ANNEX

MANAGEMENT, RESEARCH AND BUDGETTING OF AGGREGATES IN SHELF SEAS RELATED TO END-USERS

EV/18

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Acoustic habitat modelling for the mapping of biological communities

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INTRODUCTION

In the framework of the MAREBASSE project (''Management, Research and Budgeting of Aggregates in Shelf Seas related to End-users'', EV/02/18, Van Lancker *et al.* 2005) and the MESH project ("Mapping European Seabed Habitats, Interreg IIIb; www.searchmesh.net), biologically relevant habitat maps are produced, based on multibeam acoustic datasets, ground truthed with physical and biological samples.

The habitat map production comprised of the following four key steps: (1) getting the best out of the ground truth data; (2) selecting and deriving the best available input and most appropriate data coverages; (3) using the most appropriate techniques for interpreting the data through integration and modelling, and; (4) designing the map layout to create a map fit for purpose.

Results are presented where classes derived from acoustic seabed classification are translated into habitat maps. Cross tabulation is used to correlate biological ground truthing data with the acoustic classes. Finally, habitat maps are produced, representing the likely occurrences of the different macrobenthic communities occurring on the Belgian part of the North Sea (BPNS).

For the study areas of Oostende, Hinder Banken, Sierra Ventana (Figure 1), habitat maps of macrobenthic communities have been created. The habitat maps are based on a cross tabulation of acoustic backscatter classification of the multibeam images, overlaid with biological samples worked out on a macrobenthic community level.

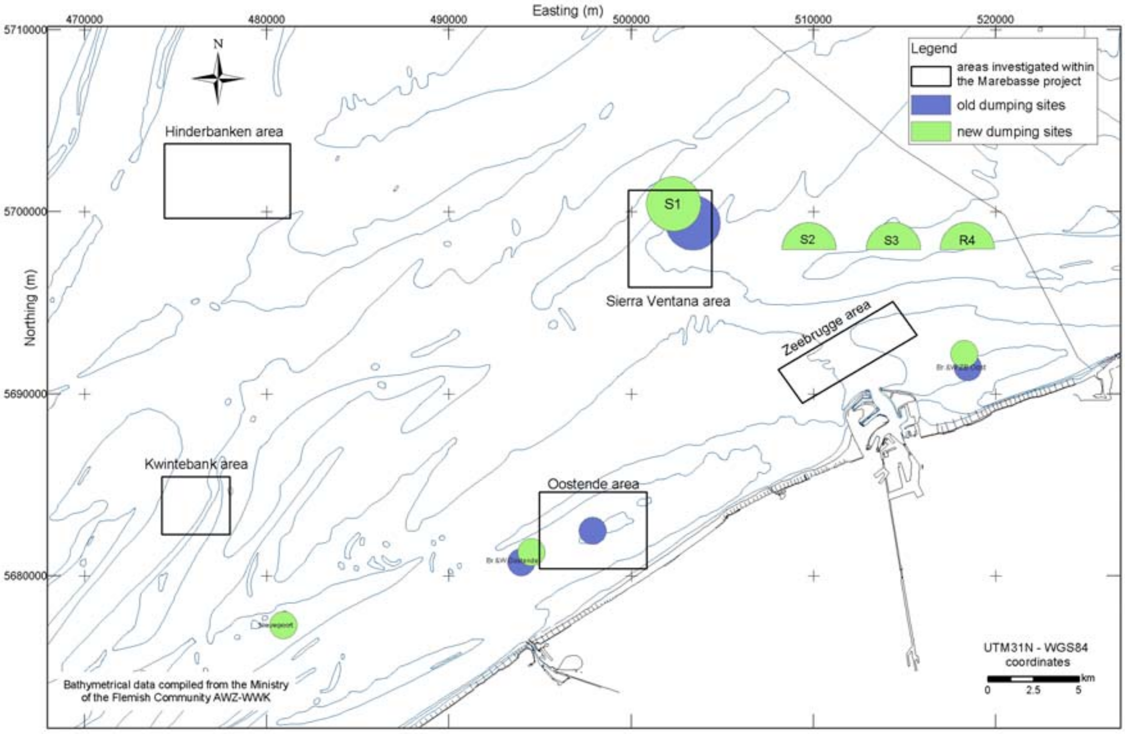


Fig. 1: Overview of the study areas.

MATERIAL AND METHODS

The multibeam images contain both bathymetrical and backscatter (BS) information. Based on these BS data, an acoustical seabed classification is established using the Tryton module of Kongsberg Simrad (Kongsberg Simrad 2001). By comparing the BS values, classes can be defined using 5 statistical features: quantile, pace, contrast, mean and standard deviation. Only the first three are used for the datasets. A class is created after identifying regions with homogeneous values of these features and afterwards the class is used on the whole dataset. In view of striving towards a restricted amount of classes, applicable over the whole BPNS, existing classes of Roche (2002) were used. These were defined in sandbank areas on the BPNS, but proved valid also in other soft sediment areas (Van Lancker *et al.* 2005).

The generalized classes of Roche (2002) are the following: (1) class 1: highest BS: sandy gravel occurring in the swales of the sandbanks; (2) class 2 and class 5: moderate BS: medium sand with shells or shell debris occurring on sand dune fields in swales and on sandbanks; (3) class 3: high BS: fine muddy sand, occurring on flat areas in the swales and generally associated with bioturbation of tube worms; (4) class 4: lowest BS: fine homogeneous sand occurring in the shallowest areas; and (5) statistical outliers.

Based on an extensive dataset of macrobenthic samples, four subtidal communities were discerned on the BPNS (Degraer *et al.* 2003; Van Hoey *et al.* 2004): (1) *Macoma balthica* community (*M. balthica*); (2) *Abra alba – Mysella bidentata* community (or *A. alba* community; Van Hoey *et al.* 2005); (3) *Nephtys cirrosa* community; and (4) *Ophelia limacina – Glycera lapidum* community (further abbreviated as *O. limacina* community).

Next to these communities, several transitional species assemblages, connecting the four communities, were defined. The described communities typically occur in a gradient of increasing grain size and decreasing silt-clay percentage. Degraer *et al.* (in press) explain how habitat suitability maps of the four macrobenthic communities have been created for the BPNS.

Cross tabulation is a technique that displays the joint distribution of two or more variables. The cross tabulation is presented as a contingency table describing the distribution of the variables simultaneously. Each cell of the table shows the frequency of each macrobenthic community per cluster. For this study, the cross tabulation was performed on the two nominal variables being macrobenthic community (dependent variable) and the Tryton class (independent variable). Per Tryton class, the percentage of macrobenthic communities was calculated. The community with the highest frequency of occurrence was considered as the dominant biological habitat. The habitat maps are simple translations from the acoustical Tryton classes towards the dominant macrobenthic communities. For each area, the following results are shown: a map of the Tryton classification with the biological samples, a graph with the cross tabulation results, a map with the translated map, showing the likely occurrences of the macrobenthic communities.

RESULTS

1) Br&W Oostende dumping region

The sedimentological results from the seabed classification (Figure 2) are described in Van Lancker *et al.* (2004). Considering the macrobenthos, Van Lancker *et al.* (2004) describe the area as density- and diversity-poor. The cross tabulation (Figure 3) and the habitat map (Figure 4) show that the likely occurrences of the following macrobenthic communities: *M. balthica*, *A. alba* and a transition between the *N. cirrosa* and *O. limacina* community. In general, the *A. alba* community is characterised by a high diversity, abundance and biomass and can be considered as one of the ecologically most important soft-sediment macrobenthic communities of the BPNS (Van Hoey, 2005). The sedimentological conditions (fine muddy sand) are most suitable for the *A. alba* community, but the dumping of dredged material in this area probably explains the low biodiversity. The *M. balthica* community appears to be associated mainly with the class of fine sand. Normally, this community occurs typically where high percentages of mud are present. However, previous investigations (Degraer *et al.*, 2003) have shown also that there is no clear relationship between acoustic facies and the occurrence of the *M. balthica* community. It appears that the presence of this community is mosty associated with areas with high concentrations of suspended particulate matter in the water column. With the vicinity of the dumping ground and the muddy deposits in the surroundings this condition is met. The *N. cirrosa* – *O. limacina* transition occurs mostly north of the former dumping site of dredged material. Although, the occurrence of such coarser-grained communities would be rather rare in dumping areas, side-scan sonar imagery has shown the existence of coarser-grained patches in the area. Moreover, the former dumping site is very shallow, hence, subdued to wave action washing out the finer fractions. The *N. cirrosa* community shows a large overlap with several transitional species assemblages and it takes a central place within the overall macrobenthic community structure of the BPNS (Van Hoey *et al.* 2004).

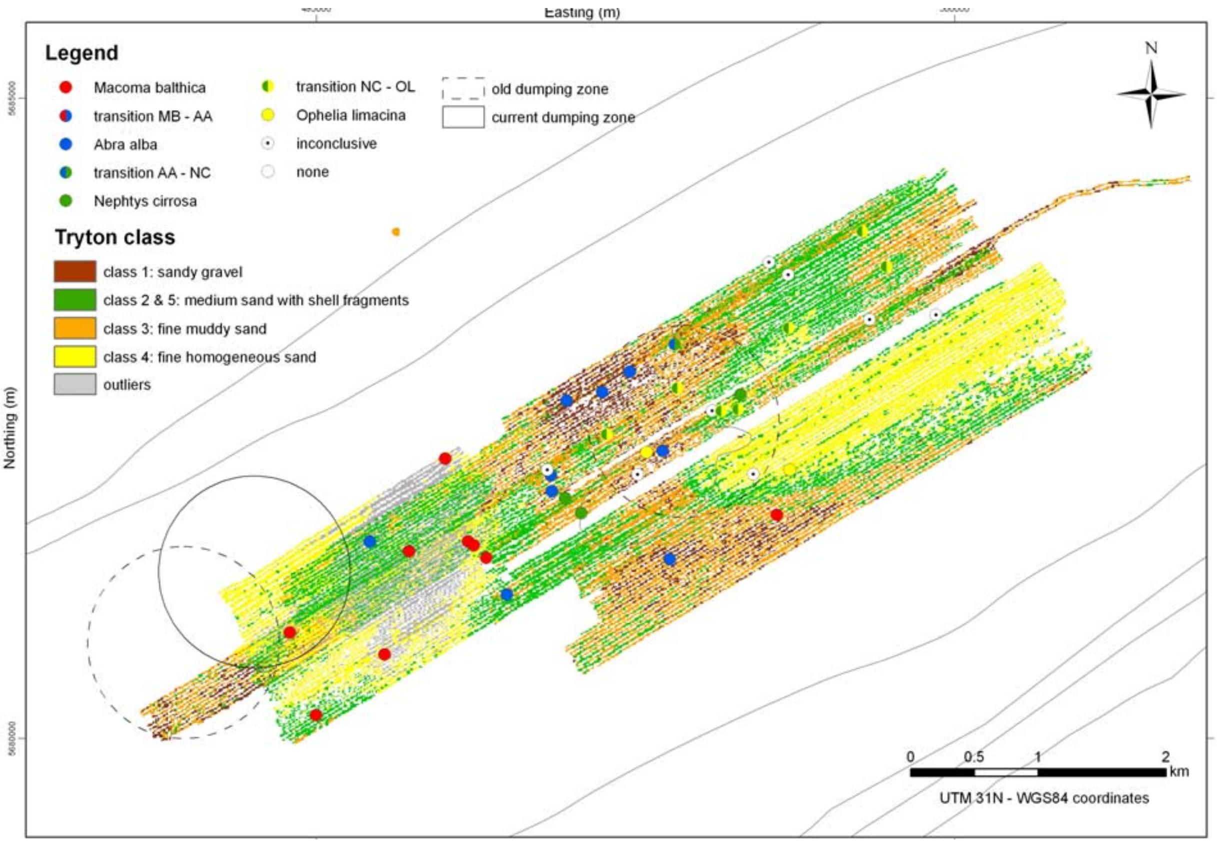
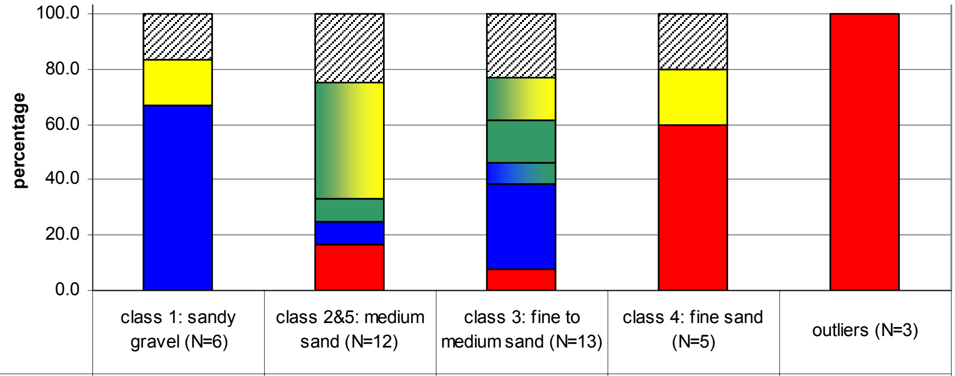


Fig. 2: Acoustical seabed classification of the Oostende area.



	class 1: sandy gravel (N=6)	class 2&5: medium sand (N=12)	class 3: fine to medium sand (N=13)	class 4: fine sand (N=5)	outliers (N=3)
▨ inconcl	16.7	25.0	23.1	20.0	0.0
☐ none	0.0	0.0	0.0	0.0	0.0
🟨 G: Ophelia limacina	16.7	0.0	0.0	20.0	0.0
🟩 F: transition NC - OL	0.0	41.7	15.4	0.0	0.0
🟩 E: Nephtys cirrosa	0.0	8.3	15.4	0.0	0.0
🟦 D: transition AA - NC	0.0	0.0	7.7	0.0	0.0
🟦 C: Abra alba	66.7	8.3	30.8	0.0	0.0
🟪 B: transition MB - AA	0.0	0.0	0.0	0.0	0.0
🟥 A: Macoma balthica	0.0	16.7	7.7	60.0	100.0

Oostende: Tryton class

Fig. 3: Cross tabulation of macrobenthic communities with the Tryton classes for the Oostende area.

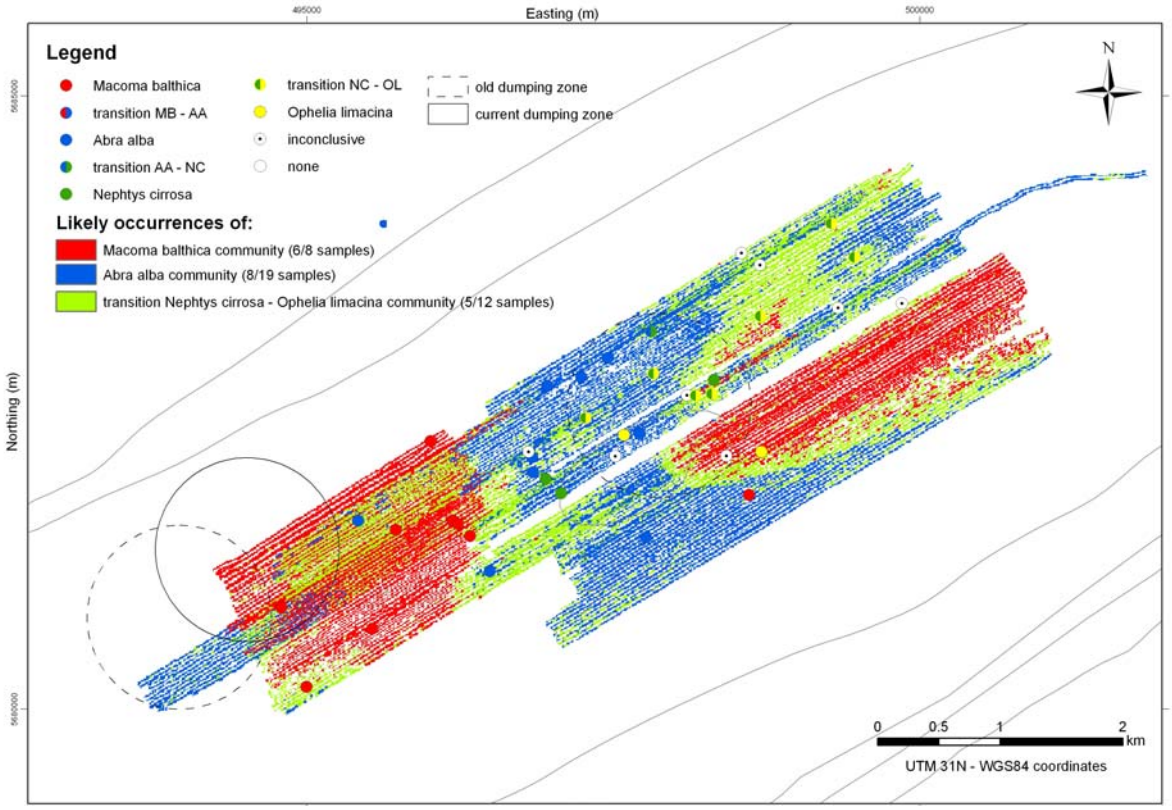


Fig. 4: Habitat map of the Oostende area

2) Hinder Banken

Figure 5 shows a sedimentological map based on an acoustical seabed classification (Van Lancker *et al.* 2005). The Westhinder and Oosthinder sandbanks are characterised by medium sand with shell fragments and fine homogeneous sand, whilst the swales in between are mainly composed of sandy gravel. All of the macrobenthic samples, except one, belong to the community of the *N. cirrosa* – *O. limacina* transition (Figure 6); as such the habitat map of the Hinder Banken area (Figure 7) shows only this community as most likely occurrence. It needs emphasis that the samples relate only to the sand layer in the area. Gravel occurring in this area is largely under-sampled and might be associated with more sessile, epibenthic organism-dominated communities than the transition community or the other described communities. Gravel can be detected with acoustical classification techniques, but only minor parts of the BPNS have been covered until now. However, gravel is a very interesting habitat with generally high biodiversities (e.g. *Ostrea edulis* and *Clupea harengus* (Houziaux *et al.* 2007), scallops (Kostylev *et al.* 2003) and *Crepidula fornicate* (Brown *et al.* 2002)). With more suitable sampling techniques for gravel areas (e.g. Hamon grabs), a more complex habitat map might be derived.

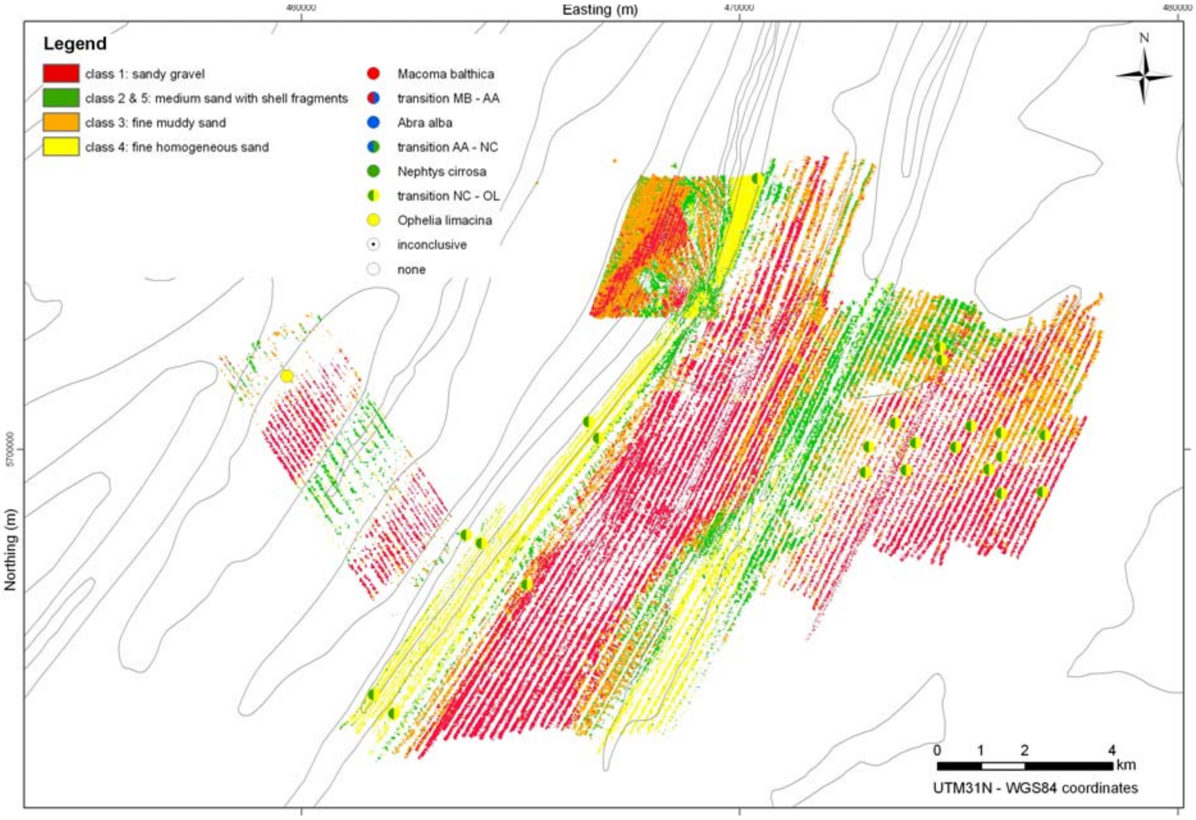
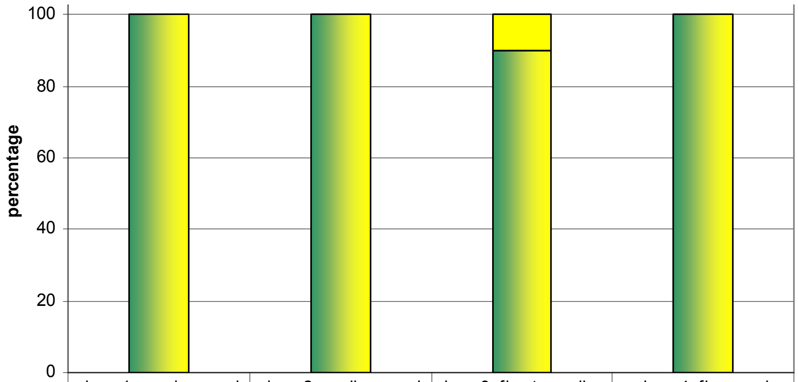


Fig. 5: Acoustical seabed classification of the Hinder Banken area.



	class 1: sandy gravel (N=7)	class 2: medium sand (N=1)	class 3: fine to medium sand (N=10)	class 4: fine sand (N=6)
▨ inconcl	0	0	0	0
☐ none	0	0	0	0
🟨 G: Ophelia limacina	0	0	10	0
🟨 F: transition NC - OL	100	100	90	100
🟩 E: Nephtys cirrosa	0	0	0	0
🟩 D: transition AA - NC	0	0	0	0
🟦 C: Abra alba	0	0	0	0
🟥 B: transition MB - AA	0	0	0	0
🟥 A: Macoma balthica	0	0	0	0

Hinderbanken area: Tryton class

Fig. 6: Cross tabulation of macrobenthic communities with the Tryton classes for the Hinder Banken area.

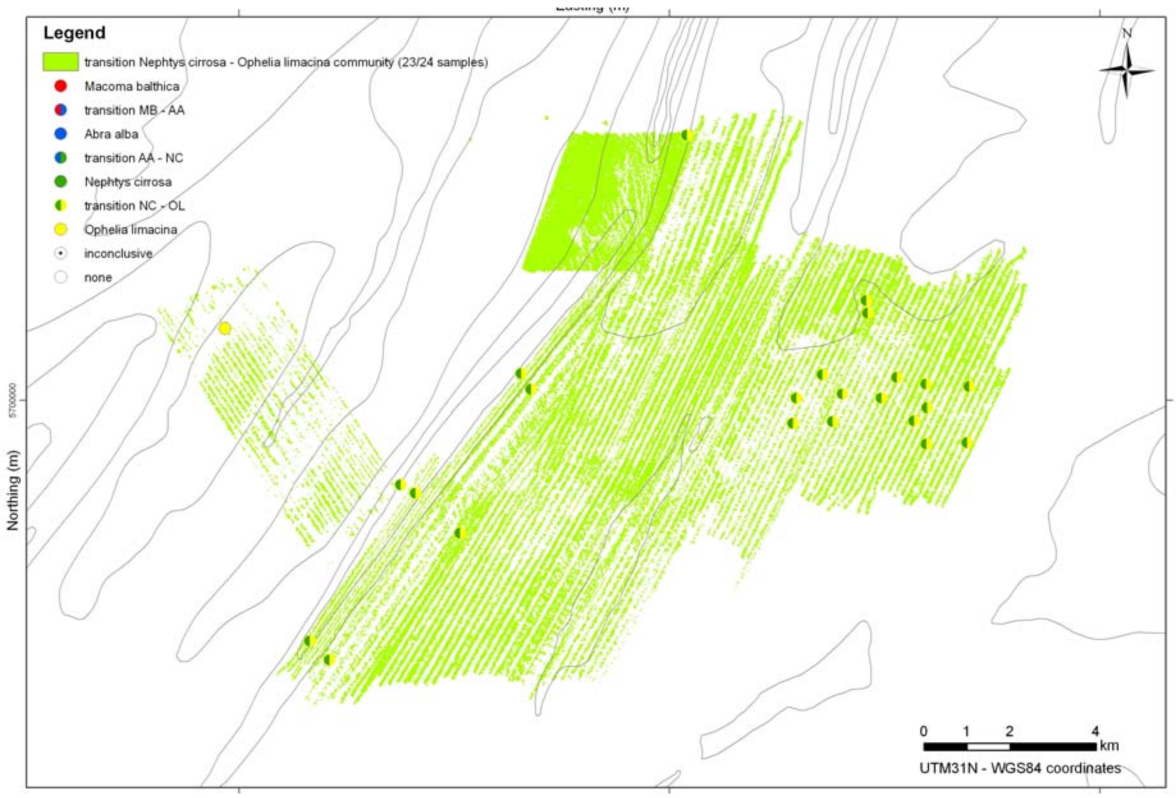


Fig. 7: Habitat map of the Hinder Banken area.

3) Sierra Ventana region

Figure 8 shows a sedimentological map of the Sierra Ventana region, based on an acoustical seabed classification (Van Lancker *et al.* 2005). The map shows the acoustical classes of Roche (2002): class 2 (medium sand), class 3 (fine to medium sand) and class 4 (fine sand). In general, there is a good correlation between backscatter strength and type of sediments, especially for the fine sediments. The cross tabulation (Figure 9) correlates the biological samples with the acoustic seabed classification. Figure 10 shows the species densities per acoustical classes. Class 2 and 4 show a relative low species density (respectively 68 and 98 ind./m²). Class 2 contains mainly the *N. cirrosa* community, being species and density poor. Class 3 shows a relative high species density being 861 ind./m². This class consists mainly out of the transition between the *A. alba* and *N. cirrosa* community. The habitat map (Figure 11) shows that especially the class with likely occurrences of the transition between *A. alba* – *N. cirrosa* is interesting (NE part of area), as the *A. alba* community is the species and density richest community of the BPNS (Van Hoey *et al.* 2005). There is a good correspondence of this class with the grainy texture and patchy pattern on side scan sonar, possibly indicating the presence of tube building polychaetes, structuring the sediment (Figure 12). The *N. cirrosa* community dominates both the old and the new dumping site.

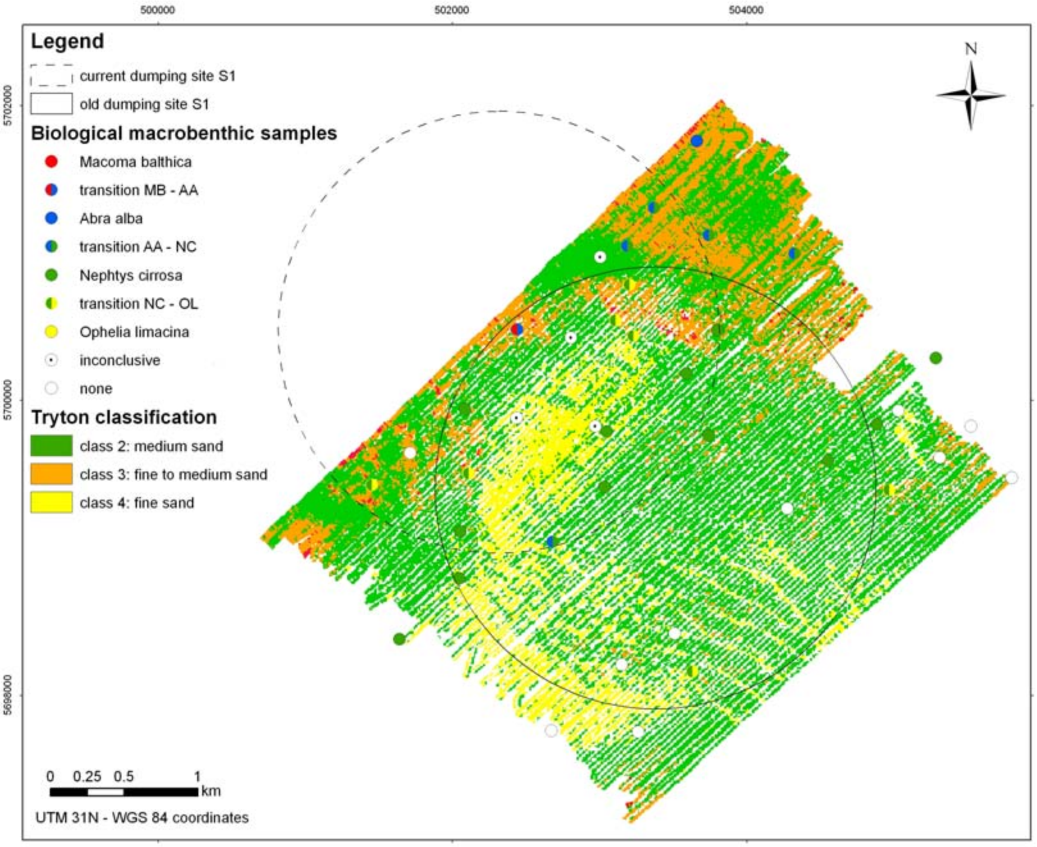
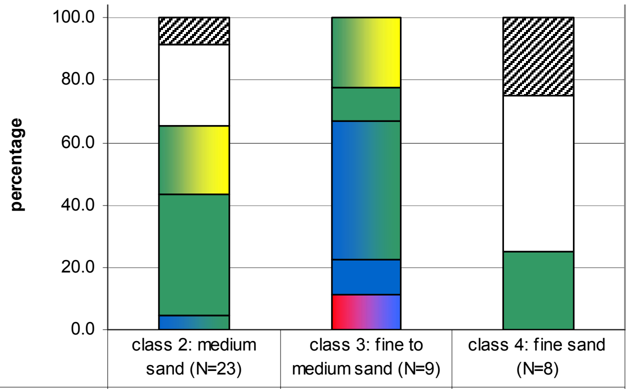


Fig. 8: **Acoustical seabed classification of the Sierra Ventana area.**



	class 2: medium sand (N=23)	class 3: fine to medium sand (N=9)	class 4: fine sand (N=8)
▨ inconcl	8.7	0.0	25.0
☐ none	26.1	0.0	50.0
■ G: Ophelia limacina	0.0	0.0	0.0
■ F: transition NC - OL	21.7	22.2	0.0
■ E: Nephtys cirrosa	39.1	11.1	25.0
■ D: transition AA - NC	4.3	44.4	0.0
■ C: Abra alba	0.0	11.1	0.0
■ B: transition MB - AA	0.0	11.1	0.0
■ A: Macoma balthica	0.0	0.0	0.0

Sierra Ventana: Tryton class

Fig. 9: **Cross tabulation of macrobenthic communities with the Tryton classes for the Sierra Ventana area.**

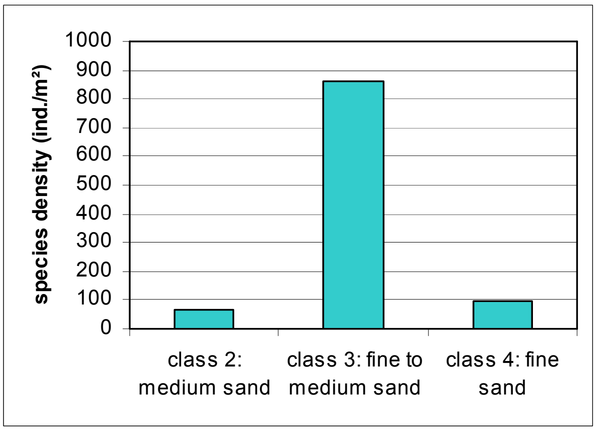


Fig. 10: Species density per acoustic class in the Sierra Ventana region.

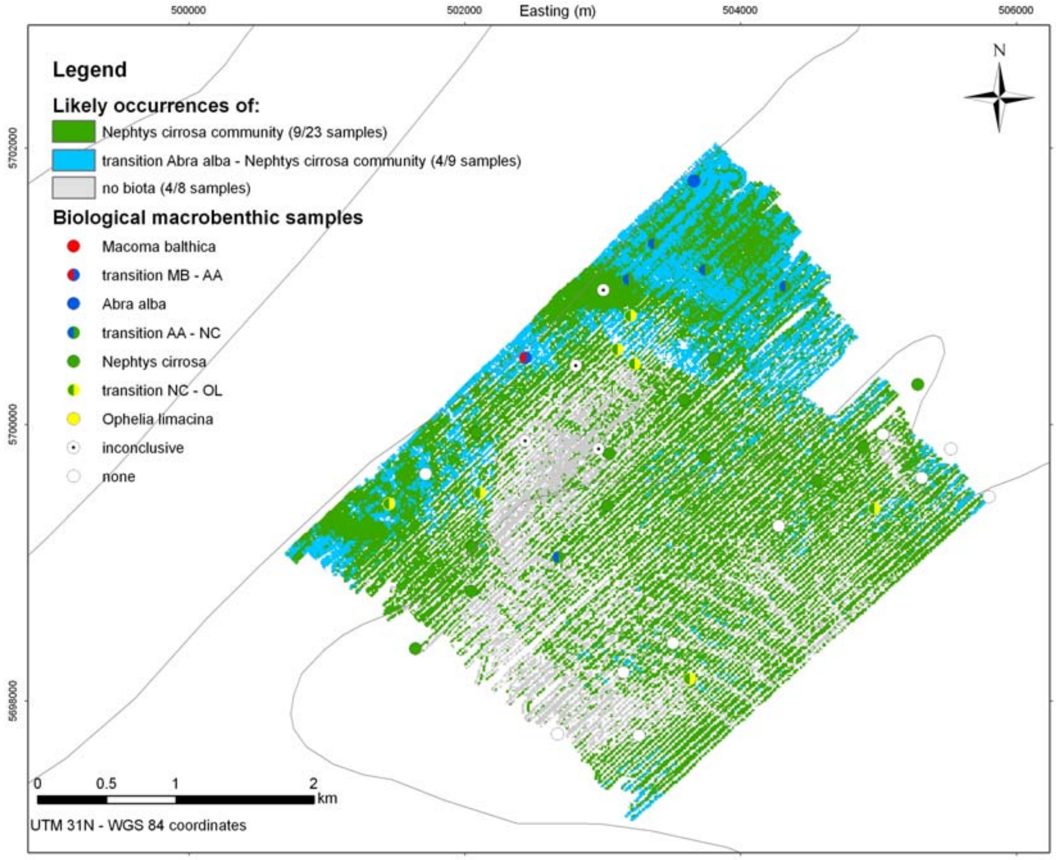


Fig. 11: Habitat map of the Sierra Ventana area.

DISCUSSION AND CONCLUSION

When all the macrobenthic samples of the different areas are summarized in one cross tabulation (Figure 13), it is clear that the transition between the *N. cirrosa and O. limacina* community largely dominates. This is due mainly to the larger amount of acoustic data in the more offshore areas, where these communities tend to prevail (Degraer *et al.*, in press). As such, it is difficult to extrapolate results from different small areas to the larger sedimentary environment.

There are indeed a number of problems with the technique of cross tabulation: (1) certain habitats are often sampled much more frequently than others (e.g., sandbank areas are sampled more than the swales) and the frequencies might need to be corrected for this bias. (2) as the number of physical habitat classes increases with cross tabulation, the number of records in each category falls – eventually to the point where the frequencies of occurrence have a low reliability. This is especially true where sampling data is scarce; (3) the map will always show the dominant habitat and this means that rare, but possibly important habitats are poorly represented. As such, cross tabulation is best suited to broad scale indicative maps. Other modelling techniques are being tested to improve the correlation between acoustic classes and the occurrence of macrobenthic communities.

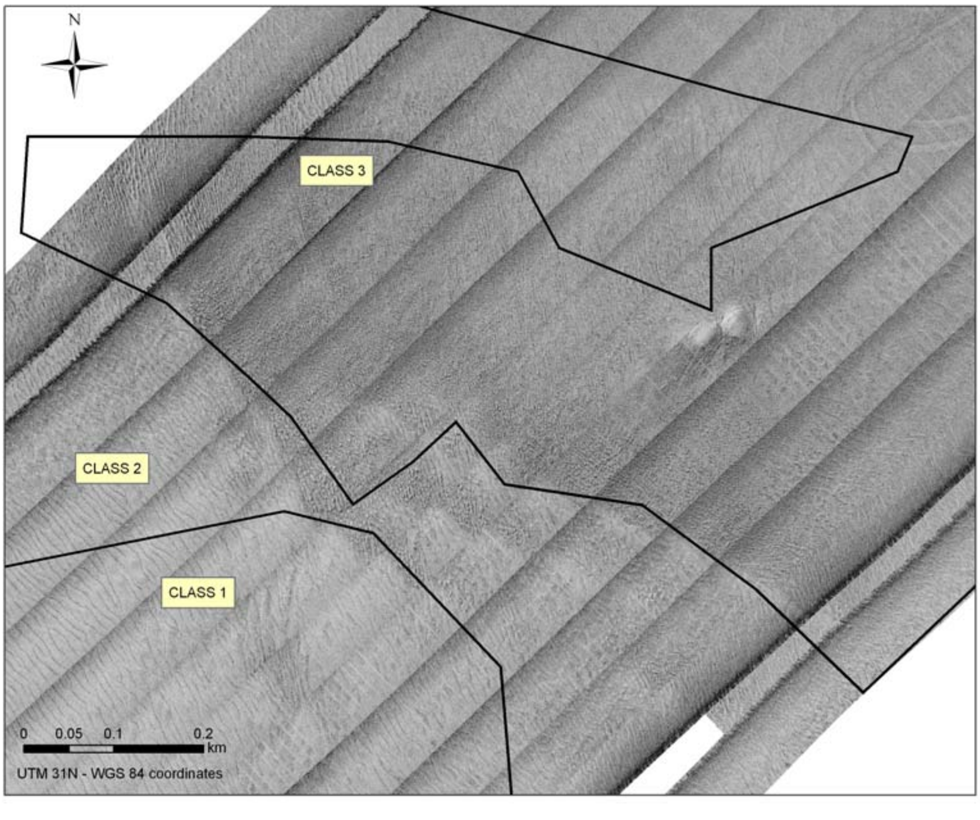
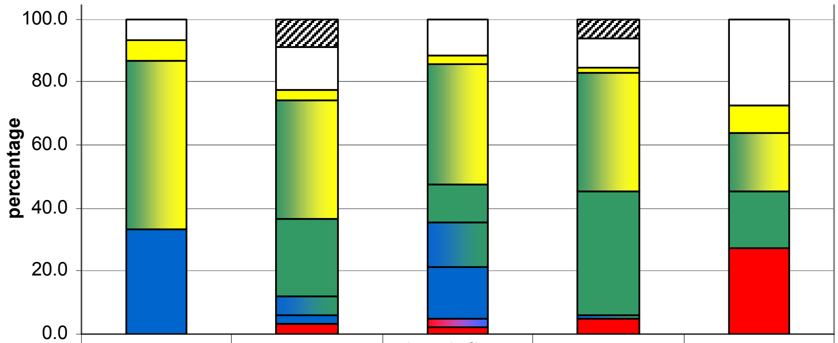


Fig. 12: Side scan sonar image zooming in on the different textures of the acoustical classes. Class 3 corresponds with the most likely occurrence of the transition bewteen the A. alba and the N. cirrosa community. Tube building polychaetes (e.g. Lanice conchilega and Owenia fusiformis) cause the mottled texture of the acoustic facies.



	class 1: sandy gravel (N=15)	class 2: medium sand (N=66)	class 3: fine to medium sand (N=42)	class 4: fine sand (N=64)	outliers (N=11)
▨ inconcl	0.0	9.1	0.0	6.3	0.0
☐ none	6.7	13.6	11.9	9.4	27.3
🟨 G: Ophelia limacina	6.7	3.0	2.4	1.6	9.1
🟩 F: transition NC - OL	53.3	37.9	38.1	37.5	18.2
🟩 E: Nephtys cirrosa	0.0	24.2	11.9	39.1	18.2
🟦 D: transition AA - NC	0.0	6.1	14.3	1.6	0.0
🟦 C: Abra alba	33.3	3.0	16.7	0.0	0.0
🟪 B: transition MB - AA	0.0	0.0	2.4	0.0	0.0
🟥 A: Macoma balthica	0.0	3.0	2.4	4.7	27.3

All areas: Tryton class

Fig. 13: Cross tabulation of macrobenthic communities with the Tryton classes in all areas.

ACKNOWLEDGEMENTS

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Physical impact of dredged material disposal sites and their recovery after cessation of dumping: a case study in the Belgian coastal zone

(Submitted to Marine Geology)

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ABSTRACT

The interaction of dumped sediments with the existing morphological and sedimentological conditions and the recovery after cessation of dumping activities is still poorly known, especially on the long-term. We present a quantitative impact study of the dumping of dredged material on two overlapping dumping sites, situated on different morphological entities; an old dumping site closed in 1999 and located on a sandy shoal, and a new one located in a tidal swale. Chrono-sequential single-beam echosoundings, high-resolution multibeam bathymetrical and backscatter data, ground-truthed with boxcores and vibrocores, were used. Dumping has caused a clear depth reduction between 1995 and 2004. Different yearly growth values and sedimentation patterns were found for the old and new dumping sites, due to the difference in morphological setting. The present morphology of the old dumping site -an irregular-shaped dump mound, with sand piles on the edges and a depression in the centre- reflects the way of disposal. On the new dumping site, a dump mound is found, which is characterised by impact features such as depressions and topographic highs. After cessation of the disposal of dredged sediments on the old dumping site, the site has restored quickly its morphodynamic equilibrium. Bedforms were formed within less than one year and their distribution and corresponding sedimentology is representative for the Belgian coastal zone. Between the large dunes, small depressions occur, which are thought to be remnants of single dumping events.

Keywords: impact study; dredge material dumping; morphodynamics; sedimentology; dynamic coastal environment; multibeam

INTRODUCTION

Worldwide, the morphology in near-coastal areas is subject to continuous short- and long-term changes on various spatial and temporal scales (McMagnus, 1998). Those changes are due to the reworking and redistribution of sediments. Consequently, many seaports and shipping channels have substantial sedimentation problems, which lead to a constant dredging need to maintain the necessary water depths. Furthermore, they have to be adapted to the increasing size of vessels. Some of the dredged material is reused for beach nourishments or infrastructural projects, but most of it is dumped on designated offshore dumping sites (OSPAR COMMISSION, 2000). This is also the case for the shipping channels in the Southern Bight of the North Sea. Around 10 million tons of dry material is dredged each year, and ensures unhindered navigation to the harbours of Zeebrugge and Antwerp; the material is mainly dumped back into the sea.

Like other anthropogenic activities, the dumping of dredged material can have a negative impact on the marine environment and due to the dynamic nature of the sea, such impacts may not only be restricted to the immediate area of dumping. Only a small number of scientific studies concerning the direct consequences of dredge spoil dumping on the seabed are available and most of them are dealing with the dispersion of dredged material (e.g. Collins, 1990; Truitt, 1988; Van den Eynde, 2004; Van Parijs *et al.*, 2002; Wurpts, 2006) and with the effect on benthic fauna and the disposal of pollutants (e.g. Fredette and French, 2004; Van Parijs *et al.*, 2002; Simonini, 2005; Smith and Rule, 2001; Stronkhorst *et al.*, 2003). In dynamic coastal areas, the knowledge on the interaction of the dumped sediments with the existing morphological and sedimentological conditions is still fragmentary, especially from a long-term perspective, although those changes can in turn have an impact on the hydrodynamic regime, sediment transport and on the ecosystem in general.

Another issue, related to the dumping activities of dredged material, is the physical recovery of the dumping place after cessation; hitherto only sporadically studied. Wienberg and Hebbeln (2005) observed a regeneration of dunes after the cessation of the dumping activities, while Stronkhorst *et al.* (2003) observed a recovery of sediment texture at a dumping site in the North Sea, near the port of Rotterdam.

The present paper presents a detailed analysis of these different disposal impact issues for a dumping site, Br&W Scheur 1 (S1), situated in the Southern Bight of the North Sea (Fig. 1). This site was chosen because: (1) it is the main dumping place on the Belgian Continental Shelf, (2) it has been relocated when the maximum dumping capacity was reached; as such the long-term effect of extensive dumping and the regeneration after the cessation of dumping can be studied; and (3) the recent dumping site is located in a tidal gully whilst the older one is located on a sandy shoal; as such a comparison can be made of the impact on both environments. The study area was surveyed with a multibeam echosounder providing bathymetrical and backscatter data. Additionally, boxcore samples were taken to validate the acoustic data. Finally, chrono-sequential single-beam echosoundings were used to investigate the morphodynamic evolution from 1995 till 2002.

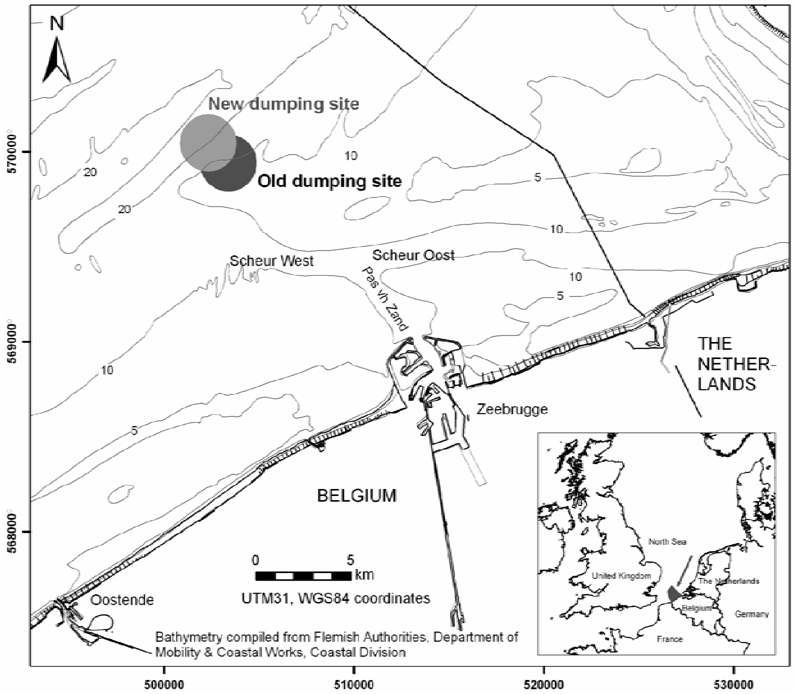


Fig. 1. Localization map of the old and new dumping site Br&W S1 on the Belgian Continental Shelf.

Study area

The dumping ground S1 is the main dumping site on the Belgian Continental Shelf. Annually, on average 5x10^6 ton dry matter (TDM) is dumped, originating mainly form the shipping channels Scheur, Pas van het Zand and the outer part of the harbour of Zeebrugge (Fig. 1). The average current velocity is 0.3 m/s, increasing to 1 m/s during flood (Lanckneus *et al.*, 2001; TVNK, 1998c). The hydrodynamics are mainly tidally driven; nevertheless wind and density currents can be important.

The dredged material consists mainly of fine-grained material. The proportion between the sand and the mud fraction is variable, partly depending on the place of dredging. Measurements indicate that 80-90% of the dumped sand stays on the dumping place, the remaining is transported back to the navigation channel Scheur West (HAECON, 1994). Tracer experiments, which were later confirmed by model results, have shown that the mud fraction is spread out over a wide area under the influence of the prevailing meteorological conditions. In calmer weather conditions, the mud is recirculated towards the coast, where a turbidity maximum occurs (Van den Eynde, 2004).

S1 came into use in 1966 and since then it has been relocated 4 times when its maximum dumping capacity was reached. The focus of this paper will be on the two most recent dumping sites. They will be referred to as the 'old' dumping site (1984-1999) and the 'new' dumping site (1999-present). Both sites are circular, with a surface area of 7.1 km^2.

MATERIAL AND METHODS

Multibeam

Multibeam imagery was acquired during campaigns in February and March 2003 using a Kongsberg Simrad EM1002 multibeam echosounder aboard the R.V. Belgica (Fig 2). In total, 12 km² was covered. The EM1002 provides both high-resolution depth data and co-registered calibrated backscatter intensity data; with up to 111 receive beams of 2° (athwart) x 3.3° (fore-aft) width. It works at a nominal frequency of 95 kHz with a ping-rate of around 4 to 6 Hz. The data are real-time corrected for the roll and heave using a Seatex MRU 5 motion sensor and for the heading using an Anschütz Standard 20 gyrocompas. The geographic co-ordinates are provided by a Thales Aquarius 02 GPS positioning system with a theoretical precision of 10 mm. The soundings are tide-corrected using the specific M2 tidal reduction method for the Belgian coastal zone (Van Cauwenberghe *et al.*, 1993) and referenced to the level of MLLWS. In water depths less than 30 m, the depth measurement accuracy is estimated to be around 10 cm RMS or 0.2 % of the depth (Kongsberg Simrad, 1999-2001a). The post-processing was done using the software packages Neptune (Kongsberg Simrad, 1999-2001b) and Fledermaus and resulted in digital terrain models with a 1-m grid resolution.

The backscatter measurements recorded by the EM1002 were processed using the software package Poseidon (Kongsberg Simrad, 1999-2001c) and resulted in mosaics at 2-m grid resolution.

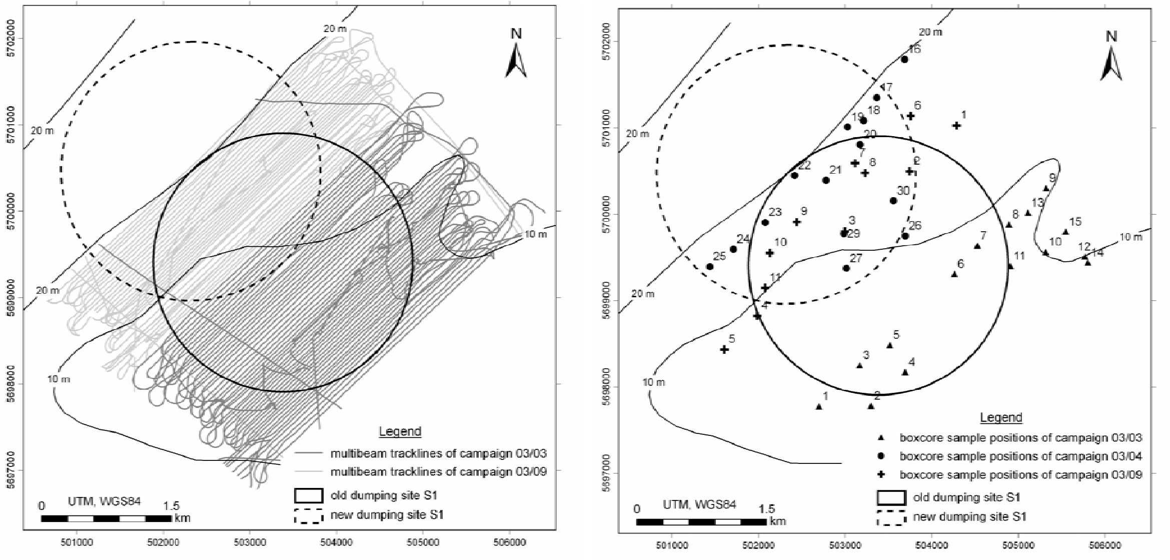


Fig. 2. Positioning of the multibeam tracklines, sailed during 2 campaigns in 2003 and of the boxcore samples, collected during 3 campaigns in 2003.

Samples

A total of 41 boxcore samples were taken during 3 campaigns in 2003. They were used to identify the grain-size characteristics and were related to the continuum of backscatter intensities observed along this site (Fig 2). The boxcore sampler penetrates 40 to 50 cm in the sediments and allows sampling individual laminae of sediment.

The subcores were cut longitudinally and of each sediment layer a subsample was taken. The subsamples were dry sieved on a column with mesh sizes every ¼ phi, ranging between 2000 and 710 μm. The coarse particles were mostly shells and shell fragments. After a destruction of carbonate, the sand fraction was sieved similarly in a range between 710 and 75 μm. Finally, the mud fraction (when present) was analyzed using a Micromeretics SediGraph 5100. Grain-size distribution curves and the sedimentological parameters of each sample (mean grain-size, sorting and skewness) were calculated.

Single-beam

Chrono-sequential single-beam data (Flemish Authorities, Agency for Maritime and Coastal Services, Maritime Access) were used to evaluate the bathymetrical and morphological changes from 1995 till 2004.

RESULTS

Morphology

General morphology

The old dumping site is circular in aspect with sand piles on the edges and a central depression, with a seafloor gradient sloping towards the NE (Fig. 3). The sand piles shoal 2 to 3 m above the depression. Water depths range from -6 to -14 m MLLWS. The new dumping site overlaps with the old dumping ground, though its location is mostly in the swale with water depths of –20 to –21 m MLLWS. In the south-western part, a dump mound is found.

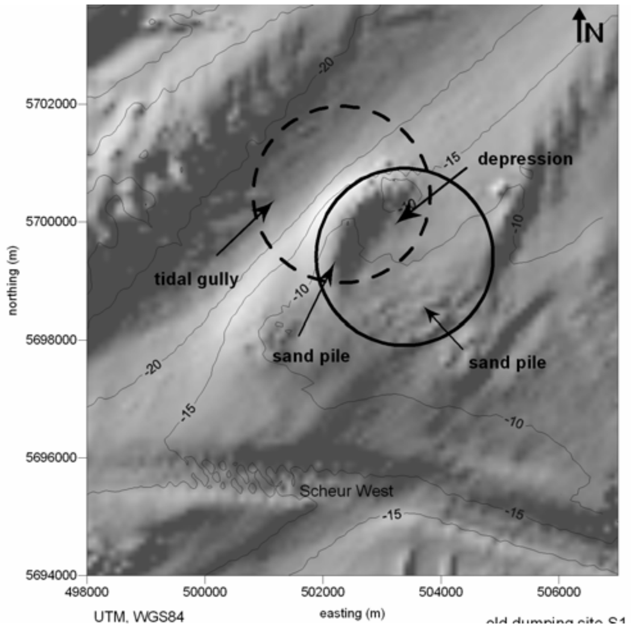


Fig. 3. Shaded relief map of the dumping site S1, based on single-beam data.

Detailed morphology

The digital terrain model, based on the multibeam recordings, reveals different morphological features (Fig. 4a/b), which are presented in more detail in figures 5a, b & c together with cross sections.

Dumping related features are found on both the old and new dumping site. Topographic highs are present on the new dumping site while negative structures are found on both, and even outside the old dumping site (Fig. 5a/b). The characteristics of the different features are summarised in Table 1.

On the old dumping ground, also an abundance of bedforms occur (Fig. 4a/b). The bedform characteristics, such as dune height (H), wavelength (L), the length of the lee (b) and stoss side (a) were investigated through 17 cross-sections aligned in a NE-SW direction (Fig. 4b). Finally, the symmetry index (SI), calculated as a/b (Tanner, 1971) was calculated (Table 2). A summary of the different bedform characteristics is given in Table 1.

Table 1. Overview of the different morphological features and their characteristics present on the old and new dumping site.

	Old dumping site			New dumpingsite
Setting	sandy shoal			tidal gully
Dumping impact features				
Topographic highs	none			0.3 – 0.6 m
Depressions				
Shape	elongated	circular		lineair to curvilinear
Depth	0.3 - 0.5 m	0.25 m		0.6 m
Dimensions	length: 30 - 50 m, wide: 15 m	diameter: 5 m		
Strike	N115E			NW-SE axis
Location	on sand piles	east part		
Bedforms				
Type (according to Ashley, 1990)	large dunes	small dunes	ripples	
Strike	NW-SE	NW-SE	NW-SE	
Height range	0.8 - 2.1 m	0.5 - 0.6 m	0.1 - 0.2 m	
Wavelength range	35 - 160 m	40 m	7 - 8 m	none
Asymmetry	mostly SW	mostly SW	mostly SW	
Location	crest of sand piles	along slope of sand piles	in depression	

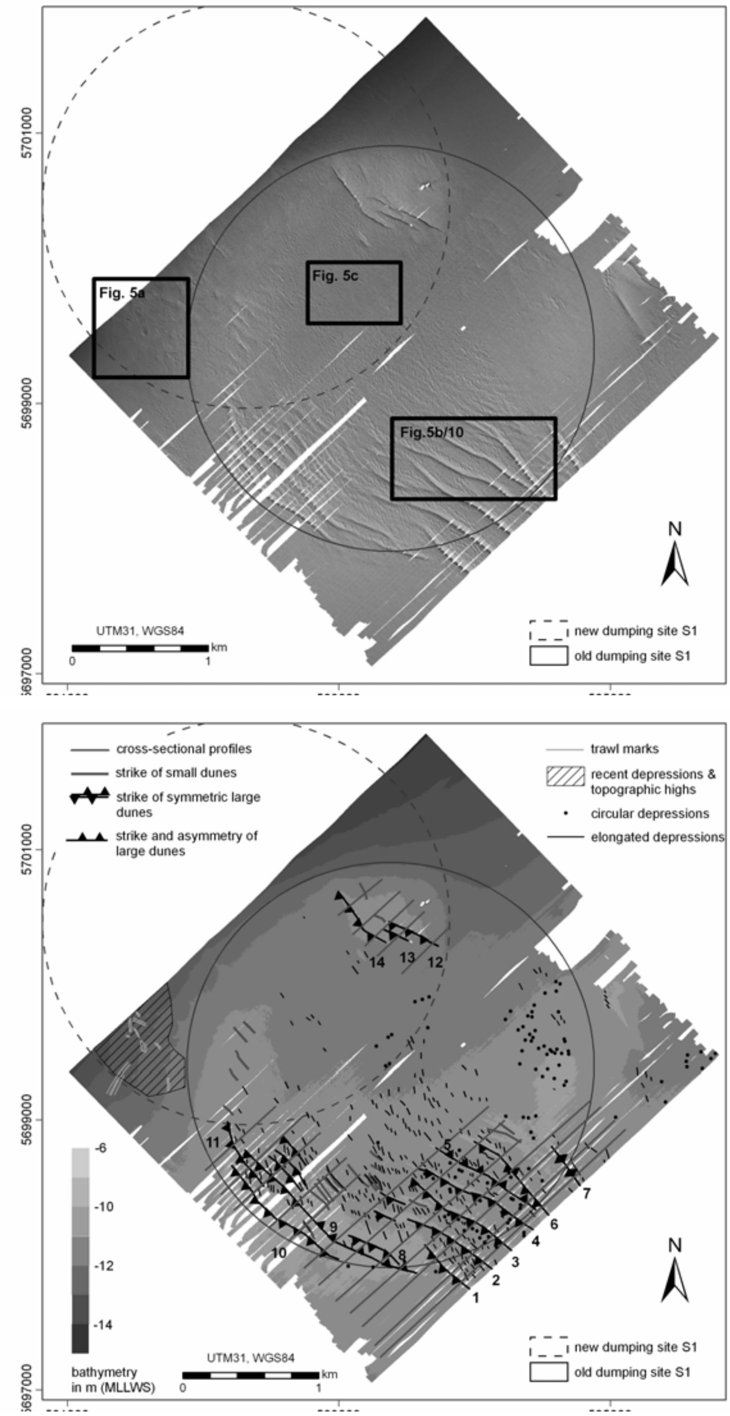


Fig. 4. (a) Shaded relief map of the bathymetry based on multibeam echosounder data (Kongsberg Simrad EM1002S). The digital terrain model is gridded to 1 m. The data was recorded during 2 campaigns in 2003. (b) Interpretation map showing isobaths every 2 m, the strike and asymmetry of the large dunes, the strike of the small dunes, the position of the cross-sections, the recent topographic highs and negative structures, the trawl marks and the circular and elongated depressions. The investigated dunes are numbered.

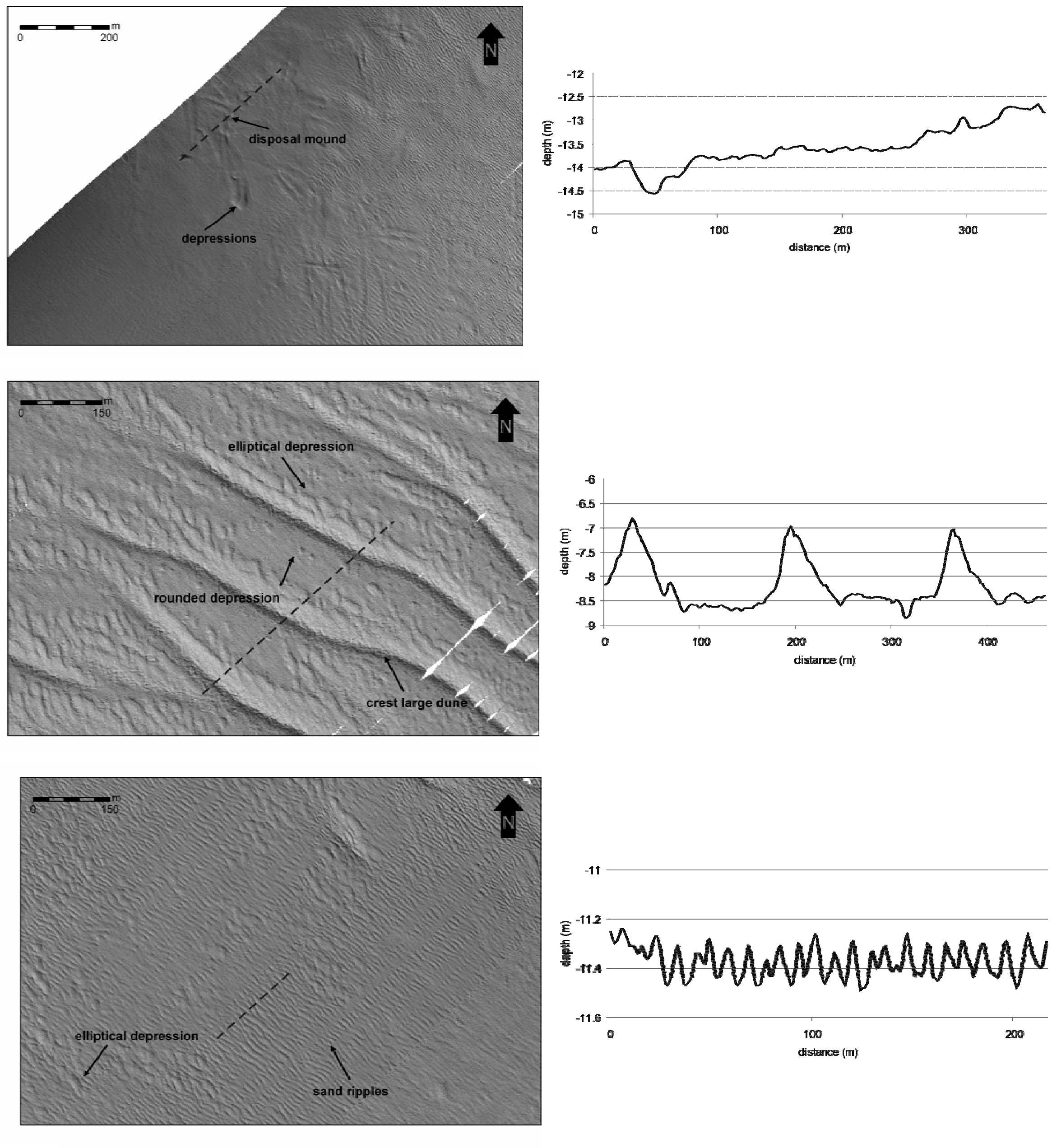


Fig. 5. Details of the shaded relief map showing the different morphological features in the study area and cross-sections from SW to the NE revealing size and heights (a) dredged spoils and depressions (b) large dunes with in between elongated and circular depressions (c) fields of ripples. View Figure 6a for the positioning.

Table 2. Overview of the dune parameters for dune 1 to 14 based on multibeam data. The position of the large dunes and the cross-sections are indicated in Figure 4b.

Dune number		1	2	3	4	5	6	7
Height (m)	max	2.6	1.9	2.3	1.5	1.7	1.7	2.0
	mean	2.1	1.7	1.8	1.4	1.4	1.5	1.7
Length (m)	max	230.0	130.0	180.0	90.0	90.0	70.0	100.0
	mean	160.0	106.0	135.0	78.3	74.0	61.7	86.7
SI	mean	1.6	1.9	1.6	1.6	1.5	1.5	1.0
Dune number		8	9	10	11	12	13	14
Height (m)	max	1.5	1.0	1.4	1.0	0.9	1.1	1.6
	mean	1.1	0.9	1.3	0.8	0.9	1.1	1.2
Length (m)	max	100.0	120.0	80.0	60.0	90.0	35.0	78.0
	mean	73.1	90.0	65.0	46.7	62.5	35.0	64.3
SI	mean	1.6	1.9	1.6	1.6	1.5	1.5	1.0

Morphological Evolution

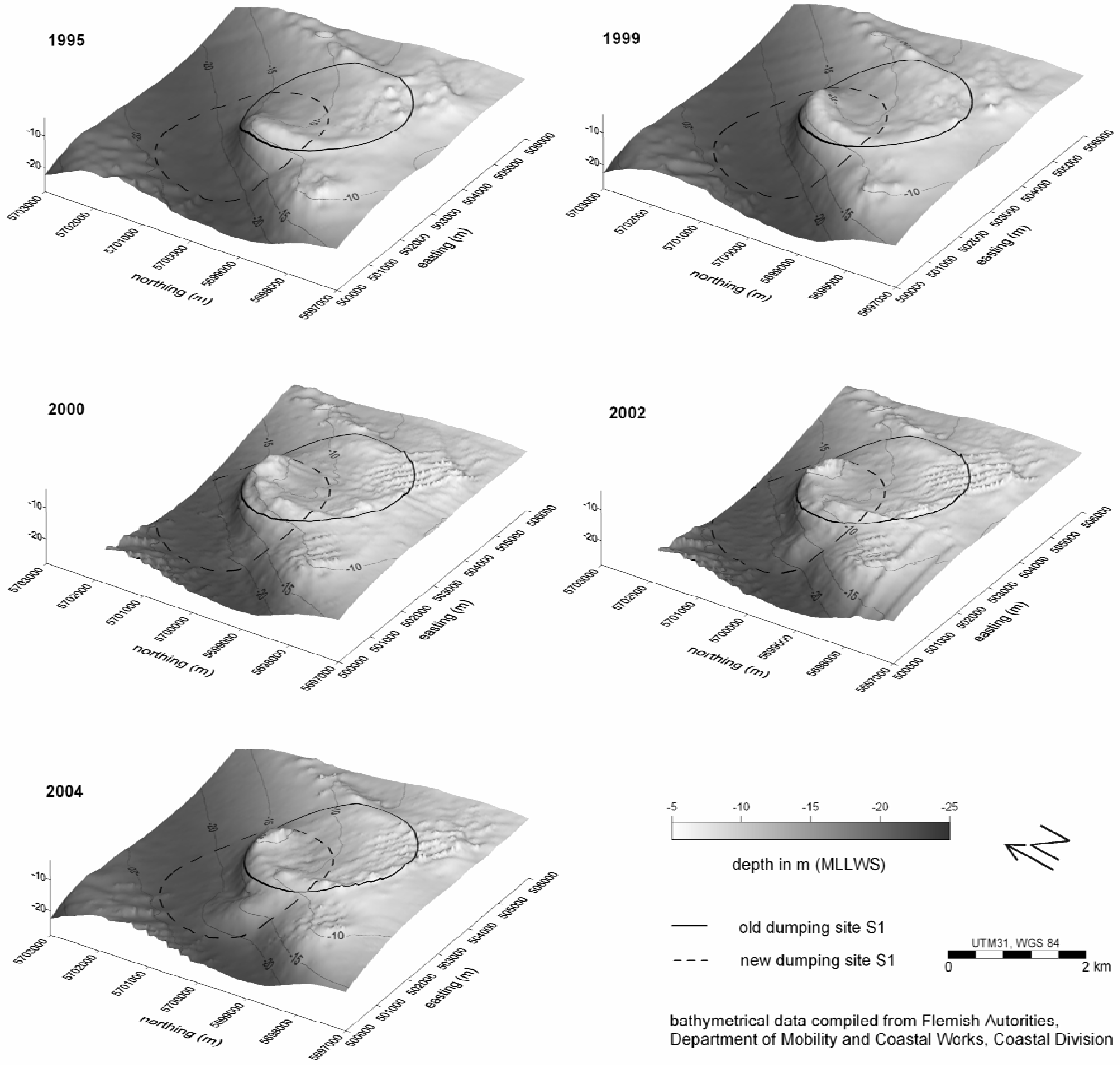
The comparison of the bathymetrical maps based on the single-beam data of 1995, 1999, 2000, 2002 and 2004 reveals that the study area has undergone major morphological changes (Fig. 6). Between 1995 and 1999, sediments clearly accumulated on the northern part of the old dumping site, extending the sand pile on the edge towards the north. From 1999 onwards, sediments merely accumulated on the south-western part of the new dumping zone, whilst on the old dumping ground, dune structures were being formed and a depth reduction occurred in the north-western part. The quantitative morphological evolution of the old and new dumping site can be evaluated by means of volume difference maps (Fig. 7a) and by means of cross-sections through the dumping sites from the NW to the SE (Fig. 7b). The major morphological patterns, described earlier, are observed: a 4 m depth reduction between 1995 and 1999 in the north-western part of the old dumping site, a decrease in depth, up to 6 m, in the south-western part of the new one between 1999 and 2004 and for the same period a deepening up to 4 m in the north-western part of the old dumping ground (Fig. 7a).

Surficial sedimentology

Backscatter images in combination with sedimentological analyses were used to study the distribution pattern of the sediments.

The backscatter map reveals different areas (Fig. 8). The south-western part of the new dumping zone is characterized by a complex pattern of high (± -15 dB, light tones) and lower backscatter (-20 dB, darker tones). Areas of high backscatter are found on the sand pile in the north of the old dumping ground. The southern area is characterized by patches of high backscatter (± -15 dB) in between the bedforms and by curvilinear streaks of low backscatter (± -30 dB). Moderate backscatter values, between -20 and -25 dB, are found in the depression.

The sediments of the old dumping site are sandy, regardless of the muddy nature of the dredged material that was dumped between 1984 and 1999 (Fig. 8a). The finest sand is present in the depression (177-250 μm), whilst coarser sandy sediments are found on the sand piles (250-290 µm) (Fig. 8b). In addition, a decreasing trend in grain-size is observed towards the NE and further towards the N, following the direction of the overall slope. Contrary to the sandy nature of the old dumping sediments, muddy sediments are present on the new dumping site (74 – 18 µmi). At first, only one sample seems to be characterised by those muddy sediments, however a sand layer of about 5 to 10 cm covers several other boxcores, with underneath silty to muddy sediments. The thickness of the sand layer changes according to the tide and the weather conditions. A thin layer of fresh mud (± 1 cm) and clay pebbles were encountered at the surface of some cores.



bathymetrical data compiled from Flemish Autorities, Department of Mobility and Coastal Works, Coastal Division

Fig. 6. Morphological evolution of the dumping site. Three-dimensional bathymetry maps based on single-beam data of 1995, 1999, 2000, 2002 and 2004.

The sorting coefficient ranges between 0 and 4 phi (Fig. 8c). The best sorted sands are found on the old dumping site. The less sorted sediments lie on the new dumping ground. A decrease in the sorting coefficient is observed towards the N.

The silt-clay fraction of the sediments on the new dumping ground reaches values up to 80 % (Fig. 8a). On the old dumping site, almost no silt-clay fraction in the sediments occurs, but a trend of an increasing silt-clay fraction in the NE direction is observed.

Generally, almost no gravel (> 2 mm), represented by shells in this study area, are found (Fig. 8a). The highest amount, up to 14 %, is present on the sand piles.

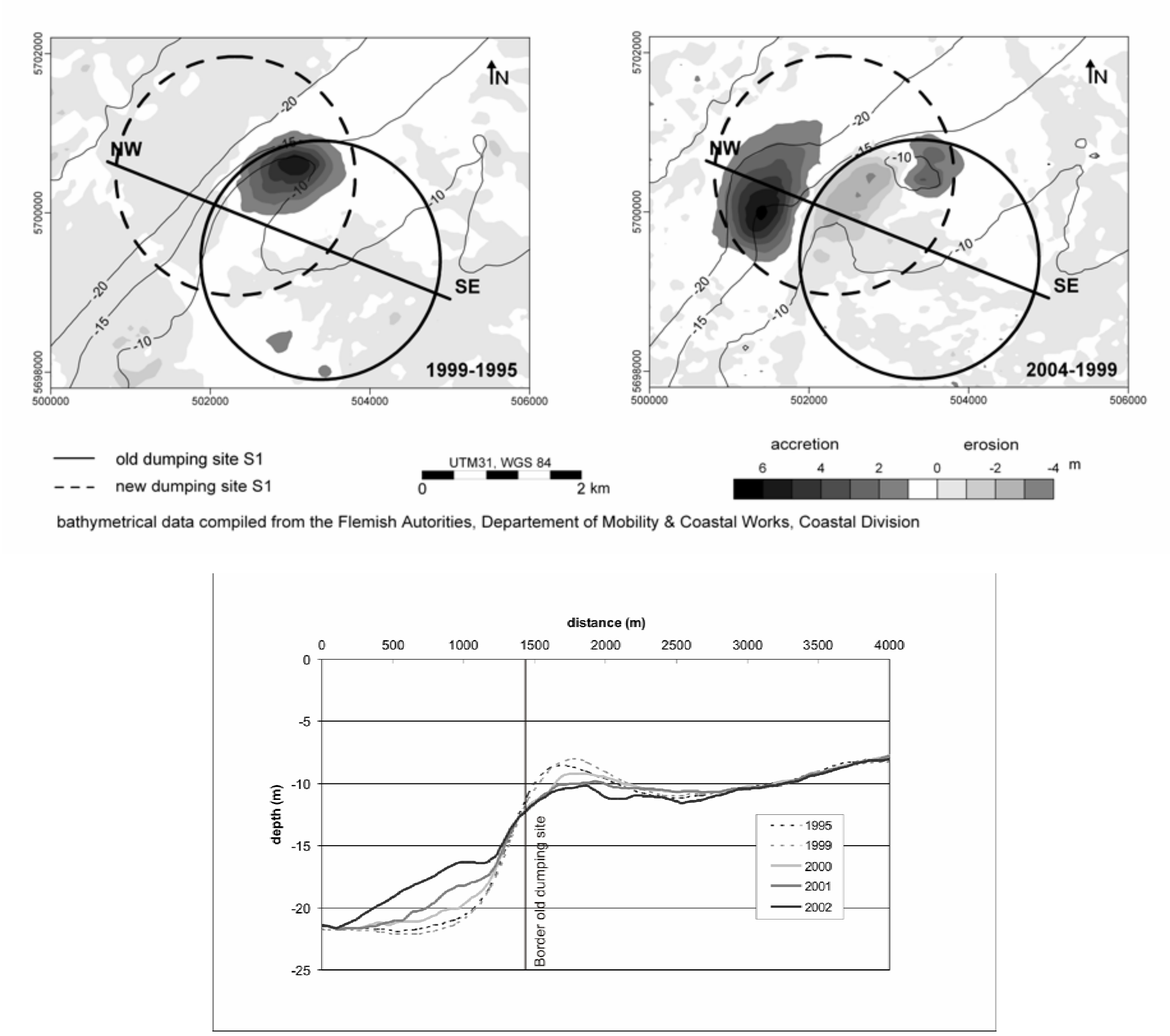


Fig. 7. (a) Volume difference map showing accretion and erosion between 1995 and 1999, 1999 and 2004. (b) Cross-section through the old and new dumping site S1 from the NW to the SE.

DISCUSSION

Physical impact of dredged material dumping

The principal impact of dredged material dumping on the dumping site S1 is the shallowing of the seabed. At the old dumping site, a depth reduction of 4 m occurred between 1995 and 1999 (Fig. 7a), with a yearly growth of ± 0.6×10^6 m^3 of sand estimated by TVNK (1998a). From 1999 onwards, accretion occurs on the new dumping site (Fig. 6). Volume calculations over a period of 5 years show that the dumping of dredged material caused a growth of 4.1×10^6 m^3. However, in the same time span, sediments on the northern part of the old dumping ground have been eroded, probably due to the dumping of a minor part of dredged sediments (<0.5 ton/m^2) on the southern part of the new dumping zone (source: dumping intensity maps, Flemish Authorities, Agency for Maritime and Coastal Services, Maritime Access) (Fig. 6 and 7a). By subtracting this amount of slumped sediments (1.8×10^6 m^3), the new dumping site grew yearly with 0.7×10^6 m^3 of sediments between 1999 and 2004, causing the tidal gully to fill up.

Although the amount of dumped sediments have been substantially reduced since 2000, the yearly growth of the new dumping site is higher than the old one. This difference is ascribed to a difference in morphological setting -the old dumping site is located on a sandy shoal, whilst the new one in a tidal gully-, which in turn causes a difference in sedimentation patterns. On the old dumping site, sandy sediments occur, regardless of the high mud content of the dumped material (Fig. 8a). This is due to a hydraulic segregation mechanism occurring during the dumping activities, which causes a separation of the sand fraction, which settles down, and the mud fraction, which is washed-out by currents (Collins, 1990 and Truitt, 1988). Malherbe (1991) demonstrated the presence of this mechanism on the old S1 dumping site, influencing a wider area than the dumping site. Sediment maps confirm his statement as the mean grain-size decreases and the silt-clay fraction increases towards the north (following the direction of the slope) (Fig. 8b and 8c). Contrary to the old one, heterogeneous sediments, consisting of mud layers, clay pebbles and sand layers, occur on the new dumping site (Fig. 8a and c and descriptions of boxcores). Although the hydraulic segregation mechanism occur also on the new one, as was indicated by Van Parijs *et al.* (2002), it seems that it is less effective than on the old dumping site.

The current morphology of the old dumping ground exist of an irregular shaped dump mound, with sand piles on the edges and a central depression. This is the result of the most cost-effective method of disposal. Split hopper suction dredge vessels navigate to the farthermost point with regard to the coastline, than turn and while sailing back to the navigation channel, they dump the dredged material by opening longitudinally their cargo, whilst describing a half circle. On a smaller morphological scale, the impact of the dumping process is still visible by means of topographic highs and depressions (Fig. 5a). Their alignment corresponds with the transport pattern of the dredge vessels discharging the dredged materials. This pattern was also recognized in mapping studies of dumping sites by the U.S. and Canadian Geological Survey (e.g. Butman *et al.*, 1998; Hart, 1992; Poppe *et al.*, 2001; Torresan and Gardner, 2000 and Valentine *et al.*, 1999). On the old dumping site depressions are mainly found on the sand piles, being the former main zones of dredged material disposal. Their alignment and morphology differ from the ones on the new dumping ground, the latter having a more chaotic alignment and a greater length. This could be due to the action of currents after cessation of the disposal activities or by the difference in sea floor nature, as the new dumping site is located in a natural mud field of Holocene origin (Fettweis *et al.*, 2005), while the old one occurs in a sandy environment (Bastin, 1974). The depressions outside the old dumping site are probably impact features of the dumping process before 1984, as their location corresponds with the former dumping sites (1970-1984) (Fig. 4b).

The physical recovery of the former dumping ground

The formation of dunes on the old dumping site within one year after the cessation of the disposal of dredged sediments shows a quick recovery of morphodynamic equilibrium (Fig. 4). Butman *et al.* (1998) and Wienberg and Hebbeln (2005) reported a similar regeneration of sand dunes. Reformation of dunes has also been observed in shipping channels after dredging of dune fields (Bartholdy *et al.*, 2002; Katoh *et al.*, 1998). The sand dunes are parallel to each other and are oriented in a NW-SE direction, indicative of a SW-NE sand transport. Model results of Fettweis and Van den Eynde (2003) show the same result.

The asymmetry of dunes can be used to deduce the residual transport direction, which is interesting in relation to the recirculation of dredged material towards the navigation channels. To use the asymmetry of dunes, following conditions need to be fulfilled: their asymmetry should be induced by the present-day hydrodynamic processes and their asymmetry should represent an equilibrium of a longer time scale than the daily tidal effect, because hydro-meteorological conditions are able to alter the asymmetry (Lanckneus *et al.*, 2001). On the old dumping site, the dunes are formed after the cessation of the dumping activities, as such they are active features shaped by the present-day hydrodynamic environment. As the tidal cycle is too short to entirely rework the dunes, their overall shape represents a state of quasi-equilibrium to the relative strength of the opposing flows, which continuously modify the bedform profile. As a result, the asymmetry is mainly defined by the dominant tidal current (Lanckneus *et al.*, 2001). In this study, the steep slopes of the large dunes are mainly oriented towards the SW, which means that the residual ebb current shapes the dunes (Fig. 6b). This finding was confirmed by the results of two other campaigns, in 2004 and 2005; as such the second condition is fulfilled (Fig. 9). The large dunes, monitored in 2005, are located in a swale, which make them even more suitable to deduce the long-term transport direction as they are more stable than smaller dunes on sandy shoals (Lanckneus *et al.*, 2001). However, measurements over an entire spring-neap tide cycle on the dumping site S1 show that the transport during flood is 1 to 3 times larger than during ebb under normal weather conditions (MAGELAS, 2001). Numerical residual transport models also indicate flood dominance (Fettweis and Van den Eynde, 2003). Although the ebb current is weaker, these results demonstrate that the transport in the ebb direction, towards the navigation channels, may not be underestimated.

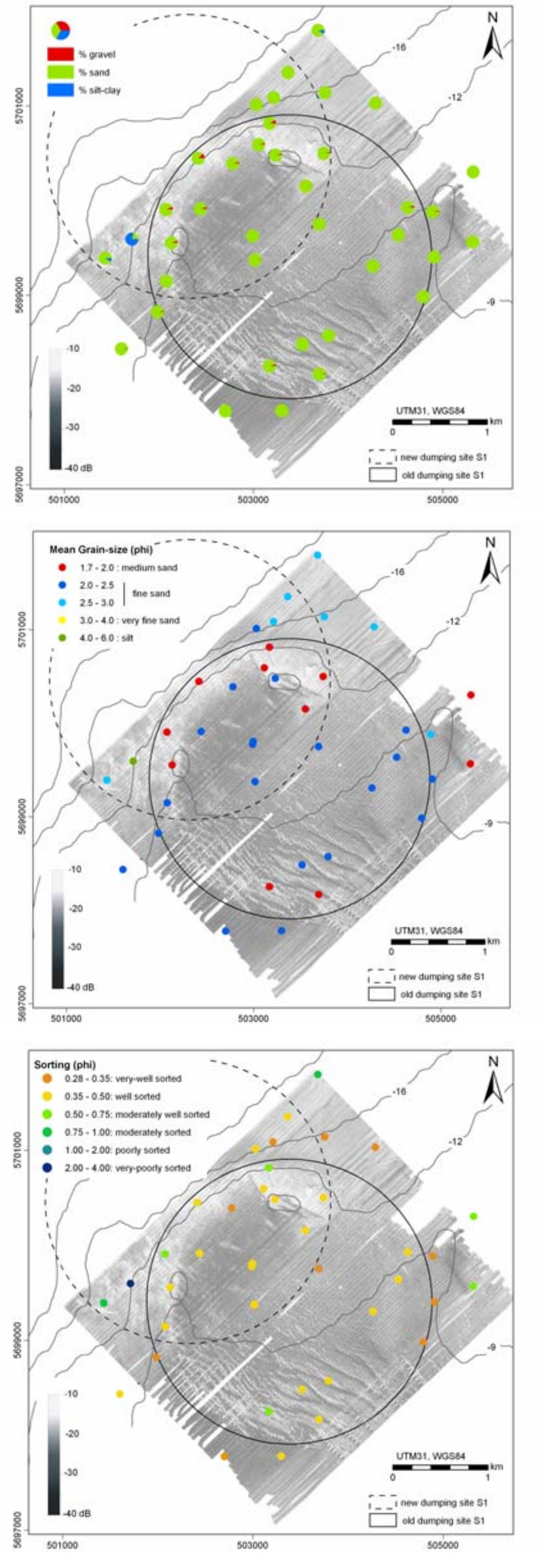


Fig. 8. Backscatter map based on multibeam data (Kongsberg Simrad EM1002S). On the map the spatial distribution of (a) the gravel, sand and silt-clay fraction (%), (b) the mean grain-size (phi), (c) the sorting (phi) are plotted (Folk and Ward, 1957).

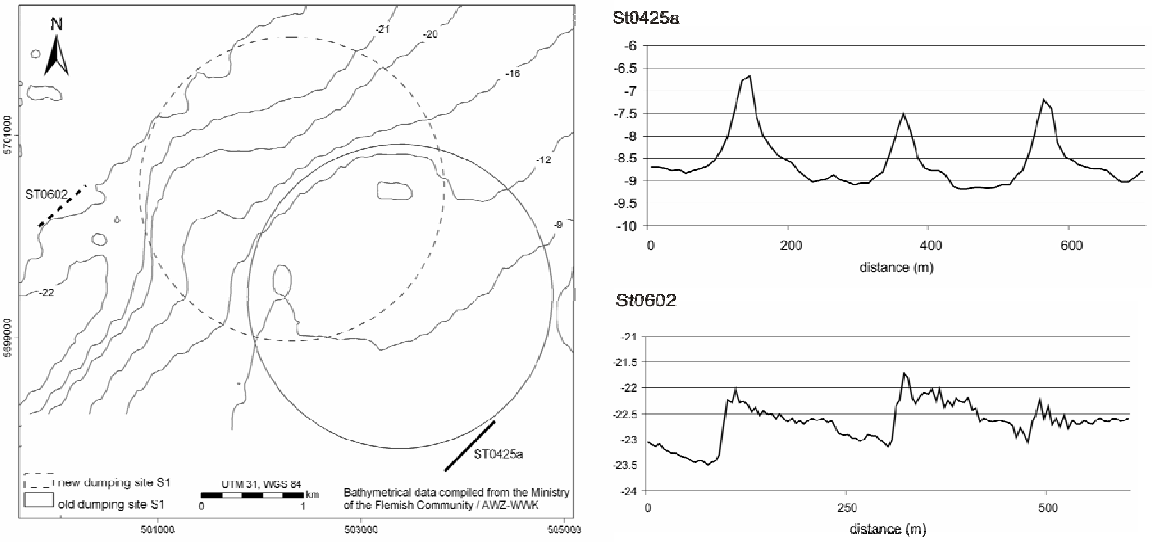


Fig. 9. (a) Location and (b) representation of cross-sections of large dunes through the study area, based on multibeam data recorded in 2004 and 2005, revealing the ebb dominance in the study area.

Another indication of the establishment of a morphodynamic equilibrium is the specific distribution of the different bedforms and their corresponding sedimentology on the old dumping site. On the shallowest part of the sand piles, where the maximum interaction of both flood and ebb currents occurs, large dunes consisting of medium sand with an admixture of shells and shell fragments are found (Fig. 4, 8a and 8b). On the backscatter map, this zone is characterized by high backscatter, indicating the presence of coarser sediments. Nevertheless, high backscatter values are not necessarily due to the presence of shell material. Consolidated sediments, as clay pebbles and mud layers can also cause high values. This explains the high backscatter at the non-overlapping zone of the new dumping site with the old one. As a result, ground-truthing of backscatter maps with sediment samples is important. On the other hand, the depression is characterized by moderate backscatter values, indicating the occurrence of fine sand with no shell fragments (Fig. 8a and b). In such an environment sand ripples have been formed (Fig. 4). These results correspond with the results found for various bank-swale systems on the Belgian Continental Shelf (Deleu *et al.*, 2004; Trentesaux *et al.*, 1994; Van Lancker *et al.*, 2000; Van Lancker and Jacobs, 2000).

On a smaller scale, a mean grain-size variability in the sand fraction is found across the large dunes (Fig. 10). The mean grain-size gradual shifts from coarser sand in the troughs (high backscatter) to fine sand at the crest and lee-side slope (low backscatter). A similar relationship was found on large dunes in the eastern North Sea off the Danish west coast (Anthony and Leth, 2002). Both Schüttenhelm (2000) and Stolk (2000) reported a relationship between the morphology and grain-size of very large dunes in the Flemish Bank area of the southern North Sea, but here the relationship was found to be the opposite. Wienberg (2005) also found coarser sediments on the crest of very large dunes in the German Bight of the North Sea. It would be more likely to find coarser grain-sizes on the crest of the sand waves due to higher current velocities and higher wave activity. However, in this study area the trough between the dunes are occupied by small-scale depressions with a depth varying between 0.25 and 0.5 m, which may act as traps for coarser sediments (Fig. 10).

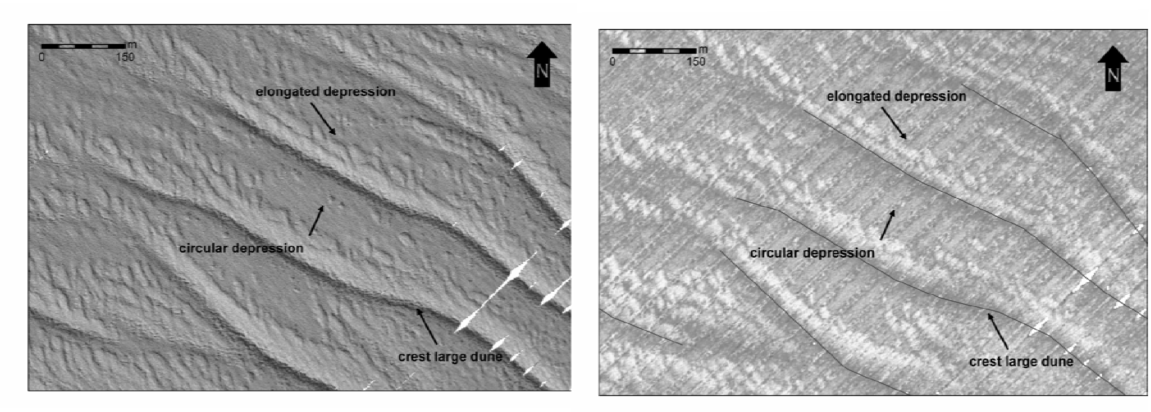


Fig. 10. Details of the shaded relief map (1x1 m) and the backscatter map (2x2 m) showing the large dunes with in between elliptical and rounded depressions. View Figure 6a for the positioning.

CONCLUSION

The combined application of multibeam bathymetrical and backscatter data, ground-truthed with boxcore samples, allowed to investigate the consequences of dumping in a dynamic coastal environment on the morphology and sedimentology. In addition, the recovery after cessation of dumping was studied.

Dumping at the old and new S1 dumping site has caused a clear depth reduction between 1995 and 2004. Due to a difference in morphological setting -the old dumping site is located on a sandy shoal while the new one in a tidal gully-, a difference in yearly growth is observed. Moreover, it also causes a difference in sedimentation patterns, with sandy sediments on the old dumping site and more heterogeneous sediments, consisting of mud layers, clay pebbles and sand layers, on the new one. On both dumping sites, a hydraulic segregation mechanism occur during the dumping activities, influencing a larger area than the dumping zone, but it seems that it is less effective on the new one.

The current morphology of the old dumping site -an irregular-shaped dump mound, with sand piles on the edges and a depression in the centre- reflects the way of disposal. On the new dumping site, a dump mond is found, which is characterised by impact features such as depressions and topographic highs. On the old dumping site, also small depressions occur, which are thought to be remnants of single dumping events.

After the cessation of the disposal of dredged sediments on the old dumping site, the site has restored quickly a morphodynamic equilibrium. Bedforms were formed within one year and their distribution and corresponding sedimentology is representative for the Belgian coastal zone. On the shallowest part, ebb-dominated large dunes consisting of medium sand with an admixture of shells and shell fragments are found, while in the depression sand ripples occur in a fine sandy environment. The asymmetry of large dunes was used to deduce the residual transport direction, which is interesting in relation to the recirculation of dredged material. Although hydrodynamic measurements and models show flood dominance, the asymmetry of the dunes indicate that the transport in the ebb direction, towards the navigation channels, may not be underestimated.

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Geological setting of gravel occurrences on the Belgian part of the North Sea

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INTRODUCTION

According to D'Olier (1981), the Flandrian sea-level rise caused a transgression over an initial surface topography whereby the present sandbank positions and shapes reflect ancient transitory islands, coalesced beaches, confluent channel bars and changing coastline positions. It is known that in this region of the North Sea, most of the underlying Palaeogene units consist of clayey sediments, alternated with only a few sandy layers (*for a synthesis see* Le Bot *et al.*, 2003). On top of these are, apart from scour hollow infillings with Pleistocene sediments, the sandbanks, which consist of Holocene sediments. A thin gravel lag veneer would form the lower part of the Holocene sediments followed by a sandy succession. Kirby and Oele (1975) found out that in the nearby Sandettié – Fairy Bank area, there is a well-developed graded succession from flint and shell gravel at the base up to shelly quartz sands. This succession indicates a decrease in energy conditions at the bed during the period of deposition and a subsequent slow regional rise in sea-level. Most probably the succession is a drape over an originally irregular seabed. This is clear in Figure 1 that the thickness of the Holocene clearly follows the present sandbank topography and reveals the initial lows and highs. Moreover, the Holocene thickness is less than 2.5m in the swales between the sandbanks, indicating possible source areas where gravel can be found (Figure 1).

Interestingly, the Top Tertiary erosion surface shows clearly identifiable scarp that traverses the region of the Hinder Banks from east to west (Figure 1). This Offshore Scarp is easily recognized in the present-day bathymetry. From south to north, it induces a depth decrease of 2 to 3m.

The distribution of gravel occurrences on the Belgian part of the North Sea is generally poorly known. The map of Veenstra (1964) did show higher gravel amounts near the southern parts of the Westhinder and Oosthinder, based on 50 Van Veen samples in the region of the Hinder Banks (Figure 2).

As already described in the past (Veenstra, 1964; Veenstra, 1969 and Tytgat, 1989), the main gravel types in the Southern Bight of the North Sea consist of flint or silex, limestone, sandstone quartz, quartzite and some igneous rocks. Considerable variation in pebble lithology is seen within this region, but flint is the dominant component (Cameron *et al.*, 1987). Most of the gravel originates from reworking by the marine transgression of deposits resting on the early Holocene land surface. These may have included fluvial-terrace deposits (D'Olier, 1975) or beach gravels formed from material of fluvial origin (Veenstra, 1971). Some of the flint pebbles show percussion marks on their surfaces, indicating beach processes, according to the early views of Veenstra (1969). A re-analysis of four samples taken by Veenstra (1969) in the Noordhinder region reveals that flint and to a lesser extent quartzite occurs more as large fragments (>8mm), whilst quartz occurs more as small fragments (1 – 4 mm). Limestone is most abundant in the grain size range between 16 and 2 mm; sandstone and igneous fragments are equally distributed over the grain size range. When averaging the four samples, 31% of the gravel is flint, 27% is limestone, 18% is quartz, 10% is sandstone, 9% are igneous rocks, 4.7% is quartzite and only 0.3% is chalk.

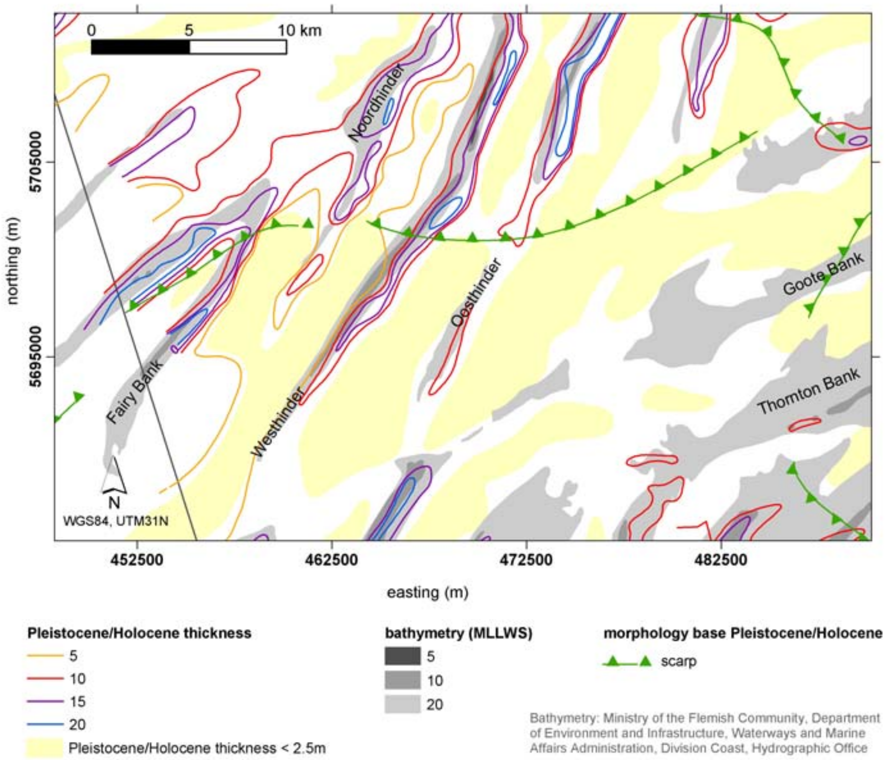


Fig. 1: Location of the Offshore Scarp in the Top Tertiary erosion surface in the southern part of the Hinder Banken. Note the limited Quaternary cover in these areas.

Most probably the large amount of flint pebbles finds its origin in the Cretaceous deposits outcropping near the mouth of the Thames whereas the more weathered light-coloured pebbles, with a nucleus, frequently occur in the Diestian formation and at the base of the Palaeogene (Tytgat, 1989). The sandstone pebbles are well rounded mostly and are either similar to those of the Diestian Formation or similar to those of the Mont-Panisel Formation (Tytgat, 1989). The smaller, well-rounded, quartz grains probably have a Rhine/Meuse/Scheldt and Thames origin. The igneous rocks might be brought in by the Rhine or Meuse and might be originally from the volcanic Eiffel area.

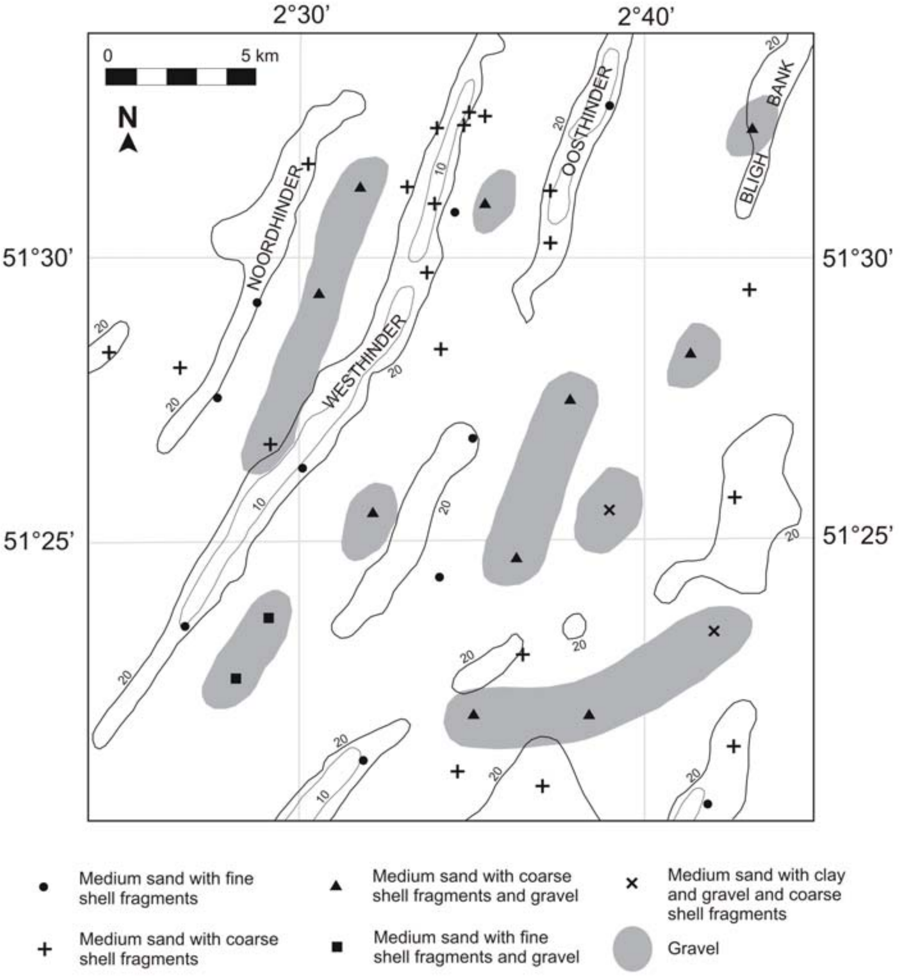


Fig. 2: Sedimentological map of the region of the Hinder Banks (Veenstra 1964).

CHRONO-STRATIGRAPHICAL FRAMEWORK

Most of the gravel, present in the swales between the sandbanks, belongs to the Kreftenheye Formation, part of it might belong also to the older Urk and Sterksel Formations. The Kreftenheye Formation has a general onland thickness of 10 to 25m and the general lithology consists of medium to very coarse sand and medium to very coarse gravel (Busschers *et al.*, 2005). The dominance of coarse-grained sands, high concentrations of gravel, numerous internal scour surfaces, small-scale fining upward sequences and a clear lag deposit at the base of the unit, point towards deposition in a fluvial channel system (Busschers *et al.*, 2005). Moreover, the upper part of the Kreftenheye Formation consists of a sheet of gravelly sand capped by a bed of strongly consolidated sandy clay. Morphologically, the top of the Kreftenheye Formation can be described as buried fluvial terraces of the Rhine (Makaske *et al.*, 2005). The geochronology of the Kreftenheye Formation is however still poorly understood (Törnqvist *et al.*, 2000), primarily due to the lack of organic matter suitable for dating. To the north, thin layers of volcanic tuff occur in the sand, being deposited from late Weichselian volcanoes active in the Eiffel area (Balson *et al.*, 1991).

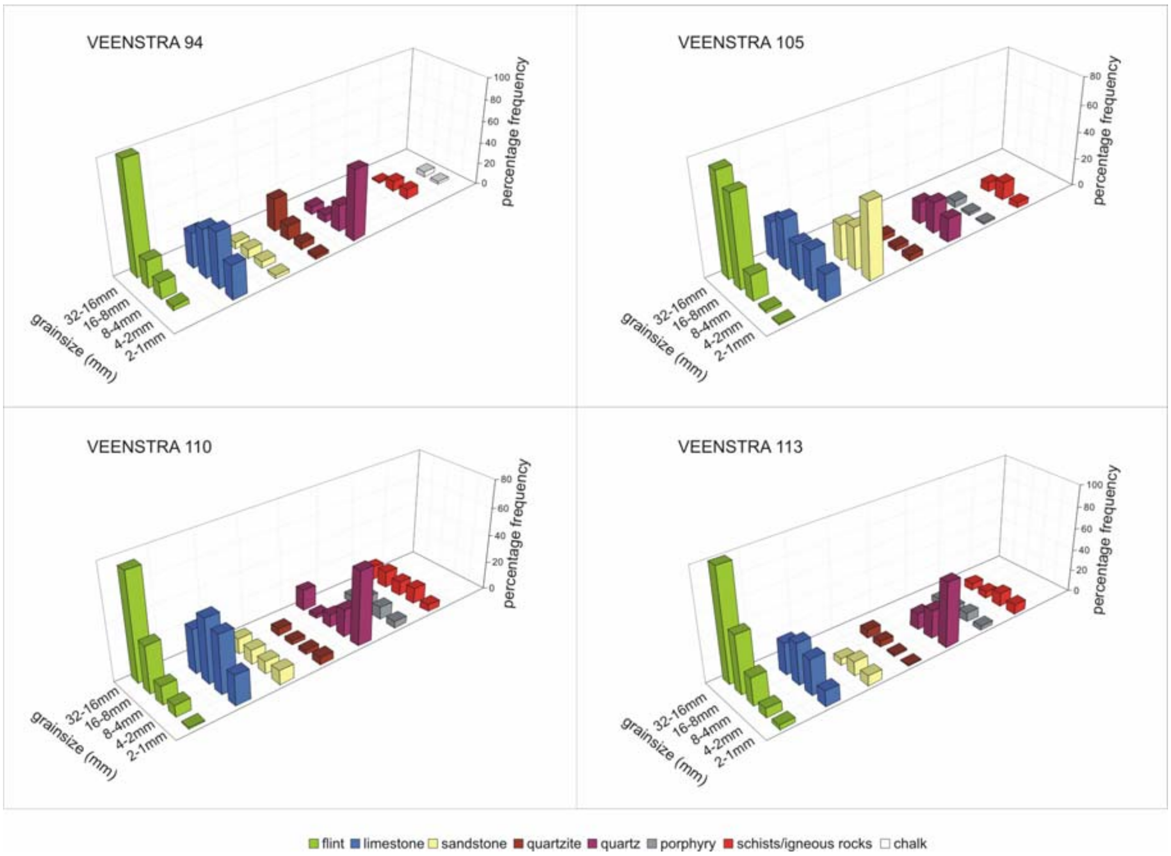


Fig. 3: Re-analysis of the gravel composition of four samples, taken in the Noordhinder region, based on Veenstra (1969).

Formation Name	**Onland thick-ness**	**General lithology**	**Genesis**	**Age**
Nl: ***Kreftenheye*** UK: *Eem/Brown Bank* B: ?	10-25m	-Medium to coarse sand -Medium to coarse gravel	-The bottom part is deposited by a braided ice marginal river flowing to the west containing fresh water and melt water of the ice cap. -The middle part consists partly of meandering Rhine deposits of the Eemian and partly of fluviolacustrine infill of the glacial IJssel Dal basin during the Late Saalian and Eemian. -The upper part consists partly of material transported by the Rhine, partly of fluvail reworked marine sediments of the Eem Formation and partly by meandering rivers.	Late Saalian to Early Holocene
Nl: ***Urk*** UK: *Egmond Ground* and upper part of *Yarmouth Roads* B:?	20-40m	-Medium fine to very coarse sand -Fine to very coarse gravel	- Fluvial Rhine deposits, downstream also freshwater deposits.	Late Cromerian to Middle Saalian
Nl: ***Sterksel*** UK: *Yarmouth Roads* B: *Lommel and Bocholt Sands, Winterslag Sands and Zutendaal Gravels*	15m	-Medium coarse to very coarse sand -Gravel -Clay layers	- The coarse sand and gravel are fluvial channel deposits of the Rhine and Meuse. - The strongly layered clays are rest channel deposits in abandoned meander turns and/or bank deposits	Latest part Early Pleistocene and Middle Pleistocene

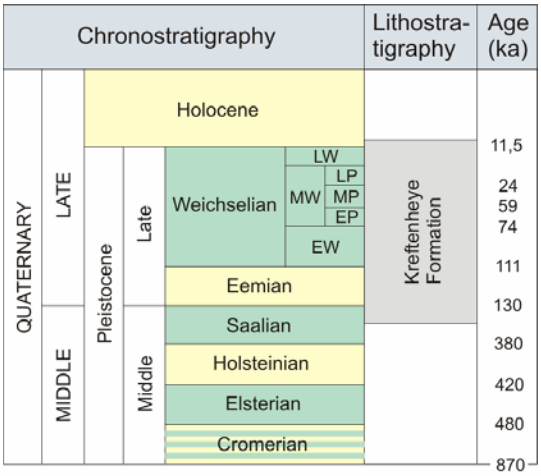


Fig. 4: Late Quaternary chronostratigraphy for Northwest Europe (after Zagwijn, 1975, 1992) and lithostratigraphic units in the study area (after Doppert *et al.*, 1975). EW = Early Weichselian, MW = Middle Weichselian, LW = Late Weichselian, EP = Early Pleniglacial, MP = Middle Pleniglacial, LP = Late Pleniglacial (table after Törnqvist *et al.*, 2000).

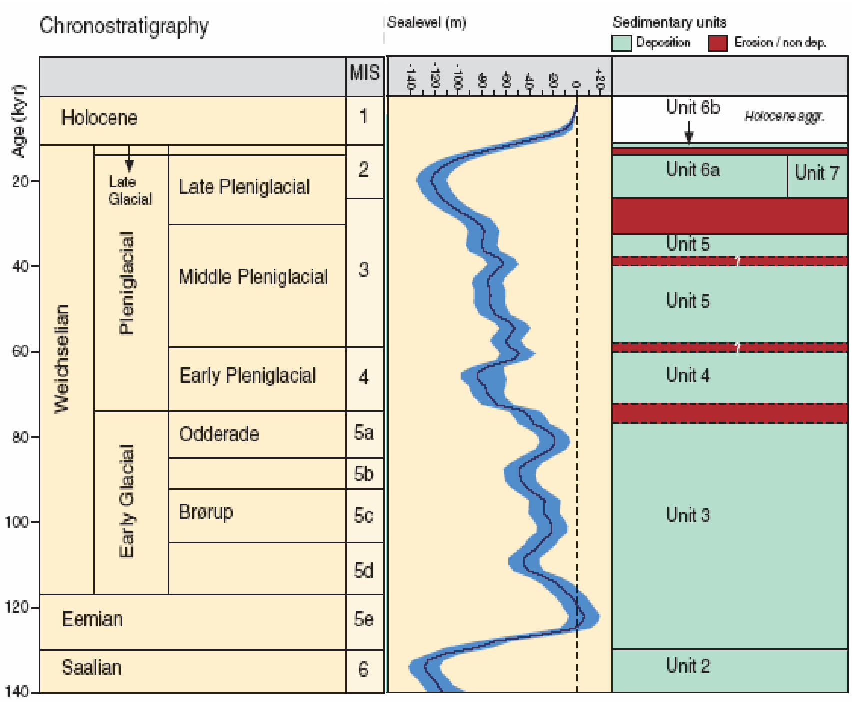


Fig. 5: Northwest European climate conditions and global sea level during the Late Saalian and Weichselian periods. Chrono-stratigraphical framework for northwestern Europe after Zagwijn (1974), Vandenberghe (1985) and De Mulder *et al.* (2003). Marine isotope record after Bassinot *et al.* (1994). Sea-level record derived from North Atlantic and Equatorial Pacific benthic oxygen-isotope data (Waelbroeck *et al.*, 2002). Error envelopes in all records were taken from the original sources. The chrono-stratigraphical position of the sedimentary units and unconformities in the study area are shown on the right. Although this figure suggests that deposition was essentially continuous, the exact time duration of the depositional units (as proportion of total covered time), especially for the older units, remains unknown with current dating accuracies (Figure from Busschers *et al.*, 2005).

HISTORY

Geological characteristics of marine gravel deposits

Most modern shelf systems have an initial lithofacies, which is a coarse, discontinuous lag, which may occur as a ridged sheet (Swift *et al.*, 1991). The leading edge of this sheet lies at the foot of the shoreface, and it forms the debris of the erosional retreat process (Swift *et al.*, 1972). Quaternary low stands rejuvenated rivers as they crossed the exposed shelf, and in many cases, the low stand shelf valleys contain gravel. The retreating shoreface has breached these gravelly valley fills and has redistributed them as a marine basal transgressive gravel (Belderson and Stride, 1966; Figueiredo *et al.*, 1981). Where they occur, such gravels typically form in thin, discontinuous, shore-parallel bands, marking successive phases of shoreface retreat. The gravel is overlain by several meters of sand. The sand is discontinuous and in areas of strong storm or tidal currents may be lacking altogether, so that the gravel is exposed at the seafloor. The basal gravel here continues to be reworked by shelf currents (Swift *et al.*, 1991).

Fluvial deposits, associated with relative sea-level fall (80-40ka), can constitute a considerable part of preserved strata ('falling-stage systems tract'). Interglacial transgressive and highstand systems tract tend to have a relatively low preservation potential (Törnqvist *et al.*, 2000). The coarse deposits transported and deposited during the cold stages have a better preservation potential than the finer interglacial deposits.

Geological history of the Ice Ages in the Southern North Sea

The Quaternary history of the Rhine-Meuse system in the Netherlands is complex, because advancing Pleistocene ice sheets and the periglacial processes at their neighbouring areas strongly modified the geomorphology, and, hence, fluvial drainage directions (Törnqvist *et al.*, 2000). Prior to the Elsterian glaciation, the Rhine and Meuse Rivers drained to the northwest and extended their courses onto the continental shelf of the North Sea during relative sea-level lowstands. During the Elsterian glaciation, the area overridden by the ice was subjected to total landscape remodelling, with old river courses destroyed or buried (Gibbard, 1988). An entirely new landscape was formed beneath the ice by glacial and glaciofluvial erosion and deposition; the sculpturing of deep glacial valleys was to have a striking palaeogeographic impact after the ice retreat. At the ice margin, major river valleys were dammed all across the region. The Thames and its tributaries were diverted southwards, the Elbe was dammed and the North German Rivers were deflected westwards. However, the most striking feature was the development of a massive ice-dammed lake in the southern North Sea, into which the Thames, Rhine, Meuse, Scheldt and possibly the Ems all discharged. Overspill of this lake almost certainly initiated the Dover Straits and greatly enlarged the Channel River system (Gibbard, 1988). This is confirmed by the deep scars, which have been found on the Channel seabed. Remnants of this lake are the lacustrine deposits found north of our study area (Figure 5).

Throughout the cold stages of the Pleistocene, the rivers overwhelmingly deposited gravels and sands derived either from periglacial weathering or glacial sources (Gibbard, 1988; reconstructions from Figure 6 to 8: http://www-qpg.geog.cam.ac.uk/research/nweurorivers/). The result is that valley systems contain vast thickness of cold-climate sediments deposited by rivers that flowed in a braided or wandering, often multi-channelled form. These sediment accumulations are generally separated by periods of non-deposition or incision outside subsiding areas. Throughout this cold stage and the following alternation of cold and warm stages and enhanced by isostatic movements there have been several incisions of rivers in older deposits creating river terraces. These have been recorded in the Thames region (Bridgland, 2000), in the Rhine area (Boenigk and Frechen, 2006) and in the Meuse area. These river terraces consist mostly of gravel deposits.

Glacio-eustatically and isostatically controlled sea level changes are characteristic of the Pleistocene. In Northwest Europe low sea levels during the cold periods caused great expansion of the drainage system onto the surrounding continental shelves. For much of the Lower and Middle Pleistocene, the southern North Sea was occupied by the huge delta complex of the North German rivers, the Rhine, Thames, Meuse and Scheldt (Gibbard, 1988). The ice sheet during the Saalian, covering the northern part of the Netherlands forced the Rhine–Meuse system to follow a route farther south, roughly similar to the present course of these rivers. However, during the latest Saalian, the Eemian and Early Weichselian, the Rhine followed a more northerly route through the country due to the creation of glacially eroded depressions. The present course was reoccupied from the Middle Weichselian onwards. It is important to note that the Meuse always approximately followed its present course since the Saalian. Pleistocene Rhine and Meuse sediments deposited after the peak of the Saalian glaciation belong to the Kreftenheye Formation. The smaller Scheldt river and some other small rivers flowed northward until they were blocked by the cuesta of the Boomse Clay which was only broken through in the late Weichselian, causing these rivers to flow westwards into the Ostend Valley. This Valley is described by Liu (1992) and is especially outspoken in the area close to the coast. The Scheldt river most probably did not bring in a lot of gravel material as it was a smaller river and no river terraces have been formed.

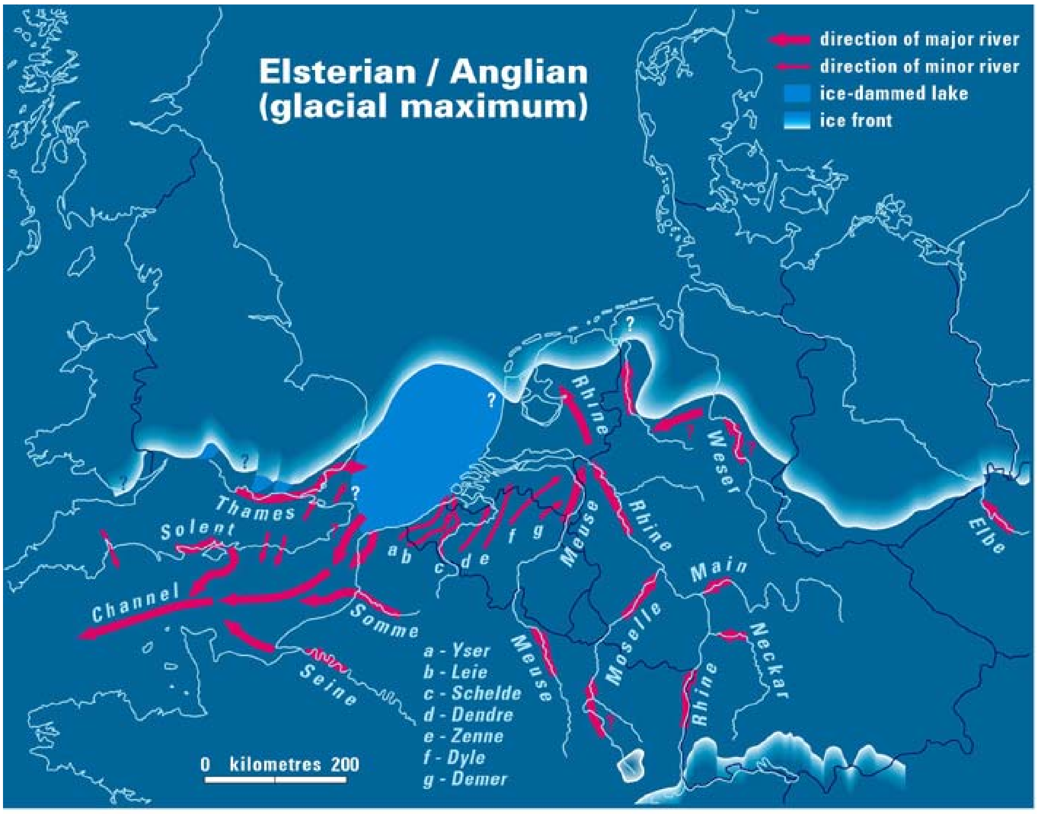


Fig. 6: Palaeogeography of the Elsterian / Anglian / Oka Stage (Gibbard).

The interglacial following the Saalian is the Eemian. The deposits of this formation have not been completely eroded on the Belgian part of the North Sea. They formed a more or less continuous layer of sandy deposits. These deposits have been preserved in the area north of the Offshore Scarp and form the basal layer of the parts of the Hinder Banks north of this scarp. This means that the initial stages of the northern parts of the Hinder Banks have been formed in the Eemian, and were then partly eroded during the following Weichselian period. The ice sheet during the Weichselian however did not extend as far south as during previous ice ages, which might explain why not all Eemian deposits in the study area have been eroded. During the following Holocene sea-level rise, the present morphology of sandbank systems has been finalised.

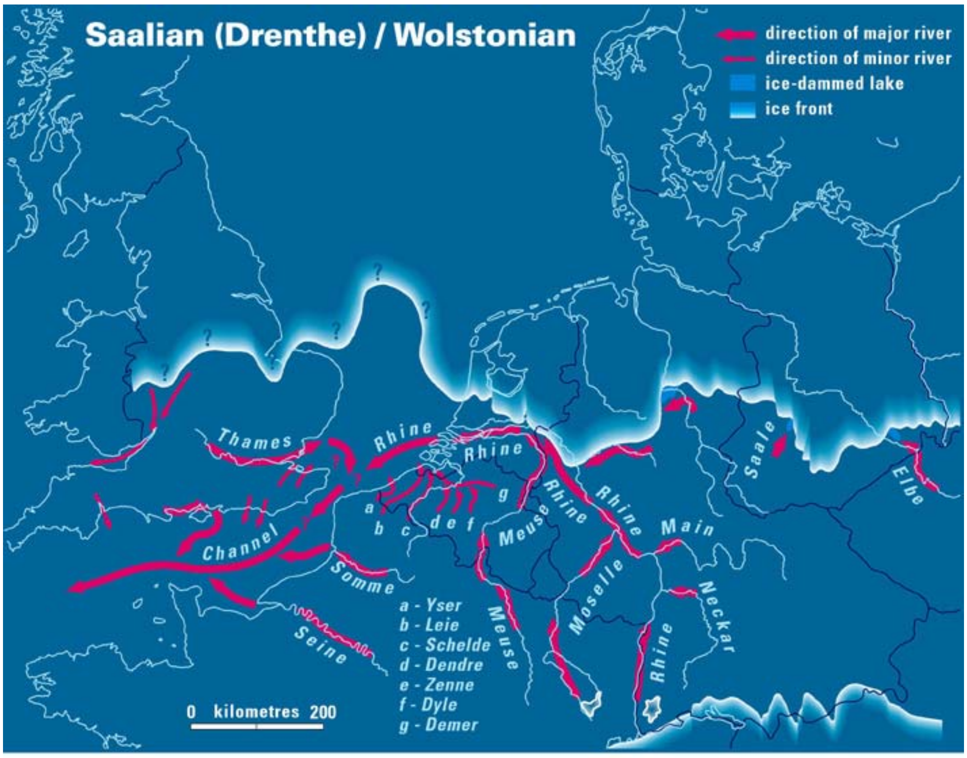


Fig. 7: Palaeogeography during the Saalian / Wolstonian glacial maximum (Gibbard).

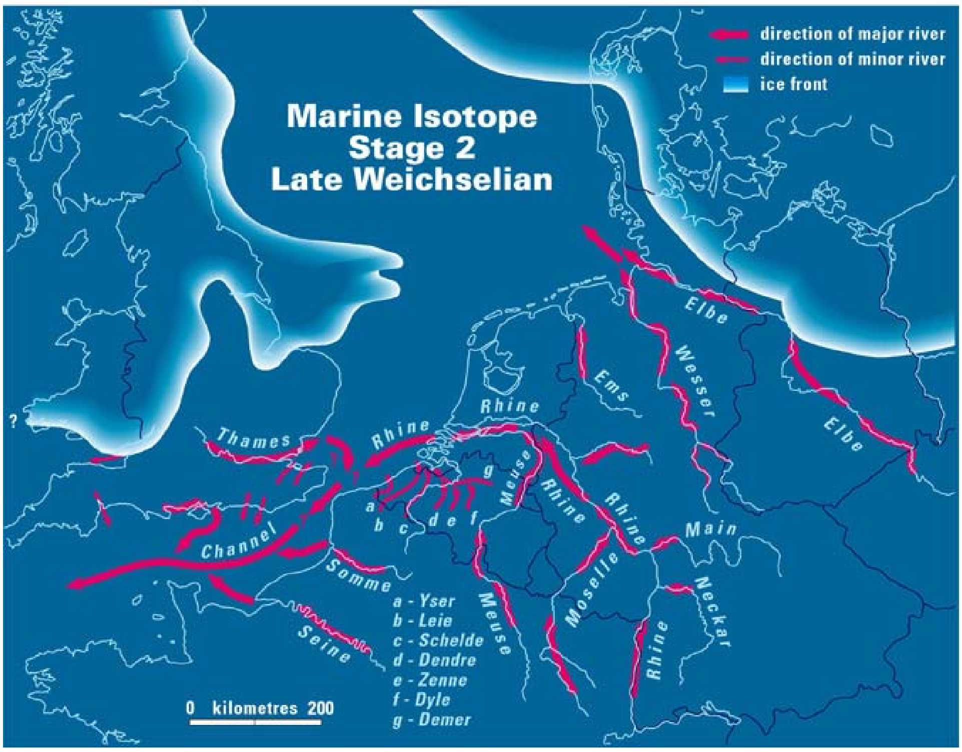


Fig. 8: Drainage during the maximum extent of glaciation in the Late Weichselian Substage and equivalents (Marine Isotope Stage 2) (Gibbard).

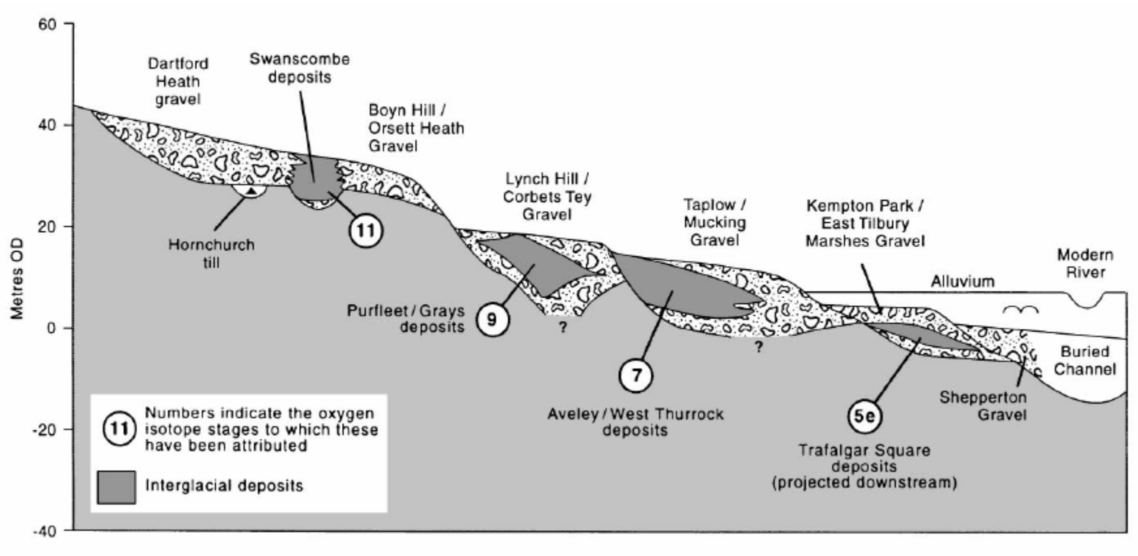
Geological history of the gravel on the Belgian part of the North Sea

During the late Saalian glaciation, the Fennoscandian ice sheet covered the northern part of the Netherlands. In front of the ice mass, an ice marginal system developed that transported coarse-grained sand and gravel (Busschers *et al.*, 2005). Transport of the coarse grained material most probably occurred during peak discharge related to spring release of glacial melt water and snow melt.

The gravel in the study area is partly glacial material, partly fluvial material. The Rhine and Meuse did not enter this area of the southern North Sea before the Saalian when the Rhine was diverted south by ice that reached the central Netherlands. Large blocks could be transported by river ice in winter periods and is then carried downstream in spring during the melting season. Spring is the period when these rivers do most of their work because of melting snow and ice. The rivers Rhine, Meuse, Scheldt and several rivers from Britain too entered the Southern Bight of the North Sea during the Saalian and Weichselian and these rivers were carrying gravel derived from land areas. They were also fed by melt water from glaciers. The largest blocks are either of Elsterian age, brought in by ice fragments transported in the proglacial lake or either from Saalian age when large ice flows brought in large blocks transported by the Thames or Rhine.

The Offshore Scarp is probably a remnant of the bedrock slope between river terraces. Both levels (above and below the scarp) are essentially fluvial landforms, altered by shallow marine action and with former surfaces some 4-8 m above the platforms now, whereby all the terrace-building-materials, except the coarsest material, are washed away by later wave action (pers. comm. K. Cohen). The area is probably the SE side of a wide valley of a joining Rhine-Meuse and Thames system. Ancient river courses seldom have paired-terraces. It is far more common for them to have remnants preserved only on one side of the valley. This results from multiple periods of incision that causes the river to off-step in a particular direction. This is also found in the Thames (Bridgland, 2000) and Rhine areas (Boenigk and Frechen, 2006). The Dover Strait itself probably has a funnelling effect, and this could preserve ancient river terraces, especially those from Saalian and Early Weichselian glacial stages, because in the last glacial, the trunk channel (Rhine, Meuse and Thames) probably carried less water (no Scandinavian melt water) than in the periods before.

As the melt water flow had to be towards the south, the flint is not brought in from the Dover Strait. The flint in the gravel can be derived from Britain or from Belgian rivers all of which drain chalk bedrock areas (e.g. almost all of the streams from East Anglia transport flint as their main pebble-forming lithology). There was no fluvial flow towards the north in the study area once the Straits were breached, except presumably tidal flow at marine highstands, although recycling of gravel probably repeatedly occurred during sea-level rise or fall events.



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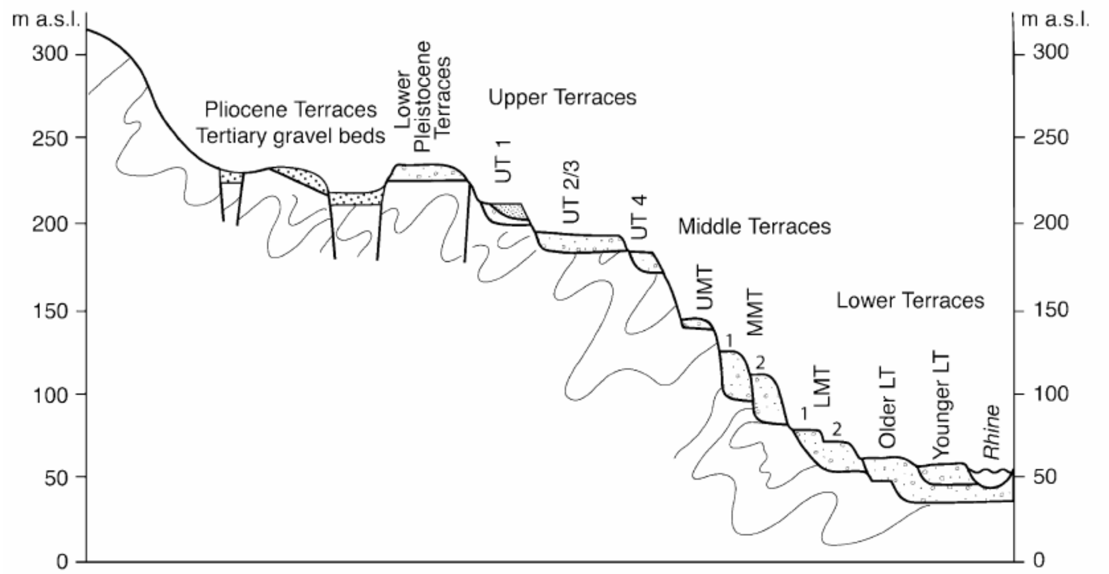

B

Fig. 9: A. Idealized transverse section through the Lower Thames terraces (Bridgland; 2000). B. Idealized sketch of the terrace staircase in the Middle Rhine area, including Tertiary terraces and gravel beds, the Lower Pleistocene terraces (LPT), the Upper Terraces (UT1-4), the Middle Terraces (UMT-LMT2) and the Lower Terraces (Older LT and Younger LT) (Boenigk and Frechen, 2006).

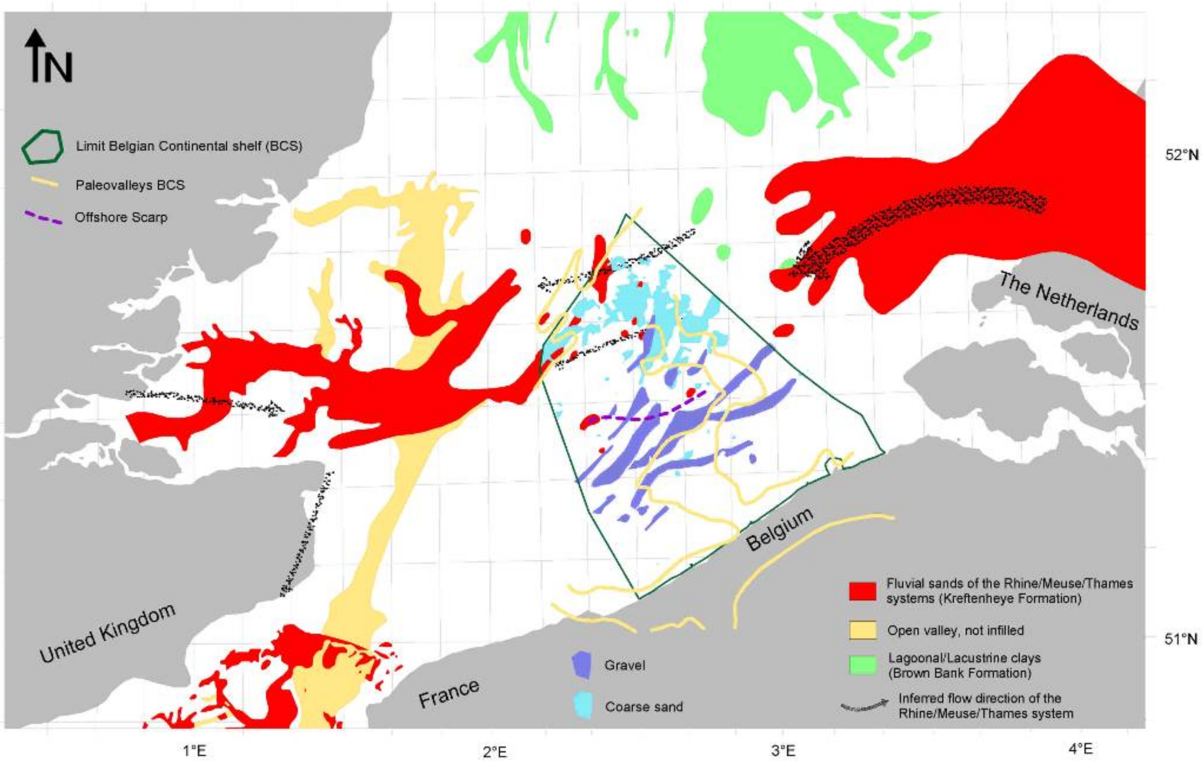

Fig. 10: Distribution of Quaternary channel deposits, reflecting the input of river sediments, forming the Kreftenheye Formation, brought in by the Thames, Rhine, Meuse and Scheldt. Base map of Balson *et al.* (1991) added with the new information on the Belgian part of the North Sea.

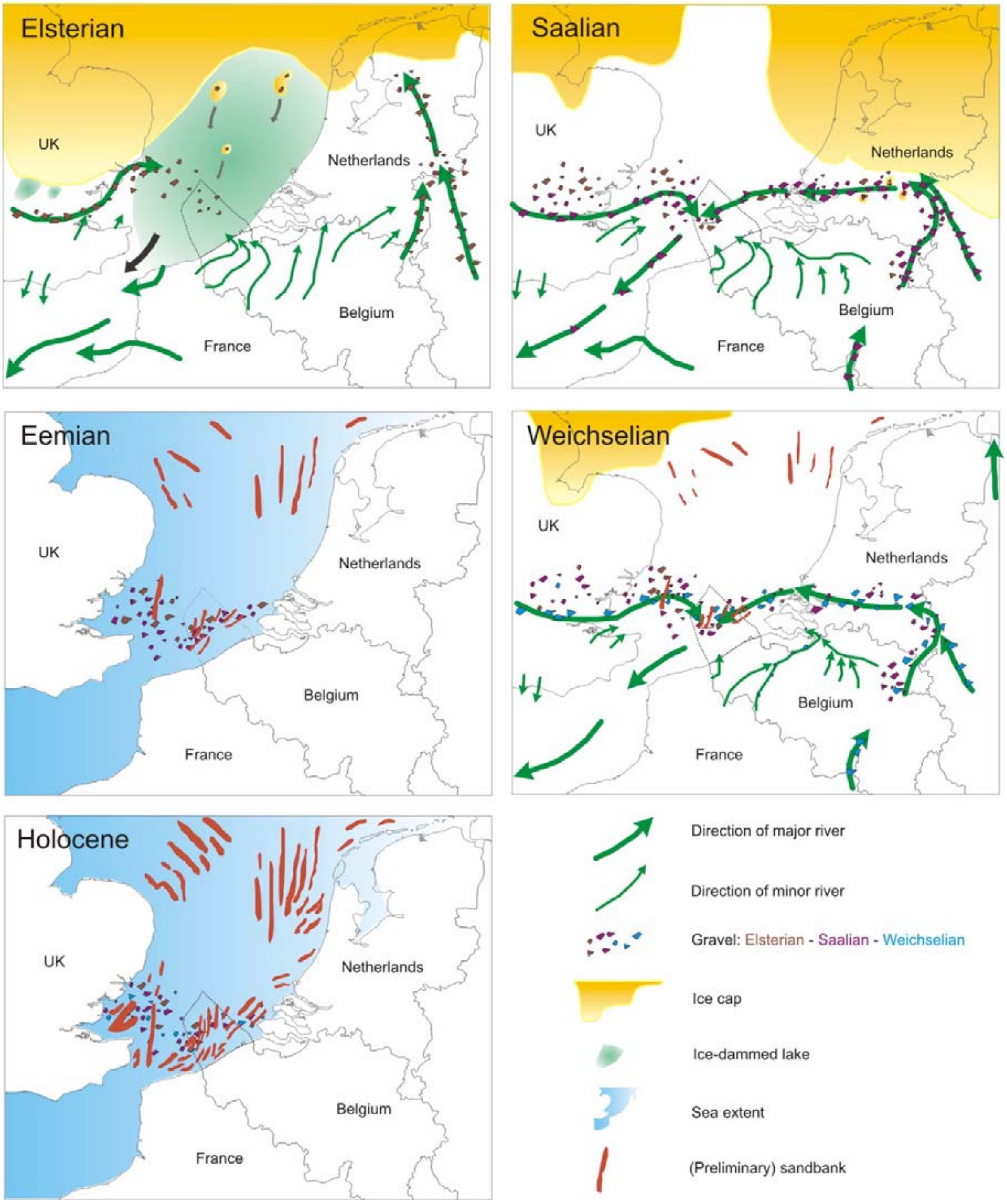

Fig. 11: Cartoon of the presumed geological evolution of gravel deposits during the middle and late Quaternary.

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Recommendations for the sustainable exploitation of tidal sandbanks

(subm. Journal of coastal Research)

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ABSTRACT

Sand extraction activities on the Belgian Continental Shelf are regulated, in the sense that no major changes to the seabed should occur and natural regeneration of the banks is considered to balance the extraction rates. However, the centre of a tidal sandbank (Kwinte Bank), exploited intensively since the 1970's, is transformed now into a depression; as such, sand extraction has ceased since February 2003. The impacted site lies more than 12 km away from the adjacent shoreline and is located in water depths of 8 to 15 m. Since the central depression was revealed in 2000, the perception related to the impact of aggregate extraction has gradually changed.

The present-day seabed characteristics and the recovery potential of this central part of the Kwinte Bank have been studied, on a multidisciplinary basis. This contribution provides an integration, synthesis and discussion of extensive results of the geo-acoustic, ground-truthing and modelling investigations, within the context of sustainable exploitation. Various space- and time-scales are addressed. Mainly, physical and ecological impacts are discussed, together with a 'suite' of criteria that can assist in limiting the environmental impact of the extraction. A methodological framework for research is proposed, whilst recommendations for future monitoring schemes are highlighted. The information provided can guide decisions on the management of the impact of aggregate extraction, within the marine environment.

Additional index words: environmental impact assessment; sustainable development; aggregate extraction; sand mining; sand winning; threshold criteria; space- and time-scales; evaluation; guidelines; global change; marine sediment; marine sand; seabed.

INTRODUCTION

The formulation of recommendations and guidelines for the 'best practice' of marine aggregate exploitation activities, which may include a risk for the marine environment, are complex issues; those are driven mainly by top-down constraints, by legislative bodies, and bottom-up constraints, imposed by the environment. The variety of stakeholders and their interactions with the marine environment adds to the disparate and complex nature of marine sand and gravel management; this is exacerbated, often, by the trans-boundary nature of marine processes. At international, European and national levels, different Conventions, Directives and, hence, national laws and decrees exist: within this framework, the activities have to be performed. Presently, several European Member States (e.g. Belgium, United Kingdom, France and Denmark) are in the process, or have just finished, revising their marine aggregate extraction regulations; this is in response to the need to incorporate European environmental Directives, such as the Environmental Impact Assessment (EIA) Directives and the Habitats Directive, into the national legislation (**RADZEVICIUS *et al.***[*]). However, the implementation of these Directives does not mean that the national regulatory framework is consistent now, and/or similar, throughout Europe. A wide variety of processes and procedures exists in relation to: marine policy, collation of data and information; and research co-ordination and dissemination. Nevertheless, there are many different interpretations on how to emphasise the content of an EIA; likewise, how to exploit and monitor the environment. This range is due mainly to the high variety of habitats that exist along the European coast, which have different characteristics and imply different risks, when being disturbed. Moreover, environmental knowledge is fragmented and mostly non-integrated. Similarly, disparities exist between different EU Member States, in the 'know-how' necessary to address effectively the various scientific problems, related to resource prospecting and the environmental impact of marine aggregate mining (**VELEGRAKIS *et al.***). Many of the effects of such disturbances will be site-specific, but synergies can also be deduced from the results of research into the impact of dredging. Nowadays developing technology and an increase in the efficiency of monitoring, in combination with effective research, permits a better estimation of the effects of marine aggregate extraction .

The specifications of marine dredging vessels presently in service, together with the economics of exploitation, constrain the extraction depths and the distance of the extraction area from the coastline (e.g. POSFORD DUVIVIER, 2000). In response both to the increasing general demand and stricter regulations on the exploitation of land-won aggregates in the EU Member States, future resource developments will need to occur in deeper waters. Export will become more important and will require international co-operation, integrated European trade and coherent environmental policies/regulations on the licensing and practice of offshore dredging operations.

Groups with industry-interest (e.g. the European Marine Sand and Gravel Group (EMSAGG), the International Council for the Exploration of the Sea (ICES)) and Non-Governmental Organisations (e.g. World Wildlife Fund (WWF)) are working already on initiatives related to sand and gravel extraction and the promotion of appropriate research, to address problems at a supra-national (regional) level. Within ICES, the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT) produces Annual Reports including overviews of (a) extraction activities; (b) seabed resource mapping programmes; (c) approaches to environmental impact assessments; and (d) related environmental research developments. The OSPAR Commission stated that coastal states should take these guidelines into account, within their procedures, for the authorization of the extraction of marine sediments. According to these

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[*] *Authors indicated in bold relate to a Special Volume on European Marine Sand & Gravel Resources: Evaluation and Environmental Impact of Extraction (Journal of Coastal Research).*

ICES guidelines (ICES, 2003), wide-ranging information is required for the physical impact assessment of marine aggregate extraction: (1) implications of extraction for coastal and offshore processes, including the possible effects on beach draw-down, changes to sediment supply and transport pathways, modifications to wave and tidal climate; (2) changes to the seabed topography and sediment type; (3) exposure of different substrates; (4) changes to the behaviour of bedforms, within the extraction and adjacent areas; (5) the potential risk of the release of contaminants by aggregate dredging, and exposure of potentially toxic natural substances; (6) the transport and settlement of fine-grained sediments, disturbed by the use of aggregate dredging equipment on the seabed, and/or from hopper overflow or on-board processing and its impact on the ambient and maximum suspended load; (7) the effects on water quality, mainly through increases in the amount of fine material in suspension; (8) implications for local water circulation resulting from removal or creation of topographic features on the seabed; and (9) the time-scale for potential physical "recovery" of the seabed. The topics (1) to (4) and (8) to (9) have been considered within the present investigation.

In order to assess the biological impact, ICES guidelines recommend studying: (1) changes to the benthic community structure and to any ecologically-sensitive species, or habitat, that may be particularly vulnerable to extraction operations; (2) the effects of aggregate dredging on pelagic biota; (3) the effects on the fishery and shell fishery resources, including spawning fish, nursery areas, over-wintering grounds for ovigerous crustaceans, and known routes of migration; (4) the effects on trophic relationships, e.g. between the benthos and demersal fish populations; (5) the effects on sites designated under local, national or international regulations (see above); (6) predicted rates and modes of recolonisation, taking into account initial community structure, natural temporal changes, local hydrodynamics, and any predicted change in sediment type; (7) the effects on marine flora and fauna, including seabirds and mammals; and (8) the effects on the ecology of boulder fields/stone reefs. In the present investigation, only topics (1) and (6) have been considered.

BACKGROUND TO THE KWINTE BANK

The range of ICES topics outlined above are discussed now with reference to the Kwinte Bank; this is a tidal sandbank located in the Southern North Sea, on the Belgian Continental Shelf, located in water depths of -8 to -25 m MLLWS (mean lowest low water, at spring tides) (Figure 1). The Kwinte Bank is socio-economically the most important of this region. Exploitation started in the 1970's and, from 1997 until 2004, 75 % (11,620,000 m^3) of all the extraction activities were focussed upon this sandbank. As such, it provides an ideal example for the investigation of the impact of marine aggregate extraction, within a tidally-dominated environment.

Within Belgium, sediment removal from sandbanks is, for each individual extraction activity, restricted to a penetration depth of 0.50 m; as such only the upper surface sediments are removed. This approach is considered to cause only minimal environmental effects; it has long been believed that sandbank maintenance processes would counterbalance the sediments that have been removed. From 1976 onwards, the sandbanks being exploited were monitored and, until recently, only limited irregularities have been reported. However, in 2000, a depression (5 m deep, 700 m wide and 1 km long) was identified along the most intensively exploited upper part of the sandbank. To allow regeneration of this section of the sandbank, sand extraction has been prohibited, since February 2003. Multidisciplinary research programmes have been set-up to address the regeneration potential, from a physical and ecological perspective; these have been based upon state-of-the-art methodology and instrumentation, covering a 2 year period. The physical impact of extraction, on the seabed, has been assessed also using hydro-, sediment- and morpho-dynamic modelling, calibrated/validated using high-quality, in-situ measurements. The ecological impact was focussed upon the macrobenthos and has included a comparison between exploited and non-exploited sandbanks. The framework for the investigations, together with the issues arising after 30 years of monitoring, are discussed in **VAN LANCKER *et al.***. The same contribution discusses the resource potential of the sandbanks, together with their maintenance mechanisms (see the relevant publications in this Special Issue, for more details).

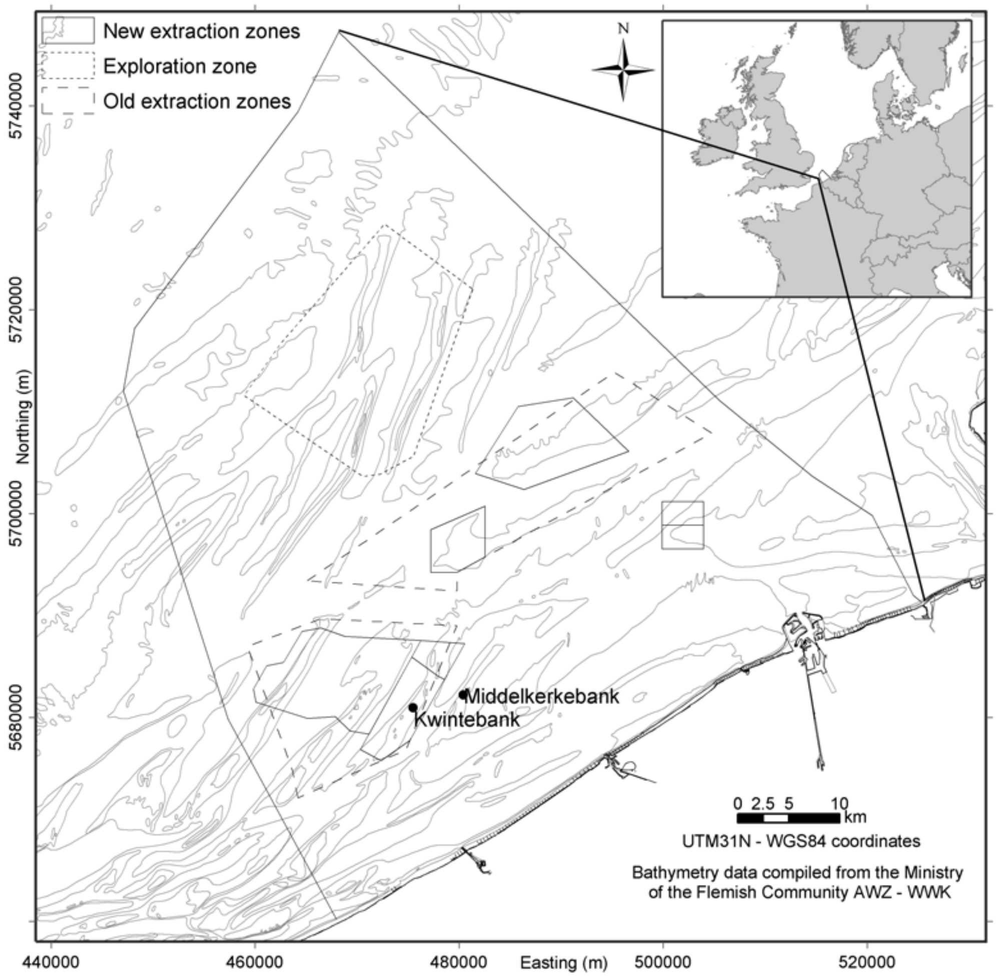


Fig. 1: Past and present concession zones on the BPNS.

Apart from the impact related to the depression, the long-term monitoring results did show a significant loss of the total bank's volume (NORRO *et al.*, 2006). Moreover, DE MOOR (2002) had reported a general erosive tendency for the whole of the Flemish Bank region, including both exploited and non-exploited sandbanks. This pattern indicates that aggregate extraction is not the only cause for the erosive trend; nonetheless, it emphasises the need for a more sustainable exploitation approach.

The present contribution provides an integration, synthesis and discussion of the results obtained from the Kwinte Bank depression area (see above). Physical, ecological and potential cumulative impacts are discussed, whilst a suite of criteria is provided which can assist in limiting the environmental impact of extraction. A more general methodological framework for research is proposed, whilst some recommendations to refine future monitoring schemes are highlighted. The information provided should assist in establishing a framework for decisions to be made on the management of the impact of aggregate extraction, within the marine environment.

SYNTHESIS OF RESULTS

Impact Assessments

Physical impact

The geology, morphology and sedimentology of the Kwinte Bank and its central depression have been studied intensively (**Bellec *et al.*** and **Degrendele *et al.***). Comparing bathymetric profiles obtained from 1992 and 1999, a difference of up to 6 m was observed between the deepest part of the depression (-16 m MLLWS) and the former topzone (-10 m MLLWS) of the sandbank; the western swale remained stable, at around –25 m MLLWS (**Degrendele *et al.***). The depression could be distinguished clearly from its surroundings, based upon acoustic imagery and seabed classification. Large dunes cross the depression, although their height is lowered locally and their steep face is progressively pointing in the flood (NE) direction (**Bellec *et al.)***. Following cessation of dredging activities, the bathymetry of the depression remained very stable and the evolution of bathymetric changes became similar to those of the adjacent non-exploited sandbank (**Degrendele *et al.***). No clear evidence could be established for regeneration processes, at least over a 2 year observation period.

Based upon intensive sediment sampling, addressing spatial and temporal variability, subareas of the sandbank could be distinguished, each with a particular sediment composition. The depression showed a wide range of fine- to medium-grained sediments, with variable shell content. These characteristics contrast to: (a) the poorly sorted and shelly coarse-grained sediments to the west; and (b) the more homogeneous, reasonably well sorted and finer-grained sediments, to the east (**Bellec *et al.***). The depression appears to act as a ‘transport corridor’ for shelly material, transported by the flood tide. Over a 2 year period, the overall sediment characteristics remained fairly stable, being indicative of no major sediment exchange with the crest of the sandbank. However, the evolution of the mean grain size of sediments, within the depression, shows trends resembling those for the more heterogeneous swale sediments; as such, these are clearly different from those anticipated for the top of a sandbank. Within the depression, observations obtained during the ebb phase of the tide (in a SW direction), have revealed the presence of ephemeral muddy deposits; this suggests that the depression, as well, has the potential to trap finer-grained sediments. Combined with the shelly coarser-grained material, brought in by the flood phase of the tide, this might initiate a very slow regeneration of the depression.

The potential for sediment transport towards the depression and, hence, for natural regeneration, has been studied on the basis of short-term hydro-sedimentary processes (**Garel**). Tidal cycle measurements, under (at the time of the measurements) reduced wave activity, indicate differences in the near-bed tidal ellipses and the across-bank component of the peak (ebb and flood) currents inside the depression, when compared to the crest of the bank. Divergent net sand transport is predicted inside the depression, being indicative of erosion. Sediment transport pathways have been studied also on the basis of grain size trend analysis (**Poulos and Ballay**). Two main transport pathways have been identified: a) NE (flood-directed) in the central depression and along the western part; and b) SW (ebb-directed) along the gentle eastern slope of the Kwinte Bank. These results contrast to that of a previous trend analysis undertaken for the Kwinte Bank, where the vectors were indicative merely of across-bank sediment transport (Gao *et al.*, 1994). In agreement with **Bellec *et al.,*** the central depression acts more as a passage way, than as a depo-centre, for the sediments.

In order to investigate the general seabed dynamics and to predict the long-term morphodynamic impact of sand extraction from tidal sandbanks in particular, process-based modelling (**Brière *et al.*** and **Van den Eynde *et al.***) together with idealized modelling of the evolution of the sandbank, have been applied to the Kwinte Bank area (**Brière *et al.***). Short-term modelling was established in support of the hydrodynamic field measurements, using three approaches. Overall, there was good agreement between the derived numerical results and the field measurements obtained. Flood and ebb tidal flows were dominant along the western and eastern flanks of the Kwinte Bank, respectively. Over the bank, the residual currents were directed mainly towards the WSW, indicating an ebb flow dominance over the bank. The area of the depression was ebb-dominated, with currents running sub-parallel to the depth contours. Further, the net sediment transport was opposed to the overall NE trending residual currents, suggesting deepening of the depression (**Garel**). In addition, distinct erosion/deposition patterns were simulated; these appeared to be similar, for different levels of dredging-induced lowering of the sandbank (**Van den Eynde *et al.***). Under such conditions, no destabilisation of the sandbank was indicated; in contrast, the modelling results favoured regeneration of the dredged areas. Modelling the interaction between wave activity and tidal currents showed a high increase in sediment transport, but also a change in direction of the net flux of sediments (**Giardino *et al.***). In particular, the crests of the shallow sandbanks are highly vulnerable to wave action and erosion/deposition patterns may change, according to superimposed wave activity. Further, the dominance of ebb currents along the eastern flank can be suppressed by southerly (or SW) winds; this is the most common wind direction over this area. The sandbanks have not been found to migrate; this might be due to the long-term 'balancing out' of sand transport, due to currents and low waves along the eastern flank, together with sand transport due to currents and more significant waves along the more exposed western flank (**Giardino *et al.***). The long-term impact of sand extraction has been modelled, using complementary approaches; these combined the benefits from complex numerical modelling and idealised models (**Brière *et al.***). The latter showed that the expected long-term trend of an excavated area is recovery, resulting in new sandbank equilibrium. Such long-term predictions contrast to the field observations (**Degrendele *et al.***) and short-term modelling results (see above); these suggest stability, to slightly deepening of the area of the depression. The modelling approaches assume an infinite source of sand, in reality, this is not the case.

The impact of the different levels of the lowering of the sandbank (see above), on the coast, has been studied also within the context that intensive dredging would increase a 1000-year wave height (Verwaest and Verelst, 2006). No significant impact could be deduced; this is considered to be due primarily to the large distance (> 12 km) of the extraction site from the coast; likewise the presence of other sandbanks between the Kwinte Bank and the coast leads to the dissipation of wave energy.

Biological/ecological impact,

The nature and vulnerability of benthic communities, to aggregate mining on the Kwinte Bank, has been investigated using macrobenthic fauna (**Bonne**). Stations were sampled within the central depression, along its sides and outside the exploited area, in coarser sand. Furthermore, stations were sampled on the adjacent non-exploited Middelkerke Bank (Figure 1). Compared to the historical data from the Kwinte Bank and the reference stations on the Middelkerke Bank, crustaceans and echinoderms have become more important over the area of the depression; this suggests a greater similarity between the depression with a swale environment. The difference in species composition in the depression can be considered within the wide niche width of the sandbank transitional species assemblages, described previously for the Kwinte Bank and the Belgian Continental Shelf. On this basis, sand extraction appears to have created a 'locally-different' habitat on the Kwinte Bank, with adaptation of the benthic fauna. However, the change is not significant, at least on the scale of the sandbank system. Here, only the macrobenthos is considered. Vanaverbeke *et al.* (2007) have discussed elsewhere the ecological effects, based upon changes in macrobenthic, nematode and copepode communties, including an evaluation of their short-term recovery, after the cessation of dredging.

Trends in the evolution of the depression after cessation of dredging are listed in Table 1, where indications of erosion and recovery are identified. In the short-term, erosion appears to dominate, whilst recovery seems appropriate over the medium- to long-term.

Table 1. Evolution of the depression, after cessation of the dredging. For the recovery processes, the time-scale and the significance of the process is provided.

Methodology	**Indications of an erosional trend**	
Multibeam bathymetry	The depression is 5 m deeper than the surrounding sandbank and since 2003, there is still a minor increase in depth (natural processes?). Large sand dunes are lower in height and move faster in the depression than outside of it (**DEGRENDELE *et al.***). The higher current speeds are likely to prevent deposition during the flood (**BELLEC *et al.***).	
Sediment grab sampling	Temporal grain size trends in the depression resemble more the evolution of sediments in the swale; they differ significantly from those along the crest of a sandbank (**BELLEC *et al.***). Along the axis of the depression, significant sediment transport is indicated, on the basis of grain size trend analysis (**POULOS and BALLAY**). The presence of the depression is more a passage-way, than a depo-centre, for the sediments (**BELLEC *et al.***; **POULOS and BALLAY**).	
Hydrodynamics (ADCP – S4)	Due to the canalisation of the flow, there is a stronger erosional potential during flood. A divergence of net sand (bed load) transport has been calculated inside the depression, with net erosion during the tidal cycle (net sediment transport between 5,3 g/m/s and 9,8 g/m/s) (**GAREL**).	
Process-based model Delft 3D	Throughout a tidal cycle, erosion over the central depression was modelled (0.001 m of erosion during 10 days, with no waves taken into account) (**BRIÈRE *et al.***).	
MU-SEDIM and SISYPHE models	Without atmospheric conditions and waves being taken into account, erosion occurs in the depression and on the western flank of the sandbank (**VAN DEN EYNDE *et al.***). **GIARDINO *et al.*** demonstrate higher sediment transport capacities and changing residual transport directions, under the combined action of tidal currents and waves.	
Biological sampling	No further impoverishment, but a species composition difference has been observed within the wide niche width of the sandbank transitional species assemblages, with lower relative polychaete and higher relative crustaceans and echinoderms abundance. Nonetheless, a similar macrobenthos density and species richness exists (**BONNE**).	
Method	**Indications of recovery**	Time-scale
Multibeam backscatter classification	Slight tendency for a relative increase in fine sediments, in the depression (**DEGRENDELE *et al.***).	3 years (Significant?)
Sediment sampling	Central depression appears to trap shelly and coarse-grained material (**BELLEC *et al.***), albeit locally. Deposition of mud, under ebb and neap tidal cycle conditions (not observed on the crest) (**BELLEC *et al.***).	Event related, Significant (Significant?)
Hydrodynamics (ADCP – S4)	Convergence of net sand transport, at the bank's crest (**GAREL**).	Tidal cycle, Significant
Process-based model (Delft3D)	Residual transport direction from the SW (swale) towards the NE, over the sandbank crest (**BRIÈRE *et al.***).	Two weeks, Significant
Idealised modelling	On the long-term (100 years), the system tends to a new equilibrium, displaying recovery of the depression (**BRIÈRE *et al.***).	100 years
Biological sampling	Macrobenthic species assemblage has changed slightly, but develops well (**BONNE**).	3 years, Significant

For environmental and resource management purposes, the physical information available from the Kwinte Bank is synthesised in Figure 2. The background plot shows the median grain size distribution of the surfical sediments (Verfaillie *et al.*, 2006). The most economically-interesting (in relation to the marine aggregate industry) grain sizes (> 300 μm) occur to the north of the concession zones. Clearly, patches of coarser grain sizes occur locally; in general, fine to medium sands dominate the Flemish Banks. Crestlines of large to very-large dunes are indicated on the Figure; generally, they are flood-dominant along the western steep slopes and ebb-dominant along the gentle eastern slopes. Modelled areas of erosion and deposition over a 30 year period (**Brière *et al.***), indicate: mostly erosive swale areas (of around 1 m) and the western steep slopes of the banks, together with the kink area. The eastern gentle slopes are depositional; similarly is the highest part of the Kwinte Bank, situated more towards the south. Not indicated on the Figure, for the sake of clarity, is the thickness of the Quaternary deposits above the underlying Tertiary clay. Such sediment cover, in the swale to the west of the Kwinte Bank, is a potential sediment supply to the depression; however, its thickness varies from 0 to 2.5 m. The major source of larger grains (> 300 μm), required to rebuild this section of the bank, is located to the North.

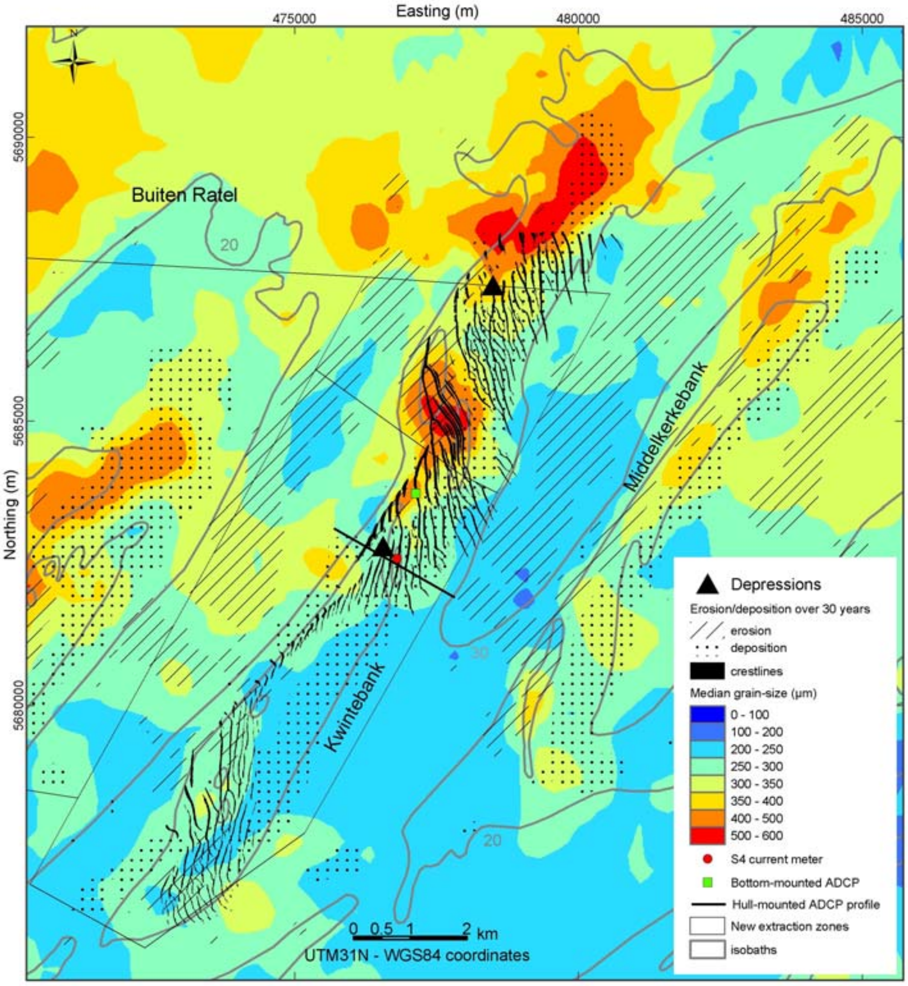


Fig. 2: Multicriteria resource map of the Kwinte Bank area (for details, see text).

DISCUSSION AND RECOMMENDATIONS, TO SUPPORT SUSTAINABLE EXPLOITATION

Introduction

Marine environments are dynamic and complex, their knowledge base is limited, and many changes are not noticed until it is too late for a rigorous demonstration of cause and effect (THRUSH *et al.*, 1998). The same applies to the Kwinte Bank, as it was only after the creation of a 5 m deep depression along the top of the sandbank, that an intensive research strategy was established. After cessation of the dredging, the results of morphological, sedimentological and biological surveys do not reveal any significant restoration of the depression, at least over a 3 year observational period. The fact that such depressions occur reveal that sandbanks should not be considered as infinite resources of renewable sand deposits.

Providing recommendations for extraction from tidal sandbanks is linked, inherently, to the consideration of whether renewable or non-renewable sediments are being extracted; this, in turn, has implications on sustainability. Guidelines on sustainable exploitation have been described by WELLMER and BECKER-PLATEN (2002), addressing the sustainability of mineral resources, in general. For renewable resources, "*the rate of consumption should not exceed the rate at which they are regenerated*". Non-renewable resources imply that "*the consumption should not exceed the amount that can be replaced by functionally equivalent renewable resources, or by attaining a higher efficiency in the use of renewable or non-renewable resources*". Moreover, these investigators observed that "*material and energy input into the environment should not exceed the capacity of the environment to absorb them with minimal detrimental effects*". Likewise, that "*the rate of anthropogenic input and environmental interference should be measured against the time required for natural processes to react and cope with environmental change*". Such guidelines are highly valuable for managing resources in the marine environment; at least, if extraction is envisaged within the system's natural variability. Since, non-renewable resources are exploited increasingly; there is a need for a higher efficient use of the seabed, a search for functionally-equivalent renewable resources, and minimising detrimental effects.

Relevance of the new results within the framework of sustainable exploitation

Physical impact

Generally, the most severe direct physical impact of marine aggregate extraction relates to substratum removal, alteration of bottom topography and re-deposition of material (e.g. DE GROOT, 1996; NEWELL *et al.*, 1998). Dredging-induced changes in sediment composition relate mostly to: (a) minor surficial grain size alterations (MCCAULEY *et al.*, 1977; POINER and KENNEDY, 1984); (b) an increase in the proportion of fine sands (DESPREZ, 2000; VAN DALFSEN *et al.*, 2000; BOYD *et al.*, 2005), or silt (VAN DER VEER *et al.*, 1985); and (c) an increase in gravel, through the exposure of coarser sediments (KENNY *et al.*, 1998).

Generally, dredged depressions or pits, created by marine aggregate extraction, have been reported to remain as recognisable seabed features, for several years. BOERS (2005) has reviewed the morphological behaviour of different pits, trenches and channels, excavated in sand on the Dutch Continental Shelf. Large variations in infill time have been reported, based upon local environmental conditions (water depth, waves, flow velocity, sediment characteristics) and pit/trench characteristics (volume, shape, orientation). The rate varies from months in shallow water, to decades or centuries in deep water. For large-scale sand extractions (> 10 million m^3), in water depths of more than 20 m, characteristic regeneration time-scales are of the order of centuries. Using process-based modelling, VAN RIJN *et al.* (2005) concludes that the orientation of the pit, towards the flow, is the most important parameter. Pits or channels lying perpendicular or oblique to the flow enhance sedimentation; those parallel to the flow reveal sedimentation, if the pit is wide (HOOGEWONING and BOERS, 2001; RIBBERINK, 1989), but only slight erosion if narrow (RIBBERINK, 1989). If pit evolution is modelled as a local topographic perturbation in the morphodynamic equilibrium of sandbanks, the system may shift to a new equilibrium profile (ROOS, 2004). The corresponding time-scale (approx. a century) is shortest for deep and narrow pits created in the bank's crest.

On the Kwinte Bank, the direct impact of dredging is revealed by the presence of elongated depressions, occurring within the former topzones of sandbanks (**DEGRENDELE *et al.***). Instead of homogeneous well-sorted medium to coarse sand, patches of fine and coarse sediment occur with, locally, areas of ephemeral mud deposits (**BELLEC *et al.***). At least over a period of 3 years, no significant sediment infill has been observed; this is somewhat unusual since crest areas are generally regarded as being highly dynamic sand convergence zones. The modelling results predict recovery of these areas, but only after a time-span of, at least, a century. The significance of the environmental impact of the depression will depend, as such, upon the grain size changes it has induced, because of its effect on the ecology of the area (see below). In addition, if the dredged sediments are very different from those that are transported easily within the system, restoration of the bank is not likely to occur. A major concern remains the indirect effect of these depressions on the tidal currents, possibly inducing different erosion/sedimentation patterns. In some cases, this difference might lead to increased coastal erosion, although no clear impacts have been described within the literature, even for areas lying adjacent to the coast (e.g. Moreton Bay (QUEENSLAND, 2005)). The same applies to the Kwinte Bank.

Biological/ecological impact

Assessing ecological changes is difficult in sandbank environments. The high mobility of species, the poverty and the wide niche width of the community, together with the extent to which the community adapts to high levels of sediment reworking, makes it difficult to isolate the effect of human-induced physical disturbance. Moreover, communities in areas of high stress are characterized by higher growth rates (JENNES and DUINEVELD, 1985); hence, they adapt more readily to the impact of any dredging operations (DESPREZ, 2000). In the case of Moreton Bay, water depth changes have caused changes to benthic fauna assemblages (QUEENSLAND, 2005). Increasing species diversity and abundances in macrobenthos have been associated with greater water depths, together with the changing composition of assemblages.

Potential cumulative impacts

In an increasingly anthropogenically-pressurised environment, cumulative effects may be anticipated, e.g. from fisheries and windmill farms. Fishery activities are restricted mainly to the swales and the base of the sandbanks; however, in high intensity trawling zones, the seabed of the latter is scraped completely (as shown on multibeam imagery (Fund for Sand Extraction, unpublished)). Since such areas act as a buffer for sand maintenance of the bank, this impact requires further investigation. Changing seabed dynamics, in relation to the installation of windmill farms, is hitherto unknown. Nonetheless, it could be relevant adjacent to aggregate concession zones. Cumulative impacts may also occur, when the potential effects of sea-level rise and increased storminess are considered; this is difficult to establish and, as such long-term datasets are required. On the Belgian Continental Shelf, DE MOOR (2002) has shown a regional erosional tendency of the seabed, related both to exploited and non-exploited sandbanks. The swales were 'stable to slightly erosional' with higher erosion rates associated with locations where sediments were extracted. On the basis of the present observations and modelling results, it appears unlikely that aggregate extraction would be responsible for this particular phenomenon. If this erosional tendency is further confirmed, it could constrain further intensive aggregate extraction.

Criteria for sustainable exploitation

Generally, the environmental impact of extraction is site-specific, due to variations in sediment type, mobility, bottom topography and hydrodynamic activity (DESPREZ, 2000); as such, the setting of criteria for minimising environmental effectsd could prove difficult. Nonetheless, in many cases, concession zones are planned in areas that are not favourable for aggregate extraction in the long-term, e.g. due to limited resource availability and/or expected environmental constraints. If criteria can be set that are measurable and quantifiable, they: (a) can provide guidance to the design of concession zones; (b) be used for monitoring; and (c) guide decisions on the management of aggregate extraction. The strictness in the application of criteria will depend strongly upon the Governments View on acceptable environmental impacts.

Geographical criteria (distance from the coast)

The most critical criterion for selecting extraction sites, with minimal environmental effects, is the impact on the coast. For many continental shelves, the appropriate government sets the depth limits for extraction: in the Netherlands, the established, simplified 20 m isobath (Dutch Ordnance Level); in Belgium, the extent of the concession zones lies beyond 12 km from the shoreline; on other shelves, the 'depth of closure' is respected (US, CAMPBELL *et al.*, 2003).

Geological criteria

Selecting areas with most suitable sands, guaranteed in the long-term, requires knowledge on the geology of sandbanks. The complexity of their internal architecture varies: some banks have complex internal structures, suggesting multi-phase formation (e.g. TRENTESAUX *et al.*, 1999), whereas others are characterised by a simple structure (e.g. COLLINS *et al.*, 1995). These differences may be related to the antecedent morphology and type of substrate, as well as the sedimentary framework in which the sandbanks were formed. Sandbanks with a multi-phase formation often have an incised base, with an infill of coarser material over which estuarine type deposits with varying lithologies (e.g. tidal flat) are draped. Only the upper part is tidally-dominated, consisting of sands representative of the present-day hydrodynamic regime. Exploitation is best restricted to this part of the sandbank, from a resource perspective (consistent quality, in terms of space and time) and in order to minimise environmental effects; its thickness should be sufficient to allow for longer-term exploitation. On the basis of the present investigation, a 5 m thick deposit appears to be minimum. Further, it is important that areas are selected where sufficient Quaternary cover is guaranteed over larger areas, including the swales; these are the primary source of sediments, for regeneration.

Morphological criteria

Less stable areas of a sandbank are best avoided, in terms of removal of sediments, i.e. 'kink' areas and extremities. SMITH (1988), DELEU *et al.* (2004) and **BELLEC *et al.*** reveal that kink areas are associated with higher dynamics; sometimes, they are somewhat lower in height (DELEU *et al.*, 2004), but bedform movement is often rapid and more subjected to varying hydro-meteorological conditions. Current speeds and direction may change rapidly, hampering any steady recovery from these areas. Modelling studies, undertaken over a 30 year period, show an erosional trend for such a kink area on the Kwinte Bank (**BRIÈRE *et al.***).

The dynamics along the broad extremities of sandbanks are less predictable.; in the Flemish Bank region, they appear to be interesting as a resource area, with higher bedforms and coarser-grained sediments. However, sediment volumes fluctuate more here and are more susceptible to storm action. On the basis of historical data, DE MOOR (2002) has identified that the northern extremities of the Flemish Banks are recent accumulations (within the last century). Indeed, a thin sand sheet only forms the tidally-induced part of the sandbanks, as revealed from seismic profiles. Because of more dynamic bedform movement here, it is very difficult to distinguish naturally- from anthropogenically-induced changes. Consequently, negative impacts will be hard to reveal, from the results of the monitoring.

Extraction over large interdune areas can have adverse environmental impacts, if the crest and trough of the dunes represent different sedimentary environments. The troughs can be very heterogeneous in terms of sediment composition; they are often richer in benthic fauna (MACKIE *et al.,* 2006).

Sediment dynamical criteria

If extraction is envisaged within the natural variability of the sandbank's volume, grain sizes should be extracted that can be regenerated easily; likewise that are available over a larger area, including the potential source areas. In addition, the concession zones should be restricted to areas known as being depositional. Sandbanks are regarded generally as zones of sediment accumulation; nonetheless, subareas can be erosional, as shown in the results of this investigation (**VAN DEN EYNDE *et al.*** and **BRIÈRE *et al.***).

A difficult criterion to define relates to the sediment volumes that can be extracted, without causing any long-term impact; the evaluation requires knowledge on the natural volume fluctuations. Based upon an extensive, extraction-related, monitoring programme, **DEGRENDELE *et al.*** has proposed a mean natural evolution of +/- 0.05 m^3/m^2/year; ideally, the rate of extraction should not exceed this variability. VAN LANCKER (unpublished) has confirmed such variability in erosion/sedimentation for the Belgian near coastal zone, but emphasises that the change is highly 'event dependent'. As such, this rate of change can occur between successive observations, in the short-term: it may be balanced out on an annual basis. Present extraction activities, on a local basis, exceed significantly this value; inside the depression, a value of 1.08 m^3/m^2 was calculated (0.47 m^3/m^2 for the surrounding area, with an overall mean of 0.64 m^3/m^2) (**DEGRENDELE *et al.***). Thus, albeit locally, the natural dynamics cannot counterbalance the extraction activities.

Biological/ecological criteria

Sustainable management of renewable natural resources should include a balance between exploitation and adverse effects on other components of the ecosystem (THRUSH *et al.*, 1998). The results of VAN MOORSEL (1994), KENNY and REES (1996) and DESPREZ (2000) have illustrated that extensive dredging may modify the sediment slightly, but the benthic communities considerably. As such, it may be preferable to concentrate dredging within small areas of the sandbank i.e. 'intensive dredging'. Nonetheless, prolonged extraction from limited sites can cause serious effects upon seabed morphology and sediment quality (DESPREZ, 2000; VANAVERBEKE *et al.,* 2007). For comparison, there exists a 'threshold scale' and a 'frequency of disturbance events' at which long-lasting ecological effects may occur, even against a background of natural disturbance (KAISER and SPENCER, 1996). The results obtained here for the Kwinte Bank support this conclusion.

Criteria related to the extraction activity itself

VAN RIJN *et al.* (2005) regards the orientation of the pit, i.e. towards the flow, as the most important parameter to establish the rate of infill (see above). From an industrial and practical perspective, it appears logical that extraction should take place along the direction of the main current. However, the present investigation (**DEGRENDELE *et al.***) has shown that the depression was located slightly obliquely to the crest and parallel to the flow; this has caused an opening of the depression, towards the swale with the flood tide becoming 'channelised' (**GAREL**); such a situation should be avoided. The most crucial criteria relate to the amount extracted on each visit and the number of consecutive abstractions, over a given time-span (SCHRIJVERS *et al.*, 2007). Thresholds might then become available, with increasing data becoming available on environmental impacts and dredging activities. Other issues relate to minimising the overflow, or screening: however, these are of less importance on the Belgian Continental Shelf.

Example of the application of some of the criteria to the Belgian Continental Shelf

The most interesting area for extraction, for the marine aggregate companies, is located along the eastern part of the Buiten Ratel sandbank (Figure 2): the geology provides a sufficient thickness for extraction; the grain size is in excess of 300 μm; the area is depositional; and the overall surface area for extraction is large enough. Bedforms over this area reach up to 4-6 m in height; their asymmetry confirms that the (modelled) depositional area is a bedload convergence zone (Baeye, 2006). Moreover, the swale, lying to the east, contains sediments suitable for regeneration, following extraction; presently, the steep western slope is dredged. At this location, the grain size is somewhat less than 300 μm, but the area is erosional; the swale, to the west, consists of gravel. The same problems as described for the Kwinte Bank are likely to occur, with regeneration hampered by a lack of source material. The ecology of the Buiten Ratel sandbank is likely to be similar to that identified for the Kwinte Bank.

Need for a scientific framework, to support sustainable exploitation

If non-renewable resources are increasingly being exploited, there is a need for an improved evaluation of resources and a more efficient and targeted use of the seabed. These requirements call for a strategic management framework, incorporating detailed resource and environmental maps, at large and small scales (Table 2). The basis of these needs remains high quality geological maps, incorporating the extent of the surficial resource and the availabilty with depth. For sandbanks, knowledge of the internal architecture is fundamental to the estimation of the resource reserves.

Table 2. Large scale information/maps needed to support sustainable exploitation.

Type of map	**Usage**
Detailed Grain Size	*target the appropriate aggregate quality* *identify potential source areas*
Thickness and Suitability of the Quaternary deposits	*ensure long-term availability and consistency in quality*
Sediment transport/ erosion-deposition maps, *supported by* Morphology/Bedform maps	*indicate areas with higher dynamics* *identify bedload convergence zones* *avoid kink areas and the bank's extremities,* in order to *maximise the chance of regeneration* *minimise detrimental physical impact*
Wave Energy Distribution	*evaluate a possible impact on the coast*
Ecological Functioning	*avoid sensitive areas, or important habitats*
Other seabed users	*minimise conflict, optimise concurrent use*

Although, the data availability will vary significantly, according to location and distance from the coast, the detail needs to be sufficiently high, to ensure a realistic evaluation of any potential impacts.

Multicriteria resource maps, as presented in Figure 2, can assist the selection of optimal locations for sand extraction, within the (often predefined) concession zones. These maps are able to integrate: (a) detailed sediment distribution maps; (b) bed form shape/size, asymmetry and dynamics; and (c) areas of erosion and deposition. Such integration assists in selecting locations where minimal environmental impact is likely to occur. Similarly, holistic seabed mobility studies (e.g. VELEGRAKIS *et al.*, 2007) can be used as an input to such decision-making processes. Erosion/deposition rates can be modelled, or derived from charts and maps. In the latter case, historical changes in sediment volume and sandbank elevation can be established providing erosional/depositional rates and regional patterns of sand movement (GAO and COLLINS, 1995).

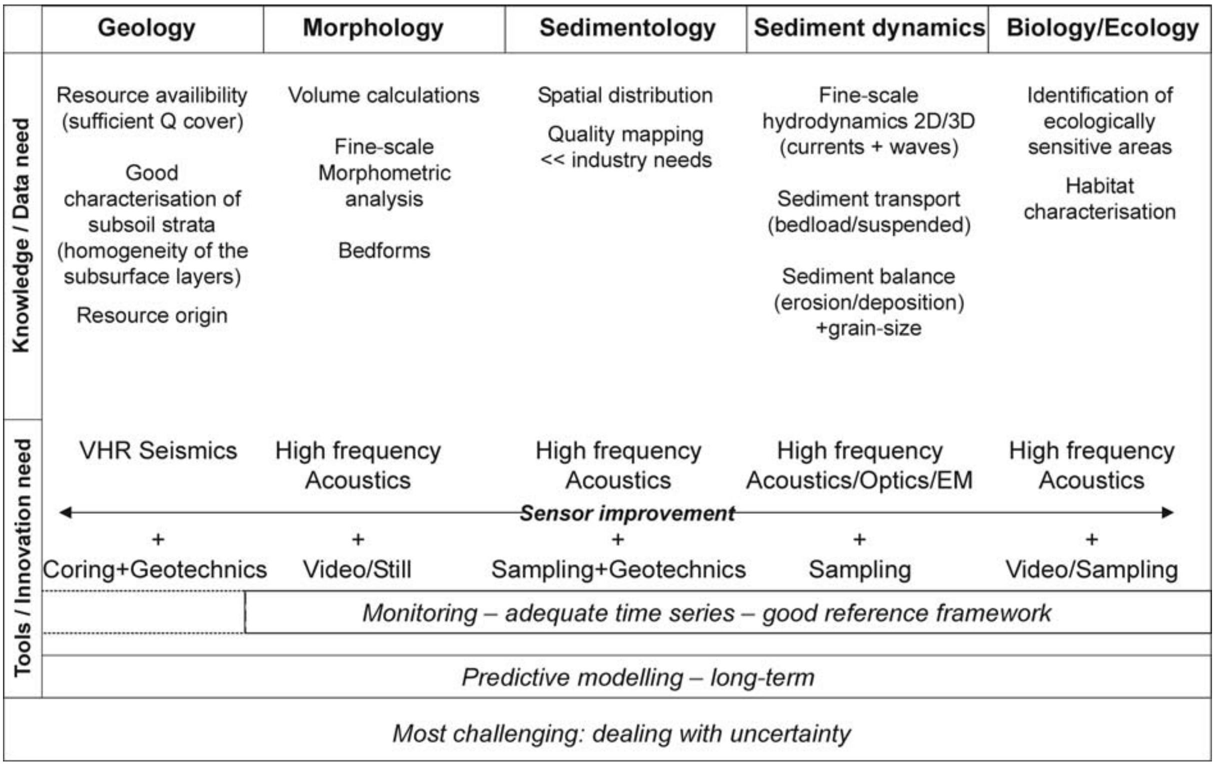
Maps showing ecological functioning are more difficult to establish, but are important within the context of the protection of sensitive or valuable habitats, communities or species. For soft substrata areas of the shelf, there might be a strong link between the physical and biological environment; as such, recent developments in predictive modelling tools may enable the prediction and mapping of ecologically-important zones, on the basis of abiotic variables alone (e.g. VAN LANCKER *et al.,* 2005). This approach has been demonstrated for the Belgian Continental Shelf, where the occurrence of macrobenthic communities was predicted successfully, on the basis of median grain size and silt-clay percentage, only (DEGRAER *et al.*, in press). Biological/ecological valuation criteria (e.g. DEROUS *et al.*, 2007) can be applied then, to obtain maps which establish the ecological value of shelf environments (DEROUS *et al.*, in press). Together with the resource maps (VAN LANCKER *et al.* 2007), the ecological maps provide an ideal basis for any spatial planning initiative (e.g. MAES *et al.*, 2007). The range of maps, albeit supported by more detailed research, establish quantitative parameters that serve as an input to decision-support systems, guiding the management of future extraction activities (e.g. SCHRIJVERS *et al.*, 2007; CALEWAERT *et al.,* 2007).

More detailed information is required for areas where extraction is envisaged. In order to support the necessary environmental assessments, such work should be addressed on a localised and multidisciplinary basis (Figure 3).

For example, details on the morpho-sedimentary and biological environment are, nowadays, increasingly derived from very high-resolution acoustic surveys (MESH CONSORTIUM, 2007). Likewise, targeted ground-truthing will remain an important component, to: (a) further establish quantitative relationships between the physical and biological environment, of use also in predictive modelling; and (b) calibrate the acoustic imagery and improve the value and meaning of automated seabed classification. For an overview of seabed mapping techniques in environmental monitoring and management, reference should be made to BOYD *et al*. (2006) and to the MESH CONSORTIUM (2007); these provide recommended operational guidelines for seabed habitat mapping.

Hydro-sediment dynamic observations (at least over a tidal cycle), together with detailed grain size and bedform data are ideally coupled to morphodynamic modelling; this in turn, should guide the observations. The results obtained should be evaluated against extraction data and varying hydro-meteorological conditions, to distinguish naturally from anthropogenically-induced dynamics. The significance of any impacts can be further estimated using long-term predictive modelling tools (see **IDIER *et al.***, for an overview).

The scientific framework of such an investigation can be managed ideally in GIS, permitting the simplified integration of spatially-diversified datasets. Advanced geostatistical tools can assist in the study of the variance of the various datasets. Spatial relationship between the data can be analysed, coupling the biological and physical environment, to provide quantitative data on the various anthropogenic uses of the seabed. The availability of datasets, together with their spatial and temporal variability, uncertainties and discontinuities, will remain challenges to environmentalists and scientists.



	Geology	Morphology	Sedimentology	Sediment dynamics	Biology/Ecology
Knowledge / Data need	Resource availibility (sufficient Q cover) Good characterisation of subsoil strata (homogeneity of the subsurface layers) Resource origin	Volume calculations Fine-scale Morphometric analysis Bedforms	Spatial distribution Quality mapping << industry needs	Fine-scale hydrodynamics 2D/3D (currents + waves) Sediment transport (bedload/suspended) Sediment balance (erosion/deposition) +grain-size	Identification of ecologically sensitive areas Habitat characterisation
Tools / Innovation need	VHR Seismics	High frequency Acoustics	High frequency Acoustics	High frequency Acoustics/Optics/EM	High frequency Acoustics
	Sensor improvement				
	+ Coring+Geotechnics	+ Video/Still	+ Sampling+Geotechnics	+ Sampling	+ Video/Sampling
		Monitoring – adequate time series – good reference framework			
	Predictive modelling – long-term				
Most challenging: dealing with uncertainty					

Fig. 3: Overview of knowledge/data and tools/innovation needs, to support the sustainable exploitation of a particular extraction site.

Future monitoring schemes and policy implementation

A comprehensive overview of monitoring practices and guidelines is provided in POSFORD DUVIVIER ENVIRONMENT and HILL (2001), adapted partly from the guidelines of FREDETTE *et al.* (1990). Monitoring should document whether any impacts, identified as unacceptable, are evident; likewise, conditions that will lead to the development of such a situation. As such, monitoring programmes should provide clearly interpretable information, on whether a threshold of an adverse condition has been, or is likely to be, reached. On this basis, decisions can be made about continued, or modified, use of aggregate extraction sites. In its guideline document, ICES (2003) suggests a number of questions that can assist in the development of a monitoring programme: *a) what are the environmental concerns that the monitoring programme seeks to address?; b) what measurements are necessary to identify the significance of a particular effect?; c) what are the most appropriate locations at which to take samples or observations for assessment and what is their natural variation?; d) how many measurements are required to produce a statistically sound programme?; and e) what is the appropriate frequency and duration of monitoring?*

Answering these questions, requires quantitative data related to present large and small spatial scales and at various time-scales (e.g. COLLINS and BALSON, 2007). The present investigation has demonstrated that intensive monitoring, with a restricted spatial spread, is required to detect irregularities related to dredging (e.g. depressions). However, the most critical part of the assessment is the evaluation of the effects, against the background of the natural conditions and dynamics of the seabed. This approach requires systematic monitoring of larger areas, albeit at a much lower spatial resolution. Defining a statistically robust programme may become very 'labour intensive': the Belgian experience has shown that surveys undertaken 4-5 times/year are unsufficient to obtain significant volume trends that should guide management decisions (NORRO *et al.* 2006). Last, but not least, baseline data is crucial and, when not available, impact assessments remain mostly inconclusive. Expert disciplinary judgements can be a solution; they can counterbalance various impacts, assist in defining and fine-tuning monitoring needs, ensuring the establishment of practical and efficient programmes. Visibility of the programmes, regular reporting and publishing in peer-reviewed journals provide extra quality control.

The management of marine aggregate activities remains complex; it requires cost-benefit analysis and an holistic, practical approach. The communication and fine-tuning of various needs, towards policy implementation, is required, e.g. the systematic 'Frame of Reference' approach of VAN KONINGSVELD and MULDER (2004). Within this frame, the following key elements were identified: (a) a strategic objective, expressing the long-term management vision and policy; and (b) an operational objective, describing how the strategic objective will be achieved. The definition of specific parameters that play a role in decision-making and the definition of thresholds become very important and are relevant at this stage of the process. This framework arose from the need for an established feedback and effective transfer of knowledge, between scientists, managers and policy-makers. In the development of a shared perspective, sustainability requires extensive discussions on the significance of processes at various time- and space-scales.

Intensive versus extensive dredging?

An important issue in marine aggregate extraction is related to whether extraction should be procured intensively, focussed on specific sites (leaving other areas undisturbed) or extensively, with a high spatial spread of the activities. Ideally, the latter option would imply that sites can recover, from a physical and biological viewpoint. This investigation has shown that this is not likely to occur, although it must be emphasised that the observed depressions resulted from intensive dredging, albeit using vessels with average capacities of less than 5,000 m³.

Future developments incorporate dredging capacities which have increased to 46,000 m³, anticipating the needs for extraction in deeper offshore waters. Demands will be driven by large beach nourishment or land reclamation projects needing huge volumes of sands to be dredged over relatively short time periods. More offshore sandbanks are, however, less dynamic, still their role in wave dissipation should not be underestimated. If the more narrow topzones of these banks are dredged systematically over larger areas, it might have far-reaching implications that extend beyond a localised impact on the physical and biological environment. As such, it would seem worthwhile investigating the extraction of suitable sands fromthe sandbanks and the swales, although the latter might have constraints from a fisheries perspective. It is to be hoped that adequate prospecting, in addition to the present-day knowledge on the living and non-living resources of the seabed, can guide the optimal selection of sites, respecting both the suitability of the resource and the minimisation of environmental impacts.

CONCLUSIONS

Investigations related to dredging of the topzone (upper part) of the subtidal sandbank, Kwinte Bank, have revealed the existence of a depression which is now a clearly distinguished environment. The sediment characteristics resemble more those of the swale sediments, i.e. differing from those of the crestline of a sandbank. Large to very large dunes (4-6 m in height) occur within the depression, but their height is lower than the surrounding bedforms, enabling a more rapid progression of the flood current. Following cessation of the dredging, the bank morphology remained remarkably stable with no cumulative effects being observed. The intensive dredging led to a change, albeit locally, of the hydrodynamic regime; at the same time, the depression acts as a transport pathway for sediments. The numerical modelling results, in the short-term, confirm the somewhat erosive nature of the depression, although regeneration is modelled in the medium- to long-term. No impact on the adjacent coast could be identified.

On the basis of the above findings, over a large scale, the depression appears to have a localised impact only. However, such aggregate extraction may not be sustainable, at least, from a physical perspective. No significant refill of dredged areas has been identified, partly because of the coarser, relict, sediments which have been extracted; their transport thus is limited by sporadic and enhanced wave conditions. Moreover, only a very thin cover of sediments (acting as a buffer) exists in the swales; these were modelled as being erosive, in the long-term. Trend analysis of observations over the whole of the Flemish Banks region have revealed overall erosion of the sandbanks. As such, it is very unlikely that aggregate extraction activities would be counterbalanced by natural regeneration. A potential sand deficiency over the larger sedimentary system remains to be investigated.

As non-renewable sediments are extracted increasingly, targeted and efficient use of seabed resources is required. Such an approach relies upon appropriate mapping and modelling approaches, good datasets and detailed analyses, within a long-term perspective. With increasing knowledge of the seabed, mapping of source areas becomes more realistic; thus, in turn, permit a more comprehensive evaluation of the impact of extraction and the regeneration potential.

In summary, criteria have been proposed that can guide sustainable exploitation, assist in selecting the most appropriate locations for extraction, from a resource perspective as to minimise environmental effects. Finally, more general recommendations on monitoring have been iterated, because of their importance of being implemented in existing monitoring programmes. However, sustainability can be ensured only if good management/policy practices are in place and implemented in a structural way.

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