Automated estimation of seabed morphodynamic parameters

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ABSTRACT: An automatic procedure is described to estimate seabed morphodynamic parameters (main bedform wavelength, height, migration direction and magnitude) from repeated multibeam echosounder (MBES) bathymetric data. The method explores successive bathymetric profiles to assess seabed morphodynamics based on wavelet analysis and cross-correlation. It is applied on 143 successive MBES surveys from a monitoring program in 10 areas of marine aggregate extraction in the Belgian part of the North Sea, resulting in 355 observations of morphodynamic parameters. These can be used to explore specific patterns such as the decrease in dune height in areas experiencing more extraction. Altogether, this method appears efficient to quickly and automatically map seabed bedforms, investigate their temporal dynamics, and points towards interesting features for further analysis.

1 INTRODUCTION

Repeated MBES measurements over time allow the investigation of seabed morphodynamics at possibly high spatial and temporal resolutions. In the Belgian part of the North Sea, the monitoring program accompanying the aggregate extraction activity (Roche et al., 2017) provides such data. When investigating the evolution of the seabed over time in the monitored areas, two main sources of bathymetric variation are observed: the human extraction and the migration of very large dunes. In order to assess the remaining variability of the seabed and the possible depletion or repletion dynamics, a method was previously developed to extract the effect of dune migration (Terseleer et al., 2016): morphodynamics were considered as homogeneous over the investigated areas, and an overall dune migration (magnitude and direction) was derived from an optimization procedure. Yet, variations in seabed morphodynamics within the investigated areas (a few square km) called for a more local approach.

In this contribution, an automated approach is presented to estimate morphodynamics parameters such as dune migration and magnitude as well as wavelengths and heights. This allows mapping bedforms as well as assessing the prospective evolution over time of such parameters. The method is applied on a MBES dataset from the monitoring program of marine aggregate extraction in Belgium, and thereafter exploited to investigate the seabed behaviour over time (and more specifically the evolution of dune heights) in extracted areas.

2 METHODS

Two sources of data can be used to investigate the seabed behaviour in marine aggregate extractions areas of the Belgian part of the North Sea. First, MBES surveys are regularly conducted over monitoring areas, providing a time series of bathymetric data (1 m horizontal resolution and 1 to 4 surveys per year; see Roche et al., 2017). Second, an electronic monitoring system (Van den Branden et al., 2017) is placed onboard of extraction vessels and records their activity and position, providing a spatio-temporal dataset of extraction in the areas.

In Terseleer et al. (2016), the dune migration was estimated based on an optimization process comparing pairs of successive bathymetric surfaces, with the older one being horizontally shifted to find the best match with the most recent one. Consequently, a unique migration pattern (magnitude and direction) was estimated for the whole area. Here, a similar principle is applied but more locally: in order to allow deriving different migration patterns (in magnitude and direction) within a single area, the comparison is done between successive bathymetric profiles taken in all directions around different centroids within the areas. Thus, contrary to other approaches where the migration is measured in the direction perpendicular to the bedforms crests, the direction here freely emerges from the automatic procedure. Successive profiles are compared on the basis of their cross-correlation, as if two time series were compared (similarly to McElroy & Mohrig, 2009): the best match corresponds to the highest correlation (i.e., the profiles are the most alike), while the migration distance is estimated from the spatial gap between them (similarly to the temporal lag separating two time series).

The procedure is fully automatic. It can be summarized into four steps which are detailed hereafter and illustrated in Figure 1.

2.1 Definition of the centroids and profiles

The centroids are the centres of the bathymetric profiles (which are distributed in all directions). They are regularly positioned over the main axis of the rectangular monitored areas. To allow the detection of bedforms with typical wavelengths up to ~300 m (very large dunes), the profiles are between 800 and 1300 m long (depending on the actual extent of the areas). Depending on the size of the monitored areas, between 1 and 6 centroids are used. For each centroid, profiles explore the bathymetry over the full 0-360° directions with intervals of 5°.

2.2 Distinction between the mobile seabed and the stable sandbank underneath

Two components are separated in a bathymetric profile: the sandbank body, which is assumed to be stable over time, and the overlaying seabed, composed of different bedforms and considered to be the mobile part of the seabed. Only the latter is thus conserved for further analysis. The approach is similar to Debese et al. (2018 a, b), who introduced the geomorphometric concept of osculatory surface matching the sandbank tangentially to the dune feet and representing a boundary between a dynamic upper part shaped by the mobile dunes and a stable internal part. Here, the sandbank body is obtained by joining all the troughs (i.e., the deepest points) between the largest successive bedforms (typically, very large dunes with wavelengths ~150-300 m; cyan line in Fig. 1a). To automatically identify the troughs and to distinguish them from other local bathymetric minima (corresponding to neighbouring seabed features or measurement noise), a wavelet analysis (Fig. 1b) is conducted on the detrended bathymetric profile. A moving window is then used over the profile to assess the corresponding dominant periodicity (i.e., wavelength of the largest bedforms) inside which the deepest minimum is selected as the trough of the bedform (Fig. 1a, cyan). This step is important to avoid the problematic influence of the sandbank signal (with a very long wavelength) on the cross-correlation analysis of the next step. The use of wavelet analysis allows the adaptive identification of the troughs of bedforms with different properties.

2.3 Cross-correlation and estimation of the migration amplitude and direction

Once the dynamic upper part of the oldest and most recent profiles is obtained (Fig. 1d, red and black lines), a cross-correlation analysis is carried out (as if they were considered as two univariate time series; Fig. 1e). Between the different investigated pairs of profiles, the one with the highest correlation is selected, assuming that migration occurs in the direction maintaining the highest degree of similarity between successive profiles. The migration distance is then provided by the spatial lag between the two profiles obtained from the cross-correlation (as would be the case for the time lag between two time series).

2.4 Bedform wavelength and height

A wavelet analysis is carried on the selected profile from step 2.3. Similarly to step 2.2, the wavelet analysis is used to scan the bathymetric profile with a moving window and select only one minimum (trough) and maximum (crest) corresponding to the dominant wavelength at each segment of the profile. Once troughs and crests are identified, the bedform height (green vertical lines in Fig. 1c) is then computed as the vertical height between the crest point (blue points) and its base joining the two neighbouring trough points (cyan points). The dominant wavelength over the bathymetric profile correspond to the period averaging the highest power of the wavelet analysis over the full profile (Fig. 1c).

3 RESULTS

The four-step procedure described above allows to automatically estimate morphodynamic parameters (bedform height, wavelength, migration rate and direction) upon availability of successive MBES datasets. This study incorporates 143 campaigns, distributed over 10 different areas over a monitoring period of 16 years, leading to 355 observations. The obtained lag correlations range from 0.80 to 0.99 (median = 0.96), indicating an appropriate match between successive profiles.

3.1 Dune migration rate and direction

Figure 2 shows the resulting dune migration rate (y axis) as a function of its direction (x axis). The largest migration rates are essentially directed towards the NNE-NE or the SSW-SW, corresponding to the main axis of the tidal ellipse in the area.

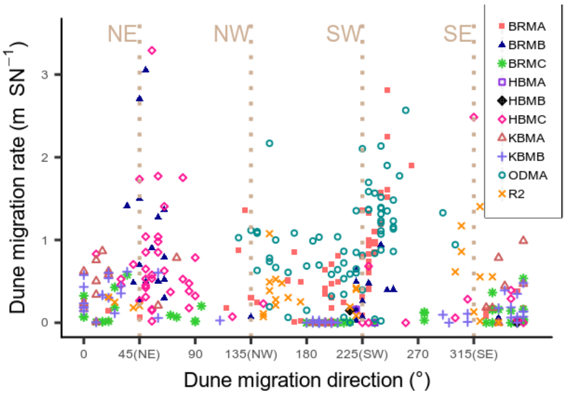

Figure 2. Results from the automatic procedure: dune migration rate (in m per spring-neap cycle, SN) *vs* the dune migration direction (0° being the East).

These dominant migration directions were identified previously and related to currents, meaning that dune migration essentially occurs as a function of the relative morphological position of the area on the sandbanks, leading to an ebb- or flood-dominated tidal regime (Terseleer et al., 2016). Some areas seem to experience a unidirectional migration (e.g., HBMC towards the NE) while others experience multidirectional migration (e.g., BRMC).
Within a same area, while the preferred dune migration direction is preserved over the area, a gradient in its magnitude can be observed, typically with higher migration rates on top of the shallower central part of the sandbank and lower ones in deeper parts (e.g., BRMA and ODMA; not shown).

3.2 Morphological parameters

Obtained bedform wavelengths and heights are shown in Figure 3. Most wavelengths range from 150 to 300 m, and observed maximum height over each profile range from 1 to 5 m. No relationship was observed between wavelength and dune heights in this dataset of limited bedforms (mostly very large dunes; not shown).

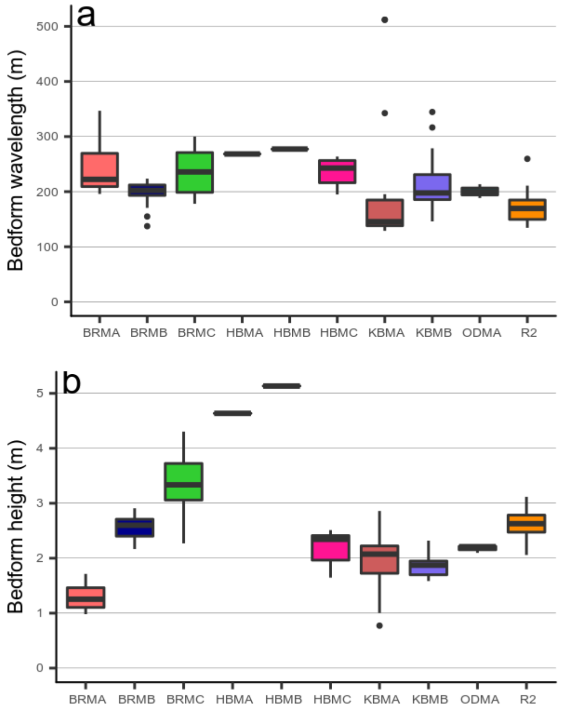

Figure 3. Morphological parameters: boxplots of (a) the dune wavelengths and (b) the dune maximum height observed over each profile.

The estimation of dune heights is affected by two main sources of uncertainty.

First, the automatic procedure itself (more specifically Section 2.4 above) can be a source of uncertainty. Visual inspection of the intermediate results revealed that, while the largest bedforms are usually well depicted be the procedure, mistakes may sometimes appear: more specifically, depending on the migration distance between two successive profiles, different bedforms may occasionally be selected, leading to a spurious comparison. The procedure is under further development to improve this behaviour.

Second, an uncertainty of about 20 to 30 cm may be associated to the MBES data acquired with a Kongsberg EM1002 and EM3002d, which are compliant respectively with IHO S44 order 1 and special order (IHO, 2008). The difference between two successive bathymetric models can thus be up to 60 cm wrong in the worst case. Successive profiles may for example show a different smoothing degree and measurement noises, which affect estimated bedforms characteristics.

Nevertheless, investigation of intermediate results suggests that the obtained parameters are realistic. These can help describing general morphological characteristics of the areas (Fig. 3), and are now used to investigate some dynamics occurring over time.

3.3 Seabed dynamics

As an illustration of the possible use of the parameters provided by the automatic procedure presented here, Figure 4 shows the difference in maximum dune heights between successive profiles. When this difference is negative, it suggests (beyond the error margin mentioned above) a decrease in bedform heights between two successive campaigns.

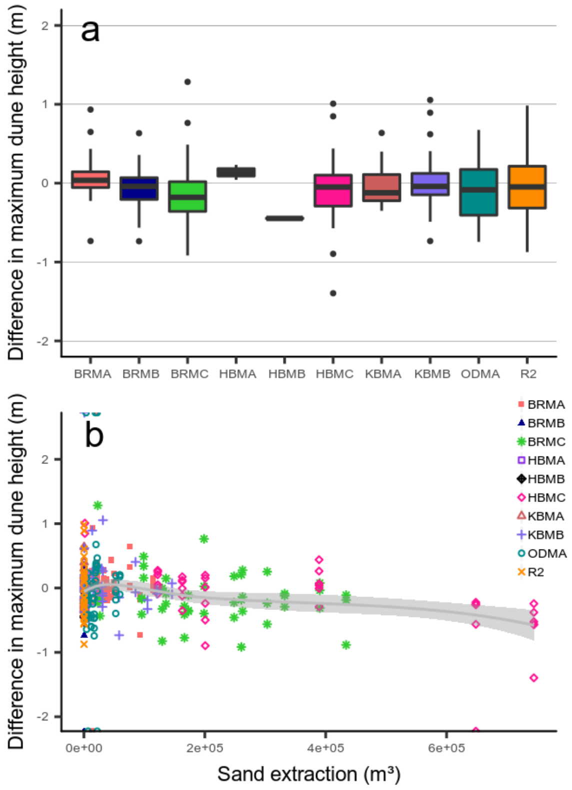

Figure 4. Seabed behaviour in areas of marine aggregate extraction: (a) boxplots of the difference in maximum dune height between successive surveys; (b) difference in maximum dune height between successive surveys *vs* aggregate extraction intensity.

Among all areas, most values are centred around zero, suggesting relatively stable bedforms (Fig. 4a). Yet, some areas appear to present more negatively distributed values, mostly BRMC (and, to some extent, HBMC and ODMA). Figure 4b shows the difference in dune heights between successive campaigns as a function of the aggregate extraction occurring in the area during this period. A loess smoothing is applied (in grey) to illustrate a prospective trend: bedform heights seem to decrease with increasing extraction values. Logically, the trend is mostly influenced by the areas experiencing larger extraction intensities (BRMC and HBMC), which tend to present a more important decrease in bedform height between surveys experiencing more extraction (Fig. 4b). For BRMC, the height decrease (beyond the depth difference due to extraction only) of the very large dunes located in the neighbourhood of an extraction spot which, on the contrary, exhibited sediment accretion, was indeed reported before (Terseleer et al., 2016). This suggests that the present automatic approach is suitable to detect such overall morphodynamic behaviours.

3.4 Advantages and limitations of the approach

The use of the wavelet analysis, allowing bedforms of different characteristics to be identified over the bathymetric profile, has proved to be efficient. It allows the procedure to autonomously adapt to bathymetric profiles with different characteristics. Although it would theoretically be possible to use this approach to also map smaller bedforms (bedforms with wavelength between ~15 and 60 m were often detected as secondary signal), their temporal evolution would be more difficult to assess. Indeed, the cross-correlation step, which provides the estimate of the migrated distance between two surveys, relies on the agreement between successive profiles. Preliminary tests on separated profiles for larger (wavelength > 150 m) and smaller (wavelength ~15-60 m) bedforms indeed showed that the procedure was not able to properly discriminate smaller bedforms and to estimate their spatial lag between successive profiles. At this scale, the procedure would require more frequent surveys to be able to identify smaller bathymetric patterns over time. The temporal resolution of the MBES data (and, to some extent, the vertical resolution) therefore limits the type of bedforms that can be studied with such an approach.

4 CONCLUSIONS

The procedure described in this contribution allows to efficiently and quickly process the vast amount of data being made available by repetitive MBES surveys such as those provided by the monitoring program of the marine aggregate extraction in the Belgian part of the North Sea. Effort was concentrated on the automated and adaptive nature of the process, which can treat data with different morphometric characteristics. Yet, it remains dependent on the intrinsic quality of the MBES data, more specifically the temporal and vertical resolutions. The procedure can be used to quickly map and classify bathymetric data, and to assess seabed dynamics. Future analyses will investigate differences in dynamics between impacted and non-impacted areas, and will account also for the morphological position of an area upon a sandbank.

5 ACKNOWLEDGEMENT

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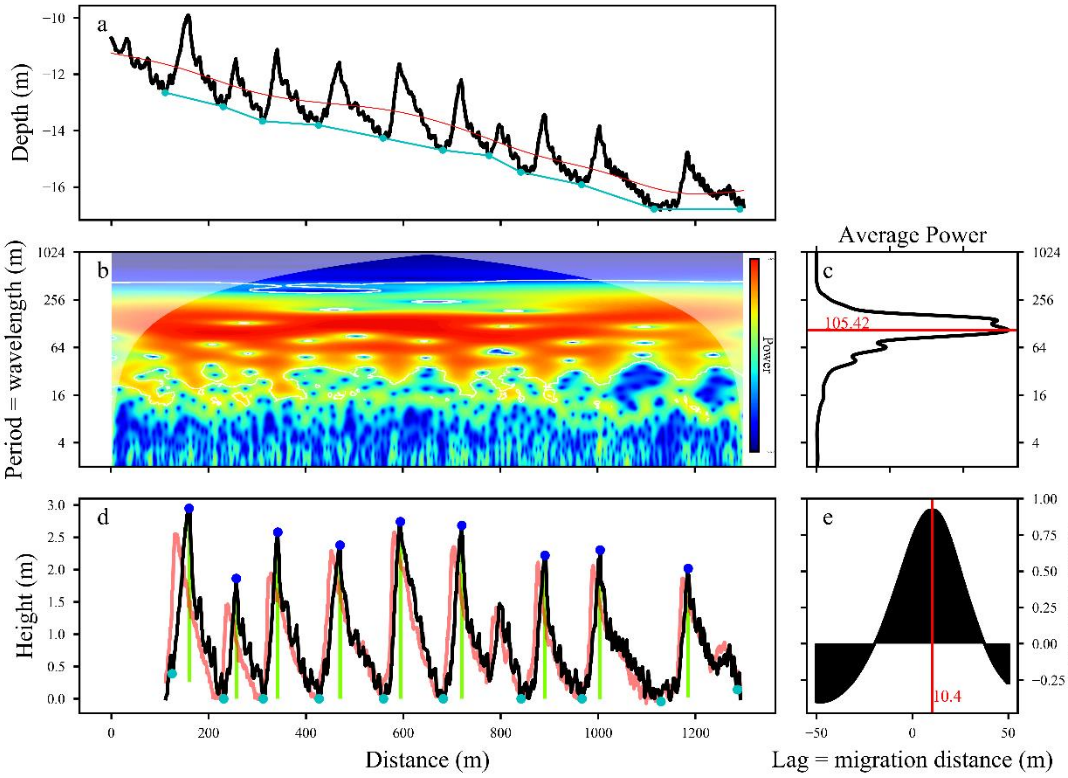

Figure 1. Automatic treatment of a bathymetric profile. (a) The original bathymetric profile (black line) is considered to be composed of one stable part corresponding to the sandbank (under the cyan line) and one mobile part on top of it (between the cyan and black lines) which is used for later analysis. The red line is a cubic regression spline used to detrend the bathymetric profile for the wavelet analysis. (b) Wavelet analysis of the detrended bathymetric profile: at each location on the profile (x axis), it indicates the preponderance (power, colour scale) of each wavelength (y axis) in the bathymetric profile. (c) Average power (x axis) of each wavelength (y axis) over the bathymetric profile. The maximum (red line) identifies the dominant wavelength (here, ~105 m). (d) Profile of the upper, mobile part of the seabed (black) with automatic detection of crests (blue) and trough (cyan) points, allowing the estimation of dune heights (vertical green lines). The bathymetric profile of the next survey is shown in red. (e) Cross-correlation between the red (old) and black (recent) profiles of (d). The maximum correlation (red line) identifies the spatial gap (i.e., migration distance) between the two profiles (here, ~10 m).