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Impact of sand extraction from the bottom of the southern Baltic Sea on the relief and sediments of the seabed

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Sand extraction
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Abstract

Investigations of the geological structure and seabed dynamics as well as the morphological and sedimentological effects of sand extraction generated by different mining techniques were carried out in Polish waters of the Baltic Sea, NW of the Gulf of Gdańsk, at a water depth of 15–17 m. Three research cruises took place: just before, directly after and 11 months after dredging operations. Seismoacoustic profiling, a multibeam echosounder, a side-scan sonar, a 3 m vibro-corer and a box-corer were used during the research cruises. The grain size distribution and ^{137}Cs content of the sand samples were determined. Marine shells were dated by the AMS^{14}C technique and pollen analyses were carried out on samples of muddy sands lying below the marine sand. A 2 to 4.5 m thick layer of marine sands lies on the boulder till and locally on late Pleistocene ice margin lake deposits. The ^{137}Cs content indicates that the 0.4–0.8 m thick sand layer is mobile during storms.

After the dredging operations, four pits with diameters from 80 to 120 m, depths from 3 to 4.5 m and slopes with gradients up to 30–55° were measured. Several smaller irregularly shaped pits and double furrows 30–150 m in length and 0.3–0.5 m in depth were found. The sonar mosaic also shows a 50–100 m buffer zone of fine sand around the pits which flowed over the dredger's side with water and settled on the bottom.

During one year after the dredging operation the furrows generated by trailer suction hopper dredging as well as the fine sand cover around the pits disappeared completely. The four post-dredging pits left by stationary suction dredging were shallower by 2–2.5 m, their diameters increased by 40–50 m, the gradient of the slopes was reduced by up to 5–10°, and the total volume was only about 3.5% smaller than directly after dredging.

1. Introduction

Sand and gravel resources in the Polish Exclusive Economic Zone of the Baltic Sea are already subject to mining procedures. Artificial beach nourishment with sand from the sea bottom is the basic method of coastal defence proposed by the strategy of coastal protection (Cieślak 2001), which has been implemented by the Polish Parliament in the Act 'Programme of coastal protection' (Official Gazette No. 67 pos. 621, 18 April 2003). This has resulted in an ever increasing demand for resources from the sea bottom in Poland, as in other EU countries, where sand and gravel mining from the sea bottom takes place on a large scale (e.g. Herrmann et al. 1999, Humphreys et al. 1999, Schwarzer 2010). Mining of the sea bed affects the environment in a number of ways. The type and scope of changes in the marine environment, mainly on the sea bottom, is determined by the method of clastic (gravel and sand) material extraction. Stationary extraction, either by bucket or suction dredgers, results in extensive depressions/pits in the sea bottom of diameters exceeding 100 m and depths of over 10 m. Trailer suction hopper dredging leaves a trace in the form of 1 or 2 parallel furrows 0.2 to 0.5 m deep and 2 to 3 m wide. By this method only a thin surface layer of deposits is removed from a large surface of the bottom. Both types of extraction disturb the marine environment in that they:

– remove a layer of deposits which constitutes a habitat for benthic organisms, resulting in a reduction of biomass,
– change the morphology of the sea bottom,
– generate a temporal plume of suspended matter in the water column, which later settles on the seabed.

The magnitude and stability of all these changes depend on the type of exploited deposit, the amount of extracted material, the method and time of extraction, as well as exposure to waves and currents.

In many countries the effect of the exploitation of clastic resources on the marine environment is extensively investigated, and special attention is given to the rate of resettlement of benthic organisms in the dredged pits (e.g. ICES 2001, Boyd et al. 2004, Cooper et al. 2005) and the rate of physical seabed regeneration (Kubicki et al. 2007, Manso et al. 2010). In Poland investigations of the effect of excavating gravel from the seabed were carried out on the Słupsk Bank in 1988–1989 (Gajewski & Uścinowicz 1993). In spite of the increasing amounts of sand and gravel extracted, however, no further scientific investigations were carried out.

The growing scale of offshore dredging has triggered an international exchange of experience and information on the impact of these activities, the minimising of their negative effects, and the development of monitoring methodology. These were the objectives of the COST 638 Action 'Investigating and managing the impacts of marine sand and gravel extraction and use'. The research project 'Impact of sand extraction from the bottom of the southern Baltic Sea on seabed structure and meio- and macrobenthos communities', financed by the Ministry of Science and Higher Education (grant No. 305/N-COST/2008/0), was connected with the objectives of the above-mentioned COST Action. This paper presents the results of investigations of the geological structure and the physical effects of sand extraction in the study area, concerning especially:

– the origin and age of the extracted sand and its immediate substratum,
– the dynamics of sediments (thickness of the mobile layer displaced during storms),
– the geomorphological and sedimentological effects of sand extraction and the rate of regeneration (disappearance) of post-dredging pits and furrows in relation to the methods of extraction.

2. Location and characteristics of the study area

The investigations were carried out in the south-eastern part of the Baltic Sea, in the shallow water area north of Władysławowo (Figure 1). It

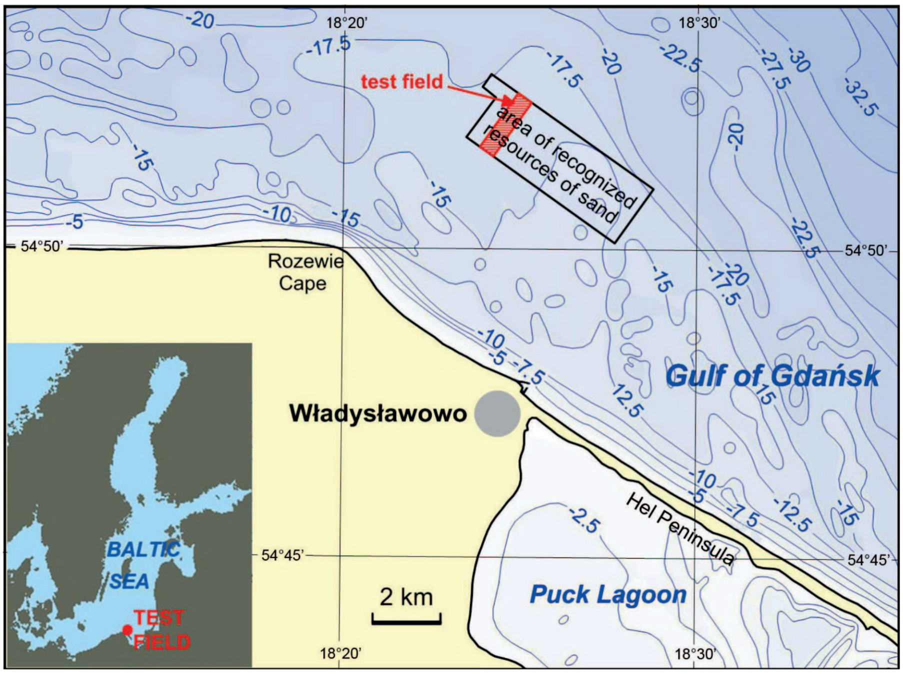

Figure 1. Location of the area of investigation within the documented sand resource 'Rozewie Field'

was known that medium and coarse sand is present on the seabed surface (Pikies & Jurowska 1992). More detailed investigations of the area were ordered in 1992 by the Maritime Office in Gdynia. Documentation of the sand accumulations was performed by the 'Petrobaltic' enterprise together with the Maritime Institute in Gdańsk. The so-called 'Rozewie Field' of coarse and medium sand was documented in an area of 2×5.5 km, located 5 to 7 km off the coast at depths between 14 and 17.3 m (Figure 1). The thickness of the sand was found to be 1.0 to 3.2 m, and the volume of the resource was assessed at 12 250 000 m^3 (Anon 1992).

For the needs of the present project, a 1 km^2 test field was selected in the western part of the documented sand field, where no sand had yet been extracted. The test field was divided into two parts of 0.5 km^2 each. In one, the extraction of 200 000 m^3 of sand was planned, while the other was to remain undisturbed to serve as a reference area (Figure 2a, see p. 864).

In the former part, mining of 150 000 m^3 of sand in a layer of 1 m thickness by trailer suction hopper dredging was planned in the south. In the north a total of 50 000 m^3 of sand was to be excavated at 4 sites by stationary suction dredging, forming 3 to 5 m deep pits (Figure 2a). The extracted sand was to be used for nourishing the open sea beach of the Hel

Peninsula at its connection with the mainland (ca 9 km southeast of the study area).

Only a general outline of the hydrodynamic conditions in the area of investigations is known. The Baltic is a non-tidal sea. The lack of tidal currents and the large variability of wind direction and speed mean that there is no clear water circulation pattern in the study area. The dominant role is played by the waves and currents generated during storms. In the investigated area storm winds, depending on direction, can generate waves with a mean height of 1.5–2.5 m (Paszkiewicz 1983, 1994) and a length of 45–80 m. Since the water depth in the test area is less than 17.3 m, wave-induced currents act directly on the sea bottom. Investigations carried out 15–20 km to the south-east of the test area showed that, at 15–20 m depth, a 0.4–0.6 m thick layer of sand could be displaced during storms (Łęczyński 2009).

3. Scope and methods of investigation

3.1. Measurements at sea

All measurements at sea were carried out on board the r/v IMOR. Three research cruises took place.

During the cruise in March 2009, immediately prior to the sand extraction, the following operations were carried out:

- 20 km of measurements with a multibeam echosounder and side-scan sonar (full coverage of the sea bottom – 10 track-lines every 50 m parallel to the longer side of the study area);
- 4.5 km of seismoacoustic profiling (profiles SBP-1, -2 and EF);
- 8 cores taken with a 3 m vibro-corer, 4 of them in the area of planned sand mining (COST-1 to 4), and 4 in the reference area (COST-5 to 8). The lengths of the cores were (from COST-1 to COST-8) 2.5, 2.3, 2.9, 2.3, 2.1, 2.4, 2.2 and 1.6 m respectively.

In May 2009, on completion of the sand extraction, the following operations were carried out:

- 20 km of measurements with a multibeam echosounder and side-scan sonar (along the same track-lines as in March 2009);
- 4 cores were taken with a 3 m vibro-corer (PKT-1 to 4).

In April 2010, eleven months after the sand had been extracted, the following operations were carried out:

- 20 km of measurements with a multibeam echosounder and side-scan sonar (along the same track-lines as in March 2009);

– 8 short cores (up to 0.3 m) taken with a box-corer in the area where the sand was extracted, including the bottoms of post-exploitation pits (BX 1–8).

During all these operations, positioning was carried out using the DGPS AG-132 Trimble navigation system with RTCM correction transmitted from the Rozewie station resulting in a horizontal accuracy better than 0.5 m. Integration of the measurement systems was ensured by the QINSy software package. This permitted the synchronisation of the measured values and positions, taking into account the spatial displacement of all sensors with respect to the antenna of the navigation system. The bathymetric, side-scan sonar and seismoacoustic profiling was carried out at a vessel speed not exceeding 4 knots. The CODA data acquisition system was used for the registration and numerical recording of acoustic signals.

Water depth measurements were carried out with a Reson SeaBat 8101 multibeam echosounder operating at 240 kHz frequency. The bathymetric data obtained were corrected for actual sea level recorded on the Władysławowo gauge, and the velocity of sound in water was measured with a Reson Sound Velocity Probe 15. The volume of sediment was obtained by comparing the results of bathymetric measurements made before and after exploitation. The calculations were performed using a Spatial Analyst extension of the ESRI ArcGIS software.

Sonar profiling was carried out with a dual frequency 100/400 kHz EdgeTech 4200 side-scan sonar with a range of 50 m for each receiving channel. Full Spectrum CHIRP technology was used, which ensures better imaging resolution than in standard sonar systems.

For seismoacoustic measurements an Oretech 3010S sediment profiler was used (frequency 5 kHz, snap time 50 ms, timing 10 ping sec^{-1}). Geophysical records were processed with MDPS MERIDATA software with sound velocity of 1.45 m ms^{-1} in water and 1.6 m ms^{-1} in sediment. Vibrocorer data were inserted into the interpretation package for correlation with geophysical data.

Cores were taken with a VKG-4 vibro-corer with a coring tube with a length of 3 m and an internal diameter of 91 mm. The locations of the coring points (COST-1 to 6, Figure 2a, see p. 864) were selected after previous analysis of the seismoacoustic profiles. The cores were taken to the laboratory, where a detailed macroscopic description was carried out and samples for laboratory investigations were taken – from each layer, in accordance with macroscopically visible differences in grain size distribution.

During the voyage in April 2010, sediment samples were taken with a box-corer with sampler 50 cm in length and 30 cm in diameter (BX-1 to 8; see Figure 2a for the locations).

3.2. Analyses

Samples for grain size analysis were taken from each layer macroscopically visible in the cores. Sieving was used for grain size analysis. The grain size fraction content was defined in 1ϕ unit intervals using sieves of mesh sizes 32.0, 16.0, 8.0, 4.0, 2.0, 1.0, 0.5, 0.25, 0.125 and 0.063 mm for cores COST-1 to 7 and box-cores BX-1 to 8. All together 120 grain size analyses of sand from the exploited layer and from the bottom of the post-dredging pits were performed. Core COST-8 was not analysed for granulometry.

Sixteen pollen analyses were carried out on samples of muddy-sand deposits occurring below the marine sand at sites COST-1, 2, 6 and 8. Samples for microscopic examination were prepared using the standard method (Fægri & Iversen 1975, Berglund 1979). Results were presented in the form of histograms obtained with POLPAL software. The percentage of each taxon in the pollen spectra was calculated in relation to the sum of trees, bushes and herbaceous plants (AP+NAP). In samples of deposits in which the low frequency of pollen grains did not permit the calculation of a percentage, the presence of single grains was indicated by a '+' sign.

Two radiocarbon dates of shells from marine sand were obtained. The shells were taken from cores COST-3 (at 2.80 m) and COST-6 (at 2.15 m). The datings were performed by the AMS method in the Radiocarbon Laboratory of the Silesian University of Technology in Gliwice.

The caesium 137 content was measured in 22 samples from 6 cores: COST-3 and 8 as well as BX-2, 3, 5 and 6. Activity was measured with a CANBERRA semiconductor high resolution spectrometer provided with a germanium type HP (high purity) detector. The sample mass was 800 g and the average time measurement was 24 hours. Soil-375 and Soil-6 standards from IAEA were used as standards of ^{137}Cs activity. The measurements were converted to Bq kg^{-1} and corrected for radioactive decay since the time the sample was taken. Measurements of ^{137}Cs content were carried out at the Institute of Physics of the Silesian University of Technology in Gliwice.

4. Results

4.1. Relief and geological structure of the sea bottom in the investigated area

The sea depth in the investigated area, measured directly before sand extraction operations, was between 15 and 17.5 m (Figure 2c). In the southern, reference part the flank slopes south-westwards, between depths of 15 and 16 m. In the northern part, designated for exploitation, the flank

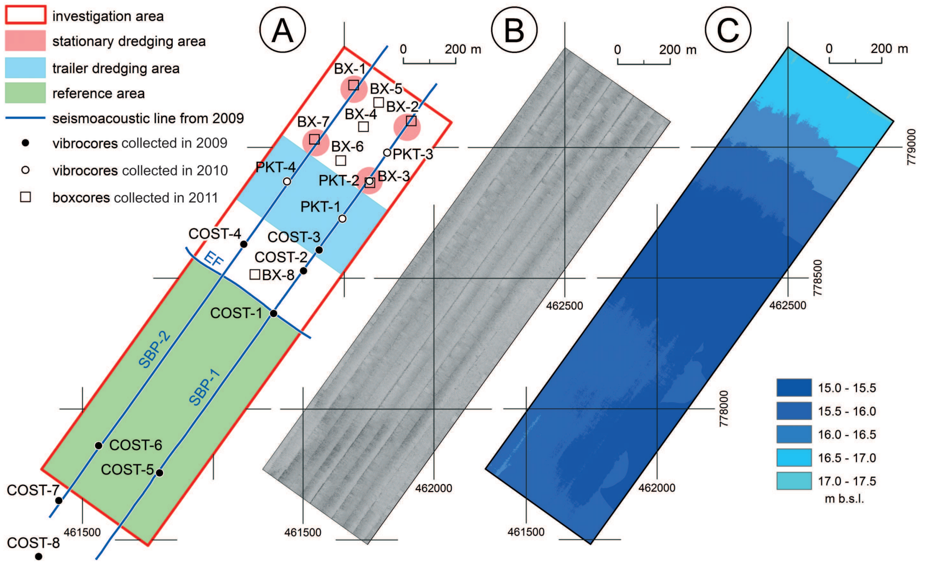

Figure 2. The area of investigation directly before sand extraction (March 2009): a) plan of the test field; b) sonar mosaic of the sea bottom; c) bathymetric map of the sea bottom

slopes north-eastwards, and the depth increases by 2.5 m over a distance of 1 km.

The sonar picture of the bottom surface before sand extraction (Figure 2b) shows, like the bathymetric map, a plane-like bottom with no visible bedforms.

The slight differences in the tone and structure of the acoustic backscatter records are caused mostly by noise and other artefacts. Slightly more distinctive differences in the tone of the records are visible only in the southern part of the investigated area, indicating a variety of sand grain sizes. The light tones in the SW part suggest the presence of a small patch of fine-grained sand and the darker tones visible more to the east indicate sand with a small admixture of gravel (Figure 2b).

Seismoacoustic profiling showed that it is mostly till that occurs in the area below the marine sand (Figure 3). The top of the till, located 17–18 m b.s.l. (below sea level), is rather even. It slopes down to about 21–22 m b.s.l. in the north-eastern part of the test area. There exist some local depressions in the top of the till with a depth of 2–3 m (maximum 5 m) and a diameter of 100–200 m. The depressions are filled with muddy-sandy, calcareous deposits with sand laminas. Their colour ranges from dark grey to olive grey. The top of those deposits is erosional, and their thickness depends on the depth of the depressions in the till. Their topmost part

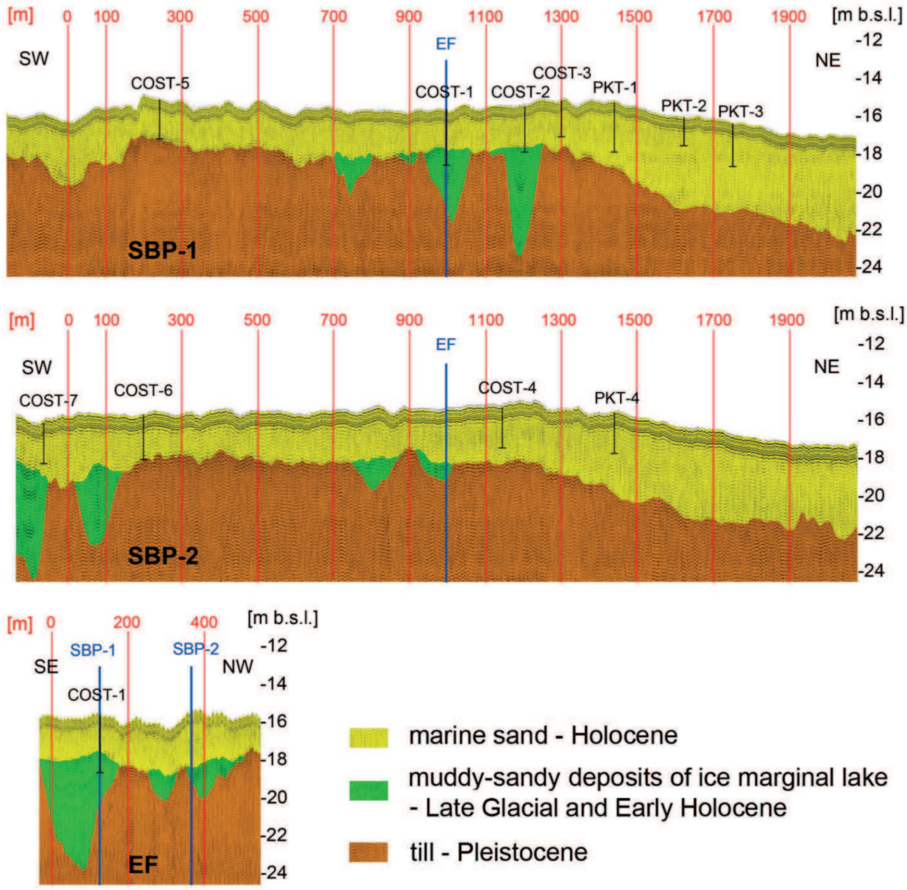

Figure 3. Interpretation of the seismoacoustic profiles (location shown in Figure 2)

was found in cores COST-1 (at 2.28 m), COST-2 (at 2.2 m), COST-6 (at 2.1 m) and COST-8 (at 0.7 m). According to the lithology those deposits are interpreted as ice marginal lake deposits, which are well known in the vicinity (Pikies & Jurowska 1992).

Palynological analysis of the deposits shows a significant proportion of the pollen of species characteristic of communities of a heliophilous cold climate vegetation, such as wormwood (*Artemisia*), goosefoot (*Chenopodiaceae*) and rock rose (*Helianthemum*), as well as a complete lack of pollen from species with higher temperature requirements (Figure 4). The dominance of pollen from anemophilous pine (*Pinus*) in all the pollen spectra must be due to the substantial involvement of long-range transport in an open tundra landscape. Among the grains of birch (*Betula*) pollen, small ones, most probably of dwarf birch (*Betula nana*), are prevalent. The

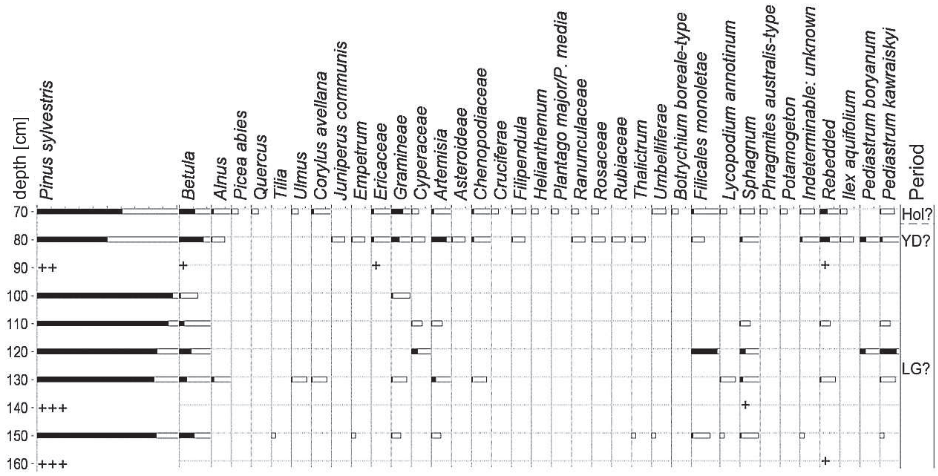

Figure 4. Pollen diagram of ice marginal lake deposits from core COST-8

cold, arctic climate is also confirmed by the presence of microspores of a spikemoss (*Selaginella selaginoides*) in the deposits at station COST-2. Single grains of lime (*Tilia*), elm (*Ulmus*), oak (*Quercus*) or hazel (*Corylus*) pollen, present in Late-Glacial deposits, come from the redeposition of older deposits. Partial redeposition is also indicated by the presence of pollen grains of Tertiary species, summed up in the histograms in the 'Rebedded' curve.

The presence of pollen grains of aquatic plants and rush vegetation, such as bur-reed (*Sparganium*), and also of water lily (*Nymphaea*), water-milfoil (*Myriophyllum*) and pondweed (*Potamogeton*), indicates that all the deposits examined were formed in a shallow body of stagnant water. This is also confirmed by the significant amounts of green algae (*Pediastrum*) coenobia, a taxon occurring in the plankton of shallow lakes and bays. The species *Pediastrum kawraiskyi* is characteristic of cold-water, oligotrophic Late-Glacial water bodies.

The pollen analyses indicate unequivocally that sedimentation of these deposits took place during the Late-Glacial period. However, the topmost sections of the deposits filling the depressions in the boulder till (stations COST-6 and 8) contain a significant percentage of juniper (*Juniperus*) and hazel (*Corylus*) pollen, which suggests that, at least locally, water bodies (lakes) occurred in the study area during the transition period from the Late-Glacial to the Holocene and also during the early Holocene.

Seismoacoustic profiling and core profiles showed a 2 to 4.5 m thick layer of sands containing marine shells lying on the till and locally on Late-Glacial ice-marginal lake deposits (Figure 3). Only in core COST-8, located outside the area designated for dredging, is the sand thickness 0.7 m. In the northern part of the study area these are mainly medium sands with admixtures of coarse sand (Figure 5, COST-2, 3 and 4); fine- and medium-grained sand occurs only locally at the surface (Figure 5, COST-1).

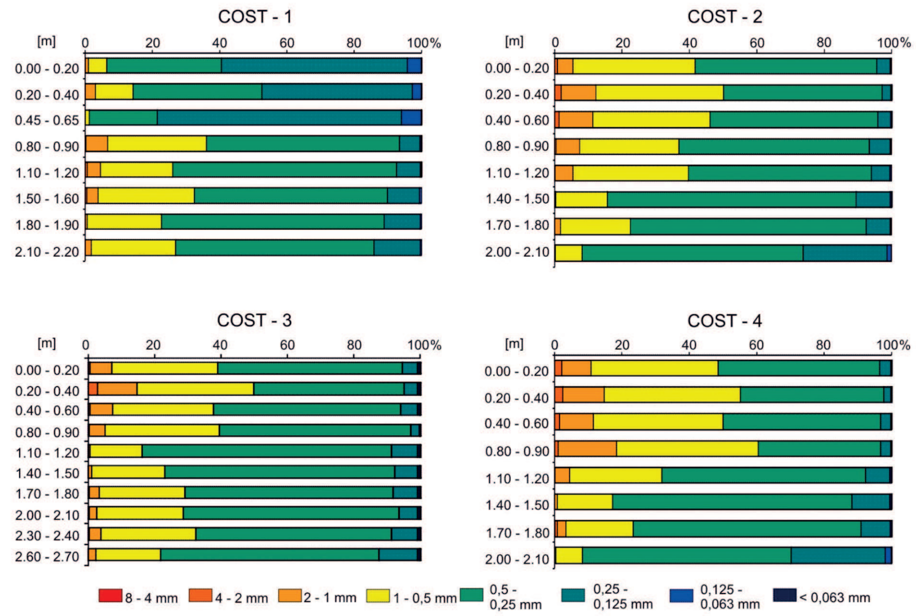

Figure 5. Grain size distribution of deposits in cores COST-1, 2, 3, 4

In the southern part of the area, i.e. the reference area, the sand grain sizes vary to a greater extent (Figure 6, COST-5, 6, 7). Medium- and coarse-grained sand here overlies fine- and medium sand (COST-5 and 7), whereas a 0.6 m thick layer of sandy gravel was found in core COST-6, below such a sequence at 1.5 m. Significant gravel admixtures also occur in the lowermost parts of marine deposits in cores COST-1 and 3. The lowermost part (below 2.1 m) of core COST-6 (Figure 6) represents muddy sands of ice-marginal lake origin.

The radiocarbon dates of the *Cerastoderma* sp. shells found on the floor of the marine sediments, within and beneath the sand/gravel layer, at depths of 2.8 m (core COST-3) and 2.15 m (core COST-6) below the seafloor, are 3275–3145 (GdA-2039) and 4775–4590 (GdA-2040) cal. y. BP respectively (95.4% probability).

The thickness of the contemporarily mobile layer of sediments, transported by currents and waves during storms, was determined by measuring

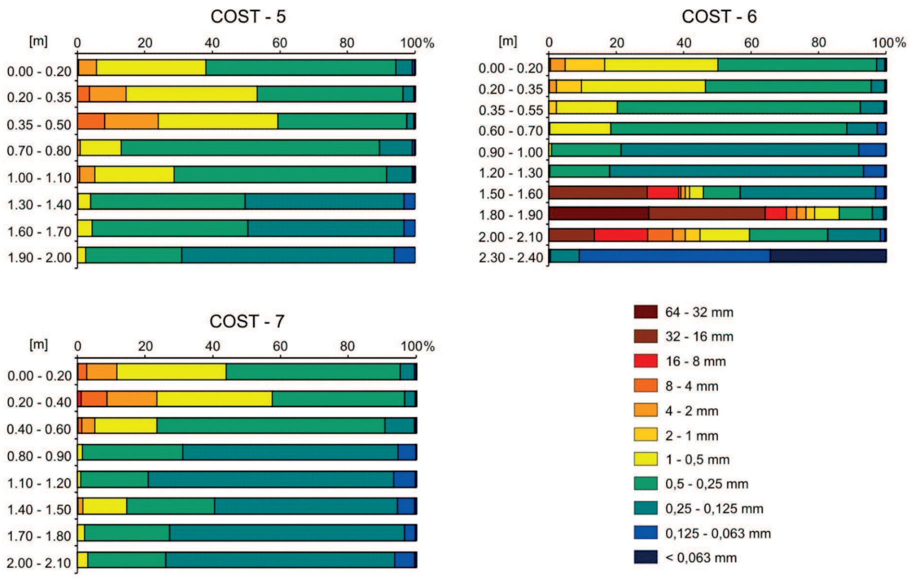

Figure 6. Grain size distribution of deposits in cores COST-5, 6 and 7

the content of ^{137}Cs in the cores. Caesium 137 is an artificial radionuclide, which entered the environment after 1945 as a result of nuclear weapons testing and accidents in nuclear power plants. Therefore the presence of caesium in sandy deposits allows the determination of the thickness of the layer undergoing redeposition during the last few decades. In the cores examined, the thickness of the sand layer containing ^{137}Cs is between about 0.40 m in core COST-8 and about 0.8 m in core COST-3 (Figure 7).

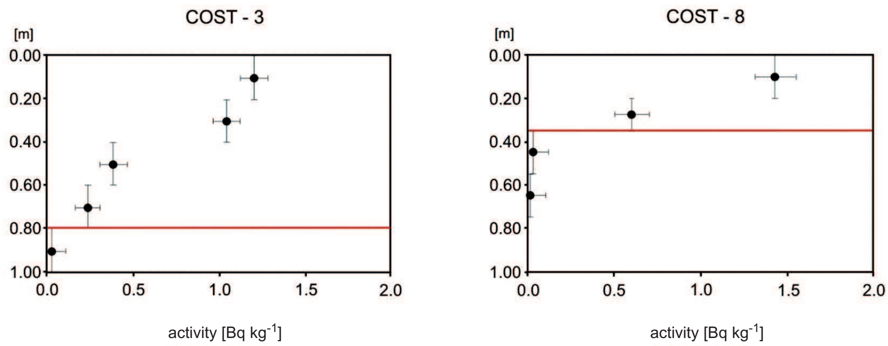

Figure 7. Caesium-137 content in the sands of cores COST-3 and COST-8

4.2. Impact of sand extraction on the bottom relief and structure of sediments

The bathymetric map and sonar mosaic, recorded directly after the sand extraction ended, show significant changes in the bottom relief and distribution of sediments resulting from the extraction. As we had planned for the experiment, four pits were formed with diameters of about 80–120 m and depths of 3 to 4.5 m in the northern part of the area designated for stationary suction mining (Figures 8a,b). The maximum gradient of their slopes was 55° (Figure 8c). The surface of the bottom of the pits was uneven with 0.5 to 2.0 m irregularities. The total volume of the pits left by stationary extraction was about 58 500 m^3.

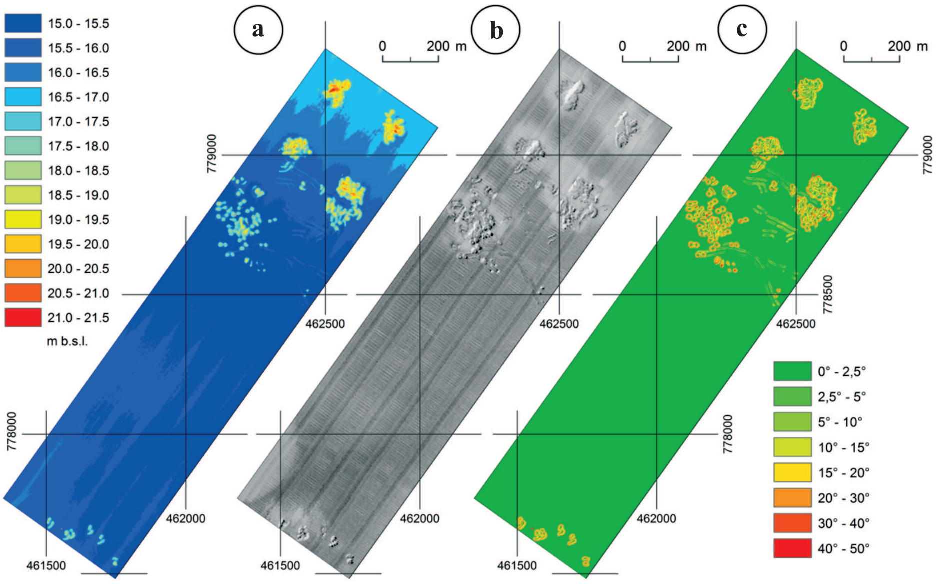

Figure 8. Area of investigation directly after sand extraction (May 2009): a) bathymetric map of the sea bottom; b) sonar mosaic of the sea bottom; c) gradient of slopes of dredging pits and furrows

In the part designated for extraction by trailer suction dredging, a 1 m thick layer of sand was to be taken off in a regular pattern of straight, neighbouring furrows. However, sand exploitation in this part was not carried out according to plan. In effect, several irregularly shaped double furrows of different lengths were formed, and several pits were left by unplanned stationary dredging (Figures 8a,b,c).

The lengths of the furrows varied from 30 to 150 m, their width from 5 to 10 m and their depth from 0.3 to 1.9 m. The gradients of the furrow slopes were between 5 and 15° (Figure 8c). The distance between the furrows of 25–30 m was rather stable – it was dependent on the suction dredger's parameters.

Although the furrows should have been the predominant trace of operations in this part of the test field, much more often there appeared small, irregularly distributed, traces of stationary dredging or dredging with the dredger moving very slowly. Such traces were also found in the south of the reference part of the test field, where extraction had not been planned. The diameters of these pits were about 20 to 70 m, their depths from 2.5 to 4 m, and their slopes had gradients as steep as 50°.

The total volume dredged by trailer suction dredging and of the small, irregular dredging pits from non-planned stationary dredging was about 52 500 m^3.

Apart from the dredging furrows and pits, the sonar mosaic (Figure 8b) also shows that the areas around the pits and furrows became covered with very fine to fine sand fractions, which flowed over the dredger's side and settled on the seabed near the dredging sites. The sonar mosaic shows them

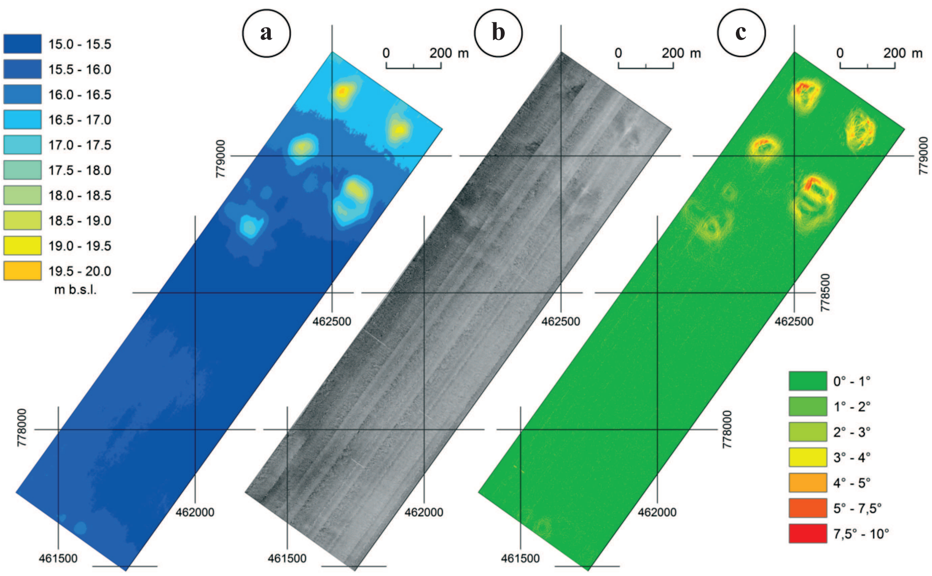

Figure 9. Area of investigation 11 months after sand extraction (April 2010): a) bathymetric map of the sea bottom; b) sonar mosaic of the sea bottom; c) gradient of slopes of the dredging pits and furrows

up as a bright buffer zone of 50–100 m around the dredge marks. This fine sand cover was up to 0.1–0.2 m thick.

Comparison of the bathymetric records made directly before and directly after the sand extraction operations (Figures 8a, 9a) allows one to assess the volume of the fine sand cover formed as a result of the dredging operations at about 15 000 m^3. The total volume of the dredging furrows and pits was estimated at ca 111 000 m^3, which, after subtracting the fine sand volume left in the area of dredging operations, makes about 96 000 m^3 of sand used for nourishing the Hel Peninsula beaches. This appeared to be 45% of the amount assigned by the Gdynia Maritime Office for beach nourishment there in spring 2009.

Measurements carried out in April 2010, eleven months after the cessation of sand extraction, showed that, depending on the method of extraction, the dredging traces had partly or completely evened out. The depths of the dredging pits were between 2.5 and 3.0 m, i.e. they had become 2–2.5 m shallower, and the bottoms of the pits were flattened. The diameters of the pits were between 120 and 170 m, i.e. they had increased by 40–50 m (Figures 9a,b). The gradients of the dredging pit slopes were also reduced. The maximum gradient was no steeper than 10° (Figure 9c). After 11 months, the total volume of the 4 pits from stationary dredging was

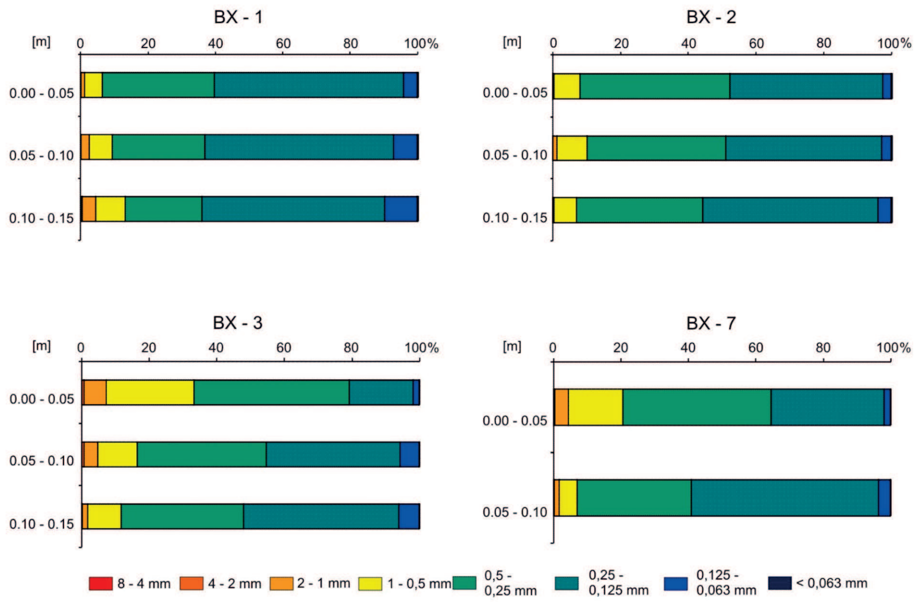

Figure 10. Grain size distribution of sediments filling the dredging pits 11 months after extraction ceased

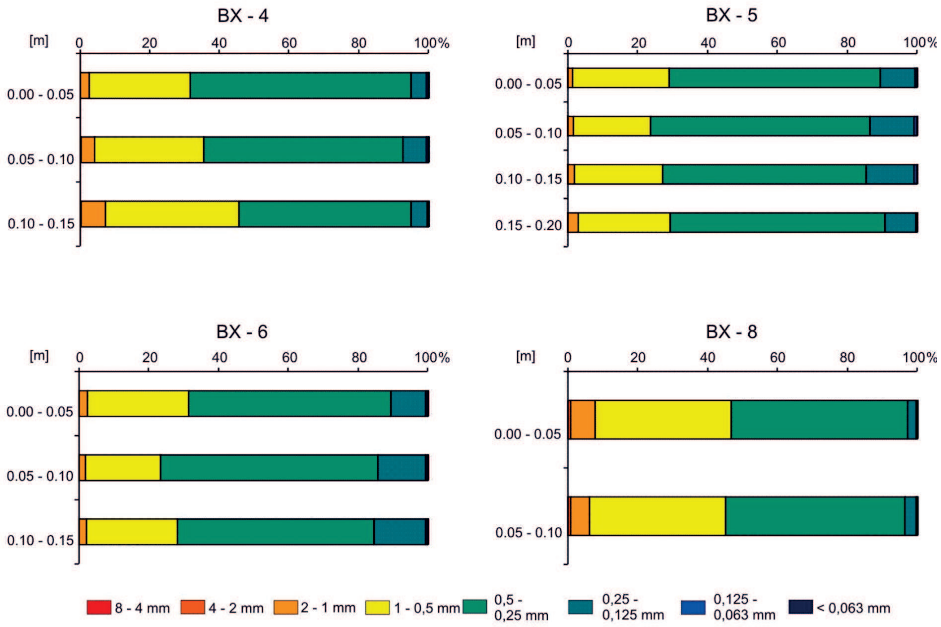

Figure 11. Grain size distribution of sediments between the dredging pits 11 months after extraction ceased

about 56 500 m^3, i.e. about 2 000 m^3 smaller than directly after the dredging.

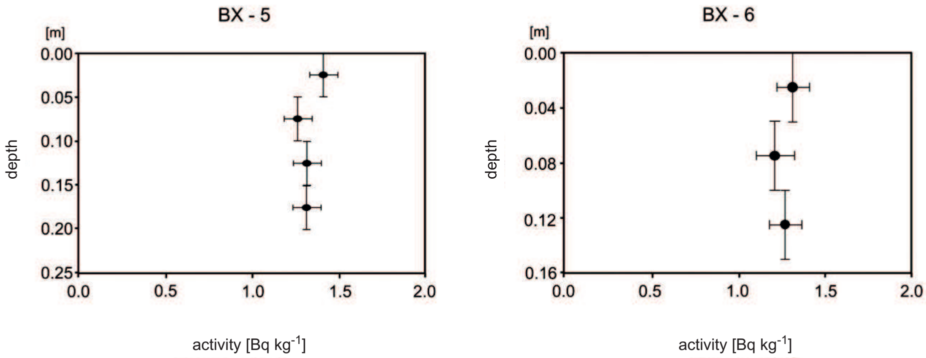

Figure 12. Caesium-137 content in sediments recovered between the dredging pits 11 months after the end of extraction

The bottom of the stationary dredging pits is covered with fine to medium sand (Figure 10). The sonar mosaic obtained 11 months after the completion of extraction operations (Figure 9b) shows no more bright patches around the post-dredging pits. This is also confirmed by the grain size distribution of sands from box-cores taken between the post-dredging pits (Figure 11). The composition of the surface layer of sediments is the same as before the dredging operations.

The proportion of fine sand transported over the seabed surface and accumulated in the pits is also indicated by the variable ^{137}Cs content. While the normal ^{137}Cs content in bottom surface deposits in this region does not exceed 1.5 Bq kg^{-1} (Figures 7, 12), the concentration in the pits was as high as 4.26 Bq kg^{-1} (Figure 13).

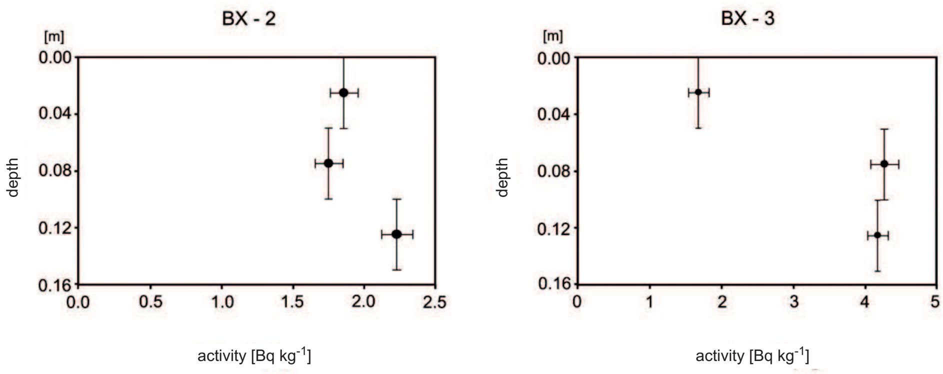

Figure 13. Caesium-137 content in sand filling the dredging pits 11 months after the end of extraction

The traces left by the smaller dredging pits derived from chaotic stationary exploitation (Figure 14 – Profiles 03 and 04) were transformed and filled to a greater extent than the pits from planned stationary operations. In the area with several adjacent pits having diameters of 20 to 70 m, depths of 2.5 to 4 m and slope gradients of up to 50°, extensive and shallow depressions were present 11 months later, with diameters of 200 to 300 m, a maximum depth of 2.0 m and a slope gradient of 4° (Figure 14 – Profiles 03 and 04).

All the furrows formed by trailer suction dredging had disappeared completely after 11 months (Figure 14 – Profiles 05, 06, 07) except for one depression 70–80 m in diameter and with a maximum depth of 0.5 m left by the deepest pair of furrows, initially 1.9 m deep.

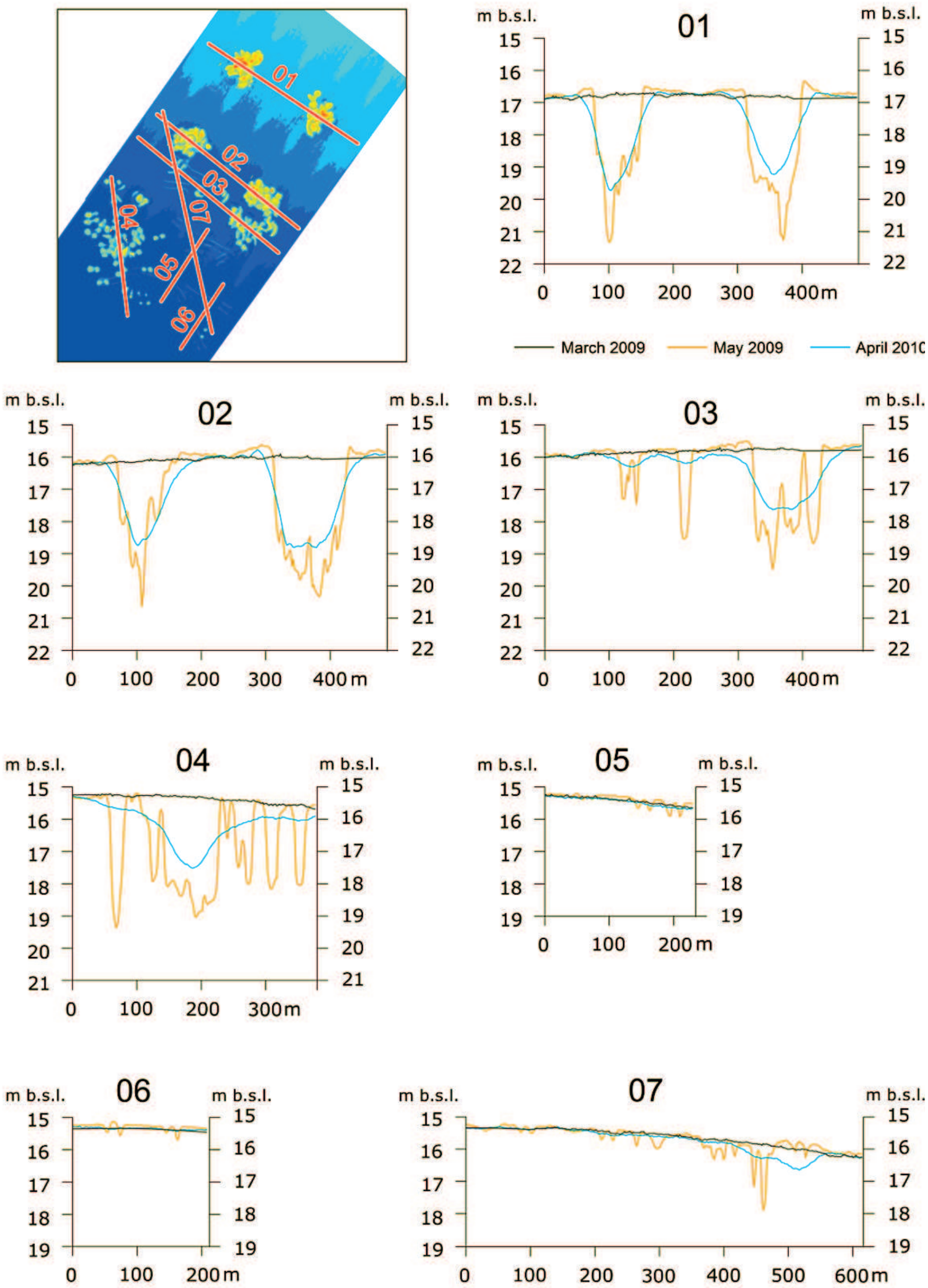

Figure 14. Morphological profiles across dredging pits formed by planned stationary dredging (Profiles 01 and 02), exploited by unplanned stationary dredging (Profiles 03 and 04), and morphological profiles across furrows left by trailer suction dredging (Profiles 05, 06 and 07)

5. Discussion

The increasing scale of offshore dredging is raising questions not only about the impact of these activities on the marine environment, but also about the availability of sand and gravel resources. There is a scarcity of sediments in many regions of the Baltic Sea owing to the low input of material. Therefore, information on the age and origin of the sand and gravel deposits as well as about their stability and potential for regeneration are of great importance.

Considering the age of the layer of marine sand under discussion and taking into account the rsl curve for the southern Baltic (Uścinowicz 2003, 2006), we can state that the transgressing sea reached the area of investigation ca 8500 years ago. The radiocarbon age of marine shells (3275–3145 and 4775–4590 cal. y. BP) and the significant admixtures of gravel in the lowermost part of the bed of sand indicate that erosion and redeposition predominated during ca 5000–4000 years, and that when transgression ceased and the sea level approached the contemporary one, the accumulation of sand started. During the following ca 3500–4500 years, a 2–4 m layer of marine sand accumulated; it would seem that at that time redeposition during storms probably did not reach the floor of the layer.

The thickness of the contemporarily mobile layer of sand, as determined by measurements of the ^{137}Cs content in the cores, is between ca 0.40 m in core COST-8 and ca 0.8 m in core COST-3 (Figure 7). A similar thickness of sands containing radiocaesium (0.4–0.6 m) was shown by investigations carried out 15–20 km to south-east of the test area at 15–20 m depth (Łęczyński 2009). The depth of radiocaesium penetration depends not only on near-bottom hydrodynamics but also on the grain size distribution of sediments. The water depth at the sites where cores COST-3 and COST-8 were taken is nearly the same: 15.1 m and 15.6 m respectively. This half-metre difference in water depth does not justify the difference in the depth of ^{137}Cs penetration into the deposits. This is most probably due to the dissimilarity in grain sizes. Coarse sand with an admixture of gravel is present in the area from which core COST-8 was taken, whereas medium sand overlies the area where core COST-3 was obtained. Medium sand needs a lower critical current velocity to initiate its movement than coarse sand, and storms can rework a thicker layer of the deposit.

Other basic questions concern the rate of regeneration, i.e. the rate of disappearance of morphological changes and changes in sediment distribution. Most previous studies have focused on tide-dominated areas of the North Sea, so comparison with the tideless Baltic Sea is difficult; the discussion will therefore be limited to the Baltic Sea.

Measurements carried out in the test field 11 months after the cessation of sand extraction showed that, depending on the method of extraction, dredging traces had partly or completely evened out.

The furrows caused by trailer suction hopper dredging in the sandy sediments disappeared almost completely during 11 months. Investigations carried out on the Słupsk Bank yielded similar results. Furrows dredged in gravelly deposits at a water depth of 16–19 m also disappeared almost completely within the space of 9 months (Gajewski & Uścinowicz 1993). This suggests that, in the open waters of the southern Baltic Sea, furrows with initial depths of ca 0.5 m produced by trailer suction dredging in both sandy and in gravelly sediments, regenerate during the course of a year, regardless of sediment type. This is in contrast to the SW Baltic Sea's less energetic coastal waters, where furrows are still visible a few years after the cessation of dredging (Manso et al. 2010).

The pits left after stationary extraction regenerated at slower rate. Although after 11 months their diameter had increased, they had become shallower and the gradients of their slopes were less steep; depressions with gentle slopes remained in the seabed. The increase in pit diameter and the decrease in slope gradient indicate that the pits became shallower mainly because of the slipping of the slopes. The uniform character of the pits' slopes and bottom (Figure 14), and their smaller volume, also suggest that these artificial depressions in the seabed acted as sediment traps, where sandy material transported by waves and currents during storms was accumulated. However, the volume of the post-dredging pits decreased only by about 3.5%. This confirms that the filling of the pits was due mainly to the slipping of the pit slopes, and that the supply of deposits from neighbouring areas was relatively small. The occurrence of fine to medium sand at the bottom of the pits (Figure 10) suggests that part of the fine sand which enveloped the pits was transported into the pits and settled together with the material from slope slipping. The sonar mosaic obtained 11 months after the end of extraction (Figure 9b) showed no more bright patches. This indicates that the patches of fine sand around the post-dredging pits, which were formed during sand extraction operations, were dispersed by currents and partly deposited in the pits. That fine sand accumulated in the pits is also indicated by the variable ^{137}Cs content. While the ^{137}Cs content in superficial sands in this region did not exceed 1.5 Bq kg^{-1} (Figures 7, 12), the level in the pits reached 2.23–4.26 Bq kg^{-1} (Figure 13). The increase in ^{137}Cs content occurred in the course of extraction, when the finest fractions, the carriers of radionuclides, flowed with water over the dredger's sides and sank to the bottom near the pits. The medium and coarse fractions remaining in the dredger's hold became poorer in ^{137}Cs.

Thus, a thin layer of fine sand with a higher ^{137}Cs level was formed on the sea bottom surface around the pits, and during storms it was transported by near-bottom currents and deposited in the pits. The inversion of the ^{137}Cs content in the deposits filling the dredging pits (Figure 13) most probably occurred owing to the prior accumulation of fine sands richer in ^{137}Cs lying closest to the pits, which then became covered by material poorer in ^{137}Cs sliding down from the slopes.

Despite the changes in morphology, the pits still existed after 11 months. The sediments covering the bottom of the pits showed no increase in the amount of mud or dead algae, which indicates that wave-induced currents can act directly on the bottoms of such pits. This is not the kind of depression in which dead algae or other harmful substances can accumulate, as was the case in the Puck Lagoon (NW Gulf of Gdańsk), where post-dredging pits became sediment traps in which organic matter accumulated and rapidly decomposed. Periodically, the chemical reduction of sulphate in the sediments caused hydrogen sulphide to occur in the Puck Lagoon pits (Graca et al. 2004).

The regeneration of post-dredging pits in the studied area of open southern Baltic waters is more similar to what happens in the SW Baltic, e.g. in German coastal waters (Kubicki et al. 2007, Manso et al. 2010). However, this experiment showed that the spatial extent of changes in the type of sedimentary cover was limited to just a few dozen metres around the post-dredging pits following the settlement of the fine sandy suspension. A year after the extraction works operations, the thin layer of fine sand had dispersed, and the surface of the sea bottom was covered by deposits with grain sizes similar to the pre-extraction situation. This is the reverse of what occurs in the SW Baltic, where the effects of dredging can also be detected in the superficial grain-size distribution. The areas affected by dredging operations (Tromper Wiek East) present a finer sediment and higher abundance of mud than non-impacted areas (Manso et al. 2010). This can be explained by differences in the composition of extracted sediments and the hydrodynamics of the areas. Sand extracted in SW Baltic coastal waters contain a more silty fraction, whereas fine fractions are almost absent in sands extracted from the southern Baltic. German coastal waters are also better protected against storms than the open waters of the southern Baltic.

6. Conclusions

- The bed of sand in the investigated area accumulated after the end of the middle Holocene (Littorina) transgression. The contemporary seabed dynamics in the area is at a relatively high level. The thickness of the currently mobile layer of sand, as determined by measurements of the ^{137}Cs content, is between 0.4 and 0.8 m and depends on the grain size distribution.

- The regeneration of dredging marks depends on the dredging technique used. Furrows caused by trailer suction hopper dredging are less stable than pits left after stationary extraction. Regeneration rates in both furrows and pits were rapid during the first year after the end of sand extraction. The furrows in sandy sediments disappeared almost completely during 11 months, while the pits became shallower and more gently sloped, although they were still visible.

- Slope slipping was the main process causing the morphological changes in the pits. The pits also acted as sediment traps for sandy material transported by waves and currents. However, the small changes in pit volume indicate that the supply of deposits from neighbouring areas played a secondary role during the study period.

- The spatial extent of the changes in type of sedimentary cover was limited to just a few dozen metres around the post-dredging pits following the settlement of the fine sandy suspension. A year after the extraction operations, the thin layer of fine sand had dispersed, and the surface of the sea bottom was covered by deposits of a grain size similar to that prior to extraction.

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