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Definition of storm thresholds for significant morphological change of the sandy beaches along the Belgian coastline

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ABSTRACT

In this paper a storm threshold for significant morphological change along the Belgian coastline is presented. Using a dataset covering topography, bathymetry and hydrodynamic conditions for the period 1983–2007, the main erosive years on the one hand, and the most severe storm events on the other hand have been selected. The topographic data were processed into erosion and accretion trends (corrected for nourished volumes) for both the supratidal beach and the dune. In total 42 storms were recognised and for each of these storms, the maximum water level, the storm duration, the wave energy and the main wind direction have been determined. To link the eroded volumes to the storm events, the total erosion of all the affected areas per year (i.e. winter season) has been compared with the total wave energy of all the storm events that occurred during the same period. Based on the five most erosive winter seasons (1984, 1987, 1990, 1994 and 1995), it is concluded that in order to cause a significant morphological impact along major parts of the Belgian coastline, as a first indication an individual storm should be characterised by the following criteria: maximum significant offshore wave height higher than 4 m, maximum water level above +5 m TAW, storm duration longer than 12 h, an induced wave energy above 6.5 E+05 J/m² and wind direction between W and NW. Although the applied methodology has its limitations due to the wide time-spacing of the topographic measurements and the lack of details on beach morphological changes, the severest storm periods from the last 25 years clearly left significant marks in the time series of recorded volume evolution. Therefore the proposed thresholds provide a valuable first estimate of the threshold for significant morphological change along the entire Belgian coastline. If in the future pre- and post storm related beach morphology measurements would be available, the above defined thresholds could be refined or even thresholds for different sectors along the Belgian coastline could be established taken into account the beach morphology.

1. Introduction

The type of morphologic change that beaches can generally undergo in response to changing coastal processes is well documented in the literature e.g. Komar (1998) and Masselink and Pattiaratchi (2001). However the impact of storms on coastal morphology is still incompletely described in the scientific literature and has been only recently tackled (Morton, 2002). Implications of variability in storminess on coastal morphologies are still scarce (Ferreira, 2005). The definition of storm thresholds above which important morphological changes or damages to urban structures can be expected, is not consistently described in the scientific literature and such thresholds have not yet been defined for several European countries, including Belgium. Often, local coastal managers and planners are interested more in the site specific understanding of the morphodynamic behaviour of the beaches along a particular coastline.

One of the methods to define such a storm threshold is to assess the coastal vulnerability during storms by linking events of major morphological change and damage, with the respective hydrodynamic forcing in order to define critical thresholds for the hydrodynamic parameters. To do this one has to (i) find out the forcing mechanisms to which coastlines react (e.g. waves, water levels or both) and (ii) to establish a threshold based on observations of significant morphological change or damage to the coastal zone.

The goal of this paper is to present a storm threshold for significant morphological change along the Belgian coastline. The threshold is based on the analysis of the impact of extreme storm events registered between 1983 and 2007 and relations between the hydrodynamic forcing and the observed coastal erosion.

2. Regional setting — study area

The study area comprises the entire Belgian coastline illustrated in Fig. 1. The Belgian coastline is about 65 km long and is part of the

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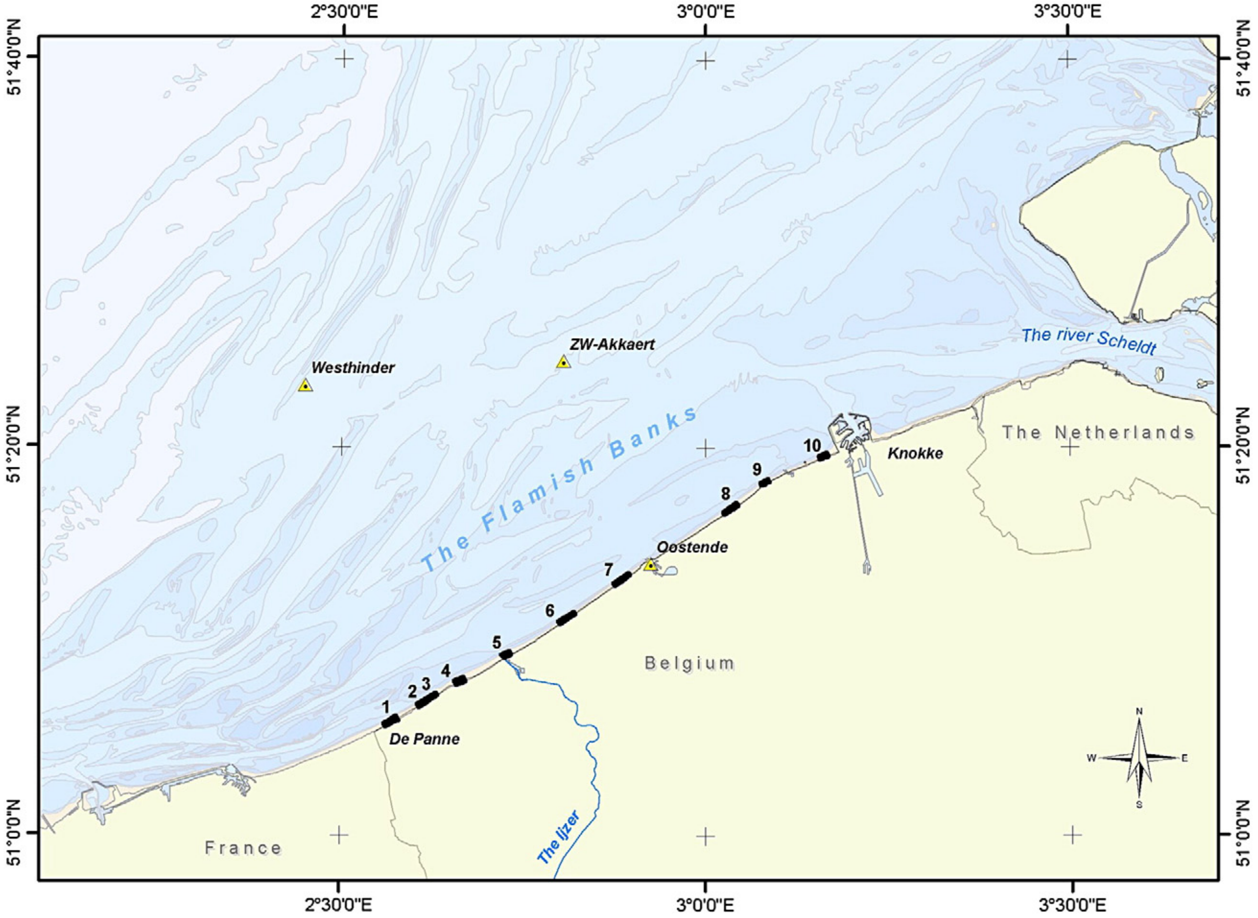

Fig. 1. Location of the Belgian coast, the 10 study sites (numbered), and the measurement locations of the Flemish banks monitoring network which have been used (triangles).

southern sandy North Sea coastline system. The coastline is oriented SW–NE and stretches from the estuary of the river Scheldt (the Netherlands) in the east to Dunkerque (France) in the west. The coastline consists of broad gently sloping sandy beaches backed by dunes, while on the shallow continental shelf numerous sandbanks occur, the Flemish Banks. The coastal dunes range in height between +5 m TAW and +30 m TAW, with the majority between +7 and +15 m TAW (TAW is a local height datum situated close to LAT — Lowest Astronomical Tide). Their width changes from about 2 km west of the *Ijzer* estuary to only a few hundred metres wide eastwards of the Ijzer (Lebbe et al., 2008). Behind the dunes a flat and vast coastal lowland is present. The beaches are in general wide and very gently sloping, characterised by spilling breakers and classified as dissipative. The slope of Belgian beaches increases from west (1.3%) to east (2.4%), resulting in narrowing of the intertidal beach width from the west (about 500–600 m in De Panne) to the east (about 200–300 m in *Knokke*) (Deronde et al., 2006). The natural beach sediments are characterised 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 (Depuydt, 1972). These observations are confirmed by recent work done by Deronde (2007) who remarked 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 400 μm (Deronde, 2007).

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 exceed 1 m/s in the nearshore areas. Offshore waves are mainly driven by westerly winds and during storms surges southwest, west or northwest directions prevail. Because of the shallow water depth and the relatively short fetch, waves are typically short crested. The dominant wave sectors are SW to N and the main significant wave height at the shore is between 0.5 and 1.0 m, characterised by a wave period of 3.5 to 4.5 s (Van Lancker, 1999). The net longshore sediment transport by wind and waves has a predominant SW to NE direction. During N and NW storms important storm surges can occur. At present, more than 50% of the coast length suffers from erosion (Deronde et al., 2004; IMDC — International Marine and Dredging Consultants, 2010).

For several centuries anthropogenic activities along the Belgian coastline have attempted to reshape the coast, to maintain the coastline position or even to claim land from the sea and the natural interaction between the beach and the coastal dunes has been disrupted. The protection of the Belgian coastline actually is a combination of natural and artificial defence. Nowadays 60% of the coast has a hard coastal protection with seawalls, revetments and groynes (Lebbe et al., 2008). For two decades, emphasis has shifted to soft protection schemes, such as beach (and shoreface) nourishment and beach scraping to construct supratidal sand berms. Without these numerous protection actions the natural evolution along the Belgian coastline would be long term erosion and landward retreat (De Moor, 1992; DeWolf et al., 1993). Coastal erosion and accretion along the Belgian coastline is described in the coastline charts and the long term coastline trends (Vito and Afdeling Kust, 2009; IMDC — International Marine and Dredging Consultants, 2010) and sand loss rates up to 20 m^3/m/year were reported. Some major accretion areas at the coastline can be related to the presence of defence structures. This makes it difficult to single out the natural evolution of the beaches along the Belgian coastline.

3. Methods

3.1. Thresholds

In principle, the threshold for significant morphological change should rely on the parameters which have an important influence on the morphology and the functions of the beach. These functions are divers, depending on the type of coast: e.g. beach recreation but also protection of the hinterland against flooding. Therefore it would make sense to define different thresholds for different functions.

The driving forces for morphological changes could be described by the water level (including storm surge), the wave height the wave direction, the storm duration and the wave energy (Kriebel and Dean, 1993). Water level plays a key role in dune toe erosion and also limits aeolian transport on the beach (Sabatier et al., 2009). Ilich et al. (2009) found that storm duration and wave height are the main drivers for beach erosion, and therefore the total wave power is a good indicator. Basco and Walker (2010) applied the Coastal Storm Impulse (COSI) parameter, which combines waves, water levels, currents and duration, to express the strength of a storm. Storms have an effect on both the sort-term processes affecting the beach/dune systems, as well as on long term patterns of development (Sabatier et al., 2009).

The total impact of a storm on a coastal stretch will also depend on the characteristics of the beach itself: the coastline orientation, the beach profile prior to the storm and the sediment characteristics (Mendoza and Jiménez, 2006). Beach morphology and the presence of bar/berm-through systems can be an important element in the process of sand supply to dune systems (Sabatier et al., 2009). Also adjacent profiles can have an influence on the evolution of an area (Basco and Walker, 2010). The effects of an event can be expressed as a coastline retreat or as an eroded volume of the beach and/or dunes. These numbers can be obtained from consecutive topographic measurements.

The methodology to compare beach erosion (volume or profile evolution) with the forcing mechanisms (wave height, wave energy) has already been applied in other regions. Ciavola et al. (2007) applied this method to define the impact of storms on the coastline of Emilia–Romagna, Italy. Mendoza and Jiménez (2006) defined beach erosion predictors for the Catalonian Coast (Spain) by comparing the storm duration and energy with the (computed) beach erosion and beach retreat. Basco and Walker (2010) applied the COSI parameter to predict beach erosion in Duck, North Carolina. Gibeaut et al. (2002) defined threshold conditions for episodic beach erosion along the southeast coast of Texas by comparing beach evolution (volumes and shoreline position) with storm characteristics (water levels, peak wave height, and storm duration).

3.2. Applied method

In order to assess the possibly varying responses of the beach morphology to storm erosion along the Belgian coastline ten coastal stretches have been selected for this study. These areas are illustrated in Fig. 1 and described in Table 1. Together, they cover about 12.2 km, representing about 20% of the Belgian coastline. For each of these study sites the beach volume losses determined from frequently conducted surveys are compared with recorded storm and wave data, for the period between 1983 and 2007.

On the forcing side, all events where the significant wave height Hs exceeds 3.75 m were included in the analysis. This means that also yearly storms are considered, since the significant wave height with a 1 year return period at *ZW-Akkaert* is about 4.50 m (IMDC — International Marine and Dredging Consultants, 2005). For each selected event the duration and the total wave energy were calculated. The duration of a storm is defined by the time between the first recorded wave height above 3.75 m and last recorded wave height above 3.75 m. The wave energy ($E = 1/8\ \rho\ g\ H_s^2$) was computed by integrating the wave energy of the registered wave height over the entire storm duration. For each storm also the maximum water level was determined. In this way the storm surge is included implicitly, which is important along the Belgian coast during N or NW storms. The available hydrodynamic data are described in Section 3.3.

Table 1
Selected areas for analysis of storm impacts on the Belgian coast.

Selected area	Coastal Section	Geographical name	Coastal length [m]	Observations since
1	7–12	*Verkaveling Westhoek, De Panne*	1420	1983
2	22–25	*Sint-Idesbald, Koksijde*	1010	1983
3	26–31	*Koksijde Bad*	1125	1983
4	40–43	*Oostduinkerke Bad*	965	1983
5	60–63	*Nieuwpoort, east of Ijzermonding*	815	1983
6	83–87	*Middelkerke Bad*	1745	1983
7	104–108	*Mariakerke beach*	1770	1983
8	151–158	*De Haan, centre*	1606	1981
9	173–176	*Wenduine Bad*	850	1981
10	202–208	*Blankenberge, De Fonteintjes*	894	1979
Total analysed coastal length			12,200	

To assess the impact on the coast, volume and volume evolutions were computed from topographic and bathymetric measurements (see Section 3.4) and plotted against time for the intertidal beach, the supra-tidal beach and the dune front of each coastal area. To separate the anthropogenic influence, the beach nourishment volumes have been taken into account by creating a corrected time series of the natural volume evolution by subtracting the volumes added by beach nourishment to the supra-tidal beach (IMDC — International Marine and Dredging Consultants, 2010). The volume differences have been standardised by dividing the results by the length of each coastal area, resulting in volumes per unit length (m^3/m). Events that caused erosion of at least 10 m^3/m of the supratidal beach or 5 m^3/m of the dune foot in two or more locations along the Belgian coastline were selected for further analysis.

Further study and comparison of these data should then reveal which thresholds (and parameters) are appropriate for the Belgian Coast.

3.3. Hydrodynamic data

Water levels and wave parameters along the Belgian coastline and offshore in the North Sea are recorded throughout the Flemish Banks Monitoring Network of the Flemish Government. The Monitoring Network, from which the three used measurement locations are illustrated in Fig. 1, is named after the group of irregular sandbanks located in the western part of the Belgian coast. The network consists of measuring piles and wave data buoys, equipped with hydro-meteorological sensors, and provides data on wave parameters (height, wave direction, wave period, wave energy), water levels and wind parameters (speed, wind direction) at several locations of the Belgian Continental Shelf. For the present analysis the records of the water levels for Ostend were used in combination with wave data from ZW-Akkaert. If data from ZW-Akkaert was not available, records from Westhinder were used (the correlation between the two locations is found to be close to 1:1). For the wind direction, Westhinder data are completed with measurements from Zeebrugge and descriptions within the storm reports of the Flemish government.

3.4. Morphological data

Data of the topography and morphology of the intertidal beach, supratidal beach and adjacent part of the sea front dunes were available through a combination of remote sensing data and bathymetric measurements.

The topography of the beach and dunes has been measured by remote sensing flights since 1979 for the eastern part of the coast and since 1983 for the entire coastline. The aerial survey flights are usually carried out in spring and additional records along the most threatened parts of the coast have also been carried out in autumn (DeWolf et al., 2006). Initially, photogrammetric plotting of height contour lines and elevation points was used to produce a digital elevation model of the beach. Since the late 1990s, dense elevation point coverage of the beach has been obtained by means of laser altimetry.

In addition to the aerial remote sensing, the nearshore has been accurately measured by means of bathymetric echo-sounding since 1985. The hydrographical surveys are carried out with a low-draught vessel or hovercraft, integrating a sufficient number of redundant sensor data to improve positioning and to correct depth measurements. In order to generate a sufficient overlap of about 150 to 300 m between topography and bathymetry, the aerial flights are performed at low tide, while the bathymetric surveys take place at high tide. Both datasets are linked to produce charts and volume data that cover the whole area from the dunes to the nearshore.

Over the 24 years considered, these surveys have been reported using elementary areas called “coastal sections”. The entire Belgian coast is covered by 254 sections, numbered from west to east. The width of a section varies between 200 and 300 m. The survey reports and recent survey data are available at the Coastal Division of the Flemish Authorities in Ostend. For reporting, division is made between three areas (Fig. 2):

- The dune front (D): part of the beach above +6.89 m TAW and up to a fixed landward boundary of the section;
- The supra-tidal beach (SB): part of the beach above the mean high-water mark (+4.39 m TAW) and below +6.89 m TAW;
- The intertidal beach (IB): the area above the low water mark (+1.39 m TAW) and below +4.39 m TAW.

The analysis of the morphological evolution of the beaches is based on volume figures obtained by subtracting the volumes of consecutive measurements. The volume differences provide an indication of beach growth (+) or erosion (−) over the period between two consecutive measurements. Longer term coastal trends are reported by Division Coast in the Coastline Charts (Vito and Afdeling Kust, 2009). The time series used in this study extend to 2007.

4. Results

4.1. Hydrodynamic storm characteristics

Based on the recorded water levels, wave and wind data (see Section 3.3), 42 storms are detected between 1983 and 2007, from which 9 were associated with a water level in Ostend above +5.50 m TAW, (see Table 2). 10% of the storms are characterised by a maximum significant wave height of more than 4.8 m. The storm duration of the selected storms is on average 9.4 h, and exceeds 24 h in 10% of the cases.

The year 1990 was exceptionally stormy: the coastline was hit by seven storm events, of which five occurred between January and March. The storms that occurred at the end of February and the beginning of March persisted for a long time (42 to 67 h) and were associated with the highest wave energy recorded during the entire period. The highest significant wave height was observed on November 14th 1993, associated with the highest water level recorded since 1983, +5.97 m TAW (compared to MHWS of +4.70 m TAW in Ostend). Also the storm duration of this event (19 h) is well above the average.

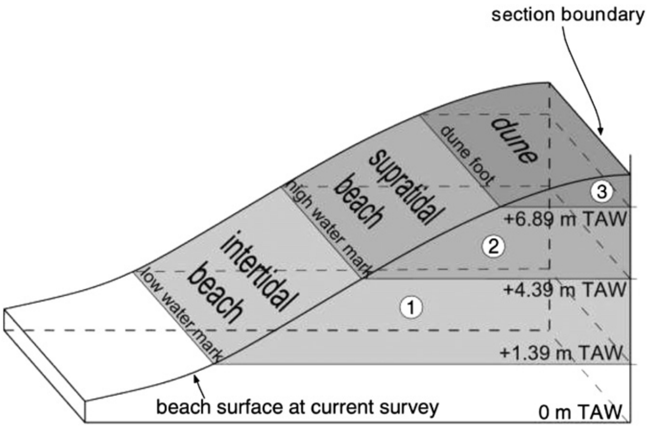

Fig. 2. Definition of the dune (3), supratidal (2) and intertidal (1) beach within a coastal section (Vito and Afdeling Kust, 2009).

4.2. Morphological evolution

Based on the results it can be observed that storm events often have a direct impact on the supra-tidal berm. Almost every winter, sand is washed away by wave erosion and erosion cliffs are formed. Regular maintenance nourishments are executed by the Coastal Division to repair this damage.

Also the calculated supra-tidal beach volume differences provide the most valuable dataset for detailed analysis. This is due to the fact that the accuracy of volume difference depends directly on the absolute error on the elevation measurement. This is typically in the order of 5 to 10 cm. The volume differences of the intertidal beach relate to relatively large surfaces as the intertidal part of the beach is flat and wide. The supra-tidal part is relatively steep and therefore represents a smaller area. As a result, the sensitivity of the volume difference figures to measurement errors is smaller. To quantify this, the errors on the volume differences are estimated to be 5 m^3/m for a 50 m wide supra-tidal beach and about 20 m^3/m for a 200 m wide intertidal beach.

Therefore, the evolution of the supra-tidal beach volume provides the most valuable dataset to identify the storm impacts in the recorded volume time series. In addition to this, the dune front evolution is used to support the conclusions. The dune front is essentially the part of the beach above +6.89 m TAW and this part of the beach is only affected during the most severe storms which overtop the supratidal beach. If volume losses occur simultaneously in the dune and supra-tidal beach graph, this provides stronger evidence of the storm impact. The intertidal volume changes are not considered in this study. The intensity of the morphological variations is quantified by the resultant volume difference per metre coastal length.

For each of the 10 selected sites, the trend in the volume differences has been studied between 1983 and 2007. Fig. 3 shows the resulting graph for area 1, De Panne. For the dunes a large decrease in dune volume is observed in 1990 and 1995 in contrast with the otherwise increasing trend (grey arrows). For the supratidal beach, the general trend shows a slightly decreasing volume. However, also here three years are indicated during which the volume decreases much more than normal (1990, 1992 and 1995; black arrows).

This large decrease in volume in a single season (with respect to the mean trend) constitutes a first indication of possible storm impact on the coast. Theoretically also a non-growth year in an otherwise linearly accreting supra-tidal beach might be the effect of a storm event. Due to the limitation on the measurement accuracy a value of 5 m^3/m volume change is near the detection limit and therefore, in Table 3, the results have been rounded to multiples of 5 m^3/m.

For all the selected areas a similar analysis has been carried out (Figs. 3 to 12). If beach nourishments have taken place in the area, the trend for the supratidal beach has been corrected with the yearly added volumes and a time series of the nourishment volumes is shown on the graph (e.g. Fig. 4). A summary of all the years where

Table 2
Recorded storm events and associated high water levels since 1980.

N°	Date	$H_{s,max}$ [m]	WL [m TAW]	Duration [Hours]	Wave Energy [J/m²]	Wave Energy [J/m²]	Dominant Wind direction	Winter
1	06/Feb/1984	4.32	5.21	12.3	6.27E+06	1.56E+06	W	1984
2	23/Nov/1984	4.81	5.63	4.5	4.95E+06	3.68E+05	WSW	1985
3	15/Jan/1986	3.95	5.24	2.0	3.17E+06	1.69E+05	W	1986
4	20/Oct/1986	4.00	5.50	0.3	2.52E+06	1.78E+05	WNW	1987
5	01/Nov/1986	3.76	5.30	0.3	2.08E+06	1.77E+04	N	
6	18/Dec/1986	4.36	5.02	13.0	4.00E+06	6.56E+05	W	
7	15/Jan/1987	4.17	3.97	17.5	3.75E+06	1.35E+06	NE	
8	10/Feb/1988	4.23	5.07	7.0	4.08E+06	5.63E+05	SW	1988
9	29/Feb/1988	4.18	4.73	24.3	4.90E+06	1.92E+06	NW	
10	20/Dec/1988	3.81	4.74	0.3	1.93E+06	3.62E+04	NNW	1989
11	14/Feb/1989	3.94	5.37	2.5	2.19E+06	2.00E+05	WNW	
12	25/Jan/1990	5.08	4.92	11.5	4.08E+06	1.11E+06	SW	1990
13	12/Feb/1990	4.05	5.20	0.8	2.88E+06	7.91E+04	W	
14	15/Feb/1990	3.80	4.82	0.3	2.25E+06	3.59E+04	WNW	
15	26/Feb/1990	4.70	5.76	42.3	5.20E+06	3.26E+06	WSW	
16	01/Mar/1990	4.70	5.47	67.2	5.95E+06	3.96E+06	NW	
17	10/Dec/1990	4.47	3.92	5.8	4.76E+06	4.56E+05	NNE	1991
18	12/Dec/1990	4.47	5.16	15.3	4.38E+06	1.21E+06	NW	
19	06/Jan/1991	4.26	5.00	3.8	3.15E+06	3.21E+05	WSW	
20	06/Oct/1992	3.86	3.80	0.8	4.50E+06	7.23E+04	NE	1993
21	14/Nov/1993	5.31	5.97	19.5	3.49E+06	2.20E+06	W–NW	1994
22	28/Jan/1994	4.08	5.88	9.8	4.31E+06	8.71E+05	WNW	
23	01/Jan/1995	4.12	5.85	13.3	4.01E+06	9.38E+05	WNW	1995
24	12/Jan/1995	4.20	4.47	8.8	3.33E+06	6.50E+05	NNW	
25	26/Jan/1995	4.11	4.20	4.5	3.35E+06	3.70E+05	SW	
26	19/Feb/1996	4.78	5.34	30.5	4.82E+06	2.33E+06	NNE	1996
27	29/Aug/1996	4.95	5.33	18.0	2.84E+06	1.60E+06	WNW	1997
28	28/Oct/1996	4.64	5.65	3.8	3.27E+06	3.90E+05	SW	
29	04/Jan/1998	3.88	4.60	0.8	4.00E+06	7.54E+04	WSW	1998
30	08/Oct/1998	3.97	5.34	1.5	2.08E+06	1.33E+05	NNE	1999
31	24/Dec/1999	3.99	5.24	2.0	2.67E+06	1.63E+05	SW	2000
32	28/May/2000	3.96	4.34	1.5	1.68E+06	1.32E+05	W	2001
33	29/Oct/2000	4.13	4.55	1.3	3.65E+06	1.21E+05	SW	
34	08/Nov/2001	4.47	4.83	17.3	3.31E+06	1.34E+06	SW–NW	2002
35	26/Oct/2002	4.38	5.00	0.5	2.83E+06	8.27E+05	N	2003
36	20/Dec/2003	3.80	5.43	0.5	2.52E+06	1.82E+04	SW–NW	2004
37	07/Feb/2004	4.10	5.44	NA	NA	NA	SW	
38	13/Nov/2004	3.80	5.73	0.5	1.96E+06	1.82E+04	N	2005
39	17/Dec/2004	3.84	5.38	0.5	1.68E+06	1.86E+04	N–NW	
40	14/Feb/2005	4.24	5.09	5.5	3.83E+06	5.04E+05	WSW–NW	
41	17/Dec/2005	3.92	5.43	2.0	2.93E+06	1.57E+05	NNW	2006
42	09/Nov/2007	4.69	5.93	11.3	4.47E+06	9.55E+05	NW	2007

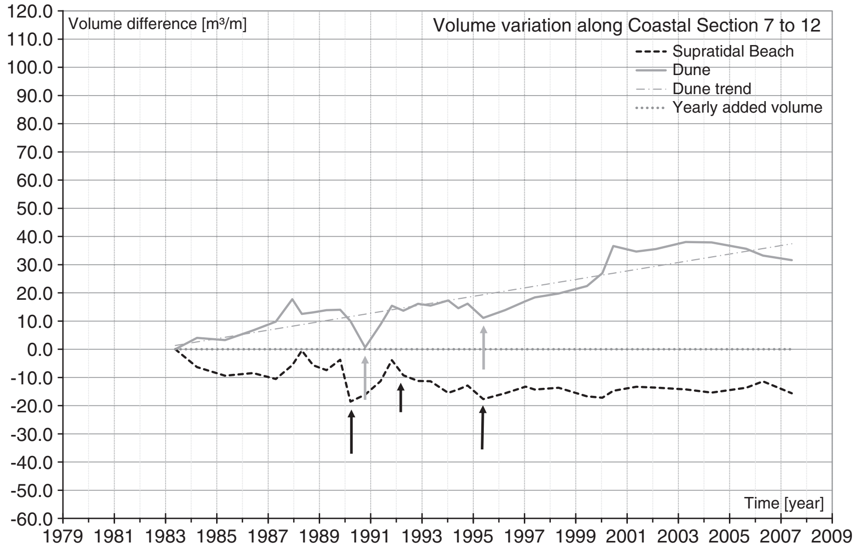

Fig. 3. Results of volume variation for coastal area 1, coastal sections 7–12, Verkaveling Westhoek, De Panne, referred to first year of registration. Significant erosion of the supratidal beach is indicated with black arrows, grey arrows indicate significant dune erosion.

Table 3
Morphological changes (erosion) of the selected areas, expressed in m^3/m of supratidal beach volume loss. The cells indicated with a (*) have no data, empty cells indicate that no discernable effect on the beach morphology was found in the time series.

		1	2	3	4	5	6	7	8	9	10
Selected area		Verkaveling Westhoek, De Panne	Sint-Idesbald, Koksijde	Koksijde Bad	Oostduin-kerke Bad	Nieuwpoort, east of Ijzer-monding	Middelkerke Bad	Mariakerke beach	De Haan, centre	Wenduine Bad	Blanken-berge, De Fonteintjes
1982	SB	(*)	(*)	(*)	(*)	(*)	(*)	(*)	15	10	
	D	(*)	(*)	(*)	(*)	(*)	(*)	(*)	5		
1983	SB										
	D										
1984	SB					**15**		10	**20**		
	D					**5**			**5**		
1985	SB								**15**		
	D								**10**		
1986	SB										
	D										
1987	SB				**10**	**15**	**15**	5	**20**	5	10
	D				**20**	**15**	**5**		**5**		
1988	SB										5
	D										5
1989	SB				10						
	D				5						
1990	SB	**15**	**20**		15	**15**	10	10	**35**	**20**	**15**
	D	**10**	**10**			**10**	5		**15**	**5**	**20**
1991	SB										
	D										
1992	SB	5									
	D				10						
1993	SB						5	5		10	
	D							5		5	
1994	SB		**15**	10	10	5			15	10	**10**
	D		**10**	5	5	15			5	5	**10**
1995	SB	5		10	5	10			20		10
	D	5		0	5						5
1996	SB									5	
	D									5	
1997	SB										
	D								10		
1998	SB										5
	D										
1999	SB					5	10		10		5
	D										
2000	SB								20	15	
	D									5	5
2001	SB								10		
	D										
2002	SB		5		10				15		
	D										
2003	SB										
	D										
2004	SB		10		10						
	D										
2005	SB										
	D										
2006	SB								10		
	D										
2007	SB							10			
	D										

Data indicated in bold represent the years for which the measured erosion was more than 20 m^3/m (SB + D).

important losses are observed and their magnitudes are presented is in Table 3. The years indicated in the table, e.g. "1990", should be interpreted as the winter in which the calendar years starts, so "1990" represents in fact the winter of 1989–1990.

The results in Table 3 illustrate that not all the selected areas show the same morphological response. Some years left no morphological marks at all, while other years show only marks in some areas. In 1990 the morphological response was recorded at almost all selected coastal areas (9 out of 10). The biggest morphological changes were registered at De Haan: a volume change of the supratidal beach of about 35 m^3/m, in combination with dune erosion around 15 m^3/m. In the other areas 10 to 20 m^3/m erosion of the supratidal beach was found and 5 to 20 m^3/m dune erosion.

Also during the winters of 1987 and 1994 a strong morphological response was noticed: erosion occurred in 7 out of the 10 selected areas. Locally important erosion occurred for example during the winters of 1984 and 1995. It is further remarked that the morphological changes of the last decade are rather small compared with those observed between 1990 and 1995 and only affected some of the selected coastal areas.

4.3. Link between storm events and morphological evolution

In Table 4 the storm events recorded between 1983 and 2007 (see Section 4.1) are shown in relation with the observed morphological changes (see Section 4.2). It is remarked that for the February 2004

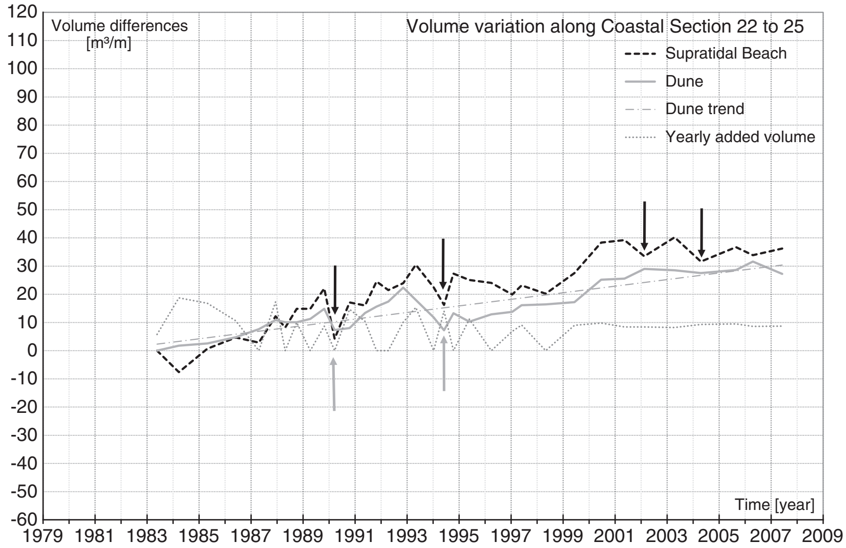

Fig. 4. Results of volume variation for coastal area 2, coastal sections 22–25, Sint-Idesbald — Koksijde, referred to first year of registration. Significant erosion of the supratidal beach is indicated with black arrows, grey arrows indicate significant dune erosion.

storm no wave records were available due to a failure of the buoy during the storm period and the wave height has been taken from the storm reports of the Flemish government.

In addition to the information already presented in Table 4, for each winter season the number of affected areas, the total amount of erosion (sum of the erosion volumes of the supratidal beach and the dunes of all the affected areas), the total storm duration and the total wave energy (during the storms) have been added.

In Section 4.2 the winters of 1987, 1990 and 1994 have been identified as those where the morphological impact was the most pronounced, corresponding with the results presented in Table 4, these three years are associated with the highest amount of erosion (indicated in bold in the grey shaded cells). Fourth and fifth in terms of impact come the years 1984 and 1995.

With regard to the total wave energy during the storms events, it becomes clear that the highest wave energy is found for 1990 and 1994, followed by 1987, 1988, 1996 (grey shaded cells, with text in bold). During the winter of 1990 the combination of storms with high water levels, high waves and a long duration (total>120 h), had an impact all along the Belgian coast. In contrast with the other years, no important morphological impact has been found during 1988 and 1996. This is possibly due to the lower (maximum) water level during the NW-storm in 1988 (+4.73 m TAW), and the main wind direction (NNE) in 1996.

Other energetic events occurred in 1984, 1991, 1995, 1997 and 2002 (grey shaded cells). Also here, the high total induced wave energy does not necessarily imply a high amount of erosion. Whereas erosion occurred in 1984 and 1995 (grey shaded cells), no clear impact was observed the other years.

The main morphological changes observed at the 1991 survey possibly occurred during the previous year, which was very stormy. In 1997 and 2002 there was only local impact since respectively one and three areas were affected. For the 1997 survey, the main event was the storm during the summer of 1996, so possibly the beach recovered (partially) later that season. In 2002 the maximum water level only reached +4.83 m TAW since the maximum storm surge occurred at

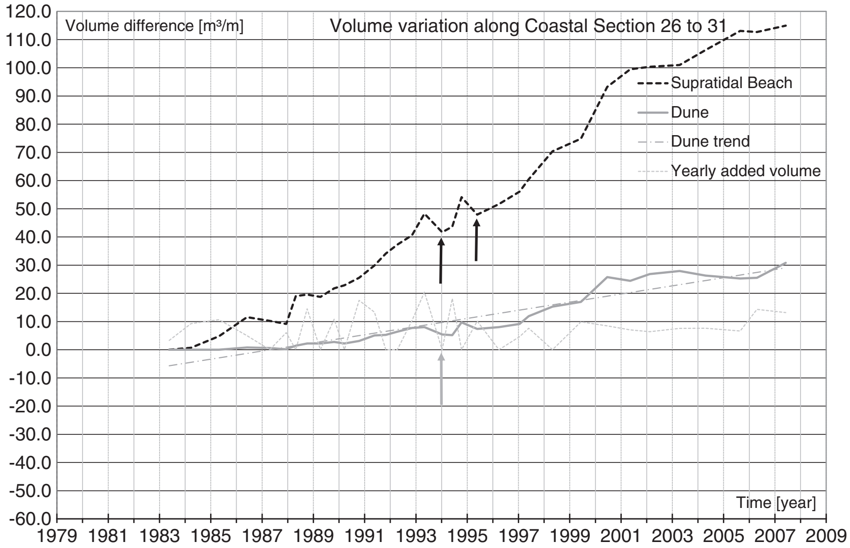

Fig. 5. Results of volume variation for coastal area 3, coastal sections 26–31, Koksijde-Bad, referred to first year of registration. Significant erosion of the supratidal beach is indicated with black arrows, grey arrows indicate significant dune erosion.

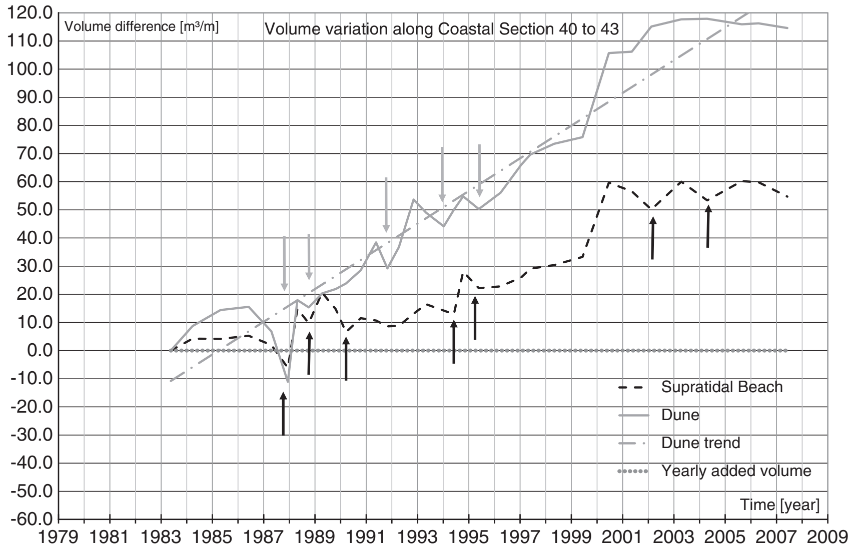

Fig. 6. Results of volume variation for coastal area 4, coastal sections 40–43, Oostduinkerke-Bad, referred to first year of registration. Significant erosion of the supratidal beach is indicated with black arrows, grey arrows indicate significant dune erosion.

low water and the event occurred during a neap tide period. Also Sabatier et al. (2009) reported that due to the influence of the antecedent beach state, no linear relationship between storm intensity and the rate of dune erosion could be found at their study sites along the French coast.

5. Discussion

5.1. Hydrodynamic parameters

The results presented above reveal a relation between the occurrence of severe storms and coastal erosion. Whereas for the three years with the biggest morphological changes (winters of 1987, 1990 and 1994) a clear correlation with the amount of induced wave energy has been found, this relation is not always that straightforward. A number of reasons can be identified for this.

First of all, in reality a combination of different parameters determines the level of impact on the coast. The water level is highly important. Due to storm surge, the maximum water level can easily exceed the normal high waters, so waves can reach the supratidal beach and eventually also the dunes. Events with a maximum water level above +5.5 m TAW typically can cause important erosion (e.g. winter of 1994). Further, the wave height and the storm duration have an important influence, since they determine the wave energy during the storm. The most severe events are characterised by either a wave height of more than 4.5 m or a storm duration of about 30 h or more and a total induced wave energy above 1.5 E+06 J/m^2. The lowest amount of energy induced by individual storms with a recorded value of 6.5 E+05 J/m^2 was observed in the winter of 1986. Due to the coastline's exposure, it is mainly north-western storms which have a big impact on the coast. South-westerly and north-easterly storm events may sometimes have a high total wave

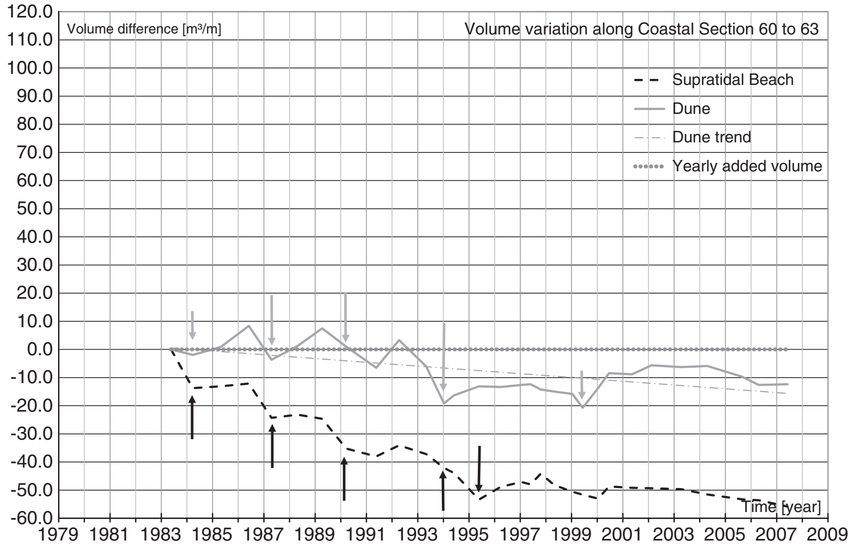

Fig. 7. Results of volume variation for coastal area 5, coastal sections 60–63, Nieuwpoort, east of the Ijzer mouth, referred to first year of registration. Significant erosion of the supratidal beach is indicated with black arrows, grey arrows indicate significant dune erosion.

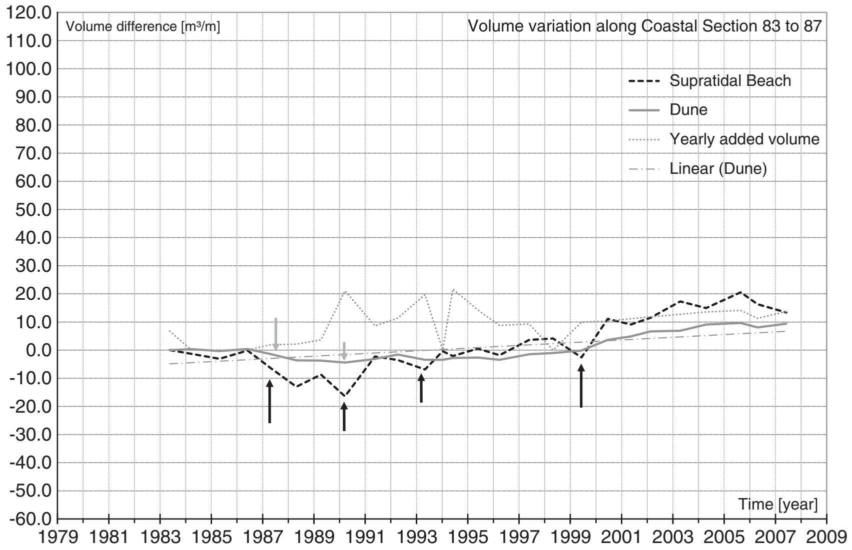

Fig. 8. Results of volume variation for coastal area 6, coastal sections 83–87, Middelkerke-Bad, referred to first year of registration. Significant erosion of the supratidal beach is indicated with black arrows, grey arrows indicate significant dune erosion.

energy, but due to their direction, the impact on the coast will be less important. An example of this is the storm of February 1996. The selected seasons with important erosion (1984, 1987, 1990, 1994 and 1995) all have in common that at least one of the individual storm events which occurred fulfilled all of the criteria below:

- Maximum significant wave height>4 m
- Maximum water level>5 m TAW
- Storm duration>12 h
- Total induced wave energy for single storms>6.5 E+05 J/m^2
- Direction between W and NW

In the majority of the five selected seasons, mostly more than one storm event occurred during the season preceding the surveys. This clearly indicates that not only individual storms are responsible for the measured erosion, but that erosion can be an effect of the occurrence of a group of storms not allowing recovery of the beaches in between successive storms. This phenomena was already recognised by Ferreira (2005) who concluded that storm groups, with each individual storm inducing relatively small amount of wave energy in comparison with single high energy storms, can provoke average erosion volumes as significant as single storms. So the use of a wave energy threshold based on one single storm event is therefore to be used in combination with the evaluation of the morphological status of a beach.

Applying the above defined five thresholds it can be observed that when one of these is not fulfilled the results show that those storms have less impact, e.g. storm of November 2007 (<12 h), 1996 (NNE) and 2001 (WL<+5 mTAW), although the reasoning therefore can be different (see below and Section 5.2).

The years 1991 and 1997 are exceptions to the criteria listed above, although high waves and relatively high wave energy was induced during these NW and WNW storms, (almost) no erosion is

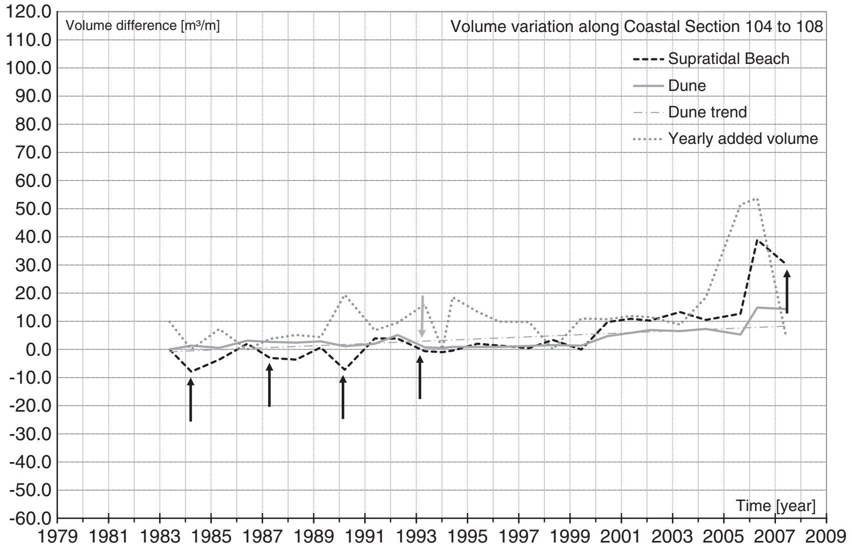

Fig. 9. Results of volume variation for coastal area 7, coastal sections 104–108, Mariakerke, referred to first year of registration. Significant erosion of the supratidal beach is indicated with black arrows, grey arrows indicate significant dune erosion.

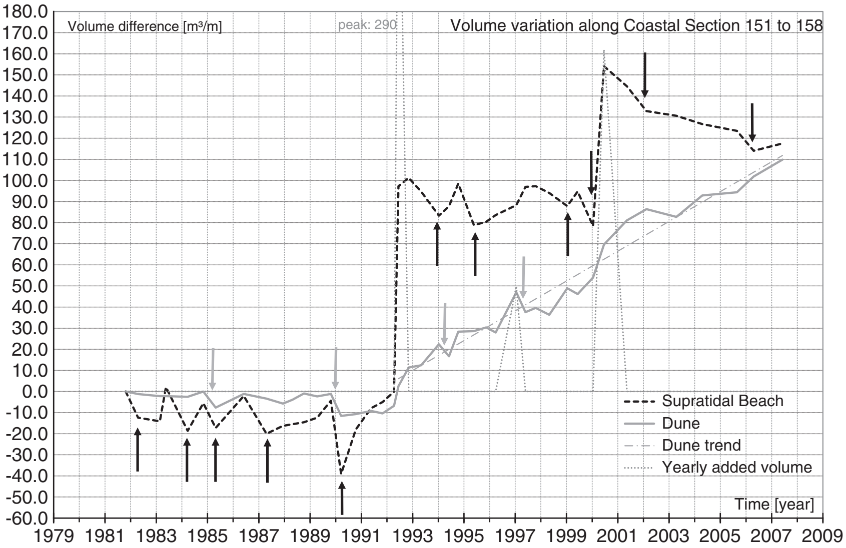

Fig. 10. Results of volume variation for coastal area 8, coastal sections 151–158, De Haan centre, referred to first year of registration. Significant erosion of the supratidal beach is indicated with black arrows, grey arrows indicate significant dune erosion (note the different Y-scale of the figure!).

observed from the surveys. This could illustrate that also the pre-storm history or the status of the beach prior to the occurrence of the storm, influences the type and magnitude of storm impact (Morton, 2002). The performed analysis showed that after the storms of 1990, the beaches did not show significant erosion in 1991, although the storm of December 1990 fulfilled all of the criteria mentioned above. With respect to 1997 the same reasoning can be followed, however also the unusual date of the storm (August) could be of importance. Possibly later that summer, some beach recovery took place, before the next survey. The alongshore variability of the storm process and the geographical location of the site relative to the storm centre (Morton, 2002) influence the type and magnitude of storm impact as well. These two parameters have not been addressed in this study, but can possibly (at least partially) explain the different morphological response along the coast. Cooper et al. (2004) found that also the interaction of swell and wind waves could produce potentially important differences in coastal response patterns.

However, not only the hydrodynamic parameters determine the storm impact on the coast, also the morphological characteristics, the coastal protection measures and human intervention influence the coastline evolution.

5.2. Morphological characteristics

Many storm events result in different impacts on the selected coastal stretches. Only for the most severe storms almost all areas are affected, but more often only 1 to 3 areas show some traces. DeWolf et al. (1993) also concluded from 10 years of monitoring that a rather complex alternation of erosive and accretional stretches exists along the Belgian coastline. One reason for this spatially differentiated morphological response could be the alongshore variability of the storm process and the geographical location of the site relative to the storm centre (as mentioned before), but the range of beach morphology types present along the Belgian coast may constitute another explanatory factor. The present

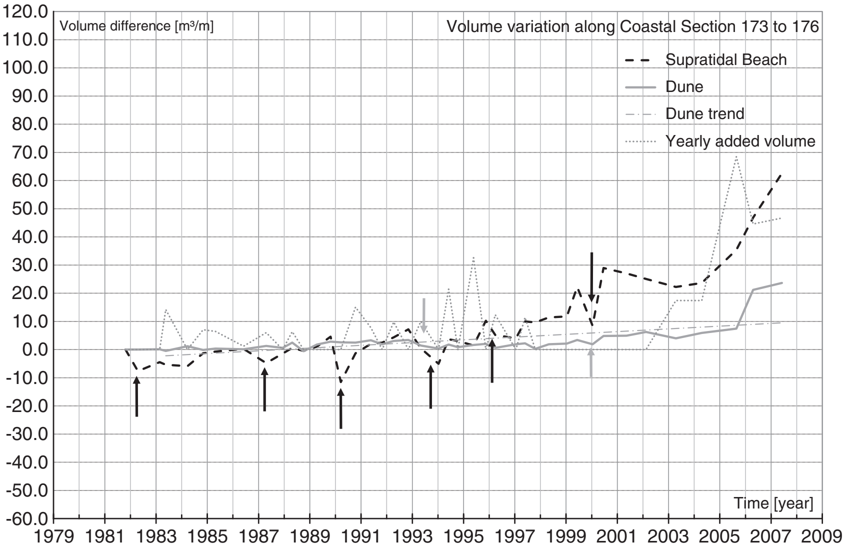

Fig. 11. Results of volume variation for coastal area 9, coastal sections 173–176, Wenduine, referred to first year of registration. Significant erosion of the supratidal beach is indicated with black arrows, grey arrows indicate significant dune erosion.

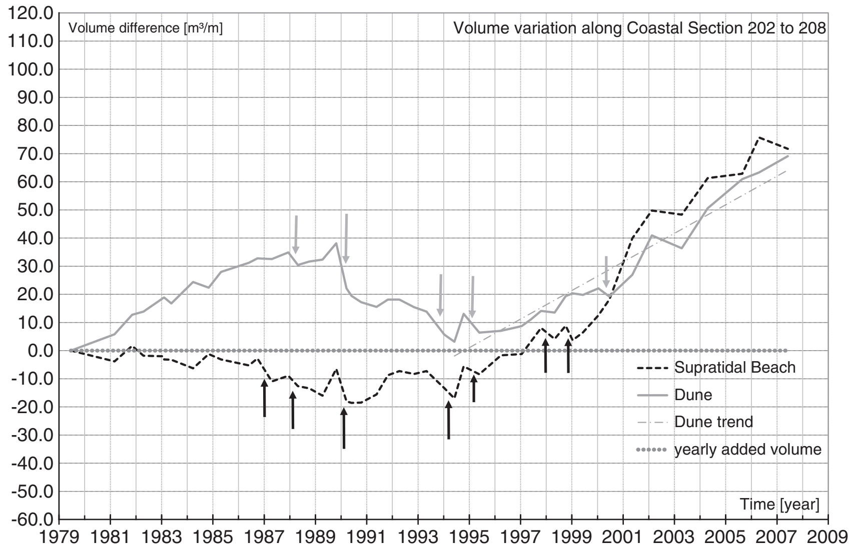

Fig. 12. Results of volume variation for coastal area 10, coastal sections 202–208, Blankenberge — Fonteintjes, referred to first year of registration. Significant erosion of the supratidal beach is indicated with black arrows, grey arrows indicate significant dune erosion.

Table 4
Overview of recorded storms event and associated erosion volumes [m³/m].

No.	Date	$H_{s,max}$ [m]	Water level [m TAW]	Storm duration [h]	Wave energy [J/m²]	Wind direction	Winter	Number of affected areas [#]	Erosion volume [m³]	Total duration [h]	Total wave energy [J/m²]
1	06/Feb/1984	4.32	5.21	12.3	**1.56E + 06**	**W**	1984	3	74,200	12.3	1.56E + 06
2	23/Nov/1984	**4.81**	**5.63**	4.5	3.68E + 05	WSW	1985	1	40,200	4.5	3.68E + 05
3	15/Jan/1986	3.95	5.24	2.0	1.69E + 05	**W**	1986	0	0	2.0	1.69E + 05
4	20/Oct/1986	4.00	**5.50**	0.3	1.78E + 05	**WNW**	1987	7	**150,500**	**31.1**	**2.20E + 06**
5	01/Nov/1986	3.76	5.30	0.3	1.77E + 04	N					
6	18/Dec/1986	4.36	5.02	13.0	**6.56E + 05**	**W**					
7	15/Jan/1987	4.17	3.97	17.5	**1.35E + 06**	NE					
8	10/Feb/1988	4.23	5.07	7.0	5.63E + 05	SW	1988	1	8900	**31.3**	**2.49E + 06**
9	29/Feb/1988	4.18	4.73	24.3	**1.92E + 06**	**NW**					
10	20/Dec/1988	3.81	4.74	0.3	3.62E + 04	**NNW**					
11	14/Feb/1989	3.94	5.37	2.5	2.00E + 05	**WNW**	1989	1	14,500	2.8	2.37E + 05
12	25/Jan/1990	**5.08**	4.92	11.5	**1.11E + 06**	SW	1990	9	**277,400**	**122.1**	**8.45E + 06**
13	12/Feb/1990	4.05	5.20	0.8	7.91E + 04	**W**					
14	15/Feb/1990	3.80	4.82	0.3	3.59E + 04	**WNW**					
15	26/Feb/1990	**4.70**	**5.76**	42.3	**3.26E + 06**	WSW					
16	01/Mar/1990	**4.70**	5.47	67.2	**3.96E + 06**	**NW**					
17	10/Dec/1990	4.47	3.92	5.8	4.56E + 05	NNE				24.9	1.99E + 06
18	12/Dec/1990	4.47	5.16	15.3	**1.21E + 06**	**NW**	1991	0	0		
19	06/Jan/1991	4.26	5.00	3.8	3.21E + 05	WSW					
20	06/Oct/1992	3.86	3.80	0.8	7.23E + 04	NE	1993	3	39,200	0.8	7.23E + 04
21	14/Nov/1993	**5.31**	**5.97**	19.5	**2.20E + 06**	**W–NW**	1994	7	**135,700**	**29.3**	**3.07E + 06**
22	28/Jan/1994	4.08	**5.88**	9.8	**8.71E + 05**	**WNW**					
23	01/Jan/1995	4.12	**5.85**	13.3	**9.38E + 05**	**WNW**	1995	6	88,800	26.6	1.96E + 06
24	12/Jan/1995	4.20	4.47	8.8	6.50E + 05	**NNW**					
25	26/Jan/1995	4.11	4.20	4.5	3.70E + 05	SW					
26	19/Feb/1996	**4.78**	5.34	30.5	**2.33E + 06**	NNE	1996	*1*	8500	**30.5**	**2.33E + 06**
27	29/Aug/1996	**4.95**	5.33	18.0	**1.60E + 06**	**WNW**	1997	1	16,100	21.8	1.99E + 06
28	28/Oct/1996	**4.64**	**5.65**	3.8	3.90E + 05	SW					
29	04/Jan/1998	3.88	4.60	0.8	7.54E + 04	WSW	1998	1	4500	0.8	7.54E + 04
30	08/Oct/1998	3.97	5.34	1.5	1.33E + 05	NNE	1999	4	42,100	1.5	1.33E + 05
31	24/Dec/1999	3.99	5.24	2.0	1.63E + 05	SW	2000	3	53,600	2.0	1.63E + 05
32	28/May/2000	3.96	4.34	1.5	1.32E + 05	**W**	2001	1	16,100	2.8	2.52E + 05
33	29/Oct/2000	4.13	4.55	1.3	1.21E + 05	SW					
34	08/Nov/2001	4.47	4.83	17.3	**1.34E + 06**	**SW–NW**	2002	3	38,800	17.3	1.34E + 06
35	26/Oct/2002	4.38	5.00	0.5	**8.27E + 05**	N	2003	0	0	0.5	8.27E + 05
36	20/Dec/2003	3.80	5.43	0.5	1.82E + 04	**SW–NW**	2004	2	19,800	0.5	1.82E + 04
37	07/Feb/2004	4.10	5.44	**NA**	**NA**	SW					
38	13/Nov/2004	3.80	**5.73**	0.5	1.82E + 04	N				6.5	5.41E + 05
39	17/Dec/2004	3.84	5.38	0.5	1.86E + 04	**N–NW**	2005	0	0		
40	14/Feb/2005	4.24	5.09	5.5	5.04E + 05	**WSW–NW**					
41	17/Dec/2005	3.92	5.43	2.0	1.57E + 05	**NNW**	2006	1	16,100	2.0	1.57E + 05
42	09/Nov/2007	**4.69**	**5.93**	11.3	**9.55E + 05**	**NW**	2007	1	17,700	11.3	9.55E + 05

morphology, the beach slope, and the grain sizes of the beach sand were identified by Morton (2002) and Reyes et al. (1999) as important factors. Along the Belgian coast different profiles are found: where the overall beach slope is less in the western part, it is somewhat steeper in the east.

Another factor that influences the spatially differentiated impact of a storm is the different nearshore and offshore sandbank morphology, interacting otherwise with swell direction and resulting in different morphological changes of the beaches. Maspataud et al. (2009) for example discovered a high spatial variability in beach response at a macro-tidal beach in Dunkirk, Northern France, which is caused by temporal and spatial variations in bar-trough beach morphology. In this study, the selected areas which were least affected by storm erosion are situated in the western part of the coast (e.g. De Panne and Koksijde, areas 1–3). In this area the beach slope is mild and the shallow Flemish banks present off this part of the coast could have a damping effect on the wave climate.

5.3. Human interference

Human activity is another factor influencing the morphological changes along the Belgian coastline. Hard coastal protection measures such as dikes and groynes have often been applied (and are still present) along the coast. The most natural beaches can be found on the west-coast, close to France. As most beaches here are accreting, human intervention was not needed during past decades. Selected coastal areas 1 (De Panne) and 4 (Oostduinkerke) are the most natural ones. In area 1, De Panne, there is however a concrete dune foot protection, which was built between 1976 and 1979 (IMDC — International Marine and Dredging Consultants, 2010). During severe storms (e.g. 1990 and 1993) overtopping of this dune foot protection was registered.

Area 8, De Haan, suffered severe erosion in the 1970s and 1980s and was artificially nourished during large-scale re-nourishments in 1992, 1996 and 2000. Area 10, De Fonteintjes, shows a predominantly natural evolution, though groynes are present. The major growth there since 1990 is related to the presence of the Zeebrugge harbour dams. They intercept the littoral drift, which is bi-directional, with a net resultant component to the east. The beaches west of Zeebrugge started to grow exponentially since the construction of the dams; the growth area reached De Fonteintjes in 1996 (IMDC — International Marine and Dredging Consultants, 2010).

Besides variations in hard coastal protection also the desired supratidal berm width varies along the coastline according to tourist needs. Most areas along the Belgian coastline are affected almost every winter by wave erosion that takes away a part of the beach berm above the high water mark (see Fig. 13). The berm is rebuilt artificially every year, partly by scraping sand from the low water mark area, partly by dumping sand dug from offshore. The repairs are normally done in April–May, so that the beaches are ready for the tourist season.

Over the last two decades emphasis in coastal protection in Belgium has shifted to soft coastal protection measures such as beach nourishment. DeWolf et al. (2006) and Mertens et al. (2008) reported that many beaches have to be maintained regularly (every 1 to 5 years) in order to mitigate beach erosion and to maintain a minimal safety level against flooding. Besides safety considerations, the beaches are also regularly nourished in order to provide a sufficiently wide beach for recreation. These volumes have been taken into account when determining the erosion trend as has been described in Section 4.2. The cumulative yearly added volumes for the six coastal areas where nourishments occurred are shown in Fig. 14.

The volumes supplied in De Haan clearly show a different behaviour compared with the other zones. Whereas in most cases a rather small volume is regularly supplied, the nourishments in De Haan took place at three distinguished times: 1992, 1997 and 2000. As can be seen from Fig. 10, severe erosion occurred in 1990 in De Haan on both the supratidal beach and the dunes. With these impacts in mind, the first nourishment could be seen as a repair (and strengthening) of the coast. Also the second nourishment could be planned following the storms of 1994 and 1995, where some important losses from the intertidal beach were observed. For the 2000 nourishment this link is less clear.

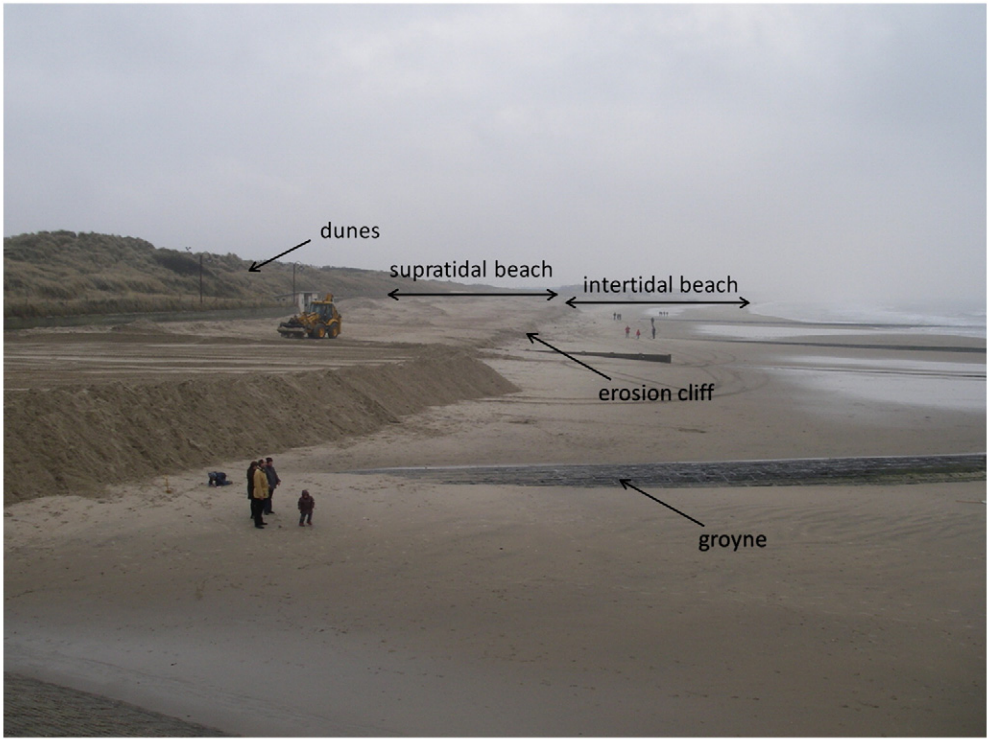

Fig. 13. Part of the beach west of Wenduine (March 2008) (photo by IMDC, 2008). The supratidal berm is rebuilt artificially each spring, after the winter storms.

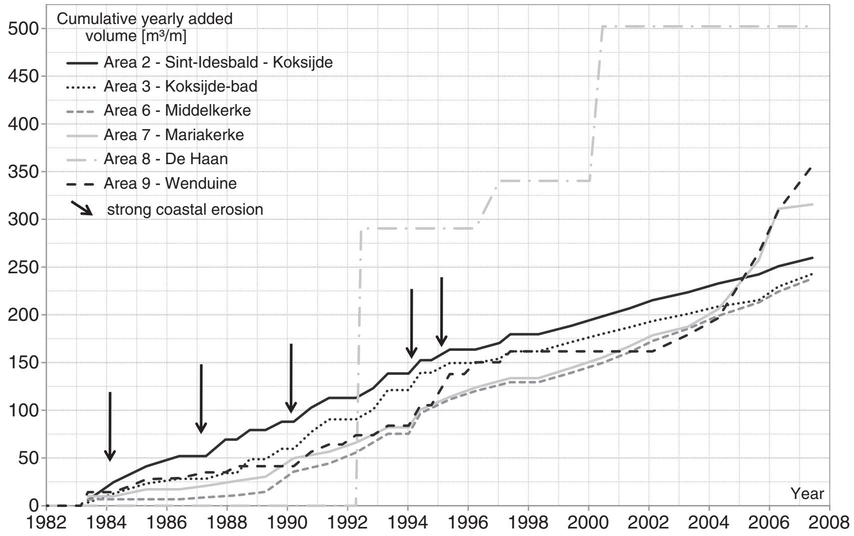

Fig. 14. Cumulative yearly added sand volumes between 1984 and 2007. The black arrows indicate the years in which important coastal erosion is registered.

In the other zones the yearly added volume is more equally spread and indicates a regular maintenance of the supra-tidal beach, however some increases in volumes can be noticed, e.g. in the period 1994–1995 in area 9 (Wenduine). This results from the storm impacts of the 1994 season. From 1997 until 2002 no nourishments took place, but they were resumed in 2002. From 2004 on, the yearly added volumes were increased. Also in area 7, Mariakerke, this increase in yearly added volumes from 2004 on is noticed, although no increased erosion was observed (see Fig. 9). It was realised however, after a coastal safety evaluation, that Wenduine and Mariakerke did not meet some safety criteria and that the beaches should be raised artificially.

This analysis thus demonstrates that the yearly beach nourishments cannot be linked exclusively to the impact of extreme storm events. Whereas in some sites the link is clear (e.g. de Haan), the volumes added continuously at the other sites point towards annual maintenance of the supratidal beach. This is partially meant for safety, but also for recreation.

5.4. Topographic measurements

Another restriction to the detection of storm impacts in the available longer-term data series is imposed by the time spacing of the surveys. The impact of storm events on the Belgian coastline should be singled out of routine measurements of the beach morphology. By comparing volumes of the supratidal beach and dune foot taken once or sometimes twice a year the storm-related process of erosion and accretion is not covered in detail. Storm signals can be disturbed by accretion processes that occurred in the period between two consecutive records. Effects of storms will only show if the volume loss is greater than the possible growth that occurred in the time between the storm and the first survey after the storm.

The methodology used implies that not all pre- and post storm processes are singled out. Only coincidentally, pre- and post storm surveys are taken close enough to the occurrence of the storms thus providing a dataset that is not affected by recovery processes. This shortcoming has also been mentioned by Ferreira (2005), by Ciavola et al. (2007) when assessing the impact of storms along the coastline of Emilia Romagna and by Cooper et al. (2004) when assessing the impact of storms along the coastlines respectively of western Portugal, the Emilia Romagna region (Italy) and western Ireland. Nevertheless the available dataset provides sufficient basic information to assess storm impact along the entire region.

In order to filter out erosive reaction of the beach due to a storm impact, more (storm triggered) measurements of the beach and the nearshore should be carried out. In view of this, more frequent surveys were undertaken during the MICORE project and it is suggested that future surveys should try to capture erosion and accretion processes during storm events by performing measurement campaigns before, during and shortly after storms.

6. Conclusion

Based on the available datasets of topography and hydrodynamic conditions for the period 1983–2007, the main erosive years on the one hand, and the most severe storm events on the other hand have been selected.

The topographic data have been processed in order to produce erosion and accretion trends (corrected for nourished volumes) for both the supratidal beach and the dune. From these data it became clear that during the years 1987, 1990 and 1994, important erosion occurred along most parts of the Belgian coastline (10–50 m^3/m). Locally important erosion occurred in 1984 and 1995 (10 to 25 m^3/m).

From the available data at Ostend, ZW-Akkaert and Westhinder, 42 storms have been selected with a maximum significant wave height exceeding 3.75 m. Since at ZW-Akkaert the wave height with return period 1 year is about 4.5 m, this implies that yearly occurring storms are included as well. For each of these storms, the maximum water level, the storm duration, the wave energy and the main wind direction have been reported.

To link the eroded volumes to the storm events, the total erosion of all the affected areas per year (i.e. winter season) has been compared with the total wave energy of all the occurred storm events during the same period. Furthermore storm specific information (e.g. direction, duration, water levels) has been included in the analysis.

The selected seasons with important erosion (1984, 1987, 1990, 1994 and 1995) all have in common that at least one of the individual storm events which occurred fulfilled all of the following criteria: maximum significant wave height higher than 4 m, maximum water level above +5 m TAW, storm duration longer than 12 h, induced wave energy during the storm of at least 6.5 E+05 J/m^2 and wind direction between W and NW. Most often more than one storm event occurred during the season. In the evaluation of the potential effect of a storm on the coastline it is clear that in the future the beach morphology should be integrated, but the above thresholds provide a first estimate of storm parameters able to induce significant erosion. So in fact this set of criteria defines the threshold for significant morphological change along the Belgian coastline.

Spatially different morphological response was observed along the coastline. Apart from local morphological characteristics such as milder slopes and shallow banks in front of the coast, which make the south-western part of the coastline somewhat less vulnerable for storm impact, no clear explanation has been found. Further research on this topic could include the alongshore variability of the storm process and the geographical location of the site relative to the storm centre. Purpose-made pre and post storm profiles may significantly improve the determination of relevant processes and parameters.

Although the applied methodology based on volume losses of the supratidal beach and dune foot over the year has its limitations due to the wide time-spacing of the topographic measurements which mostly do not include pre- and post-storm surveys, the severest storm periods from the last 25 years clearly left significant marks in the time series of recorded volume evolution. Therefore the proposed thresholds provide a valuable first estimate of the threshold for significant morphological change along the entire Belgian coastline.

Acknowledgements

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