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Variability of surface sediment re-distribution in the high-energy coastal shelf environment at German Bight, North Sea

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Abstract. The present study attempts to apply an alternative of multivariate geostatistics method for point interpolation, Cokriging, to produce a high-resolution median grain-size distribution map. The general aim is to test whether the hypothetically natural relationship between the surficial sediment distribution and complex bathymetry could be used to improve the quality of surficial sediment mapping. From the two sets median grain-size data of the Spiekeroog Barrier Island of 1987 and 2005, the first important observations are that the sediment patches have markedly changed from the measurements in 1987 to the one in 2005. Particularly in the trough between the two parallel ridges, the coarse sand patch was elongated in the trough with distal shift of almost 1 km away northwesterly. Providing the sediment samples were taken during the fair weather in November 1987, the finest sediments occur on the seaward flanks and coarsest in the troughs and on the landward flanks. The difference of the 2005 sediment distribution from the situation in 1987 may be explained by the obvious different state of climatology of both measurements during air weather and post-storm conditions. Through storm events, fine sand trapped in the trough most probably will oscillate locally and temporarily, before entrained once again during the fair weather condition. The present study, thus, shows the benefit of using the methodology used in this study (Cokriging) in a way that the bathymetry, as a covariable in the interpolation, serves as a consistently unique dependent variable to objectively compare the results of median grain-size distribution of the two datasets, while at the same time it helps to produce a physically meaningful interpolation to produce a realistic mapping.
Key Words: median grain size, sediment, Cokriging, habitat mapping.

Introduction. In coastal environment, large benthic organisms are often patchily distributed. Several studies have concluded that the patchiness has a strong relationship with their physical environment. For instance, for benthic organisms and demersal fish, one of the most important components of the habitat is the surface seabed sediment (Ellis et al 2000; McConnaughey & Smith 2000; Moore et al 2009). Particularly on a high-energy shallow shelf, the physical environment is often characterized by sandy surface covering complex seabed features of various geometric scales, such as, sand banks, sand waves, shore-connected ridges and flat surface (Diesing et al 2006; Verfaillie et al 2006; Leecaster 2003; Sisson et al 2002; Antia 1993). In contrast, at the bottom of a lake, the energy condition is low which allows sedimentary depositional process to take place, resulting in the predominant layers of finer sediment types such as gravel, sandy gravel and gravelly mud (Purnawan et al 2015).

The interplaying forcing factors such as wave, tidal currents and storm surge promote intense and frequent seabed surface sediment sorting and distribution on a daily basis. It has been recognized that increasing intensity and frequency of storm events are the prominent effects of climate change in the last century. On top of that, the seabed features are migrating with certain rates under certain hydrodynamic circumstances. Significant changes of this physical environment will ultimately influence the structuring of biotic habitat, such as demersal and pelagic fishes (Reiss et al 2010; Sisson et al

2002; Lezama-Ochoa et al 2011). Nowadays, no information on the influence of storm events on the surficial sandy patches distribution as to the question of whether such environmental condition were available, for instance, as the feeding ground of fish community or give some sort of protected zone for fish growth. Such information on morphological differences is crucial to contributing the importance information in relation to plan a better management and conservation strategies (Muchlisin et al 2014). Therefore, the monitoring program is required to analyse the shifting physical environmental condition. The present study investigates the patches distribution of surficial sediment of the nearshore of a highly-energetic coastal environment at the German Bight of the North Sea. Two sets of coupled surficial grain-size and bathymetry which measured in 1997 and 2005 will be used to examine the behaviour of sandy patches under different hydrodynamic conditions.

Until now, the most commonly used grain-size descriptor has been the sand median, also known as the D_{50}. The median diameter of the sand fraction (defined as the fraction between 63 micron and 2 mm), is the midpoint of the grain-size distribution: 50% (by weight) of the sediment is coarser and 50% is finer than the median grain size (Verfaillie et al 2006; Gruijters et al 2005; Leecaster 2003). The median is the most widely known grain-size descriptor, because it is easily measured or estimated. Since the nature of sands on the surface of the seabed generally are patchily distributed, the point sample datasets have to be transformed into raster grids in a way that they will provide a full coverage mapping of the area of interest. The Cokriging method was used to produce a high-resolution median grain-size distribution map in the present study, this is a multivariate geostatistics interpolation method which virtually produces a high-resolution median grain-size distribution maps. Hypothetically, surficial sediment has a natural relationship with the bathymetry (Verfaillie et al 2006).

The method makes use the natural relationship between seabed form and surface sediment distribution to investigate the sandy patches distribution on a highly-energetic storm-driven shallow coastal environment. It has been investigated in Swift & Field (1981) and Verfaillie et al (2006) that both variables have moderate correlation. This can be of benefit on using them to calibrate the geostatistical modelling (e.g. using semi-variogram and cross-variogram) being used in producing the physically meaningful interpolation in the present study.

Material and Method

Datasets and study location. The median grain-size data derived from the existing sedimentological database hosted by Senckenberg Institute in Wilhelmshaven were utilized in this study. The dataset were a compilation of sediment samples with inclusive bathymetric point recorded in two different periods, during 1987 and 2005 at the shoreface of the Spiekeroog Barrier Island of the German Bight at the Southern North Sea (Figure 1a). The sediment sampling grids were 250 m x 250 m where measurement points in 2005 were taken as close as possible to the points in 1987 (Location in Figure 1b). As input data, full measured grain-size distributions were used. For the Spiekeroog there were 2 sets of measurements available; i.e., both the grain size of sediment and the associated bathymetry from measurements in 1987 and 2005. Main characteristics of each set of measurement are: (1) the grab samples taken in both years were analysed in 0.25 phi intervals between -1.25 to 4.00 phi. Mud content was further analysed for the 2005's, but not so for the 1987's. The fraction > 2 mm (the gravel fraction, including shells and shell fragments) was missing, probably because protocols are not always followed when pre-processing samples for analysis; (2) sample collection spans a long period, during which various analytical instruments and techniques have been used to measure grain size: several generations of laser-particle sizers (wet and dry), sieving (wet and dry), and the pipette method. Because of these shortcomings in the data, we focus on the sand fraction only.

Bathymetry of the seabed between 1987 and 2005 shows no significant migration. Maintain its shore-normal obliqueness. The shoreface-connected ridges and swells depicted in the study location (Figure 1b) belong to the southeastern flank of the shore-connected ridges which has dimension of > 10 km in length, 1-2 km wide, 3-5 m high, <10° steep, and tend to converge toward the proximal (ESE) end of the island shoreline, with a west-ward-opening acute-angle of 14-170° (Antia 1996).

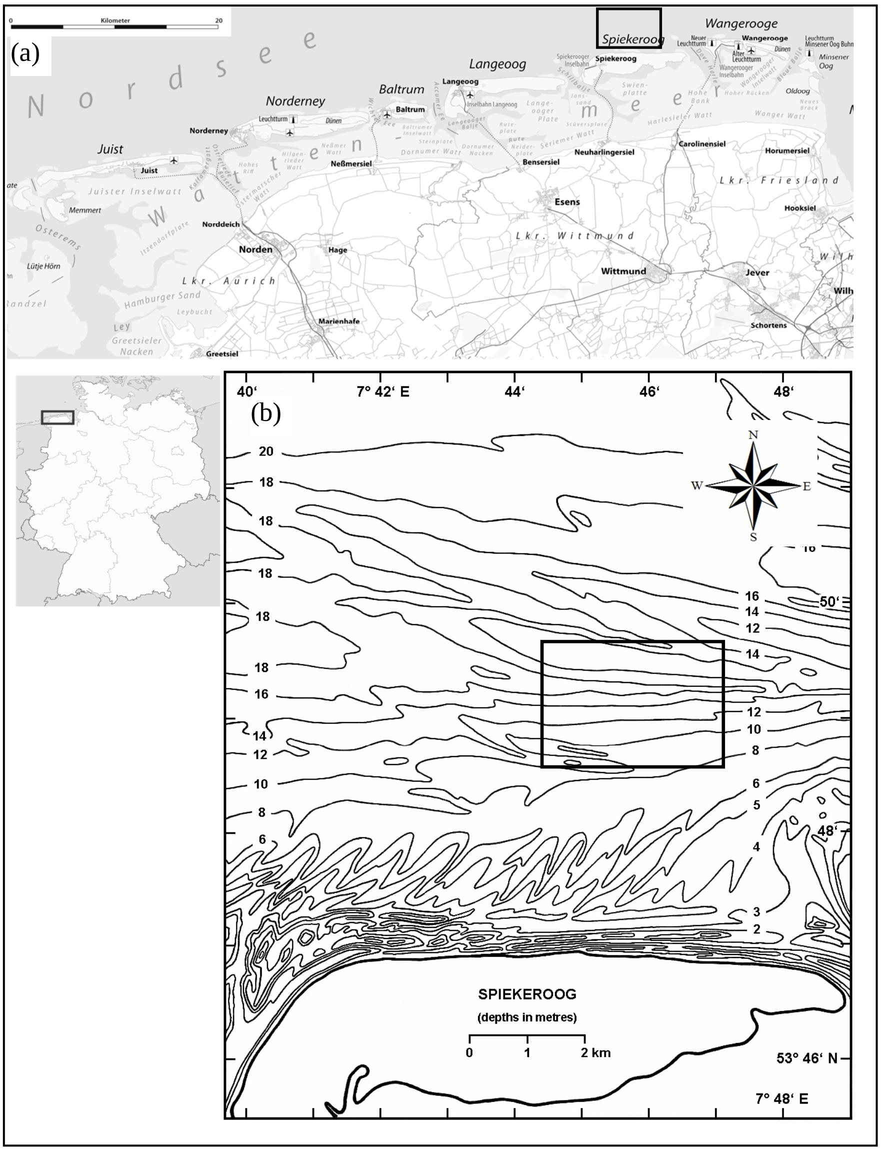


Figure 1. Study location - Spiekeroog Barrier Island situated at the southern North Sea of Germany. Location of grab sampling and accompanying bathymetry (denoted by the square box) which occupies 12 square-km of the whole shallow water shoreface of the Spiekeroog.

Cokriging. Cokriging is a statistical method based on the theory of regionalized variables and taking advantage of secondary observed values as the covariable to improve estimates (predictions) of the first variable (Cressie 1993). It calculates estimates for a variable exhibits low spatial correlation (predict and; in this case grain-size samples), but likely to have some level of correlations with the one that shows relatively high continuity (covariable; in this case bathymetry). In Cokriging, the semi-variogram values of predictand $Z_A(x_i)$, covariable $Z_B(y_i)$ and the cross-variogram of A and B are used as the input parameters (Deutsch & Journel 1992):

$$\hat{Z} = \sum_{i}^{m} w_i Z_A(x_i) + \sum_{j}^{n} \eta_j Z_B(y_i)$$

In this way it is possible to examine the autocorrelation for each of them and cross-correlation between them.

In GIS-based multivariate geostatistics module, Cokriging can be seen as a point interpolation, which requires a point map as input which returns a raster map with estimations. Cross variogram calculates experimental semi-variogram values for two variables (the predictand and the covariable) and cross-variogram values for the combination of both variables (Wackernagels 2003). It is obviously a complex geostatistical technique and much more demanding than other Kriging techniques. Thanks to the advanced GIS-based geostatistics technology which allows performance of these demanding tasks being done effectively, for instance, ArcGIS™ or ILWIS™ which we were using in the present study.

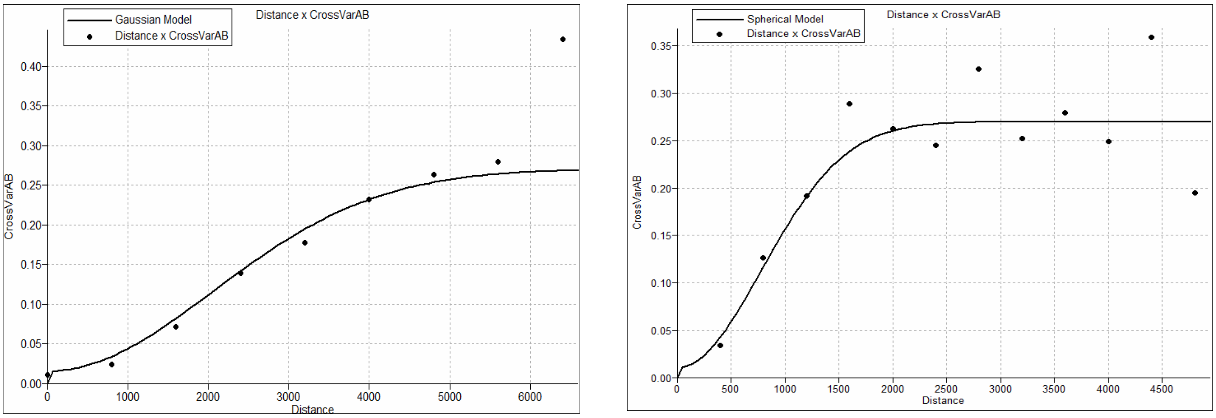
Besides the input point maps and also the Pearson correlation between the two variables (*r*), the following parameters should be specified for the interpolation with Cokriging; (1) a semi-variogram model for the predictand; (2) a semi-variogram model for the covariable; and (3) a cross-variogram model for the combination of both variables. The resulting parameters of range, sill, nuggets and lag spacing from the most fitted cross-variogram model are used for the input parameters to interpolate with Cokriging.

Data examination. The present study makes use the median grain-size (D_{50}) as the predictand and the bathymetry as the covariable to produce a high-resolution raster map of median grain-size distribution using the Cokriging interpolation. For evaluating the distribution and quality of the datasets, a descriptive statistical analysis was performed (e.g. mean, median, standard deviation and spatial distribution) for both the median grain-size and bathymetry datasets. In this way the quality control of the sampled values was obtained, by assuming the samples inside the same zone are more similar than samples from different zones. On this basis, an insignificant number of outliers were randomly removed out of the median grain-size datasets, while no outliers were found in the bathymetric datasets. Before spatially analysed, 30% of well-distributed data points were extracted from each dataset. These small portions of datasets were used at a later stage to validate the resulting interpolation by cross-validation with the other 70%.

Cross-variogram model. The ILWIS™ software was used herein to calculate the spatial auto-correlation of sample points in each datasets. The maximum diagonal distance of the sampled area was approximately of 5 km. By this distance the cross-variogram was calculated using the 7 lags of 750 m spacing. This was based on the convention that the number and space of lags should not exceed half of the diagonal distance of the sampled area (Verfaillie et al 2006).

Median grain-size as the predictand. It was observed that a certain directional tendency of the median grain-size distribution shown in Figure 2. Such distribution characteristics of the median grain-size were analysed for each datasets of 1987 and 2005 using the variogram surface analysis, which results clearly show anisotropy (Figure 2a and 2b). The pseudo colour of the variogram surface indicates whether or not the semi-variogram values close to the origin of the output map. Each cell of the ‘raster’ plot contains the semi-variogram value for the specific distance class and the specific direction of the cell in relation to the origin of the plot where the distance and the direction are zero. Values of points which distances are very short are expected to be similar, which means that the semi-variogram values close to the origin of the output map is small. The blue raster cells are presenting this situation. The anisotropy revealed by the colour representation that gradually changed from blue (at the origin) to green and to red (away from the origin) in a certain direction going through the origin.

Since our median grain-size distribution from both datasets show anisotropy, the semi-variogram of the median grain-size data were calculated using the bidirectional method, which normally otherwise using omnidirectional method that considers all distances between point pairs. The semi-variogram values were calculated for the principle axis and the perpendicular ‘direction’ of anisotropy with additional tolerance angle and band width (m). In this case, an angle direction of 105° was assigned with angle tolerance of 45° and the bandwidth 3 for both median grain-size datasets of 1987 and 2005. The graphs in Figure 2a and Figure 2b show the experimental cross-variogram values (γ) against the distance (h) of the median grain-size distribution of the respective 1987's and 2005's datasets using the associated bathymetry as the covariables, based on those parameters. Subsequently, the parameters such as nugget, sill, range and lag spacing were manually adjusted to fit the cross-variogram model curve to the experimental cross-variogram point values using ILWIS™.



(a) (b)

Figure 2. Experimental cross-variogram of median grain size against bathymetry approached by the Gaussian model. a) for measurements in 1987; b) for measurements in 2005.

It was found that the best fitted modelling curve to fit the experimental cross-variogram is the Gaussian model. Gaussian model creates the parabolic shape at the nugget, that it expresses a smooth spatial variation of the variables as it approaches the sill at the range that closely following the trend of point values from the experimental cross-variogram for the median grain-size datasets (Figure 2a and Figure 2b). Table 1 shows the final sets of parameters (sill, nugget, range and lag spacing) being used and errors generated in the semi-variogram model of each datasets. With this range, the median grain-sizes as the predictand and the bathymetry as the covariance tend to vary jointly and the spatial dependency was progressively decreased as it approaches the cross-variogram points fitted to the flat curve (the sill) at 0.052 mm^2 and 0.11 mm^2 for the respective 1987's and 2005's datasets. The flat region indicates that the dependency between the two variables is vanishing while still maintaining their own spatial auto-correlation. Beyond this distance (approximately starts beyond the range of 2000 m for 1987 and 1400 m for 2005) the cross-variograms of the two datasets show off-track values from the trend line at the sill with slightly different behaviours. For either distribution, both suggested that the interpolation with Cokriging will only use the strongest correlation between the median grain-size distribution and bathymetry, which are those point values that fall within the range of the given best-fitted Gaussian model.

Table 1

Cross-variogram parameters and errors

Datasets	*Sill (mm^2)*	*Nugget (mm^2)*	*Range (m)*	*Lag spacing (m)*	*Gaussian model error*
1987	0.052	0.0019	2000	750	0.0031
2005	0.11	0.04	1400	400	0.00002

The final sets of those parameters shown in Table 1 were picked up as the input for the interpolation with Cokriging. Two sets of semi-variogram model which represent the geometrical anisotropy were obtained. The trend direction of the median grain-size distribution seems to have the largest continuity corresponding to the direction of the prominent seabed features; i.e. the ridges and troughs of the ridges (about 105° or trending WNW-ESE direction). This indicates that the sole grain-size data set has already shown the strong bathymetric influence on its spatial variability.

Bathymetry as a covariance. Bathymetric data was generated into a set of Digital Elevation Model (DEM) as a means to provide the secondary variable (covariance) in the interpolation using Cokriging technique. This means that it has to demonstrate the highest possible continuity of the dataset and accuracy of the modelling prediction to enhance the interpolation of the predictand (median grain-size). Similar procedure to examine the spatial auto-correlation and semi-variogram calculation as for the median grain-size data was applied herein. The variogram surface result shows no anisotropy for our bathymetric data. In addition, the spatial auto-correlation of the bathymetry data shows a very good spatial correlation between the distance and the semi-variogram values.

Results and Discussion

Interpolation with Cokriging. Figure 3a and Figure 3b show the full-coverage (raster) maps with spatial resolution of 10 x 10 m pixels size, which were produced by the interpolation of the median grain-size of the surficial sediments with Cokriging, for the datasets of 1987 and 2005, respectively. Herein, the ArcGIS^{TM} was used to carry out the interpolation by adopting the resulting semi-variogram model for the input parameters (nugget, sill and range).

As mentioned earlier, sediment grain size distributions themselves, for both datasets, have shown anisotropic tendency towards the seabed morphology (bathymetry). By incorporating the bathymetric datasets as the covariable during the interpolation with Cokriging, the detailed depth-dependent distribution of sediment, which naturally inherited, could be captured in a considerable detail. This is shown by the patchiness of different grain-size classification depicted in Figure 3a and Figure 3b. The errors of the interpolation (MEE) were estimated by comparing the predicted data with the measured data (the 30% taken-out data).

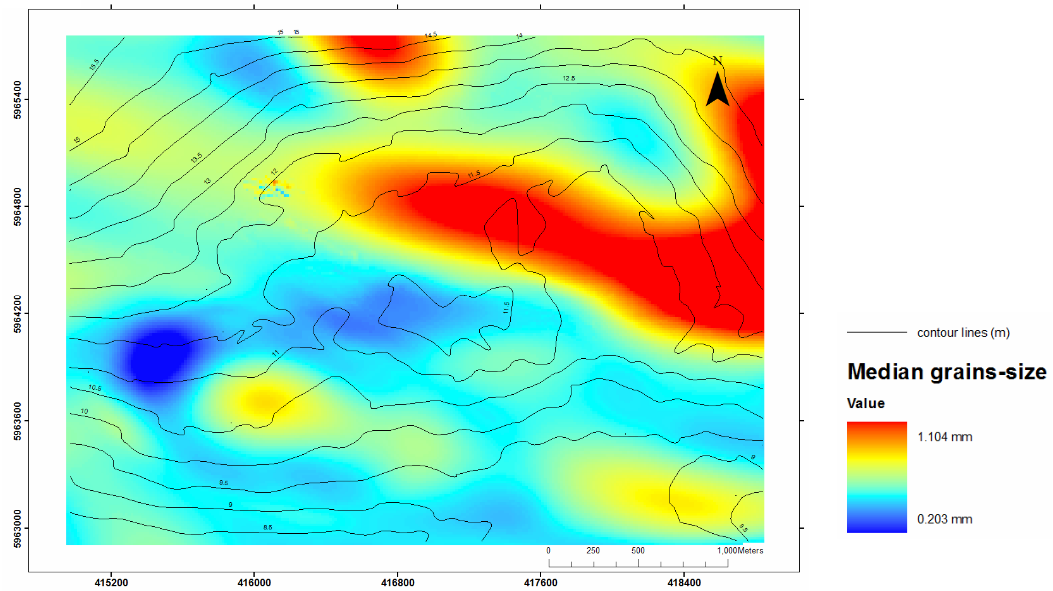
The error results in merely 0.0031 and 0.00002 for the respective data of 1987 and 2005 indicates a good performance of the modelling. Such numbers also indicate the high quality interpolation results, that it can be used as the covariance for the interpolation to produce the reliable and high-resolution median grain-size distribution map with Cokriging. Using also the other parameter values, i.e. nugget and sill, a raster map of 10 x 10 m pixels size was generated by the interpolation with the Cokriging.

Surficial sediment distribution during fair weather and after storm. One of the first important observations from the interpolation results with Cokriging in the present study is that the sediment patches have markedly changed from the measurements in 1987 to the one in 2005 (Figures 3 and 4). Particularly in the trough (shallow bathymetry), the coarse sand patch was elongated in the trough with distal shift of almost 1 km away northwesterly (see also the difference of median grain sizes at cross section 1, 2 and profile 3 in Figure 4). More patches of medium sand were also found in the shoreward flank of the shelf in 2005 while otherwise silt and clay patches were also formed along the ridges crest.

The three-dimensional view of the median grain size distribution from measurements in 1987 and 2005 on top of the DEM of the associated bathymetry in Figure 4a and Figure 4b, respectively, show that the bathymetry has markedly changed since 1987, particularly at the eastern flank of the area. Some representative cross sections in Figures 5 and 6 also reveal similar phenomena. There, the markedly changed grain-size regime could be seen at which most of the coarser grain size in the trough (deeper water depth) significantly deminished in 2005. From all the comparable cross sections in Figures 5 and 6, the sediment distribution at the shallow bathymetry in all of the cross shore profiles are consistently consisted of finer median grain sizes; while on the deeper counterparts show more variability on the distribution of coarser grain size.

These results are in agreement with observations by Antia (1993) who suggests that under fair weather during the sampling campaign in November 1987, the finest sediments occur on the seaward flanks and coarsest in the troughs and on the landward flanks of the shore-connected ridges.

(a)



(b)

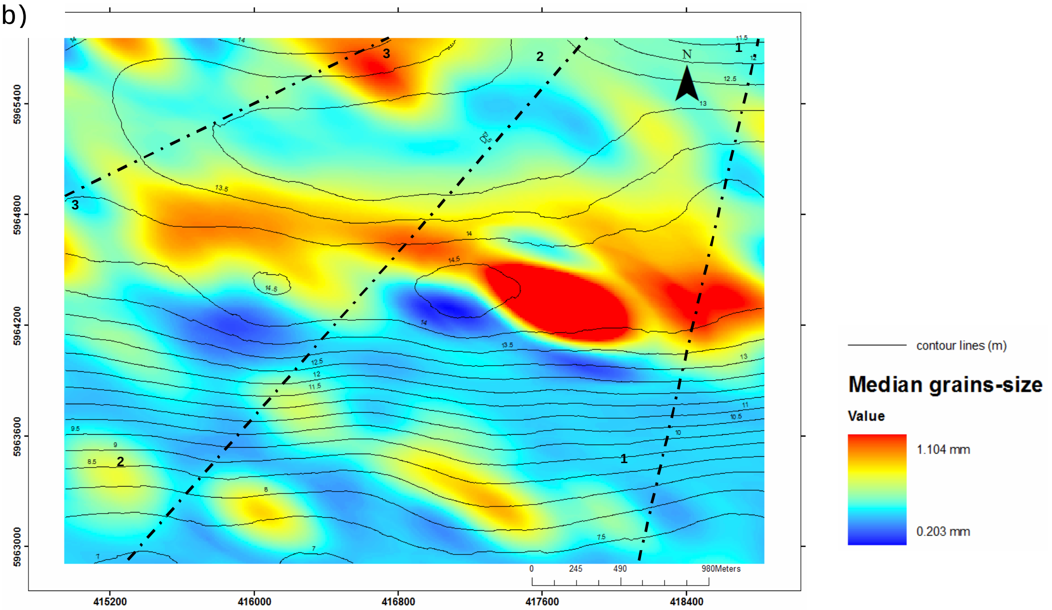


Figure 3. The results of the interpolation of the median grain-size of the Spiekeroog in 10 x 10 m pixel size resolution using the CoKriging; (a) from the measurements in 1987; and (b) from the measurements in 2005.

This also suggests the overall distally difference of median sediment grain size in the deeper bathymetry, most probably due to the changes of the morphodynamic regime in this particular area in the past decades. The dynamic of the shore-connected ridges had been observed by Antia (1996) covering the time interval 1950 to 1987. The observation suggests that the ridges must be in a state of morphodynamic equilibrium, for in spite of the ridges have not only persisted in time but have also retained their general shoreline-oblique orientation. This is, however, inconsistent with the comparably significant changes of bathymetry shown by the two datasets of 1987 and 2005 at the selected studied location (Figure 4). The reason might be because the studied location of the present study is located closer to the nearshore, where hydrodynamic regime is more dynamic compared to the deeper counterparts. Also, it seems that there is a potential of high frequency of mobility of bottom sediments on the shoreface as a result of the prevailing non-storm flow field. Previous studies in this area by Son (2009) suggested such process explained as the following. The medium and fair sands in this shallow water were mobilized daily as frequently as 80% of the time. In case of 2005, the samples were taken shortly after storm events in February 2005 (Son 2009). In this case, only the sediments along the troughs show dramatic seasonal changes in their textural attributes. Through storm events, fine sand trapped in the trough most probably will oscillate locally and temporarily, before entrained once again during the fair weather condition. Both observations, therefore, conclude that poor sediment sorting distally northwesterly in the trough between the ridges has been driven by the prevailing non-storm flow field, more precisely noted by Antia (1996), oriented along the ridge trend, rather than shore-normal to it.

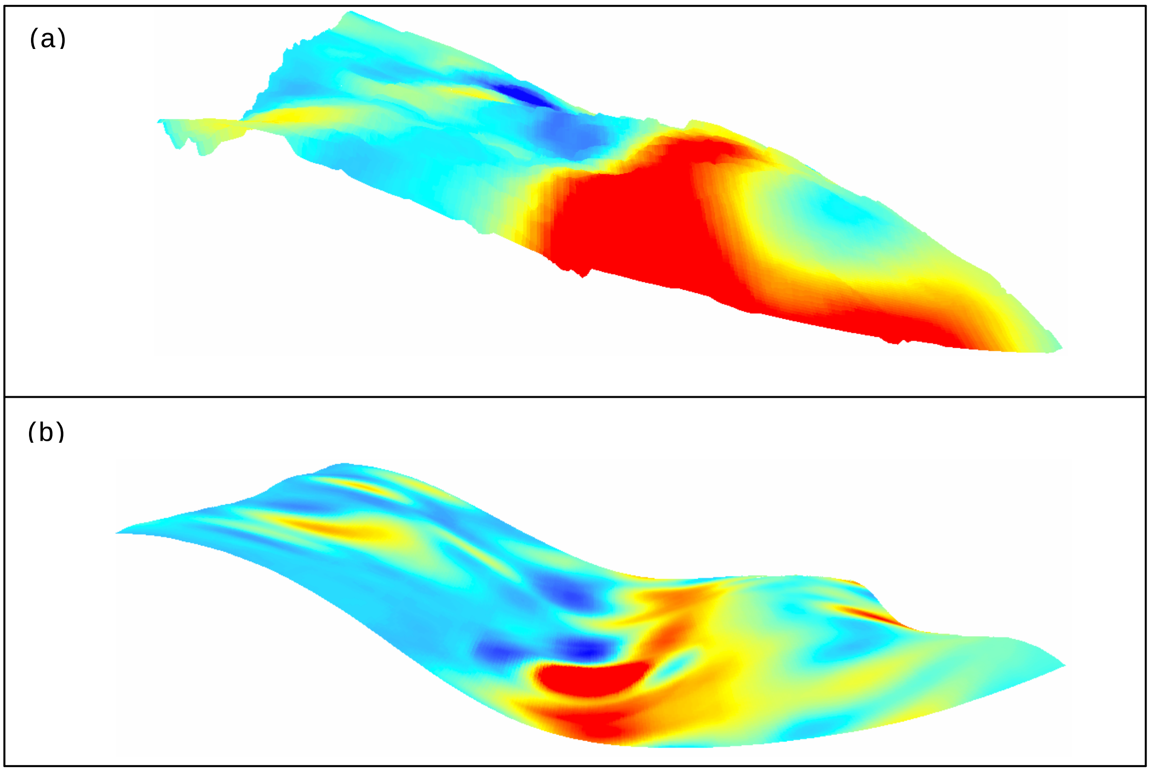


Figure 4. The view of the median grain-size distribution on top of the three-dimensional bathymetry generated from the Digital Elevation Model (DEM), a) for the 1987 data; b) for the 2005 data.

Almost similar distribution pattern to the grain size distribution of 1987 (Figure 3a and Figure 4a), sediment distribution in 2005 (Figure 3b and Figure 4b) is generally well to moderately well sorted on the seaward flank, the crest, and the landward flank of the outer ridge, and again on the seaward flank of the inner ridge and on the upper shoreface. Along the troughs, however, the sediments are moderately to poorly sorted and the facies of sediment in 2005 which patches are markedly different from the one of 1987 (Figure 4a and Figure 4b). We observe fining and rather poor sediment sorting distally northwesterly. The difference of the 2005 sediment distribution from the situation in 1987 may be explained by the obvious different state of climatology of both measurements, i.e., fair weather against post-storm conditions. Here, the sediment consists of fine sand regardless of the weather conditions, probably reflecting its proximity to the upper shoreface which consists of the same sediment type.

The delineation of seabed abiotic habitat; i.e. sandy patches and their grain-size compositions, is an important element to support the fisheries management. It provides the ground-truth synoptic spatial scales on which fish populations exists, thus, on type of fisheries should operate. It can also act as an indicator of the habitat degradation, for instance, by the methods of fishing, the advancement of coastal structures, or the climate-change-induced increasing storminess. For instance, examination of the associations between surficial sediment grain size and demersal fish distributions by Methratta & Link (2006) revealed that several species were consistently associated with particular sediment grain-size types. Consistently high abundance of specific fish species in a particular sediment facies would suggest a possible functional relationship with that facies or with some factor(s) that covaries with substrate type (McConnaughey & Smith 2000).

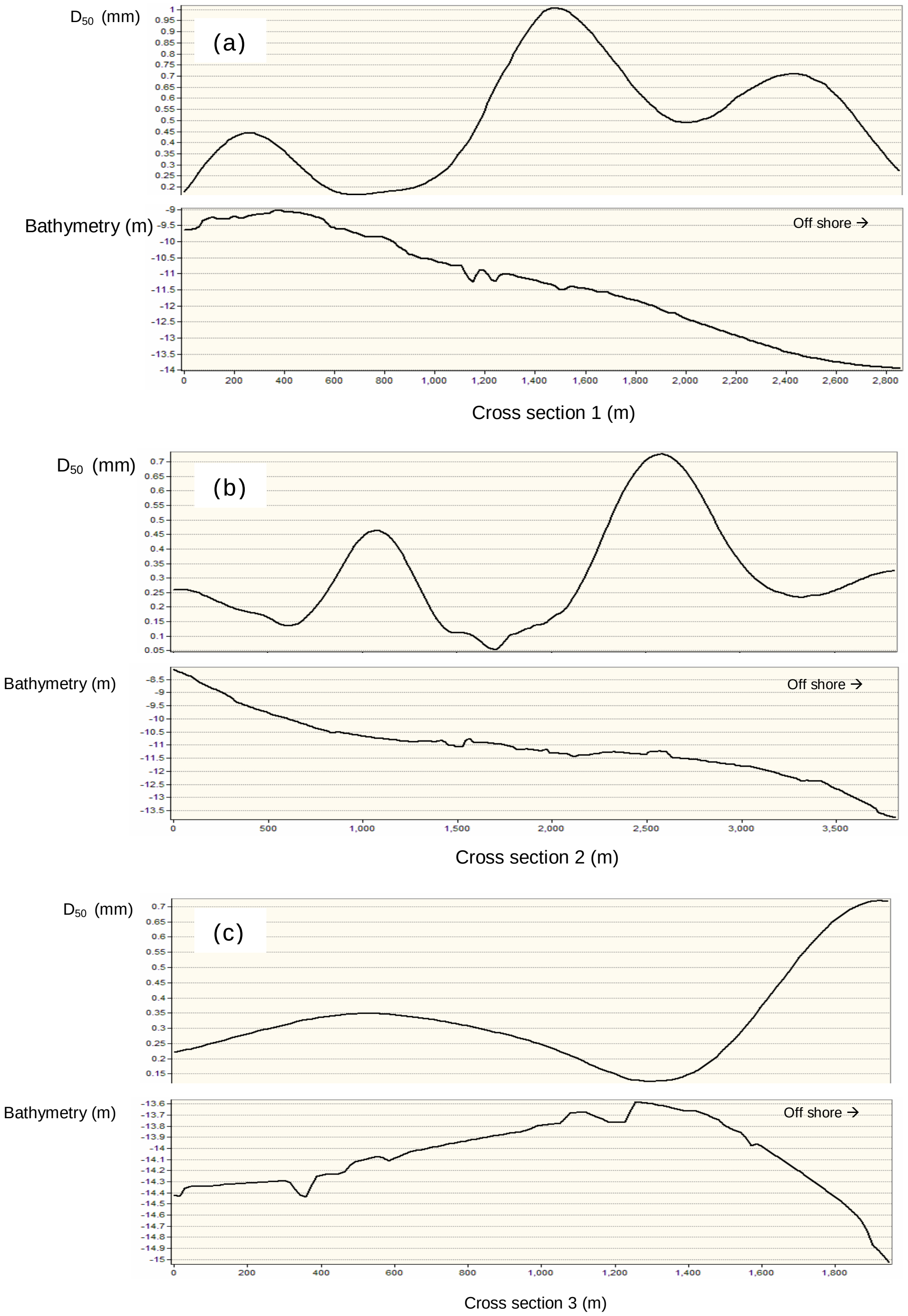


Figure 5. Graphs showing different cross sections derived from the median grain size maps accompanied with the bathymetric profiles of 1987 (see Figure 3 for cross section locations). (a) cross section 1, (b) cross section 2) and (c) cross section 3.

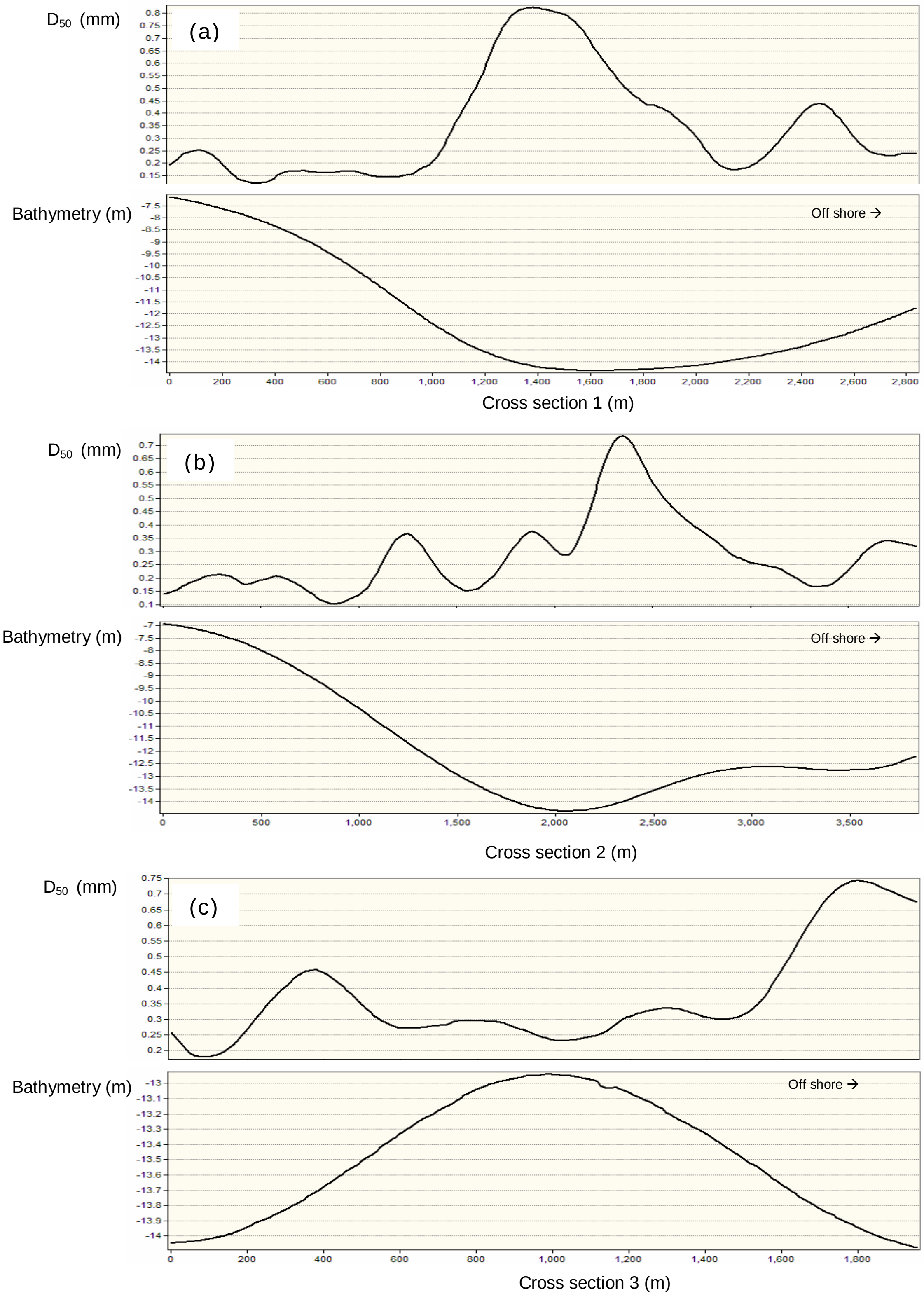


Figure 6. Graphs showing different cross sections derived from the median grain size maps accompanied with the bathymetric profiles of 2015 (see Figure 3 for cross section locations). (a) cross section 1, (b) cross section 2) and (c) cross section 3.

In this case, the present study provides a good indication of the most possible covariable that can potentially explain the functional relationship between the biotic (fish) and the abiotic (surficial sediments) habitats. Further analysis should address the question of whether the changing surficial sediment composition through times observed; i.e. from the median grain-size mapping of 1987 and 2005, was transient or it simply indicates the habitat degradation due to, for instance, increasing storminess as the effect of climate change. The present study, thus, shows the benefit of using the methodology used in this study (Cokriging) in a way that the bathymetry, as a covariable in the interpolation, serves as a consistently unique dependent variable to objectively compare the results of median grain-size distribution of the two datasets, while at the same time it helps to produce a physically meaningful interpolation to produce a realistic mapping

Conclusions. From the two sets median grain-size data of the Spiekeroog Barrier Island of 1987 and 2005, the first important observations are that the sediment patches have markedly changed from the measurements in 1987 to the one in 2005. Particularly in the trough between the two parallel ridges, the coarse sand patch was elongated in the trough with distal shift of almost 1 km away northwesterly. Providing the sediment samples were taken during the fair weather in November 1987, the finest sediments occur on the seaward flanks and coarsest in the troughs and on the landward flanks. The difference of the 2005 sediment distribution from the situation in 1987 may be explained by the obvious different state of climatology of both measurements during air weather and post-storm conditions. Through storm events, fine sand trapped in the trough most probably will oscillate locally and temporarily, before entrained once again during the fair weather condition.

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