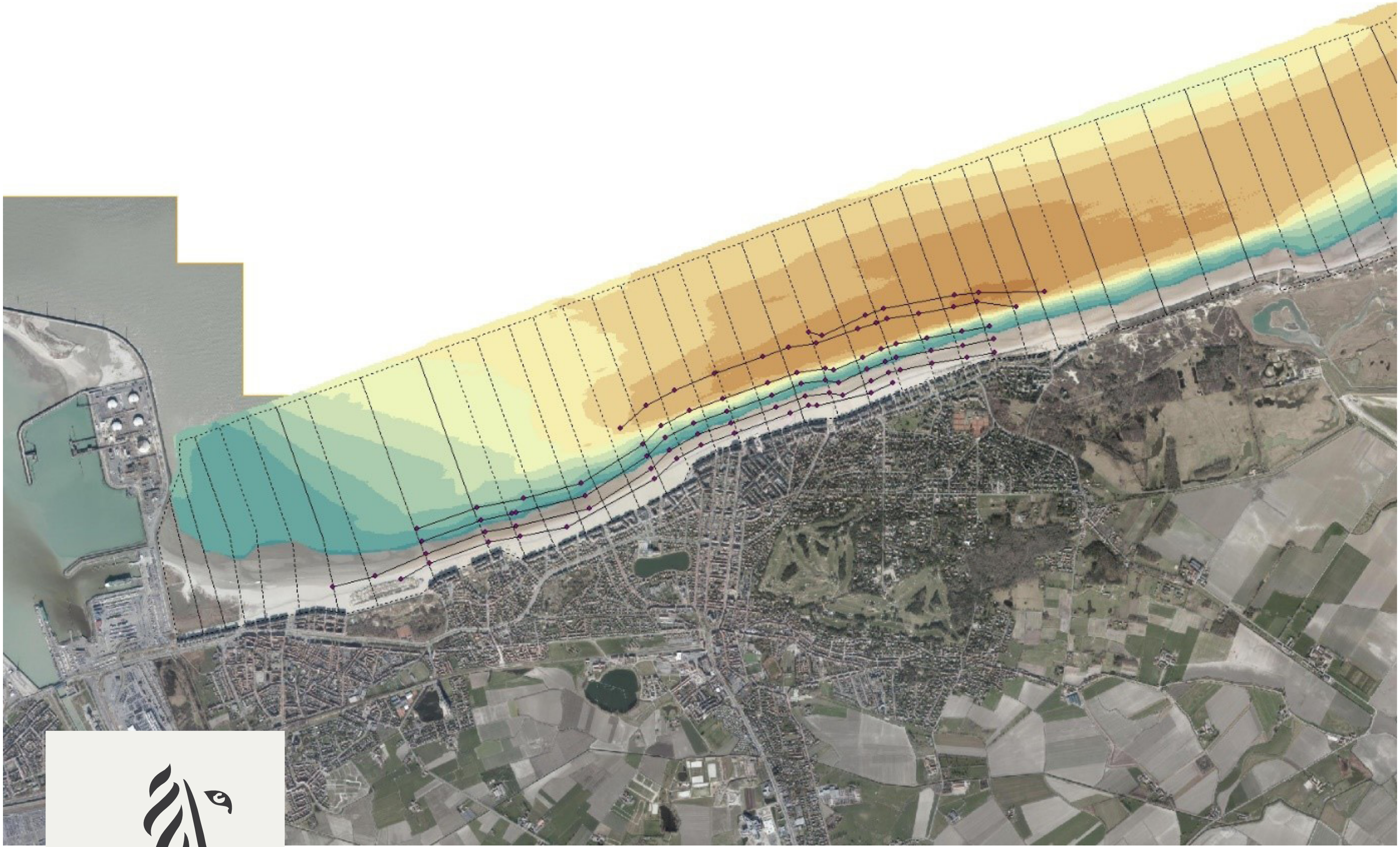


Flanders
State of
the Art

19_118_1
FHR reports

Evolution of a large coastal nourishment at Knokke

First year progress report

DEPARTMENT
MOBILITY & PUBLIC WORKS

www.flandershydraulicsresearch.be

Evolution of a large coastal nourishment at Knokke

First year progress report

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

Flanders Hydraulics Research
Flanders State of the Art

Legal notice

Copyright and citation

D/2021/3241/290

This publication should be cited as follows:

Montreuil, A-L.; Dan, S.; Verwaest, T. (2022). Evolution of a large coastal nourishment at Knokke: First year progress report. Version 3.0. FHR Reports, 19_118_1. Flanders Hydraulics Research: Antwerp.

Document identification

Customer:	Coastal Division MDK	Ref.:	WL2022R19_118_1
Keywords (3-5):	Coastal processes, Morphology, Wave regime, Literature review		
Knowledge domains:	Coastal protection against erosion > Morphodynamics > Literature and desktop studies		
Text (p.):	59	Appendices (p.):	11
Confidentiality:	☒ No	☒ Available online	

Author(s):	Montreuil, A.L.; Dan, S.

Control

	Name	Signature
Reviser(s):	Verwaest, T.	Getekend door:Toon Verwaest (Signature Getekend op:2022-11-03 09:44:01 +01:0 Reden:Ik keur dit document goed Toon Verwaest
Project leader:	Dan, S.	Getekend door:Sebastian Dan (Signature Getekend op:2022-10-31 17:52:44 +01:0 Reden:Ik keur dit document goed Sebastian Dan Vlaanderen

Approval

Head of Division:	Bellafkih, K.	Getekend door:Abdelkarim Bellafkih (Sign Getekend op:2022-10-28 15:35:49 +02:0 Reden:Ik keur dit document goed Abdelkarim Bellafkih

Abstract

Beach erosion occurs along a large part of the Belgian coast, especially in the Knokke area. One of the most applied and successful measure to prevent and to cope with erosion is the artificial nourishment of the active beach and shoreface system. Under the framework of this project, a combined large beach and shoreface nourishment of a total approximately 3 million m^3 of sand is planned for the Knokke area in the period 2020 – 2025. The aim of this project is to understand the hydrodynamics and morphodynamics of the Knokke area and to evaluate the nourishment efficiency. This first year progress report focuses on a literature review of the coastal morphodynamics and processes along the east Belgian coast from Zeebrugge to Zwin, as well as a pilot campaign of measurements at sea. An inventory of the existing topographic and hydrodynamic data as well as an analysis of the wave regime are presented.

Contents

List of tables

List of figures

1 Introduction

Parts of the Belgian coast has been eroding, which increases risk of flooding during extreme storms and decreases the economic and ecological potential of the beach area. One of the most used and successful measure to cope with erosion is the artificial nourishment of the active beach and shoreface system. This measure was widely applied in the last decades at the Belgian coast. A long-term erosive trend has occurred at the area of Knokke-Heist in the last decades. Under the framework of this project, a meganourishment of the beach and shoreface is planned for the Knokke area in the period 2020 – 2024. The nourishment will take place in several steps, consisting of a total approx. 3 million m^3 of sand, as communicated by Coastal Division.

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;
- 2021: 920 000 m^3 on the shoreface; sections 223 - 229;
- 2024 or 2025: beach nourishment 2.000.000 m^3.

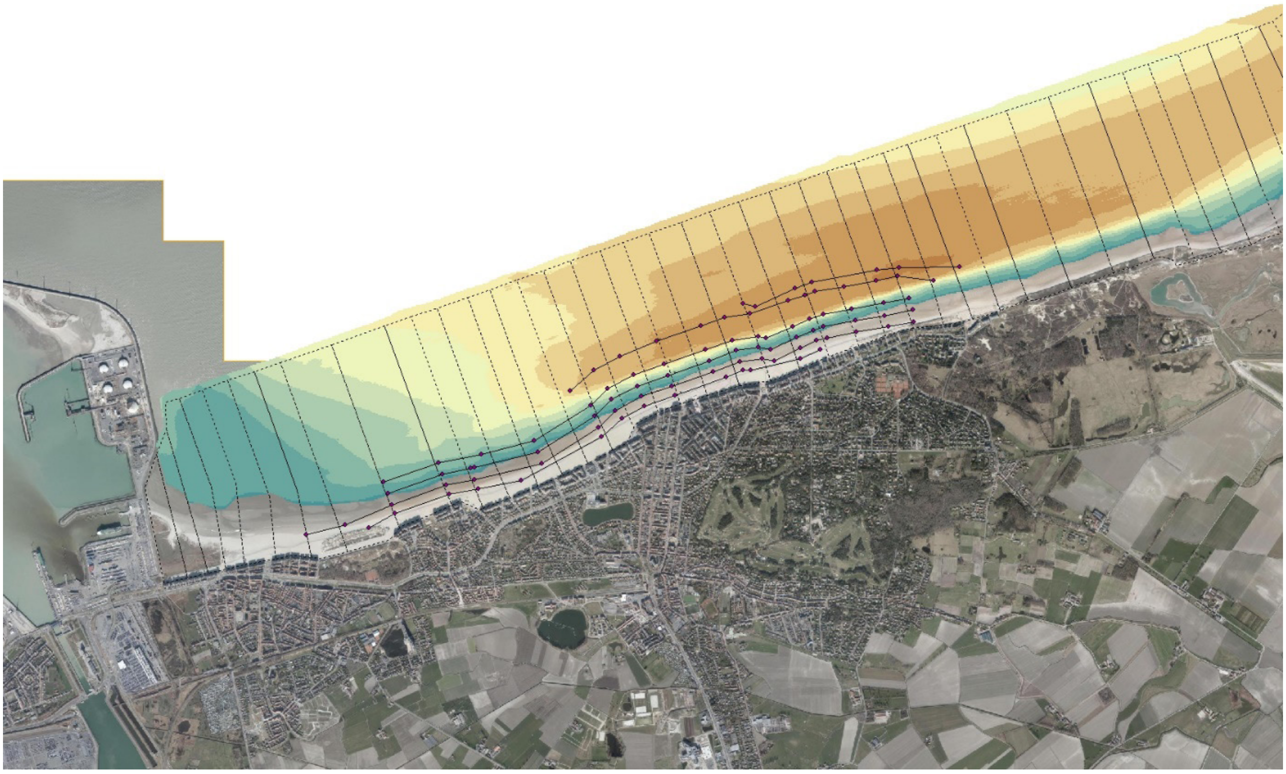


Figure 1 – The design of the Knokke nourishment.
The solid lines with points approximately parallel with the present shoreline describe the future nourishment.

The 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. A number of 4 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 a literature review of the coastal morphodynamics and processes along the east Belgian coast from Zeebrugge to Zwin. In addition, an inventory of the existing topographic and hydrodynamic data as well as an analysis of the wave regime are presented.

2 Literature Review of the East coast

2.1 Background

The eastern part of the Belgian coast, stretching from the outer port of Zeebrugge to the Zwin inlet has a complex dynamics (Figure 2 and Figure 3). The morphodynamics are influenced by the presence of the Zeebrugge breakwaters where a large accretional area extends up to 4 km at the Baai van Heist due to wave sheltering effect as well as the asymmetry of the tidal currents. Blockage of the eastward directed littoral drift results in a positive gradient of longshore sediment in Knokke-Heist which drives erosion. The coastline at Knokke locally protrudes seaward due to the position of the sea dike. Sand loss further increases due to the presence of regional geomorphologic marine bedforms such as the Appelzak tidal channel which in turn seems to be controlled by the influence of the Paardenmarkt sand bank. The cumulative effect of beforementioned 3 driving mechanisms is severe erosion in Knokke. The coastal stretches west of the Zwin inlet also experience long-term erosion. In general, the seabed has eroded along the east coast over the last decades. The morphological trends of the emerged beach and the shoreface vary in time and space. Although on average the sediment budget is stable along the east coast, erosion is locally problematic. This chapter aims to summarize the available information on morphodynamics and evolution of the east coast.

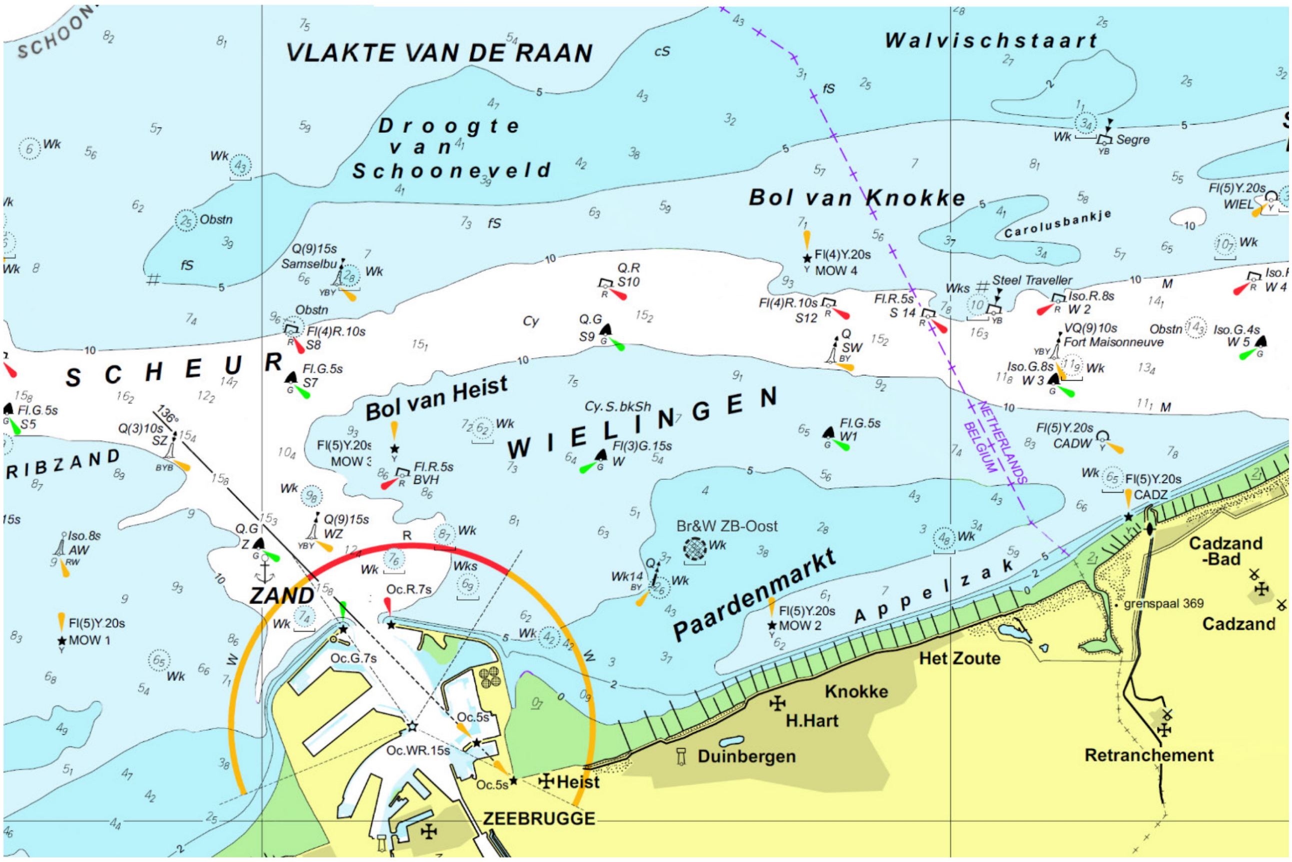
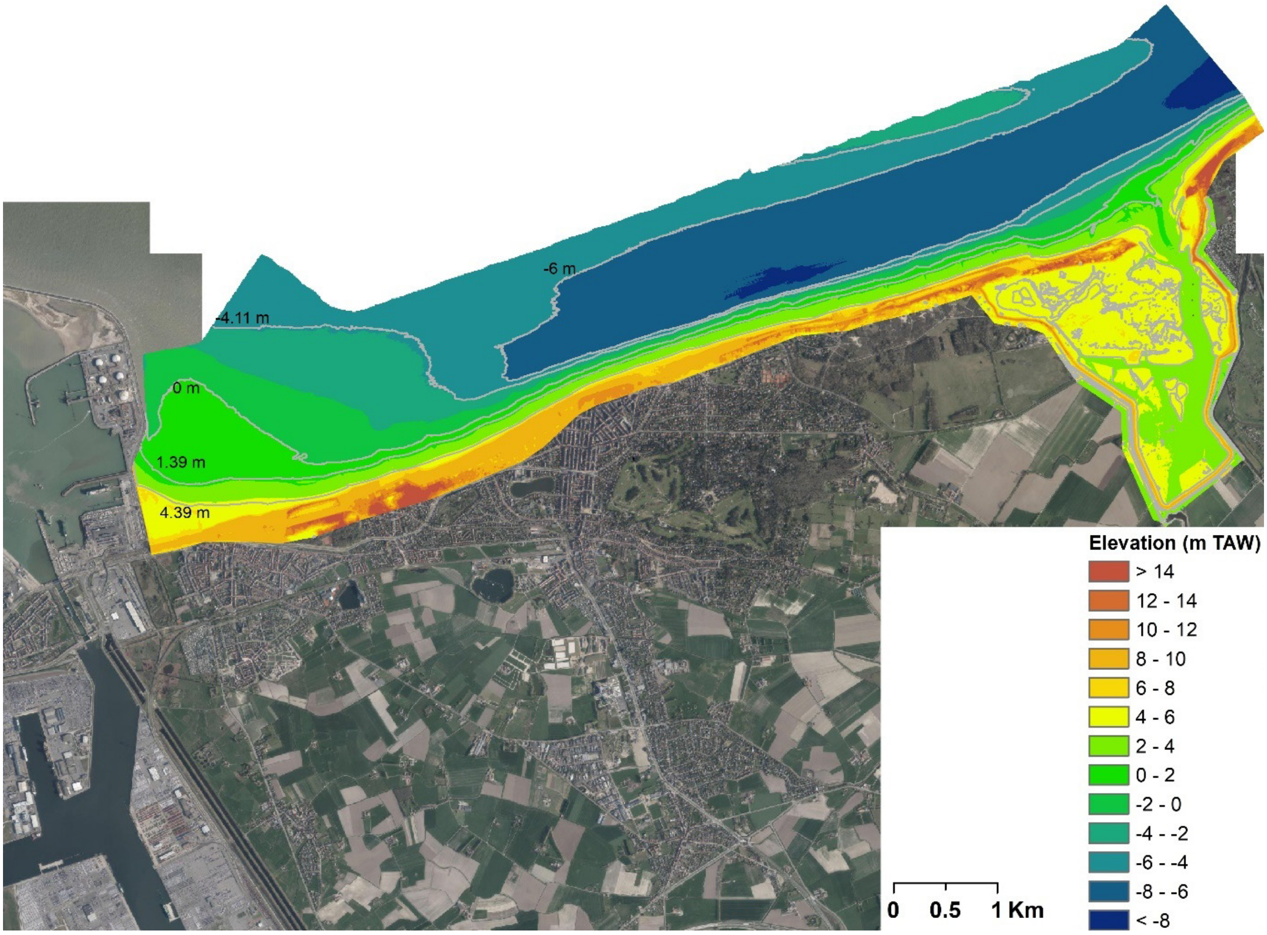


Figure 2 – Nautical map with distinct geomorphological marine bedforms.



Note: LiDAR and bathymetric surveys in 2019.

Figure 3 – Topography of the east coat with contour lines.

2.2 East coast morphology

The east coast is 10.1 km long and fringes a low-lying sandy coastal plain, extending up to 20 km into the hinterland (Figure 2 and Figure 3). The beach is generally dissipative characterized by a width from 100 to 300 m and a gentle mean slope of 1.5-2.5% on the intertidal zone (Deronde et al., 2008). The coastline is relatively straight and oriented SW-NE. However, it is shifted offshore in front of Knokke-Heist, and between the Zwin and Nieuwvliet (Netherlands).

Holocene sand deposits up to 10 m dominate the nearshore area (Van Lancker, 1999). In the vicinity of Zeebrugge port, surface clay deposits are also present, causing higher water turbidity. While, the hinterland mainly consists of clay-rich polders. Over the past millennium, the coast has slowly and progressively evolved from a system with several small tidal inlets to the current straight and almost uninterrupted coastline (Houthuys et al., 1993). The Zwin inlet, between the Belgian and Netherlands border, was formed as a result of a heavy storm in 1134 (the 'Elisabethstorm'), causing a break-through of the narrow beach barrier. It is connected to the sea through a tidal channel. Along the east coast, one of the major geomorphic marine bedforms is the Appelzak tidal channel or gully, a geomorphologic marine bedform situated at 0.5 -1 km from the shore (-6 m TAW) and extended further to the Zwin. Just North, the shallow Paardenmarkt sand bank is present around -3 to -4 m TAW and is aligned with the coast. It is documented that the Appelzak channel was flood-dominated before the extension of Zeebrugge port in 1980s (Trouw et al., 2015). The channel was situated around 1 km from the sea dike under the absence of the breakwaters, allowing a continuous longshore drift toward east (Bastin, 1974). At that time, Paardenmarkt bank was very shallow, assuring a protection of the coast against waves. Before 1930, Appelzak was at its most offshore position and bordered by Paardenmarkt. This latter was oblique to the coastline and attached near Cadzand. After 1930, Paardenmarkt bank was no longer connected to the shore and decreased in height. Over time, Paardenmarkt bank progressively became lower and the Appelzak channel moved to the shore. By 1974, the channel approached to within 500 m of the dyke (Kerckaert, 1986) but it could not move further landward due to the presence of the groynes. Based on tracer-experiments in 1964 (before the extension of the port), the research suggested that the Appelzak is an ebb-channel where the residual sediment transport is directed to south-west and bypasses the groynes (Bastin, 1983). However, opposite results with a dominance of north-east transport was found from further tracer-experiments between 1977-1979. Bastin (1983) also suggested that the Appelzak might represent an evacuation channel of water piled up during high tide. Further offshore, Vlakte Van de Raan, a shallow area (from -3.5 to -4 m TAW), is situated in front of the estuary of the river Scheldt (Figure 2).

2.3 Physical divisions of the coast

The east coast is divided into sections from 217 to 255 (Figure 4). These administrative sub-units cover the cross-shore domain from the foredune or the sea dike up to 1500 m offshore and span approximately 200-300 m longshore. Their boundaries are determined by the position of 24 groynes and the port of Zeebrugge, but a more uniform spacing is adopted in the case of absence of engineering structure. These sections are merged to 8 coastal stretches numbered from 44 to 51 (Table 1) for morphological studies (Houthuys, 2012).

Figure 4 – Division of the east coast.

Table 1 – Description of the stretches.

Sections	Stretches	Location	Length (m)	Area (m^2)
217-218	44	Heist near Oostdam Zeebrugge	346	342,813
219-221	45	Heist near Heldenplein	626	933,868
222-224	46	Heist-Duinbergen	973	1,534,342
225-226	47	Duinbergen-centrum	700	1,129,986
227-232	48	Albertstrand	1410	2,304,734
233-241	49	Knokke-Zoute	2237	3,265,446
242-249	50	Lekkerbek	2310	3,528,142
250-255	51	Zwin	1590	2,638,635
217-255		Total	10100	15,677,965

Figure 5 defines the divided layers of the emerged beach including dune foot, dry beach, and intertidal beach; and the submerged beach below LW from the shoreface to the seabed. The elevations of the divisions are approximate boundaries and not defined on the basis of tidal datums. The active zone is considered as the area above the depth of closure, corresponding to the seaward limit of the shoreface where morphodynamics is less influenced by waves. In the CREST project (http://www.crestproject.be/en), the depth of closure depth varies from -1.6 to -8.0 m TAW, which was determined from bathymetric surveys from 2007-2019 (Montreuil et al., 2020a). Shallow closure depth is observed around Zeebrugge, while deep or no closures are found along the Grote Rede and Appelzak tidal channels.

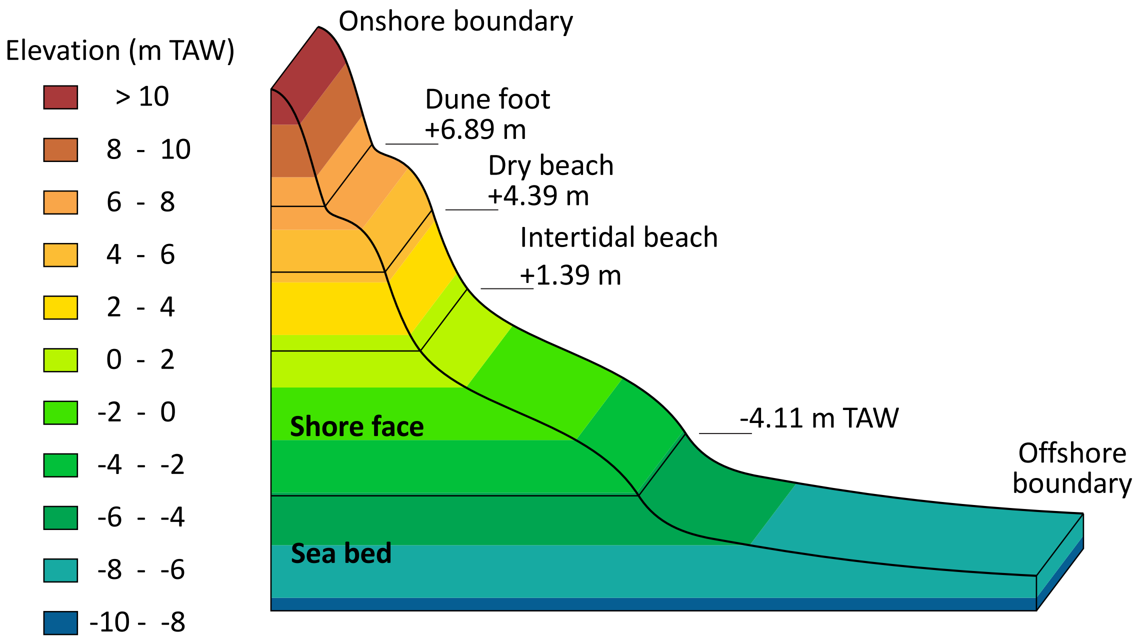


Figure 5 – Definition of the beach layers (adapted from Haerens et al., 2012).

2.4 Past coastal defence measures

The east Belgian coast has a long history of coastal defence measures to protect the coastal plain situated below storm surge level and the infrastructure and people living near the beach (e.g. on the sea dikes). Table 2 lists the past human interventions from Zeebrugge to the Zwin inlet.

Table 2 – Summary of the past human interventions

Date	Interventions
1848	First groynes
1867	Construction of sea dikes
1896-1905	Construction of the first outer port of Zeebrugge
1920	First nourishment at Heist
1928	Closure of the Claire-voie in the port of Zeebrugge. Start (?) of erosion near Heist
1952	Plan for the construction of 25 new groynes
1955-1957	Nourishments over the whole coast east of Zeebrugge (1.25 mill. m^3) to counterbalance erosion from the big storm in 1953
1955-1960	Extension and reinforcement of the groynes
1968	Nourishment at Heist (0.6 mill. m^3)
1973-1977	Dredged material from Scheur dumped in the Appelzak to counter erosion
1977-1979	Large nourishments between Heist and Knokke (8.4 mill. supplied, 6.5 million m^3 over 9 km)
1979-1986	Construction of the new outer harbour of Zeebrugge, extending up to 3 km offshore
1984	Nourishment Heist (volume not confirmed)
from 1985	Dredged material is dumped at the B&W Zeebrugge-Oost site
1986	Nourishment at Knokke-Zoute (sections 232 -243) of 850 000 m^3
1986	Nourishment at Heist with sediments from the dredging works in the harbour. The beach volume in sections 217-218 received 0.34 mill m^3 and 0.178 m^3 for the upper-part of the shoreface of sections 218-221.
1992-1993	Sand borrowing in sections 217-218 (near LW-line and upper-part of the shoreface) during the construction of the landfall of Zeepipe
1993-1995	Nourishments at Heist (section 217-218) of 100 000 m^3 to compensate the removal of unwanted mud sedimentation
1999	Nourishment at Knokke-Zoute (sections 233-243 length 2700 m) of 0.41 mill m^3
2004	Nourishment at Knokke-Zoute (sections 232-243 length 2800 m) of 0.33 mill m^3
From 2006	Annual small nourishments at Knokke-Zoute
2016	Zwin management program to extend the area to 120 ha
Aug 2016-Mar 2017	Zwin dune excavation (section 255-256) mostly used for the construction of the new dyke
Feb-19	Dyke opening in Zwin

Sand nourishments are commonly performed for coastal safety and tourism along the east coast (De Moor, 1988). The first significant nourishment was performed on the beach in front of Knokke in 1956. Over a distance of about 2 km, a volume of about 1 million m^3 was pumped to the beach supplied by the dredging of an artificial lake in the backing dune belt from Knokke to Zegemeer (De Moor, 1988). The beach and shoreface underwent a major beach replenishment from the port of Zeebrugge (section 217) to Lekkerbek (section 250) in 1977-1979. This was carried out to counteract erosion due to the interruption of the longshore sediment transport after the extension of the Zeebrugge port from 1977 and the impact of the stormy period in 1976. The nourishment was done in two stages by first strengthening the beach and then extending its width (Eurosense, 1994a). In total 8.5 million m³ of sand was supplied to the coastal zone of approximately 9 km, corresponding to an average supply of 950 m³/m. Following this, subsequent nourishments were undertaken and in particularly at Knokke-Zoute (section 232-243) in 1986 with 850 000 m^3, in 1999 with 410 000 m^3 and 2004 with 330 000 m^3 (Annex A). Since then, annual small-scale nourishments of the dry beach are quasi continuously applied to extend the recreational beach. The volume per site is then limited to a few 1000 m^3/m and most of the additional sand is brought in by trucks. Protection efforts have been intensified under the implementation of the Master Plan for Coastal Safety since 2011.

Moreover, the access channel of Zeebrugge port is dredged yearly in order to maintain a navigable depth. Dredged sediments are usually dropped at Zeebrugge-Oost (Br&W ZB-Oost) dumping site, located several kilometres east of the port (Figure 2). About 4 million m^3 of sediment per year is dumped there (Magelas, 2001). Sediments consist of more than 50% of mud (fraction <63 µm) and the rest is fine sand up to 250 µm. Also, beach reshaping is frequently carried out to avoid nuisance by aeolian sediment transport. The dry beach is flattened to a certain elevation and the excess sand is pushed seaward which result to a cliff shape of the upper-beach.

Aside from that, the Zwin inlet was subject to large intervention works from August 2016 to the opening of the dyke in February 2019. The objective is to reduce sediment silting and accretion processes by increasing the amount of water flowing in and out of the inlet. Montreuil et al. (2020b) describe in more details the interventions and their effect on the morphodynamics of the Zwin inlet. Under the framework of the Zwin expansion, the dunes from the Belgian side in section 255-256 were excavated between August 2016 and March 2017 (removed sand volume of 124 9867 m³). Most of it was used for the construction of the new inland Zwin dyke.

2.5 Hydrodynamics

The east coast is macro-tidal with a mean range from 3.7 m at neap tides to 4.3 m at spring tides (Table 3). The tides are semi-diurnal with a slight asymmetry as the flood duration is shorter than the ebb duration (Haerens et al., 2012). Tidal currents in Knokke can exceed 1.3 m/s during spring tide, while the average velocity is around 1 m/s in the nearshore area (Vlaamse Hydrografie, 2017). In general, maximum current velocity directed to the east occurs 1 hour before high water, while it is lower and toward the south-west 3 hours before and after high tide (Figure 6). Thus, the flood flow (to east) is faster than the ebb flow (to west). The magnitude of the flood increases towards the east under the influence of the Western Scheldt estuary (Atlas, 1992). Also, the velocity of the tidal currents is generally stronger in spring than in neap condition.

Table 3 – Tidal datums based on the port of Zeebrugge.

Datum	Description	Elevation (m TAW)
HOWL	Highest observed water level	6.690
MHWS	Mean high water spring	4.583
MHWS	Mean high water	4.209
MHWN	Mean high water neap	3.730
MTL	Mean tide level	3.645
MSL	Mean sea level	2.294
MLWN	Mean low water neap	0.919
MLWN	Mean low water neap	0.564
MLWS	Mean low water spring	0.281
LOWL	Lowest observed water level	-0.830
TRS	Tide range (spring)	4.302
TRM	Tide range (mean)	3.645
TRN	Tide range (neap)	2.811

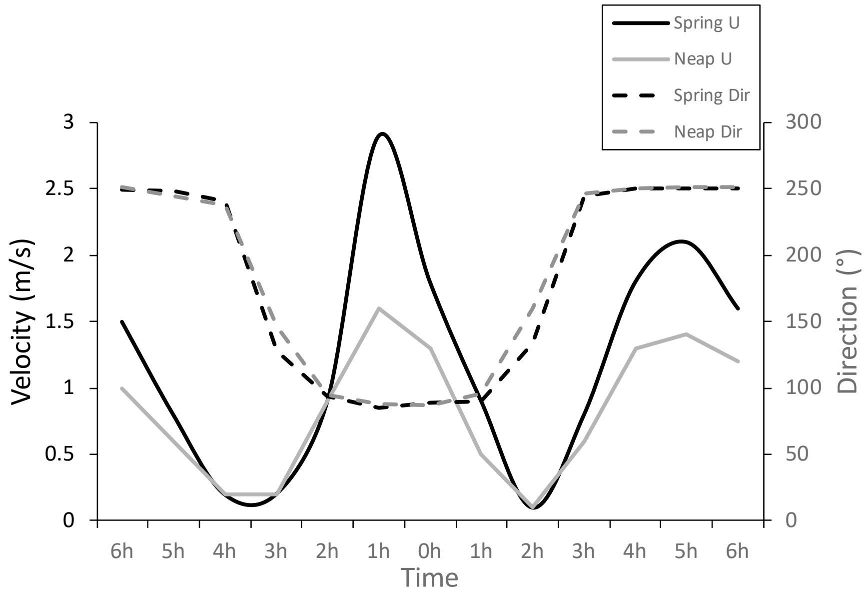
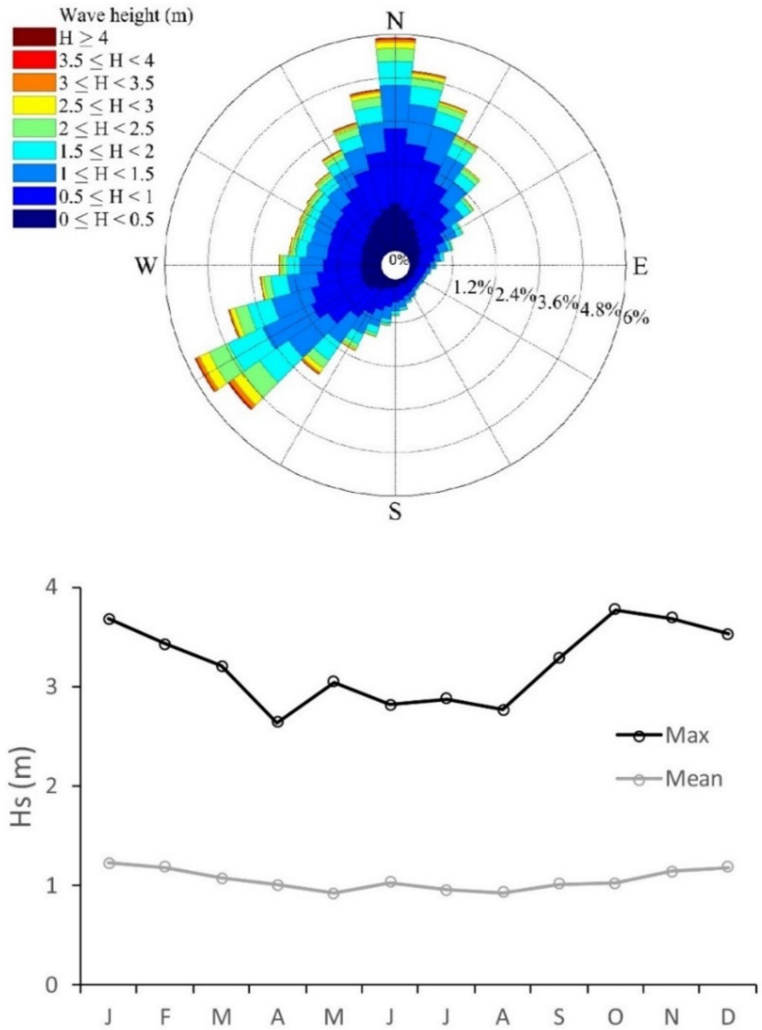


Figure 6 – Velocity and direction of currents in Knokke during a tidal cycle (based on Atlas, 1992).

The east coast is subject to low-moderate wave energy with a dominance of SW to N directions, but it is also exposed to storms. Recorded offshore wave heights are >1.5 m for more than 80% of the time and <0.5 m for 20% of the time (Figure 7, Montreuil et al., 2020b). Waves are characterized by periods between 3.5 and 6 s, and they are typically short crested due to the shallow water depth and the short fetch. Storms are recorded at least once per year when water level and offshore wave from southwest to north sector height often reach 5 m TAW and 4 m respectively (Haerens et al., 2012). Annex B presents the recorded storm events associated with high water levels between 1988 and 2020 (Afdeling kust, 2020).



Wave data covers 17-years from 2000 to 2017 (from Montreuil et al., 2020b).

Figure 7 – Annual offshore wave rose (upper panel) and mean and maximum significant wave height (lower panel) from Westhinder wave buoy located 30 km from the shore.

2.6 Sediment dynamics

Waves at the coast generate a net longshore sediment transport which is directed to north-east. The potential average annual longshore sediment transport rate is estimated from 135 000-146 000 m^3/y along the east coast (Vandebroek et al., 2017). Svasek (2012) reported that a gross sediment transport of 400 000 and 200 000 m3/year eastward and westward respectively based on wave modelling. Under the Budget project, sediment dynamics including bed and suspension load were studied based on measurements (Figure 8, Lanckneus et al., 2001). The results suggest that 0.05 m^3/m/day of sand was transported as bedload from the north towards the Plaat van Heist, while the suspended transport was directed to the northeast (flood dominated) in front of Knokke beach and also further offshore.

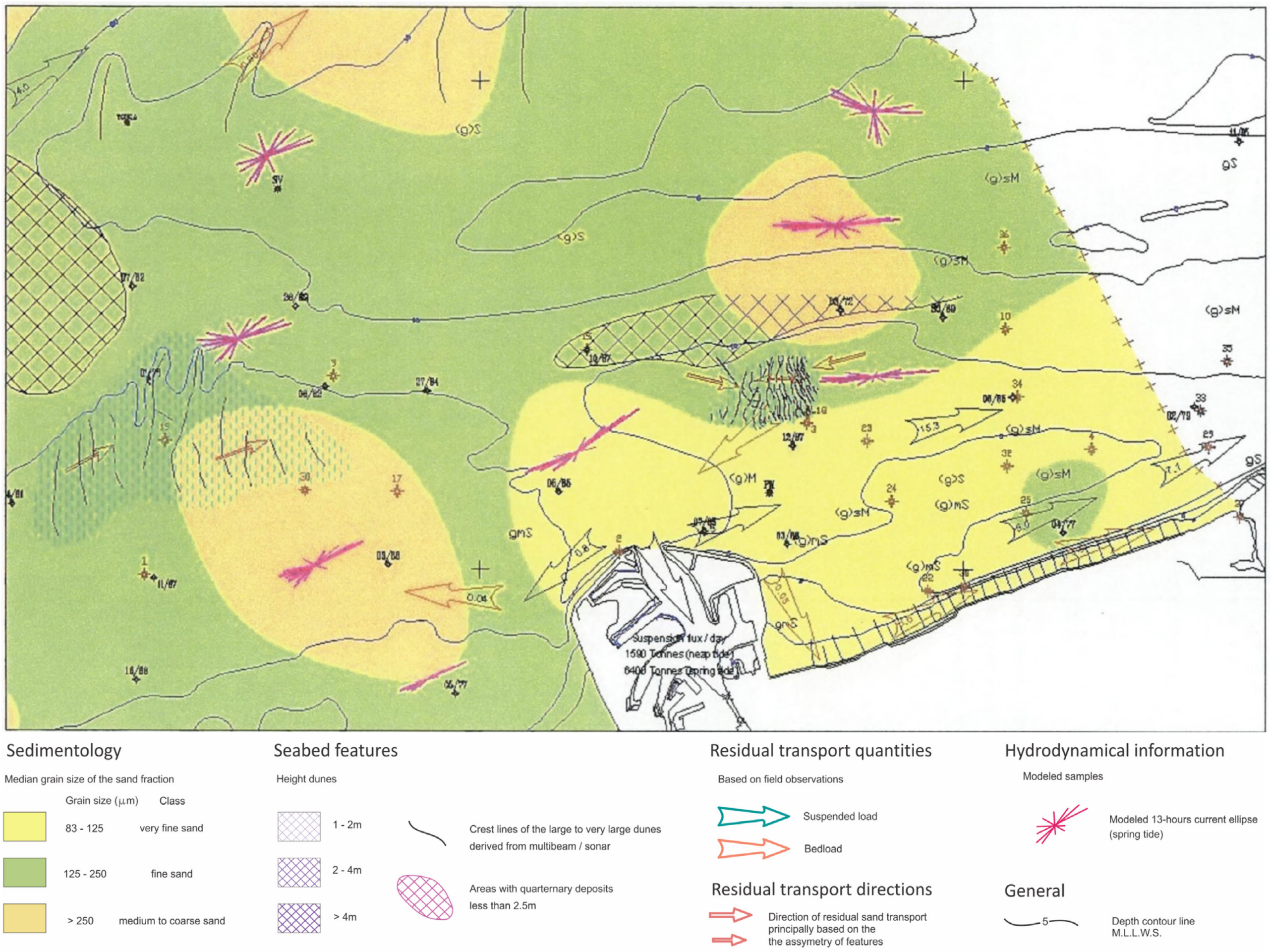


Figure 8 – Map of the natural sediment transport along the east coast (from Lanckneus et al., 2001).

Currents velocity and sediment concentration were measured at the shoreface of Baai Van Heist under calm and energetic condition in 1990, 1991 and 1993 (Eurosense, 1991a, b, c, 1994a). Annex C.1 shows the location and time series of the measurements. Most significant conclusions are: (1) velocities increase strongly with distance from the shore; (2) flow is flood dominated at all locations with an increase of asymmetry closer to the coast; (3) sediment concentration is controlled by current velocity, with a time lag from 0.5- 1 hour; (4) peaks in sediment concentration are short with a duration of <1 hour; (5) most of the sediments are settled near reverse of tidal currents during calm weather conditions; (6) the sediment concentration significantly increases during storm conditions, especially during ebb; (7) sediments in suspension (from 0.25 m to 1.5 m above the bottom) consist for roughly 33% of sand. In front of Zeebrugge port, an area of several km^2 erodes at a rate of 400 000 m^3/year (Trouw et al., 2015). The currents are strongly flood dominated so that sediment is probably transported to the east coast of which 150 000 m^3/y is deposited to the north of Baai van Heist (i.e. outside the active zone).

Further similar measurements by Eurosense (1994b) were undertaken at the shoreface (-3 m TAW) at the eastern boundary of the Appelzak channel in front of the Zwin coast (Annex C.2). The results suggest: (1) 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; (2) the amount of sand in suspension is less than 10% of the total amount of suspended transport at 25 cm above the bottom (i.e. lowest measurement location); (3) 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; (4) under energetic conditions, the longshore sediment transport is much larger than calm conditions, with 6000 kg/m (1000 kg/m) during flood and 5000 kg/m (500 kg/m) during ebb tides.

2.7 Sediment characteristics

The sediments are heterogenous along the east coast, ranging from mud/silt (D_{50}<63 µm) in the Baai van Heist to coarse sand (D_{50}>350 µm) where beach nourishments took place. Figure 9 presents the grain size characteristics based on measurements collected under the Quest4D project (Van Lancker et al., 2007). Sea bed is often covered with a thin layer of sand above a clay layer. The presence of mud/silt on the sea bed is controlled by the hydrodynamics conditions related to tidal currents and waves.

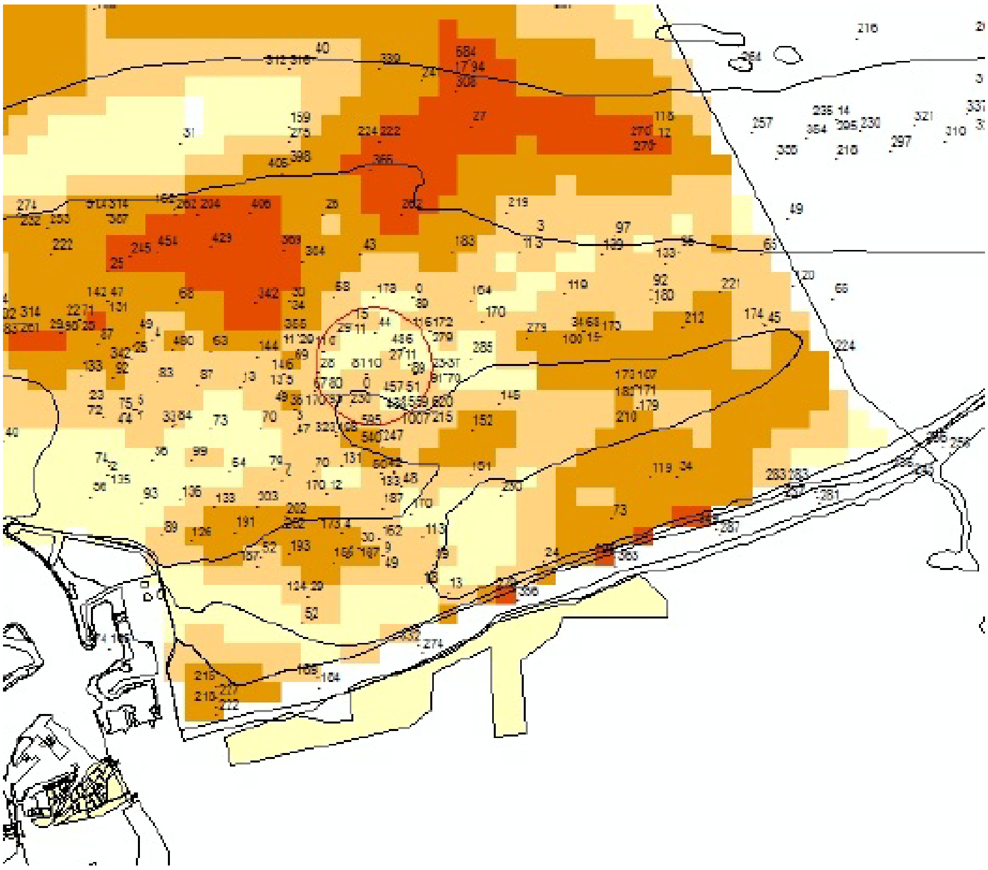


Figure 9 – Grain size characteristics along the east coast (D_{50}) (adapted from Van Lancker et al., 2007).

Van Lancker et al. (2007) reported that sediment transport entering in the coastal zone from the outer of the Zeebrugge port is a mixture of mud and sand (Figure 10). Other in-situ measurements in Baai Van Heist indicated that the top layer of 80 cm above the sea bed consisted 67% of mud/silt. The sediment grain size generally become larger toward the east along the shore, while there is a certain spatial variability of the finer particles below the low water line.

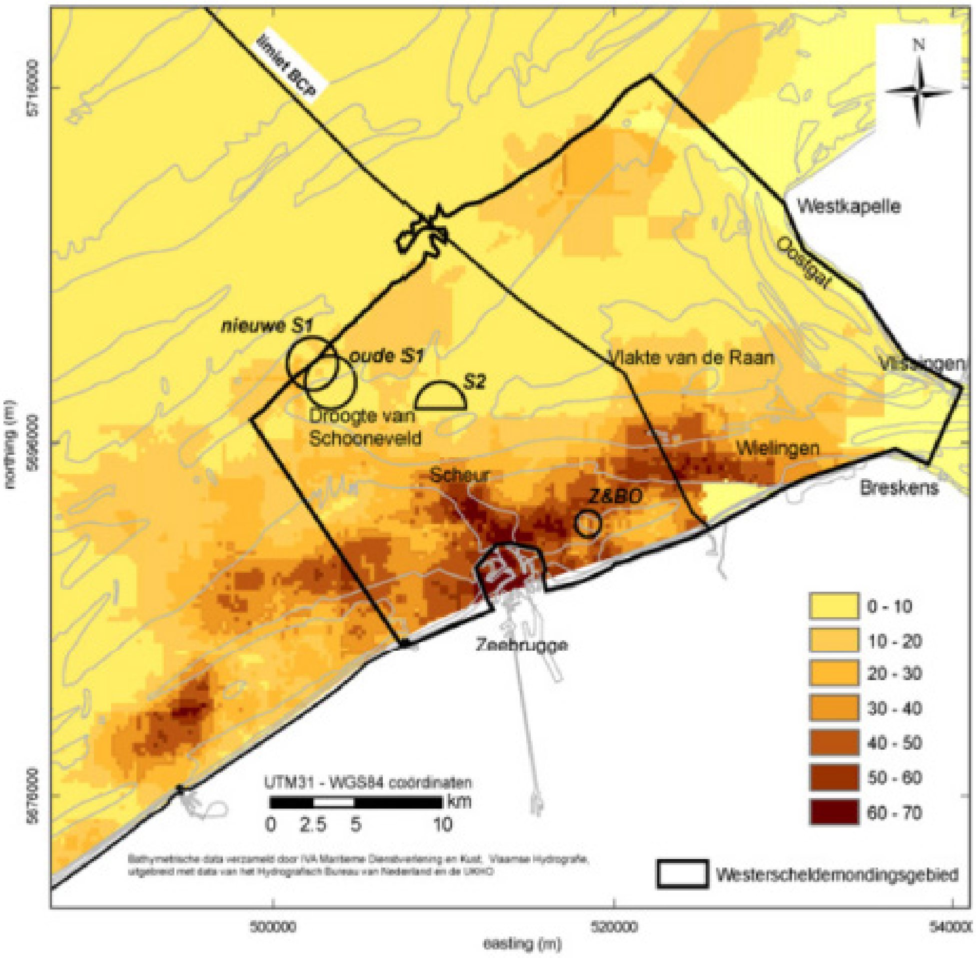


Figure 10 – Occurrence of material < 63 µm in the bottom sediments (in %) (from Van Lancker et al., 2007).

Deronde (2007) analysed in detail the beach sediment characteristics based on airborne hyperspectral remote sensing method. He found a cross-shore gradient of the sediment grain size from fine-grained sand at the low water line to coarser sand with shell fragments on the dry beach (Figure 11). There is a clear trend for the sand to be coarser (up to 400 µm) in the areas where beach nourishment took place. Additionally, a temporal variability of sediment characteristics occurs during calm and post-storm conditions. For instance, the muddy sand often present on the lower part of the beach may correspond to a temporary layer of mud deposited under calm hydrodynamic conditions.

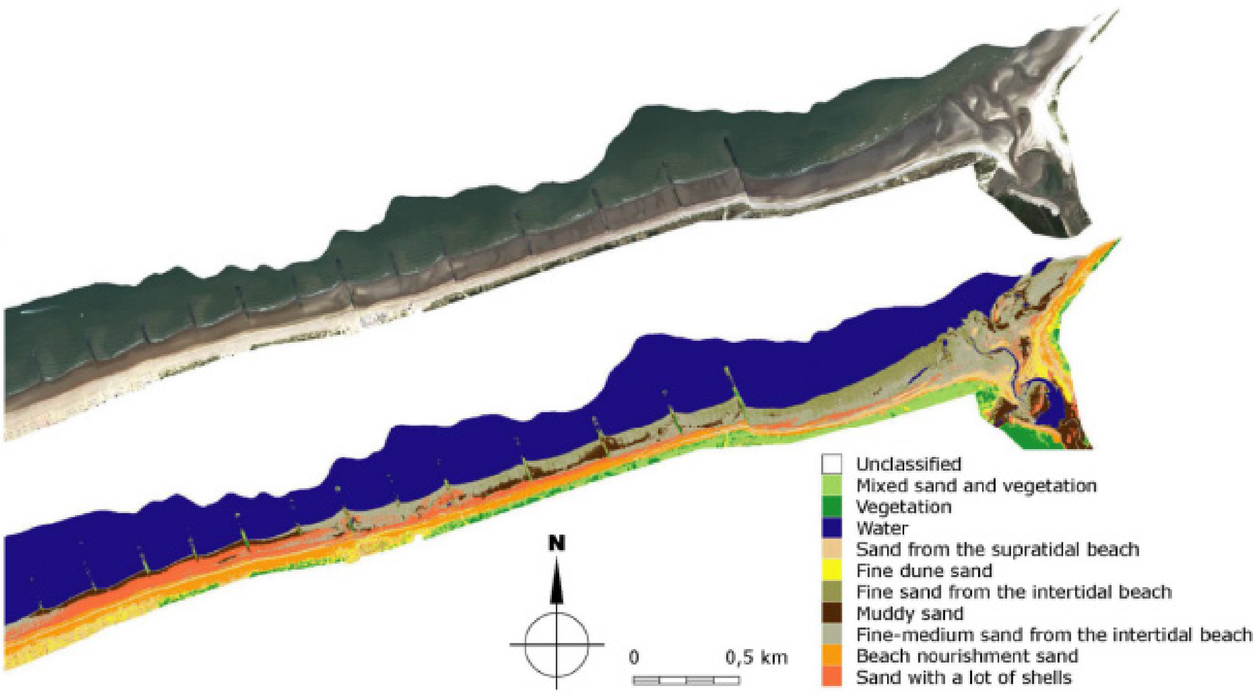


Figure 11 – Classification of the coast in Knokke-Heist (from Deronde, 2007).

2.8 Morphological trend and evolution

2.8.1 East coast from Zeebrugge to the Zwin inlet (from stretch 44 to 51)

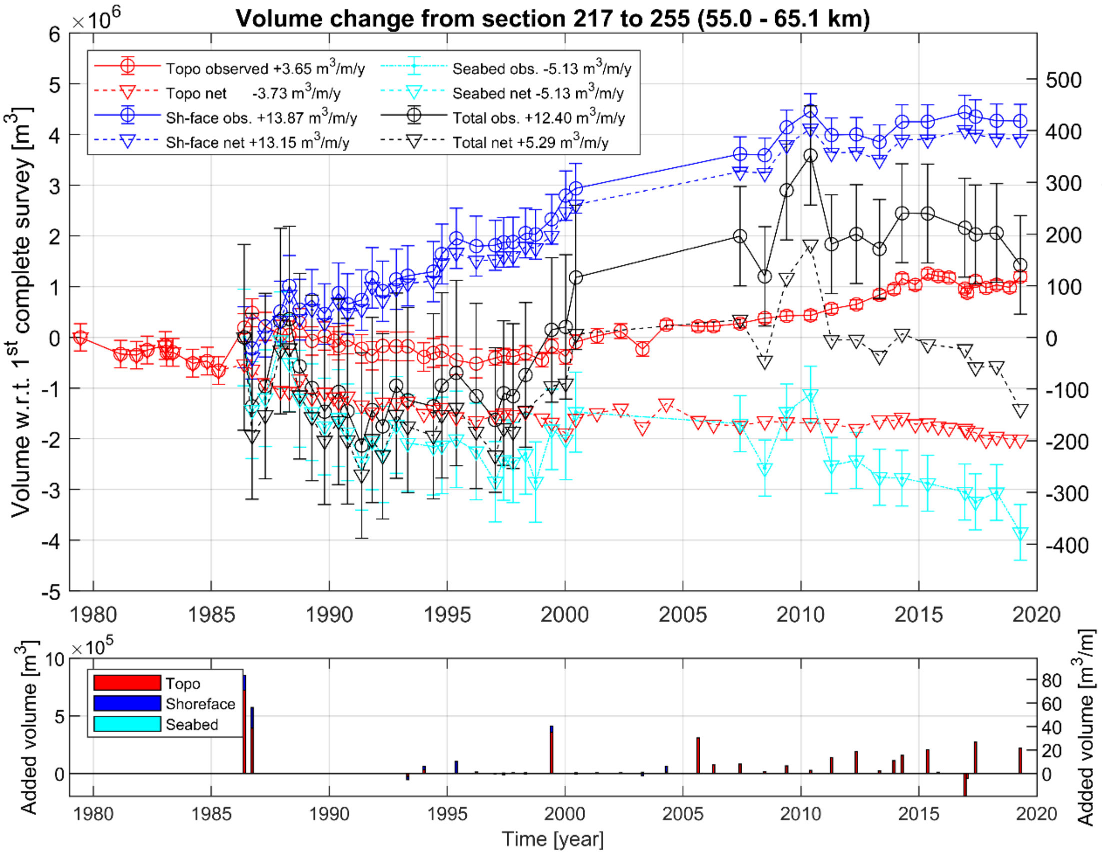
This part summarizes the available information on the morphological evolution of the coastal zone:

- Under the CREST project, it is reported the evolutionary trend for the entire east coast of the beach, shoreface and seabed including the influence of nourishments between the first survey late 1970s or beginning of 1980s and 2019 (Montreuil et al., 2020a). Annex D presents the volumetric changes of the emerged and submerged beach;

- Houthuys et al. (2020) describes the evolution of the beach (dunes, dry and wet beach), and the shoreface up to 1500 m offshore including the influences of human intervention. The research it is based on linear trends at least over the last 10 years;

- Janssens et al. (2013) carried out morphological trend analyses of the shoreface and seabed between 1997 and 2010.

The coastal zone from the east of Zeebrugge port to the Zwin inlet presents an evolution of natural feeding (+5.29 m^3/m/y) (Figure 12). However, different volumetric trends are observed for the emerged beach (erosion -3.73 m^3/m/y), shoreface (accretion + 13.15 m^3/m/y) and seabed (erosion -5.13 m^3/m/y). Up to 2 km from the east breakwater of the Zeebrugge port, a large accretional trend occurs in the Baai van Heist by natural processes. However, the rate of accretion has decreased in recent years. A large erosional trend is found from Knokke coast to the Zwin inlet. The following sub-sections describe the morphological evolution of each stretch along the east coast (Houthuys et al., 2020).



Nourishment and dredging activities (from Montreuil et al., 2020a). Observed values correspond to the measured volume, while the corrected values are the ones subtracted from the artificial sand supply.

Figure 12 – Time series of volume changes along the east coast from stretch 44-51 (upper-panel).

2.8.2 Coastal stretches

Stretch 44

Stretch 44 (section 217-218) of a length of 346 m is located at Heist near the Oostdam breakwater of Zeebrugge port (Figure 13). Beach is flat and large up to 645 m wide (i.e. from the sea dike to the low water line) and back by a nature reserve called Baai van Heist composed of foredunes and saltmarshes. A sea dike is present along the entire stretch. A general accretion of 5.48 $m^3/m/y$ occurs there, however the beach and the shoreface experience opposite trends over time (Figure 14). The evolution of stretch 44 is different to the rest of the Heist section due to the past human interventions such as beach nourishments in 1977-1979 and in 1986 and the extension of the eastern breakwater of the port of Zeebrugge (Oostdam) from 1977-1986. Also, sand extractions were undertaken due to the construction of a gas pipeline in 1992-1993 and further beach excavations of unconsolidated sediments for coastal safety and recreation. After 1995, most of this coastal stretch has become a nature reserve where no large-scale interventions have been performed anymore. Since 2007, this entire stretch has experienced accretion with the development of Plaat van Heist shoal, protecting the beach against waves. Sand gain results from natural processes. Under tidal floods, the accreted zone around the port of Zeebrugge is probably an important source of supply, which compensates in some extent the blocked longshore transport caused by the presence of the port breakwaters. Moreover, the Appelzak channel might be another supplier, although the morphological evolution of the beach and seabed points to positive and negative fluctuations over time. There are no morphological indications that the beach would receive sand from the adjacent beaches at the east side. Also, the growth of the Plaat van Heist shoal at its seaward flank has a limitation due to the constraints of the ebb currents at low tide (i.e. increase of velocity leading to erosion).

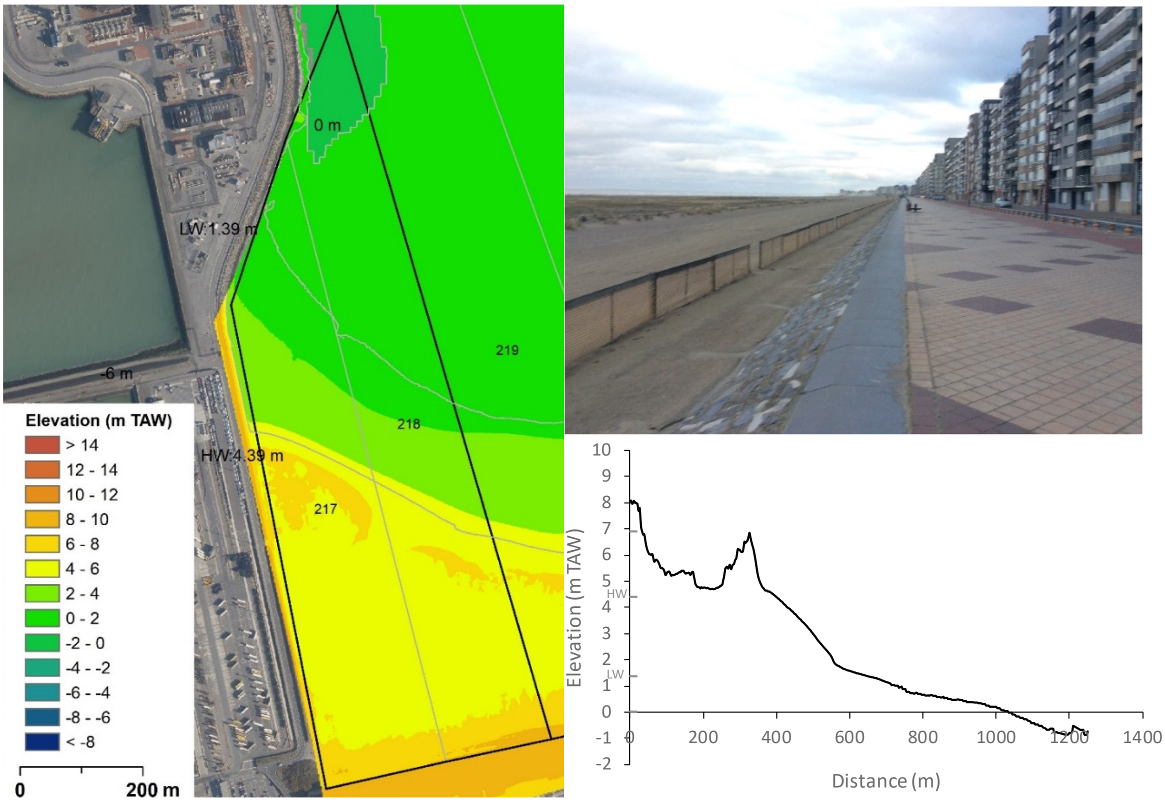


Figure 13 – General characteristics of the coast for stretch 44: Heist - Oostdam:
Elevation model with datum contour lines in 2019, ground photograph, and cross-shore profile.

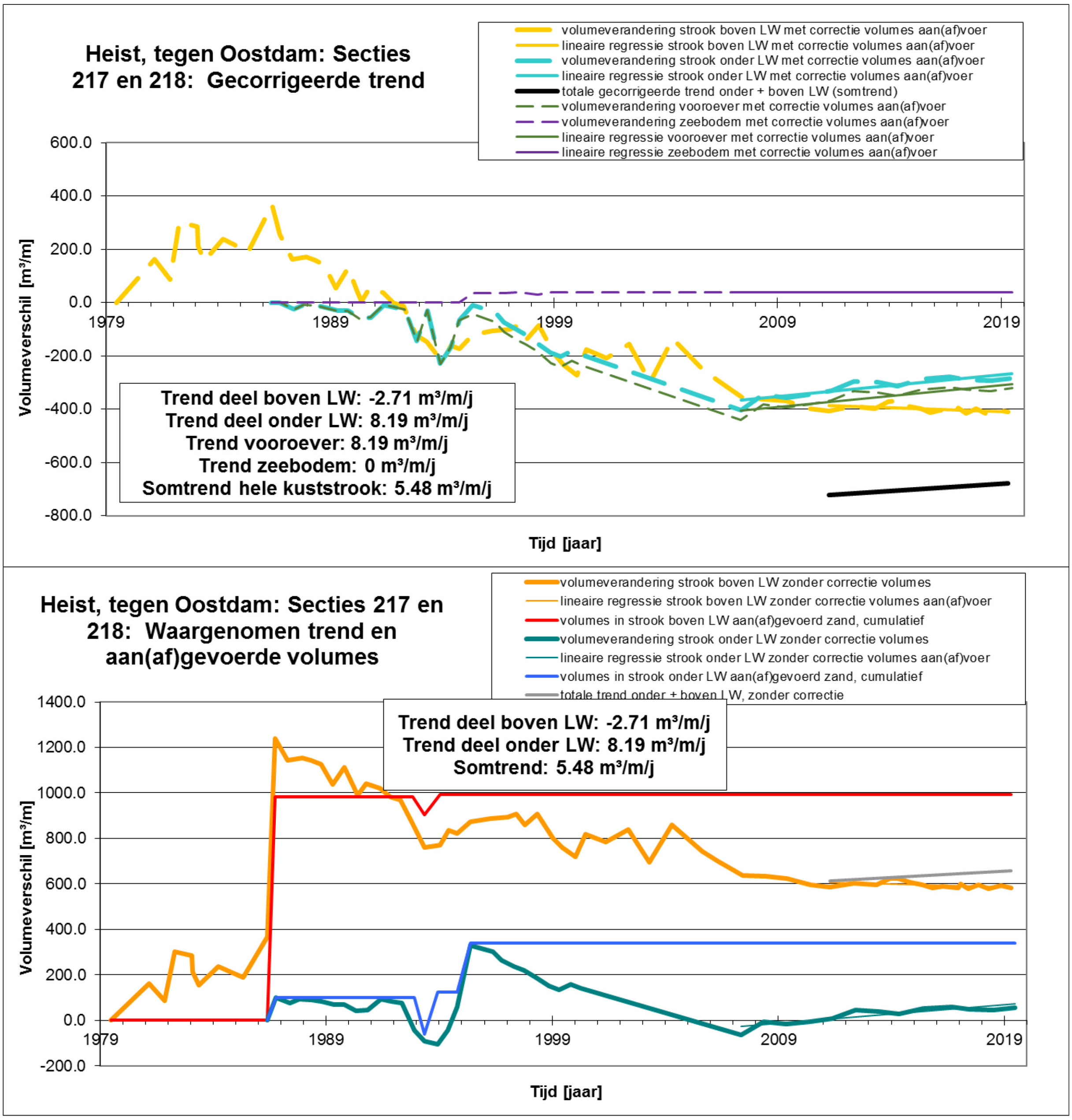


Figure 14 – Morphological trend for stretch 44: Heist – Oostdam.

Stretch 45

The stretch 45 (section 219-221), of a length of 626 m, is located at Heist near Heldenplein. The beach is characterized by a large beach ranging from 485 to 530 m width, and located behind a sea dike (Figure 15). A general positive morphological evolution for the entire beach occurs with an average net sediment gain of 50.64 m^3/m/y (Figure 16). After 2012, no nourishments have been carried out. The rate of accretion of the submerged beach has reduced since 2010. The shoreface growth started after the completion of the Oostdam in 1986. Plaat van Heist shoal has developed to such an extent that a large area of it is now exposed at low tide. Thus, it can protect the emerged beach against waves, and in particular section 220-221. Similar to stretch 44, there are no morphological indications that the beach would receive a natural sediment supply from the adjacent eastern beaches. Since 2010, a decrease of accretion rate and local erosion of the seaward flank of the shoal are observed. This suggests that a new morphological equilibrium is about to be reached. Sediment flows in the shoreface and it converges westward, and in particular in section 220-221 (i.e. counterbalance between Plaat van Heist growth and the erosion in the seaward area of the Zeebrugge outer port) (see Figure 31). After being disrupted by the Zeebrugge breakwater, the currents forced around the breakwater are re-attached, and thus leading to a long-term net landward sediment transport. In general, the morphological changes of this stretch are controlled by both the natural processes and human interventions.

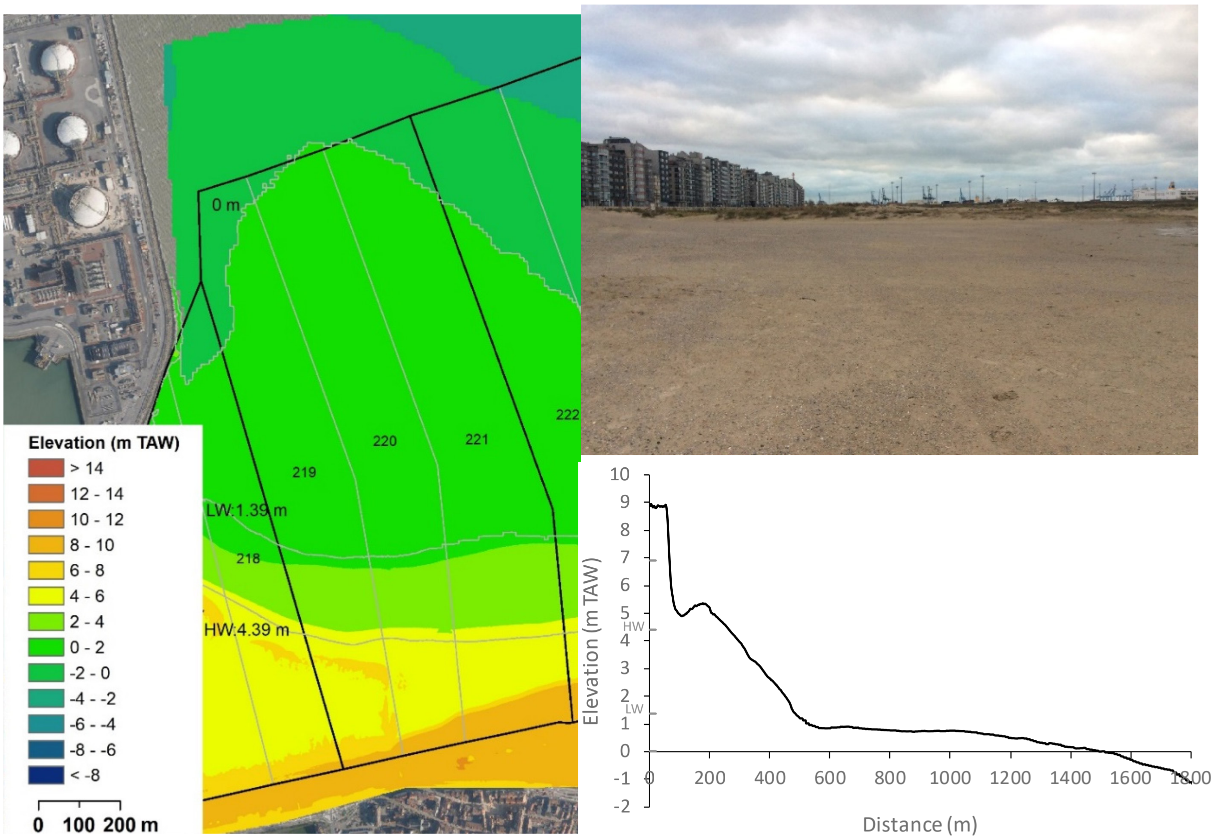


Figure 15 – General characteristics of the coast for stretch 45, Heist - Heldenplein:
Elevation model with datum contour lines in 2019, ground photograph, and cross-shore profile.

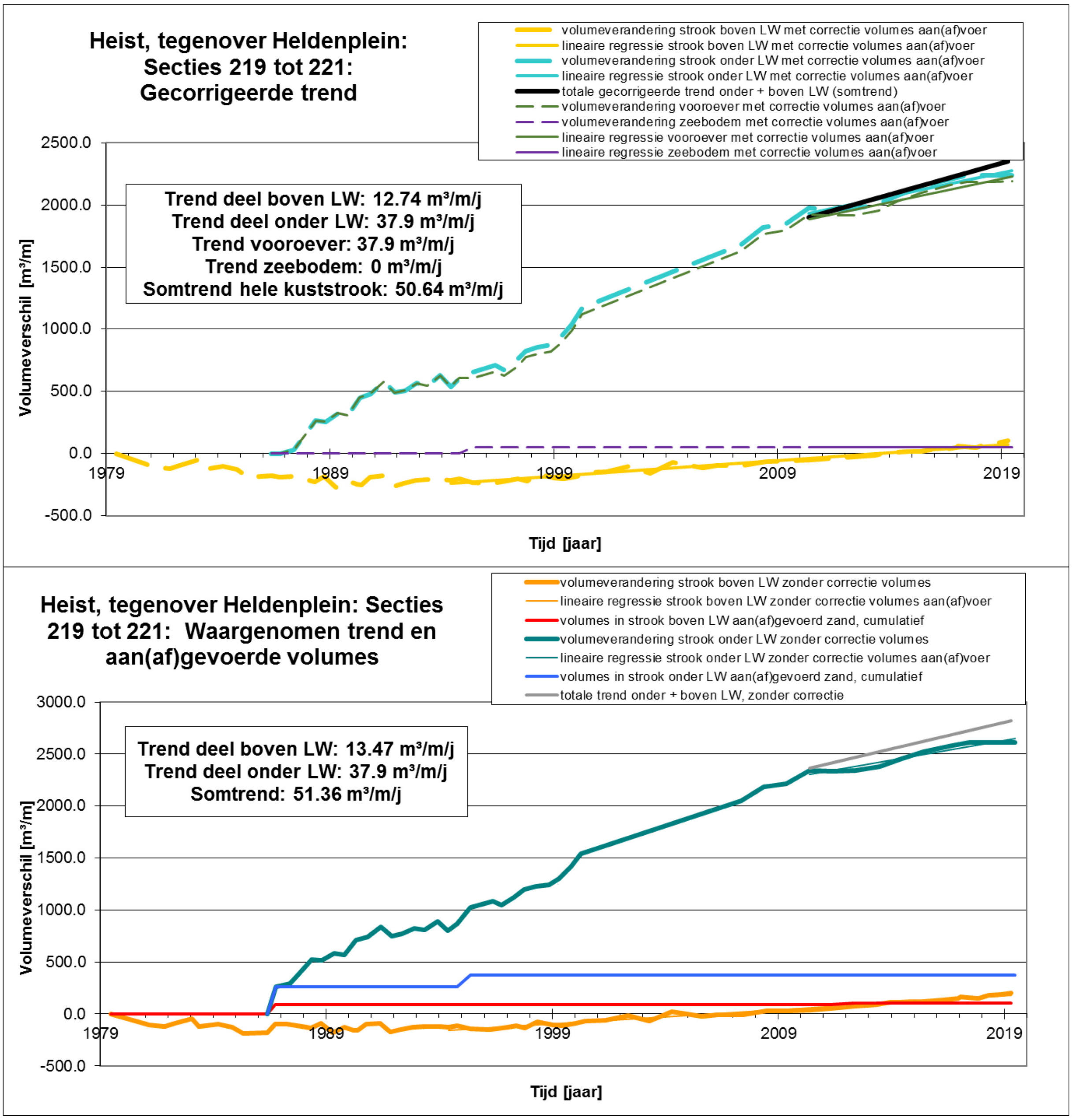


Figure 16 – The morphological trend for stretch 45: Heist – Heldenplein.

Stretch 46

The stretch 46 (section 222-224) has a length of 973 m and it is located between Heist and Duinbergen. The beach width ranges from 380 to 440 m and it is backed by foredunes (except in section 222) and a sea dike landward (Figure 17). The long-term morphological trend is clearly positive for both beach and shoreface with a net gain of 45.02 $m^3/m/y$ (Figure 18). Some local sand nourishments have been carried out for recreation purpose, in particularly around the center of Duinbergen, between 2008 and 2017. The growth on the emerged beach is a recent phenomenon, which is related to the vertical development of the Plaat van Heist shoal. As a result, the beach in sections 222-223 is more sheltered from waves than in the past. The eastward extension of the shoal suggests that sand accretion occurs here by re-attachment of sediment transport which is then directed toward east (see Figure 31). There are no morphological indications for natural sand supply along the beach so that the sand gain is more likely to take place through cross-shore sediment transport. Also, the growth on the beach is probably the result of morphological adjustments after the extension of the outer port of Zeebrugge.

Regarding the submerged beach, the positive morphological evolution is related to the development of the Plaat van Heist. The accretion rate of the shoreface has declined since 1999, which might reflect a trend towards a new morphological equilibrium. Since 2000, erosion of the seaward side of the Plaat van Heist has occurred with local deepening of 0.3 m and landward retreat of 75 m.

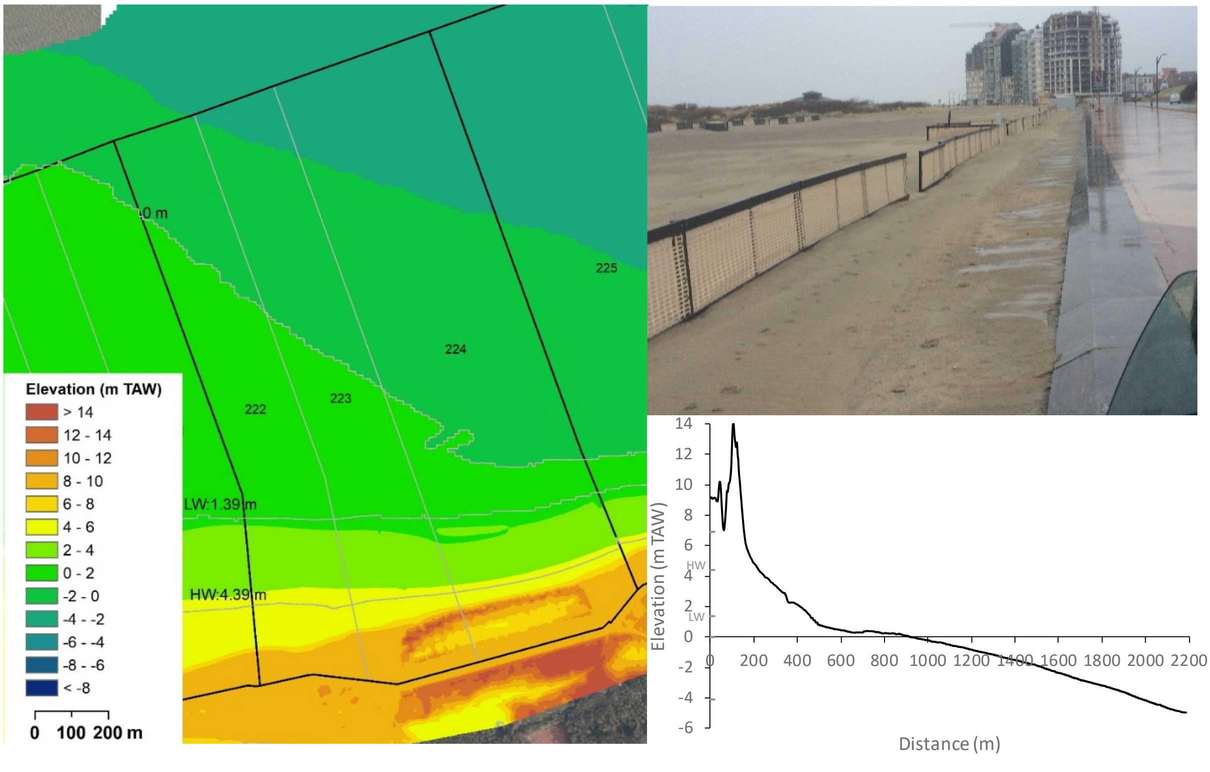


Figure 17 – General characteristics of the coast for stretch 46, Heist - Duinbergen:
Elevation model with datum contour lines in 2019, ground photograph, and cross-shore profile.

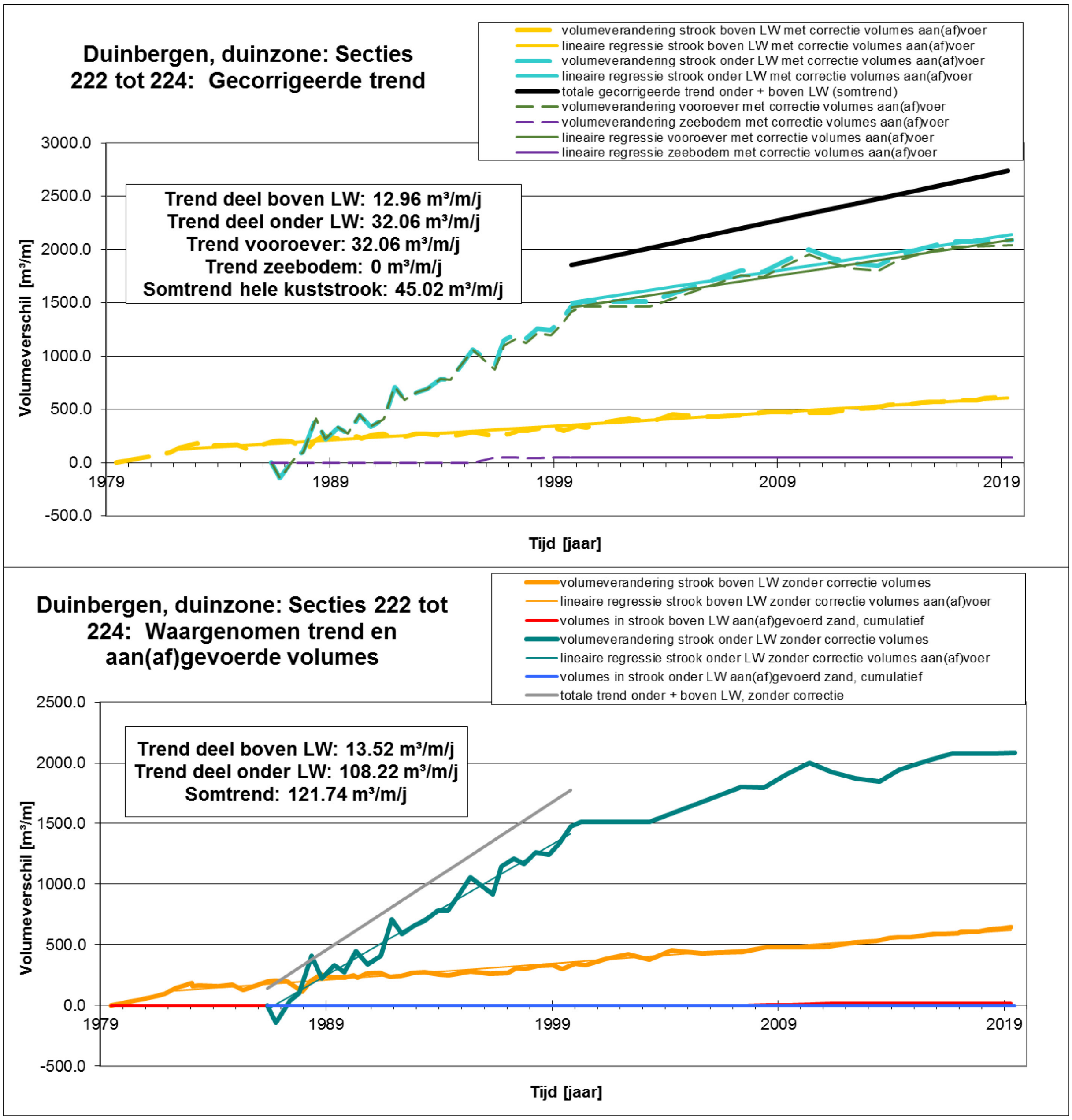


Figure 18 – Morphological trend for stretch 46: Heist -Duinbergen.

Stretch 47

The stretch 47 (section 225-226) of a length of 700 m is located at Duinbergen-centrum. The beach is flat with a width of 235 m and directly backed by a sea dike (Figure 19). Negative morphological trend of the beach and shoreface occurs there with a net sand loss of -21.17 m^3/m/y over the last decade (Figure 20). The sand loss for the emerged beach is in average -8.44 m^3/m/y. However, greater erosion would take place without annual sand nourishments carried out on the dry beach between 1997 and 2017. It is reported that just approximately 54% of the supplies remained on the emerged beach along this stretch (Houthuys et al., 2020). The submerged beach is subject to a long-term accretion up to 62 m^3/m/y between 1986 and 2000. Since then, the rate has decreased to 13 m^3/m/y in the last decade. This reflects an opposite morphodynamics between the growth of Plaat van Heist shoal and the erosion of the Appelzak channel. The former is characterized by a growth on its two eastern banks located at approximately 200 m from the low-water line, and the latter is at approximately 750 m (nowadays in section 225 and 228) (see Figure 31). These two eastern sand spits morphology of the Plaat van Heist are controlled by the current flows in the westward extension of the Appelzak, named Branch 1, located at 600 m from the low water line. Along this stretch and also observed in stretch 46, there is still a development of the Plaat van Heist shoal, however erosion occurs on its seaward flank.

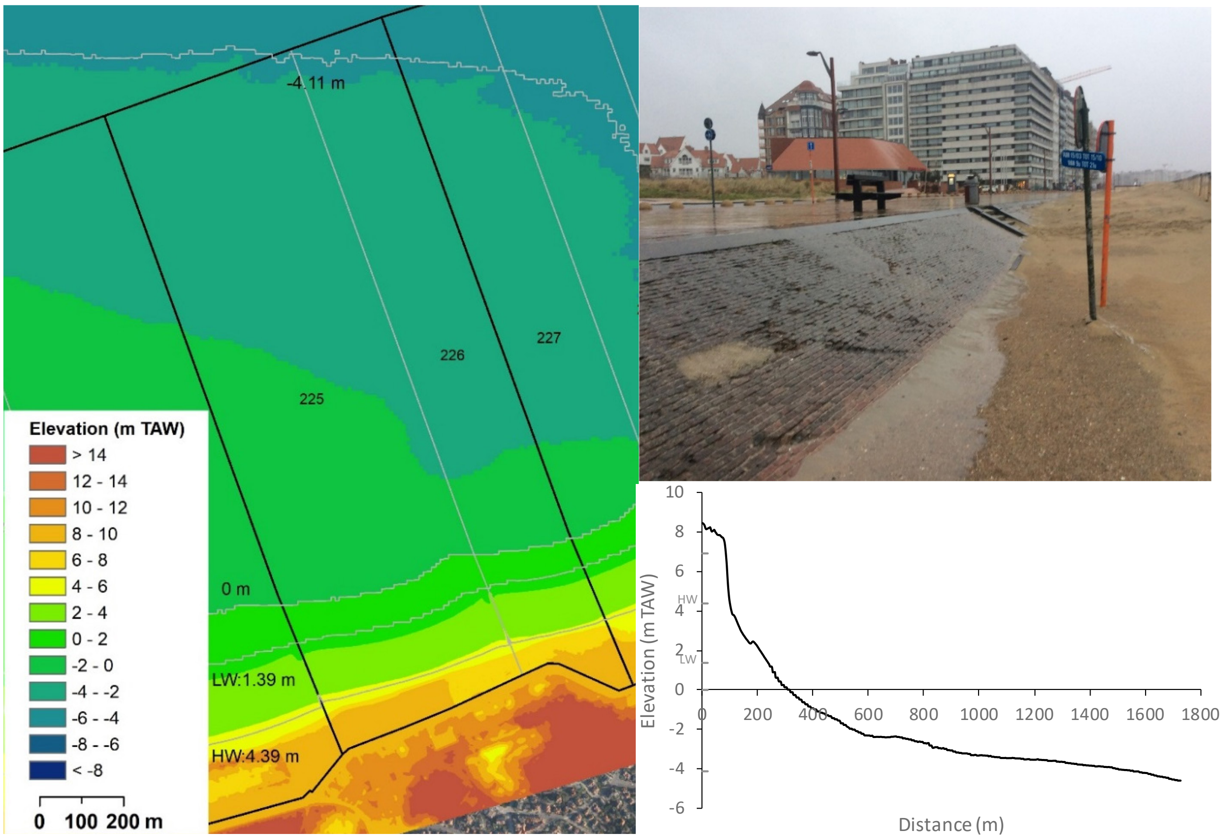


Figure 19 – General characteristics of the coast for stretch 47, Duinbergen-centrum:
Elevation model with datum contour lines in 2019, ground photograph, and cross-shore profile.

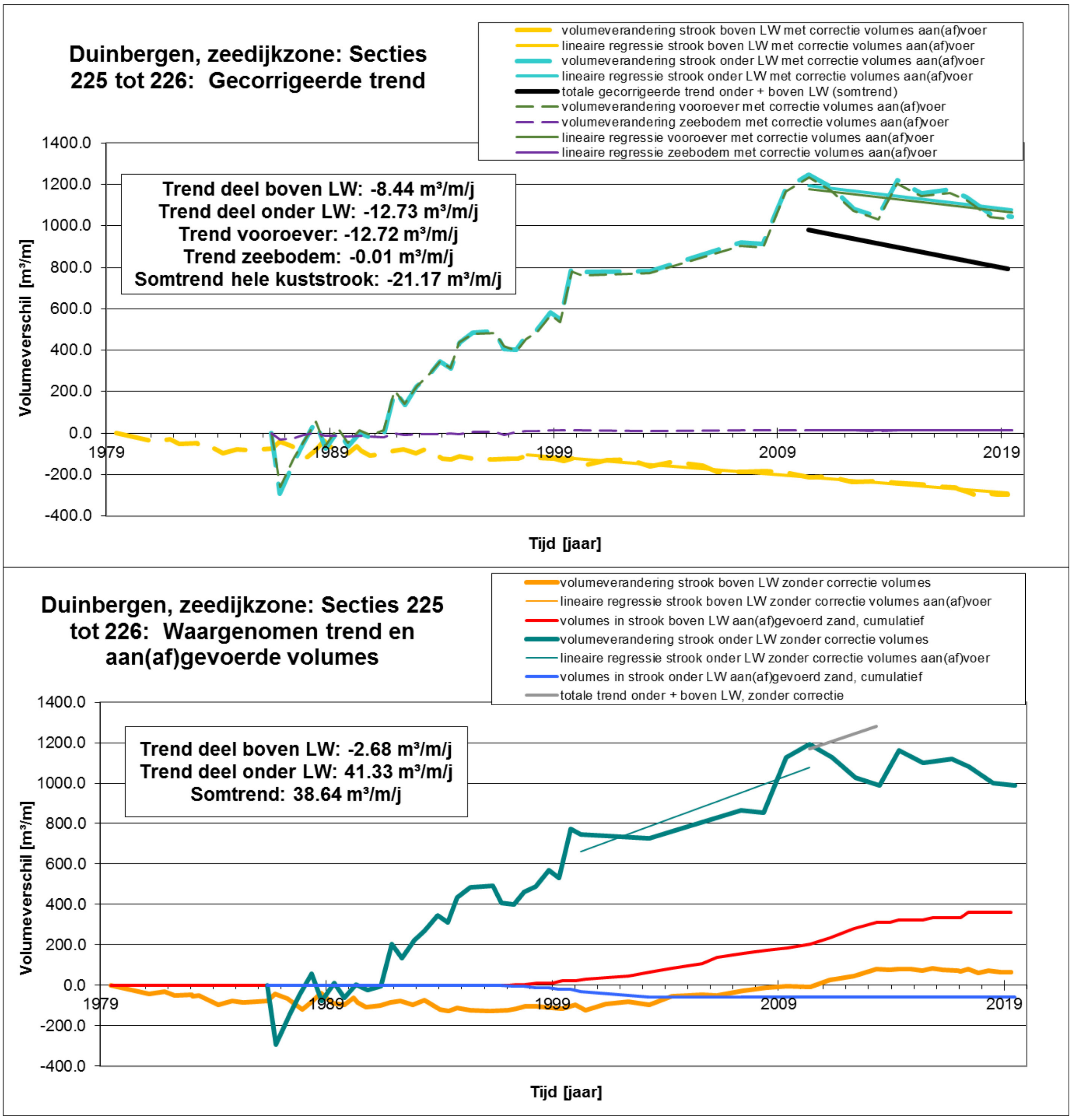


Figure 20 – Morphological trend for stretch 47: Duinbergen-centrum.

Stretch 48

The stretch 48 (section 227-232) of 1410 m in length is located at Albertstrand. The beach is around 300 m wide and is directly backed by a sea dike (Figure 21). The orientation of the coastline is shifted in section 231-233, which causes weak scouring spots along the dyke. A general negative morphological trend of -8.73 $m^3/m/y$ occurs in this coastal stretch (Figure 22). Large artificial sand was supplied between 1977-1979 and in 1986 (section 232) followed by annual small nourishments which were carried out on sections 232, 231 and 227 (Duinbergen) between 2009 and 2017 in order to prevent erosion. Accretion of the emerged beach was observed between 2004 and 2015. Stability or a relatively small sand loss trend of -1.5 $m^3/m/y$ have occurred since 2015. The evolution of this stretch is related to the local sand nourishments and to the sand inputs from the neighboring nourished beaches. The submerged beach has experienced a slight sand loss of -8.69 $m^3/m/y$ since 2000. This is probably related to the opposite dynamics of the development of Plaat van Heist shoal and the deepening of Branch 1 of the Appelzak channel.

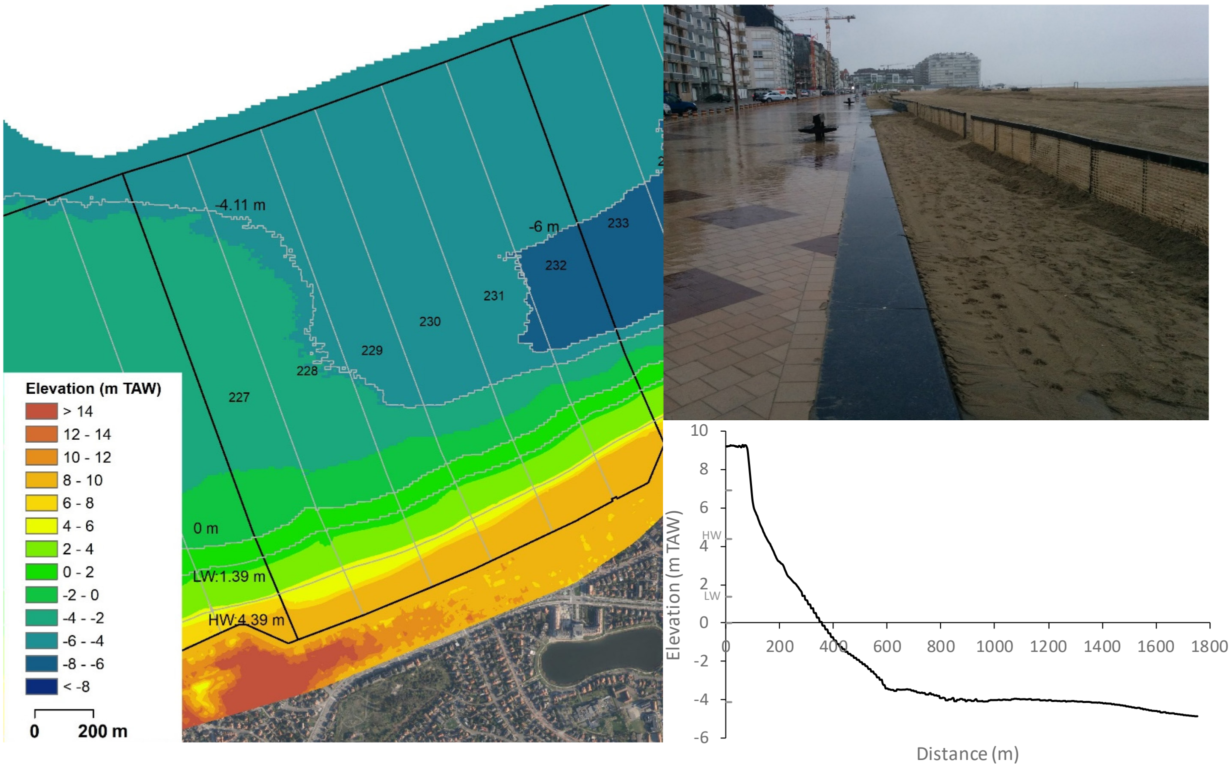


Figure 21 – General characteristics of the coast for stretch 48, Albertstrand:
Elevation model with datum contour lines in 2019, ground photograph, and cross-shore profile.

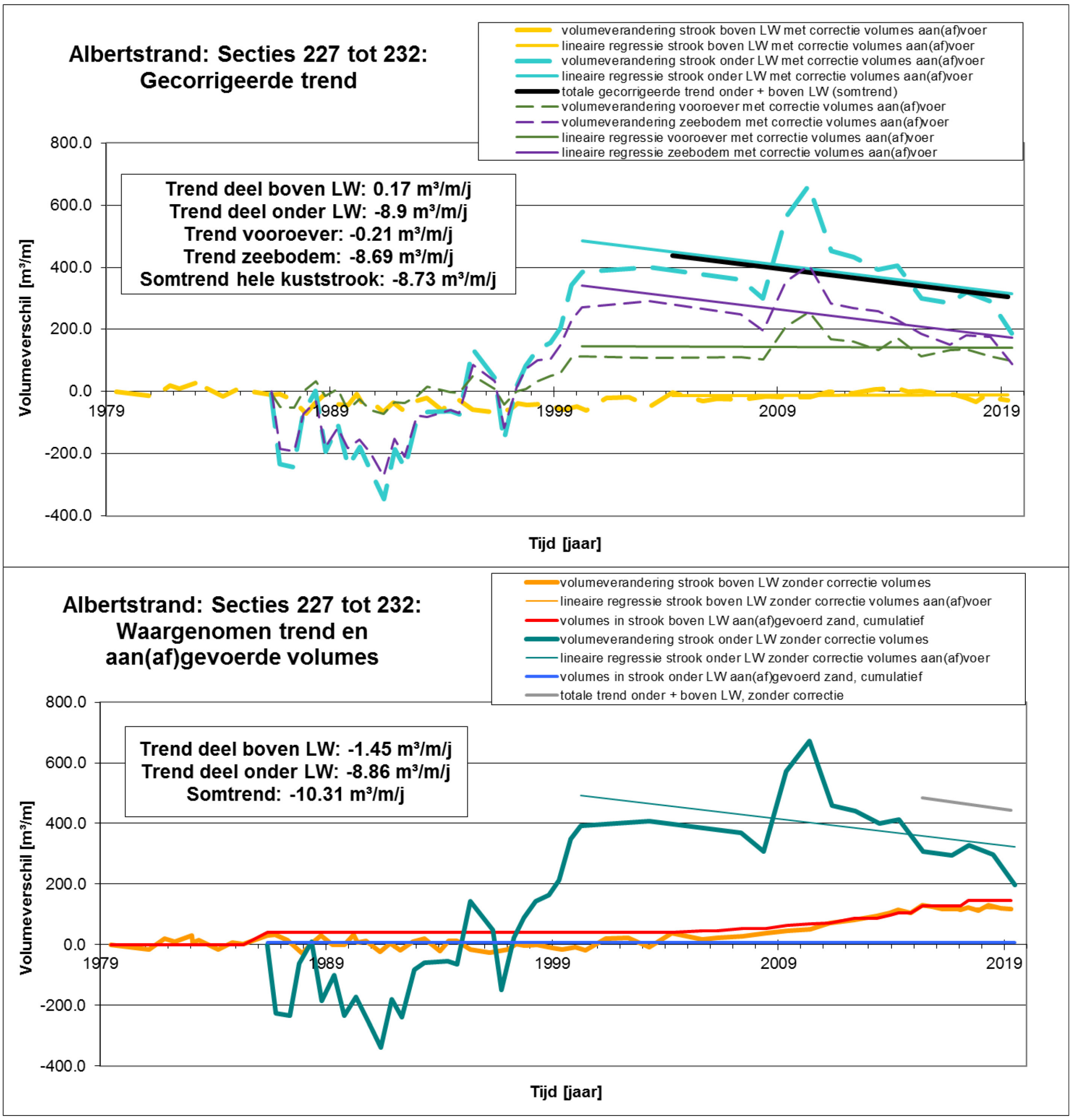


Figure 22 – Morphological trend for stretch 48: Albertstrand.

Stretch 49

The stretch 49 (section 233-241) of 2237 m length is located at Knokke-Zoute. The beach is between 180 and 250 m wide, locally reflective (Figure 23). A sea dike is present, except in section 241 where shallow dunes are present. This stretch is one of the weakest coastal zones with a net erosion for the beach and shoreface of -42.16 m^3/m/y (Figure 24). Large sand supplies were carried out in 1977-1979 and in 1986, and also annual small nourishments between 2006 and 2019 (except in 2018). Trouw et al. (2015) reported that the groynes, extending down to -3 m TAW along this stretch and already present 100 years ago, might still be effective, and especially between LW and MW, and at lesser extent below LW. The change in effectiveness can have an influence on the morphological behaviour at rather small longshore distance. The emerged beach has experienced a long-term erosion of -20 m^3/m/y, which has been constant between 1979-2019. In contrast, the sand loss of the submerged beach has fluctuated over time. Less erosive behaviour was observed in 2000s when a calmer storm period happened. Also, the groynes became more pronounced and exposed due to erosion and less artificial nourishments, which might have stabilized this stretch (Trouw et al., 2015). Since 2010, the erosion rate is of -22.28 m^3/m/y. The large sand loss is mainly related to the deepening of the tidal Appelzak channel located around 100 m from the coastline. The landward slope below the low water line is steep (>2°), which limits the possibility of the beach to recover after storms. Eroded sand is expected to return to the beach under constructive wave conditions, but it is only possible if the slopes are not too steep (Masselink et al., 2015). Over the last four decades, the beaches of Knokke-Zoute lost about 2400 m^3/y, corresponding to an elevation decrease of more than 1 m/y.

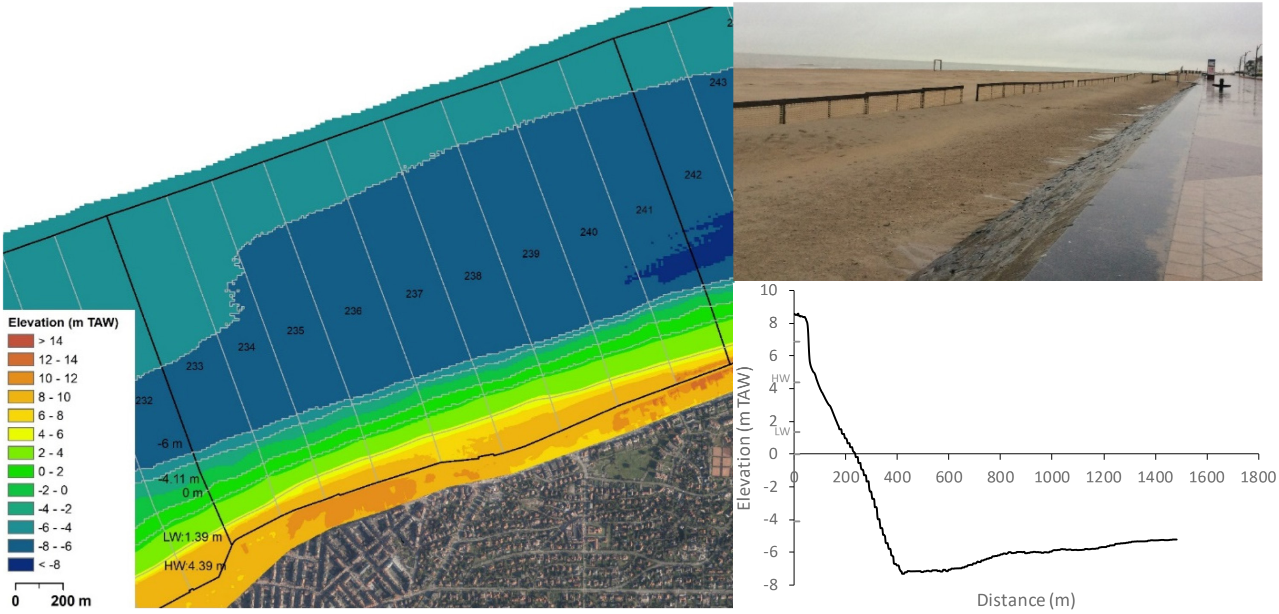


Figure 23 – General characteristics of the coast for stretch 49, Knokke-Zoute:
A) Ground photograph, B) Profile, C) Elevation model with datum contour lines in 2019.

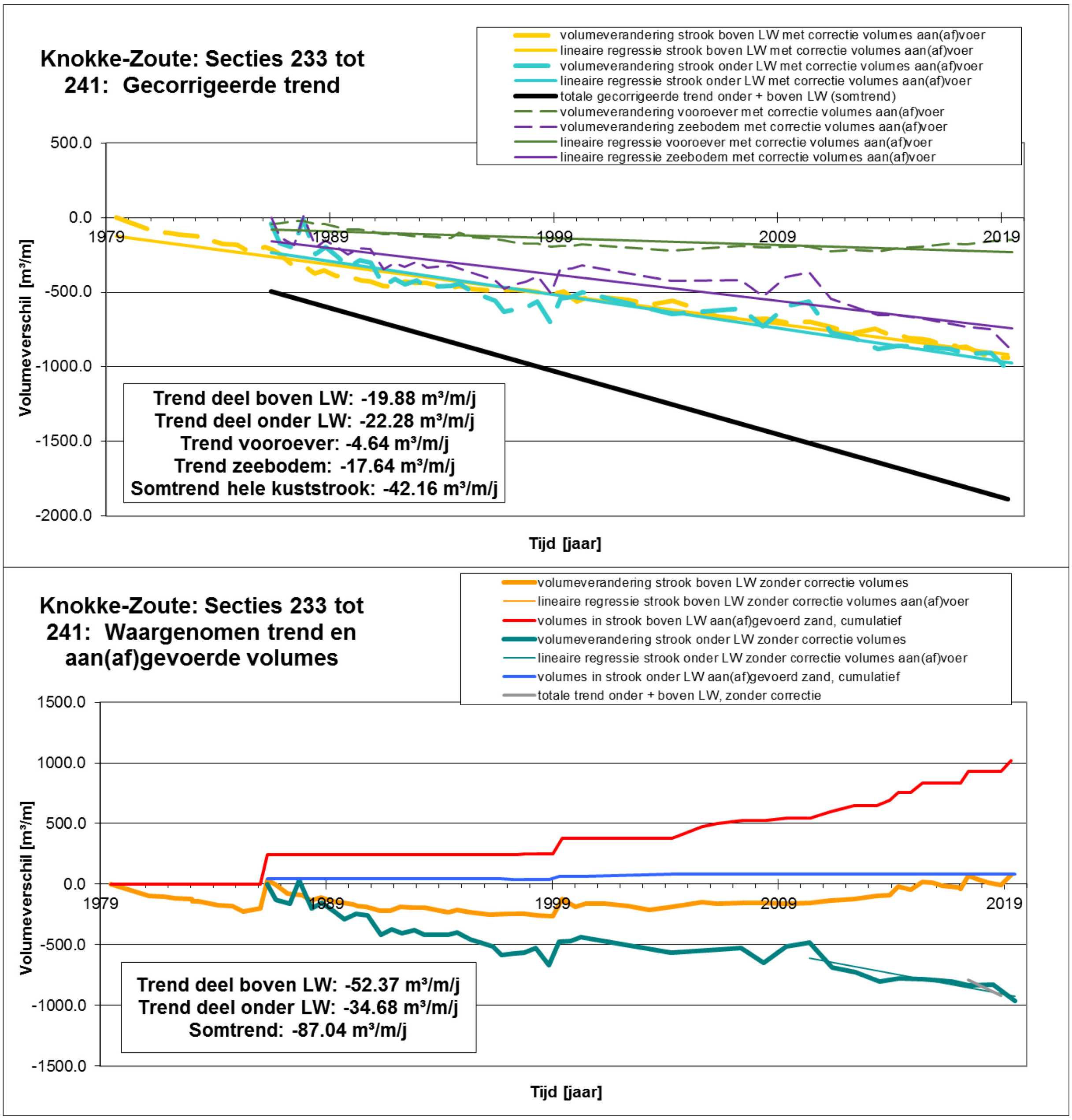


Figure 24 – Morphological trend for stretch 49: Knokke-Zoute.

Stretch 50

The stretch 50 (section 242-249) of 2310 m length is located at Lekkerbek. The beach is narrow and dunes are present with a height up to 11 m (Figure 25). The entire beach is characterized by a long-term erosion of -13.73 m^3/m/y (Figure 26). Repeated nourishments mostly in section 242 were carried out in 1979, 1986, 1996 (after storm), 1999, 2004, 2013, 2017 and 2019. The emerged beach has alternated between negative and positive morphological trend from -11 to 2 m^3/m/y over time. In contrast, the part under LW experienced a large sand loss between 1986 and 2000, which then gradually decreased. Since 2011, the erosion rate has been constant (-13.7 m^3/m/y). Sand loss occurs on the shoreface due to the steep slope. The gradient is on average 5% compared to 2% for the intertidal beach and further extends seaward where the seabed is characterized by a narrow and deep strip/valley from section 242-243. It is the continuation of the erosive Branch 1 of the tidal Appelzak channel as observed from at stretches 47 to 49. Since artificial sand supply is limited to section 242, the submerged beach erodes and moves inland. The lower part of the shoreface retreats more than its upper part, leading to a steep slope. Part 1.9 further describes the dynamics and influences of the marine geomorphologic bedforms on the beach dynamics.

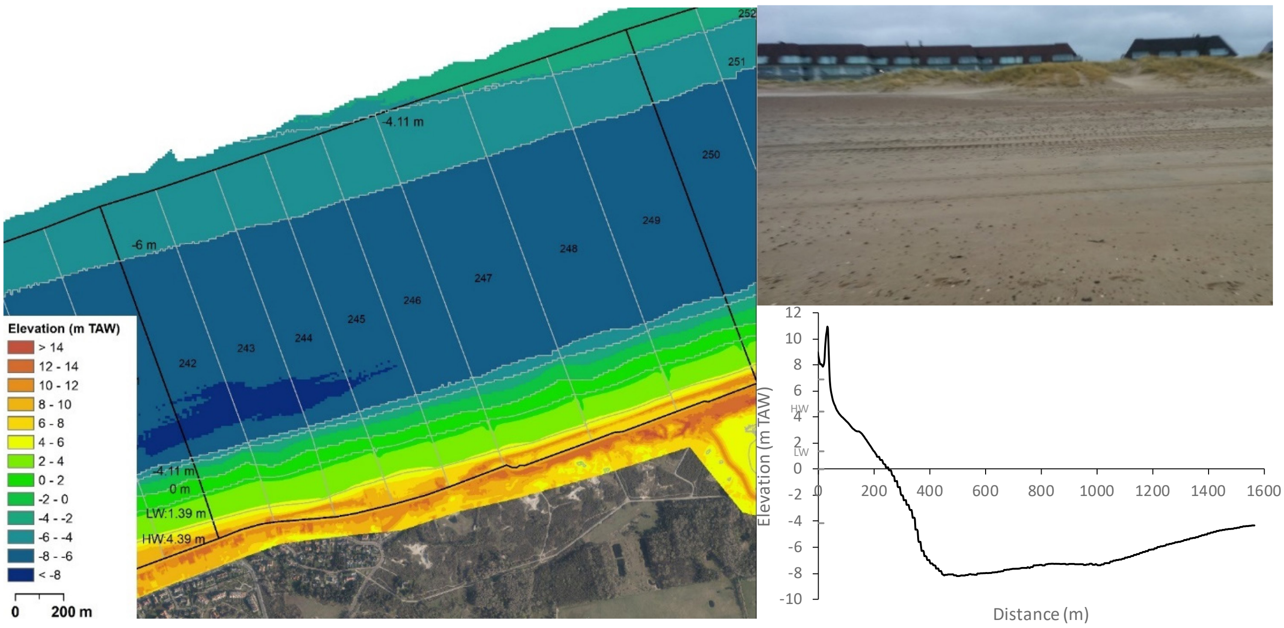


Figure 25 – General characteristics of the coast for stretch 50, Lekkerbek:
A) Ground photograph, B) Profile, C) Elevation model with datum contour lines in 2019.

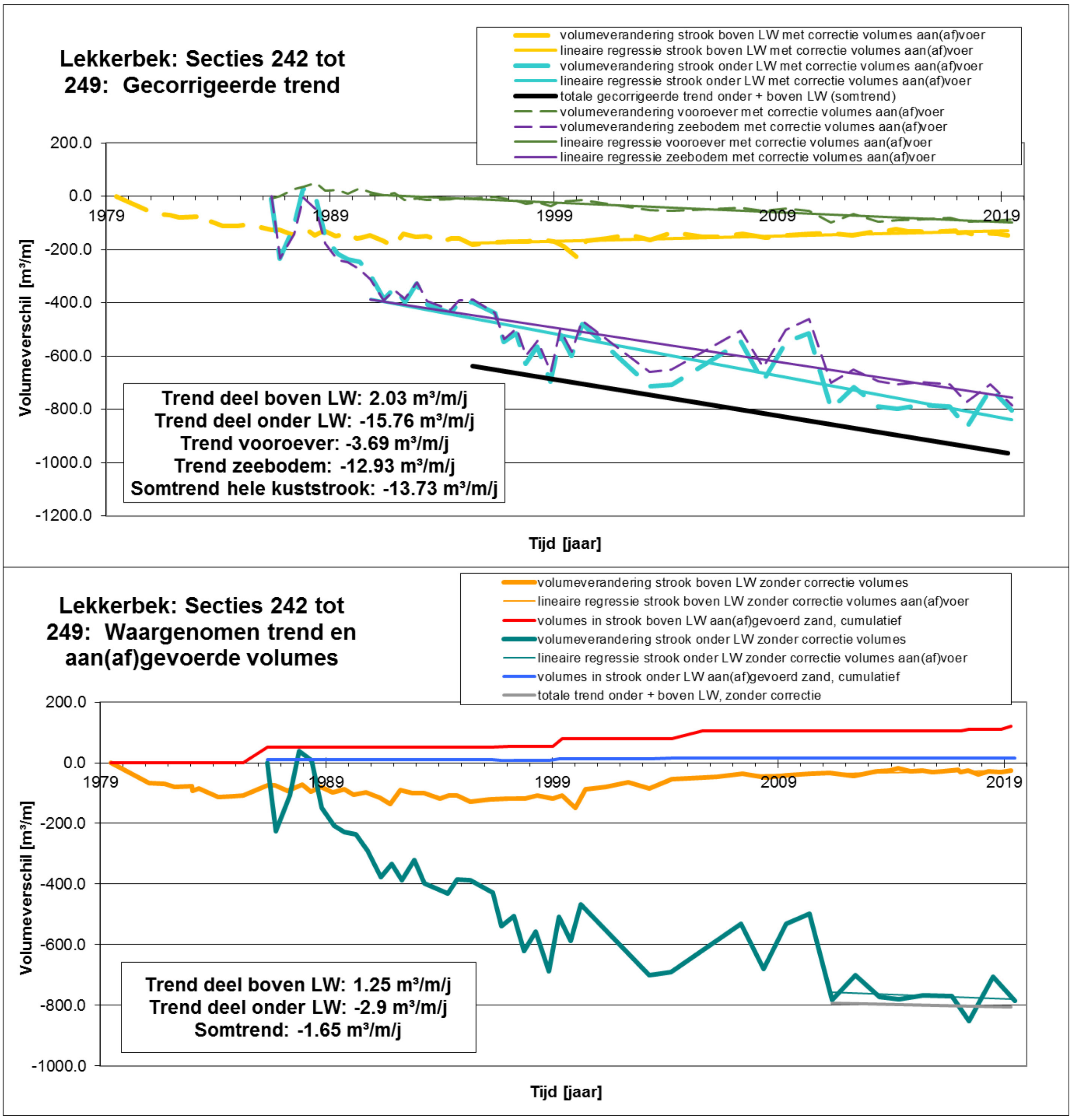


Figure 26 – Morphological trend for stretch 50: Lekkerbek.

Stretch 51

The stretch 51 (section 250-255) of 1590 m in length is located at the Zwin. The beach ranges from 200 to 410 m, backed by foredunes (Figure 27). Intertidal bars are present at some locations. Section 255 is characterized by the mouth of Zwin associated with a channel, small meanders, bars and sand spits. A general sand loss of nearly -7.72 m^3/m/y occurs in this stretch where no artificial supplies are carried out (Figure 29). The emerged beach has been subject to a temporal variability of negative or positive morphological changes over time. Accretion dominated between 1979 and 1987 due to the influence of the large supplementation of 1977-1979 in Knokke-Heist, which was followed by rapid erosion there. It was reported that the silting up of the Zwin saltmarshes accelerated during this period. The following years were characterized by sand gain and loss mainly due to human interventions. After a major dune erosion caused by the storms in 1993-1995, a sand nourishment was carried out on the upper part of the emerged beach in sections 252 and 253. After the large expansion of the Zwin inlet between 2016 and 2019, more intense morphodynamics and increased sediment movement occurred. In particular, significant morphological changes occurred in the channel at the inlet entrance which becomes nearly 0.5 m deeper and wider up to 18 m (Figure 28, Montreuil et al., 2020b). Also, the channel becomes wider and migrates toward east. However, the west side of the inland inlet is accreting with the development of sand banks. On the beach, the sand spit at the Belgian side located above 4 m TAW is a formed and dynamic bedform for which the development depends mainly on the longshore sediment transport. It probably benefits from the nourishments in Knokke-Zoute. The submerged beach, positive and negative morphological changes have alternated over time. Therefore, no clear long-term evolutionary trend can be drawn there, although erosion has dominated with a rate of -15 m^3/m/y after 2010. The behavior and evolution of the shoreface vary spatially. The growth and spatial development of the shoreface were observed for the period of 1998 and 2010, and in 2012-2013. The source of supply was likely from the beach between the Zwin channel and the Uitwateringskanaal (Netherlands). Also, thesand supplied frequently at Cadzand beach around the low water might have been transported by the longshore drift toward west and then deposited to the shoreface of this stretch (i.e. local influence on the direction of sediment transport due to the shift of the coastline orientation near Cadzand). In general, the regional evolution of the shoreface-seabed with the Appelzak channel and Paardenmarkt sand bank influences the morphodynamics of stretch 51.

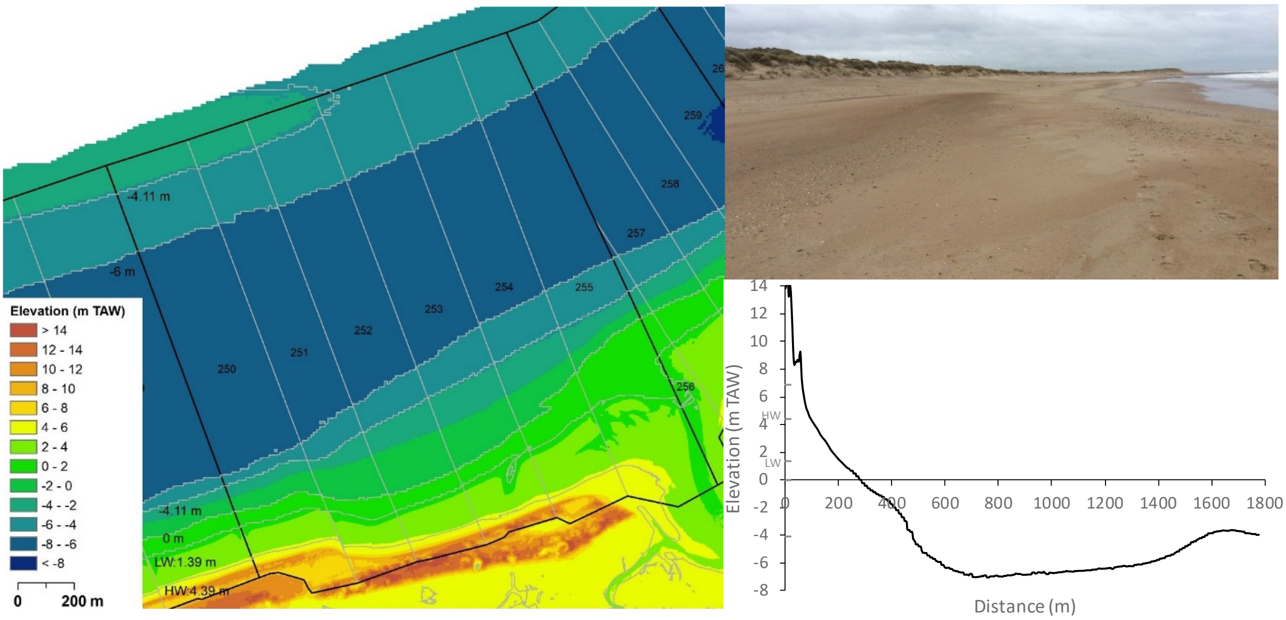


Figure 27 – General characteristics of the coast for stretch 51, Zwin:
A) Ground photograph, B) Profile, C) Elevation model in 2019.

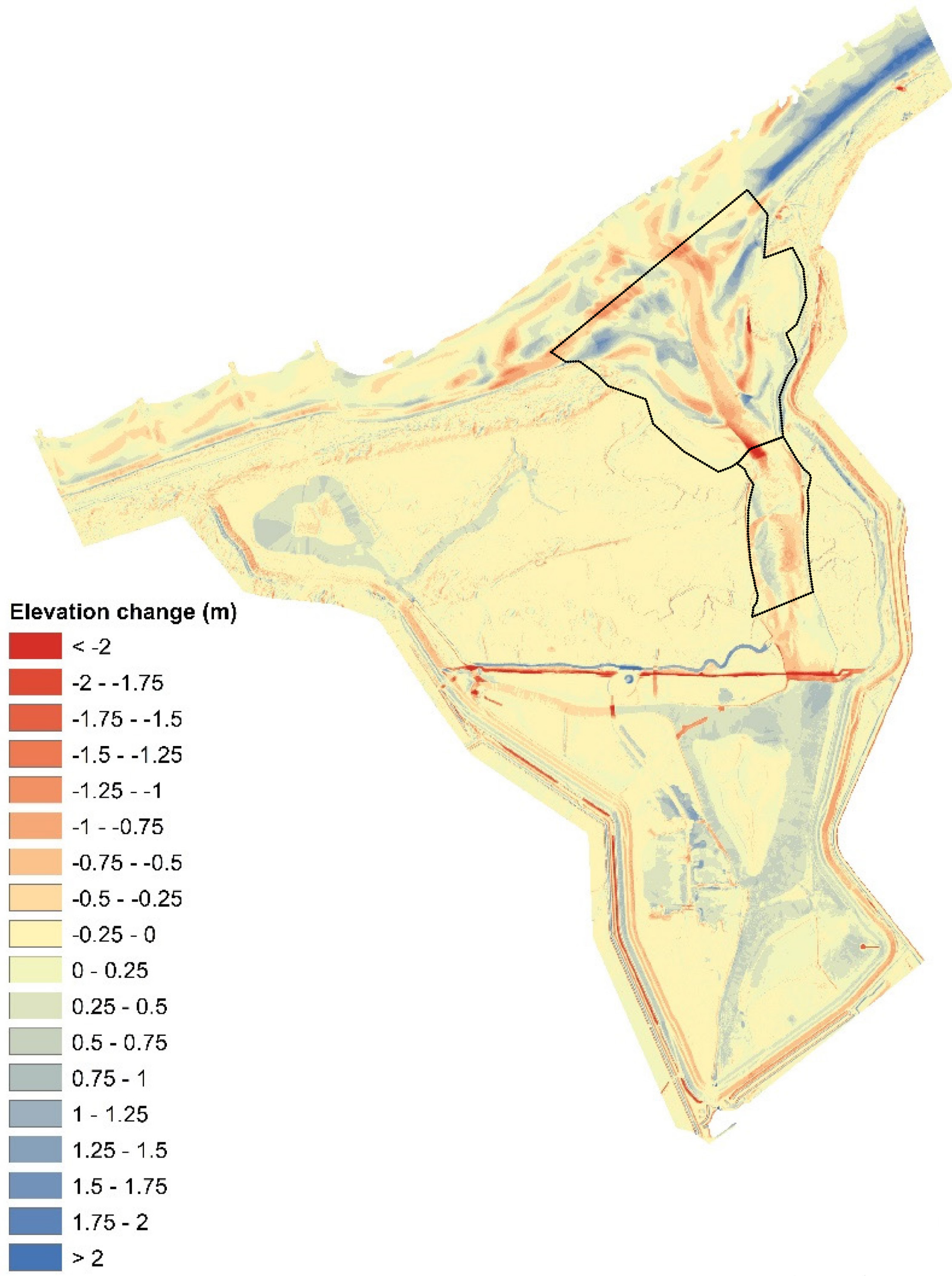


Figure 28 – Morphological changes in the Zwin between 06/11/2018 (pre-opening of the dyke) and 20/04/2019 (Montreuil et al., 2020b).

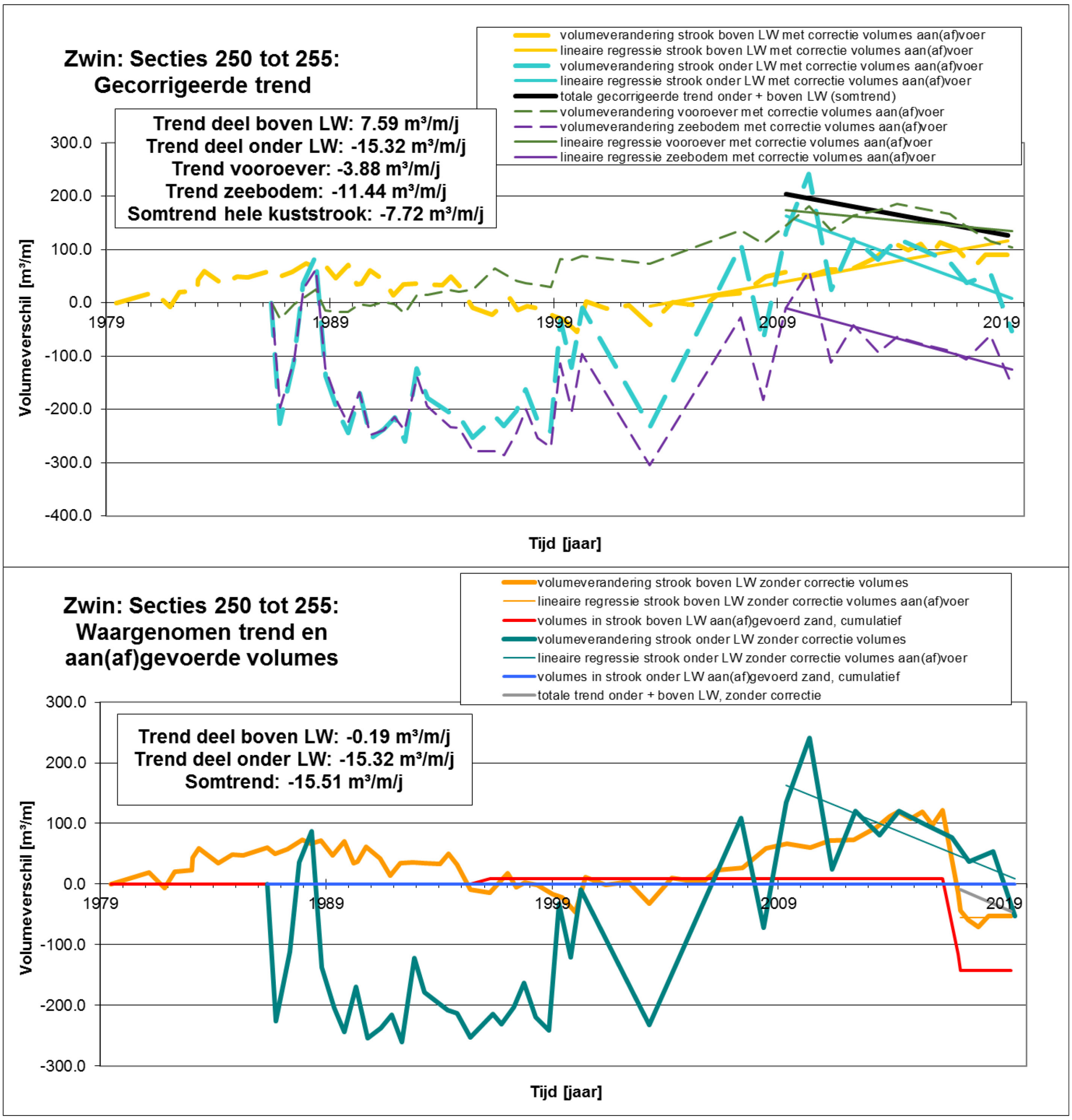


Figure 29 – Morphological trend for stretch 51: Zwin.

2.9 Marine geomorphologic bedforms

The Appelzak tidal channel and the Paardenmarkt sand bank are the two major geomorphic marine bedforms along the east coast. They locally control hydro and sediment dynamics, which in turn influence the morphodynamic of the entire beach, and in particular of the shoreface. Figure 30 presents a map of erosion (blue) and sedimentation (red) trend along the east coast between 1997 and 2010. It clearly illustrates the evolutionary trend of the main geomorphic marine bedforms.

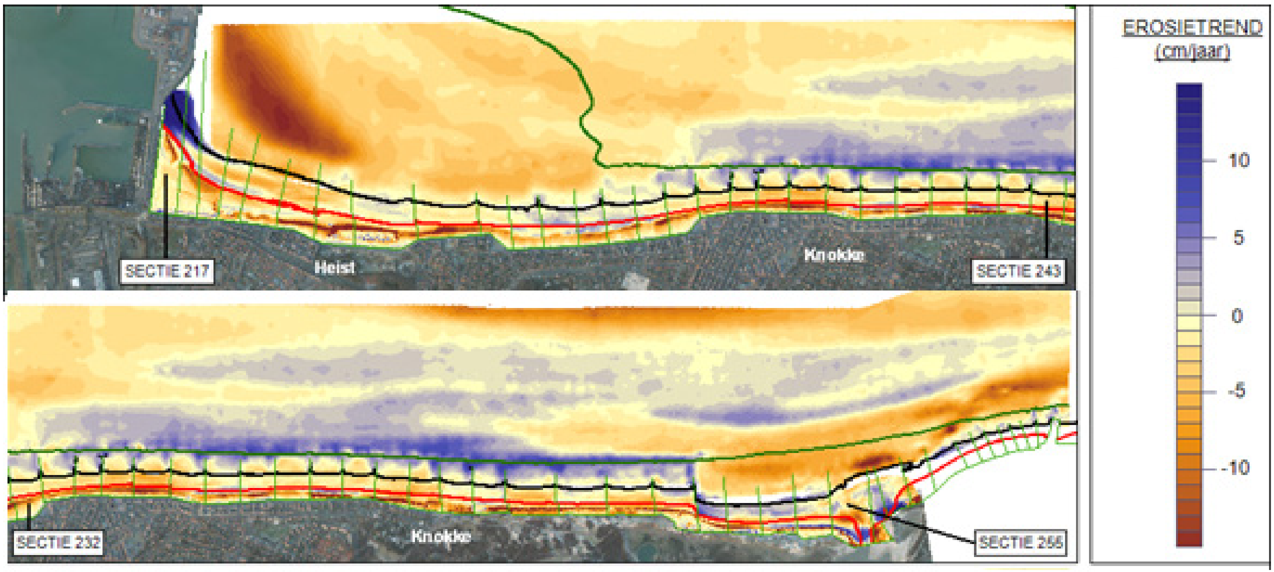


Figure 30 – Erosion/sedimentation trend along the east coast between 1997 and 2010 (adapted from Janssens et al., 2013).

2.9.1 Evolution of the Appelzak channel

The Appelzak channel becomes deeper, which is a morphological response associated to the erosive tidal currents. It varies spatially with a relatively uniform spread in the cross direction for the eastern side of the channel, while its western side is more shallow (Trouw et al., 2015). The squeezing between the landward movement of the Paardenmarkt at the seaside and the groynes at the landside would then force the Appelzak channel to deepen (Bastin, 1983). Over time, the Appelzak has extended toward the east and also to the west with development of Branch 1 and Branch 2 stretching up to section 231 and 235 respectively (Figure 31). Houthuys et al. (2020) reports for the first time their presence, which suggests either a relatively recent formation or absence of past bathymetric surveys to observe them. The deepest areas of the Appelzak are located in the centre of the channel, in Branch 1 and Branch 2. The continuation of the erosive Branch 1 has formed a deep strip/valley at sections 242-243. In the recent years, a connection has been established between the deepening area of the channel and Branch 2, so that the dynamics of this bedform is in line with the large-scale, regional evolution (Houthuys et al., 2020).

Moreover, the Appelzak channel is probably fed by the sand loss from Knokke-Zoute and Lekkerbek beaches (i.e. 50 000 m³/y over 4.5 km) (Trouw et al., 2015). However, its continuous erosion suggests that most of this sand input is transported away from the channel to surrounding areas. Erosion is concentrated at the landward flank of Appelzak which has a harmful impact for the beaches at Knokke-Zoute as described in previous section. The proximity of the beach to Appelzak constraints tidal currents, causing erosion and deepening the channel. In contrast, a zone parallel to the coast in sections 250-252 (stretch 51) in front of the Zwin located at 700 m from the sea dike and part of the Appelzak tidal channel has accreted in 2000-2020. Its development is probably related the morphodynamics of the coast in the Netherlands between the Zwin and the estuary of the Uitwateringkanaal where frequent nourishments take place.

2.9.2 Transport in the Appelzak

The tidal channel is thought to evacuate sediments from the area after storm erosion (Figure 31). During storms, the sand is transported to the Appelzak, and then is further transported by the longshore tidal current in both directions either flood or ebb tidal currents. Thus, this zone is characterized by two large opposing fluxes which, on average, sum to approximately zero, leading to large spatial gradients. The Appelzak has the shape of a ebb dominated channel open to the Scheldt. However, only few data exists to estimate whether the net sand transport in the channel is ebb or flood dominated. The tracer experiments before the harbour extension and the numerical modelling indicate opposite and unclear results. Sand is probably transported in both directions and the net transport depends on the wave climate (Trouw et al., 2015).

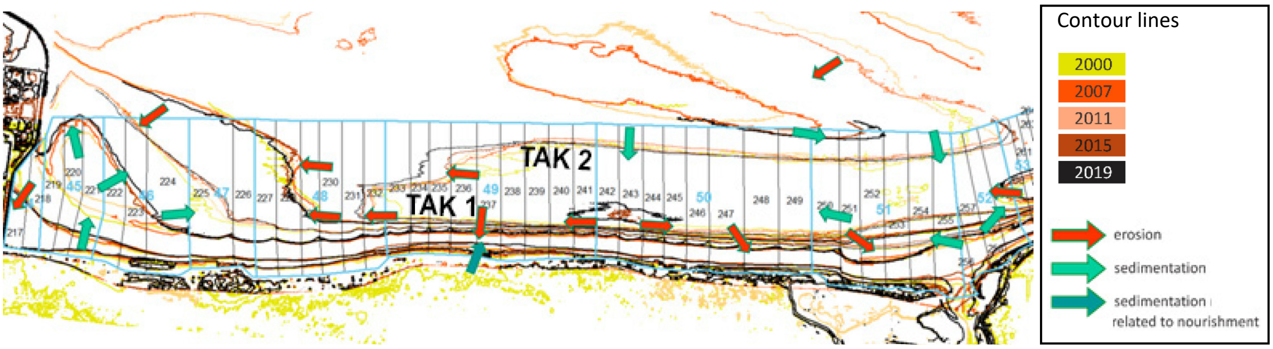


Figure 31 – Map of contour lines and morphodynamics between 2000 and 2019 (from Houthuys et al., 2020). Arrow indicate the shifts of the contour line.

2.9.3 Evolution of the Paardenmarkt

Nowadays, the Paardenmarkt bank is located at more than 4 km from the shore (-4 m TAW) and its highest part is situated in front of stretch 51. It has accreted up to 1.5 m high and it gradually expanded eastward to Cadzand in 1997-2010 (Figure 30). The landward flank of the bank has migrated landward between 50 and 60 m in 1997-2010 (Janssens et al., 2013). It is constituted of a sand and mud particles mixture, which source is probably the dumping zone at Br&W Zb Oost. Missiaen and Henriet (2002) reported that Paardenmarkt bank was subject to erosion between 1954 and 1976. After the extension of Zeebrugge port, significant accretion occurred up to 4 m elevation in its south-west side, and sediment was lost in the north. Paardenmarkt features several submerged large dunes approximately perpendicular to the coastline (Charlet, 2001). The western dunes have a flood dominated asymmetry while the dunes at the eastern part are usually ebb-dominated. Both are separated by a zone of symmetrical dunes. These indicate that this large dunes field corresponds to a zone of bedload convergence, which spatially migrate in function of the hydrodynamic conditions. Currently, it is unclear how much the material from the Br&W Zb Oost dumping site located north of Paardenmarkt moves landward (i.e. southward transport) and contributes to the sediment balance of the active zone but the morphological interaction of the shoreface-beach system and the Paardenmarkt-Appelzak system is evident.

2.10 Morphological response after nourishments

A total of 2 3000 000 m³ of artificial sand supply, corresponding to approximately 230 m³/m of coastal length, was placed along the east coast between 1985 and 2019 (Annex A). As a result, the volume above LW has now risen in 2019 to an average of approximately 100 m³/m over the level of 1979. However, only a third of the supply remains in the layer above the low water line.

Severe storms occurred in 1976 when the beach at Knokke-Zoute was severely eroded. In addition, the events accelerated the chronic erosion and landward migration of the Appelzak channel (Charlier and De Meyer, 1995). Therefore, the first large nourishment took place between sections 217 and 250 in 1979. About 8.5 million m³ of sand was supplied to the beach and the upper part of the shoreface along approximately 9 km. It corresponded to an average supply per linear meter of almost 950 m³/ m. In general, the beach gained up to 4 m in elevation (Figure 32), but it decreased over the following years. The nourishment influenced the dynamics of the Appelzak which moved about 100 m offshore from its location after the storm (Figure 33). The size and depth of the channel decreased between 1979 and 1984. These might be explained by cross-shore transport of nourished sand, however, the decrease in depth occurred over a long cross shore distance up to 1984. In addition, the -5 m contour moved offshore between 1979 and 1984, while the -1 and -3 m TAW contour were already moving onshore. After the port extension and the large nourishment in 1986, the landward migration continued at all depths at a rate of 2 m/y for the slope at the onshore side of the channel while the slope at the offshore side was stable. However, the maximum depth of the channel increased. In addition, it is hypothesized that Branch 1 is likely to be filled up after beach sand nourishment but it would re-appear naturally over time (i.e. under the absence of further human intervention).

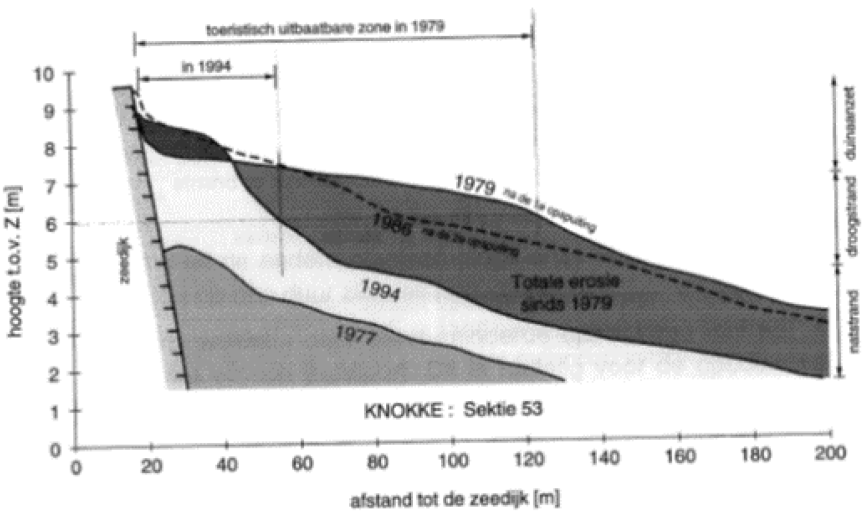


Figure 32 – Average of beach profile at Knokke-Zoute.
The backshore berm protecting the sea dike continuously welded to the beach (Eurosense, 1994a).

Generally, the shoreface at Knokke-Zoute strongly eroded immediately after the beach nourishments. It was clearly observed in 1986 and 1999 (Trouw et al., 2015). However, the shoreface was stable in a decade following the nourishment in 1986 (Houthuys et al., 2012). This contrasts with the tendency after the nourishments at Knokke in 1999 and 2004 when a remarkable sedimentation of the shoreface took place as observed on the topographic surveys in 2000 and 2007. Houthuys et al. (2020) reports that the efficiency of the sand supply at Knokke was of 77% in 1986 based on pre and post surveys between 1986 and 1987.

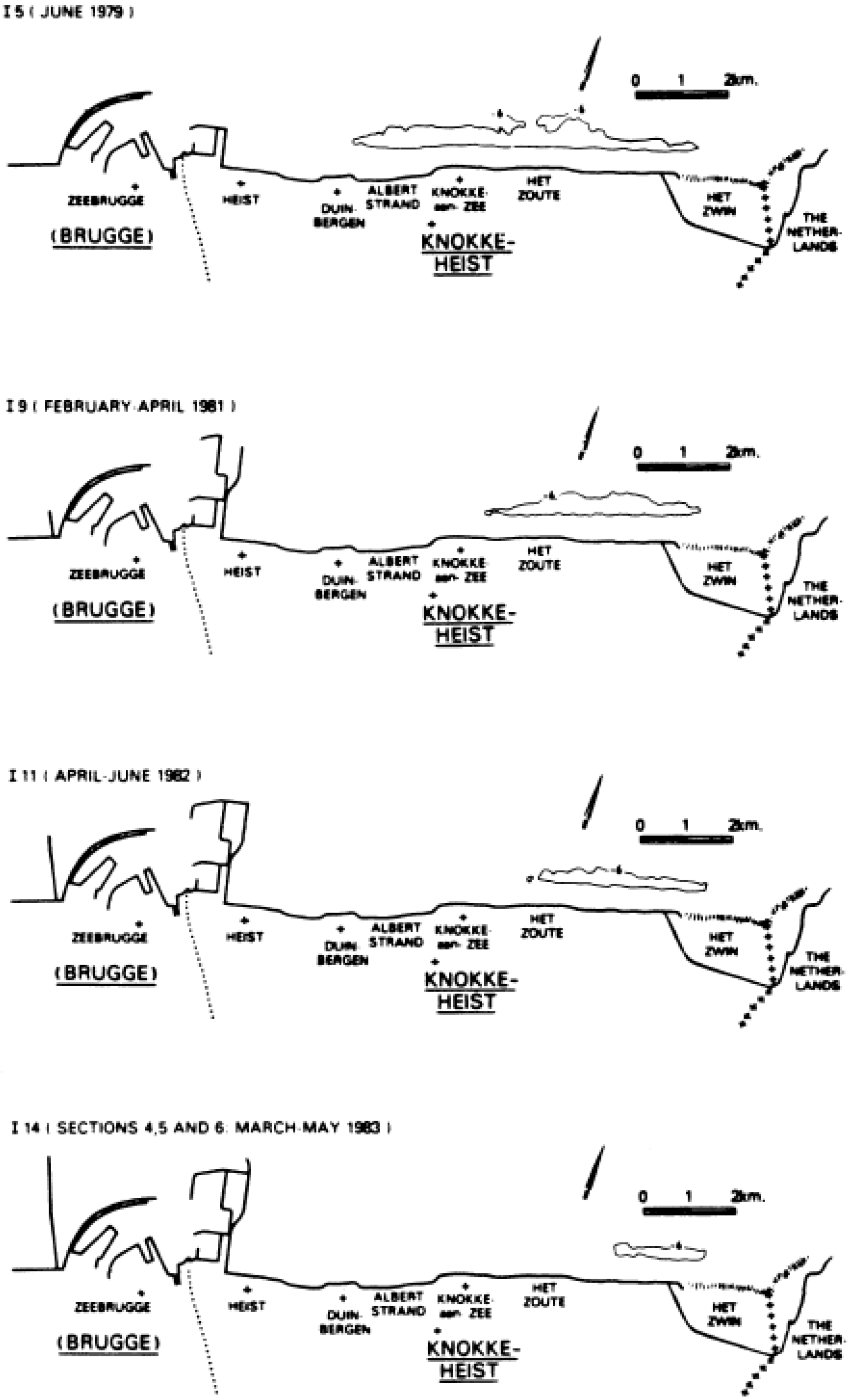


Figure 33 – Morphodynamics of the Appelzak tidal channel after the large nourishment in 1979 (Charlier and De Meyer, 1995).

Furthermore, the morphological impact of the beach nourishments in Knokke on the Zwin nature reserve was undoubted in the 1980s-1990s (Houthuys, 2013). The natural tendency of the Zwin inlet is to be filled-up and its channel to move eastward during storm events occurred for decades before any beach nourishment at Knokke. However, an increase of the vertical sedimentation of the saltmarshes and the channel migration rate took place. Sand supply at Knokke in 1986 was characterized by red shell fragments, which were observed in the inland of the Zwin a few years after (Houthuys, personal communication). The typical dynamics of the Zwin is filling up with sand coming from the coast and driven by the longshore transport, which then enters in the inlet under storm conditions. Therefore, a part of sand supply at Knokke naturally ends in the Zwin inlet anyway. Also, sections 246, 250 and 253 could be considered as transit areas for sediment moving from Knokke to Zwin. However, no eastward migration of sand features or patches on the beach is seen in relation to nourishments (Houthuys, 2013). In addition, the artificial sand supplies in Knokke have probably no influence at the long-term accretion at the Baai van Heist.

2.11 Summary

The east 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 undulated position of the coastline/sea dikes. The coast experiences two large opposing sediment fluxes alongshore that sum to approximately zero, leading to large spatial gradients and morphological variability. On average the sediment budget shows natural feeding (+77 063 m^3/y between 1980s and 2019), yet locally erosion is problematic. Table 4 summarizes the volumetric evolution trend including human interventions along the east coast. Time series of volumetric changes are presented in Annex D. Spatial variability of volumetric trends is observed for the emerged beach (erosion), the shoreface (accretion) and the seabed (erosion) over time.

Up to 2 km from the east breakwater of the Zeebrugge port to Duinbergen (stretches 44-46), a large accretional trend occurs in the Baai van Heist by natural processes. 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 (stretch 47-51) is erosional. The largest erosional trend occurs at Knokke-Zoute with a rate of -42.16 m^3/m/y. This is probably related to the natural deepening of the Appelzak tidal channel, which is thought to evacuate sediments from the area after storm erosion, and also related to the protrusion of the coastline/sea dike in this stretch. The channel has extended eastward and with the development of Branch 1 and Branch 2 in its west side. The accretion and landward migration of the Paardenmarkt sand bank force the Appelzak channel to deepen and to move onshore.

A total of 2 3000 000 m^3 of artificial sand supply, corresponding to approximately 230 m^3/m of coastal length, was placed along the east coast between 1985 and 2019. A part of this volume was transported towards the Appelzak channel and the Zwin by natural hydrodynamic processes.

Table 4 – Volumetric evolution per stretch (based on the recent linear trend of the last 10 years by Houthuys et al., 2020).

				Volume (m^3/y)		
Stretch	Section	Location	Length (m)	Entire coastal zone	Emerged beach area above LW	Submerged beach area below LW
44	217-218	Heist - Oostdam Zeebrugge	346	1896	-938	2834
45	219-221	Heist - Heldenplein	626	31700	7975	23725
46	222-224	Heist-Duinbergen	973	43804	12610	31194
47	225-226	Duinbergen-centrum	700	-14819	-5908	-8911
48	227-232	Albertstrand	1410	-12309	240	-12549
49	233-241	Knokke-Zoute	2237	-94312	-44472	-49840
50	242-249	Lekkerbek	2310	-31716	4689	-36406
51	250-255	Zwin	1590	-12275	12068	-24359
Total zone	217-255	Total	10100	77063	45046	31916

Note: green (accretion) and red (erosion).

Table 5 – Qualitative evolution per stretch (based on Houthuys et al., 2020).

Stretch	Section	Location	Length (m)	Emerged beach, area above LW	Submerged beach, area below LW	Shoreface between LW to -4.11	Seabed -4.11 to sealimit	Human intervention
44	217-218	Heist near Oostdam Zeebrugge	346					
Period	1979 (1986)-1991			++	-	-	/	low
	1991-2008			- -	- -	- -	/	low
	2008-2019			-	+	+	/	low
45	219-221	Heist near Heldenplein	626					
Period	1979 (1986)-1996			-	+	+	/	low
	1996-2019			+	+	+	/	low
46	222-224	Heist-Duinbergen	973					
Period	1979 (1986)-2019			+	++	++	/	low
47	225-226	Duinbergen-centrum	700					
Period	1979 (1986)-2009			-	++	++	/	mid
	2009-2019			-	-	-	/	mid
48	227-232	Albertstrand	1410					
Period	1979 (1986)-1992			+	--	--	--	high
	1992-2007			+	++	++	++	high
	2007-2019			+	-	-	-	high
49	233-241	Knokke-Zoute	2237					
Period	1979 (1986)-2019			- -	- -	-	- -	high
50	242-249	Lekkerbek	2310					
Period	1979 (1986)-1996			-	- -	-	- -	high
	1996-2019			+	- -	-	- -	high
51	250-255	Zwin	1590					
Period	1979(1986)-1988 (2003)			+	-	+	-	low
	1988 (2003)-2000 (2009)			-	++	+	++	low
	2000 (2009)-2019			+	- -	-	- -	low

Note: green (accretion) and red (erosion). Period in bracket is related to the area below LW.

3 Inventory of monitoring data

3.1 Coastal surveys

The coast from stretch 44 to 51 is regularly surveyed for the assessment of coastal safety and to monitor erosion/accretion trends (Figure 34). The surveyed area covers the coast over 1500 m in cross-shore direction, extending seaward from the first row(s) of dunes or top of the sea dike. The surveys consist of both beach topography and bathymetry, but differencing in coverage and applied techniques. Topographical surveys cover the emerged beach from the first row(s) of dunes to the low water line. From 1977 to 1997, stereo photogrammetry was used for beach topographic survey (i.e. data only available from 1985). Since then, airborne Light Detection And Ranging (LiDAR) surveys have been carried out once or twice per year (spring and autumn).

Bathymetric surveys consist of Single Beam Echo Sounding (SBES) measurements along pre-defined shore-normal transects from the mean sea level seaward. These transects are spaced approximately 100 m longshore. The first survey was performed in 1986. Then, bathymetric surveys have been undertaken at least once per year except in 2001, 2002, 2005, and 2006. Occasionally, a multi-beam survey was performed on a limited area.

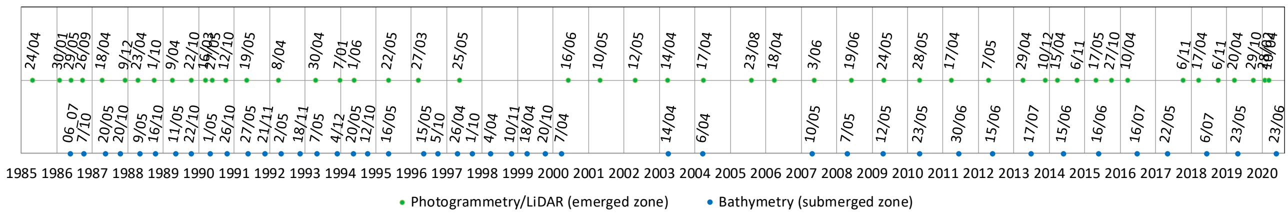


Figure 34 – Time series of topographic and bathymetric measurements.

The most recent LiDAR and bathymetric surveys were carried out on 10/04/2020 and 23/06/2020 respectively and are presented in Figure 35. As previously described, topography of the beach and shoreface along the east coast is characterized by a spatial variability with the beach larger and shallower on the west side, while the beach zone is narrower where the Appelzak channel is located. The deepest elevation in the Appelzak was -8 m TAW in 2020.

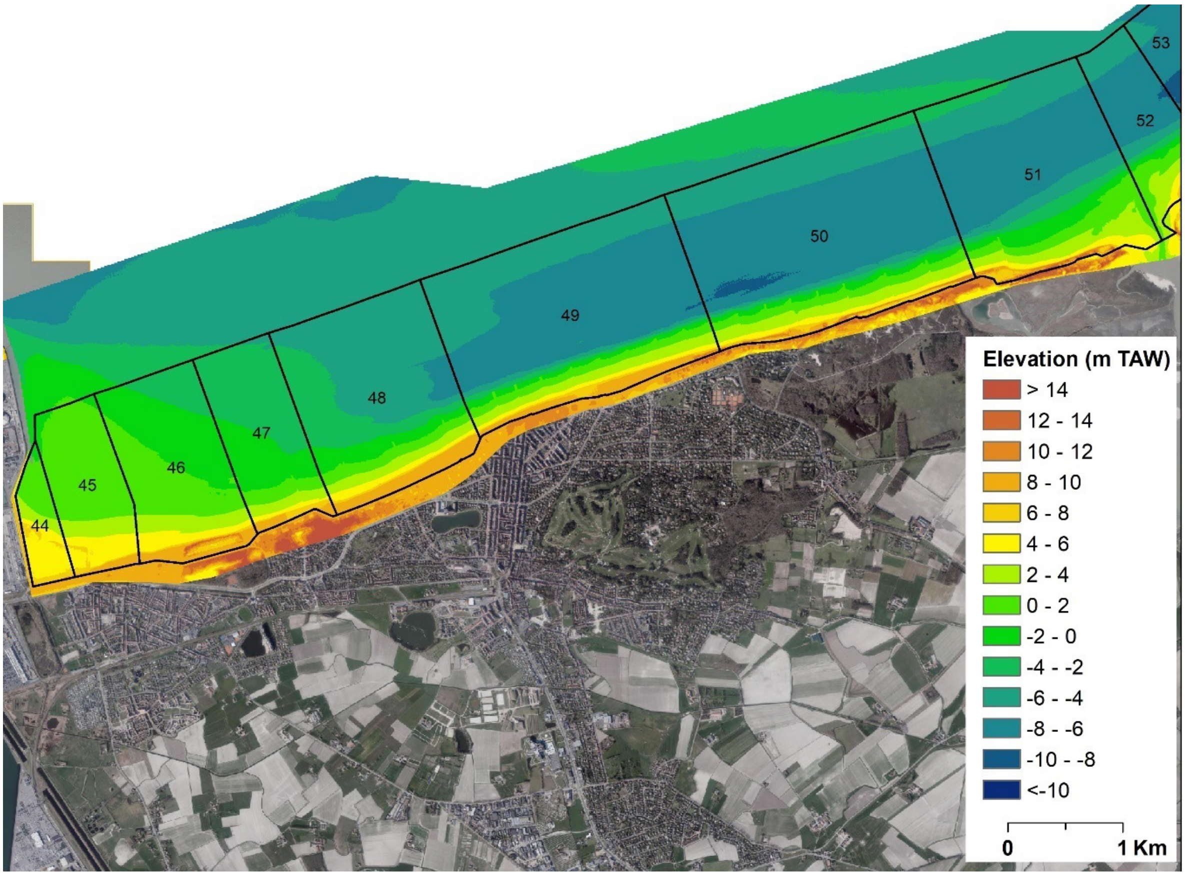


Figure 35 – Elevation of the beach and shoreface in 2020 (DEM combined LiDAR and single beam bathymetric survey in 2020).

3.2 Meteo-marine data

For the project, the monitoring records available from Meetnet Vlaamse Banken platform and future additional in-situ devices will be used to explore the hydrodynamics at the study site (Table 6).

In situ of 13-hour measurements campaign will be carried out along the study site from strook 48-50 at the depth from -4 to -6 m TAW with the RV ship Simon Stevin (hull mounted current profiler-ADCP) (Figure 36). The purpose of these measurements was to quantify marine currents in the Appelzak channel in order to estimate their contribution to sand transport. These measurements will take place two times per year, covering preferably spring tide condition. The position and extension of the profiles are shown in Figure 36. Due to the large total length (approx. 9.5 km) and the low speed of the research vessel (3 to 5 knots), it is not possible to cover all the area at high frequency so that half of the profiles can be measured in the first campaign and the other half in the second campaign during one year. The measurements dates will be established in consultation with the RV responsible. In addition, up looking ADCPs will be installed at the landward side of the Appelzak around -6 m TAW and preferably at three locations, depending on the availability of the instruments at Flemish Hydrography Department (Coastal Division). The exact locations are shown in Figure 36.

Table 6 – Description of the measurement stations.

Frequency records	Parameter	Station and instrument	Coordinates	Location	Temporal resolution	Recorded period
Permanent	Water level (m TAW)	Scheur *Radac Waveguide Server*	51° 25' 05"N 3° 17' 54"E	Distance c. 5 km normal to the coast Depth of - 9.7 m TAW	5 min	Continuous
	Offshore wave records: -Average wave height (m) -10% highest wave (m) -Average period (s) -Direction (°)	Bol Van Heist *Datawell - Directional Waverider*	3° 12' 02"E - 51° 23' 30"N	located 6 km from the study coast Depth of -9.3 m TAW	30 min	Continuous
	Onshore wave records: -Average wave height (m) -10% highest wave (m) -Average period (s)	Scheur *Datawell Waverider*	51° 24' 05"N 3° 18' 07"E	Distance c. 5 km normal to the coast Depth of - 9.7 m TAW	30 min	Continuous
	Current: -Velocity (m/s) -Direction (°)	Scheur *Radac Waveguide Server*	51° 25' 05"N 3° 17' 54"E	Distance c. 5 km normal to the coast Depth of - 9.7 m TAW	10 min	Continuous
Semi-permanent	Waves: -Velocity (m/s) -Direction (°) - Water level (m)	MOW2 MP2-Meetpaal2 *RDCP600 wave rider*	51°21'46.46"N 03°17'24.16"E	Located in the Appelzak at about 1 km from the study coast Depth of -7 m TAW	10 min	from 09/05/2012 21/01/2013 30/05/2017-25/07/2017
	Currents: - Velocity (m/s) - Direction (°)	Up-looking *ADCP*		Landward side of the Appelzak at less than 400 m from the coast)	High-resolution 1 min averaged every 10 min Cell size of 0.5 m	Under the project
Campaigns	Currents: - Velocity (m/s) - Direction (°)	Simon Stevin vessel *ADCP*	Navigation following cross and alongshore profiles		High-resolution for 13hours	Under the project

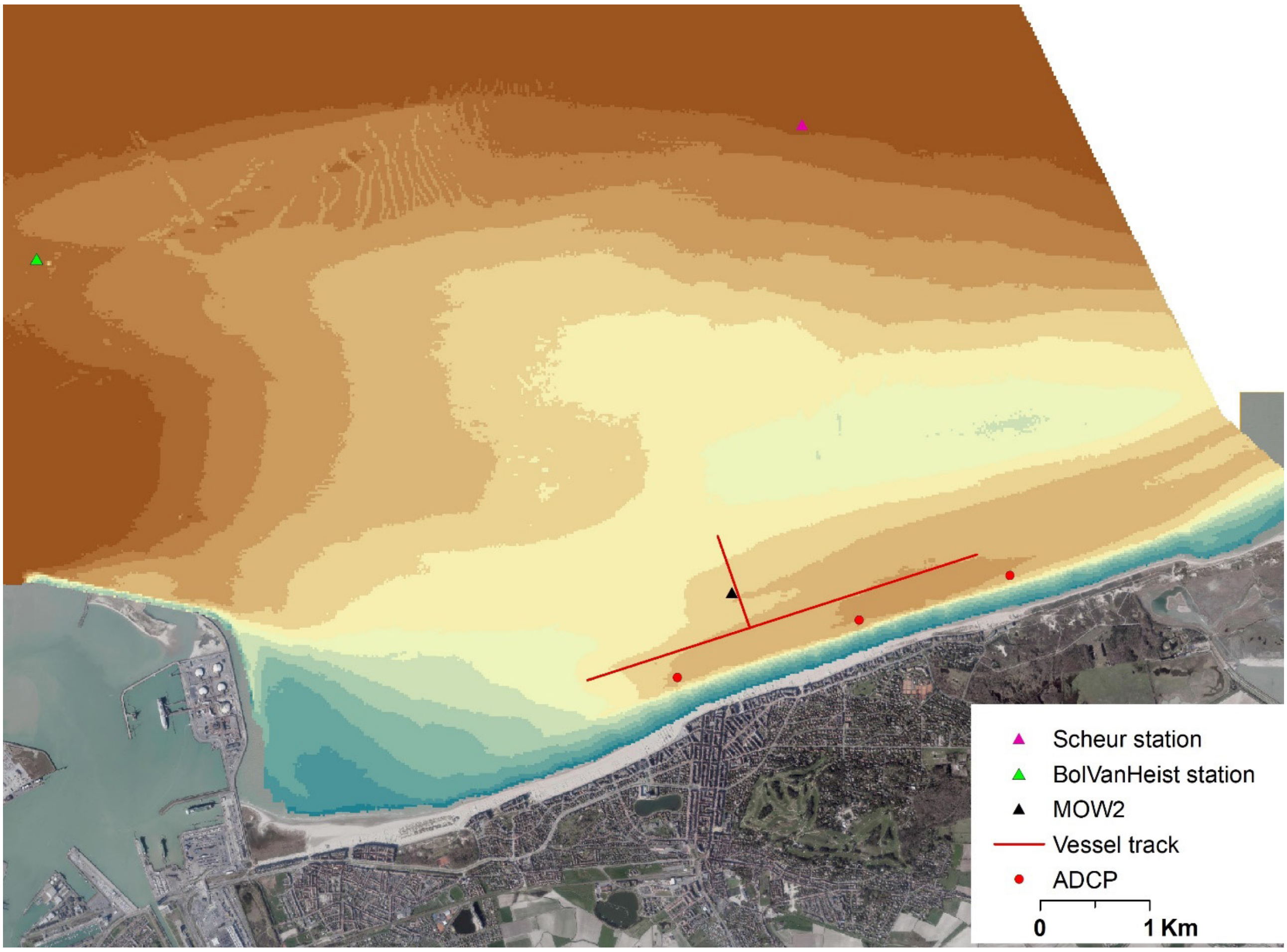


Figure 36 – Location of the continuous and in-situ measurements

4 Hydrodynamic analysis

4.1 Typical wave regime

The wave data records for past years at Bol Van Heist buoy is not complete, therefore the wave regime is assessed using measurements from Westhinder station located 32 km from the coast. The wave roses plotted in Figure 37 clearly show primary wave directions from the north-north-east and the south-west sectors. In general, the wave energy is from low-medium with an average wave height < 1 m. Wave (H_{m0}) regime in 2019 was consistent with the typical wave condition. Figure 38 displays a scatterplot of measured significant wave height versus peak period, indicating that waves are usually characterized by a period below 7 s. In contrast, waves considered as swell with period exceeding 12 s are less common.

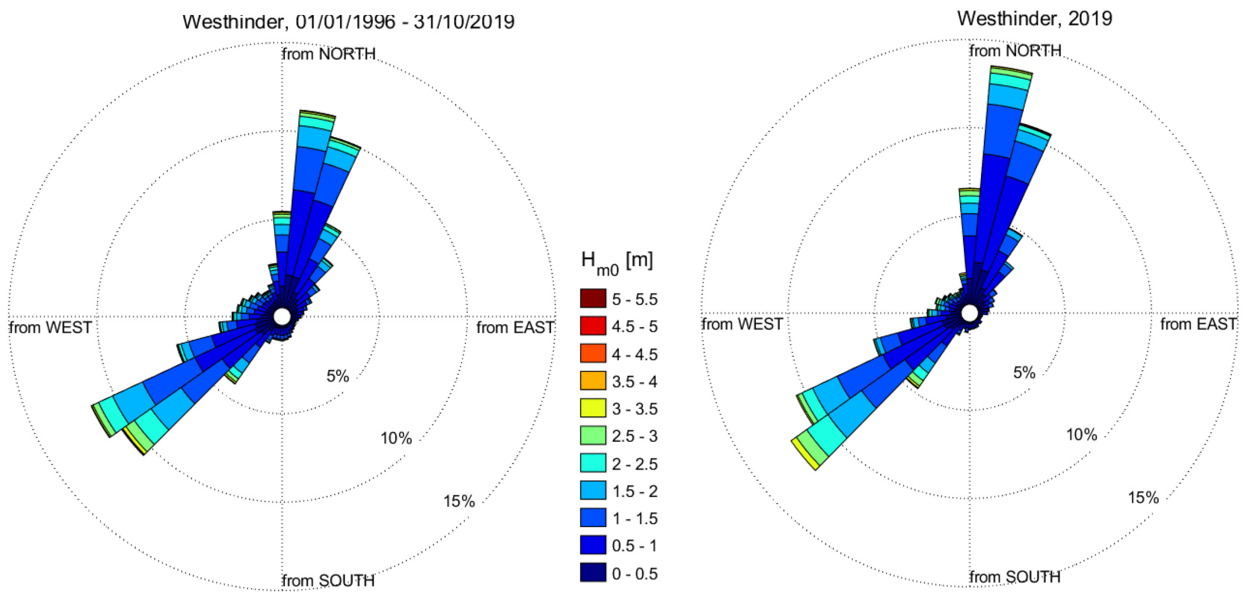


Figure 37 – Wave roses: A) from 2006-2019 and B) in 2019 from Westhinder offshore buoy (Dujardin, 2020).

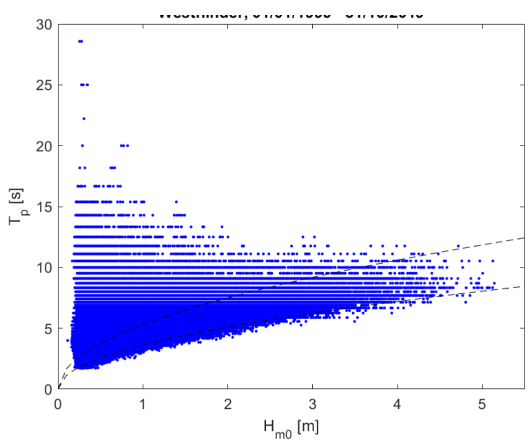


Figure 38 - Scatterplots of measured H_{m0} vs. T_p for the period from 1996 to 2019.
Dashed lines show the applicability range of the JONSWAP-spectrum (Dujardin, 2020).

4.2 Typical currents

The average current velocity was around 0.50 m/s at Scheur from January to October 2020 (Figure 39, Table 7). The peak of current velocity was 3.5 times greater (> 1.75 m/s) occurring in March and April The highest velocity was recorded by the cell 1 (top), while it gradually decreased closer to the surface bed.

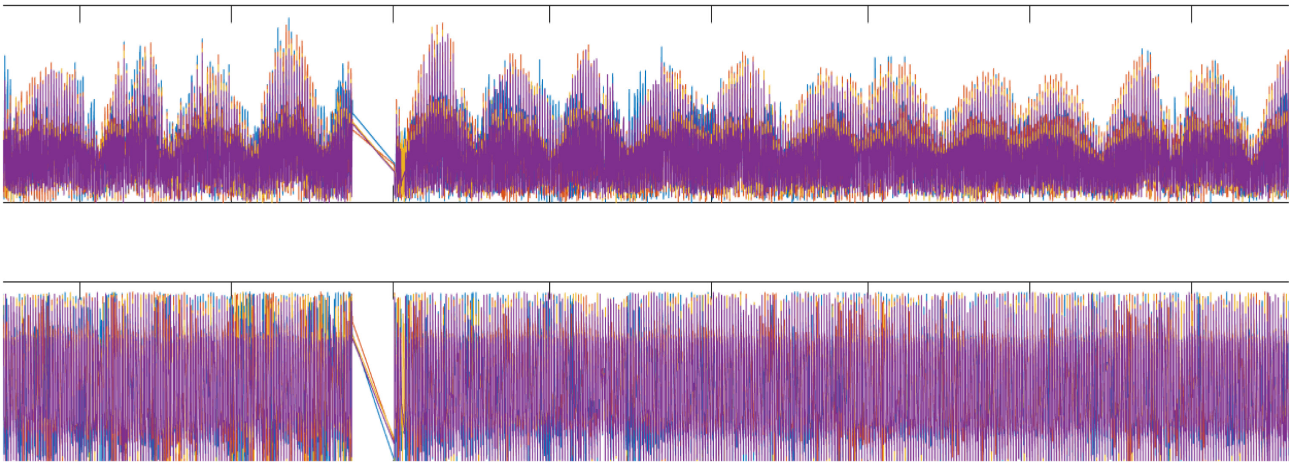
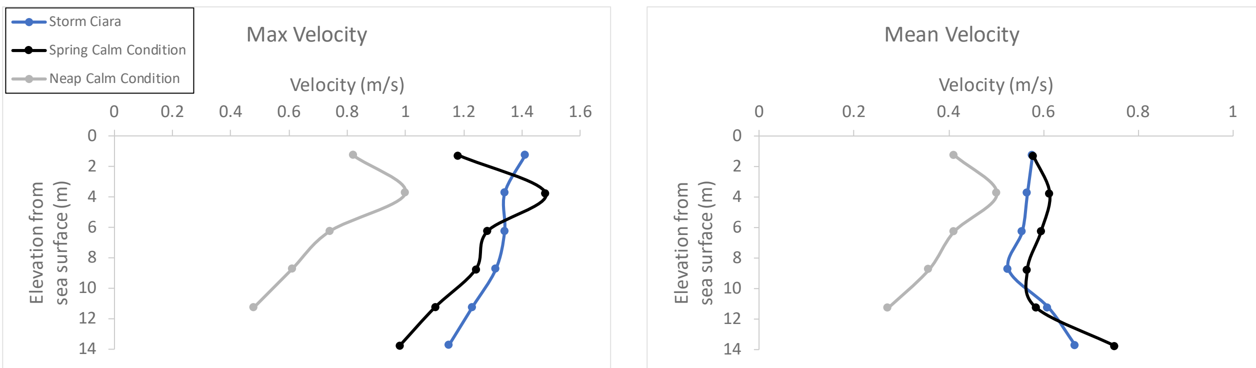


Figure 39 – Time series of wave and currents at Scheur from Jan-Oct 2020.

Table 7 – Statistics of current velocity at Scheur from Jan-Oct 2020.

	Velocity (m/s)	
	Mean	Max
cell 1	0.51	1.87
cell 2	0.50	1.82
cell 3	0.51	1.78
cell 4	0.48	1.71

The average of current velocity is usually below 0.8 m/s in the offshore area at Scheur. However, currents exceeds 1 m/s during spring stormy conditions. As expected, velocity profiles show some vertical variabilities in the water column. Interestingly, the shape of the velocity profiles is relatively similar under spring and stormy conditions.



Note: the difference of x-axes. Ciara storm occurred on 9-10/02/2020.

Figure 40 – Typical current velocity direction profiles at Scheur.

4.3 Current characteristics in the Appelzak channel

4.3.1 Large-spatial scale

Description of the campaign

A pilot measurement campaign was carried out with the RV Simon Stevin on 12/12/2019. The purpose was to assess the hydrodynamics of the Appelzak tidal gully in order to evaluate its influence on the future nourishment. The specific objectives of this pilot campaign is to find out what is the ideal boat speed for the ADCP measurement and appropriate time interval of measurements at the same location.

Low tide was at 6:30 on 12/12/2019 when the water level was of 0.72 m TAW (Figure 42). High tide with water level of 4.49 m TAW occurred at 12:20. In the early afternoon (14h), bigger waves above 0.6 m high were recorded as soon as the S-SW wind got stronger (>12 m/s, not presented here). In general, the conditions were good for all the measurements undertaken between 10:49 to 14:30 (UTC time).

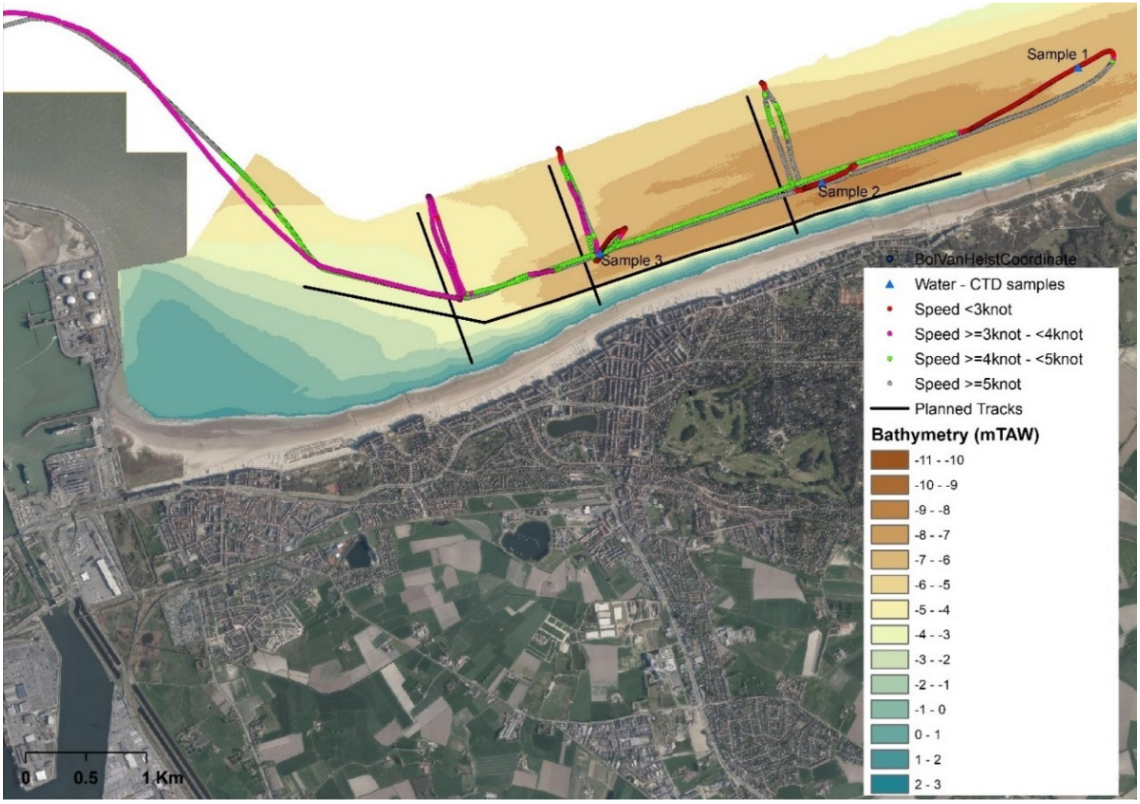
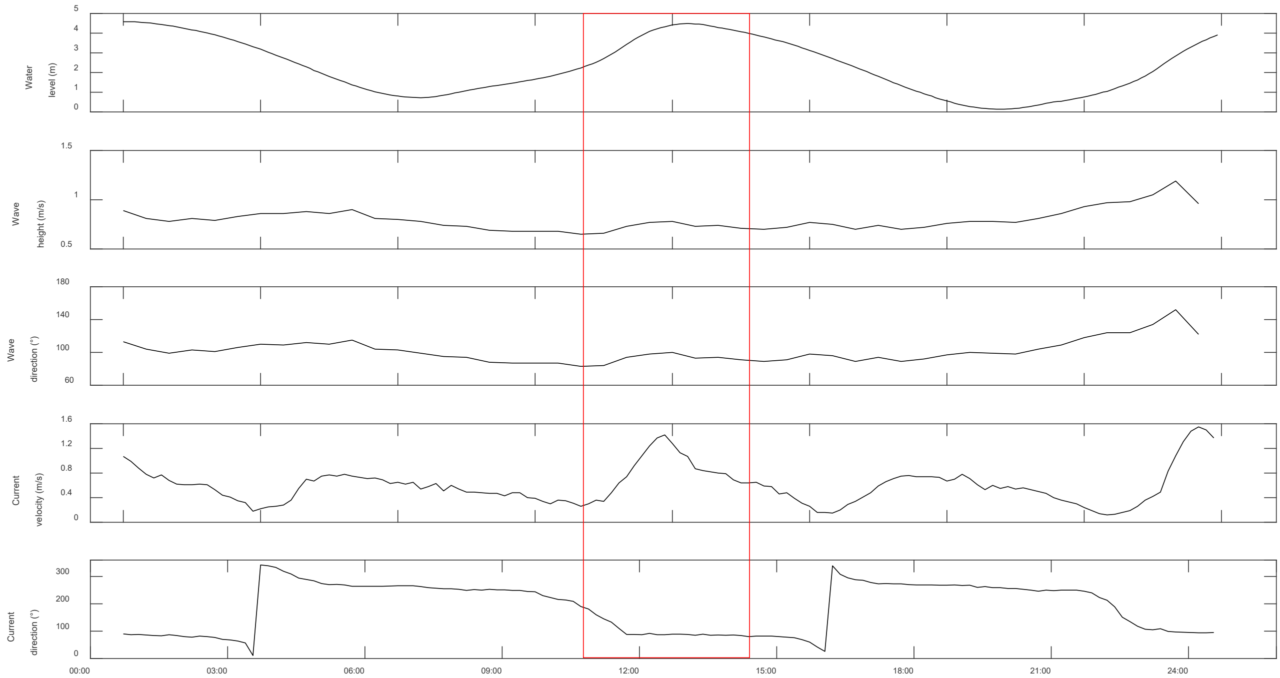


Figure 41 – Map of the study site with the navigation and planned track.
Background corresponds to the bathymetry on 25/05/2019.



The red box corresponds to the measurement period. Note: Bol van Heist wave buoy is located around 5.5 km offshore from the study site. The current records are measured from cell 3 (between 3.75 and 6.25 m below water surface).

Figure 42 – Time series of water level, average wave height, wave direction, current speed and direction from cell 3 of the wave rider at Bol Van Heist wave buoy.

The measurements consisted of continuous current speed and direction as well as the depth using the Acoustic Doppler Current Profiler on board (model Workhorse Mariner ADCP from Teledyne range 560 m, 600 kHz), a sonar-based devise. The general settings of the ADCP were recording with a maximum depth of 15 m, cell size of 1 m, and logged every 1.4 s. Navigation location and depth were measured every 5 s from the on board speed log system. Also, water samples were taken at 3 locations with the Niskin bottles (Figure 41). In the meantime, CTD measurements were collected.

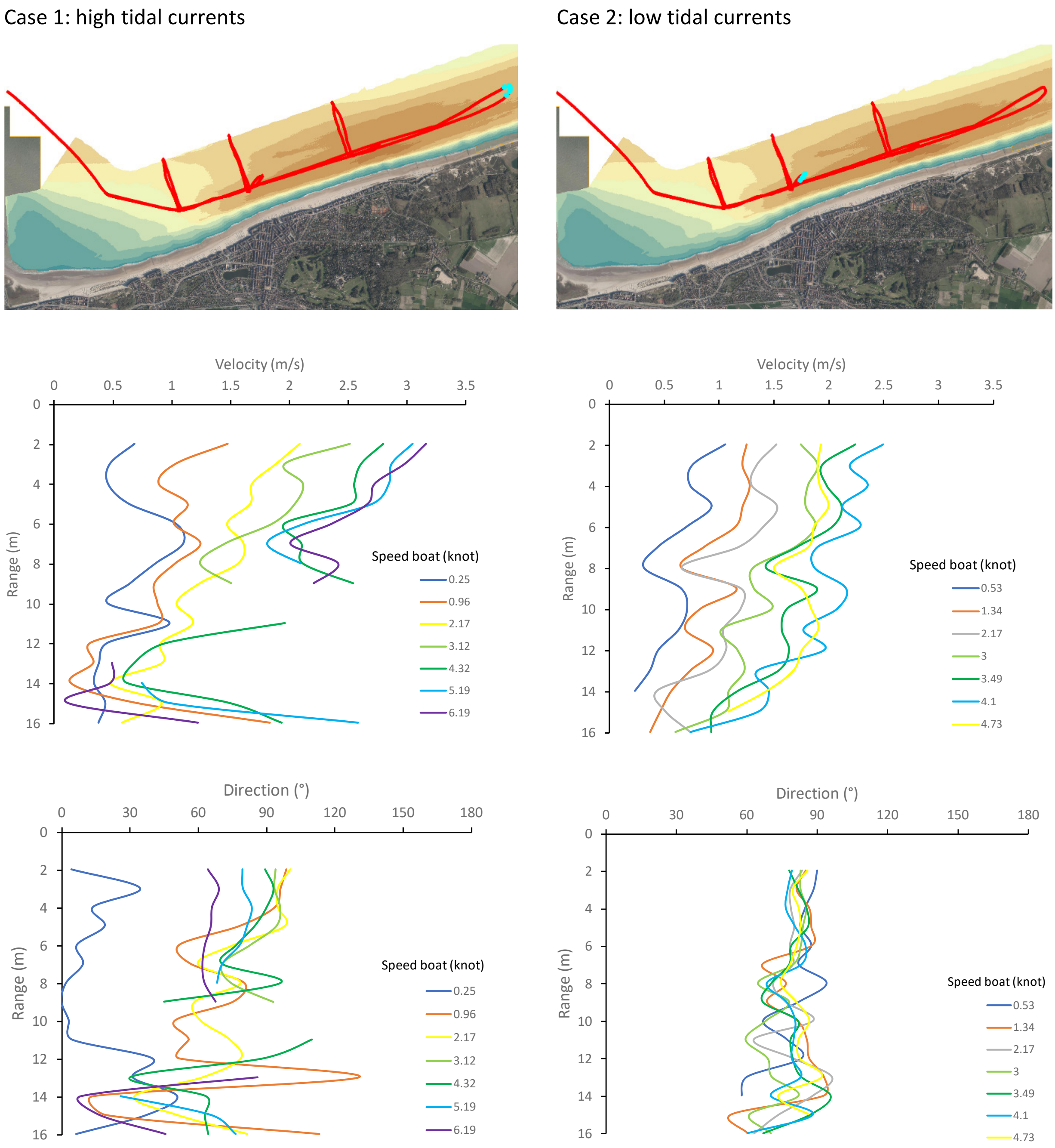
Regarding the navigation and measurement tracks, the boat had to navigate more offshore than the planned route due to the shallow area (Figure 41). The total length of the measurement track including alongshore transect (5.6 km) and 3 perpendicular transects (from 1.2 - 1.3 km) is about 9.4 km. Theoretically, the time necessary to cover the total length of the measurement track should be 1 h at 5 knots speed, 1h16 at 4 knots speed and 1h40 at 3 knots. Measurement Track 1 was Zeebrugge to the east point (near Zwin) and the boat navigated with a speed of 5 knots. Measurement Track 2 was the east point to Zeebrugge and the boat speed was around 3-4 knots.

Influence of boat speeds on current velocity

The influence of the boat speed on the current velocity measurements is assessed by comparing records at different navigation speeds from 0.25 knots (0.13 m/s) to 6.19 knots (3.18 m/s) taken at a short time interval (i.e. less than 3 min) (Figure 43). The velocity of tidal current was measured under two tidal conditions: Case 1 high tidal currents and Case 2 low tidal currents. These measurements took place during the flood phase respectively 10 min before high tide with a current velocity of 1.13 m/s (Case 1) and 1h10 after high tide with a current velocity of 0.65 m/s at Bol Van Heist buoy (Case 2). Appendix E.1 describes the marine conditions and velocity measurements per ADCP cells.

Table 8 – Statistics summary of the current velocity measurements for
Case 1 of high tidal currents and Case 2 of low tidal currents for different boat speeds.

	Case 1 high tidal currents			Case 2 low tidal currents		
Range (m)	Velocity range (m/s)	Diff between 0.25 - 3.12 Knot (m/s)	Diff 3.12 - 5.19 Knot (m/s)	Velocity range (m/s)	Diff between 0.53 - 3.00 Knot (m/s)	Diff between 3 - 4.73 Knot (m/s)
1.96	0.683-3.16	1.83	0.535	1.052-2.493	0.695	-0.181
2.96	0.474-2.981	1.486	0.91	0.754-2.19	1.146	0.003
3.96	0.457-2.846	1.656	0.733	0.733-2.352	1.078	-0.106
4.96	0.632-2.709	1.415	0.662	0.928-2.121	0.862	-0.206
5.96	1.014-2.363	0.822	0.277	0.703-2.284	1.177	0.015
6.96	1.099-2.099	0.355	0.356	0.438-1.894	1.254	-0.121
7.96	0.863-2.413	0.376	0.855	0.312-1.866	1	-0.188
8.96	0.646-2.539	0.858		0.648-2.153	0.668	-0.431
9.96	0.453-1.042			0.705-2.074	0.776	-0.358
10.96	0.887-1.959			0.632-1.903	0.389	-0.882
11.96	0.303-0.95			0.445-1.958	0.721	-0.59
12.96	0.33-0.92			0.368-1.679	0.863	-0.448
13.96	0.138-0.616		0.742	0.231-1.436	0.857	-0.348
14.96	0.434-1.482		0.968	0.464-1.358		-0.032
15.96	0.376-2.583	1.214	0.993	0.373-0.928		



No speed correction is applied here.

Figure 43 – Influence of the boat speed on the current velocity and direction (0° (North), 90° (East), 180° (South), 270° (West) and measurements under Case 1 of high tidal currents and Case 2 of low tidal current (bottom panels) and locations of the measurements (top panel).

Although the shape of the current profiles are quite similar, the navigation speed clearly influences the results. For instance under Case 1 (Figure 43) high tidal current, the difference of velocity measurement at a range of 15.96 m (closest to the bed) between a boat speed of 0.25 knot and 3.12 knot is of 1.214 m/s. It is of 0.993 m/s between 3.12 knot and 5.19 knot. Thus the difference of velocity decreases with higher boat speeds above 3 knots. Under low tidal current (Case 2), similar results are found but the difference of current measurements is much lower, especially for a navigation speed above 3 knots. Noteworthily, the change of measurement locations (depth) and time (phase of the tide) could also have an effect (maximum distance between measurements of 137 m). For both cases, the measurements with speed boats between 2 and 3 knots are the closest to the magnitude of the current velocity measured from Bol Van Heist buoy. By assuming that this latter is representative of the hydrodynamics in the Appelzak, this suggests that a speed boats between 2-3 knots is the most suitable for the current velocity measurements. A boat speed of 2 knots is too low for keeping a straight navigation track, so a boat speed of 3 knots is recommended from this point of view. The current direction is affected by the navigation speed, especially under high currents (Table 9). Case 1 indicates a difference up to 100°, while it is much lower (generally around 20°) under low currents (Case 2). It is also clear that the difference increases toward the sea floor. There are some suspicious records for both velocity and direction. For instance, the velocity and the direction at a range of 16 m suddenly increase up to 2 m/s and 100° in Case 1. A high error is usually associated with these records (Case 1: average 0.173 m/s with a maximum of 0.869 m/s). This suggests that the data needs to be first filtered based on the measurement error. Appendix B presents the measurement error per ADCP cell.

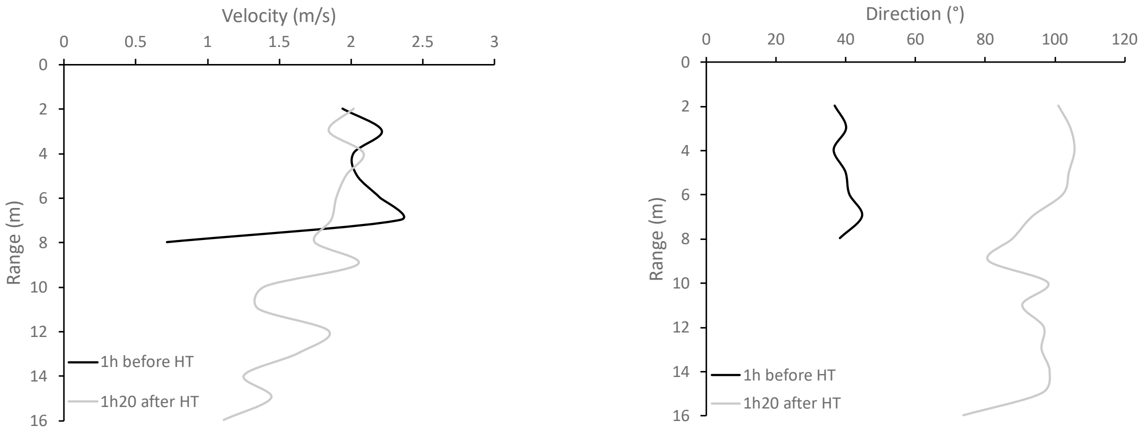
Table 9 – Statistics summary of the current direction measurements for Case 1 of high tidal currents and Case 2 of low tidal currents for different boat speeds.

	Case 1 high tidal currents			Case 2 low tidal currents		
Range (m)	Direction range (°)	Diff between 0.25-3.12 Knot (°)	Diff 3.12 - 5.19 Knot (°)	Direction range (°)	Diff between 0.53 - 3 Knot (°)	Diff between 3 - 4.73 Knot (°)
1.96	4.3 - 100.5	89.6	-14.4	78.0 - 89.9	-6.9	2.8
2.96	34.4 - 96.1	59	-13.7	77.3 - 88.4	-5.4	-3.4
3.96	13.7 - 95.9	82.2	-12.3	76.5 - 86.5	0.6	-3.3
4.96	18.9 - 98.1	75.3	-12.7	80.1 - 87.4	1.2	-1.1
5.96	6.7 - 82.7	76	-4.4	78.3 - 87.6	-4.3	-1.8
6.96	9.4 - 70.5	61	0.2	66.5 - 83.2	-2.1	-1.4
7.96	2.0 - 96.3	72.3	-6	64.7 - 93.9	-29.2	9.9
8.96	0.0 - 92.9	92.9	-92.9	66.7 - 82.2	-4.1	3
9.96	3.2 – 61.0	-3.2		67.0 - 88.2	1.2	18.4
10.96	4.5 – 110.0	-4.5		59.4 - 82.1	-17.6	22.7
11.96	39.8 - 88.6	-39.8		68.8 - 86.5	-14.6	13.7
12.96	31.2 - 130.5	-31.2		60.2 - 96.2	10.5	21.2
13.96	8.5 - 63.4	-50.7	25.8	57.9 - 95.7	24.2	-8.6
14.96	16.7 - 65.8	-37.1	65.8	53.2 - 87.1	61.1	25.2
15.96	6.4 - 113.1	60.2	9.9	60.1 - 70.3	70.3	-70.3

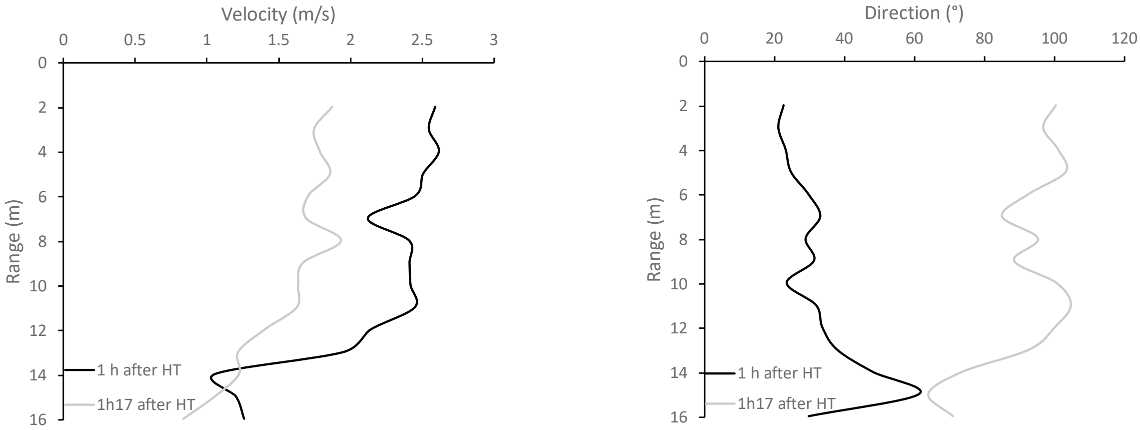
Time and cross-shore measurements

The current velocity and direction measurements are compared at two period intervals at the same location along a cross-shore transect (Figure 44). The boat speed was consistent, ranging from 3.38 to 5.62 knot. The marine conditions during the measurements are presented in Appendix E.2. A spatial and temporal variability of the current velocity and direction is clearly observed as well as through the water column (Figure 44). To further investigate these, more repeated records should be measured at the same location over time under the same navigation speed. It was suggested to measure the same point every 40 min, this appears to be coherent and realistic, but the length of the measured track has to be smaller.

Location A: depth -6 m TAW



Location B: -6.5 m TAW



Location C: -6.5 m TAW

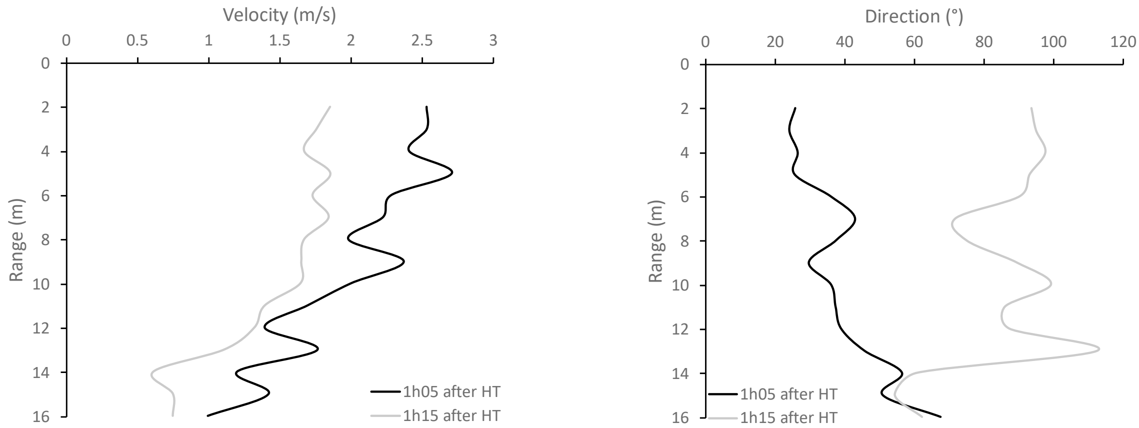


Figure 44 – Comparison of current velocity and direction (0° (North), 90° (East), 180° (South), 270° (West) measurements at two period intervals along a cross-shore transect at 3 locations (bottom panels) and location (top panel).

Error assessment based on consecutive measurements

Table 10 presents a statistic summary of the current velocity and direction records and the associated error of 20 consecutive measurements taken during a short period of ½ minute (from 11:22:01 to 11:22:36) in alongshore direction when the pitch, roll and heading were low. Although the navigation speed (4.4 knots) and depth (around 4.8 m) were relatively constant, there is a remarkable variability of the average velocity and direction through the water column for repeated measurements. This is also highlighted in the standard deviation (SD) of the current velocity. Data error is assessed by calculating the average and standard deviation (SD) of the velocity error directly retrieved from the ADCP records. The average and SD error range from 0.067 to 0.263 m/s and from 0.054 to 0.235 m/s respectively. Following the empirical rule of 2*SD error (here: 0.292 m/s), data with an error above 0.3 m/s should be filtered, and thus not considered. This is slightly higher than the 2 times the SD velocity of 0.244 m/s. Teledyne (2017) reports an uncertainty between 0.14 m/s and 0.07 m/s for a range at 38 m and 42 m respectively.

Table 10 – Statistics summary of the current velocity, direction, and error for 20 consecutive samples.

Range (m)	Current velocity (m/s)						Current direction (°)			
	Avg	Max	Min	SD	Avg Error	SD Error	Avg	Max	Min	SD
1.96	2.060	2.251	1.856	0.103	0.082	0.060	36.015	41.900	31.300	2.866
2.96	2.043	2.215	1.863	0.112	0.085	0.060	38.440	43.700	32.800	3.361
3.96	1.982	2.159	1.721	0.115	0.084	0.071	38.680	43.600	30.600	3.460
4.96	2.185	2.296	1.998	0.061	0.067	0.054	38.780	42.600	34.800	1.749
5.96	2.287	2.876	1.859	0.229	0.207	0.132	39.580	50.400	29.400	6.193
6.96	1.997	2.471	1.406	0.284	0.287	0.235	37.690	52.000	22.100	7.573
7.96	1.861	2.438	0.645	0.465	0.307	0.203	36.335	77.000	4.700	16.353
8.96	1.797	2.860	1.244	0.457	0.338	0.229	73.053	180.000	25.400	38.224
9.96	1.496	2.507	0.627	0.442	0.249	0.203	54.630	180.000	29.100	33.517
10.96	1.006	1.945	0.496	0.339	0.230	0.185	39.360	59.200	19.100	10.138
11.96	0.935	1.492	0.502	0.228	0.263	0.215	47.290	180.000	14.800	16.589
12.96	1.095	1.407	0.586	0.211	0.197	0.171	40.815	75.300	1.300	15.050
13.96	1.174	1.703	0.614	0.250	0.189	0.121	50.930	86.800	32.600	14.084
14.96	1.169	1.638	0.657	0.182	0.195	0.119	46.645	65.000	21.100	9.266
15.96	1.123	1.392	0.640	0.184	0.150	0.135	57.730	180.000	21.500	12.756

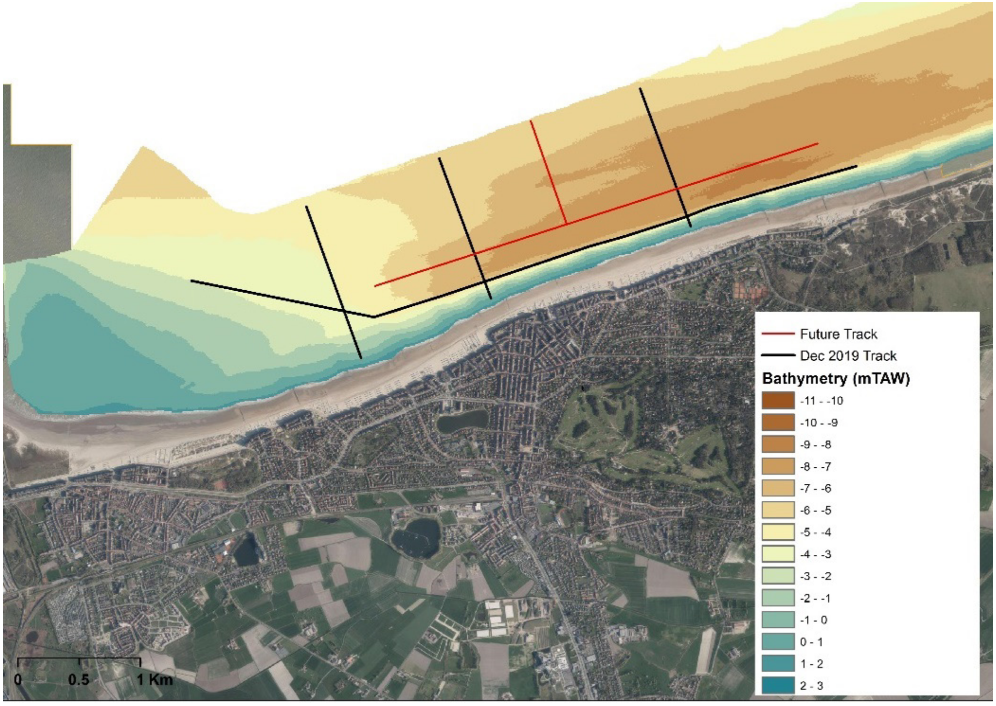


Figure 45 – Map of the recommended track for future campaigns.
Total length of the survey coverage is 4.4 km. Transect is located in section 236.

Conclusions and recommendations for future measurements

From this pilot campaign, some recommendations are suggested for future measuring campaigns:

A) The measurements along Appelzak should be undertaken more offshore following the navigation tracks on 12/12/2019.

B) The navigation speed boat should be between 3 and 4 knots.

C) For further investigations of the hydrodynamics under different tidal periods, repeated measurements of the same location should be measured within a time interval of 40 min over a total period of 13 hours.

To reach C, the coverage of the study site and the length of the track must be reduced. For the next campaign, the survey will cover only one cross-shore transect located in section 236 (Figure 45). The total length of the track is 4.7 km (3.8 km alongshore and 0.9 km cross-shore). Under a speed of 3.5 knots (equivalent to 6.5 km/h), it would take just 45 min to cover the total length.

D) The dual hydrodynamic system at 33 kHz (OdomDepth33khz) corresponding to the entire water column records should be considered for converting the ADCP range to water depth. The draught of 3.5 m must be subtracted from the depth measurement.

E) Navigation data (coordinates, depth) should be measured every 1 s (and not 5 sec). This must be mentioned in the cruise planning sent at least one week before the campaign.

F) Water samples will be collected only at the barnacle location (if deployed) beginning and end of the campaign.

G) Clarify the height of the freeboard (total hull depth=draught+freeboard). Information received from VLIZ and the ship personnel is not very precise.

H) Following the empirical rule of 2*SD error (here based on 20 consecutive measurements: 0.292 m/s), data with an error above 0.3 m/s should be filtered, and thus not considered. Same test considering both SD records and SD error should be undertaken with more samples.

4.3.2 Local scale

Hydrodynamic measurements were carried out at a location in the Appelzak channel (MOW2 station, MP2-Meetpaal2) for 8.5-months in 2012 (09/05/2012-21/01/2013) and two months in summer 2017 (30/05/2017-25/07/2017) (Figure 46, Table 11). In 2012, the average of the current velocity over the water column ranged from 0.45 to 0.56 m/s. A maximum of 1.64 m/s was reached for the upper cell 1. Both current velocity and direction reflected the tidal cycle. The average of current velocity per cell in summer 2017 was similar to 2012. However the maximum recorded values per cell were lower (<1.40 m/s).

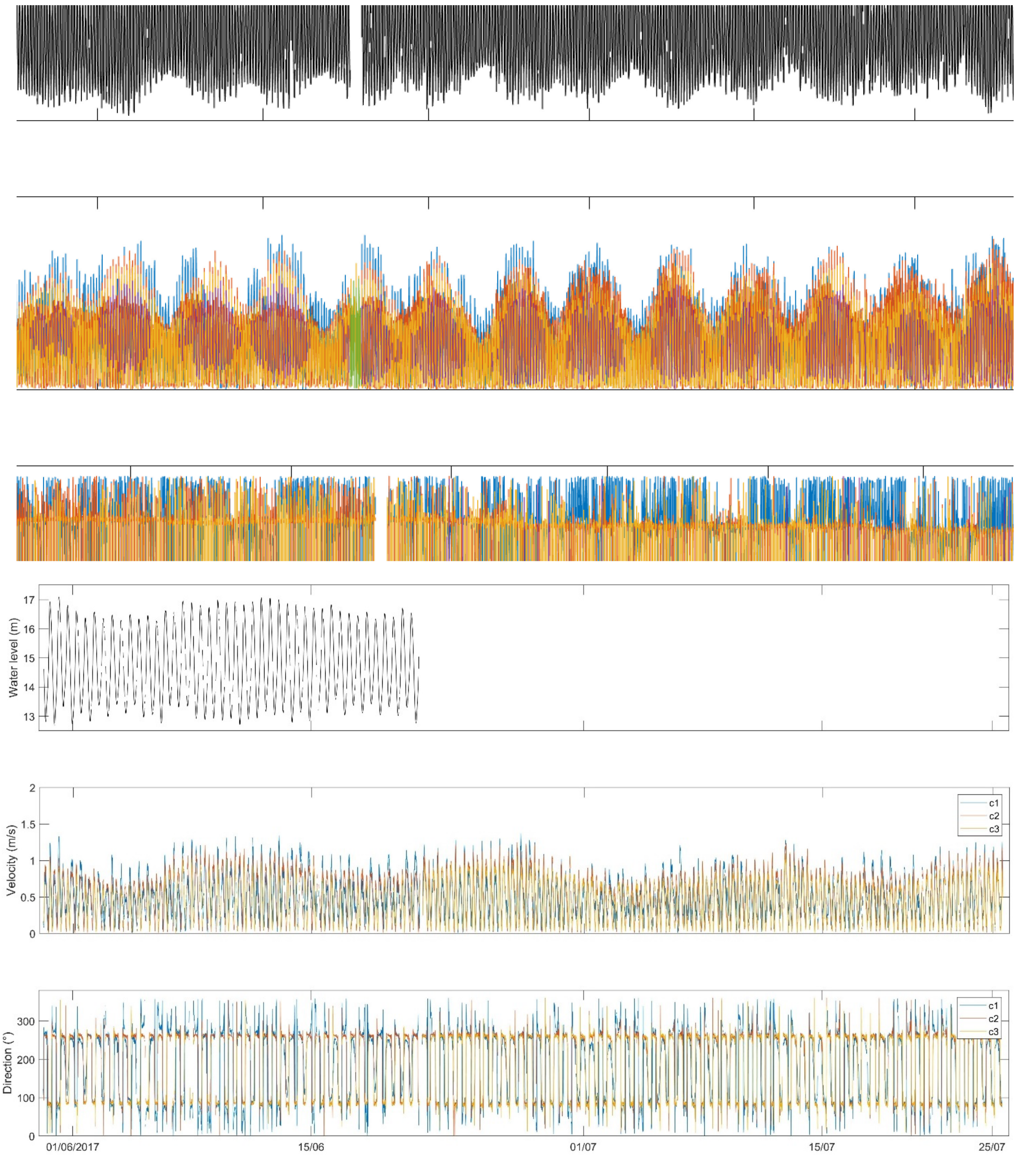


Figure 46 – Time series from 09/05/2012-21/01/2013 and from 30/05/2017-25/07/2017 in the Appelzak channel (MOW2 station).

Table 11 – Statistics of current velocity in the Appelzak channel (MOW2 station) from 09/05/2012-21/01/2013 and from 30/05/2017-25/07/2017.

		Velocity (m/s)	
		Mean	Max
09/05/2012-21/01/2013	cell 1	0.56	1.64
	cell 2	0.52	1.56
	cell 3	0.45	1.41
	cell 4	0.47	1.18
	cell 5	0.47	1.15
30/05/2017-25/07/2017	cell 1	0.52	1.37
	cell 2	0.50	1.25
	cell 3	0.44	1.10

5 Conclusions

Long-term coastal erosion occurs at Knokke, up to -42.16 m^3/m/year in section from 233-241. In order to reduce this erosion rate, a combined large beach and shoreface nourishment will be carried out on the beach and shoreface between 2020 and 2024. Under the framework of this project, the aim is to understand the hydrodynamics and morphodynamics of the Knokke area and its surroundings by measurements of topography and hydrodynamics of the pre and post-nourishment period and to assess the efficiency of the nourishments. Literature review of the east Belgian coast highlights the spatial morphological variability dominated by accretion in the west side, while erosion occurs from Duinbergen-centrum to Zwin. This erosion is probably related to the gradient in the littoral drift caused by the sheltering of Zeebrugge harbour and the natural deepening of the Appelzak tidal channel, which is consider it to evacuate sediments from the area after storm erosion. Also, Paardenmarkt sand bank might control the morphological evolution of the Appelzak. The severe erosion in Knokke is might also be related to the protrusion of the coastline/sea dike in that area. A part of the past nourishments was transported towards the Appelzak channel and the Zwin by natural hydrodynamic processes.

An inventory of the beach and shoreface topo-bathymetry and marine conditions (continuous, semi-permanent and 13 hour campaign) has been established preparing for future investigations of coastal processes in the study area especially to evaluate the effects of the combined meganourishment.

6 References

Afdeling Kust (2020) Stormrapporten. Access on 20/05/2020 https://www.afdelingkust.be/nl/stormrapporten

Atlas (1992) Noordzee Vlaamse banken Stroomatlas, Dienst der Kusthavens Hydrografie Oostende, 29p.

Bastin, A. (1974) Regionale sedimentologie en morfologie van de zuidelijke Noordzee en van het Schelde estuarium PhD Thesis Katholieke Universiteit Leuven (KUL): Leuven. VI, 91 p.

Bastin, A., Malherbe, B., Caillot, A. (1983) Zeebrugge Port extension sediment transport: measurement on and off the Belgian coast by means of tracers in: KVIV 8ste Internationaal Havenkongres, 85p.

Charlier, R., H., De Meyer, C., P. (1995) New developments on coastal protection along the Belgian coast. Journal of Coastal Research, 11(4), 1287-1293.

De Moor, G. (1988) General nature of the coastline in H.J. Walker (ed) Artificial structures and shorelines, 115-126.

Deronde, B. (2007) The sediment dynamics along the Belgian shoreline, studied with airborne imaging

spectroscopy and LIDAR PhD Thesis Universiteit Gent: Gent. 204 p

Deronde, B., Houthuys, R., Henriet, J-P., Van Lancker, V. (2008) Monitoring of the sediment dynamics along a sandy shoreline by means of airborne hyperspectral remote sensing and LIDAR: a case study in Belgium. Earth Surface Processes and Landforms, 33, 280-294

Dujardin (2020) Coastline model West Coast – Hydrodynamic boundary conditions. Versie 0.1 WL Memo's, 20_017_1. Waterbouwkundig Laboratorium: Antwerpen.

Eurosense (1991a) Evaluatiestudie "Stabilisatie van het onderwaterstrand d.m.v. vertikale kunststofdoeken"– Knokke-Zoute en Zwin – Beginsituatie Voorjaar 1990 – Administratie Waterinfrastructuur en Zeewezen. Dienst der Kusthavens: Oostende

Eurosense (1991b) Evaluatiestudie "stabilisatie van het onderwaterstrand d.m.v. vertikale kunststofdoeken": Knokke-Zoute en Zwin. Situatie zomer 1991: bodemtransport, duikersverslagen en side-scan sonarregistraties. Administratie Waterinfrastructuur en Zeewezen. Dienst der Kusthavens: Oostende.

Eurosense (1991c) Evaluatiestudie "stabilisatie van het onderwaterstrand d.m.v. vertikale kunststofdoeken": Knokke-Zoute en Zwin. Situatie zomer 1991: hydrodynamica en sedimentologie. Administratie Waterinfrastructuur en Zeewezen. Dienst der Kusthavens: Oostende

Eurosense (1994a) Bufferzone Heist Sedimentdynamica. Metingen van spring- naar doodtij (9-16 feb.1993) enbij storm (18-20 feb. 1993). Tekst & Figuren. KDN 94.004, Eurosense, Wemmel.

Eurosense (1994b) VooroeverZwin, Sedimentdynamica. KDN 94.005

Haerens, P., Bolle, A., Trouw, K., Houthuys, R. (2012) Definition of storm thresholds for significant morphological change of the sandy beaches along the Belgian coastline. Geomorphology, 143-144, 104-117.

Houthuys, R.; De Moor, G.; Sommé, J., (1993) The shaping of the French-Belgian North Sea coast throughout recent geology and history, in: Hillen, R. et al. Coastlines of the Southern North Sea. Coastlines of the World, : pp. 27-40.

Houthuys, R. (2012) Morfologische trends van de Vlaamse Kust in 2011, publication by Afdeling Kust, 151 p.

Houthuys, R., Verwaest, T., Dan, S., Mostaert, F. (2020) Morfologische evolutie van de Vlaamse kust tot 2019. Versie 2.0. WL Rapporten, 18_142. Waterbouwkundig Laboratorium: Antwerpen, 225p.

Janssens, J.; Delgado, R.; Verwaest, T.; Mostaert, F. (2013) Morfologische trends op middellange termijn van strand, vooroever en kustnabije zone langsheen de Belgische kust: Deelrapport in het kader van het Quest4D-project. Versie WL2011R814_02_2rev3_0. WL Rapporten. Waterbouwkundig Laboratorium: Antwerpen, België.

Kerckaert, P., Roovers, P.P.L., Noordam, A., De Candt, P. (1986) Artificial beach nourishment on Belgian East coast. Joournal of Waterway, Port, Coastal, Ocean Engineering. 112 (5), 560-571.

Lanckneus, J., Van Lancker, V.R.M., Moerkerke, G., Van den Eynde, D., Fettweis, M., De Batist, M., Jacobs, P. (2001) Investigation of the natural sand transport on the Belgian Continental shelf (BUDGET). Final report. Federal Office for Scientific, Technical and Cultural Affairs (OSTC), 104 p.

Magelas (2001) Mobag 14: Mobag 2000. Studie inzake de ecologische impact van de baggerwerkzaamheden in de Vaarpassen van de Noordzee inbegrepen de haven van Zeebrugge. Turbiditeit op de loswallen B&W Zeebrugge Oost en S1 (meetperioden september 2000 - januari 2001): wetenschappelijke validatie van de turbiditeitsregistraties en bepaling van hydrometeorologische invloeden op de achtergrondturbiditeitNatural Beach Reserve 'De Baai van Heist': the Flemish beaches: sterile sand boxes or natural heritage?. VLIZ Special Publication 9.

Masselink, G., Hughes, M., Knight, J. (2015) Introduction to coastal processes and geomorphology. In Routledge 2nd Ed, 432p.

Missiaen, T., Henriet, J.-P. (2002) Evaluatie van de Paardenmarkt site, in: (2002). Duurzaam Beheer van de Noordzee: presentatie van de onderzoeksresultaten, 21-22/01/2002. Scientific Support Plan for a Sustainable Development Policy (SPSD I): Programme "Sustainable Management of the North Sea" = Plan voor wetenschappelijke ondersteuning van een beleid gericht op duurzame ontwikkeling (PODO I): Programma "Duurzaam beheer van de Noordzee".

Montreuil, A.-L., Brand, E., Strypsteen, G., Roest, B., De Sloover, L., Rauwoens, P., De Wulf, A., Houthuys, R., Chen, M., Verwaest, T. (2020a). Scientific Report on Coastal Resilience. Deliverable D 3.4.1 CREST (Climate Resilient Coast) VLAIO/IWT project 150028. 108 pp.

Montreuil, A-L., Dan, S., Verwaest, T., Mostaert, F. (2020b) Monitoring the morphodynamics of the Zwin inlet: intern report 1 year after the works, version 0.1 FHR reports, 16_89_1. Flanders Hydraulic Research, Antwerp, 74.

Montreuil, A-L., Chen, M., Brand, E., Verwaest, T., Houthuys, R. (2020c) Post-storm recovery assessment of urbanized versus natural sandy macro-tidal beaches and their geomorphic variability. Geomorphology, 356.

Svasek (2012) Morfologie Zwakke Schakel Cadzand-Bad, ref. 1638/U12221/SPo/B.

Teledyne (2017) Workhorse Mariner 1200, 600, 300 kHz ADCP, Convenient hull-mounted ADCP for coastal vessel applications, 2pp.

Trouw, K., Zimmermann, N., Wang, Li., De Maerschalck, B., Delgado, R., Verwaest, T., Mostaert, F. (2015) Scientific support regarding hydrodynamics and sand transport in the coastal zone: Literature and data review coastal zone Zeebrugge - Zwin. Version 4_0. WL Rapporten, 12_107. Flanders Hydraulics Research. Antwerp, Belgium, 74p.

Vandebroek, E., Dan, S., Vanlede, J., Verwaest, T., Mostaert, F. (2017) Sediment Budget for the Belgian Coast: Final Report. Version 2.0. FHR Reports, 12_155_1. Flanders Hydraulics Research: Antwerp & Antea Group.

Van den Eynde, D., Kerckhof, F., Francken, F., Haelters, J., Lauwaert, B. (2006) Ontwikkeling van de zandbank ter hoogte van Heist, Eindrapport (ZAHE/1/DVDE/200710/NL/ER).

Van Lancker, V.R.M. (1999) Sediment and morphodynamics of a siliciclastic near coastal area, in relation to hydrodynamical and meteorological conditions: Belgian Continental Shelf = De sediment- en morfodynamiek van de kustnabije zone in relatie tot de impact van hydrodynamische en meteorologische factoren in een silicoclastische omgeving, Belgisch continentaal plat. PhD Thesis. University of Gent: Gent. 194 p.

Van Lancker, V., De Batist, M., Fettweis, M., Pichot, G., Monbaliu, J., (2007) Management, Research And Budgetting Of Aggregates In Shelf Seas Related To End-Users - Marebasse (SPSD II project).

Vlaamse Hydrografie (2017) Stroomatlas Belgisch Continentaal Plat 2017. Dutch. Tech. rep. D/2017/3241/172. Brussels, Belgium: Vlaamse Overheid, Ministerie van Mobiliteit en Openbare Werken, IVA Maritieme Dienstverlening en Kust, Afdeling Kust. 100 p.

Annexe A Artificial sand supplies along the east coast (over time)

Stretch 47 - Duinbergen-centrum				
jaar	Emerged beach sand volume (m³)	Submerged beach (m³)	Sand borrowed above LW (m³)	Sand borrowed below LW (m³)
1997	7049		3500	-3500
1998	10617		5300	-5300
1999	12411		6200	-6200
2000	12000		*6000*	-6000
2001	12000		*6000*	-6000
2002	12000		*6000*	-6000
2003	13597	4855	11700	-6800
2004		13124	13100	0
2005		18146	18100	0
2006		19372	19400	0
2007		14000	14000	0
2008*		11400	11400	0
2009*		7800	7800	0
2010*		14700	14700	0
2011*		21600	21600	0
2012		10600	10600	0
2012, voor VJ		20722	20700	0
2013, voor VJ		22600	22600	0
2014, voor VJ		6300	6300	0
tussen VJ en NJ 2015		10000	10000	0
voor 31-03-2017		16900	16900	0
Total zones (m³)	79674	212119		
Total stretch (m³)	251993			

Stretch 48 - Albertstrand					
Period	Section	Length (m)	Effectif volume (m³)	Part above LW (m³)	Part below LW (m³)
voorjaar 1986	sectie 232	235	67400	57300	10100
juni 2004	sectie 232	76	9000	7700	1400
2007	sectie 232	235	8500	8500	0
2007	sectie 232	118	1400	1400	0
2009	secties 231-232	470	14800	14800	0
2010	sectie 232	118	7300	7300	0
2011	sectie 232	118	3600	3600	0
2012, voor VJ	sectie 231, 232	470	16300	16300	0
2012, voor VJ	sectie 232	171.5	7000	7000	0
2013, net na VJ	sectie 232	235	11800	11800	0
2014, voor VJ	sectie 227	235	2100	2100	0
2014, voor VJ	sectie 232	125	8800	8800	0
2015, voor VJ	sectie 232	235	33200	33200	0
voor 31-03-2017	sectie 232	235	24600	24600	0
Total zones (m³)	**204400**	**11500**			
Total stretch (m³)	**215900**				

Stretch 49-Knokke-Zoute					
Period	Section	Length (m)	Effectif volume (m³)	Part above LW (m³)	Part below LW (m³)
voorjaar 1986	secties 233-241	2237	641700	545400	96300
maart-mei 1999	secties 233-241	2237	339100	288200	50900
juni 2004	secties 233-241	2237	264800	225100	39700
2006	secties 236-240	1318	55500	55500	0
2007	sectie 233-237 en 166 m	1282	46500	46500	0
2007	sectie 233-236	958	11100	11100	0
2009	secties 233-237 en 170 m	1300	41000	41000	0
2010	233-237, deel 239-240	1533	94300	94300	0
2010	234-236, deel 239-240	1052	15400	15400	0
2011	233-237, deel 239-240	1533	47300	47300	0
2011	233-237, delen 239-240	1533	60800	60800	0
2012, voor VJ	sectie 231, 232	470	16300	16300	0
2012, voor VJ	sectie 232	171.5	7000	7000	0
2013, net na VJ	sectie 232	235	11800	11800	0
2014, voor VJ	sectie 232	125	8800	8800	0
2015, voor VJ	sectie 232	235	33200	33200	0
voor 31-03-2017	sectie 232	235	24600	24600	0
Total zones (m³)	**1532300**	**186900**			
Total stretch (m³)	**1719200**				

Stretch 50 - Lekkerbek					
Period	Section	Length (m)	Effectif volume (m³)	Part above LW (m³)	Part below LW (m³)
voorjaar 1986	secties 242-243	491	140900	119800	21100
na storm 29 augustus 1996	Sectie 242	240	0 (opvoer strandzand)	2500	-2500
maart-mei 1999	secties 242-243	491	74400	63200	11200
juni 2004	secties 242-243	491	58100	49400	8700
2013 (na VJ)	secties 247-249	1098	VOLUME NIET GEKEND		
voor 02-05-2017	sectie 242	240	10000	10000	0
23/02/2019 t.e.m. 17/03/2019	sectie 242	240	24700	24700	0
Total zones (m³)	**269600**	**38500**			
Total stretch (m³)	**308100**				

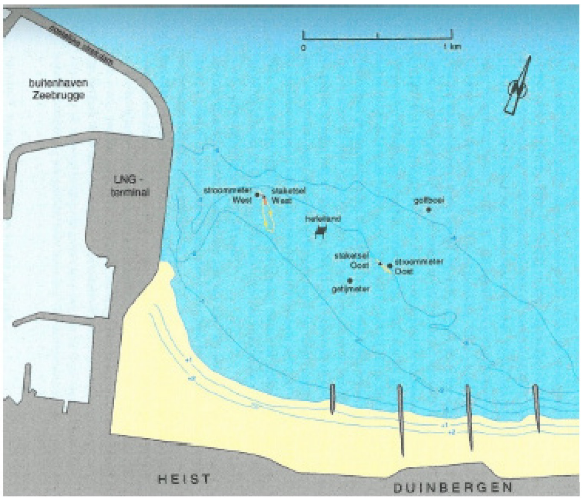
Annexe B Past of severe storms

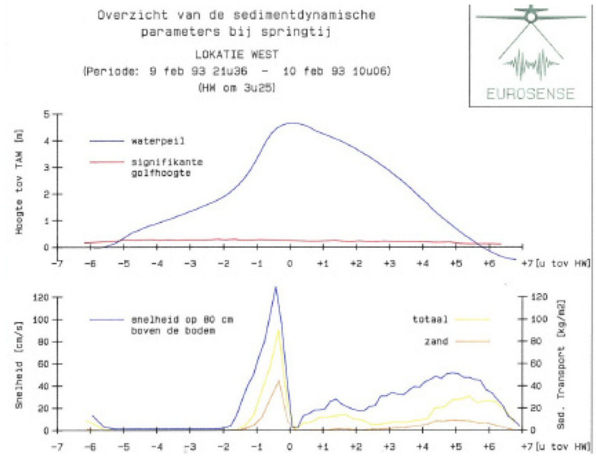
Year	Nb of storm	Date
1988	1	06-07Oct
1989	1	23-24Mar
1990	5	25Jan, 3Feb, 26-27Feb, 28Feb, 25-28Dec
1993	4	10Jan, 24Jan, 14Nov, 8Dec
1994	3	26Jan, 27Jan, 30Dec
1996	4	19Feb, 29Aug, 04-05Nov, 06-07Nov
1997	3	12-13Feb, 18-20Feb, 24-25Feb
1998	1	03-04Mar
2000	4	02-03Mar, 26-27May, 29-30Oct, 12-13Dec
2001	2	08-09Oct, 29Oct
2002	6	25-29Jan, 19-21Feb, 23-24Feb, 26-27Feb, 15-16Oct, 26-27Oct
2003	1	20-22Dec
2004	8	07-08Feb, 31Jan-02Feb, 19-21Mar, 23-24Jun, 17Jul, 21Oct, 12-13Nov, 17-18Dec
2005	4	06Jan, 14-14Feb, 24-25Nov, 16-17Dec
2006	5	25Nov, 3Dec, 04-05Dec, 07Dec, 30-31Dec
2007	6	11Jan, 18Jan, 3Mar, 18-21Mar, 08-10Nov, 24-26Nov
2008	6	31Jan, 29Feb, 11-12Mar, 21Mar, 13Aug, 20Nov
2009	2	23Jan, 10Feb
2010	2	28Feb, 11-12Nov
2011	2	8Dec, 15Dec
2012	3	03-05Jan, 23-24Sept, 24-25Nov
2013	2	05-06Dec, 23-24Dec
2014	2	08-09Feb, 14-15Feb
2015	6	14Jan, 29Mar, 5May, 25Jul, 21Nov, 23-30Nov
2016	1	20Nov
2017	3	12-14Jan, 23Feb, 12Sept
2018	2	03Jan, 18Jan
2020	1	09-11Feb

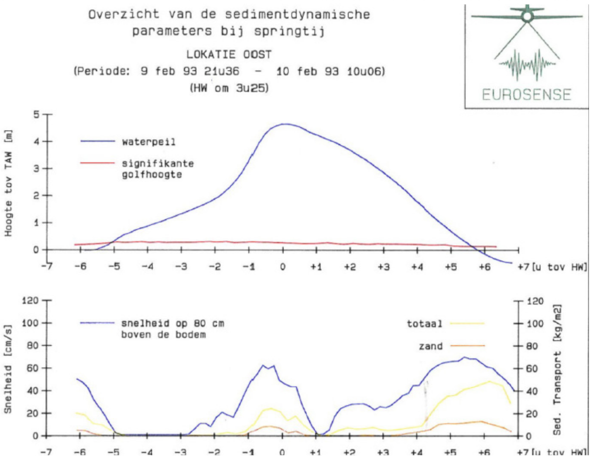
(Source: https://www.afdelingkust.be/nl/stormrapporten)

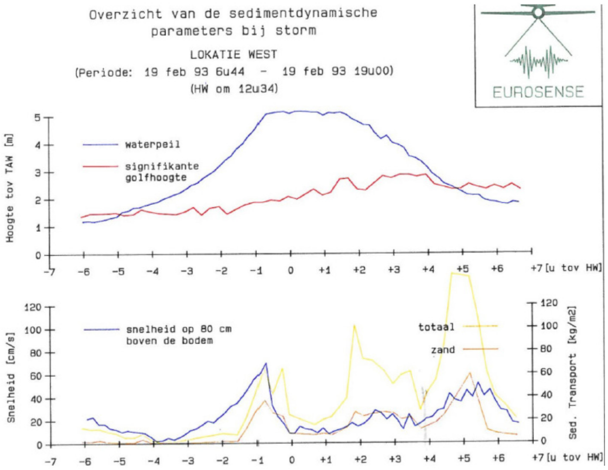
Annexe C Eurosense Measurements

1. Baai Van Heist

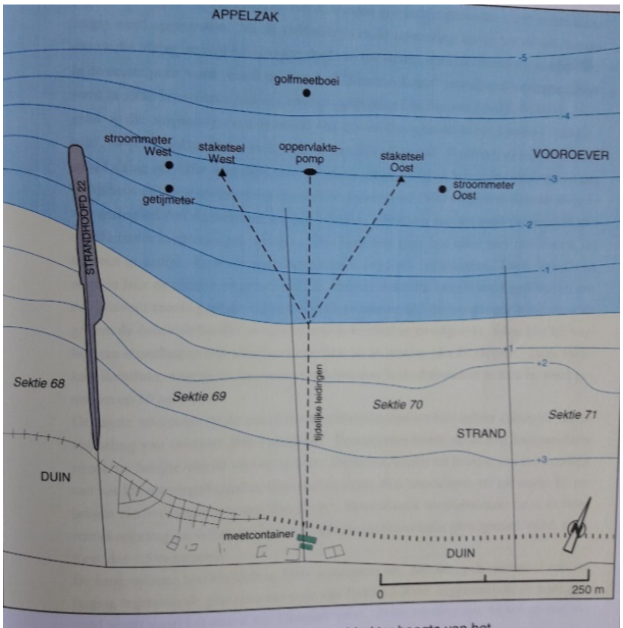




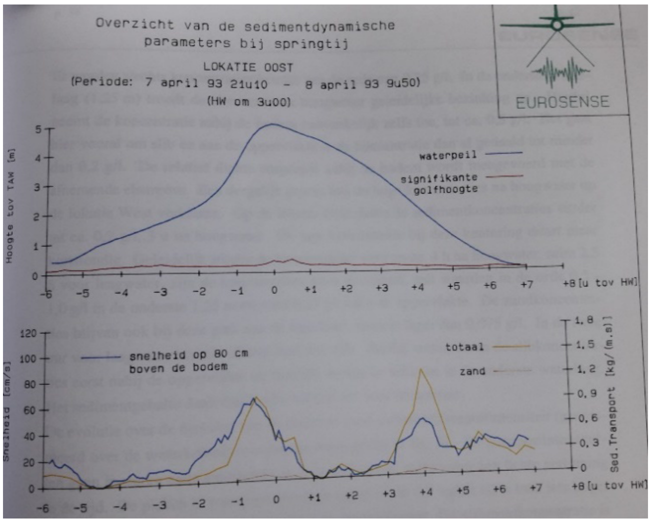


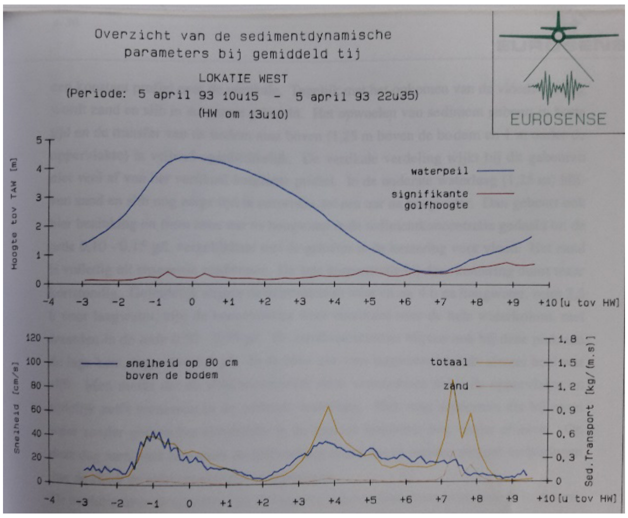


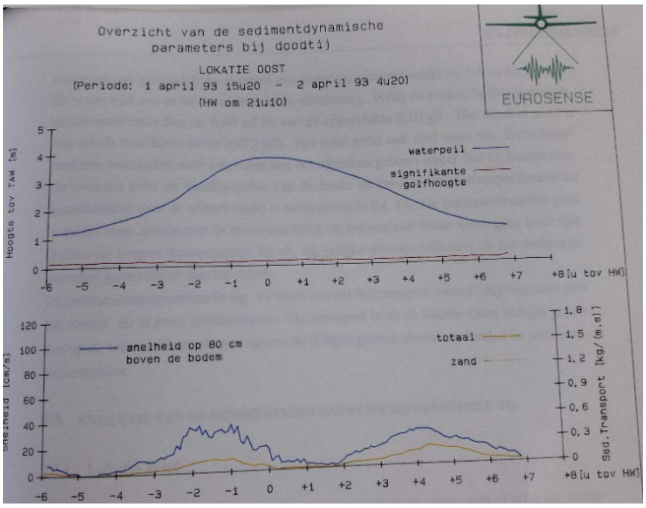
2. Zwin



Overzichtskaart van het projektgebied ter hoogte van het natuurreservaat "Het Zwin", met aanduiding van de hoogtelijnen tot 5 m onder Z. en de positie van de diverse meetinrichtingen.



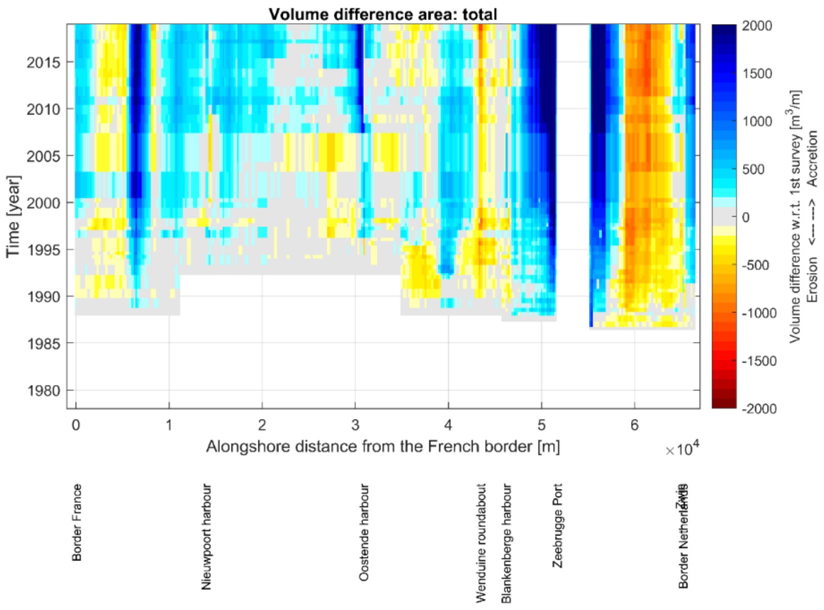




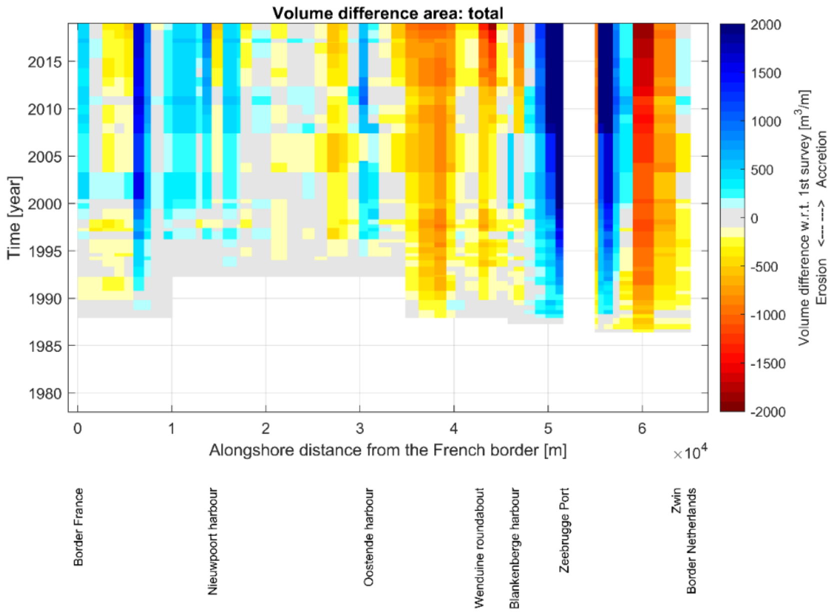
Annexe D Volumetric changes over time

Entire beach (from dunes/ dyke to 1.5 km offs.

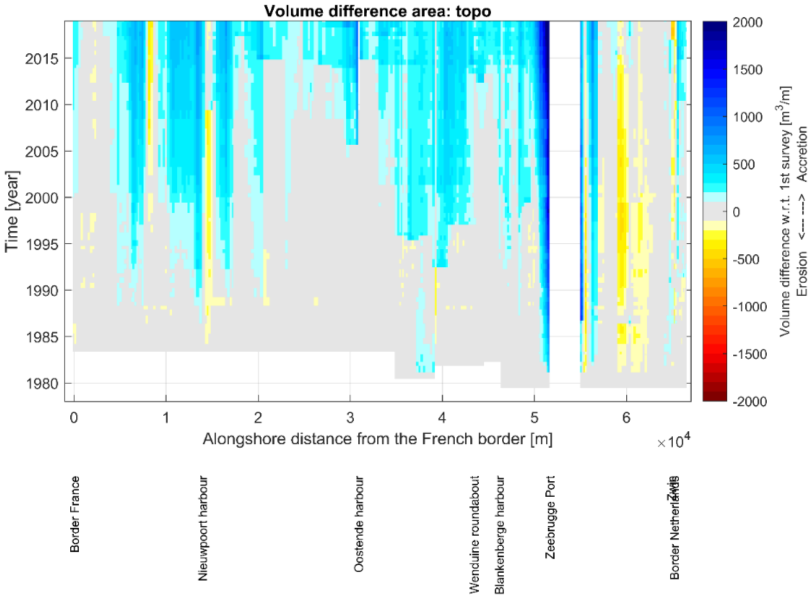
Observed volume changes

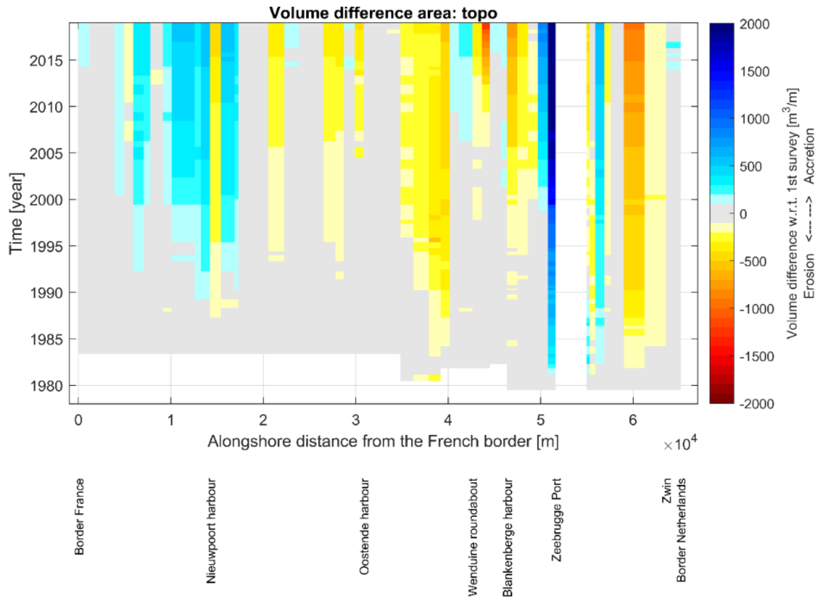


Corrected volume changes

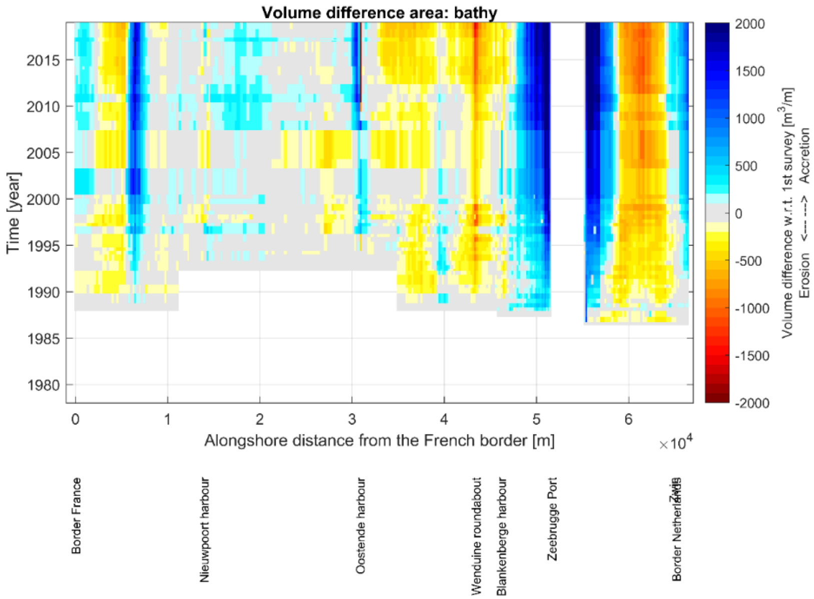


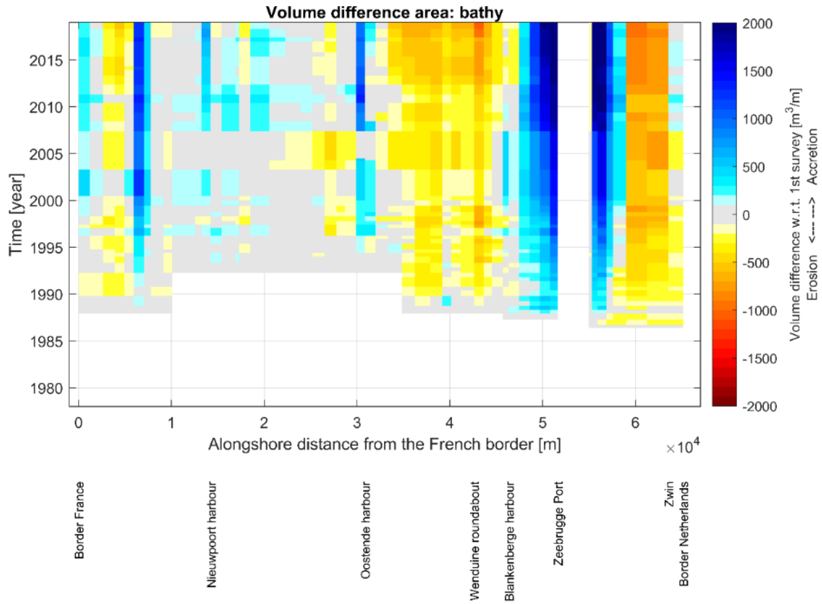
Emerged beach (>+1.39 m TAW)





Submerged beach (< +1.39 m TAW)





Annexe E Description of the marine conditions from Bol Van Heist buoy during the measurements.

1. Boat speeds on current velocity

Case 1: high velocity current (10 min before high tide)									
Ens	Time	Depth (m TAW)	Speedlog (knot)	Speedlog (m/s)	Water level (m TAW)	Current velocity (m/s)	Current direction (°)	Average wave height (m)	Wave direction (°)
2669	12:09:21	6.32	0.25	0.129	4.47	1.13	89	0.78	242
2707	12:10:29	6.34	0.96	0.494					
2716	12:10:45	6.38	2.17	1.116					
2724	12:11:00	6.34	3.12	1.605					
2732	12:11:14	6.29	4.32	2.222					
2740	12:11:29	6.32	5.19	2.670					
2763	12:12:10	6.42	6.19	3.184					

Case 2: low velocity current (1h20 before high tide)									
Ens	Time	Depth (m TAW)	SpeedLog (knot)	Speedlog (m/s)	Water level (m TAW)	Current velocity (m/s)	Current direction (°)	Average wave height (m)	Current direction (°)
5999	13:49:31	7.32	0.53	0.273	3.9	0.65	82	0.70	212
6007	13:49:46	7.37	1.34	0.689					
6012	13:49:55	7.34	2.17	1.116					
6023	13:50:15	7.44	3	1.543					
6032	13:50:31	7.5	3.49	1.795					
6040	13:50:45	7.55	4.1	2.109					
6057	13:51:16	7.68	4.73	2.433					

2. Cross-shore measurements (section 2.1.2)

Location	Period	Ens	Time	Depth (m TAW)	Speed log (knot)	Speed log (m/s)	Water level (m TAW)	Current velocity (m/s)	Current direction (°)	Average wave height (m)	Wave direction (°)
A	1h before HT	1199	11:25:07	6.00	4.53	2.330	3.99	1.24	92	0.77	246
	1h20 after HT	5656	13:59:12	6.00	4.29	2.207	3.99	0.64	80	0.71	226
B	1 h after HT	5148	13:23:55	6.63	5.12	2.634	4.11	0.69	86	0.71	226
	1h17 after HT	5594	13:37:20	6.47	3.88	1.996	3.99	0.64	80	0.7	212
C	1h05 after HT	5195	13:25:20	6.52	5.62	2.891	4.11	0.64	84	0.71	226
	1h15 after HT	5530	13:35:25	6.48	3.38	1.739	4.04	0.64	80	0.7	212

Description of the marine conditions from Bol Van Heist buoy during the measurements.

A.1. Boat speeds on current velocity (section 2.1.1)

Case 1: high velocity current (10 min before high tide)									
Ens	Time	Depth (m TAW)	Speedlog (knot)	Speedlog (m/s)	Water level (m TAW)	Current velocity (m/s)	Current direction (°)	Average wave height (m)	Wave direction (°)
2669	12:09:21	6.32	0.25	0.129	4.47	1.13	89	0.78	242
2707	12:10:29	6.34	0.96	0.494					
2716	12:10:45	6.38	2.17	1.116					
2724	12:11:00	6.34	3.12	1.605					
2732	12:11:14	6.29	4.32	2.222					
2740	12:11:29	6.32	5.19	2.670					
2763	12:12:10	6.42	6.19	3.184					

Case 2: low velocity current (1h20 before high tide)									
Ens	Time	Depth (m TAW)	SpeedLog (knot)	Speedlog (m/s)	Water level (m TAW)	Current velocity (m/s)	Current direction (°)	Average wave height (m)	Current direction (°)
5999	13:49:31	7.32	0.53	0.273	3.9	0.65	82	0.70	212
6007	13:49:46	7.37	1.34	0.689					
6012	13:49:55	7.34	2.17	1.116					
6023	13:50:15	7.44	3	1.543					
6032	13:50:31	7.5	3.49	1.795					
6040	13:50:45	7.55	4.1	2.109					
6057	13:51:16	7.68	4.73	2.433					

A.2. Cross-shore measurements (section 2.1.2)

Location	Period	Ens	Time	Depth (m TAW)	Speed log (knot)	Speed log (m/s)	Water level (m TAW)	Current velocity (m/s)	Current direction (°)	Average wave height (m)	Wave direction (°)
A	1h before HT	1199	11:25:07	6.00	4.53	2.330	3.99	1.24	92	0.77	246
	1h20 after HT	5656	13:59:12	6.00	4.29	2.207	3.99	0.64	80	0.71	226
B	1 h after HT	5148	13:23:55	6.63	5.12	2.634	4.11	0.69	86	0.71	226
	1h17 after HT	5594	13:37:20	6.47	3.88	1.996	3.99	0.64	80	0.7	212
C	1h05 after HT	5195	13:25:20	6.52	5.62	2.891	4.11	0.64	84	0.71	226
	1h15 after HT	5530	13:35:25	6.48	3.38	1.739	4.04	0.64	80	0.7	212

Annexe F Boat speeds and current velocity measurements

B.1. Boat speeds on current velocity

	Case 1 high tidal currents							Case 2 low tidal currents						
	Speed log (knot)							Speed log (knot)						
	Velocity error (m/s)							Velocity error (m/s)						
Range (m)	0.25	0.96	2.17	3.12	4.32	5.19	6.19	0.25	0.96	2.17	3.12	4.32	5.19	6.19
1.96	0.116	0.028	0.172	0.295	0.317	0.316	0.492	0.141	0.086	0.168	0.068	0.158	0.045	0.047
2.96	0.083	0.087	0.14	0.022	0.086	0.018	0.003	0.002	0.032	0.104	0.079	0.016	0.189	0.001
3.96	0.02	0.029	0.022	0.097	0.075	0.089	0.014	0.111	0.137	0.127	0.108	0.212	0.051	
4.96	0.068	0.1	0.057	0.071	0.119	0.083	0.05	0.064	0.053	0.161	0.006	0.013	0.068	0.014
5.96	0.025	0.029	0.129	0.101	0.173	0.018	0.036	0.104	0.06	0.007	0.007	0.065	0.021	0.122
6.96	0.055	0.161	0.021	0.114	0.136	0.384	0.063	0.025	0.097	0.01	0.176	0.05	0.126	0.104
7.96	0.051	0.262	0.335	0.033	0.065	0.057	0.093	0.312	0.12	0.1	0.104	0.044	0.099	0.032
8.96	0.036	0.009	0.478				0.083	0.118	0.011	0.043	0.047	0.019	0.175	0.164
9.96	0.203	0.212	0.402					0.258	0.08	0.162	0.167	0.054	0.277	0.043
10.96	0.222	0.031	0.585					0.255	0.145	0.148	0.051	0.205	0.03	0.089
11.96	0.193	0.395	0.115		0.043			0.051	0.13	0.104	0.075	0.234	0.093	0.115
12.96	0.019	0	0.298		0.241		0.582	0.047	0.003	0.172	0.061	0.29	0.193	0.075
13.96	0.231	0.025	0.047		0.56		0.251	0.172	0.061	0.197	0.155	0.01	0.097	0.197
14.96	0.133	0.029	0.542		0.122	0.473	0.198		0.122	0.006	0.075	0.112	0.018	0.055
15.96	0.301		0.374	0.811	0.869		0.011		0.168	0.126	0.013	0.08	0.094	
Mean for all records	0.173							0.099						
Max for all records	0.869							0.312						

B.2. Cross-shore measurements

Range (m)	Location A: depth -6 m TAW	Location B: depth -6.5 m TAW		Location C: depth -6.5 m TAW		
	Velocity error (m/s)					
	1h before HT	1h20 after H	1h after HT	1h17 after HT	1h05 after HT	1h15 after HT
1.96	0.052	0.155	0.057	0.118	0.054	0.087
2.96	0.014	0.184	0.136	0.05	0.201	0.122
3.96	0.118	0.135	0.007	0.126	0.112	0.026
4.96	0.003	0.058	0.194	0.144	0.154	0.026
5.96	0.048	0.047	0.168	0.197	0.119	0.007
6.96	0.313	0.086	0.193	0.1	0.071	0.032
7.96		0.089	0.022	0.062	0.356	0.205
8.96		0.42	0.12	0.17	0.051	0.036
9.96		0.294	0.129	0.208	0.042	0.183
10.96		0.05	0.083	0.09	0.072	0.123
11.96		0.003	0.295	0.112	0.571	0.115
12.96		0.377	0.087		0.109	0.033
13.96		0.287	0.244	0.172	0.154	0.058
14.96		0.164	0.243	0.209	0.057	0.026
15.96		0.525	0.184	0.173	0.557	0.29
Mean	0.163	0.192	0.141	0.129	0.135	0.091
Max	0.525	0.525	0.295	0.209	0.571	0.29

DEPARTMENT **MOBILITY & PUBLIC WORKS**
Flanders hydraulics Research

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