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A bi-dimensional approach to assessing the volumetric evolution of an exploited sandbank

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We analyse the multi-annual evolution of bathymetry along several cross-sections of the Kwintebank (one of the Flemish Banks). An important issue in the area is the intensive exploitation under regulations imposed by the Belgian authorities that aim to guarantee sustainability of extractions. All bathymetric data collected during the period 1987–2000 at a frequency of approximately four surveys per year are analysed, to identify volumetric temporal trends. The errors inherent in the measurements taken with a single-beam instrument are examined. The lack of indisputable quality criteria led to the choice of robust statistical methods. A statistically significant annual decline of approximately 1.5% in bank volume is shown. Another practical conclusion is that a big increase in sampling frequency is necessary if the authorities set a criterion regarding the long-term sustainability of the bank and wish to have a swift guarantee that this criterion is being observed.

Keywords: aggregate extraction, bathymetry, exploited sandbank, sampling strategy, southern North Sea.

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Introduction

The demand for marine sand in Europe is increasing. In the marine waters under Belgian jurisdiction, exploitation more than tripled over the past 20 years, reaching annual exploitation levels of approximately 1.8 million m^3 from 2000 (SPF Economie, 2005). Operations are concentrated largely on the Kwintebank, owing to the good quality of its sand and its proximity to the coast (10 nautical miles from the port of Oostende). The Kwintebank is part of the Flemish Banks, which lie more or less parallel to the Belgian coast (Figure 1).

Although studies have been carried out to assess the ecological impact of the extraction of sand (Lauwaert, 1993; Spirlet, 2002), there is still need to estimate whether or not the extraction significantly alters the morphology and hydrodynamics of the area. In the present study, the focus is on the volumetric evolution of the Kwintebank.

In the early 1980s, monitoring of the bathymetry of the Kwintebank by the authorities in charge of managing marine sand operations was commenced, on board the oceanographic vessel RV "Belgica". The results of this monitoring, which became reliable from 1988 onwards, have been published by De Moor and Lanckneus (1991, 1994), Vernemmen (2001), and De Moor (2002). Monitoring consisted of bathymetric measurements using a single-beam sonar along linear transects perpendicular to the main bank axis (Figure 1). The measurements were taken at least four times a year until 1999, when a multi-beam sonar survey began.

In this paper we consider the complete data set for the years 1987–2000. After a discussion of the errors in such bathymetric measurements, the volume of sandbank sections is computed, and time-series of these volumes are analysed for trend detection. The efficiency of the sampling strategy for management purposes is discussed, and conclusions are drawn.

Methods

All bathymetric data were reduced to the same reference surface of Mean Low Low Water Spring (MLLWS). In order to calculate volumes of bank sections, a basal reference elevation is needed (Figure 2). For this study, an elevation

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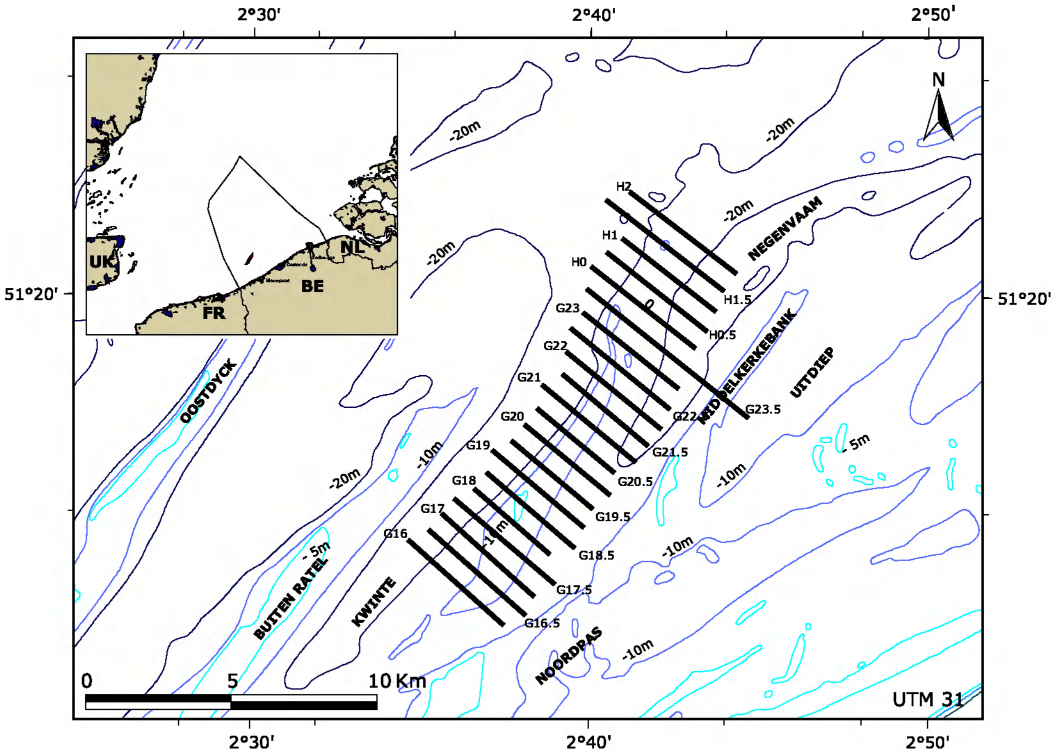

Figure 1. Locality of the Kwintebank. Monitoring transects are shown as bold lines across the bank.

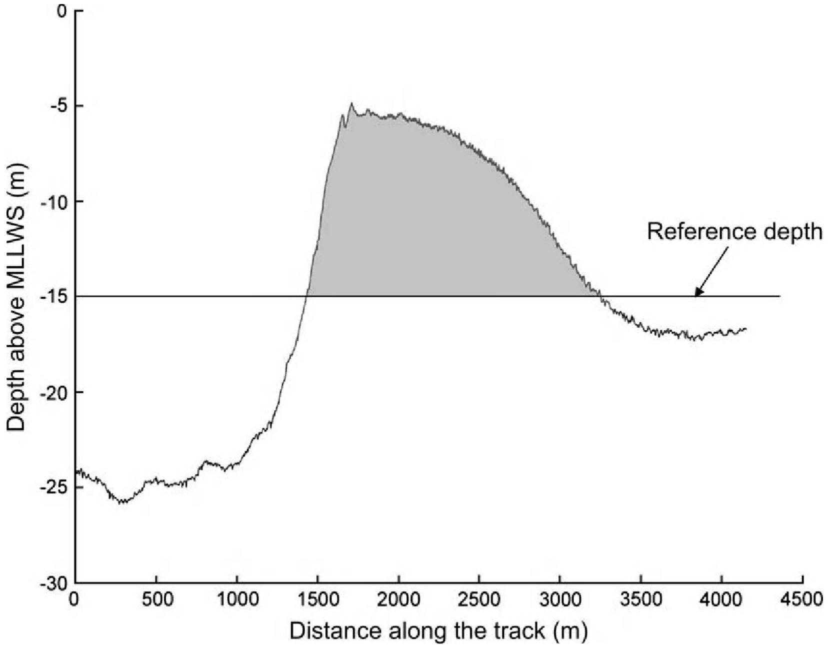

Figure 2. Definition of the section volume used herein. The grey zone indicates the area of cross-section used above the basal reference elevation. Assuming a thickness of that section of 1 m, the volume is then expressed in $m^3 m^{-1}$.

of −15 m is used to allow clear distinction between the sandbank and the surrounding area, as well as to preclude there being any localized effect.

The 895 profiles measured on the Kwintebank in the period 1987–2000 (Table 1) were collected, checked, and saved on a structured basis, for subsequent use. The data set is described in Table 1. Certain profiles only existed on paper and had to be digitized. When the profiles existed in both digital and analogue forms, preference was given to digital profiles. Survey profiles included errors relating primarily to the accuracy of navigation and the quality of the tidal correction. Information on the accuracy of navigation is only available for the digital profiles. Only rarely do the hydro-meteorological conditions allow the survey vessel to follow the theoretical line according to the nominal precision of the positioning systems on a permanent basis.

Figure 3 shows the distance from the theoretical line along transect G19 of the 27 digital profiles, and Figure 4 depicts the 57 profiles used in the study for the same reference line. Departures from the theoretical line (Figure 3) obviously have an impact on the measured profile and therefore on the section volume of the bank calculated. However, along the southwestern bank, the alongbank slopes are small. Differences between profiles (Figure 4) are more than likely attributable to the quality of vertical alignment (i.e. the tidal reduction). This is perhaps less evident in the northeastern part of the bank, where there are large sand dunes. In order to assess the impact of navigation errors on the computed volumes, we decided for each transect to investigate the values of the volume impact index $|V_k(t) - \overline{V}_k|/\sigma_k$ (where k refers to the transect number, and $\overline{V}_k$ and σ_k are the mean and standard deviation values, respectively, of the time-series of digital profiles available for that transect) as a function of the accuracy of navigation, defined by the mean value of the absolute value of the distance with respect to the theoretical line. Results are presented on Figure 5. Clearly, almost everywhere along the bank, most of the variability observed in the computed volumes cannot be ascribed to navigational error. For morphodynamic studies, De Moor (2002) doubted the reliability of profiles that deviate by more than 20 m from the reference line. The results presented on Figure 5 indicate that the application of such a strict criterion, that would have required elimination of three-quarters of the digital profiles along transect G19, is not really justified within the framework of the present study. For the sake of completeness, the penultimate column in Table 1 indicates the number of profiles with navigational error >50 m, and the last column of the same Table gives the number of profiles for which the calculated volume is outside the range defined by the mean ±(3 × the standard deviation of the time-series of volumes available for the transect in

Table 1. Summary of the available data.

Transect	First year of measurement	Number of analogue profiles	Number of digital profiles	Number of profiles used, excluding analogue profiles for which there is a digital duplicate	Number of profiles potentially doubtful owing to the navigational quality criterion	Number of profiles potentially doubtful owing to the quality of vertical realignment
G16	1988	33	26	46	11	0
G16.5	1992	10	12	16	5	0
G17	1988	34	26	47	10	1
G17.5	1990	14	14	25	5	1
G18	1988	39	27	52	11	1
G18.5	1990	12	13	22	5	1
G19	1987	44	27	57	10	1
G19.5	1990	12	15	25	8	0
G20	1988	43	27	59	9	0
G20.5	1990	13	14	22	5	1
G21	1988	26	25	49	9	0
G21.5	1989	16	13	26	6	0
G22	1988	42	28	58	8	1
G22.5	1989	16	14	27	4	0
G23	1992	0	27	26	14	0
H00	1988	50	30	63	12	1
H00.5	1989	15	16	26	6	0
H01	1988	47	28	62	14	2
H02	1990	20	27	26	1	1
Total		486	409	734	153	11

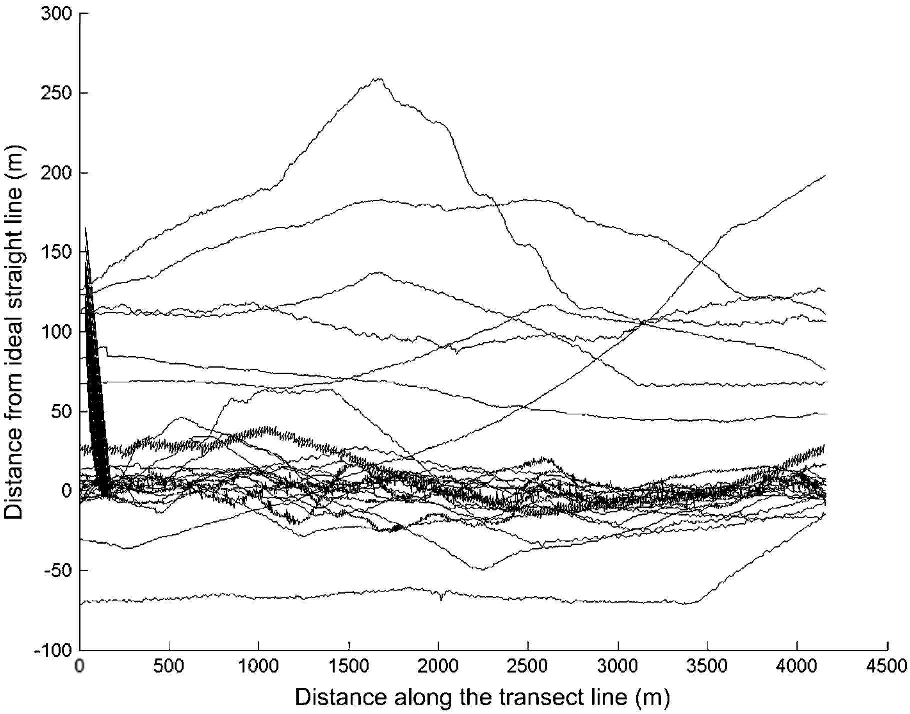

Figure 3. Distance from the ideal straight line of the 27 digital profiles available for transect G19 over the Kwintebank during the period 1987–1999.

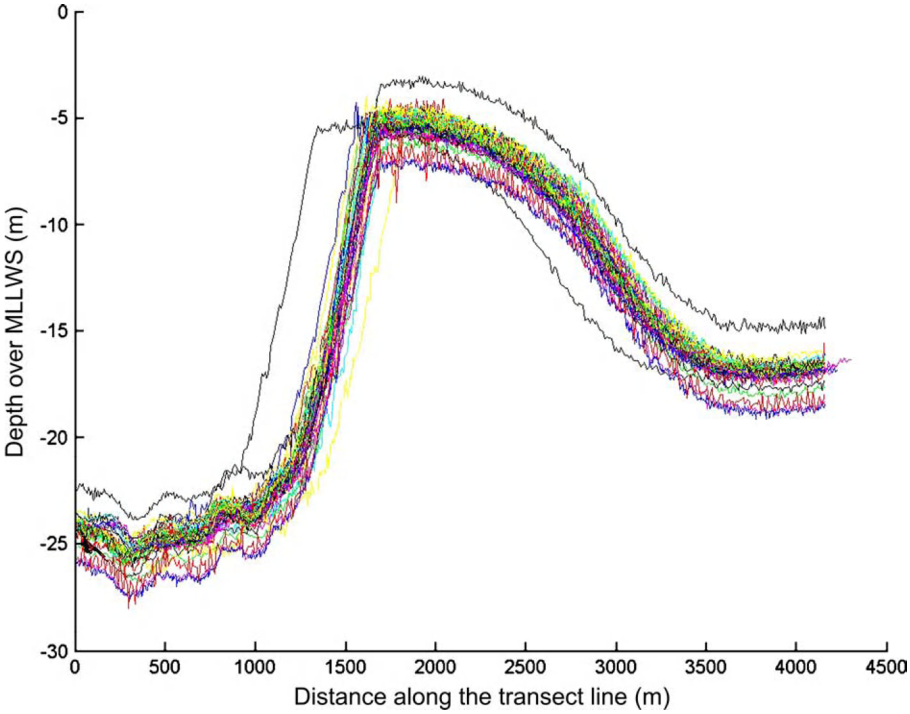

Figure 4. The 57 profiles available for transect G19 on the Kwintebank.

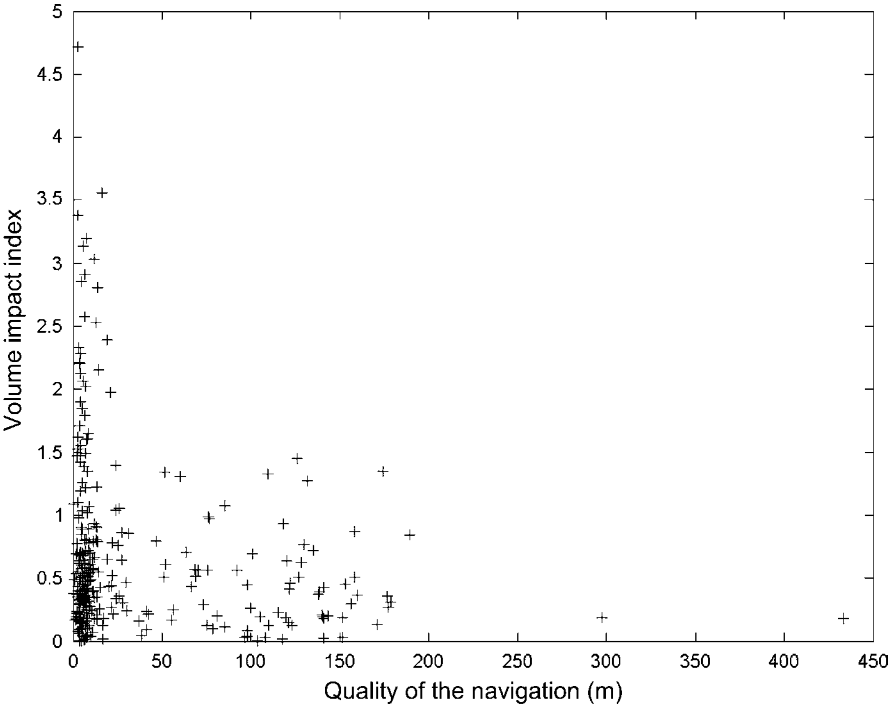

Figure 5. The impact of navigational error on computed volume for all digital profiles available for the Kwintebank (for details, see text).

question). Navigational error influences 21% of the available information, and just 1.5% of the computed volumes are outside the range.

For the purpose of this study, therefore, it was decided to use all the information available, and consequently to opt in favour of sufficiently robust statistical methods to identify temporal trends.

Error analysis

The errors relating to the various components of bathymetric measurement mentioned by the suppliers of the instruments and the designers of the methods, commented upon in the literature (e.g. Vande Wiele, 2000) or estimated by users, have been examined. Typical error values for a sounding in a water depth of 20 m are listed in Table 2. For such error values, their causes are independent, so the total error is the square root of the sum of the square of the individual errors. The total error is compatible with order 1 of the standards defined in Publication S-44 of the International Hydrography Organization (IHO, 1998).

As is the case for most long time-series of measurements, the instruments and methods have evolved and improved over time. Here, for instance, installation of a heave compensator and sophistication of the tidal reduction method introduced significant improvement in precision after 1993. However, it still remains an open question whether

Table 2. Estimated errors in the bathymetric measurements made by RV "Belgica" (confidence interval 95%). The values refer to a depth of 20 m and slopes of 3°. Static draught is the distance between the transducer of the echosounder and the water surface, and is measured at the start and end of the cruise; it changes with the load of the vessel.

Source of error	Error to 1993 (cm)	Error from 1993 (cm)
Error in recording		
Echosounder	±4.0	±4.0
Speed of sound	±2.5	±2.5
Heave	±10.0	±2.5
Presence of slopes	−3.0	−3.0
Subtotal	+10.0/−13.0	+4.0/−7.0
Error in reduction procedures		
Tidal reduction	±32.0	±13
Static draught	±5.0	±5.0
Variation in static draught	±5.0	±5.0
Subtotal	±33.0	±15.0
Navigational error		
Navigational error	±8.5	±8.5
Total error	+34.0/−37.0	+16.4/−19.4

changes in instrumentation or methods have produced changes in the trend of the measurement results.

The precision of the Atlas Deso 20 echosounder, operating at a frequency of 210 kHz, amounts to ±(1.5 + 0.12% of the water depth) cm, and that of the TSS 320B heave compensator connected to the ship's echosounder is equal to ±5 cm, or 5% of the range (according to the manufacturers; Vande Wiele, 2000). If three consecutive measurements sampled at 2 Hz relate to the same seabed point, computing the difference in depth at the central point according to

$$\Delta h(t) = h(t) - 0.5(h(t+\Delta t) + h(t-\Delta t)), \qquad (1)$$

where h(t) is the sounding corrected for heave, then this may be a way to assess the impact of all short-term errors (e.g. related to echosounder, heave compensation, and roll and pitch). Calculation of Δh has been done for depth readings taken during the cruises from 1993 to 1998 (in all, 608 172 readings). If we denote δh as the random error affecting each depth reading, then

$$\sigma_{\Delta h} = \sqrt{\frac{3}{2}}\sigma_{\delta h}.$$

Figure 6 shows values of $2\sigma_{\delta h}$ as a function of h.

Fitting a straight line through the data points allowed us to retrieve the 0.12% slope provided by the manufacturer of the echosounder. However, the background error was more than double that indicated in Table 2. This variance can probably be explained by the fact that Equation (1) could incorporate other effects of pitch and roll and, more generally, the condition of the sea. This assumption seems to be confirmed by the variability observed when the error is calculated cruise by cruise.

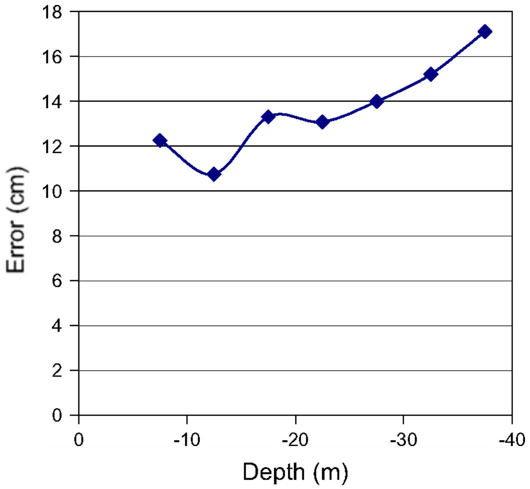

Figure 6. The error attributable to the echosounder and the swell by depth.

Given the acoustic beam width of the echosounder, the presence of slopes introduces errors in the sounding. In a water depth of 20 m, and assuming a slope of the order of 3° (typical for the steep western slope of the Kwintebank), the order of magnitude is −3 cm. It should be borne in mind that Syledis or DGPS horizontal positioning systems have a precision of the order of ±5 m. These slopes affect the bathymetric measurements with an error of ±8.5 cm, attributable to uncertainty in knowledge of the real position.

Tidal reduction of the bathymetric measurements uses the Van Cauwenberghe method (Van Cauwenberghe, 1977, 1992; Van Cauwenberghe and Denduyver, 1993; Van Cauwenberghe *et al.*, 1993). Water elevation at sea is extrapolated from the value measured at a reference station along the coast. For the Kwintebank, the reference station is Nieuwpoort. The tidal reduction error can be calculated by comparing the elevation obtained from the method with that at a point where it is measured. The exercise has been carried out at the station Westhinder for the period April–September 2004, using either tidal predictions (no wind effect) or *in situ* data. Results are presented on Figure 7. The maximum error attributable to tidal reduction is comparable with that indicated in Table 1, and there are no significant differences between situations with and without wind. The most important point, however, is that error varies during the tidal cycle, and is just ±8 cm during the 4 h following high tide, when surveying is best performed.

Applying the hypothesis that the shape of the bank is stable through time, it is possible to translate the profiles vertically and horizontally to minimize their variances. Figure 8 shows the results for transect G19, taking the first profile as reference. A statistically significant trend is present in the time-series of the vertical translations, indicating that these translations could contain more than just error. Nonetheless, the method could prove useful in ensuring an objective analysis of data quality.

Discussion of the error is not academic, because the error (with the sampling frequency and the length of the series of measurements) is an important parameter in the statistically valid evaluation of the temporal evolution of sandbank volume. This evolution can be expressed as an annual percentage by standardizing the regression slope obtained from the observations available for a given period with respect to the average volume calculated for the same period. If the authority sets a criterion such as that exploitation is acceptable provided it does not entail an annual decline in the volume of the bank in excess of, for example, −2.5%, the issue arises of verification (with a degree of confidence of 95%) of whether this criterion is or is not observed.

Figure 9 shows as an example the case of transect G19; its annual rate of decline is about −1%. During the first years of monitoring, and bearing in mind the errors prevalent prior to 1993 (Table 2), such a rate is subject to considerable uncertainty, and it was only after four years that statistical certainty was obtained that the criterion was

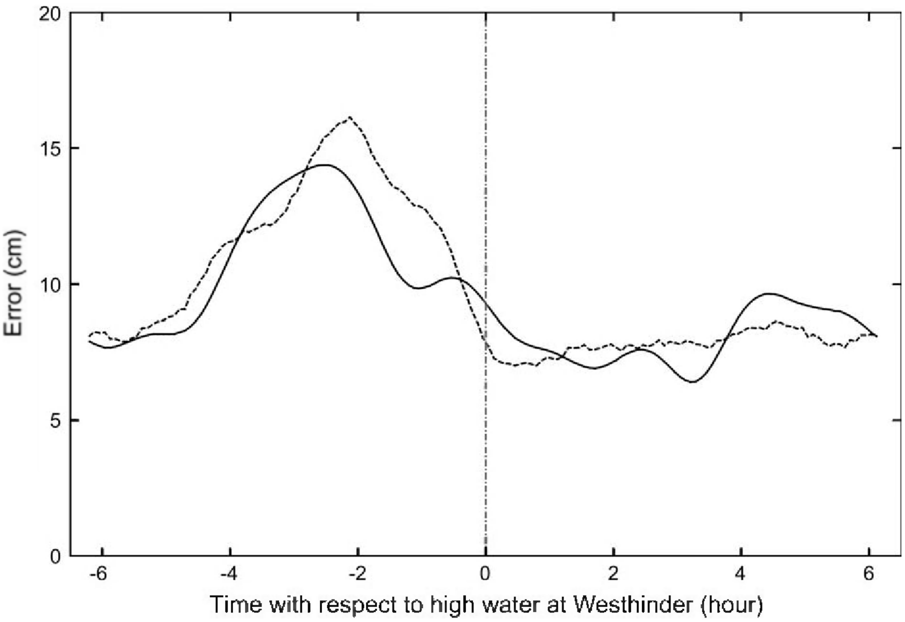

Figure 7. Time-series of the error during the lunar semi-diurnal tide attributable to tidal reduction at the Westhinder station when the Nieuwpoort station is used as reference station. The continuous line indicates the error when the elevation is due to the tide alone, and the dashed line the error for the actual elevation data.

actually being observed. Table 3 gives the time needed for the criterion to be verified for each transect. In most cases, the periods are long, and even unacceptable from the perspective of responsible management, but the decline in errors from 1993 onwards is, admittedly, likely to shorten them. However, as the possibilities for improving the precision of the measurements are limited, setting a period within which a guarantee is to be obtained that the criterion is or

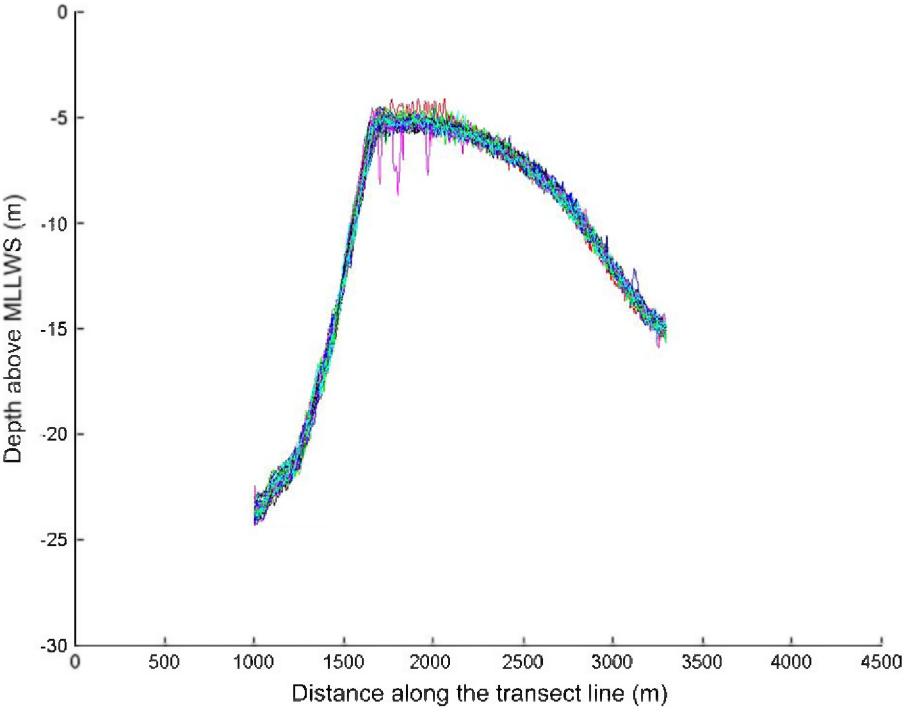

Figure 8. Results for the 57 profiles of transect G19, realigned against the first. Information on the method used for the realignment is given in text.

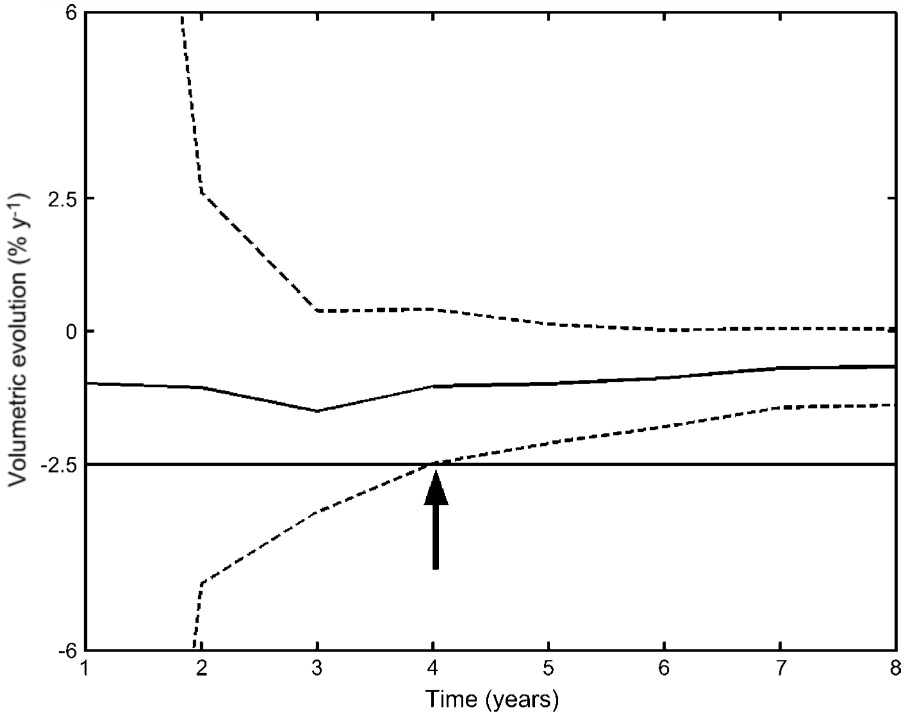

Figure 9. The rate of decline in transect G19 and the associated margins of error. The arrow indicates when criterion of −2.5% per year would be verifiable.

is not being observed comes down to establishing an appropriate sampling frequency, because the frequency of four times annually adopted here seems inadequate. It should be noted that use of the multi-beam sonar from 1999 provides an interesting spatial perspective of the bank, but one that is not in line with the need to intensify the temporal frequency of the monitoring.

A bi-dimensional approach to assessing volumetric changes

The 734 bathymetric profiles collected since 1988 (Table 1) can be used to assess the evolution over time of the volume of the Kwintebank, divided into 21 cross-sections (Figure 1). To obtain time-series that are as long as possible for each transect, one profile has been extracted, by interpolation, from the multi-beam data collected in 1999 and 2000 and processed by the Fund for Sand Extraction (Degrendele *et al.*, 2002).

The first method used to discern temporal trends is the parametric ordinary least-squares method (OLS). Although there are no general rules that define a value for the multiple determination coefficient (R^2) to guarantee significance of the regression, this method does assume a normal distribution of residuals (the observation variances compared with the regression slope). However, in this specific case, several observations differ from normality, and there are no grounds for ignoring them *a priori* without indisputable justification.

It is therefore advisable to consider such non-parametric methods as robust regression analyses, e.g. the Mann–Kendall (MK) rank-based method (Helsel and Hirsh, 1991), or the robust least absolute residuals regression

Table 3. The time needed to verify that the criterion of −2.5% per year is or is not being observed. There are no data for H01.

Transect	Years
G17	8.5
G17.5	4.8
G18	9
G18.5	3.8
G19	4
G19.5	6.8
G20	2.7
G20.5	2.6
G21	2.3
G21.5	4.2
G22	1.8
G22.5	4.5
H00	5.3
H00.5	5.5
H01	
H02	5.7

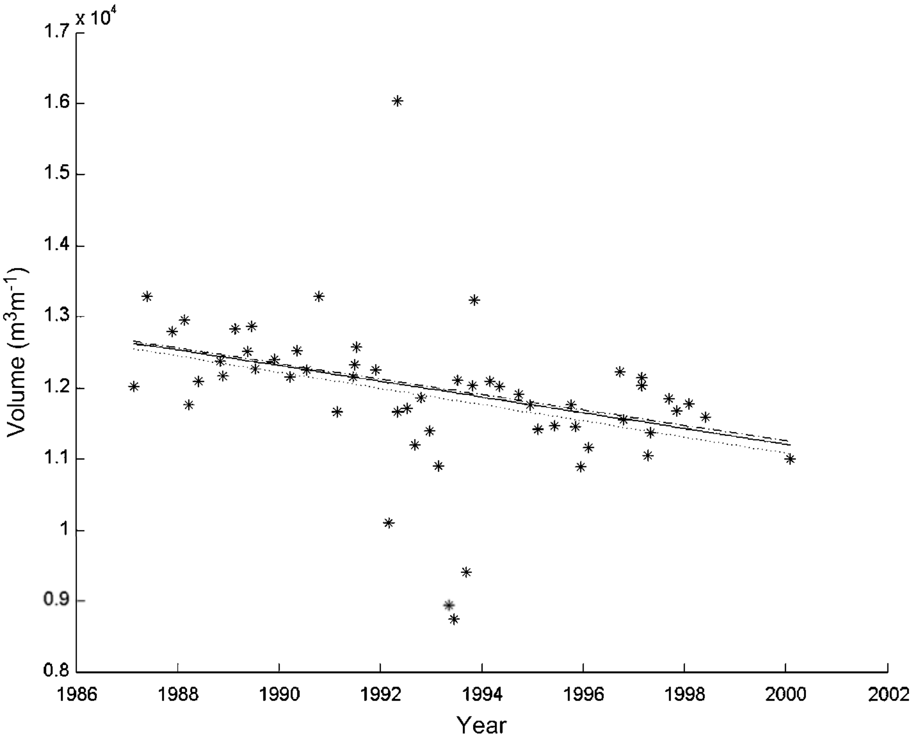

Figure 10. The trend of volumetric evolution of transect G19 obtained by the three methods proposed: ordinary least-squares methods (OLS), robust least absolute residuals regression (ROB—LAR), and the Mann—Kendall rank-based method (MK). Details of the methods are given in text.

(ROB—LAR) method (Kleinbaum *et al.*, 1987). These methods minimize the absolute difference in residuals, reduce the impact of outliers on the regression, and do not require that the residuals follow a normal distribution.

In order to illustrate the proposed methods, Figure 10 presents the results of three regressions obtained for reference line G19, and Table 4 lists the details of the same regressions. The slopes (ρ) provided by the different methods are close, but not identical, and the statistical significance of the slope is derived for the two non-parametric methods. The ROB—LAR regression provides a higher R^2.

Owing to the simplicity and the efficiency of the Mann—Kendal method, however, the time-series for all transects were analysed using that method. The results are given in Table 5. They show that, in all cases where the trends are statistically significant, the volume of the bank declined. Volume loss is highest for transects G20.5, G21, and G21.5, the main locations of sand-extraction operations (Degrendele *et al.*, 2002).

Table 4. Characteristics of the regression methods applied to transect G19. R^2 is the multiple determination coefficient, ρ the regression slope in m^3 per m and per year, and α is the associated significance parameter, where α must be <0.05 for the regression to be significant with a degree of confidence of 95%.

Methods	R^2	ρ	$\alpha(\rho)$
OLS	0.12	−114.3	—
MK	0.14	−109	<0.001
ROB—LAR	0.73	−110.2	<0.001

The regressions are not significant ($\alpha > 0.05$) for the time-series for transects G16, G16.5, and G23. Using the RTrend method (Fryer and Nicholson, 1999) for transect G16, however, does indicate a significant declining trend of −3.8% per year. For G16.5, the same method produces a decline of less than −14.9%.

The average decline in volume across all transects is approximately 1.5% per year. De Moor (2002), working with data for the period 1988—1994, noticed a decline in the value of mean depth above different reference levels almost everywhere, but his results cannot be compared with those obtained within the framework of this study. The question, however, is whether the reason for the decline can be ascribed to extractions? The answer is very likely positive around transects G20.5, G21, and G21.5, because soundings and data on sand-extraction rates seem to support that conclusion (Degrendele *et al.*, 2002). Extraction in these areas is now prohibited. To investigate the prime question further, though, requires in-depth analysis of the bathymetric and sand-extraction data, something not

Table 5. Volumetric evolution of the Kwintebank over 21 cross-sections. In the right-hand column, the slope is expressed as an annual percentage of the average volume calculated with the available data. α is the strength of evidence or p-value, and ρ is the slope of the regression line (in $m^3\ m^{-1}\ y^{-1}$).

Transect	α	ρ	% y^{-1}
G16	0.25	−40.5	−0.4
G16.5	0.9	8.7	0.07
G17	0.004	−109.0	−0.7
G17.5	<0.001	−167.0	−1.1
G18	0.004	−109.1	−0.8
G18.5	<0.001	−113.5	−0.8
G19	<0.001	−109.1	−0.9
G19.5	<0.001	−165.1	−1.7
G20	<0.001	−131.9	−1.6
G20.5	<0.001	−221.4	−3.9
G21	<0.001	−241.9	−5.1
G21.5	<0.001	−215.2	−6.7
G22	<0.001	−71.1	−3.3
G22.5	<0.001	−44.0	−2.9
G23	0.83	25.7	1.3
H00	<0.001	−100.3	−10.3
H00.5	<0.001	−58.9	−11.4
H01	0.004	−11.4	−4.5
H02	0.003	−26.0	−13

attempted here. Nonetheless, over the period of data collection and analysis, there has clearly been an imbalance between erosion, extraction, and sedimentation, calling into question the sustainability of long-term extraction activity on the Kwintebank in future.

Summary

During this study, bathymetric profiles taken between 1987 and 2000 perpendicularly to the main axis of the Kwintebank, a sandbank on the Belgian continental shelf subject to intensive sand extraction, have been reconsidered. Analysis of the errors indicates a precision of ±20 cm in a water depth of some −20 m, and among these errors, that attributable to tidal reduction appears to be the largest. The error can be reduced if surveys are taken at specific hours during the tidal cycle. As quality criteria are open to debate, it was decided to use all the information available and to adopt robust statistical methods to identify temporal trends. Statistical verification of these trends required many data, but the main conclusion was that a big increase in sampling frequency is required if the authorities set a criterion for extraction related to the long-term sustainability of extraction from the bank and want a swift guarantee that the criterion is being observed.

This study has shown a statistically significant annual decline of the volume of the bank of approximately 1.5%. This indicates that, over the period 1987–2000, there was an imbalance between erosion, sedimentation, and exploitation in the area. This calls into question the possibility for long-term sustainability of extraction from the bank.

Acknowledgements

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