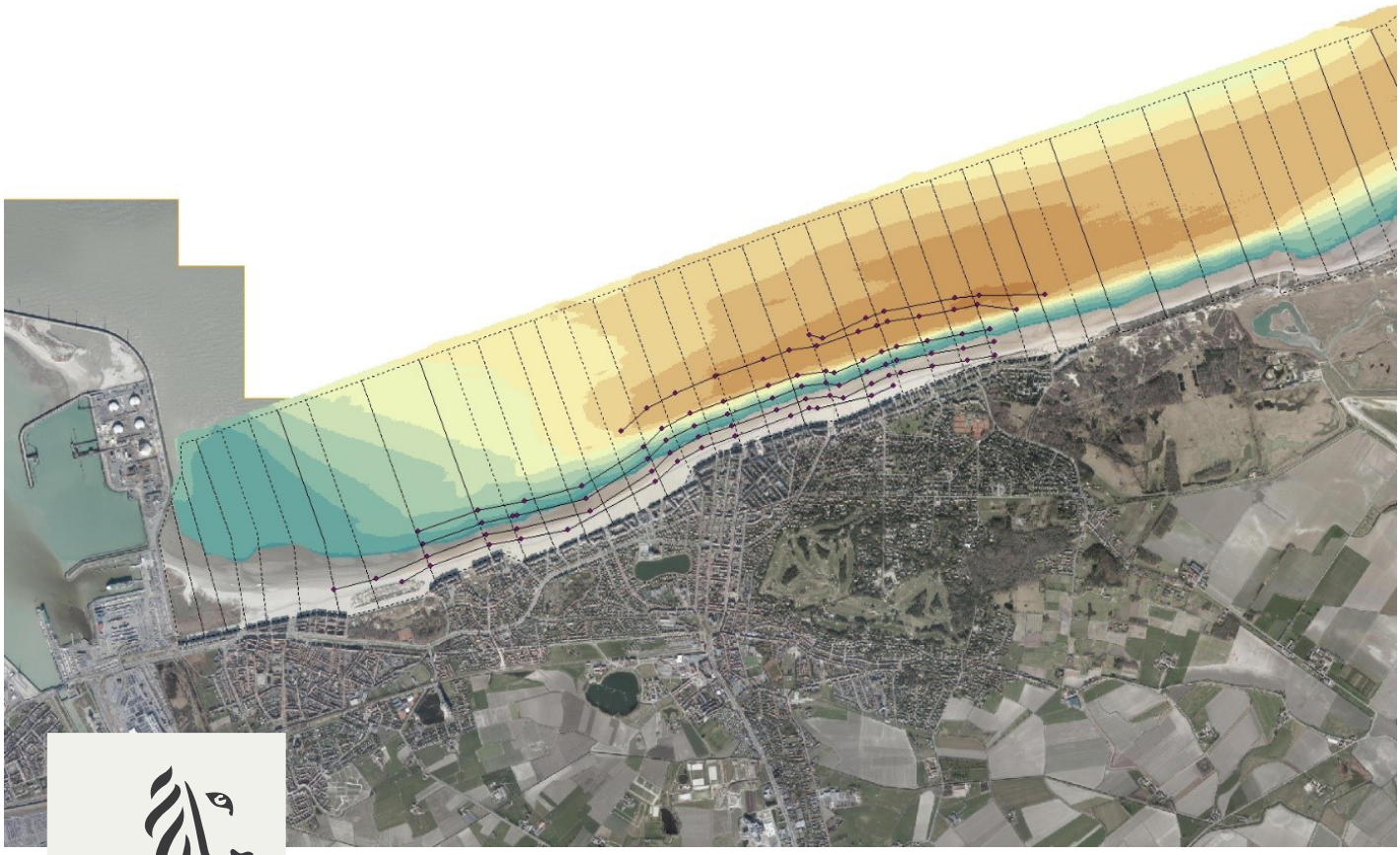

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Evolution of a large coastal nourishment at Knokke

2nd year progress report

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Evolution of a large coastal nourishment at Knokke

2nd year progress 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. 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 shoreface nourishment of a total of approximately 3 million m^3 of sand for the Knokke area in the period 2020 – 2025. The aim of this study is to understand the hydrodynamics and morphodynamics of the Knokke area and to evaluate the mega-nourishment. This 2nd year progress report focuses on coastal morphodynamics along the Belgian coast from Zeebrugge harbour to east of the Zwin between 2018-2021. The results clearly indicate the significant effect of the nourishments on the beach and shoreface morphology. Future topographic and bathymetric monitoring and use of digital survey data of the morphology immediately after each nourishment stage will allow to document and understand the ensuing morphological development and efficiency of the nourishments.

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1 Introduction

Parts of the Belgian coast are eroding, which increases the risk of flooding during extreme storms and decreases 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 across the Belgian coast. A long-term erosive trend has been observed in the area of Knokke-Heist in the last decades. After repeated beach nourishments over that period, a major scheme is now being implemented, as communicated by Coastal Division: a meganourishment of the beach and shoreface is planned for the Knokke area in the period 2020 – 2025 (Figure 1). In the period 2020 - 2022, it is planned to use a total of approximately 2.9 million m^3 of sand from the new lock construction site in Terneuzen (NL) as foreshore replenishment. The nourishment will take place in several steps spread over several years and adaptable according to circumstances.

The updated calendar of the nourishment is detailed below:

- 2020: shoreface nourishment : first phase 14 800 m^3 in May and June, second phase November and December 130 000 m^3 covering section 235-240;
- 2021: shoreface nourishment from February to March of 982 000 m^3 on the shoreface from sections 223 - 230 and in August 150,000 m^3 on the shoreface from sections 232-240
- 2024 or 2025: beach nourishment 2 000 000 m^3.

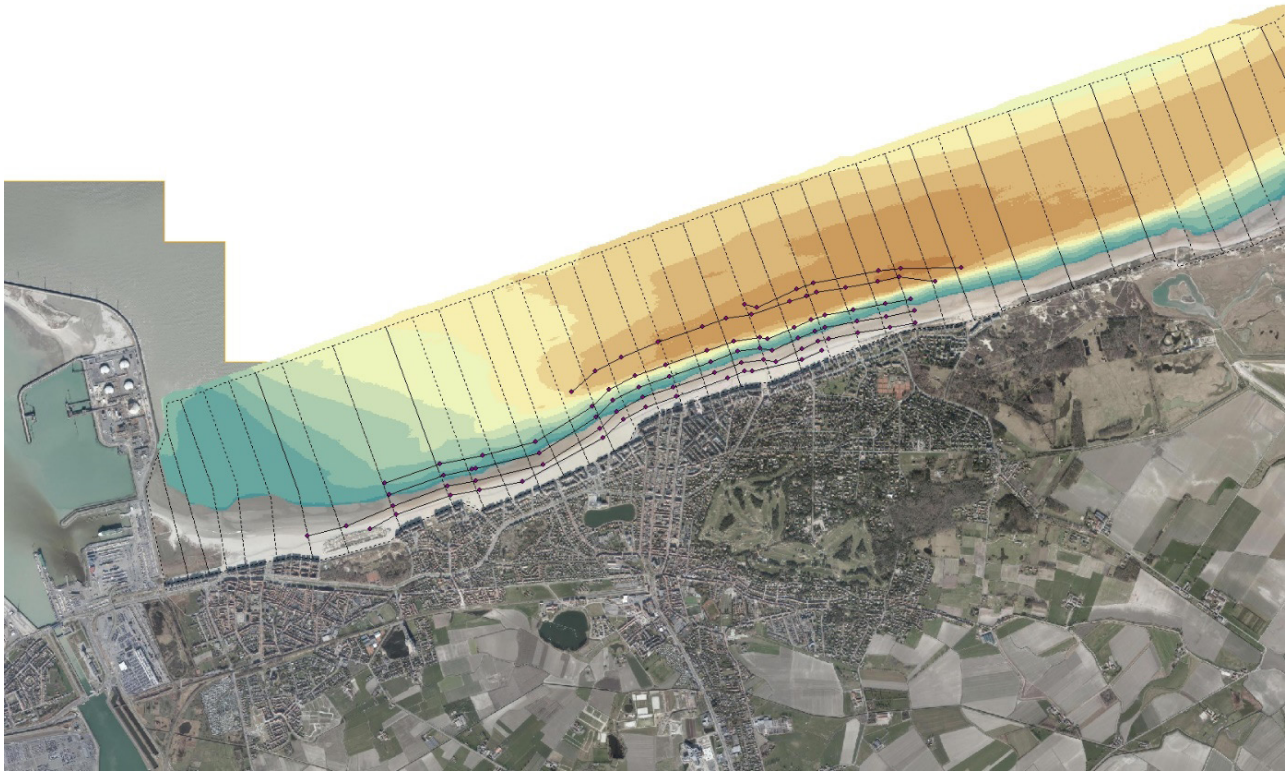


Figure 1 –The design of the Knokke nourishment.
The solid lines with points approximately parallel with the present shoreline describe the future nourishment.

The coast between the outer port of Zeebrugge and the Zwin is a complex morphodynamic zone due to the presence of the harbour of Zeebrugge, the geomorphologic marine bedforms, frequent artificial sand supplies and the undulating trace of the coastline/sea dikes. The coast experiences two large opposing sediment fluxes alongshore that sum to a small net flux, leading to large spatial gradients and morphological variability (Montreuil et al., 2019). On average the sediment budget shows natural feeding (+77 063 m^3/y between 1980s and 2019), yet local erosion is problematic.

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 by natural processes (Houthuys et al., 2021). However, the rate of accretion has decreased in recent years. Toward the east, the long-term evolution of the coast from Duinbergen-centrum to Zwin (stretches 47-51) is erosional. This is related to the blockage of the littoral drift by the harbour of Zeebrugge.

The largest erosional trend occurs at Knokke-Zoute with a rate of -42.16 m^3/m/y (stretch 49). This is probably related to the natural deepening of the Appelzak tidal channel, which is thought to be fed with beach-derived sand during storm erosion but then cleared by tidal currents. Locally stronger tidal currents and the high erosion rate may also be related to the protrusion of the coastline/sea dike in this stretch. An expression of tidal current erosion is the trend of the channel's eastward prolongation. The tidal currents have two parallel flow axes, named Branch 1 (close to the shore) and Branch 2 (close to Paardenmarkt sandbank). It has also been put forward that natural accretion and landward migration of the Paardenmarkt sand bank, coupled with the stationary position of the shore due to repeated nourishment, which hampers the Appelzak channel to move onshore, forces this channel to deepen its bed (Houthuys et al, 2021).

The aim of this project is to better understand the hydrodynamics and morphodynamics of the Knokke area and its surroundings and to evaluate the effects of the nourishment. 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 report focuses on the coastal morphodynamics and processes along the east Belgian coast from Zeebrugge to the Zwin between 2018 (pre-nourishment) and 2021.

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 (Figure 2).

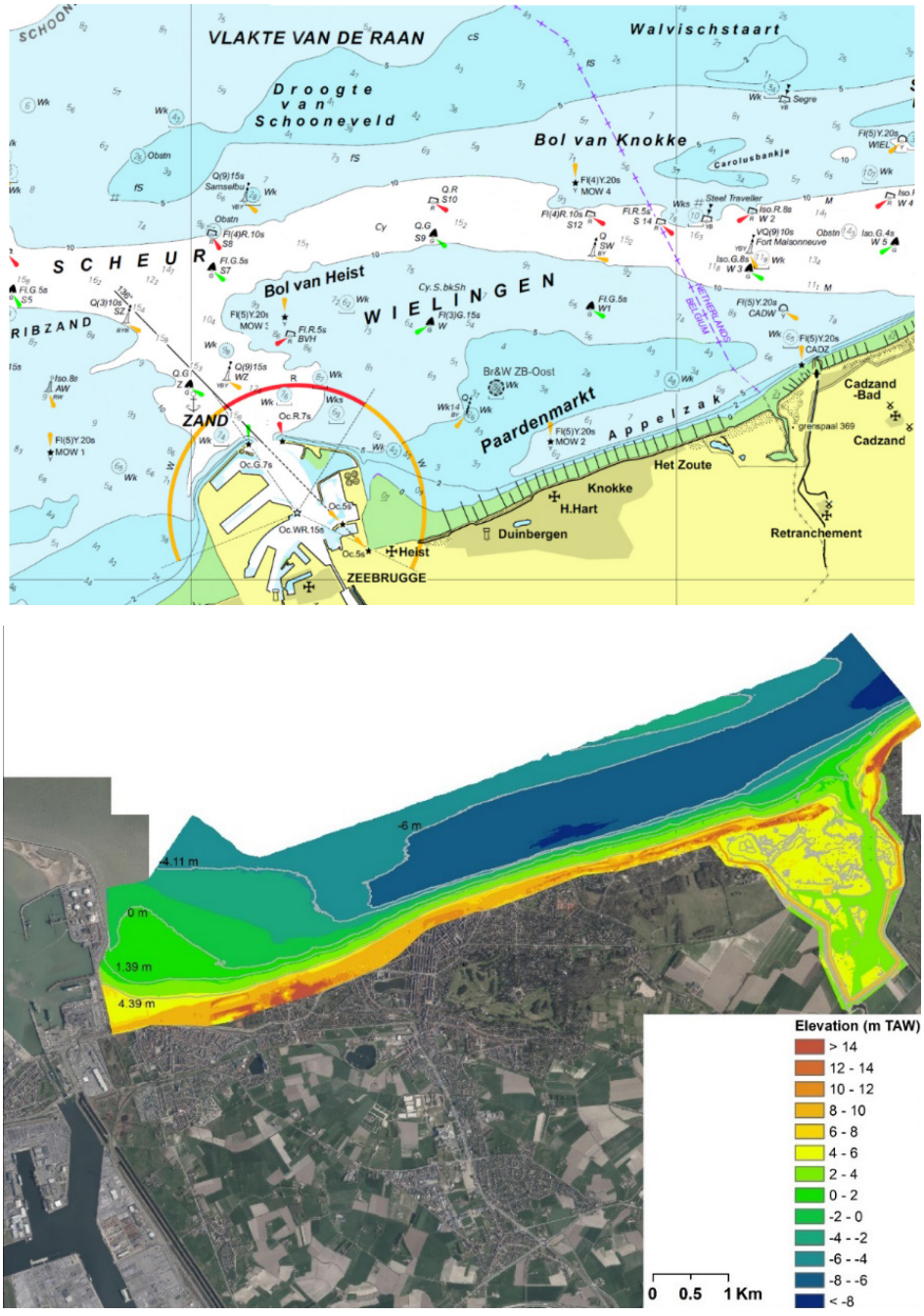


Figure 2 – A) Nautical map with distinct geomorphological marine bedforms; B) Topography of the east coat with contour lines.

The morphodynamics is influenced by the presence of the Zeebrugge breakwaters where a large accretional area extends up to 4 km into the Baai van Heist due to wave sheltering effect as well as the asymmetry of the tidal currents. Blockage at the west side of Zeebrugge of the eastward directed littoral drift results in a positive gradient of longshore sediment transport in Knokke-Heist which drives erosion. The coastline at

Knokke-Zoute locally protrudes seaward due to the position of the sea dike, which induces locally an increased coastline erosion. Sand loss further increases due to the presence of regional large-scale marine morphologic units namely the Appelzak tidal channel which in turn seems to be (partly) controlled by the influence of the Paardenmarkt sand bank. The cumulative effect of these mechanisms leads to severe erosion in Knokke-Zoute. The coastal stretches west of the Zwin inlet also experience long-term erosion. The morphological trends of the emerged beach and the shoreface vary in time and space. Although the sediment overall budget is positive in the study area, erosion is locally problematic. Further details about morphology, human interventions and regional hydrodynamics are presented in the first annual report (Montreuil et al., 2021).

The east coast is about 12 km long and is divided into sections from 217 to 266 (Figure 3). These morphological monitoring sub-units cover the cross-shore domain from the foredune or the sea dike up to 1500 m offshore and span approximately 200 to 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 (Table 1). Sections A to D were extended seaward in order to include the area where the wave induced cross-shore transport is still significant. For sections E to I the seaward limit was considered function of the closure depth and the presence of the Appelzak gully.

Figure 3 – Defined coastal zones.

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	217-255	52	Zwin geul	1 070	935 345
I	256-266	53	Cadzand-west	685	1 207 360

3 Methodology

3.1 Topographic and bathymetric survey acquisition and processing

Airborne LiDAR (Light Detection And Ranging) surveys are routinely conducted to measure the emerged beach above the low water line. These data is owned and kept at MDK Coastal Division and is made available in ASCII format (X, Y in Lambert 72 and Z in TAW). The morphology evolution between 2018 and 2021 is here analysed for the surveys presented in Table 2. The spatial resolution of the surveys is always at least 1 point/m^2, mostly up to 5 points/m^2. These data were used to generate Digital Elevation Models (DEMs) with 2 m grid size. They extend from the dyke or dunes 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 is owned and kept 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 2021 in order to assess the morphodynamics of the study zone and the evolution of the nourishment. The differences between consecutive years were carried out to observe possible sudden changes in the erosion/deposition pattern which might have occurred.

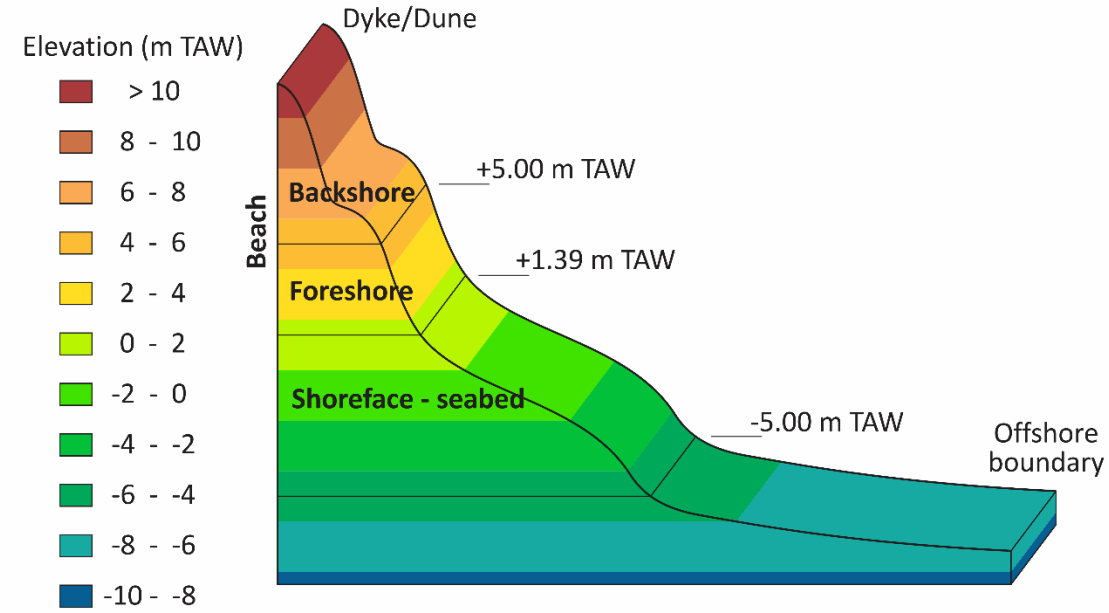
Table 2 – Timeline of topographic and bathymetric measurements, as well as the nourishments between 2018-2021.

Date	Description
17/04/2018 (pre-nourishment)	LiDAR survey
28, 30/05 and 06/07/2018	Bathy survey
02-03/2019	Beach Nourishment (section 234-243) 292 502 m^3
20/04/2019	LiDAR survey
23/05/2019	Bathy survey
10/04/2020	LiDAR survey
05-06/2020	Beach Nourishment (section 235-240) 14 800 m^3
23/06/2020	Bathy survey
11-12/2020	Beach Nourishment (section 235-240) 130 000 m^3
02-03/2021	Beach Nourishment (section 223-230) 982 000 m^3
28/04/2021	LiDAR survey
31/05/2021	Bathy survey
08-09/2021	Shoreface Nourishment (232-240) 150 000 m^3

Note: In 2019, beach nourishment of 150 000 m^3 in Cadzand

3.2 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 TAW (Figure 4). This division is slightly different from Houthuys (2021) because the new limit is defined also function of the area were the nourishments are performed. 'Beach' is a sum-up of the backshore and foreshore. 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. The shoreface-seabed zone is considered as the area above the depth of closure. The latter is defined as the seaward limit of the shoreface-seabed below which morphodynamics is less influenced by waves, which is approximately at -5 m TAW. The layer definitions were applied on the 2018 survey, after which the boundaries shown in Figure 4B are 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.



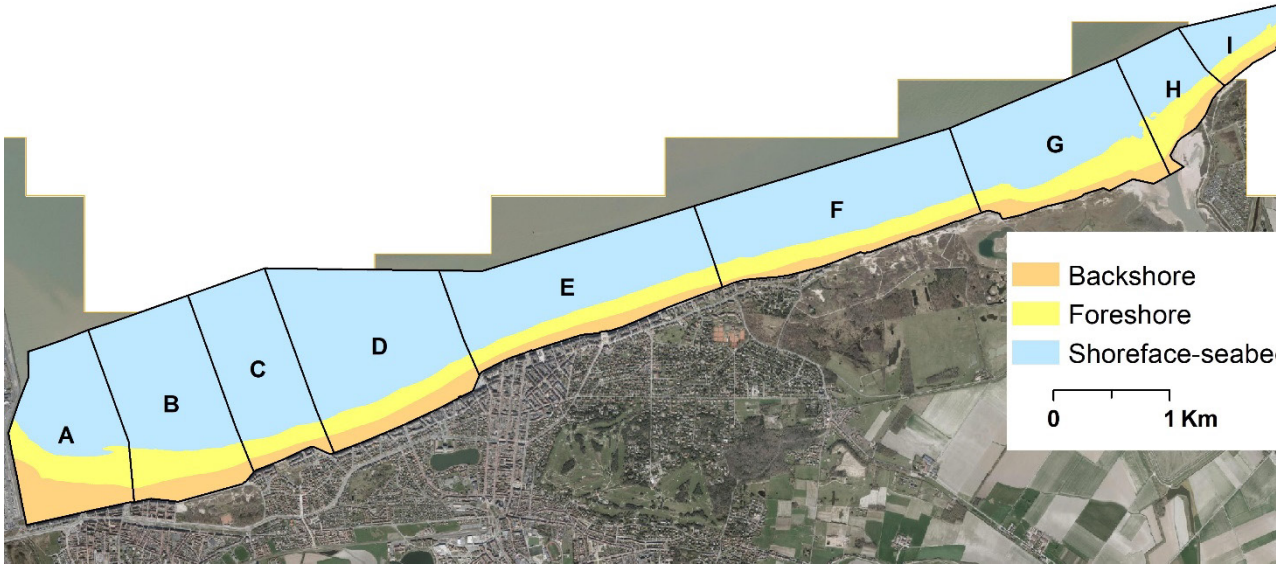


Figure 4 – Definition of the sediment layers in cross-shore, alongshore (B) direction.

4 Sand nourishments

In the current major nourishment scheme for Knokke, sand supply of the shoreface was carried out in 3 phases between 2020 and 2021 (Table 2). Sand nourishments that took place on the beach in 2019 and 2020 were discussed in the 1st progress report (Montreuil et al., 2021).

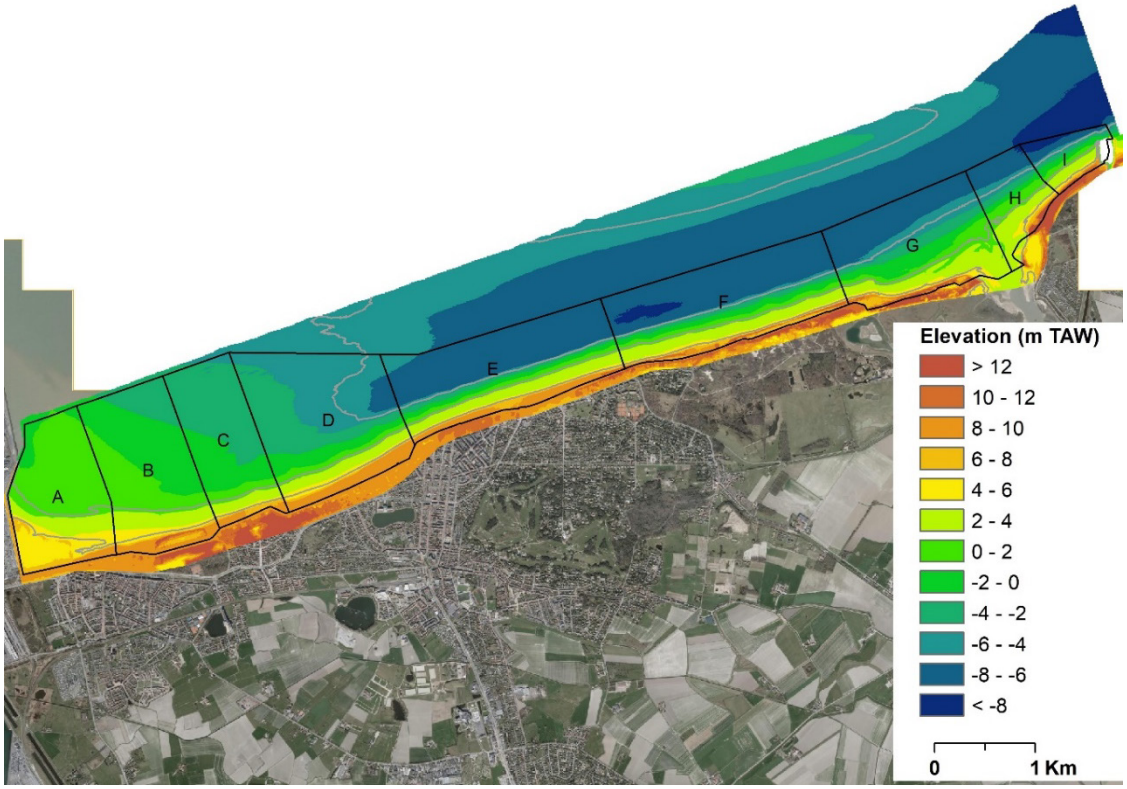
The design at Duinbergen (Figure 1) leads to a protrusion of the beach in sections 225-226 connected by a smooth curve to the pre-existing profile in the neighbouring sections west and east. The nourishment carried out in 02-03/2021 realized the design almost perfectly, except in the easternmost section (slightly underfilled). In the most protruding sections, the low-water mark was moved 90 m seawards by the nourishment and the high-water mark 120 m. The vertical accretion amounts to 3 m in the most heavily nourished sections. The nourishment affected the profile from +7 m TAW down till -1 m TAW. Appendix A displays maps and some pre- and post-nourishment cross-shore profiles of the phase carried out along 2 km at Duinbergen (223-230) in 02-03/2021. Although nourishment data are digitally available, they have not been provided to us. They would however be interesting to determine the efficiency of the nourishment.

5 Results

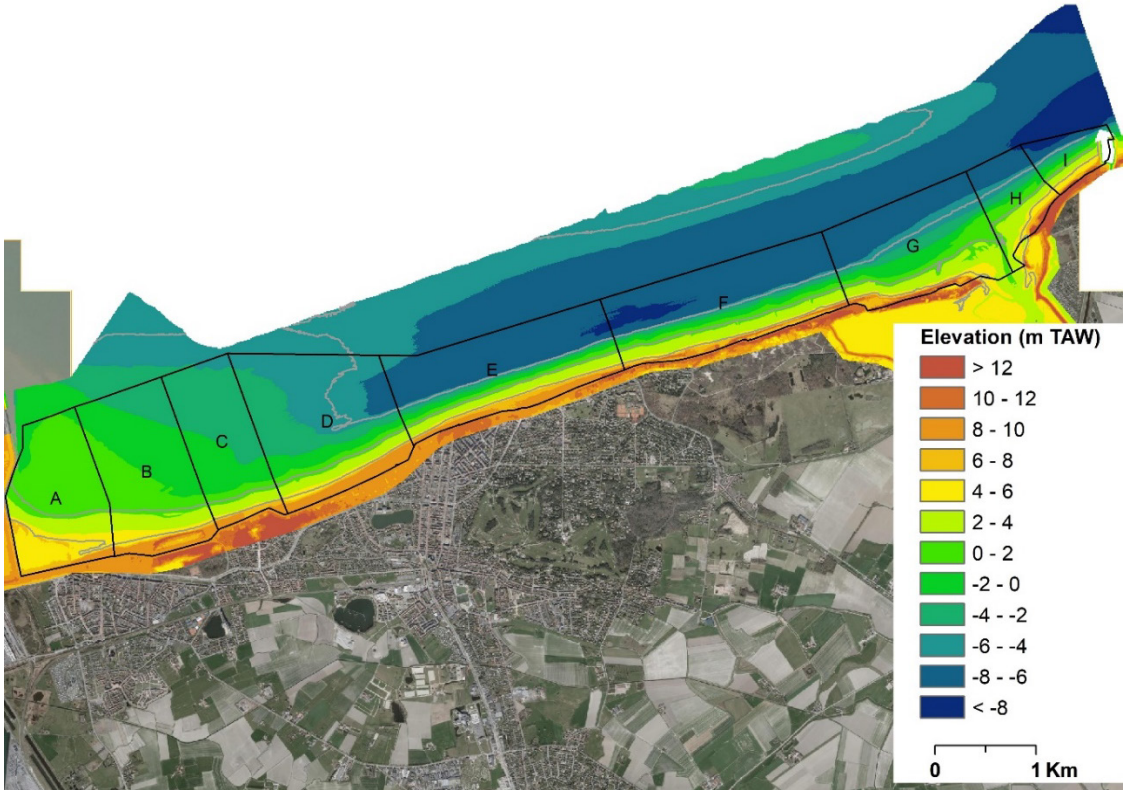
5.1 Morphological changes

The topography of the beach and shoreface along the east coast is characterized by spatial variability with the beach wider and shallower on the west side, while the beach zone is narrower where the Appelzak channel is located (from zone D to the east of the study site) (Figure 5). Beach width from the dune to the low water line ranges from 210 m in Knokke-Zoute and Lekkerbek (zone E and F) to 500 m at Heist-west (zone A). The deepest elevation in the Appelzak is about -8 m TAW. The coastline is relatively straight and oriented SW-NE. However, it is shifted offshore in front of Knokke-Zoute, and between the Zwin and Nieuwvliet (the Netherlands).

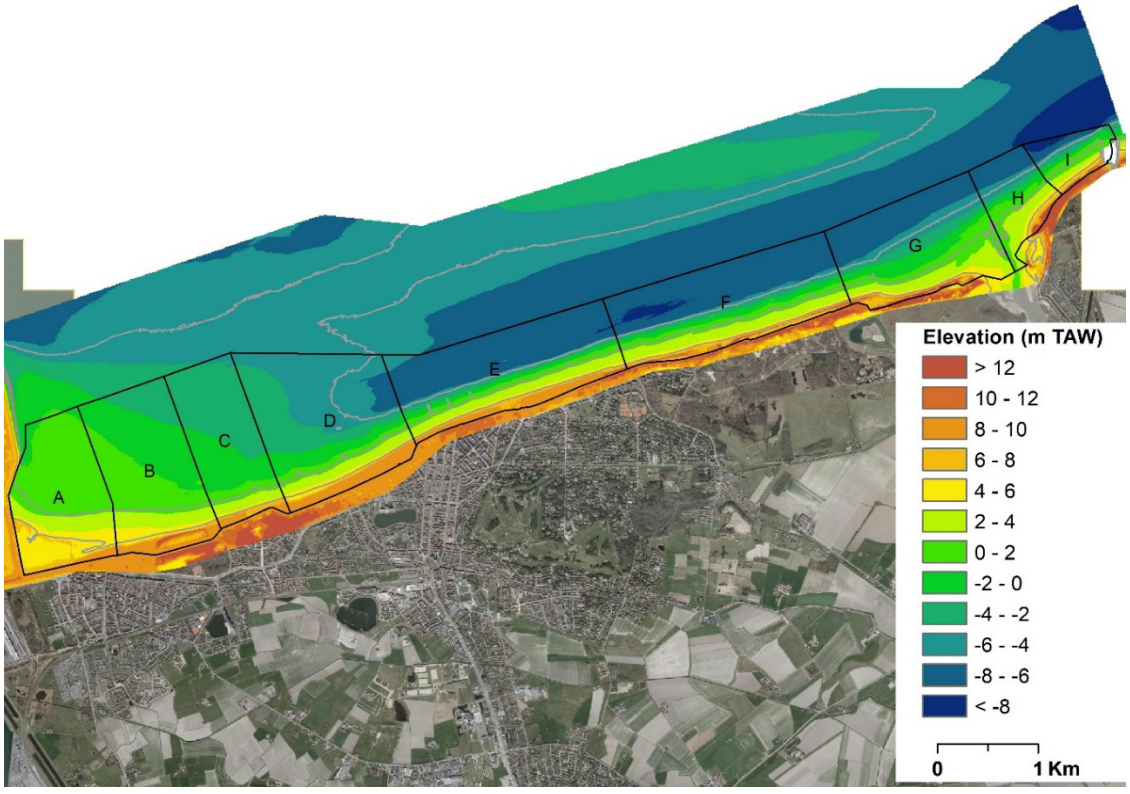
A) 2018 (pre-nourishment)



B) 2019


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

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

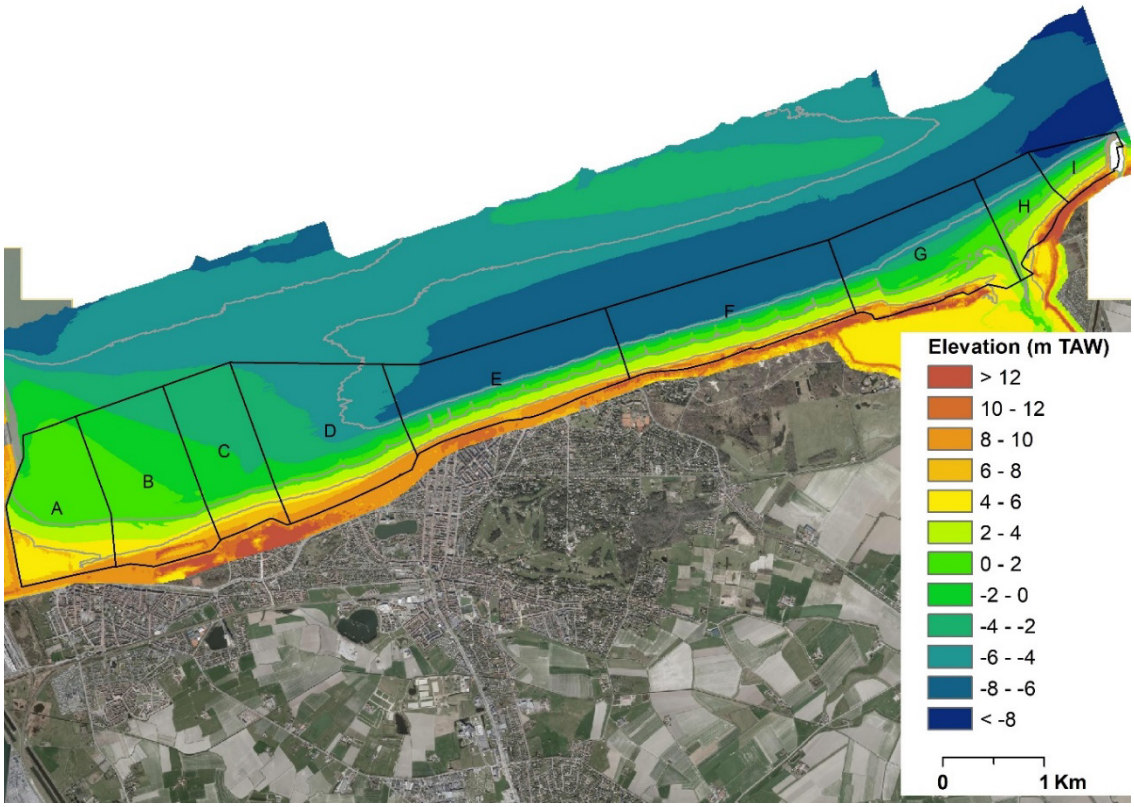


Figure 5 – Generated DEMs of the merged beach and shoreface surveys.
Grey lines represent contour lines of +5, +1.39 m and -5 m TAW

Figure 6 presents three cross-shore profiles extracted from the time series of DEMs and covering the areas nourished or to be nourished:

- 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. After the large nourishment in 02-03/2021, the beach from +7 to +1 m TAW generally gained 2 m height, while the sand gain was much lower on the upper part of the shoreface (till -1 m TAW).
- 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 area nourished in 2021.
  Sand nourishments were carried out in Knokke-Zoute (Profile 3) in 2019 and 2020 (none in 02-03/2021). However, the beach including the backshore and the foreshore till +2.7 m TAW was higher in 2019 compared to the situation in 2021. The shoreface below +0.5 m TAW shows a gradual accretion from 2018 to 2020, by small amounts. This may be related to local beach erosion (cross-shore seaward transport from the beach to the shoreface).

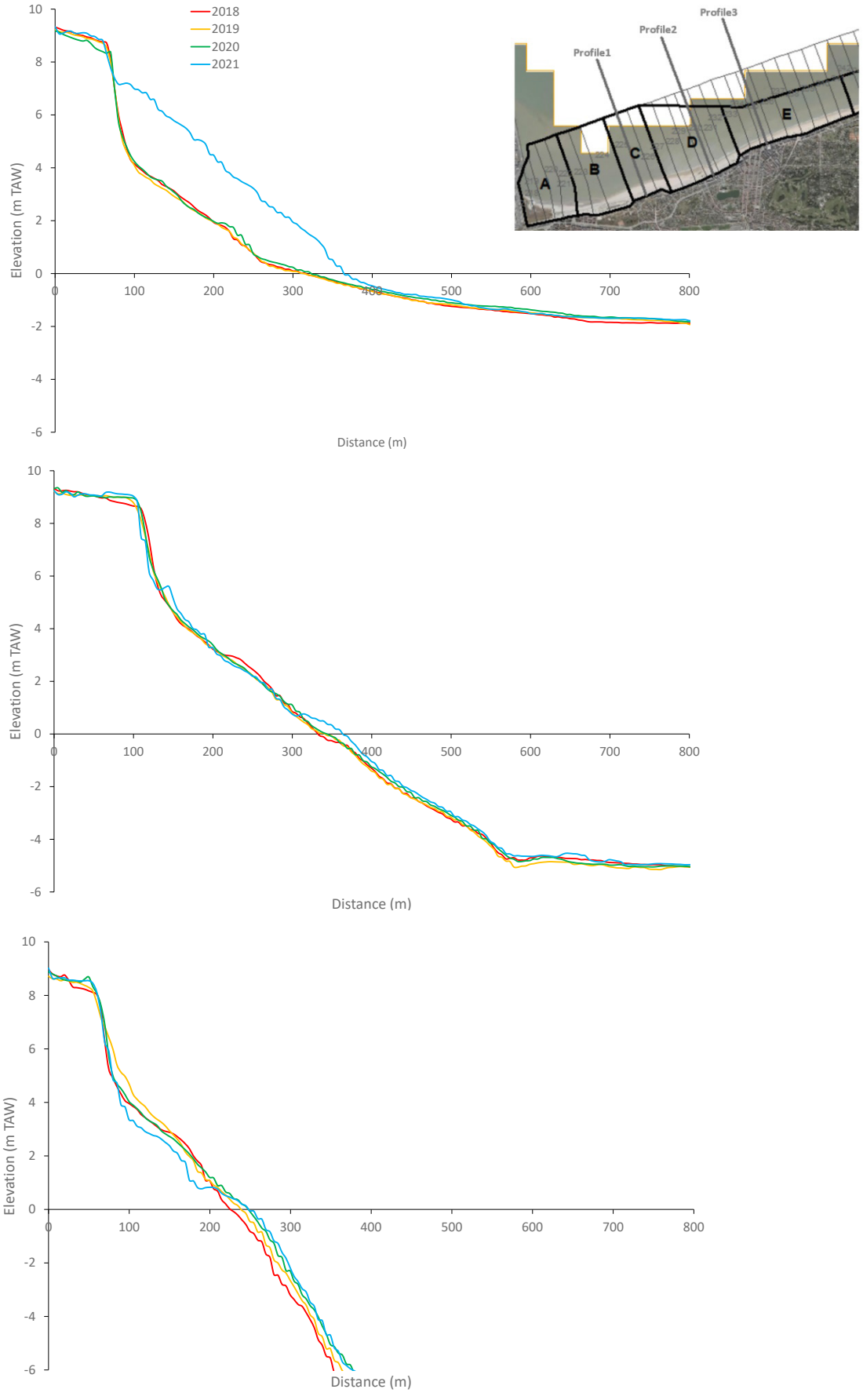


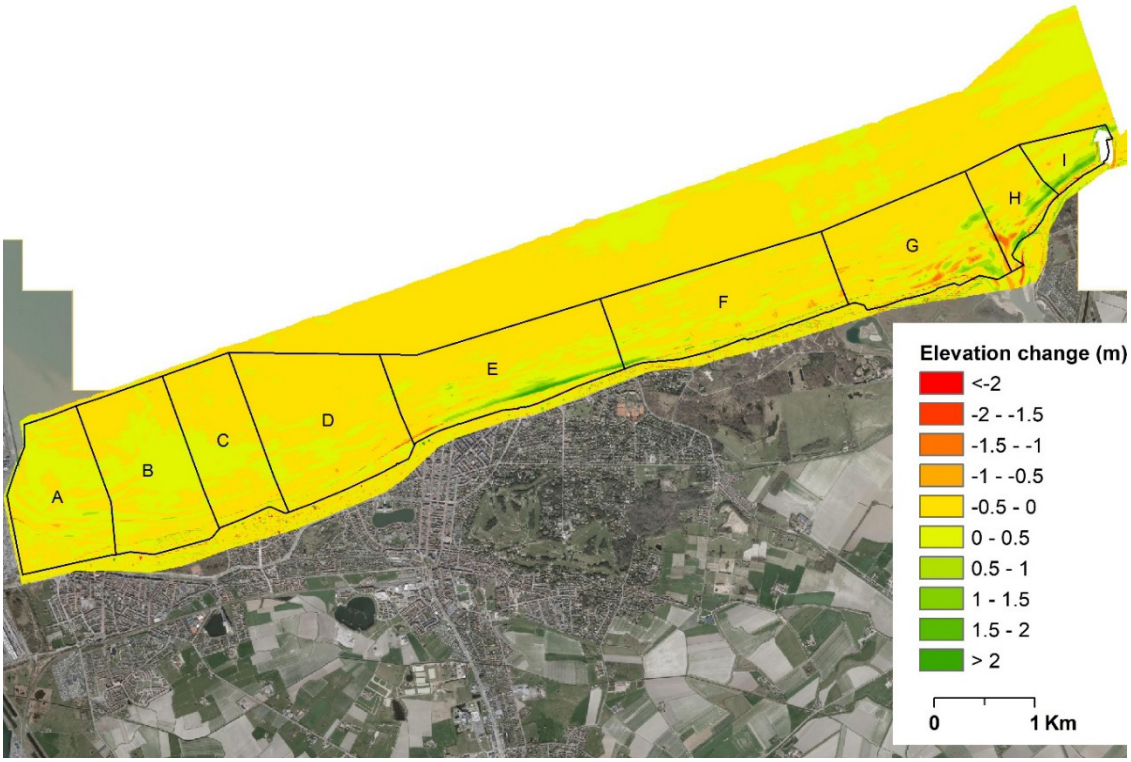
Figure 6 – Cross-shore profiles (Profile 1 in section 225, Profile 2 in section 230 and Profile 3 in section 235) extracted from the DEMs.

The DoDs between consecutive surveys are displayed in Figure 7, in which red and green indicates erosion and accretion, respectively.

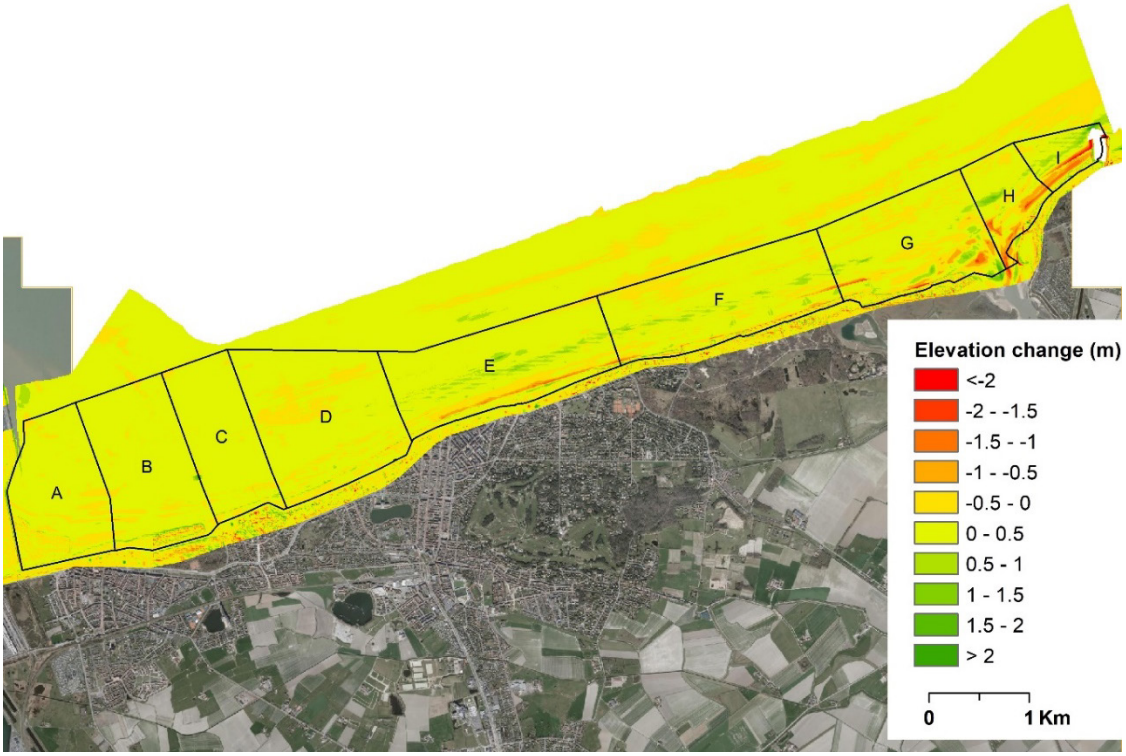
- A clear accretion on the beach from the sand supply nourished in 02-03/2019 (Table 2) in sections 234-243 (Knokke-Zoute, zone E, and Lekkerbek, zone F) is observed on the DoD between pre-nourishment in 2018 and 2019 (Figure 7A). This sand gain was concentrated above +3 m TAW and extended along 2.1 km of coast. In contrast, a narrow corridor of significant erosion (elevation change > 0.5 m) with a width of 20 m and along 1 km characterized the sections 230-233 (Albertstrand, zone D and Knokke-Zoute, zone E) where no human intervention was carried out. This is an expression of an accelerating littoral drift at this location: sand is mobilized at the most westward tip of the protruding coastline at Knokke-Zoute.
- Between 2019 and 2020, negative morphological change occurred in zone E where the early 2019 beach nourishment was carried out (Figure 7B). This suggests that much of the supplied sand was removed in less than 1 year. At the same time, the upper part of the shoreface gained some sand material. As the accretion strip faces the beach erosion strip, a dominant action of cross-shore transport processes can be inferred. The small beach nourishment carried out in sections 235-240 in 05-06/2019 cannot be observed on this annual DoD because the LiDAR survey was acquired earlier than the intervention. However, the LiDAR survey in 11/2020 indicates accretion above +5 m TAW at the nourished area (not presented here).
- The DoD between 2020-2021 (Figure 7C) shows the effect of the large shoreface nourishment in Duinbergen in sections 223-230 (Heist-east to Alberstrand, zone B to D) in 02-03/2021. There, a 2 km long accretion area with its long axis situated between +1 and 0 m TAW (2018) is observed. A maximum positive elevation change of nearly 3 m was recorded. The substantial nourishments buried the groynes. An opposite trend characterized Knokke-Zoute with a dominance of erosion on the beach and the upper part of the shoreface. The rest of the shoreface experienced a slight accretion.

The DoDs referred to the pre-nourishment 2018 survey confirm the previous observations (Figure 8). The large shoreface 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 cross-shore supply from the local erosional beach in zone E. Zwin and Cadzand-west experienced a high spatial and temporal variability which are reported in Montreuil et al. (under review).

A) 2018 (pre-nourishment) – 2019



B)2019 – 2020



C) 2020 – 2021

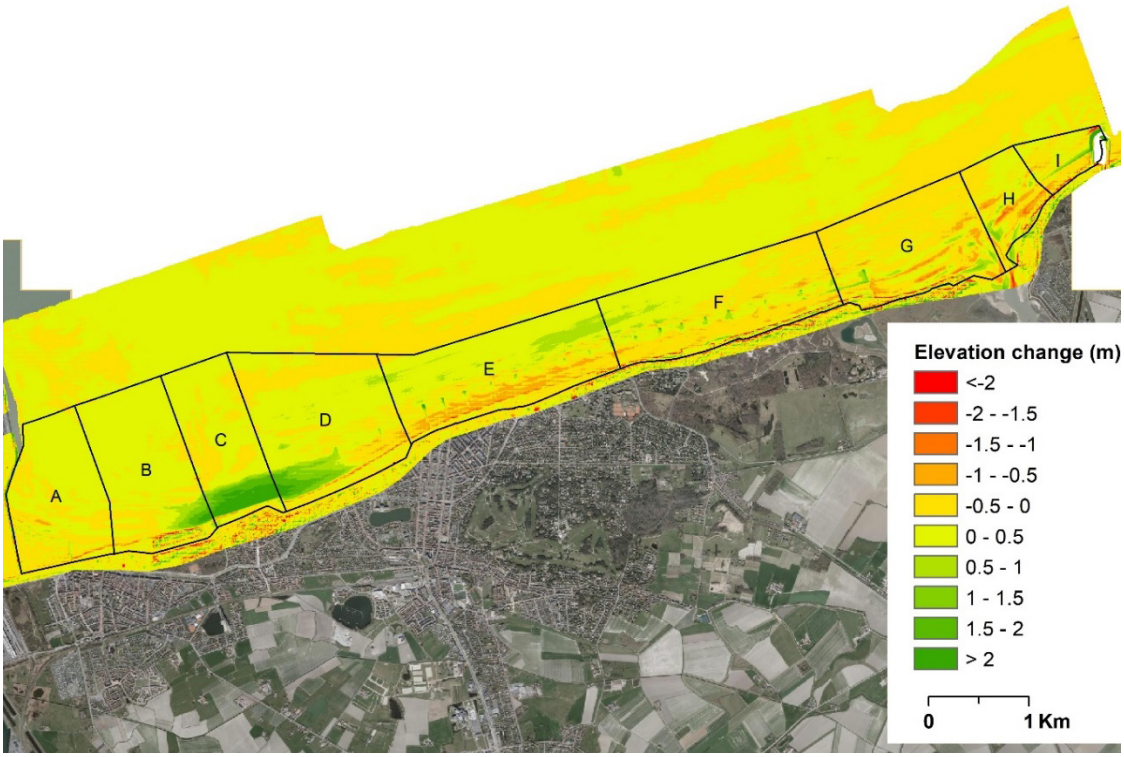
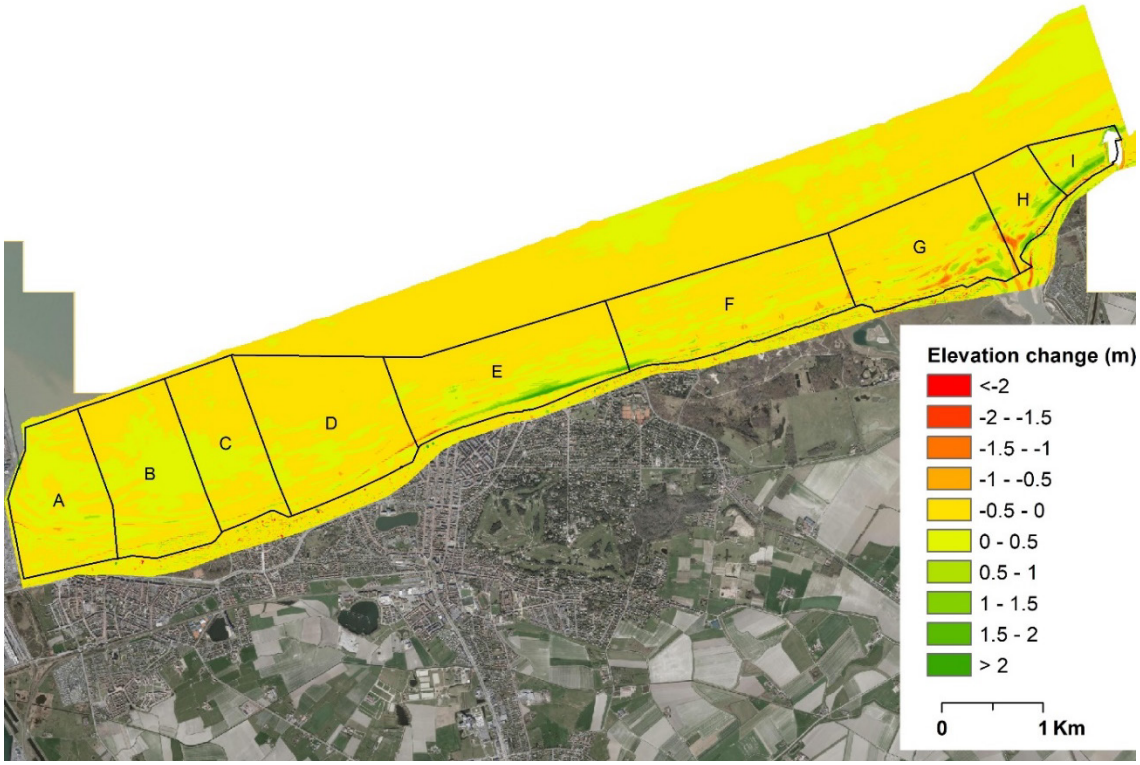
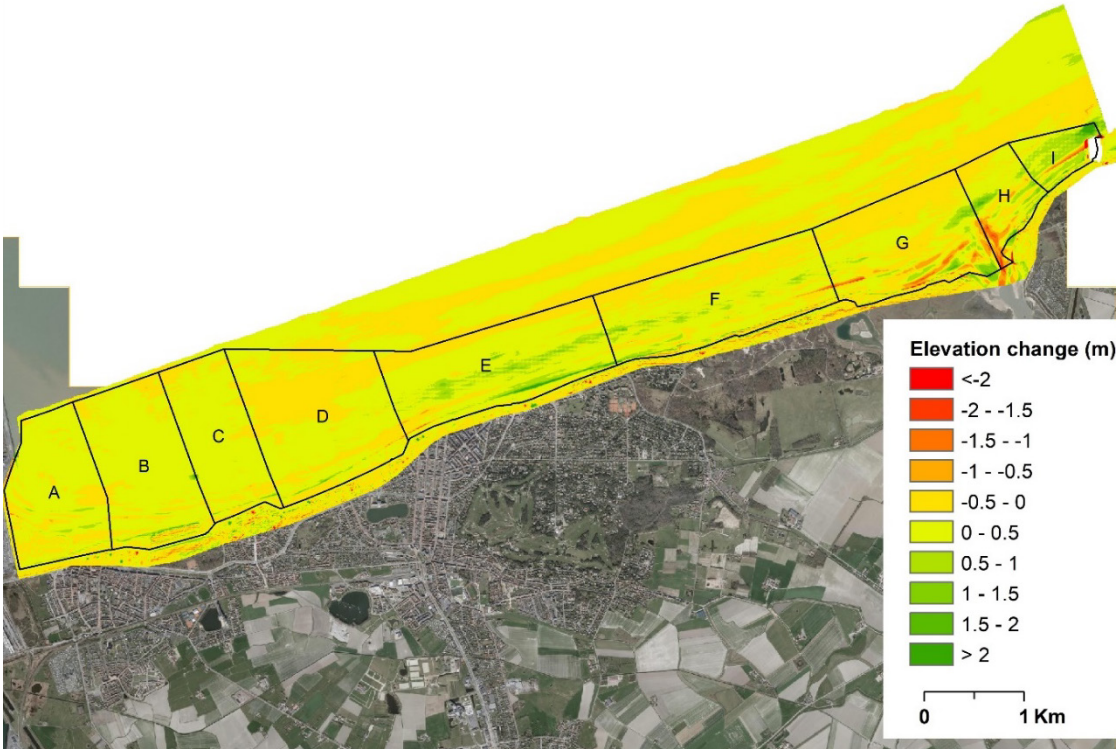


Figure 7 – Consecutive DEMs of difference of the merged beach and shoreface.

A)2018 (pre-nourishment) – 2019



B)2018-2020



C)2018 – 2021

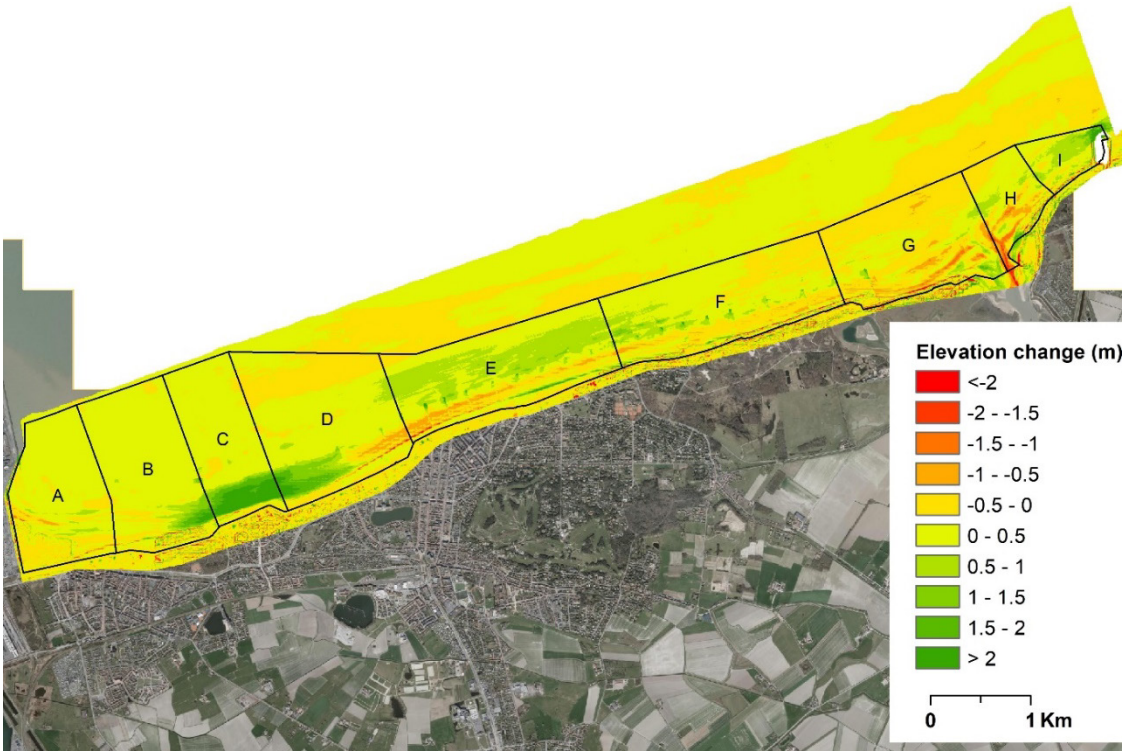


Figure 8 – DEMs of difference merged beach and shoreface from the reference survey in 2018.

5.2 Volumetric changes

Numbers for 2018-2019, 2019-2020 and 2020-2021 are presented in (Table 3):

- The volume changes in the backshore and foreshore of zones E and F (Knokke-Zoute and Lekkerbek) were usually positive between 2018-2019 thanks to the beach nourishment of 292 502 m^3 carried out there in 02-03/2019. Zone G near the Zwin, where no nourishment was carried out during this period, experienced erosion. The rest of the backshore showed no significant change. In contrast, a loss of sediment for the foreshore of zone C and D, between Duinbergen and Alberstrand, was observed, 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. Between 2018-2019, the shoreface didn't show significant change along the whole study coast.
- Both backshore and foreshore gained sand material from zone B to D between 2019-2020. Interestingly, 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 an average decrease of elevation around -0.17 m. This might suggest that in 10 months, sand was removed and transported, such as suggested by the accretion figures of neighboring areas, partly to the local backshore (aeolian transport) in zone E, partly to the adjacent zones F and D by alongshore processes, and partly to the local shoreface (cross-shore transport) in zone E. The foreshore of zones H and I was subjected to erosion which was probably related to natural processes occurring in the Zwin inlet system and the sand nourishment done in Cadzand in 2019.
- The effect of the large nourishment of 982 000 m^3 in 02-03/2021 from zone B to D is clearly observed with accretion of 498 000 m^3 across the entire beach along these zones. Zone E, where a small nourishment took place in 11-12/2020 but none in 02-03/2021, beach suffered erosion (-168 340 m^3) whereas its shoreface gained sand material (326 720 m^3). It suggests that the nourished sand was transported in cross-shore The rest of the shoreface in the study site did not show change. A complete impact of the shoreface nourishment in 08-09/2021 can only be revealed by the future topo-bathymetric monitoring.

Table 3 – Sediment budgets of the coastal delimited zones from 2018 to 2021
Red, green and grey colour indicates negative, positive and stable trends, respectively.

		Volumes (m^3)			Error (m^3) +/-			Volumes (m^3)			Error (m^3)
Layer	Zone	2018-2019	2019-2020	2021-2020		Layer	Zone	2018-2019	2019-2020	2021-2020	
Back shore	A	-8260	16150	-17420	19940	Fore shore	A	9040	26240	360	18920
	B	-2980	23680	-1340	11800		B	740	21920	93090	16600
	C	-2990	6360	12880	4540		C	-12520	10150	244070	7120
	D	-9500	15620	6330	13950		D	-33020	19380	142980	14240
	E	32240	13480	-35500	13000		E	94180	-47450	-132840	19940
	F	12270	-5470	-13930	10360		F	-22300	31340	-73050	22680
	G	-4440	7880	-22490	10730		G	-35860	-18420	-23130	21440
	H	2450	-21430	-13490	5020		H	15400	-51340	-27670	10160
	I	-2690	6470	-13610	2430		I	62410	-71970	27030	5180
Beach	A	780	42390	-17060	38860	Shore face	A	10990	57260	50970	151580
	B	-2240	45600	91750	28400		B	7390	122210	107750	236950
	C	-15510	16510	256950	11660		C	-12120	96800	172510	202290
	D	-42520	35000	149310	28190		D	-118970	135690	241310	325900
	E	126420	-33970	-168340	32940		E	-117360	353580	326720	276010
	F	-10030	25870	-86980	33040		F	-79570	177080	155760	284510
	G	-40300	-10540	-45620	32170		G	-112690	99620	-107590	228570
	H	17850	-72770	-41160	15180		H	-20760	56260	-5650	72030
	I	59720	-65500	13420	7610		I	21840	76190	44860	45800

Note: 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).

6 Conclusions

In the framework of the Knokke mega-nourishment project, nearly 1 280 000 m^3 of sand was supplied to the coast from Duinbergen (zone C) to Knokke-Zoute (zone E) between 2019 and 2021. The annual morphological changes and sediment budget are reported here.

Sand supplied to Knokke-Zoute and Lekkerbek beach in 02-03/2019 was removed in less than a year and was partly transported to the shoreface by cross-shore processes. The rest of the material was probably further transported to the adjacent coast by alongshore diffusion and partly evacuated from the Appelzak by tidal currents.

The large beach nourishment in Duinbergen in 02-03/2021 resulted in an increase of the beach width of 100 m. The first signs of erosion are already observed at the Spring 2021 survey. An evaluation of nourishment efficiency based on the immediately after-nourishment survey and future topographic and bathymetric surveys will allow to assess the intensity of the initial erosion and to project how long the sand will be available there. As previously reported, Appelzak tidal channel, located in average about 350 m from the coast, strongly controls the morphodynamics of the coast along Knokke (Houthuys et al., 2021). It is fed by the sand loss from Knokke-Zoute and Lekkerbek beaches (i.e. 50 000 m^3/y over 4.5 km) (Trouw et al., 2015). Also, Appelzak might evacuate sediments from the area: after local supply from the beach, mainly due to storm erosion, tidal currents are thought to further evacuate the sand in both the flood and ebb directions. This means that in the end, sand is lost from the local coastal system near Knokke-Zoute. The estimated sediment budget in the Appelzak shows no significant change over 2018-2021 (Appendix B). However, this budget covers a large area and may conceal local significant erosion or accretion. This influence of the Appelzak on the nourished coast will be evaluated further when the next monitoring surveys become available.

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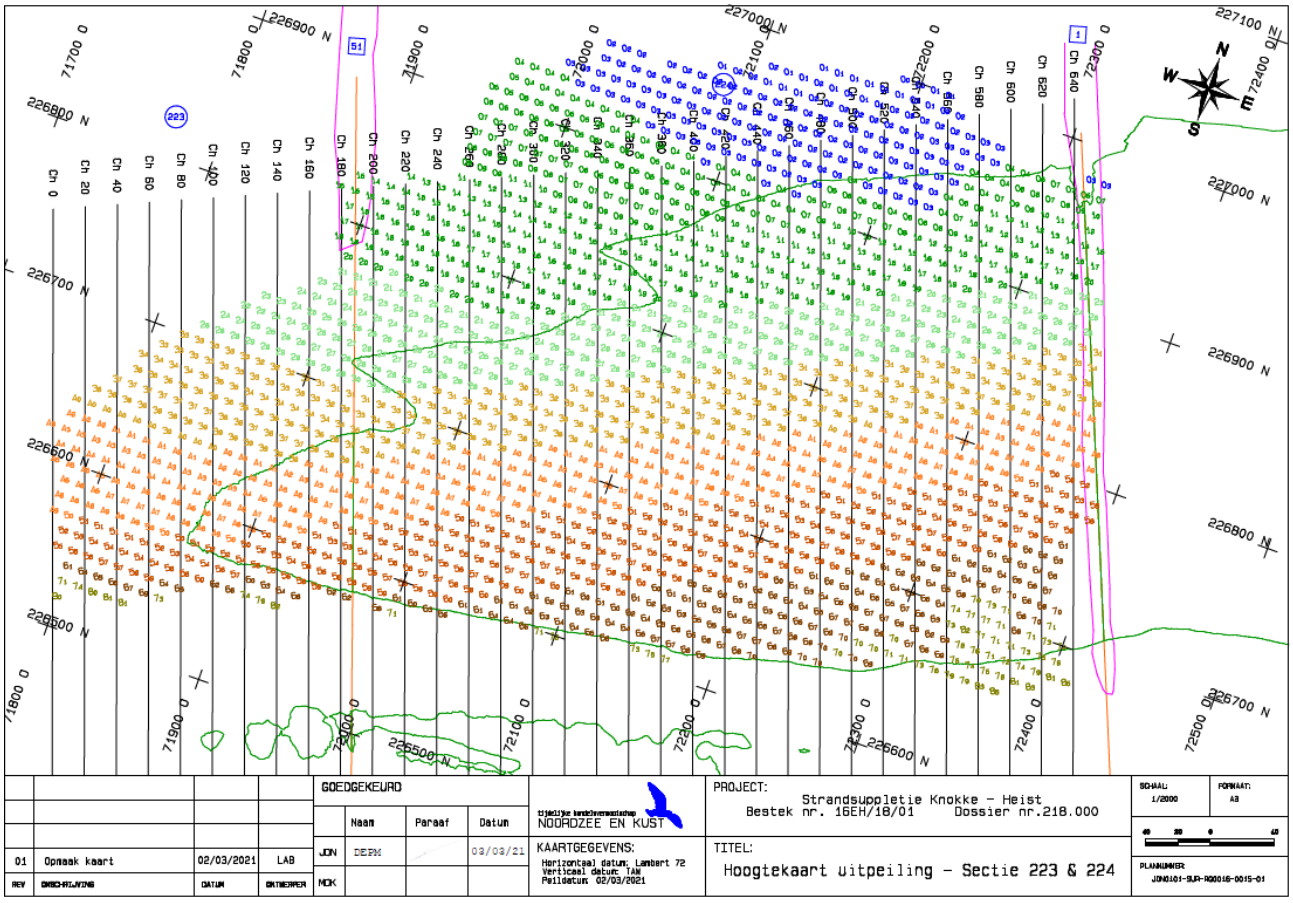
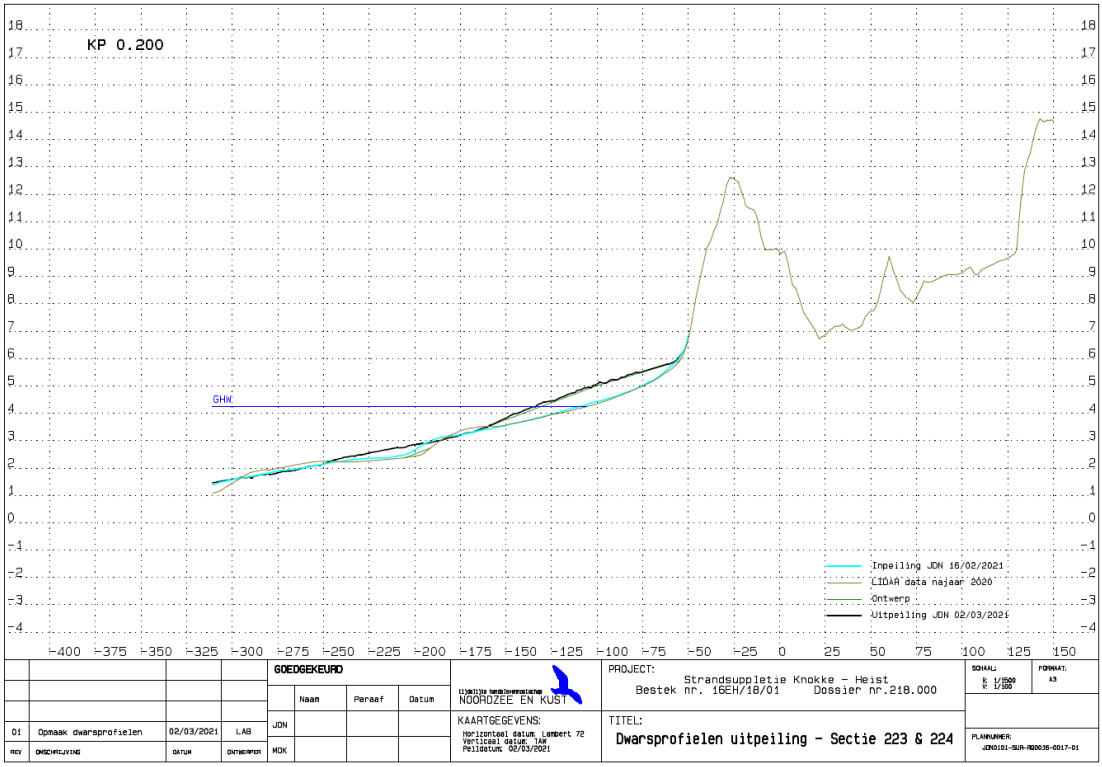
Appendix A Maps and Cross-shore profiles of Duinbergen nourishment

Pre- and post-nourishments at Duinbergen (223-230) between 02-03/2020. Cross-shore profiles were carried out every 20 m along 2 km. Several relevant profiles are presented here.

Section 223-224

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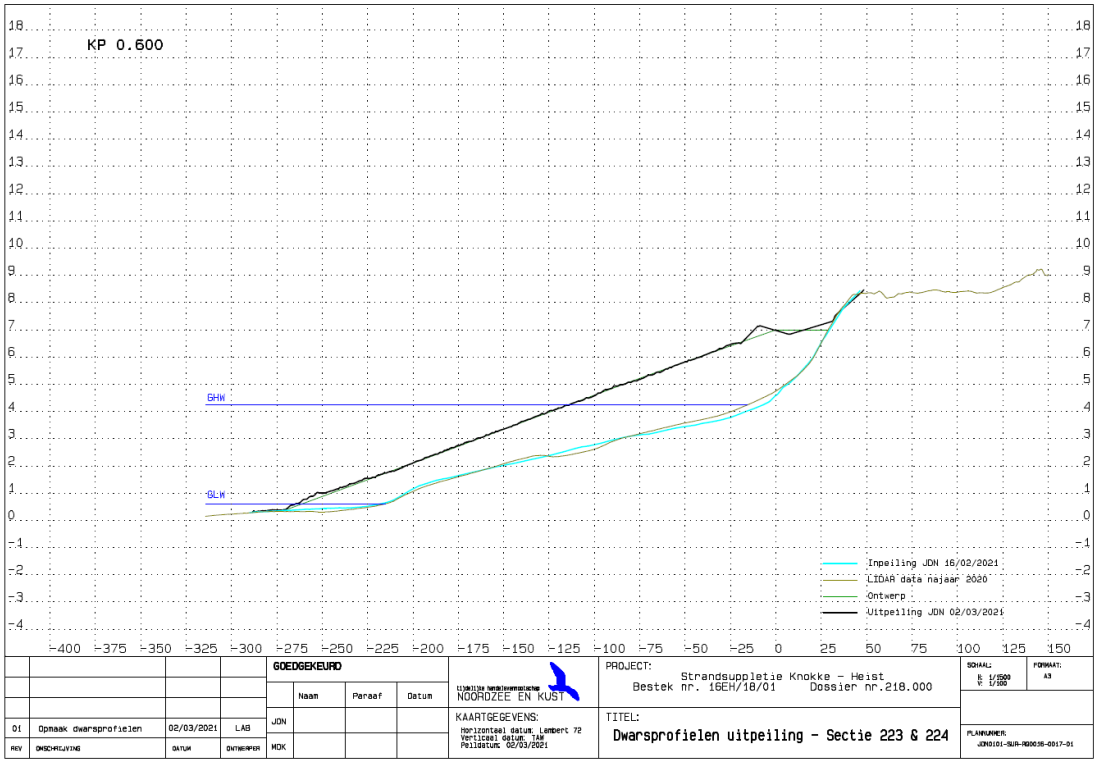
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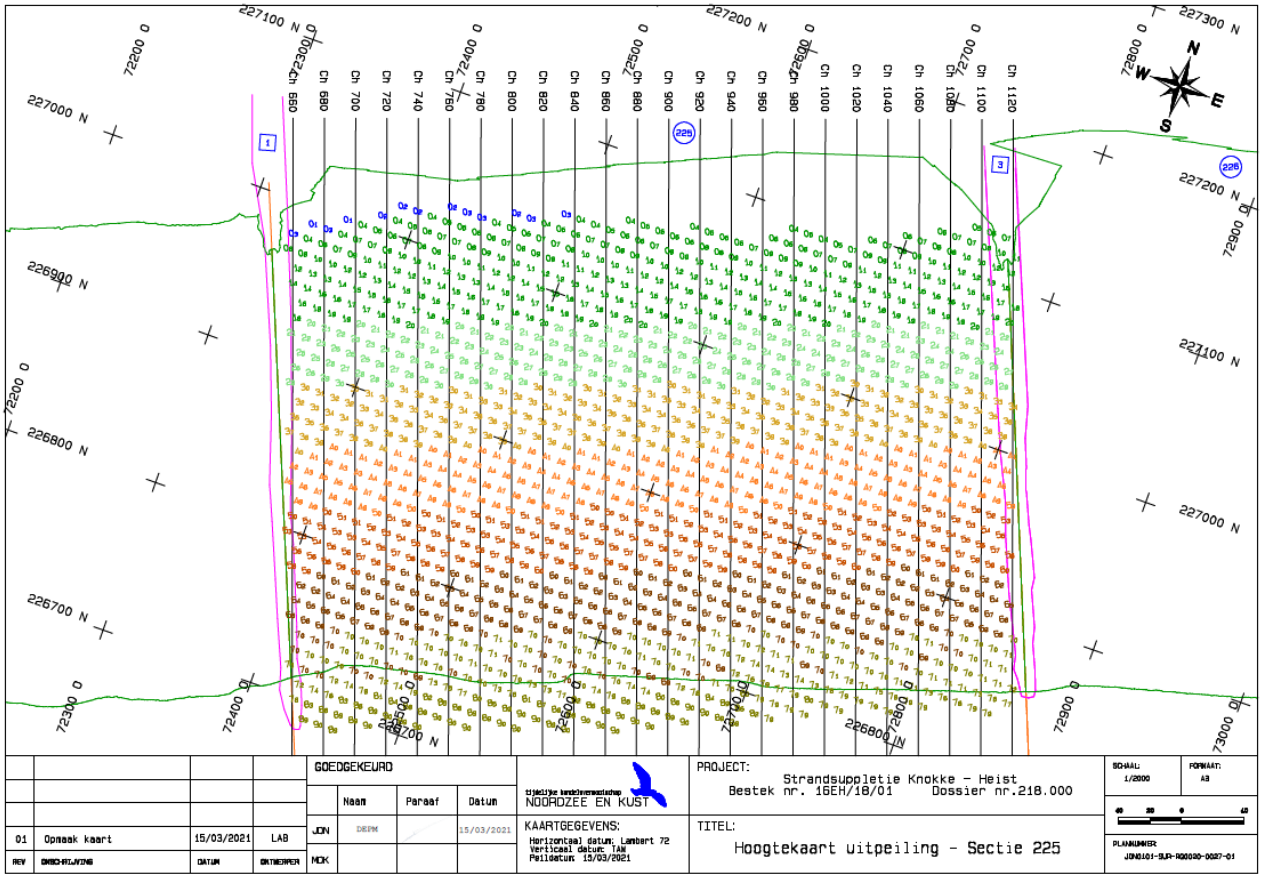
Section 225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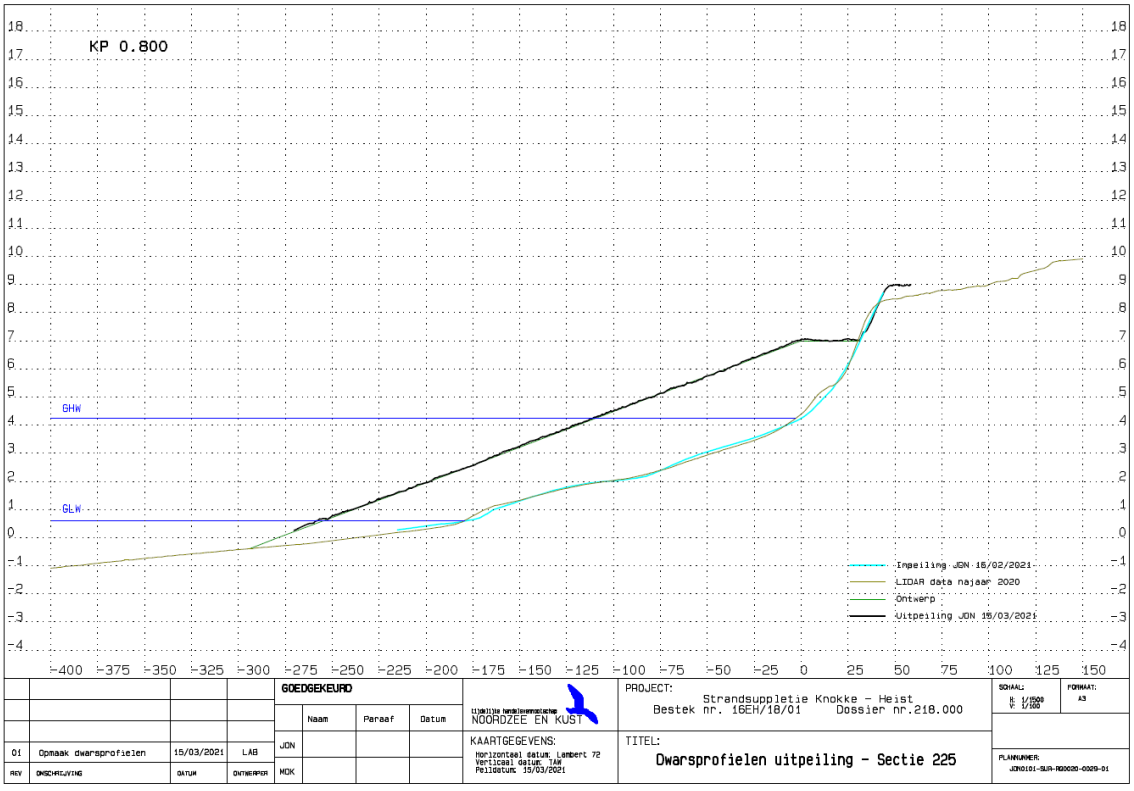
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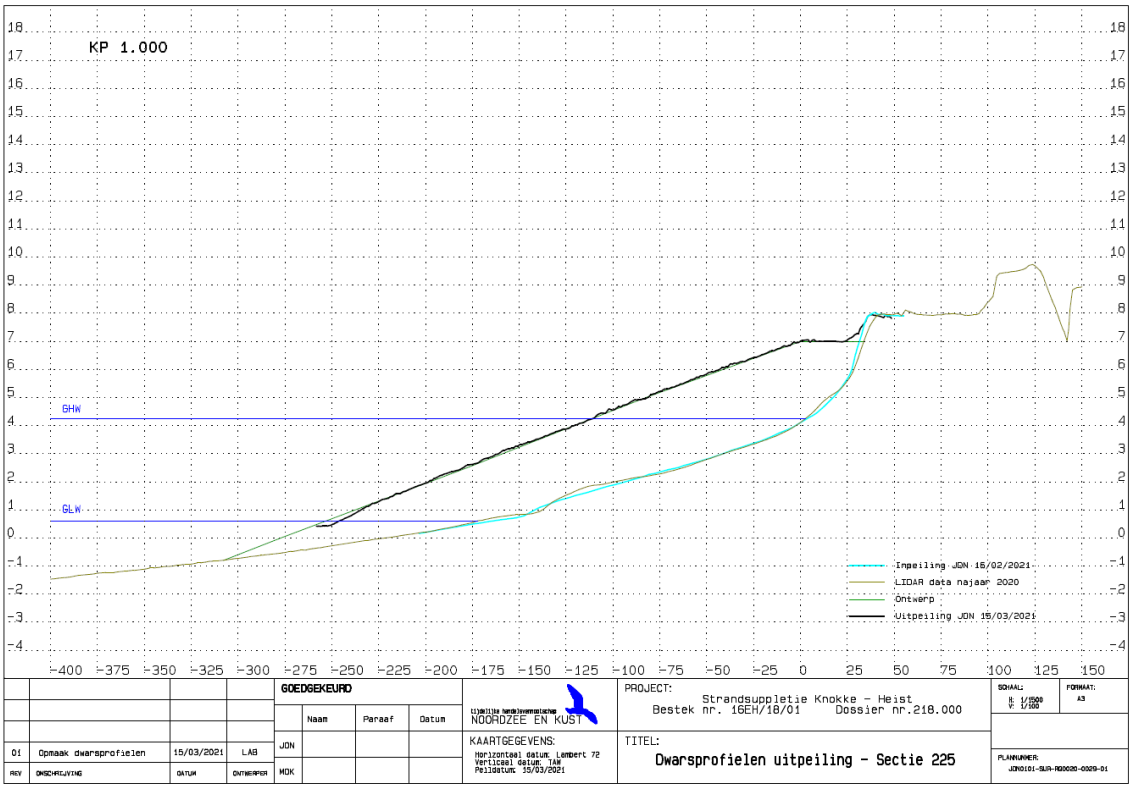
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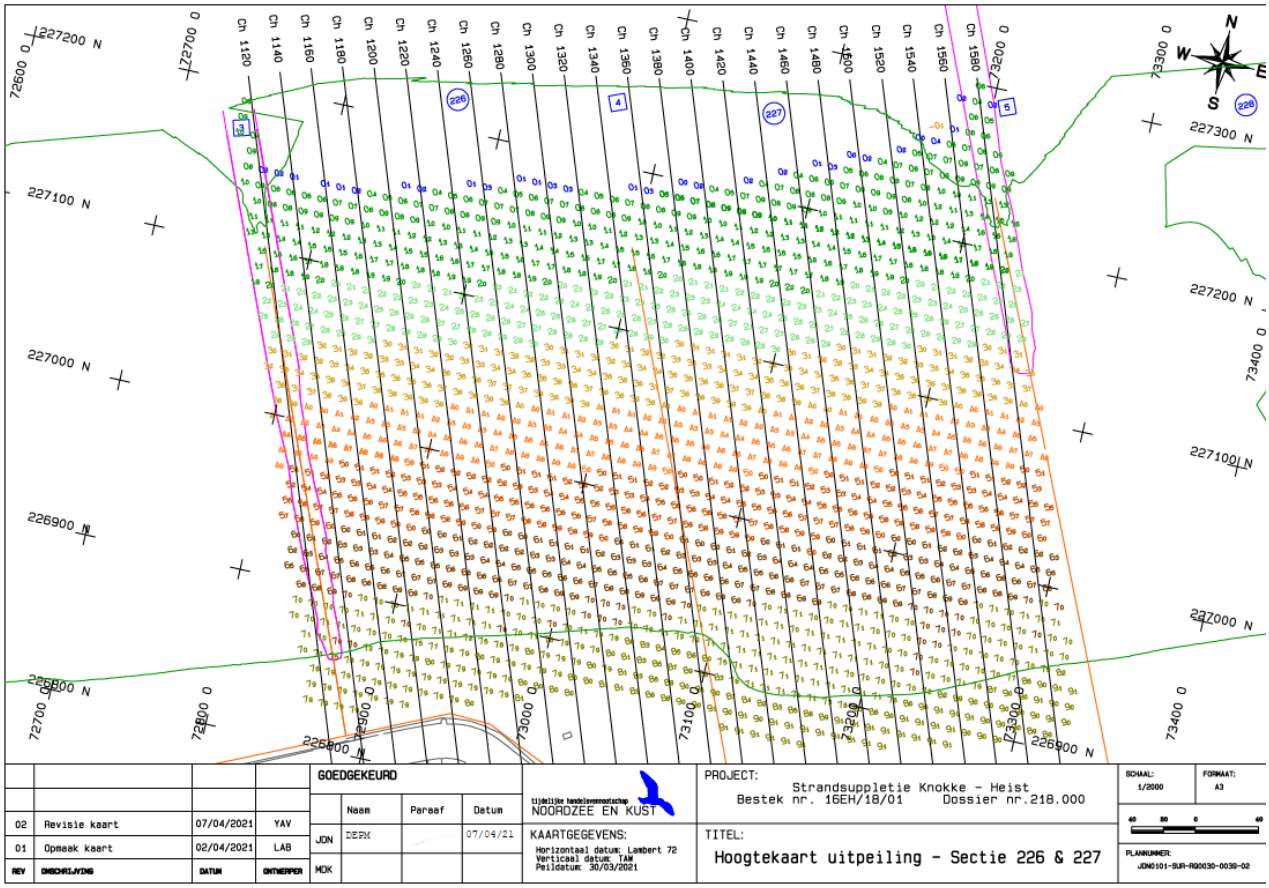
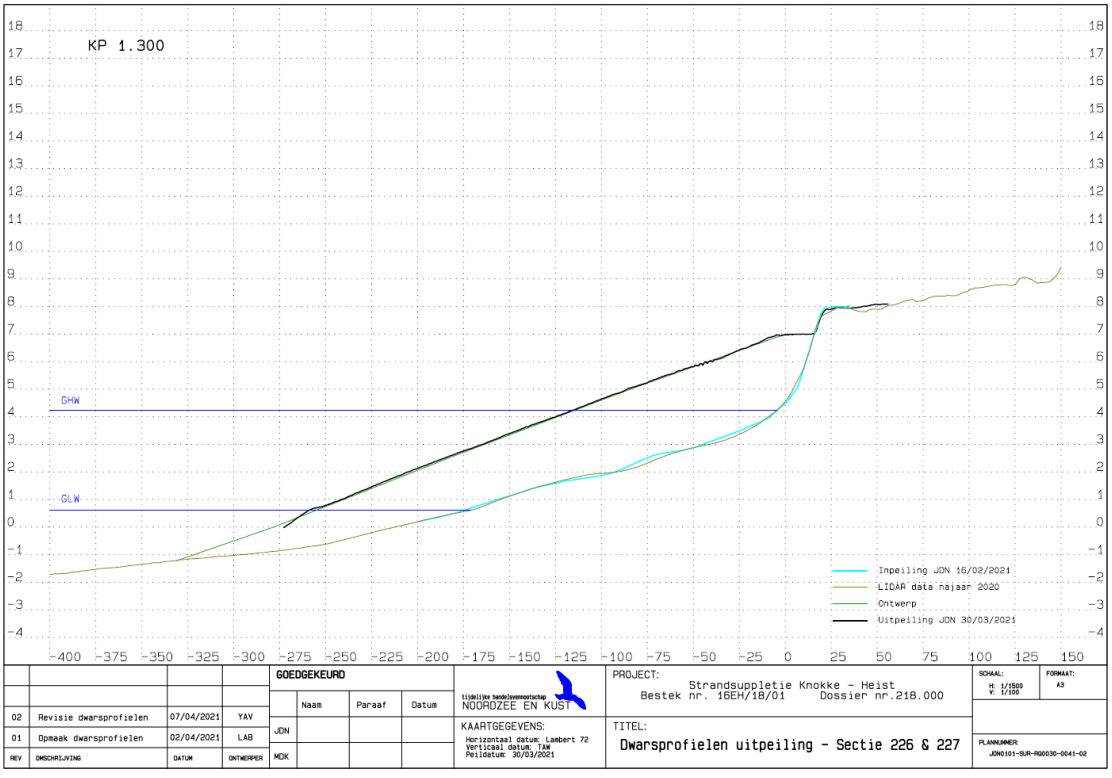
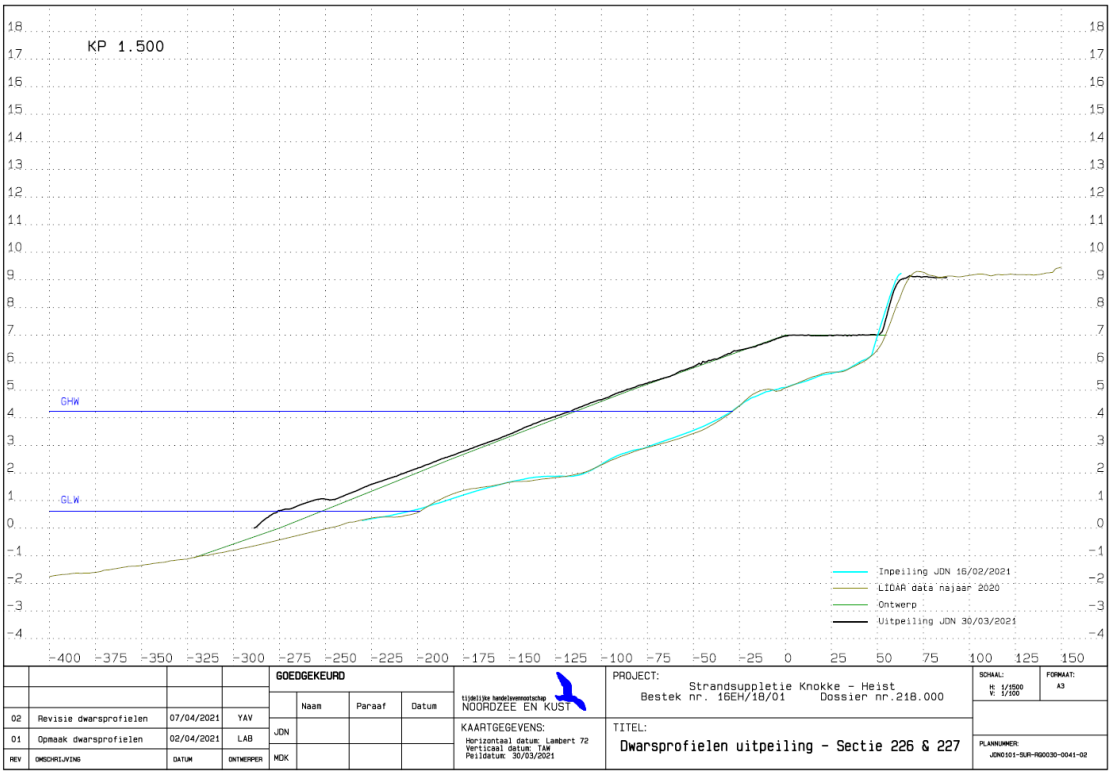
Section 226-227



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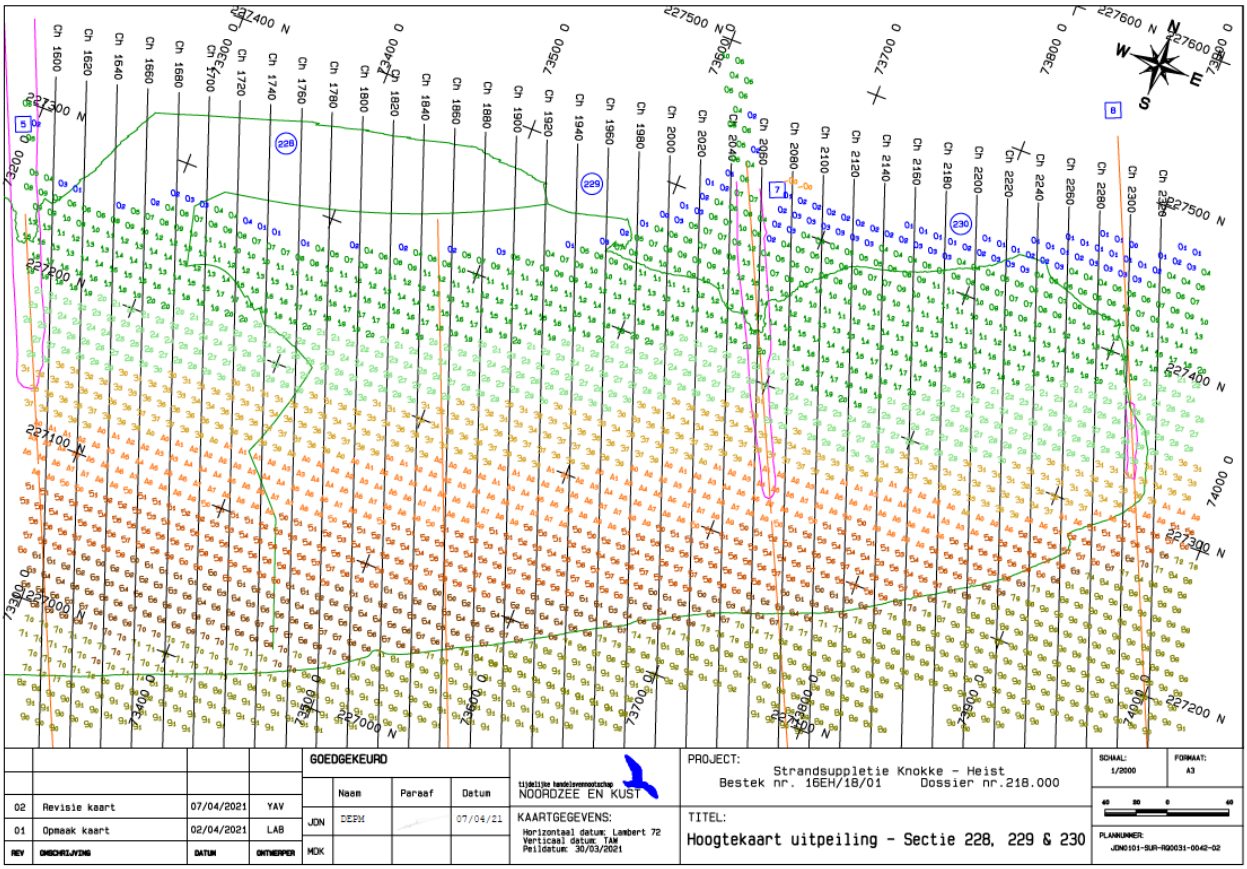

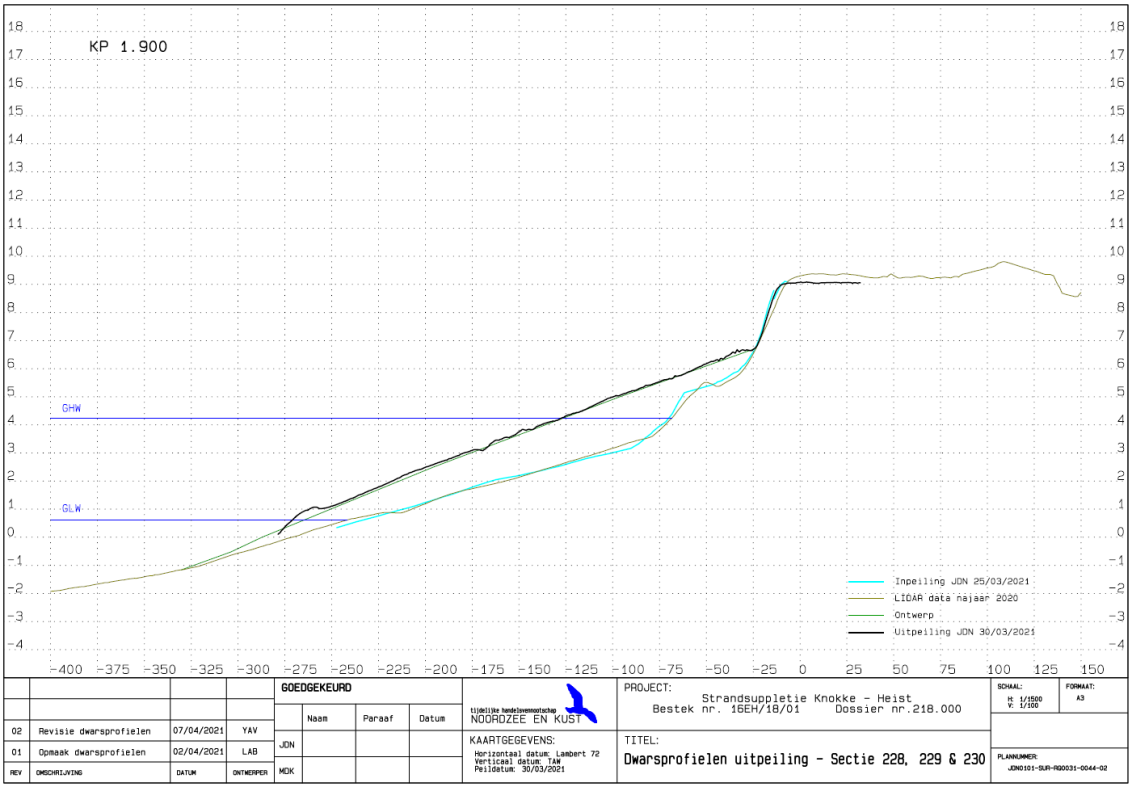

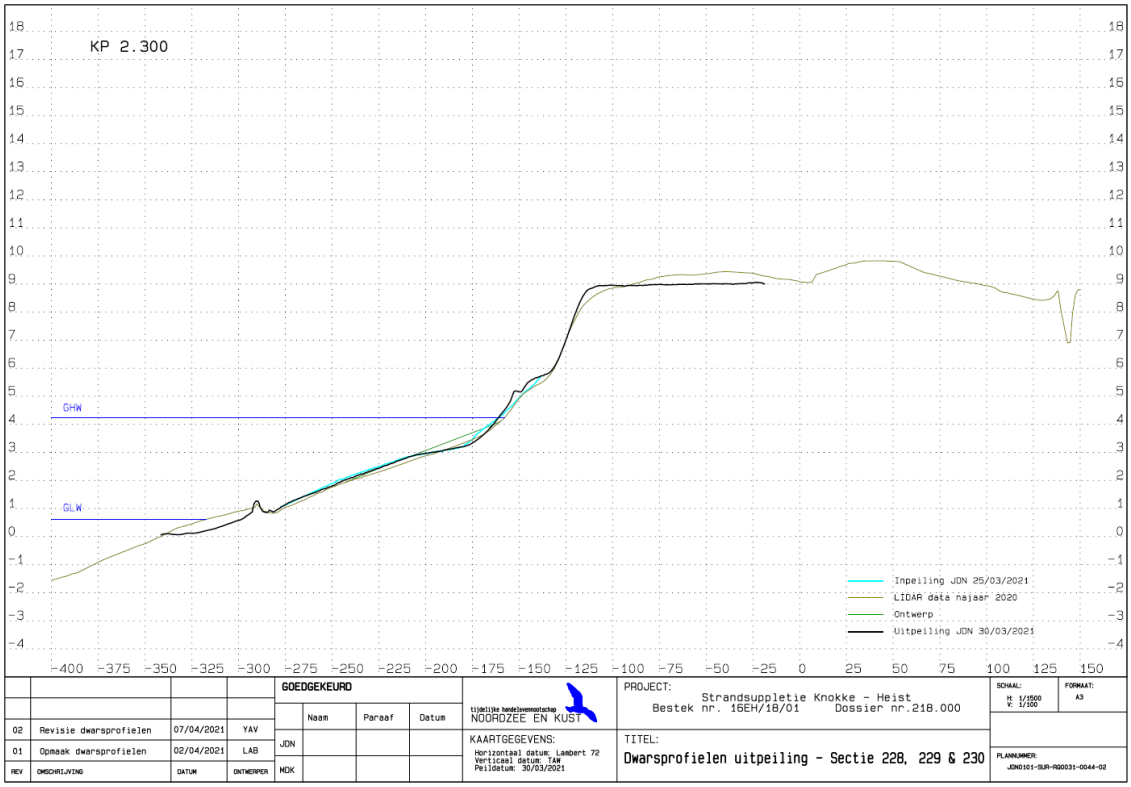
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Appendix B Appelzak sediment budget

	Volume (m^3)			
	2018-2019	2019-2020	2021-2020	Uncertainty (m^3)
Appelzak	-748070	950120	644690	1571042

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