CREST
CLIMATE RESILIENT COAST

# Morphological analysis and decadal trends at Groenendijk, Mariakerke and De Haan until Summer 2019

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# 1 Abstract

Long-term (since 1983/1992) morphological trends and processes are described for the CREST project areas and, for comparison, also of the coast at De Haan (since 1981/1987). The coast at Mariakerke and at De Haan suffers long-term structural erosion. In both cases, the tidal flow channel found just off the beach tends to deepen and to shift landward. This makes the shoreface steeper and narrower, and is followed by more intense storm erosion of the beach. In De Haan, the 1992-1997 large-scale beach and nearshore nourishments effectively repaired the coast. The erosion rates of the upper shoreface and beach have significantly declined since then and no significant storm erosion occurred. However, an increased frequency of maintenance nourishments is now observed and it is remarked that this may reflect the end of the protective action of the shoreface nourishment and the renewed encroachment of the tidal channel on the coastal barrier. At and near Mariakerke, the successive nourishments reached the same protective effect. The longer-term evolution will also there be renewed encroachment of the tidal channel Kleine Rede. The shore at Groenendijk shows pluri-decadal growth. This is possible because the shoreface is wide and shallow. The seaward side of the shoreface is affected by mild, long-term erosion. This might eventually affect the beach at Groenendijk. However, nourishments are taking place at De Panne and Koksijde. A part of the supplied sand disappears offshore and may well contribute to temporary accretion of the shoreface at Groenendijk. Also, the shoreface-attached sandbank Broers Bank, situated 4 km westward, shows a long-term, slow migration eastward by 15 m/yr. The study location at Groenendijk probably benefits indirectly from the nourishments more to the west and natural supply from the offshore by way of the Broers Bank.

# 2 Outline and methods used

This report covers the contribution by Rik Houthuys in subtask A3.3.1, "Morphological analysis and sediment balance: identification of decadal morphological trends" of work package A3.3 "Morphological analysis and characterisation of forcing and response" of activity A3, "Improving the understanding of coastal processes: analysis of resilience capacity of the natural and built coastal system".

This is the final version. It is an update of an interim version of the report, containing survey data until Spring 2017, made for the use of the other contributing partners in Activity 3, so that they could position their observations in the longer-term morphological trends of the CREST project areas. This version is an update with survey data until Summer 2019. This version makes use of the insights gained in the subtask A3.3.3, "Assessment of data uncertainty". Margins for accuracy are added where possible and needed. The result tables contain values for the standard deviation on estimated values and trends, obtained from the regression calculation.

Geographical extent of the study

The Belgian coast is an almost rectilinear sand beach barrier at the south edge of the shallow southern Bight of the North Sea. It protects a 5 to 15 km wide, low-lying coastal plain against floods and high water. The tidal range is 4.0 to 4.5 m. The tidal amplitude varies according to the neap-spring cycle and decreases from west to east. All altitudes of maps and surveys used by the management of the coast, the Flemish Authorities' Coastal Division at Oostende, are referenced in TAW (Tweede Algemene Waterpassing, approximately low-low water level).

The project areas extend transversally from the seawall or summit of the sea fronting dunes to about 1.5 km seawards. The research areas are defined as follows:

Groenendijk West sections 44-53: stretch representative of a natural beach where Aeolian transport can act freely. In sections 49-51, the sediment exchange between the beach and the dunes is studied in the field by CREST project partners. The volume and trend update involves stretch 10 of Houthuys (2012) over a coastal length of 2475 m.

Mariakerke sections 98-108: part of the coast subject to a beach nourishment in 2013-2014. In section 103, field surveys are conducted by CREST project partners. The volume and trend update involves stretches 21, 22 and 23 of Houthuys (2012) over a coastal length of 3510m.

De Haan sections 151-155: the aim is to provide a comparison basis for Mariakerke in an area showing similar morphology and an earlier nearshore nourishment. The volume and trend update involves stretch 32 of Houthuys (2012) over a coastal length of 1006 m.

The morphology of the project areas is described in detail below. The present study looks at a few sections east and west of the partners' focus areas. They are an integral part of a larger-scale morphological system, whose evolution determines also what happens at a local scale. The larger-scale trends till 2011 are described in Houthuys (2012) and a sediment balance between 2000 and 2009 is found in Vandebroek et al. (2017). An update of the morphological trends using the same methodology covering the entire Belgian coast is currently being made by Flanders Hydraulics and Coastal Division and will be available around the transition 2019-2020. The updates in volumes and trends for that project are already used in this report. Sediment budgets and trends per zone also covering the entire coast are also available inside CREST in Delivery D3.3.1, of which this report can be considered as a part containing more detail on the project sites.

Overview of data

The data used are survey results put at the project's disposal by Coastal Division of the Flemish Authorities in text format files listing the measurement points by their X, Y, Z coordinates. These surveys are part of the routine monitoring of the Flemish coast. The intertidal beach, backshore and dunes or seawall are covered by an airborne LIDAR1 survey, at least once a year, since 2013 twice a year in spring ("voorjaar", "VJ") and autumn ("najaar", "NJ"), occasionally also just after a significant storm. The nearshore area to about 1.5 km from the dune foot or seawall is covered by singlebeam (SB) echosounding performed on a shallow vessel that goes back and forth on tracks perpendicular to the coast. The tracks have usually about 100 m separation. Singlebeam means that only lines of points underneath the vessel are measured. On the line, the points are closely spaced, about every 0.25 m. Occasionally, a specific area of interest is covered by multibeam (MB) echosounding. This method produces many point measurements in a swath following the navigation line. The lines are planned so that the survey area is completely covered by points. A dense cover by points is realized. Of this, a DEM with 1 m cell size is derived. Echosounding surveys are usually performed at least once a year for the complete Flemish coast, and in areas of specific interest, additional surveys may be carried out. Normally, the dates of the SB surveys are around the date of the spring LIDAR survey; however, due to limitations in vessel disponibility, the 2018 and 2019 were at the end of the spring and in the beginning of the summer, thus depending on the site 2 to 4 months after the corresponding LIDAR survey.

Related to the Mariakerke nourishment scheme and the test subtidal nourishment, terrestrial profiles are measured on the beach at higher frequency, almost monthly, since September 2015, by the Coastal Division. The profiles are used to check the continuity of proposed morphological processes.

Decadal trends are determined on observed volumes and on volumes corrected for sand nourishment. The correction makes use of volumes reported by the Coastal Division.

## 2.1 Analysis method

The method for the morphological analysis is described in Houthuys (2012) and can be summarized as follows:

Expand the time series of DEMs2 (2 x 2 m for the beach and 10 x 10 m for the shoreface). The data sets used are listed below.

Expand the volume time series per section and elevation slice and determine trends.

Expand the volume time series per stretch ("strook"), with both observed volumes and volumes corrected for nourishments, disposals or borrows, and determine "observed" and "corrected" trends.

Propose a link of the observed trend to natural and human-induced morphological processes based on an interpretation of the observed geomorphological changes. The analysis involved takes geographical changes of geomorphological features into account.

Note that different terms can be used to describe parts of the coast in function of elevation and exposure to tides and waves. Fig. 1 gives the formal definition of elevation slices, used when calculating volumes and volume differences, and in use in the monitoring practice by the Flemish authorities. It is important indeed that volumes are always calculated using the same methodology. When listing and comparing volumes in this analysis, the names in capitals in Fig. 1 are of application. The terms have been borrowed from morphology, where they are often used

1 LiDAR: Light Detection And Ranging, survey method of the terrain's altimetry using an active light source

2 DEM: digital elevation model, GIS data layer in grid format describing the terrain's elevation in square cells

according to their morphological meaning and the interaction with the forces acting on the morphology: shoreface = the subtidal, shallow area where waves deform when they approach the coast; foreshore = the intertidal part of the beach; backshore = the supratidal part of the beach, only affected by storm waves or under surge conditions. The boundaries of these units shift because the levels of low water etc. shift according to the tidal cycle, the hydrodynamic conditions, etc. When dealing with volume figures, there is a "DUNE" slice present even in seawall sections whenever a part of the beach exceeds altitude +6.89 m TAW, which is most often the case. However, when discussing the shapes and morphology of that section, it would be more appropriate to name that slice also "backshore" or "backshore berm" or "backshore platform", because this flat area in front of the seawall, without vegetation, is not perceived as a dune. The context makes clear how to interpret these terms.

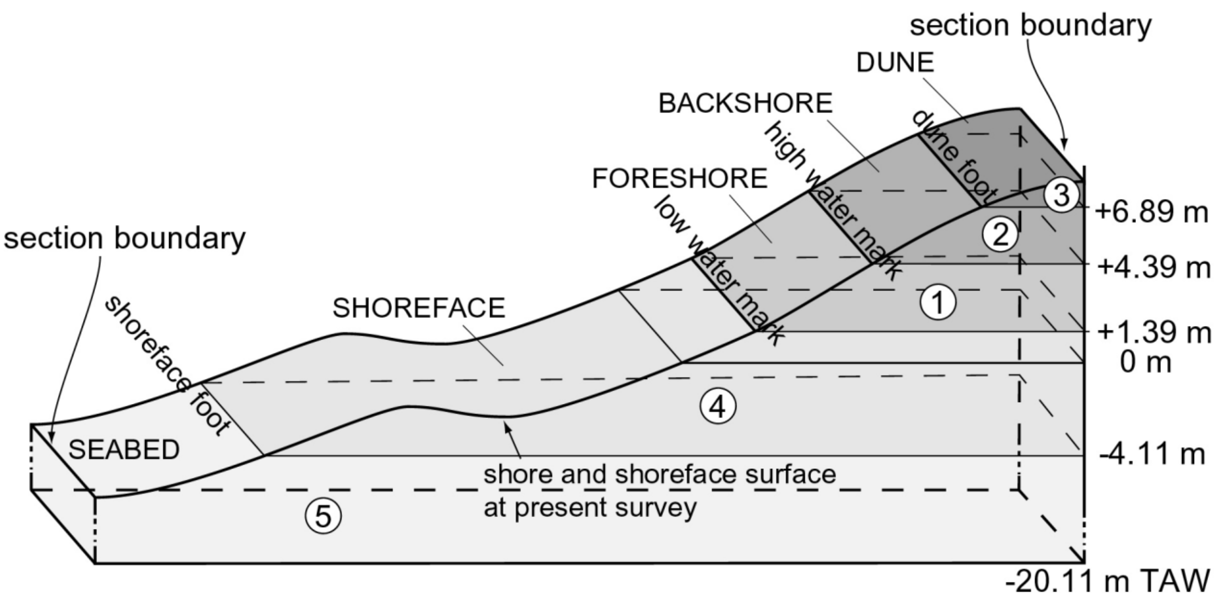



*Figure 1. Terminology used for the standard morphological processing of surveys at the Belgian coast. Note that the names in capitals are formal elevation slice denominations. The terms are often used also in their morphological meaning.*

## 3 Data sets used

The spatial coverage of the project sites is defined by the fixed boundaries of
Stretch 10, Oostduinkerke-Bad eastern part and Groenendijk-Bad, sections 44-53
Stretch 21, Raversijde-Oost, sections 98-102
Stretch 22, Mariakerke, sections 103-105
Stretch 23, Oostende-West (Wellingtonrenbaan), sections 106-108
Stretch 32, De Haan-Centrum, sections 151-155
Houthuys (2012) reports on all available surveys till 2011. The expansion for the CREST project areas makes use of the following surveys:

**Table 1. Overview of LiDAR surveys processed for this analysis. In italic: not yet processed or future flight missions.**

| Survey Period | Survey and DEM Code | Flight number | Date of Flight |
|---|---|---|---|
| **Spring 2012** | 2012 | 67 | 7-may-12 |
| **Spring 2013** | 2013_1 | 68 | 29-apr-13 |
| **December 2013 (after "Sinterklaas storm")** | 2013_3 | 69 | 10-dec-13 |
| **Spring 2014** | 2014_1 | 70 | 15-apr-14 |
| **Autumn 2014** | 2014_2 | 71 | 6-nov-14 |
| **Spring 2015** | 2015_1 | 72 | 17-may-15 |
| **Autumn 2015** | 2015_2 | 73 | 27-okt-15 |
| **Spring 2016** | 2016_1 | 74 | 10-apr-16 |
| **Autumn 2015** | 2016_2 | 75 | 14-dec-16 |
| **January 2017 (after "Dieter storm")** | 2017_0 | 76 | 17-jan-17 |
| **Spring 2017** | 2017_1 | 77 | 26-may-17 |
| **Autumn 2017** | 2017_2 | *78* | 6-nov-17 |
| **Spring 2018** | 2018_1 | 79 | 17-apr-18 |
| **Autumn 2018** | 2018_2 | 80 | 6-nov-18 |
| **Spring 2019** | 2019_1 | 81 | 20-apr-19 |

**Table 2. Overview of nearshore surveys processed for this analysis. Between brackets: survey cannot be combined to LiDAR survey because of large time lapse between survey dates; in bold: section area not completely covered by survey, cannot serve to compute volumes. SB: singlebeam survey, MB: multibeam survey, S: section.**

| Survey Code | Survey ("koppeling") | Average Survey Date | Area |
|---|---|---|---|
| **2012** | 37 | 24/05/2012 | SB complete coast S1-256 |
| **2013_1** | 38 | 25/06/2013 | SB complete coast S1-257 |
| **(2013_2)** | (39) | 16/08/2013 | MB Potje S4-33 and Wenduine S171-177 |
| **2014_1** | 40 | 7/05/2014 | SB complete coast S1-257 |
| **(2014_2)** | (41) | 24/09/2014 | MB Middelkerke – Oostende S91-115 **no complete coverage of section area at seaward side** |
| **(2015_0)** | (42) | 24/01/2015 | MB zone Bkb-Zb S183-196 **no complete coverage of section area at seaward side** |
| **2015_1** | 43 | 2/06/2015 | SB complete coast S1-266 |
| **(2015_2)** | (44) | 31/07/2015 | MB zone Mrk-Ost s. 89-111, Bkb s. 199-216, Knokke 225-250 **not completely covered** and Zwin 251-267 |
| **2016_1** | 45 | 4/05/2016 | SB Blankenberge-Zeebrugge s. 183-197 **not completely covered** |
| **2016_2** | 46 | 5/09/2016 | SB complete coast S. 1-266 |
| **2017_02** | 47 | 7/02/2017 | SB Oostduinkerke (S. 44-53), Mariakerke (S. 98-108), Oostende Oost (S. 122-123) and **Knokke S. 232-235, the latter area not completely covered** |

| | | | |
|---|---|---|---|
| **(2017_03)** | (48) | 15/03/2017 | SB Oostduinkerke (S. 44-53), Mariakerke (S. 98-108), Oostende Oost (S. 122-123) and Knokke (S. 232-237) |
| **(2017_04)** | (49) | 27/04/2017 | SB Oostduinkerke (S. 44-53), Mariakerke (S. 98-108), Oostende Oost (S. 122-123), Wenduine (S. 169-177) and Knokke (S. 232-237) |
| **2017_1** | 50 | 10/06/2017 | SB complete coast (S. 1-266) |
| **2017_2** | 51 | 17/10/2017 | SB Groenendijk 43-53, Mariakerke 97-109 |
| **2017_11** | 52 | 9/11/2017 | SB Groenendijk 43-53 |
| **2018_01** | 53 | 28/01/2018 | SB Mariakerke 97-109 |
| **(2018_1)** | 55 | 5/07/2018 | SB complete coast (S. 1-266) |
| **(2019_1)** | 57 | 20/06/2019 | SB complete coast (S. 1-266) |

Sand nourishments are carried out by Coastal Division who also collects volume data on the works. In Groenendijk, no sand nourishments take place. In the past, small-scale nourishments have been performed in the sections immediately east of the study area, between Leopoldplein and Kinderlaan at Nieuwpoort-Bad (Table 3).

**Table 3. Volumes applied to replenish a backshore berm in sections 54-56 just east of Groenendijk. LW: low water plane, here defined as the +1.39 m TAW horizontal plane. The volumes "part above/below LW" are used for the "correction" in the volume tables per stretch.**

| Year | Location | Sea sand trucked in (m³) | Scraped beach sand (m³) | Part above LW | Part below LW |
|---|---|---|---|---|---|
| **1994** | section 56 and 57 | 8900 | 0 | 3600 | 0 |
| **1995** | sections 54-56 | 0 | 9840 | 4900 | -4900 |
| **1996** | sections 54-56 | 7750 | 0 | 7800 | 0 |
| **1997** | sections 54-56 | 7250 | 0 | 7300 | 0 |
| **1998** | sections 54-56 | 7200 | 0 | 7200 | 0 |
| **1999** | sections 54-56 | 6241 | 0 | 6200 | 0 |
| **2000** | sections 54-56 | 5563 | 0 | 5600 | 0 |
| **2001** | sections 54-56 | 7132 | 0 | 7100 | 0 |
| **2002** | sections 54-56 | 4350 | 0 | 4400 | 0 |
| **2003** | sections 54-56 | 5148 | 0 | 5100 | 0 |
| **2004** | sections 54-56 | 5091 | 0 | 5100 | 0 |
| **2005** | sections 54-56 | 5040 | 0 | 5000 | 0 |
| **2006** | sections 54-56 | 4397 | 0 | 4400 | 0 |
| **2007** | sections 54-56 | 8377 | 0 | 8400 | 0 |
| **2008** | sections 54-56 | 4117 | 0 | 4100 | 0 |
| **2009** | sections 54-56 | 5398 | 0 | 5400 | 0 |
| **2010** | sections 54-56 | 5025 | 0 | 5000 | 0 |
| **2011** | sections 54-56 | 4800 | 0 | 4800 | 0 |
| **2012** | sections 54-56 | 3455 | 0 | 3500 | 0 |
| **2013** | no nourishment | | | | |
| **2014** | no nourishment | | | | |
| **2015** | no nourishment | | | | |
| **2016** | no nourishment | | | | |
| **2017** | no nourishment | | | | |

| | | | | | |
|---|---|---|---|---|---|
| **2018** | no nourishment | | | | |
| **2019** | no nourishment | | | | |

At Mariakerke and the neighbouring resorts, in the past, small-scale nourishments have been performed in order to create and maintain a backshore platform (Table 4). They involve sand supply at Raversijde-Oost, section 99 (Table 4), Raversijde-West and Oost (Table 5), Mariakerke (Table 6) and Oostende-West (Table 7). In 2013-2014, a large-scale nourishment scheme has been carried out at Mariakerke and Oostende-West (Table 8).

**Table 4. Volumes applied to replenish a backshore berm in section 99 at Raversijde-Oost. LW: low water plane, here defined as the +1.39 m TAW horizontal plane. The volumes "part above/below LW" are used for the "correction" in the volume tables per stretch. These nourishments were expanded over a larger area in 2006. (Table 5).**

| Year | Scraped beach sand | Sea sand trucked in | Part applied above LW | Part applied below LW |
|---|---|---|---|---|
| **1983** | | 3500 | 3500 | |
| **1987** | | 1500 | 1500 | |
| **1989** | | 1500 | 1500 | |
| **1993** | | 7000 | 7000 | |
| **1994** | | 7800 | 7800 | |
| **1995** | 2356 | | 1200 | -1200 |
| **1996** | | 1900 | 1900 | |
| **1997** | | 3150 | 3200 | |
| **1998** | | 3200 | 3200 | |
| **1999** | | 3086 | 3100 | |
| **2000** | | 3058 | 3100 | |
| **2001** | | 3038 | 3000 | |
| **2002** | | 2104 | 2100 | |
| **2003** | | 2538 | 2500 | |
| **2004** | | 2523 | 2500 | |
| **2005** | | 2525 | 2500 | |
| **2006** | | 2438 | 2400 | |

**Table 5. Volumes applied to replenish a backshore berm in sections 97-102 at Raversijde-West and Oost. The volumes in the two columns at right are the distribution applied in the tables per stretch used for the "correction". In 2014, a large-scale beach nourishment was carried out. An "efficiency" (= rate of sand supplied versus net increase of beach volume) of 85% is assumed.**

| Year | Location | Total volume sea sand trucked in (m³) | Part in section 97 | Part in sections 98-101 |
|---|---|---|---|---|
| **end 2006** | sections 97-101 | 45000 | 12300 | 32700 |
| **end 2007** | sections 97-101 | 30600 | 8400 | 22200 |
| **end 2008** | sections 97-100 | 37776 | 12700 | 25100 |
| **end 2009** | sections 97-100 | 68966 | 23100 | 45900 |
| **2010** | sections 97-100 | 26850 | 9000 | 17900 |
| **2011** | sections 97-100 | 17235 | 5800 | 11400 |
| **2012** | sections 97-101 | 17051 | 3100 | 14000 |
| **2013** | geen | | | |
| **2014** | sections 97-102 | 190904, at 85% "efficiency" | 35200 | 127100 |
| **2015** | no nourishment | | | |
| **2016** | no nourishment | | | |

| | | | | |
|---|---|---|---|---|
| **2017** | no nourishment | | | |
| **2018** | no nourishment | | | |
| **2019** | no nourishment | | | |

**Table 6. Volumes applied to replenish a backshore berm in sections 103-105 at Mariakerke. The volumes "part above/below LW" are used for the "correction" in the volume tables per stretch. These nourishments stopped in 2012.**

| Year | Location | Sea sand trucked in (m³) | Scraped beach sand (m³) | Volume imported in part above 1.39 m (m³) |
|---|---|---|---|---|
| **1988** | section 104 | 1178 | | 1200 |
| **1990** | sections 103 to 105 | 21200 | 13200 | 27800 |
| **1991** | sections 104 and 105 | 7000 | | 7000 |
| **1992** | sections 104 and 105 | 10700 | | 10700 |
| **1993** | sections 104 and 105 | 13000 | | 13000 |
| **1994** | sections 104 and 105 | 11500 | 9300 | 16200 |
| **1995** | sections 103 to 105 | 17327 | | 17300 |
| **1996** | sections 103 to 105 | 13000 | | 13000 |
| **1997** | sections 103 to 105 | 14050 | | 14100 |
| **1998** | sections 103 to 105 | 12900 | | 12900 |
| **1999** | sections 103 to 105 | 13199 | | 13200 |
| **2000** | sections 103 to 105 | 13032 | | 13000 |
| **2001** | sections 103 to 105 | 13954 | | 14000 |
| **2002** | sections 103 to 105 | 12338 | | 12300 |
| **2003** | sections 103 to 105 | 15590 | | 15600 |
| **2004** | sections 103 to 105 | 16057 | | 16100 |
| **2005** | sections 103 to 105 | 15963 | | 16000 |
| **2006** | sections 103 and 104 | 15000 | | 15000 |
| **2007** | | | | 0 |
| **2008** | sections 103 to 105* | 68700 | | 68700 |
| **2009** | sections 103 to 105** | 15400 | | 15400 |
| **2010** | sections 103 to 105 | 7100 | | 7100 |
| **2011** | sections 103 to 105 | 6500 | | 6500 |
| **2012** | sections 103 to 105 | 16000 | | 16000 |

**Table 7. Volumes applied to replenish a backshore berm in sections 106-108 at Oostende-West. The volumes "part above/below LW" are used for the "correction" in the volume tables per stretch. These nourishments stopped in 2012.**

| Year | Location | Trucked-in sea sand (m³) | Scraped beach sand (m³) | Supply in part above 1.39 m (m³) |
|---|---|---|---|---|
| **1983** | sections 106 and 107 | 17356 | | 17400 |
| **1985** | sections 106 and 107 | 12760 | | 12800 |
| **1987** | sections 106 and 107 | 6550 | | 6600 |
| **1988** | sections 105-107 | 7931 | | 7900 |
| **1989** | sections 106 and 107 | 7800 | 4100 | 9900 |
| **1990** | sections 106 and 107 | 9100 | 6000 | 12100 |
| **1991** | sections 106-108 | 5000 | | 5000 |
| **1992** | sections 106 and 107 | 6100 | | 6100 |
| **1993** | sections 106-108 | 15300 | | 15300 |
| **1994** | sections 106 and 107 | 12000 | | 12000 |

| | | | | |
|---|---|---|---|---|
| **1995** | sections 106 and 107 | 6431 | | 6400 |
| **1996** | sections 106-108 | 4500 | | 4500 |
| **1997** | sections 106 and 107 | 3100 | | 3100 |
| **1998** | sections 106 and 107 | 5100 | | 5100 |
| **1999** | sections 106 and 107 | 6257 | | 6300 |
| **2000** | sections 106 and 107 | 6010 | | 6000 |
| **2001** | sections 106 and 107 | 7030 | | 7000 |
| **2002** | sections 106 and 107 | 8065 | | 8100 |
| **2003** | sections 106 and 107 | 7119 | | 7100 |
| **2004** | sections 106 and 107 | 7527 | | 7500 |
| **2005** | sections 106 and 107 | 6456 | | 6500 |
| **2006** | sections 106-108 | 15000 | | 15000 |
| **2007** | section 108 | | 8000 | 4000 |
| **2008** | sections 106 t/m 108 | 47100 | | 47100 |
| **2009** | sections 106 t/m 108 | 10600 | | 10600 |
| **2010** | sections 107 and 108 | 21300 | | 21300 |
| **2011** | sections 106 and 107 | 6500 | | 6500 |
| **2012** | sections 106 and 107 | 16000 | | 16000 |
| **2013** | no nourishment | | | |
| **2014** | included in large-scale Mariakerke nourishment | | | Table 8 |
| **2015** | no nourishment | | | |
| **2016** | no nourishment | | | |
| **2017** | no nourishment | | | |
| **Before VJ2018** | large-scale nourishment in sections 105-109 | | | Table 8 |

**Table 8. Volumes involved in the subtidal (first line) and beach (second line) nourishment in sections 102-106(8) at Mariakerke. The columns with heading "S(ection) + number" are the distribution of the nourishment volumes applied per stretch and part above/below low water (i.e. the +1.39 m TAW plane). An "efficiency" (= rate of sand supplied versus net increase of nearshore and beach volume) of 90% and of 85% is assumed for the shoreface and the beach nourishment, respectively. A new beach replenishment in has been carried out in 2018, only on the backshore and foreshore part of the beach).**

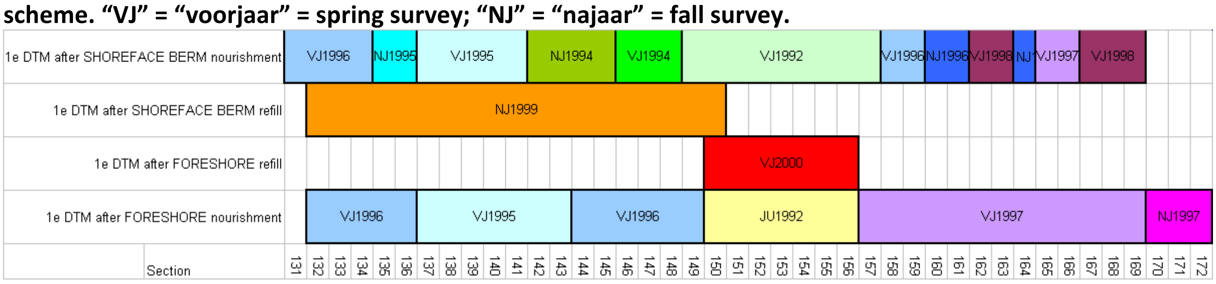
| Year | Location | Total supplied volume | s102, > 1.39 | S102, < 1.39 | S103-105, >1.39 | S103-105, <1.39 | S106-108, >1.39 | S106-108, <1.39 |
|---|---|---|---|---|---|---|---|---|
| **2014** | sections 102-108 | 303837, at 90% "efficiency" | | 7000 | | 182100 | | 84300 |
| **2014** | sections 102-106 | 681243, at 85% "efficiency" | 39000 | 19500 | 298000 | 148900 | 49300 | 24600 |
| **2018** | sections 105-109 | 315381, at 85% "efficiency" | | | 72600 | | 134000 | |

At De Haan, large-scale nourishments, both on the supratidal and intertidal beach as subtidal, have been carried out in 1991-1997. The beach at De Haan was re-nourished in 2000, and recently again in early 2016. The detail of the coastal defence scheme, the spatial and temporal phasing, and the subsequent morphological evolution is described in (Houthuys 2014). The volumes supplied are summarized in Tables 9 and 10.

**Table 9. Timing and amounts involved in the 1990s nourishment scheme at and near De Haan (Houthuys, 2012) and subsequent maintenance replenishments.**

| *Timing* | *Nourishment type* | *Location* | *Length (m)* | *Volume onboard (m³)* | *Volume increment between 2 surveys (m³)* | *Efficiency ship vs. in situ volume based on measurements at other fill projects* | *part assumed above LW* | *part assumed below LW* |
|---|---|---|---|---|---|---|---|---|
| **Feb-Jul 1991 & Dec91-Mar92** | underwater berm phase 1 | sections 148-157 | 2170 | 661787 | 556100 | 0.78 | | 1 |
| **Apr-May 1992** | beach phase 1 | sections 149-158 | 2200 | 794365 | 583200 | 0.85 | 0.8 | 0.2 |
| **Nov93-Sep94 & Oct-Dec95** | underwater berm phase 2a | sections 131-148 | 4043 | 649128 | 477600 | 0.78 | | 1 |
| **Nov94-Nov95** | beach phase 2a | sections 132-149 | 3250 | 1439964 | 1049200 | 0.85 | 0.9 | 0.1 |
| **Jan96-Feb98** | underwater berm phase 2b | sections 158-169 | 2400 | 471493 | 205700 | 0.78 | | 1 |
| **Mar-Oct96** | beach phase 2b | sections 157-172 | 3200 | 1002385 | 696400 | 0.85 | 0.9 | 0.1 |
| **Feb98-Aug99** | supplementary dumps at underwater berm | sections 132-150 | 4318 | 94989 | ? | 0.78 | | 1 |
| **May-Jun 2000** | maintenance beach replenishment | sections 150-156 | 1200 | 260493 | ? | 0.85 | 0.8 | 0.2 |
| **Before Spring 2016** | maintenance beach replenishment | sections 151-155 | 1006 | 85051 | - | 0.85 | 1 | 0 |
| **Around Spring 2019 (in stretch 32, sections 151-155, about half of the increase is situated before the VJ2019 survey)** | maintenance beach replenishment | Sections 150-158 | 1871 | 229735 | - | 0.85 | 1 | 0 |

**Table 10. Overview of timing and location of the several components in the 1990s De Haan coastal restoration scheme. "VJ" = "voorjaar" = spring survey; "NJ" = "najaar" = fall survey.**



# 4 Deliverables related to this report

This report. Annexes 1 (volume evolution tables per section and overview table with trends), 2 (tables per stretch), 3 (DEM map series), 4 MorphAn Introductory study profile series for sections 50 and 103 (not updated until 2019). Note: the TINs, the 2 x 2 m (emerged part) and 10 x 10 m (submerged part) DEM grids and DEM of difference (DoD) grids are no deliverables. Images of these using contrasting colours have been made and included in the DEM maps series PowerPoint files per project area, which are added in annex 3.

# 5 Description of the nearshore and beach morphology at the Spring 2017 and 2019 surveys

Unless stated otherwise, the observations and measures In the descriptive part of this section relate to coastal sections 50, 103 or 152 at the Spring 2017 survey, but checked and updated for Spring 2019 (the general morphology didn't change significantly). All map views shown in this report have north at a negative angle of 30° with the vertical edges of the picture (the views were rotated -30° in order to have the coastline horizontal).

## 5.1 Groenendijk

This location is characterized by a very mildly sloping intertidal beach (gradient of 0.010 m/m) continued in an even milder sloping upper shoreface (0.007) followed by a slightly steeper lower shoreface (0.012) between altitudes -2.0 and -3.0 m. The further part of the shoreface has a very low gradient of less than 0.002 (Fig. 2). This very gently sloping shallow nearshore area is part of a wide shore-connected ridge named "Broers Bank" (more to the west) and here locally "Den Oever". This most offshore part of the shoreface is not completely smooth. Some vague, large-scale but low-altitude bedforms appear to be present. Their low crests are more or less coast-parallel (Fig. 2), though the echosounding survey, performed on tracks 100 m apart, probably doesn't reveal the full detail of these features. There is no multibeam survey available of this part of the nearshore, but in 2013, a multibeam survey has been done of the area of the Potje channel, extending unto section 34 a few km west of Groenendijk. The part of the deeper shoreface, most corresponding to the surface described here at Groenendijk, is in sections 32 to 34 characterized by a surface-covering field of large subaquatic dunes (megaripples), with heights ranging between 0.2 and 0.6 m and crest distances of about 9 to 10 m (Fig. 3). The crests are perfectly coast-normal, suggesting they form under the influence of the coast-parallel tidal currents. Moreover, part of the survey area has sharp lee sides facing east while another part has blurred shapes showing decayed lee sides facing east and a superposed pattern of crisscrossing smaller bedforms. These areas probably represent partial areas surveyed at different dates. It can be deduced that the subaquatic dunes are active bed features during some stages of the tidal cycle (most probably at least during spring tides). They probably change shape (lee facing east during flood and west during ebb) during each phase of the tidal cycle. At other stages, or possibly as a response to times with strong wave action, the subaquatic dunes are flattened and blurred.

If the same morphology is present in the most seaward part of the nearshore at Groenendijk, the observed morphology of more or less coast-parallel, low-relief bedforms may be an artefact, possibly an interference phenomenon due to the parallel character of the subaquatic dunes and the survey lines.

A the foot of the slightly steeper middle part of the shoreface, around the depth contour of -3 m, the transition in surface morphology is sharp. The more landward, shallowest part of the shoreface, though barred, has a smooth surface appearance. This may reveal the greater importance of wave action on the bed.

The upper part of the shoreface shows three coast-parallel breaker bars of which the middle one, with crest at -0.75 m , is the most prominent and continuous feature (Figure 2). The separation between the bars decreases to the east, but the bars can be individualized all the way to Nieuwpoort harbour entrance, in spite of the fact that there, three long groins extend from the shoreface down to the uppermost of the three bars.

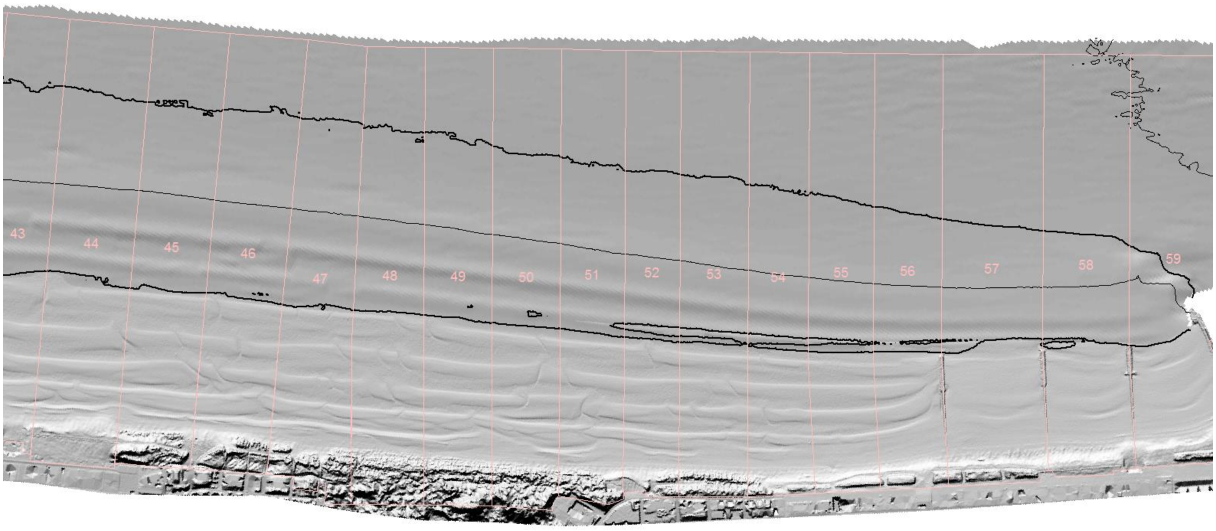



*Figure 2. Hillshade view of Spring 2017 DEM. Illuminated from NW, height exaggeration x5. Elevation contours of 0, -2, and -4 m added for reference. Section boundaries and numbers in pale pink. Nieuwpoort harbour entrance is at the right edge. Mind the different resolution of the submerged (top, cell size 10 m) and emerged (bottom, cell size 2m) parts of the survey DEMs.*

The intertidal part of the beach is characterized by a succession of up to 5 breaker bars. The crest area of the bars is smooth and flat, while the trough area shows a rougher surface (in fact, small ripples are present here, but the individual ripples are beyond the scale of the 2 x 2 m grid representation used). The bars are typically about 40 to 50 m wide and have altitudes of about 0.1 – 0.3 m with respect to the troughs. The steeper face invariably is at the landward side. The troughs are just a shade narrower than the bars they accompany. Pools may be present at low tide in the troughs, always at the deepest, most seaward part, near the steep face of a bar. The bars are coast-parallel and are often interrupted by small channels (rip channels). It has been noted at previous surveys that the number of bars, their alignment and even their presence may change at each survey. At some locations, it was noted that during storm, the bar morphology is wiped out and the beach has a smooth surface (it has not been documented whether this also occurred at Groenendijk). However, in most surveys, the bars are there in about the same configuration as here at the Spring 2017 survey. The bars form as a response to the interplay of tides and waves and are especially a morphological expression of the spatial and temporal asymmetry of offshore and onshore transport by waves (Wijnberg & Kroon, 2002; Masselink et al., 2006). The dynamics of these coast-parallel bars, their morphological behaviour and possible contribution to coastal reconstruction after storm is largely unknown. Higher-frequency surveys are needed to address this matter. This question is addressed in the 2018-2020 BELSPO research project "RS4MoDy"

(Remote Sensing for coastal MorphoDynamics). Intermediate results of that project showed the bars may move (most often landward) up to 1 m/day; but on the month timescale, based on land-surveyed profiles in 2017-2019, no clear movement pattern was recognized. Over 2000-2019, using the (twice-)yearly LIDAR surveys, periods of clear landward shift varied with "abrupt" returns to the pre-shift position. Of course, it is uncertain whether on this time scale, the "individuality" of the bars is preserved. Nevertheless, in the RS4ModY project, the current working hypothesis is that the bars alternate times of landward movement with rebuilding them at more or less their original location. In the subsequent analysis, the morphological evolution is treated at a smaller morphological scale, disregarding the beach bars.

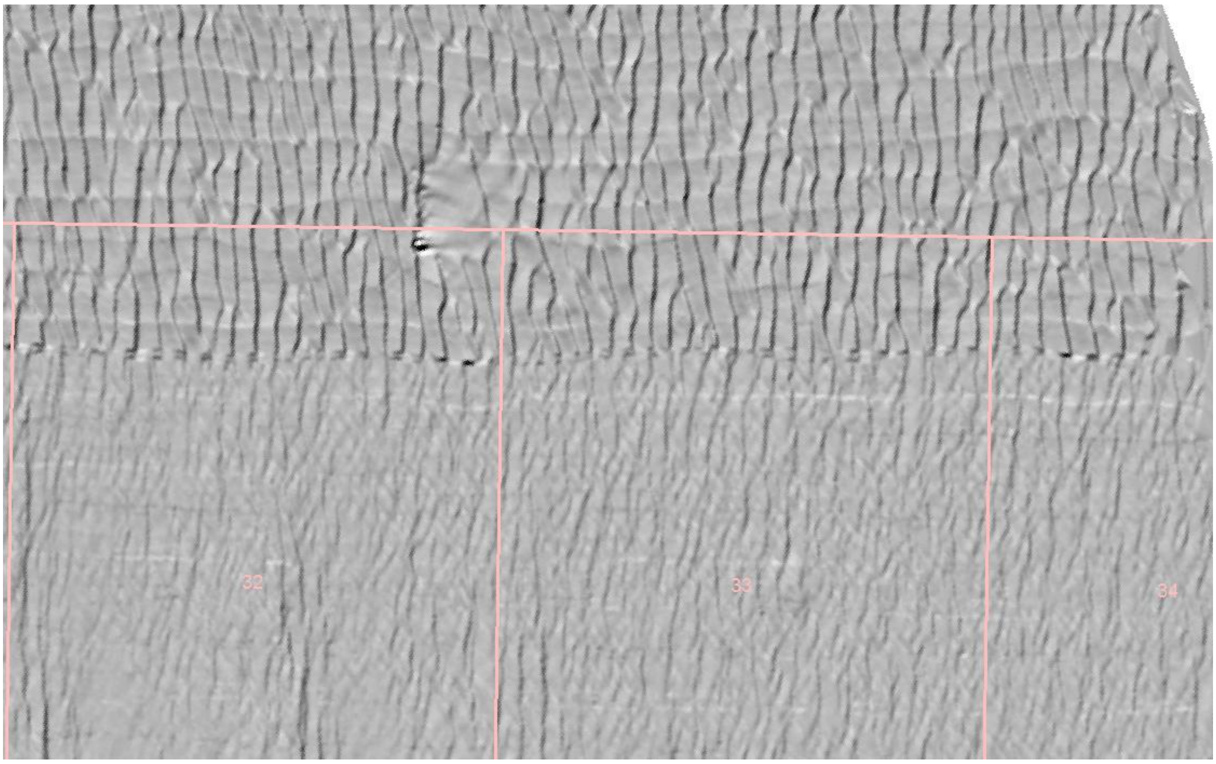



*Figure 3. Hillshade view (height exaggeration 5x) of subaquatic dunes in the seaward part of sections 32 to 34 (boundaries in pale pink) of 1 x 1 m DEM grid of multibeam survey 29 August and 8 October 2013. Possibly, the upper half of this view, showing sharp-crested subaquatic dunes, was made on one of these dates, and the lower half on the other. Coast-parallel marks are artefacts, i.e. stitches of the multibeam swaths. For scale, section 33 is 240 m wide.*

The dunes start at the elevation of +6.5 m. An 85 m wide, about 3 to 5 m high recent, embryonic dune ridge sits in front of the older dune massif, that reaches culminations of 25 m TAW at a distance of 65 m landward of the present-day dune front. The morphology of the dunes (i.e. the orientation of small partial summits and ridges, of the steepest lee side and in some cases the shape and orientation of blowout troughs and the related accretional dunes, though this latter feature can better be observed on DEM difference maps between successive surveys) indicates a major Aeolian sand supply from the west.

## 5.2 Mariakerke

This location has since many decades a seawall and groins extending offshore to the 0 m level mark. As the landmost part of the beach, a backshore platform is present: it is artificially created by small-scale nourishments that take place when needed, usually every few years. The top part of that platform is flat and is situated at about +7.5 to +7.7 m TAW. The width of the platform is about

25 to 50 m from the steep slope at the seaward side to the base of the exposed part of the seawall. On this plateau, Aeolian processes cause sand mounds and small blowouts to be formed. If these relief features become too prominent for easy and safe touristic use of the platform, it is flattened by bulldozing. The promenade on top of the seawall is at an elevation of +9 to +10 m TAW.
The backshore platform connects to the intertidal beach via a steep slope section. The slope is created at a gradient of 0.075 to 0.10 when nourishments take place. Waves tend to take away the base part of this slope section and cliffs often form under stormy conditions. Small to over 2 m high, vertical cliffs may then form. If this is the case, they are flattened for safety by bulldozers. In the Spring 2017 survey, the slope section connecting the backshore platform to the intertidal part of the beach had a concave profile with the steepest part situated near the brink of the platform with a slope gradient of about 0.2.
The intertidal part of the beach is about 200 m wide. Though this part of the beach profile has been raised by a large-scale beach nourishment in the first months of 2014, with a smooth, gently sloping surface, it has since then eroded and lowered so that the groins emerged from their sand cover and partition again the beach. Smooth-surface coast-parallel bars are now present in the sections between the groins (Fig. 3). Shallow troughs characterized by a locally rough (rippled) surface separate the bars. At the Spring 2017 and Spring 2019 surveys, the overall slope gradient of the intertidal beach was about 0.02.
The subtidal continuation of the beach , i.e. the shoreface, has a mildly sloping upper part (mean gradient of 0.017) situated at +1 to -2 m TAW, followed by a steeper lower part (gradient of 0.026) between -2 and -4 that becomes gradually milder (0.012) between -4 and -6 m TAW (the gradients are valid for the sections where no subaquatic nourishment has been carried out, like in sections 98 to 101). Near the transition of the upper, flatter part to the lower, steeper part of the shoreface sits a long coast-parallel breaker bar. It is about 20 to 30 m wide and 0.2 m high with respect to the trough at its landward side. It has a smooth surface. The trough at the landward side is partitioned in depressions. The Spring 2017 singlebeam survey suggests they are about 100 to 200 m long (Fig. 4; similar shape at Spring 2019) but the Autumn 2014 and Summer 2015 multibeam surveys show they are almost circular scour pits about 50 to 70 m long, systematically situated at the seaward tip of the groins. The groin tips probably promote local turbulence giving rise to the presence of scour depressions. They may be 0.5 – 0.7 m deep. The shoreface slope in sections 99-102 shows some depression marks with blocky objects inside them. The marks didn't shift position between the Autumn 2014 and Summer 2015 multibeam surveys. They are interpreted as stone loads (dumped astray or washed away from the groins' revetments?) and the scour marks around them.
Below -6.5 m TAW, the profile becomes almost flat, though a weak generalized slope of 0.0025 remains present, so that at a distance of 1.2 km from the low-water mark, depths of -8.5 m TAW are attained. This deepest part is at the centre of the coast-parallel tidal flow channel "Kleine Rede". The seabed of the "Kleine Rede" channel is generally smooth though small-scale bedform features are present. The 2017 nearshore survey based on singlebeam echosounding shows apparent low-relief coast-parallel ridge structures (see Fig. 4); they are considered an artefact due to interpolation between the survey tracks and the fact that small-scale bedforms are indeed present. The morphological structure of the seabed in this area is covered in more detail by the 1x1 m DEMs based on the Autumn 2014 and Summer 2015 multibeam surveys (extracts in Fig. 5 and 6). The 2015 multibeam survey extends seaward beyond the section boundaries. It shows a "Kleine Rede" channel floor which is in general smooth and featureless, but has also wide patches of small bedforms (also in the part of the "Kleine Rede" channel inside the section boundaries). The nature

of the bedforms is not clear. They are at most 5 to 15 cm high. They may represent decayed subaquatic current dunes or erosion-resistant harder irregular features. Low-relief reefs do occur in the area. They are created by the benthic species *Lanice conchilega* (English: sand mason; Dutch: schelpkokerworm) and *Owenia fusiformis* (e.g. INSHORE project (2010) and references therein). Apart from this general bed morphology, the 2014 multibeam survey also shows a few 0.3 – 0.4 m deep potholes in sections 104 and 108 and a couple of circular, about 75 m wide mounds (a 0.6 m high mound in section 103 and a 0.3 m high mound in section 109). The same features are present at the same location in the 2015 multibeam survey, and a couple of additional potholes in sections 101 and 104. The mounds must be related to hard objects (wrecks? Fishing gear?) or well-cemented biological reefs; the potholes most probably mark scour related to the presence of hard objects.

The Summer 2015 multibeam survey covered also an area seawards of the section boundaries. Half a kilometre offshore of the seaward section boundaries is the crest of a coast-parallel sandbank, "Stroombank", that has a "steep" landward slope (gradient of 0.06) covered by low (less than 5 cm high), coast-perpendicular, small subaquatic dunes, a smooth crest at -2.8 m TAW, and a "mild" seaward slope (gradient of 0.15) again covered by small subaquatic dunes but on this flank their crest is at an oblique angle to the sandbank's crest.

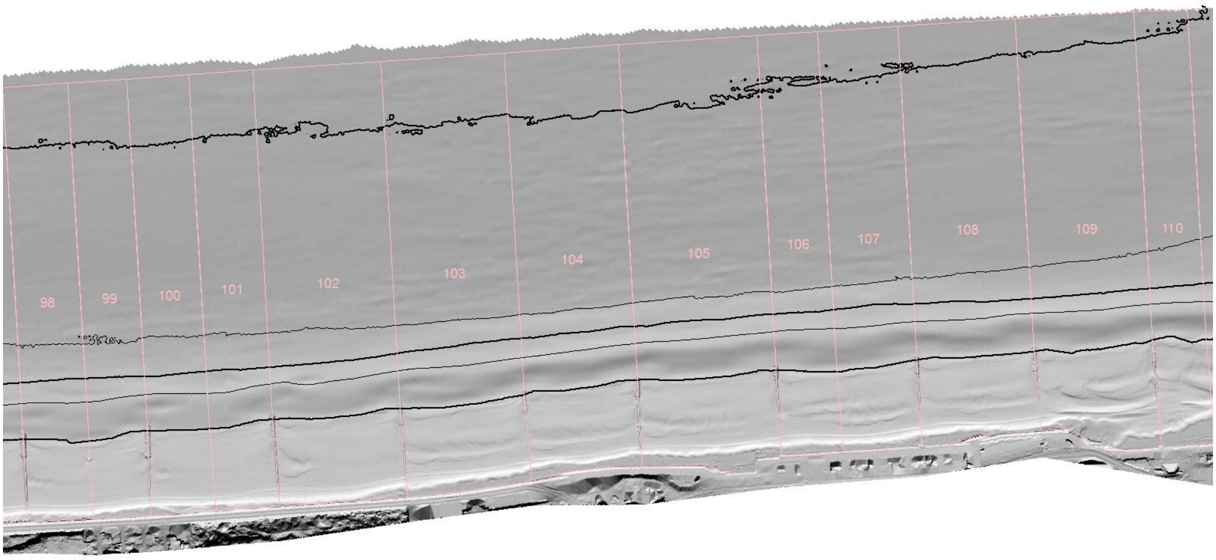



*Figure 4. Hillshade view of Spring 2017 DEM. Illuminated from NW, height exaggeration x5. Elevation contours of 0, -2, and -4 m added for reference. Section boundaries and numbers in pale pink. Mind the different resolution of the submerged (top, cell size 10 m) and emerged (bottom, cell size 2m) parts of the survey DEMs.*

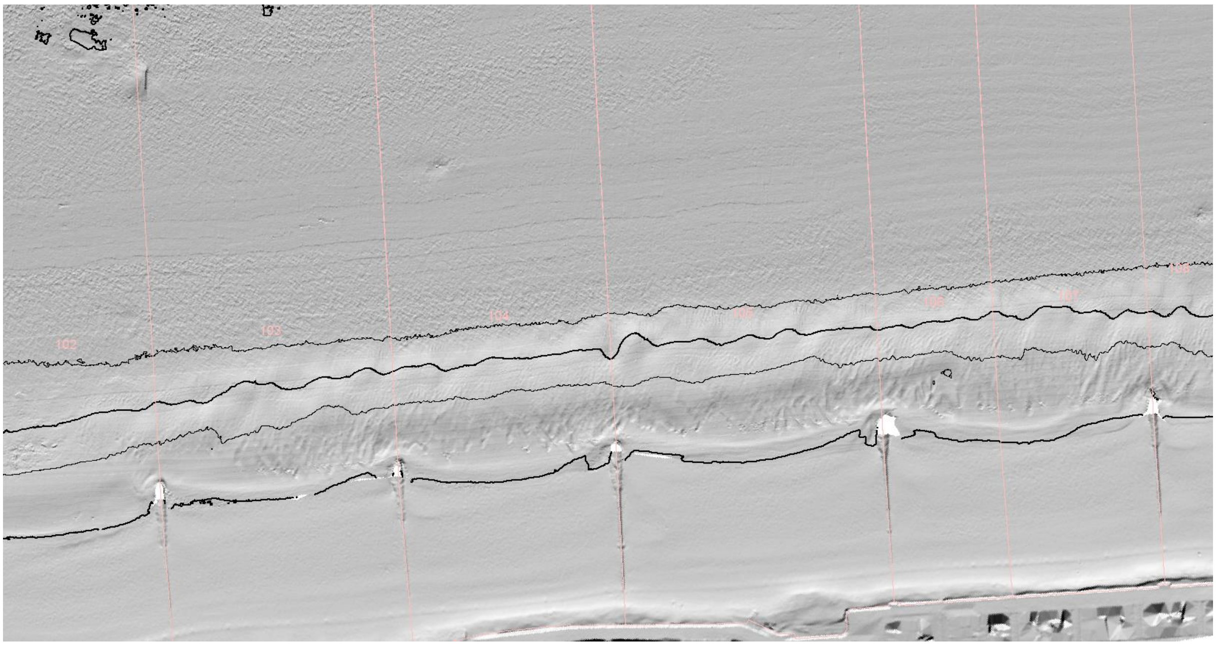


*Figure 5. Hillshade view (height exaggeration 5x) of the beach, shoreface and part of the seabed of sections 102 to 107 (boundaries in pale pink) of 1 x 1 m DEM grid of multibeam survey 15 September to 3 October 2014 (upper part of figure, with contour lines of 0, -2, -4, -6 and -8 m TAW) and of 2 x 2 m DEM grid of LiDaR survey 24 September 2014 (lower part). Immediately seaward of the groin tips, a shallow trough with dunes separates them from the bar, created by the 2014 underwater nourishment. Then follows the shoreface slope (brighter) and the flat part of the seabed. This shows 0.3 – 0.4 m deep potholes in sections 104 and 108 and a circular 0.6 m high mound at the boundary of sections 102 and 103. Some areas of the seabed are completely flat, other areas show low-relief bedforms. For scale, section 103 is 425 m wide.*

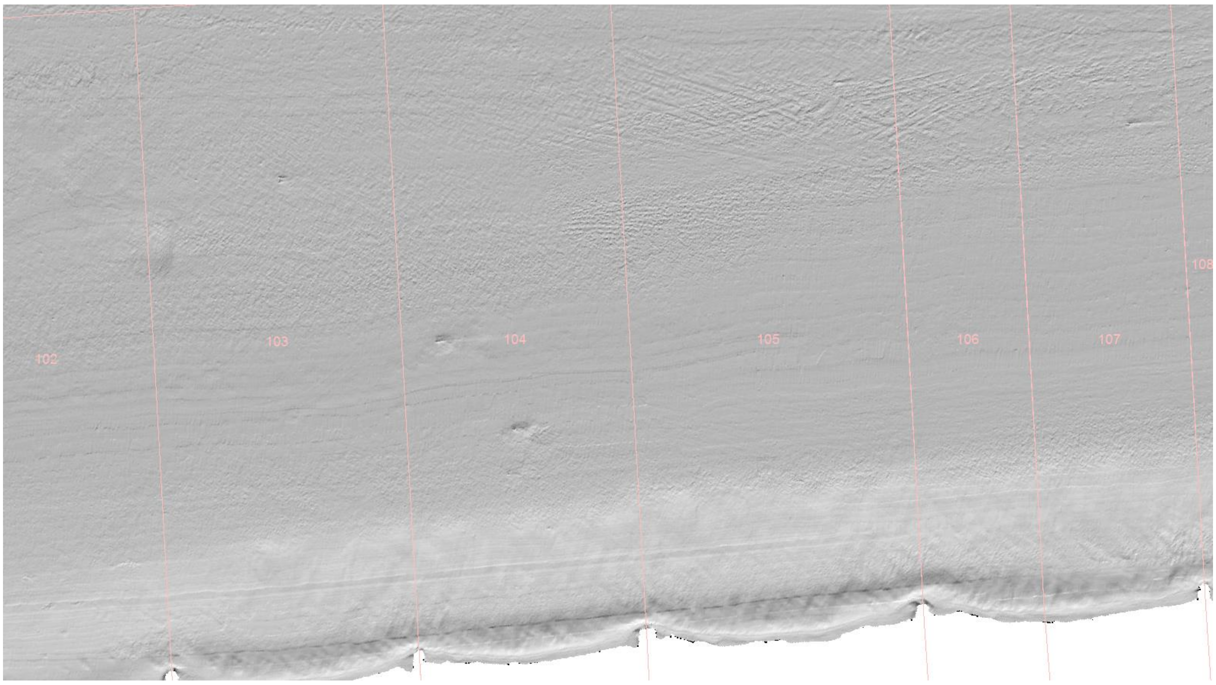


*Figure 6. Hillshade view (height exaggeration 5x) of the shoreface and seabed part of sections 102 to 107 (boundaries in pale pink) of 1 x 1 m DEM grid of multibeam survey 30 July to 6 August 2015. Near the bottom of this view, the tips of the groins separating the different sections are visible as blank indentations of the imaged area. Immediately seaward of them, the bar, fed by the 2014 underwater nourishment, can be seen, followed by the shoreface slope (brighter) and the flat part of the seabed. This shows a few 0.3 – 0.4 m deep potholes in section 104 and a circular 0.5 m high mound at the boundary of sections 102 and 103. Some areas of the seabed are completely flat, other areas show low-relief bedforms. For scale, section 103 is 425 m wide.*

In sections 103 to 107, a subaquatic nourishment was carried out in the first months of 2014 (amounts involved: see Table 8). This was a test to study its possible contribution to beach stability or recovery after storm. The nourishment created an expanded and somewhat seaward protruding version of the long subtidal bar present just above the shoreface slope break around the depth of -2 m. The shape of the enlarged breaker bar is well recognizable in the Autumn 2014 and Summer 2015 multibeam surveys (Fig. 5 and 6). Bedforms appear to cover large areas of both the nourished bar and the trough landward of it in the Autumn 2014 multibeam survey (Fig. 5). Smooth, long-crested bumps characterize the seaward slope of the bar. They are 0.1 – 0.3 m high, have crests slightly oblique to the coast-normal direction and separated by 70 – 80 m. They don't seem active bedforms. They may well be relics of the construction operation and represent adjoining shipload dumps. The top area of the bar, especially near its eastern tip, shows sharp-crested subaquatic dunes. They are 10 to 15 cm high and have 5 to 10 m wavelengths; their crests are about north-south and thus oblique to the coast-normal direction. They most probably represent active flood-current subaquatic dunes. The 75 m wide trough at the landward side of the bar also has bedforms, some of them 0.3 to 0.5 m high. They are interpreted as modulated (partly reversed by the ebb flow and also flattened by waves?) 3D-dunes mainly testifying to flood flow.
The bedforms described appear as smoothed or degenerated features in the Summer 2015 multibeam survey. They now show an overall diamond-shaped pattern. Those on the crest and seaward slope of the bar are only 2 – 3 cm high; those in the trough are 5 – 10 cm high. The bedforms are at this survey not in active tidal current transport mode, or are subject to wave action with a strong morphological impact. In this shallow area, waves will soon smoothen and flatten current dunes. The seaward slope of the submerged berm, around depths of -3 and -4 m TAW, is smooth. Beyond the base of the slope, around depths of -6 m TAW, the part of the seabed next to the submerged berm shows again a rough character of low-relief bedforms, only 2 to 5 cm high; this was also the case in the Autumn 2014 multibeam survey. These bedforms may either represent decayed subaquatic dunes or biological reefs. Though showing much less detail, the overall shape of the nourished submerged berm is still well recognizable in the Spring 2017 singlebeam echosounding survey, proving that it has a multiyear lifespan. However, at Spring-Summer 2019, the submerged berm is hardly distinguishable from the pre-existing upper shoreface morphology that was dominated by a large single breaker bar. However, in comparison with the pre-submerged morphology of Spring 2013, the complete beach-shoreface profile takes in a more seaward position, by some 30 to 50 m.

## 5.3 De Haan

The coast at the seaside resort of De Haan is studied as it underwent similar coastal defence works as those in Mariakerke. The works have been applied over two decades earlier. They were necessary after years of coastal erosion, culminating in severe erosion during the early 1990 storms. After the 28 February – 1 March 1990 storm, the seawall was at risk of collapse. Large-scale nourishments, both on the supratidal and intertidal beach, and on the subtidal part, have been carried out in 1991-1997. The beach at De Haan was re-nourished in 2000, and once again in early 2016. Aroudn the time of the Spring 2019 LIDAR survey, another re-nourishment was taking place; it was at about half of its completion and had already replenished sections 153 and 155. The detail of the coastal defence scheme (also summarized in Tables 9 and 10), the spatial and temporal phasing, and the subsequent morphological evolution is described in (Houthuys et al., 2014). The present analysis focuses on the evolution since 2008 to demonstrate the long-term effects of a submerged nourishment.

The site bears quite some morphological similarities to the coast at Mariakerke. The main difference is the lack of hard coastal protection infrastructures such as groins and seawalls. The resort of De Haan itself (sections 151-155) is, however, defended by a seawall. Its role in the morphological changes of the beach can be ignored, as the wall is almost completely buried beneath the backshore berm. Since the 1991-1997 coastal defence works, waves never attacked the seawall directly.

But overall, the morphological situation is quite similar to that at Mariakerke. The promenade on top of the seawall is at an elevation of +11 m TAW. There is a 40 m wide backshore platform at the altitude of about -7.5 m TAW, which after maintenance nourishment temporary extends over 60 m. This connects to the intertidal beach via a relatively steep slope section at a gradient of approximately 0.05. Maintenance nourishments are relatively rare, the first one had taken place in 2000, a second one in 2016 and a third one in 2019. Waves rather exceptionally reach this connection slope.

The intertidal part of the beach is about 200 m wide. The overall slope gradient of the intertidal beach is about 0.013. There are in most surveys three intertidal bars. At Spring 2019, there are only two of them but they are wider than previously.

The upper shoreface (part between +1 and -2 m TAW) has a mild slope (mean gradient of 0.011). Both based on the slope and the fact that two prominent breaker bars are present, this section is a worthy subtidal continuation of the foreshore. The two bars have a strikingly regular, coast-parallel profile (fig. 7 – largely still valid for Spring 2019). The lower shoreface is the transition slope towards the seabed. It is concave, i.e. it starts by a steeper part (gradient of 0.020) between -2 and -4 that becomes gradually milder (0.008) between -4 and -5 m TAW. The seabed continues to descend in the offshore direction, at very low angles (0.002). The Spring 2017 singlebeam survey suggests there is a field of coast-parallel, low-relief bedforms present on the seabed. Like in the other project areas, it is thought that this feature is an artefact of the survey technique and the interpolation to make the 10 x 10 m DEM. Nevertheless, some bedforms must be there, probably low or decayed, coast-normal subaquatic dunes. The seabed at De Haan Centrum is the locally very mild flank of the "Grote Rede" tidal channel. The seabed continues to descend to depths of about -7 to -8 m TAW. This area is part of the 3 km wide bottom of the "Grote Rede" tidal channel.

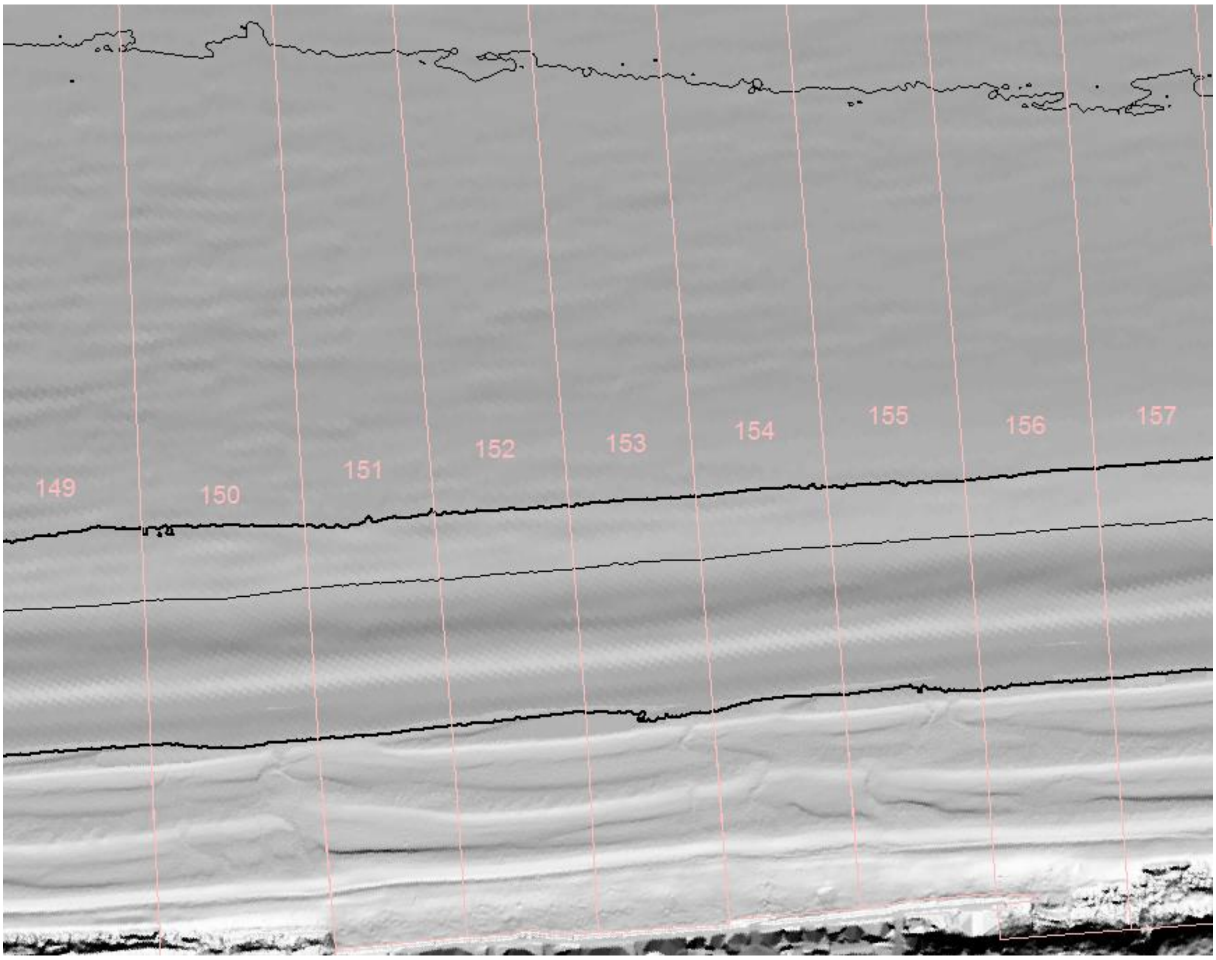



*Figure 7. Hillshade view (height exaggeration 5x) of the seawall (bottom), foreshore, shoreface and seabed part of sections 151 to 155 and a few neighbouring sections with dunes (boundaries in pale pink) of 2 x 2 m (dunes and foreshore) and 10 x 10 m (nearshore) DEM grid of Spring 2017 survey. The 0, -2, -4, -6 and -8 m contours have been added for topographic reference. For scale, section 153 is 190 m wide.*

# 6 Evolution of the nearshore and beach morphology from 1983/1992 until Spring 2019

## 6.1 Groenendijk

The coastal stretch encompassing sections 44 of "Oostduinkerke-Bad" to 53 of "Groenendijk-Bad" shows strong linear growth. The emerged part has an annual growth rate of 17 m³/m ($r^2$ = 0.979, StD on rate = 0.4 m³/m.yr, StD on Y's = 28 m³/m) (Fig. 8). The evolution can be split in two periods: stronger growth of 17.1 m³/m/yr ($r^2$ = 0.903) over 1983-2003 followed be a milder trend of 13.7 m³/m/yr ($r^2$ = 0.948) over 2003-2019. About half of the accretion occurs in the dune part, and the remainder is equally spread over the backshore and foreshore part. Altitude differences are thus highest at the dune foot and gradually decline towards the low-water mark, as the gradients also decline in this direction.

The submerged part shows a small accretional trend, +1.7 m³/m/yr over 1992-2019, but with a weak determination coefficient of 0.049. The annual variations are much more important than the growth over 27 years. Actually, the trend clearly changed around 2007: while it was +11 m³/m/yr in 1992-2007, over 2007-2019, the evolution is a mild erosion of -11 m³/m/yr, albeit with a weak determination coefficient value of 0.653, but the standard deviation on the trend being 2 m³/m/yr, it is significant.

The observed trends summarize a very slow, gradual erosion of the shoreface base. The submerged profile thus tends to become a very little bit steeper. The longer-term erosion of the shoreface base connects to an area west of Groenendijk where the erosion is more explicit. To the east, near the resort of Nieuwpoort, the shoreface base becomes almost stable over the time considered, though widespread very slow deepening is taking place anywhere on the submerged part.

The growth of the emerged part at Groenendijk results in a wider beach that allows the dunefront to grow. Its growth rate is among the highest observed at the Belgian shore.

In most of the sections of this stretch, exemplified here by section 50, a striking and continuing feature is the growth of a new dune ridge, lower than the existing dune front and situated next to it at the beach side, since 2000 (see DoD3 map series) and probably since around 1987, as is suggested by the volume time series of the dune part of the section (cfr. volume table of section 50). Actually, the rate of growth of the volume slice above +6.89 m is +7.9 m³/m/yr over the period 1987-2019 ($r^2$ = 0.982; StD on rate = 0.2 m³/m/yr). The foreshore and backshore part of that section shows a corresponding growth rate of +10.5 m³/m/yr ($r^2$ = 0.962; StD on rate = 0.3 m³/m/yr). The continuing accretion of the intertidal beach is the condition needed for the backshore and dune foot area to grow. The accretion of the foreshore is in turn a morphological response to the shoreface accretion. That process appears to show more variation in time. To start with, before 2007, a slight growth seemed to occur, of +7.5 m³/m/yr, but oscillations in volumes per survey were larger than the complete 15-yr period growth. Since 2009, there is a clear shoreface erosion trend of -9.5 m³/m/yr ($r^2$ = 0.559; StD on rate = 2.4 m³/m/yr). The map series shows the erosion is concentrated on the lower shoreface, where it amounts locally to over 0.5 m deepening since 2000. Section 50 is located in the middle of a naturally accreting coastal stretch. It is, together with the resort of Oostduinkerke, located east and thus downdrift of a small "promontory" in section 37 ("Sint-André"). This configuration possibly favours natural accretion. Verwaest et al. (2019) forward the hypothesis that actually, the shoreface connected submerged ridge “Broers Bank” present about 4 km west of the site, acts as a transport path for offshore sand towards the shore. Large subaquatic dunes are present on that ridge. It also shows a clear trend of eastward movement, of the order or about 15 m/yr.

Little can be said about the role of the subtidal and intertidal bars. They seem to move from survey to survey, but there is no clear line in the changes. Sometimes, a westwards shift, sometimes an eastwards shift seems to occur. Also the shape and orientation of the bars' long axis with respect to the coastal direction show variations. The frequency of the surveys is too low to allow clear deductions about possible bar movements to be made. Actually, it is also possible that they are relatively stable during some time and then at a storm event, are wiped out. The December 2013 survey, made 10 days after the "Sinterklaas storm", reveals a beach poor in bars, with a smoothed, aligned morphology. These observations have also been made in the framework of a Belspo funded research project, “RS4MoDy” (2018-2020). Here, high time frequency profile series are available. They clearly show days- to months-long periods of landward movement of the bars. But on a longer time scale, much uncertainty arises over the bar identity and it is much more difficult to do observations of any clear movement.

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3 DoD: DEM of Difference (elevation difference map)

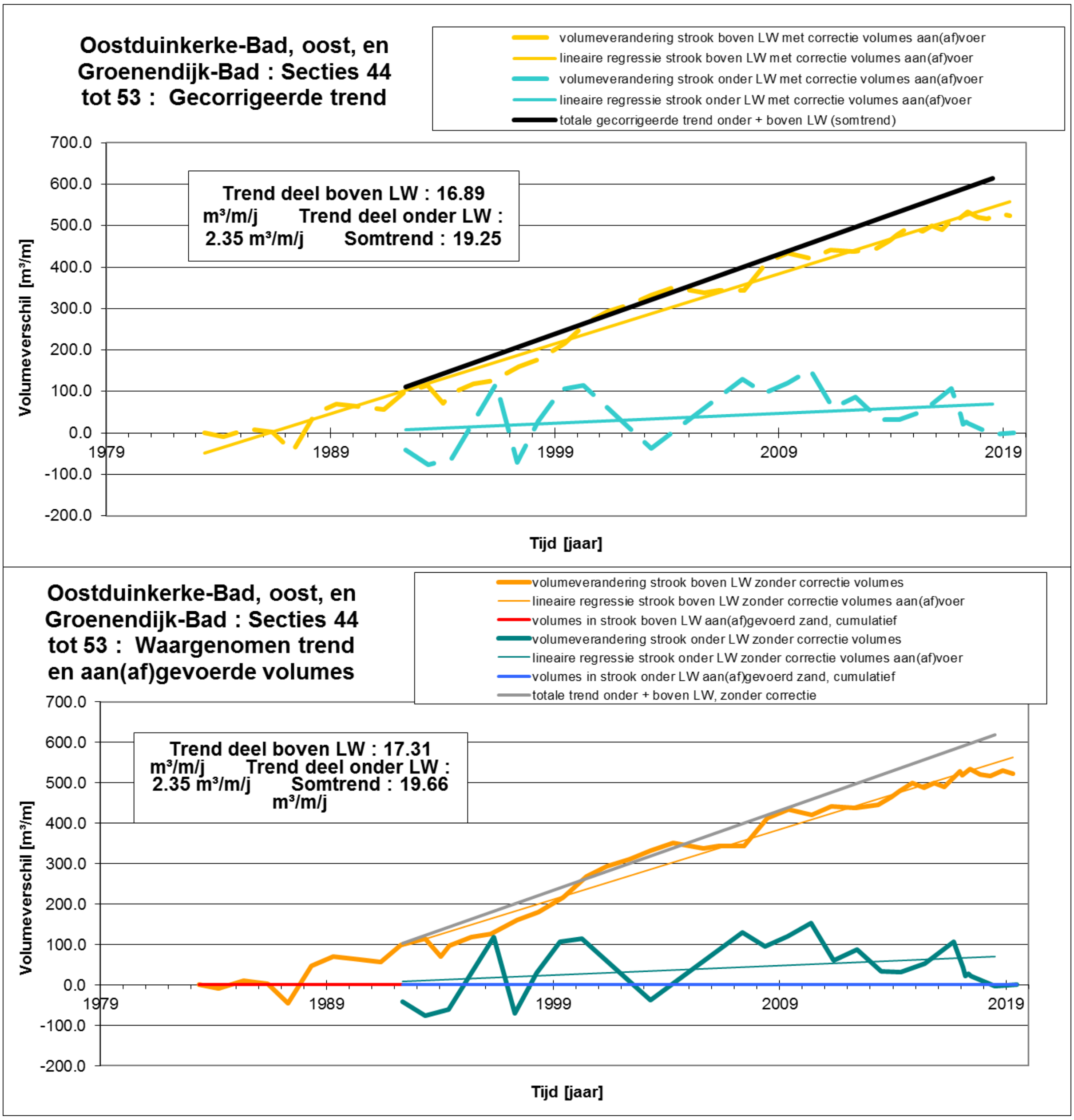


*Figure 8. Decadal evolution and recent trends in coastal stretch n° 10 (Oostduinkerke-Oost and Groenendijk-Bad).*

Also the subtidal bars change shape (mostly amplitude, i.e. elevation difference of crest minus trough) and position. The crest lines occur at successive surveys at varying distances from the coastline, but they appear to fluctuate around a central, mean position. It is not clear whether the bars migrate back and forth, or they are destroyed and rebuilt at slightly varying positions.

The long-term (2000 – 2019) elevation difference of the shoreface does show a resultant pattern. The upper, barred part of the shoreface only shows shifts in bar crest location but the mean location and altitude of that part of the shoreface hasn't changed. The lower part (the steeper slope and the flatter, ripple-covered part seaward of it) shows erosion. The degree of erosion decreases from the sections west of section 50, where locally at the base of the "steep" part 0.8 to 0.9 m of erosion occurs, in the direction of Nieuwpoort, where three long groins and the harbour dams fixate the coastline. The most seaward part (with the small subaquatic dunes) seems to have remained largely stable though widespread minor erosion seems gradually to take over. The erosional lower part of the shoreface may raise some concern. However, nourishments are taking place at De Panne and Koksijde. The matter that is disappearing offshore of these nourishments may well be carried along by the flood current and contribute to temporary accretion of the shoreface at Groenendijk. This location would then benefit indirectly from the nourishments more to the west. In the absence of nourishments west of Groenendijk, long-term slow erosion could well be the natural trend. Moreover, if the shoreface connected ridge Broer Bank continues to migrate eastward, it will significantly feed the shoreface at Groenendijk in the decades to come.

## 6.2 Mariakerke

The coastal stretches 21 (Raversijde-Oost, sections 98-102), 22 (Mariakerke, sections 103-105) and 23 (Oostende-West, sections 106-108) have been receiving nourished sand since around 1990. The amounts trucked or shipped in were drastically upscaled since 2006. When the supplied amounts are subtracted from the observed time series of volumes, an approximation of the "natural" or "autonomous" trend is reconstructed. This shows clear erosion: the emerged part has a trend of -2 ($r^2$ = 0.595, StD on trend = 0.3), -10 ($r^2$ = 0.968, StD on trend = 0.3) and -10 $m^3/m/yr$ ($r^2$ = 0.942; StD on trend = 0.4) over the 1983-2017 period in stretches 21, 22 and 23, respectively. The submerged part of the stretches show a long-term (1992-2017) stable reconstructed volume evolution, though large fluctuations in reconstructed volume occur.

The observed volume trend is accretion, but the time graphs of volume difference clearly show that all accretion is due to nourishments. In fact, the emerged part repeats erosion phases between the several nourishments. After the large 2014 nourishment and until Autumn 2017, stretch 21 eroded by -5, stretch 22 by -18, and stretch 23 by -11 $m^3/m/yr$. The intensity of erosion was stronger in the first year after the nourishment, afterwards, the rate decreases. Maintenance nourishments are carried out well in advance of the complete loss of sand of the previous replenishment.

A maintenance nourishment took place early in 2018, before the Spring 2018 LIDAR survey. It involved the supply of 315,381 $m^3$ of sand and was applied in sections 105-109 by pressure pumping. This method usually induces a net volume increase by about 85% of the supplied volumes. Using a linear distribution over the sections involved, 72,600 $m^3$ would have been supplied in stretch 22 and 134,000 $m^3$ in stretch 23 (Table 8). The intervention created a wider supratidal beach and only affected the part above the low-water mark. Like expected, relatively intense erosion occurred in the first year after the intervention. Between Spring 2018 and Spring 2019, the erosion rates were -8 (+/- 0.9) $m^3/m/yr$ in stretch 21, -37 (+/- 7) $m^3/m/yr$ in stretch 22, and -51 (+/- 6) $m^3/m/yr$ in stretch 23. The volumes of the replenishment were so big that more of the nourished sand is still in place than has been removed by erosion. Much of the sand is redistributed over the neighbouring beaches and the upper shoreface. The net observed evolution is beach growth that is completely due to the successive replenishments. The nearshore part, especially the upper shoreface, tends to show accretion: it clearly catches sand eroded from the foreshore.

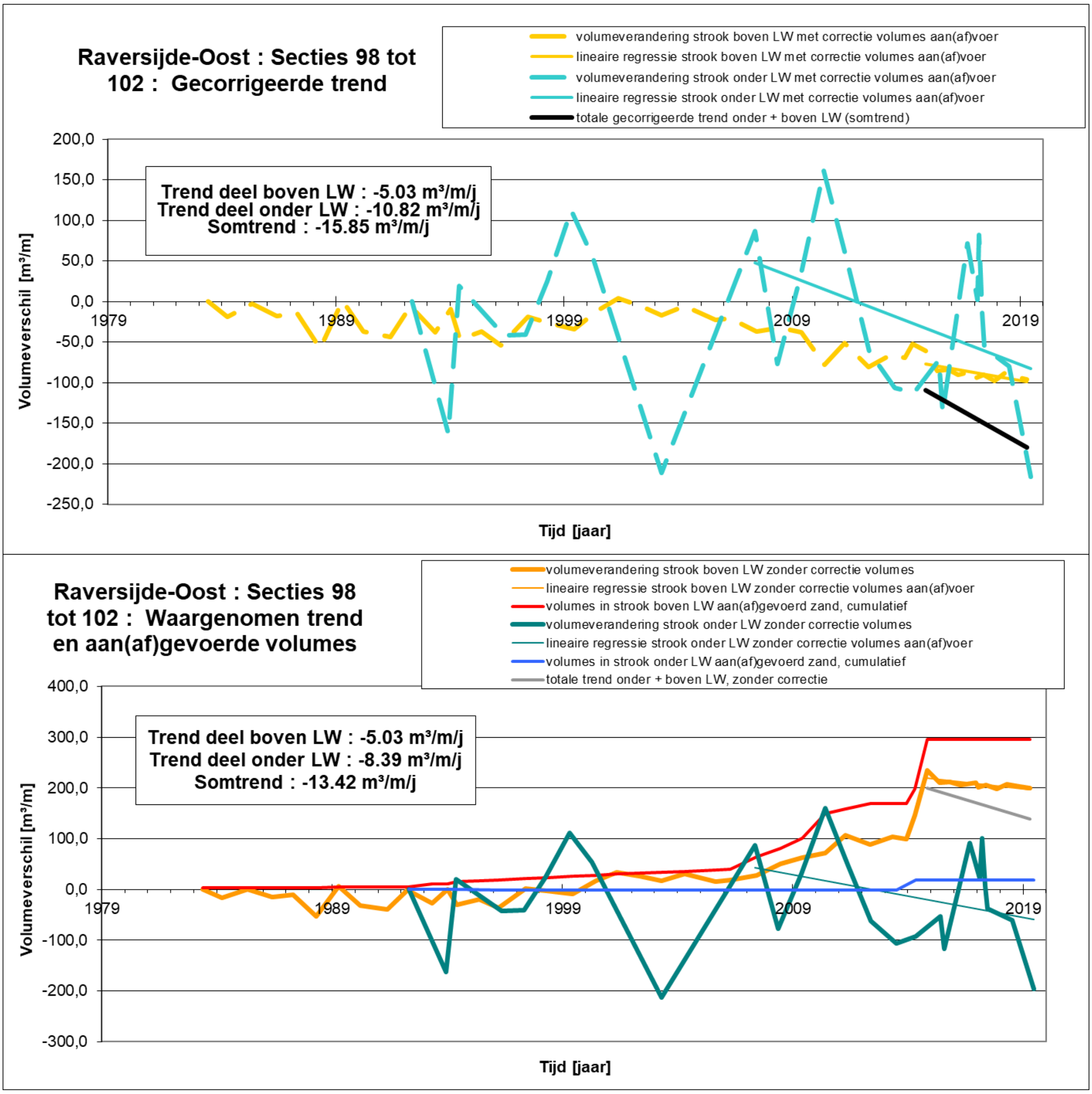


*Figure 9. Decadal evolution and recent trends in coastal stretch n° 21 (Raversijde-Oost).*

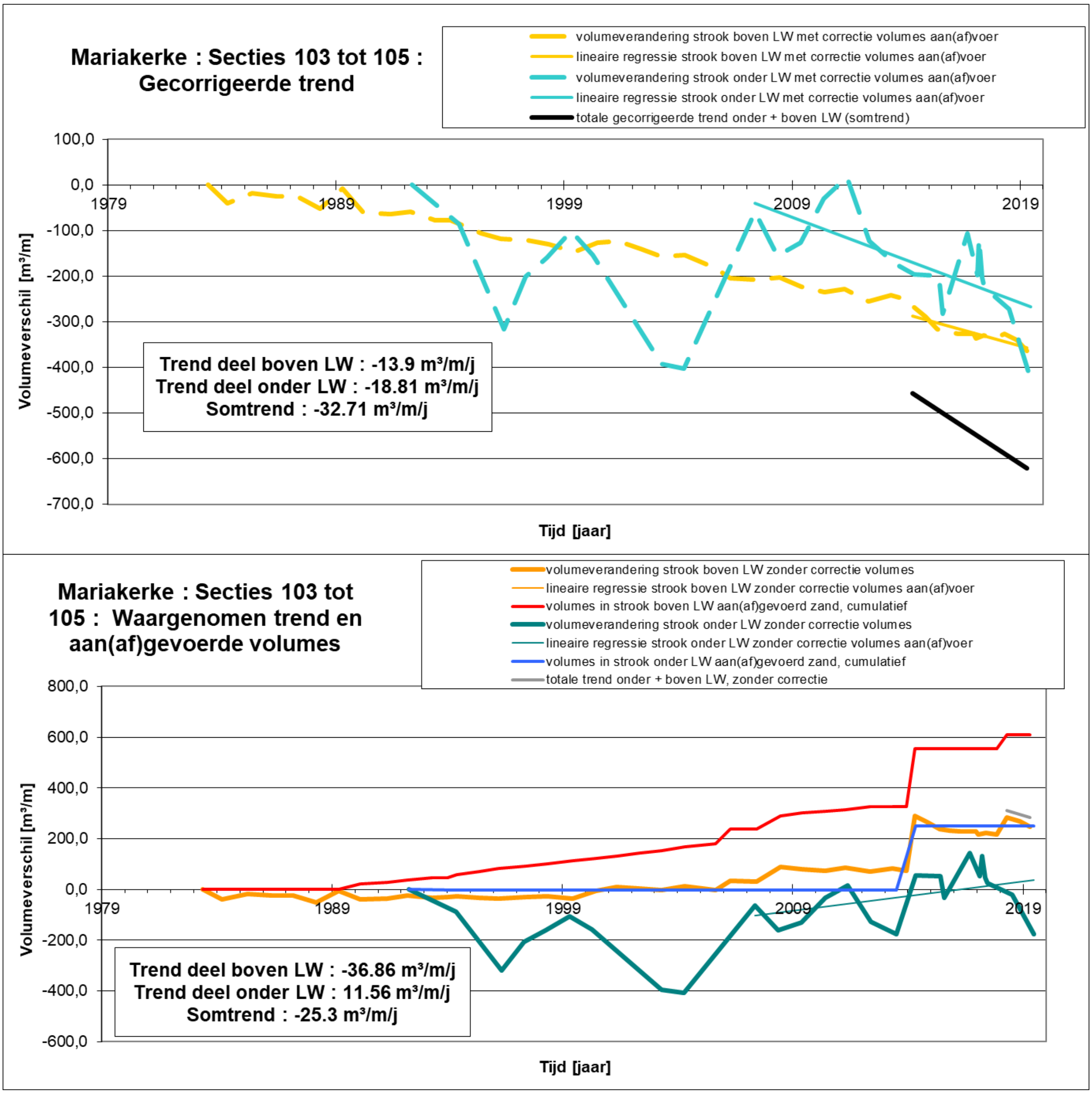


*Figure 10. Decadal evolution and recent trends in coastal stretch n° 22 (Mariakerke).*

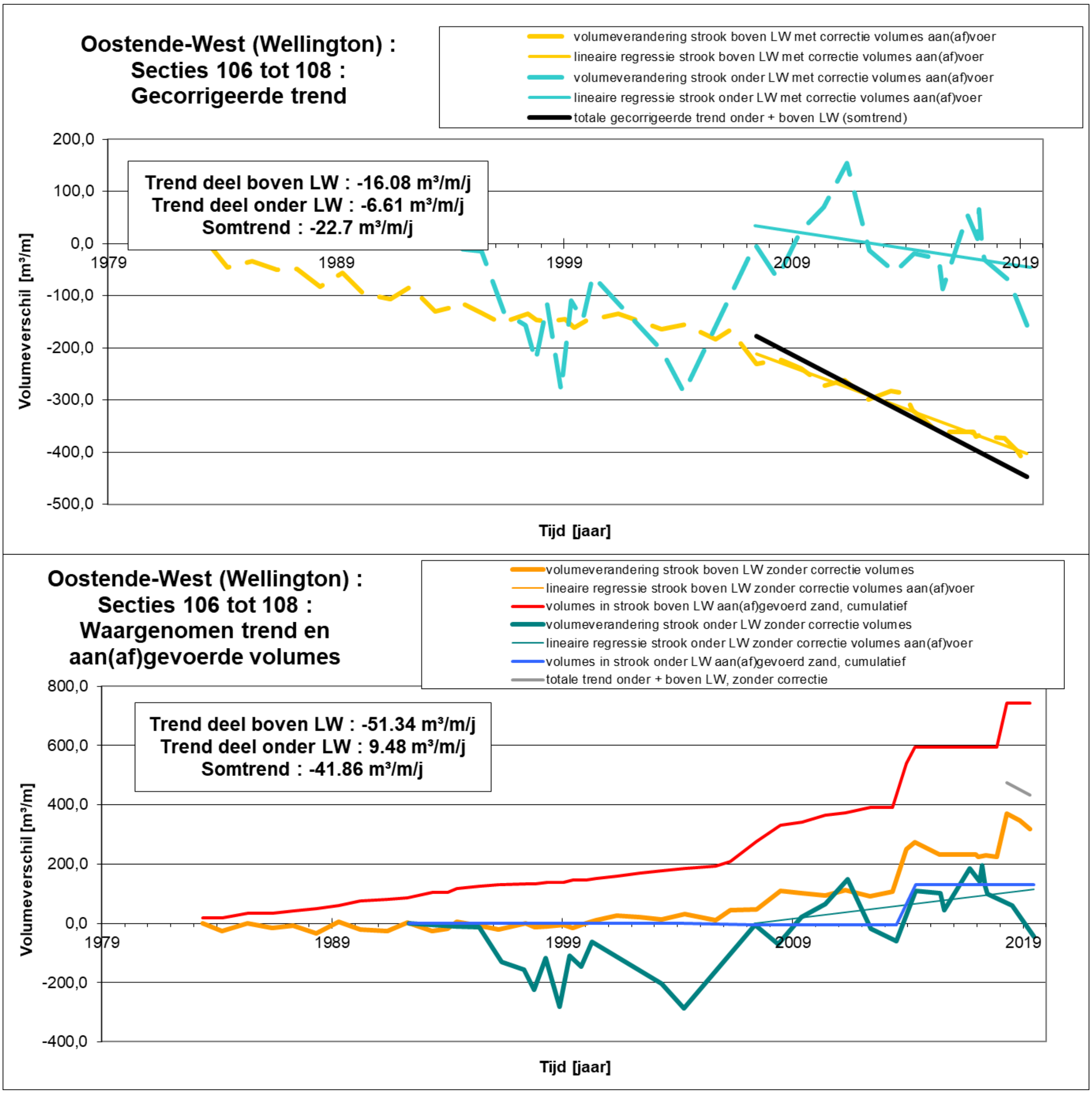


*Figure 11. Decadal evolution and recent trends in coastal stretch n° 23 (Oostende-West).*

The DoD map series reveals large spatial differences in accretion and erosion in the submerged part.

In general (meaning here in the sections outside 103-108 where in 2014 the submerged berm nourishment was carried out), the upper shoreface (+1 to -2 m TAW) tends to accrete, especially since 2012. In these sections, the long breaker bar at around -2 m TAW clearly "benefited" from the small scale beach scrapings and backshore nourishments in the sections concerned and probably also when such nourishments took place in neighbouring sections. The efforts to nourish the backshore area were amplified in 2007 and even more in 2010. Another boost was provided by the 2013-2014 large-scale beach nourishment in Mariakerke and east of it, and the 2014 underwater nourishment in Mariakerke. As a result, the mildly sloping upper part of the shoreface shows accretion of 0.5 m and more, locally over 1.0 m.

The lower shoreface, and especially the top of the slope immediately adjoining the upper shoreface, show erosion that started in 2011. Actually, such erosion also used to characterize this area at stages before 2011, but the net trend was often set back following beach replenishments. The erosion process can be understood as an emanation of the natural dynamics of the "Kleine Rede" flow channel, that tends to encroach on the coast. The natural supply of sand eroded from the nourished parts of the beaches at Middelkerke, Raversijde and Mariakerke effectively counteract the natural dynamics of the flow channel. The resulting present-day evolution is a yo-yo dynamics of alternating, natural flow erosion related to the tidal flow in the "Kleine Rede" and supply from the backshore and foreshore following beach nourishments. Even so, at Raversijde, the lower shoreface, and in particular the upper part of the slope immediately below the upper shoreface, is now lower than in 2000 by about 0.5 to locally over 1.0 m (see 2019-2000 DoD map in the Mariakerke map series slide show).

Since 2012, a 350 m wide strip-shaped area situated at depths of about -7 m, tended to accrete. The vertical amounts were modest, between 0 and 0.3 m. Much of the accretion was lost between Spring 2018 and Spring 2019. This strip is nevertheless a structural accretion feature that not only is found in the stretches of the project area, but also farther to the west and east. Farther offshore, at around -8 m depth, a similar strip showing moderate erosion is found. The accumulated erosion of this strip surpasses the accumulated sedimentation in the first strip. Though difficult to establish, the variations of these strips in time may show the influence of beach nourishment, that temporarily reverses or checks the observed evolution. When zooming out, the accretion strip at around -7 m appears to be attached to the Nieuwpoort dredge slurry dump site, situated in sections 72 to 82 at Westende. Houthuys (2012) detected that dumping operations there affect a wide area on the seabed east of it. The evolution also shows sediment advection from the west, i.e. by the flood current. The erosive strip at depths of around -8 m is at the centre of the "Kleine Rede" flow channel. It shows a (very mild) erosive trend. It can be inferred that sediment, derived from the beach and advected into the flow channel, will not settle there but will be cleared away by the tidal currents. Though mild in vertical magnitude (up to around 0.5 m since 2000), the erosion trend is very coherent from survey to survey and we must conclude that deepening of the Kleine Rede tidal channel is a natural trend likely to proceed in the future.

The 2013-2014 large-scale beach nourishment started in the east and proceeded westward. At the December 2013 survey, sections 109, 108 and 107 were already carried out; the subsequent Spring 2014 survey shows the nourishment was finished in sections 106, 105, 104, 103 and part of 102. Finally, between Spring and Autumn 2014, also the foreshore of sections 97 to 102 was raised, but with smaller amounts involved (the foreshore was raised by about 0.5 – 0.75 m). In the part affecting sections 102-109, the profile applied was constant over the nourishment scheme: a 30 m wide platform was created at altitude +7.5 m TAW, adjacent to the seawall. A relatively steep slope of about 0.04 gradient connected this platform to the intertidal part of the beach, which was given a slope of 0.02, the same gradient as the one existing before, but the nourishment raised the profile by about 1.75 m. Towards the lower connection to the pre-existing profile, the lower part of the foreshore was given a slope of 0.03. The connection was situated in the subtidal part, at about a depth of -1 m TAW. This means that the beach nourishment also raised the upper part of the shoreface, on average by about 1.25 m. The nourishment filled here a pre-existing trough so that no steeper gradient was needed to connect it to the existing profile.

The construction of the submerged berm in sections 103-107 affected a coast-parallel, strip-shaped subtidal area situated 75 to 175 m off the connection point just mentioned. It raised the upper part of the slope present in the lower shoreface by about 1 to 1.5 m and the shape of the sand fill mimicked (or was by natural processes remodelled to) a subtidal bar. The Spring 2014

survey clearly shows it as the continuation of the main subtidal bar, present in all the surrounding sections of this part of the coast, just off the seaward tip of the groins, but here as a bulkier bar lodged in a protruding position.
The morphological evolution of the nourishment was, apart from the volume tables and DoD map series, also studied on the profile series for 2012-2017 in section 103 made in the Introductory Study for MorphAn Vlaanderen (Houthuys, 2018).
Between Spring 2014 and Spring 2019 (Autumn 2017 for the dune and intertidal beach part in the sections where in early 2018 a maintenance replenishment has been carried out), the trends listed in Table 11 are observed. All sections show moderate growth of the dune slice and moderate to strong erosion of the backshore and foreshore slice. Section 103 is the most strongly affected by foreshore erosion. The map series shows this is because it is situated at the western end of the nourished area, and thus most exposed to the coastal processes that much of the time involve longshore transport from west to east. The neighbouring sections benefit during the first years after the 2014 nourishment from erosion in the eroding nourished area. The effect didn't extend beyond one section west and east of the beach nourishment, and it was temporary.

**Table 11. Linear volume trend between Spring 2014 and Spring 2019 (*Autumn 2017) in m³/m/yr (with standard error of trend (+-) followed by coefficient of determination) for sections 102-109.**

| Section | Dune slice (backshore platform) | Backshore + Foreshore slice | Shoreface slice | Seabed slice |
|---|---|---|---|---|
| **102** | **+6.87** (+-0.6; 0.949) | -3.66 (+-5.3; 0.064) | +6.47 (+-6.2; 0.119) | -5.48 (+-17.2; 0.013) |
| **103** | +2.62 (+-1.0; 0.402) | **-26.13** (+-4.2; 0.795) | -15.00 (+-3.8; 0.665) | -14.67 (+-16.8; 0.087) |
| **104** | +2.31* (+-1.0; 0.435) | -13.36* (+-3.3; 0.699) | -7.46 (+-3.8; 0.322) | -21.58 (+-15.7; 0.190) |
| **105** | +3.18* (+-0.6; 0.629) | -14.34* (+-3.8; 0.667) | -3.63 (+-4.5; 0.075) | -27.28 (+-14.1; 0.319) |
| **106** | +2.73* (+-1.0; 0.519) | -9.95* (+-2.7; 0.654) | +3.50 (+-3.3; 0.123) | -30.69 (+-13.6; 0.389) |
| **107** | +1.03* (+-1.1; 0.109) | **-19.89*** (+-4.8; 0.712) | -1.02 (+-3.9; 0.009) | -30.44 (+-12.6; 0.423) |
| **108** | **+3.35*** (+-0.8; 0.728) | -11.84* (+-3.3; 0.645) | +16.83 (+-4.0; 0.684) | -20.87 (+-13.6; 0.228) |
| **109** | +1.64* (+-0.3; 0.274) | **-21.59*** (+-3.2; 0.867) | **+16.04** (+-2.8; 0.867) | -24.44 (+-12.7; 0.425) |

The largest erosion was observed in the first year after the nourishment scheme.
The shoreface trend is often not significant as it agglomerates a mostly accretional upper shoreface and erosional lower shoreface. The sea bed part inside the survey section suffers strong erosion. This is a new phenomenon. Before 2009, this part was stable or locally accretional. The change in trend may be related to the construction of the new harbour dams at Oostende, about 2 km east of the project area. They protrude up to 500 m from the alignment of the seawall. They thus significantly affect the tidal currents. Future monitoring will more clearly outline if this is the effect at play.
The morphological response differed according to the location inside the 2014 nourishment scheme. Let's first see how this is expressed in **profile** view, such as documented for section 103 (MorphAn Introductory Study).
In the first year, the backshore platform accreted in wide areas by up to 0.5 m. This is thought to be the result of Aeolian growth. The exposed fetch on the beach had indeed increased. Because the municipality maintains a flat backshore platform by bulldozing the excess towards the connection slope to the foreshore, the Spring 2015 survey shows the platform is a few decimetres

lower, but up to 25 m wider in the seaward direction. At the Autumn 2016 survey, a trench appears at the foot of the seawall. This has been dug by the municipality to intercept Aeolian transport so that the promenade on the seawall doesn't get cluttered. The January 2017 survey shows the connection slope was attacked; witnesses reported cliff formation during storm Dieter (see also Montreuil et al., 2018). The slope receded about 5 m and was much steeper after the storm. The steep slope is degenerated (milder) at the Spring 2017 survey. Part of that change is also the result of breaking the cliffs by bulldozing.

Erosion of the foreshore started immediately after the nourishment works and was equally spread over the nourished area, i.e., the profile lowered in its totality (the backshore platform remained more or less stable). In the Autumn 2015 survey, a first beach bar shape appeared in the upper part of the foreshore. This shape disappeared at the Spring 2016 survey, which again showed a smooth foreshore. At the Autumn 2016 survey, several poorly developed bars were visible in the foreshore profile. They were gone at the January 2017 survey, which was carried out after the Dieter storm. The Spring 2017 survey took place after a prolonged quiet period. Two pronounced bars were then present, again situated in the upper part of the foreshore, near the high-water mark. The shape of the profile didn't change much until Autumn 2017, the last survey before a relatively important re-nourishment. It can be concluded that erosion affected the complete surface of the nourished foreshore. The development of the beach bars confirms the general idea about them: they are generated under waves but only in the mild wave regime; storm waves wipe them out. The volume evolution graph of section 103 shows that the intensity of the erosion was highest in the first year after the nourishment and then gradually diminished.

Let's now look at the **spatial** expression of the morphological evolution after the nourishment, such as best documented by the DoD view series with base Spring 2014.

In the first year after the submerged berm construction, its crest moved 50 m shoreward, thereby shallowing by 0.5 m. The seaward slope of the berm lost only 0.1 to 0.2 m of sediment. This movement continued into the Autumn 2016 survey: the crest was even 0.5 m shallower and another 50 m more shoreward. Between Autumn 2016 and Spring 2017, there was a general but modest erosion.

Already in the interval time between Spring and Autumn 2014, the complete foreshore length of the nourishment was lowered, especially in the upper 2/3 of the profile, by 0.2 to 0.4 m. The western end of the nourished area was most affected, but all replenished sections showed similar lowering. A coast-parallel strip around the low-water mark, covering the transition of the foreshore to the upper shoreface, accreted by 0 to over 0.3 m. This area benefited from the erosion higher in the profile, but the accretion area was smaller than the foreshore erosion area. Clearly, there was already a net loss in the offshore direction. It is possible that also some transport to neighbouring sections occurred. The sections 97-102 at Raversijde, west of the large Mariakerke nourishment, were subject to a smaller-scale nourishment between Spring and Autumn 2014; these works obscured a possible natural advection from the Mariakerke area. The sections east of the Mariakerke beach nourishment (Groot Strand at Oostende) showed no accretion. The submerged berm had erosion by 0.3 to 0.7 m at its seaward slope; locally even more than 1 m where bumpy bedforms were first present. This last effect may be an artefact: the elevation difference map involved a singlebeam survey, Spring 2014, and a multibeam survey, Autumn 2014. Most likely, the troughs between the bumps on the seaward berm slope were already present at the creation due to spatially uneven dump operations. There was no accretion area on the shoreface updrift or downdrift of the nourished submerged berm. Also, no diffuse accretion of the seabed was observed4. The crest of the berm moved onshore and accreted by about 0.5 – 0.6 m. This is seen as a clear illustration of the coast-building action of the quiet waves during the summer. Under the reserve made in the footnote, it appears that a net loss occurred of the Mariakerke shoreface erosion in the first half year after the nourishment.

The dynamics described for the first half year, continued in the second half year. The Spring 2015 survey showed an upper 2/3 of the foreshore that was 0.3 – 0.7 m lower than at Spring 2014, and even locally up to 1.5 m, at the edge of the backshore platform at its western tip in section 102. Apart from more intense lowering at the transition slope from foreshore to backshore platform, the erosion was spread evenly. The accretion strip around and just below the low-water mark now showed growth of 0.3 – 0.8 m. Small areas inside sections 102 and 109, near the low-water mark, also accreted by about the same amount. Both areas appeared to act as a first sink, but as they were smaller than the eroded area, net loss of the nourishment occurred. The morphodynamics described for the submerged berm in the first half year after nourishment, continued. The Spring 2015 – Spring 2014 elevation difference maps shows localized accretion on the lower shoreface slope in sections 102 and 108, testifying to cross-shore transport. The crest of the bar continued to move onshore and accrete, and also adjoining, localized areas east and west of the nourishment showed some accretion, this time testifying to longshore transport. The seabed at the base of the submerged berm had a narrow, about 50 m wide, strip with accretion between 0 and 0.3 m. The further seabed showed widespread accretion of the order of 5 cm. This is smaller than the error on the measurement, but it may be an indication of accretion thus revealing a (temporary) sink of matter eroded from the nourishment area.

The morphodynamics observed in the first year after the nourishment continued to proceed, but at much reduced intensities, in the two subsequent years. This is partly due to interference with other small-scale nourishments that had been carried out in neighbouring parts of the coast. It may also evoke the fact that the coastline approaches an equilibrium position in function of all the nourishments carried out locally and further updrift and downdrift, and also near the new extended harbour dam at Oostende (section 116).

The early 2018 maintenance nourishment in sections 105-109 locally set back the morphology to a state close to the 2014 situation. The consequent evolution will probably follow the same story as explained above. Actually, the first year after the maintenance nourishment showed a decrease by 89,500 m³ from the backshore and foreshore of sections 104-108, i.e. around 43% of the estimated nourishment increase of 206,600 m³.

To summarize the morphodynamics of the Mariakerke subaerial and submerged early 2014 nourishment scheme, the loss at the beach could at the Spring 2017 survey be estimated at about 40% of the increase measured at the nourishment. The intertidal erosion affected the upper 2/3 of the foreshore profile. The backshore platform was unscathed and even showed a small expansion at the top of the slope to the foreshore. This is probably the morphological expression of Aeolian accretion on the platform followed by levelling and bulldozing works. No lateral benefit

4 It was noted during this analysis that the surveys of the type "multibeam" produce DEMs that appear to be 0.1 to 0.2 m lower than DEMs based on singlebeam echosounding. This was detected when making time series of elevation and elevation difference maps: the data points based on multibeam survey result in "low" outliers in the time series. This effect has been studied in cooperation with Coastal Division. The results are reported in the separate CREST report concerning the accuracy and processing of bathymetric surveys. The calculation of volumes for MB surveys has been carried out using simulated SB surveys, like described in that report.

could be documented in the sections west and east of the beach nourishment. The seabed and shoreface showed still the same volume as that observed at Spring 2014. But that observation is a lump figure. The seaward flank of the submerged berm is in 2019 about between 0.5 and 1.5 m lower than at Spring 2014, the berm crest moved onshore and represents a significant strip-like accretion by about 0.75 to over 1 m on the upper shoreface. All observations taken together, it can be put forward that the submerged nourishment acted in a beneficiary way for the beach nourishment scheme as it helped to reinforce the upper shoreface, which in turn will help to reduce foreshore erosion. The 2018 maintenance nourishment further increased the sand volume in the coastal barrier, in spite of 43% loss in the first year after its completion. The coastal barrier is stronger now than ever before in the observation period. A new trend seems to affect the Kleine Rede channel bed, though. Since about 2009, and possibly under the influence of the new harbour dams then constructed at Oostende, it deepens at a structural, coherent rate. It is now 0.3-0.5 m lower than in 2009.

## 6.3 De Haan

The evolution till 2011 was studied by Houthuys (2014). In the first months after the 1991 construction of the subtidal berm, sand was immediately removed from the top of the berm to the upper shoreface trough between the berm and the low-water mark, which indicated wave transport, but sand was also redistributed in a longshore direction west and east of the nourishment site. After the first morphological adaptations, most of the nourished sand remained in the nearshore area and was thus – theoretically – available for building up the shore by the natural processes.

It was demonstrated that the shoreface nourishments also gave rise a short-lived seabed accretion, at the shoreface foot near the nourishment site, while shoreface nourishments at neighbouring sites were going on.

After the first nourishment leg (1992), focused on De Haan-centre, beach erosion rates had almost dropped to half the corrected rates before 1992.

The evolution well after the soft nourishment scheme in and around De Haan (2000-2011), was characterised by even milder erosion rates. The beach erosion was now only one quarter of its corrected rate before 1992. The upper shoreface even continued to grow. As this “mild” evolution was far separated in time from the 1990s nourishments, a milder wave climate and the coarser grain sizes present in the area were considered more likely factors to explain this trend.

In the same period, the lower shoreface profile had resumed its structural trend of retreating. The net overall effect of the shoreface nourishments may well have been a time delay of 15 to 20 years in the natural erosion trend at De Haan.

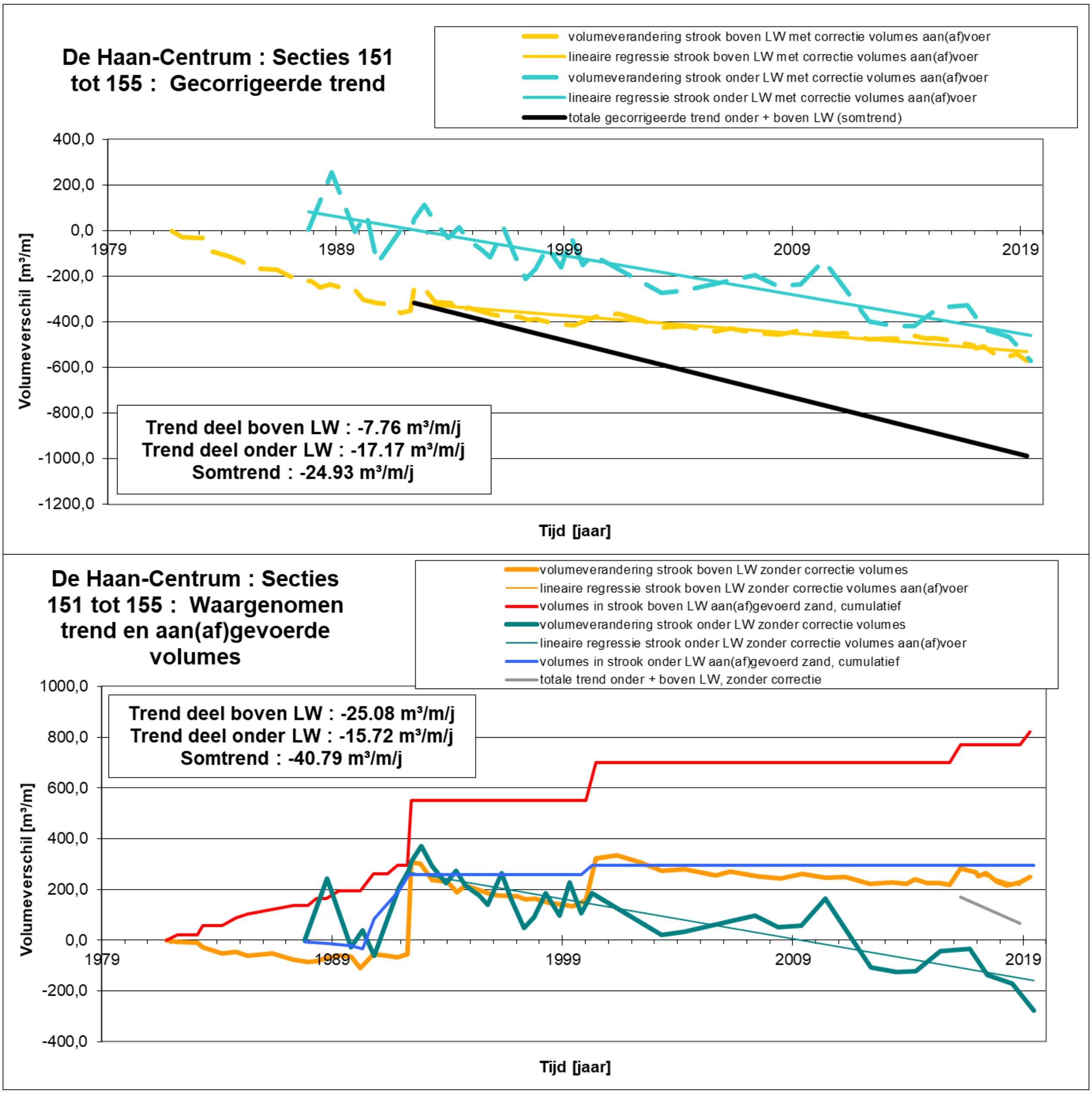


*Figure 12. Decadal evolution and recent trends in coastal stretch n° 32 (De Haan-Centrum).*

The main evolution over 10-15 years after the beach and outer breaker bar nourishments was redistribution of sand in the profile so that the area of the upper shoreface between the beach and the outer bar was a net beneficiary of sand. This development is beneficial for the stability of the local coastline. Waves will less affect the foreshore and backshore, and the beach is wide enough to allow natural processes to redistribute the sand present in the profile.

The present study allows to extend the analysis after 2011. The processes and trends described by Houthuys (2012) appear to go on at the same rate and in the same sense.

**After correcting** for the sand volumes shipped and trucked in (see Fig. 12), the emerged part of the survey area in sections 151 to 155 shows a milder average erosion rate, i.e. -8 m³/m/yr ($r^2$ = 0.873, StD on trend = 0.5 m³/m/yr) over 1992-2019, compared with -33 m³/m/yr ($r^2$ = 0.979, StD on trend = 1 m³/m/yr) over 1981-1992. For the submerged part of the survey area, no break can be reported due to the fact that echosounding surveys only started in 1987. The overall corrected erosion over 1987-2019 is -17 m³/m/yr ($r^2$ = 0.818, StD on trend = 1.3 m³/m/yr).

The **observed** evolution for the emerged part is mild erosion over 1983-1992: -6 m³/m/yr ($r^2$ = 0.507, StD on trend = 1.4 m³/m/yr). The reason is that yearly small nourishments have also in that time been carried out to keep the beach in good shape for recreational use. After the 1992 beach nourishment, the observed trend over 1992-2000 was -19 m³/m/yr ($r^2$ = 0.811, StD on trend = 2.5 m³/m/yr). After the 2000 maintenance beach nourishment, the observed trend over 2000-2015 was -6 m³/m/yr ($r^2$ = 0.838, StD on trend = 0.7 m³/m/yr). The short time after the early 2016 maintenance nourishment till Autumn 2018 yields a trend of -25 m³/m/yr ($r^2$ = 0.901, StD on trend = 5.6 m³/m/yr); a higher figure is always characteristic of the first time after a nourishment. A new maintenance nourishment was going on before and after the Spring 2019 survey. The overall observed evolution since 2000, after the large nourishment scheme, is slight erosion, i.e. -3.8 m³/m/yr ($r^2$ = 0.506, StD on trend = 0.7 m³/m/yr). The maintenance nourishments carried out after 9, 16, and 19 years are keep a stable beach. However, the protective effect of the shoreface nourishment seems to have fallen away as the frequency of maintenance nourishments is increasing.

The submerged part shows an averaged trend of -16 m³/m/yr ($r^2$ = 0.799, StD on trend = 1.4 m³/m/yr) over Fall 1992 – Spring 2019. This figure lumps two partial trends: stronger erosion on the lower shoreface and seabed on the one hand, and accretion on the upper shoreface. Between Spring 2000 and Spring 2019, the deepest part of the seabed lowered by 0.3 to 0.6 m. This evolution is part of the large-scale evolution of the tidal channel "Grote Rede": it tends to clear its bed and even erode it. The part of the seabed between the "Grote Rede" and the base of the shoreface lowers as well, but at a milder rate, between 0 and 0.3 m since 2000. The lower shoreface represents the slope of the relatively flat complex of upper shoreface and intertidal beach. It deepened since 2000 by 1 to 1.5 m. Especially the upper part of the slope, just beneath the outermost breaker bar, recedes. This evolution is seen over the complete coastal part between Oostende and Wenduine. Taking all observations together, there is an undeniable trend for the tidal flow channel "Grote Rede" to deepen and shift shorewards. This evolution may constitute a longer-term source for concern and must be well monitored. It is well possible that the increasing frequency of maintenance nourishments at De Haan reflects a response to this evolution.

The large-scale nourishments in and around De Haan were an adequate answer to nearshore channel encroachment, so much so that the sand volumes present in the upper shoreface, foreshore, backshore and sea fronting dunes remain more or less stable. This is illustrated by the situation at De Haan, such as described by the long-term volume graphs.

# 7 Comparison of the project areas and Discussion

The situation at De Haan has been monitored for over 30 years. As a combination of large-scale beach and subtidal nourishments was already carried out in the period 1992-1997, the subsequent evolution allows to serve as a template for what can be expected near Mariakerke. There are two main conclusions for the De Haan case: the beach is under danger of being undermined by the long-term dynamics of the tidal channel "Grote Rede". The large-scale nourishments of the 1990s were an adequate response causing stability of the beach and upper shoreface. It is noted that no severe storm damage occurred at De Haan after the 1990s, apart from the occasional small cliff formation in the slope of the dune foot or backshore berm. This favourable evolution is obtained at the expense of only small-scale and localized maintenance nourishments. However, erosion, be it at lower rates than before the nourishment scheme, continues to affect the beach and it is clear that, once detached from the beach – upper shoreface system, sand is swept along by the currents in the "Grote Rede" channel and is lost for the local coast barrier.

The situation with respect to the large-scale morphology and the long-term trends at Mariakerke is certainly comparable to the De Haan case. Similar mitigation of the existing, structural trend of erosion may there now be expected. It remains to be seen whether the erosive trend characterizing the nearshore channel Kleine Rede will again encroach on the coastal barrier. This is what now seems to occur near De Haan with the Grote Rede channel.
In Groenendijk, long-term structural accretion of upper shoreface, foreshore and dune front may eventually slow down or ultimately be reversed if the tendency of the lower shoreface to lose sand would become the structural future morphological evolution trend. However, nourishments are taking place at De Panne and Koksijde. The matter that is disappearing offshore of these nourishments may well contribute to temporary accretion of the shoreface at Groenendijk. This location would then benefit indirectly from the nourishments more to the west. Likewise, slow eastwards migration of the shoreface connected ridge Broers Bank is taking place. This natural process may constitute an additional source of sand feeding the Groenendijk area. It remains to be seen whether these nearshore processes will overcome the long-term slow erosion of the lower shoreface.

# 8 References


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# 9 List of Annexes

## 9.1 Annex 1: volume tables per section till Spring 2019

Excel files for sections 44-53 (Groenendijk), 98-108 (Mariakerke) and 151-155 (De Haan) containing volume differences per height slice since the first remote sensing and nearshore surveys and trend calculations.

## 9.2 Annex 2: volume tables per stretch till Spring 2019

Excel files for Stretches 10 (Groenendijk), 21-23 (Mariakerke) and 32 (De Haan) containing volume differences per height slice since the first remote sensing and nearshore surveys, trend calculations, and time series corrected for sand nourishment, dredging and disposal.

Annex 3: map series since 2000 for the 3 study sites

PPT shows allowing to visualize the bathymetric and topographic change since 2000.


AGENTSCHAP
INNOVEREN &
ONDERNEMEN

Vlaanderen
is ondernemen