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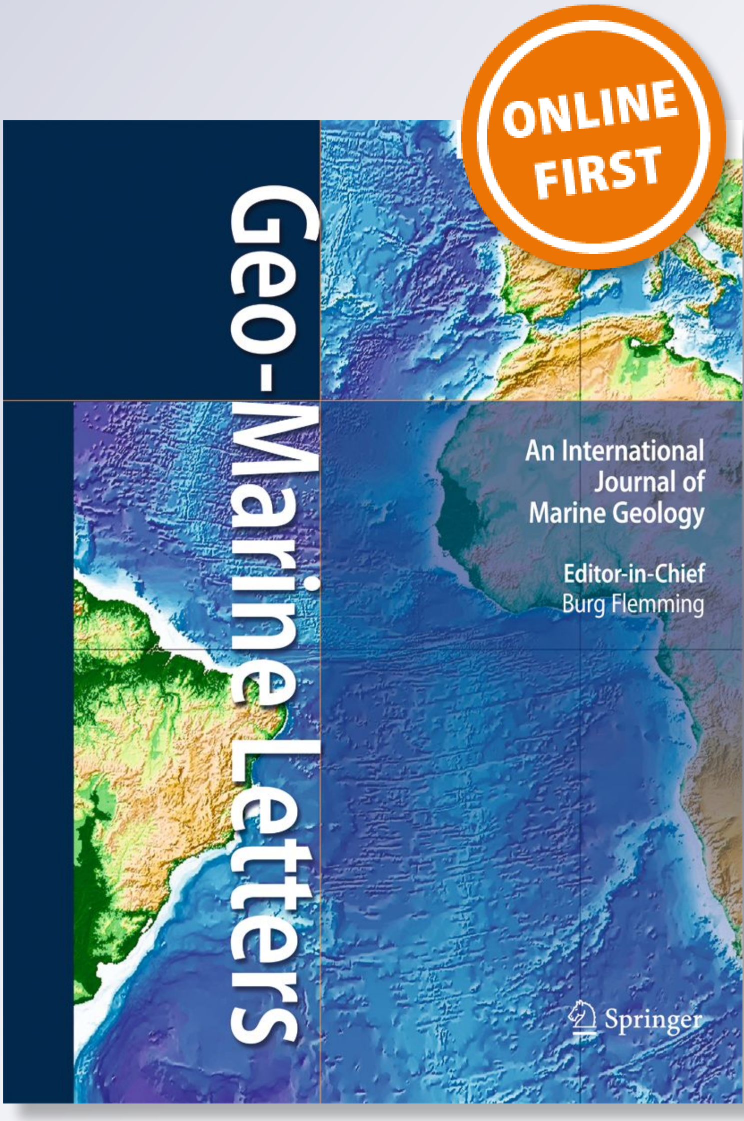

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Morphological changes due to marine aggregate extraction for beach nourishment in the German Bight (SE North Sea)

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Abstract

Facing the predicted rise in global sea level, sandy shorelines are under increasing pressure. In order to counteract the loss of material at eroding coastlines, beach nourishment is considered to be an environmentally friendly approach worldwide. This has resulted in a rising demand for aggregates, which are frequently extracted from the seafloor near the coast. In order to explore the long- and short-term morphological changes of such mining on the seabed, the largest extraction area in the German Bight (*Westerland Dredging Area*, established in 1984) was investigated in this study. Several measurement campaigns were conducted between the years 1994 and 2017 using a set of hydroacoustic techniques. The measurements revealed that up to 20-m-deep pits with diameters of more than 1 km were dredged into the seafloor. The depressions caused by this sand mining are still detectable more than 30 years later. Because of slope failures that mainly consist of fine sand, the formerly steep rims at fresh dredging pits smoothed within a few months. However, after approximately 1 year, muddy sediments dominated the deposition. Since the sedimentation rates are slow, a complete backfill of the post-dredging pits is likely to take many decades. A natural regeneration towards the former seafloor conditions is only visible at the shallow rims of the oldest dredging pits.

Introduction

The last decades have shown that soft coastal protection approaches like beach nourishment are an environmentally friendly and sustainable approach to counteract coastal erosion at retreating coasts worldwide (Hanson et al. 2002; Danovaro et al. 2018). These measures are considered to be viable alternatives to hard coastal protection structures such as dikes, groins, breakwaters, and revetments (Hamm et al. 2002).

During the past, increasing sea level and intensified use of coastal areas has resulted in a consistently growing number of sediment nourishment projects which lead to a higher demand of marine sand (Kim 2009; Bonne 2010; Gopalakrishnan et al. 2017). Consequently, one of the greatest coastal management challenges is the acquisition of materials for beach nourishment. Suitable sediments are rarely found onshore and the costs of obtaining usable marine sediments increase with increasing distance to the coast. Hence, sand deposits in water depths < 20 m less than 10 nm to the nourishment site are preferred as extraction areas (Temmler 1994).

In the 1960s, marine aggregates as resources started to attract the attention of the construction industry worldwide and they started to extract materials in great amounts (Zeiler et al. 2004). In Denmark, for example, the demand of sand for beach nourishment increased from 30,000 m^3 in the year 1976 to 2.5 Mm^3 in 2008 (Sørensen 2013). In the Netherlands, a mega-nourishment project called "Zandmotor" was started in 2011, where approximately 21.5 Mm^3 of sand were dumped in a relatively small area in order to automatically feed the adjacent beaches and dunes downstream (Stive et al. 2013; Brown et al. 2016).

In fact, several studies have already focused on environmental conditions and morphodynamic processes within dredging areas worldwide (e.g., Boyd et al. 2004; Diesing et al. 2006a; Degrendele et al. 2010; Van Lancker et al. 2010; Schwarzer 2010). Moreover, joint research projects (e.g., SANDPIT (Sand Transport and Morphology of Offshore Sand Mining Pits/Areas; Van Rijn et al. 2004) and EUMARSAND (European marine sand and gravel resources; Bonne 2010)) dealt with this topic. However, information on backfill processes regarding the extraction pits after a few months (Cooper et al. 2007; Gonçalves et al. 2014) is still sparse, especially in areas with low sedimentation and weak transport rates as given in the area west of Sylt (SE North Sea).

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The last decades have brought major advances and precise methods to detect environmental and morphological changes using multibeam echo sounders and optical devices (Wille 2005; Harris and Baker 2012, Jones et al. 2016). The use of such techniques provides more accurate data on a higher spatial and temporal resolution allowing more reliable insight into seabed conditions, changes, and impacts.

For this study, the largest German dredging sites as well as the adjacent areas were surveyed, aiming to evaluate the morphological development regarding short-term changes (after ~6 months) and long-term changes (after ~25 years). Additionally, investigations were performed to identify the sedimentary characteristics of the materials involved in natural backfill processes.

Study area

The island of Sylt suffers from significant erosion along the west coast caused by waves and storms from westerly directions. Coastal protection projects in the form of sediment nourishment started as early as 1971 and continue generally annually since the 1980s until today.

The investigation site for this study comprises the largest dredging areas in the German Bight, known as *Westerland Dredging Area* (WDA). It is located approximately 7 km west of Sylt and includes recent dredging zones (W-III) and previously exploited sand deposits (W-II), as well as untouched seafloor. With a length of approximately 5 km in north-south direction and a maximal width of 2.8 km, it has a size of approximately 10 km^2 (Fig. 1). Water depths range between 14 and 34 m.

The seafloor west of Sylt is mainly covered with fine sand that accumulated during the Holocene (Figge 1981; Zeiler et al. 2000). Occasionally, coarse sand, gravel, and stones can be found as relicts of Pleistocene deposits of the Saale glaciation (~345–126 kyr BP). This moraine core is aligned in western direction across the island of Sylt and the adjacent shallow sea (Köster 1979). Pleistocene materials can also be found as sorted bedforms, which appear as coast-normal bands of coarse-to-medium sand in the surroundings of the dredging area (Tabat 1979; Diesing et al. 2006b; Mielck et al. 2015).

Before the dredging activities started in 1984, Temmler (1983) evaluated the amount of suitable sediment potentially available for beach nourishment in this area. In order to assess this potential, a range of seismic survey techniques was used to investigate the study area (Prasad 1983). Based on these surveys, four sediment cores (up to 40 m deep) were drilled in the year 1982. These investigations show that the thickness of available sand deposits suitable for nourishment (i.e., medium-to-coarse grained kaolin sand of Pleistocene and Pliocene origin) is usually greater than 10 m and that the material is not interspersed by interglacial silty clay sequences. Based on estimations by Temmler (1983), up to 1500 Mm^3 of suitable material are available in an area of approximately 100 km^2 in the west of Sylt.

After 10 years of dredging, WDA became subject to repeated investigations on the backfilling of the post-dredging pits and the surrounding morphology using singlebeam echosounders (Temmler 1994). The last research on the regeneration and backfilling within the study area was made in the years between 1998 and 2001 (Zeiler et al. 2004).

The aggregates withdrawn from *WDA* were almost exclusively used to protect the 40-km-long west coast of the island of Sylt. Based on annual evaluation reports of the coastal authority, especially hot spots of strong coastal retreat were preferred while coastal areas in good condition were omitted. In 2017, at total volume of 2 Mm^3 was extracted and used to nourish the coast. Nearly half of the sediment was placed on the beaches, the other part was dumped near the coast several hundred meters off the beaches as a shoreface nourishment to force wave dissipation near the coast and reduce wave energy at the beaches (Hanson et al. 2002; LKN-SH 2017).

Materials and methods

For this study, hydroacoustic and ground truth data were collected between the years 2008 and 2017 (Table 1). From 2008 until 2013, the surveying was carried out using the research vessel *Heincke*. The data from 2016 and 2017 were acquired using the research vessel *Mya II*. In order to explore the impact on the shallow sandy seafloor, the survey was carried out directly after the dredging season in September 2016. A second survey was accomplished in the spring 2017 to investigate the natural short-time regeneration potential of the effected seafloor.

All hydroacoustic measurements for this study were performed in north-south direction at a survey speed of approximately 4–6 knots with varying track distances depending on the devices used.

Hydroacoustic setup

In the years 2008 and 2009, surveying was done with the singlebeam echosounder RoxAnn in order to obtain bathymetric information of the study site. In 2008, six north-south profiles with a track spacing of 500 m were surveyed. One year later, five additional transects were surveyed to fill the gaps between the older transects in a distance of 250 m to get a higher density of data for interpolation of a bathymetric map. These data were only used to show the extent of the dredging area in the years 2008/2009 and were not utilized to calculate backfill rates. In 2013, a parametric sediment echosounder (SES-2000) was used for sea bottom detection along seven transects within the study area. Accurate positioning during all surveys was achieved using PHINS II, IXSEA.

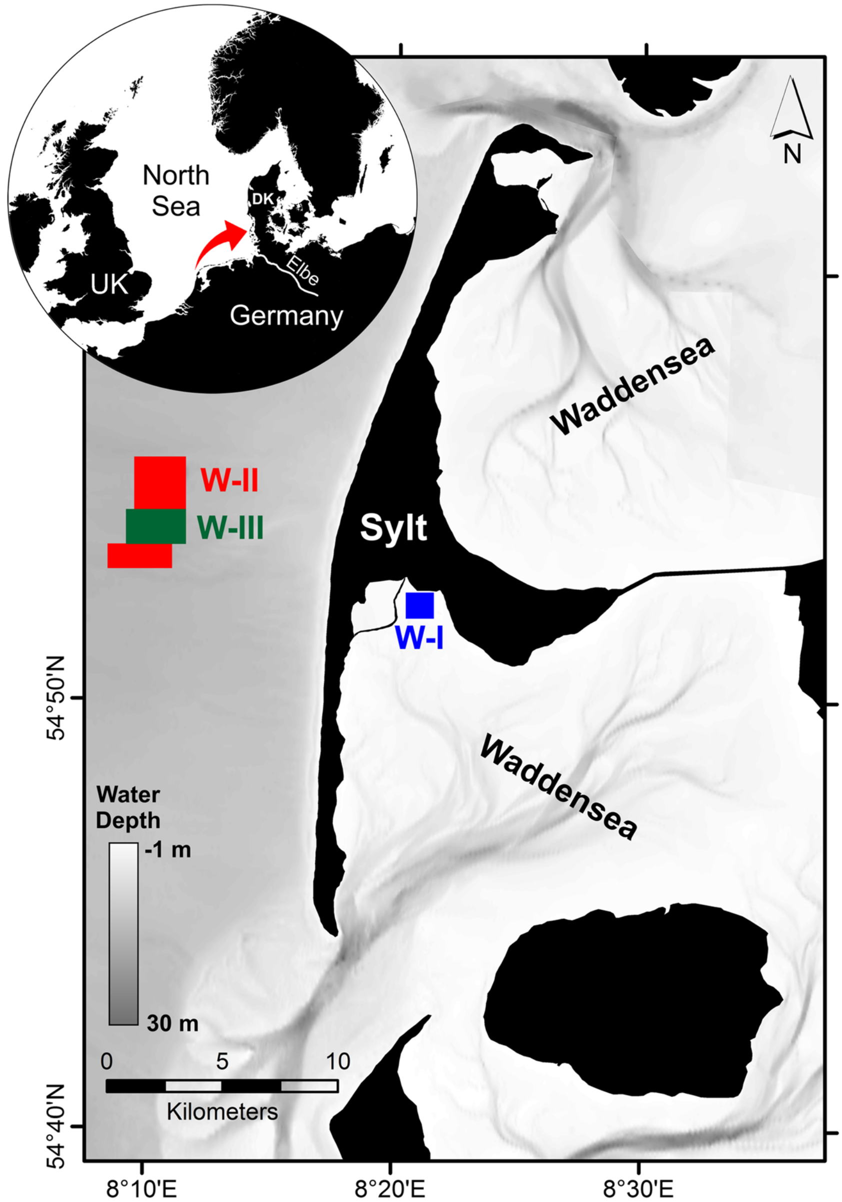


Fig. 1 Research area WDA consisting of Westerland II (W-II) and Westerland III (W-III) located west of the barrier island of Sylt as well as the abandoned dredging site Westerland I (W-I). Depth values are indicated in meters below MSL (mean sea level), according to the Federal Maritime and Hydrographic Agency, Germany, and own singlebeam measurements from 2008/2009

In September 2016 and spring 2017, more comprehensive surveys done in WDA were continued using a shallow water multibeam echosounder (SeaBeam 1180). This provided—compared to singlebeam echosounders—high-resolution bathymetric data of the study site in full coverage. The swath width was at 150 degrees. Due to varying water depths and alternating water levels, a full coverage survey could only be accomplished using varying track distances between 60 and 100 m.

Positioning and ship motion compensation in 2016/2017 surveys were achieved using a dGPS-aided motion sensor system (Coda Octopus F180). For the correct calibration of all echosounder systems, a CTD-probe (Sea & Sun 48M) was deployed to measure sound velocity profiles from the water column during the surveys. All depth values given in this study are indicated in meters below MSL (mean sea level).

Ground truthing

In order to obtain information about the sediment characteristics in the study area, an underwater video system equipped with a Kongsberg OE1366 camera and an additional consumer-grade action camera (GoPro Hero3+) was used to visually record the seafloor conditions. In total, observations along four tracks with an overall length of ~2.000 m were made at low vessel speed (track positions are shown in the next section in Fig. 2c).

To link the bathymetry to the local sediment characteristics, 18 grab samples were taken with a van Veen grab sampler in selected areas (i.e., old/new dredging pits and surrounding area which represent the pre-dredging conditions; the positions are shown in Fig. 2d). The selection of the positions was mainly based on sidescan observations, which were

Table 1 Data acquisition in the years 2008 to 2017

Vessel	Date	Devices	No. of profiles	Frequency	Grab samples	Underwater videos
RV *Heincke*	Sep. 2008	RX	6	200 kHz	–	–
RV *Heincke*	Aug. 2009	RX	5	200 kHz	–	–
RV *Heincke*	Oct. 2013	SBP	7	6 kHz	–	–
RV *Mya II*	Sep. 2016	SB	27	180 kHz	10 (WDA-01 to WDA-10)	4
RV *Mya II*	Mar.–May 2017	SB	46	180 kHz	–	–
RV *Mya II*	Aug. 2017	–	–	–	8 WDA-11 to WDA-18)	2

RX RoxAnn (singlebeam echosounder), *SB* SeaBeam 1180 (multibeam echosounder), *SBP* sub bottom profiler (SES-2000), *WDA* grab samples taken in Westerland Dredging Area

additionally made during the survey in September 2016. The surveys took place in 2016 and 2017.

Grain-size analyses for all samples were carried out with a CILAS 1180L diffraction laser particle-size analyzer that provides a measuring range between 14.6 φ and 1.4 φ (0.04–2500 μm). Prior to the measurements, the samples were chemically treated to remove carbonate and organic matter (Hass et al. 2010). To calculate the statistical parameter for a subsequent analysis, the software package GRADISTAT (Blott and Pye 2001) was used. The grain-size scale refers to Folk and Ward (1957).

Post-processing of hydroacoustic data

The depth values acquired with the singlebeam echosounder RoxAnn were manually filtered for bad soundings. Gaps between the track lines were closed using "natural neighbor" interpolation in ArcGIS 10.3. The singlebeam data from the year 1993 were digitized from an isobathic map and interpolated using the same procedure. This map was originally created by Temmler (1994) based on track lines with a distance of 50 m and has an isobathic resolution of 1 m.

The bathymetric profiles measured with SES-2000 were edited using the software ISE2. The multibeam data were post-processed using Hypack 2016a. Cleaning of the data was achieved using built-in filters and manual processing tools in order to remove outliers. Subsequently, the bathymetric maps were exported to ArcGIS with a grid size of 2 m. Here, small gaps within the matrix were closed by the interpolation technique *IDW* (*inverse distance weighting*), which is optimal, when the data points are dense enough to capture the extent of local surface variations needed for analysis (Vojinović and Abbott 2012). All soundings were tide corrected using data from the gauge "Westerland Messpfahl" which is located 6 km east of the study area. After the implementation of ground truth information, it was possible to analyze and classify the different hydroacoustic data sets using ArcGIS. Additionally, the impact of the dredging activities and natural regeneration with time was determined using *Spatial/3D Analyst Tools* and *Raster Calculator* in ArcGIS.

Results

Bathymetry

Between 1984 and 1995, the dredging activities were concentrated on the northern part of the study area (*W-IIA*, Fig. 2a). Here, singlebeam data were collected in May 1993 (Temmler 1994). The measurements show that the dredging pits have a depth of approximately 12 m below the seafloor and are located in a water depth of 25.5 m. In 1995, the extraction area was expanded to the south (*W-IIB*, Fig. 2b). The post-dredging pits in *W-IIA* show depths of 23 m, while in 2008, the maximum water depth in *W-IIB* is ~ 24.5 m. At this point of time, the excavation work was almost completed in these areas (with few exceptions at the edges in the north of W-IIA and in the southeast of W-IIB), because sufficient material was no longer available. Since 2009, the dredging operation mainly focused on *W-IIIA*.

Figure 2c illustrates the results of the multibeam measurements recorded after the dredging season in September 2016. This bathymetric map shows the full extent of *W-IIIA* consisting of deep pits and furrows with maximum water depth of 33 m. The coastal authorities stopped the extraction of sand in this area in September 2016, because of the exhaustion of the sand resource at this place (LKN-SH 2017). In spring 2017, new excavation work had already started a few weeks before the following multibeam survey took place in May 2017. The position and extent of the new site called *W-IIIB* is indicated in Fig. 2d. Here, the deepest pits have a water depth of ~ 34 m. The progression of sand removal/depletion is highlighted through the changes in bathymetry. Since natural backfill processes make it difficult to calculate the exact amount of withdrawn material, accurate data from the coastal authority were used (see Table 2).

By comparing the two bathymetric maps from 2016 and 2017 (Fig. 2c and d), the short-term changes within *W-III* become visible (Fig. 3). Within the yellow areas, no bathymetric change could be detected. The figure shows that in W-IIIB, ~ 19-m deep pits (this corresponds to a water depth of ~ 33 m) were dredged within 6 weeks of continuous extraction in

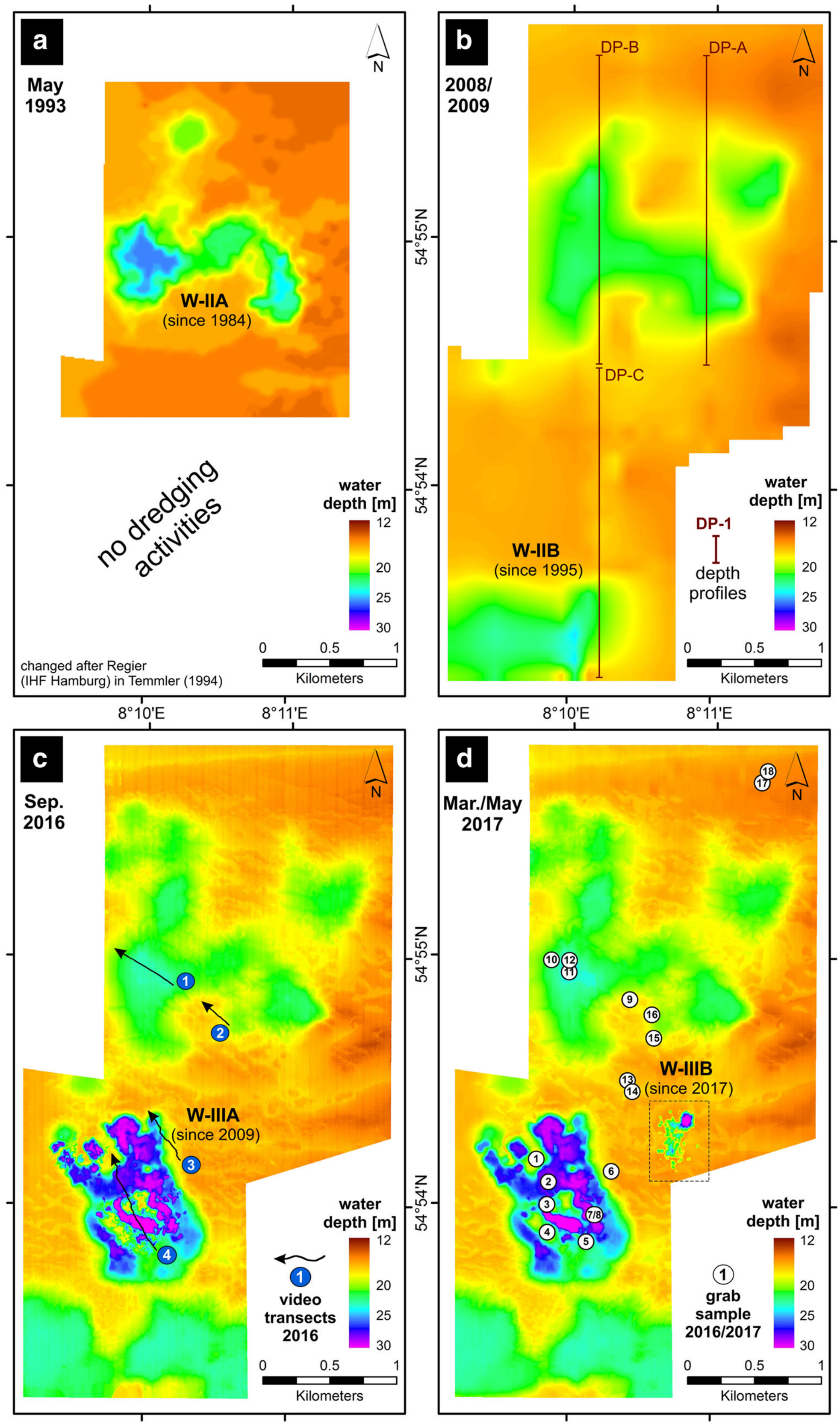


Fig. 2 Bathymetric maps of the study area W-II and W-III from **a** the year 1993 (modified after IHF Hamburg), **b** 2008/2009, including position of the bathymetric profiles **c** 2016, and **d** 2017. Video transects and grab sample stations are shown in **c** and **d**. The year beneath the name of the dredging area indicates the start of the dredging activities in the respective areas

2017. According to LKN-SH, ~430,000 m^3 of sediment have been extracted in this time frame from W-IIIB.

Weak vertical red stripes visible in Fig. 3 are artifacts produced by roll-offset errors along the track lines during the

Table 2 Dredging zones within Westerland II and III and withdrawn material

Dredging zone	Dredging activity	Approximately area in [km^2]	approximately withdrawn material in [Mm^3]*
WDA-IIA	1984–1994	2.6	20
WDA-IIB	1995–2009	1.6	15
WDA-IIIA	2009–2016	1.2	9
WDA-IIIB	Spring 2017	0.12	0.43

*According to LKN-SH (2012, 2017)

survey in 2016 (cf. Schmitt et al. 2008). If any, these have only minor influence on the calculations presented in this figure. They mainly appeared in the nadir of the multibeam swath and could not be filtered out afterwards.

In order to assess the amount of sediment loss and gain over a longer period, the bathymetric data from 2017 were compared with soundings from the years 1993 and 2013. Figure 4 shows three bathymetric profiles that cross the study area in north-south direction (positions are illustrated in Fig. 2b). A comparison between the cross sections from the years 1993, 2013, and 2017 shows a strong sediment loss in the surrounding of W-IIA from up to 5 m (Fig. 4a and b) as well as approximately 8 m in the area of W-IIIA (Fig. 4c) due to dredging activities in the last decades. Minor sediment losses are also detectable at the rims of the fresh dredging holes (Fig. 4c). Within the pits, sediment gains are observable: ~3 m between 1993 and 2017 in W-IIA, ~0.5 m between 2013 and 2017 in W-IIB.

Grain-size analysis

In order to characterize the sedimentary composition of the areas undergoing morphological change, 18 grab samples were taken from the seafloor. The positions are shown in Fig. 2d. Sampling was done in both the topographic lows at *W-IIA* (old dredging area) and *W-IIIA* (new dredging area). Additionally, samples were taken from the surrounding areas, where bathymetry shows no influence of the extraction activities. The analyses of all surface samples are summarized in Table 3. They reveal mean grain-sizes (arithmetic method of moments) between 10 and 916 µm. The finest material

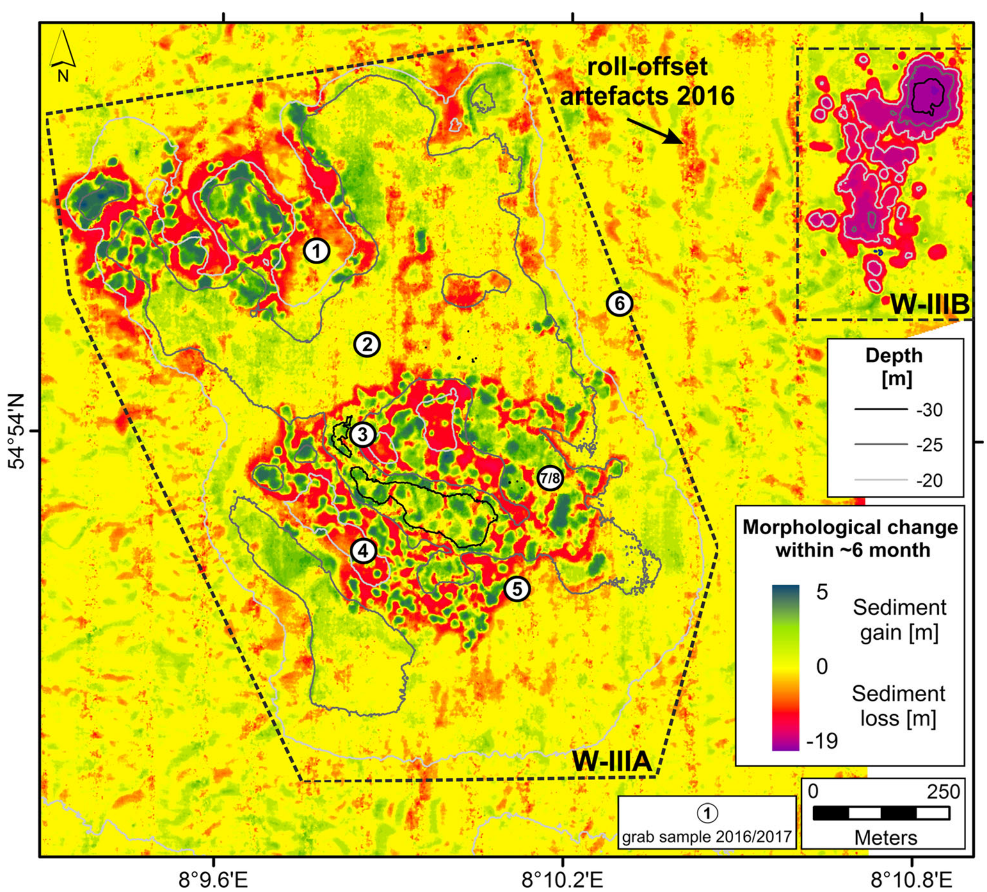


Fig. 3 Short-term morphological change in the seabed. Differences between September 2016 and spring 2017

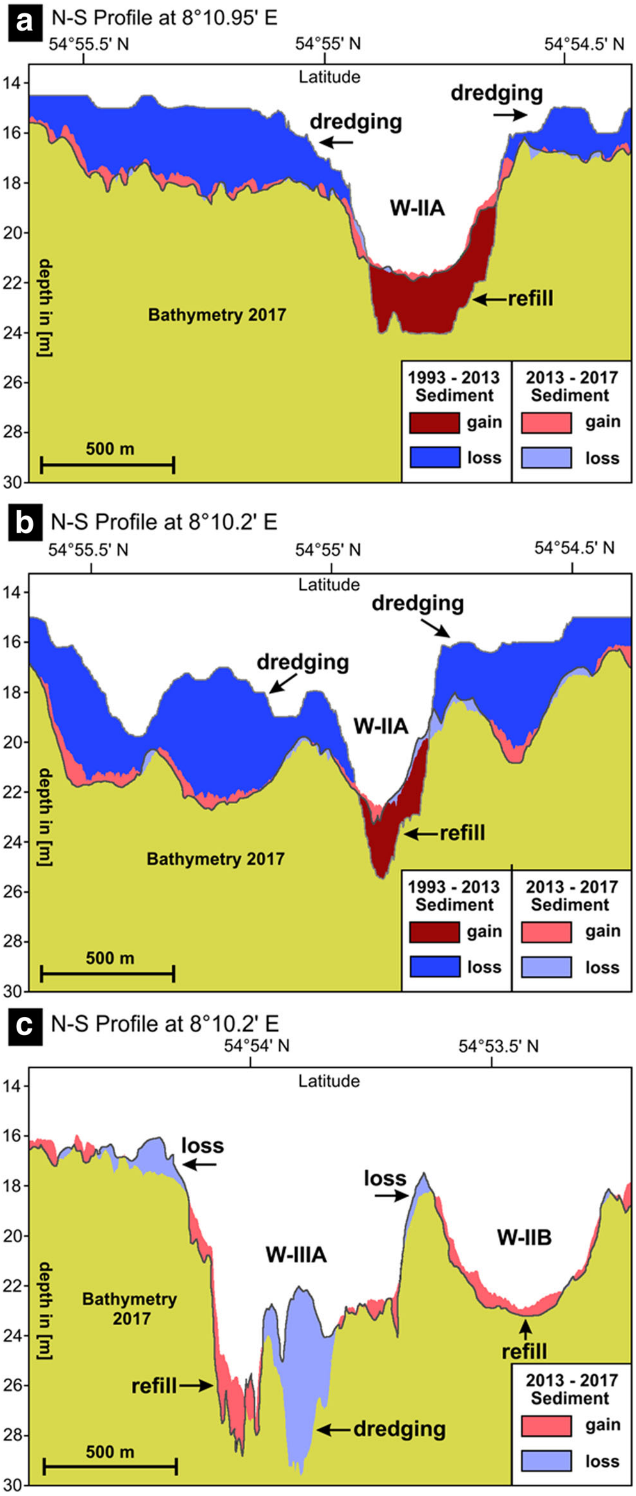


Fig. 4 Comparison of three vertical bathymetric profiles (**a-c**) of the years 1993, 2013, and 2017. The location of the profiles is shown in Fig. 2b

(medium silt) can be found in the old dredging site in *W-IIA*. This material is either poorly or very poorly sorted. In *W-IIIA*, at the most recent dredging pits, poorly sorted coarse silt was found. The surrounding areas, unaffected by the dredging activities, reveal fine to medium sand and better sorting. Here, one sample shows well-sorted coarse sand. The gravel fraction of all samples makes lower than 0.2%.

Underwater videos

For a more precise insight on the seafloor character, four underwater video transects were surveyed (for positions see Fig. 2c). The first transect run through *W-IIA*. The recordings show muddy material with occasionally shell fragments (Fig. 5a). In the deeper parts, stones and shell fragments are very rare. Here, the videos allow to identify evidences of mass movements perpendicular to the slopes of the pits (Fig. 5b).

Video Transect no. 2 leads from *W-IIA* on a slight slope into shallower water. The deeper part shows a relatively homogenous seafloor with many brittle stars (*Amphiura filiformis*) settling on a flat muddy seafloor (Fig. 5c). In the northwest, the seafloor characteristics changes upslope to more sandy material that displays small bedforms with crest distances of ~ 10 cm (Fig. 5d).

Video Transect no. 3 started at the edge of *W-IIIA* and leads along the slope across an approximately 10-m-deep dredging pit (corresponding to a water depth of ~ 25 m). In the shallower part, long-crested ripples consisting of sand are observable (Fig. 5e). In the deeper parts of *W-IIIA*, a mix of fine dark and bright sediments becomes apparent (Fig. 5f). The bright sediment seems to form small flat bedforms, while the darker material fills the troughs of the ripples. The amount of dark sediment increases with increasing water depths.

The last video survey (Transect no. 4) runs along a transect crossing a fresh dredging mark in *W-IIIA*. Here, the last sand extraction was carried out by a suction hopper dredger only a few days prior to our investigation. At the edge of the fresh dredging pit, irregular sediment structures (Fig. 5g) and piles of stones were recorded (Fig. 5h). In the deepest part with a water depth of 33 m, a similar sediment mixture as presented in Fig. 5f was identified.

Discussion

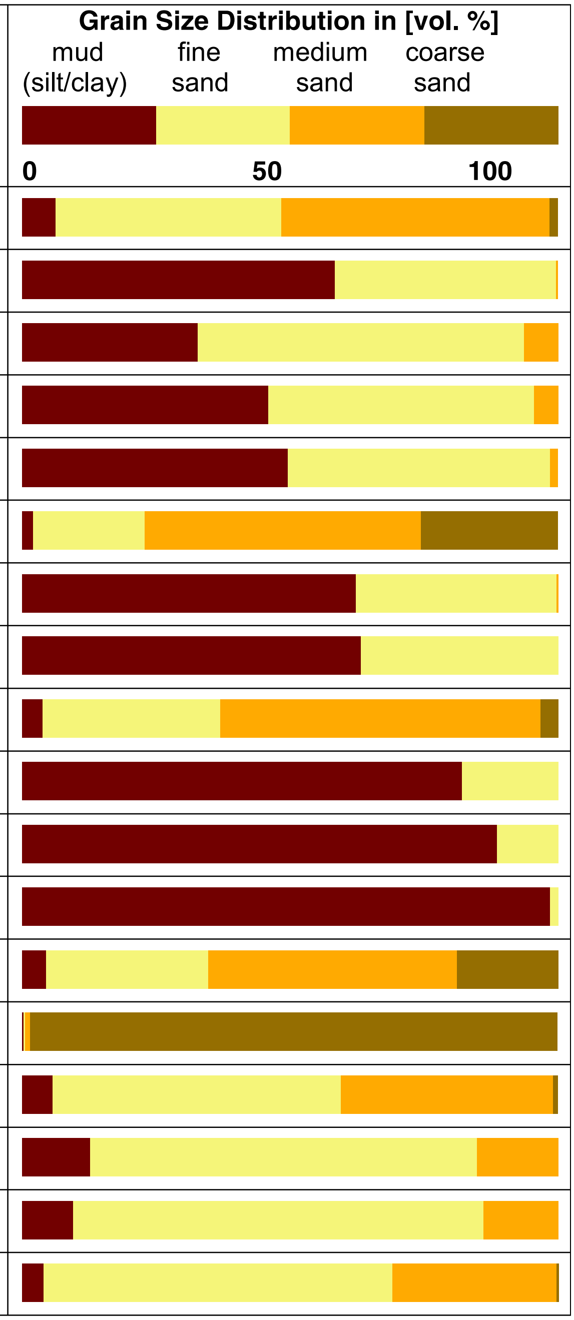
In order to determine the impact of dredging activities on the seafloor and the sedimentary characteristics of the study area, comprehensive investigations within a time frame of several years using different hydroacoustic techniques and ground truth methods were made.

Since sand mining with an extraction volume of more than 1 Mm^3 per year from a relatively small dredging site is a grave interference with the natural seafloor habitat, it is important to monitor the backfill rates of the dredging pits to assess the sustainability of sediment extraction as well as the potential of seafloor regeneration.

The results of this study show that at relatively new dredging pits, both accumulation and erosion processes became visible 6 months after the end of the mining activities.

Table 3 Samples taken in September 2016 and May/August 2017

Sample #	Folk and Ward MEAN [µm]	SORTING	Description after Folk & Ward
WDA-01	238	moderately	Fine Sand
WDA-02*	43	poorly	Very Coarse Silt
WDA-03*	86	poorly	Very Fine Sand
WDA-04*	54	poorly	Very Coarse Silt
WDA-05*	49	poorly	Very Coarse Silt
WDA-06	358	moderately	Medium Sand
WDA-07*	33	poorly	Very Coarse Silt
WDA-08*	32	poorly	Very Coarse Silt
WDA-09	275	moderately	Medium Sand
WDA-10*	14	very poorly	Medium Silt
WDA-11*	13	very poorly	Medium Silt
WDA-12*	10	poorly	Medium Silt
WDA-13	299	moderately	Medium Sand
WDA-14	916	well	Coarse Sand
WDA-15	218	moderately	Fine Sand
WDA-16	149	poorly	Fine Sand
WDA-17	170	moderately	Fine Sand
WDA-18	206	moderately	Fine Sand



WDA Westerland Dredging Area

*Material directly taken from dredging pits

Excavation marks dredged in 2016 (Fig. 2c) became smoother in 2017 (Fig. 2d). Steep slopes caused by the dredging process reveal a loss of sediment (Fig. 3) likely due to slope failure. This was also concluded based on the underwater videos and the cross sections (Fig. 5g and Fig. 4c). The material from the slopes seems to have backfilled sections of the ~12-m-deep dredging pits up to 5 m in less than 7 months. Such relatively quick backfillings were also observed by Temmler (1994) and Zeiler et al. (2004) based on comparative investigations. Older excavation pits dredged more than 1 year before our measurements showed no visible erosion or backfilling in the period of analysis.

Despite intense storm contribution to accelerate the backfill of dredging pits (Diesing et al. 2006a), data from the Weather Service MeteoGroup (2017) showed that the winter of 2016/2017 was relatively mild with no intense storm events, which often occur in the German Bight. Hence, we hypothesize that observed erosion and backfilling processes are also

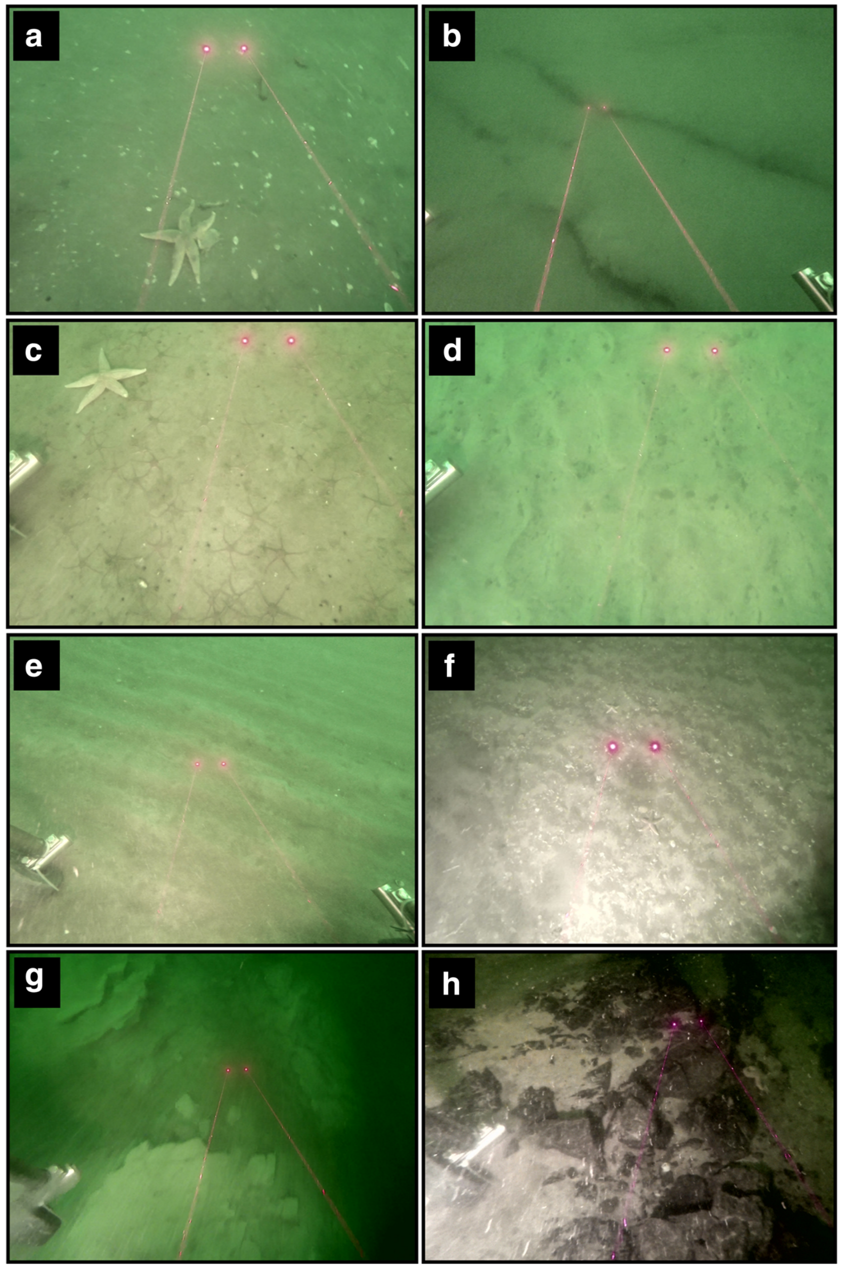


Fig. 5 Snapshots of relevant underwater features (**a**, **c** muddy seafloor; **b** mass movements; **d**, **e** bedforms; **f** mixed fine sediments; **g** fresh dredging pit; **h** stones). Distance of 10 cm between laser points serve for size comparison

significant during normal sea state conditions, mainly driven by moderate energy events and tidal currents.

A comparison of our measurements with the bathymetric map of Temmler (1994) indicates a backfilling of up to 3 m between 1993 and 2013. Data from Zeiler et al. (2004) reveal that similar dredging depths (~ 33 m water depth) were also achieved in the year 1991. This suggests that backfillings of up to 10 m are possible in a period of ~ 20 years regarding freshly dredged pits with steep flanks where sand slumps occur.

When comparing the bathymetries of 2013 and 2017 (Fig. 4), the backfill rate appears to have strongly decreased and even ceased at the older dredging pits. Backfillings of only ~ 0.5 m were detected. Such decreasing backfill-rates were also observed by Zeiler et al. (2004).

Our underwater videos and the sediment analyses of the fill material in the pits revealed that fine materials (i.e., mud) play an important role in the backfilling process. With increasing age of the excavation, also the content of mud increases. While the relatively fresh pits in W-IIIA show a mud content between 33 and 63% and poor sorting, the older dredging sites in W-IIA have a significant higher mud proportion of 82–98% and even worse sorting (Table 3). While mud enters the pits as suspended load, the currents within the pits are not strong enough to transport fine sand in higher quantities. According to Zeiler et al. (2004), the current velocity within the pits is approximately only half of that outside the pits. Apparently, bottom currents are only able to move the fine sand across the rims of the pits. Inside the pits, the sand is not transported much farther and, hence, the sand contents decrease significantly towards the centers of the pits. In contrast to the (muddy) backfill sediment found in the pits, samples from the seafloor outside the pits revealed only little mud contents (~ 2.5%), which poses the question as to where the mud in the pits originates from.

The drill cores taken from the study area investigated by Temmler (1994) also showed only small silt and clay fractions. This fine material can be found as a small fraction within the kaolin sand and as homogeneous silt layers of several centimeters in the subsoil. Hence, sediment with a small silt fraction is the source of the beach nourishment material and it is unlikely that the large amount of mud that fills the extraction pits originates from the extraction process itself. Due to the "vacuum cleaner," effect not much turbidity is produced at the seafloor (Miedema 2012). Almost all of the fine sediment that is released in the dredging process would need to settle from the sea surface after being washed out of the hopper dredger's cargo bay. At a tidal current speed of up to 1 m/s and the slow settling speed of the muddy sediment, the turbid cloud would be diluted and distributed over a wide area. As a result, only a small amount of the finer sediment fractions would fall back into the pits even if there were considerably more fine fraction in the dredged sands. Consequently, the main origin of the silty backfilling material must lie somewhere else.

According to Lohse et al. (1995), sustained sediment deposition occurs in only a few depocenters in the North Sea. Besides the Skagerrak—the most prominent depocenter—Hebbeln et al. (2003) extensively described an area approximately 80 km south of WDA called *Helgoland Mud Area*. Here, the interactions of longshore coastal currents, tidal dynamics, and sediment discharged from the big rivers Elbe and Weser, as well as disintegration of nearby islands, led to a continuous sediment deposition (Hertweck 1983; Hebbeln et al. 2003). The former holes of halotectonic origin (Schmidt-Thomé 1982) were filled with a mud deposit that reaches a thickness of up to 30 m. The sedimentation rate was between 2 and 18 mm/year (Dominik et al. 1978; von Haugwitz et al. 1988).

Geochemical analysis from Zeiler et al. (2004) of the deposition material in the dredging pits revealed organic contaminants, which point to the Elbe river as a source. However, recent studies showed that high amounts of suspended sediment also seem to enter the study area from the western North Sea (Valerius et al. 2015). If we assume similar sedimentation rates as in the *Helgoland Mud Area*, which were also predicted by Putzar and Malcherek (2015), it would take ~ 500 years until the trenches are completely re-filled.

Along the rims of W-IIA, for example, indicators for a natural regeneration towards the former seafloor conditions become visible. This is where the shallow outer margins of the depressions have already filled up to the level of the ambient untouched seafloor while the dredging pits have become slightly smaller with time. This is in accordance with Diesing et al. (2006a) who investigated extraction sites in the Baltic Sea and concluded that shallow extractions favor faster regeneration while deep extractions might not backfill within years to decades.

Similar processes of recovery after sand extraction were also found by Van den Eynde et al. (2010) and Degrendele et al. (2010) at a dredging site on the Kwinte Bank (Belgian Continental Shelf). Their work showed that a backfill of the trenches is possible if enough sandy material is available.

Strong backfilling processes were also observed at an extraction site on a sandy shoal southeast of Port Royal Sound (South Carolina, USA) for example. According to Xu et al. (2014), here, also mud originated from nearby estuaries accumulated in the dredging pits after a few months. However, these accumulations were rapidly buried by sand deposits and the area remained usable for sand mining. Yet, a lack of mobile sediment and weak transport rates in the area west of Sylt lead to much lower sedimentation rates (Valerius et al. 2015), implying considerable more time for a significant backfill.

A subsequently possible reuse of an exhausted WDA-II and III in the near future can be largely excluded, since the available refill material (i.e., mobile mud and fine sand) is not compatible with the beach environment. This was also the case at several other sand mining sites all over the world (Van Dalfsen et al. 2000; Fraser et al. 2006; Crowe et al. 2016). Consequently, and due to the high amount of material needed for beach nourishment on Sylt, it does not seem to be feasible to limit the dredging depth in WDA to a shallow level that favors fast natural regeneration. To do that, it would be necessary to dredge significantly larger seafloor sections, which would extend the detrimental effects to natural habitats in a larger area. Since the coast of Sylt will continue to be affected by strong erosion, the sand extraction for beach nourishment is likely to increase in the future rather than cease. That also means that the dredging areas will grow larger. It is, thus, of great importance to initialize future management activities especially in the framework of the Schleswig-Holstein Wadden Sea Strategy 2100 (Wattenmeerstrategie 2100, MELUR-SH 2015) with adequate monitoring to detect positive developments regarding habitat stability and natural regeneration potential, but also adverse effects at an early stage.

Conclusions

In this study, we determine the impact of dredging activities and discuss the potential for subsequent natural regeneration of the seafloor in the largest German dredging area west of Sylt. Hydroacoustic methods in combination with ground truthing were used to evaluate the present conditions, to reconstruct the development through the past decades, and to discuss future conditions in this heavily disturbed area. We conclude that (1) the steep slopes of new dredging pits cause slope failure (sand-slips, slumps) and erosion. (2) Sluggish bottom currents within the pits prevent sand transport and allow mud to settle. Based on the available data, the time for the complete re-establishment of natural conditions is difficult to estimate. Most likely, it will take many decades to few centuries. However, even after more than 30 years, the traces of the deeper excavations are still clearly recognizable.

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