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On the morphological long-term development of dumped material in a low-energetic environment close to the German Baltic coast

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Abstract

The development of the bed bathymetry of an experimental dumping area was followed over three and a half years by means of multibeam echosounder techniques. Two types of material were discharged in the bight of Mecklenburg in the Baltic Sea in approximately 20 m of water depth. One set of the discharges was 2900 m³ of glacial till and the other set was a 2400 m³ mixture of glacial till, sand and minor amounts of cohesive matter. Only approximately 2500 m³ (86 %) of the glacial till and 1500 m³ (63 %) of the mixed soil materials were deposited on the seabed. This means that already during the dumping process a considerable part of the sediment material drifted away. The glacial till formed crater-like rings of 30 m diameter with peaks up to 1.4 m above seabed, whereas the spatial structure of the mixed soil material was somewhat more diffuse, but with similar magnitudes in the peaks and troughs.

The morphological changes were small and their quantification required a high measuring precision in the order of few cm in the vertical. The dominant processes of surface deformation was flattening of peaks and filling of troughs. The speed of this process decreased with horizontal scale: structures of less than 4 m horizontal extension had a trend to disappear within less than five years, whereas structures of larger than 8 m extension showed little change and are estimated to remain detectable for many decades. In contrast to the reworking of the matter inside the dumping structures, no net transport of material out the dumping area could be detected. Extrapolating the observed morphological changes into the future it is estimated that without significant decrease in internal shear strength of the disposed till the structures will persist for at least 70 years. This can be attributed to the high internal stability of the dumped glacial till and the low hydrodynamic forces present at the seabed in this region.

Keywords: Coastal morphology, Material dumping, Sediment dynamics, Multibeam echosounder, Germany, Baltic coast

1 Introduction

Harbours, rivers and estuaries all over the world have to be dredged to remain navigable for modern sea traffic. Periodical maintenance is necessary, because by the influence of currents and tides the dredged areas silt up again or new sand dunes appear (Pagliai and Varriale 1985).

The effects of dredging or dumping are very site-specific and are highly dependent on the type of the dredged or dumped materials. As the dredged material often contains high loads of pollutants and alters sediment distributions and the turbidity in the water column, the impact of dredging and dumping on the chemical (van den Hurk 1997, Roberts and Forrest 1999) and biological state (Harvey et al. 1998, Essink 1999) was of main concern and comprised majority of investigations on dumped material.

To date, few publications deal quantitatively with the morphology and bed sediment dynamics of the dumped materials. The dredged material usually is dumped downstream the dredging site or transported offshore to minimise its direct return. Thereby the dumping method influences the dispersal of the dumped materials and consequently comes to affect the later development of the dumping site (Bokuniewicz and Gordon 1980). During the dumping process the basic part of the dumped materials descends to the seabed and spreads circularly, depending on its kinetic energy. Simultaneously, some part of the material is formed into a surface plume within the water column (Delo 1987). The recovery of sand waves in dredged areas was investigated thoroughly in the Bisanseto Sea, Japan. Sand waves tend to regain their shape after dredging (Katoh and Kume 1998). Using an amplitude-evolution model based on the Landau equation, Knaapen and Hulscher (2002) were able to model this regeneration process correctly and concluded that the application of their procedure was an important step for the optimisation of the maintenance dredging.

With improved echosounder technologies, a comprehensive investigation of the morphological development became possible. Wienberg et al. (2004, 2005a,b), for example, investigated morphological changes on a tidally influenced dumping site in the outer Weser estuary, surveying sand dunes with a height up to 3 m. Their results indicate that under the tidal forces the dumped material was removed from the dumping site within few months. Additionally, the dumped sediments had no persistent effect on the bedforms and even completely buried dunes began to regenerate within few months.

To study the development of dumping mounds under low energy conditions, two experimental dumps with different sediment composition were conducted in June, 2001, within the framework of the DYNAS-project (Dynamics of Natural and Antropogenic Sedimentation, Harff et al. 2003). A general issue addressed in DYNAS was the potential initiation of enhanced silting and dispersion of pollutants into the Baltic Sea. The dumping site was located close to the German Baltic Coast, offshore from the city of Warnemünde, and the dumped material was typical for the routine dredging of the shipping channel close to Warnemünde harbour. The first set of dumps consisted of compressed glacial till chunks, the second set contained a mixture of medium sand and glacial till. The area was closed for further human activity to study the development of the dumping sites under well-defined, nearly undisturbed, conditions. The aim of this specific study was to estimate typical time-scales for the disappearance of the dumping mounds, to quantify the amount of material that was dispersed over time, and in this way to gather background information for an assessment of the dumping practice of the local harbour authorities. The sheltered position of the dumping site (Kuhrts et al. 2004, Harff et al. 2005) suggested that the morphological changes should be small. To yield unambiguous information about mass balances, surface deformations, changes in surface roughness and magnitude and direction of bed sediment transport, data precision of the overall mapping system was given specific consideration.

2 Materials and Methods

2.1 Study site

The dumping experiment was carried out in the Bight of Mecklenburg (Baltic Sea) some 6 km offshore from Nienhagen and 16 km west of Rostock/Warnemünde (Fig. 1). This site was selected because it was free of anthropogenic use and similar to official disposal sites with respect to water depth, hydrodynamical conditions, sediment type and relative distance to areas with other type of coastal utilisation. The water depths ranged from 18 to 19 m. One-year model results including events with significant storm events underline the sheltered character of the study area: flows in the lowest model layer (0-1.5m above bed) were typically between 1 and 4 cm s^{-1} with no priority direction (T. Seifert, personal communication), bed shear stresses generated by currents never exceeded the critical threshold for bed erosion and those generated by waves only in cases of severe storms (Kuhrts et al. 2004). Natural bed sediments of the site consisted of consolidated, well-sorted, very fine sand with a medium grain-size between 110 and 120 µm. The grain-size composition in this area was very consistent over the survey period (Harff et al. 2005). According to diver observations, bed structures consisted of ripples of 0.2 m wavelength with amplitude of 0.02 m. As the area was generally used as a fishing ground, a prohibited zone with an extension of 500 m × 500 m was established around the dumping area to prevent any anthropogenic disturbance.

2.2 Experimental setup

On June 20 and 21, 2001, a volume of approximately 2900 m³ of glacial till and 2500 m³ mixed soil was dumped. The glacial till material consisted of compressed chunks with a diameter up to 1 m. The mixed soil was composed of some nearly equal amounts of glacial till and medium sand with minor admixtures of organic silt and turf. There were four dumps of glacial till from a stationary vessel and three dumps of the mixed soil from a moving vessel.

The bed relief of the surveyed area was mapped by coupling MBES-technique with high accuracy positioning. Bed detection was carried out by means of the multi-beam echosounder EM 3000™ from Simrad-Kongsberg. This system is designed to work in water depths from 3 to 200 m. It operates at a frequency of 300 kHz with a ping repetition rate of 15 Hz. The nominal apex angle is 1.5° along-track and 120° across-track during transmission, and 30° along-track and 1.5° across-track during receiving. This results in an array of 127 individual beams with an effective 1.5° • 1.5° apex angle per single beam arranged with some overlap over an arc of 120°. The corresponding across-track swath width amounts to 64 m at 18.5 m water depth.

A gyro-compass (Anschütz 20™, 4™) and a motion sensor (DMS-05™, TSS UK LTD.) monitored the movement of the vessel to compensate for the orientation of the sonar head at each time incident. Three dimensional ship positions were accurately determined by real-time kinematic global positioning (Trimble 4000 ssi™). The relative positions of all components onboard the ship were measured with an accuracy of less than 1 mm. Three-dimensional sonar head positions and orientations were finally fixed by combining antenna position, gyro-compass and motion sensor data. Vertical sound velocity profiles were recorded two times per day. They showed a step of 6 – 10 m/s between water depths of 3 and 14 m, depending on the campaign, which reflected the thermocline typical for the Baltic Sea (Siedler and Hatje,1978). Within the daily survey time of some six hours, the position of the thermocline was stable within 40 cm. After compensation for ship motion and ray-refraction the resulting soundings were cleared from outliers. Positions and altitudes are output in World Geodatic System 1984 (WGS 84). For mapping horizontal positions were projected on to Universal Transverse Mercator 32 (UTM32) map projection and altitudes transformed with respect to the normal chart datum. The individual measurements were further processed in a digital terrain model (DTM). The DTM employed used the “Seabed” algorithm (Roxar 2003). In this method, for each grid node a surface paraboloid is computed from a weighted fit through all data points within a user-definable search radius. The altitude of each DTM cell is defined by the value of the parabolic surface at the grid node point. The grid size of the terrain model was 1 m × 1 m. All results shown in the following are based on this DTM. To assure that positioning precision, or repeatability, for each grid cell was not limited by the area density of data points, it was increased as much as the survey times allowed. Due to sound refraction at the thermocline, precision of the side beams was expected to be less than for the central beams. To minimize this systematic effect the vessel manoeuvred along a perpendicular network of tracks half a swath width apart; if allowed by the time schedule, 45^{o}-tracks were further added above the location of the dumped material. Using this scheme, each DTM grid cell was surveyed at least four times and contained 25 to 50 data points.

Around the dumping site an area of 1000 m × 1000 m was surveyed directly before and after the dumps in June 2001, in August 2001, and in October 2002, 2003 and 2004. The two June 2001 and the October 2002 surveys were discarded from this analysis because of problems in the positioning system and suboptimal tuning of the inertial adjustment of the ship motion sensors for strong ship pitch and roll movement.

2.3 Data Analysis

In general, the bathymetric changes have to be measured with respect to a fixed vertical reference level. For the study area there is good reason to assume that the mean altitude of the seabed somewhat distant from the dumped material did not change over the years. In the south-western part of the surveyed area a 2 m wide and 0.30 m deep trace of a fishery drag-board was detected at all instances (Fig. 1). Within less than a centimetre, the profile of this trace remained unchanged (Fig. 2), indicating the high stability of the seabed in this part of the study site. Therefore, the mean altitude of an area defined around the drag-board trace ((“reference area”, s. Fig. 1) was defined as the vertical reference level separately for each survey. All changes in the dumping structures were analysed with respect to these survey dependent reference levels.

For each survey, the remaining volumes of the dumped material were determined. As the mapping immediately before the dumping failed, “pristine planes”, representing the undisturbed seabed below the dumped material instead, were locally constructed by a bilinear interpolation between four borderlines defined around the deposition areas (outer margins, s. Fig. 1). The volumes of the dumped material were then computed by the altitude differences between the actual digital terrain model and the corresponding “pristine planes”.

The magnitude and direction of the displacements of the dumped material was derived by means of the optical flow analysis (Jähne 1997). Optical flow is a concept to display direction and speed of the motion of objects within a number of images based on the conservation of grey levels of moving objects. If objects change their position on these images, the grey values of the objects (in this application the altitude of the DTM grid cells) stay constant in the direction of their movement as long as the conditions of “illumination” do not change. In this simple case, the spatio-temporal gradient of the grey values is perpendicular to the motion direction and an equation of continuity for the grey values (“optical flow”) can be formulated. In the general case, when changes in light intensity (in this application the mean altitude), in surface structures or noise alter the grey level of the objects the continuity equation has to be replaced by a variance method where the magnitudes of motion can be derived from the trace and the directions from the smallest eigenvalue of the diagonalized grey-value tensor. By setting a lower threshold for the trace, artefacts caused by noise or a loss of volume can be suppressed. Details of the procedure are described in Stockmann (2005).

The roughness of the surfaces of the dumped material was analysed in dependence of the horizontal spatial scale. For this purpose, a Laplacian pyramid of the seabed image was generated subtracting a low-pass filtered copy of the image from the image itself (Burt and Adelson, 1983). The resulting image only includes structures of lower wavelengths. In the seabed DTM, low wavelength is the equivalent to small horizontal structures and vice versa. This procedure was recursively applied four times with the low-pass filtered copies of the image. In this way, a sequence of band-passed images, i.e. the Laplacian pyramid, is obtained (see Table 2), where each image shows the structures of specific wavelength domains. For the glacial till mounds, this is illustrated in the Fig. 8 of chapter 3. Wavelengths above 64 metres were not considered because the extensions of the dumping mounds were below one hundred meter. For better comprehensibility, in the following horizontal scales are given as half of the wavelengths domains thus resembling the extension of crests or troughs.

A calculation of the variance V_n of each level n of the Laplacian pyramid is synonymous with the mean square height of the structures as a function of scaling:

$$V_n = \frac{1}{N_x N_y} \sum_{\substack{x=1:N_x \\ y=1:N_y}} g_{nxy}{}^2 \quad (1)$$

where g_{nxy} is the depth anomaly of the grid cell in level n and $N_x N_y$ the number of grid cells in the image. In the following, spatial scale dependent roughness is expressed by the square root of V_n .

3 Results

As an overview, the bathymetry of the dumping area as obtained in August 2001 is shown in Fig. 1. The digital terrain model exhibits the general flat seabed with water depths changing smoothly from 18 m below normal chart datum in the south-eastern corner to 19 m in the north-western corner. The dumped glacial till is located in the northwest part of the dumping area. It covers the bed in the form of crater-like rings of approximately 30 m in diameter with a typical height of 0.5 to 1.4 m. The dumped mixed soil is located in the central parts and extends 120 m in south-north and 80 m in west-east direction. Here, the ring structures are washed out but still recognisable, reflecting the ship movement during dump operation and the horizontal dispersal of part of the settling material that was observed from airplane (Siegel et al. 2003). Here, the maximum height of the peaks is about 1.3 m. Scour holes around the anchor stones of the four marker buoys are clearly visible. In the western part of the area the above-mentioned trace of a fishing drag board runs in east-southeast direction (Figs. 1 and 2).

The temporal development of the glacial till craters between August 2001 and October 2004 can be seen in the maps of Fig. 3. Generally, there is little change in the size of the craters, but the peaks and troughs seem to be increasingly smeared. This is quantitatively illustrated in Fig. 4. Here, the seabed profiles from the three surveys are plotted along a transect which crosses one of the craters (see Fig. 3). The peaks become gradually flattened by 5 to 15 cm and the inner troughs are filled up by a comparable height. The rate of change per year is most pronounced between August 2001 and October 2003, with less change in the following year. Outside the dumping mounds no bed level change is detected.

The same development, but at a higher rate, was also observed for the dumped mixed soil (Figs. 5 and 6). In the example shown in Fig. 6 the flattening of the highest peak amounts to more than 50 cm between August 2001 and October 2004. The peaks and troughs with horizontal extension to 8 meter, present in August 2001, disappeared and bottom of the troughs rose by 10 cm.

The considerable exaggeration of vertical axis in Figs. 4 and 6 with the resulting impression of steep peaks and troughs gives a wrong association of the dumping structures because the structures are very flat (compare Fig. 3). The real proportion of height to width is approximately 1:50.

In contrast to the surface deformations, the volumes of the dumped material showed little change. The first survey in August 2001 yielded deposited volumes of approximately 2500 m^3 for the dumped glacial till, corresponding to 86 % of the dumped volume, and 1500 m^3 for the dumped mixed soil, corresponding to 63 % of the dumped volume (see Table 1). The volumes measured at the October 2003 and 2004 surveys differed only very little from these first measurements. With respect to the August 2001 survey, the absolute change was less than 25 m^3 or 1 % for the glacial till and 2 % for the mixed soil (Table 1).

The optical flow analysis yielded displacements of the bed structures in the dumping sites of only few metres (Fig. 7). From August 2001 to October 2003 the structures seem to move basically in southern direction with a 1.6 m (90% percentile) for the glacial till and a 6 m (90% percentile) for the mixed soil. Going from October 2003 to October 2004 the structure displacement of the glacial till was in northern direction with a magnitude of 1.5 m (90% percentile). For the mixed soil the optical flow analysis was not applicable since the structures had become too flat.

Surface roughness, as measured by the square root of the variances of seabed elevation on the different Laplacian pyramid levels, changed significantly with horizontal spatial scale (Fig. 8, Table 2). In August 2001, there was a monotonic decrease from 11 cm in the 1-2 m scale down to 7.2 cm in the 8-16 m scale for the glacial till, and for the mixed soil from 7.9 cm in the 1-2 m scale down to 4.4 cm in the 8-16 m scale. Over time, surface smoothing occurred: roughness in smaller horizontal scales dropped and approached each other and the magnitude of change decreased with scale (Fig. 9). For the glacial till, all structures more extended than four metres were essentially stable, whereas the variances in the 1-2 m scale dropped from 11 cm in August 2001 to 8.4 cm in October 2004 and in the 2-4 m scale from 9.3 cm in August 2001 to 8.5 cm in October 2004. In contrast, smoothing of the mixed soil material was detectable in scales up to sixteen metres. Variances in the 1-2 m scale dropped from 7.9 cm in August 2001 to 4.4 cm in October 2004, in the 2-4 m scale from 4.8 cm to 3.7 cm, in the 4-8 m scale from 5.1 cm to 4.4 cm, and in the 8-16 m scale from 4.1 cm to 3.6 cm.

4 Discussion

The conditions for the present study were, to the knowledge of the authors, in several aspects unique when compared to the previously published studies mentioned in the introduction: keeping the dumping site free of any further anthropogenic disturbances allowed the study of the disposal mounds to develop under comparably controlled conditions over several years; two types of material were deposited close-by to allow comparisons under identical environmental conditions; MBES technology coupled with high precision positioning, gyro-compass and motion sensors provided highly precise and complete surveying of the seabed; the relatively sheltered location and highly stable material lead to very slow changes in the shape of the mounds which could be followed on the basis of yearly surveys. The latter makes the situation quite complementary to the situation in the outer Weser estuary where significant tidal currents and dumped material consisting exclusively of sand lead to substantial erosion and net outward flux of the dumped material within weeks to few months (Wienberg et al. 2004).

4.1 Shape of the disposals

The morphological features of the dumping sites exhibit remarkable stability within the first three and a half year after disposal. Between the first successful mapping, about two months after dumping, and the final survey, no change in the volumes of the deposited material was detectable. It is reasonable to hypothesize that the main material losses, estimated from the volume differences between the quoted discharged material and its mapped deposits already took place during disposal. Delo (1987) describes this phase qualitatively in some detail for predominantly silty sediments. Following the release, the material falls downwards as a well-defined jet. Large Volumes are entrained in the jet while the part of the material with lower settling velocities becomes separated from the jet and is advected away as a near-surface plume. The descending part collapses as a result of the impact on the bed. The not deposited material moves out radially under its own momentum until it comes to rest when sufficient energy has been dissipated. By then, diffusion processes will mix material into the lower water column until it is finally transported away. This conceptual model nicely describes both the material loss as well as the radial bed forms of the disposed material in this study. In the case of the mixed-material dumps the surface plume was clearly observed from an airplane. Compared to the glacial till disposals, the mixed soil contained a much larger fraction of sand and silt that could be advected away. Parallel observations of water temperature, salinity and turbidity revealed that in the specific situation the sinking surface plume material was collected at the thermal boundary layer in 12 m water depth and transported far outside the surveyed area before it could settle at the seabed (Siegel et al. 2003). Hence the differences in the relative loss of matter of 15 % by volume for the glacial till and 40 % by volume for the mixed soil can be well understood qualitatively. The more diffuse bed structures of the latter material can probably be attributed to dispersed sand disposals, but also to the fact that, in contrast to the glacial till, the ship moved during dumping.

4.2 Reproducibility of the bathymetric measurements

All further detected vertical changes in the bathymetry were of the order of a few centimetres. Ernstsen et al. (2006) report a horizontal precision of ± 30 cm and a vertical of ± 8 cm (95 % confidence level) for a state-of-the-art MBES coupled to a high-accuracy position system in a shallow water coastal environment for repetitive measurements taken during a single survey. When comparing surveys from different years, the achieved precision was ± 30 cm and ± 8 cm, respectively. These are the only so far published numbers for conditions comparable to this study. The here detected interannual vertical changes are just in the order of and partly below these numbers and therefore the statistical significances of the effects require some detailed discussion.

Ernstsen et al. (2006) used a fixed ship wreck as a reference, which was assumed to be stable in position. Such a feature did not exist in the vicinity of this study site. As discussed earlier (chapter 2.3) there is good reason to hypothesize that the seabed around the fishing drag-board trace was very stable and the mean altitude of this “reference area” was taken as the vertical reference individually for each survey. The interannual vertical precision of some bed features with respect to this reference was determined from the pair-wise difference DTM's of the surveys.

The vertical precision for a single DTM grid cell (1m×1m) is derived from the histograms of the height differences between two surveys of each grid cell of the evidently undisturbed "reference area" around the drag board trace and for the cells between the outer and the inner margins of the "pristine planes" (s. Fig. 1) around the disposals (see chapter 2.3). In both cases, the vertical precision for a single DTM grid cell amounts to ± 5 cm (range between the 2.5% and 97.5 % percentiles, corresponding to 95 % confidence interval) (see Fig. 10), nearly the value found by Ernstsen et al. (2006). Fluctuating components due to incomplete compensation of the ship movement, clearly visible in the difference DTM's, movement of sand-ripples, and other random noise contribute to this value. Effects of incorrect reconstruction of ray refraction at the thermocline, which affects mostly the outer beams, were estimated based on the observed daily shifts in the sound velocity profiles. Applying Snells law yields in an error of maximal 3.5 cm in the horizontal and 0.5 mm in the vertical direction.

The situation becomes worse if one would use an absolute vertical reference, e.g. the normal chart datum . The mean altitude of the "reference plane" then differs up to ± 15 cm between the surveys. The origin of this systematic shift in the altitudes was not resolved, but is probably caused by a long-term drift in the positioning system.

The complete disappearance of the drag-board trace in the difference DTM's (see Fig. 2) indicates that this bed feature is also well reproduced horizontally. Hence the horizontal precision is below the DTM grid cell scale of one metre, well below the horizontal scales discussed here, and therefore not considered further.

The error in the volumes of the disposal volumes consists of two parts: (1) a random error related to the vertical precision of each individual DTM grid cell $\sigma_{rand}(d)$ (≈ 5 cm) and (2) a systematic error estimated from the mean vertical shift of the margins of the "pristine planes" with respect to the fixed "reference plane" from survey to survey $\sigma_{syst}(d)$. Using the mean of the between survey differences in the vertical heights of these margins, one ends up with $\sigma_{syst}(d)$=5.5 mm (the mean value of the grey histogram of Fig. 10).

The random error $\sigma_{rand}(V)$ in the volumes scales with square root of the number of considered DTM cells n

$$\sigma_{rand}(V) = \frac{\sigma_{rand}(d) \cdot a}{\sqrt{n}} n = \sigma_{rand}(d) \cdot a \cdot \sqrt{n} \quad (2)$$

where a is the area of one DTM cell (i.e. = 1 m^2). For both the glacial till and the mixed soil n is approximately 10.000. Hence, $\sigma_{rand}(V)$ amounts to 7.5 m^3 and for the volume differences to 10.5 m^3 (95% confidence level).

The systematic error $\sigma_{syst}(V)$ scales with the dumping site area

$$\sigma_{syst}(V) = \sigma_{syst}(d) \cdot a \cdot n \quad (3)$$

and amounts to approximately 50 m^3. It is evident that the systematic contribution dominates the total error in the volume differences. Related to the total volume of the disposals this error is in the order of two to three percent, but it is not possible to assign an exact confidence level to this value.

The error of the variances in the Laplacian pyramide σ_{var} is related to $\sigma_{rand}(d)$ *by*

$$\sigma_{\mathrm{var}} = \frac{\sigma_{rand}(d)^2}{4} \quad (4)$$

and amounts to $5 \cdot 10^{-4}$ m^2 (95% confidence level), corresponding to a standard deviation of 2.5 cm. This number was verified by the computation of the variances for the planar part of the reference survey area around the drag board trace (Stockmann 2005).

4.3 Temporal development of the disposals

The measured changes in the disposal volumes between August 2001 and October 2004 are on the order of 1 percent and hence below the estimated error in the volume changes. At a high level of probability it can be stated that no further removal of the disposals or volume decrease by bed consolidation took place. In addition, the optical flow analysis did not reveal any horizontal movement of the structures larger than a few meters. All observed effects are close to the estimated detection limit of this method (Stockmann 2005). The only significant bathymetric changes were the smoothing of the surface roughness that on horizontal scales below 16 m could be detected well above or close to the 95%-confidence level. As can be expected, smoothing took place fastest on the smaller scales and was faster for the mixed soil with the higher fraction of moveable material as compared to the glacial till. A similar effect of surface smoothing somewhat outside the dumping mounds was qualitatively observed in sonar side-scan images taken in parallel to the MBES surveys (Harff et al., 2005). They show that micro-relief bed structures, present directly after the dumping, disappeared over the survey period.

The conservation of the overall disposed material may be explained by the relatively sheltered location of the dumping site which generally experiences low bed shear stresses from currents and waves. Continuous observations of flow speeds and suspended sediment concentrations carried out at the dumping sites 1.3 m above the bed between October and December 2001 indicate that flow speeds that erode and resuspend fine sand never occurred during that period (Leipe and Bahlo 2003). As current and wave observations were not carried out, further indications on the distribution of bed shear stresses at the dumping site were drawn from numerical model computations on a 1 nautical mile grid of currents and waves from December 1992 to November 1993 (Kuhrts et al. 2004, Harff et al. 2005). This period was selected as it contained a longer period of significant storms and yielded flow speed and wave height distributions that were statistically comparable to a 3 nautical mile grid computation conducted for the survey period between August 2001 and October 2004 (Harff et al. 2005). For the south-western Baltic Sea ("Belt Sea"), the most probable bed shear velocities generated by currents alone are between 0.5 to 1.5 cm s^{-1}. For the model area as a whole, the waves dominate the bed shear velocities, which are typically between 1 and 3 cm s^{-1}, but can exceed 4 cm s^{-1} for west to north-east wind speeds higher than 15 m s^{-1}. Compared to these large scale conditions, the DYNAS-dumping site is located at a remarkably sheltered position: the coupled current-wave bed shear velocities exceeded 1.5 cm s^{-1} only at significant wave heights (H_s) above 3.5 m. On the other hand, Bohling and Lemke (2003) observed that the fine and medium sands found in the DYNAS area start to erode only above bed shear velocities of 1.5 cm s^{-1}. According to wave climate diagrams derived from wave model results (grid resolution six nautical miles) of the German Federal Maritime and Hydrographic Agency ("Bundesamt für Seeschifffahrt und Hydrografie", BSH) this wave height was exceeded with a probability of less than 0.5 ‰

between January 2000 and December 2005 at the DYNAS site grid cell (Schrader, BSH, private communication). The sheltered position of the DYNAS dumping site may be responsible for the high temporal stability of the seabed features.

A second contribution to the high overall stability of the dumping mounds is the high erosion threshold of the deposited material. Backscattering strength of side-scan sonar signals strongly indicate that not only the deposits of the glacial till site but also those of the mixed-material consists to a large fraction of glacial till (Harff et al. 2005). To move the glacial till chunks as a whole would need extraordinarily high bed shear stresses. Also the internal shear strength of the compressed clay minerals will clearly exceed the estimated bed shear stresses by at least one order of magnitude (see e.g. Peirce et al. 1970, Benn and Evans 1998). The gradual reworking of the dumping mounds is possibly caused by water permeation and softening of the glacial till surfaces and, for the mixed soil mounds, by downhill movement of the sand grains.

Will gradual reworking dominate the future development or may extreme storm events lead to a significant erosion of the dumping mounds in the future? As estimation it was firstly investigated to what extent the hydrodynamical forcing during the observational period represents a more or less typical situation. To this end, the wave climate statistics from 2000 to 2005 obtained from the operational BSH-model were compared to a corresponding wave climate situation for the period from 1988 to 1992. For that period, model results of a grid point (grid resolution 15.875 km) corresponding to the DYNAS dumping site were available from a former study (Gayer et al. 1993). In the period from 1988 to 1992 the percentage of stormy events with wind speeds > 15 m s^{-1} was 6.5 % and thus two times higher than in between 2000 and 2005 (2.6 %). This difference is also reflected in the statistics of significant wave heights: the percentage of H_s > 3.5 m was 2

‰, compared to 0.5 ‰ between 2000 and 2005. The observational period hence was somewhat calmer, but not significantly. Secondly, extreme wave statistics derived from the BSH-model results of the 40 most severe storms of the years 1956 – 1993 showed a return period of about 35 years for H_s > 3.5 m. Similar results are published in Gayer et al. (1995) and refer to a location close to Warnemünde harbour.

From the most likely high erosion thresholds of the settled dumped material, the lack of observed bed erosion and the model wave statistics one may therefore conclude that for the next decades the occurrence of a wind event, which may lead to significant bed erosion at the DYNAS dumping site, has low probability. Assuming that gradual smoothing will dominate the further development the results from the surface variance analysis on the different levels of the Laplacian pyramid are extrapolated into the future using two different approaches: (1) by a linear function, i.e. assuming a constant smoothing rate, and (2) by an exponential, i.e. assuming a smoothing rate proportional to the surface variance. The survey period was too short to allow a discrimination of the two models on observational basis of three surveys. In Table 3 the times, when the seabed variances become zero (linear model) or decreased to 1/e of the start variances, are listed for horizontal scales up to 8 m. Above this scale no changes in variances were detected. If one uses the results of the linear extrapolation as the lower and of the exponential extrapolation as the upper limit, one may estimate that for the glacial till mounds all structures below a horizontal scale of 8 m will disappear within 70 to 134 years. For the mixed soil this time horizon is shorter by a factor of 5 to 7. Here, the structures below 2 m extension nearly disappeared within the survey period. One may conclude that the mounds, as a whole, will persist for many decades or even hundreds of years (glacial till). Clearly, this holds only if the internal stability of the material and the occurrence of intensity of severe storms will stay unchanged.

5 Summary and Conclusions

In the framework of this study, the temporal development of two experimentally dumped disposals made of glacial till and a mixture of glacial till with silt and medium sand was followed over three-and-a-half years. MBES technology coupled with high-precision positioning technology allowed for the detection of changes in the seabed deformations in the range of few centimetres per year.

The settled disposals showed distinctive ring-like structures with a diameter of some 30 m reflecting the transfer of vertical into horizontal momentum when the disposals hit the bottom. In the case of glacial till chunks large gaps between the individual mounds persisted over the survey period. For the mixed soil the coverage was more complete but showed significant variation in the coverage thickness. Material loss occurred obviously only during the settling phase of the dumps, as afterwards no volume changes of the settled mounds were detected. The lost material most likely consisted of silt and fine sand, which separated from the falling material, collected at the thermocline and was transported away as a plume with the flowing water.

The dumping mounds kept their locations on the average within a few meters. No further loss in total volume was observed, but reworking of the material occurred. In general, the peaks in the mounds flattened and troughs were filled up. Smoothing was fastest on smaller horizontal scales and at the same spatial scales faster for the mixed soil mounds than for the glacial till mounds.

The high stability of the mounds may be attributed to the sheltered positioning of the dumping site and the high bed shear stresses needed to move the glacial chunks and to erode the material. As the hydrodynamical situation with respect to current/wave statistics and resulting bed shear stresses was not untypical during the survey period one may conclude that an extreme event that may erode and remove significant amounts of the disposals from the dumping site is quite unlikely within the next decades. Under these considerations the glacial till mounds are expected to persist for about a century and the mixed soil mounds for more than two decades. This time horizon may shorten if uptake of water or bioturbiation decreases the internal shear strength of the till chunks and/or fishery activity directly plough the bed material. This should be monitored in future surveys with a repetition time of several years as the observed processes proceed slowly.

The observations have some consequences for the dumping management. As long as glacial till is dumped at comparably sheltered sites the loss and further dispersal of the dredged material is negligible over decades. Dumped material consisting of silt and sand may be transported away to a substantial degree in form of plumes and widely dispersed due to low settling velocities and the prevailing existence of a thermocline that significantly reduces vertical turbulent exchange. As silt is the material with the lowest settling velocities in dredged sediment mixtures and also the mostly polluted material, coastal zone management must focus on the handling of this fraction of the dredged material. At the same time, glacial till chunks have a limited use in covering highly polluted seabed. Although they possess a high stability when deposited on the bed it will be most demanding to achieve a sufficient area-wide coverage as the radial dispersion of the settled material is very limited and further spreading very slow.

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References

Benn, D.I. and Evans, D.J.A., 1998. Glaciers and Glaciation. Arnold, London, New York, Sydney, Auckland

Bokuniewicz, H.J. and Gordon, R.B., 1980. Deposition of Dredged Sediment at open Water Sites. Est. Coast. Mar. Sc., 10: 289-303

Bohling, B. and Lemke, W., 2003. Erosionsexperimente. In Harff, J. (ed.), Projekt: DYNAS - Dynamik natürlicher und anthropogener Sedimentation; Vorhaben: Sedimentationsprozesse in der Deutschen Bucht. Final Report: 22-27. Rostock-Warnemünde (in German)

Burt, P.J. and Adelson, E.H., 1983. The Laplacian Pyramid as a Compact Image Code. IEEE Transaction on Communications, COM-31: 532-540

Delo, E.A., 1987. Dispersal of dredged material at open-water disposal sites. Dredging and Port Construction, June 87:35 –37

Ernstsen, V. B., Noormets, R., Hebbeln, D., Bartholomä, A. and Flemming, B. W., 2006. Precision of high-resolution multibeam echo sounding coupled with high-accuracy positioning in a shallow water coastal environment. Geo-Mar. Lett., 26 (3): 141-149

Essink, K., 1999. Ecological effects of dumping of dredged sediments; options for management. Journal of Coastal Conservation, 5: 69-80

Gayer G., Günther, H. and Rosenthal, W., 1993. Seegangsstatistik für die Hafeneinfahrt Warnemünde Rostock. Final GKSS report for the German Federal Waterways Engineering and Research Institute, BAW. Geesthacht, Germany (in German)

Gayer, G., Günther, H. and Winkel, N., 1995. Wave Climatology and Extreme Value Analysis for the Baltic Sea Area off the Warnemünde Harbour Entrance. German Journal of Hydrography, 46(2): 109-130

Harff, J. et al., 2003. Projekt: DYNAS - Dynamik natürlicher und anthropogener Sedimentation; Vorhaben: Sedimentationsprozesse in der Deutschen Bucht. Final Report: 160 pp. Rostock-Warnemünde (in German)

Harff, J. et al., 2005. Projekt: DYNAS - Dynamik natürlicher und anthropogener Sedimentation. Vorhaben: Sedimentationsprozesse in der Deutschen Bucht – Phase II. Final Report: 249 pp. Rostock-Warnemünde (in German)

Harvey, M., Gauthier, D. and Munro, J., 1998. Temporal changes in the composition and abundance of the Macro-benthic invertebrate communities at dredged material disposal sites in the Anse à Beaufils, Baie des Chaleurs, Eastern Canada. Mar. Poll. Bull., 36(1): 41-55

Jähne, B., 1997. Practical Handbook on Image Processing for Scientific Applications. CRC Press LLC, New York

Katoh, K. and Kume, H., 1998. The development of sand waves and the maintenance of navigation channels in Bisanseto Sea. In Proceedings Coastal Engineering 1998, Coastal Engineering Research Council, Copenhagen, Denmark, pp. 3490-3502

Knaapen, M.A.F. and Hulscher, S.J.M.H., 2002. Regeneration of sand waves after dredging. Coast. Eng., 46: 277-289

Kuhrts, C., Fennel, W. and Seifert, T., 2004. Model studies of transport of sedimentary material in the western Baltic. Journal of Marine Systems, 52: 167-190

Leipe, T. and Bahlo, R., 2003. Ergebnisse des Eventsamplereinsatzes. In Harff, J. (ed.), Projekt: DYNAS - Dynamik natürlicher und anthropogener Sedimentation; Vorhaben: Sedimentations-prozesse in der Deutschen Bucht. Final Report: 74-78. Rostock-Warnemünde (in German)

Pagliai, A.M.B. and Varriale, A.M.C., 1985. Environmental Impact of Extensive Dredging in a Coastal Marine Area. Mar. Pol. Bul., 16 (12): 483-488

Peirce, T.J., Jarman, R.T. and de Turbille, C.M., 1970. An experimental study of silt scouring. Proc. Inst. Civ. Engrs., 45: 231-243

Roberts, R.D. and Forrest, B.M., 1999. Minimal impact from long-term dredge spoil disposal at a dispersive site in Tasman Bay, New Zealand. New Zealand Journal of Marine and Fresh Water Research, 33: 623-633

Roxar Software Solutions AS, 2003: "Seabed" algorithm, Cfloor Version 6.2.2, Users Guide. Oslo

Siedler G. and Hatje,G., 1978. Temperatur, Salzgehalt und Dichte. In Magaard, L. und Rheinheimer, G. (eds.), Meereskunde der Ostsee: 43-60. Springer, Berlin (in German)

Siegel, H., Gerth, M., Heene, T., Kraft, H., Ohde, T. and Rühs, D., 2003. Hydrografie, Strömung und Schwebstoffverteilung während der Verklappung am 20./21.06.2001. In Harff, J. (ed.), Projekt: DYNAS - Dynamik natürlicher und anthropogener Sedimentation; Vorhaben: Sedimentationsprozesse in der Deutschen Bucht. Final Report: Appendix 1: 20 pp.. Rostock-Warnemünde (in German)

Stockmann, K., 2005. Quantifizierung morphologischer Veränderungen verklappter Sedimente vor der Küste Mecklenburg-Vorpommerns. Diplom thesis. External report GKSS 2005/5, 132 pp.. GKSS-Forschungszentrum GmbH, Geesthacht (in German)

Van den Hurk, P., Eertman, R.H.M. and Stronkhorst, J., 1997. Toxicity of harbour canal sediments before dredging and after off-shore disposal. Mar. Poll. Bull., 34 (4): 244-249

Wienberg, C., Dannenberg, J., and Hebbeln, D., 2004. The fate of dumped sediments monitored by a high-resolution multibeam echosounder system, Weser Estuary, German Bight. Geo-Marine Letters, 24: 22-31

Wienberg, C. and Hebbeln, D., 2005a. Impact of dumped sediments on subaqueous dunes in the outer Weser Estuary, German Bight, southeastern North Sea. Geo-Marine Letters, 25: 43-53

Wienberg, C. and Bartholomä, A., 2005b. Acoustic seabed classification in a coastal environment (outer Weser Estuary, German Bight) - a new approach to monitor dredging and dredge spoil disposal. Continental Shelf Research, 25(9), 1143-1156

Figures

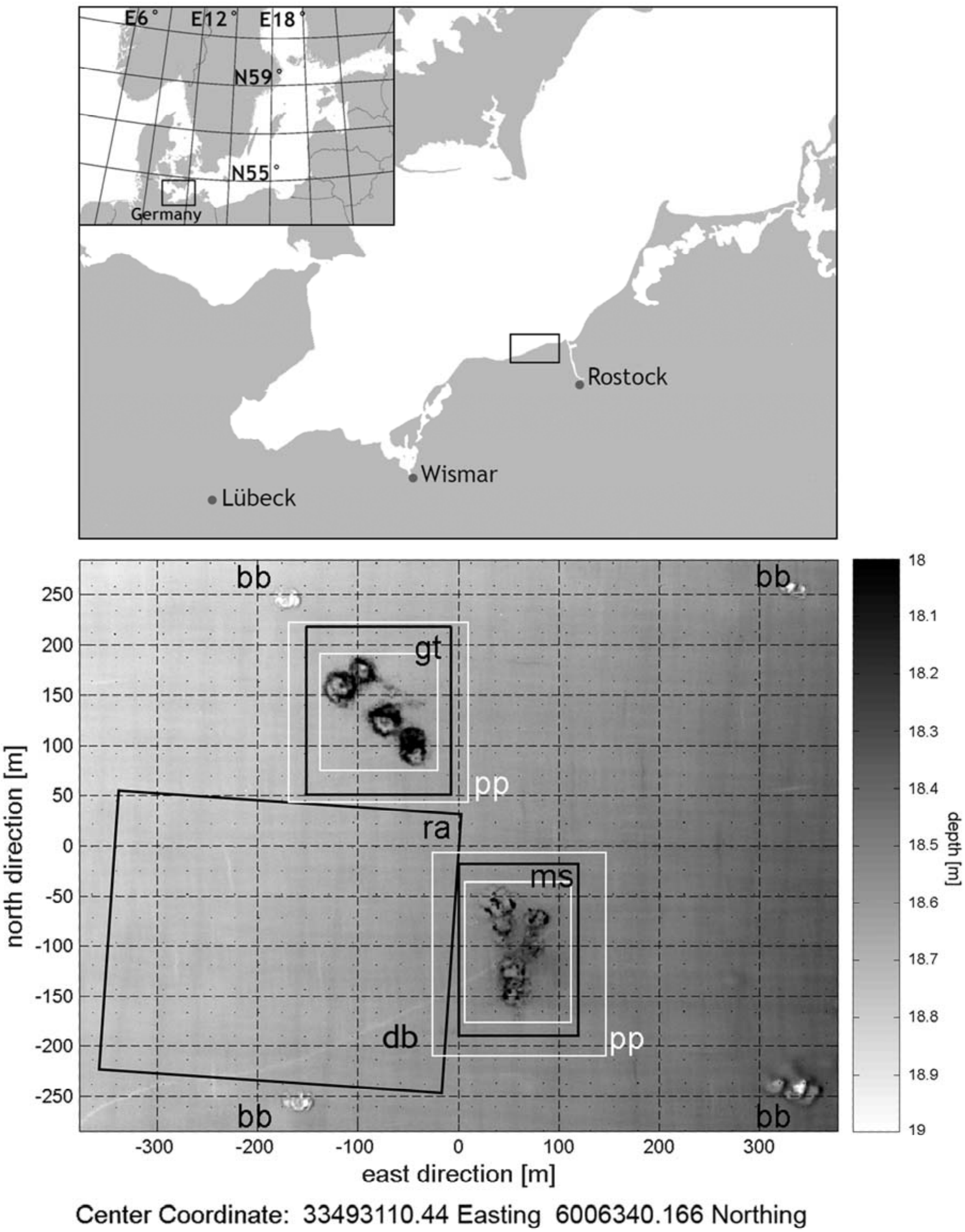
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Fig. 1. Map of the study site located at the German Baltic coast.

The lower panel represents the DTM of the August 2001 survey. The centre coordinate is given in UTM32 projection. The corresponding WGS 84 co-ordinates are N 54° 12.08', E 11° 54,14'. The depth is given with respect to the normal chart datum. The mounds of the dumped glacial till (gt) and the mixed soil (ms) are clearly visible. Other bed features are a fishing drag board trace (db) and the scour holes around the anchor stones of the boundary buoys (bb). The black frame (ra) shows the margin of the "reference area", and the white frames (pp) the outer and inner margins of the "pristine planes" (see text).

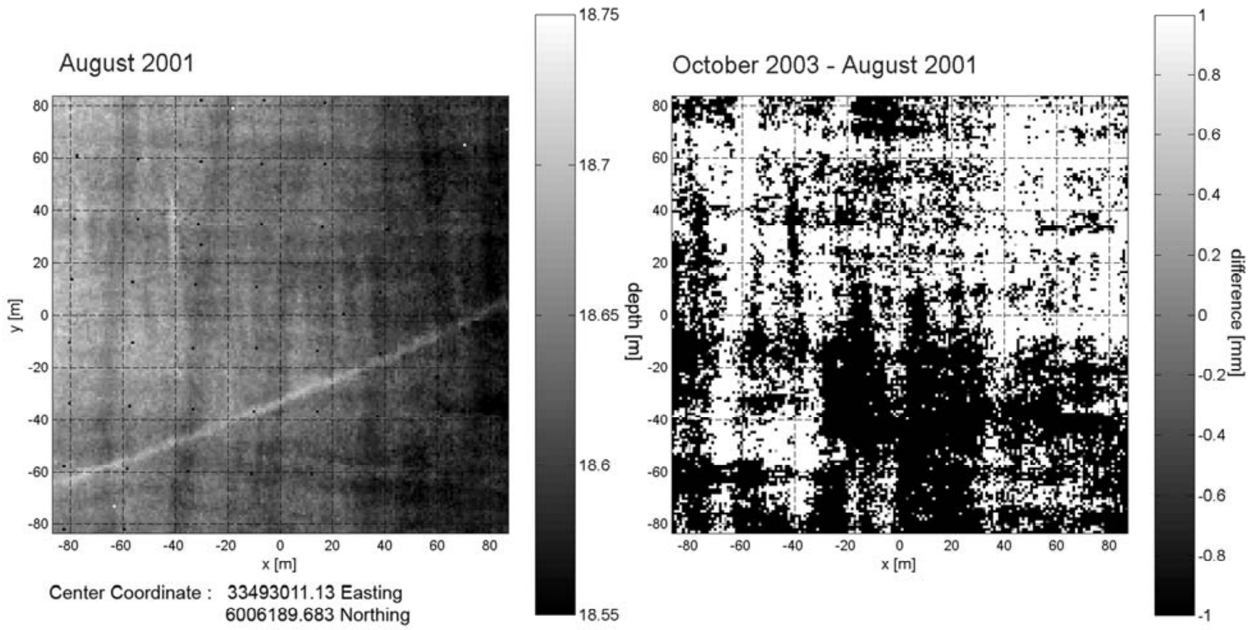

Fig. 2. Left: DTM around the drag board trace as obtained in August 2001. The centre coordinate is given in UTM32 projection. “y”-axis is in North direction. Depth is with respect to the normal chart datum.

Right: Difference DTM plot October 2003 - August 2001 . The mean difference is set to zero. Note the expanded vertical scale at the right hand side of the panels, which for the right panel ranges from –1 to + 1 mm.

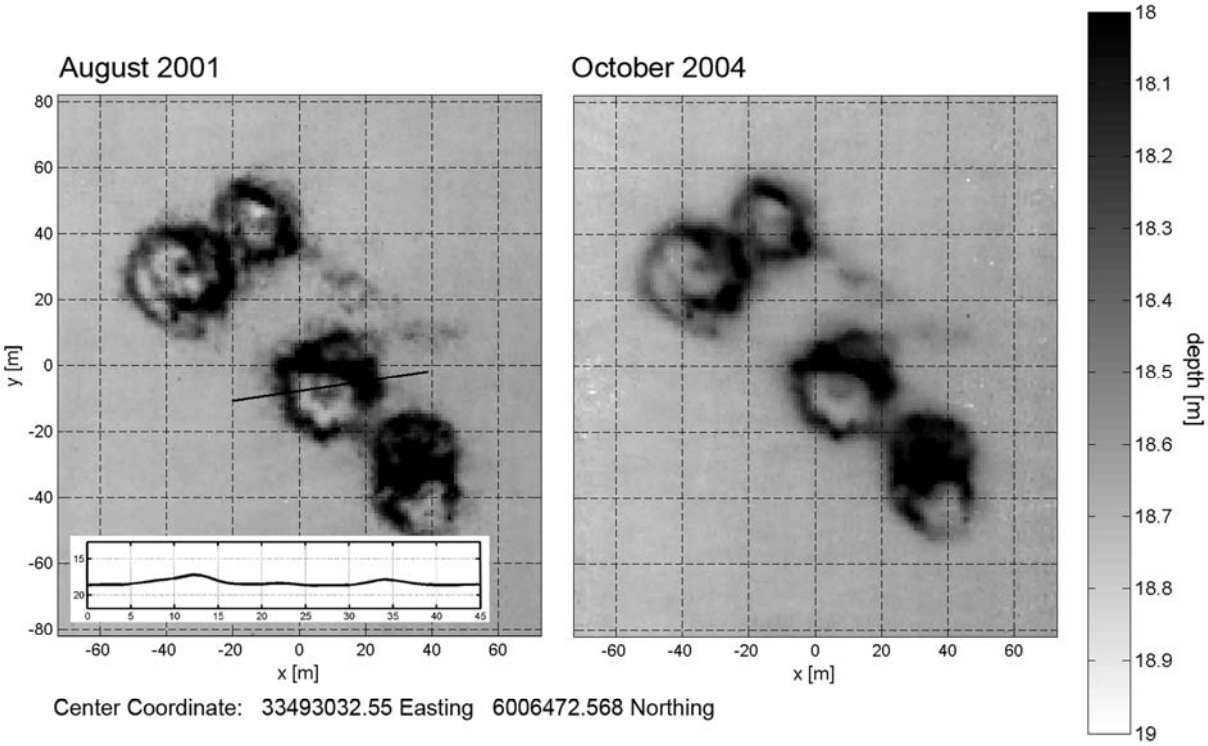

Fig. 3. DTM of the glacial till dumping site as obtained in August 2001 and October 2004. The centre coordinate is given in UTM32 projection. “y”-axis is in North direction. Depth is with respect to the normal chart datum. The inset in the left panel shows the not exaggerated bed elevation profile along the transect across one of the ring structures as indicated by the black line.

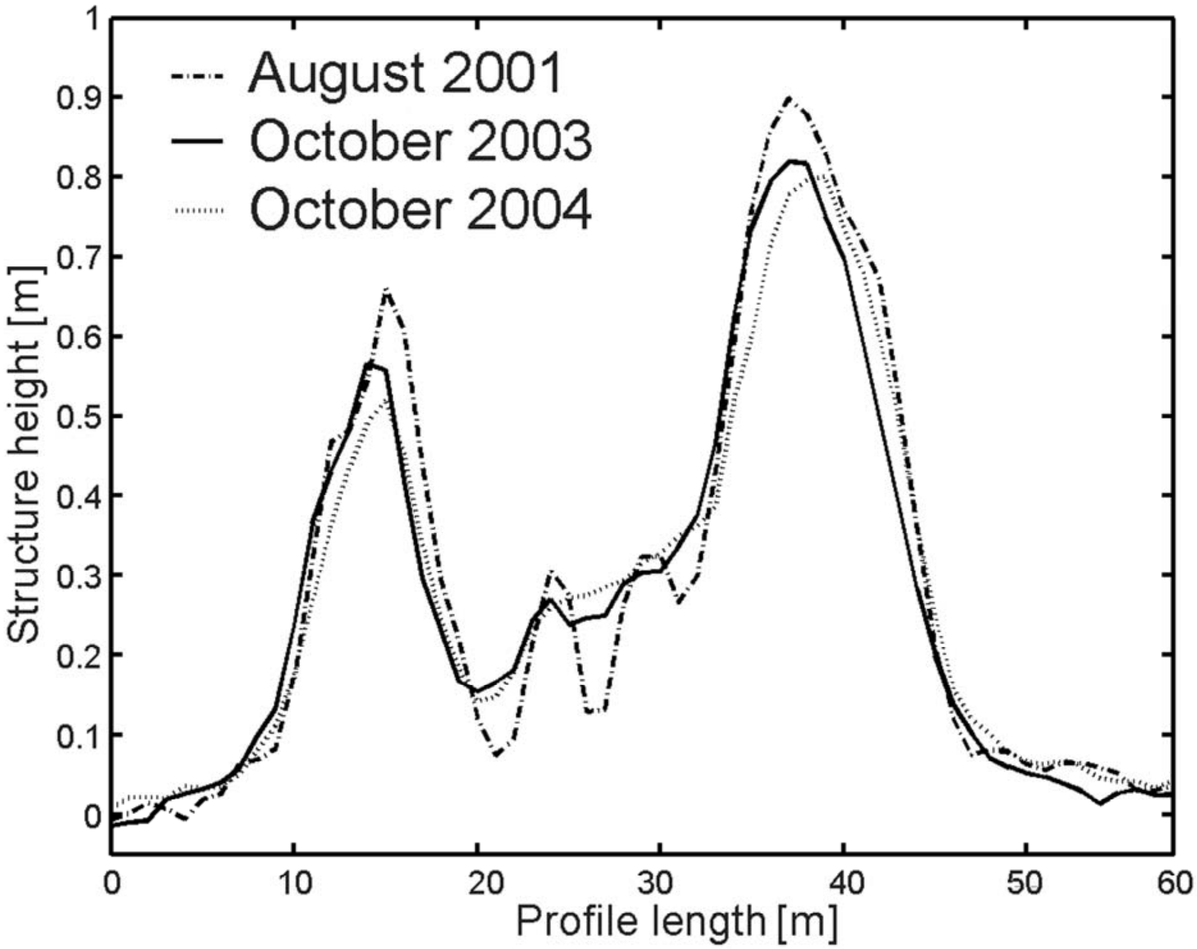

Fig. 4. Bed elevation profiles across the glacial till transect shown in Fig. 3 as obtained in August 2001, October 2003, and October 2004. The structure height is given with respect to the reference area, but is somewhat shifted to start the profiles around height zero. The error in the structure height for each individual DTM grid cell amounts to ± 5 cm (95 % confidence level); for the structure as a whole an error of ± 2.5 cm was derived from the variances in the Laplacian pyramid level of the undisturbed reference area (see text).

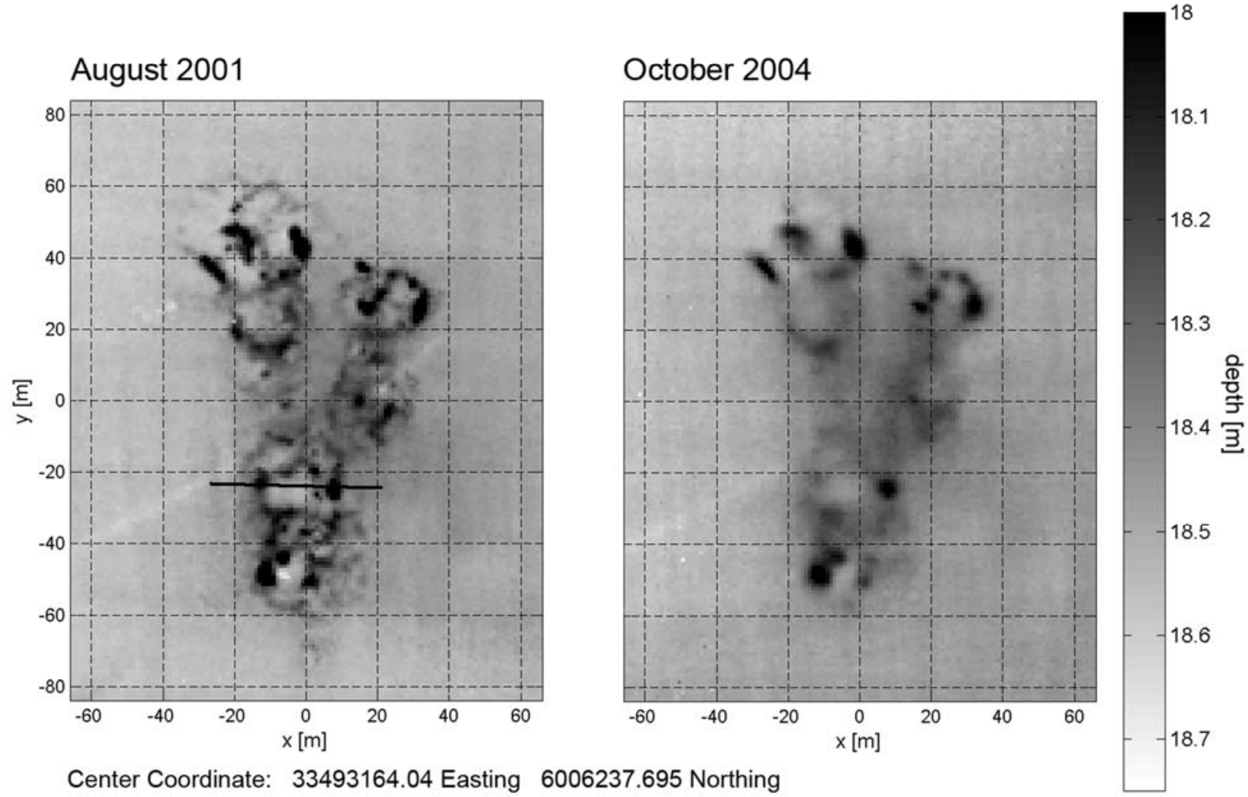

Fig. 5. DTM of the mixed soil till dumping site as obtained in August 2001 and October 2004. The centre coordinate is given in UTM32 projection. "y"-axis is in North direction. Depth is with respect to the normal chart datum. The black line in the left panel indicates the transect of the bed elevation profiles shown in Fig. 6.

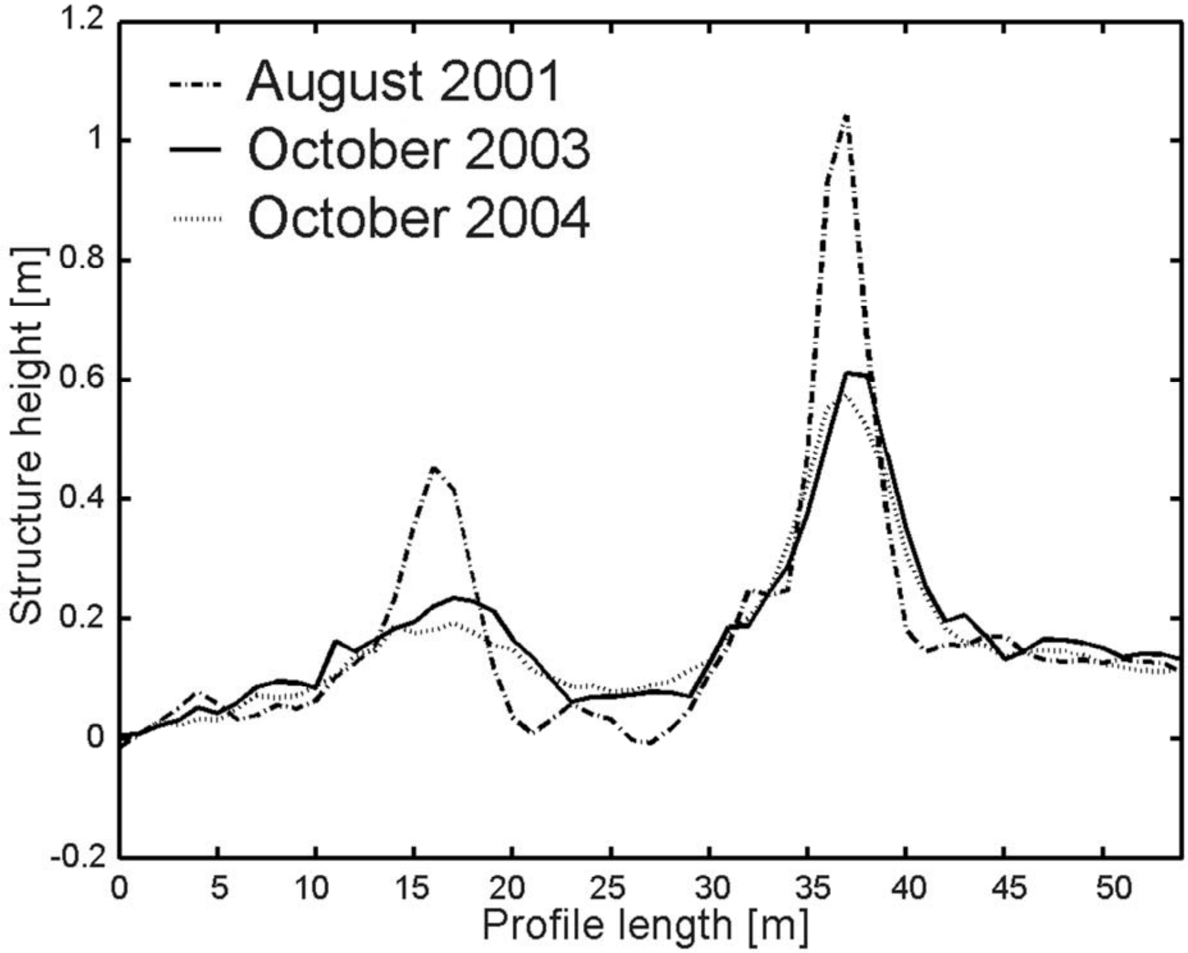

Fig. 6. Bed elevation profiles across the mixed soil transect shown in Fig. 5 as obtained in August 2001, October 2003 and October 2004. The structure height is given with respect to the reference area, but is somewhat shifted to start the profiles around height zero. For errors in the structure height see Fig. 4.

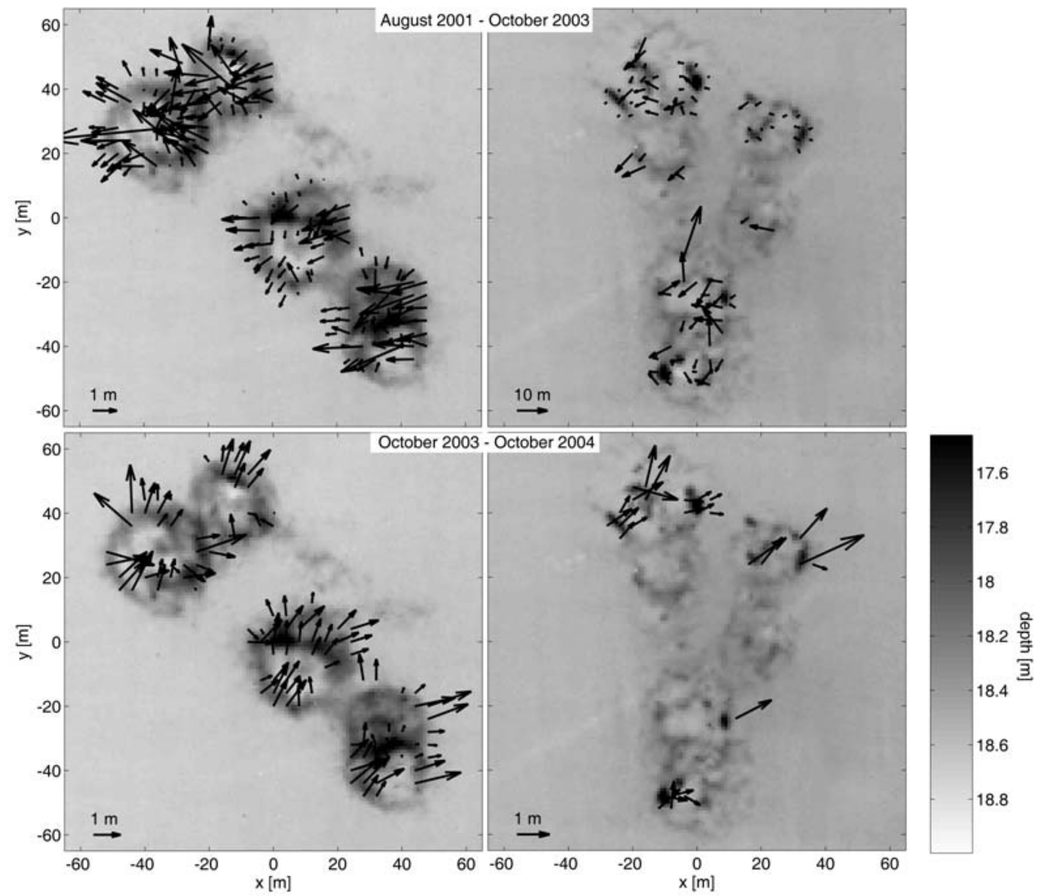

Fig. 7. Displacements of the disposal mound structures as obtained from optical flow analysis.

Left panels: glacial till mounds; right panels: mixed soil mounds; upper panels: August 2001 to October 2003; lower panels: October 2003 to October 2004; Co-ordinates as in Fig. 3 or 5, respectively. Scale bars for the arrows are in the lower left corners; please note the different scale in the upper right panel.

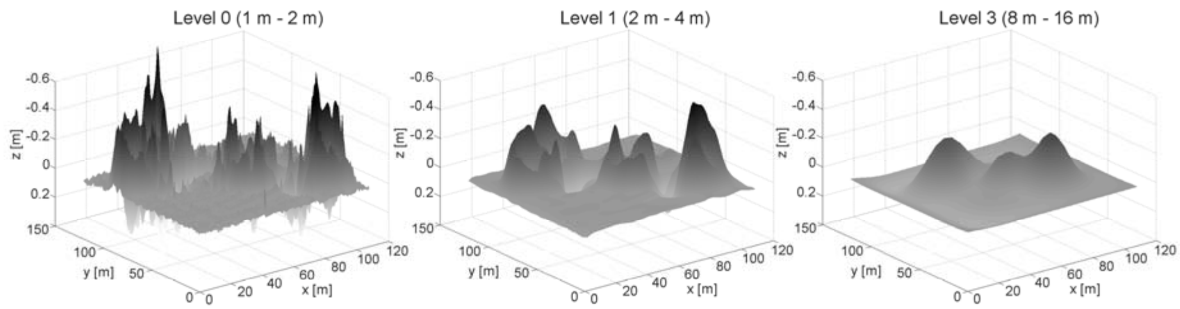

Fig. 8. Bed structures of one of the glacial till rings for level 0, 1 and 3 of the Laplacian Pyramid as obtained in August 2001. Please note the considerable exaggeration of the vertical axis. Co-ordinate origin is arbitrary.

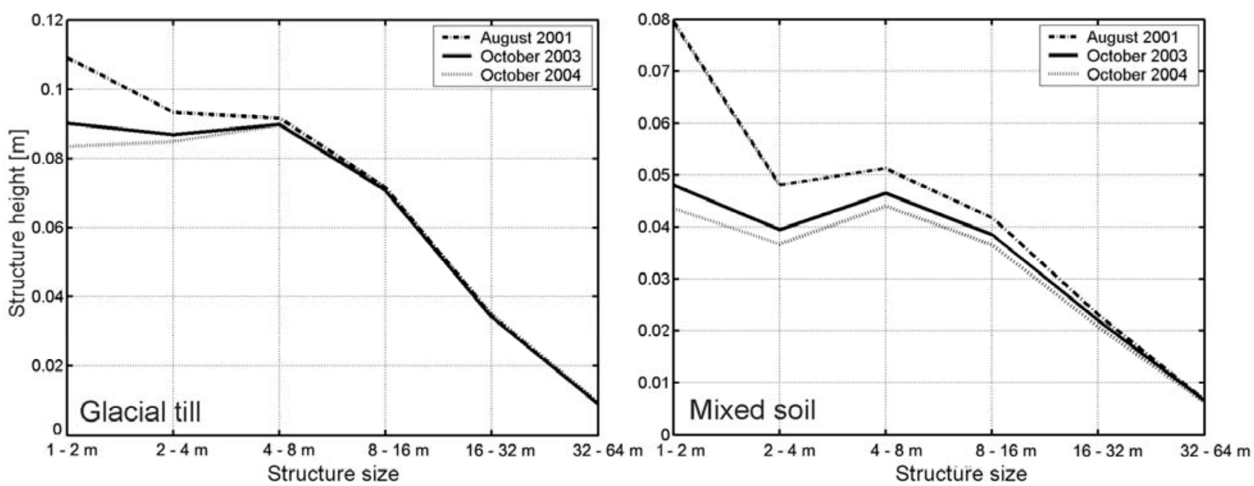

Figure 9: Mean structure height of the seabed structures versus the horizontal scales of the Laplacian pyramid for August 2001, October 2003 and October 2004. The left panel shows the results of the glacial till, the right panel those of the mixed soil mounds. Horizontal structure size corresponds to half of the wavelength domain.

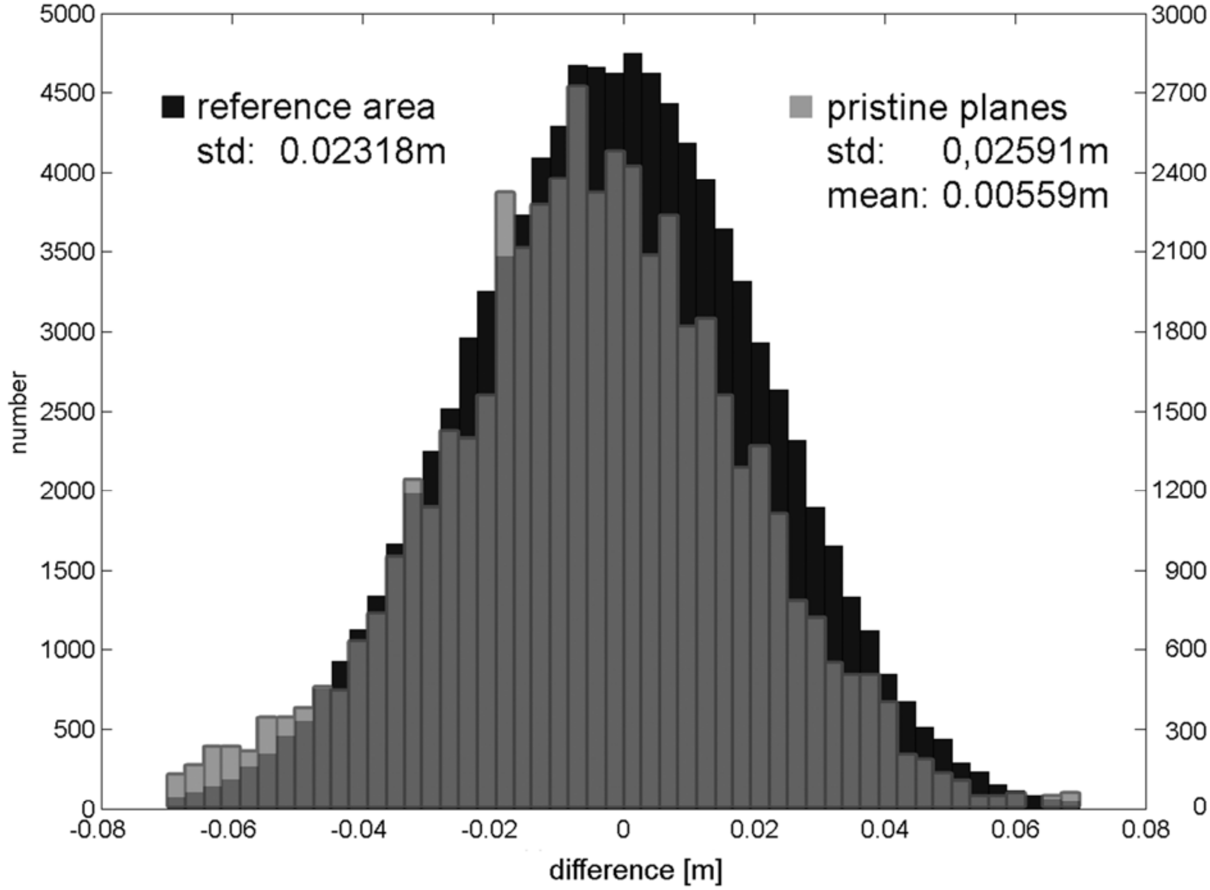

Fig. 10. Histogram of height differences of corresponding DTM cells between the October 2003 and August 2001 and between the October 2004 and October 2003 surveys. The black shaded histogram contains the data of the "reference area" round the drag board trace, the grey shaded area those of the margins of the "pristine planes" around the dumping sites. For convenience, the vertical scales of both histograms are adapted to nearly identical maximum values.

Tables

Table 1

Volumes of the dumped and the settled material and the volume changes of the dumping mounds

	Glacial till	**Mixed soil**
Volume dumped in June 2001	~2900 m^3	~2400 m^3
Volume measured in August 2001	~2500 m^3	~1500 m^3
Volume change from August 2001 to October 2003	– 17 m^3	+ 6 m^3
Volume change from October 2003 to October 2004	– 4 m^3	– 23 m^3
Volume change from August 2001 to October 2004	– 21 m^3	– 17 m^3

Table 2

Roughness in seabed height for increasing levels of the Laplacian pyramid as determined in August 2001, October 2003 and October 2004

Horizontal structure size corresponds to half of the wavelength domain; roughness is given as square roots of variances in seabed height.

Bandpass filter	Level of Laplacian Pyramid			
	0	1	2	3
	Horizontal structure size [m]			
	1 – 2	2 – 4	4 – 8	8 – 16
Time	Roughness of glacial till structures [cm]			
August 2001	11.0	9.3	9.2	7.2
October 2003	9.1	8.7	9.0	7.1
October 2004	8.4	8.5	8.9	7.2
Time	Roughness of mixed soil structures [cm]			
August 2001	7.9	4.8	5.1	4.1
October 2003	4.8	4.0	4.7	3.9
October 2004	3.7	3.7	4.4	3.6

Table 3

Estimated surface flattening times for increasing horizontal wavelength domain. Horizontal structure size corresponds to half of the wavelength domain.

	Scaling method	Horizontal structure size [m]		
		1 – 2	2 – 4	4 – 8
		Surface flattening times [a]		
glacial till	linear	6	16	70
	exponential	12	35	134
mixed soil	linear	4	6	11
	exponential	5	12	27