Methods for Analysing Bedform Geometry and Dynamics

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Abstract

Rhythmic bedforms of different spatial scales are common in the marine environment. In shallow seas, the monitoring of bedforms is important because changes in morphology may interfere with offshore infrastructure and navigation. In addition, investigating bedform dynamics improves our understanding of the processes that cause their behaviour. Quantified bedform characterization also contributes to the validation of morphodynamic models. Modern, high-precision and high-resolution bathymetric data enable the detailed analysis of bedforms. Several semi-automated methods (e.g. geostatistical and spectral techniques) have been developed to quantify the geometry (size and shape) and dynamics (growth, change in shape and migration) of subaqueous bedforms. An overview of these different approaches is given and differences in use and potential are described.

Keywords

Bedform analysis • Spectral analysis • Kriging • Bedform geometry • Sand wave dynamics • Review

2.1 Introduction

Rhythmic bedforms are a common feature in marine environments in either contemporary or relict forms (Allen 1980; Ashley 1990; Albarracín et al. 2014). Bedforms of different scales may be superimposed; for example, megaripples (wavelengths *O* tens of metres) may overlie sand waves (wavelengths *O* hundreds of metres), which in turn may overlie sand banks (spacings *O* of kilometres) (see left panel of Fig. 2.1). Each type of bedform changes at a different temporal scale, causing a complex dynamic behaviour of the seabed (Ernstsen et al. 2006; Van Dijk et al. 2008). Determining bedform geometry (size and shape) and dynamics (growth, change in shape and migration) is important for understanding the spatial variation in seabed dynamics. Insight into the changing geometry, growth and migration of bedforms contributes to the understanding of the processes that drive bedform dynamics under local environmental conditions (Van Dijk and Kleinhans 2005; Van Santen et al. 2011) and quantified results are important for validating morphodynamic models. In shallow waters, the study of bedforms is also important for safe navigation and offshore engineering. For instance, the growth of sand waves at critical water depths increases the grounding danger for ships on shallow marine traffic routes (Dorst 2009; Dorst et al. 2011), and sand wave migration may affect the stability of offshore wind turbines and pipelines (Morelissen et al. 2003; Santoro et al. 2004).

Bedform monitoring started with single-beam echo sounding, but determining dynamics was still problematic due to the low precision in horizontal positioning and low

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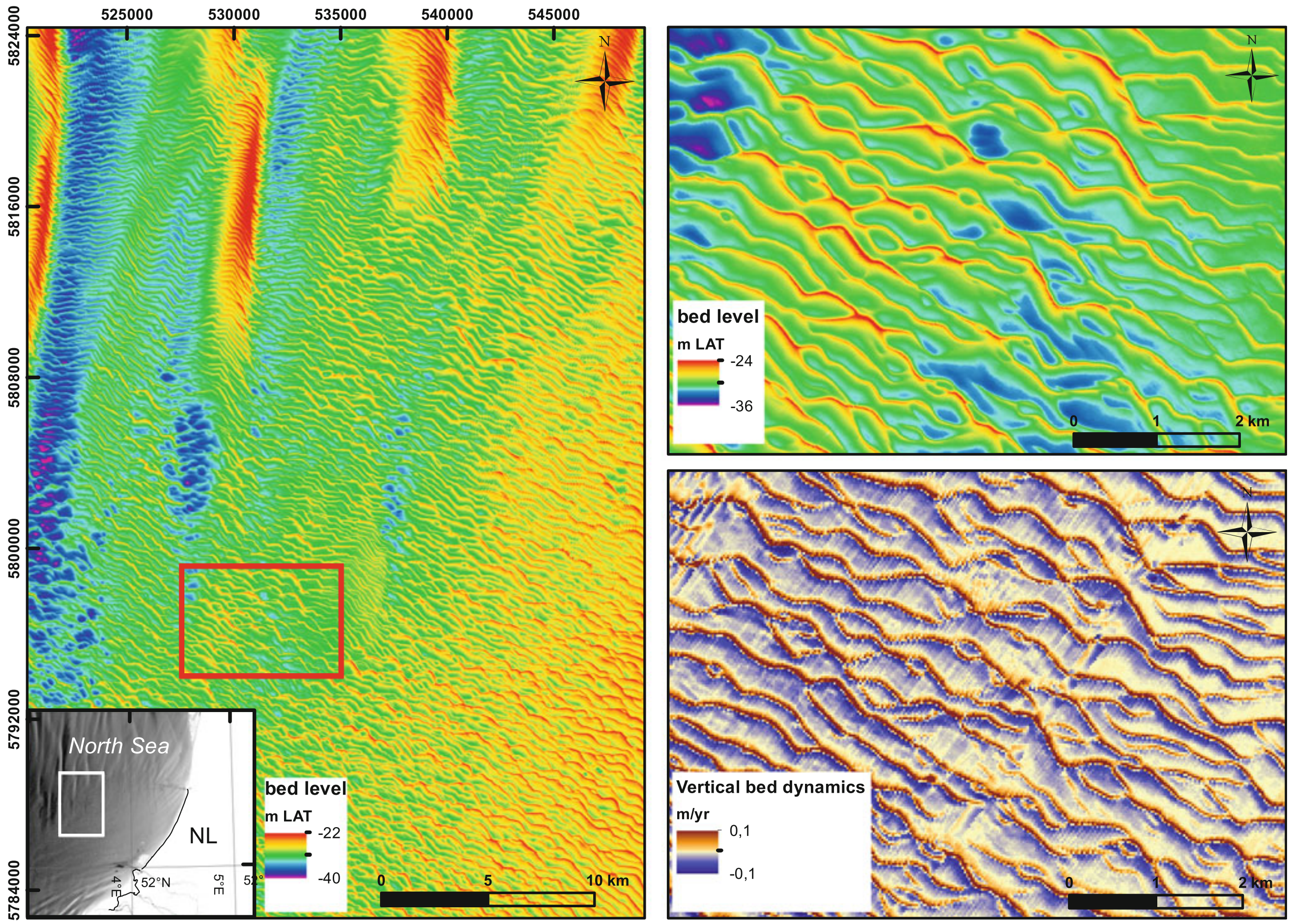

Fig. 2.1 *Left panel* Offshore sand waves superimposed on sand banks on the Netherlands Continental Shelf in the Southern Bight of the North Sea (UTM31N WGS84 coordinates). The map comprises 5-m (where available) and 25-m resolution overlays with bed levels in meter below LAT. *Top right* Zoom of rhythmic bedforms (5-m resolution grid). *Bottom right* Quantified vertical dynamic trends (m/y) per grid node

spatial resolution of the data (McCave 1971; Terwindt 1971; Lanckneus and De Moor 1991). The spatial resolution of modern multibeam echo soundings is up to several tens of observations per m^2 (Lurton 2002). The vertical precision of the echo-sounding data essentially has not increased, still being around 0.1–0.5 m, depending on the applied survey requirements (IHO 2008), the beam angle and the quality of the post-measurement corrections, such as tidal reduction (Hughes Clarke 2012). In shallow and clear water, bedforms can also be monitored using bathymetric LiDAR (Galparsoro et al. 2010) at a comparable quality.

With the progress in survey techniques, the analysis of bedform geometry and migration rates also developed. From manual measurements on plotted maps, present-day methods of bedform analysis have progressed to quantifying digital, high-resolution spatial data in automated or semi-automated ways. The review given in this chapter focuses on methods for analysing marine bedforms (for a review on aeolian dunes, see Hugenholtz et al. 2012). The methods described are applicable to all types of rhythmic bedforms and are not specific to the Mediterranean, being employed in different areas of the world.

2.2 Review of Methods

Methods for analysing bedforms vary from analysing regional morphological patterns to individual bedforms and to the spatial and quantitative analysis of vertical seabed elevation (*dz*/*dt*) from digital elevation models (DEMs).

2.2.1 Bedform Orientation and Wavelength

The dominant orientations and wavelengths of bedforms in an area can be characterized by a *variability analysis*, in which anisotropic, experimental variograms display the lengths in the *x*- and *y*-directions (Goovaerts 1997; Dorst

2004; Pluymaekers et al. 2007). Basically this means that depth variations in different directions are assessed and averaged. For a regular bedform field, the variability along the crest direction is expected to be low, in contrast to the direction perpendicular to the crests. The variogram analysis allows these directions to be detected in an automated way and allows the length of the bedform to be estimated. Alternatively, a *2-D spectral* (*Fourier*) *analysis* returns the dominant orientations and wavelengths, also in the x- and y-directions (power-frequency in the wavenumber domain, kx-ky) (e.g. Van Dijk et al. 2008; Lefebvre et al. 2011; Cazenave et al. 2013). These methods can be used to infer dominant orientations and wavelengths of distinct groups of bedforms in an area, such as sand banks, sand waves and megaripples. However, the geometries and dynamics of individual bedforms are not revealed.

2.2.2 Superimposed Bedforms and Identification of Crests and Troughs

For the 1-D and 2-D separation of superimposed bedforms into different components that each represent a bedform of particular length scale, Van Dijk et al. (2008) compared two well-known, automated signal-processing methods for bathymetric data derived from multibeam echo soundings. The application of *Factorial Kriging* and a *Fourier decomposition* to two case studies of the North Sea shows that both methods are successful and that the results correspond well. Using Kriging interpolation at an appropriate spatial scale, first a surface is estimated through the observations at the scale of the largest bedforms, in this case sand waves. By subtracting the sand wave surface from the original surface, a residual surface is created that represents bedforms at a smaller scale (e.g. megaripples). Consecutively, crest and trough points of sand waves and megaripples are identified by simple along-profile identification of local extrema in the respective surface.

The 2-D spectral method (discrete Fourier transform, DFT), using densely spaced profiles in two directions, separates bedforms by truncating the Fourier series at frequencies discriminating the different types of bedforms (Van Dijk et al. 2008). Crest, trough and inflection points of the sand wave or megaripple signals are identified semi-automatically, using second derivatives in the 1-D method and curvatures in the 2-D method. These are then used to quantify the geometrics and—when applied in time series—dynamics. The spectral method of Van Dijk et al. (2008) may also identify brink points and toe points, as defined in Allen (1968). Duffy (2012) identified crest and trough points by row-by-row *scanning* of a surface (DEM). The scanning must be done on a rotated DEM, since most depth variation occurs in the direction perpendicular to the sand wave crests. Therefore, this approach is most suitable for 2-D straight-crested sand waves. For the identification of crest points, curvature was also used, and for trough points the steepest descent method was used to overcome less regular cross-sectional shapes of bedforms in the Bay of Fundy, Canada. This method adds to previous methods by correcting locations of crest and trough lines to the unsmoothed bathymetric data, and by quantifying all bedforms in geographical space. The latter allows geographic distribution and morphometric relationships to be presented in histograms and scatter plots.

Cazenave et al. (2013) used a Fourier decomposition to analyse orientation and wavelength, as described by Van Dijk et al. (2008), and added to the method by calculating adjusted heights from the 2-D wavenumber domain, which corrects for underestimation due to spectral leakage in the DFT method, and by comparing the method performance with a synthetic dataset. Both Van Dijk et al. (2008) and Cazenave et al. (2013) present methods for spatial representation of propagated error estimates within the different steps of the spectral analyses.

A 1-D Fourier analysis was also applied by Winter and Ernstsen (2007) to separate superimposed smaller dunes of compound bedforms in a tidal inlet in Denmark. Knaapen et al. (2005) used a low-pass Manning filter to separate bedforms and to map crests and troughs of megaripples. Knaapen et al. (2001) earlier used a Fourier analysis and discovered a new type of bedform: ‘long bed waves’, with a wavelength and orientation between those of sand banks and sand waves.

Another known method for a frequency analysis of quasi-harmonic forms is a *wavelet transform*, which can deal with more irregular records and has also been applied to bedforms (e.g. Cataño-Lopera and Garcia 2006; Cataño-Lopera et al. 2009; Fraccascia et al. 2011). Although a wavelet transform is less prone to the effects of sample size, its performance relies on the choice of wavelet, depending on the size and shape of the investigated bedform (Cazenave et al. 2013). Moreover, a discrete Fourier transform allows for 2-D analyses, whereas wavelet transform is a 1-D technique, and a Fourier analysis results in good representations of heights and lengths (Cazenave et al. 2013).

2.2.3 Bedform Dynamics

The shift of bedform patterns can be quantified using a spatial *cross-correlation analysis* (e.g. Duffy and Hughes Clarke 2005; Buijsman and Ridderinkhof 2008a, b; Van Dijk and Egberts 2008; Franzetti et al. 2013). This technique calculates the maximum correlation of two 3-D surfaces (DEMs) in time, by shifting the earlier surface one grid cell at a time and adding up the nodal products of the overlapping surfaces for each shift. The correlation coefficients provide the strength of the correlation. This analysis results in a local migration vector, which therefore has a distance and direction of displacement, or a full migration vector field. The differences in the application of this method in the literature largely comprise the choices of (i) the analysed areas and (ii) pre-imposed restrictions, such as limiting the distance or direction of displacement. Duffy and Hughes Clarke (2005) compared three different cross-correlation techniques: that of maximum correlation (free in distance and direction but limited to the grid resolution), weighted centroid (allows for oblique migration) and least distance to regression line (thereby accepting an assumed migration normal to the crests), all applied to sand waves on a banner bank offshore of New Brunswick, Canada. Similarly, Buijsman and Ridderinkhof (2008a, b) created a vector field for sand waves in the Marsdiep, a tidal inlet of the Wadden Sea, Netherlands, using the maximum correlation technique (i.e. method 1 in Duffy and Hughes-Clarke 2005). Van Dijk and Egberts (2008) applied the maximum correlation technique to larger patterns (including several sand waves) in order to increase pattern recognition abilities and to minimize a priori restrictions. Their result was merely one regional migration vector. They combined the cross-correlation technique with a Fourier analysis on profiles in the cross-correlation direction, thereby accurately analysing the maximum migration rates of individual sand waves. Their finding that maximum migration rates in the cross-correlation direction are significantly higher than migration rates normal to the bedform crests implies that the assumption of crest-normal sand wave migration made by most morphodynamic modellers and in the regression method of Duffy and Hughes-Clarke (2005) is invalid. Franzetti et al. (2013) used the weighted centroid method, resulting in a vector field for giant sand waves at the Banc du Four, Brittany, France.

Furthermore, geodetic *deformation analysis* was used to analyse the geometry and dynamics of bedforms (Lindenbergh 2004; Dorst et al. 2009, 2011). A deformation analysis estimates parameters from relatively simple kinematic models, while explicitly incorporating measurement uncertainty and model deficiencies. In this method, the seabed morphology is considered as a composition of different types of bedforms. A drawback is that it works with idealized morphology and kinetics (for example, regularly moving sinusoidal sand waves), although any misfit is reported in the corresponding quality analysis. A comparison of the deformation analysis results with Fourier analysis results (Van Dijk et al. 2011) showed that wavelengths correspond well (heights were not specified by Dorst et al. 2011), but also that migration rates at one location with back-and-forth migration were either estimated to be zero or not detected by the deformation analysis method.

A different approach of analysing seabed dynamics is to calculate nodal vertical dynamics (*dz*/*dt*). Previously, calculating differences in bed elevations between two DEMs (in metres) was simply done in GIS software. However, to deal with large numbers of surveys of different extents, varying periods of data acquisition and different periods between surveys, a *vertical dynamic trend* (in metres/year) would be a better measure of quantified seabed dynamics (see Fig. 2.1, bottom right panel). This fully automated analysis was recently performed on the Netherlands Continental Shelf (Van Dijk et al. 2011, 2012a, b), now also taking into account areas of human interference, such as dredging (Van Dijk et al. 2014). All datasets from the late 1980s to 2010 for the entire shelf were gridded into DEMs of 25 m resolution. Knowing the periods of data acquisition per record, a rate of change (*dz*/*dt*) was calculated from the vertical stacks of bed elevations in time at each grid node. Other labels (metadata, precision, etc.) can potentially be attached to the nodal dynamics, taking into account the different sounding methods, precisions and resolutions. In a macro-scale analysis of the German Bight (Winter 2011), although presented as elevation differences in metres, the dynamic pattern corresponds very well to that of the Netherlands Continental Shelf. These methods are not directly aimed at analysing bedform geometry, but the vertical dynamic trends reveal growth or migration of bedforms by aggrading-degrading couplets in the pattern of bedforms.

2.3 Discussion

The methods for the analysis of bedform geometry and dynamics described here all have advantages and disadvantages in performance, dependency on assumptions and input parameters or in the “user-friendliness” of the software and/or procedures. In terms of performance, the geostatistical methods (Kriging, scanning) perform best when bedforms are two-dimensional in shape. The discrete Fourier transform for the separation of bedforms of different length scales performs best when distinct groups of frequencies represent the bedforms. Curvature for the crest, trough and inflection points works well when the cross-sections of bedforms are fairly sinusoidal, e.g. sand waves on continental shelves. However, for less regular cross-sections, e.g. isolated bedforms on a nearly flat bed, the steepest descent method would be more appropriate for troughs. The wavelet transform deals with irregular cross-sections, but is a 1-D method. Most methods (Kriging, DFT and wavelet) are dependent on well-chosen input parameters of wavelength and, in the case of a wavelet transform, on the choice of the wavelet applied. The scanning method also requires a priori insight into the orientation of the bedforms.

The scanning-analysing script of Duffy (2012) is available online from www.ria.ie/publications/journals/irish-journal-of-earth-sciences.aspx. Bathymetric DEMs of the Netherlands Continental Shelf in time series are available at Open Earth of Deltares (https://publicwiki.deltares.nl/display/OET/OpenEarth). The applications (*dz*/*dt* and 1-D DFT-methods) of Van Dijk et al. (2008, 2011) will become available at Open Earth as well.

Computational efficiency is becoming increasingly important for contemporary studies that are dealing with increasing amounts of high-resolution data in time series and more often include macro-scale investigations. Apart from Van Dijk et al. (2008), who specify that for N observations the 2-D DFT needs $O(N \log_2 N)$ calculations and the Kriging method needs a maximum of $O(N^3)$ calculations, not many authors have provided information on computational efficiency. In general, the efficiency increases with lower resolutions and with the use of pre-set limits such as the distance of migration in the cross-correlation technique. The *dz*/*dt* method is fully automated and deals in principle with an unrestricted number of surveys and observations in reasonable calculation times (e.g. just over one day for time series since the late 1980s for the entire Netherlands Continental Shelf, >80 GB), thereby providing several statistics of the time series per grid node (e.g. the number of surveys, minimum and maximum water depths, most recent bathymetric map, vertical dynamic trends and goodness of fit). However, the latter does not result in specific bedform quantification of individual bedforms.

A data-related issue when assessing bedform dynamics from bathymetric data from multiple epochs is the temporal sampling versus the temporal variation in bedform dynamics. Empirical results are net changes, thereby not specifying whether changes occurred during one single event, such as storms (Van Son et al. 2009), or at a continuous rate over time. In extreme cases this may lead to the conclusion that no dynamics took place, whereas in reality large changes during a high-energy event may have been compensated for by regular opposite changes between events. Short-term monitoring data of bedforms are scarce, but have revealed that, during one tidal cycle (Ernstsen et al. 2006), seasons (Buijsman and Ridderinkhof 2008a) and storms (Houthuys et al. 1994), the dynamics of bedforms are variable. Contemporary research (e.g. Van Dijk et al. 2014; SMARTSEA-project, 2014–2019) investigating the impact of storms on sand wave dynamics, therein combining modelling and empirical approaches, relates dredging to bedform dynamics and will try to incorporate precision estimates into spatial analyses supporting resurvey policies.

For quantified morphometrics and dynamics of bedforms to serve the validation of morphodynamic models, the same entities need to be analysed. For example, modellers often work with spacings between crests (horizontal equivalents), whereas marine geologists often define bedform length as the real distance between two troughs. The methods described in this chapter (e.g. Kriging, DFT and scanning) should be able to define these different values effortlessly.

To our insight, the next step in the spatial analyses of bedforms would be to add precision estimates. For example, propagated errors per grid node for the entire path from measurements to the last step in the method, including temporal issues of the surveys, would provide the horizontal and vertical precision of the results. Furthermore, combining morphometrics and dynamics with local environmental conditions is expected to increase our understanding of the processes and temporal variations that control the behaviour of marine bedforms. Specific monitoring for short-term variations is crucial in explaining event-driven bedform dynamics.

2.4 Conclusions

Present-day methods for quantifying the geometry and dynamics of marine bedforms may analyse nearly unrestricted amounts of data in space and in time at a data-mining level and covering country-wide continental shelves. A spatial cross-correlation technique allows for the determination of bed pattern shifts, resulting in a migration vector field of a bedform field. Bedforms of different length scales can be separated, in order to determine the geometries and dynamics of the different types of bedforms by methods such as factorial Kriging, geographical “scanning” and 2-D spectral analyses. Semi-automated identification of crest, trough and inflection points allows for the quantification of geometry and dynamics of individual bedforms. A deformation analysis works the other way around, building up a seabed morphology from different components. The spatial analysis of vertical seabed dynamics reveals the vertical dynamic trends per grid node (in metres/year). Improvements to the existing methods include good estimates of precision (propagated errors) that include all steps in the method, from data acquisition to the effects of the analysing methods themselves.

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