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Morphological Evolution of the Kwinte Bank Central Depression Before and After the Cessation of Aggregate Extraction

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ABSTRACT

Analyses of the records of ships registers and Electronic Monitoring Systems, of the trailer suction hopper dredgers, operating on the Belgian Continental Shelf, reveal that since the beginning of extraction in 1976, 75% of the total extracted volume originates from only one sandbank, the Kwinte Bank. At present, two morphologically-distinguished depressions are observed along the two most dredged areas of this sandbank: one in the central; and one in the northern part of the bank. In order to limit the impact of sand extraction on the bathymetry, the central depression of the Kwinte Bank was closed for exploitation, in February 2003.

An understanding of the morphological evolution of this central depression is based upon data obtained: (a) from November 1999, until the closure for extraction in February 2003; and (b) on the subsequent post-dredging evolution, until June 2005. During this 5-year period, a total of 17 surveys were carried out with a multibeam echosounder over the area of the central depression (KBMA) and over a reference zone on an adjacent non-exploited sandbank. The resulting time-series of bathymetrical digital terrain models, together with backscatter strength maps, permit a detailed comparison of the bathy-morphological and sedimentary evolution of both of the monitored areas.

Since the commencement of multibeam monitoring in 1999, an overall deepening (by 0.5m) of the entire KBMA monitoring zone is observed, until the cessation of dredging, in February 2003. Subsequently, the deepening slowed down and the variation in sediment volumes became similar to that of the adjacent non-exploited sandbank. From this, marine aggregate extraction appears to have only a local impact.

ADDITIONAL INDEX WORDS: *North Sea; sandbank; dredging; multibeam echosounder; bathymetry; morphology; seabed imagery; monitoring; marine sand extraction; aggregate extraction.*

INTRODUCTION

Numerous tidal sandbanks characterise the sediment deposits of the Belgian Continental Shelf. From an economical perspective, these sandbanks represent an important resource of sandy aggregates (Van Lancker *et al.,* this volume). Gravel occurs in some of the swales, but its exploitation is limited, due to the low industrial quality of the gravel deposits.

Within Belgium, sand exploitation commenced in 1976, with an annual volume extracted of around 29,000m^3. This volume increased to 220,000m^3 in 1977; it has increased, steadily, to reach 1,700,000m^3 in the middle of the 1990's. In 2001, production exceeded 1,900,000m^3 (or nearly 3,000,000 tonnes, at a mean density of sand of 1.55tonnes/m^3). Since 2002, the production has stabilised at around 1,600,000m^3.

The exploitation of marine aggregates (MA) on the Belgian Continental Shelf is confined to three seabed areas. These areas were defined by the Royal Decree of September 1, 2004 related to the requirements, the geographical delimitation and the appropriation procedures for concessions for the exploration and exploitation of mineral and other non-living resources in the territorial sea and on the continental shelf (see Degrendele *et al.*, 2005; and Radzevicius *et al.*, this volume).

Extraction activities have been subjected to a monitoring programme, almost from the commencement of exploitation in 1976. The monitoring undertaken is two-fold: (1) the activity of the extraction vessels is followed (volume dredged, location and time), using extraction registers and, since 1996, Electronic Monitoring Systems (EMS or 'black-boxes'); and (2) the physical impact of the extraction on the environment (since 1999, studied with a multibeam echosounder).

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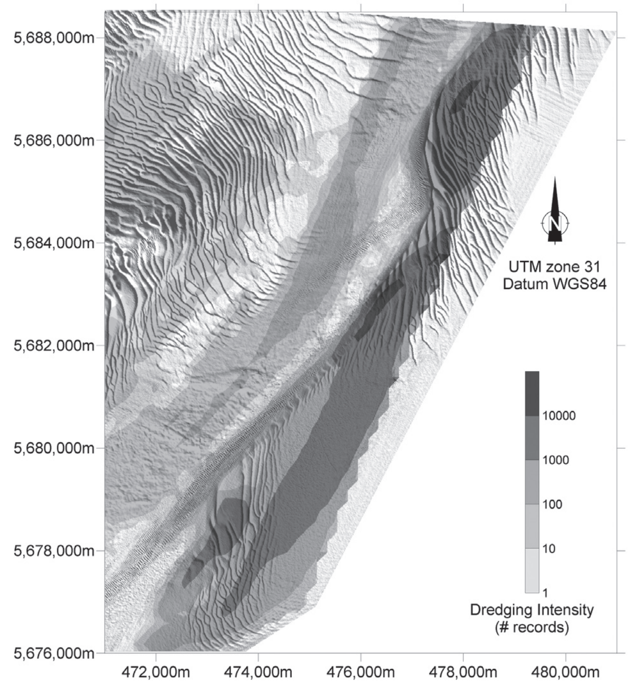

Figure 1. Superposition of extraction intensity on a shaded relief map of the Kwinte Bank (number of dredging records, from 05/11/1996 to 30/03/2005; each record represents 30s of operation of a trailer suction hopper dredger).

According to the ships registers database and the EMS records, the extraction is concentrated mainly on one particular sandbank: 75% (11,620,000m^3, of a total of 15,570,000m^3, from 1997 until 2004) is extracted on the Kwinte Bank. The superposition of the dredging intensity on the general digital terrain model (DTM) of the Kwinte Bank reveals the spatial coincidence between areas, which are most dredged, together with two morphological depressions in the central and northern parts of this sandbank (Figure 1.).

According to the Federal Legislation, the extraction level is limited to a maximum of 5m below the seabed, as defined by the most recent hydrographic chart. As the hydrographic charts are updated regularly and incorporate potential depressions, this would imply that the limit of 5m is never reached. However, when comparing the oldest reliable single-beam profiles and the recent multibeam data, such a difference has been observed along the central depression. These findings led to the closure of this zone, in 2003 (Degrendele, Roche, and Schotte, 2002).

The Kwinte Bank central area is impacted upon regularly by trailer hopper dredgers, but is subjected also to the natural dynamics of the sandbank. As such, it is an ideal case to study the effect of MA extraction from a tidal sandbank; likewise, to evaluate the potential of restoration of the sandbank, following the cessation of MA extraction. This contribution focuses upon the bathy-geomorphological and sedimentary evolution of the sandbank, during and after sediment extraction in the central depression; similarly, the relationship between this evolution and the extraction activities.

ENVIRONMENTAL SETTING

The Kwinte Bank is part of the Flemish sandbank system (Figure 2.), a group of Quaternary sand bodies deposited on Tertiary (Ypresian) units (mainly clays) (Le Bot *et al.*, 2005, for an overview). The sandbank, NE-SW aligned, is about 15km in length, 10-20m in height, and 1 to 2km in width (i.e. about 400 Mm^3 in volume); it shows an asymmetric profile, being steeper towards the NW. Water depths are around 5 to 25m MLLWS (Mean Lowest Low Water at Spring). Macrotidal (4-5m), semi-diurnal tides characterise the area. The tidal currents rotate counter-clockwise, with maximum currents (1 m/s) observed generally during the flood, towards the NE (Van Cauwenberghe, Dekker, and Schuurman, 1993). Waves of 0.50–1m in height (period of 3.5 – 4.5s) are most common; waves of more than 3m originate from the W to WNW (Ministerie Van De Vlaamse Gemeenschap, 1993). Large to very-large dunes (*sensu* Ashley, 1990; with heights of respectively >0.75m and >5m) cover the sandbank extensively. The Kwinte Bank is characterized by fine to medium-sized sand. The grain-size coarsens from south to north; 180 to 240 µm is found over the southern part, whilst coarser sediment (of up to about 400 µm) characterises the middle and northern part (Verfaillie, Van Lancker, and Van Meirvenne, 2006). The specific morphological and sedimentological characteristics are discussed in Bellec *et al.* (this volume); the hydrodynamics are particularly dealt with in Garel (this volume) and Van den Eynde *et al.* (this volume).

METHODOLOGY

Monitoring of the Extraction Activities

The activities of the extraction vessels are monitored using two approaches: the registers; and, since 1996, an EMS system. For each trip, a register is completed and provides the general location (which sandbank) of the extraction, the date and the volume extracted. This volume is obtained by multiplying the weight of the aggregate load, by 1.55tonnes/m^3, the average density of compacted sand. Based upon these data, the extraction volumes for each ship and for each sandbank are calculated. In addition, the rate at which each ship dredges, together with the average dredging speed are obtained. Because of the absence of any detailed positions in the registers, only the overall quantities for the entire sandbanks can be evaluated. In contrast, the EMS records all relevant parameters (e.g. ship ID, trip number, date, time, GPS position), at an acquisition rate of 30sec, during the dredging operations. These data are collected, analysed and stored in a single GIS database. The average dredging speed of each vessel is multiplied by the frequency (number of 30sec records), to obtain the extracted volumes within specific time intervals and for delimited areas; these can be shown on maps and in data Tables, in a GIS.

Multibeam Echosounder

Within the framework of the MA extraction 'follow-up', the Fund for Sand Extraction acquired a Kongsberg Simrad EM1002 multibeam echosounder. This system is installed aboard *RV Belgica*. The system has 111 beams of 2° (athwart) x 3.3° (fore-aft) width, working at a nominal frequency of 95kHz, with a ping-rate of around 4 to 6Hz. The data are corrected in real-time, for roll and heave, using a Seatex MRU5 motion sensor and, for heading, using an Anschütz Standard 20 gyrocompas. A Sercel NR103 (from 1999 until January

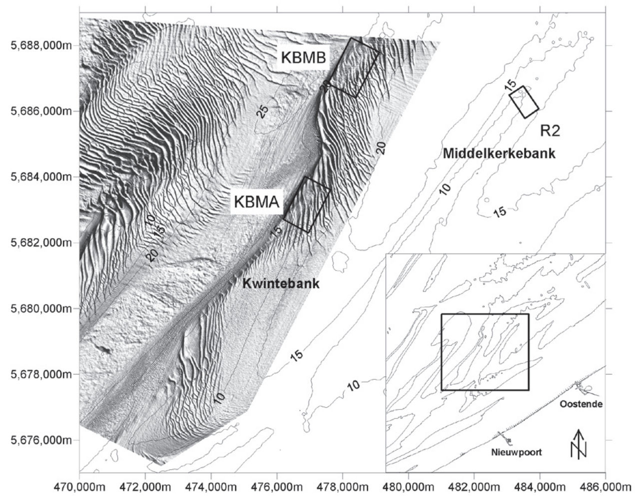

Figure 2. Location of the monitoring areas, KBMA, KBMB and R2.

2003) and a Thales Aquarius 02 (since January 2003) are used as GPS positioning systems; these have a theoretical precision of <5 m and 10mm, respectively. The datum used is WGS84.

The depth measurement accuracy of the EM1002 is up to 10cm RMS, or 0.2% of the depth (KONGSBERG SIMRAD, 1999-2001), in water depths of less than 30m. According to HAGA, PØHNER and NILSEN (2003), and HAMMERSTAD (2001), the EM1002 is compliant to the IHO S-44 standard.

The soundings have been tidally-corrected using the M2 tidal reduction method for the Belgian coastal zone (VAN CAUWENBERGHE, DEKKER, and SCHUURMAN, 1993). The water level is measured continuously at three reference stations (tide gauges) along the Belgian Coast. These values are used to calculate the water level, during the measurements. The depths are corrected during post-processing and referenced to the level of mean lowest low water, at spring tide (MLLWS). The swath width of a multibeam system allows 'full coverage' data to be obtained from the seafloor; from these, to construct highly accurate terrain models. A global bathymetric error (2σ) of 0.35% of the depth has been estimated, on the basis of the variance between bathymetrical digital terrain models of 4 successive surveys of the same area within a single tidal cycle (Fund for Sand Extraction, unpublished results). This global error on the final product, the terrain model, is the combination of the independent errors of the EM1002 multibeam echosounder, the auxiliary sensors, the draught and the tide correction.

The backscattered acoustic signal was processed using Poseidon (KONGSBERG SIMRAD, 1999-2001) for seabed image mosaicing. This involves merging of data from overlapping survey lines, applying systematic corrections which are required, filtering and interpolation. Poseidon normalises the backscatter using Lamberts Law. This is an optic approximation, and does therefore not take into account volume scattering or attenuation. Since multibeam echosounders receive most of the data in the domain where both volume and surface scattering contribute to the overall scattering strength; Lamberts Law can be used only as an approximation where scattering is caused by surface scatter (i.e. harder sediments) (HUGHES CLARKE, DANFORTH, and VALENTINE,1997). In order to eliminate the influence of bedform morphology, when comparing results from successive surveys, the mean backscatter strength over large areas is calculated. The resolution of the measured backscatter strength values, due to the variation in transducer sensitivities, is estimated to be typically ±1dB (HAMMERSTAD, 1994 and HAMMERSTAD, 2000).

Monitoring of the Bathymetry and Nature of the Seabed

Three small zones (total surface area around 1km^2) are surveyed several times a year: the central (KBMA) and northern

Table 1. *Overview of the surveys on the KBMA and R2 monitoring areas.*

Survey	Month Year	KBMA	R2	Month	Interval months
9925	November 1999	16/11/1999	18/11/1999	0	
0023	September 2000	28-29/09/2000	29/09/2000	10	10
0104	February 2001	21/02/2001	22/02/2001	15	5
0131	November 2001	27/11/2001	30/11/2001	24	9
0203	February 2002	12-13/02/2002	13/02/2003	27	3
0219	September 2002	04-05/09/2002	06/09/2002	34	7
0229	December 2002	12/12/2002	12/12/2002	37	3
0306	March 2003	03-04/03/2003	04/03/2003	40	3
0315	June 2003	10-11/06/2003	11/06/2003	43	3
0324	October 2003	01-02/10/2003	02-03/10/2003	47	4
0406	March 2004	18-19/03/2004	19-22/03/2004	52	5
0415	July 2004	09/07/2004	08-09/07/2004	56	4
0420	September 2004	15-16/09/2004	16-17/09/2004	58	2
0423	October 2004	12/10/2004		59	1
0429	December 2004	07/12/2004	07/12/2004	61	2
0504	March 2005	08-09/03/2005	09/03/2005	64	3
0514	June 2005	15-16/06/2005	14-15/06/2005	67	3

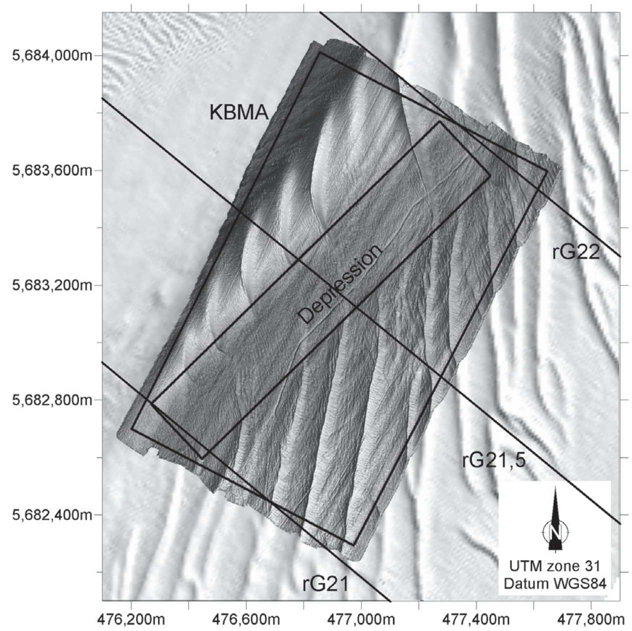

Figure 3. Detail of the monitoring area KBMA, with delineation of the central depression and the location of the single-beam tracks (rG21, rG21.5 and rG22).

parts (KBMB) of the Kwinte Bank; and a reference area, outside the extraction zone (Figure 2.). The latter area, defined as R2 (Flemish Authorities, Maritime Services, Van Cauwenberghe, 1996), is situated on the northern part of the Middelkerke Bank; it is a sandbank with a similar morphology as the Kwinte Bank. This particular sandbank is not exploited, permitting the study of the bathy-geomorphological evolution of a relatively natural environment. In this paper, only results from the KBMA and the R2 monitoring zones will be presented.

From November 1999 until June 2005, a total of 17 multibeam surveys were carried out on the KBMA monitoring area and 15 surveys on the R2 monitoring area (Table 1). Both areas were surveyed within the same week. The application of a standardised operating and processing procedure, for all surveys, allows comparison of the bathymetrical and backscatter strength models.

For each survey, a high resolution DTM of 1x1m is computed, using an inverse distance interpolation algorithm. Comparison of the successive DTM's permits the evaluation of the mobility of the morphological structures and the bathymetrical evolution. From comparison of some cross-sections from each DTM, the shifts from large to very-large dunes can be quantified. Histograms and statistical analyses undertaken of the depth values, of each DTM, provide additional information on the bathymetrical evolution. Similarly, the mapping and the statistical analysis of backscatter strength, recorded during successive surveys, are used to evaluate any changes in the sedimentary nature of the seabed. Based upon the morphology of the monitoring area KBMA, a distinction was made within KBMA, between the depression *sensu stricto* and the remainder of the zone (Figure 3.).

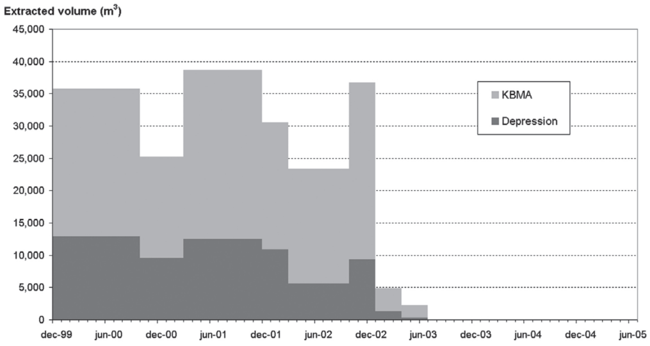

Figure 4. Extracted sediment volume inside the KBMA monitoring area and in the depression. In February 2003, the depression was closed for extraction; any values after this date are due to the infringements of some vessels.

Until 1999, the morphology and topography of the sandbanks were monitored using a single-beam echosounder, along track lines perpendicular to the bank (Figure 3.). At that time, the evaluation of the bathymetrical changes was restricted to individual profiles and was limited by the need of accurate navigation, to permit comparison between successive recordings. Such profiles were surveyed up to 4 times a year and their evolution was studied by calculating and comparing the sandbank volume, beneath each profile (De Moor, 1985; De Moor*et al.*, 1994; and Vernemmen and Degrendele, 2002). Since 1992, the profiles were recorded digitally and corrected in real-time for the heave of the ship, with a depth accuracy of 12cm (Vandewiele, 2000; and Hartsuiker, 1992 *In*: Vernemmen and Degrendele, 2002). The accuracy of the position fixing was comparable to the present GPS standards (Vanzieleghem, 1998 and Vernemmen and Degrendele, 2002). In the present study, the evolution of the bathymetry along a reference line, crossing the central depression (rG21, Figure 3.), is investigated for the period 1992-1998. For each of the profiles, the depth values are compared to the corresponding depths, extracted from the multibeam model of the Kwinte Bank. As the exact position of the soundings is respected, errors, based on the navigation deviation during the recordings, are eliminated.

RESULTS

Extraction Activity

Based upon EMS data from November 1999, an average MA extraction rate of 0.64m^3/m^2 (825.10^{3}m^3/1290.10^{3}m^2) can be calculated for the KBMA monitoring zone (Figure 4.). In the depression, this rate increases to 1.08m^3/m^2 (394.10^{3}m^3 (48 % of KBMA) for a surface area of only 366.10^{3}m^2 (i.e. 28 % of the total surface); for the remainder of KBMA, 0.47m^3/m^2 is derived.

Bathymetrical Evolution

Based upon the bathymetrical evolution in the depression (period 1992 until 1999), a gradual deepening is observed (Figure 5.). In 1992, the depression is barely visible and exists only as a trough between the larger bedforms. In 1995, the trough became broader and, by 1998, it evolved into a small depres-

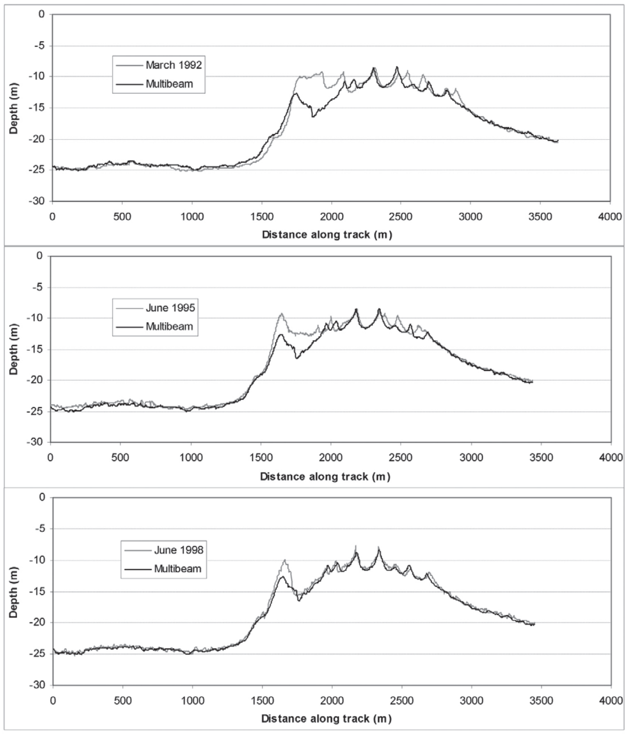

Figure 5. Comparison of single-beam profiles along reference line rG21 across the KBMA monitoring area against the multibeam data of December 1999 (depths referenced to MLLWS).

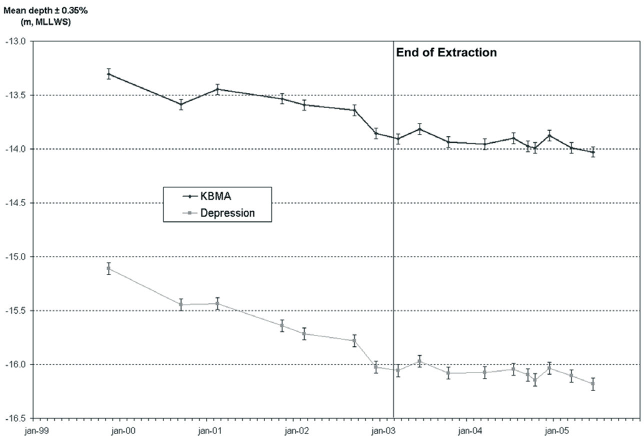

Figure 7. Evolution of the mean depth in the KBMA monitoring area and within its depression.

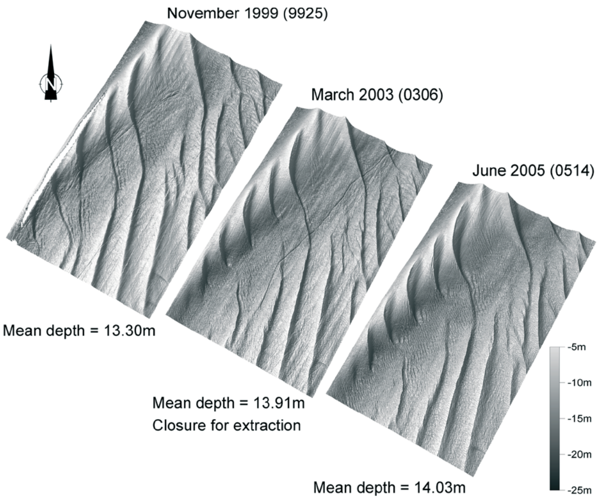

Figure 6. Successive terrain models of the KBMA monitoring area (depth in negative values and referenced to MLLWS). Notice the trailer-dredged furrow marks within the depression, in November 1999 and March 2003.

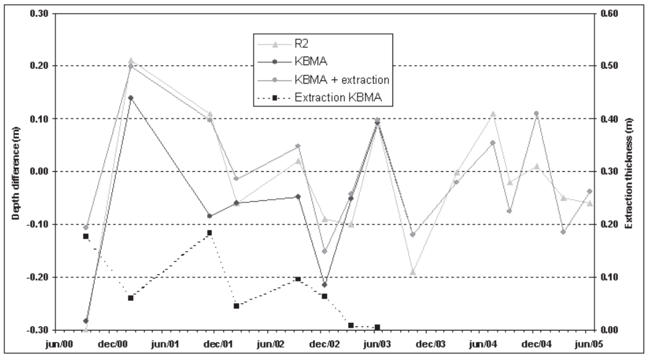

Figure 8. Depth evolution of the monitoring areas KBMA and R2, the evolution of the extracted thickness on KBMA and the depth evolution of KBMA, together with the extracted thickness.

sion. Only small changes, due probably to bedform movement, are observed outside this depression.

The bathymetrical evolution from 1999 until 2005 shows an overall deepening of the entire KBMA, with a depth increase of 0.5m between November 1999 and March 2003 (Figure 6.).

Figure 7 shows the overall increase in mean depth. After the closure of the site for further dredging, the mean depth variation becomes relatively stable. For the central depression, the deepening is more pronounced (0.9m), than for the KBMA monitoring area. The evolution of both the KBMA and R2 monitoring areas is shown in Figure 8 and listed in Table 2.

Similar trends are observed, but the erosion is higher for KBMA, at least until February 2003. After the cessation of dredging, there is still a deepening of the depression (0.12m from March 2003, until June 2005); in the same period, a similar deepening is observed over the R2 (0.11m) and KBMB monitoring areas (0.10m) (for locations, see Figure 2.). The dredged volumes in KBMA can be converted into a dredged volume per surface unit, or thickness of the extracted volume (Table 2.). Adding these values to the depth differences, provides the evolution of KBMA, without the extracted quantities. Compared

Table 2. *Bathymetric and extraction evolution over the KBMA and R2 monitoring areas. Depths given relate to MLLWS.*

SURVEY ID	KBMA					R2	
	mean depth (m)	**depth difference (m)**	**extracted volume (m³)**	**Thickness of extraction (m)**	**depth difference + thickness extraction (m)**	**mean depth (m)**	**depth difference (m)**
9925	-13.30					-10.88	
0023	-13.59	-0.28	228640	0.18	-0.11	-11.18	-0.30
0104	-13.45	0.14	78085	0.06	0.20	-10.97	0.21
0131	-13.53	-0.09	236126	0.18	0.10	-10.86	0.11
0203	-13.59	-0.06	59093	0.05	-0.01	-10.92	-0.06
0219	-13.64	-0.05	124389	0.10	0.05	-10.90	0.02
0229	-13.86	-0.22	82168	0.06	-0.15	-10.99	-0.09
0306	-13.91	-0.05	10533	0.01	-0.04	-11.09	-0.10
0315	-13.82	0.09	5838	0.00	0.10	-11.00	0.09
0324	-13.94	-0.12	0	0	-0.12	-11.19	-0.19
0406	-13.96	-0.02	0	0	-0.02	-11.19	0.00
0415	-13.90	0.05	0	0	0.05	-11.08	0.11
0420	-13.98	-0.08	0	0	-0.08	-11.10	-0.02
0429	-13.88	0.11	0	0	0.11	-11.09	0.01
0504	-13.99	-0.11	0	0	-0.11	-11.14	-0.05
0514	-14.03	-0.04	0	0	-0.04	-11.20	-0.06

to the "natural" evolution of R2, the differences, observed before February 2003, are now reduced (Table 2. and Figure 8.).

The linear correlation coefficient between the 'corrected' KBMA and R2 values (Figure 9.) is highly significant (R=0.83). Hence, by correcting the bathymetric evolution, with the extracted sediment volume, a close to natural evolution is obtained. This result, together with the limited decrease in depth, since the closure, suggests that the extraction is the main cause of the deepening of the depression. Also, the time-series do not indicate a further cumulative effect on the bathymetry, after the closure of the depression.

The difference in evolution inside KBMA was studied in more detail: clearly, more erosion is observed within the depression, than outside of it (Figure 10.). After correction of the extracted sediment volumes inside both areas, the depth differences became (once again) very similar. Apparently, the higher extraction in the depression has had no additional effect on the surrounding area, where the extraction is less important. This observation suggests a rather localised impact of the extraction activities.

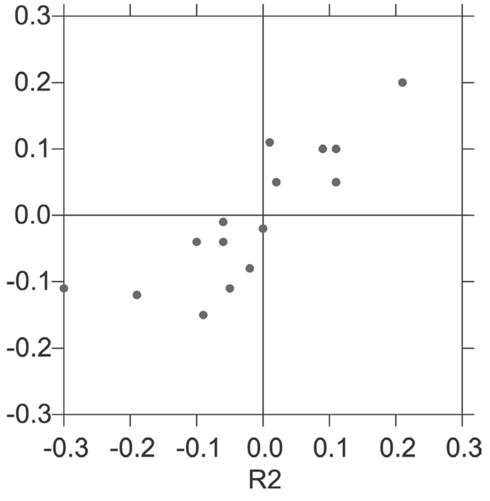

Figure 9. Scatter plot of the depth difference between successive surveys of the monitoring areas KBMA (corrected for extracted volume) and R2. The linear correlation coefficient (r) =0.83 is highly significant.

Morphological Evolution

The heights of the large to very-large dunes are consistently smaller in the depression; they decreased slowly whilst extraction took place (Cross-Section 2, Figure 11.). Within the depression, the dunes are clearly asymmetric towards the NE and have a migration rate of 20m/year. To the west of the depression, the dunes move in the same direction, at a rate of 10m/year; to the east of the depression, the dunes become more symmetrical and the migration rate reduces to 5m/year (Cross-Sections 1 and 3, Figure 11.). In the depression, medium dunes are observed as being abundant; together with the higher migration rate of the larger bedforms, this reflects the stronger dynamic character of the central part of KBMA, compared to the peripheral area. After the closure, the migration rate did not change, however, the slow decrease in the dune heights, in the depression ceased. Dredging furrows are observed, with their depths varying from 10 to 50cm (Figure 6.).

Evolution of the nature of the seabed

The nature of the seabed is derived indirectly from spatial variability in backscatter strength values. On this ba-

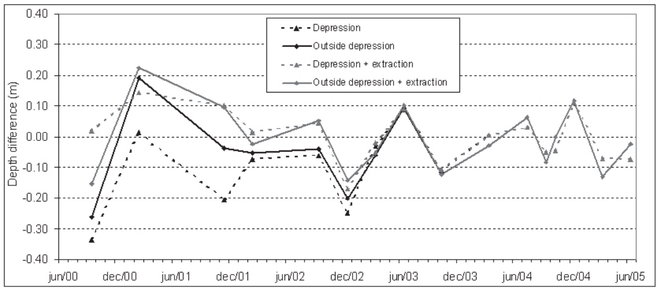

Figure 10. Depth evolution of the depression and its surroundings; the depth evolution plus the extracted thickness is indicated also.

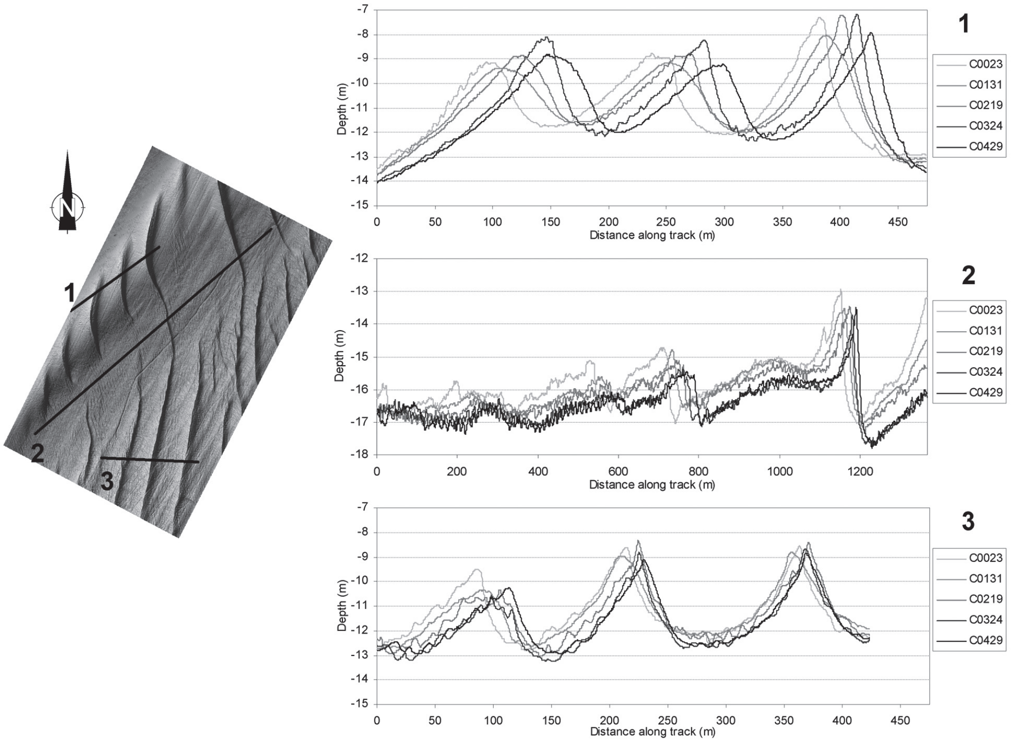

Figure 11. Evolution of bedform position across the KBMA monitoring area. Locations of Cross-Sections shown on the inset. The identification of the different surveys is given.

sis, the surficial sediments in the depression appear to differ clearly from those outside of the depression (Figure 12.). The central depression has a mean backscatter strength value of –24dB, which, compared to data presented in the literature, corresponds to medium- to coarse-grained sand (De Moustier, 2001). The mean backscatter strength values, along the eastern side of the KBMA area, extends up to –27dB, suggesting the dominance of very-fine sand. To the west, more intermediate backscatter strength values are observed; these correspond with medium to coarse sand, as validated by the grab samples obtained (see Bellec *et al.*, this volume). The backscatter strength values are fairly stable and do not show a clear evolution, before or after the cessation of dredging (Figure 13.). Similar results are obtained for the R2 monitoring area.

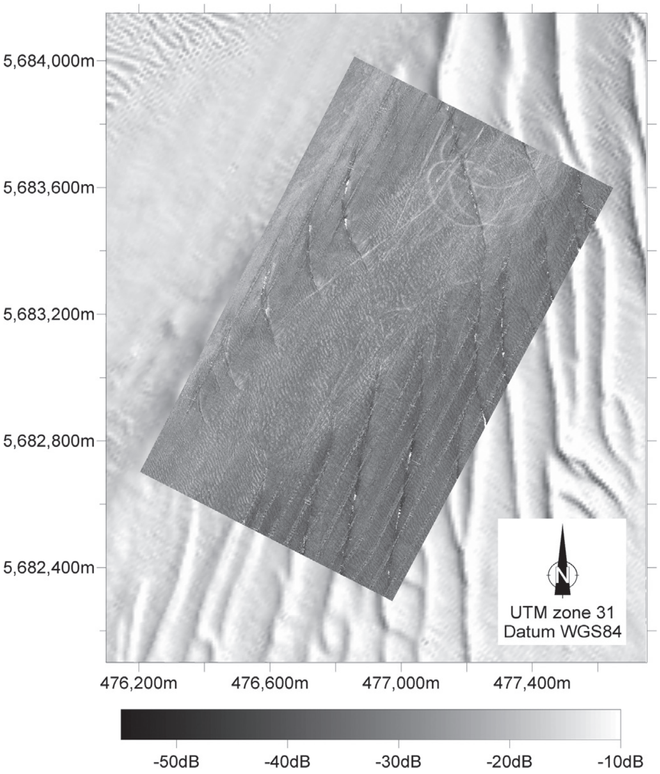

Figure 12. Backscatter strength image of the KBMA monitoring area (September 2002).

DISCUSSION

Local versus regional impact of MA extraction

The spatial relationship between the extraction intensity data and the depression, along the crest of the Kwinte Bank, suggests a local impact of the MA extraction. This conclusion is consistent with the findings of Brière *et al.*; Garel, and Van den Eynde *et al.* (this volume), based, respectively, on hydrodynamic measurements, numerical model output and stability analyses. In the short-term, these results show reveal erosional behaviour of the depression; in the long-term, regeneration of the sediment volumes is predicted. This interpretation contrasts to the findings of De Moor *et al.* (1994) and Norro *et al.* (2006), studying the sediment volume changes along fixed

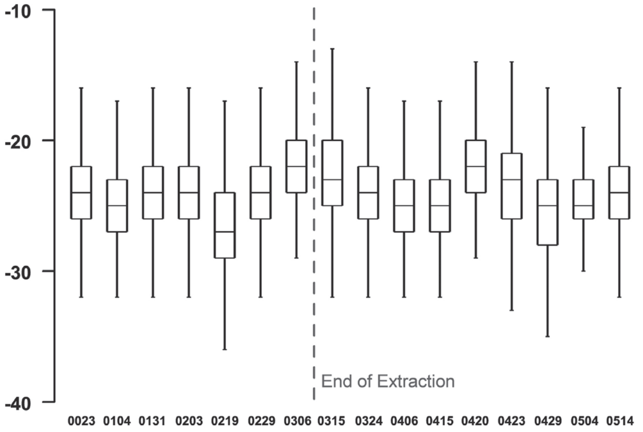

Figure 13. Box plot of the backscatter strength values derived from DTMs from successive surveys (x-axis, also Table 2.) undertaken on the KBMA monitoring area (the values are in dB; the central line is the median; the box represent the interquartile 25 % and 75 %; the 'whiskers' show the range of values, falling within the quartiles ± 1.5 interquartile; outside values are not represented).

tracklines covering entire sandbank areas (see Van Lancker *et al.* (this volume), for an overall discussion). On the basis of single-beam data obtained during the period 1987-2000, Norro *et al.* (2006) calculated, for the Kwinte Bank, a statistically significant, annual decline of +/- 1.5%, which questioned the long-term sustainability of the MA extraction. However, it must be highlighted that only limited knowledge is available on the natural evolution of the seabed, whilst the balance against the anthropogenically-induced dynamics is not clear – here and elsewhere. Furthermore, the EMS records obtained, within the KBMA monitoring area, represent only 18% of the total number of records on the Kwinte Bank obtained during the period November 1996 to March 2005; as such, only a limited part of the extraction activities are considered in this study. Future research should focus both upon a detailed, as well as on a regional, approach to clarify the real impact of MA extraction.

Natural Evolution

When the sediment volume variation is considered, without the extraction-induced changes, there is an overall similarity between the KBMA and R2 monitoring areas (i.e. a slight decrease of +/- $0.05m^3/m^2$/year). On the basis of this observation, a simple model for the sedimentary balance inside the KBMA area was suggested; with the total sediment volume variation being the sum of the natural component and the amount of sediments extracted. However, it might be questioned whether the R2 area, located on the Middelkerke Bank, is representative of 'natural' regional sedimentary conditions, unaffected by the nearby intensive extraction on the Kwinte Bank. Indeed, the volume differences per surface unit, for both the KBMA and R2 areas, fluctuate considerably during the extraction period: for both areas, the differences stabilise after cessation of the dredging. Likewise for the R2 area, the results show very high variability, of 0.3m/year, between the two first surveys (November 1999 and September 2000) (Table 2.). Analysis of coincident hydro-meteorological datasets could not explain this variance. This study has proposed an average sediment volume variation of $0.05m^3/m^2$/year; this would be the result of only naturally-driven processes. On the Belgian Continental Shelf, only limited studies are available to validate these findings: trend analyses undertaken are based upon the comparison of widely-spaced single-beam profiles, from which the results are difficult to compare to those based upon multibeam echosounder data, covering the full extent of an area. More detailed information is available (e.g. Houthuys, Trentesaux, and De Wolf , 1994), but the temporal spread of the surveys is much too broad (once or twice a year), inhibiting the study of the natural evolution of a sandbank area. However, closer to the coast, a small sandbank area has been monitored intensively (Van Lancker, 1999). From 12 DTM's, based upon closely-spaced single-beam measurements (1996-1998), a mean sediment volume variation of $0.05m^3/m^2$ was deduced, with a maximum of +/- $0.1m^3/m^2$. These values are comparable to the evolution observed on the R2 monitoring area located on the northern part of the Middelkerke Bank. In the same investigation, sediment volume changes were studied over the southern part of the Middelkerke Bank; these were subtle and varied around zero. Vincent, Stolk, and Porter (1998) have shown previously a difference in sediment transport along the southern and central part of the NW flank of the Middelkerke Bank. Over a 49-day period, the sediment flux was different over both areas, with values of 0.05 and 0.9tonnes/m/day (at 0-0.3m above the bed), respectively. Similarly, the analyses of De Moor *et al.* (1994) have identified a higher sediment flux, to the north of the Flemish Banks.

Morphological Changes

Based upon successive DTM's (Figure 6.), cross-lines (Figure 11.) and backscatter strength images (Figure 12.), the evolution of dunes and dredging furrows was investigated. The data show the impact of the extraction activities, on the height of the large dunes inside the depression; outside of it, the height differences are much less. Following cessation of the dredging, the decrease in dune height ceased: two years afterwards, the height of these dunes was stable and no trend of restoration of the dune height, in the depression, was observed. The migration rate of the dunes in the KBMA and R2 areas agree well with values reported previously for the Kwinte Bank and the Middelkerke Bank; in the short- to medium-term, this is dependent upon the dominant tidal currents and meteorological events (e.g. Degrendele, Roche, and Schotte , 2004; Houthuys, Trentesaux, and De Wolf, 1994; Lanckneus and De Moor, 1994;, andLanckneus *et al.,* 1992, 2001). However, the higher migration rates of the dunes in the central depression is related to the higher current speeds in the depression, due to canalisation of the flood flow (Garel, this volume).

The longevity of trailer dredging marks in the medium sands on the Kwinte Bank has been studied. The furrows on the borders of the central and northern depressions, on the Kwinte Bank, remain visible for a maximum of 6 months; this is based upon the results of the bathymetric models and on the backscatter strength images. Within the central depression, the MA extraction is too intense to deduce any life span of the furrows. A reduced ship speed during the MA extraction explains, probably, the large variability in the depth of the furrows (10 to 50cm). The infill of the furrows could result from local sedimentation, combined with (or activated by) the MA extraction itself. However, the time-scales of regeneration of the dredge furrows will vary according to substrate, water depth, currents and wave climate. Hitchcock, Newell, and Seiderer (1998) reported on the disappearance of the dredged furrows on sandbanks, over 2-3 tidal cycles whereas, in areas with low sediment mobility, dredge furrows may be visible for up to a decade. In the fine to medium sands of the Graal-Müritz area in the Baltic Sea, similar furrows, in 8-10m water depths, refilled rapidly within months (Manso *et al.*, this volume).

Sedimentary Stability

Despite short-term hydrodynamic measurements, indicating erosional behaviour in the depression (Garel, this volume), evolution of the backscatter strength did not show a significant change in the inferred nature of the seabed, before or after the cessation of dredging. Similar conclusions were reached, based upon 4 successive and detailed sediment sampling campaigns, inside and outside of the depression (Vanaverbeke *et al.,* 2007). Even on a longer time-scale, several authors have confirmed the general stability of the sediment characteristics over the Kwinte Bank (De Moor *et al.*, 1994; and Vernemmen and Degrendele, 2002).

CONCLUSIONS

The bathymetrical, morphological and sedimentological impact of marine aggregate extraction on a tidal sandbank has been evaluated, based upon the results of an intensive and detailed monitoring programme. Over the period 1976 to 1999, the monitoring was based upon a follow-up of single-beam profiles, that were widely-spaced. Afterwards, multibeam technology permitted highly accurate digital terrain models to be obtained, of both bathymetry and backscatter strength values. Results from successive surveys, over exploited and non-exploited sandbanks, were evaluated against extraction statistics, derived from ship registers and EMS data.

Over the period 1992-1999, MA extraction on the Kwinte Bank has changed significantly the shape of the sandbank, with the creation of a local depression of 5m. The creation of this depression has led to the closure of the extraction site, permitting the study of the potential regeneration of the morphology and the nature of the seabed. Considering the period from 1999, up to the closure of the site in 2003 (i.e. 4 years), an overall deepening of 0.5m could be observed. The results show that two years after the closure, the site has not undergone sedimentation, nor has there been a significant change in nature of the sediment. The morphological changes, identified during the extraction, ceased, but no significant regeneration took place after cessation of the dredging. If the sediment volume variation, during extraction, is compensated for the amount of extracted sediments, the resulting variation is similar to the natural evolution of a non-exploited sandbank; this would imply that MA extraction has only a local impact.

At present, a new depression is being observed over the northern part of the sandbank, where the MA extraction is still highly concentrated. The monitoring of this new depression, together with the central depression, remain important; this will provide further knowledge on the impact of MA extraction on tidal sandbanks.

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