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The fate of dumped sediments monitored by a high-resolution multibeam echosounder system, Weser Estuary, German Bight

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Abstract With the development of high-resolution multibeam echosounder systems (MBES) for surveying shallow-water areas a new tool is available to monitor rapid changes in seabed morphology as, e.g., caused by the dumping of dredge spoil in coastal waters. In this study, four data sets of repeated bathymetric surveys with a MBES were processed and analyzed. The data were collected in a 1.94-km^2 dumping site in the outer Weser Estuary (German Bight). Between June and December 1998, 2.6 million m^3 of dredged sediment were deposited there. The bathymetric maps generated in the course of this study reveal features such as subaqueous dunes, scour holes, and mounds of dumped dredge spoil. The mean water depth decreased by about 1 m during the dumping period. Furthermore, difference grids showing changes in sediment volume allowed a calculation of the sediment budget for the monitored area. After a time period of only 5 months, 0.5 million m^3 of the originally dumped 2.6 million m^3 of dredge spoil had already been removed from the dumping site.

Keywords Multibeam echosounder system · Dumping site · Bathymetric maps · Sediment budget · Weser Estuary

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Introduction

Many coastal areas are strongly affected by tidal and wave energies. These hydrodynamics generate high bottom stresses, which, in turn, are responsible for an extensive reworking and a constant redistribution of sediments. Thus, the morphology in near-coastal areas is subject to continuous short- and long-term changes on various spatial and temporal scales (Perillo 1995b; McMagnus 1998). For this reason, many seaports, such as Rotterdam, Bruges, Hamburg or Esbjerg, all situated along the southeastern North Sea coast, have substantial problems due to sedimentation. These problems also affect channels used as shipping lanes. They permanently change their morphology and course, which may result in decreasing navigation depths and the need for permanent monitoring and maintenance dredging. Furthermore, shipping channels have to be adapted to the continuously increasing size of vessels, nowadays primarily to the development of container vessels with increasing length and draft, to guarantee an access to the respective harbors. This often requires the extraction of relatively large amounts of sediment. In some cases, these sediments are used for infrastructural projects, but mostly, the material is dumped somewhere in the area, preferably at near-by sites outside the main shipping channel to reduce the operational costs.

This is also the case for the shipping channel in the outer Weser Estuary (German Bight), which has been artificially modified and deepened for more than 100 years, in order to ensure unhindered navigation to the harbors of Bremerhaven and Bremen (Wetzel 1987; Wienberg 2003). The last deepening to a water depth of 14 m (below German sea chart datum) took place in 1998. During this intervention, more than 8 million m^3 of sediment was removed, and around one-third of this material was dumped at the dumping site Rotergrund, situated next to the dredged channel.

Local waterway and shipping authorities have extensive experience with the dumping of sandy material in this area, the main aspects being (1) during the dumping, no significant turbidity at the sea surface is recognizable, (2) almost the total amount of dumped material is deposited at the seabed, (3) the dumped sediments accumulate in form of a distinct mound, whereas the surrounding seabed is not affected, and (4) after deposition, the dumped material is further transported in the direction of the dominant tidal current (Wasser- und Schiffahrtsamt Bremerhaven 1996). Nevertheless, adequate scientific studies investigating dumped sediments are relatively rare (e.g., Smith 1976; Healy et al. 1999; Brack et al. 2000), and the main problem, therefore, is to predict the ultimate fate of dumped sediments.

In the present study, four datasets of repeated bathymetric surveys with a high-resolution multibeam echosounder system (MBES) were processed to monitor dumped sediments and their morphological influence on the local seabed. MBESs are a useful tool to generate high-resolution bathymetric maps of shallow-water areas with the highest resolution quality today available. Furthermore, because these systems enable surveys of large areas in relatively short time spans, they allow the monitoring of anthropogenic interventions on the natural sediment cycle in the coastal environment, and an estimation and prediction of future developments.

The purpose of the present study was to investigate what effect dumping of a relatively large amount of dredge spoil (2.6 million m^3) would have on the morphology of the local seabed at the dumping site Rotergrund, situated in the Weser Estuary (Fig. 1A, B). By comparing bathymetric maps generated from high-resolution data of repeated surveys with a MBES, the modification of small- to large-scale seabed features at

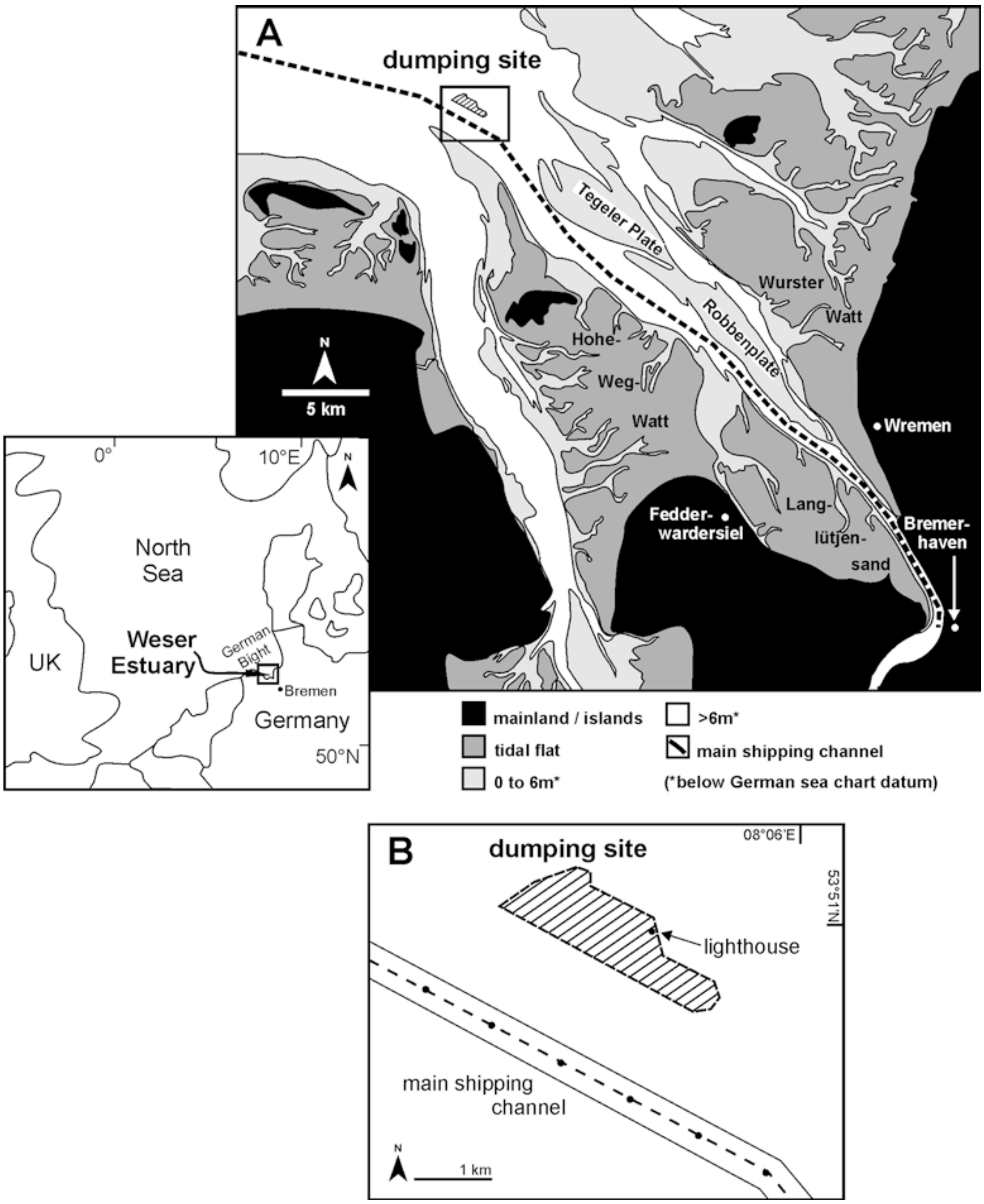

Fig. 1 **A** Map of the outer Weser Estuary (German Bight). **B** Map of the study site

the dumping site were documented. In addition, the change in sediment budget associated with the export of dumped material was quantified.

Regional setting

The seabed of the southern North Sea, including the German Bight, largely consists of fine to medium sand. The bottom sediments of the outer Weser Estuary, which discharges into the German Bight (Fig. 1A), also consist mainly of fine to medium sand (silt and clay content $<1\%$; Wetzel 1987). Zeiler et al. (2000) showed that the spatial distribution, of what these authors called ''mobile bottom sediments'' or ''North Sea sands'' in the inner German Bight, can be divided into three distinct zones. Due to the longshore sediment transport from west to east (Johnson et al. 1982), the innermost part of the German Bight, including the estuary mouths of the German rivers Weser and Elbe, is characterized by the highest sediment accumulation in this region. In water depths between 0 and 10 m (below German topographic chart datum), the thickness of the North Sea sands amounts to $\sim$10 m. Further offshore, at a depth of 10–15 m (below German topographic chart datum), a zone of sediment depletion (sediment cover: <1.5 m) has been identified, which can be explained by shore-normal bedload transport. In water depths >15 m, the layer of North Sea sands increases again to about 2–3 m (Zeiler et al. 2000).

According to the conventional geomorphological classification by Pritchard (1952, 1967), the Weser Estuary would be classified as a drowned river valley or as a coastal plain estuary that occupies a former river valley along a low relief coast (Perillo 1995a). The outer part of the Weser Estuary starts at the seaport of Bremerhaven, where the estuary broadens from a channel-like inner part to a progressively widening funnel (Fig. 1A). In the outer Weser Estuary, two tidal channels are developed that are separated by flow-parallel elongated sand bars and that bend out in a northwesterly direction. Inshore, the channels are lined by extensive tidal flats of the German Wadden Sea, followed seawards at water depths between 6 and 20 m (below German sea chart datum), by shallow subtidal shoals. Due to the absence of off-shore islands at its mouth, the outer estuary is highly exposed to hydrodynamic processes.

The Weser Estuary, like all estuaries and bays of the inner German Bight, is tide-dominated. The semi-diurnal tides penetrate with unhindered energy in a northwest–southeast direction into the estuary. Furthermore, distinct spring and neap tidal cycles are recognizable. The distortion of the tidal wave propagation due to friction at the seabed and convergence of the estuary margins produces differences in magnitude and duration of ebb and flood tidal currents, resulting in a tidal asymmetry and residual sediment transport (Dronkers 1986). The Weser Estuary is characterized by the dominance of the ebb tide with a slightly longer ebb duration and higher current velocities; therefore, the residual sediment transport is directed towards the open sea. The main channel is separated into an ebb and a flood channel (Bundesanstalt für Gewässerkunde 1992). The Weser Estuary belongs to the hypersynchronic type, i.e., the tidal amplitude increases from the mouth towards the head (Nichols and Biggs 1985). Due to the funnel-shaped geometry of the outer part of the estuary and the existence of elongated sand bars, the incoming flood is progressively compressed into a smaller cross-sectional area. The tidal range increases from 2.8 m at the mouth to about 4.2 m at the weir in Bremen, which is the highest tidal range along the entire German North Sea coast. Following Davies (1964) and Hayes (1975), the Weser Estuary can be classified as a meso- to macrotidal estuary. The high tidal range associated with maximum current velocities of 1.0–1.3 m s^{-1} (Bundesanstalt für Gewässerkunde 1992) results in strong vertical mixing of seawater and freshwater delivered by the Weser River (Grabemann and Krause 1989).

Study site

The dumping site Rotergrund is situated in the exposed part of the outer Weser Estuary, east of the main shipping channel (Fig. 1A, B). The water depth at this site averages at 12.5 m (below German sea chart datum). The Waterways and Shipping Office of Bremerhaven is responsible for the deepening of the shipping channel and for dumping the dredge spoil in the outer Weser Estuary. To control the process of dumping in the course of the last deepening of the main shipping channel, the office subdivided the declared 1.94-km^2 dumping site into 97 rectangular units with a size of 100x200 m (Fig. 2). During the dumping operation, each of these units was filled with a predefined amount of dumped material, as shown in Fig. 2.

Because the surface sediments are originally composed of fine to medium sands, this dumping site was only used for the dumping of sandy material removed out of the shipping channel. Another important reason for choosing this area for dumping was the advantageous economic factor, i.e., the short distance (1.3 km) to the dredged channel (Fig. 1B), which meant a substantial reduction in operational costs (Rodiek and Steege 2001). In addition, it was hoped to fill up scour holes that had developed at the base of a lighthouse, situated approximately along midway at the eastern margin of the site (Fig. 1B) in order to enforce the stability of the building.

Methods

Data acquisition

The repeated surveys in the outer Weser Estuary were performed by a private surveying company, which was authorized by the Waterways and Shipping Office of

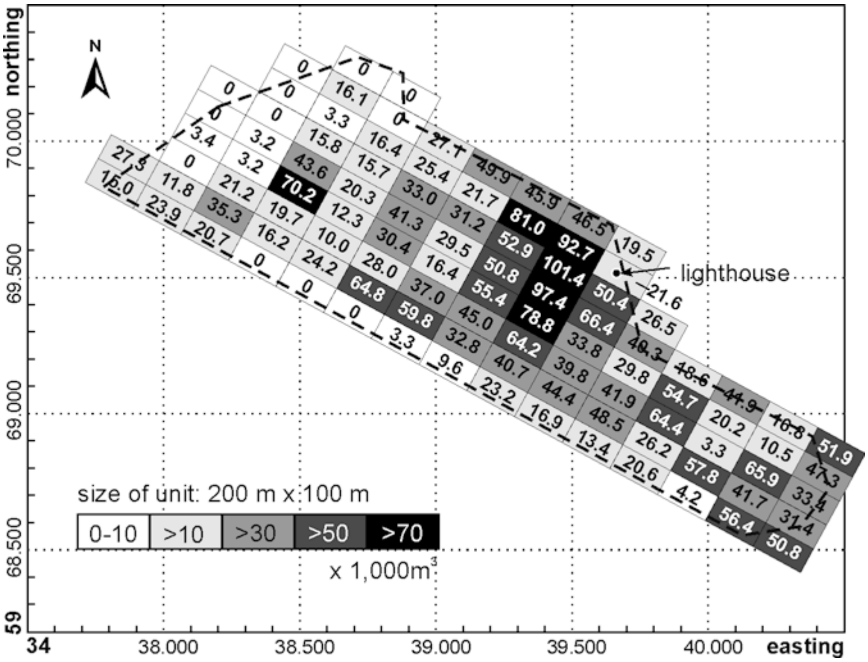

Fig. 2 Distribution of the actually dumped amount of dredged material during the whole dumping period in 1998. To control the dumping, the site has been subdivided into a grid of 97 rectangular units of 100x200 m. The *numbers* indicate the predefined amount of dumped material in m^3 x1,000

Bremerhaven to monitor the process of dredging and dumping during the deepening of the Weser Estuary in 1998. The applied multibeam echosounder system (MBES) was a Reson SeaBat 8101. This system operates at a frequency of 240 kHz and is designed for surveying shallow-water areas in the depth range of 0.5 to 500 m (Reson 1999). During the surveys of the dumping site Rotergrund, the transducer of the MBES was rigged over the bow of a 26-m-long survey vessel. The surveys were carried out with a swath width of 143° across-track by 1.5° along-track (ConsultING-Team 1999). In water depths between 10 and 20 m, the maximum swath width covers a seabed area of about six times the water depth. The swath consists of 101 individual beams (1.5x1.5°, beam-spacing 1.5°), which means that 101 depth values are obtained with every single ping. The speed velocity of the survey vessel was 7 knots and, with an adjusted update rate of 7.5 pings per second, a swath line was measured every 38 cm (ConsultING-Team 1999). The individual survey-tracks had a width of approximately 80 m and were spaced to have a slight overlap.

The high frequency and a high sample rate of the Reson SeaBat 8101 results in high-resolution bathymetric data. However, the accuracy of the MBES can be affected by a variety of errors, for instance by inaccuracies of the system settings, inaccuracies of sound velocity and tide corrections, and, most importantly, navigational inaccuracies in determining the geographical position (Lurton 2002). The latter are complicated by movements (heave, roll, pitch, yaw) of the survey vessel. As a result, correction of the measured raw data is an important step before data processing for map generation can be started.

During the surveys of the dumping site Rotergrund, the geographical positions were fixed with a differential global positioning system (DGPS) Type NR203. The differential correction data were received from several reference stations installed on-shore in the region. According to the surveying company, a position accuracy of approximately 30 cm was achieved. To compensate for the variations in ship movements, a motion sensor of the type TSS DMS-05 was used, which is designed specifically for surveys with a MBES. Because sound velocities within estuaries change over short time periods due to the influence of the tides and rapid changes in salinity, the sound velocity in the tide-dominated Weser Estuary was measured every hour, and the soundings were corrected in real time. All these procedures were carried out by the authorized surveying company (ConsultING-Team 1999).

Data processing

The corrected sounding data were processed with the computation and visualization software of MATLAB. The files containing the corrected sounding data were stored in the form of binary triplets (XYZ). Between 2.6×10^6 and 7×10^6 soundings per survey were recorded (Table 1). A regular data grid with a 4-m node spacing in the N–S and E–W directions was defined and the sounding data within each grid cell element were averaged to produce a digital terrain model.

Furthermore, a geostatistical analysis was carried out for each data set to obtain get information about minimum, maximum, and mean water depth of the dumping site (Table 1), as well as the change in water depth conditions during dumping. As a by-product, it was detected that the data sets still contained some erroneous soundings. Such erroneous soundings or outliers from the bathymetry can occur due to acoustic and electronic effects (e.g., surface reflection, low signal-to-noise-ratio

Table 1 Data acquisition information as well as minimum, maximum, and mean water depth at the dumping site during the bathymetric survey campaign. Water-depth information relates to meters below German sea chart datum, i.e., mean low water springs

Date of surveying	Measurement period	Number of survey tracks	Number of soundings	Number (percentage) of erroneous soundings	Water depth (m)		
					Min.	Max.	Mean
30 June 1998	?	17	2,602,447	428 (0.016%)	8.3	17.0	12.5
21 July 1998	1 h 33 min	15	4,969,270	1,272 (0,026%)	7.4	17.0	12.0
30 August 1998	1 h 44 min	18	5,058,962	2,169 (0.043%)	5.1	16.5	11.6
1 December 1998	2 h 33 min	21	6,993,949	1,504 (0.021%)	5.2	16.1	11.4

in bad weather conditions, gas bubbles in front of the transducer). It was thus necessary to detect dubious soundings and to remove these from the data set. Most cleaning methods in use are manual, despite some algorithms based on geostatistical techniques (Bisquay et al. 1998; Debese and Bisquay 1999). On the whole, the processed data sets were of good quality, and only the outer edges of the swath (outer beams) showed some incorrect water depths (0.02–0.04% of all measured data; Table 1), which were removed manually.

Difference grids

To facilitate a quantitative comparison between the surveys, grids of bathymetric differences (grid size: 4x4 m) were produced by subtracting corresponding depth values in two bathymetric grids. On this basis, regions of accumulation and erosion within the dumping site were identified and visualized. In this case, difference grids between the data sets of later surveys were generated. Finally, the initial state of the dumping site was compared with the last mapping to obtain the total volume change and a potential export of deposited material out of the dumping site. The amount of accumulated sediment, as well as the total amount of redistributed sediment (accumulation + erosion), was calculated.

Results

Bathymetric maps

On the generated map of the first bathymetric survey (carried out at 30 June 1998), the morphological state of the dumping area before dumping of dredged sediment began is shown (Fig. 3A). The mean water depth at that time was 12.5 m (all depth information relates to meters below German sea chart datum, i.e., mean low water springs). The seabed deepens slightly by about 1.5 m along a NE–SW transect through the dumping site. All measured depth values range between 8.3 and 17.0 m (Table 1). The undisturbed seabed at the dumping site is covered with subaqueous dunes, which are described in the literature as common features in the mouths of estuaries discharging into the southern German Bight (Reineck 1963; Göhren 1965; Ulrich 1973; Reineck and Singh 1980; Wever and Stender 2000). The dunes are 2–6 m high and their average wavelengths, measured from trough to trough, vary between 160 and 410 m. According to Ashley (1990), they would be classified as very large dunes. The crestlines of the dunes are sinusoidal, partly bifurcated, and orientated transversely to the main tidal direction. Furthermore, the dunes are asymmetrical in cross-sectional profile with the steep lee slope facing towards the sea.

After 22 days (21 July 1998), the bathymetric survey of the dumping site was repeated. The mean water depth now amounted to approximately 12 m, whereas the water depths ranged from 7.4 to 17.0 m (Table 1). In general, the morphological situation of the site did not change significantly (Fig. 3B). An exception is the central part of the survey area (south of the lighthouse, see Fig. 3B), where substantial sediment accumulation occurred marked by the filling of the dune troughs.

Two months after the beginning of dumping (30 August 1998), more than half of the total amount of the 3 million m^3 of sediment had already been dumped (Fig. 3C). At this time, the mean water depth of the dumping site was 11.6 m, i.e., 90 cm less than before dumping started (Table 1). As mentioned before, the seabed in the central part of the site showed strongest shoaling from formerly 9–12 to 8–10 m water depth. With 50,000 to 100,000 m^3 dumped sediments per 200x100-m unit (Fig. 2), this is also the region of the highest dumping rates. The subaqueous dunes are still traceable, but their troughs have strongly filled up with dumped sediment. As a result, most of the dunes have heights of less than 2 m, especially in the eastern part of the dumping site. In the western and eastern zone, individual mounds of dumped dredge spoil are recognized by their almost circular shape. The biggest mounds have diameters of up to 120 m and a height of about 1.5 m. Finally, two scour holes with diameters of 70–120 m were detected on the bathymetric map. These are developed to the north and the northwest of the lighthouse (Fig. 3C).

The last bathymetric map (1 December 1998) shows the situation after 2.6 million m^3 of dredged sediments had been deposited at the site (Fig. 3D). Between the first and last bathymetric survey, the mean water depth decreased by about 1 m, from formerly 12.5 to 11.4 m, resulting in water depths of between 5.2 and 16.1 m in December (Table 1). The filling of the dune troughs had increased further. Some individual dumping mounds are

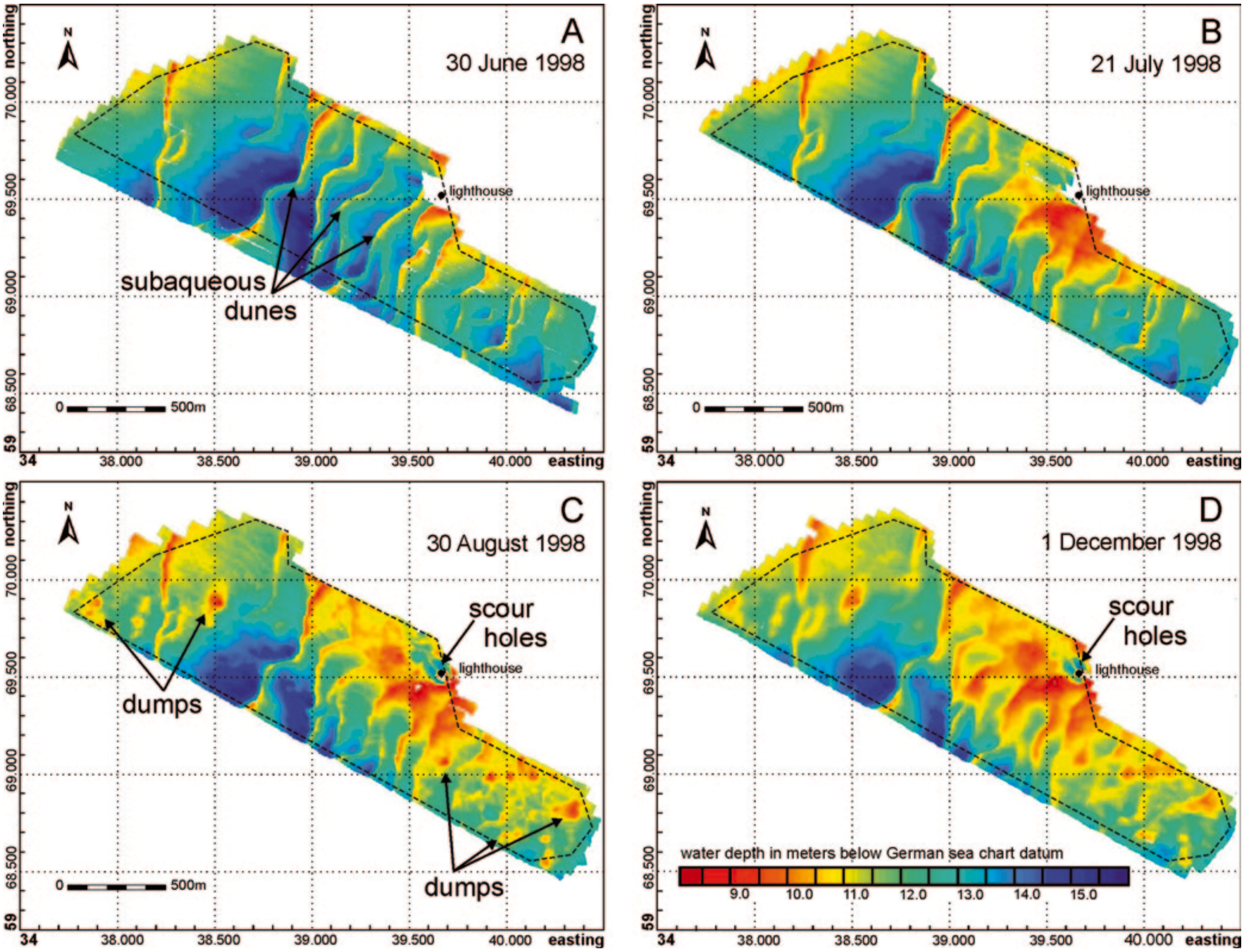

Fig. 3A–D Bathymetric maps of the investigated dumping site: **A** 30 June, **B** 21 July, **C** 30 August, and **D** 1 December 1998. *Red to yellow* indicates low water depths, and *green to blue* high water depths. Water depth information relates to meters below German sea chart datum, i.e., mean low water springs, and the *grid numbers* are Gauss–Krueger coordinates

still recognizable, but with flattened tops and edges slightly smoothed. The two scour holes at the base of the lighthouse were still present at the end of the dumping operation.

Discussion

Scour holes

An important criterion for choosing this dumping site was the development of scour holes at the base of the lighthouse, which is situated midway along the eastern margin of the site (Fig. 3A–D). It was hoped that, as a side-effect of the dumping, the scour holes would be filled up and thereby enforce the stability of the building. One difficulty in filling up the scour holes was to get close enough to the building with the hopper dredgers that were used for the removal of sandy material. They suck seabed sediment of the channel up through a pipe into their own hold, and then transport it to the designated dumping site. Figure 2 shows that the dumping unit (size: 200x100 m), surrounding the lighthouse, indicates a relatively low amount of dumped sediment, i.e., just 22,000 m^3. Higher values are observed in the adjacent units, with amounts of dumped material between 50,000 and 100,000 m^3.

During the two first bathymetric surveys (30 June, 21 July), no depth data were acquired in the direct surrounding area of the lighthouse (Fig. 3A, B). On the maps of the two last bathymetric surveys (30 August, 1 December), two scour holes are recognizable in the north and the northwest of the lighthouse (Fig. 3C, D), reflecting the dominance of the ebb current in the Weser Estuary. The anticipated filling of these holes thus failed to materialize. A cross section in a northeast–southwest direction across the two scour holes shows that they have a maximum water depth of around 14 m (Fig. 4), being approximately 3 m deeper than the surrounding seabed. Their oval shape has a dimension of ~70 m from northeast to southwest and of ~120 m from northwest to southeast. Between the two cross sections

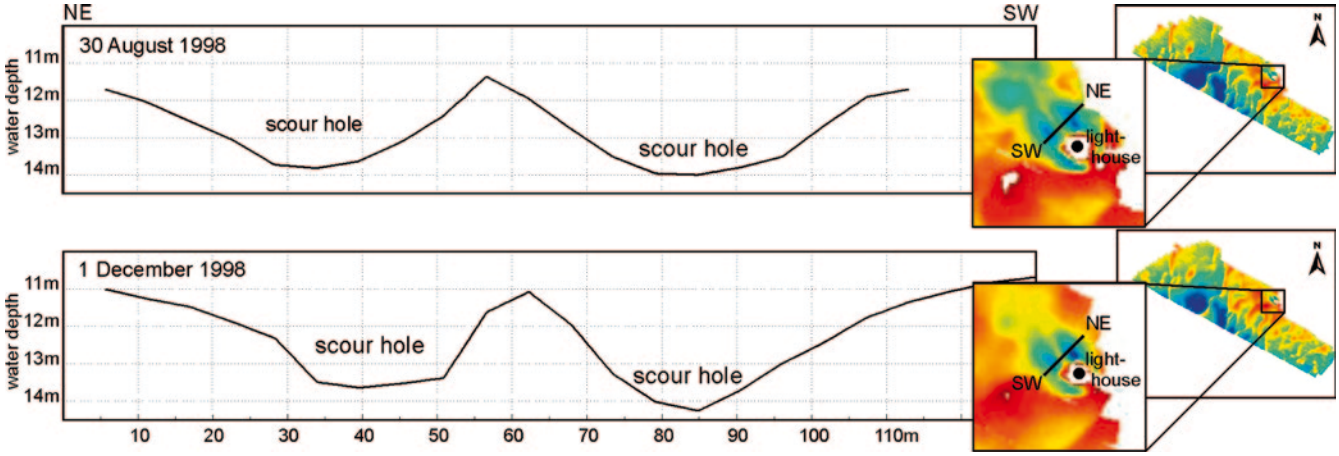

Fig. 4 Cross sections placed across scour holes (30 August and 1 December 1998), which have developed at the base of a lighthouse situated midway along the eastern margin of the dumping site

(timeframe: 30 August–01 December 1998) no significant change in shape was recorded.

Accumulation–erosion balance

In Fig. 5A–C, the difference grids generated between the four following bathymetric surveys are shown. Regions of accumulation and erosion within the dumping site are highlighted on these maps. The difference grid between the first and second survey (30 June–21 July) indicates that regions of erosion occurred in small spots only, primarily in dune troughs, and do not exceed values of 1 m. Therefore, during the time period between the first two bathymetric surveys (22 days) an overall accumulation of sediment took place at the site, reaching mean values of 0.5 m. Maximum rates of up to 4 m were observed in the central part of the dumping site. A total amount of accumulated sediment of approximately 0.833 million m^3 was calculated (Fig. 6).

A different situation is displayed on the difference grid between 21 July and 30 August (time period: 40 days; Fig. 5B). Even though, in this period, a similar volume increase of 0.809 million m^3 was computed (Fig. 6), more substantial fields of erosion occurred. These were most pronounced in the central part of the site, which has previously been described as the zone with the highest accumulation rates (Fig. 5A). Before the survey of 21 July, which forms the baseline for this difference grid, the seabed of the central part of the dumping site shoaled considerably as a result of the intense dumping. The occurrence of erosion at these spots might be explained by increased exposition of the seabed to tidal currents. In this case, the natural equilibrium between current strength and seabed morphology would have been disturbed, a feature reflected by a planing-off of the dune crests, suggesting that the natural system had already started to re-establish a balanced state.

This explanation might also be true for the presence of areas of erosion apparent on the difference grid generated between the survey of 30 August and 1 December (time period: 93 days; Fig. 5C). Erosion with maximum values of 0.8 m occurred in regions where highest accumulation rates were recorded, and where the water depth had decreased markedly. The total volume increase between the two last surveys amounted to 0.413 million m^3 of sediment (Fig. 6).

Finally, to estimate the total volume change over the entire survey campaign, a difference grid between the initial and the final state of the dumping site was computed (Fig. 5D). It reveals that almost the entire area of the site experienced sediment accumulation. The highest accumulation of up to 5 m was found in the central part of the dumping site where the highest amounts of sediment were deposited (between 50,000 and 100,000 m^3 per 200x100-m-unit; Fig. 2). Over the entire survey and dumping period, erosion occurred along the border area of the dumping site, and did not exceed 1.5 m. Furthermore, zones of erosion can be used as an indicator for the migration rate of the subaqueous dunes because they mark the position of the dune troughs and, therefore, show the process of migration with erosion at the stoss side and deposition at the lee side of the dunes. Between 30 June and 1 December 1998, about 2.6 million m^3 of the total amount of 3 million m^3 of dredged sediment had been deposited at the site. The difference grid reveals a volume increase of 2.040 million m^3 between the first and last survey, indicating a sediment loss of 0.563 million m^3 (Fig. 6).

Net sediment transport

Due to the dominance of the ebb current in the Weser Estuary, which is apparent in the asymmetry of subaqueous dunes (with the lee slope facing towards the open sea), it is assumed that the predominant sediment transport also runs towards the open sea in line with the dominant ebb current. This mechanism of sediment transport across asymmetrical large-scale bedforms in the direction of the lee slope is described in several studies (Langhorne 1982; McCave and Langhorne 1982; Twichell 1983; Aliotta and Perillo 1987; Harris 1988). For

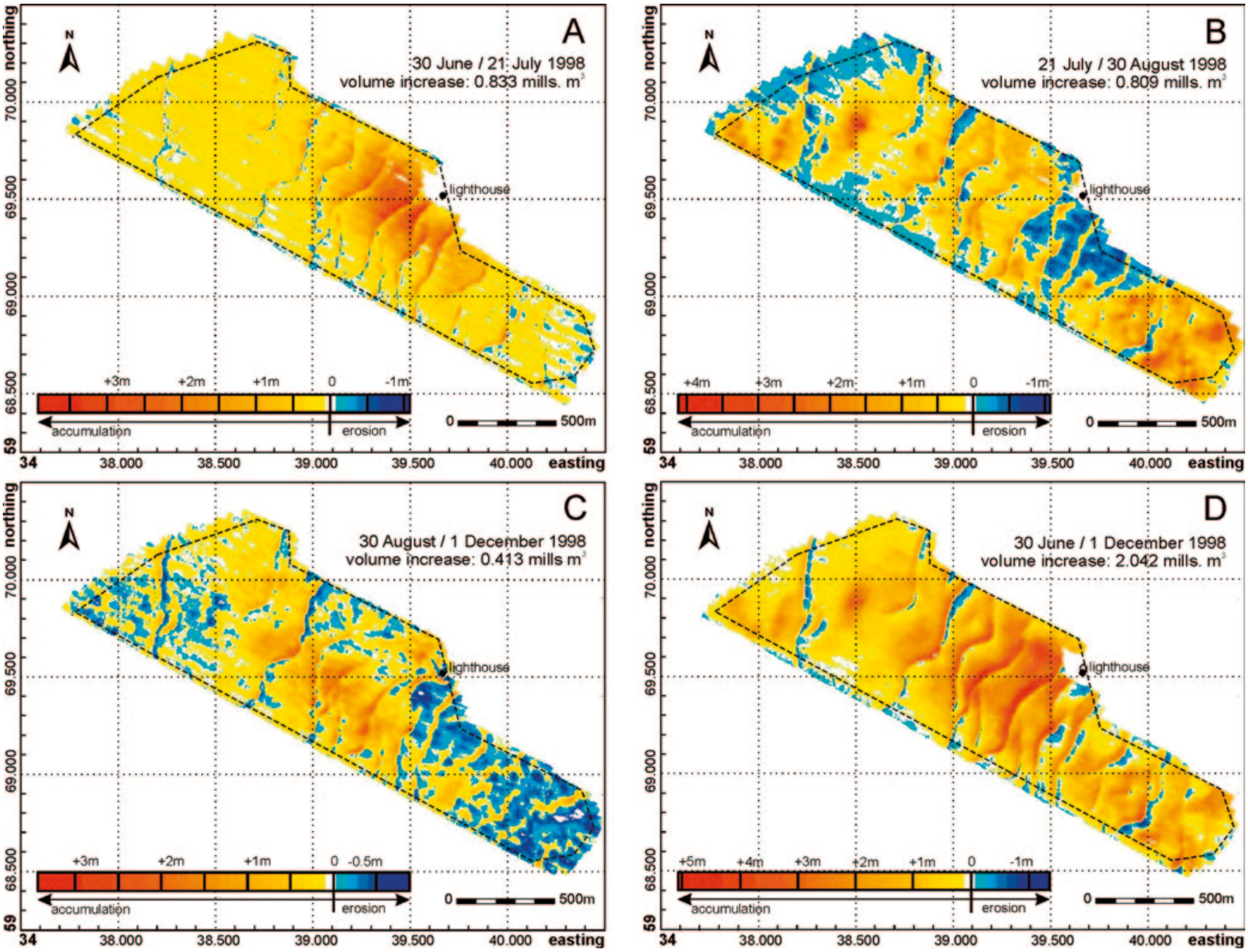

Fig. 5A–D Difference grids between the different bathymetric data sets: **A** 30 June/21 July, **B** 21 July/30 August, **C** 30 August/1 December, and **D** 30 June/1 December 1998. *Yellow to red* indicate zones of accumulation, and *blue* indicates zones of erosion. The *grid numbers* are Gauss–Krueger coordinates

instance, Langhorne (1982) investigated the migrational behavior of dunes along the southern coast of England (Start Bay, Devon), and showed that the asymmetry of a dune is indicative of net sediment transport as well as of the direction of bedform migration.

Conclusions

The shipping channel of the outer Weser Estuary has been enlarged and deepened several times during the last 100 years. Furthermore, a continuous need for maintenance dredging exists to ensure safe navigation and unhindered access to the harbors of Bremerhaven and Bremen. However, the dredged sediments need to be disposed of somewhere in the area. Experience and observations of local waterway- and shipping-authorities during the dumping of sandy material showed the following local effects to the seabed:

– Almost the total amount of dumped material is directly deposited at the seabed of the dumping site.
– The dumped sand accumulates in the form of a mound.
– After deposition, some of the dumped material is transported in the direction of the dominant tidal current.

These previously made observations are confirmed by the results of this study in the outer Weser Estuary. High-resolution MBESs are thus suitable for the monitoring of natural rapid changes in seabed morphology, as well as morphological changes initiated by the dumping of dredge spoil. For example, individual dumping mounds can be easily identified as they are clearly silhouetted against the surrounding seabed without loosing much of their shape and position, even after a period of 3 months.

The initial aim of also filling up existing scour holes at the base of a lighthouse failed. The bathymetric maps, as well as cross sections, showed that the two scour holes still existed at the end of the survey. To achieve such potential side effects, a more careful design of the dumping procedure is evidently required.

Furthermore, several very large dunes occurred on the seabed of the dumping site. By comparing the

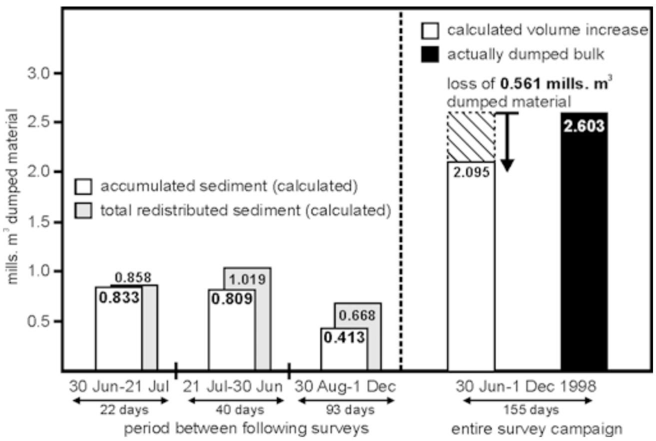

Fig. 6 Calculated change of the sediment volume between following surveys with information about the amount of accumulated sediment and the total amount of redistributed sediment (accumulation + erosion). The *two right columns* show the calculated volume increase about the entire survey campaign compared with the actually dumped bulk during this period (in million m^3)

bathymetric map time series, a migration trend towards the open sea was recognized. The dunes thus indicate the dominance of the ebb tide in the Weser Estuary as well as the direction of the predominant sediment transport. This predominant sediment transport towards the North Sea thus, in all likelihood, explains the sediment loss of ~20% over a time period of 5 months.

Further investigations are required to obtain a more detailed picture of the transport paths of dumped sediments. In particular, information is required about the local hydrodynamic parameters such as current velocity and direction, compiled with more accurate data on the grain size distributions of the dumped sediments and the sediments at the dumping site itself. In combination with high-resolution MBES surveys, such data could form the basis for a predictive sediment-dispersal model of the outer Weser Estuary.

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