# Co-analysis for the Mariakerke (Belgium) nourishment site

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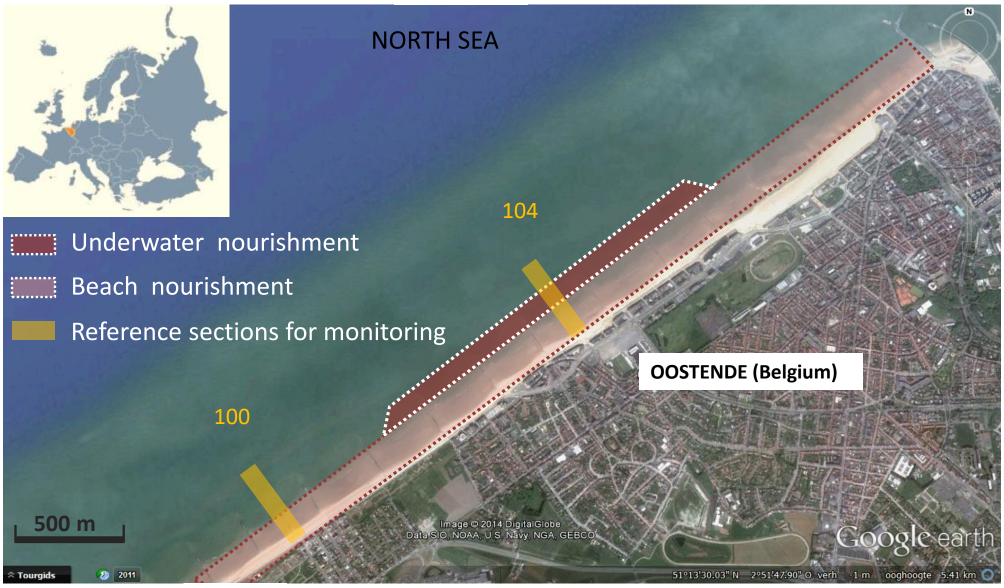
# 1. Introduction

Safety against storm induced flooding at the Belgian coast is one of the most important topics for the local coastal management. Historically, hard constructions were buildt for coastal protection, but in the present decades soft methods such as nourishments are preferred. The large majority of the nourishments were carried out on the intertidal and dry beach. This method is very efficient to reduce wave overtopping but is more costly than shoreface nourishments and has a greater impact on the use of the beach while being carried out. Therefore shoreface nourishment was suggested as possible alternative. This method would still preserve the safety function by assuring a sufficient volume of sand in the nearshore area, but at significantly lower costs and less disturbance at the coast. At the area Mariakerke – Raversijde [1](just SW from Ostend harbour, Figure 1) a nourishment experiment was designed to observe the behaviour of the coast when nourished just on the dry and intertidal beach (Section 100 , Raversijde, see figure below) compared to the coast nourished on both beach and shoreface (Section 104 , Mariakerke).

Figure 1 - Pilot site for shoreface nourishment experiment, Mariakerke coastal area, and the reference sections 100 and 104.




# 2. Description of coastal system and local area

The Belgian coast, stretching 67 km between the borders with France and the Netherlands, was historically characterized by sandy beaches and wide sand dunes, backed by mudflats and tidal marshes. The coast is oriented SW-NE and consists of a nearly continuous dune belt which constitutes the primary natural defence of the low-lying hinterland polder areas against flooding. The polder areas extent over a width ranging between 10 km and 18 km, with an elevation between 0 and 5 m above the mean spring low water level. The

[1] See figure 2 for the exact locations of the different coastal areas

Belgian continental shelf is shallow and dominated by sand banks (Van Lancker, 1999). Coastal banks are the most important since they merge to the nearshore area at several locations alongshore.

The dune barrier has two arcs, one stretching from Dunkirk to Wenduine and a second arc from Wenduine to Breskens (The Netherlands). Its continuity is interrupted by the estuaries of the river IJzer in the west, het Zwin in the east and the harbours of Ostend, Blankenberge and Zeebrugge. The coastal dunes range in height from + 5 m TAW[2] (local reference level for water surface elevation) to + 30 m TAW, with the majority between + 7 m TAW and + 15 m TAW. At the western Belgian coastal plain (west of the IJzer estuary) the dunes are approximately 2 km wide. East of the IJzer estuary the dune belt is only a few hundred meters wide, except for three places (Westende, De Haan, and Knokke) where the maximum width of dunes is about 2 km (Lebbe *et al*., 2008). The beaches are in general wide and very gently sloping, characterized by spilling breakers and classified as dissipative. The slope of Belgian beaches increases from west (1.3%) to east (2.4%), having associated the narrowing of the intertidal beach width, from 500–600 m to 200–300 m (in Knokke), respectively (Deronde *et al*., 2006).

For about one century both waterfront and polder-lowlands knew an intensive urban and resort development, combined with hard coastal defence structures and protruding sea dikes, turning it into a “squeezed coast”, with little space left for any ecological, economical or residential developments anymore. A large part of all 255 coastal sections[3] are subject to structural erosions of beach and dune systems, making the plain vulnerable to extreme storm-events. The protection of the Belgian coastline is nowadays a combination of natural and artificial defence. 60% of the coast has hard coastal protection with seawalls, revetments and groynes, but for the last two decades, emphasis has shifted to soft protection schemes, especially along the most erosive coastal stretch of Ostend – De Haan, such as beach and shoreface nourishment. (Lebbe *et al*., 2008). Coastal erosion and accretion along the Belgian coastline is described in coastline charts and long term trends, reporting erosion and accretion rates that variate in a significant way depending on the location of the coast. .

The tide along the coastline is semi-diurnal with a small asymmetry. All beaches are situated in a macro-tidal regime and the tidal range is typically between 3.5 m at neap tide and 5 m at spring tide. This important tidal range is linked to quite significant tidal currents, of which the peaks generally slightly exceeds 1 m/s in the nearshore (Haerens *et al*., 2012). The mean tidal amplitude decreases by 0.5 m from west to east (Van Lancker, 1999). Offshore waves are mainly driven by westerly winds. Because of the shallow waters and the relatively short fetch, waves are typically short crested (Haerens *et al*., 2012). Fetches of more than 200 km can only be attained from the north, implying that storms from north-western to northern direction are the most severe (Van Lancker, 1999).

The sediments on the shore are almost exclusively well sorted fine to medium sands. The natural beach sediments are characterized by fine to medium sand, mostly quartz grains, with a median diameter varying between 180 and 250 µm, and a natural peak of around 300 µm in the east. These observations were confirmed by recent work, remarking that in general, along the Belgian coastline a gradient exists from fine-grained sand at the low water level to coarser sand on the dry beach. In areas where beach nourishment took place, the grain size tends to be coarser, up to 400µm (Haerens *et al*., 2012).

## 2.1 General morphological and hydrodynamic characteristics

[2] The Belgian datum level (TAW, Tweede Algemene Waterpassing, Second General Leveling) corresponds with the lower low water at Ostend (1839–1858); 0 m TAW is 2.0 m below mean sea level and 2.33 m below 0 m NAP (Datum Level of the Netherlands, corresponding to the average mean sea level during the last 300 years).

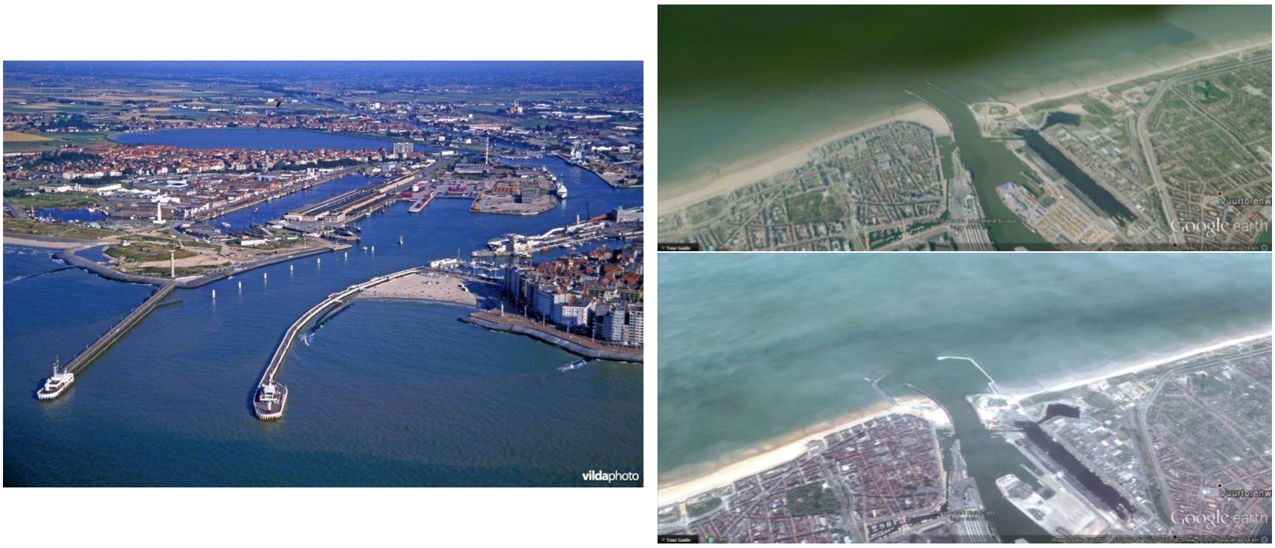
[3] A coastal section is an area of the coast typically between 2 groynes, or when groynes are lacking: an area of a few 100 m long alongshore

## 2.2 Coastal infrastructure and earlier nourishments

The study zones, Middelkerke - Mariakerke, is situated just southwest from the Ostend town, but the area until the city's harbor jetties was also included in the analysis since it is strongly influencing the dynamics of its adjacent area. The historic town of Ostend was situated in the seafront where the sea dike is protruding 200 m into the sea. The coastal defenses protected the city throughout the $16^{th}$ – $20^{th}$ centuries, while the surrounding coast was allowed to erode and the coastline to retreat. In the beginning of the 2000's, the coastal safety of Ostend center, where severe inundations had occurred in the 1953 stormsurge, was evaluated by the Flemish coastal authorities to be the lowest at the Flemish coast with acute risk of overtopping and breaching of the existing old seawall. For public safety, an emergency beach nourishment was carried out in 2004. This fill was meant to raise the safety level immediately and awaiting the construction of a new western harbor dam in 2010, which will give rise to a naturally accreting coast (Bertels *et al.*, 2012).

Long jetties extend over more than 500 m distance from the coast in order to protect the entrance to the harbor (Figure 1 – ). The stretch of coast within a 5 km radius from Ostend is characterized by a sandy shore with visible cross-shore hard structures (groins), spaced 200 – 500 m alongshore. The largest part of Ostend city develops west of the harbor jetties. The eastern part consists of a wide system of dunes that connects Ostend to De Haan and  few nourishments occurred in this part.

Figure 1 – Ostend harbor overview before 2004 (INSHORE, left), in 2007 (GoogleEarth, right top) and in 2011 (GoogleEarth, right bottom).




Before 2004, the beach in Ostend center consisted of a narrow strip in low tide and no beach at all at high tide. The emergency nourishment raised the beach profile, so that at high tide, a strip of about 200 m of dry beach was created. The nourishment took place between April and June 2004. The median grain size before nourishment was about 0.2mm and after nourishment 0.3-0.35mm, locally up to 0.4mm (Bertels et al., 2012).

Middelkerke and Mariakerke are seaside villages located southwest of the seaport, where before the approval of the Coastal Safety Masterplan yearly small-scale beach fills maintained a dry backshore berm in front of the seawall. Since the approval of the Coastal Safety Masterplan, 2011, the intensity of nourishments intensified in a significant way.

# 3. Nourishment description

## 3.1 Nourishment goals

The nourishment had two main goals:

- Assess the differences between two coastal stretches nourished in different way: Raversijde area just with beach nourishment and Mariakerke nourished both on the beach and shoreface.
- Increase the coastal safety for a vulnerable area.

## 3.2 Nourishment design

The pilot nourishment was in three steps during year 2014 at Raversijde-east and Mariakerke area sections 97 to 108, using sand extracted from the sea (locations of the coastal sections in Figure 2). Before the nourishment experiment numerous smaller nourishments took place in the study zone in order to maintain the coastal safety. The nourishments from 2008 to 2011 are presented in Table 1.

Table 1 - The historical nourishments done at the study area starting 2008.

| Date | Sections | Volume ($m^3$) | Description |
|---|---|---|---|
| 2008 | 97-100 | 37,800 | Small beach nourishment with sea sand using truck |
| 2008 | 103-108 | 130,000 | Large beach nourishment with sea sand |
| 2008 | 103-108 | 24,800 | Small beach nourishment using truck |
| 2009 | 97-100 | 52,800 | Small beach nourishment with sea sand using truck |
| 2009 | 99 | 16,100 | Small beach nourishment with sea sand using truck |
| 2009 | 103-108 | 26,000 | Small beach nourishment with sea sand using truck |
| 2010 | 97-101 | 16,750 | Small beach nourishment with sea sand using truck |
| 2010 | 97-101 | 10,100 | Small beach nourishment with sea sand using truck |
| 2010 | 103-109 | 14,200 | Small beach nourishment with sea sand using truck |
| 2010 | 107-109 | 26,300 | Small beach nourishment with sea sand using truck |
| Mar-apr 2011 | 97-101 | 17,200 | Small beach nourishment with sea sand using truck |
| Jan 2011 | 105-107 | 13,000 | Small beach nourishment with sea sand using truck |
| Jan-Feb2012 | 97-101 | 17,100 | Small beach nourishment with sea sand using truck |
| Jan-Feb2012 | 103-109 | 32,000 | Small beach nourishment with sea sand using truck |

The nourishments carried out in the area Middelkerke – Ostend harbour during the monitor period 2013 to 2018 were as follows:

1. Beach nourishment of 681 200 $m^3$ at coastal sections 102 to 106 in January – February 2014;
2. Beach nourishment of 190 900 $m^3$ at coastal sections 97 to 102 in 2014 in June 2014;
3. Shoreface nourishment of 303 800 $m^3$ at coastal sections 102 to 108 in April – May 2014.

Other beach nourishments with sea sand were conducted at adjacent coastal areas:

4. Beach and shoreface nourishment of 822 200 $m^3$ at coastal sections 109 to 115 in October 2013 - February 2014;

5. Beach nourishment of 968 800 $m^3$ at coastal sections 74 to 89 in April – June 2014.

Nourishments performed at the study zone later:

6. Beach and shoreface nourishment of 315 380 $m^3$ at coastal sections 105 to 109 in February – March 2018;
7. Beach and shoreface nourishment of 424 630 $m^3$ at coastal sections 110 to 116 in February – March 2018.

Figure 2 – Coastal sections at Raversijde-east and Mariakerke (pilot site) and nearby coastal areas.


## 3.3 Placement

The placement of the nourishments can be observed when comparison between consecutive years was made. The nourishments presented in sub-chapter 3.2 are visible in Figure 3, Figure 4 and Figure 5. The nourishment number 5 it is not visible in these figure since was placed at the southwestern boundary of the extended study zone.

Figure 3 – Volume differences between the pre-nourishment DEM (2013) and post-nourishment DEM (2014).

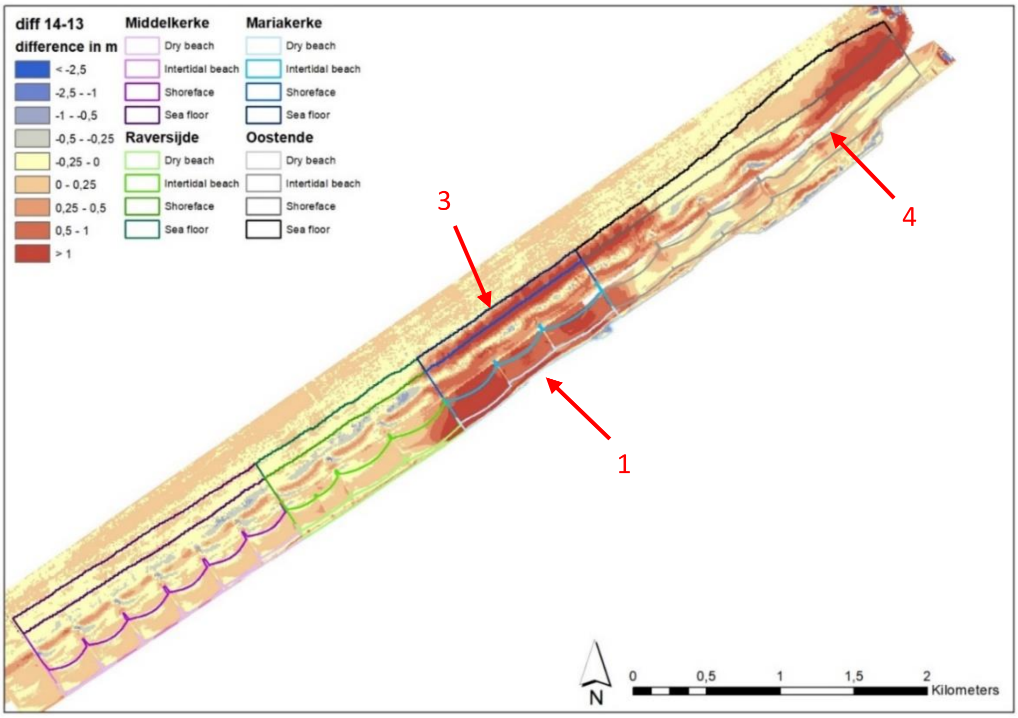



Figure 4 – Volume differences between the pre-nourishment DEM (2013) and post-nourishment DEM (2015).

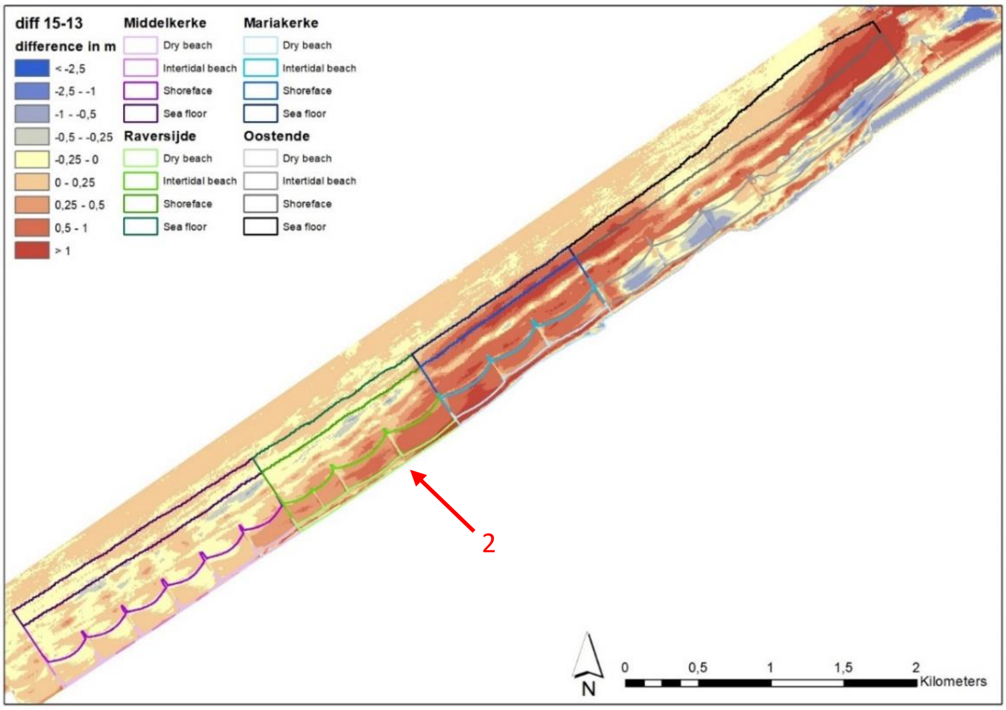
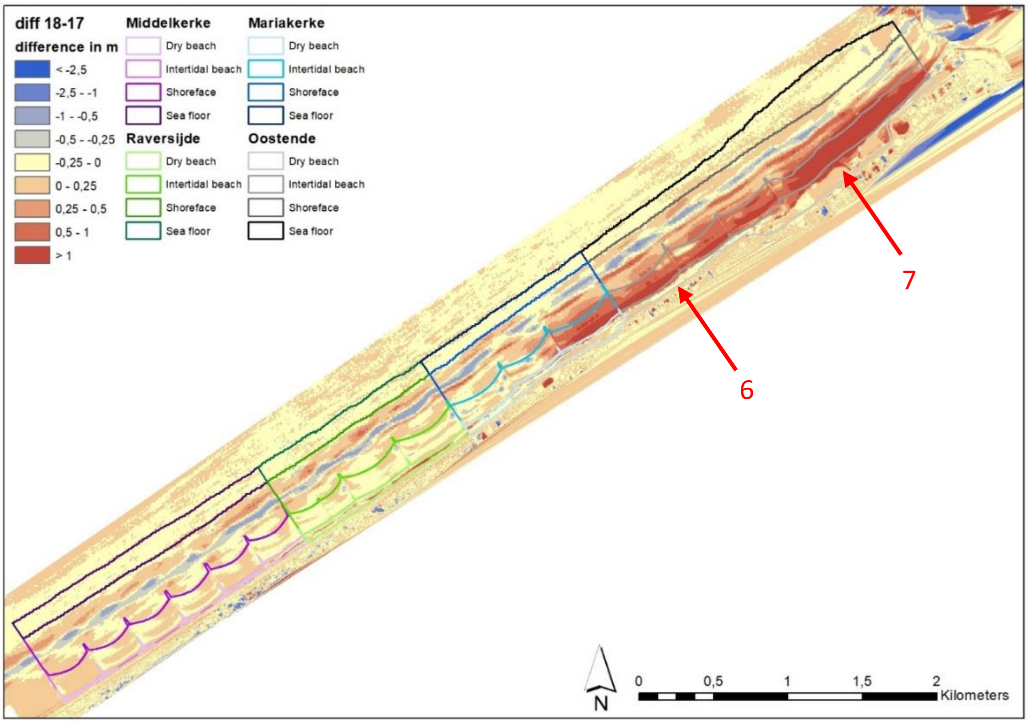


Figure 5 - Volume difference between 2018 and 2017.




## 3.4 Available survey data

### 3.4.1 Transects

Three cross-shore profiles have been carried out at both section 100 at Raversijde-East and section 104 at Mariakerke every month between September 2015 and December 2018 (Figure 6A). Extra surveys were done before the storms of 14/01/2016 and 12/01/2017; and after the storms on 18/01/2016 (extended just until 110 m seaward) and 16/01/2017. Also beach was surveyed twice in March 2017 but none in October 2016 and November 2017 and during the summer season from July to August. A RTK-GPS system was used in walking mode. The distance interval between profiles is around 150 m and extend from the dyke to 300 m towards the sea. The measurements were not accurately following the profile, therefore the points were projected on the designed profile.

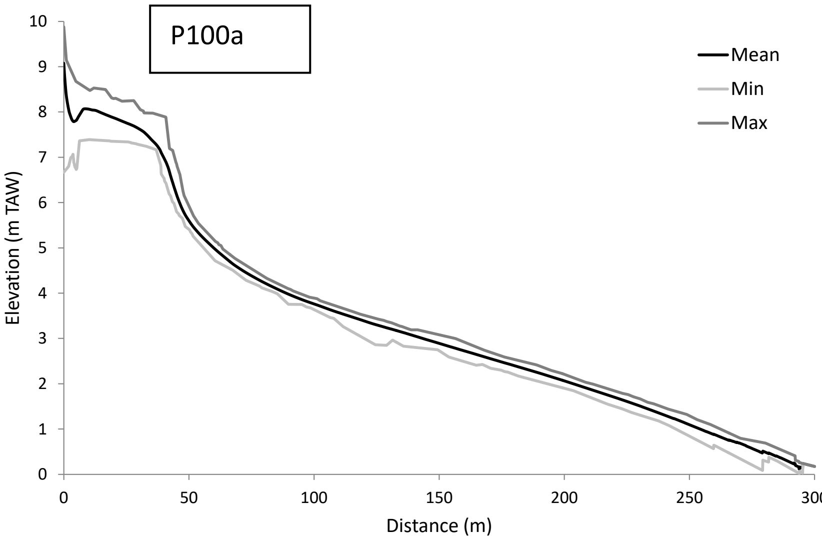
A shift (deviation from the straight line) up to 26 m was observed between cross-shore profiles located at the same position due to walking survey error (Figure 6B). Therefore a correction was applied by re-projecting all the profiles using referenced profiles in ArcGIS environment. Then, the indicators such as intertidal width and slope of the intertidal beach and the dry beach were extracted from the re-projected, interpolated profiles. The references to calculate the  intertidal beach width (intertidal beach slope are the MLWL and MHWL; and the MHWL and the sea dyke for the dry beach width (dry beach slope).

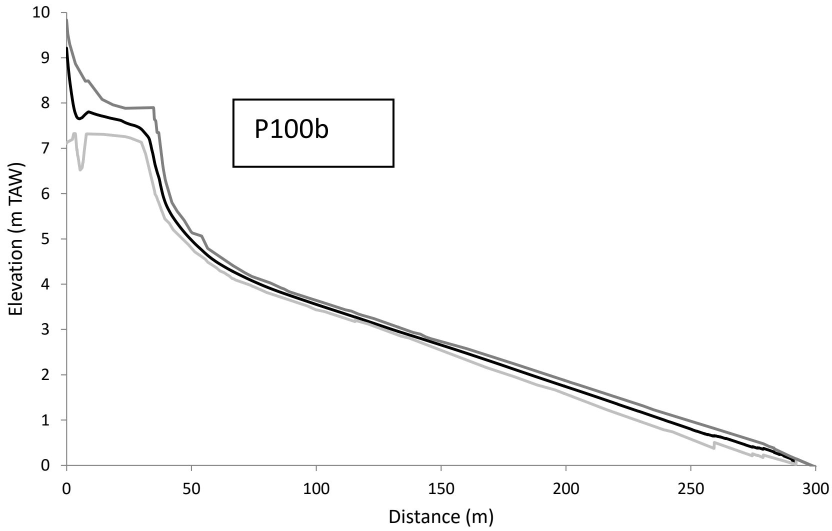
Figure 7 and Figure 8 show the envelope of the three re-projected cross-shore profiles for section 100 (a,b,c) at Raversijde-East and section 104 (a,b,c) at Mariakerke from September 2015 to December 2017. Both sections indicate the presence of a berm of the dry beach above +7.0 m TAW while the intertidal beach is with featureless and a gentle slope. The greatest elevation variability is found on the upper beach at a distance of less than 50 m from the dyke while the changes of the intertidal beach are usually minor (except for profile P104a and P104b). Thus, a spatial and temporal variability of the elevation is observed at a monthly scale. As expected at location 104 were more both types of nourishments were performed the variations are larger than at location 100.

Figure 6 – A) Map of the location of the cross-shore profiles at reference sections 100 and 104; B) Example of observed shift of a profile.

A) B)


Figure 7 – Envelope of the cross-shore profiles for section P100 (a, b, c) at Raversijde-East from September 2015 to December 2017.





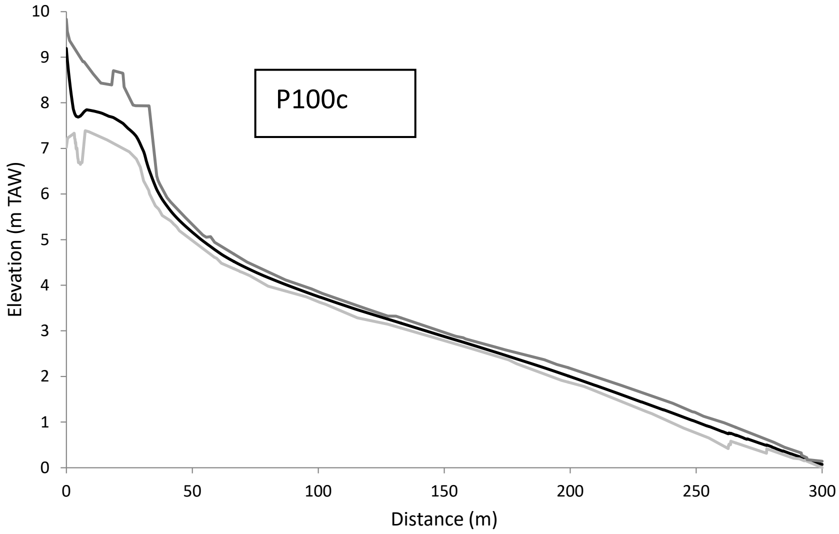
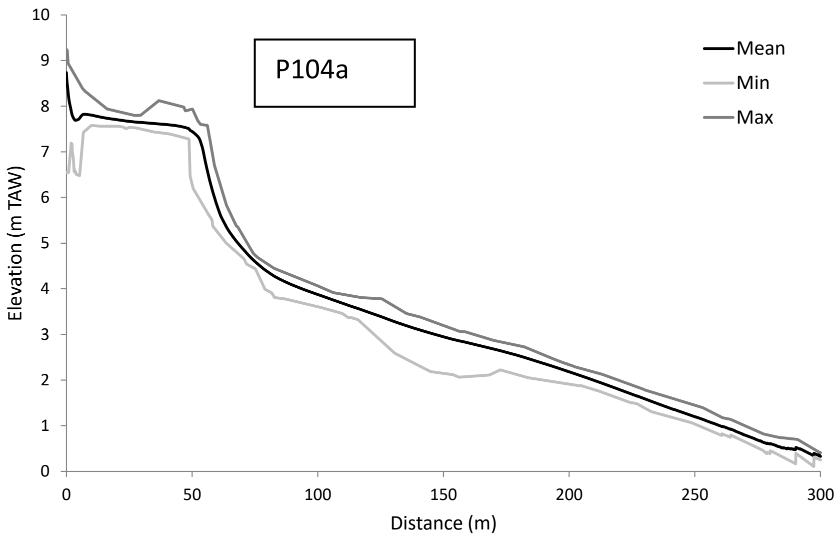
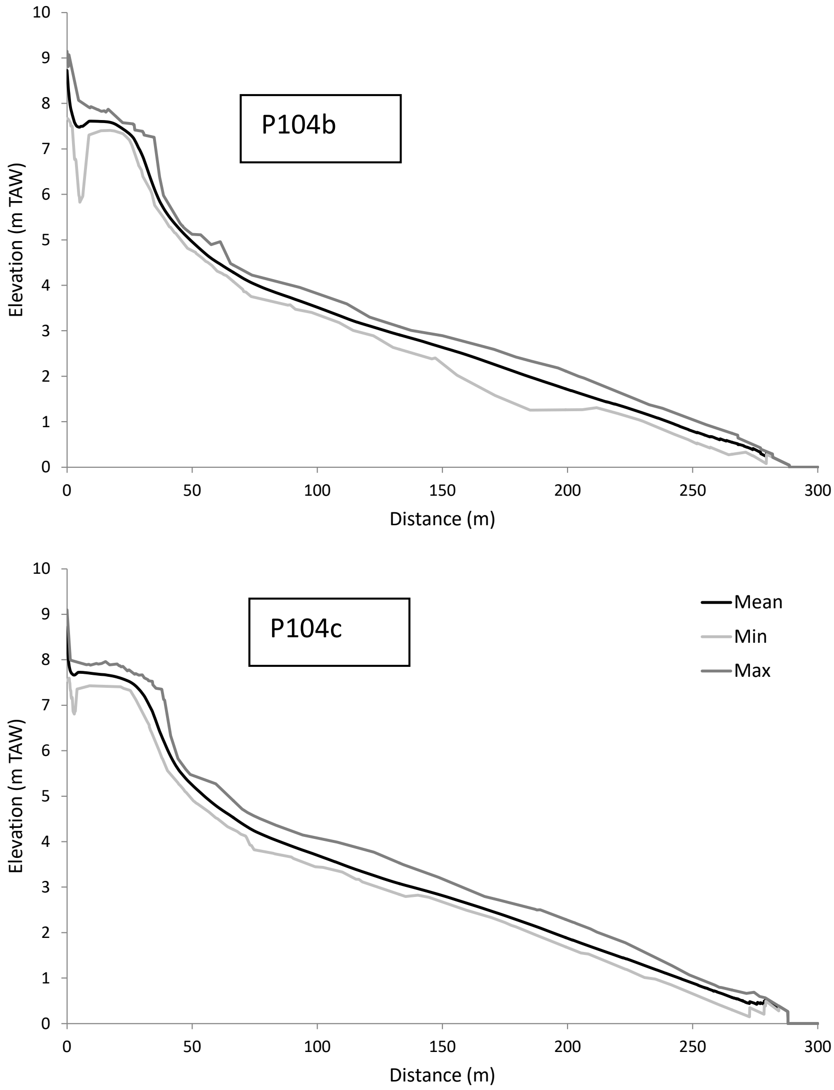




Figure 8 – Envelope of the cross-shore profiles for section P104 (a, b, c) at Mariakerke from September 2015 to December 2017.






### 3.4.2 Surveys

The surveys performed by Coastal Division were realised once and/or twice a year using two different techniques. The dune foot, the dry and intertidal beach were measured using LIDAR system, while the underwater part (shoreface and sea floor) were measured using single or multibeam echosounders (detailed chronology in Table 2).

Table 2 – The topographic (beach) and bathymetric (shoreface) surveys carried out at the study zone during period 2013 to 2018 (location of the sections in Figure 2).

| Date | Sections | beach | shoreface |
|---|---|---|---|
| 29 April 2013 | 83-117 | LiDAR survey | |
| 25, 26, 28 June - 02, 15 July 2013 | 83-117 | | single-beam survey |
| 10 December 2013 | 83-117 | LiDAR survey | |
| 15 April 2014 | 86-117 | LiDAR survey | |
| 19 - 20 May 2014 | 83-105 | | single-beam survey |
| 15, 16, 18, 23 September - 2, 3 October 2014 | 91-116 | | multi-beam survey |
| 06 November 2014 | 90-116 | LiDAR survey | |
| 17 May 2015 | 86-117 | LiDAR survey | |
| 04, 05 June 2015 | 83-117 | | single-beam survey |
| 27 October 2015 | 83-117 | LiDAR survey | |
| 30, 31 July, 3 - 31 August, 14 -29 September, 02 - 06 October 2015 | 91-114 | | multi-beam survey |
| 10 April 2016 | 86-117 | LiDAR survey | |
| 13, 14 September 2016 | 83-117 | | single-beam survey |
| 14 December 2016 | 86-117 | LiDAR survey | |
| 17 January 2017 | 83-117 | LiDAR survey | |
| 02 May 2017 | 83-117 | | single-beam survey |
| 26 May 2017 | 83-117 | LiDAR survey | |
| 06 November 2017 | 95-117 | LiDAR survey | |
| 30 January 2018 | 98-109 | | single-beam survey |
| April 2018 | 90-117 | LiDAR survey | |
| July 2018 | 83-117 | | single-beam survey |
| November 2018 | 90-117 | LiDAR survey | |

### 3.4.3 Additional data

Additional data was represented by the local hydrodynamics. The wave climate was measured with a directional wave rider at the Raversijde station which is located in front of Mariakerke area close to the Raversijde boundary, about 740 m from the dike. This data is provided by Coastal Division-Flemish Hydrography as time series of significant wave height, peak period, and wave direction at 30-minute intervals. For a better representation classes of velocity and direction were defined. Figure 9 presents the wave rose at Raversijde wave buoy plotted using the daily wave data during the three-year period, 01 July

2014 – 30 June 2017. The full black line represents the coastline orientation. It is clear that the most predominant waves are from the west which form an angle of about 30°-50°with the coastline. The dominant wave heights are smaller than 1 m but very high waves (Hs > 2.5 m) are also observed.

Figure 9 – Wave distribution at Raversijde wave buoy (-5.0 m TAW) during the period July 2014 – July 2017.

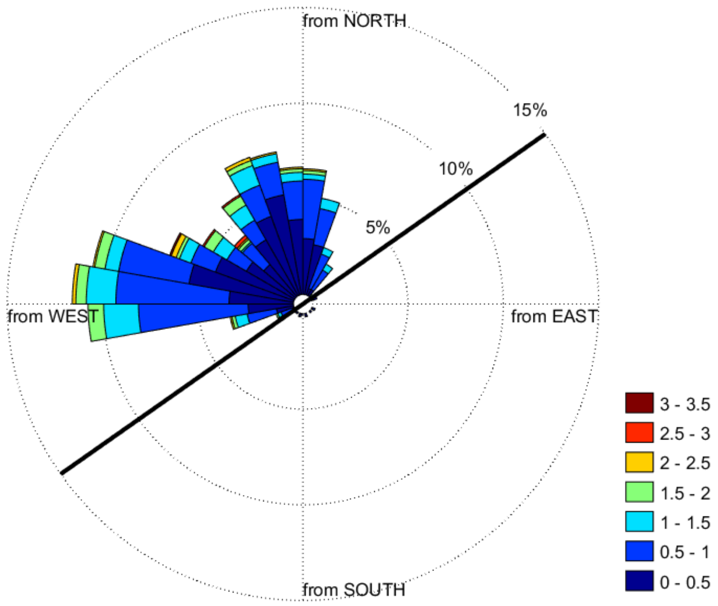
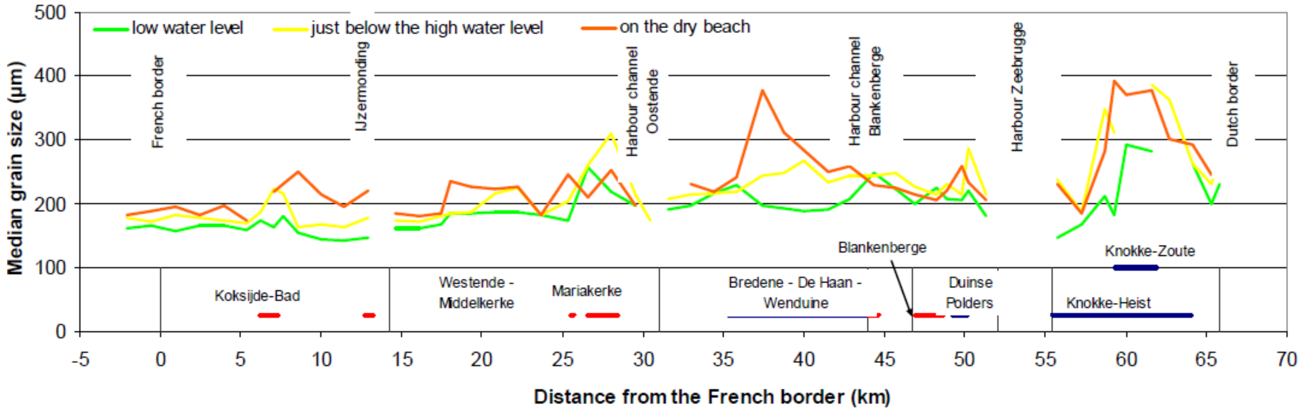



Figure 10 – Longshore variation of the median grain size for three positions on the beach (after Deronde, 2007).




Deronde (2007) presented the median grain size for three cross-shore positions on the beach: at the low water level, just below the high water level, and on the dry beach based on the analysis of 357 samples collected on the Belgian beach in the years 2001 and 2002 (Figure 10). The areas where beach nourishment (e.g. Knokke-Zoute) or beach scraping (e.g. Mariakerke) at that time are indicated in red and blue, respectively. The figure shows a clear trend of the increase in grain size along the Belgian coast from the southwest (French border) to northeast (Dutch border), ranging from 170 µm to about 400 µm in De Haan and Knokke-Zoute. There is also the trend of increased grain size towards the dry beach. At Mariakerke, most of the samples show the median grain size in the range of 170-250 µm.

### 3.4.4 Accuracy of the data

The LIDAR measurements starting 2003 have an absolute vertical deviation of 3 cm and the standard deviation is about 5 cm. The bathymetrical surveys from the same period have a standard deviation on vertical of 7 cm (Houthuys et al., 2019).

# 4. Nourishment development

## 4.1 Qualitative Morphological development

For a better understanding of the nourishments evolution, four cross-shore areas were defined, based on depth contours at -4,11 m TAW, +1,39 m TAW, 4,39 m TAW, 6,89 m TAW, based on the classification of Houthuys (2102) and schematically depicted in Figure 11. The area was also divided in four alongshore boxes using as main criteria the location of different type of nourishments. The entire area is divided in 16 boxes for a detailed investigation of the sediment circulation after the nourishment were executed (Figure 12). The delimitations of the boxes follow isolines at the above mentioned elevation/depths using the pre-nourishment situation. The cross-shore delimitation is based on the cross-shore profile proposed by Houthuys (2012), but the dry beach and dune foot were merged for this case and their inland boundary is the first human made structure, the seawall. The shoreface box is including most of the submerged active beach. A forth box, named sea floor was added to extend the study zone to a depth of -6.00 m TAW. This box covers an area just outside of the calculated closure depth, but still considered in the study.

Figure 11 - Schematic representation of the cross-shore divisions at the Belgian coast (after Houthuys, 2012).

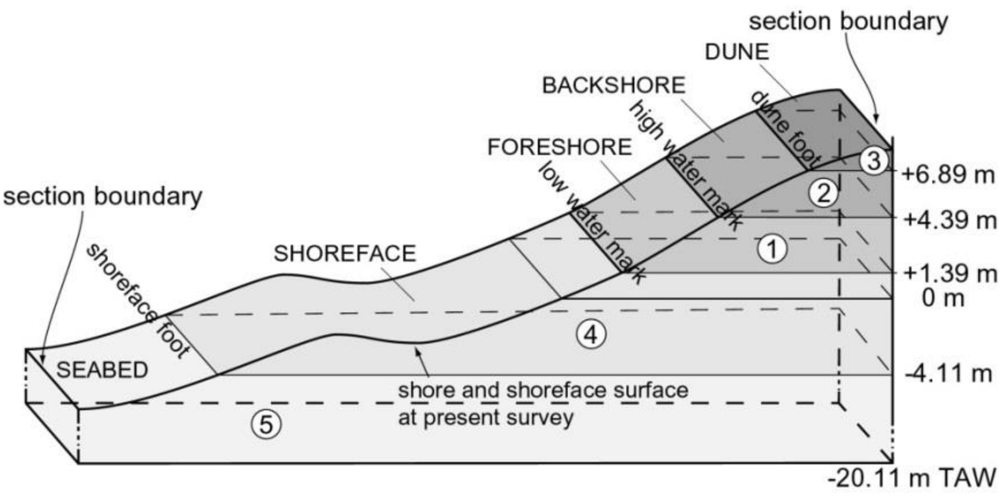
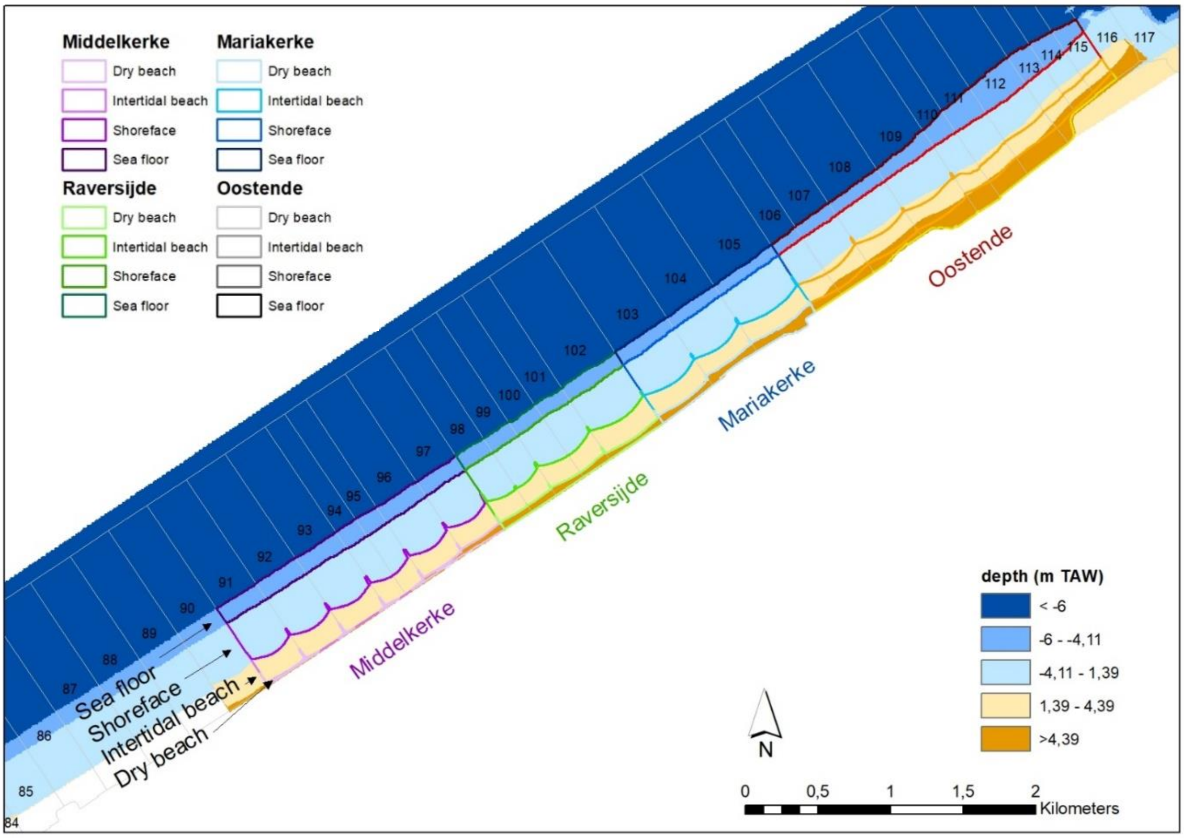


Figure 12 – Delineation of alongshore and cross-shore research boxes.

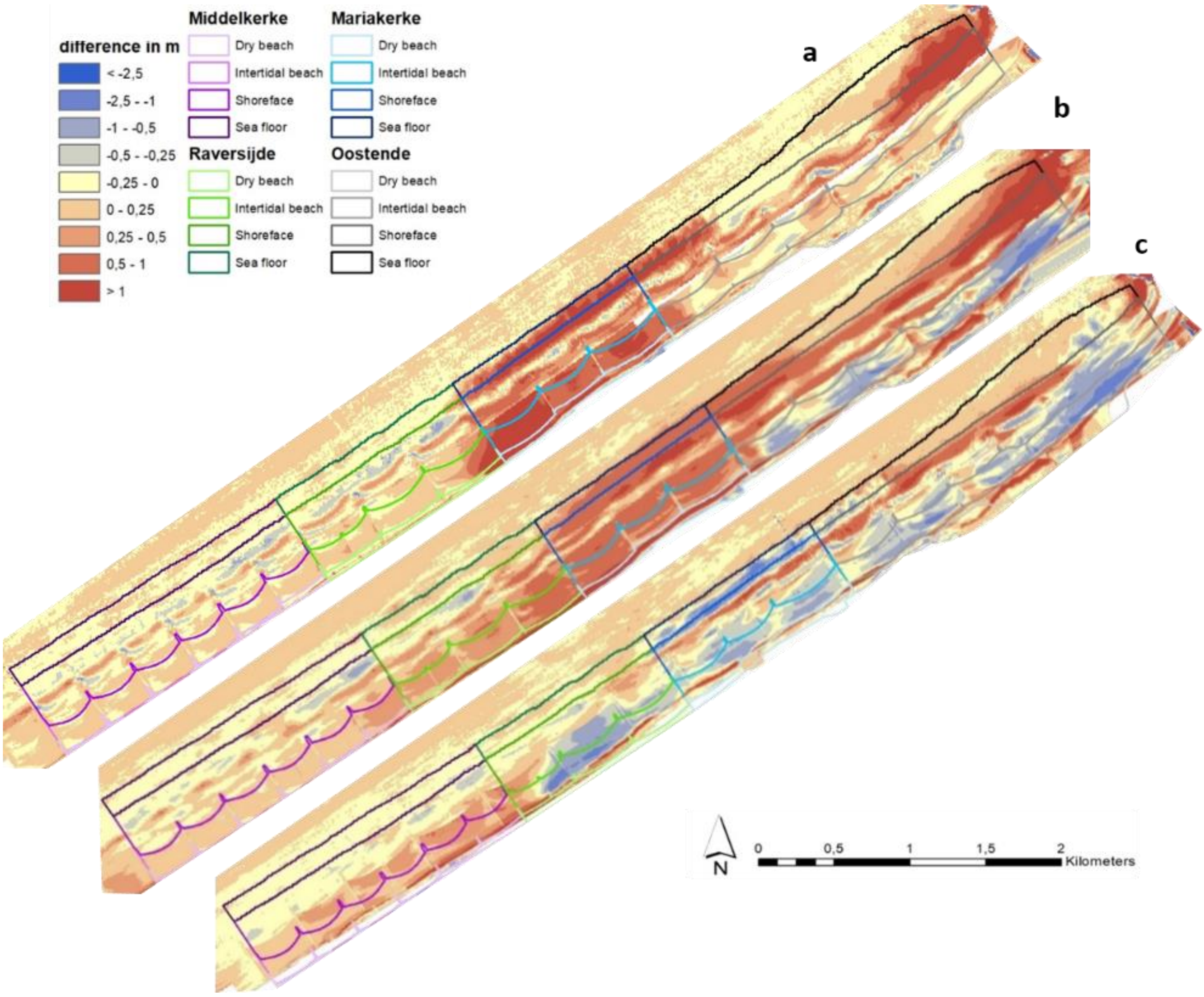



To investigate the morphological changes before and after the nourishment volume differences maps were built. The differences between the situation pre-nourishment (2013) and immediately after most of the nourishments execution (2014) is presented in Figure 13a. Comparison between the pre-nourishment (2013) and situation in 2017 (Figure 13b) was performed in order to assess the evolution of the study zone in general. The differences between the situation post-nourishment (2014) and the situation in 2017 (Figure 13c) was performed to explain the evolution of the nourishment. The period considered for analysis extends just until 2017. In 2018 a beach and shoreface nourishment was performed in the study area with a volume of 0.74 million $m^3$ of sand that was deployed between profiles 105 and 116, partially covering the Mariakerke box and totally covering the Ostend box. To avoid perturbation from this more recent intervention analysis of the nourishments evolution realized in 2013 – 2014 is limited to 2017. Even for this time period the study zone evolution was significantly influenced by the beach nourishments performed in the immediate vicinity, at the south-western boundary, in 2014 and 2015 and with a cumulated volume of 1.16 million $m^3$ of sand.

As expected, sand from the shoreface is eroded for both areas subject of the experiment, Raversijde and Mariakerke, and, most probably, large parts of this sand is deposited on the shoreface of the Ostend sector. However, at Mariakerke, the sand deployed on the shoreface is reorganized into a submerged bar. The sand deposited on the intertidal beach is eroding. Apart from alongshore redistribution this material is in cross-shore migrating into two distinct directions: 1) to the dry beach, by aeolian transport as a main driving force, but also due to the local human interventions and 2) to the shoreface.

One particular finding is a correction of the local closure depth at yearly scale when the evolution of the sea floor sector is investigated. This value was estimated on a decadal scale at -4.11 m TAW by Houthuys (2012) and calculated at -5.25 m TAW by Dan and Vandebroek (2017). When digital elevation models are compared for a period of approximately 4 years it is clearly visible that the circulation of the sand can be considered insignificant at the depth of -6.00 m TAW, the offshore limit of the study zone.

Figure 13 - The digital elevation model difference between different years: a) difference between 2014 and 2013; b) difference between 2013 and 2017; c) difference between 2014 and 2017.




Evolution of the study area with the reference the 2013 pre-nourishment situation

Figure 14 shows the volume differences between the pre-nourishment and immediately post-nourishment situations, except for the Raversijde nourishment. Beach and shoreface nourishments at Mariakerke as well as the nourishment at Ostend are clearly visible (see details on nourishments in sub-chapter 3.2. The last mentioned nourishment was performed both on the beach and shoreface, but the proportion between the two is not precisely known, so it was assumed to be divided in equal parts. However, the beach nourishment executed at Raversijde is not visible since it was performed after the seasonal topographic survey.

Along with the expected accumulations visible in Figure 14 due to the nourishments, some erosion areas can be observed especially at the middle depths on the shoreface area at Mariakerke and both at the shoreface and beach at Ostend area. The surveys used to construct the 2014 DEM were carried out 2 – 3 months after the nourishments, therefore the erosion spots indicate the incipient re-organisation of the deployed sand into the active equilibrium of the beach. This is confirmed by the comparison with the surveys carried out in 2015 (Figure 15). In this comparison the beach survey carried out at Raversijde is visible and the sand accumulation is less than at Mariakerke beach. In Figure 16 (2016 – 2013) the re-organisation of the deployed sand is continuing through formation and shore migration of a large bar at the Mariakerke shoreface, faster alongshore circulation of the sand deployed on the shoreface and erosion of the intertidal beach at Ostend. The later one could also have human induced causes since intense beach preparation for the touristic seasons was observed.

In Figure 17 (difference between 2017 and 2013) the sand circulation follows the same trends, but for Middelkerke – Raversijde areas a sand bar on the shoreface is formed and migrates towards the shore. The erosion areas at Ostende appear larger than the previous year.

Figure 14 – Volume difference between 2014 and 2013.

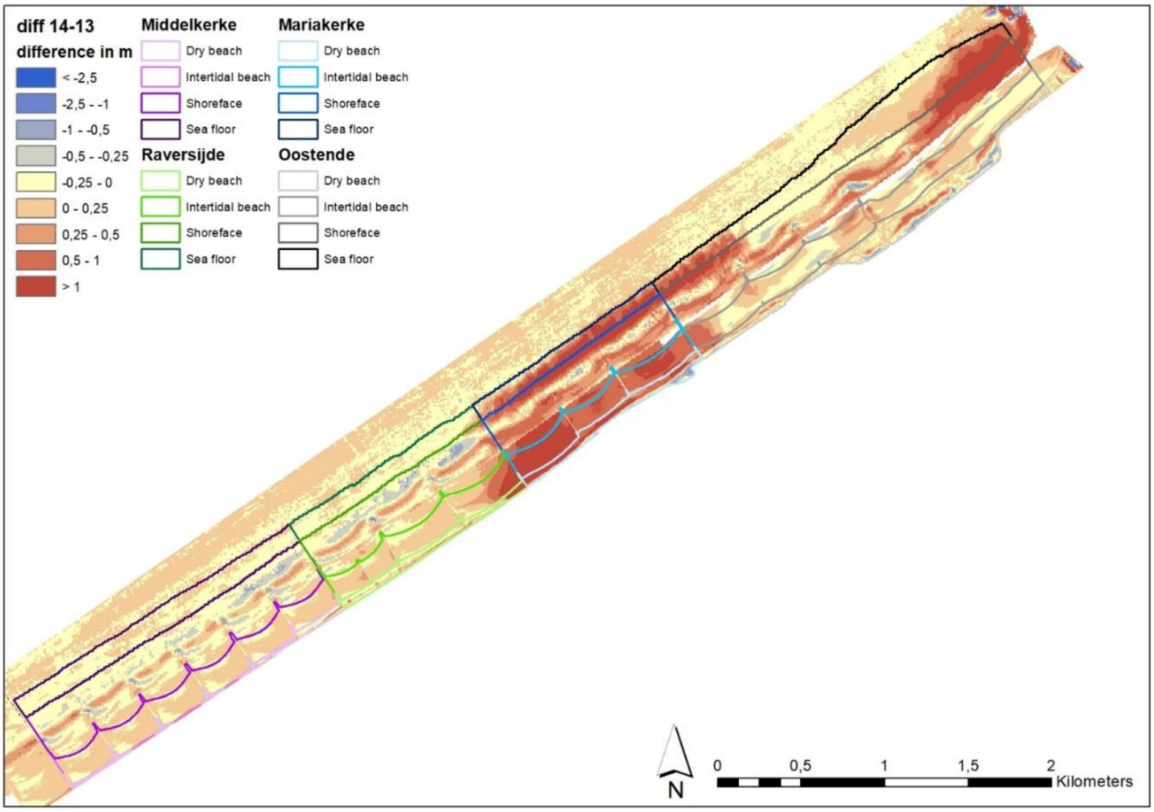


Figure 15 – Volume difference between 2015 and 2013.

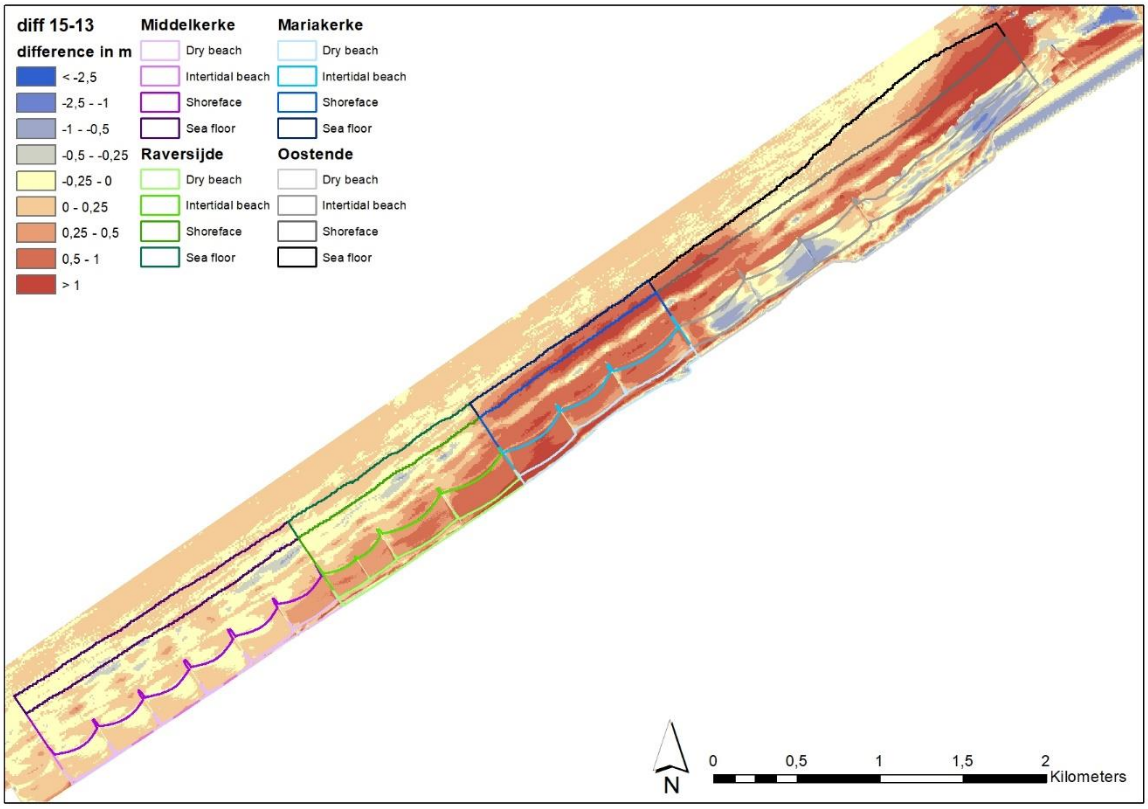



Figure 16 – Volume difference between 2016 and 2013.

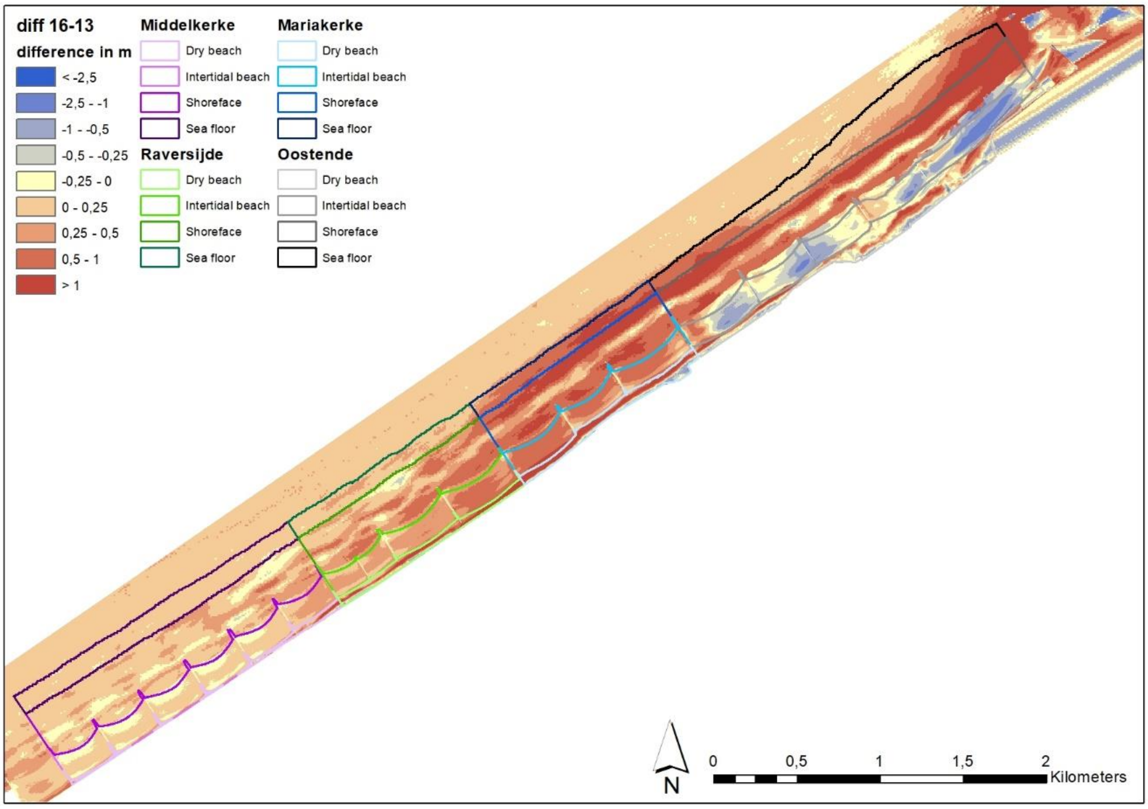
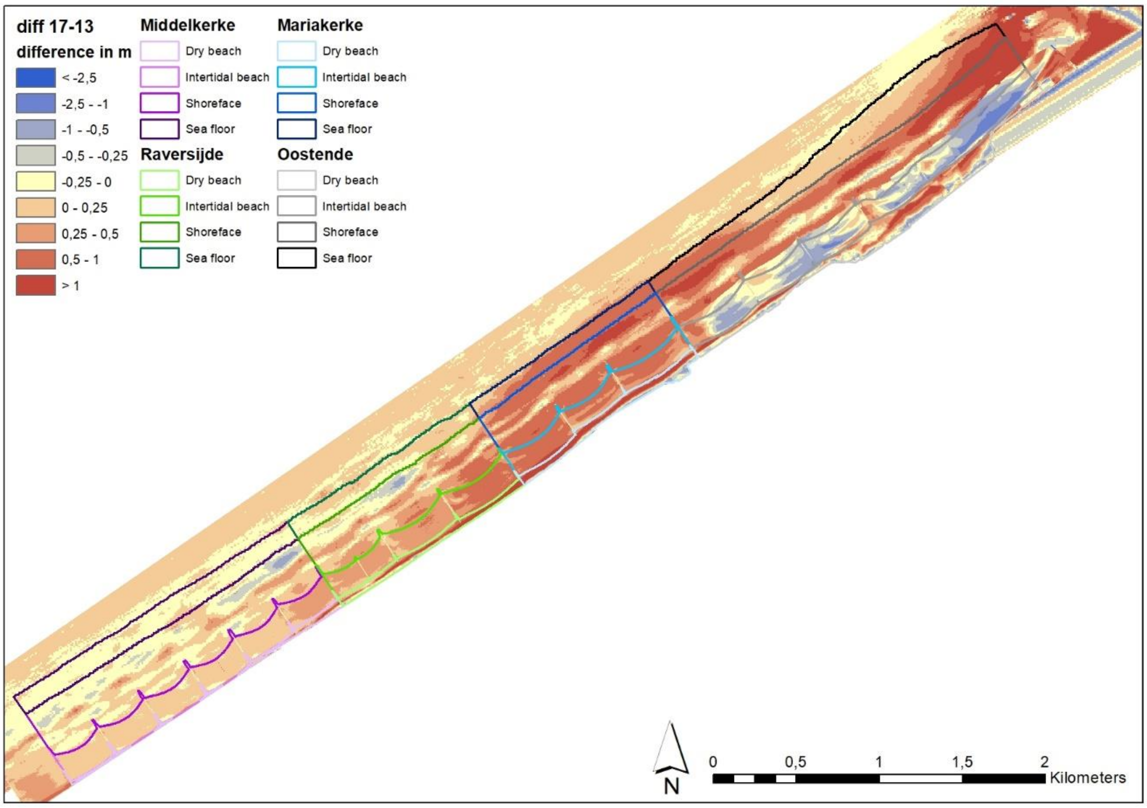


Figure 17 – Volume difference between 2017 and 2013.




<u>Evolution of the study area with the reference the 2014 post-nourishment situation</u>

The beach volume comparisons having as reference the first surveys after the main nourishments were carried out show the same trends as for the comparison with the pre-nourishment situation. However, these trends are easier to observe since the volumes are smaller. A clear trend is visible at intertidal beach (Figure 18) where the nourished sand rapidly moved to the dry beach and to the shoreface. Formation of two sand bars and migration towards inland are also visible at Mariakerke and Ostend, due to the fast re-organisation of the nourished sand. At Mariakerke the formation of a trough is visible around the -5.00 m TAW depth and it formed as a consequence of the sand bars migration. Two years after the nourishment the sand bars at shoreface are still in place at Mariakerke, but at Ostend sector the two sand bars tend to merge into just one bar (Figure 19).

In 2017, there is just one sand bar at both Mariakerke and Ostend on the shoreface, significant volumes of sand moved from the intertidal beach and upper shoreface to the dry beach (significant growth) and to the lower shoreface. Similar situation can be observed at Raversijde, but less at Middelkerke (Figure 20).

Figure 18 - Volume difference between 2015 and 2014.

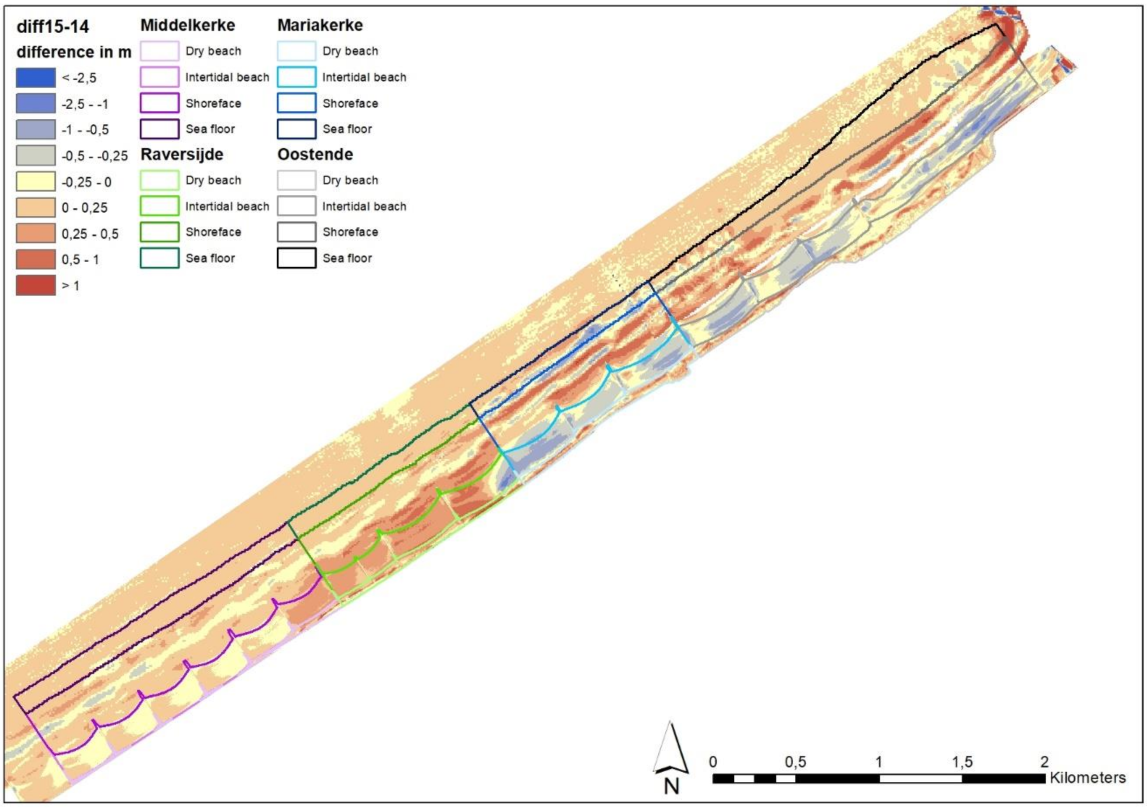



Figure 19 - Volume difference between 2016 and 2014.

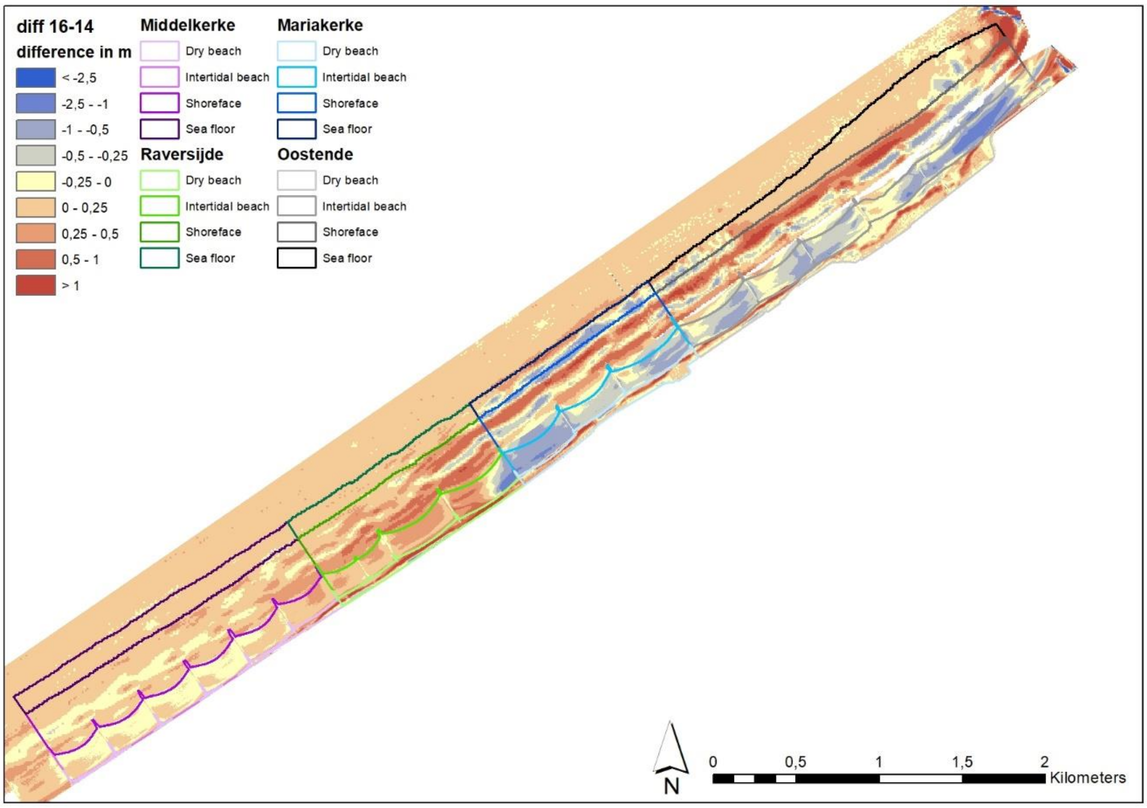
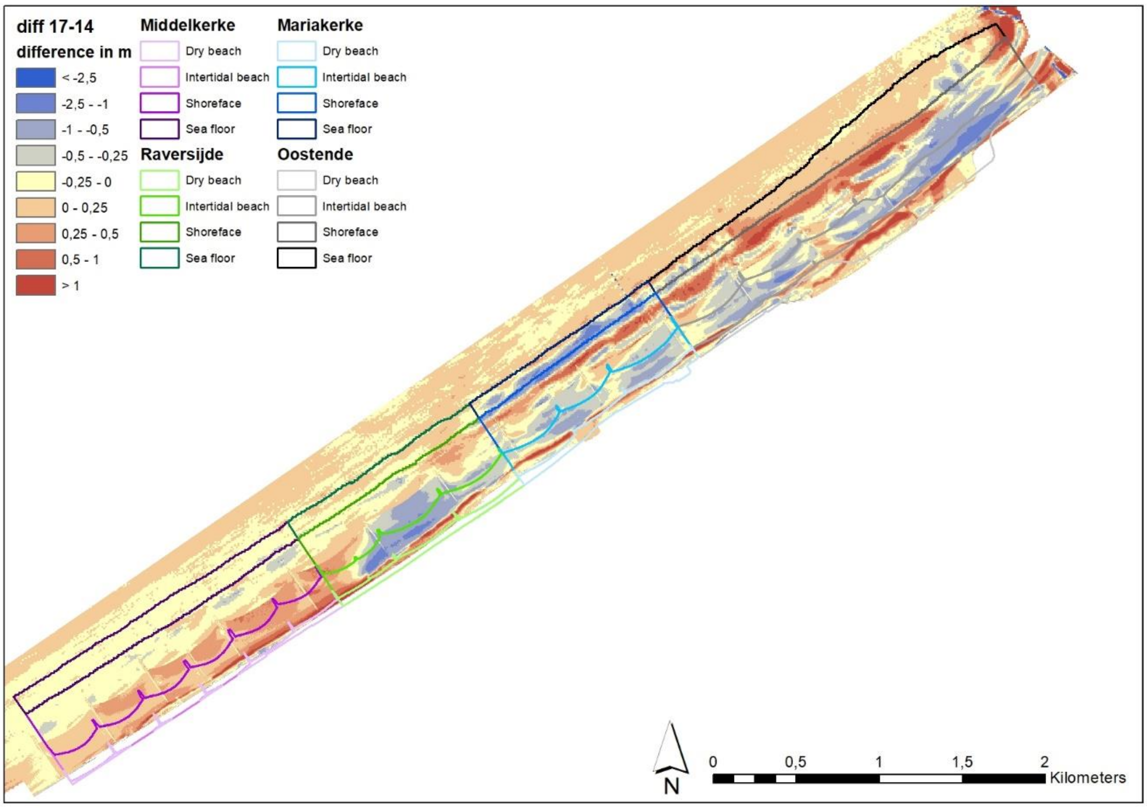


Figure 20 - Volume difference between 2017 and 2014.




### 4.1.1 Shoreface

The shoreface and sea floor sectors display a very similar evolution, with a gain in volume in the first two years and loss in the last year. Probably, the sand lost from this area can be found close to the port jetty accumulating further seaward, outside of the study area as it was defined before the nourishment experiment. The extension of Oostende port was performed relatively recent, in 2011, therefore the accommodation space created here is still to be filled out in the next years, as these jetties are impermeable to the alongshore sediment transport. However, accumulation against the jetties created a shallow area which make possible the transfer of sediments outside of the study zone (Figure 21 and Figure 22).

### 4.1.2 Beach

The intertidal beach show consistent evolution with rapid initial volume decrease due to the fact that the majority of the beach nourishment was placed in this area, so easier to erode in the initial stage. However, in the later years this area start to accumulate sand, most probably as results of human interventions (local redistribution of sand, additional nourishments). Although at slower pace, the dry beach volume increased in the three years of its post-nourishment evolution, mostly due to the aeolian transport (Figure 21 and Figure 22).

Figure 21 - Evolution of the four beach parts having as reference the pre-nourishment situation.

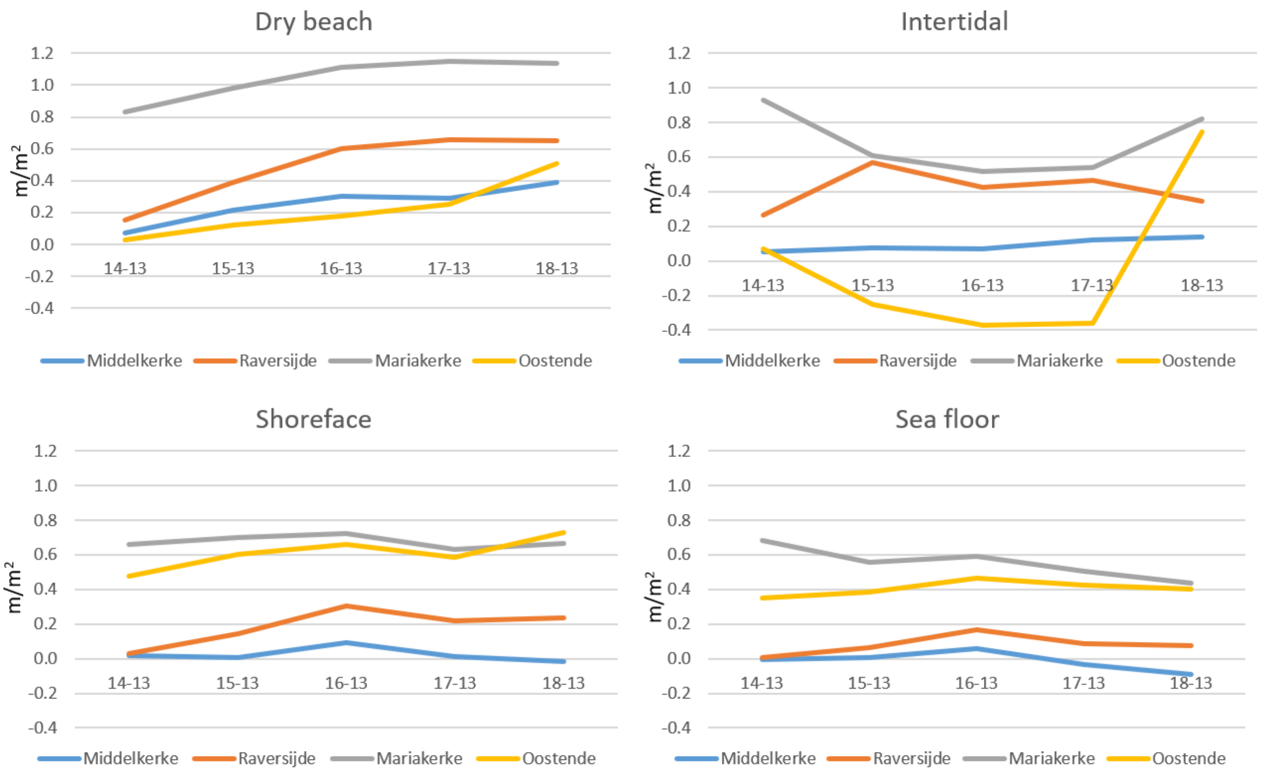
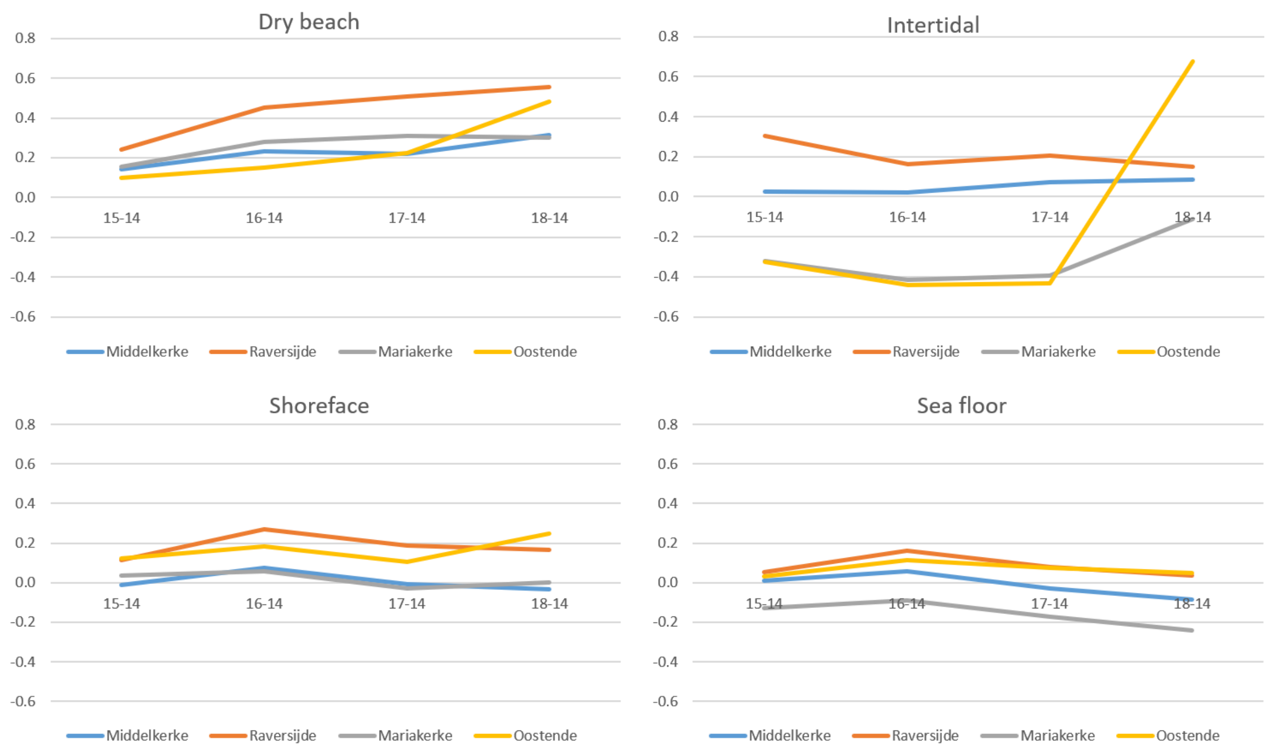



Figure 22 - Evolution of the four beach parts having as reference the post-nourishment situation.



### 4.1.3 Dunes/Cliff

Most of the study zone is confined landwards by hard structures such as sea walls and transport infrastructure, therefore an investigation of the effects of the nourishments to the dunes was not performed. Berms on the upper beach with a height above 7.00 m TAW and at a distance around 40 m from the dyke were always present. They were also characterized by a steep slope either driven by natural processes (storm) or human interference (bulldozers scraping beach). Under storm diving process, these berms could be referred as cliffs. Ridges of a few decameters high and above 4 m TAW were observed after some storms, last time in September and December 2019 and they were built by wave processes under energetic conditions.

### 4.1.4 Overall

## 4.2 Coastal state indicators

### 4.2.1 Volume changes 1D

The nourishments carried out at the study zone between 2013 and 2013 strongly influenced the evolution of the entire active beach. In order to evaluate the changes in relation with the beach trend evolution during a longer period a comparison in trends was made for three periods: 2006 – 2019, 2013 – 2017 and 2014 – 2017 (Table 3).

The coast evolution trends were calculated for the period 2006 to 2019 by Houthuys et al. (2019). The active beach was divided in two parts, mainly based on the survey method: dry and intertidal beach measured twice a year using a LIDAR system and shoreface and sea floor measured yearly using mostly single beam system, but also on the definition of the coastal divisions (Figure 12). The trends for the active beach were calculated for two distinctive parts: 1) the emerged beach including the dry and intertidal beach and 2) the submerged beach including the shoreface and the sea floor. The trends were calculated for two situations, first for the corrected volumes, so the sand supplied or dredged from the system by human activities was subtracted and secondly, for the observed volumes as they were measured on the active beach.

In the present study the approach was different, the volumes of sand were expressed in two ways, first as total per sediment budget box and then as volume per unit of surface in order to detect the changes in beach morphology due to the nourishments performed at the study zone. However, to compare the beach evolution trends on a longer period to the shorted post-nourishment period (3 years) the volumes of sand were expressed in the same way as in Houthuys et al. (2019). Two periods were defined for comparison: 2013 pre-nourishment to 2017 and 2014 post-nourishment to 2017 (Table 3).

It is clear that the beach trends for the period 2013 to 2017 are showing an increase in volume when compared to a longer period (2006 – 2019) due to the large volumes deployed in the area. Even areas such as Middelkerke with no nourishment of sand nourished show a reversed trend with most of the beach parts increasing in volume. The cause of this trend is the large nourishment carried out just updrift of Middelkerke in 2014 (no. 5 in sub-chapter 3.2). However, the submerged beach in this area is losing sand, but at slower rate than on the longer period.

At Raversijde despite the low volumes of sand nourished, there is a clear reversal of the trends from erosive on long term to accumulative for the short post-nourishment time period.

At Mariakerke there is a clear trend of erosion for the long period and this trend was reversed or slowed down by the large volumes of sand deployed here. This large volume also led to faster redistribution of this sand after nourishment, but three years after the nourishment the trends are still of a strong increase for the entire active beach. Evolution of the nourishment after 2014 show that the sand is still removed from the this area, but at slower rates than for the longer period. The area losing most of the sand is the intertidal beach while the shoreface nourishment is eroding at modest rates, 10 – 20 times lower than before. The loss of sand from the sea floor is significant, but it is believed that this loss is supporting the inshore migration of the shoreface sand bar/s.

At Ostend area the erosive trend observed for the longer period was also reversed by the nourishments. Most of the beach still show considerable increase for the short period, excepting for the intertidal beach where a decrease in volume was observed. This evolution is partially natural due to inherent re-organisation of the nourishments, but also due to human activities related to beach preparation for various activities.

Comparing the evolution of the beach evolution trends for two periods, long term (2006 – 2019) term and medium term (2013 – 2017) at the entire study zone show generally reversion of the coastal trends from erosive to accumulative, indicating the success of the nourishment. There is still some erosion in some beach sector, but at much lower rates than before. This erosion area were inevitable as the sand is redistributed in the nearshore system with clear morphological trends, the same as those observed in the DEMs comparisons:

1. Accumulation at the dry beach.
2. Intertidal beach, accumulation at Middelkerke and Raversijde, erosion at Mariakerke and Ostend.
3. Shoreface: accumulation at Raversijde and Ostend, erosion at Middelkerke and Mariakerke.
4. Stability of the sea floor, except for Mariakerke.

Table 3 - Comparisons between the measured beach trends for the medium term (report Houthuys et al., 2019) and the trends for short term (2013 to 2017) at the study zone. Location of the sections in Figure 12.

| **Sections** | **Report Houthuys, 2019 Period from 2006 to 2019 in m³/m/year** | | | | **Present study in m³/m/year** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Corrected volumes* | | *Observed volumes* | | *Trend pre-nourishment 2013 to 2017* | | | | *Trend post-nourishment 2014 to 2017* | | | |
| | Dry and intertidal (emerged) | Shoreface and sea floor (submerged) | Dry and intertidal (emerged) | Shoreface and sea floor (submerged) | Dry beach | Intertidal beach | Shoreface | Sea floor | Dry beach | Intertidal beach | Shoreface | Sea floor |
| Middelkerke 88-92 | **Increase** +3.5 | **Decrease** -16.3 | **Increase** +9.78 | **Decrease** -16.3 | **Increase** +1.1 | **Increase** +5.0 | **Increase** +1.0 | **Decrease** -1.1 | **Increase** +1.1 | **Increase** +4.0 | **Decrease** -0.8 | **Decrease** -1.3 |
| | Trend entire beach: **decrease** -16.3 | | Trend entire beach: **decrease** -6.5 | | | | | | | | | |
| Middelkerke 93 – 97 | **Decrease** -0.5 | **Decrease** -20.5 | **Increase** +5.5 | **Decrease** -20.5 | | | | | | | | |
| | Trend entire beach: **decrease** -20.9 | | Trend entire beach: **decrease** -14.9 | | Emerged beach: **increase** +3.1 | | Submerged beach: **decrease** -0.1 | | Emerged beach: **increase** +2.5 | | Submerged beach: **decrease** -1.1 | |
| Middelkerke 88 - 97 | Trend entire beach: **decrease** -18.6 | | Trend entire beach: **decrease** -10.7 | | Trend entire beach: **increase** +1.5 | | | | Trend entire beach: **increase** +1.5 | | | |
| Raversijde 98-102 | **Decrease** -5.6 | **Decrease** -10.8 | **Decrease** -5.0 | **Decrease** -8.4 | **Increase** +9.6 | **Increase** +16.1 | **Increase** +14.8 | **Increase** +2.0 | **Increase** +9.8 | **Increase** +9.4 | **Increase** +16.8 | **Increase** +2.4 |
| | | | | | Emerged beach: **increase** +12.9 | | Submerged beach: **increase** +8.4 | | Emerged beach: **increase** +9.6 | | Submerged beach: **increase** +9.6 | |

| | | | | |
|---|---|---|---|---|
| | Trend entire beach:<br>decrease -16.4 | Trend entire beach:<br>decrease -13.4 | Trend entire beach: increase +10.7 | Trend entire beach: increase +9.6 |
| Mariakerke 103-105 | Decrease -13.9 / Decrease -18.1<br><br>Trend entire beach:<br>decrease -32.7 | Decrease -36.9 / Increase +11.5<br><br>Trend entire beach:<br>decrease -25.3 | Increase +13.0 / Increase +20.9 / Increase +44.5 / Increase +14.1<br><br>Emerged beach: increase +17.0 / Submerged beach: increase +29.3<br><br>Trend entire beach: increase +23.2 | Increase +4.70 / Decrease -20.4 / Decrease -2.7 / Decrease -6.5<br><br>Emerged beach: decrease -7.9 / Submerged beach: decrease -4.6<br><br>Trend entire beach: decrease -6.3 |
| Ostend 106-108 | Decrease -15.8 / Decrease -6.6<br><br>Trend entire beach:<br>decrease -22.5 | Decrease -51.3 / Increase +9.5<br><br>Trend entire beach:<br>decrease -41.9 | Increase +5.0 / Decrease -12.3 / Increase +37.3 / Increase +15.3 | Increase +5.9 / Decrease -19.7 / Increase +9.1 / Increase +3.6 |
| Ostend 109-112 | Increase +1.8 / Decrease -23.9<br><br>Trend entire beach:<br>decrease -22.1 | Decrease -66.5 / Decrease -6.9<br><br>Trend entire beach:<br>decrease -73.4 | Emerged beach: decrease -3.7 / Submerged beach: increase +26.3 | Emerged beach: decrease -6.9 / Submerged beach: increase +6.3 |
| Ostend 113-117 | Decrease -14.5 / Decrease -20.0<br><br>Trend entire beach:<br>decrease -34.5 | Decrease -39.9 / Increase +16.4<br><br>Trend entire beach: :<br>decrease -23.5 | | |
| Ostend 106 – 117 | Trend entire beach:<br>decrease -26.4 | Trend entire beach:<br>decrease -46.6 | Trend entire beach: increase +11.3 | Trend entire beach: decrease - 0.3 |

### 4.2.2 Volume changes 2D

The dynamics of the nourished volumes is significant and keeps constant trends. In Table 4 a detailed situation of the absolute volumes is presented and the warm colours show deposition, while the cold colours indicate erosion. The analysis of the volumes reflects the trends observed in the sub-chapter **Fout! Verwijzingsbron niet gevonden.** while quantifying the changes for each along and cross-shore beach unit.

In Table 5Table 6 the efficiency of the nourishments is presented by calculating the remaining sand in each of the four areas every year: Middelkerke, Raversijde, Mariakerke and Ostend; from the dyke until the -6 m TAW depth contour. As sometimes the nourishment locations do not exactly coincide with the defined areas, a new calculation was made and every nourishment was divided proportionally to each box area.

| | | 14-13 | 15-13 | 16-13 | 17-13 | 18-13 | 15-14 | 16-14 | 17-14 | 18-14 | 16-15 | 17-15 | 18-15 | 17-16 | 18-17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Middelkerke | Dry beach | 2 112 | 6 266 | 8 758 | 8 400 | 11 183 | 4 097 | 6 647 | 6 279 | 9 090 | 2 425 | 2 179 | 4 998 | -1 229 | 2 798 |
| | Intertidal | 16 196 | 24 831 | 22 266 | 39 460 | 43 806 | 8 587 | 7 275 | 23 321 | 27 606 | -4 238 | 14 745 | 17 268 | 14 018 | 4 277 |
| | Shoreface | 12 400 | 5 127 | 56 102 | 7 692 | -8 270 | -7 091 | 43 905 | -4 477 | -20 453 | 47 528 | 2 746 | -16 437 | -54 143 | -15 920 |
| | Sea floor | -871 | 1 801 | 13 903 | -8 832 | -22 842 | 2 782 | 14 831 | -7 860 | -21 858 | 10 855 | -10 526 | -25 732 | -24 609 | -13 883 |
| Raversijde | Dry beach | 11 548 | 30 017 | 46 361 | 50 539 | 50 263 | 18 448 | 34 812 | 38 960 | 42 913 | 15 320 | 18 262 | 23 951 | 2 104 | 4 597 |
| | Intertidal | 48 115 | 103 683 | 77 757 | 85 057 | 62 267 | 55 597 | 29 632 | 37 009 | 27 294 | -27 130 | -20 889 | -29 487 | 4 988 | -9 681 |
| | Shoreface | 11 330 | 51 941 | 107 542 | 77 915 | 84 033 | 40 664 | 96 279 | 66 721 | 59 593 | 53 498 | 24 489 | 16 948 | -33 429 | -7 171 |
| | Sea floor | 1 047 | 7 567 | 20 226 | 10 524 | 9 380 | 6 567 | 19 273 | 9 549 | 4 379 | 11 915 | 2 529 | -2 805 | -10 974 | -5 012 |
| Mariakerke | Dry beach | 49 752 | 58 927 | 66 450 | 68 763 | 67 932 | 9 376 | 16 692 | 18 619 | 18 153 | 6 753 | 7 670 | 8 009 | 380 | -444 |
| | Intertidal | 191 373 | 125 610 | 106 379 | 110 497 | 168 292 | -65 795 | -84 997 | -80 900 | -23 100 | -20 069 | -17 525 | 42 002 | 1 571 | 57 753 |
| | Shoreface | 245 457 | 259 019 | 267 552 | 235 126 | 246 057 | 13 545 | 22 056 | -10 541 | 380 | 6 883 | -27 722 | -14 406 | -36 375 | 10 798 |
| | Sea floor | 100 677 | 82 034 | 87 398 | 74 517 | 64 595 | -18 763 | -13 257 | -25 738 | -35 826 | 4 665 | -8 806 | -18 069 | -14 296 | -9 868 |
| Ostend | Dry beach | 5 741 | 25 750 | 37 025 | 52 131 | 104 912 | 20 276 | 31 145 | 46 400 | 99 343 | 10 327 | 22 689 | 77 328 | 12 102 | 53 082 |
| | Intertidal | 25 645 | -90 790 | -133 466 | -129 848 | 268 988 | -116 461 | -159 119 | -155 502 | 243 309 | -44 256 | -44 317 | 358 439 | -1 953 | 398 689 |
| | Shoreface | 318 725 | 401 362 | 443 140 | 392 255 | 486 144 | 80 967 | 122 478 | 71 535 | 165 495 | 38 378 | -13 066 | 81 600 | -59 197 | 93 681 |
| | Sea floor | 132 913 | 144 873 | 176 046 | 160 870 | 150 703 | 11 554 | 43 109 | 28 204 | 17 779 | 30 200 | 15 093 | 4 893 | -18 770 | -10 308 |

Table 4 – Volume differences matrix between all surveyed years and all along- and cross-shore divisions (in $m^3$) in absolute values. Colour code correspond to the one used in Figure 14 to Figure 20.

Table 5 – Volume differences matrix between all surveyed years and all along- and cross-shore divisions (in m³), normalized for the surface of every unit (in m²). Colour code correspond to the one used in Figure 14 to Figure 20.

| | | 14-13 | 15-13 | 16-13 | 17-13 | 18-13 | 15-14 | 16-14 | 17-14 | 18-14 | 16-15 | 17-15 | 18-15 | 17-16 | 18-17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Middelkerke | Dry beach | 0.07 | 0.22 | 0.30 | 0.29 | 0.39 | 0.14 | 0.23 | 0.22 | 0.31 | 0.08 | 0.08 | 0.17 | -0.04 | 0.10 |
| | Intertidal | 0.05 | 0.08 | 0.07 | 0.12 | 0.14 | 0.03 | 0.02 | 0.07 | 0.09 | -0.01 | 0.05 | 0.05 | 0.04 | 0.01 |
| | Shoreface | 0.02 | 0.01 | 0.09 | 0.01 | -0.01 | -0.01 | 0.07 | -0.01 | -0.03 | 0.08 | 0.00 | -0.03 | -0.09 | -0.03 |
| | Sea floor | 0.00 | 0.01 | 0.06 | -0.04 | -0.09 | 0.01 | 0.06 | -0.03 | -0.09 | 0.04 | -0.04 | -0.10 | -0.10 | -0.06 |
| Raversijde | Dry beach | 0.15 | 0.39 | 0.60 | 0.66 | 0.65 | 0.24 | 0.45 | 0.51 | 0.56 | 0.20 | 0.24 | 0.31 | 0.03 | 0.06 |
| | Intertidal | 0.26 | 0.57 | 0.43 | 0.47 | 0.34 | 0.31 | 0.16 | 0.20 | 0.15 | -0.15 | -0.11 | -0.16 | 0.03 | -0.05 |
| | Shoreface | 0.03 | 0.15 | 0.30 | 0.22 | 0.24 | 0.11 | 0.27 | 0.19 | 0.17 | 0.15 | 0.07 | 0.05 | -0.09 | -0.02 |
| | Sea floor | 0.01 | 0.06 | 0.17 | 0.09 | 0.08 | 0.05 | 0.16 | 0.08 | 0.04 | 0.10 | 0.02 | -0.02 | -0.09 | -0.04 |
| Mariakerke | Dry beach | 0.83 | 0.98 | 1.11 | 1.15 | 1.13 | 0.16 | 0.28 | 0.31 | 0.30 | 0.11 | 0.13 | 0.13 | 0.01 | -0.01 |
| | Intertidal | 0.93 | 0.61 | 0.52 | 0.54 | 0.82 | -0.32 | -0.41 | -0.39 | -0.11 | -0.10 | -0.09 | 0.20 | 0.01 | 0.28 |
| | Shoreface | 0.66 | 0.70 | 0.72 | 0.63 | 0.66 | 0.04 | 0.06 | -0.03 | 0.00 | 0.02 | -0.07 | -0.04 | -0.10 | 0.03 |
| | Sea floor | 0.68 | 0.56 | 0.59 | 0.50 | 0.44 | -0.13 | -0.09 | -0.17 | -0.24 | 0.03 | -0.06 | -0.12 | -0.10 | -0.07 |
| Oostende | Dry beach | 0.03 | 0.12 | 0.18 | 0.25 | 0.51 | 0.10 | 0.15 | 0.22 | 0.48 | 0.05 | 0.11 | 0.37 | 0.06 | 0.26 |
| | Intertidal | 0.07 | -0.25 | -0.37 | -0.36 | 0.75 | -0.32 | -0.44 | -0.43 | 0.68 | -0.12 | -0.12 | 1.00 | -0.01 | 1.11 |
| | Shoreface | 0.48 | 0.60 | 0.66 | 0.59 | 0.73 | 0.12 | 0.18 | 0.11 | 0.25 | 0.06 | -0.02 | 0.12 | -0.09 | 0.14 |
| | Sea floor | 0.35 | 0.38 | 0.47 | 0.43 | 0.40 | 0.03 | 0.11 | 0.07 | 0.05 | 0.08 | 0.04 | 0.01 | -0.05 | -0.03 |

Table 6 – The volumes of sand remaining after nourishment realised in 2013-2014 considering an efficiency of 85% of the sand volumes measured on the ship.

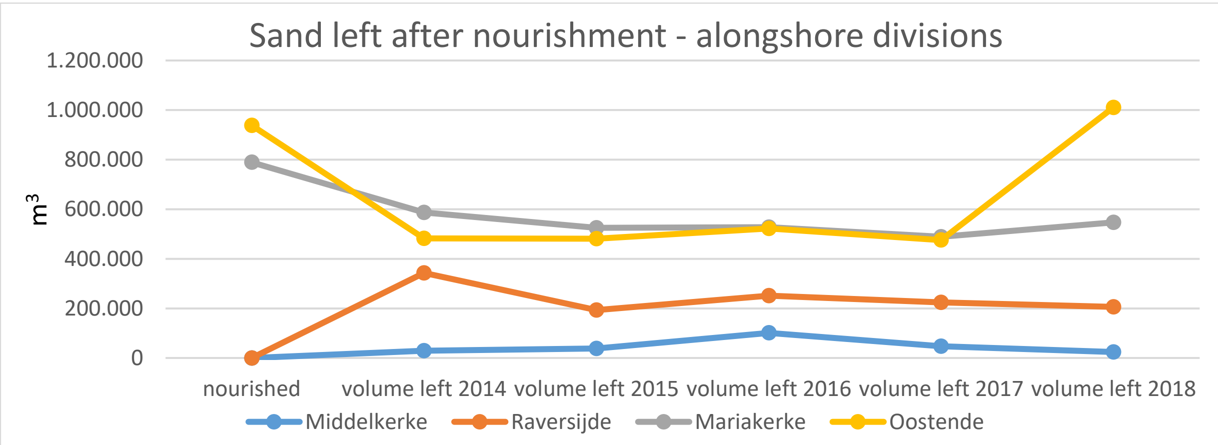
| Sand volumes m$^3$ | Middelkerke | Raversijde | Mariakerke | Ostend |
|---|---|---|---|---|
| Total nourished until survey 2014 | 0 | 68,000 | 670,693 | 797,428 |
| Beach | | 68,000 | 477,020 | 383,435 |
| Shoreface | | 0 | 193,673 | 413,993 |
| Volume left 2014 | 29,837 | 72,040<br>**106%** | 587,259<br>**88%** | 483,024<br>**61%** |
| Volume added in 2014 after survey | | 162,265 | | |
| Volume left in 2015 | 38,025 | 193,208<br>**84%** | 525,589<br>**78%** | 481,195<br>**60%** |
| Volume left in 2016 | 101,029 | 251,887<br>**109%** | 527,779<br>**79%** | 522,745<br>**66%** |
| Volume left in 2017 | 46,719 | 224,035<br>**97%** | 488,904<br>**73%** | 475,408<br>**60%** |
| Volume added in 2018 | | | | 360936 |
| Volume left in 2018 | 23,877 | 205,944<br>**89%** | 546,876<br>**82%** | 1,010,748<br>**87%** |

During the period 2013 – 2014 a total volume of 1,807,200 m$^3$ of sand was nourished to the study zone. Apart from the morphological processes, there are also practical reasons for the loss of the initially nourished sand volume. Houthuys (2012 and 2019) estimates a typical loss of the nourished volume of 15% due to sand compaction (water and air expelled from the porous area existent in the sand), reporting and measurement errors. Accounting for these losses the total initial volume is estimated at 1,536,120 m$^3$. Three years after 1,188,347 m$^3$ of sand is still present in the area, this representing an average efficiency of 77% for the areas Raversijde, Mariakerke and Ostend. For Middelkerke there is no calculation of the efficiency since there was no nourishment carried out in that area. However, this area probably received sand from the nourishment realized just updrift in 2014 explaining the rise in volume in 2016.The Raversijde area shows the best efficiency and this can be explained by the relatively low volume of sand placed here but also by the constant supply of sand from the updrift area. Mariakerke has an average efficiency caused by a large amount of sand deployed here over a larger part of the beach profile increasing the sediment transport. Ostend area show the lowest efficiency and the most probable explanation is related to the accumulation of sand outside of the control box, defined for the bathymetry of 2013. In the years following the sand accumulated in this area very rapid also promoting the transport around the port due to increasing shallower water depths (Figure 23).

The volumes of sand at the two adjacent areas have a very different evolution (Figure 24): Middelkerke has a rather constant evolution while the Ostend area starts with a decrease of the sand volume and it continues with an increase in the volume due to both natural circulation of the net alongshore, but also due to human interventions such nourishments in the vicinity of the study zone. The two areas subject of the nourishment experiment have also a different evolution. For the Raversijde area the increase at the beginning of the period is explained by the later beach nourishment, therefore not recorded in the comparison 2013 – 2014. The later evolution is normal, with constant, but slow loss of sand. At Mariakerke the evolution is the most dynamic because the largest amounts of sand were deployed here, placing the active beach out of the local equilibrium and resulting in rapid erosion in the first year. The later evolution show a slight increase for the sand volume due the influx from the Raversijde area and then slightly decrease.

Figure 23 – The submerged (during high tide) groin attached to the southern jetty of the Ostend port which is trapping large volumes of sand (Google Earth 2019).


Figure 24 – Variation of the nourished volumes at the study zone.




The possible causes for the 23%, approximately 347 000 $m^3$, sand loss from the study zone three years after the nourishments are listed below in the estimated order from larger to smaller:

1. Sand circulating alongshore towards NE, further from the partially submerged groin attached at the lee side to Ostend port southern jetties.
2. Aeolian transport transporting sand over the landward boundary of the active beach.

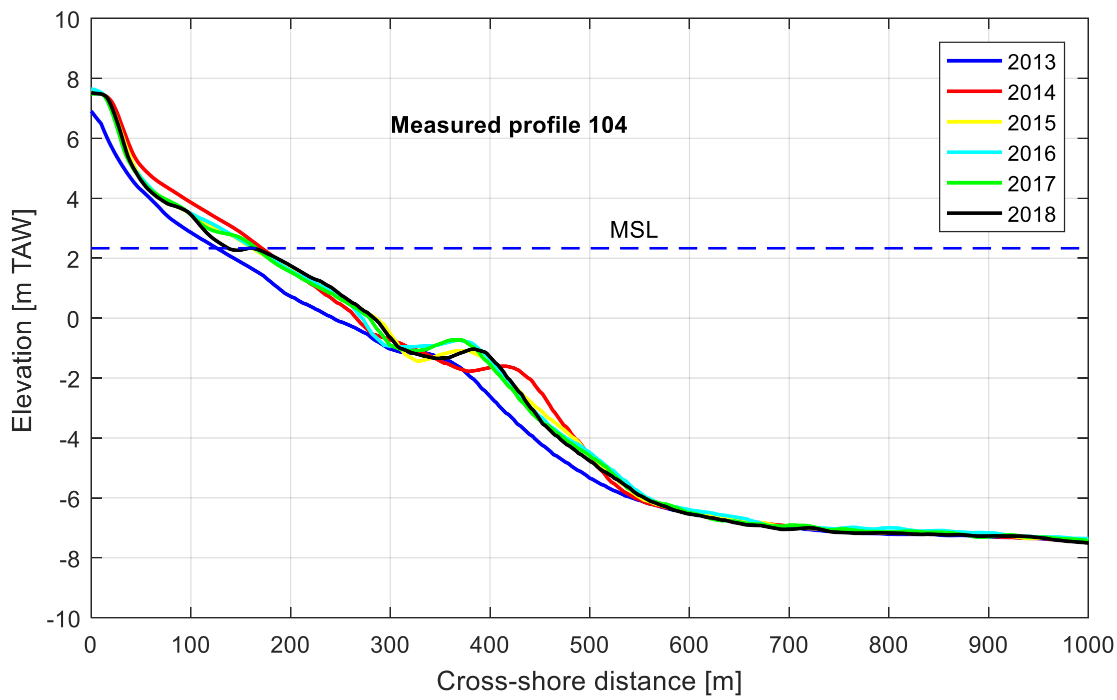
3. Small losses offshore, not visible on the digital elevation models comparison since they are below the margin error for topo-bathymetric surveys and processing error.
4. Further compaction due continuous re-arranging of the nourished sand.
5. Accommodation space created by the sea level rise.

### 5.2.3 Bar development

Figure 25 shows the changes of the representative cross-shore profile for the Mariakerke coastal area (profile 104, middle of the section) from 2013 to 2018. Both the beach and shoreface nourishment were conducted in 2014. The bathymetry in 2014 is measured in May right after the shoreface nourishment while beach topography was conducted in April, about two months after finishing the beach nourishment. As the results of the beach and shoreface nourishment, the seaward movement of the profile 2014 (after nourishment) compared to that in 2013 (before nourishment) is clearly observed. The beach is widened up to 80m and the berm of about 55 m is observed at the level of -2m TAW.

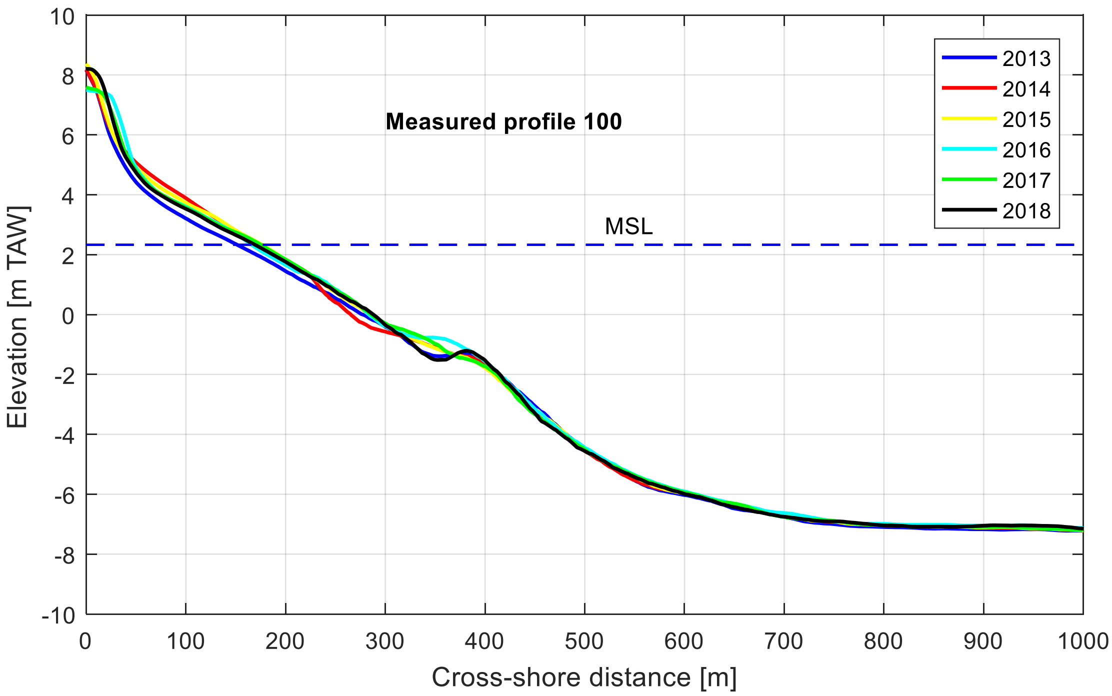
After nourishment, the strongest morphological changes are observed in the first year 2014-2015. The nourished beach was eroded and the shoreface nourished sand seems to be transported landward. The artificial sand berm (as the result of the shoreface nourishment) moved landward and raised about 1m to the level of -1.5m TAW after one year. The process continued in the next year in 2016. Little change is observed in the year 2016-2017. In 2018, the berm returned to its position of 2015.

Figure 25 – Evolution of the cross-shore profile at Mariakerke: profile 104



The changes of the profile 100 located in Raversijde (middle of the section) are also analyzed (Figure 26). This profile represents for the coastal area where only beach nourishment was carried out (in June 2014). Note in this analysis that the topo-bathymetry of the beach in the Raversijde area for 2014 was conducted in November (i.e. five months after beach nourishment campaign in June 2014). Compared to the profile in 2013, the one in 2014 moved seaward due to the beach nourishment in June 2014. The changes are  much smaller than that for the Mariakerke case. This is mainly is due to the fact that the amount of nourished sand is smaller for Raversijde and the topography used in the analysis is measured much longer after conducting beach nourishment for Raversijde than for Mariakerke.

Figure 26 – Evolution of the cross-shore profile at Raversijde: profile 100




# 5. Local Characteristics (during lifespan nourishment)

## 5.1. Tides

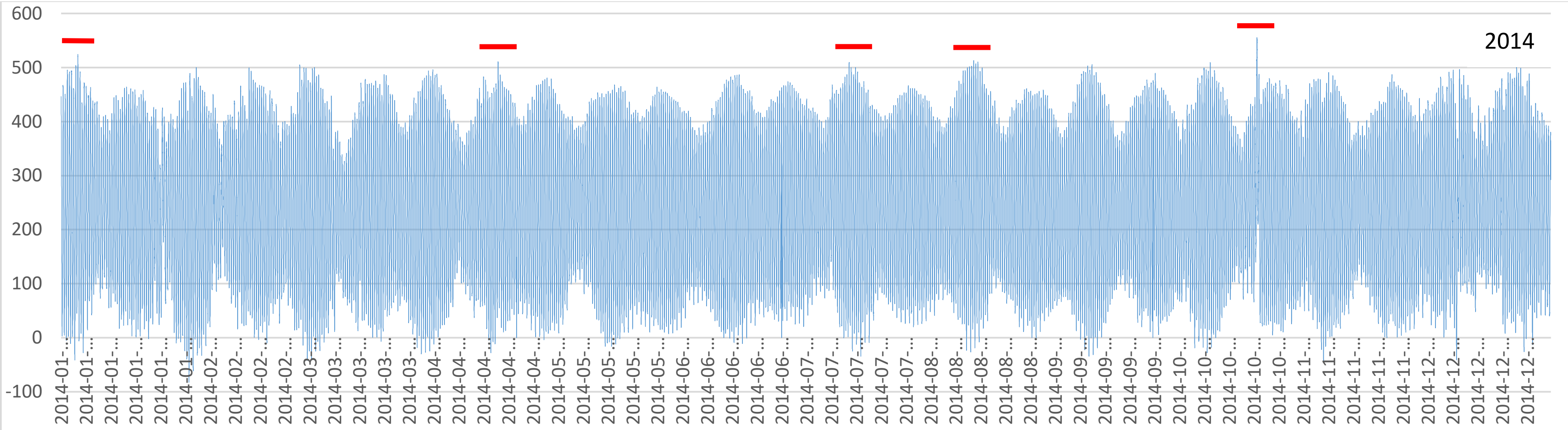
No evidence of the tides changing after the nourishment.

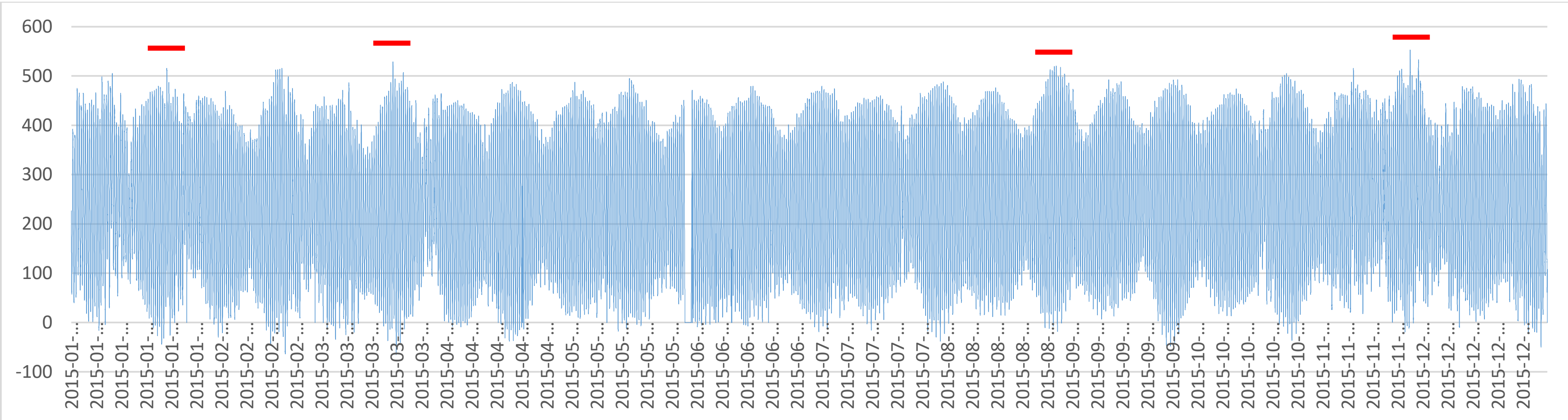
## 5.2. Storm surges

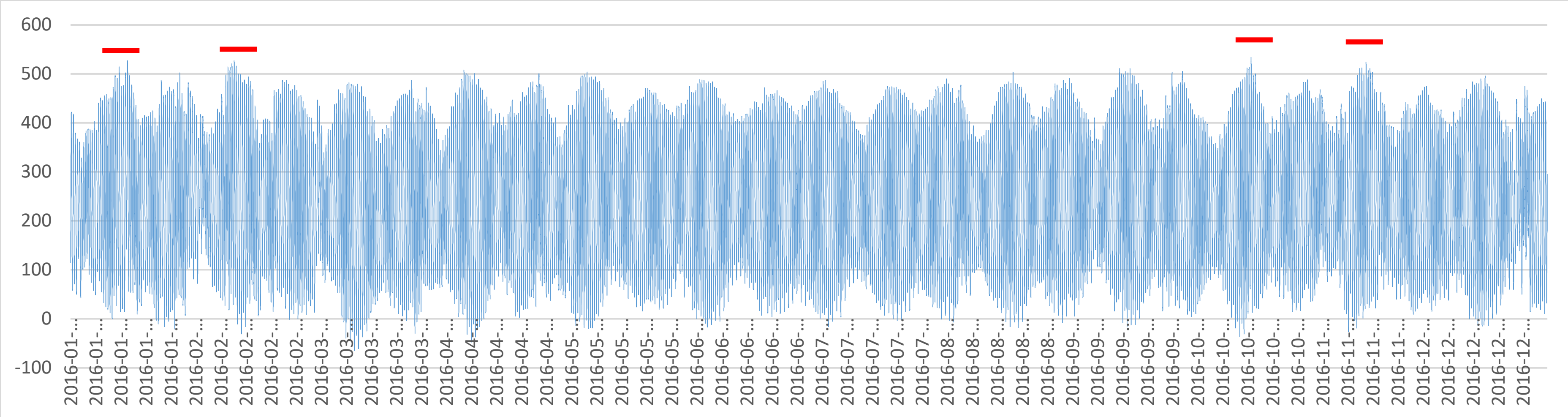
The impact of the storm surges during the study period was not assessed in detailed, but a number of significant surges took place as indicated in Figure  27. The red lines indicate the moment when the water level was larger than 5.00 m TAW, which can be considered the highest water level due only spring tide at calm weather. The water levels exceeding this threshold can be considered storm surges.

This storm surges occurred 4 to 6 times per year, especially during autumn and winter. The largest water level during the study period occurred on 14 January 2017 and it was 5.65 m TAW.

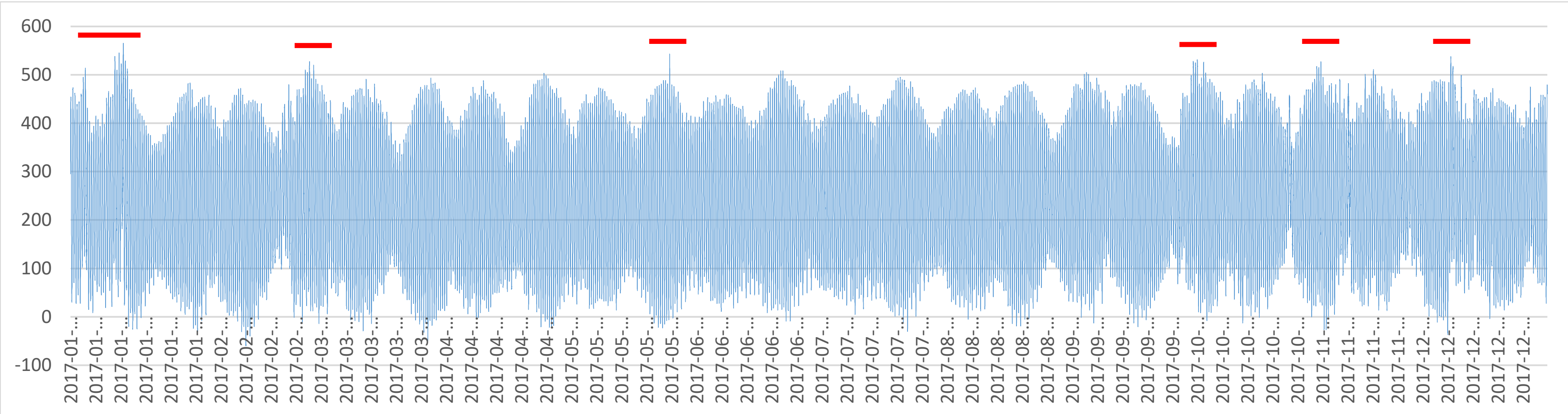
Figure 27 – Water level measured at Ostend harbor.





600
500
400
300
200
100
0
-100

600
500
400
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200
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0
-100

# 6. Conclusions

The present study investigated the evolution of a coastal nourishment experiment during the period 2013 and 2018. Two adjacent coast areas Raversijde and Mariakerke were supplied both with beach nourishment (sand deployed on the intertidal and dry beach) while the last also with a shoreface nourishment (placed on the submerged beach down to depths of -5.00 TAW). For a better understanding of sand dynamics two more areas neighbouring the experiment coast areas were considered, one situated downdrift, Middelkerke and one situated updrift, Ostend.

<u>Evolution of the sand volumes deployed into the area.</u>

The nourished sand at the entire study zone show generally low rates of erosion. The majority of the sand is still in the coastal system three years after the nourishments were carried out. The average efficiency three years after the nourishment is 77% for the three coastal zones where the nourishments were performed, decreasing in the direction of the alongshore transport from 97% at Raversijde to 73% at Mariakerke and 60% at Ostend. The estimation of the efficiency was limited to three years due to new nourishments which were performed in the area in 2018.

Possible explanations for the retention of the sand in the area are related to: 1) the accommodation space created at the downdrift side of the study area by the extension of the Ostend port; 2) the mild wave climate in the study area during monitoring period; 3) continuous human interventions at the study site by local redistribution of the sand on the intertidal and dry beach and by performing nourishments at the adjacent areas; 4) the grain size of the nourished sand being coarser than the local sediment.

However, not all the nourished sand can be found in the area and the possible explanations are related to: 1) further sand compaction after deployment; 2) various errors in measuring the volumes of sand, topo-bathymetric surveys and processing; 3) in particular for the Ostend area the accumulation of sand outside of the control box, defined for the pre-nourishment bathymetry (2013) - in the years following the sand accumulated in this area very rapid and enhance the transport around the port due to increasing shallower water depths; 4) losses of sand at the landward boundary (sand blown by the wind on the promenade or on the tramline) and at the offshore boundary of the study zone; 5) accommodation space created by the sea level rise during; the last two are quantitively minor, but still contributing to the total sand budget.

<u>Evolution of different parts of the study zone.</u>

The morphological evolution of the coastal areas after nourishment is showing rapid re-organisation of the sand. The intertidal beach has the most dynamic evolution due to the large amount of sand that was placed here and, due to the intense hydrodynamic forcing even during mild weather conditions and due to human interventions (beach levelling). The sand nourished on the shoreface at the Mariakerke evolved rapidly and while part of it migrated downdrift, most of it formed a submerged bar which moved predominantly landwards. The dry beach gained volume by aeolian transport supplying sand from the intertidal beach. The sea floor sector considered initially outside of the active beach displays a similar dynamics as the shoreface resulting in a new value for the closure depth at a yearly scale at approximately -6.00 m TAW.

Middelkerke area gains sand from the updrift adjacent area (large nourishment performed there), Raversijde keeps much of the relatively small volume of sand nourished here, Mariakerke area lost sand at a rather constant rate, Ostend area lost sand more rapid than the other sectors, mostly in the alongshore towards NE.

There are two clear migration patterns for the sand: cross-shore with tendency for the sand to accumulate on the dry beach and on the shoreface as a dynamic sand bar; and alongshore towards the Ostend port.

Although the volume difference maps indicate the dry and intertidal areas as being dynamic the analysis of the beach profiles carried out monthly for several years do not show any clear trend for the slope or width variation. The comparison between the medium term and the short term evolution of the study area reveals that the erosive trends were reversed for most of the beach parts highlighting the stability of the nourishments. Three years after nourishment the trends are consistently positive and they are expected to maintain on medium term enhancing the coastal safety at the study zone.

Sediment transport

The cross-shore transport played a significant role on short term (probably months) in the local redistribution of the sand just after the nourishment, as indicated by migration of the sand bars at the Mariakerke and Ostend area as well as relatively rapid redistribution of the sand nourished on the intertidal beach. On the medium and long term the alongshore sediment transport is the main driving force for the evolution of the study zone. Several facts support this evidence: gain in sand volumes at Middlekerke area from the updrift area, relatively stability at Raversijde and accumulation of sand close to the Ostend port jetties.

Reference sections

Sections 100 and 104 situated at Raversijde and Mariakerke, respectively were selected for comparison between different types of nourishment. Both section indicate accumulation with respect to the situation pre-nourishment, but in the case of Mariakerke the shoreface nourishment is clearly visible as a submerged sand bar which migrates back and forth, but at a location closer to the shore than the initial deployment. At Mariakerke, section 104, the entire active beach is more dynamic as a consequence of the larger volume of sand nourished here. Three year after the nourishment elevation of the profile 104 increased more than in the case of section 100, Raversjide, clearly increasing the safety against the severe storms.

Efficiency of the shoreface nourishment

The shoreface nourishment provides a certain protection against flooding by decreasing the wave height during different wave conditions. The shoreface nourishment is rather stable, most of the initial volume being still in place after three years. After a rapid loss the volume of the submerged bar seems to stabilize and fed with sand by the adjacent areas.

A very precise estimation of the shoreface nourishment is difficult to be done due to many influences on the study zone such as nourishments performed in the vicinity or inside of the study zone during the experiment and re-distribution of the sand on the dry and intertidal beach performed by the local authorities before summer and before winter. However, the shoreface area shows a large increase in volume when compared with the pre-nourishment situation and much lower rates of erosion than during the decade before.

An indirect positive influence on the safety of the coast generated by the shoreface nourishment is the increase of the active beach volume. As a strong storm decrease the safety level of the beach a larger sand volume at shoreface is available for the rebuilding of the aerial and intertidal beach during calmer periods.

A shoreface nourishment is a good measure for coastal protection and its protection effects is clear on medium term and probably also on long term. The safety against extreme storms, such as the one with the return period in 1000 year was not estimated in the current project since a different project will investigate this for the entire Belgian coast. To meet all the safety criteria at the Belgian coast it is recommended to use the shoreface in combination with the beach nourishment because the shape of the entire active beach profile is influencing the probability of the flooding

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