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Bedform characterization through 2D spectral analysis

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ABSTRACT

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Bedforms both reflect and influence shallow water hydrodynamics and sediment dynamics. A correct characterization of their spatial distribution and dimensions is required for the understanding, assessment and prediction of numerous coastal processes. A method to parameterize geometrical characteristics using two-dimensional (2D) spectral analysis is presented and tested on seabed elevation data from the Knudedyb tidal inlet in the Danish Wadden Sea, where large compound bedforms are found. The bathymetric data were divided into 20x20 m areas on which a 2D spectral analysis was applied. The most energetic peak of the 2D spectrum was found and its energy, frequency and direction were calculated. A power-law was fitted to the average of slices taken through the 2D spectrum; its slope and y-intercept were calculated. Using these results the test area was morphologically classified into 4 distinct morphological regions. The most energetic peak and the slope and y-intercept of the power-law showed high values above the crest of the primary bedforms and scour holes, low values in areas without bedforms, and intermediate values in areas with secondary bedforms. The secondary bedform dimensions and orientations were calculated. An area of 700x700 m was used to determine the characteristics of the primary bedforms. However, they were less distinctively characterized compared to the secondary bedforms due to relatively large variations in their orientations and wavelengths. The method is thus appropriate for morphological classification of the seabed and for bedform characterization, being most efficient in areas characterized by bedforms with regular dimensions and directions.

ADITIONAL INDEX WORDS: *Fast Fourier Transform, seabed classification, Knudedyb inlet*

INTRODUCTION

Bedforms, such as ripples, dunes and sandwaves, are common features of sandy coastal waters which both reflect and influence diverse hydrodynamic and sediment dynamic processes. A precise characterization of their spatial distribution, orientation and dimensions is therefore essential to describe the current state of a coastal system and to understand and predict its natural and anthropogenically-influenced evolution.

Developments in hydroacoustic mapping and 3D positioning have led to high-resolution bathymetry of various bedform assemblages in different coastal settings. The high variability of these features in space and time requires approaches to describe and analyze their characteristics, i.e. a measure of the topographical roughness of the seabed. Although common statistical measures may quantify the variability of the seabed elevation, they do not provide any information on the size, spacing and orientation of seabed features. Spectral analysis, on the other hand, has the potential to do so, as it characterizes the periodicity of the seabed topography in the frequency domain.

Spectral analysis has been applied on profiles of seabed topography to characterize its roughness (e.g. Fox and Hayes, 1985) and describe bedforms (e.g. Winter and Ernstsen, 2008). While one-dimensional (1D) analysis should be sufficient for an isotropic seabed, which by definition is the same in every direction, it can be very limiting in the study of anisotropic seabed (e.g. a bedform field) as a profile should be selected perpendicularly to the bedform direction in order to compute correct bedform dimensions. To overcome the limitations of 1D spectral analysis, a two-dimensional (2D) spectral analysis can be applied to images of seabed elevations. The 2D roughness spectrum (spectral power plotted as a function of spatial frequency) of an anisotropic seabed is typically characterized by several peaks with low energy and does not exhibit any preferential directionality. Conversely, the spectrum estimated from seabed topography with bedforms generally exhibits a directionality that is associated with the bedform orientation and a highly energetic peak associated with the bedform wavelength.

The spectral power estimated from a seabed elevation profile usually presents a logarithmic decay with frequency and so a power-law regression can be fitted to the spectral power in log-log space (Jackson and Richardson, 2007). From a 1D dataset, the power-law can be fitted directly on the roughness spectrum in the frequency space (e.g. Briggs *et al.*, 2001). From a 2D spectrum, a 'slice' can be taken through the 2D spectrum and a power-law regression fitted on the 1D roughness power spectrum thereby calculated (Lyons *et al.*, 2002). The power-law regression fitted to the power spectrum P(f) has the form:

$$P(f) = \omega f^{-\gamma} \qquad (1)$$

where γ (slope of the power-law) is the spectral exponent and ω (y-intercept at a spatial frequency of 10^0) is the spectral strength. The spectral exponent and strength of the power-law are related to the roughness type of the seabed. Generally, an isotropic seabed

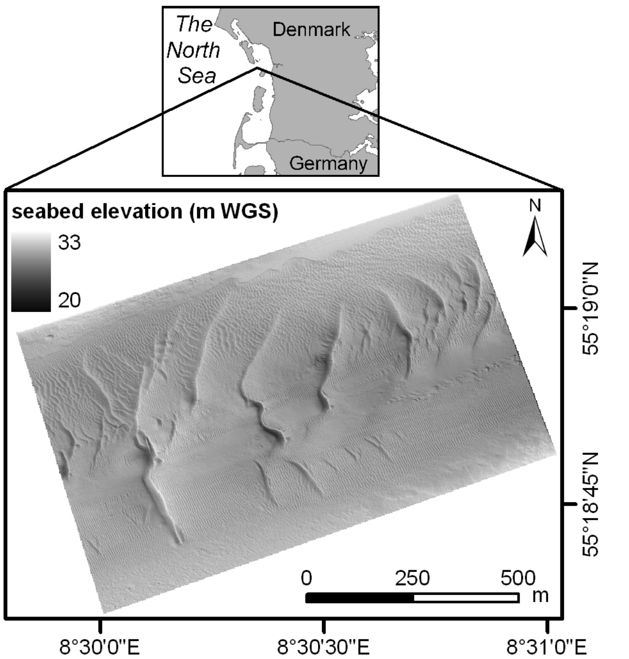

Figure 1. Location of the test area and detailed bathymetry (m WGS84). Mean sea level is equivalent to 39.39 m WGS84.

will yield lower spectral exponent and strength than an anisotropic seabed (Briggs *et al.*, 2001).

Therefore, 2D spectral analysis of seabed elevation can be used to calculate bedform wavelength and orientation (Cazenave, Lambkin, and Dix, 2008; Van Dijk, Lindenbergh, and Egberts, 2008) and quantitatively classify seabed roughness (Lefebvre *et al.*, 2009). These principles have been used previously to characterize small-scale roughness of the seabed (see Jackson and Richardson, 2007 for a review), but it has seldom been tested over large areas with complex morphology. It is of particular interest to assess the variations of the spectral exponent and strength at different length scales and to determine if they can be used to characterize roughness types. This study explores the potential of 2D spectral analysis applied on high-resolution seabed elevation data for seabed morphological characterization and estimation of bedform orientation and dimensions when present.

METHODS

Test area

The test area is located in the Knudedyb tidal inlet in the Danish Wadden Sea (Figure 1), which connects the Knudedyb tidal basin with the adjacent North Sea. The tidal inlet is around 8.5 km long and 1 km wide with an average water depth of about 13 m. The tides in the area are semi-diurnal with a tidal range of about 1.5 m. The seabed of the inlet is covered with sand and previous surveys showed the presence of compound bedforms: large, ebb-oriented, primary bedforms with wavelengths of several hundred meters and heights of several meters and smaller superimposed secondary bedforms, which reverse direction and migrate in the direction of the tidal currents. Although the secondary bedforms cover most of the study area, some parts appear to be devoid of them. Furthermore, variations in the dimensions and orientation of the primary and secondary bedforms can be observed across the inlet.

Data acquisition and analysis

During a cruise in the Knudedyb inlet in October 2009, an area of around 1 km^2 was mapped with a vessel mounted high-resolution Seabat 8125^{TM} (RESON) multibeam echosounder (MBES) system (Figure 1). For a detailed description of the applied MBES system and its performance in terms of horizontal and vertical resolution and precision cf. Ernstsen *et al.* (2006).

The bathymetric data were gridded with a grid-cell size of 0.5 m. The whole dataset was subsequently divided into boxes (quadratic squares) of regular size (e.g. Figure 2a) with an overlap between adjacent boxes of half a box size. Within each box, the mean elevation was subtracted from each point and detrended before being tapered (using a Discrete Prolate Spheroidal Sequences taper) in order to remove the spectral leakage associated with the spectral analysis of a finite dataset (Jenkins and Watts, 1968). They were then spectrally transformed using a 2D Fast Fourier Transform (FFT):

$$S(u,v) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} s(x,y) e^{-i2\pi(ux+vy)} dxdy \qquad (2)$$

where s(x,y) is the spatial signal in the x and y directions and S(u,v) is the signal in the u and v frequencies (also referred to as x and y spatial frequencies). The spectrum was then given in its logarithmic form:

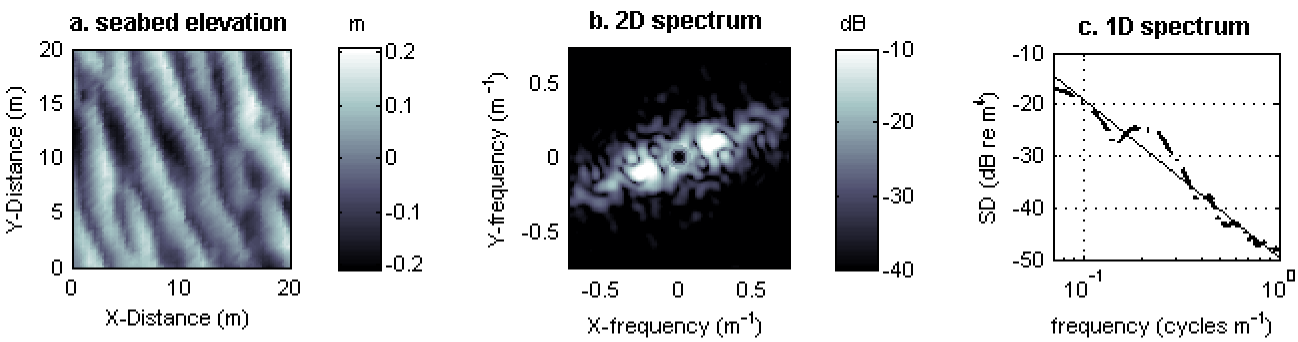

Figure 2. a. Box of seabed elevations (relative to the box mean seabed elevation) taken from the whole dataset; b. associated 2D spectrum showing the peak (mirrored) associated with the bedforms and c. 1D spectrum (dotted line) calculated by averaging the Spectral Density (SD) of the slices taken through the 2D spectrum and power-law fitted to the 1D spectrum (solid line).

$$Sp = 10 \log_{10} (|S|^2) \quad (3)$$

where Sp is the spectral power in dB. Although the data were detrended before being spectrally transformed, large-scale features (long wavelengths i.e. low frequencies) were still present and contained high power in the FFT, which masked the higher frequencies that are of interest. Frequencies smaller than a certain value were thus artificially put at low values; which the value should be used is examined in the discussion. The output of a Fourier transform comprises positive and negative components hence the spectrum has two peaks which mirror each other (Figure 2b). Only half the spectrum (0-180°N) was considered for further analysis and therefore, all the orientations are given modulo 180°. For each spectrum, the energy, direction and spatial frequency of the peak containing the maximum energy were calculated. The root-mean-square of the surface of the box was also computed as an approximation of bedform height. 'Slices' were taken through the spectrum in one degree steps from 0° to 180°N. A power-law regression (Eq. 1) was fitted to the 1D spectrum calculated from the average of all the slices (Figure 2c) and its slope and intercept were calculated. Two box sizes were used in order to investigate the 2 classes of bedforms present in the area: 700 m to characterize the primary bedforms and 20 m to identify the orientation and dimensions of the secondary bedforms.

RESULTS

Morphological mapping

The results of the spectral analysis applied on the 20 m-sized boxes showed significant variations of the parameters within the test area (Figure 3). The most energetic peak displayed high values along the crests of the primary bedforms, low values in areas deprived of bedforms and intermediate values in areas with secondary bedforms. Furthermore, the spectral exponents and strengths were high in areas dominated by bedforms (large scale roughness) while they were low in areas without bedforms (small scale roughness). These three parameters were used together with the seabed elevation to carry out morphological mapping of the area. Four regions with distinct characteristics were recognized (Figure 4 and Table 1):

- Region 1: primary bedform crests and scour holes. This region regroups the crests of the primary bedforms and the scour holes found in some of the troughs of the primary bedforms; both displayed the same spectral characteristics with high energy of the main peak (6.5 dB on average) and high spectral strength (2.5 10^5 m^4 average).
- Region 2: secondary bedforms. This region was further divided into region 2a in the southern part of the inlet and region 2b in the northern part, due to variations in the secondary bedform orientations and wavelengths. The energy of the main peak and the spectral exponent and strength values in these regions were intermediate (around -4 dB, 3.3 and 1.6 10^5 m^4 on average) and showed values close to the average of the whole dataset.
- Region 3: areas without bedforms. The central part of the inlet was characterized by an absence of secondary bedforms. Due to the lack of regular oriented features, this region was characterized by the lowest energy of the main peak (-10.1 dB on average). The spectral exponent and strength were also lowest in this area (3.0 and 0.9 10^5 m^4 on average).
- Region 4: channel sides. This region was identified as shallower areas (mean depth of 10.6 m under Mean Sea Level) situated on each side of the inlet which were characterized by low energy of the main peak and the spectral

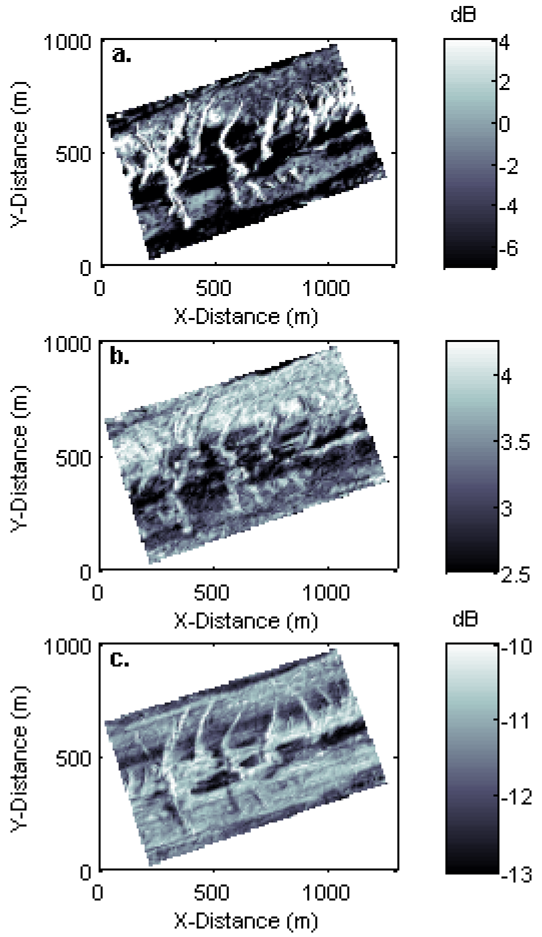

Figure 3. a. Energy of the main peak of the spectrum in each box (20 m side); b. spectral exponent and c. spectral strength (logarithmic form) of the power-law applied on the average of the slices taken through the 2D spectrum of each box.

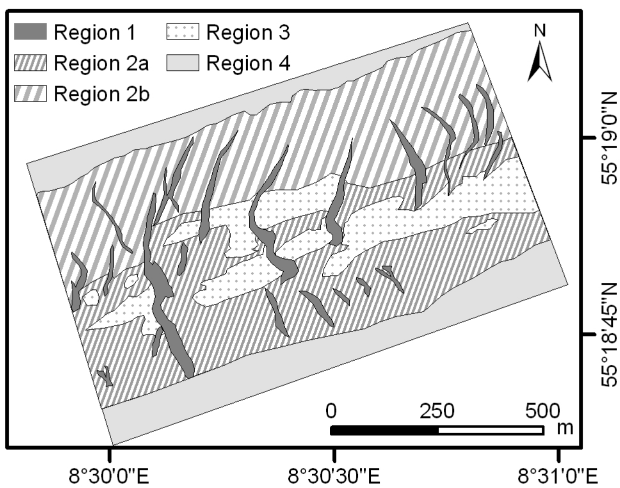

Figure 4. Morphological mapping of the test area based on the spectral analysis results. See text for description of the regions.

Table 1: Summary of the parameters calculated from the spectral analysis applied on the bathymetry of the 20 m boxes. The average value calulated in each region defined in the text (see also Figure 4) is given as well as the standard deviation in bracket.

	area (km^2)	wavelength (m)	rms height (m)	orientation (mod 180°N)	energy (dB)	spectral exponent	spectral strength (10^5 m^4)
Region 1	0.05	11.7 (0.5)	0.75 (0.30)	81.3 (29.6)	6.5 (4.6)	3.7 (0.3)	2.5 (5.8)
Region 2a	0.23	4.9 (1.0)	0.20 (0.05)	66.9 (10.8)	-4.3 (3.4)	3.0 (0.3)	1.8 (0.7)
Region 2b	0.15	7.0 (1.1)	0.23 (0.05)	73.8 (25.7)	-4.1 (2.8)	3.7 (0.3)	1.4 (0.7)
Region 3	0.10	11.2 (1.7)	0.17 (0.15)	95.7 (52.4)	-10.1 (6.2)	3.0 (0.5)	0.9 (0.8)
Region 4	0.23	10.9 (1.8)	0.17 (0.09)	94.7 (58.1)	-8.5 (4.7)	3.3 (0.4)	1.0 (1.2)
All	0.76	9.3 (3.0)	0.27 (0.20)	81.3 (41.2)	-4.2 (6.2)	3.4 (0.5)	1.4 (1.8)

exponent (-8.5 dB and 1.0 10^5 m^4 on average), reflecting an absence of bedforms.

Secondary bedforms

Secondary bedforms were identified in most of the test area and displayed significant variations across the inlet. In the southern part, they had a uniform orientation (67 mod 180°N on average) and were regularly spaced (mean wavelength of 4.9 m). Due to their regular orientation and wavelength, they exhibited a clear signal on the 2D spectrum. Their mean height (rms of the seabed elevation) was estimated to be 0.2 m. In the northern part of the channel on the other hand, the secondary bedforms were less regular, making automatic identification on the 2D spectrum more difficult. They were also larger than in the southern part with a mean wavelength of 7.1 m and a mean height of 0.23 m. Their mean orientation was 74 mod 180°N.

Primary bedforms

Due to the high variability in the orientation and wavelength of the primary bedforms (caused in particular by crest bifurcation), results of the 2D spectral analysis applied on the larger box (700 m) were highly variable and strongly dependant on the origin of the area analyzed. Overall, the primary bedforms were best described using an area situated in the middle of the inlet which encompassed several bedforms (Figure 5a). The spectrum estimated from the seabed elevation shows a certain degree of anisotropy but no pronounced peak in energy (Figure 5b), primarily reflecting the variations in the orientation and wavelength of the primary bedforms. Nevertheless, the most energetic peak seen (calculated after masking frequencies smaller than 0.005 m^{-1}, i.e. wavelengths larger than 200 m) shows a characteristic orientation of 82 mod 180°N, aligned with the orientation of the inlet. It also corresponds to the average orientation calculated from the boxes situated in region 1, i.e. the region with the primary bedform crests and the scour holes. The wavelength associated with this peak was 145 m, which is close to the wavelength of the primary bedforms calculated using a zero-crossing method applied to seabed elevations along a transect line in the middle of the inlet. The height of the primary bedforms (rms of the seabed elevation) was estimated to be 3.3 m. The spectral exponent of the power-law applied on the average of the slices through the 2D spectrum was 3.6 while the spectral strength was 1.5 10^{-5} m^4.

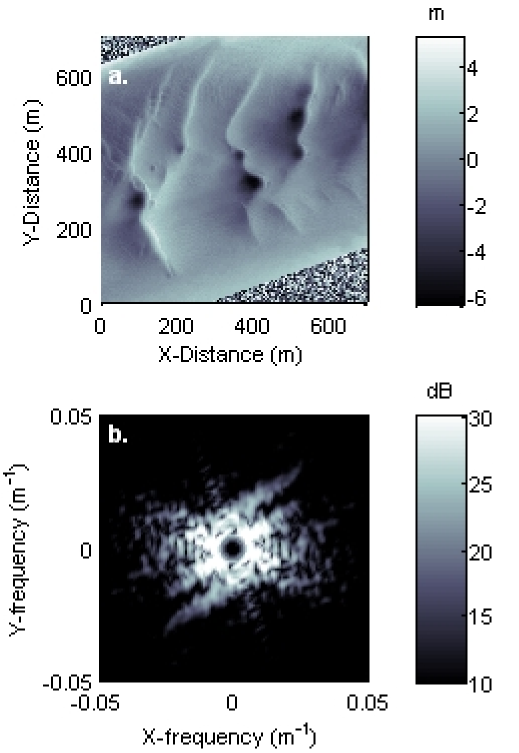

Figure 5. a. Box of seabed elevation (700 m x 700 m) taken from the whole dataset (areas without bathymetric data are padded with random values which are not 'seen' by the spectral analysis) and b. associated 2D spectrum.

DISCUSSION

Several studies have used the slope and intercept values of the power-law regression applied on a 1D spectrum or slices taken through a 2D spectrum in an attempt to distinguish roughness types (see Jackson and Richardson, 2007 for a review). However, these parameters proved to be highly variable between studies and a clear distinction between roughness type based solely on the spectral strength and exponent was difficult to identify (Briggs *et al.*, 2005). The results of the present work show that they can be used to characterize topographical roughness within a large area. The energy of the main peak has not previously been used for roughness characterization but was seen to follow the trends derived from the spectral strength and exponent and therefore helps to discriminate roughness type. Although the morphological mapping process is not fully automated, the method described herein allows a spectral characterization of the different areas which helps in distinguishing morphologically distinct regions within the area under investigation.

Additionally, bedform wavelength can be calculated using 2D spectral analysis without relying on measurements to be taken along a transect line perpendicular to the bedforms to yield correct results. More importantly, their orientation can be quantified from the 2D spectrum instead of being estimated by eye. Furthermore, the wavelength, orientation and height of bedforms can be calculated in subdomains of a large area allowing the study of their lateral and longitudinal variability. For example, the area with the secondary bedforms was divided in two, because the spectral analysis showed that the bedforms in the northern part were larger and with a different orientation than those in the south. These variations are likely to reflect spatial variations in hydrodynamics and sediment transport in the inlet.

Some limitations also appeared. The method is most efficient when several regularly spaced and oriented bedforms are present within the area analyzed, as this creates a very energetic peak on the spectrum. When the bedforms have variable dimensions and orientations, the energy is spread over several directions and wavelengths and the automatic detection of their characteristic may not work. Furthermore, the frequency at which to filter the low frequencies (high wavelengths) before detecting the highest peak in energy of the spectrum is somewhat related to the dimensions of the bedforms under investigation. In the present study, wavelengths larger than 12 m were filtered out when working on the 20 m boxes because the secondary bedforms were expected to have wavelengths between 4 and 10 m. In the case of the 700 m box, wavelengths larger than 200 m were filtered out because the primary bedforms wavelengths were expected to be between 150 and 200 m. Filtering out wavelengths larger than 300 m results in a characteristic wavelength of 284 m and a direction of 123 mod 180°N, which does not correctly represent the primary bedforms wavelength and orientation. Therefore, a rough estimate of the bedforms under investigation is required before applying the spectral analysis.

The most energetic peak of a spectrum estimated from a seabed without bedforms will usually be very close to the value chosen for filtering out large wavelengths because of the increase of power with decrease of frequency (Eq. 1). That is illustrated by the mean wavelengths calculated in regions without bedforms (regions 1, 3 and 4) being very close to 12 m (Table 1), the wavelength above which the power was artificially lowered. Because a spectrum will always display a most energetic peak, the method automatically calculates a characteristic wavelength within each box, although this may not correspond to any given bedform. Therefore, wavelengths close to the filtered wavelength should be analyzed with caution. For this reason, wavelengths between 11 and 12 m (and associated parameters) were not taken into account before calculating the average wavelength in regions 2a and 2b.

CONCLUSIONS

Two-dimensional spectral analysis applied on seabed elevation data allowed morphological mapping and bedform characterization in a test area in the Knudedyb tidal inlet in the Danish Wadden Sea. The energy of the main peak of the 2D spectrum as well as the spectral slope and intercept of the average slices taken through the 2D spectrum were used to distinguish the different regions using a box covering an area of 20x20 m. The value of these parameters were highest over the primary bedform crests and scour holes, lowest in regions without bedforms and intermediate over secondary bedforms. This morphological characterization through spectral analysis helps in classifying the seabed although the process is not fully automated. In areas with secondary bedforms, the bedform dimensions and orientations were calculated. The primary bedforms were investigated using a box covering an area of 700x700 m. However, they were more difficult to spectrally characterize due to their variable dimensions and orientations.

A change in the spatial distribution of secondary bedform dimensions in the inlet was observed. Further investigation of the hydrodynamics and sediment dynamics is required to explain those changes. Furthermore, the reasons for the lack of secondary bedforms in the area in the middle of the channel should be examined.

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