 presents volume and the grain size of the sediment material from the Terneuzen lock between May 2020 to November 2021 as reported in Sassevaart vof (2020a, 2020b, 2021, 2024a, 2024b). The material selected for the application consists of medium to fine sand with a median (D50) of 150 µm as a lower limit. The material may not contain peat or other elements that could wash up on the coast. Sourced from the works of the new lock in Terneuzen project, the available sand was added to the shoreface of the section 231-244 between 12th October 2023 and 29th February 2024 in Knokke-Heist (Figure 8).

A)



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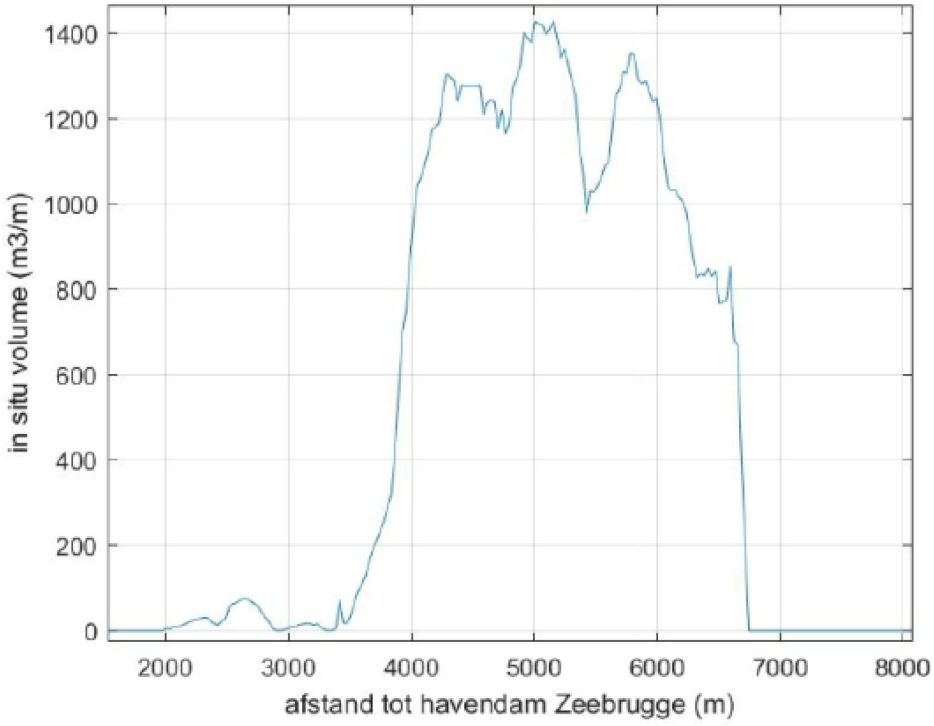


Figure 8 – Study area of the shoreface/foreshore nourishment execution in Knokke-Heist in 2023-2024; B) Volume distribution as a function of the distance from Zeebrugge harbour (extracted from Boerema et al., 2023)

Table 3 – Volume and grain size of the sand supplies from Terneuzen lock.

Time	Volume (m^3 , measured in the ship)	Average grain size D50 (µm)	Location (Defined nourished zone)
20-31/5/2020	14 839	181.4	West side
30/10-21/11/2020	130 928	174.8	West side and center
8-25/06/2021	161 708	171.5	Spread
11-25/10/2023	178 073	176.7	Mainly west side (section 233-235)
6/11-29/2/2024	1 016 107	232.6	Spread from section 233-241

End 2023: sand dumping originating from the new lock in Terneuzen was carried out before 11 October. This is evident on the multibeam survey on 2/10/2023 when local dumping spots could be observed in sections 235 to 240 on the edge of the trench Appelzak near Knokke-Zoute. Quantity and specific dumping period have not been provided.

From 11 to 25/10/2023, an underwater nearshore nourishment of 178,073 m^3 of sand from the new lock in Terneuzen was carried out with a dumping/rainbowing boat method which was mainly in sections 232 to 234 at Knokke-Zoute (Sassevaart vof; 2024a).

This nourishment continued from 6/11 to 31/12 with 496,228 m^3 of sand in sections 232 to 244 (Sassevaart vof, 2024b).

The period from 1/1-29/2/2024 was the last stage of the nearshore nourishment when 519,879 m^3 of sand was supplied over the entire zone in sections 232 to 244. During this phase, the nourishment was done on the foreshore in sections 232-234, on both the foreshore and the offshore shoreface in sections 237-241 and in sections 242-244 mainly on the offshore shoreface. Little nourishment was done in sections 235-236. The total deposited and rainbowed volume over the period 11 October 2023 to 29 February 2024 is about 1.2 million m^3.

In the updated coastal trend project (24_015), the volume distribution over the sections and below/above the low water line will be reported for each nourishment.

5 Results

5.1 Long-term morphological changes

Figure 9 displays the DEM of difference during the entire monitoring program from 2018 to 2024. Erosion and accretion are indicated in red and green respectively. More than 55% of the study site area experienced significant positive morphological changes. This was concentrated in the zones from A to F with a maximum of 83% significant positive change reached in zone E. Furthermore, the maximum sand gain was recorded on the upper foreshore of zone C and the shoreface of zone E. Accretion occurred not only on the backshore and foreshore but also on the shoreface and in the Appelzak. The large areas of accretion over the 5 years reflect the deployments of 6 beach and 4 nearshore nourishments from Duinbergen to west of Lekkerbek where a total of 2 400 000 m^3 of sand was supplied (volumes measured in the ship). The total observed accretion in the beach-shoreface system along the entire study site (from zone A to zone I) is 4 613 720 m^3 (with an uncertainty of +/-2 051 700 m^3) over the last 5 years which is equivalent to 386 m^3/m/y (Table 4). Although the uncertainty is large, this suggests that all of the nourished sand is still present in the coastal cell which might have received natural sand material from the offshore area, e.g. in the sedimentation area close to harbour of Zeebrugge (Heist-Albertstrand). Also, in CREST project a natural feeding from the sea towards the coastline of the east coast was observed for the east coast as a whole, namely an average growth of +12 mm/year for the entire active area over a 30 year period (Monbaliu et al., 2020).

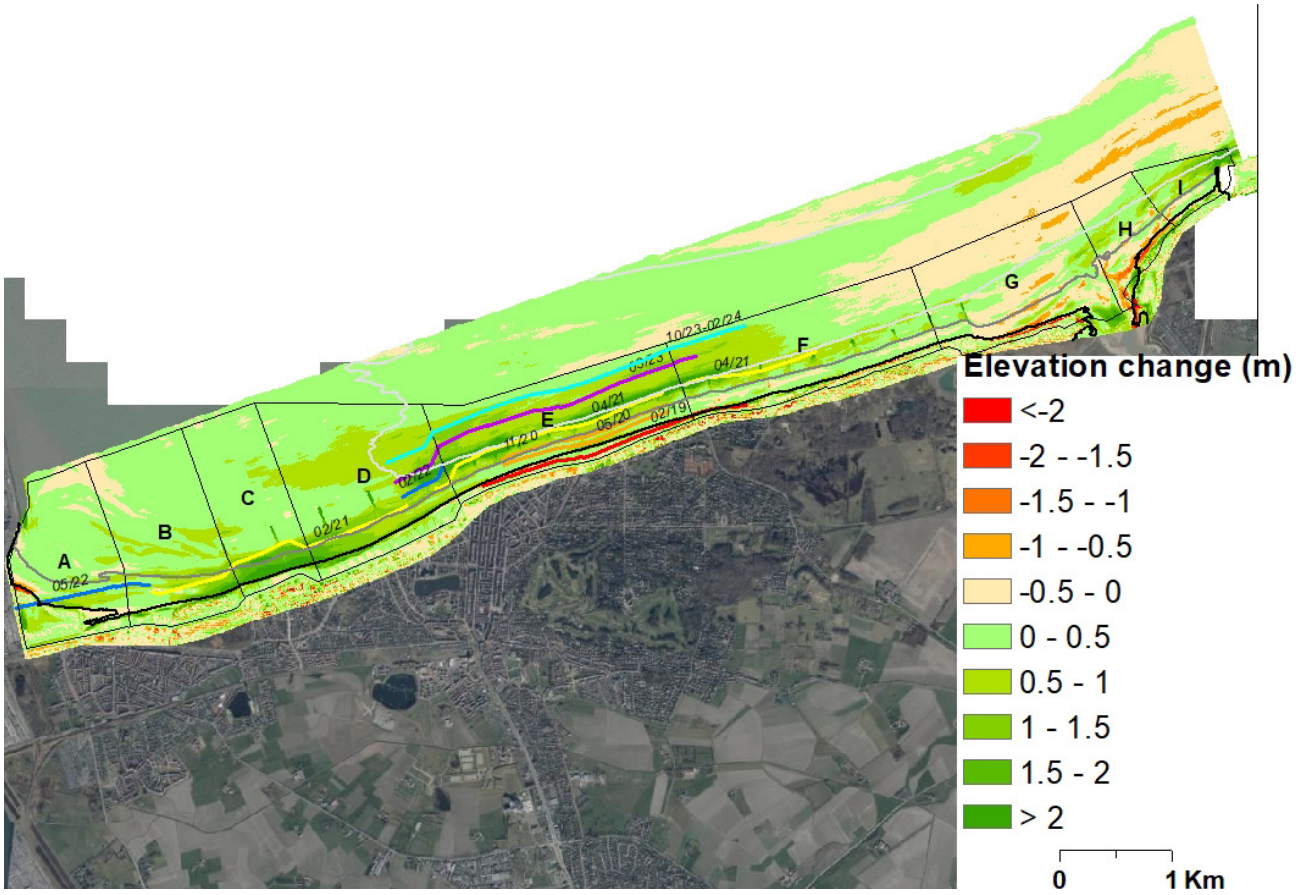


Figure 9 – DoD of the merged beach and shoreface between 2018 and 2024 with indications of the nourishment locations. Black, dark grey and light grey contour lines correspond to +5, 1.39 and -5 m TAW in 2018.

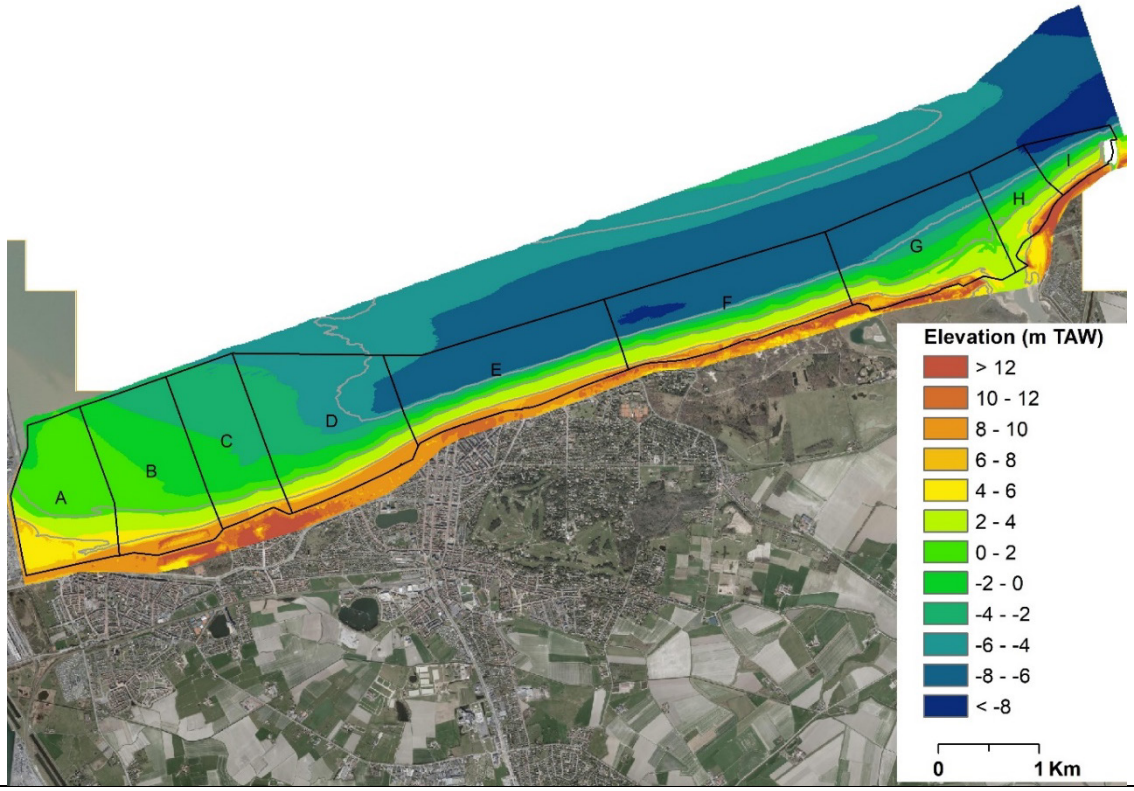
Table 4 – Sediment budgets of the delimited zones of the beach-shoreface system between 2018 and 2024. Beach is the sum of the sediment budgets over the backshore and foreshore. Red and green colour indicates significant negative or positive differences respectively while no colour values are not significant.

Layer	Zone	Volume (m^3) 2018-2024	Uncertainty (m^3)	Layer	Zone	Volume (m^3) 2018-2024	Uncertainty (m^3)
Backshore	A	89 820	19 940	Foreshore	A	93 240	18 920
	B	67 770	11 800		B	171 350	16 600
	C	37 710	4 540		C	218 460	7 120
	D	92 340	13 950		D	233 810	14 240
	E	33 790	13 000		E	98 280	19 940
	F	24 340	10 360		F	30 530	22 680
	G	8 990	10 730		G	-43 880	21 440
	H	-18 450	5 020		H	-57 600	10 160
	I	7 570	2 430		I	3 520	5 180
	Total	343 880	91 770		Total	747 710	136 280
Beach	A	115 460	38 860	Shoreface	A	156 860	151 580
	B	222 820	28 400		B	310 030	236 950
	C	250 710	11 660		C	353 040	202 290
	D	302 350	28 190		D	931 990	325 900
	E	105 790	32 940		E	1 297 920	276 010
	F	35 680	33 040		F	591 520	284 510
	G	-24 040	32 170		G	-149 620	228 570
	H	-84 080	15 180		H	25 490	72 030
	I	3 760	7 610		I	168 040	45 800
	Total	928 450	228 050		Total	3 685 270	1 823 640

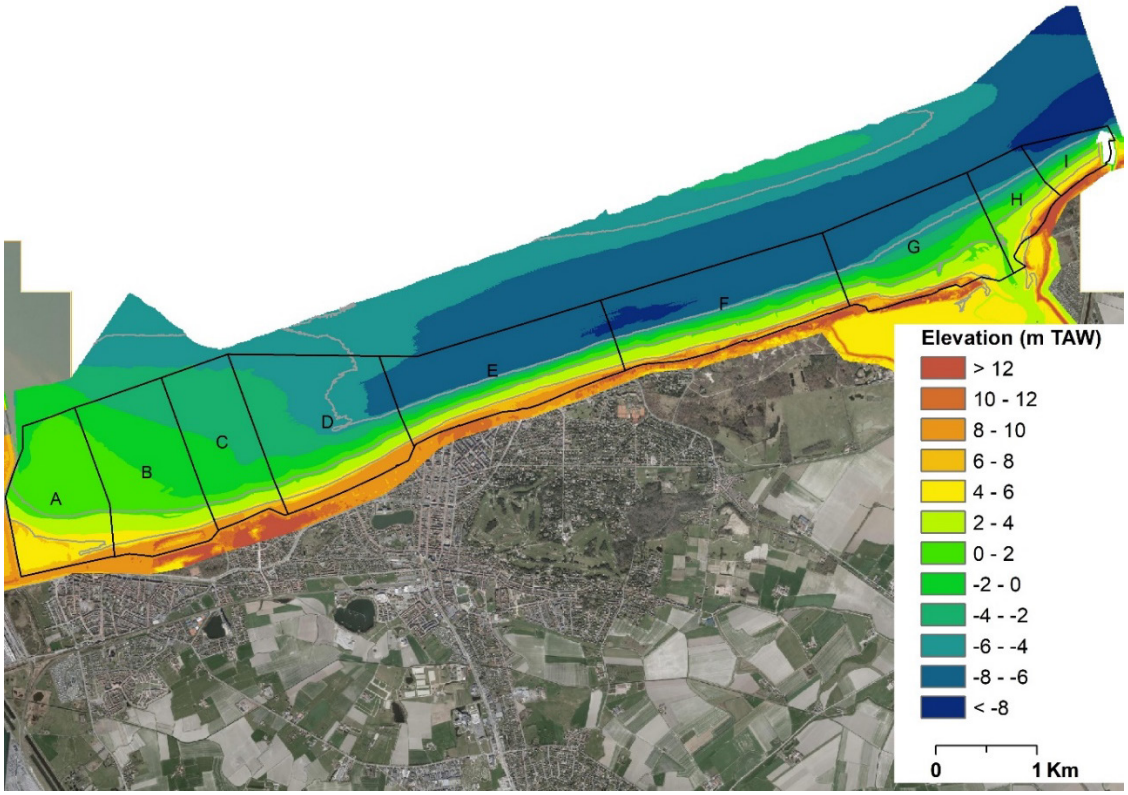
5.2 Annual morphological changes

The topography of the beach and shoreface along the east coast is characterized by spatial variability with the beach wider and shallower in the west side (zones A-C) (Figure 10). In contrast, the beach zone is narrower where the Appelzak channel is located (from zone D to the east of the study site). The deepest elevation in the Appelzak is about -8 m TAW. The coastline is relatively straight and oriented SW-NE. The DEMs display the evolution of the beach and its response after nourishments between 2018 and 2024.

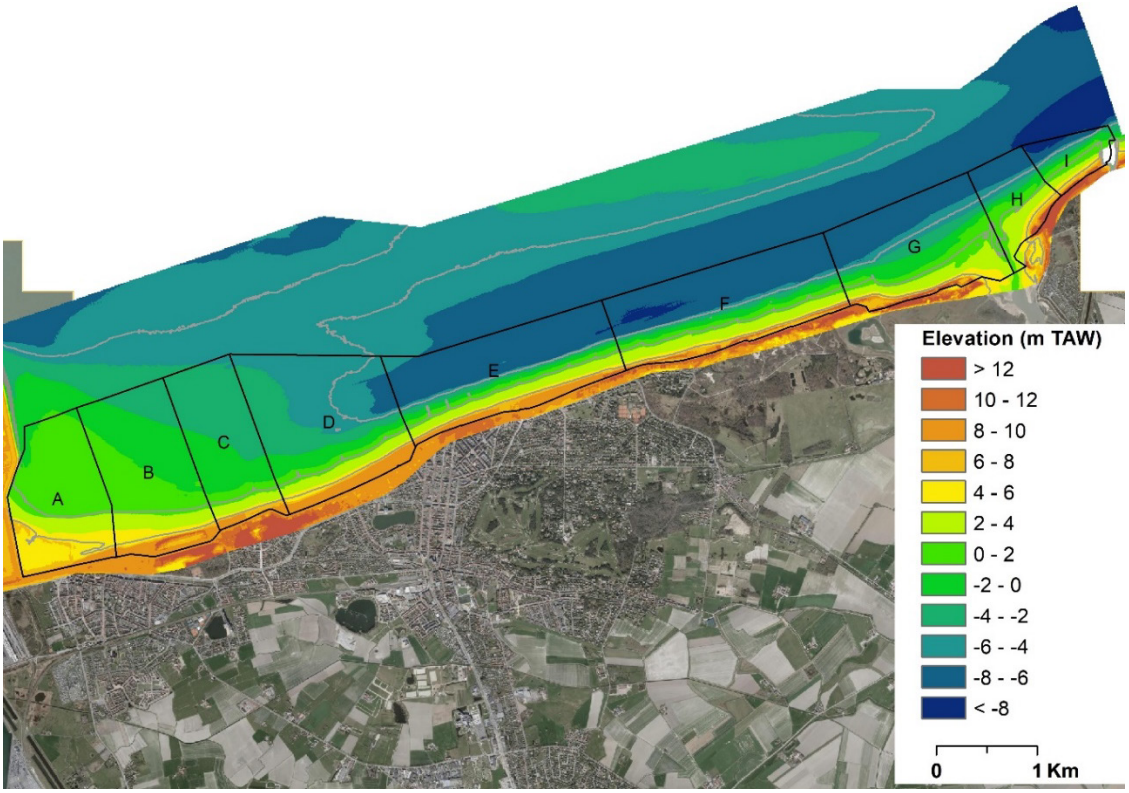
A) 2018 (pre-nourishment)



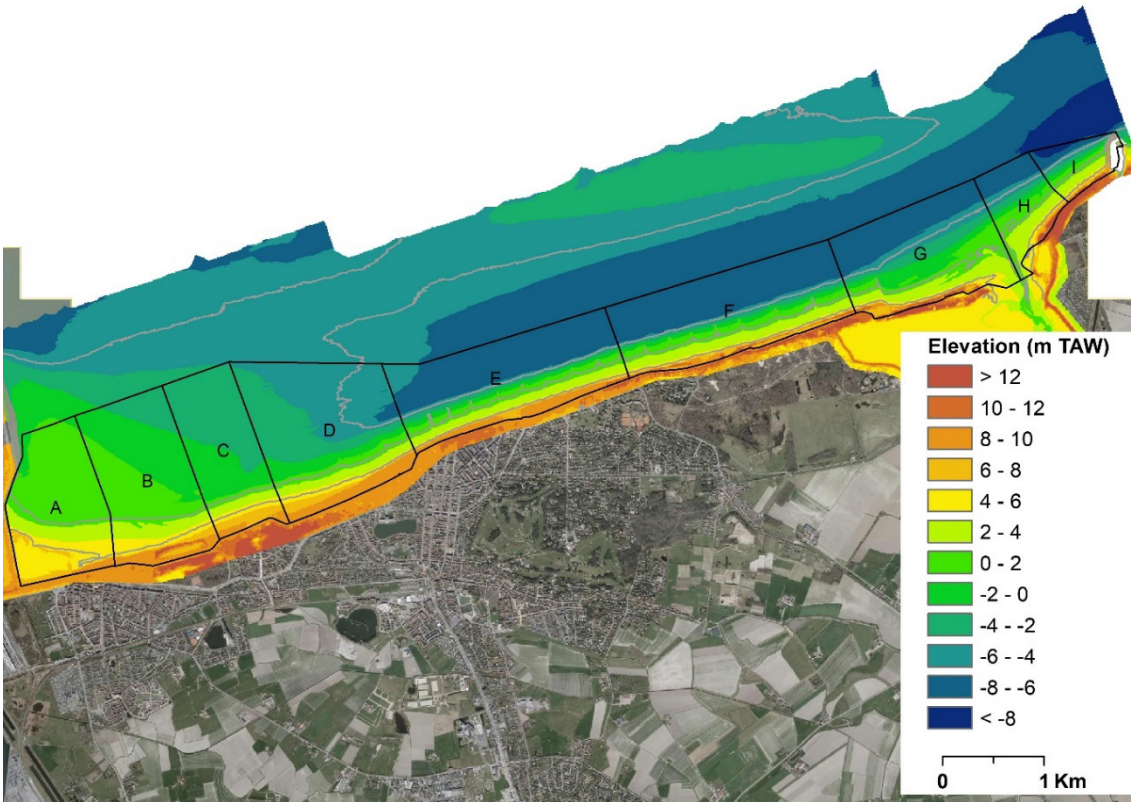
B) 2019



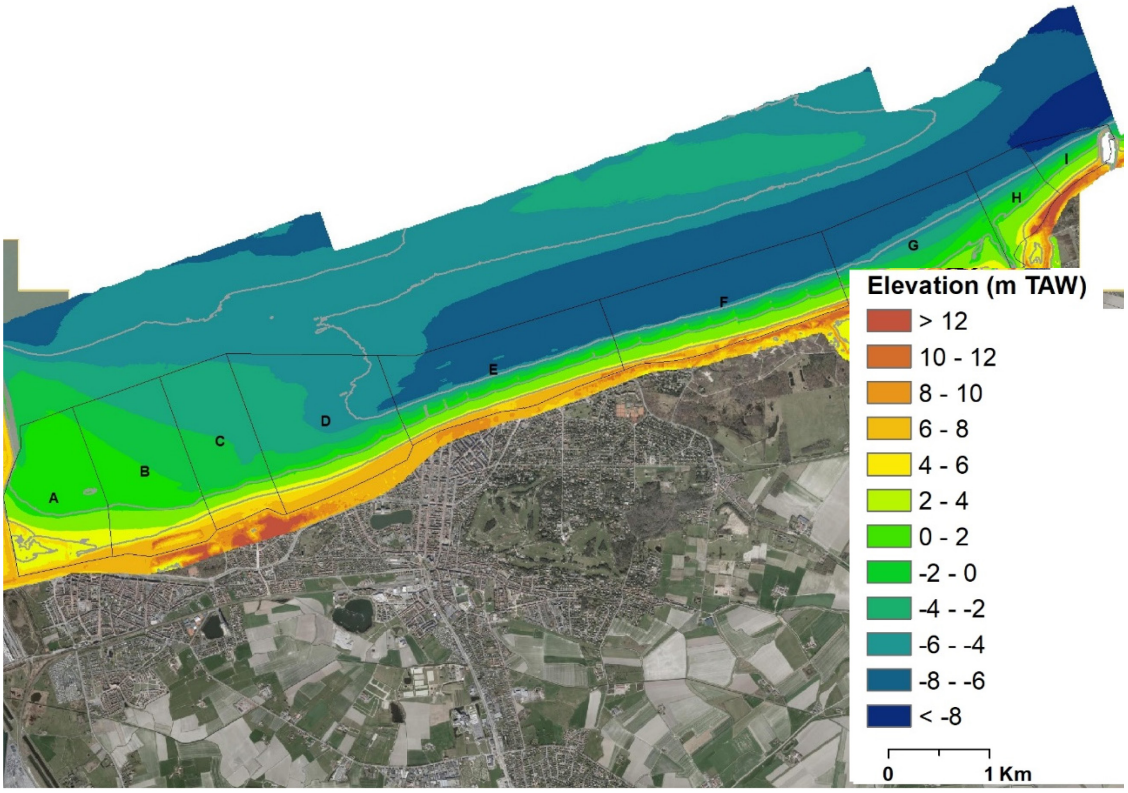
C) 2020


A
B
C
D
E
F
G
H
I
Elevation (m TAW)
> 12
10 - 12
8 - 10
6 - 8
4 - 6
2 - 4
0 - 2
-2 - 0
-4 - -2
-6 - -4
-8 - -6
< -8
0
1 Km

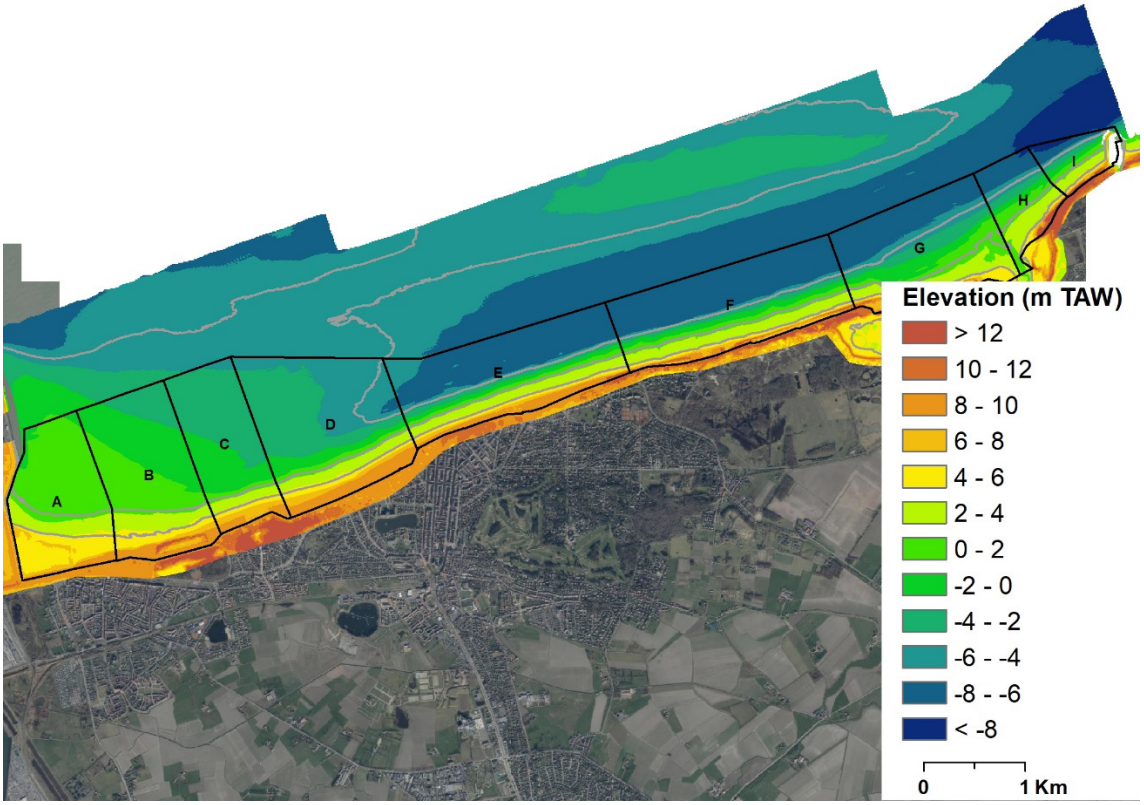
D) 2021


A
B
C
D
E
F
G
H
I
Elevation (m TAW)
> 12
10 - 12
8 - 10
6 - 8
4 - 6
2 - 4
0 - 2
-2 - 0
-4 - -2
-6 - -4
-8 - -6
< -8
0
1 Km

E) 2022


A
B
C
D
E
F
G
H
I
Elevation (m TAW)
> 12
10 - 12
8 - 10
6 - 8
4 - 6
2 - 4
0 - 2
-2 - 0
-4 - -2
-6 - -4
-8 - -6
< -8
0
1 Km

F) 2023


A
B
C
D
E
F
G
H
I
Elevation (m TAW)
> 12
10 - 12
8 - 10
6 - 8
4 - 6
2 - 4
0 - 2
-2 - 0
-4 - -2
-6 - -4
-8 - -6
< -8
0
1 Km

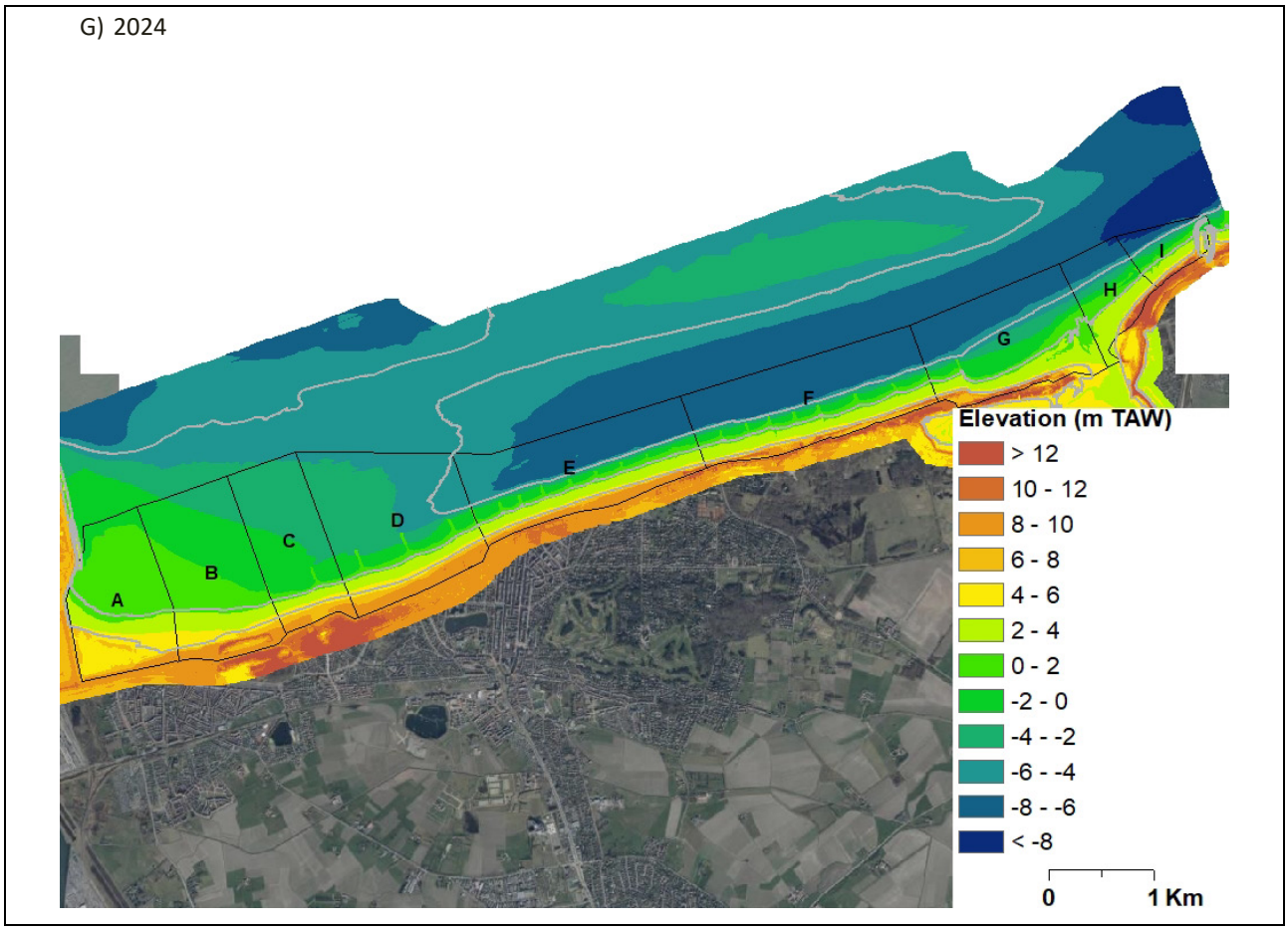


Figure 10 – Generated DEMs of the merged beach and shoreface surveys.
Grey lines represent contour lines of +5, +1.39 m and -5 m TAW.

Figure 11 presents three cross-shore profiles extracted from the time series of DEMs. Profile 1 located in section 225 at Duinbergen indicates little change at the beach and shoreface between 2018-2020 when no human intervention was done. In contrast, the beach from +7 to +1 m TAW generally gained 2 m height after the large nourishment in 02-03/2021. The height gain on the upper part of the shoreface (till -1 m TAW) gradually transitioned to the no-nourished part of the lower shoreface. Over the last three years, the upper-beach progressed seaward by 20 m, while the beach-shoreface system gradually lost sand while keeping a similar shape and slope. The average of elevation lost between 2021 and 2024 was 0.2 m. Interestingly, an accretion up to 0.4 m in the seaward shoreface (distance >500 m) occurred over the last year. Future surveys are necessary to confirm this trend in the future.

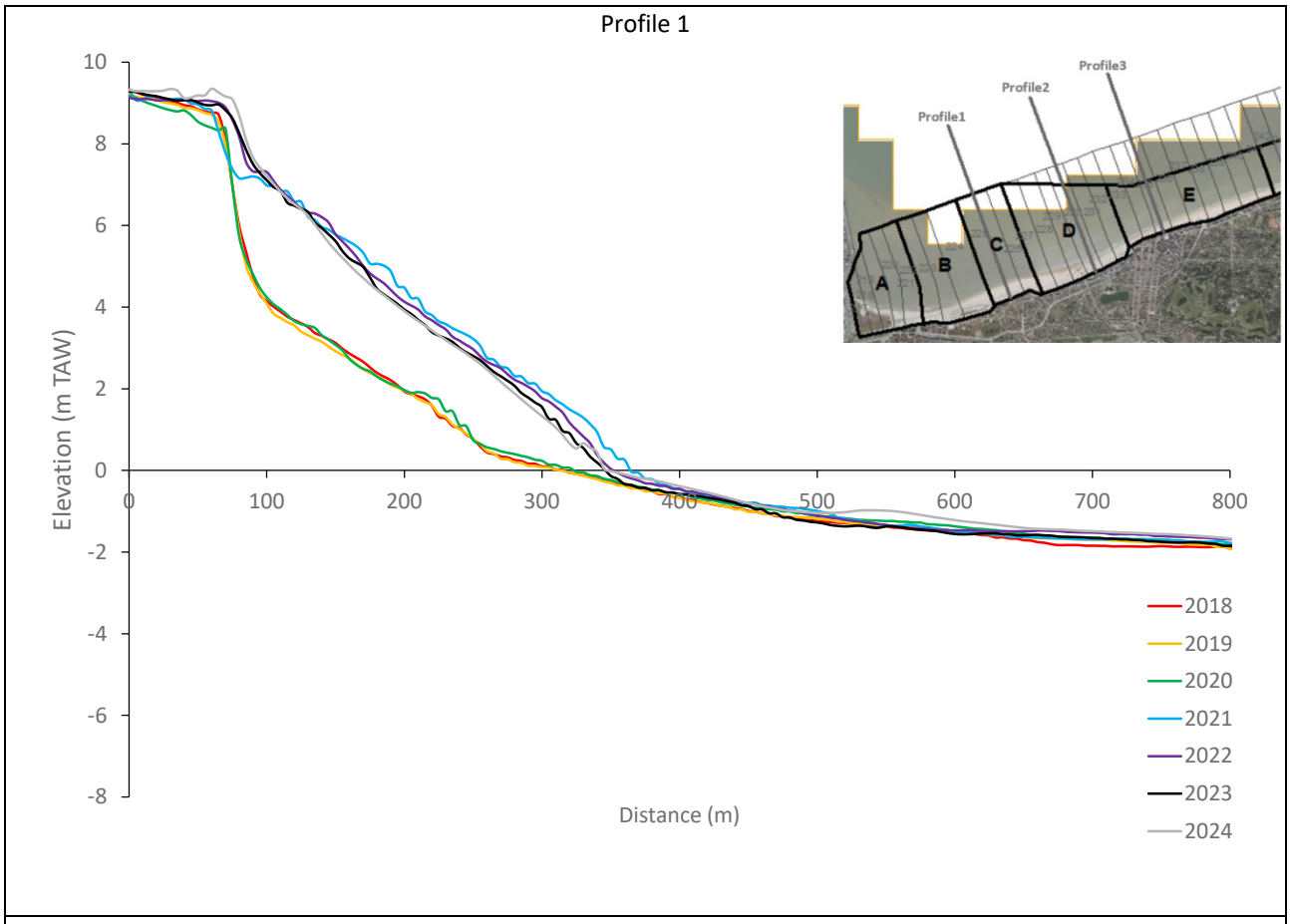
Similar observations apply to section 230 of Albertstrand (Profile 2) between 2018-2020. After the large nourishment in 2021, a small profile change is seen between +0.7 to -2 m TAW, as this profile is right at the eastern tip of the Duinbergen nourished area. Sand nourishments were carried out in Knokke in 2019 and 2020. It is clear that the beach including the backshore and the foreshore till +2.7 m TAW was in 2019 higher than in 2018 and then it has progressively increased over time. The shoreface below +0.5 m shows a gradual accretion from 2018 to 2020 which may be related to the neighboring erosion areas. Generally, the beach-shoreface system gained sand there between 2021-2022 with a maximum difference of height of 1.4 m for the backshore and 0.7 m for the foreshore. This is probably related to the small beach nourishment carried out beginning of 2022 in front of Knokke centrum (section 231-232).

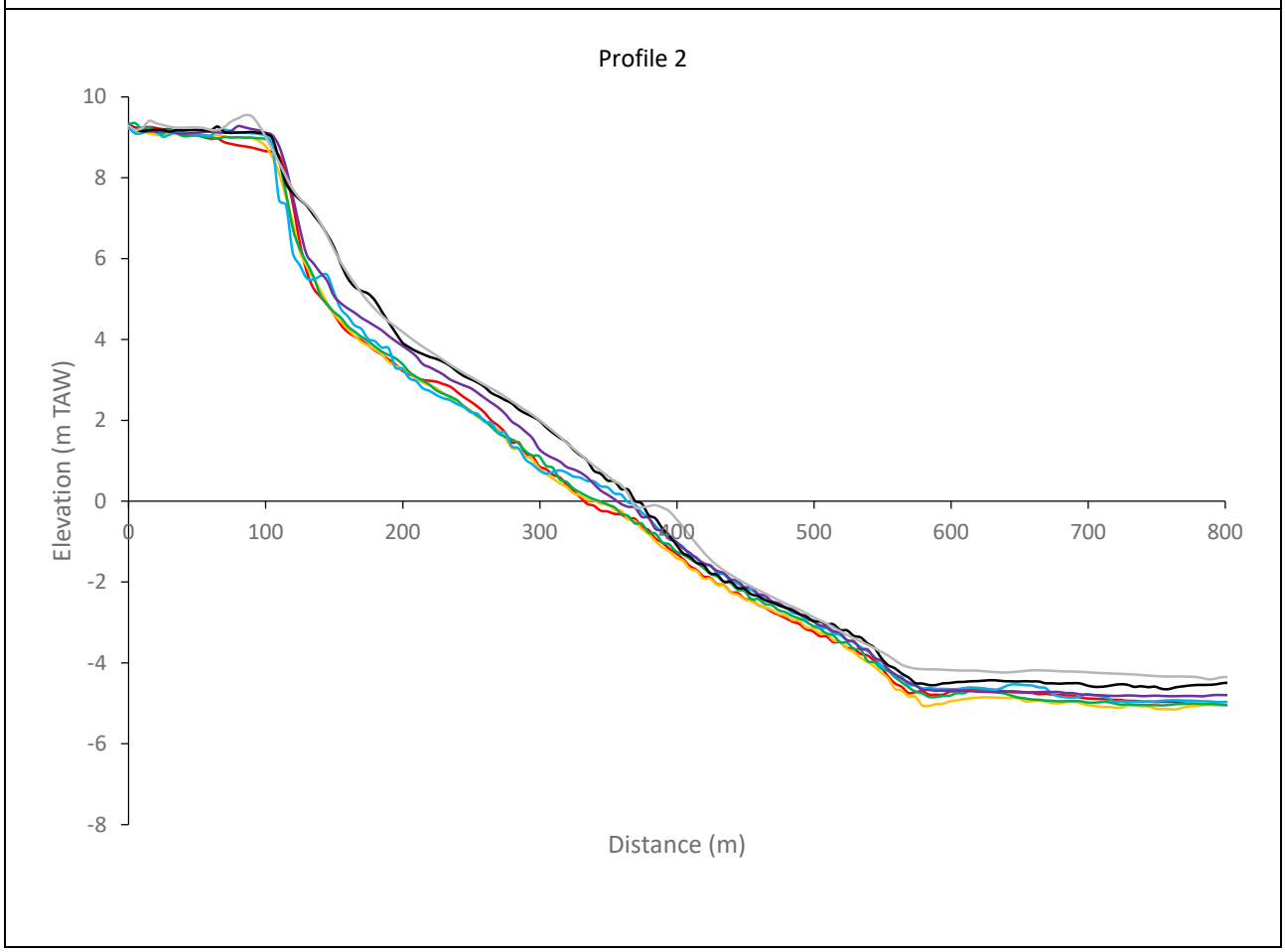
Between 2022-2024, the plateau of the upper-beach did not change while its slope and the rest of the beach-shoreface system reflected the beach nourishment carried out in 02-03/ 2022. The section at the distance 425-500 m was stable compared to an overall gain of 0.5 m high of the lower-shoreface and on the channel floor.

Profile 3 (Knokke-Zoute section 235-240) indicates that the beach lost sand in 2021, whereas the shoreface was stable or slightly gained sand between 250 and 300 m which is possibly related to the small nearshore nourishment in 05-06/2020. Also, we can observe some spatio-temporal variabilities of the seafloor below -6 m TAW. However, a clear landward retreat of the backshore up to 10 m is observed between 2021 and 2022 contrasting with the sand accumulation in the shoreface at a distance between 95-205 and below -6 m TAW. In contrast with the stability of the shoreface from 2022 to 2023, the beach from 5 m TAW to the low water line experienced a significant accretion with a gain up to 0.7 m high and a gentler slope than the previous year thanks to the beach nourishment in Knokke. The effect of the recent large nearshore nourishment is clearly observed in 2024 with an average increase of 1.8 m high in the shoreface from 0 m TAW and also in the deeper zone.

Furthermore, the small scale marine bedform features in 2022 and 2023 are noteworthy in the channel. It is also equally remarkable that the bumps are stationary across the one year time interval between the nearshore surveys of 2022 and 2023. Their origin is likely due to the nearshore nourishment in Knokke carried out in 06/2021 and then visible on the annual bathymetric survey in 2022 and 2023. It is hypothesized that these marine bedform features content clay which would explained their stationarity despite the flow current in the channel reaching relative large velocities. However, these bedforms disappeared in 2024 which was probably due to filling-up after the large nearshore nourishment which is typical a few months after. Finally, it is remarkable to observe a gradual fill of the channel through time, by between 0.5 and 1.3 m over 2018-2024.

As expected, the beach slope in Duinbergen (between 7 m TAW and the low water line) was gentle (2%) after the large beach nourishment in 02-03/2021 (Figure 11, Profile 1). In contrast, the slope of the shoreface was stable over the entire study period. In Albertstrand (Profile 2), the upper-beach slope was steep between 2018 and 2021 while the shoreface slope was gentle and also stable. After the nourishments in 2023, a ramp along the slope of the upper beach was present till 370 m where the slope of the shoreface near the low water line was slightly steeper. Interestingly, a bar of 1 m high was formed at 390 m. The beach nourishment in 2023 caused an increase of the elevation of the beach and gentle the slope. While the shoreface slope was relatively steep until 2023 in contrast to the other profiles. In parallel to an advance seaward of the shoreface, its mild slope (3%) was stable after the large nearshore nourishment in 2024.


Profile 1
Elevation (m TAW)
Distance (m)
Profile1
Profile2
Profile3
A
B
C
D
E
2018
2019
2020
2021
2022
2023
2024


Profile 2
Elevation (m TAW)
Distance (m)

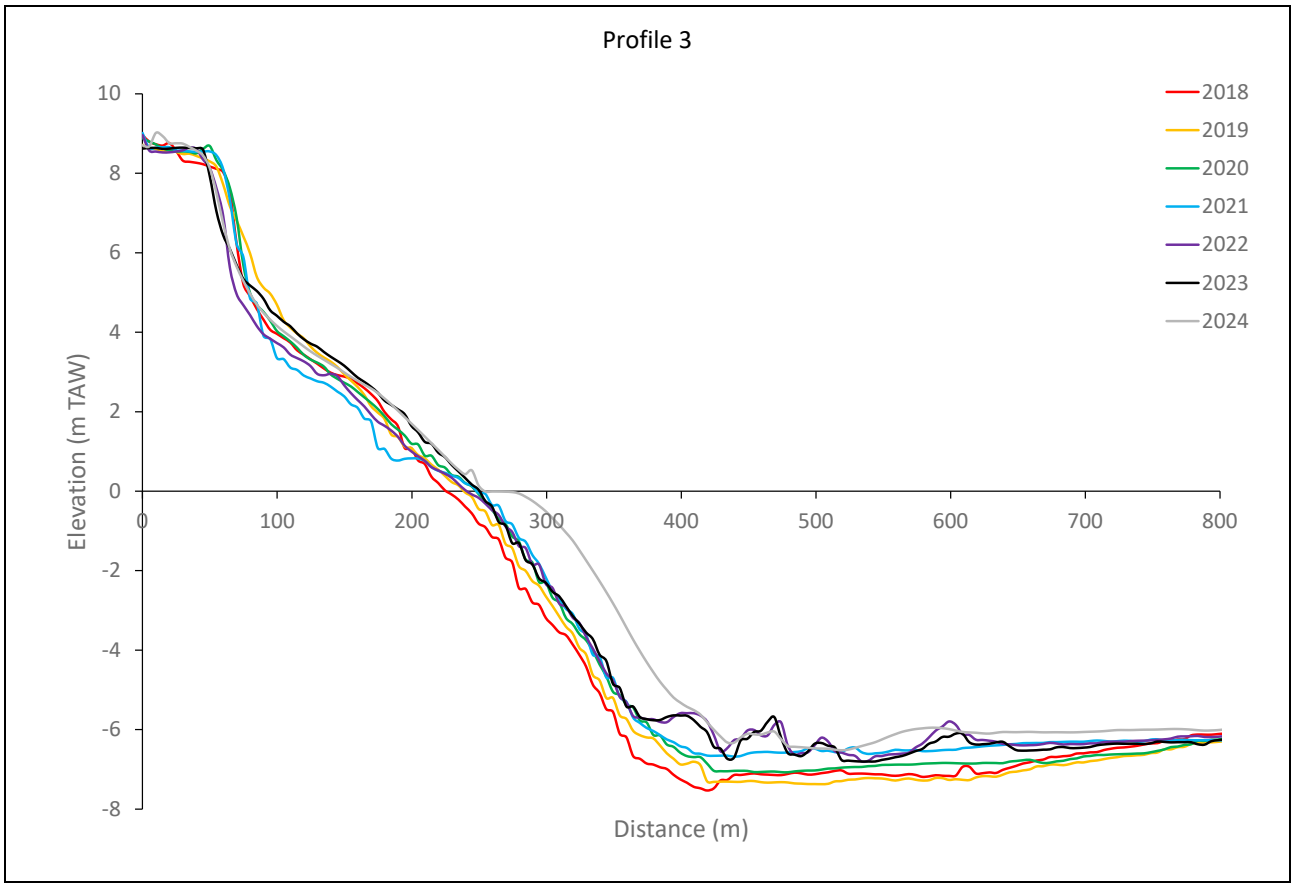


Figure 11 – Cross-shore profiles (Profile 1 in section 225, Profile 2 in section 230 and Profile 3 in section 235) extracted from the LiDAR surveys at Duinbergen.

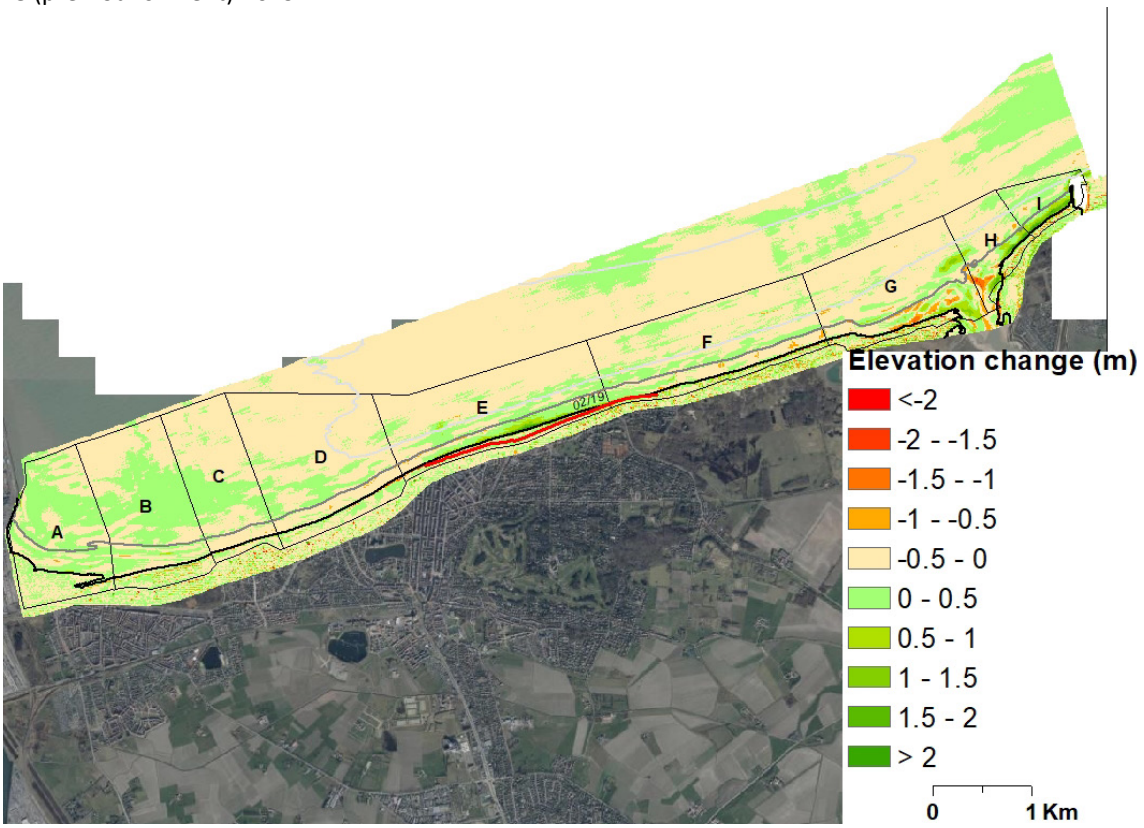
The DoD time series in Figure 12 shows an initial growth of the shoreface between 2019 and 2020, of which the only nearby source would be the erosion of the backshore berm in zone E. Most of the accretion happened between 2020 and 2024. A clear accretion on the beach concentrated above +3 m TAW and extended alongshore for 2.1 km (Figure 12). From the sand supply nourished in 02-03/2019 (Table 2) in sections 234-243 (Knokke-Zoute, zone E, and Lekkerbek, zone F) is observed on the DoD between pre-nourishment in 2018 and 2019 (Figure 13). In contrast, where no human intervention was carried out, a narrow corridor of significant erosion (elevation change > 0.5 m) with a width of 20 m and a length of 0.5 km characterized the section 232-233 (Albertstrand, zone D and Knokke-Zoute, zone E).

Between 2019 and 2020, negative morphological change occurred in zone E where the early 2019 beach nourishment was carried out (Figure 12B) suggesting that a part of the supplied sand was removed in one year. At the same time, the upper part of the shoreface gained some sand material. The accretion strip faces the beach erosion zone, while more spread out and shifted somewhat to the east at the same time.

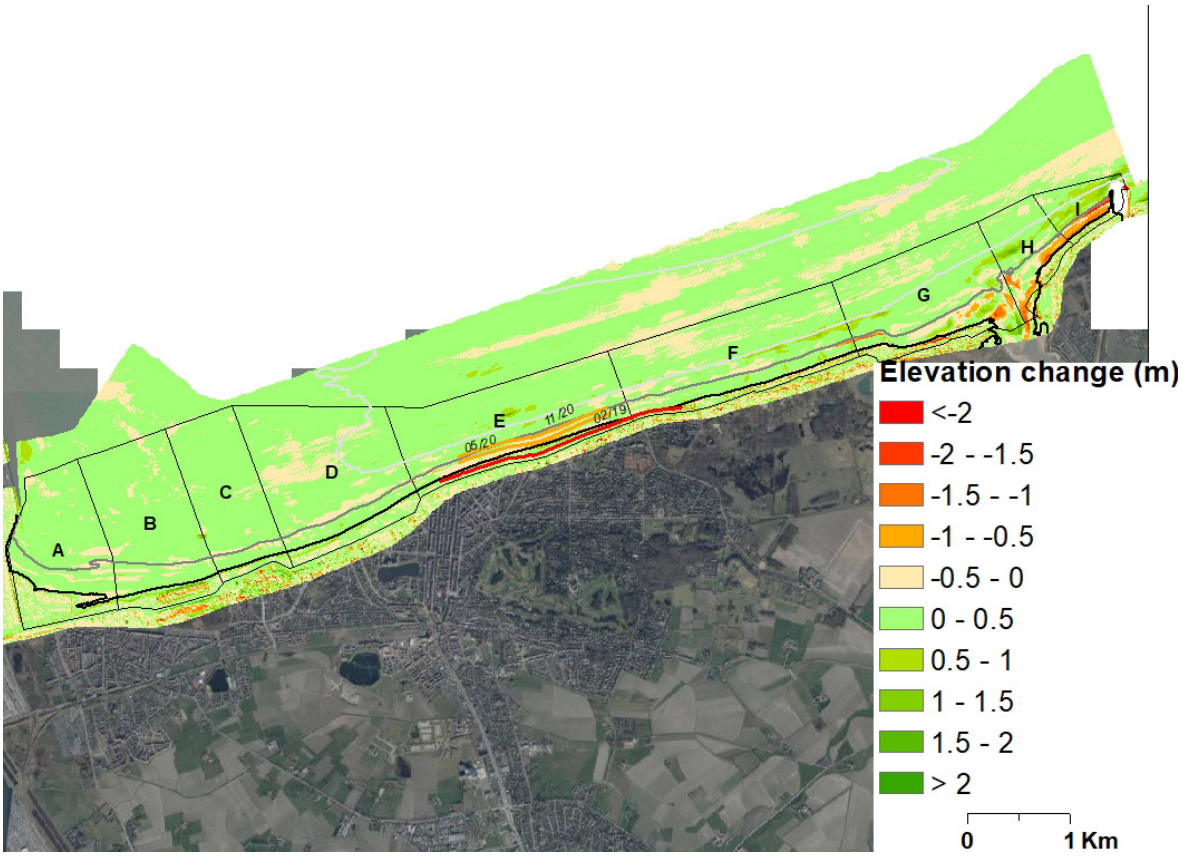
A dominant action of cross-shore transport processes affecting the beach at high tide can be inferred. The DoD between 2020-2021 shows the effect of the large beach nourishment in Duinbergen in sections 223-230 (Heist-east to Alberstrand, zones B to D) in 02-03/2021. There, a 2 km long accretion area with its long axis situated in the complete foreshore and the upper shoreface between +1 and 0 m TAW (2018) is observed with a maximum positive elevation change of nearly 3 m. The substantial nourishments buried the groynes. An opposite trend characterized Knokke-Zoute (zone E) with a dominance of erosion on the beach and the upper part of the shoreface. Most of the shoreface in this zone experienced a slight and spread-out accretion which likely constitutes a deposit sourced from the beach erosion.

Generally, the backshore experienced accretion between 2021 and 2022, except at Knokke-Zoute where a 2 km long erosion strip is located at 125 m from the dyke. This erosion of the backshore concentrated on the berm is likely caused by an individual or consecutive storms. In addition, sand accumulation was observed in the foreshore, while the shoreface was stable over this period. Localized accretion occurred on the seabed, such as shown in Profile 3. The DoD between 2022-2023 displays the nourishment in Knokke carried out in 2023 with an accretion up to 2.2 m high and spread in Zone D and E. In contrast, the shoreface in zone E experienced erosion the landward of the Appelzak. Thus, there was a counter morphological behaviour between the beach and the shoreface. The rest of the beach-shoreface system was relatively stable of this period. Sand gains up to 2.5 m occurred in the shoreface from the low water line to the landward of the Appelzak and between the east side of Zone D to the west side of zone F. These reflect the location of the dumping zones during the recent large nearshore nourishment in 2023-2024 (Figure 8). After 2 months, no spreading seems to happen. Also, accretion is observed in the center of Appelzak around -6.6 m TAW with the largest gain in section 240-241. In contrast, the beach experienced sand loss along a corridor of 120 m wide between 6 m to 2.5 m TAW along the section of 231-244 (Zone east of D, E and west of F).

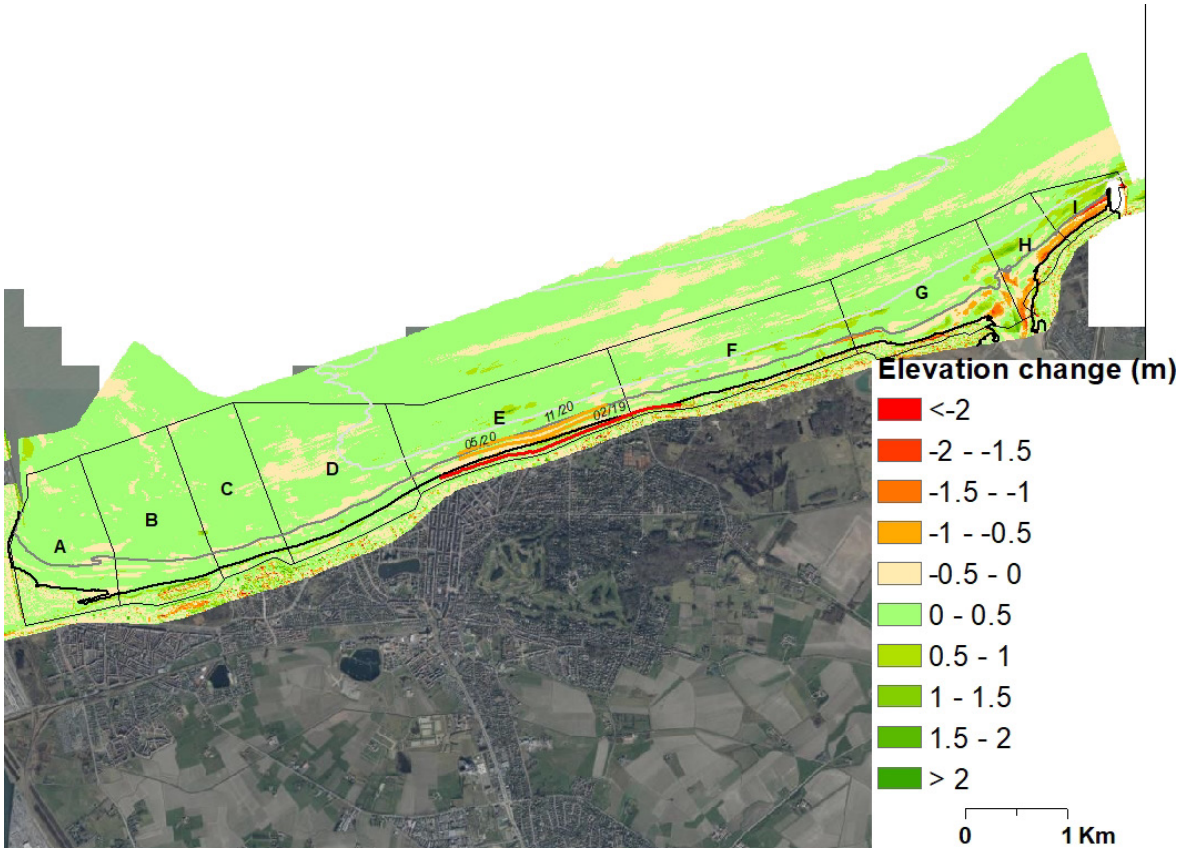
A) 2018 (pre-nourishment)-2019



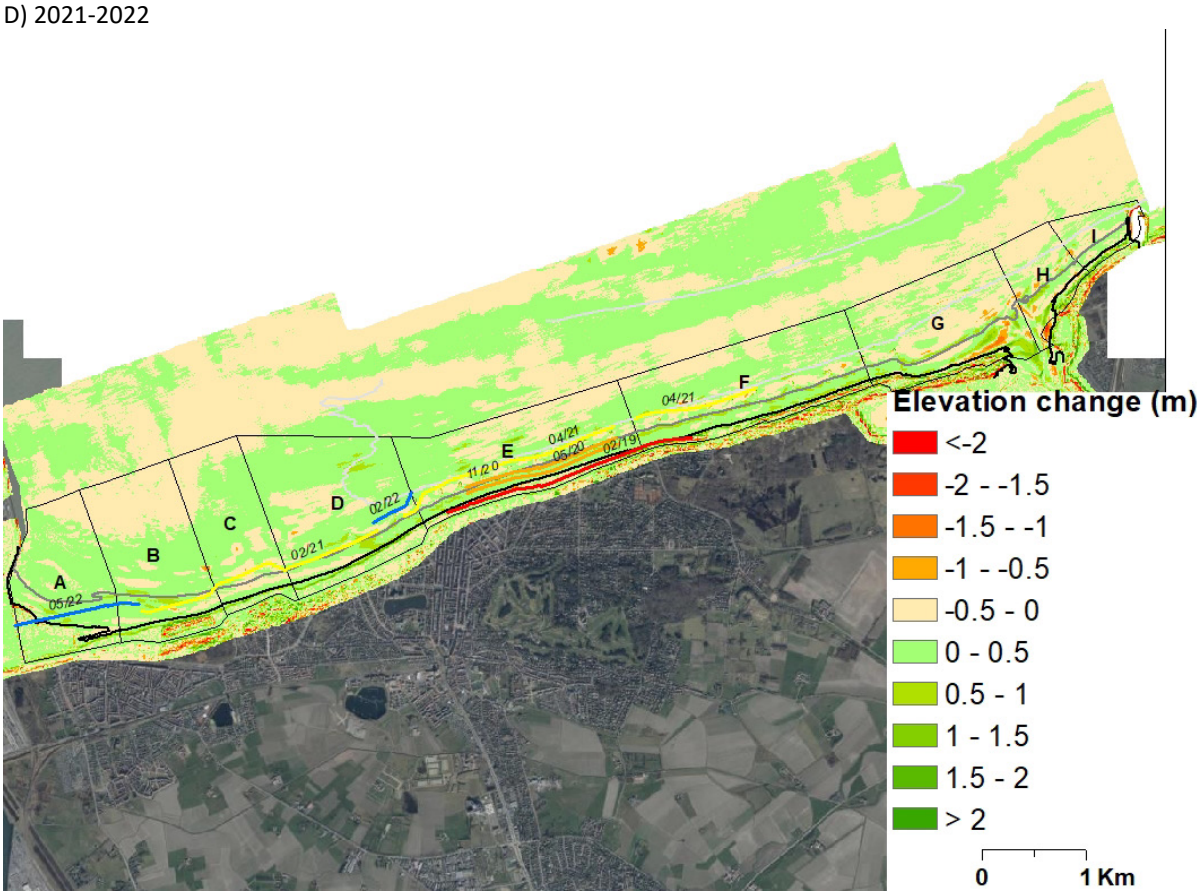
B) 2019-2020



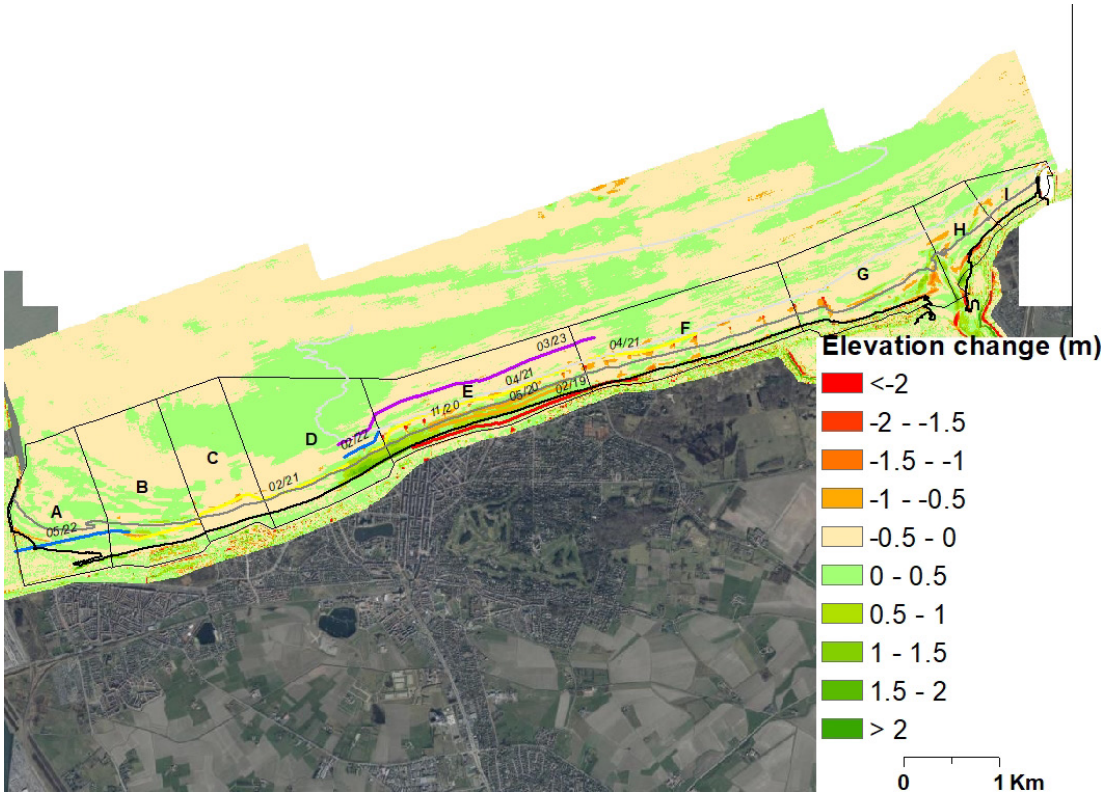
C) 2020-2021



D) 2021-2022



E) 2022-2023



F) 2023-2024

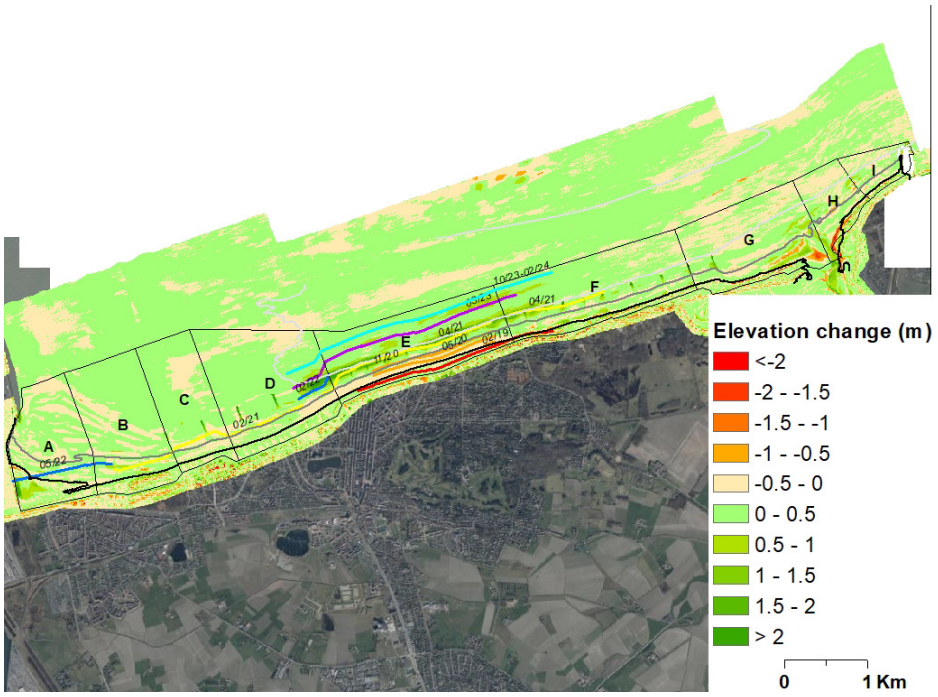
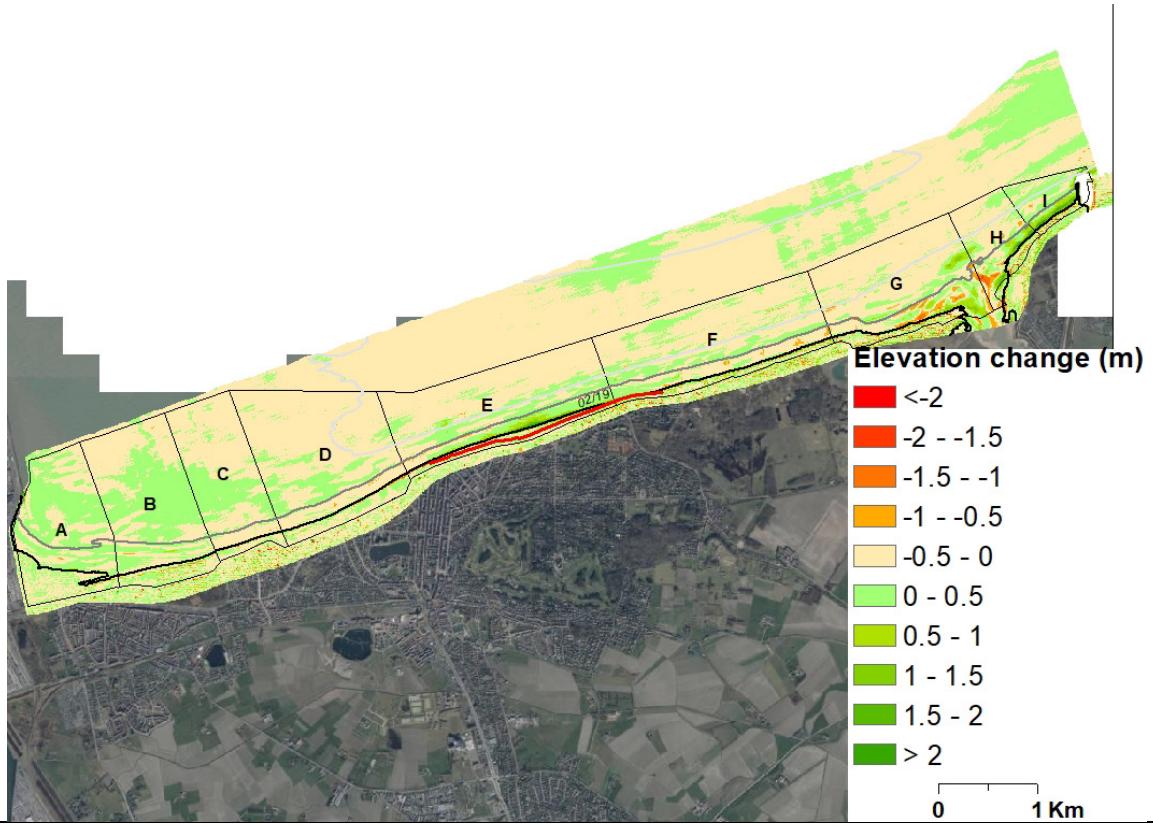
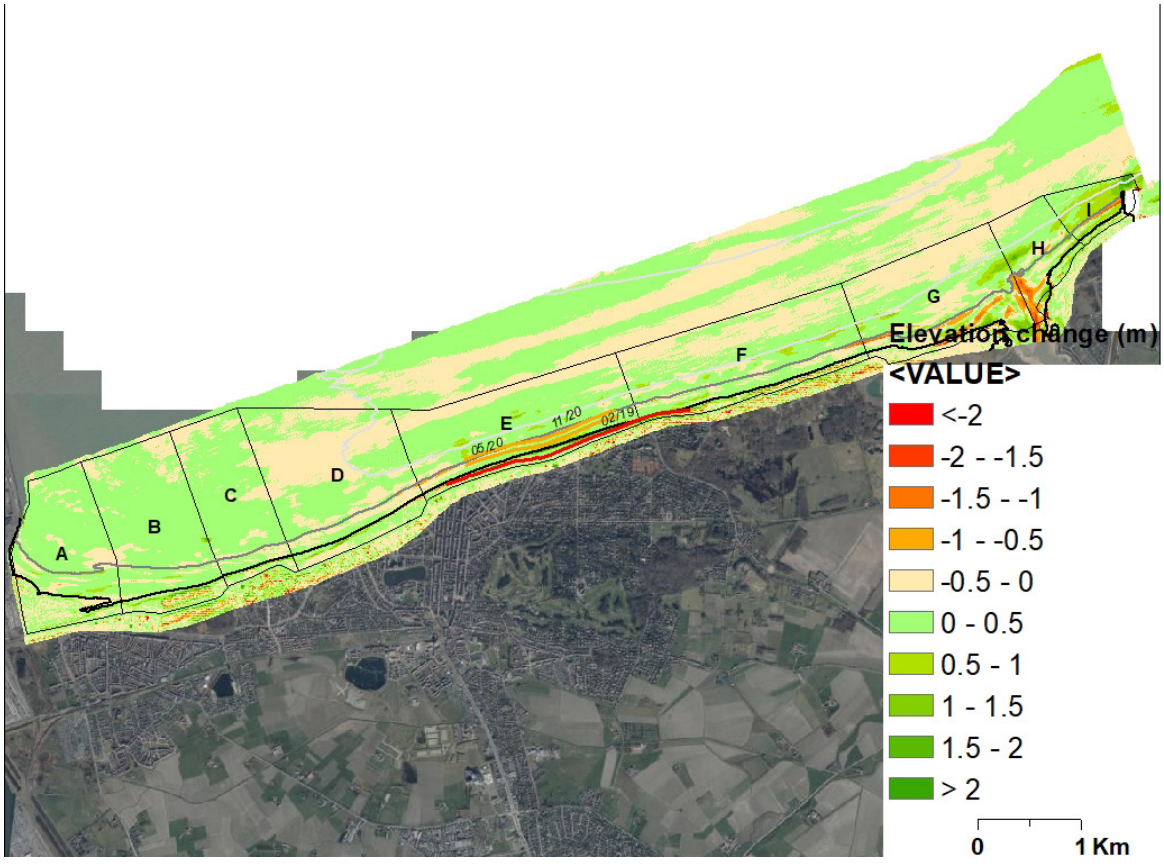


Figure 12 – Consecutive DoDs of difference of the merged beach and shoreface with indications of the nourishment locations. Black, dark grey and light grey correspond to +5, 1.39 and -5 m TAW in 2018.

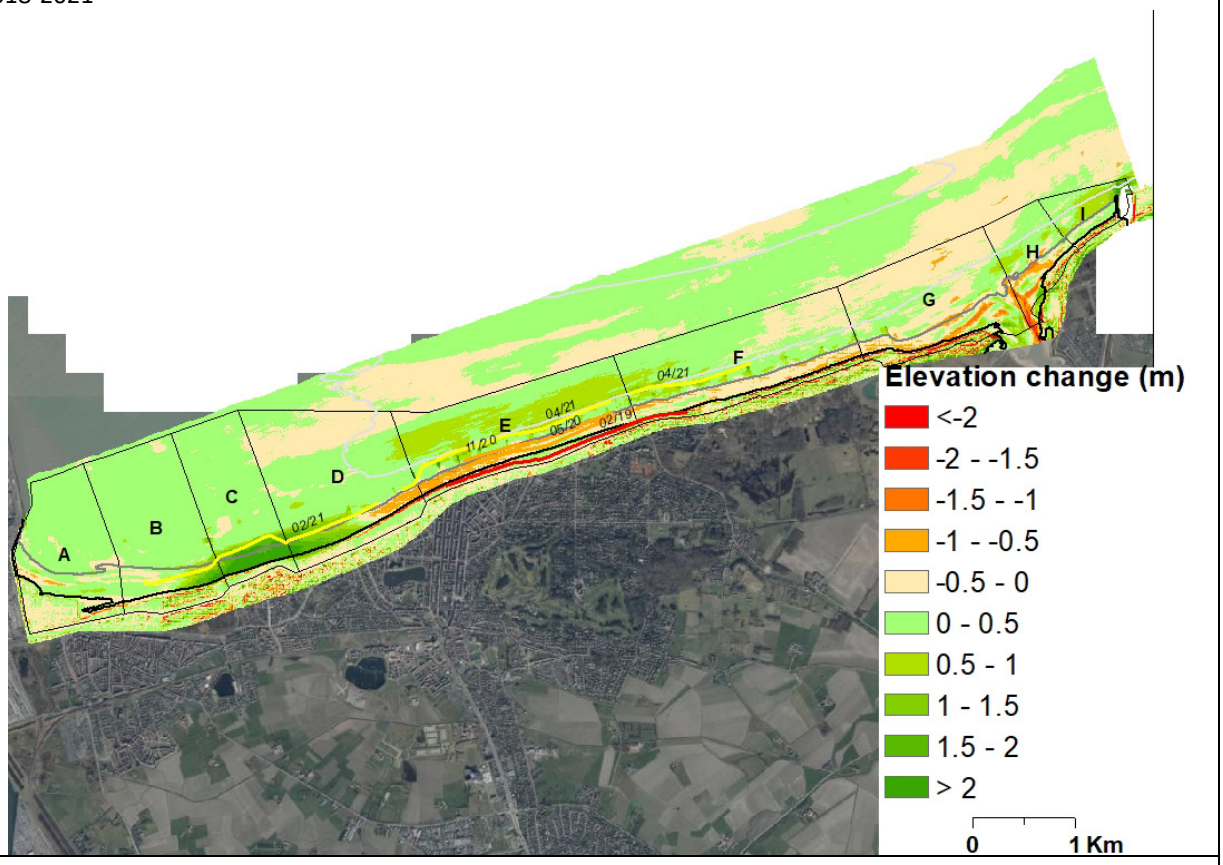
A) 2018-2019



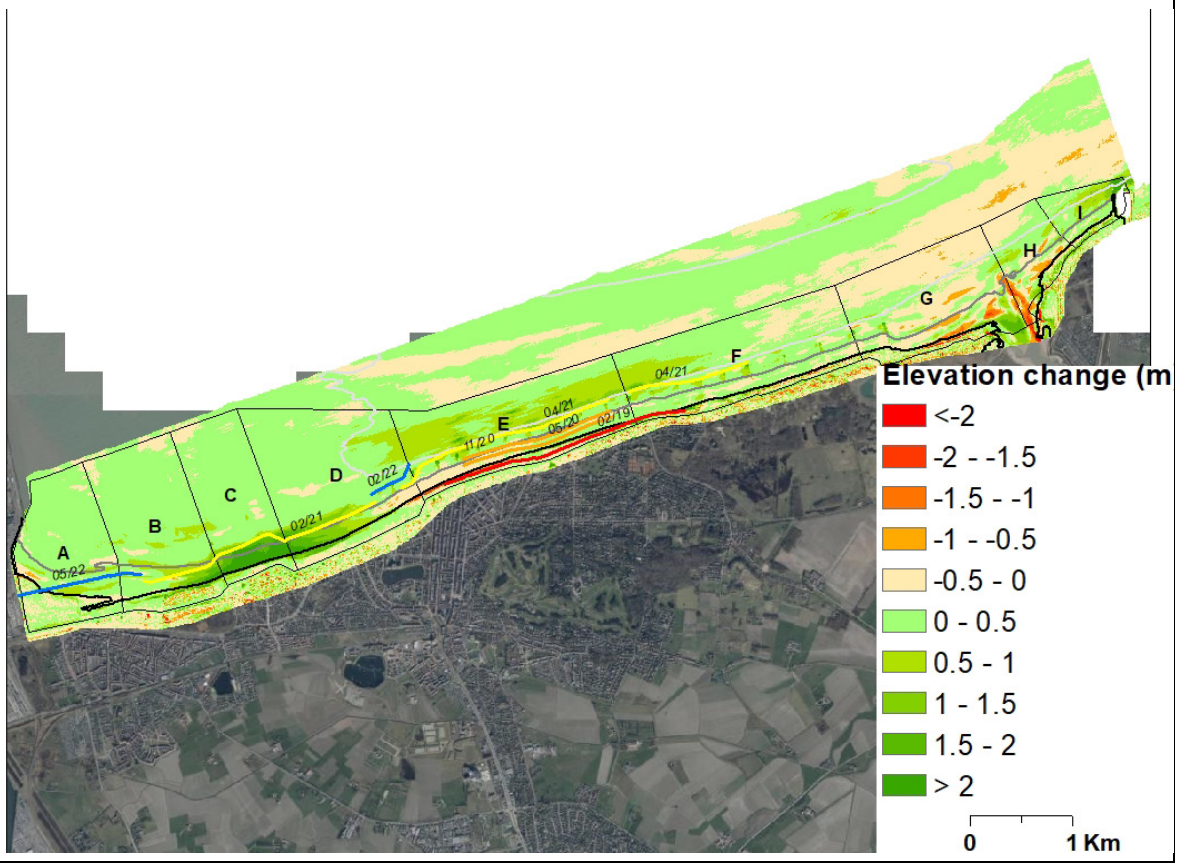
B) 2018-2020



C) 2018-2021



D) 2018-2022



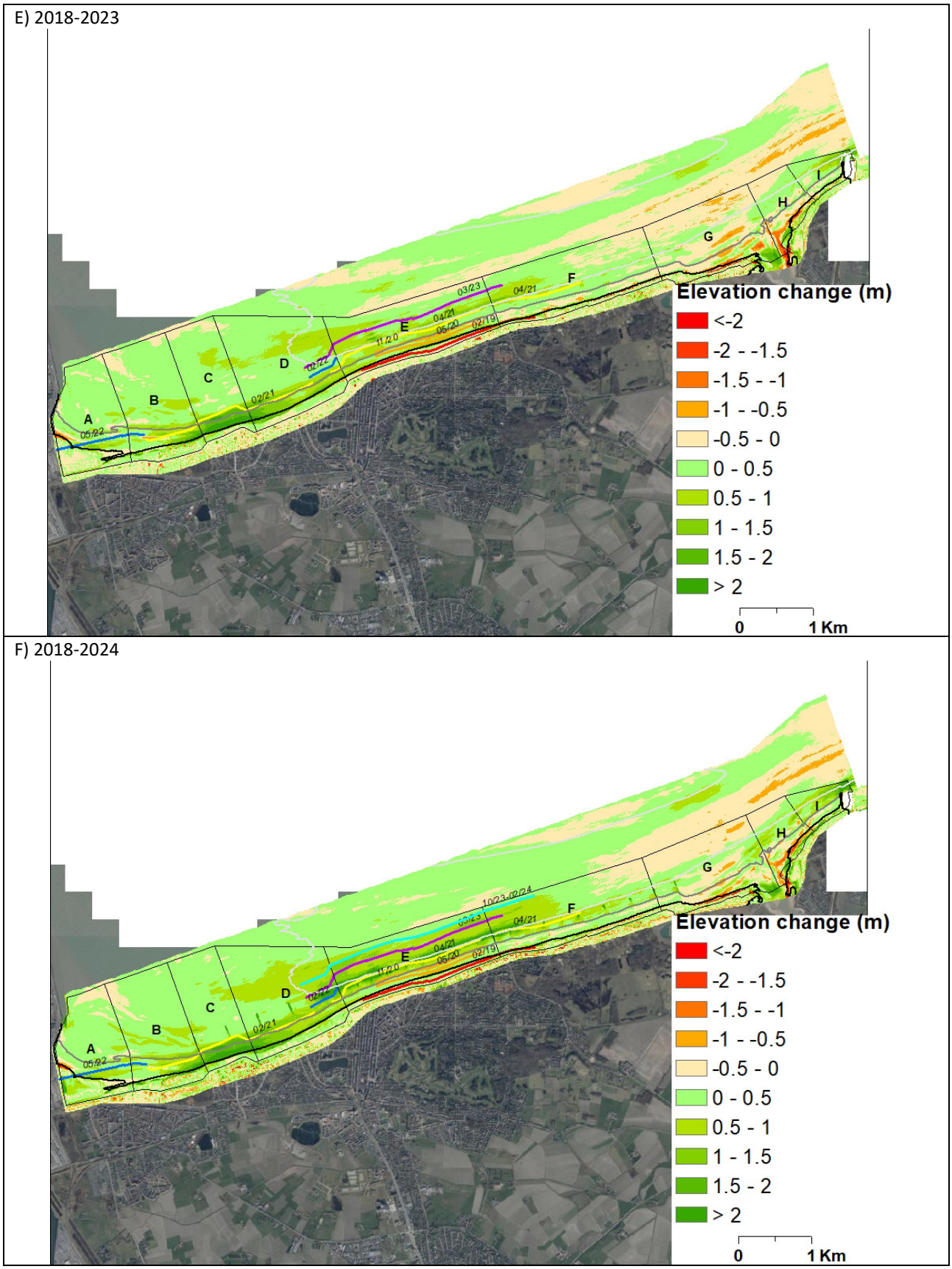


Figure 13 – DoDs of the merged beach and shoreface from the reference survey in 2018 with indications of the nourishment locations. Black, dark grey and light grey correspond to +5, 1.39 and -5 m TAW in 2018.

The DoDs referred to the pre-nourishment 2018 survey confirm the previous observations (Figure 13). The large nearshore nourishment in Duinbergen in 02-03/2021 had an accretive effect on the foreshore from +5 m TAW to the upper part of the shoreface (130 m from the +1.39 m TAW contour line) and extended from section 224 to 229 (zone B to D, Figure 8C). In contrast, eastward of this part of the coast, negative morphological changes dominated on the foreshore in sections 231 to 236 (zone D and E). The shoreface showed no change or slight accretion from Duinbergen to the middle of Lekkerbek zone (zone B to F). The accretional area of the shoreface in zone E suggests a supply from the nearby erosional beach in zones D and E. These accretional areas spread in alongshore direction (both west and eastward) as displayed on the DoD between 2018-2023. Zwin and Cadzand-west experienced a high spatial and temporal variability which are reported in Montreuil et al. (2021). Between 2018 and 2022, the beach for Zones D (east side) and E (from 8 to 0 m TAW) was in erosion while opposite trend occurred in 2023 due to the beach nourishment in Knokke. The sand supply seems to not have spread out in alongshore since most of the material was still located between section 230-241 after 3 months. The accretion is there further enlarged by the large nearshore nourishment between October 2023-February 2024. After 2 months, no spreading seems to have happened. However, a long-term eastward spreading of sand material up to 1.6 km long occurred and was concentrated landward of -5 m contour line. This emphasizes the importance of littoral drift in disseminating sand along the coast. In addition, the seabed up to -6 m TAW experienced long-term accretion along Zone D and E.

The volume changes in the backshore and foreshore of zones E and F (Knokke-Zoute and Lekkerbek) were mostly positive between 2018-2019 thanks to the beach nourishment of 292 502 m^3 carried out there on 02-03/2019 (Table 5 and Table 6). However, the sand supplied artificially on the beach there was removed in two years and it was partly transported to the shoreface by cross-shore processes. In 2023, zone E was in accretion due to the beach nourishment of 510 574 m^3 in the beginning of that year. The observed accretion was +177 850 m^3 (+/- 33 000 m^3) on the beach. A part may have also fed zone D, but the observed volume increase was much less than the supplied volume in zone E.

A loss of sediment for the foreshore of zone C and D, in Duinbergen and Alberstrand, was observed between 2018 and 2019, by around -12 520 m^3 and -33 020 m^3, equivalent to a decrease of elevation of around -0.12 m and -0.16 m, respectively. Between 2018-2019, the shoreface did not show significant change along the whole study coast. Both backshore and foreshore gained sand material from zone B to D between 2019-2020. A small beach nourishment of 14 800 m^3 took place in 05-06/2019 in zone E where the sediment budget of the backshore was slightly positive. Nevertheless, its foreshore where most of the sand supply was deposited experienced an erosion of -47 450 m^3 equivalent to a decrease of elevation around -0.17 m. This might suggest that in 10 months, the nourished sand was removed and transported. The foreshore of zones H and I were subjected to erosion which was probably related to natural processes occurring in the Zwin inlet system and erosion following the sand nourishment done in Cadzand in 2019.

The effect of the large beach nourishment of 982 000 m^3 in 02-03/2021 from zone B to D is clearly reflected in the volumes where a total accretion of 498 000 m^3 and 480 000 m^3 over the entire beach and in the shoreface along these zones, respectively, was observed. This suggests that not much sand material was lost a couple of months after the completion of the nourishment. The period from 2021-2022 was still characterized by positive volumetric changes and thus no material was lost one year after the large nourishment. In addition, a small alongshore spreading of the sediment occurred inside the nourished zone.

In zone E, where a small nearshore nourishment took place in 11-12/2020 but none in 02-03/2021, the beach suffered erosion (-168 340 m^3) whereas its shoreface gained material (326 720 m^3). This significant sand gain can partly be explained by the nearshore nourishment carried out in 05-06/2021 and end of 2021 in section 235-240 (+145 000 m^3). Also, it might have been partly fed by alongshore transport from the westward beach nourished zones in section 223-230 where a large artificial sand supply had been carried out.

There, the rest of the shoreface did not show any change. The beach in zone D and E gained 94 650 m^3 and 177 850 m^3 respectively (equivalent to an elevation gain of 0.24 m and 0.38 m) between 2022-2023 thanks to the nourishment in the beginning of 2023. In contrast, the beach in zone C experienced erosion of - 14 810 m^3, equivalent to a decrease of -0.09 m in height. The DoD between 2022-2023 indicates that the sand loss was spread in the foreshore and also the upper-shoreface. The shoreface along the entire study site was stable between 2022-2023.

A total of 2 180 120 m^3 in Zone E and F were observed 2 months after the recent large nearshore nourishment. This corresponds to an increase of 0.18 m^3/m^2. As observed on the DoD (Figure 12), the foreshore between 6 and 2.5 m TAW experienced a stability and sand loss in Zone E and F respectively. In contrast, accumulation dominated in the backshore with a gain of 45 470 m^3, corresponding to an increase of 0.14 m^3/m^2 over one year. This may probably result from natural processes of the littoral drift transporting sand there from the westward nourished zones.

From 2018 to 2021, the beach volume of the entire study site (zone A-I) was stable while it was positive from 2022 to 2024 thanks to the frequent nourishments. Regarding the shoreface for the entire study site, a stability dominated, although a slight accretion took place in the last year of the monitoring program, due to the large nourishment done at the end of 2023 and begin 2024.

Table 5 – Consecutive sediment budgets of the delimited zones of the backshore and beach from 2018 to 2024. Red and green colour indicates significant negative or positive differences respectively while no colour values are not significant.

		Volume (m^3)									Volume (m^3)						
Layer	Zone	2018-2019	2019-2020	2020-2021	2021-2022	2022-2023	2023-2024	*Uncertainty (+/-m^3)*	Layer	Zone	2018-2019	2019-2020	2020-2021	2021-2022	2022-2023	2023-2024	*Uncertainty (+/-m^3)*
Backshore	A	-8 260	16 150	-17 420	25 300	6 450	67 600	*19 940*	Foreshore	A	9040	26240	360	37780	5540	14280	18920
	B	-2 980	23 680	-1 340	25 640	6 470	16 300	*11 800*		B	740	21920	93090	34400	-80	21280	16600
	C	-2 990	6 360	12 880	12 080	3 920	5 460	*4 540*		C	-12520	10150	244070	-6180	-18730	1670	7120
	D	-9 500	15 620	6 330	35 940	20 150	23 800	*13 950*		D	-33020	19380	142980	25860	74500	4110	14240
	E	32 240	13 480	-35 500	-22 400	19 690	26 280	*13 000*		E	94180	-47450	-132840	57370	158160	-31140	19940
	F	12 270	-5 470	-13 930	14 910	-2 630	19 190	*10 360*		F	-22300	31340	-73050	78690	-9350	25200	22680
	G	-4 440	7 880	-22 490	38 350	540	-10 850	*10 730*		G	-35860	-18420	-23130	22500	-18880	29910	21440
	H	2 450	-21 430	-13 490	10 270	-4 280	8 030	*5 020*		H	15400	-51340	-27670	11100	-7570	2480	10160
	I	-2 690	6 470	-13 610	10 570	-500	7 330	*2 430*		I	62410	-71970	27030	-4190	-9920	160	5180
	Total	16 100	62 740	-98 570	150 660	49 810	163 140	91 770		Total	78070	-80150	250840	257330	173670	67950	18920

Table 6 – Consecutive sediment budgets of the delimited zones of the foreshore and shoreface from 2018 to 2024. Red and green colour indicates significant negative or positive differences respectively while no colour values are not significant.

		Volume (m^3)									Volume (m^3)						
Layer	Zone	2018-2019	2019-2020	2020-2021	2021-2022	2022-2023	2023-2024	*Uncertainty (+/-m^3)*	Layer	Zone	2018-2019	2019-2020	2020-2021	2021-2022	2022-2023	2023-2024	*Uncertainty (+/-m^3)*
Beach	A	780	42 390	-17 060	63 080	11 990	14 280	*38 860*	Shoreface	A	10 990	57 260	50 970	23 350	-6 510	20 800	*151 580*
	B	-2 240	45 600	91 750	60 040	6 390	21 280	*28 400*		B	7 390	122 210	107 750	19 690	-23 960	76 950	*236 950*
	C	-15 510	16 510	256 950	5 900	-14 810	1 670	*11 660*		C	-12 120	96 800	172 510	11 070	11 710	73 070	*202 290*
	D	-42 520	35 000	149 310	61 800	94 650	4 110	*28 190*		D	-118 970	135 690	241 310	168 530	205 890	299 540	*325 900*
	E	126 420	-33 970	-168 340	34 970	177 850	-31 140	*32 940*		E	-117 360	353 580	326 720	88 090	-112 380	759 270	*276 010*
	F	-10 030	25 870	-86 980	93 600	-11 980	25 200	*33 040*		F	-79 570	177 080	155 760	57 200	-76 340	357 390	*284 510*
	G	-40 300	-10 540	-45 620	60 850	-18 340	29 910	*32 170*		G	-112 690	99 620	-107 590	-23 470	-75 290	69 800	*228 570*
	H	17 850	-72 770	-41 160	21 370	-11 850	2 480	*15 180*		H	-20 760	56 260	-5 650	-17 470	-10 500	23 610	*72 030*
	I	59 720	-65 500	13 420	6 380	-10 420	160	*7 610*		I	21 840	76 190	44 860	2 320	-14 680	37 510	*45 800*
	Total	94 170	-17 410	152 270	407 990	223 480	67 950	228 050		Total	-421 250	1 174 690	986 640	329 310	-102 060	1 717 940	1 823 640

Notes: Beach is a sum-up of the backshore and foreshore.
Error corresponds to the uncertainty on elevation difference estimated to be 0.07 m for the LiDAR and 0.21 m for the shoreface surveys. Uncertainty was determined according to Wheaton et al., (2008). Backshore limit: dyke to 5 m TAW, Foreshore: 5 m to 1.39 m TAW, Shoreface: 1.39 m to -5 m TAW.

Volumetric analysis indicates that the Duinbergen 2021 nourished beach area only lost 14 370 m^3 of sediment between 2021 and 2022 and about 72 000 m^3 between 2022 and 2023 (Table 7 and

Figure 14). Then a slight accretion of 20 950 m^3 took place in 2024. The loss of measured increase of the Duinbergen nourishment in 2021 (981 821m^3) was of 7% after nearly 3 years (see “Nourished Duinbergen": (-14370 -72440+20950= -65 860 m^3 (2021-2024) ". This may be even larger, because some erosion may already have occurred between the completion of the nourishment and the LiDAR and nearshore surveys in 2021.

Knokke (Zone E) and the neighbouring part of Alberstrand (Zone D) are liable to erosion. To counteract it, a beach nourishment of 510 574 m^3 was done in these zones in 02-04/2023. The loss of measured increase was about 29% of the sand supplied in these zones after 9 months see “Nourished Knokke": 339160 +25800 = 364 960 m^3, 2022-2024) The lost sand material might be partly transported to the shoreface by cross-shore processes and then partly evacuated from the Appelzak by tidal currents. Another part was probably further transported to the adjacent coast by the eastward littoral drift. Also, the nourished sand in Duinbergen has probably supplied the beach in Knokke as hinted by the observed attachment of the accretive zones (section, Figure 13F). The first signs of beach erosion after the beach nourishment at Knokke and Albertstrand are already observed in the LiDAR survey in 01/2024.

It can for now be concluded that the two large beach nourishments suffered less intense beach erosion than at previous nourishments, since most of the sand is still present mid-2024. However, the observation period is smaller than a year at Knokke-Zoute. From the reference DoDs (Figure 13), an alongshore spreading of the nourishments can be observed eastward but also westward.

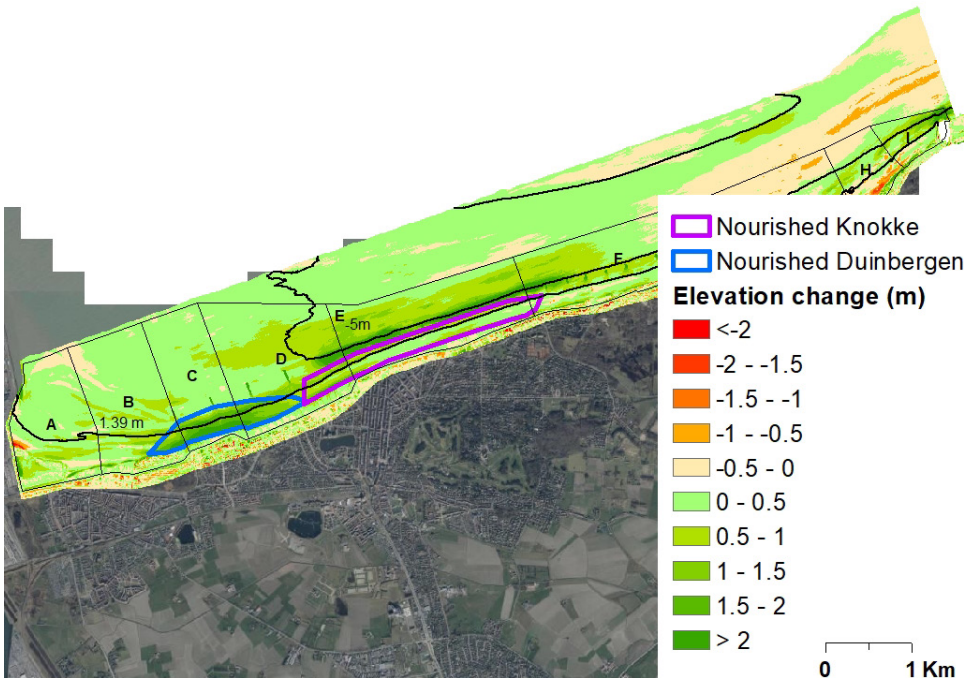


Figure 14 – Delimitation of the observed beach nourished areas of Duinbergen and Knokke on the DoD 2018-2024. The black contour lines correspond to 1.39 m and -5 m TAW respectively in 2024.

Table 7 – Sediment budgets of the beach nourished aeras from 2018 to 2024. Values in bracket correspond to the volume in $m^3/m^2/y$. Red and green colours indicate significant negative or positive trends respectively and no colour values are not significant.

	Volume (m^3)						
	2018-2019	2019-2020	2020-2021	2021-2022	2022-2023	2023-2024	Uncertainty (m^3)
Duinbergen 2021Nourished area	-27700 (-0.06)	51550 (0.11)	731300 (1.62)	-14370 (-0.03)	-72440 (-0.16)	20950 (0.04)	31660
Knokke 2023 Nourished area	85170 (0.14)	-1120 (0)	-186300 (-0.30)	79030 (0.13)	339160 (0.54)	25800 (0.04)	43630

Notes:
Values in brackets indicate sand budget (m^3/m^2).
Error corresponds to the uncertainty on elevation difference estimated to be 0.07 m for the LiDAR and 0.21 m for the shoreface surveys. Uncertainty was determined according to Wheaton et al., (2008).

5.3 Monthly morphological changes of the large nearshore nourishment

Pre-, during and post-nourishment surveys were carried out from 10/2023 to 06/2024. The surveys in 10/2023 and 04/2024 were acquired by DEME. The beach and the shoreface were surveyed by UAV and multibeam method respectively. The UAV and MB in 10/2023 did not overlap in the shoreface (i.e. gaps ranging from 20 to 170 m) are so that a linear interpolation was applied to generate DEM (Figure 15). This seems to be a good approximation of the topography.

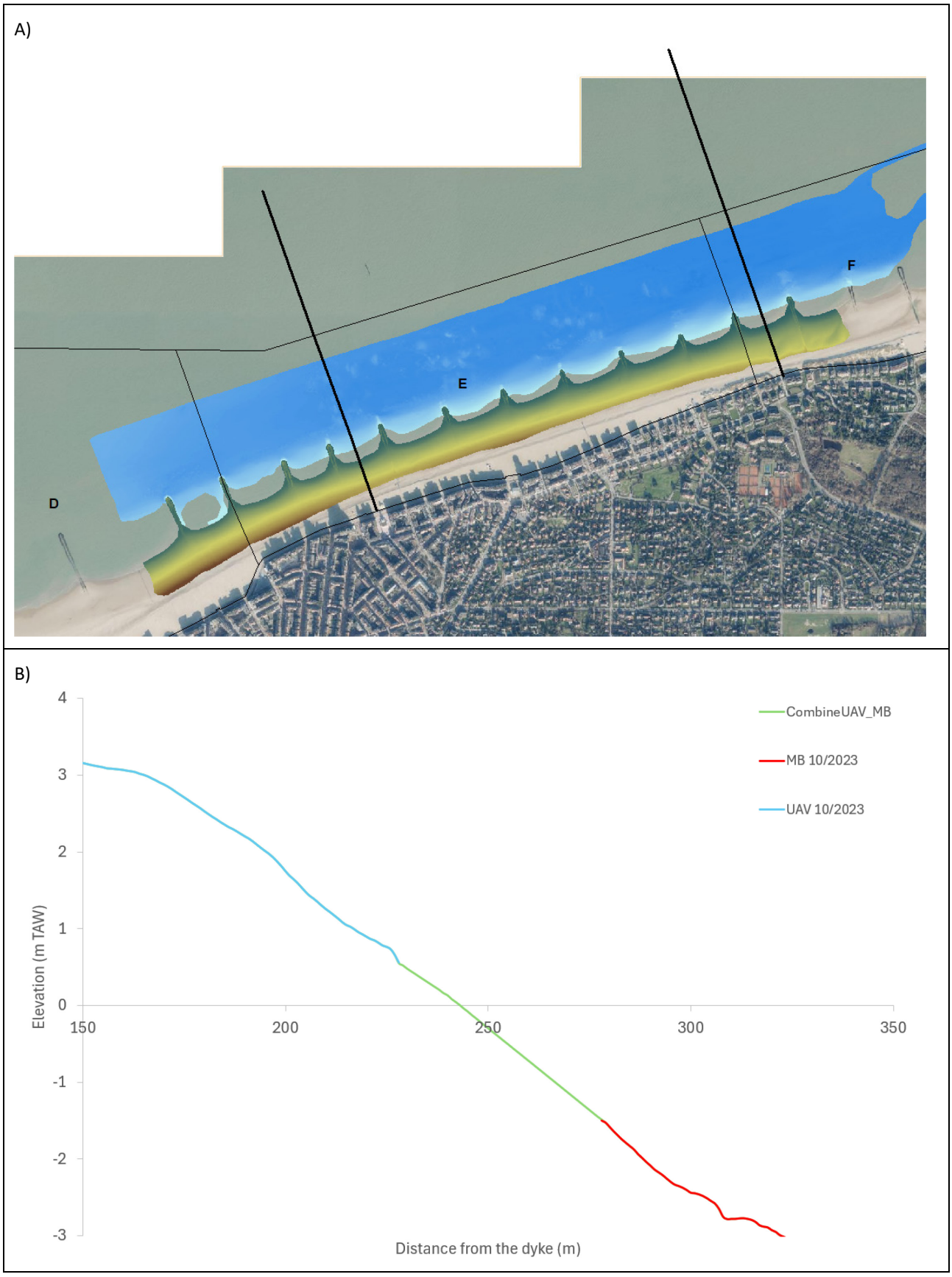
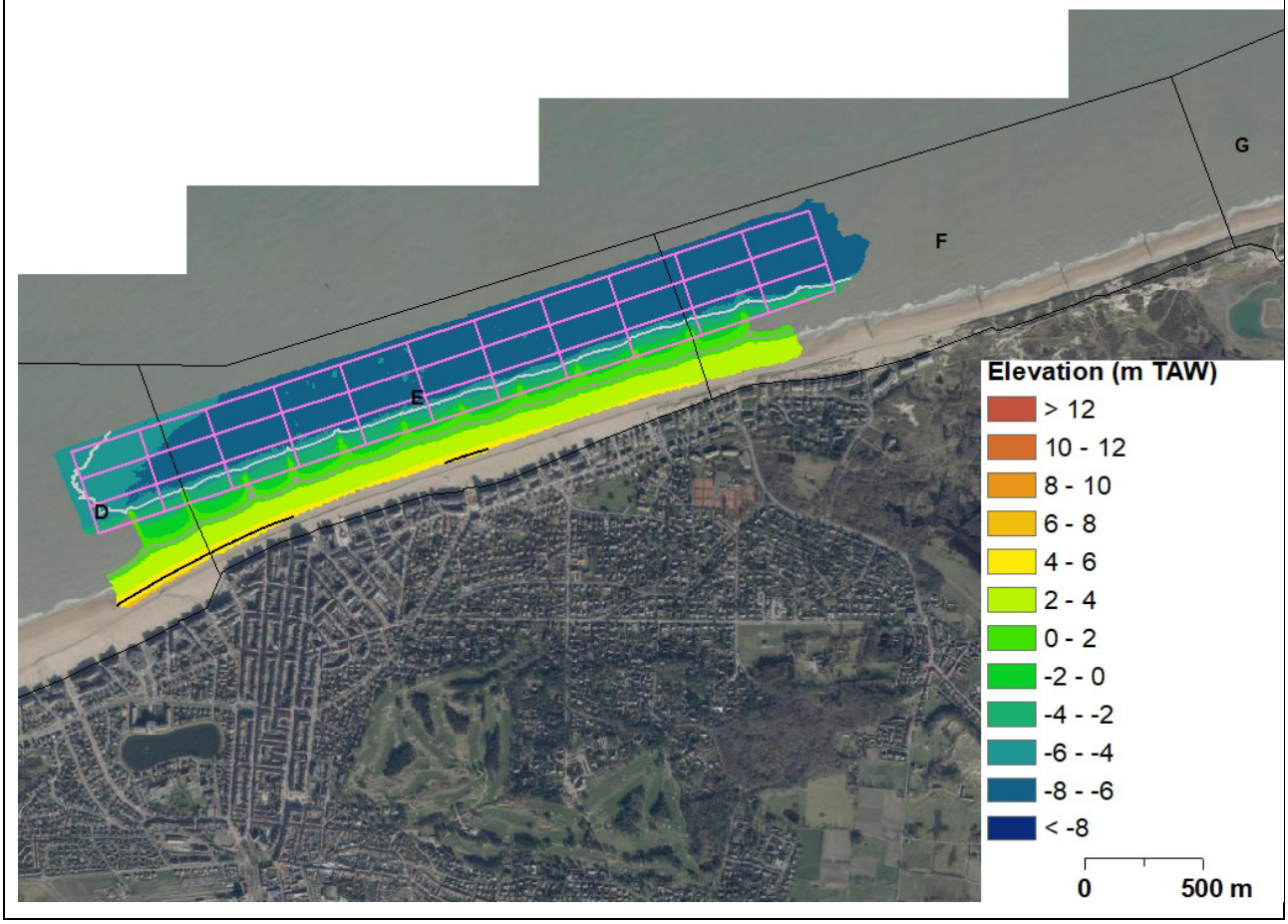


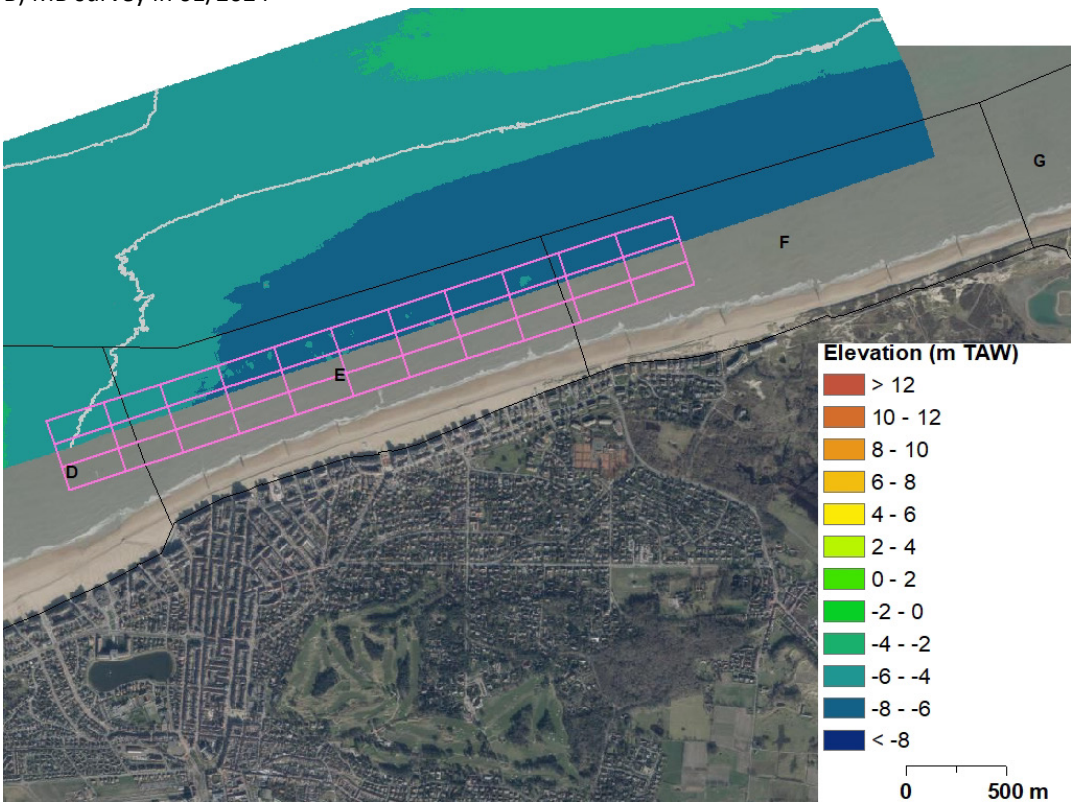
Figure 15 – A) UAV and MB DEM, B) example of extracted profiles

Figure 16 displays the consecutive DEMs between the pre-nourishment in 10/2023 and 3 months after (6/2024). In general, the -5m TAW contour line was located 13 m seaward in 03/2024 after the nourishment. The contour line of 1.39 m TAW was stable since the nourishment was carried out below the water line.

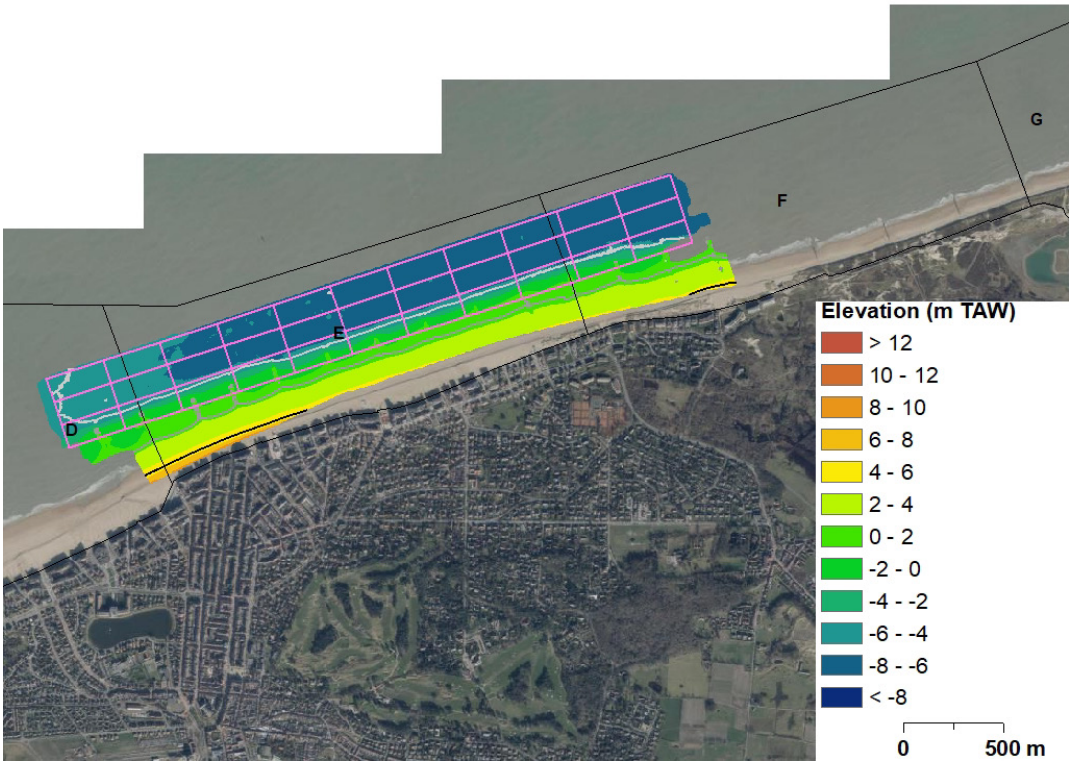
A) MB pre-nourishment survey in 10/2023



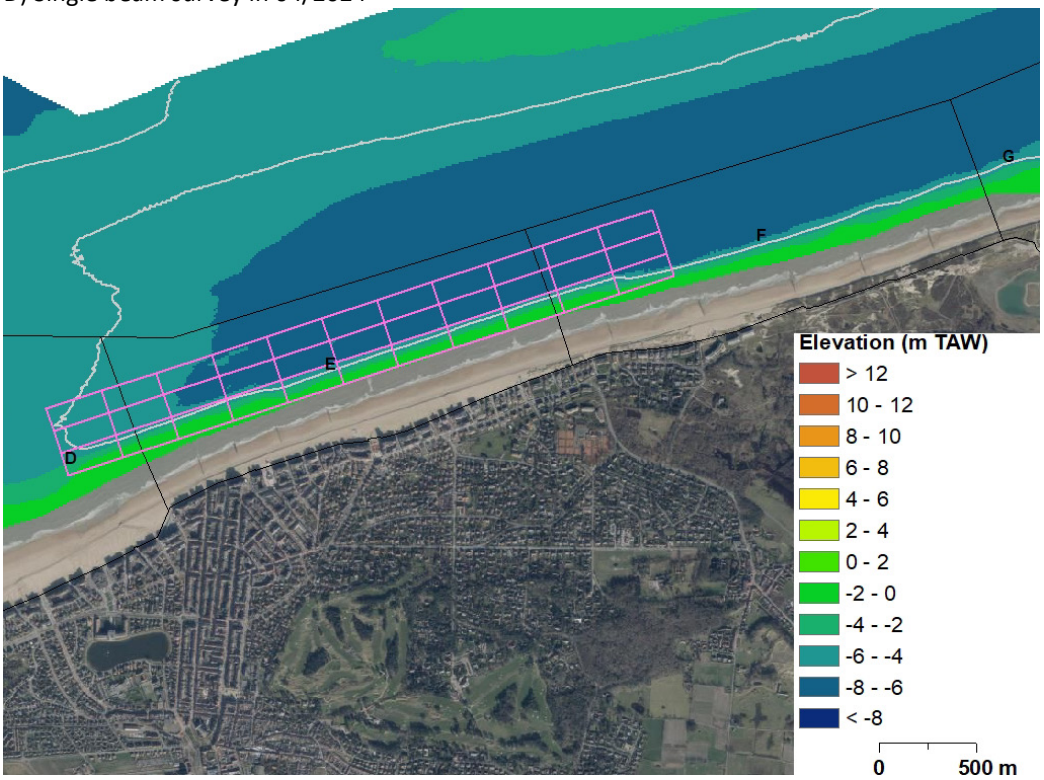
B) MB survey in 01/2024



C) MB post-nourishment survey in 03/2024



D) Single beam survey in 04/2024



E) MB survey in 06/2024

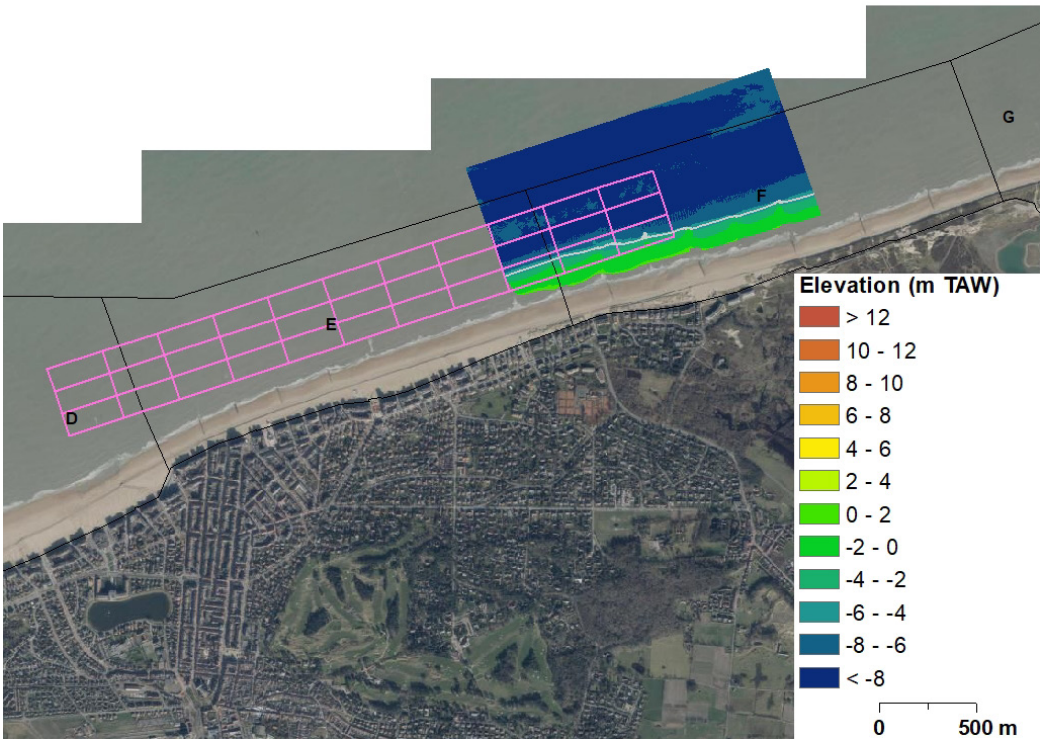


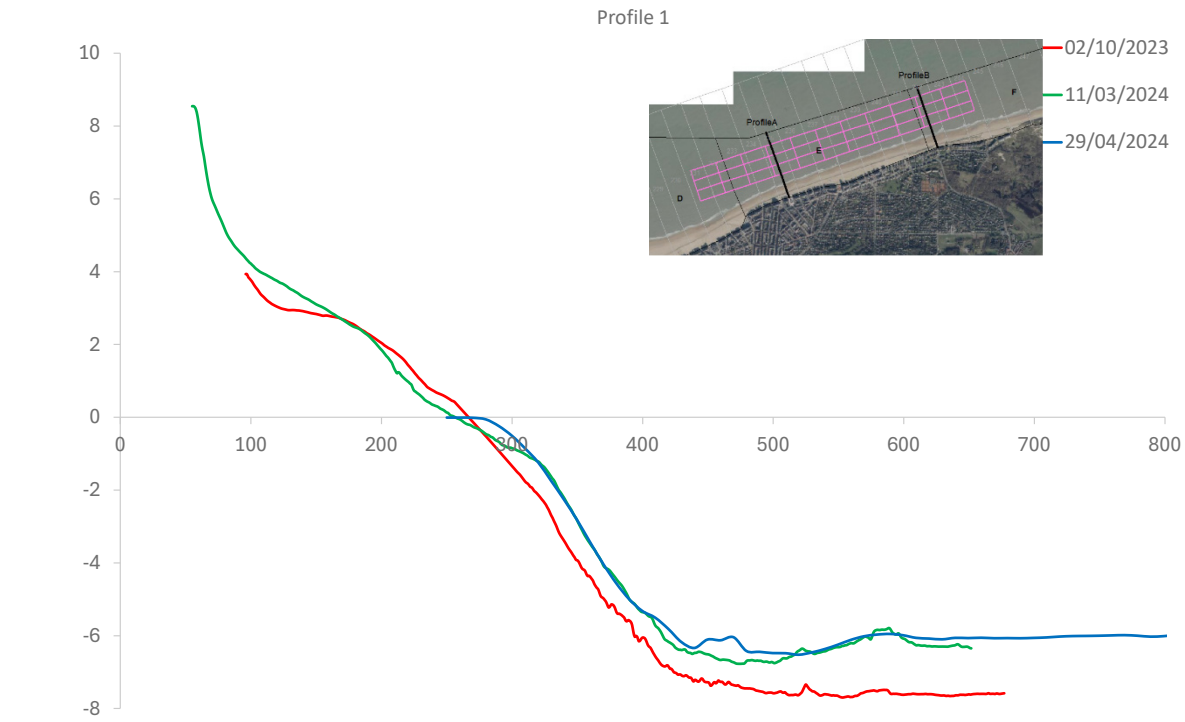
Figure 16 – DEM of the pre and post nourishment surveys in the area of the large nearshore nourishment in October 2023-February 2024. The black, dark grey and light grey lines correspond to 5 m, 1.39 m and -5 m TAW respectively. The pink grid corresponds to the location of the dump area. MB and SB stands for multibeam and single beam bathymetric surveys

DEM of difference between pre-and post-nourishment is presented in Figure 17. An accretion up to 2.5 m is observed surrounding the groynes between the low waterline and -5 m TAW. Also, the lower part of the profile (below -5 m TAW) was subject to a sand gain with an average of 0.4 m as well as higher concentrated spots up to 1.7 m which were more offshore and eastward. In contrast, negative morphological changes ranging from -0.05 to -0.7 m characterized the beach and in particular the westward from section 232-239. This was likely due to the spreading of the beach nourishment carried out in 02-04/2023.

Figure 17 – DoD of the pre and post nourishment surveys in the area of the large nearshore nourishment in October 2023-February 2024.

Figure 18 displays the time series of the bathymetric profiles of the pre- and post-nourishment, and 1 month after. As already observed on the DEMs (Figure 16), the shoreface shifted seaward between 20 m (Profile 1) to 40 m (Profile 2) after the sand supply. Also the seaward part shoreface at a distance of > 400 m from the coastline was shallower gaining up to 1.5 m in high for Profile 1 and 0.8 m for Profile 2. There, the dumping effect can be clearly observed with the development of features of an average 20-25 m high in the eastward of the nourished zone (Profile 2) on the multibeam survey in 03/2024.

A)



B)

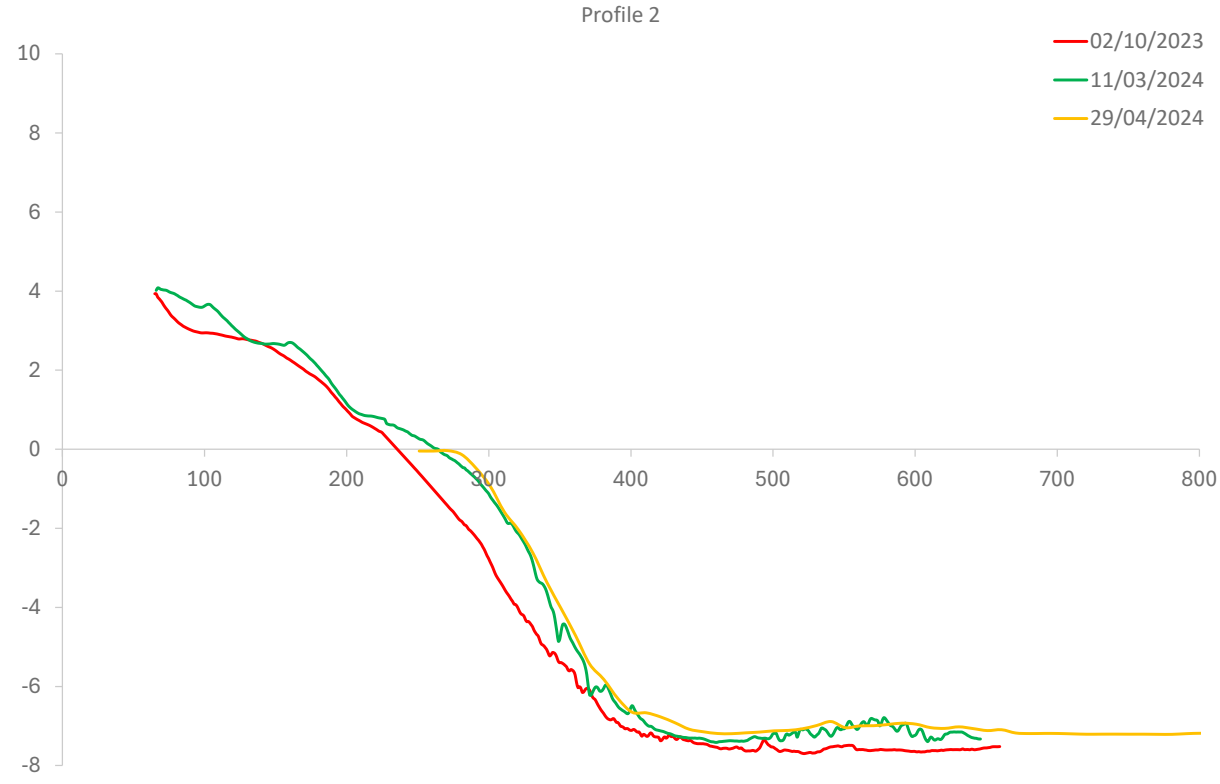


Figure 18 – Extracted profiles in the large nearshore nourishment zone. Inset: locations of the profiles

6 Discussion

The aim of this project is to evaluate the efficiency and subsequent morphological evolution of the 5-years nourishment scheme in response to the different stages of conducted works. However, there is a lack of precise and reliable data about the execution of the several stages of the nourishments east of Zeebrugge: in- and out-surveys of the beach nourishments, same for the nearshore nourishments and here even the exact location is not known. This is a limitation in the morphological assessment. Another limitation is caused by the lack of information on the grain size of the supplied material. Therefore, the present report describes the general annual evolution of the study area and the monthly morphological changes after the large nearshore nourishment in 10/2023-03/2024 characterized by fine supplied sand of > 150 µm. Observed evolution is described using defined coastal zones and in this chapter the results are related to the long-term coastal trends between the 1980's and 2019 (Table 8, Houthuys et al., 2022). Noteworthy, these morphological trends will be updated at the end of 2025 (project 24_015). After that the corrected sediment budgets along the entire study zone will be reported as well as a conceptual model of sediment transport based on the morphological changes and evolution in order to compare the morphological trend and evolution with and without human interventions.

Table 8 – Corrected sediment budget based on the long-term coastal trend from 1980's to 2019 (Houthuys et al., 2022).

		Volume ($m^3/m/y$)				
Coastal zones	Location	Section	Above LW	Below LW	Shoreface	Seabed
Zone A	Heist-west	217-221	5.02	23.05	18.95	2.74
Zone B	Heist-east	222-224	12.96	32.06	32.06	0
Zone C	Duinbergen	225-226	-8.44	-12.73	-12.72	-0.01
Zone D	Albertstrand	227-232	0.17	-8.9	-0.21	-8.69
Zone E	Knokke Zoute	233-241	-19.88	-22.28	-4.64	-17.64
Zone F	Lekkerbeek	242-249	2.03	-15.76	-3.69	-12.69
Zone G	Zwin	250-255	7.59	-15.32	-3.88	-11.4

6.1 Volume increase at Duinbergen 2021 beach nourishment

The large beach nourishment at Duinbergen (Zone C) in 02-03/2021 (supplied volume: 981 820 m^3) resulted in an increase of the beach width of 90 to 120 m and a measured increase (2020-2021, beach of zones B, C, D) of about 498 010 m^3 +/- 68 250m^3 (Table 6). The real volume increase is very poorly confined by the surveys. The typical reported volume loss during a nourishment deployment is about 15% of the total nourished material (Houthuys et al., 2022). This corresponds to 147 280 m3 for the case of Duinbergen beach nourishment (981 820-147 280=834 540 m3). Based on this, the efficiency of the beach nourishment was of a minimum of 60% since sand material could have been already removed between the end of the nourishment and the LiDAR survey carried out nearly two months after. After 2021, the volume evolution in the entire zone C ranges from 520 000 m^3 and +/- 830 000 m^3 between 2021 and 2024. Specifically, the volume evolution of zone "Duinbergen Nourished area" delimits the location of the probable nourishment area (

Figure 14). After 2021, the volume evolution in the entire zone C ranges from 520 000 m^3 and +/- 830 000 m^3 between 2021 and 2024. Specifically, the volume evolution of zone "Duinbergen Nourished area" delimits the location of the probable nourishment area (

Figure 14 and Table 7). The gain in 2021 (+731 300 ± 31 660 m³) is followed be a decrease of 87 000 over 2021-2023 but a slight accretion of 20 950 m^3 (equivalent to 0.05 $m^3/m^2/y$) was observed in 2024.

Summary: *The observed volume decrease of the beach in the nourishment area after nearly 3 years was only 7% of the measured increase of the Duinbergen nourishment in 2021 (981 820 m³) [see "Nourished Duinbergen": -14370 -72440+20950= -65 860 m³ (2021-2024)] ". This may in reality have been larger, because some erosion may already have occurred between the completion of the nourishment and the LiDAR and nearshore surveys in 2021.*

6.2 Volume increase at Knokke-Zoute 2021 to 2023 beach nourishment

Zone E (Knokke) and the neighbouring part of zone D (Alberstrand) are liable to erosion (Houthuys et al., 2022). A middle beach nourishment of 292 800 m^3 was carried out in 02-03/2019. More than 60% of the sand supplied artificially to Knokke-Zoute and Lekkerbek beach was removed in two years and it was partly transported to the shoreface by cross-shore processes (Montreuil et al., 2022). The rest of the material was probably further transported to the adjacent coast by the eastward littoral drift and partly evacuated from the Appelzak by tidal currents. This is in agreement with the local long-term negative coastal trend of the beach-shoreface system (Table 8).

From 2021 to 2023, a succession of small beach nourishments followed by a large one was carried out at Knokke-Zoute: +33 500 m³ (beach, 2021), +33 000 m³ (beach, 2022), +510 000 m^3 (beach, 2023). Thus, a total of +576 500 m³ of sand was artificially supplied on the beach in Knokke over 5 years (Table 2). Though the precise area of nourishment does not completely match zone E, the volume evolution of that zone gives some indication of the observed morphological evolution over the same time interval from 2021 to 2024 (Table 5 and Table 6): +181 680 m³ (± 33 000 m³) in the beach part. This value can be compared with the reported supply volumes which indicates that 69% of the efforts were lost over the 2020-2024 period.

More specifically, based on the "Knokke nourished area" (Table 7), about 29% of the sand supplied in 2023 disappeared after 9 months: "Knokke nourished area": 339 160 +25 800 = 364 960 m³ (2022-2024). This suggests that the erosion is a fast process occurring immediately after nourishment. Taking account of an average 15% of volume loss of the reported nourished sand, the measured loss was more than 4 times bigger than the typical reported loss after works.

Summary: *Knokke and Lekkerbek are prone to erosion. In 2019, a nourishment lost over 60% of its sand within two years due to cross-shore transport, littoral drift, and tidal currents, reflecting a long-term erosion trend. Between 2021 and 2024, about 69% of the nourished sand in Zone E was lost. In 2023, roughly 29% disappeared within nine months, with erosion rates more than four times higher than typical post-nourishment losses, indicating that much of the sand is removed soon after placement.*

6.3 Volume increase at Knokke-Zoute 2020 and 2021 nearshore nourishment

A set of 3 nearshore nourishments of 14 839 m^3, 130 930 m^3 and 161 708 m^3 was carried out in 05-06/2020, 11-12/2020 and 06-07/2021 respectively in Zone E (Knokke) from section 236 to 241 (Table 2). In total, 307 500 m^3 sand was placed between the -5.5 and -7 m TAW depth contours in the Appelzak channel in an area of 403 000 m^2. The vertical accretion in this area in 2024 ranged from 0.3 to 1.7 m. The nourishments were done by dumping shiploads of fine sand (Table 2). They created "bumps" on the floor of Appelzak channel (see Profile 3 in Figure 11, 2022 and 2023). The bumps did hardly change shape over the interval from 2022 to 2023. This is difficult to explain for loose sand in a current-dominated channel, unless the dumped slurry had some consistency.

Since there were important nourishments just after the 2021 survey, the volumetric analysis is based on the period from 2019-2022. The nearshore nourishment area was subject to a volume increase of 121 770 m^3 between 2019-2020 and 148 820 m^3 between 2020-2021, corresponding to a total of 270 590 m^3 (Figure 19 and Table 9). This volume is 93 % of the total amount nourished between the two surveys (130 930 + 161 708 = 292500 m^3). The nearshore accretion contrasted with the eroded beach (section 231-237) between 2019 and 2022 when the sand loss was there -128 677 m^3 (Figure 19).

In addition, the wider environment of the Appelzak channel (i.e. difference between entire offshore area and nearshore nourishment area) showed rates of vertical accretion much greater to the rates observed in the nearshore nourishment area (Figure 19). Thus, this exceeds far the possible amounts spread out from the nearshore nourishment. Other sources of sediment must have fed the nourishment area and its surroundings. One such source is the erosive beach in sections 231-237 at Knokke-Zoute. Another source may have been sand lost during the 2021 nourishment of Duinbergen. The gain inside the nourishment area can nevertheless mainly be attributed to the nearshore nourishment in 2020-2021.

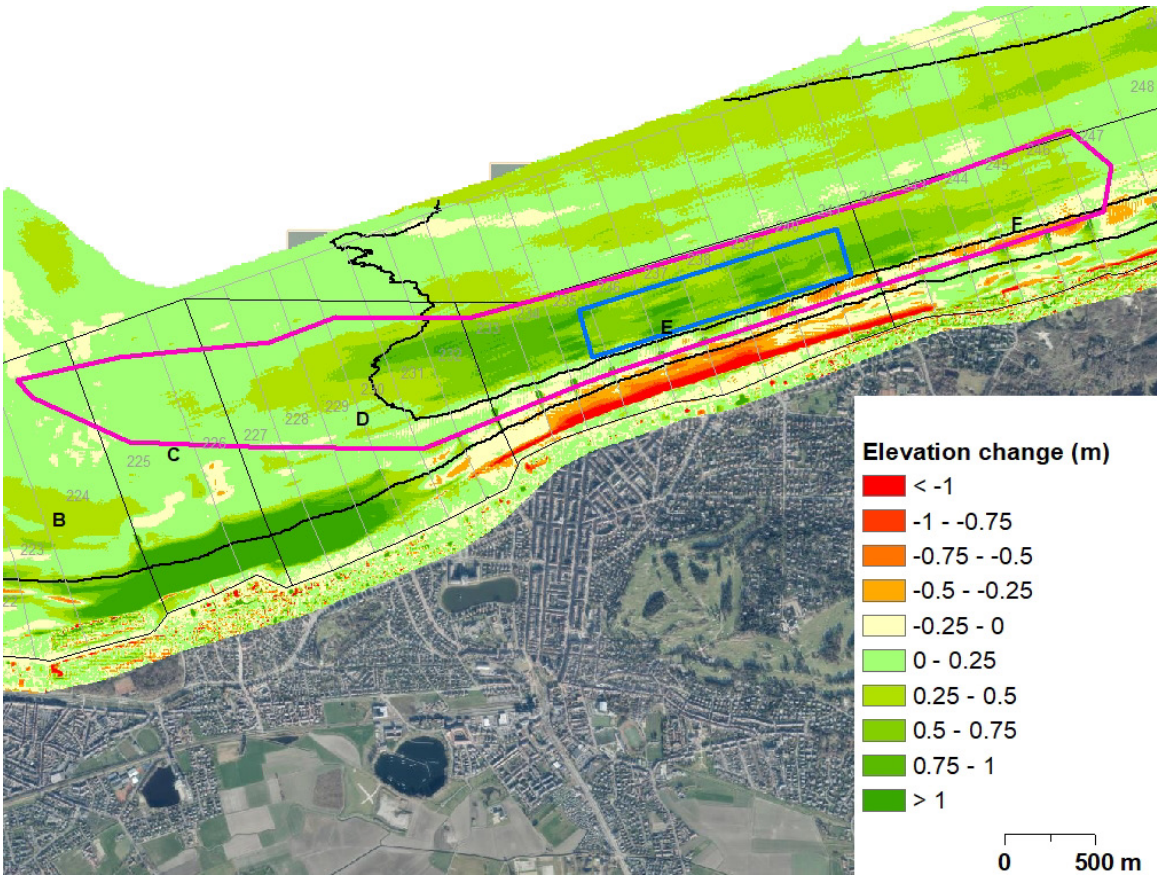


Figure 19 – DoD between 2019 and 2022 i.e. the period including the 2020 and 2021 Knokke-Zoute nearshore nourishments, with the nourishment area shown in blue. The pink polygons correspond to the investigate offshore area (section 6.6). Contour lines correspond to -5 m, 1.39 m TAW in 2018.

Table 9- Sediment budget in the area of the nearshore nourishment in 2018-2022. Values in 4th column correspond to the volume in $m^3/m^2/y$. Green colour for the volume indicates significant positive trends differences and no colour values are not significant.

	Volume (m^3)			
	2019-2020	2020-2021	2021-2022	Uncertainty
Nearshore nourishment area	121 770	148 820	27 200	84 630
Entire offshore area	505 030	716 230	243 090	657 800
Difference between entire offshore area and nearshore nourishment area	383 260	567 410	215 890	742 430

Summary: *In 2020–2021, nearshore nourishments in Zone E (Knokke) formed stable seabed "bumps" that persisted into 2023. From 2019–2022, the area retained about 93% of added sand, while nearby beaches eroded. Extra sediment likely came from eroding beaches and the 2021 Duinbergen nourishment, though most gains were from the 2020–2021 works.*

6.4 Volume increase at Knokke-Zoute - nearshore nourishment in 2023-2024

The efficiency of the recent large nearshore nourishment in Knokke of 1.2 million m^3 can be assessed using the collected data. Here, a good coverage is available to observe the nourishment-related morphology change, both as pre- and a post-nourishment survey performed at dates shortly before and after the works have been performed.

On the pre- to post-nourishment DoD (Figure 20), accretion can be observed in the nearshore nourishment area in mainly two longitudinal strips: one near the offshore boundary of the nourishment area, with local accretion spots up to +1.7 m, and another, with vertical accretion exceeding 1 m throughout, at the landward boundary. This shoreface strip extends landwards on the shoreface in the area between the groin tips outside the nourishment box. Nevertheless, it is thought that the accretion here also is due to the nearshore nourishment. Therefore, the nourishment area was taken to include the upper- shoreface till 1.39 m TAW because the extending nourishment there with the rainbow boot (described in section 4).

Allowing for an estimated 15% volume loss during dumping, the deposited volume is calculated to be 1 020 000 m^3. The sand gained in the replenished zone was 731 950 m^3 with an uncertainty +/- 92 190 m^3 (Table 10). This value corresponds to only 61% of the reported nourished sand and 72% of the assumed nourished volume when allowing for volume losses during operation of the nourished sand in this area.

Several reasons can be put forward to account for this difference. Possibly, a part of the nourishment was carried out on the upper shoreface and therefore was not included in the purple outlined zone of Figure 20. The pre-nourishment DEM here does not present a measured seabed but only a linear interpolation between the UAV and multibeam survey data. Finally, a sand spreading is likely to have already occurred during and just after the nourishment operations (the post-nourishment MB bathymetric survey was carried out 11 days after the operations and the UAV survey after 14 days). Nevertheless, the "efficiency" of this large nearshore nourishment with very fine sand, defined as the bed volume increase observed from just before and after nourishment operation surveys divided by the reported (assumed) nourished volumes would probably not have been much larger than 61% (72%).

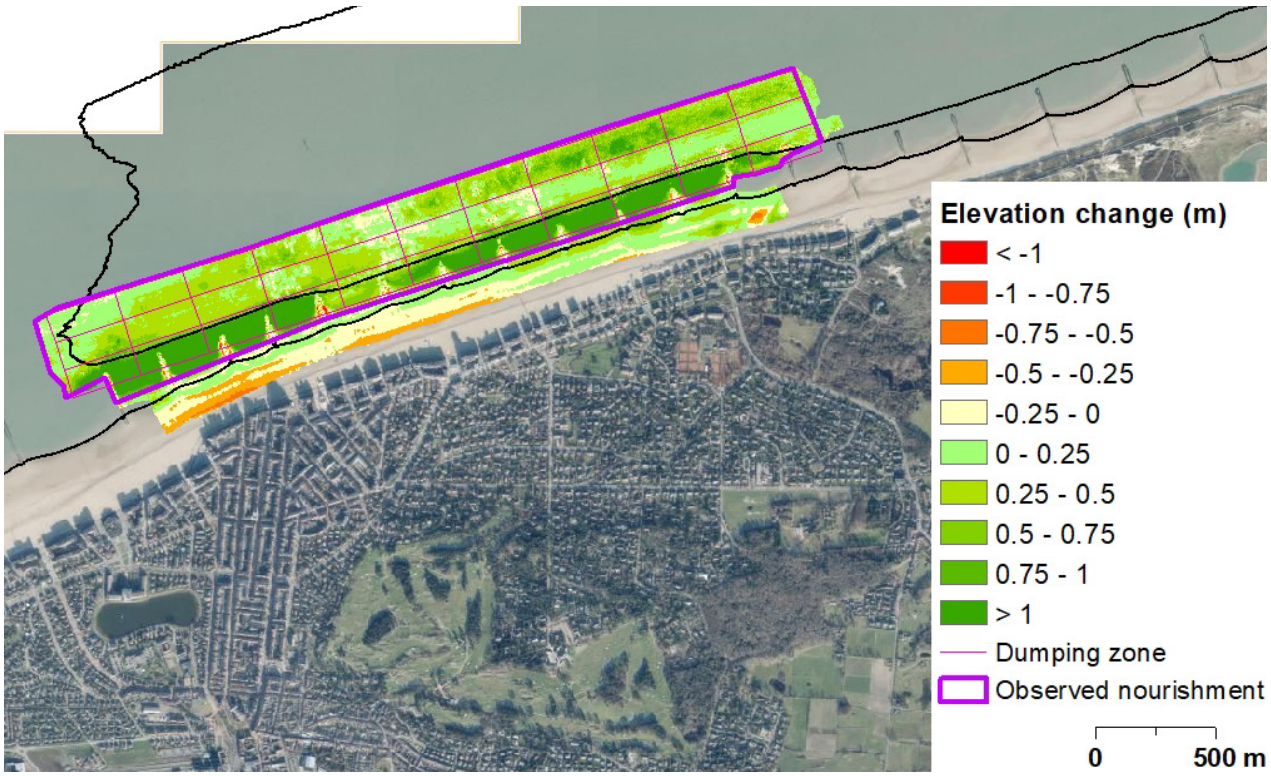


Figure 20 – DoD between 2023-2024 pre- and post-large nearshore nourishment MB and drone surveys, with the area of the nourishment (purple rectangle).

Table 10 – Sediment budget in the area of the nearshore nourishment in 2023-2024. Values in bracket correspond to the volume in $m^3/m^2/y$. Red and green colours for the volume indicate significant negative or positive trends respectively, while no colour values are not significant.

02/10/2023-11/03/2024	Area (m^2)	Volume (m^3)	Volume/area (m^3/m^2)	Volume uncertainty (m^3)
Knokke nearshore nourishment area	1 316 950	731 950	0.56	92 190

Summary: *A large nearshore nourishment in Knokke in 2021 showed, based on surveys before and shortly after the works, that only 61% of the reported sand volume—or 72% when accounting for expected operational losses—remained in the nourished zone. The shortfall is attributed to sand placed outside the measured area, data gaps in pre-nourishment mapping, and rapid spreading during or soon after the works.*

6.5 Morphological evolution of the beaches after the beach nourishments

This section describes the morphological behaviour and evolution after the carried-out beach nourishments along the study site.

Duinbergen (Zone C) was in the last decades characterized by slow positive morphological changes on the beach while the shoreface is stable. Based on the long-term coastal trend, there is a relatively large sand availability on the shoreface, providing supply to the beach (Table 8). This explains the small loss of sand on the foreshore and upper shoreface after the reported beach and upper nearshore nourishment of 981 820 m^3 in 2021 observed in Profile 1 (Figure 11). The total observed volume increase of the nourishment was of 731 300 m^3 after the nourishment.

The beach gained 2 m^3/m^2 in 2021 while a very small fraction was lost between 2022 and 2024 (<0.5 m^3/m^2). This was followed by a slight decrease of elevation in 2023 and 2024 along the entire profiles. After 3 years, the sand loss of the nourishment zone was only 7%. Thus, the beach-shoreface profile in Duinbergen has a very mild erosional morphological evolution. In addition to the in-situ evolution, alongshore evolution can be observed with the spreading of the sand material westward towards Baai van Heist (Figure 13) as well as the eastward. Thus, the nourished sand in Duinbergen has probably supplied the beach in Knokke as observed by the attachment of the accretive zones.

The beach nourishment of Duinbergen in 2021 was carried out in a part of the shoreline which received sand from the westward beach-shoreface system of Heist (Houthuys et al, 2022). Also, regular sand nourishments are carried out since 1997, limiting erosion process there. Therefore, this nourishment had a positive effect on the beach and also gradually to the adjacent ones over time. Its morphological evolution deviates from what is often observed at Knokke-Zoute.

Zone E (Knokke) and the neighbouring part of zone D (Alberstrand) are liable to erosion (Houthuys et al., 2022). The first signs of beach erosion after the beach nourishment at Knokke and Albertstrand are already observed in the LiDAR survey in 01/2024. The shape and position of the negative morphological areas ranging from -0.05 to -0.6 m and concentrated between the high water level and 1.39 m TAW can be linked to the erosion processes. At various times, either or both of these erosion area shapes emerge: (1) less intense erosion of the beach, but over relatively wide areas; (2) more intense erosion of a narrow strip along and just above the low-water mark. The lost sandy material might be partly transported to the shoreface by cross-shore processes and then partly evacuated from the Appelzak by tidal currents. Another part was probably further transported to the adjacent coast by the eastward littoral drift which transport sediment to the beach in Lekkerbek zone (Figure 13F). The nourishment in 2023-2024 at Knokke can be expected to show further ongoing erosion, in line with the evolution observed after earlier nourishments. However, this time also an important nearshore nourishment was carried out. This may positively impact on the evolution of the beach.

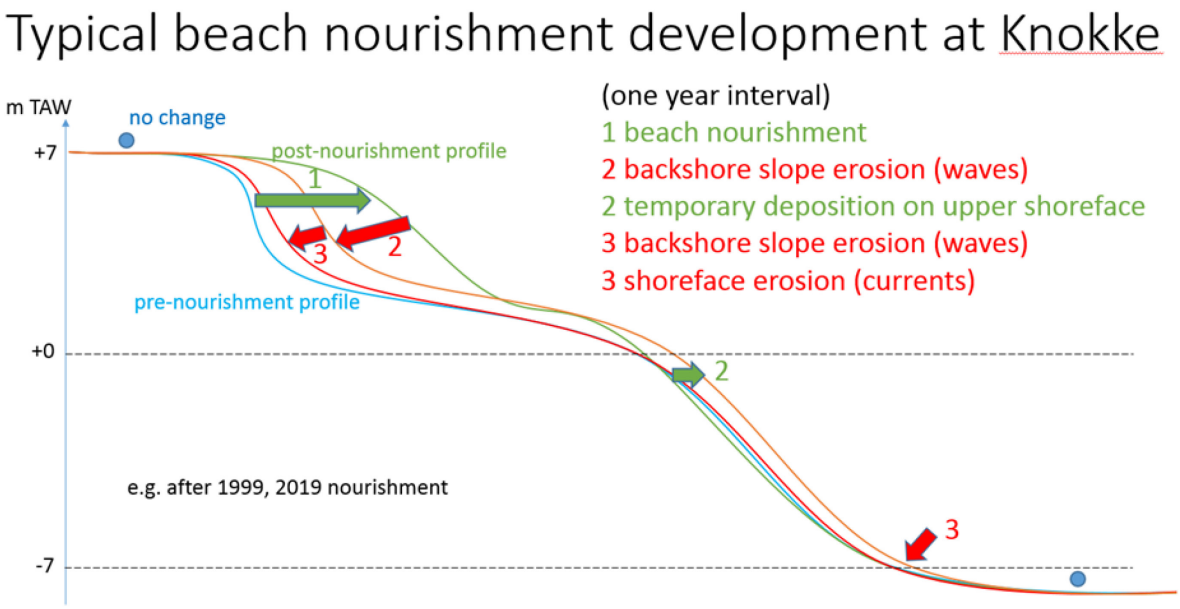


Figure 21 – Conceptual model for the evolution of a nourishment in the coastal are of Knokke.

A conceptual model is proposed (Figure 21) to summarize the typical evolution of a beach nourishment, based on observations over the past 25 years. This model shows rapid evolution of the nourishment where the sand of the intertidal beach is transported outside of the interest area by wave-induced currents. In contrast, the shoreface-deposited sand is transported primarily by tidal-induced currents, although at slower rates than for the beach.

Summary: *Duinbergen (Zone C) showed slow, positive change after a large 2021 nourishment, losing only 7% of sand over three years, with sand spreading to nearby beaches. In contrast, erosion began by 2024 at Knokke (Zone E) and Alberstrand (Zone D), with sand lost offshore and alongshore. A 2023–2024 nourishment at Knokke may face further erosion, though nearshore works could help.*

6.6 Morphological evolution of the shoreface after the nearshore nourishments

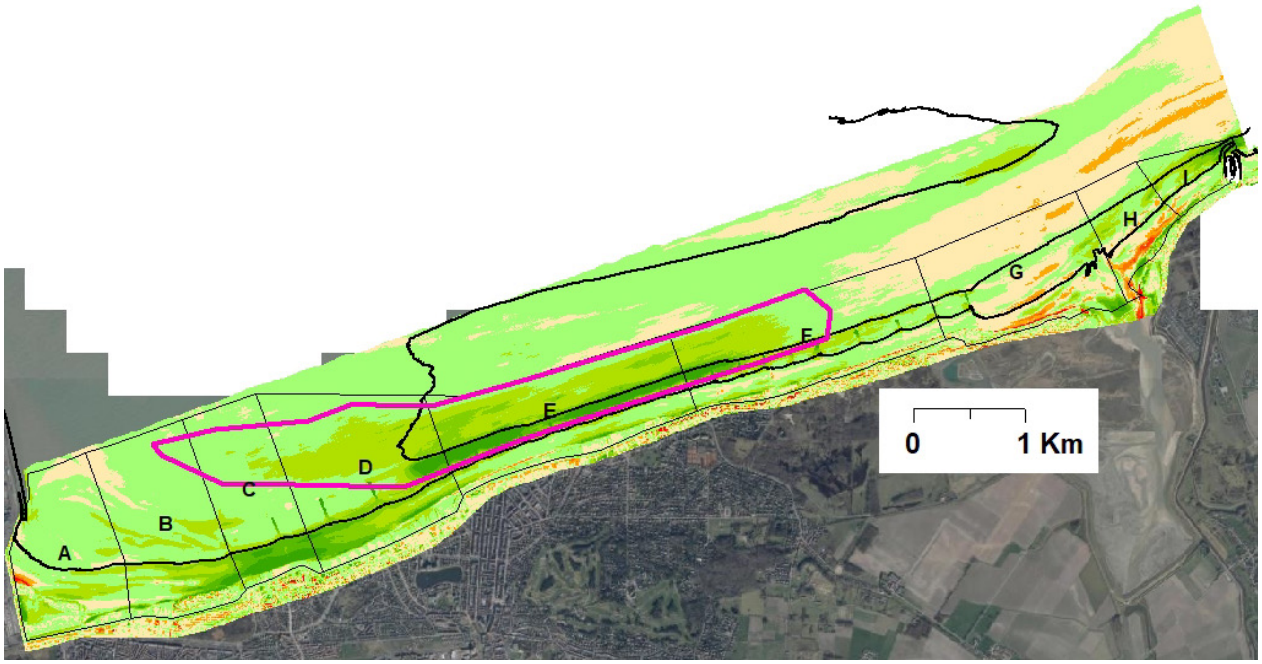
This section describes the morphological behaviour and evolution after the nearshore nourishments carried out in the study site.

Along Knokke coast, the nearshore nourishments caused significant morphological changes over the study period. Before, the area was characterized by a long-term coastal trend of -4.64 $m^3/m/y$ and -17.64 $m^3/m/y$ for the shoreface and seabed respectively (Houthuys et al., 2022). When focussing on the offshore delimited zone excluding the 2023-2024 nearshore nourishment area (Figure 22B), it is clear that a spreading from the nearshore nourishment area occurred both to east and west contributing to filling the Appelzak channel bed. While both sediment transport directions, eastward flood and westward ebb transport, have been suspected earlier to occur, here the sequence of DoD maps over the observation period for the first time proves this longshore transport in both directions do take place. The sand gain in this surrounding zone is also significant with a budget of 790 540 m^3 corresponding to an average elevation gain of 0.44 m (Table 11).

The Appelzak channel significantly gained sand between 2018-2024. Inside a delimited zone encompassing the entire offshore accretion area (Figure 22A), an accretion of 2.4 million m^3 occurred over the 5 years which is equivalent to an elevation gain of 0.78 m (Table 11). Although the uncertainty is large (657 800 m^3), the sand gain is significant. This value exceeds the total amount of the nearshore nourished sand of approximately 1.5 million m^3 along the entire study coast between 2020 and 2024 (Table 2). Sand transfer from the nourished beach-shoreface in Cadzand was limited during the study period since only 150 000 m^3 of material was supplied in 2019 (Deltares, 2022). A large sand supply of 600 000 m^3 in 2019 was also carried out in Herdijkte Zwarte Polder Cadzand Bad but sand transfer would have probably been limited due to the distance from Knokke (i.e. 12 km with coastline with kinks). The excess of over 1 million m^3 may contain a supply from nearby beach erosion, especially from the Knokke-Zoute 2023 beach nourishment, but then a significant excess still remains. This implies an additional offshore supply. The nearshore nourishments might have induced a reduction in tidal currents (blocking of the part of the tidal channel just in front of the shoreface and diverting flows more offshore inside Appelzak channel). The long-lived "bumpy" morphology (nourishment bumps remain present on the channel bed for a year, see 2022 and 2023 bed profile between distance 400 and 600 m in Figure 11C) supports this interpretation. This local hydrodynamic effect may have induced sand deposition on the channel bed west and east of the nourishment area.

Indeed, at a local scale, the morphology of the shoreface bed clearly shows the nourished dumping with the formation of positive seabed features (i.e. bumps) characterized by a height up to 1 m in 2022 and 2023 (Figure 11C). Also, the large nourishment in 2023-2024 caused localized bumps of which some can still be recognized in the 29/04/2024 SB survey, months after the completion of the nourishment.

A)



B)

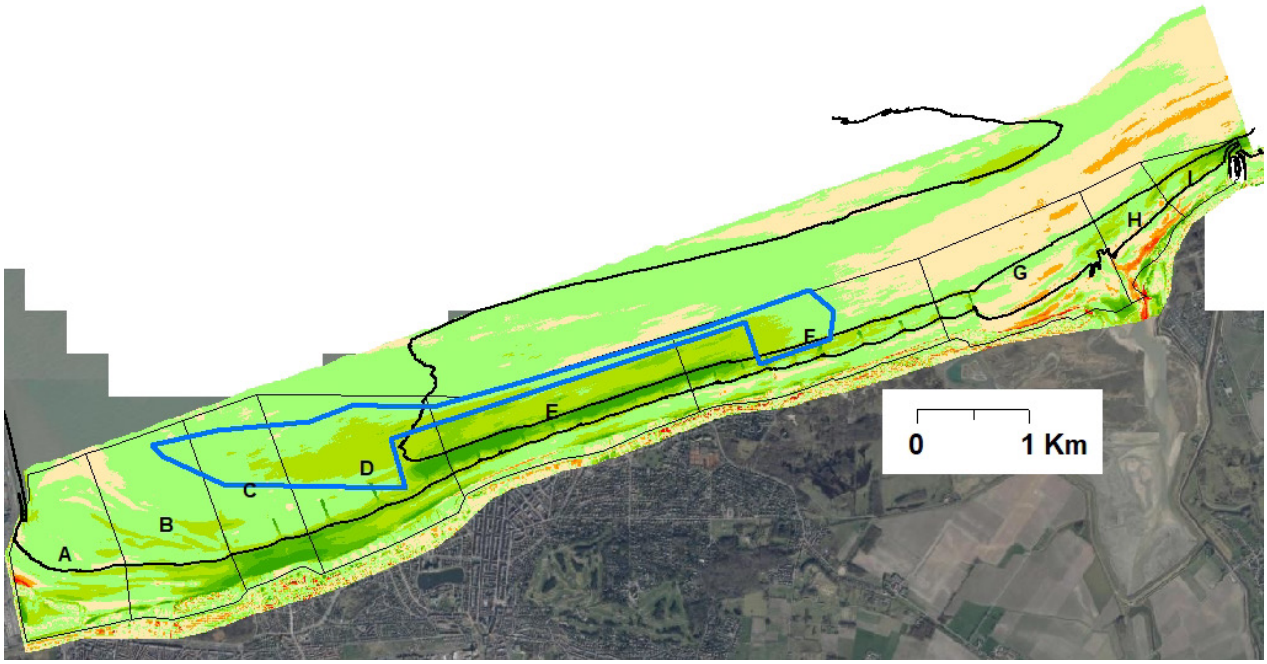
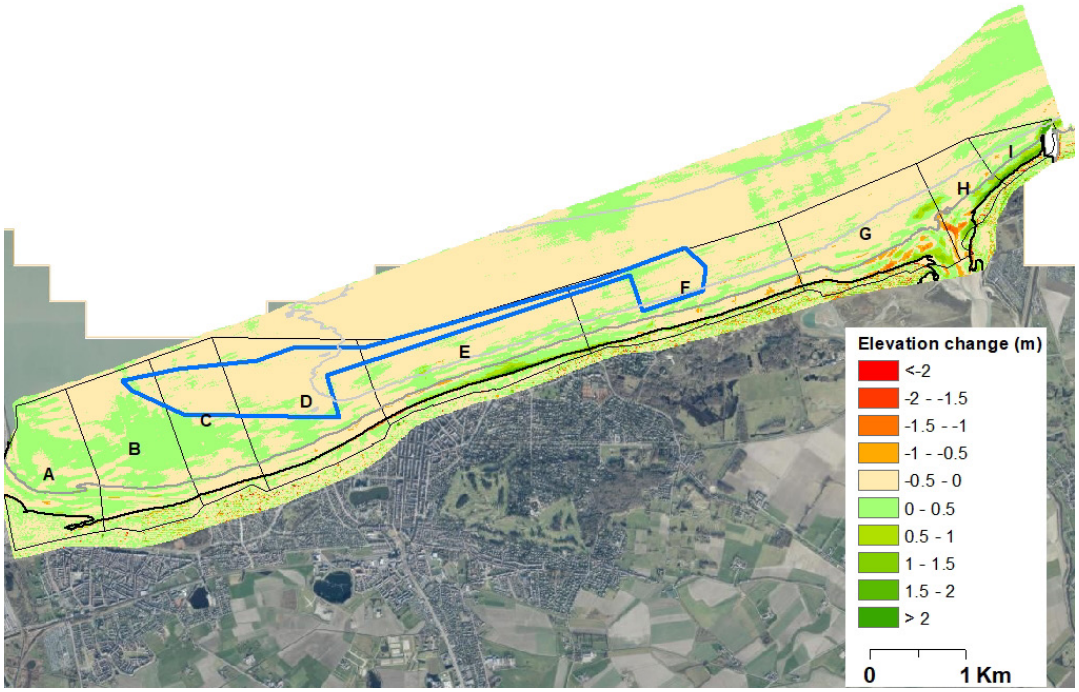


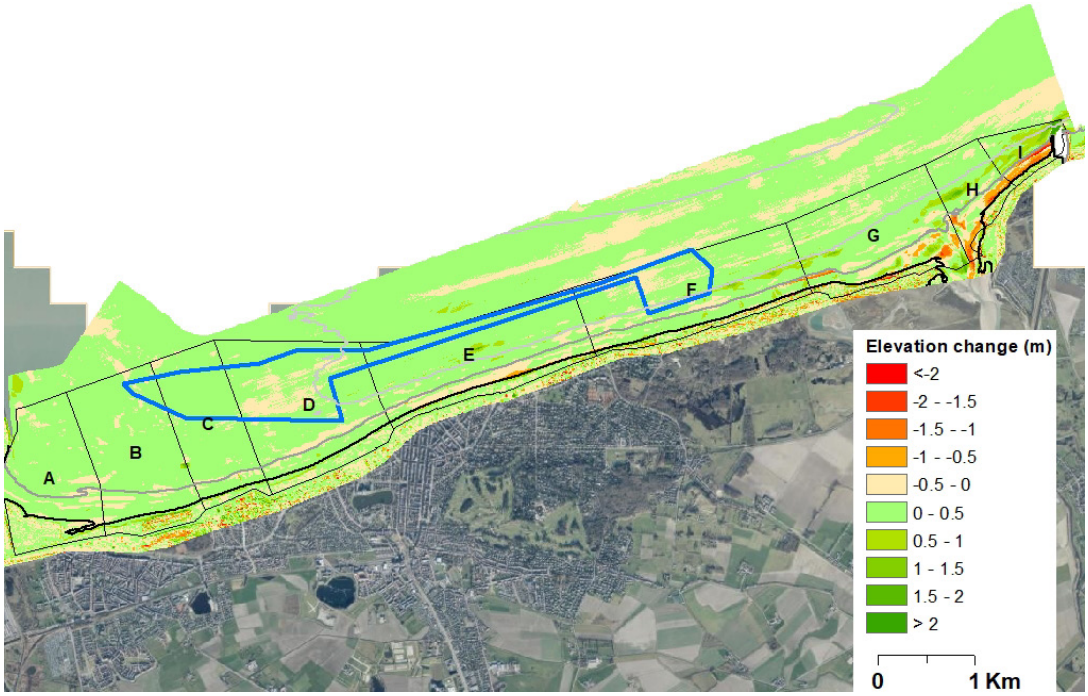
Figure 22 – DoD between 2018 and 2024 delimiting A) the entire offshore area (pink polygon), B) the offshore area excluding the large nearshore nourishment zone in Knokke in 2023-2024 (blue polygon). The black contour lines correspond to 1.39 m and -5 m TAW respectively in 2024.

Figure 23 displays the year to year evolution of the extra sand coming from the offshore area. It is clear that there is a progressive input of sand since 2019 filling up the Appelzak channel. It would be interesting to assess by extending the period of the study before 2018 under the framework of the coastal trend project.

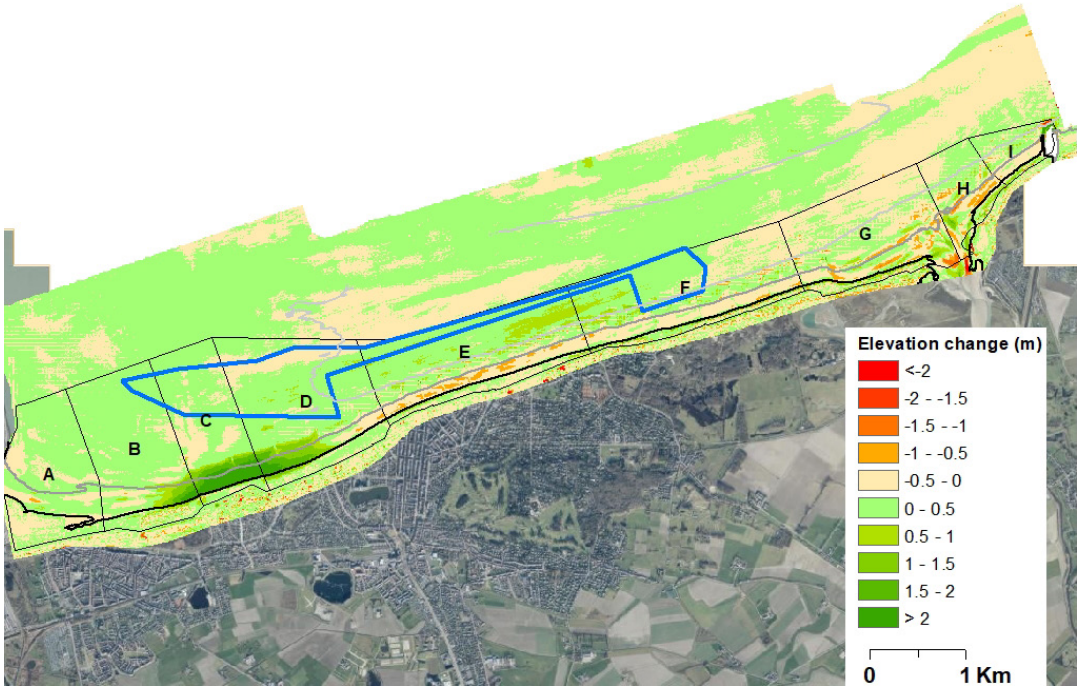
A) 2018-2019



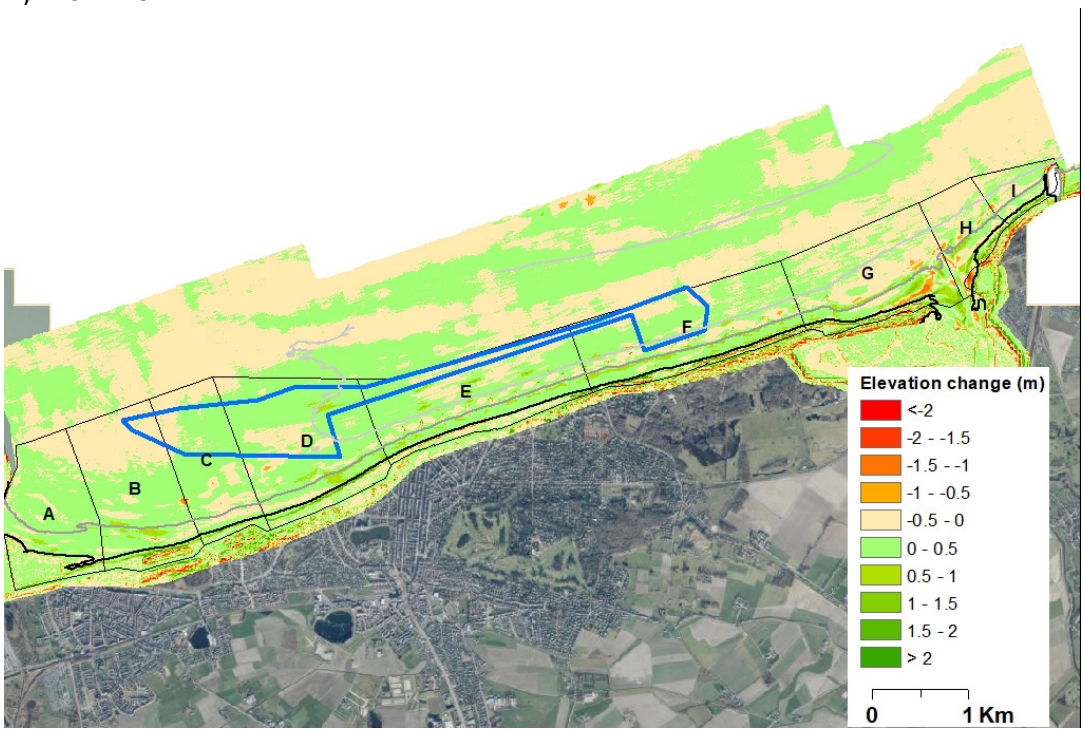
B) 2019-2020



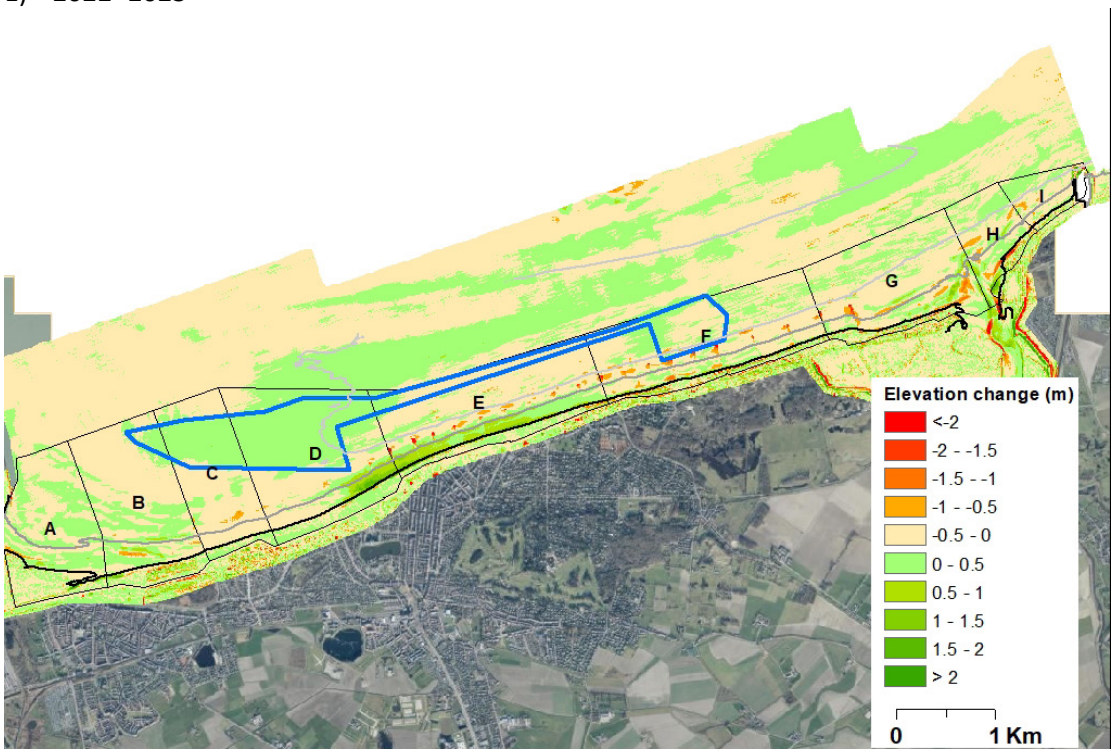
C) 2020-2021



D) 2021-2022



E) 2022- 2023



F) 2023-2024

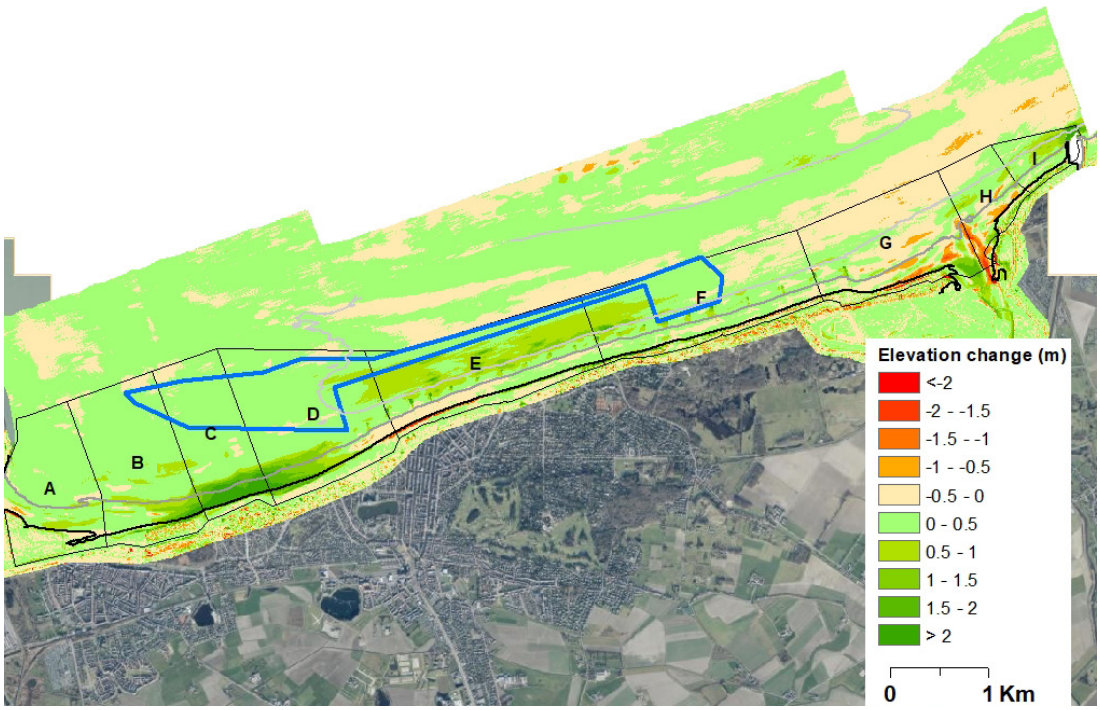


Figure 23 – Annual DoDs between 2018 and 2024 delimiting the offshore area excluding the large nearshore nourishment zone in Knokke in 2023-2024 (blue polygon). The black contour lines correspond to 1.39 m and -5 m TAW respectively in 2024.

Table 11 – Sediment budgets from 2018 to 2024 of the entire offshore area and the offshore area excluding the large shoreface nourished zone in 2023-2024. Values in bracket correspond to the volume in $m^3/m^2/y$. Red and green colour indicates significant negative or positive trends respectively and no colour values are not significant

	2018-2019	2019-2020	2020-2021	2021-2022	2022-2023	2023-2024	2018-2024	Uncertainty (m^3)
Entire offshore area	-253 460 (-0.08)	505 030 (0.16)	716 230 (0.23)	243 090 (0.08)	86 020 (0.03)	1 191 140 (0.38)	2 442 560 (0.78)	657 754
Offshore area excluding nearshore nourishment in 2023-2024	-181 250 (-0.1)	132 250 (0.07)	290 500 0.16)	118 180 (0.07)	209 930 (0.12)	241 030 (0.13)	790 540 (0.44)	379 016

Summary: *Nearshore nourishments along the Knokke coast caused significant morphological changes from 2018 to 2024. Despite a prior long-term negative coastal trend, sand spread both east and west from the nourishment area, filling the Appelzak channel. Over five years, a large sand accretion occurred offshore, exceeding the total nourished volume, suggesting additional sediment sources such as nearby beach erosion and offshore supply. The nourishments also altered local hydrodynamics, reducing tidal currents and causing persistent seabed "bumps" up to about one meter high that remained visible years after placement. Sand input to the channel has progressively increased since 2019, highlighting ongoing sediment accumulation beyond the nourishments themselves.*

6.7 Implications on the morphological processes

Zones A to B (Heist) are characterized by slow positive morphological changes on the beach and the shoreface. This is in agreement with the past long-term trend (Table 8) and explained by the sheltered hydrodynamic conditions east of Zeebrugge harbour driving sediment to these zones. However, hydrodynamics and sediment transport processes are complex there. Since the construction of the Zeebrugge dams, a large sand shoal has developed seaward of the low-tide line, which is dry at low tide. This shoal is still gradually growing both in size and height. The shallow channel between the beach and the shoal in front of the beach is maintained by the currents. At low tide, the ebb current accelerates as the water present on the beach has to drain away around the Zeebrugge dam. The current can be large in the channel between the shoal and the dam, and on the north side of the shoal, and it is directed seaward around the Zeebrugge outer harbour. Just after high tide, there is a weak local current, approximately at the level of the channel and directed seaward. This weak current makes a large circular movement (Figure 24). The flood current comes from around the harbour and flows towards the Schelde. In the sheltered zone to the east of the harbour dam, the beach has to be filled with water when the tide rises. Due to the inertia of the tidal current, the flow towards the beach only occurs beyond Heist. Due to the presence of the harbour dam, the water also has to flow back towards the sea near the dam at high tide, creating the large current around the sandbar.

Zone F Lekkerbek experienced a minor morphological change (79 570 m^3 over 5 years, equivalent to 0.01 $m^3/m^2/y$) of the beach compared to Knokke zone. The general evolution over the 5 years was a mild accretion. This is in accord with the long-term coastal trend (Table 8). As reported in section 6.5, an alongshore spreading of the nourished sand from Knokke supplies the beach in Lekkerbek zone.

Zone G and H (Zwin) is characterized by large morphological changes at the annual and decadal scale due to the continuous development and disappearance of marine features such as sand spit at the westward side of the Zwin, the channel, sand bars. Undoubtfully, they are driven by the complex hydrodynamics. Eurosense (1994b) undertook measurements on the shoreface around -3 m TAW at the eastern boundary of the Appelzak channel in front of the Zwin coast. The results suggest that the net sediment transport is directed to the west,

reflecting the ebb-dominance during calm condition, while the direction of the net transport is to the east when the onshore wave height exceeded 0.5 m high. Also, the longshore sediment transport is estimated at 3000 kg/m (240 kg/m of sand) and 4000 kg/m (260 kg/m of sand) during flood and ebb tides respectively under wave heights below 0.5 m. Under energetic conditions, the longshore sediment transport is much larger than calm conditions, with 6000 kg/m (1000 kg/m) during flood and 5000kg/m (500 kg/m) during ebb tides.

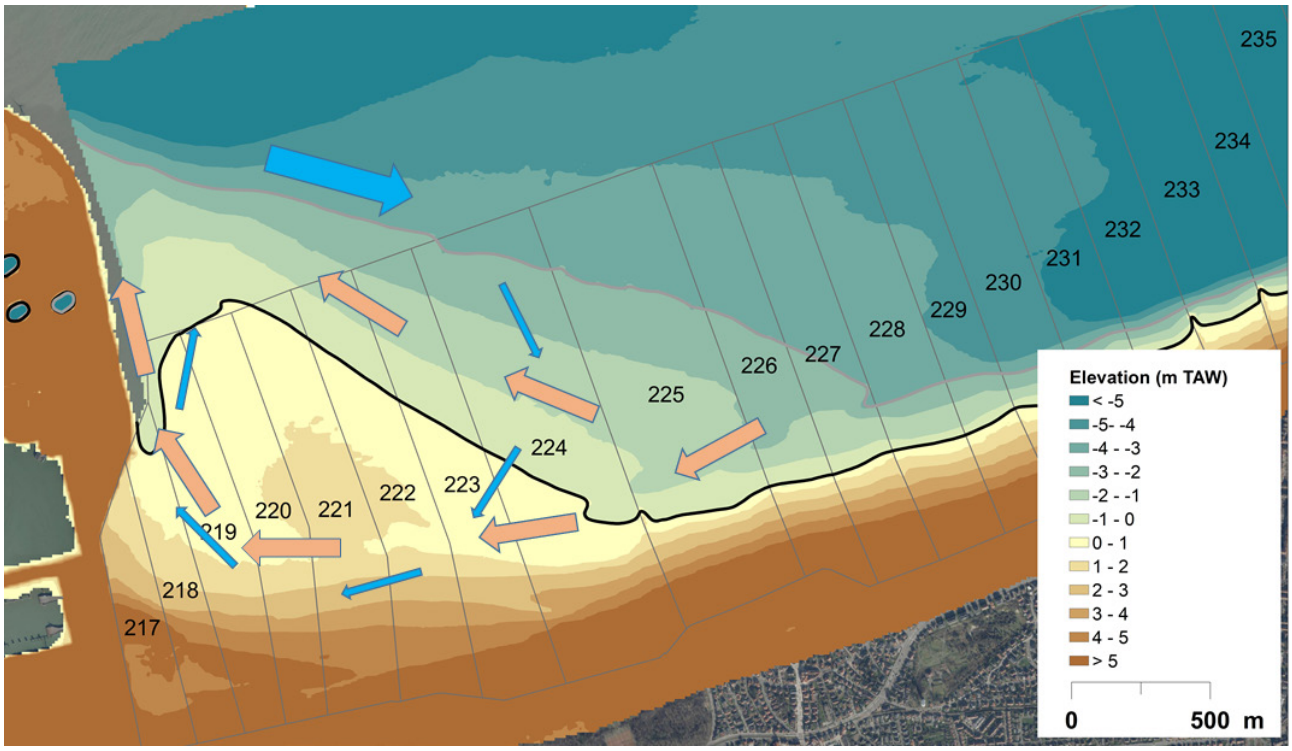


Figure 24 – Conceptual model of the hydrodynamic flow patterns derived from the configuration with the harbour dam, and the morphological development of the seabed and foreshore, near Heist. Blue arrows show flow at high tide, orange arrows at low tide. (Houthuys et al., 2023)

The beach alternated to accretion and erosion between 2018 and 2022 and then was volumetrically stable. Over the entire study period, the sediment budget of the beach-shoreface system at the Zwin is of -235 070 $m^3/m/y$ (+/- 347 950 $m^3/m/y$) which is much lower than the nourished zones. Generally, the shoreface has been stable over the 6 year period. However, the long-term trend of the shoreface in the Zwin is negative (-15.32 $m^3/m/y$) (Table 8).

Figure 25 presents the long-term evolution of the main morphological features along the study site which makes possible to get insights about the sediment transport processes. The recent elevation with the location of the Appelzak branches is displayed in Figure 26. The foreshore volume is no longer increasing from 2010. Heist still grows vertically and towards the beach, but on the seaward side it has experienced erosion since 2010. The shoal is probably the cause of local beach growth during the two most recent decades in sections 220-223. It plays an important role in breaking wave energy. On its eastern side, the sandbar is segmented by the Appelzak channel and its successive morphological features which are mainly located seaward of the foreshore ("Tak 1" located at 470 m from the coast, see Figure 25). It can be suggested that the sand supply from and around the foreshore determines the temporary reduction of this flow channel.

The seabed experienced two phases of strong erosion: first between 1986 and 1995 and second between 2010 and 2019. Both phases are separated by 15 years with roughly stable volumes. It mainly concerns deepening of the tidal channel Appelzak. At least since 2000, the deepening has mainly taken place in two coastal parallel branches. The most landward "Tak 1" temporarily extends into the Baai van Heist. The most seaward "Tak 2" (i.e. located at 120 0 m from the coast) connects in recent years to an erosion zone on the seaward flank of the Baai van Heist. The seaward section boundary is at the level of the sandbank Paardenmarkt. Also, it extends eastwards towards Cadzand and the landward flank also grows towards the coast, roughly 50 m since 2000.

A number of elements in the development of the Appelzak channel reflect the morphological predominance of the flood and ebb tides. The availability of sand determines which component temporarily dominates. In Heist, the erosion channel "Tak 1", parallel to the coast and located just in front of the foreshore, extends with varying degrees of distance into the sandbank of Baai van Heist. Time-varying supply of sand around Zeebrugge harbour might determine which morphological process temporarily dominates. We can expect that a reduction in hydrodynamics in Tak 1 counterbalances to an increase of flow discharge shifted seaward in Tak 2 where erosion dominates. Thus, the Appelzak has its own system reflecting the interactions between hydrology and morphology.

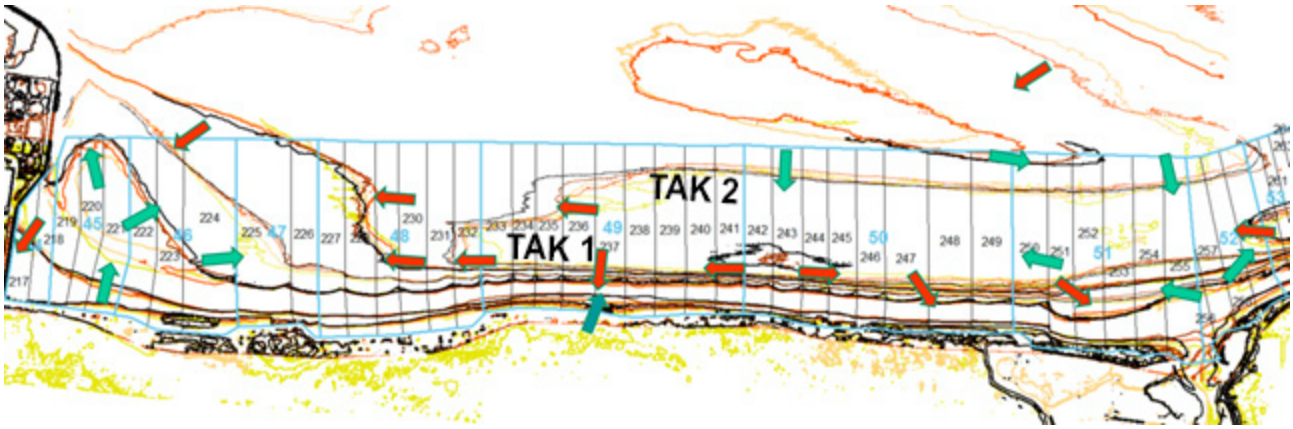


Figure 25 – Contour lines evolution between 2000-2019 (Houthuys et al., 2022).

Note: Schematic indication with thick arrows of the shift of the contour lines between 2000 and 2019. The arrows show the direction of movement of the contour lines, and thus not the direction of actual sediment transport. Red: natural erosion, light green: natural sedimentation, dark green: accretion directly following sand supply works. Height lines above 0 m TAW every 4 m; below 0 m TAW every 2 m. Yellow: 2000, orange: 2007, red: 2011, brown: 2015, black: 2019. Coastal strips outlined in blue, sections in black.

To improve our understanding of the sand transfer mechanisms from the shoreface to into the Appelzak channel (below closure depth), a combination of conceptual and numerical models can be employed. The hypothesis formulated based on observation can be tested using reduced complexity models such as ShorelineS (link with the project 20_79 MOZES) and processes based models such as ScaldisCoast.

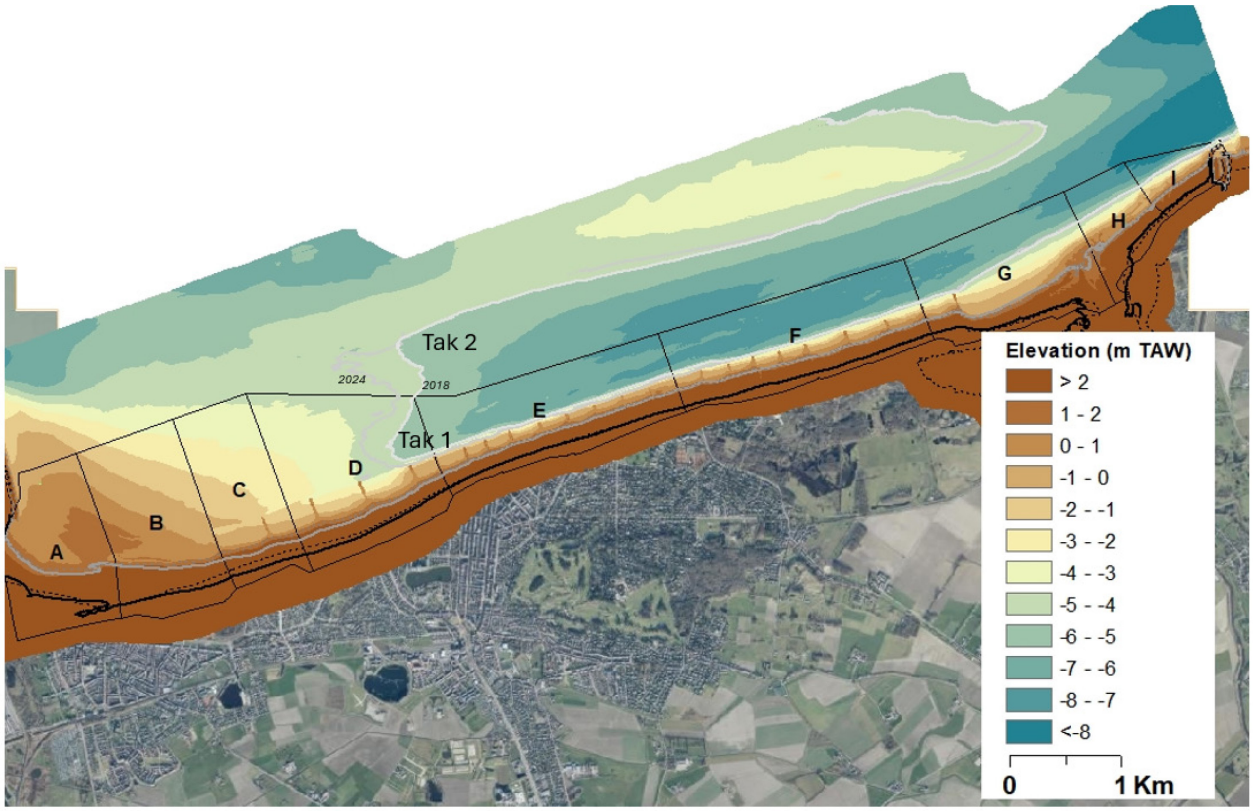


Figure 26 – DEM in 2024 with contour lines evolution between 2018 (bold line) and 2024 (dashed line).

Summary: *Zones A-B (Heist) show slow positive growth influenced by sheltered hydrodynamics and a growing sand shoal affecting local currents.*
Zone F (Lekkerbek) has minor, mild accretion over five years, supported by sand spreading from Knokke.
Zones G-H (Zwin) experience large morphological changes driven by complex ebb- and flood-tide hydrodynamics, with shifting sediment transport and alternating beach accretion and erosion until stabilization after 2022. The long-term shoreface trend remains negative.
Heist's foreshore volume stabilized since 2010, with seaward erosion linked to the sand shoal. The Appelzak channel shows two major erosion phases, reflecting tidal dominance and sand availability, with shifting erosion and deposition zones.
Conceptual and numerical models are proposed to further understand sand transfer processes between the shoreface and the Appelzak channel.

6.8 Local morphological impacts

A higher sand concentration in the water and also zones of choppy sea were reported by the Surf club in April 2024. These are probably a temporary consequence of the shoreface replenishment carried out in Knokke-Zoute. The DEM from 11/03/2024 shows on the lower foreshore with the presence of 0.5 m high underwater dunes (also called megaribbles), reflecting a mobilisation of sand mainly driven by flood current (i.e. the megaribbles are asymmetrical with deposition slope on their east side). Then this sand moves towards the Zwin.

The observed shallow zones probably correspond to an accretion zone around the high-tide line and one on the upper foreshore between +1 and +2 m TAW in sections 245 and 246, near the surf club (see Figure 7). These can only be explained by the erosion of the beach supplemented in Knokke-Zoute in 02-04/2023. As a result, the beach near the surf club is more profiled with a system of ridges and troughs.

Since April 2024, the deeper foreshore near the surf club shows no growth that can be related to the shoreface replenishment at Knokke-Zoute. However, the bottom of the Appelzak channel here has become shallower between 0.1 and 0.4 m, as a result of spreading sand from the shoreface replenishment zone (Figure 27). Near the surf club, it is expected that no permanent shallows or breaker banks will be created in front of the beach. The current and turbulence will recover to the pre-existing regime fairly quickly. As long as there is a disequilibrium of the beach-shoreface morphology and sea state, swimmer and beach user must be slightly more vigilant in this zone. The more strongly profiled morphology on the beach is expected to disappear rapidly due to erosion of the intertidal beach, after which the morphology and hydrodynamics will return to pre-existing behaviour. In the longer term, the foreshore and Appelzak will evolve to the pre-supplementation depth. In general, morphological developments on the foreshore and seabed are slower than on the beach. Thus, this evolution will take several years.

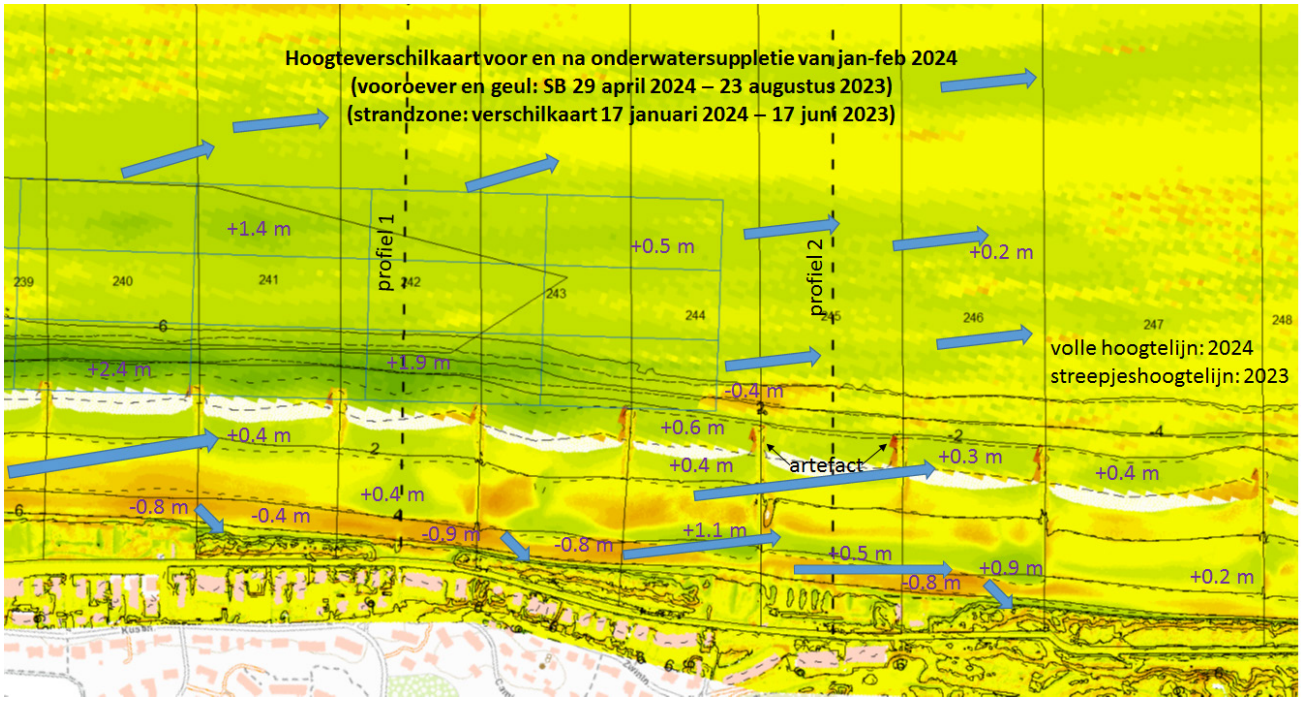


Figure 27 – Interpretation of sediment transport based on sediment transport processes in section from 240-247 superimposing on the pre-post nourishment DoD. The thick blue arrows show the sediment transport derived from the morphological development over the period. Purple values are the height difference at some selected points. Green is accretion and red erosion. The area of the nearshore nourishment is indicated by the rectangles in sections 239 to 244. (Houthuys et al., 2024)

Summary: *Higher sand concentrations near Knokke-Zoute likely stem from recent shoreface replenishment. Underwater dunes on the lower foreshore, shaped by flood currents, are moving sand toward the Zwin. Accretion near the surf club reflects beach erosion supplemented by nourishment in early 2023, creating a more ridged beach profile. Since April 2024, the deeper foreshore shows no significant growth, but the Appelzak channel bottom has slightly shallowed due to sand spreading. No permanent shallows or breaker banks are expected, and currents should soon normalize. Beach morphology changes will erode quickly, with foreshore and seabed gradually returning to pre-nourishment conditions over several years.*

7 Conclusions

In the framework of the Knokke mega-nourishment project, 3 359 174 m^3 sand was supplied to the coast from Duinbergen (zone C) to Knokke-Zoute (zone E) between 2019 and March 2024. The main observations of the annual morphological changes and a sediment budget of zones covering the study site are:

Within the framework of the Knokke mega-nourishment project, a total of 3,359,174 m^3 of sand was supplied along the coast from Duinbergen (Zone C) to Knokke-Zoute (Zone E) between 2019 and March 2024. The main observations concerning the annual morphological changes and sediment budget across the study zones are as follows:

a) The Duinbergen coast exhibited generally slow positive morphological changes on the beach, while the shoreface remained stable. The large beach nourishment conducted in February–March 2021 resulted in a beach width increase of approximately 90 meters. In the subsequent years, the nourished sand largely persisted, with beach profiles maintaining a shape similar to those immediately after nourishment. Minimal morphological evolution was observed after one year, characterized primarily by slight alongshore spreading of sand both westward and eastward. Although some sand loss occurred between 2021 and 2023, minor accretion was noted in 2024. Consequently, approximately 93% of the nourished sand remained after three years, indicating that the beach-shoreface system at Duinbergen exhibits relatively mild morphological changes compared to other nourished sites within the study area.

b) Zone E (Knokke) and the adjacent part of Zone D (Alberstrand) are prone to erosion driven by hydrodynamic processes. Between 2021 and 2024, a series of beach nourishments totaling 576,500 m^3 was carried out at Knokke-Zoute. However, 69% of this nourishment volume was lost over the period. Specifically, following the most recent nourishment in February–March 2023, 29% of the sand had already disappeared within nine months. This rapid erosion highlights the dynamic nature of the Knokke coast, where both alongshore and cross-shore sediment transport contribute to sediment redistribution.

c) The efficiency of the nearshore nourishment conducted in 2020–2021, characterized by fine-grained sediment, was estimated at 93%. In contrast, the efficiency of the larger nourishment carried out in 2023–2024 ranged between 61% and 72%. It is important to note that accurately quantifying morphological “efficiency” is challenging, as before-and-after surveys are often not perfectly aligned in terms of spatial and temporal resolution.

d) The Appelzak channel experienced significant sand accretion between 2018 and 2024. Within the delimited zone encompassing the entire offshore accretion area, an estimated 2.4 million m^3 of sand accumulated over five years, exceeding the total nearshore nourished sand volume along the entire study coast by approximately 1.4 million m^3 between 2020 and 2024. This surplus likely includes contributions from adjacent beach erosion—particularly from the Knokke-Zoute 2023 nourishment—but a substantial excess remains unexplained, suggesting an additional offshore sediment source. It is hypothesized that nearshore nourishments may have altered tidal currents by partially blocking the tidal channel in front of the shoreface, diverting flows further offshore into the Appelzak channel. The persistence of “bumpy” morphological features on the channel bed for over a year in 2022 and 2023 supports this interpretation. This localized hydrodynamic effect may have facilitated sediment deposition on the channel bed both west and east of the nourishment area.

e) The nourishments in the study area were carried out in different years, and especially the most recent ones have yet to exhibit their full evolution. Therefore, the long-term development of the nearshore nourishment at Knokke-Zoute should be further examined in the coming years.

8 Recommendations

A series of recommendations can be formulated to enhance the understanding and quantification of the processes controlling the Knokke-Zwin coastal area.

1. The conceptual model of sediment transport along with the corrected volumes (human interventions subtracted) should be further developed. This will be updated in the ongoing project 24_015 Morphological trends. It should be mentioned that human interventions can be corrected in terms of volumes, but the morphological feedback induced by these interventions can only be interpreted in correlation with historical evolution and local conditions.

2. The system of Appelzak channel and its adjacent shoreface area is unique and it requires continuous monitoring and research in order to inform the appropriate coastal protection measures. It is recommended to continue the monitoring through topographic and bathymetric surveys. In recent years, the Appelzak has shown positive behavior, potentially due to offshore sediment supply and milder shoreface slopes that may mitigate erosion trends at Knokke-Zoute. Special attention should also be given to potential sediment sinks and sources, such as the Zwin inlet and nourishments conducted by Dutch beach managers in the Cadzand area.

3. The evolution of the finer-sand nourishment performed in 2024 already shows preliminary trends, but the monitoring period is too short to fully assess its efficiency. Given the planned additional nourishment of the Knokke area in 2026, it is recommended that monitoring will continue in order to capture its long-term effects on beach stability.

The Knokke area is expected to maintain an erosive state in the future due to factors including the presence of the Appelzak channel and boundary conditions such as the blockage of littoral drift by the Zeebrugge harbour. A potential sediment source is the sand accumulation southwest of the Zeebrugge harbour, which could be periodically redistributed to zones experiencing maximum erosion. To strengthen coastal resilience, protect inland low-lying areas, and address accelerated sea-level rise, promoting the growth of sand dunes in front of hard sea defenses is advised.

4. It is expected that the Knokke area will also maintain its erosive state in the future due to the presence of Appelzak channel and other boundary conditions such as the blockage of littoral drift by harbour of Zeebrugge. A potential sediment source is the sand accumulation at the southwestern side of the Zeebrugge harbour, which could be periodically redistributed to zones experiencing maximum erosion. To strengthen the local coastal resilience, protect inland low-lying areas, and address accelerated sea-level rise, promoting the growth of sand dunes in front of hard sea defenses is advised.

5. Several ongoing projects at Flanders Hydraulics and other Belgian institutions are advancing knowledge on the interactions between the active beach and adjacent systems, such as the coastal dunes and the offshore sandbanks. It is recommended that further research on the Knokke area integrate these new developments, considering its distinctive morphology characterized by a narrow beach and frequent cliff formation following storms.

9 Highlights

- ✓ The large beach nourishment at Duinbergen in 02-03/2021 resulted in an increase of the beach width. A minimal evolution of this zone occurred after 3 years. Thus, the coastal system in Duinbergen has a very mild morphological evolution.
- ✓ Knokke and Lekkerbek are liable to erosion by hydrodynamic processes. A succession of beach nourishments was carried from 2021-2024 when 69% of the efforts were lost.
- ✓ Efficiency of the Knokke nearshore nourishment in 2023-2024 characterized by small grain size ranged from 61% to 72%. Erosion is a fast process there where both along- and cross-shore sand transfers occur.
- ✓ Appelzak channel gained significantly sand between 2018-2024. Inside a delimited zone encompassing the entire offshore accretion area, an accretion of 2.4 M m^3/5y. This value exceeds the total amount of the nearshore nourished sand of approximately 1.4 M m^3 along the entire study coast between 2020-2024.
- ✓ The excess of over 1.4 million m^3 may contain a supply from nearby beach erosion, especially from the Knokke-Zoute 2023 beach nourishment, but then a significant excess still remains so that it implies an additional offshore supply.
- ✓ Analysis of the Knokke nourishment will be completed with data from 2025 in the new coastal trend project.

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