Journal of Coastal Research	SI	51	187-194	West Palm Beach, Florida	Summer 2010

Nearshore dredging in the Baltic Sea: Condition after cessation of activities and assessment of regeneration

Faustino Manso[1*], Rolandas Radzevicius[2], Nerijus Blažauskas[3], Arnaud Ballay[4***] and Klaus Schwarzer[1]**

[1] Christian Albrechts University
Institute of Geosciences
Sedimentology, Coastal and Continental Shelf Research
Ludewig Meyn Strasse 10
D-24118 Kiel, Germany

[*] Present address:
Fugro-Geoteam AS
Address Hoffsveien 1C
0213 Oslo (Norway)
f.manso@fugro.it

[2] Department of Marine Sciences
School of Environment
University of the Aegean
University Hill
Mytilene 81100, Greece

[**] Present address: Department of Marine Research. Institute of Geology and Geography
Vilnius 03223, Lithuania

[3] Klaipeda University Coastal Research and Planning Institute
H.Manto 84,LT-92294, Klaipeda, Lithuania

[4] Department of Geography and Climatology
Faculty of Geology and Geoenvironment
National and Kapodistrian University of Athens
Panepistimioupolis, Zografou
15784 Athens, Greece

[***] Present address: EcoPlage
100 route de Clisson F44200
Nantes. France.

ABSTRACT

Using hydro-acoustic survey techniques (side-scan sonar and multibeam), high-resolution bathymetric and acoustic images (sonographs) of former marine aggregate extractions, from Tromper Wiek (Rügen Island, Baltic German Coast) were obtained. These data, together with ground-truthing (underwater video and seabed sediment samples) are used to describe the present condition of marks generated by mining, in terms of their morphology and superficial grain size distribution. Different features (pits and furrows), generated by different extraction techniques (anchor suction dredging and trailer hopper suction dredging, respectively) were detected at both of the study sites: Tromper Wiek 1 (sandy gravel seabed) and Tromper Wiek East (sandy seabed). Regeneration varies, depending upon the material extracted and the mining technique applied. In general, it is rapid during the first years following the extraction, becoming almost undetectable over a longer period of time. However, the marks are still detectable after more than 10 years, since they were generated.

ADDITIONAL INDEX WORDS: *Marine aggregates; dredging effects; regeneration; western Baltic Sea.*

INTRODUCTION

Marine aggregate dredging consists of transferring sediment, generally using powerful pumps on a suction pipe, from the seabed to the dredging vessel. Investigation into the physical impact generated by such activities has been undertaken previously (i.e. Boyd *et al.*, 2004; Dickson and Lee, 1973; Gajewski and Uscinowicz, 1993; and Price *et al.*, 1978); however, most of these studies have focused mainly upon tidally-dominated, sandy, areas of the seabed. The objective of this contribution is to describe the present state of former extraction sites in a non-tidal area, where the sediments are mainly relict. For the investigation, high-resolution hydro-acoustically-based approaches were used. These will permit: 1) evaluation of the results of dredging operations, in terms of the morphology and superficial grain size distribution; and 2) the investigation of trends and processes related to the evolution of the area. Subsequently, regeneration rates can be established through the comparison with previous datasets; this will provide an indicator of the suitability of these extractions, in the long-term.

The Baltic Sea can be considered as being "sediment starved", due to the low input of material. As such, the regeneration of marine aggregate extraction sites extends over longer periods of time, in comparison to more active areas (Diesing *et al.*, 2006). During the early phase of dredging operations in the Baltic Sea, the vessel was stationary, or anchored, whilst the dredge pipe excavated the seabed. Material was often screened onboard, with the unwanted fractions (undersize or oversize) being returned immediately to the overlying waters. This technique, "anchor" or "static" dredging, generated deep pits on the seabed. Elsewhere, previous studies have evaluated the recovery of such pits, over several years, in gravelly substrates (Dickson and Lee, 1973); over a year, in the case of pits in channels associated with high current velocities (Van Der Veer, Bergman, and Beukema, 1985). In order to minimise the impacts on the seabed, dredging marine aggregates has evolved towards "trailer (suction) hopper" dredging. In this case, the lower end of the suction pipe is trailed slowly (at around 1-2 knots) across the seabed. Such an approach generates long shallow furrows.

DOI: 10.2112 / SI51-017.1 received 14 January 2007; accepted in revision 27 February 2008.

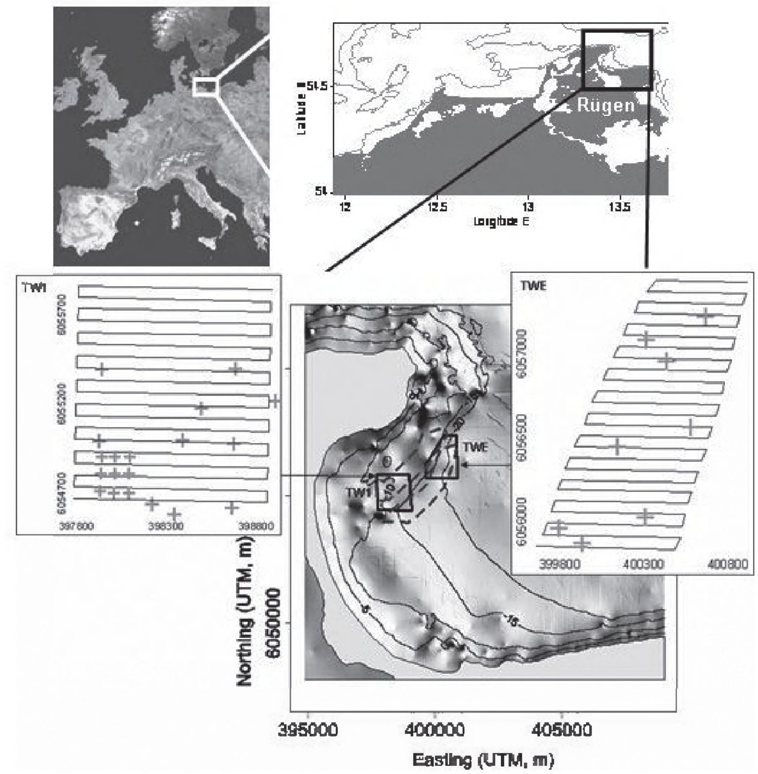

Figure 1. Location of the study area, within Europe and the Baltic Sea. In the Tromper Wiek image, the dashed lines correspond to the overall extent of the areas commissioned for dredging; solid lines to the zones of interest selected for the present study. The grids followed for the data acquisition are also presented, together with the location of the specific sites for which detailed data sets are investigated (grey crosses).

The study area

The study was undertaken within Tromper Wiek, a semi-enclosed bay located to the NE of Rügen Island (Figure 1). Tidal currents are hardly discernable (the tidal range is a few cm). Although wind driven currents may have some significance, the waves are the most important hydrodynamic agent for sediment mobility. The bay is located east of a spit, between two headlands (Figure 1). Due to this coastal configuration, Tromper Wiek is exposed only to waves from the 0-90° quadrant, with a maximum fetch of about 90km. Throughout the year, westerly winds dominate. High waves are only generated during the late winter and early spring (February to May), when strong easterly to northeasterly winds prevail (MOHRHOLZ, 1998).

Various sedimentological environments on the seabed, ranging from gravel to mud, are associated with several extraction sites, located close to each other; here, different materials are extracted. For the purpose of this study, two sites were selected for investigation (not under exploitation presently): Tromper Wiek 1 (TW1); and Tromper Wiek East (TWE). At Tromper Wiek 1, 231.000m^3 of gravel has being extracted, in water depths ranging between 9 and 14m, from 1988 to 1999-2000. At Tromper Wiek East, sand has been extracted from water depths of around 20 m, on two occasions: in 1989 (151.000m^3); and in 2000 (104.000m^3) (DIESING *et al.*, 2006).

In order to facilitate establishing the effects related to dredging activities, the present study has focused upon locations, from the commissioned areas, where the extraction of material was most intense (ZEILER *et al.*, 2004).

DATA ACQUISITION AND ANALYSIS

Multibeam and side-scan sonar data were collected, simultaneously, onboard *RV Littorina* (IfM-GEOMAR) in 2003. The survey lines were designed in such a way as to ensure data overlapping, in relation to the swath width of instruments. The vessel speed was set at 5 knots. Due to technical problems, groundtruthing (seabed grab samples and underwater video) was performed in October 2004, onboard *RV Alkor* (IfM-GEOMAR).

Multibeam Data

The multibeam unit was a hull-mounted L3 ELAC NAUTIC SEABEAM 1185 (126 beams, emitting pulses at 180 kHz). Measurements were carried out in water depths of between 9 and 20m. To ensure full coverage of the seafloor, at all depths, the beams were set at 150°; this permitted a swath width of 7.5 times the working depth. The resolution of the multibeam (ranging from 0.26 to 0.52m) depends upon the ensonified area, which can be computed on the basis of the width of the emitted beams (1.5°x1.5°) and the water depth (from 10 to 20m). Utilising this equipment, two different datasets have been acquired: bathymetry and sonographs, based mainly upon the amplitude of the backscattered signal (FISH and CARR, 2001).

Following sound velocity and water level calibration, the data were processed using HDP-Edit® (Elac Nautik®). 3D editing with Fledermaus®6.1.4b-pro (IVS 3D®) was undertaken to correct artefacts caused by MRU (motion reference unit) calibration problems. Subsequently, data from the outer beams were rejected, due to interferometric noise. Data were visualised using Surfer 8® (Golden Software®) and Fledermaus®6.1.4b-pro.

Data from the German Hydrographic Service, BSH (acquired in 1999) was collected using a hull-mounted Atlas Hydrosweep MD (80 beams, emitting pulses of 50 kHz).

Side-Scan sonar Data

Side-scan sonar data were acquired using a dual frequency (100-500kHz) high-resolution side-scan sonar (Klein Assoc. Inc., USA, Model 595). The 500 kHz frequency (beam width 0.2°) was selected and the range was set at 50m. The side-scan sonar data were processed with a resolution of 0.25m, since an along-track resolution (mainly beam width dependent) of 0.2m and an across-track resolution (based of the pulse length) of 0.075m was computed. The side-scan sonar fish was fixed underneath a larger buoyancy fish, to maintain the system in a stable position, minimising the effect of ship motion (SCHWARZER *et al.*, 1996). The data were processed with the ISIS Sonar®6.06 software (Triton Elics®), performing corrections on the vessel speed, slant range, layback, time-varying gain and navigation. For visualisation Delphmap 2.9 (Triton Elics®), Erdas Imagine® and Surfer 8 (Golden software®) were used. Generally, in the case of shallow surveys, when comparing two side-scan sonar sonographs from the same area, various effects can generate fluctuation on the position of the features (up to few tens of metres) in relation to: positioning errors, due to rapid changes of position of the dGPS antenna; current-generated drifting of the towed sonar fish, etc.

Hydro-acoustic data implementation

Side-scan sonar and multibeam backscatter maps were used to estimate seabed nature, based on differences in reflectivity (as a backscattered signal) (BLONDEL and MURTON, 1997; FISH and CARR, 2001; and ROBINSON *et al.*, 1995). Higher reflectivity represents acoustically-hard material and is, in this study, darker on the imagery. On the basis of the higher geometrical accuracy of the multibeam backscatter map, compared with the side scan sonar mosaics, this multibeam backscatter was merged with the multibeam bathymetry. Still, the resolution of the side-scan sonar mosaics is higher.

Ground-truthing

Based upon the side-scan sonar mosaic and the underwater video (towed Mariscope MICRO underwater video system, with black and white CCD), sample sites were selected from

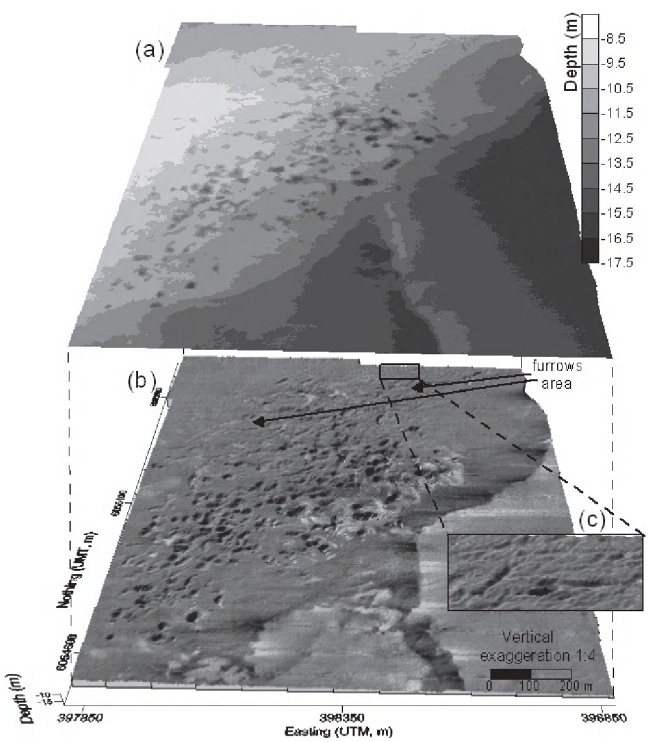

Figure 2. (a) bathymetric chart; (b) composite surface (multibeam bathymetry, merged with multibeam backscatter) of TW1. Detail of an area of furrows is presented in (c). Depths presented are relative to mean sea level.

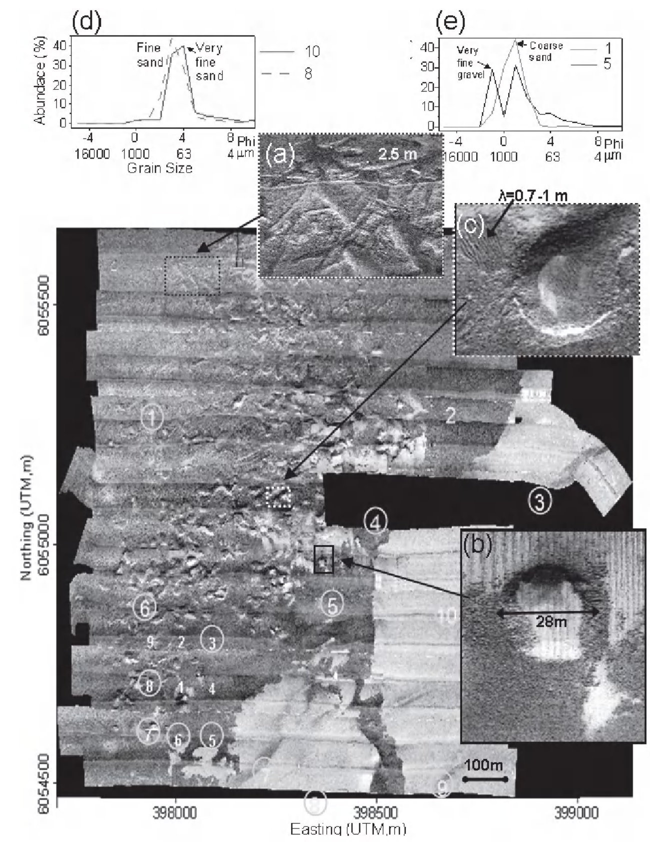

Figure 3. Side-scan sonar mosaic of TW1, with detailed images of relevant features ((a), (b), (c)). Numbers represent sample locations; only those shown by circles were recovered. The grain size distributions of undisturbed sediments from the low reflectivity (d) and high reflectivity (e) areas are presented.

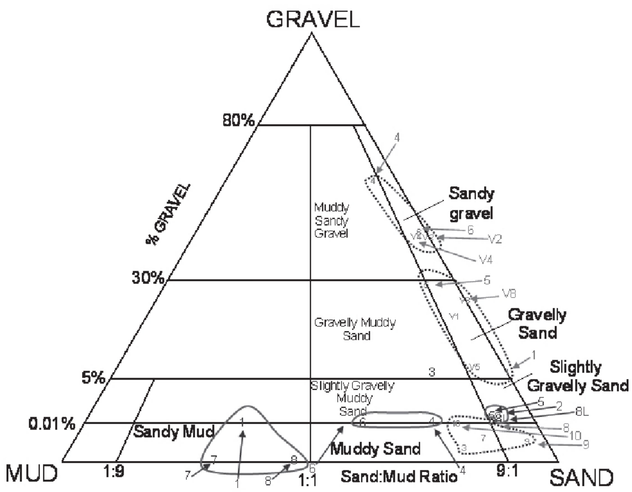

Figure 4. Ternary diagram of the gravel-sand-mud percentage of the samples from the study area. Dashed lines group TW1 samples, whist solid lines group TWE samples. V stands for the samples related with the small grid on the southwestern part of TW1 (see Figure 3.). L stands for the subsurface sample taken from TWE Sample 8 (Figure 6.).

representative locations, i.e. dredged 'impacted' and 'unimpacted' parts of the seabed. Seabed samples were collected using an 80 kg Van Veen grab (HELCOM standard). Samples were obtained from the upper 5-10 cm; at one station, two depth intervals (0-5 and 10-15 cm) were sampled to investigate granulometric changes, between the superficial and the underlying sediment deposits.

Grain size analysis

Sediment samples were analysed by combining the results of a Beckman Coulter LS 13320 laser diffraction particle analyser (fraction <2000 μm) and of dry sieving (fraction >2000 μm). For the very-coarse sediments, dry sieving was undertaken using sieves of 4000, 2800, 1400, 1000, 710, 500, 355, 250, 180, 125, 90 and 63 μm. All the grain size data were transposed into phi units, with a 1Φ interval. Based upon the logarithmic grain size distribution of the sediments, the mean grain size and sorting coefficient were calculated, according to the Folk and Ward method (1957). Calculations were performed using the GRADISTAT program (Blott and Pye, 2001).

RESULTS

Tromper Wiek 1 (TW1)

On the composite image of the Tromper Wiek 1 site, established using multibeam bathymetry and backscatter datasets (Figure 2), a sharp contact between two areas of different reflectivity is observed, partly because of a change in the slope of the seabed.

Furrows, generated by trailer suction hopper dredging, appear in the upper part of the image. However, the main features consist of abundant deep pits, generated by anchored suction dredging; around these, patches of lower reflectivity can be identified. In terms of reflectivity some horizontal artefacts (related to the

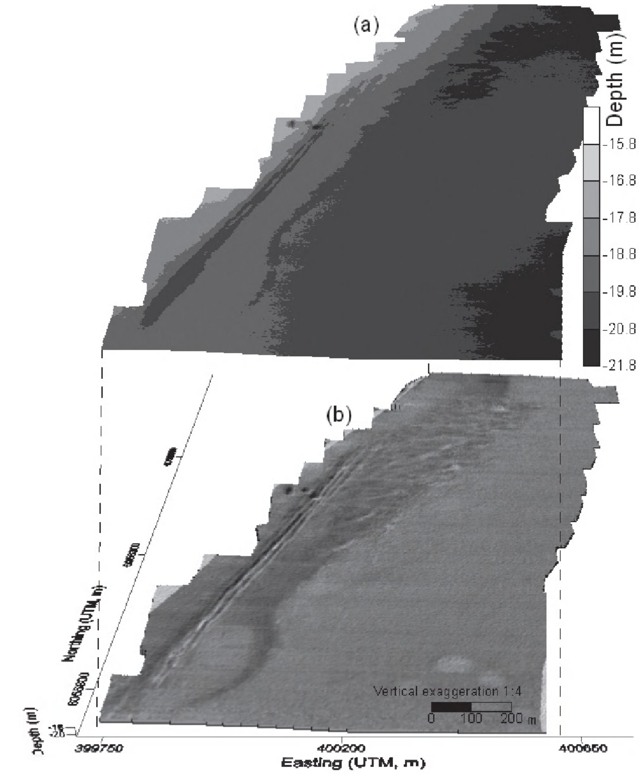

Figure 5. Bathymetric map (a), together with a composite surface (multibeam bathymetry merged with multibeam backscatter), of TWE (b).

tracks followed by the vessel) are visible; this pattern is related to the automatic gain of the multibeam attempting to adjust the signal, in response to the sharp changes in reflectivity of the different seabed materials. From the imagery, it appears that areas where dredging activities took place correlate with high reflectivity zones. In these zones, around 21% consists of pits, and 3% of furrows. The average size of the pits is 16±5.4m in diameter (on the basis of 47 measurements) and 1.7±1m in terms of the average water depth (on the basis of 82 measurements). The length of the furrows range between 15m and 290m, with an average width of 2.4±0.5m. A mosaic of the side-scan sonar tracks reveals the same general features, as observed on the multibeam backscatter map (Figure 3), i.e. sharp contact between areas of different reflectivity, including furrows (Figure 3a) and pits (Figure 3b).

This higher resolution image permits detailed features to be examined, such as the area of lower reflectivity around the pits (~32% of the total area). Looking into more detail, some observations can be made about the composition of the seabed, prior to the ground-truthing. On the high reflectivity area, lower reflectivity patches occur only around the pits, indicating their dredging-related origin. This finer material (associated with lower reflectivity) is related to the "undersize" particles spilled back to the water during dredging operations, as established during previous studies undertaken on the same area (Klein, 2003). The presence of ripples on the deeper part of the pits (Figure 3c), instead of the same material (in terms of reflectivity) observed on the unimpacted seabed, indicates that spilled material accumulates on these features. The wavelength of the ripples (0.7±0.15m) and their crestline orientation (from 45° NE, to 174° NW), have been computed, on

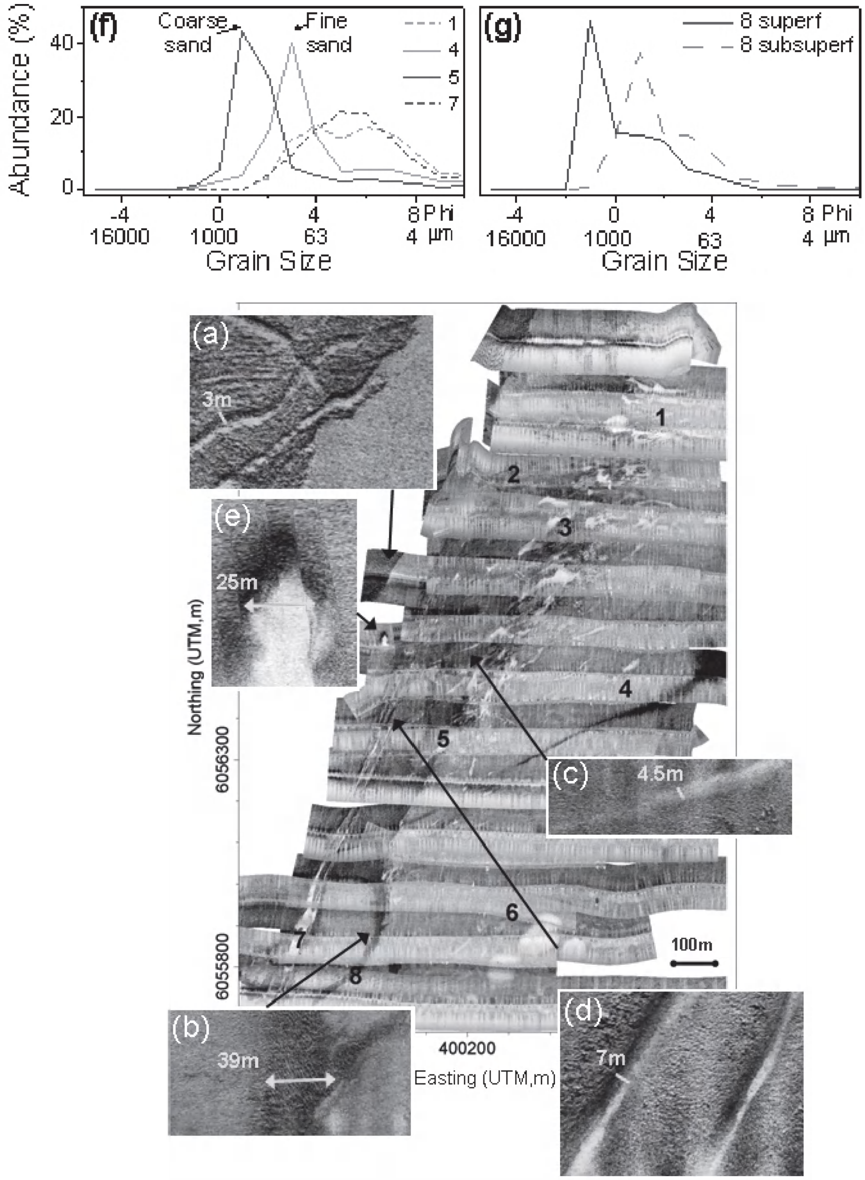

Figure 6. Side-scan sonar mosaic of TWE, with detailed images of relevant features ((a) to (e)). Numbers represent sediment sample sites. The grain size distribution of characteristic samples (f) and differences between superficial and subsurface samples (g) are also presented (see also, Figure 3.).

the basis of 89 measurements. Fourteen samples were collected from TW1 (Figure 3); 9 in the higher reflectivity zone and 5 in the area without dredging features, to characterise the lower reflectivity area. The superficial sediments vary from gravel to sand. On the basis of sonographs and ground-truthing, from each of the reflectivity areas, the relevant features and the superficial sediment distribution can be described. The studied surface area was 1.301.000m^2, within which the low reflectivity zone (~21% of the area) consisted of poorly sorted very fine sands; these increase in grain size (fine sand) in the vicinity of the higher reflectivity area (Figure 3d). The remainder of the area (~79%) is characterised by higher reflectivity; here poorly sorted sand and gravel (Figure 3e) occurs. Finally, the spilled material (lower reflectivity, around the pits) corresponds to coarse sand. Samples rich in spilled material showed a slight increase in their mud content (from 0.2% to 4.8%). To evaluate any trends regarding sediment composition, samples were plotted on the Folk ternary diagram (% gravel-sand-mud) (Folk, 1954; Figure 4). Three different groups were observed: sandy gravel from the undisturbed areas, showing high reflectivity; sand and muddy sand, from the lower reflectivity area; and an elongated group of gravelly sands, corresponding to the dredged areas. The more intense the impact of the extraction, the richer the samples are in finer-grained materials.

Tromper Wiek East (TWE)

The composite image of the Tromper Wiek East site shows a contact between two areas of slightly different reflectivities, i.e. higher in the west and lower in the east (Figure 5).

The sharp contact between gravel and sand, observed in TW1 (Figure 2), is also visible on the westernmost part of the area. Some diffuse furrows are observed within the northern part of the high reflectivity area. Crossing the area from SW to NW, some deep well-defined furrows appear, lying very close to each other. Depending upon the location, from 2 to 4 individual furrows, with a maximum width of 8m, 1.3km maximum length and 2.4 maximum depth, can be identified. Some pits appear also in the vicinity of the northern end of the deep furrows, with maximum diameters of 28.5m and maximum depths of 2.5m. The diffuse furrows were generated during the extractions taking place in 1989; more distinct furrows are seen in 2000 (DIESING, 2003). No side-scan sonar data are available from this area, from the 2003 survey. Nevertheless, given the low dynamics of this area (DIESING, 2003), another mosaic, generated from data collected in 2004, was used (Figure 6). In this sonograph, the same features as shown in the composite multibeam image are presented: the contact between gravel and sand (Figure 6a); the contact between the two areas with different reflectivity, where ripples are observed in the acoustically darker area (Figure 6b); the (1989) diffuse furrows (Figure 6c); the (2000) well-defined furrows (Figure 6d); and the pits (Figure 6e).

In order to correlate reflectivity with superficial grain size distribution, 8 samples were collected over this area; these were from undisturbed locations from each reflectivity zone, in the extraction sites and on the seabed surrounding the extraction sites (Figure 6). On the basis of these data, it can be established that the low reflectivity zone (~60% of the study area, i.e. 1.266.100m^2) corresponds to poorly sorted very fine sand; the remainder (~40%) with higher reflectivity, to poorly sorted medium sand (Figure 6f). Within the high reflectivity area, the newer furrows extend over roughly 9% of the area, showing superficial sediment finer than that of the surrounding seabed (poorly sorted, very coarse silt). The area covered by the older furrows, corresponding to very poorly sorted fine sand, could not be established (due to their diffuse profile). The effect of extraction on the superficial sediments can be detected also in relation to the mud content. On the undisturbed medium sand, the mud content is around 8%; in samples affected by dredging activities, this content is higher (~70% on the 2000 furrows; ~66% on the 1989 furrows).

Vertical grain size variations, observed on the subsamples from Station 8, indicate that the effects of dredging affect also the area surrounding the extraction sites. The superficial sample is associated with a grain size distribution, which is similar to that from the newer extraction site sample (Sample 7); it has high a mud content, but not as high as in the extraction area (~54% and ~70%, respectively). The sample from the underlying sediment presents a grain size distribution (poorly sorted, medium sand) and mud content (~7%), which lies within the same range as the undisturbed sediment from the high reflectivity area (Figures 6f and 6g).

On a ternary diagram (% gravel-sand-mud), the samples from TWE can be classified into 3 groups (Figure 4). Two of the groups relate to undisturbed sediments from the main areas, as observed on the sonographs: slightly gravelly sand, on the high reflectivity area (Samples 2, 5 and the sub-surface sample of Station 8); and slightly gravelly muddy sand, on the low reflectivity area (Samples 4 and 6). The third group, the sandy mud samples, are associated with sites impacted upon by dredging (Samples 1, 7 and 8); here, an increase in the mud content, coinciding with a decrease in the percentage of sand, is observed. The grain size distribution of Sample 3, located within a high reflectivity area, lies closer to that of the undis-

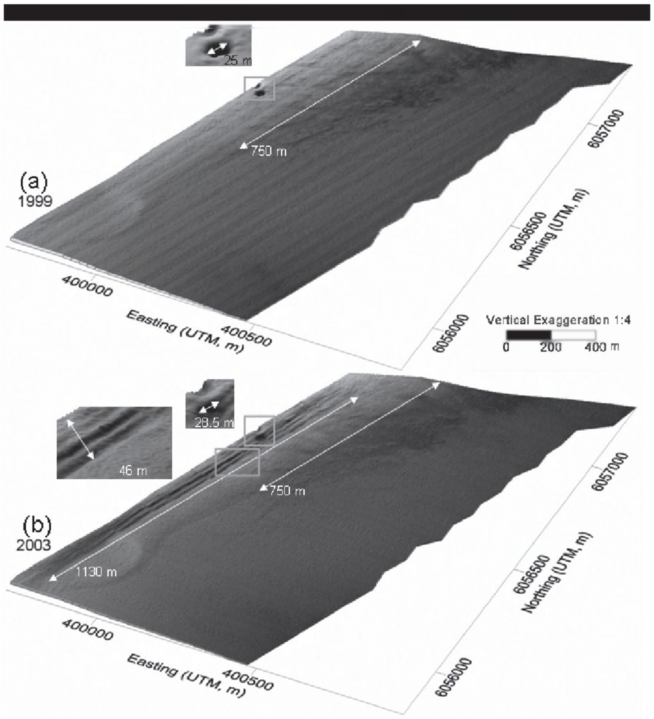

Figure 7. Multibeam surfaces derived from the 1999 (a) and 2003 (b) surveys: TWE. Details of some relevant features are also presented.

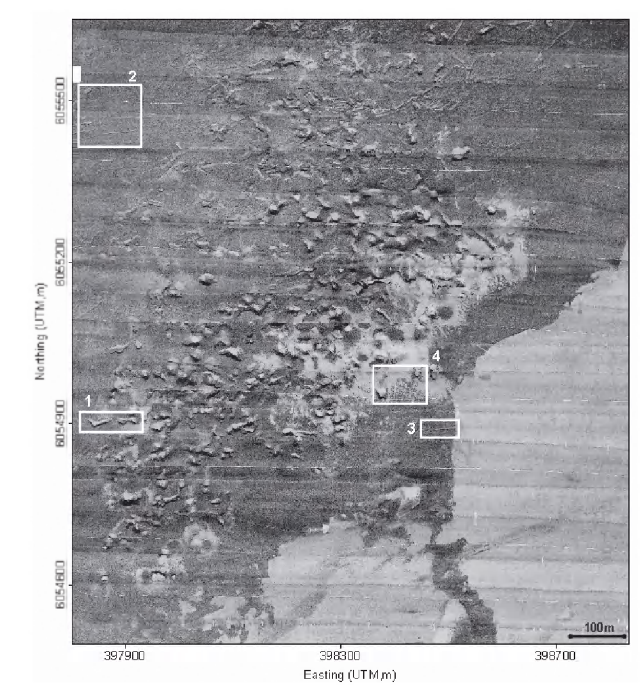

Figure 8. 2000 Mosaic of TW1. Note: the zones marked (1 to 4) are shown, in detail in Figure 9.

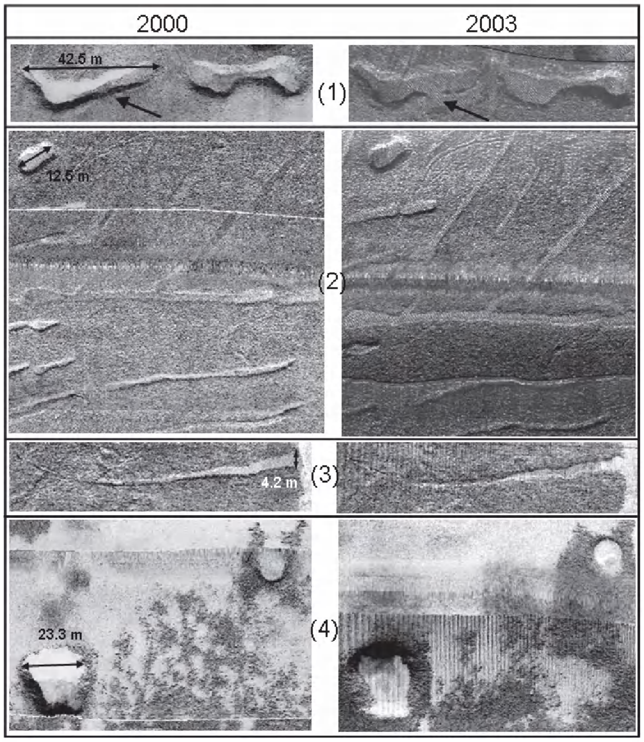

Figure 9. Comparison of the changes observed in some areas of TW1, from 2000 (first column) to 2003 (second column) (for locations, see Figure 8.).

turbed sediments, from the lower reflectivity area. An explanation of this effect will be discussed later.

Seabed Evolution along Dredging Sites

Datasets acquired within the framework of other projects, undertaken in 1999 and 2000, are compared now with the datasets available from 2003 and 2004. The seabed evolution along TWE is studied on the basis of multibeam bathymetry comparisons (Note: no backscatter information is available from the older dataset); TW1 by side-scan sonar, since no multibeam data are available.

Dredging mark evolution on a sandy seabed (TWE)

Figure 7 represents the multibeam surfaces of both the 1999 and 2003 surveys. Overall, both surfaces show the same features, except for the noise within the 1999 dataset and the deep, well-defined furrows, running parallel (from SW to NW) on the 2000 dataset (Figure 7). The diameter of the pit has increased between the two surveys, likely to be related to collapsing of the walls (Figure 7). No volumetric differences were calculated between the two surfaces, because of the noise of the 1999 dataset, due to calibration problems. Significant changes can be seen along the furrows; i.e. after 4 years, a maximum vertical variation exists of almost 2.5m.

Dredging mark evolution on a gravel seabed (TW1)

Dredging operations on TW1 were undertaken, continuously, from 1989 to 2000. The 2000 mosaic from TW1 (Figure 8) shows similar features to those of 2003.

Major differences can be observed within the pits (Figure 9), independent of their dimensions; this permits direct recognition of the various pits, after a 3 year period. Generally, there appears to be some correlation between the diameter and the depth of the pits: as a result, the potential for wall-collapsing will be higher in the case of the deeper pits; the smaller ones are more stable in their shape (Figures 8 and 9, Locations 1 and 2). Such an effect is even more marked on the furrows where, due to their shallow bathymetric profile, their edges remain highly stable. Further infilling within the furrows, by finer–grained sediments, is less intense (Figures 8 and 9, Location 2). Even infilling of furrows associated with the area of sand is not significant (Figures 8 and 9, Location 3). The main change observed is related to the area with spilled sand (Figures 8 and 9, Location 4). The surface area covered by this material decreases with time, remaining observable inside the pits. This corroborates the role of pits, as traps of such sediments (Diesing, 2003).

DISCUSSION

Results obtained from the hydro-acoustic surveys, for both study areas, reveal morphological features on the seabed, related to dredging activities. The effects of dredging can be detected also in the superficial sediment grain size distributions. Areas affected by dredging operations are associated with finer-grained sediments and a higher amount of mud, in relation to unimpacted areas; this has been observed previously, in other studies (Boyd *et al.*, 2004). On the gravel area, the finer-grained sediments are the result of the spilling of undersized material, during extraction. Such material is easily detectable on sonographs, as lower reflectivity patches around the pits themselves. On the area with sand, the extraction sites have revealed the presence of sandy-mud material, whilst the unimpacted sediment consists of slightly gravelly muddy sand. The mud content of the unimpacted sediment is around 8%, whilst it is around 66% at the older extraction sites (1989) and 70% on the more recent site (2000). Areas lying adjacent to the extraction sites have similar superficial sediment grain size distributions, together with slightly lower mud contents, than the directly-impacted zones.

In order to assess regeneration of the extraction sites, the dredging technique adopted and the nature of the material dredged are considered. No pit has been observed, within any of the datasets, in an advanced stage of regeneration, independent of the material dredged. The pits from the gravel area are associated with sharp edges, even though some of them were formed some 15 years before the present dataset was collected. Some refilling has occurred in response to accumulation of spilled sand, generating ripples in the craters, as cited previously (Boyd *et al.*, 2004). Likewise, the re-suspension and transport of material, around the pits, has been investigated elsewhere (Garel and Lefebvre, this volume; Klein, 2003;). Pits lying within a sandy seabed (TWE) are associated with more diffuse edges; this is related to "wall collapsing" effects, as described by other investigators (Boers, 2005). Furrows generated by trailing suction hopper dredging have been observed, in an advanced state of refilling, but only on the sandy beds. Furrows generated in the gravel part of the seabed are shown to remain almost constant in their expression, even when lying close to an area containing an abundance of finer-grained material.

Based upon the above observations, a change from anchor suction dredging to trailing hopper suction dredging appears to be an appropriate decision. In the case of the areas studied, the furrows show enhanced regeneration; as such, they impact less upon the environment, than the pits. Nevertheless, multiple dredging profiles, over the same transect, generate deeper features within the seabed, complicating their regeneration; this is the case of the 2000 extraction, from TWE. In relation to the extracted material, the dredging of the gravel areas of the seabed creates a deeper impact. Reworking of coarser-grained materials over the area follows a very slow pattern of recovery; this is corroborated by other studies (GAREL and LEFEBVRE, this volume; KLEIN, 2003;).

CONCLUSIONS

(1) Hydro-acoustic survey techniques have generated detailed images of the seabed, where the morphology of areas of extraction can be described. In the case of Tromper Wiek, the impacts from anchor suction dredging (pits) and trailing hopper suction dredging (furrows) can be observed, in both of the areas studied. On the gravel area (TW1), deep pits and dredging-related spill material represent the main observable features. Over the sandy area (TWE), long and deep furrows are the main detectable features.

(2) Dredging activities can be identified also from information obtained from the grain size distribution of the superficial sediments. Dredged areas reveal a finer superficial grain size distribution and higher mud content, than the unimpacted areas. In some cases, this effect is detectable on the sonographs, due to the presence of spill material (e.g. after anchor suction dredging, on a gravel bed).

(3) Regeneration depends upon the adopted dredging technique and the nature of the dredged material. Pits remain more stable than furrows, indicating a higher impact of anchor suction dredging, in comparison with trailing hopper suction dredging. In relation to the type of dredged seabed material, representative marks on gravel areas are more stable than those on a sandy bed.

(4) Seabed evolution in the sandy gravel area, studied on the basis of sonographs, indicates high stability of the dredging marks. The main observed processes were collapsing of the pit walls and refilling by spilled sand.

(5) Seabed evolution in the sandy area, examined on the basis of multibeam bathymetry, shows that regeneration is rapid during the first years after the extraction; subsequently, this becomes hardly detectable, but marks are still visible, even after a decade.

ACKNOWLEDGEMENTS

Firstly, the authors would like to acknowledge the support provided by the EUMARSAND Research Training Network (HPRN-CT-2002-00222). We would like to thank also German Rodriguez, AZTI (San Sebastian, Spain), for undertaking the grain size analyses used in this study. Finally, the German Hydrographical Service (BSH) is acknowledged, especially Dr. M. Zeiler, for granting EUMARSAND to have access to their broad database. The multibeam dataset of 2000 was acquired as part of the project "Regeneration of aggregate extraction sites in the North Sea and Baltic Sea" (funded by the German Ministry of Education, Science and Technology).

LITERATURE CITED

BLONDEL, P. and MURTON, B., 1997. *Handbook of Seafloor Imagery*. Willey & Sons, New York, 314p.

BLOTT, S.J. and PYE, K., 2001. Gradistat: A Grain Size Distribution and Statistics Package for the Analysis of Unconsolidated Sediments. *Earth Surface Processes and Landforms*, 26, 1237-1248.

BOERS, M., 2005. *Effects of a deep sand extraction pit. Final report of the PUTMOR measurements at the Lowered Dump Site*. Rijkswaterstaat National Institute for Coastal and Marine Management (RIKZ), 87p+CD.

BOYD, S.E.; COOPER, K.M.; LIMPENNY, D.S.; KILBRIDE, R.; REES, H.L.; DEARNALEY, M.P.; STEVENSON, J.; MEADOWS, W.J., and MORRIS, C.D., 2004. *Assessment of the re-habilitation of the seabed following marine aggregate dredging*. CEFAS Science Series. Technical Report, 121, 154p.

DICKSON, R.R. and LEE, A., 1973. Gravel extraction: effects on seabed topography. *Offshore Services*, 6(6), 32-39.

DIESING, M., 2003. Regeneration von Materialentnahmestellen in der südwestlichen Ostsee unter besonderen Berücksichtigung der rezenten Sedimentdynamik. Kiel, Germany: (unpublished) University of Kiel, Ph.D. Thesis, 158pp.

DIESING, M.; SCHWARZER, K.; ZEILER, M., and KLEIN, H., 2006. Comparison of Marine Sediment Extraction Sites by Means of Shoreface Zonation. *Journal of Coastal Research*, 2, 783-788.

FISH, J. P. and CARR, H. A., 2001. *Sound reflections*. Lower Cape Publishing. Orleans, MA, 272p.

FOLK, R.L., 1954. The distinction between grain size and mineral composition in sedimentary rock nomenclature. *Journal of Geology*, 62(4), 344-359.

FOLK, R.L. and WARD, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. *Journal Sedimentary Petrology*, 27, 3-26.

GAJEWSKI, L. and UŚCINOWICZ, S.Z., 1993. Hydrologic and sedimentologic aspects of mining aggregate from Stupsk Bank. *Marine Georesources and Geotechnology*, 11, 229-244.

GAREL, E. and LEFEBVRE, A., this volume, Wave-induced Sand re-Suspension at Dredged Gravel Pits based upon Hydrodynamic Measurements (Tromper Wiek, Baltic Sea). *Journal of Coastal Research*.

KLEIN, H., 2003. Investigating sediment re-mobilisation due to wave action by means of ADCP echo intensity data: field data from the Tromper Wiek, western Baltic Sea. *Estuarine, Coastal and Shelf Science*, 58(3), 467-474.

MOHRHOLZ, V., 1998. Transport and mixing processes in the Pomeranian Bight. Marine Science Reports, 33, 106p. (in German)

PRICE, W.A., MOTYKA, J.M., and JAFFREY, L.J., 1978. The effect of offshore dredging on the coastlines. *In: Proceedings of the 16th Coastal Engineering Conference*, 1347-1358.

ROBINSON, A.H.; MORRISON, J.L.; MUEHRCKE, P.C.; KIMERLING, A.J., and GUPTILL, S. C., 1995. *Elements of Cartography*, John Wiley & Sons, New York, 688p.

SCHWARZER, K.; RICKLEFS, K., AND SCHUMACHER, W. and ATZLER, R., 1996 Beobachtungen zur Vorstranddynamik und zum Küstenschutz sowie zum Sturmereignis vom 3./4.11.1995 von dem Streckelsberg/ Usedom. *Meyniana*, 48, 49-68.

VAN DER VEER, H.W.; BERGMAN, M.J.N.; and BEUKEMA, J.J., 1985. Dredging activities in the Dutch Wadden Sea: Effects on Macrobenthic Infauna. *Netherlands Journal for Sea Research*, 19, 183-190.

ZEILER, M.; FIGGE, K.; GRIEWATSCH, K.; DIESING, M., and SCHWARZER, 2004. Regenerierung von Materialentnahmestelln in Nord-und Ostsee. *Die Küste*, 68, 67-98.