The impact of dredge spoil dumping on coastal morphodynamics monitored by high-resolution acoustic measuring instruments (outer Weser Estuary, German Bight)

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Abstract

Estuaries all over the world are the location of a great number of important harbors. To guarantee a safe access for sea traffic to these harbors, shipping channels have to be dredged continuously. The dredge spoil is preferable dumped close to the dredged channel to reduce operational costs. In this context, a common problem is the choice of a suitable dumping site. Particular hydrodynamic and morphological conditions have to be prevailed to guarantee that the dumped sediments remain at the dumping site or are further transported towards the open sea by the predominant tidal currents. Finally, the main ambition is to avoid re-infilling of shipping channels to minimize cost-intensive maintenance dredging. Therefore, detailed knowledge about the ongoing hydro- and morphodynamical processes in the dumping area is needed.

The investigation of the fate of dumped sediments in a dynamic estuarine environment is difficult, especially on a quantitative manner. Adequate scientific studies investigating dumped sediments and their impact on morphological and sedimentological conditions are relatively rare. Recent progress in acoustic technology in surveying shallow-water areas offers new opportunities to fill this gap. In particular, the development of sophisticated multibeam echosounders and echosounder-based seabed classification systems enables repeated surveys of large seabed areas in a cost- and time-efficient mode, and thus the monitoring and investigation of morpho- and sedimentdynamical processes in a high spatial and temporal resolution.

The goal of this work is to contribute to a better understanding of the natural dynamic processes and the consequences of dredge spoil dumping in a coastal area. It is intended to use a shallow-water multibeam echosounder and an acoustic seabed classification system to survey a dumping site situated in the seaward exposed outer Weser Estuary (German Bight). The aim is to answer following questions concerning the naturally and artificially changed state of the dumping area:

- How does the sediment budget change due to the supply of sediment by dredge spoil dumping?
- What are the predominant sediment transport pathways?
- How strong is the impact of dumped material on morphological seabed features?
- How variable is the spatial distribution of sediments in the dumping area?

The results of this thesis show that the dumping of dredge spoil caused an abrupt and intensive change of the local seabed. A comparison of successive bathymetric surveys reveals the morphological change of seabed features such as subaqueous dunes, scour holes, as well as mounds of dumped dredged spoil. Furthermore, a sediment loss of ~0.561 million m^3 within a time period of 5 months is calculated.

The asymmetrical shape of subaqueous dunes with a lee slope facing towards the sea emphasizes the dominance of the ebb tide in the outer Weser Estuary and is used as an indicator for a predominant sediment transport towards the sea. This assumption is further confirmed by a slight migration trend of the dunes towards this direction. During the dumping activities some of the subaqueous dunes were completely filled. Nevertheless, despite the huge supply of sediment, they reshaped even after a relatively short time period of a few weeks.

The seabed of the surrounding area of the dumping site, including a part of the shipping channel, is composed of fine to coarse sands with an increasing content of shell fragments. The sediment distribution can be associated to local morphological seabed structures such as large subaqueous dunes partly superimposed by ripples and expanded ripple fields. It is demonstrated that maintenance dredging as well as dumping of this material constitute a strong impact on the sediment distribution.

Zusammenfassung

Weltweit sind Ästuare wichtige Standorte bedeutender Häfen. Um der Seeschifffahrt eine sichere Zufahrt zu diesen Häfen zu gewährleisten, müssen Fahrrinnen kontinuierlich ausgebaggert und vertieft werden. Der dabei anfallende Baggerabraum wird aus finanziellen Gründen vorzugsweise in unmittelbarer Nähe zur ausgebaggerten Fahrrinne verklappt. Ein generelles Problem in diesem Zusammenhang ist die Auswahl geeigneter Klappstellen. Spezielle hydrodynamische und morphologische Bedingungen müssen vorherrschen, um zu garantieren, dass das verklappte Material im Bereich der Klappstelle verbleibt oder von den vorherrschenden Strömungen weiter in Richtung offene See transportiert wird. Ein Wiedereintrieb von Sedimenten in die Fahrrinne soll in jedem Fall verhindert werden, um kostenintensive Unterhaltungsbaggerungen zu minimieren. Aus diesem Grund ist es notwendig detaillierte Kenntnisse über die hydro- und morphodynamischen Prozesse im Gebiet einer Klappstelle zu erlangen.

Untersuchungen zum Fortgang verklappter Sedimente in einem dynamischen Ästuar waren bislang mit herkömmlichen Messmethoden schwierig, insbesondere im Bezug auf quantitative Fragestellungen. Daher gibt es auch nur wenige wissenschaftliche Arbeiten, die sich mit dieser Problematik beschäftigen. Erst heute ist es durch den technischen Fortschritt der letzten Jahre möglich, diese Wissenslücke zu füllen. Mit der Entwicklung akustischer Messgeräte, wie Flachwasser-Fächerecholoten und Meeresbodenklassifizierungssystemen, ist man nun in der Lage, Vermessungen großer Flächen unter zeit- und kostengünstigen Bedingungen durchzuführen, und somit morpho- und sedimentdynamische Prozesse in hoher räumlicher und zeitlicher Auflösung zu untersuchen.

Ziel dieser Arbeit ist es, dazu beizutragen, ein besseres Verständnis über natürliche dynamische Prozesse zu erlangen und die Auswirkungen von Baggergutverklappung auf diese Prozesse zu untersuchen. Es ist beabsichtigt, zur Vermessung einer Klappstelle in der Außenweser (Deutsche Bucht) ein Flachwasser-Fächerecholot sowie ein Meeresbodenklassifizierungssystem einzusetzen. Dabei sollen folgende Fragen im Hinblick auf den natürlich und anthropogen veränderten Zustand des Verklappungsgebietes beantwortet werden:

- Wie verändert sich der Sedimenthaushalt im Zuge einer Verklappung?
- Was sind die vorherrschenden Sedimenttransportwege?
- Wie stark wirkt sich die Verklappung auf vorhandene Bodenstrukturen aus?
- Wie variabel ist die Sedimentverteilung im weiteren Bereich der Klappstelle?

Die Ergebnisse dieser Arbeit zeigen, dass die Verklappung von Baggerabraum eine abrupte und intensive Veränderung der lokalen Meeresbodenmorphologie verursacht. Mit dem Vergleich aufeinander folgender bathymetrischer Vermessungen können Veränderungen von Bodenstrukturen wie subaquatischen Dünen, Kolken und einzelnen größeren Verklappungsereignissen detailliert nachgezeichnet werden. Ein Sedimentverlust von ~0,561 Mio. m^3 innerhalb eines Zeitraumes von 5 Monaten ist ermittelt worden.

Die asymmetrische Form subaquatischer Dünen, mit einem zur offenen See hin orientierten Leehang, verdeutlicht die Dominanz der Ebbtide in der Außenweser, und ist als Indikator für einen Haupt-Sedimenttransport in Richtung Nordsee zu sehen. Dies wird weiter untermauert durch einen schwachen Wanderungstrend der Dünen in die gleiche Richtung. Im Zuge der Verklappung wurden einige der subaquatischen Dünen vollständig mit verklapptem Material verfüllt. Dennoch zeigt sich, dass sich bereits nach einer relativ kurzen Zeitspanne von wenigen Wochen Sohlfomen neu formiert haben.

Die Oberflächensedimente im weiteren Bereich der Klappstelle, der auch einen Abschnitt der Fahrrinne umfasst, setzen sich aus Fein- bis Grobsand zusammen, die einen zunehmenden Schillgehalt aufweisen. Die Sedimentverteilung ist eng mit lokalen morphologischen Bodenstrukturen wie subaquatischen Dünen, zum Teil von Rippeln überlagert, und ausgedehnten Rippelfeldern assoziiert. Unterhaltungsbaggerungen sowie die Verklappung dieses Materials haben einen stark verändernden Einfluss auf die Sedimentverteilung.

General Introduction

1.1 Motivation and main objectives

Coastal areas are subject to the most energetic conditions on the earth surface, where the hydrodynamic plays an important shaping role. An extensive reworking and permanent redistribution of sediments is caused by e.g. currents and waves, which induce high bottom stresses on the seabed. Due to this cyclic process based on erosion, transport, and sedimentation, a constant morphological alteration takes place, which can range from a few seconds to centuries and from centimeters to thousands of kilometers on a temporal and spatial scale (Perillo, 1995b; McMagnus, 1998).

Additionally, in the past decades, the human impact has become of increasing importance to coastal and nearshore environments all over the world. This development can be explained by the economic significance of the coastal zone. It is one of man's most populous living environments on earth. Today 50 to 70 % of the world's population are estimated to live in coastal areas and up to 75 % of the world population could be living within the 60 km of the shoreline by 2020 (Edgren, 1993). These areas are subject to a great number of diverse demands as e.g. fishery, oil and gas exploitation, generation of wind energy, tourism, navigation, shipbuilding, and ports. To optimize the utilization of coastal areas, the environmental conditions have been modified consistently and increasingly. Anthropogenic interferences like enlargement of shipping channels, dumping of dredge spoil, construction of embankments, groynes, and dikes, as well as the installation of pipelines, bridges, and off-shore windparks occur, which trigger physical responses like changes in flow patterns, morphodynamics, and sediment budget (Nichols, 1988; Trenhaile, 1997). Due to the forecast of an increase of economic demands on the estuarine environment and the resulting increase of anthropogenic interferences, more knowledge about the consequences of these interferences is needed.

One goal of this thesis is to obtain detailed information about the direct consequences of dredge spoil dumping on the seabed in a dynamic coastal environment. Only a small number of studies concerning this problem are presently available, which are mainly based on investigations dealing with the effect of dumping on benthic fauna and the disposal of pollutants (e.g. Smith, 1976; Healy et al., 1999; Carpentier et al., 2002; Stronkhorst et al., 2003). In the present study, a dumping site situated in the tidally dominated outer Weser Estuary (German Bight) is investigated in order to gain insight into the morphodynamic of this area, such as the change of the sediment budget, the alteration of seabed structures as well as the variabilty of sediment distribution. The monitoring and investigation of morphodynamic in coastal areas is very difficult due to the wide variety of processes and their highly energetic character. Nevertheless, with the recent development of sophisticated measuring instruments survey strategies of large areas can be optimized in terms of cost- and time-efficiency. The present thesis focusses on the application of a multibeam echosounder, designed for surveying shallow-water areas (chapters 2 and 3), and a seabed classification system (chapter 4). These tools, which operate based on the backscatter of an acoustic signal, provide new opportunities to monitor and investigate morphological seabed structures and their natural and human induced change in high spatial and temporal resolution.

1.2 Estuaries: a general overview

Estuaries, as one of the most important environments in the coastal area, represent a transition zone between fluviatil-terrestrial (river with its catchment area) and marine (open sea) environments. In the last decades, many different definitions of estuaries have been developed. This discrepancy might be explained by the fact, that estuaries are investigated for a great number of purposes. One of the today most widely used definition refers to a publication of Pritchard (1967), in which an estuary is described as '*a semi-enclosed coastal body of water, which has a free connection to the open sea and within which sea water is measurably diluted with fresh water derived from land drainage*'. This definition is somewhat problematic due to the fact that the effect of tides is missing, which is a very important parameter in most estuaries. Therefore, the recently developed definition of Dyer (1997) by combining earlier definitions is more precise and useful: '*an estuary is a semi-enclosed coastal body of water which has free connection to the open sea, extending into the river as far as the limit of tidal influence, and within which sea water is measurably diluted with fresh water derived from land drainage*'.

The specific nature of an estuary depends on the local climatological, geographic, geological, and hydrodynamical characteristics (Perillo, 1995b). Some of the most important controlling factors are listed in Table 1.1. The interaction between these controlling factors is very complex, and thus, the natural variability of estuaries can be extremely high, even over an annual cycle. A strict classification is very difficult to find because some estuaries may fit into more than one class (Wells, 1995). Furthermore, an accurate classification has become more complicated due to the fact that in the past decades many estuaries have been strongly modified by dredging, dumping, coastal constructions, or upstream engineering interferences.

For this reason, a great number of classifications exist using a variety of criteria as e.g. genetic and morphological considerations (Pritchard, 1952; Fairbridge, 1980; Perillo, 1995a), physical parameters like tides (Hayes, 1975) and salinity distribution (Cameron and Pritchard, 1963; Dyer, 1979), or evolutionary patterns (Dalrymple et al., 1992).

The Weser Estuary belongs to the coastal plain of northern Europe which covers an area of 156,000 km^2 including the shores of the North and Baltic Seas (Colquhoun, 1968; Bokuniewicz, 1995). It is geomorphologically classified as a coastal plain estuary which occupies a former river valley at a low relief coast, which has been artificially modified for more than 100 years. The following chapters explaining geological, sedimentological, hydrodynamical, and morphological characteristics of estuaries are therefore referring to coastal plain estuaries only.

Table 1.1 Factors controlling the formation of estuaries (modified after Perillo, 1995b).

Climate	polar and subpolar temperate tropical and subtropical	Tidal Range	macrotidal mesotidal microtidal
Type of Coasts	marginal sea collision trailing edge	Marine Diffusive Forces (waves, littoral & tidal currents, etc.)	high low
Coastal Lithology	hard-rock soft-rock	River Discharge & Sediment Load	high low
Coastal Stability	submerging emerging stable	Atmospheric Influence (winds, temperature, humidity, etc.)	high low

1.2.1 Geology and sedimentology of coastal plain estuaries

Coastal plain estuaries are relatively young with respect to their geological evolution. They are a product of ancient valleys that were incised by fluvial erosion during the last glacial stage (Russell, 1967; Bokuniewicz, 1995). At that time (~17,000 yr BP), when the sea level stood at its minimum with ~130 m below present (Emery, 1967), most of the world continental shelves were converted into extensive coastal plains. Rivers had to find their way through the continental shelves, where they cut down deep valleys. During the Holocene, these valleys were drowned by the rising sea level of the post-glacial transgression and afterwards increasingly filled with sediments. In the German sector, the Holocene marine transgression started around 8,600 yr BP and fully marine conditions existed in the southern German Bight after 7,000 yr BP (Eisma et al., 1981). Since 2,000 yr BP the sea level has fluctuated around its present level (Streif, 1996).

Nowadays, estuaries are playing an important role in the natural sediment cycle because they are highly efficient sediment traps (Nichols and Biggs, 1985). Most of the approximately 13.5×10^9 tons of sediment generated worldwide by erosion and transported by rivers are deposited on continental margins, and there especially in estuaries (Milliman and Meade, 1983). The total amount of sediments trapped in estuaries is still unknown due to the strong influence of hydrodynamical parameters like currents and waves and the resulting continuous cycle of erosion, transport, and sedimenation (Milliman and Meade, 1983). This means that sediments do not simply accumulate on the seabed by slow, steady-state process of deposition. Rather, they undergo exchange with the overlying water column (currents and waves) on time scales which range from hours to years (Wells, 1995).

However, sediments of estuaries, in which tides are playing a major role, are not only composed of material originated from riverine input, a significant amount of sediments also derived from the shelf or from coastal erosion. Generally, finer sands and muds stem from fluvial sources, whereas coarser sands derive from marine sources (Harris, 1988). The sediments are transported both as bedload and as suspended load.

1.2.2 Hydrodynamics of tide-dominated estuaries

Estuaries are permanently changing environments, which are subject to strong water motion and sediment transport caused by hydrodynamic factors like currents and waves as well as river inflow and estuarine circulation (Perillo, 1995b). However, most estuaries of the world are influenced, at least to some degree, by tidal currents, in which tidal energy serves as a mechanism for mixing riverine and marine waters, resuspending and transporting sediments, creating bedforms, and scouring channels (Wells, 1995).

When tides propagate upstream towards the estuarine head, they become modified by two different processes: friction and convergence. On the one hand, the tidal energy is concentrated due to the convergence of the estuary shores, which becomes apparent in an increasing tidal range (e.g. North Sea, Bay of Fundy, and Yellow Sea have especially large tidal ranges because of their specific basin geometry). On the other hand, tides loose energy due to frictional damping at the estuary seabed. In this context, we differentiate between hypersynchronous, synchronous, and hyposynchronous estuaries (Salomon and Allen, 1983). Most common are hypersynchronous estuaries, in which the effect of convergence is more significant than friction. In this type of estuaries, the tidal range increases landward into the estuary before eventually decreasing towards the river. Hyposynchronous estuaries are characterized by a dominance of the frictional energy loss, thus, the tidal range progressively decreases landward. In synchronous estuaries, the effects of friction and convergence initially compensate each other.

Furthermore, as tides move upstream through smaller cross-sectional areas, tides become progressively more asymmetric. This tidal asymmetry can be expressed in terms of differences in the peak ebb and flood current velocity, as well as in differences in the duration of ebb and flood flows (Wells, 1995; Trenhaile, 1997). Since current velocities in estuaries are a function of the size of the tidal prism and the volume of river discharge, a change in either will cause a change in current velocity. Besides seasonal discharge fluctuations and spring-neap tidal cycles, any man-induced change in volume flux will inevitably affect current velocities.

1.2.3 Morphology of tide-dominated estuaries

The morphology of sand deposits in coastal-plain estuaries is controlled by the interaction of numerous process parameters, including tidal range, tidal currents, wave action, and storms, whereas the tidal range seems to have the broadest effect on the coastal morphology (Hayes, 1975). At first, Davies (1964) recognized the importance of the tidal range and proposed the following classification of tides: microtidal (tidal range: 0-2.0 m), mesotidal (tidal range: 2.0-4.0 m), macrotidal (tidal range: >4.0 m). Hayes (1975) completed this classification by relating specific morphological features to the different tidal regimes. For instance, in microtidal estuaries, where wave action and storms are more significant than tides (wave-dominated), river deltas and barrier islands are best developed (Hayes, 1975; Davis and Hayes, 1984). Whereas in macrotidal estuaries, offshore linear sand ridges, tidal flats, and salt marshes are most common and barrier islands are lacking due to the dominance of tidal currents. Such tide-dominated estuaries are usually broadmouthed and funnel-shaped with muddy tidal flats at the shore and a concentration of sand deposition in the central part of the estuary (Hayes, 1975).

Moreover, the transport of sediments in tide-dominated estuaries induces the development of bedforms like linear sand bars, subaqueous dunes, and current ripples, which range in size from several hundred meters to centimeter-scale (Dalrymple and Rhodes, 1995). In particular, subaqueous dunes are a widespread bedform in most tide-dominated estuaries. They are intensely studied all over the world (Ludwick, 1972; Langhorne, 1973; Boothroyd and

Hubbard, 1975; Bokuniewicz et al., 1977; Dalrymple et al., 1978; Dalrymple, 1984; Aliotta and Perillo, 1987; Harris, 1988; Fenster et al., 1990; Berné et al., 1993; Ikehara and Kinoshita, 1994). Subaqueous dunes are also widespread in estuaries of German rivers such as Ems, Jade, Weser, and Elbe, which discharge into the German Bight (North Sea) (Reineck, 1963; Göhren, 1965; Pasenau and Ulrich, 1973; Ulrich, 1973; Reineck and Singh, 1980; Wever and Stender, 2000).

Size (wavelength and height) and shape of a dune is the result of a complex interplay of many variables, the most important of these being water depth, current speed, grain size, and sediment availability. According to Ashley (1990), subaqueous dunes are classified by descriptors of first, second, and third order. First order descriptors are size and plan-form shape. With regard to their wavelength (Fig. 1.1), dunes are partitioned into four distinct classes: small: 0.6-5 m, medium: 5-10 m, large: 10-100 m, and very large: >100 m. Furthermore, one differentiates between 2-dimensional dunes with straight and 3-dimensional dunes with sinusoidal crestlines. The superposition by smaller bedforms (compound dunes have superposed bedforms; simple dunes do not) and sediment size and sorting are second order characteristics. Finally, third order descriptors are useful to describe details of dune morphology such as stoss and lee slope lengths and angles (Fig. 1.1), fullbeddeness or sediment starvation, migration history of dunes, and symmetry of dune profile (Ashley, 1990). If one tidal phase dominates over the other one dunes become asymmetric, with their lee side facing towards the direction of the dominant tidal phase, and therefore in the direction of the net sediment transport (Jones et al., 1965; Langhorne, 1982; McCave and Langhorne, 1982; Twichell, 1983; Aliotta and Perillo, 1987; Harris, 1988). Furthermore, due to their large size relative to the flow depth, subaqueous dunes may have an important influence on the dynamics of an estuary (Dalrymple and Rhodes, 1995).

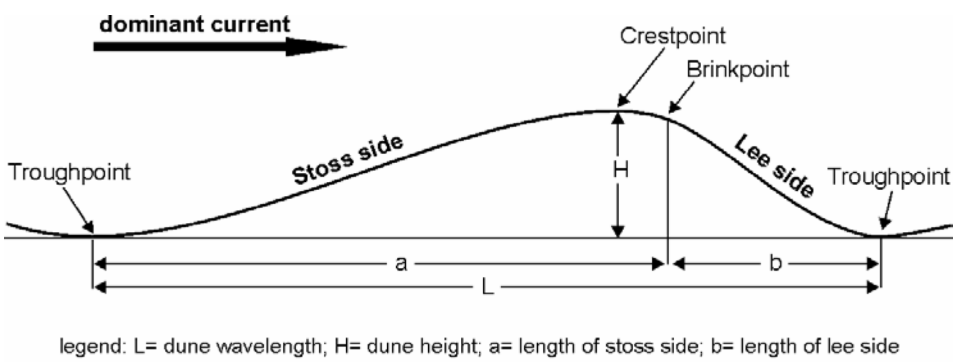

Fig. 1.1 A schematic profile of an asymmetric subaqueous dune. Morphological dune parameters have been depicted (modified after Reineck and Singh, 1980).

1.3 A regional case: The Weser Estuary

1.3.1 The Weser River

The Weser River originated and developed during the Pleistocene cycle of glacial and interglacial stages. At present, it starts at the confluence of the Werra and Fulda Rivers close to the city of Hannoversch Münden (Fig. 1.2). From this point northward, the water masses of the Weser River run over a total distance of 485 km and overcome 120 m of altitude before they drain into the German Bight of the southeastern North Sea (Fig. 1.2). The catchment area extends over 46,000 km^2 between the central highlands of Germany and the German Wadden Sea. The averaged yearly river runoff amounts to ~320 $m^3\ s^{-1}$ with high discharge in February and March and low discharge values in August and September (Niedersächsisches Landesamt für Ökologie, 1999). The estuarine section of the Weser River starts 360 km further downstream next to the city of Bremen (Fig. 1.2).

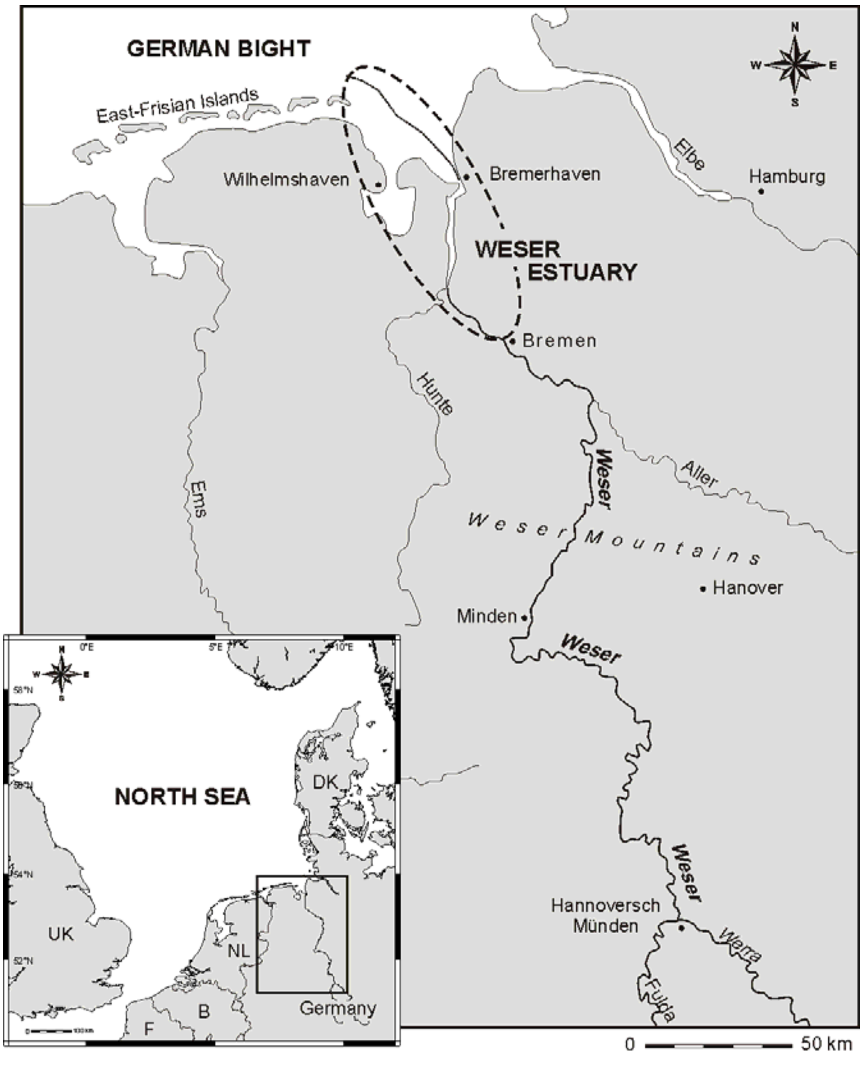

Fig. 1.2 The Weser River; the extension of the Weser Estuary is marked by a dashed circle.

1.3.2 Geomorphology of the Weser Estuary

The Weser Estuary is partitioned into an inner and an outer section, which have a different morphological appearance. The channel-like inner estuary has a length of 65 km and exhibits at present a minimum water depth of 9 m (below German sea chart datum). Furthermore, it exists a continuous line of dikes next to the channel to protect the hinterland (salt marsh) from tidal and stormsurge flooding. At the seaport of Bremerhaven, the Weser Estuary broadens to the funnel-shaped outer estuary with a high width-to-depth ratio (Fig. 1.3). The outer Weser Estuary has a longitudinal extension of 60 km. Inshore, it is lined by extensive tidal flats of the German Wadden Sea (Fig. 1.3), followed seawards by at water depths between 6 and 20 m (below German sea chart datum) shallow subtidal shoals.

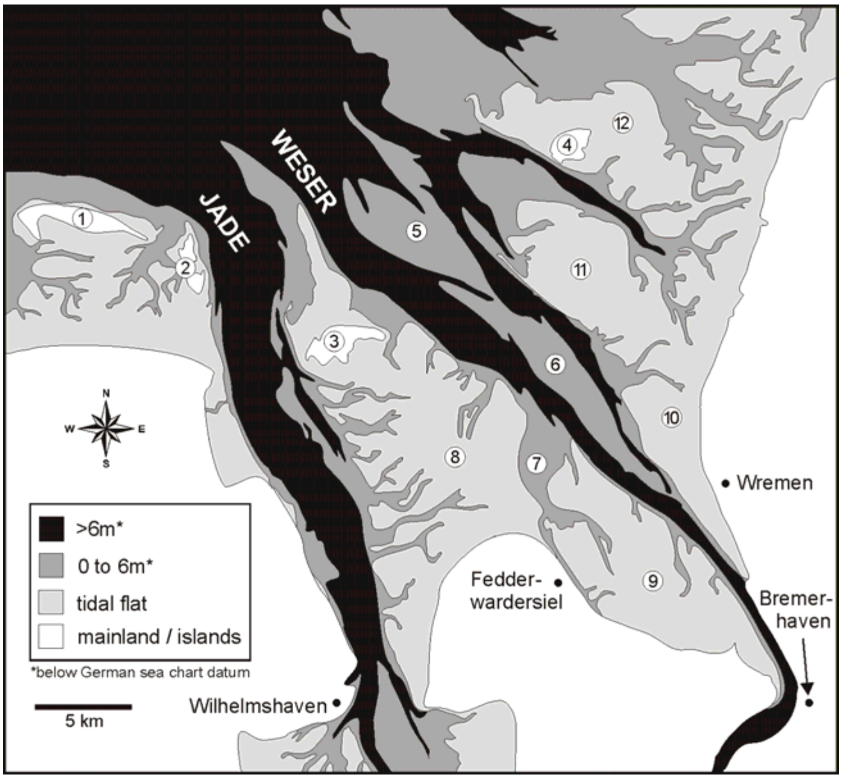

Fig. 1.3 The outer Weser Estuary. Islands: (1) Wangerooge, (2) Minsener Oog, (3) Alte Mellum, (4) Hoher Knechtsand; sand bars: (5) Tegeler Plate, (6) Robbenplate; tideway: (7) Fedderwarder Priel; tidal flats: (8) Hohe-Weg-Watt, 9) Langlütjensand, 10) Wurster Watt, 11) Eversand, 12) Knechtsand.

In the outer Weser Estuary, two tidal channels are developed which are separated by flow-parallel elongated sand bars. The westerly main shipping channel currently has a minimum depth of 14 m (below German sea chart datum). It is separated into an ebb- and a flood channel (Bundesanstalt für Gewässerkunde, 1992), in which the ebb and flood currents each tend to flow close to the right side of the channel due to the coriolis force (Hovers, 1973). The channel bends out in a northwestern direction. It is merged at its northernmost point with the shipping channel of the Jade Bay, which is situated to the west of the outer Weser Estuary (Fig. 1.3). Both the outer Weser Estuary and the outer Jade Bay are closely linked in terms of morphodynamical processes.

At the beginning of the 20^{th} century, first detailed studies concerning morphological changes in the outer Weser Estuary were carried out by Krüger (1911) and Poppen (1912). They assumed that the sand bars with their intermediary tidal channels situated in the seaward part of the region migrate in a northeastward direction. By comparing historical sea charts, it became apparent that this is a continuous process and similar conditions reoccured periodically in time intervals of ~60 years (Poppen, 1912). During these intervals, sands in the west of the region came off, migrated northeastward, passed a channel, and finally, merged with another sand bar further to the east. 40 years later, Plate (1950) made similar observations with an indicated time interval of 60-70. Whereas, Göhren (1965) supposed that this migration rate is too fast and a time interval of 110-120 years is more probable. However, this natural process is nowadays strongly disturbed due to impacts like dredging of channels, reinforcement of sands and banks as well as dumping of dredge spoil in the estuarine region.

1.3.3 Hydrodynamics of the Weser Estuary

The Weser Estuary is strongly exposed to hydrodynamic processes due to the absence of off-shore islands at its mouth (Fig. 1.3). It belongs to the innermost part of the German Bight, where the influence of tides is much more significant than the effect of wave energy (Dieckmann and Pohl, 1991). The semidiurnal tides penetrate from a northwestern direction into the estuary. They are characterized by a distinct spring and neap tide cycle. Due to friction at the seabed and convergence of the estuary margins, the tidal wave has a slightly asymmetrical shape, which is expressed in higher ebb current velocities as well as a longer ebb duration compared to the flood tide. This discrepancy increases upstream. The dominance of the ebb tide in the Weser Estuary induces a residual sediment transport towards the open sea (Bundesanstalt für Gewässerkunde, 1992; Wasser- und Schiffahrtsamt Bremerhaven, 1996).

The tide-dominated Weser Estuary belongs to the hypersynchronous type of estuaries. The incoming tide is progressively compressed into a smaller cross-sectional area due to the funnel-shaped geometry and the existence of elongated sand bars. As a consequence, the tidal range increases towards the riverine section. The mean tidal range varies from 2.8 m at the estuary mouth to 4.0 m at the estuary head, close to the city of Bremen (Müller, 1992). This is the highest tidal range along the entire German North Sea coast. Thus, the Weser Estuary is classified as a meso- to macrotidal estuary.

Current velocities in the Weser Estuary are mainly determined by tides, whereas in the inner estuary an upstream increased influence of the river runoff is recognizable. During ebb tide, for the uppermost part of the water column, mean current velocities of 1.0 to 1.3 ms^{-1} with maximum values of up to 2.6 ms^{-1} are common, whereas 2 m above the seabed mean values generally range from 0.5 to 0.7 ms^{-1}. During flood tide, the mean and maximum current velocities for the surface water are on the whole lower with 0.7 to 1.0 ms^{-1} and up to 2.0 ms^{-1}, respectively. Close to the seabed, mean current velocities during flood tide range from 0.5 to 0.7 ms^{-1} (Bundesanstalt für Gewässerkunde, 1992). In the surface water, the difference of current velocities between ebb tide and flood tide are considerably higher, than 2 m above the seabed. Therefore, even if the current conditions change slightly, the estuary will immediately respond with a change of its seabed morphology.

The high tidal range associated with high current velocities results in a strong vertical mixing of the salt water coming from the North Sea and the freshwater transported by the Weser River. The outer Weser Estuary with a salinity between 18 and 30‰ is described as the transition zone between the North Sea (30-35‰) and the brackish water zone (1.8-18‰) within the inner estuary. The brachish water zone extends between the city of Bremerhaven and the tributary Lune River, which is situated 52 km downstream of the weir in Bremen (Wasser- und Schiffahrtsamt Bremerhaven, 1996). The seaward border is defined by a salinity which shows only small intratidal and interannual differences (Grabemann and Krause, 2001).

1.3.4 Sediment transport in the inner German Bight

The seabed of the German Bight comprises a Holocene-Pleistocene basement mainly covered by fine to coarse sands which are composed of reworked sediments of these deposits (Figge, 1981; Zeiler et al., 2000). The rivers Ems, Weser, and Elbe are the most important sources for riverine sediment supply into the German Bight (Fig. 1.2). However, a comparison between the amount of riverine sediment load delivered during the last 7,500 years and the present day total volume of the sediment deposits in this area shows, that only ~10% of the material derived directly from riverine sources, whereas about 90% originated from marine sources (Hoselmann and Streif, 1997).

In general, sandy material of the German Bight is predominantly remobilized by tidal current and wave action, especially during storm surges, and is transported as bedload (Hoselmann and Streif, 1997; Zeiler et al., 2000). However, a detailed knowledge of sand transport mechanisms and net bedload transport pathways is far from complete. Only a small number of studies concerning the German Bight are presently available, which are based on observational investigations (Aigner and Reineck, 1982; Johnson et al., 1982; Zeiler et al., 2000) or modeling results (Gerritsen and Berentsen, 1998; van der Molen, 2002).

Nevertheless, Zeiler et al. (2000) developed a descriptive conceptual model of the net sediment bedload transport operating on the shoreface of the German Bight (Fig. 1.4). They showed that the spatial distribution of the upper layer of North Sea sands can be partitioned into three distinct shoreparallel zones (Fig. 1.4), which are a result of both longshore and shore-normal bedload transport reflecting the long-term net sediment flux on the shoreface. Between the East-Frisian and North-Frisian Islands an area of strong sand accumulation is observed (Fig. 1.4). In this innermost part of the German Bight, the sand cover reaches a maximum thickness of up to 10 ±2.5 m (Zeiler et al., 2000). This assumption is further supported by modeling results of simulated tide-induced net sedimentation balances (Gerritsen and Berentsen, 1998), also reflecting a net sand accumulation in this area. This zone of bedload convergence can be attributed to longshore coastal currents, which flow eastward along the East-Frisian Islands (Johnson et al., 1982) and primarily southward in the offshore area of the North-Frisian Islands (Mittelstaedt et al., 1983). The longshore transport component is restricted to a nearshore conveyor belt between 0 and 10 m water depth (water depths are given in German topographic chart datum), where the prevailing wave and current conditions cause sediment bypassing (Fig. 1.4) and suppress a final storage of material on the upper shoreface. Adjacent to this thick sediment wedge, in water depths between 10 and 15 m the North Sea sands form only a thin layer of 0.4-1.5 m (Fig. 1.4), whereas in deeper waters between 15 and 20 m, the thickness increases again to 2-3 m (locally up to 6 m) (Zeiler et al., 2000).

The depth-dependent sediment distribution between 10 and 20 m water depth is controlled by shore-normal bedload transport operating during storms. Storms with N-NW wind directions induce strong hydrodynamic forces on the shoreface, which are characterized by offshore direction of the cross-shore near bottom flow (Mittelstaedt et al., 1983). As a result, the offshore bedload transport accumulates sediments in water depths >15 m. A subordinate onshore sediment transport into shallower waters (<15 m) takes place during storms induced by S-SE wind conditions (Mittelstaedt et al., 1983). As a consequence, a net sediment transport towards the open sea can be observed (Zeiler et al., 2000).

The outer Weser Estuary belongs to the zone of the inner German Bight with the highest sand accumulation (Fig. 1.4). Due to the longshore bedload convergence causing a substantial sediment supply to this area, no sediment depletion between 10 and 15 m water depth can be observed. Furthermore, the availability of a substantial volume of sands in combination with the macrotidal regime causes intensive morphological variability of the seabed within this area.

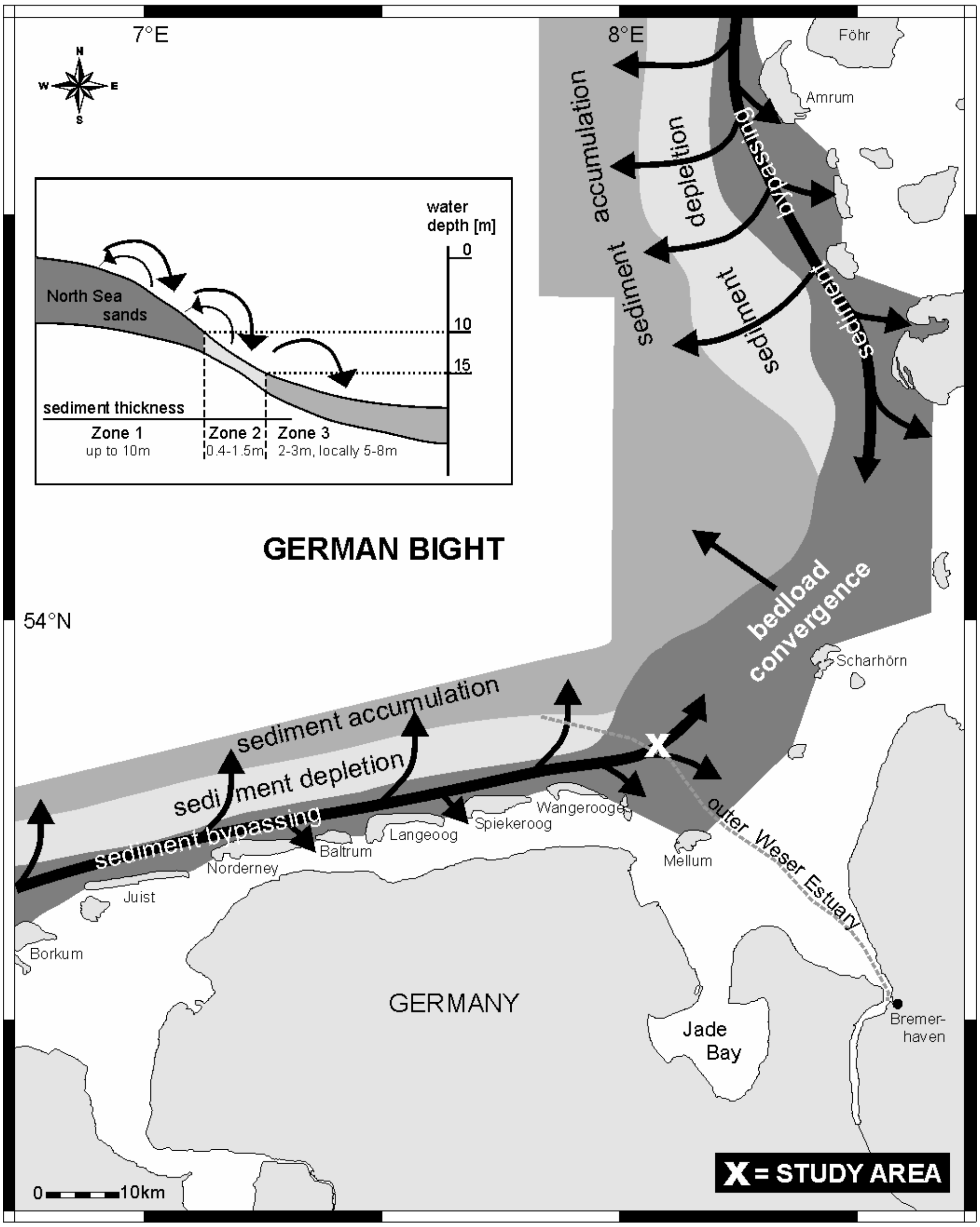

Fig. 1.4 Conceptual model of the net bedload transport pathways on the German North Sea shoreface. Inset: generalized cross-shore bedload transport regime in the inner German Bight (modified after Zeiler et al., 2000).

1.4 Human impact on the Weser Estuary

1.4.1 Historical review of anthropogenic interferences

The Weser River, with its estuarine section in particular, is one of the most regulated rivers in Europe. Primarily, since the end of the 19th century, its morphological appearance has been systematically and successively modified and several coastal engineering constructions have been built up (Table 1.2). Various reasons can be quoted for these anthropogenic interventions. First of all, the increased shallowing of the channel since the 17th century is to name. Especially, after the Middle Ages, the depth of the inner Weser Estuary decreased strongly due to increasing erosion caused by deforestation upstream and the initiation of dyking in the estuarine section (Busch et al., 1989). In 1750, this resulted in a navigational water depth of less than 0.8 m close to the city of Bremen (Rohde, 1970). For this reason, in the 18th century first efforts to dredge small-scale parts of the channel were carried out to remove these local shallows, and thus, to ensure an economic competitiveness of the harbors of Bremen. However, these interventions were of limited success.

Table 1.2 Anthropogenic impacts on the natural appearance of the Weser Estuary (a: inner part, b: outer part).

a	inner Weser Estuary	
	1643	→ first construction of groynes
	1738 - 1743	→ first small-scale dredging
	1827 - 1830	→ construction of a new port in Bremerhaven (65 km downstream of Bremen)
	1887 - 1893	→ deepening of the shipping channel to a continuous water depth of 5 m*
	1906 - 1911	→ construction of a tidal weir in Bremen as a reaction to the increasing tidal range
	1913 - 1916	→ deepening of the shipping channel to a continuous water depth of 7 m*
	1925 - 1930	→ deepening of the shipping channel to a continuous water depth of 8 m*
	1930 - 1939	→ construction of several groynes
	1953 - 1959	→ deepening of the shipping channel to a continuous water depth of 8.7 m*
	1973 - 1977	→ deepening of the shipping channel to a continuous water depth of 9 m***

*depth is related to the potential vessel draft; ***below German sea chart datum (= low water springs)

b	outer Weser Estuary	
	1891 - 1895	→ construction of embankments, first dredging in the main shipping channel
	1896 - 1899	→ deepening of the main shipping channel to a continuous water depth of 8 m** → construction of groynes
	1906 - 1913	→ deepening of the main shipping channel to a continuous water depth of 10 m**
	1922 - 1928	→ deepening of the main shipping channel to a continuous water depth of 10.3 m**
	1968 - 1971	→ deepening of the main shipping channel to a continuous water depth of 12 m***
	1998 - 1999	→ deepening of the main shipping channel to a continuous water depth of 14 m***

**below low water tide; ***below German sea chart datum (= low water springs)

Between 1827 and 1830 a new port was founded, called Bremerhaven, where the inner estuary starts to broaden to the funnel-shaped outer Weser Estuary (Rohde, 1970; Flügel, 1987). Bremerhaven has developed to an important German seaport and belongs today to the top twenty of the biggest container harbors worldwide (Rodiek, 1997).

The first deepening of the channel in the inner Weser Estuary showing substantial results was done from 1887 to 1893 (Rohde, 1970; Flügel, 1987). Subsequently, seagoing vessels drawing 5 m, could reach the harbors of Bremen. During the 20th century 4 further periods of channel deepening and dredging took place: 1913-1916 to 7 m, 1925-1930 to 8 m, 1953-1959 to 8.7 m, and 1973-1977 to 9 m (below German sea chart datum) (Table. 1.2).

The hydrodynamical and morphological situation of the outer Weser Estuary sufficed the navigational requirements until the end of the 19th century (Rohde, 1970). Morphological changes like shifts of tidal channels and sand bars were controlled by the dynamic forces of tides and waves. Between 1825 and 1922, the eastern tidal channel of the outer Weser Estuary was used as a main shipping channel (Fig. 1.5), due to its greater water depths and more favorable hydrodynamic conditions compared to the western channel.

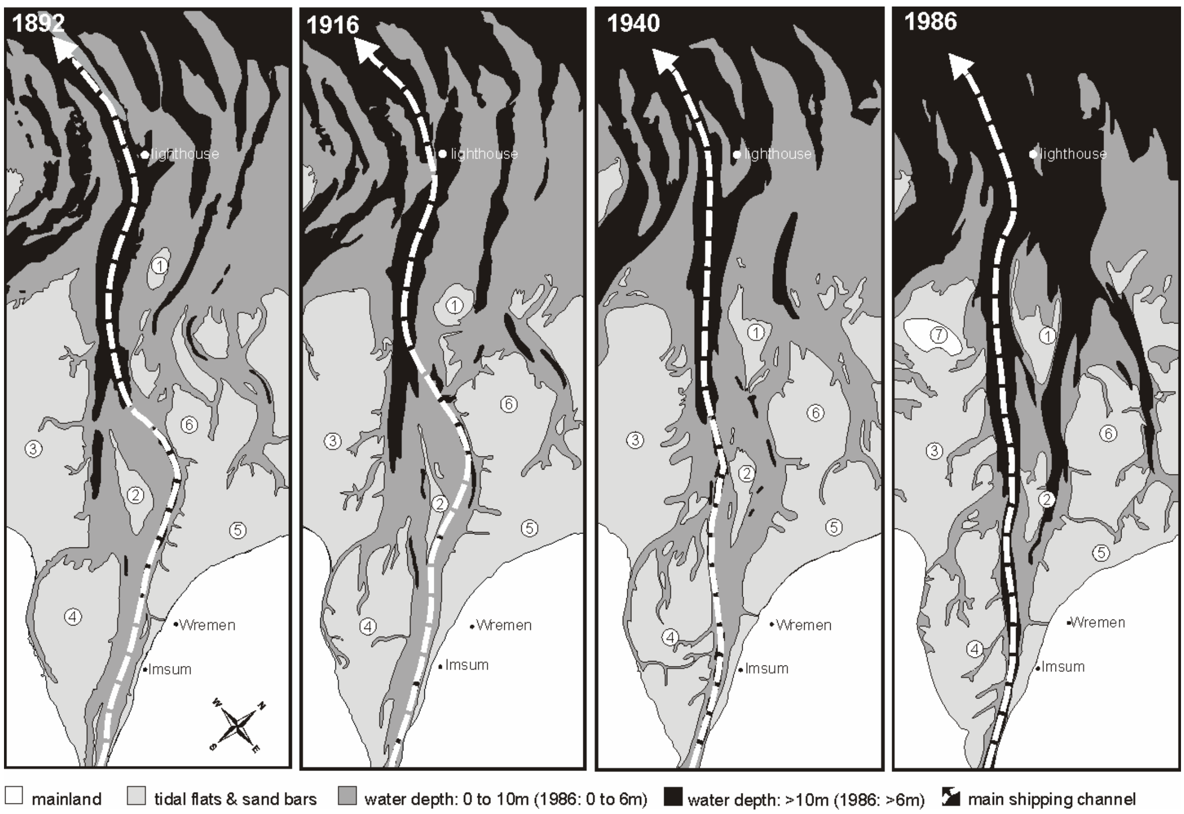

Fig. 1.5 Morphological change of the outer Weser Estuary between 1892 and 1986 (modified after Dieckmann, 1991). Sand bars: (1) Tegeler Plate, (2) Robbenplate; tidal flats: (3) Hohe-Weg-Watt, (4) Langlütjensand, (5) Wurster Watt, (6) Eversand; island: (7) Alte Mellum.

However, in 1891 first local dreding activities were initiated and during the following 20 years the channel was successively deepened over its entire length: 1896-1899 to 8 m and 1906-1913 to 10 m (depths relate to meters below low water tide) (Table 1.2). In 1922, the main shipping channel was relocated to the western tidal channel of the outer Weser Estuary (Fig. 1.5) and deepened to a continuous water depth of 10.3 m (below low water tide) (Table 1.2) (Hovers, 1973; Wetzel, 1987).

In recent years, the size of container vessels, in particular length and draft, has increased considerably. Therefore, seaports all over the world, such as the container terminal of Bremerhaven, have to adapt their shipping channels to this development to guarantee a safe access to their harbors, and thus, to stay on competitive basis. As a consequence, between 1968 and 1971 the western main shipping channel of the outer Weser Estuary was again deepened to a water depth of 12 m (below German sea chart datum), and finally, in 1998/1999 to a depth of 14 m (below German sea chart datum) (Table 1.2).

1.4.2 Consequences of the human impact

Before human impact has started, many estuaries were in a state of equilibrium, in which the ability of the rivers to supply sediments was roughly matched by the ability of the tides to remove it. However, human interferences have complicated the estuarine dynamics and provoked significant changes in hydrodynamics, sediment distribution, and morphology. As a consequence, the balanced system between erosion and sedimentation is dramatically disturbed. This includes e.g. an increase in river-borne sediments caused by deforestation, urbanization, mining, and quarrying. Whereas, a decrease in riverine input results from dam and tidal barrage constructions (Trenhaile, 1997). Furthermore, dredging of shipping channels and dumping of dredge spoil, as well as dock and marina constructions may have a significant influence on the sediment budget.

This is also true for the Weser Estuary. The environmental conditions of the Weser Estuary changed drastically during the last 100 years in the course of the numerous interferences. An outstanding example is the strong increase of the tidal range. In the range of Bremen, the tidal range increased from ~0.13 m (1882) to over 4 m (1990) during a time period of approximately 100 years (Fig. 1.6) (Müller, 1992). This was the result of a strong lowering of the mean low water and a slight increase of the mean high water caused by the repeated dredging of the channel (Wetzel, 1987). As a consequence, the tides could intrude much further up the Weser River (Rohde, 1970; Busch et al., 1989), resulting in an increased erosion of the seabed. To prevent a further lowering of the low water levels and the increased erosion, a tidal weir at Bremen-Hemelingen was built between 1906 and 1911 (Table 1.2) (Dirksen and Reiner, 1987; Wetzel, 1987).

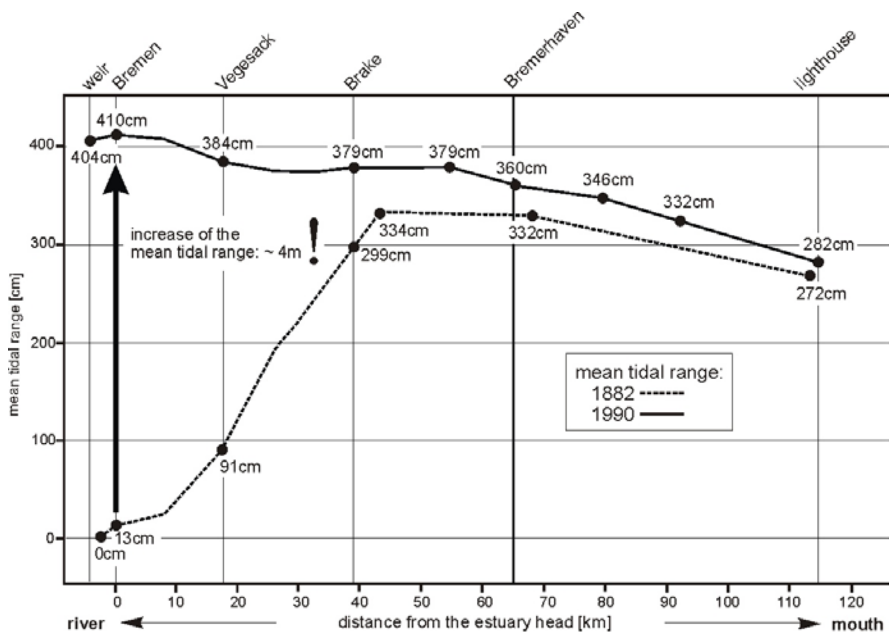

Fig. 1.6 Increase of the tidal range in the Weser Estuary between 1882 and 1990 (modified after Müller, 1992).

1.4.3 Dreding and dumping

Dredging can be categorized as either hydraulic (pumping) or mechanical (digging). Most typically is the use of a hopper-type hydraulic dredge to remove sandy sediment from the seabed. Hydraulic dredging involves the use of a large centrifugal pump to lift a sediment-water slurry from the seabed through a pipe, discharge the material into the ship's own hold (Fig. 1.7) and then transport it to a specific dumping site (Huston, 1970; Herbich, 1975; Smith, 1976). In 'open water dumping', the dredge spoil is discharged without any type of confinement, typically forming underwater mounds.

A general problem in dredging operations is the recycling of the dredged sediments. If the dredge spoil is mainly composed of sands, it can be used as a building material for infrastructural projects. For example, during the last deepening of the shipping channel in the outer Weser Estuary in 1998, approximately 8 million m^3 of sediments were removed out of the channel, whereof 5 million m^3 were used for the infilling of an ancient dock in Bremen and building projects in the local region. However, the dredge spoil is mostly dumped somewhere close to the dredging area. In this context, it is necessary to choose suitable dumping sites, and referring to this, many aspects have to be considered. Dumping activities should not negatively influence the ecological environment. But also economical facets are important, as e.g. the distance between the dredged channel and the specified dumping site, which should be as short as possible to minimize the operational costs. Furthermore, the composition of the seabed sediments have to be similar to that of the dredge spoil and most important, particular hydro- and morphodynamic conditions in the environment of the dumping site are preferred to guarantee that the dumped sediments remain at the dumping site or will be transported towards the open sea. Thus, the effect of re-infilling of shipping channels, which can be observed to an increasing degree directly at the end of dredging campaigns, has to be reduced, otherwise cost-intensive maintenance dredging continues.

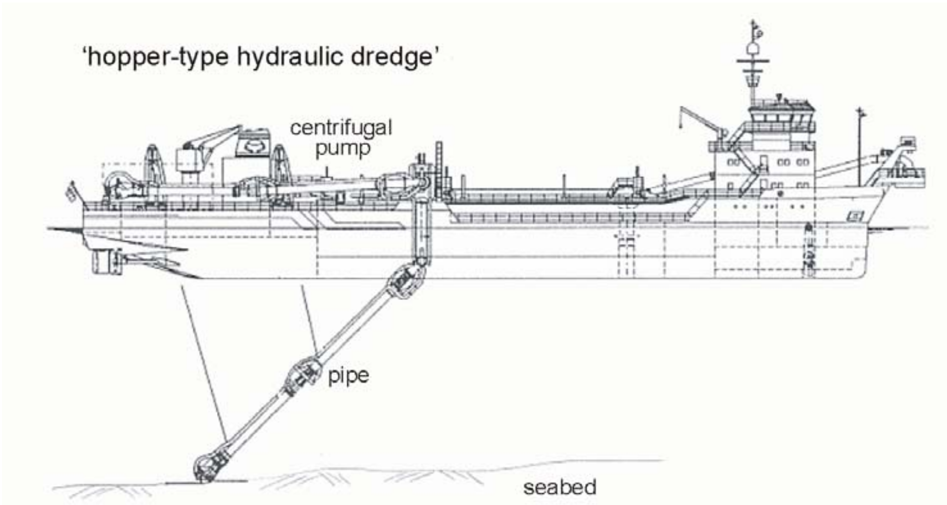

Fig. 1.7 Diagram showing the function of a hopper-type hydraulic dredge (Waterway and Shipping Office Bremerhaven: http://www.wsv.de/wsa.bhv/).

1.5 Acoustic measuring methods in coastal areas

1.5.1 Multibeam echosounder systems

The development in surveying the seabed started in the early 19th century. At these times, the water depth was measured by lowering of a lead weight on a long line from the side of a vessel. Since that time, a big progress in physics and electronics has been made. Nowadays, the seabed is mapped via acoustic remote sensing in a more detailed and accurate way. The advantage of using sound waves is their physical attribute of being easily transmitted and little absorbed while travelling through the water column. Depth measurements can be deduced from the travel time of echoes reflected by the seabed (Fig. 1.8). Sound waves propagate in water with a velocity of ~1500 m/s, local variations occur due to variations in water temperature, salinity, and hydrostatic pressure.

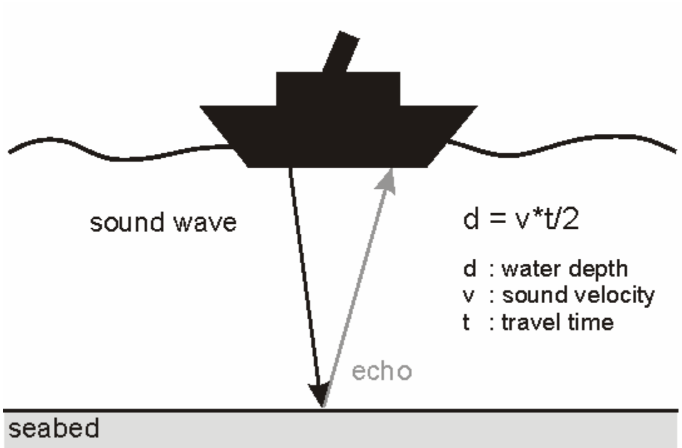

Fig. 1.8 Sound wave propagation in a water column and reflection at the water-seabed-boundary.

With the development of singlebeam echosounders in the 1930s, it became possible to perform bathymetric surveys, line by line and at slow vessel speed (Urick, 1982). Echosounders transmit pulses of controlled length, repetition rate and frequency to an underwater acoustic transducer and accurately time the returning echoes (Tucker, 1966). The size of an echosounder footprint is a function of the beamwidth and the water depth.

Multibeam echosounder systems (MBES) appeared in the 1970s and primarily consisted of an extension of a singlebeam echosounder. Instead of transmitting and receiving a single vertical beam, the MBES transmits several tens of beams (typically 100 to 200) with small individual widths (1°-3°) in the form of a fan perpendicular to the navigation line (Fig. 1.9). This configuration provides depth information out to several meters each side of a vessel which allows to survey large areas of the seabed with a high spatial and temporal resolution.

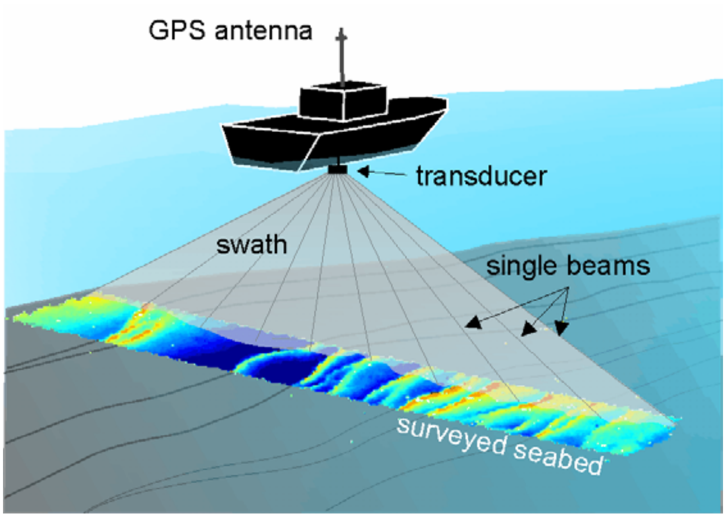

Fig. 1.9 Scheme of a seabed survey with a multibeam echosounder system.

During recent years, MBES have greatly evolved and nowadays they are a broadly accepted tool for seabed mapping. Acoustic transducers have been developed with frequencies ranging between a few hertz and several megahertz depending on the region and the water depth surveyed. Low frequencies between 12 and 30 kHz are used for research in deep waters (deep ocean, continental slope), whereas high frequencies between 200 and 300 kHz are applied for the investigation of shallow-water areas such as rivers, lakes, and coastal seas (Lurton, 2002).

In the present study, a MBES for surveying shallow-water areas was used. Data sets of a SeaBat 8101 of the Danish manufacturer RESON were processed and interpreted. This MBES operates with a frequency of 240 kHz. It is applied in water depths ranging from 0.5 to 500 m (below the transducer). In water depths of 1 to 70 meters, the configuration of the SeaBat 8101 measures a swath width of 7.4 times the water depth. This ratio of water depth to swath coverage decreases in depths >70 m (Table 1.3). The swath can be adjusted to a maximum width of 150° across-track by 1.5° along-track and exists of 101 individual beams, each with a width of 1.5°x1.5° (1.5° beamspacing). Small beam widths are essential in surveying shallow waters to generate beam footprints as small as possible, and thus to optimize the accuracy of the depth measurements. The maximum update rate of the SeaBat 8101 system of 40 pings per second allows obtaining ~ 4,000 depth values per second.

Table 1.3 The area of the seabed covered by the swath of the SeaBat 8101 system is dependent on the water depth. All calculations assume the center of the swath to be vertical (Reson, 1999).

Water depth (m)	→ Coverage of the seabed (x water depth)
0.5-70	→ 7.4
70-100	→ 4.2*
100-150	→ 2.7*
150-200	→ 2.0*
200-250	→ 1.6*
250-300	→ 1.3*

* typical value

To achieve survey data as accurate as possible the application of a positioning system is required. A differential global positioning system (DGPS) provides the opportunity to obtain a geographical position for each acquired depth value with a today available accuracy of less than 1 m. Nevertheless, the determination of the geographical position can be complicated through movements of the supporting survey vessel (heave, roll, pitch, and yaw). Therefore, it is imperative to simultaneously know the attitude of the survey vessel. State-of-the-art attitude sensors (gyrocompass) compensate and correct relative movements of the survey vessel (especially roll and pitch) with accuracies of a few degrees (Trethewey et al., 1999).

1.5.2 Seabed classification systems

Sound waves provide much more information than just the water depth. The acoustic backscatter is affected by a wide variety of factors, e.g. morphological characteristics of the seabed surface (roughness) and its intrinsic nature such as composition and density (Blondel and Murton, 1997). In recent years, acoustic classification methods, like seismic techniques, analysis of sidescan sonar images, or echosounder-based classification systems, have become of increasing importance in classifying the seabed.

Echosounder-based techniques are newly developed for scientific applications and are useful tools to classify a large area of the seabed with high spatial and temporal resolution. These systems can be connected to the transducer of any common singlebeam echosounder system. The echo received by the transducer of the echosounder is sent to the classification system, which analyzes the shape of the returning acoustic signal to extract useful information about the seabed characteristics.

The shape of an echo signal is a measure of the acoustic energy returning to the echosounder transducer. The acoustic backscatter is affected by seabed characteristics such as sediment grain size and sorting, seabed roughness, bedforms, and benthic fauna and flora (Collins et al., 1996; Collins and Lacroix, 1997). Generally, the harder or rougher the seabed, the more energy is scattered back to the transducer. Therefore, a smoothed simple seabed may have a high percentage of energy directed back to the transducer with minimal scattering, resulting in an echo trace with a relatively narrow peak and no tail (Fig. 1.10).

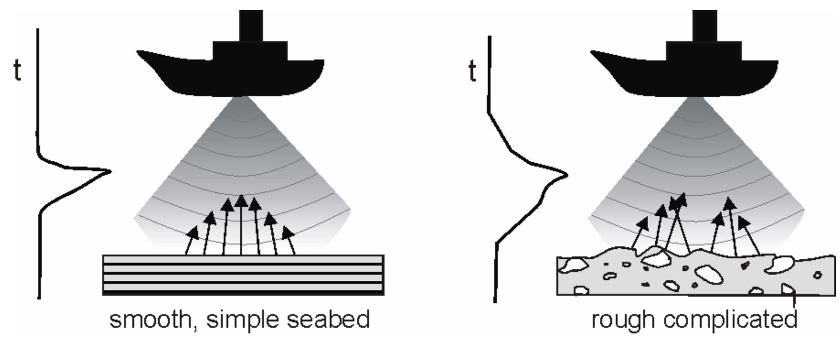

Fig. 1.10 Schematic representation of two hypothetical seabeds and corresponding echo traces: The symbol t represents the echo trace in time (Quester Tangent Corporation, 1998).

Moreover, a significant percentage of energy is absorbed by the smoothed substrate. In contrast, the signal of a rough complicated seabed will exhibit a high degree of scatter with the echo trace having a wide peak and a tail (Fig. 1.10) (Collins et al., 1996; Collins and Lacroix, 1997).

The two best known commercial echosounder-based seabed classification systems are RoxAnn developed by the Marine Microsystems Ltd. (Scotland) and QTC View™ of the Canadian manufacturer Quester Tangent Corp. In the present study, the seabed classification system QTC View™ was applied. It is connected to a singlebeam echosounder between the transducer and sounder (Fig. 1.11). It captures and digitizes the transmitted signal from the echosounder as well as the returning acoustic signal.

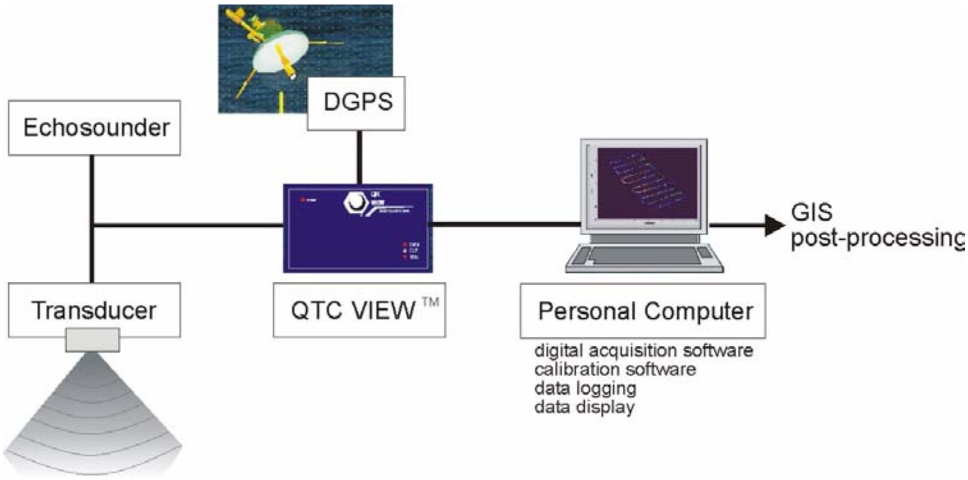

Fig. 1.11 System configuration of the seabed classification system QTC View™.

In contrast to the RoxAnn system, which classifies the seabed by analyzing the energy contained in the first and second echo, QTC View™ uses the shape of the first returning echo only (Fig. 1.12) (Collins et al., 1996; Quester Tangent Corporation, 1998). The full shape of each echo is analyzed by a series of five algorithms, which use energy and spectral components to characterize the waveform. The result of this analysis is a digital characterisation of the echo shape consisting of 166 elements, called full feature vectors (FFV) (Collins and Lacroix, 1997). To reduce this large quantity of information, a Principal-Component-Analysis is carried out, which determines the three most useful descriptors to discriminate the waveforms. These values are labeled Q-values (Q1, Q2, and Q3). When represented in a three-dimensional space (Q-space), points from a similar seabed type tend to cluster close to each other, forming an acoustic class (Collins and Lacroix, 1997; Tsemahman et al., 1997).

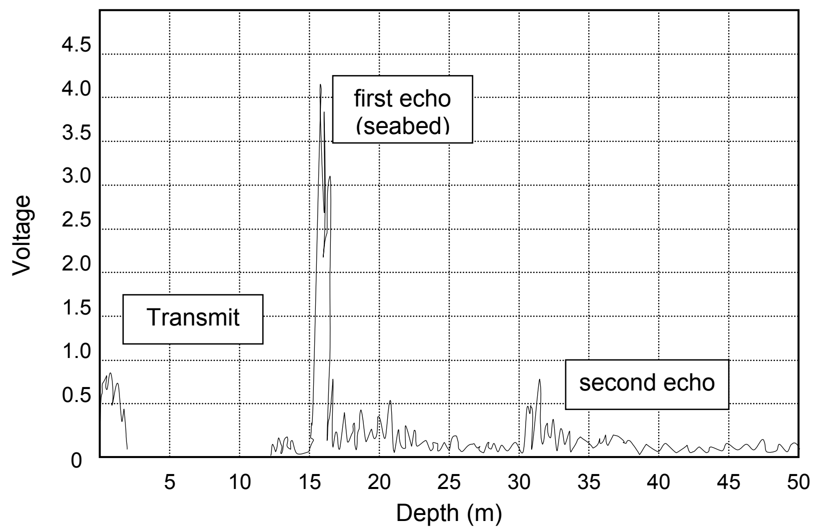

Fig. 1.12 A single echo trace showing the tail of the transmitted pulse, the reflection of the seabed (first echo), and the second echo(Collins and McConnaughey, 1998).

The QTC View^{TM} system can be used under two survey strategies, depending on the target application and the available groundtruthing information: supervised and unsupervised classification modes (Collins and Lacroix, 1997; Collins and Rhynas, 1998). Using a supervised classification, a series of echoes are systematically collected from seabeds with known characteristics in order to calibrate the system. The data sets of processed and analyzed echo features form the database for producing a catalogue of discrete acoustic classes. The stored analysis results of the generated catalogue include the information used to reduce the 166 feature elements to three Q-values as well as the description of the cluster corresponding to each calibrated data set. During following surveys, the incoming echoes are assigned to a given catalogue class with a confidence degree (Collins et al., 1996). New acoustic classes can be determined during post-processing. For unsupervised classification, the user collects and stores raw echoes along a predefined survey line, each with a corresponding position fix. This method makes use of post-processing software (QTC Impact) to determine the range of acoustic variability of the surveyed seabed. The acoustic data are submitted to cluster analysis and classified into a set of acoustic classes. Once this is completed, each acoustic class is further associated with a particular seabed type by groundtruthing (e.g. sediment sampling, analysis of photographs or videos).

It should be mentioned that QTC View^{TM} shows some similarities to sidescan sonar in classifying the seabed. Nevertheless, there are basic differences which become apparent by comparing the operating principles (Bornhold et al., 1999).

Penetration of acoustic signals into the seabed decreases with frequency of the transmitted pulse. More precisely, high frequencies penetrate the seabed less but are more discriminating, while lower frequencies penetrate deeper into the seabed and are less discriminating. Bornhold et al. (1999) showed that seabed classification by a QTC View™ system is more related to the surface, whereas sidescan sonar provides combined information about the surface sediment cover and the underlaying basement. In contrast, sidescan sonar classification is tied to grain size, seabed roughness, and other physical features, but the connection is looser for smaller grain sizes and for admixtures (Bornhold et al., 1999).

Furthermore, the beam width determines the size of the acoustic footprint; a larger footprint yields a signal that has been averaged over a larger area of seabed (Collins and Rhynas, 1998). A sidescan sonar insonifies a flat seabed at between 45° and 10° from horizontal, which emphasizes rugged bathymetry by producing shadows (Fig. 1.12). Singlebeam echosounders that provide echoes to QTC View™ systems use vertical insonification (Fig. 1.12). The resulting acoustic backscatter is influenced by both seabed roughness and the contrast in acoustic impedance over all bottoms.

Consequently, the sidescan sonar image enables full coverage with good topographic detail and substrate information of varying quality, while QTC View™ provides detailed substrate classification over a wide range of seabed types (Bornhold et al., 1999).

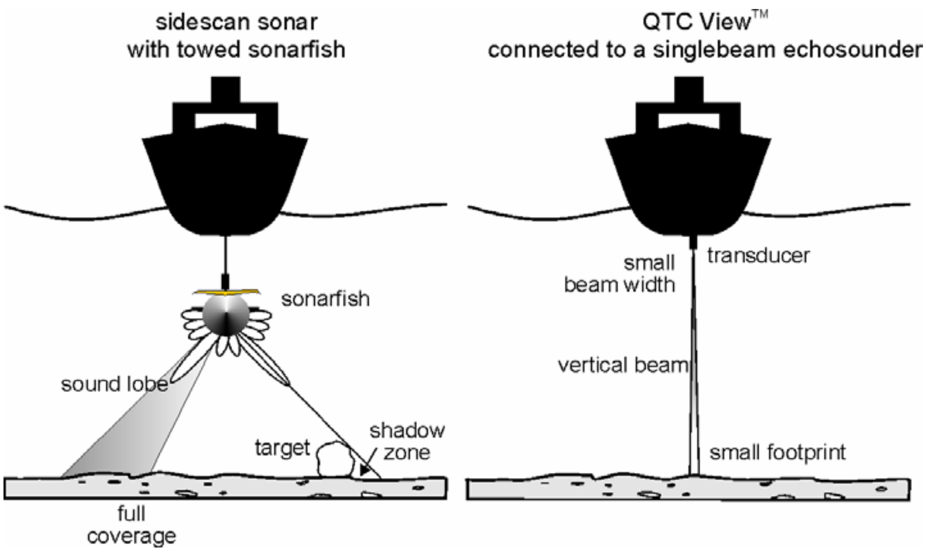

Fig. 1.12 Differences in operating principles between sidescan sonar and QTC View™ connected to a singlebeam echosounder.

1.6 Overview of own research

The aim of this thesis is to monitor morphological changes due to the human impact by the dumping of dredge spoil in a highly dynamic coastal environment. The results are presented and discussed in three manuscripts, which are submitted to or already accepted by reviewed international scientific journals.

Manuscript I

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

Wienberg, C., Dannenberg, J. and Hebbeln, D.

accepted by Geo-Marine Letters

The first manuscript (chapter 2) aims to provide bathymetrical maps of successive surveys with a high-resolution multibeam echosounder system. These maps are compared against each other in order to get information about existing natural and artificial seabed features and their alteration due to the supply of dredge spoil. Furthermore, a change of the sediment budget is calculated by generating difference grids between the different bathymetric surveys.

Manuscript II

'Subqueous dunes in the outer Weser Estuary (German Bight) and the impact of dumped sediments'

Wienberg, C. and Hebbeln, D.

submitted to Marine Geology

In the second manuscript (chapter 3), a detailed analyzes of subaqueous dunes covering the seabed of the dumping site is carried out. Their morphological characteristics, migration behaviour as well as their change due to the dumping of dredge spoil are presented.

Manuscript III

'Acoustic seabed classification in a dynamic environment (outer Weser Estuary, German Bight) – quality control of human impact'

Wienberg, C. and Bartholomä, A.

submitted to Continental Shelf Research

The third manuscript (chapter 4) is dealing with the composition and spatial distribution of sediments, which are found in the surrounding area of the dumping site. Acoustic data of an echosounder-based classification instrument are processed, which analyse the shape of a returning acoustic signal in order to classify of the seabed characteristics.

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

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accepted by *Geo-Marine Letters*

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

2.1 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 infrastructional 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 were 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: a) during the dumping no significant turbidity at the sea surface is recognizable, b) almost the total amount of dumped material is deposited at the seabed, c) the dumped sediments accumulate in form of a distinct mound, whereas the surrounding seabed is not affected, and d) 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 realtively 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. 2.1a, 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 the dumping site were documented. In addition, the change in sediment budget associated with the export of dumped material was quantified.

2.2 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. 2.1a), 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 0–10 m (below German topographic chart datum), the thickness of the North Sea sands amounts to ~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 which 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. 2.1a). In the outer Weser Estuary, two tidal channels are developed which are separated by flow-parallel elongated sand bars and which bend out in a north-westerly 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.

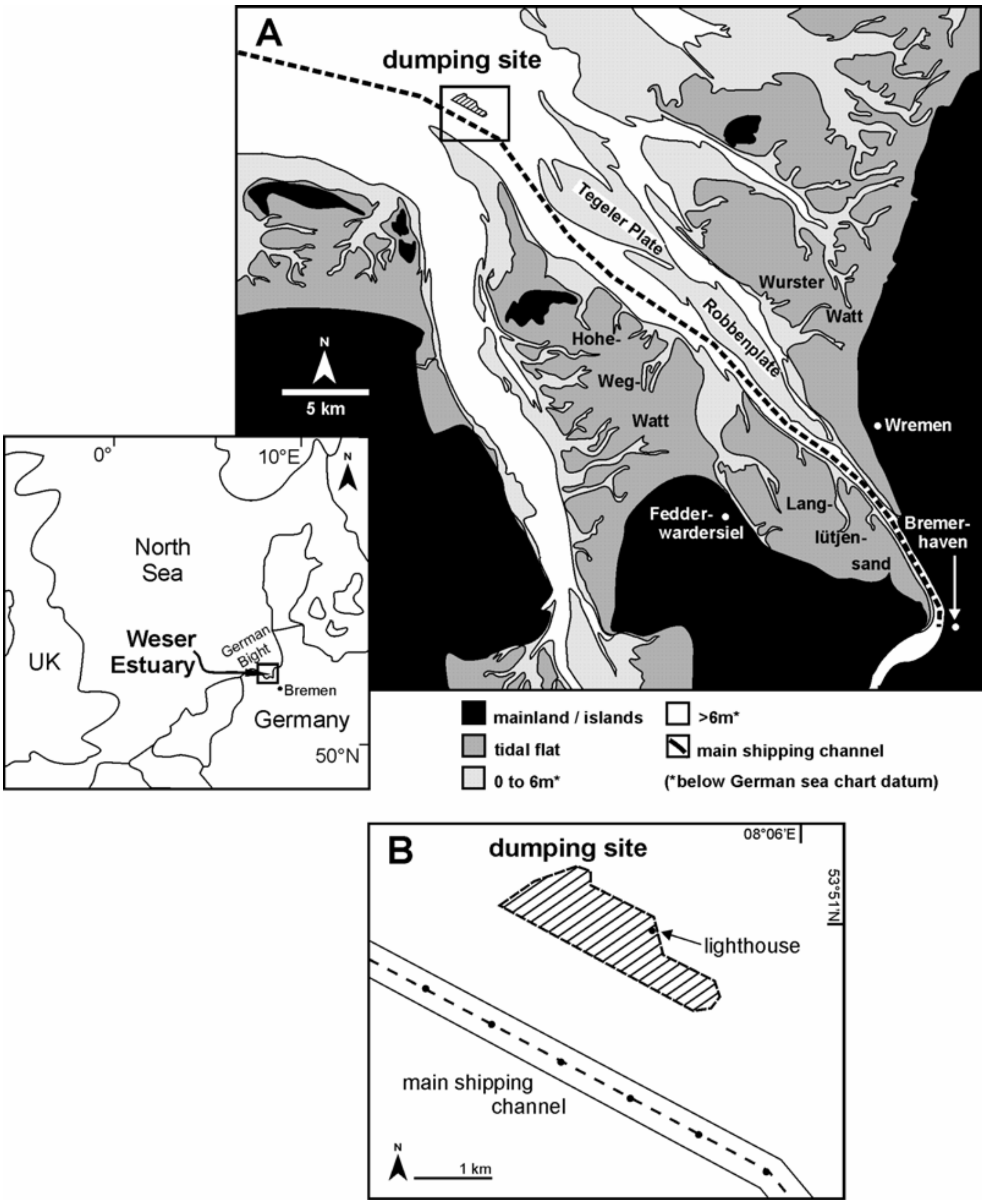

Fig. 2.1a-b a) Map of the the outer Weser Estuary (German Bight), b) map of the study site.

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, a distinct spring and neap tidal cycle is 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 a residual sediment transport (Dronkers, 1986). The Weser Estuary is characterized by a dominance of the ebb tide with slightly longer ebb duration and higher current velocities, and 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 ms^{-1} (Bundesanstalt für Gewässerkunde, 1992) results in strong vertical mixing of seawater and freshwater delivered by the Weser river (Grabemann and Krause, 1989).

2.2.1 Study site

The dumping site 'Rotergrund' is situated in the exposed part of the outer Weser Estuary, east of the main shipping channel (Fig. 2.1a, 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 the dumping of 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 100 m x 200 m (Fig. 2.2). During the dumping operation, each of these units was filled with a predefined amount of dumped material as shown in Fig. 2.2.

Because the surface sediments are originally composed of fine to medium sand there, 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. 2.1b), which meant a substantial reduction of the operational costs (Rodiek and Steege, 2001). In addition, it was hoped to fill up scour holes which had developed at the base of a lighthouse situated approximately along midway at the eastern margin of the site (Fig. 2.1b) in order to enforce the stability of the building.

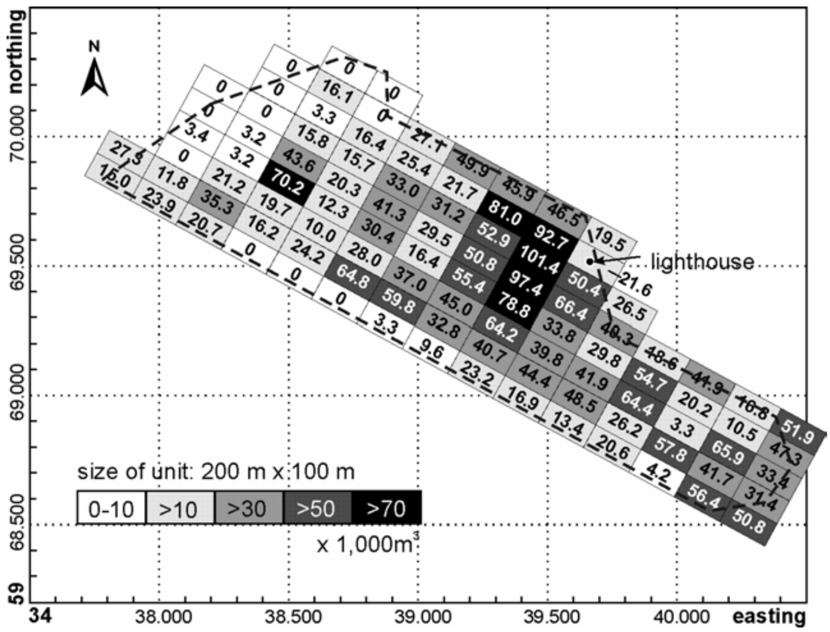

Fig. 2.2 Distribution of the actually dumped amount of dredged material during the entire dumping operation in 1998. To control the dumping, the site has been subdivided into a grid of 97 rectangular units of 100 m × 200 m. The numbers indicate the predefined amount of dumped material in m³ × 1,000.

2.3 Methods

2.3.1 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 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 m and 20 m, the maximum swath width covers a seabed area of ~6 times the water depth. The swath consists of 101 individual beams (1.5° x 1.5°, beamspacing 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 such as to have a slight overlap.

The high frequency and a high sample rate of the Reson SeaBat 8101 results in high-resolution bathymetric data. Nonetheless, 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 important, navigational inaccuracies in determining the geographical position (Lurton, 2002). The latter being 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) of the 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 the variations of the ship movements, a motion sensor of the type TSS DMS-05 was used which is designed specifically for surveys with a MBES. Since 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).

2.3.2 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 million and 7 million soundings per survey were recorded (Table 2.1). A regular data grid with a 4 m node spacing in the N-S and E-W direction 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 get information about minimum, maximum, and mean water depth of the dumping site (Table 2.1), as well as the change of the water depth conditions during the dumping. As a by-product, it was detected that the data sets still contain 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 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 2.1) which were removed manually.

Table 2.1 Data acquisition information as well as minimum, maximum, and mean water depth at the dumping site during the bathymetric survey campaign. Water depths 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	1h 33min	15	4,969,270	1,272 (0.26%)	7.4	17.0	12.0
30 August 1998	1h 44min	18	5,058,962	2,169 (0.043%)	5.1	16.5	11.6
1 December 1998	2h 33min	21	6,993,949	1,504 (0.021%)	5.2	16.1	11.4

2.3.3 Difference grids

To facilitate a quantitative comparison between the surveys, grids of bathymetric differences (grid size: 4 m x 4 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 visualised. In this case, difference grids between the data sets of following 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.

2.4 Results and Discussion

2.4.1 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. 2.3a). The mean water depth at that time is 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 2.1). 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 classified as very large dunes. The crestlines of the dunes are sinusoidal, partly bifurcated, and orientated transverse 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 2.1). In general, the morphological situation of the site did not change significantly (Fig. 2.3b). An exception is the central part of the survey area (south of the lighthouse, see Fig. 2.3b), where substantial sediment accumulation occured 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. 2.3c). 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 2.1). As mentioned before, the seabed in the central part of the site showed strongest shoaling from formerly 9-12 m to 8-10 m water depth. With 50,000 to 100,000 m^3 dumped sediments per 200 m x 100 m unit (Fig. 2.2), 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 ones have diameters of up to 120 m and a height of about 1.5 m. Finally, two scour holes with a diameter of 70-120 m were detected on the bathymetric map. These are developed to the north and the north-west of the lighthouse (Fig. 2.3c).

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. 2.3d). Between the first and last bathymetric survey, the mean water depth decreased by about 1 m, from formerly 12.5 m to 11.4 m, resulting in water depths between 5.2 and 16.1 m in December (Table 2.1). The filling of the dune troughs had increased further. Some individual dumping mounds are 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.

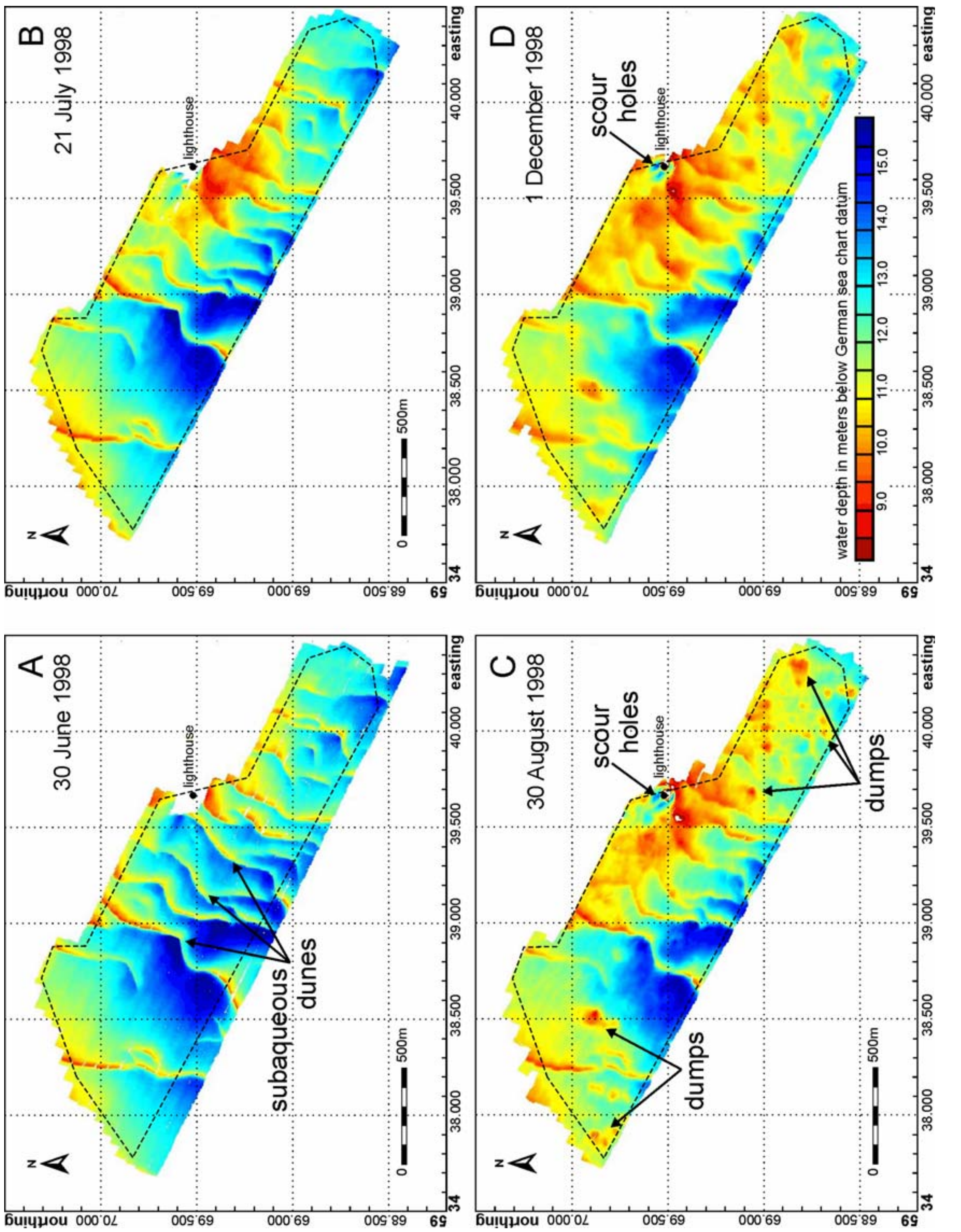

Fig. 2.3a-d Bathymetric maps of the investigated dumping site: a) 30 June, b) 21 July, c) 30 August, and d) 1 December 1998. Red to yellow indicates low water depths, and green to blue high water depths. Water depth information relates to meters below German sea chart datum, i.e. mean low water springs, and the grid numbers are Gauss-Krueger coordinates

2.4.2 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. 2.3a-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 which 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 2.2 shows that the dumping unit (size: 200 m x 100 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. 2.3a, 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. 2.3c, d), reflecting to 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 (timeframe: 30 August–01 December 1998) no significant change in shape was recorded.

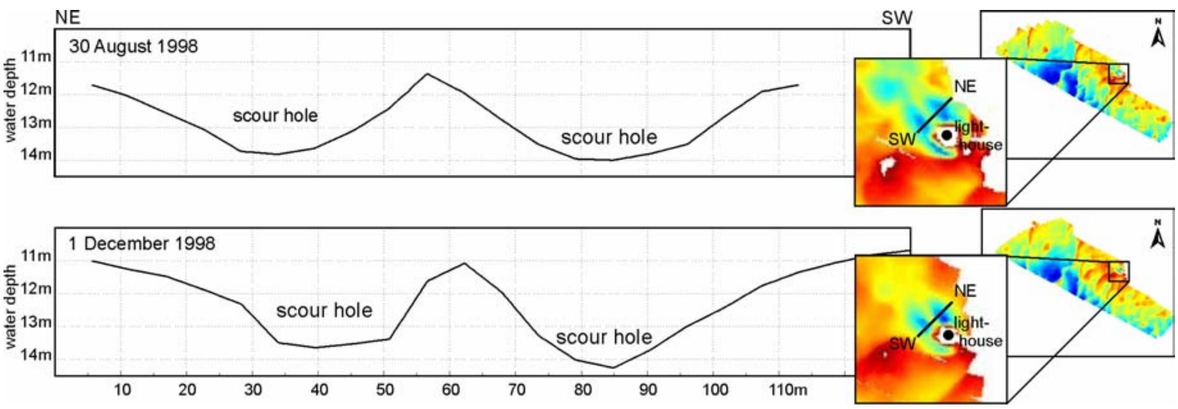

Fig. 2.4 Cross-sections placed across scour holes (30 August and 1 December 1998), which have developed at the base of a lighthouse situated midway along the eastern margin of the dumping site.

2.4.3 Accumulation-erosion balance

In Figure 2.5 a-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 occured 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 was 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. 2.6).

A different situation is displayed on the difference grid between 21 July and 30 August (time period: 40 days) (Fig. 2.5b). Even though in this period a similar volume increase of 0.809 million m^3 was computed (Fig. 2.6), more substantial fields of erosion occured. 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. 2.5a). 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 an 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. 2.5c). Erosion with maximum values of 0.8 m occured 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. 2.6).

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 computet (Fig. 2.5d). It reveals that almost the entire area of the site experienced sediment accumulation. The highest accumulation of up to 5 m were found to occur 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 200 m x 100 m-unit) (Fig. 2.2).

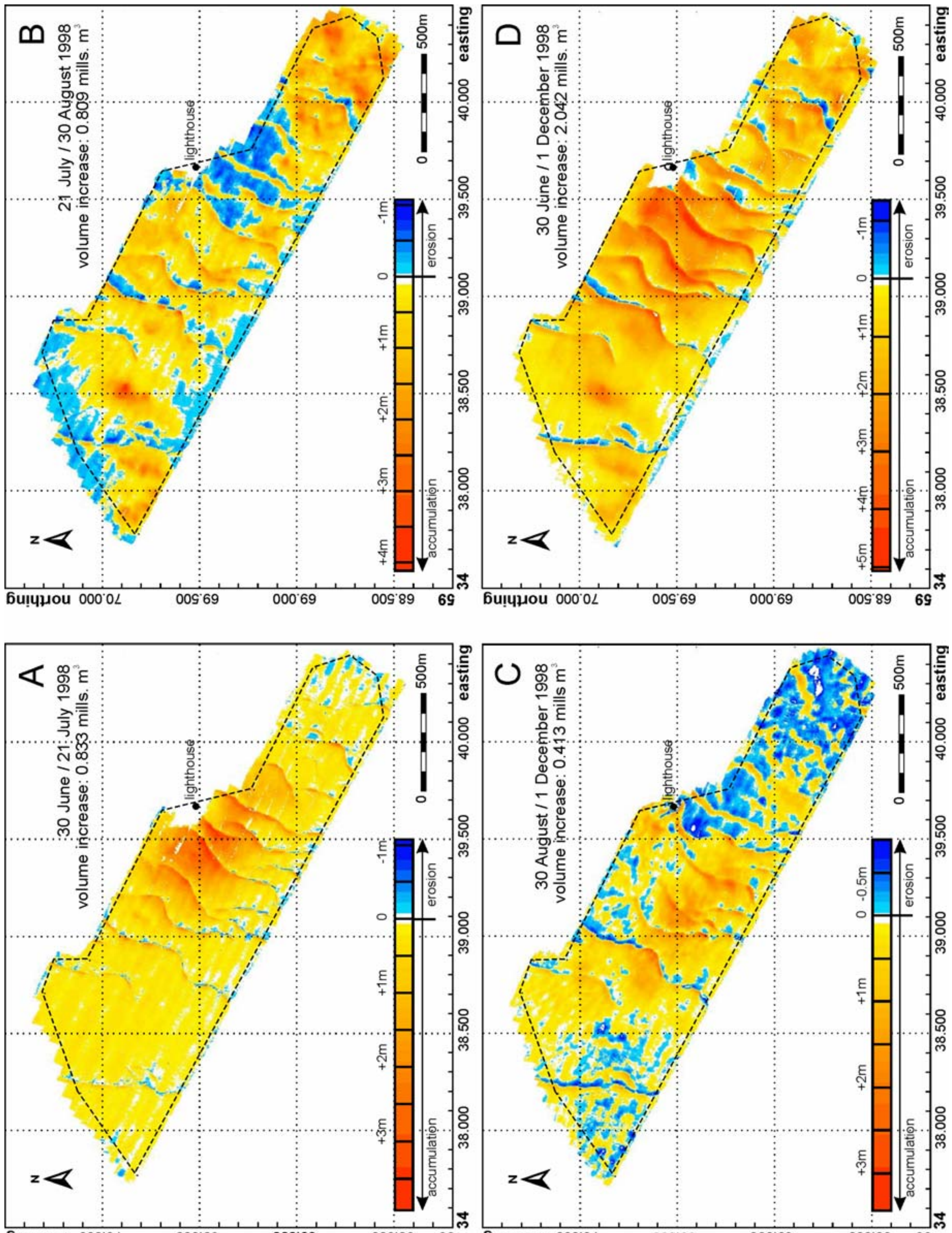

Fig. 2.5a-d Difference grids between the different bathymetric datasets: a) 30 June / 21 July, b) 21 July / 30 August, c) 30 August / 1 December, and d) 30 June / 1 December 1998.
Yellow to red indicate zones of accumulation, and blue indicates zones of erosion.
The grid numbers are Gauss-Krueger coordinates

Over the entire survey and dumping period, erosion occurred along the border area of the dumping site, not exceeding 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 2.042 million m^3 between the first and last survey, indicating a sediment loss of 0.561 million m^3 (Fig. 2.6).

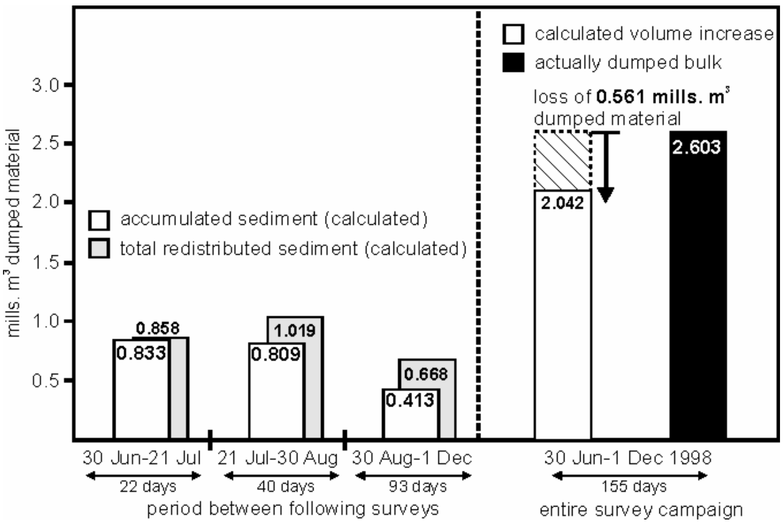

Fig. 2.6 Calculated change of the sediment volume between following surveys with information about the amount of accumulated sediment and the total amount of redistributed sediment (accumulation + erosion). The two right columns show the calculated volume increase about the entire survey campaign compared with the actually dumped bulk during this period (in million m³).

2.4.4 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 instance, Langhorne (1982) investigated the migrational behaviour 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 bedfrom migration.

2.5 Conclusions

The shipping channel of the outer Weser Estuary has been enlarged and deepened for 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 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 easily be 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 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 0.563 million m^3 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 like 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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Subaqueous dunes in the outer Weser Estuary (German Bight) and the impact of dumped sediments

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submitted to *Marine Geology*

Abstract

Subaqueous dunes are extensively developed in many estuaries. Repeated bathymetric surveys with a multibeam echosounder system revealed that they also exist at a shallow water area in the outer Weser Estuary (German Bight, North Sea). In 1998, this area was used as a dumping site where around ~3 million m^3 of dredge spoil were deposited. Bathymetric maps and cross-sections are used to analyze the morphology of the large-scale bedforms covering the entire seabed of the dumping site. The very large dunes are asymmetrical in shape with the lee slope facing the open sea. They have heights of up to 6.7 m, whereas their maximum wavelengths vary between 159 and 407 m. By comparing cross-sections based on bathymetric data sets of three successive surveys (30 June, 30 August, 1 December 1998), an intense morphological change of the bedforms due to the dumping can be recognized. However, dunes which have been completely buried by dumped sediments seem to reshape. Finally, a slight migrational trend towards the open sea, indicating a seaward going net sediment transport, can be determined for the 5-month period of investigation.

Keywords: subaqueous dunes, morphological change, dumping site, dune migration, multibeam echosounder system, Weser Estuary

3.1 Introduction

The classification and nomenclature of flow-transverse bedforms developed in rivers, tide-dominated and marine environments is extremely heterogeneous due to the fact that many different groups of scientists like e.g. sedimentologists, oceanographers, and engineers are concerned with the investigation of their morphology as well as the hydrodynamic factors controlling their development. As a result, diverse names exist for the same bedform or one name for different bedforms. In a straightforward manner, Ashley (1990) introduced the single term dune for the wide variety of flow-transverse bedforms with sizes from 0.6 to over 100 m spacing and heights between 0.05 and >3 m. This classification is also applied for the bedforms presented in this study.

Subaqueous dunes are extensively developed in many estuaries, and have been studied all over the world (Ludwick, 1972; Langhorne, 1973; Boothroyd and Hubbard, 1975; Bokuniewicz et al., 1977; Dalrymple et al., 1978; Dalrymple, 1984; Aliotta and Perillo, 1987; Harris, 1988; Fenster et al., 1990; Berné et al., 1993; Ikehara and Kinoshita, 1994). They are also common features of the seabed at the estuary mouth of German rivers like Ems, Jade, Weser, and Elbe which discharge into the German Bight of the North Sea (Göhren, 1965; Pasenau and Ulrich, 1973; Ulrich, 1973; Reineck and Singh, 1980; Wever and Stender, 2000). For example, Reineck and Singh (1980) described well developed asymmetrical and flow-transverse bedforms for the channels of the Jade and Weser Estuary with wavelengths and heights ranging between 93 and 248 m, and between 1.7 and 5.5 m, respectively.

Dunes arise on the seabed wherever the conditions of sufficient sand supply, water depth, and currents capable of transporting the bottom sediments are fulfilled. Their size and shape are a result of a dynamic equilibrium between these controlling factors. Therefore, each bedform can be related to flow characteristics like flow depth, current velocity and direction (Rubin and McCulloch, 1980; Ashley, 1990), as well as water depth (Allen, 1968; Lobo et al., 2000) and sediment grain size (Allen, 1968; Aliotta and Perillo, 1987). In general, subaqueous dunes are developed in any sediment coarser than 0.13 mm (2.9 phi), and at current velocities exceeding 0.5 ms^{-1}, whereas this limit is rising as the grain size of sediments and the water depth is increasing (Dalrymple and Rhodes, 1995). Consequently, dune size (wavelength and height) and morphology cannot be explained by a single variable but rather by a complex interplay of the different controlling factors, which is recently not completely understood.

If the hydrodynamic conditions change, a dune will change its morphology to re-establish a new equilibrium. However, flow conditions in nature change too rapidly for dunes to remain in equilibrium, due to the restricted time required for transporting sufficient sediment to change the bedform morphology (Allen, 1976). Especially, large-scale bedforms have a long response time and only undergo minor morphological changes (Ikehara and Kinoshita, 1994), therefore they are good indicators of a long-term average bedload transport (Berné et al., 1993). Furthermore, the height of a dune varies much more rapidly than the average wavelength. The amount of sediment, which must be moved to increase or decrease the height of a dune, is much smaller than the amount needed to change the wavelength (Dalrymple and Rhodes, 1995).

This complex natural system is further complicated or even disturbed by the impact of human activities. In particular, dumping of dredge spoil causes a strong impact on the natural morphodynamical processes and changes remarkably the morphology of the affected seabed. In 1998, such a human impact took place at a dumping site in the seaward part of the outer Weser Estuary (German Bight, Fig. 3.1), where ~3 million m^3 of dredge spoil were dumped in the course of the deepening of the main shipping channel to a water depth of 14 m (below German sea chart datum) (Rodiek and Steege, 2001). To control the dumping activities as well as to monitor the influence of the dredge spoil on the local seabed, the site was repeatedly surveyed by a high-resolution multibeam echosounder system (Wienberg et al., accepted). Besides a considerable decrease of the average water depth, the bathymetric data show that large-scale seabed features like dunes are completely buried by dumped sediment, and consequently, the ordinary sediment bedload transport is strongly disturbed. Nevertheless, it is obvious that the investigated large-scale dunes try to reshape their particular morphology already on monthly timescales, and thus, to re-establish a new equilibrium as a response to the changed environmental conditions.

3.2 Study area

3.2.1 Geomorphology and sedimentology

The Weser Estuary, situated at the German North Sea coast, has a total length of 125 km and consists of a channel-like inner section followed by a funnel-shaped outer estuary. The outer Weser Estuary runs from the seaport Bremerhaven to its discharge into the German Bight over a distance of 60 km (Fig. 3.1). The southern and south-eastern parts comprise periodically flooded 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. Two tidal channels are developed and separated by flow-parallel elongated sand bars, which bend out in a north-west direction. Currently, the westerly main shipping channel has a continuous minimum depth of 14 m (below German sea chart datum) and is separated into an ebb- and flood channel (Bundesanstalt für Gewässerkunde, 1992).

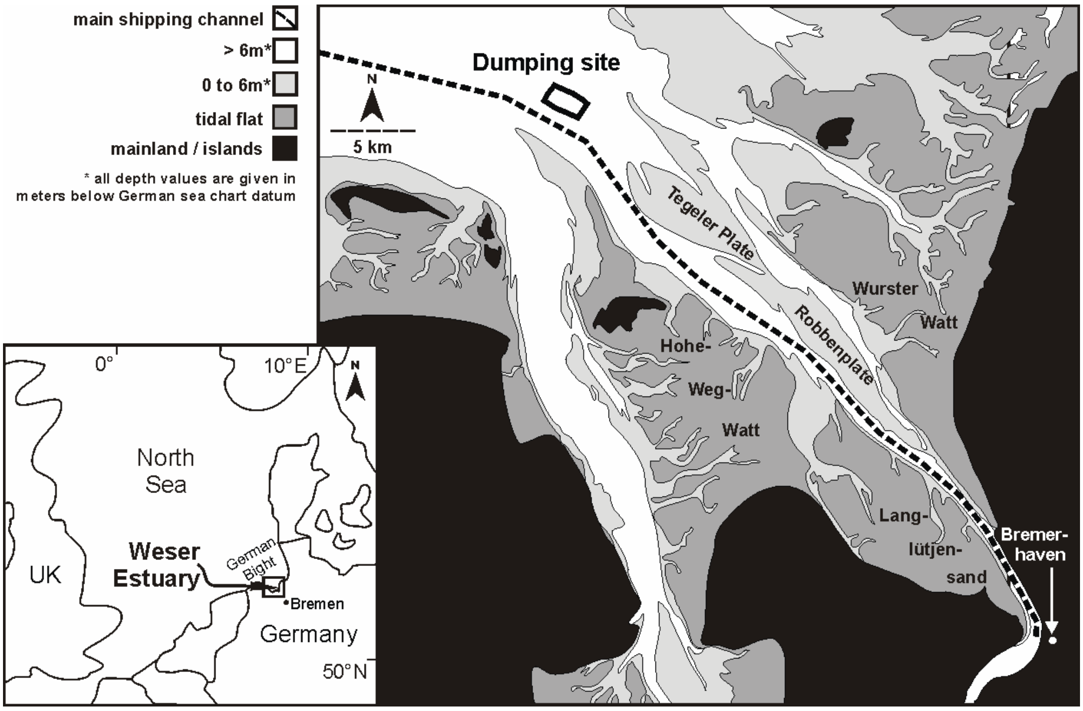

Fig. 3.1 Map of the the outer Weser Estuary (German Bight) showing the position of the surveyed dumping site.

The investigated dumping site is situated in the seaward shallow-water area of the outer Weser Estuary, 1.3 km far from the dredged channel (Fig. 3.1). Some important criteria for choosing this area for the dumping of sandy dredge spoil were its exposed seaward position, the relatively great water depths with a mean water depth of 12.5 m (below German sea chart datum), and the sandy material at the seabed (Bundesanstalt für Gewässerkunde, 1992). The bottom sediments of the outer Weser Estuary are mainly composed of fine to medium sand with a silt and clay content of less than 1% (Wetzel, 1987). The spatial distribution of North Sea sands in the inner German Bight are partitioned into three distinct zones (Zeiler et al., 2000). The outer Weser Estuary belongs to the innermost part of the German Bight with the highest sediment accumulation caused by longshore sediment transport from west to east along the East-Friasian Islands (Johnson et al., 1982). In water depths between 0–10 m (below German sea chart datum), the thickness of North Sea sands amounts to ~10 m (Zeiler et al., 2000). Further offshore, in water depths between 10 and 15 m (below German sea chart datum), a zone with sediment depletion follows. There, a thin layer of bottom sediments of less than 1.5 m is explained by predominant shore-normal bedload transport with a net directional transport towards the open sea. However, this depletion is not observed in the range of the outer Weser Estuary because of sufficient sediment supply by longshore drift. A third zone is developed in water depths >15 m (below German sea chart datum), where the sediment thickness amounts to 2-3 m (Zeiler et al., 2000).

3.2.2 Hydrography

Due to the absence of off-shore islands at its mouth (Fig. 3.1), the outer Weser Estuary is strongly exposed to hydrodynamic processes. Mean maximum current velocities of 1.0 to 1.3 ms^{-1} are common for the uppermost part of the water column, whereas the maximum current velocities at the seabed are much lower with a mean of 0.7 ms^{-1} (Bundesanstalt für Gewässerkunde, 1992). Like all estuaries and sandy bays of the inner German Bight, the Weser Estuary is tide-dominated. The tides penetrate semi-diurnal with unhindered energy from northwest into the estuary. Furthermore, a distinct spring and neap tide cycle is recognizable. The distortion of the tidal wave propagation due to friction of the seabed and convergence of the estuary margins produce differences in magnitude and duration of ebb and flood tidal currents, resulting in a tidal asymmetry and a residual sediment transport. The Weser Estuary is distinguished by a slight dominance of the ebb tide, and therefore, the residual sediment transport runs towards the open sea (Bundesanstalt für Gewässerkunde, 1992; Wasser- und Schiffahrtsamt Bremerhaven, 1996). Furthermore, the Weser Estuary belongs to the hypersynchronous type of estuaries with a tidal range of 2.8 m at the mouth and 4.2 m at the head, classifying it as a meso- to macrotidal estuary (Davies, 1964; Hayes, 1975).

3.3 Methods

3.3.1 Multibeam echosounder surveys

Between June and December 1998, the investigated dumping site in the outer Weser Estuary was bathymetrically surveyed with a high-resolution multibeam echosounder system (MBES). Three repeated surveys of the site (30 June, 30 August, and 1 December) were performed by a private surveying company which was authorized by the responsible authority (Waterways and Shipping Office of Bremerhaven) to monitor and control the process of dredging and dumping during the last deepening of the shipping channel in 1998.

The applied MBES (SeaBat 8101) operates at a frequency of 240 kHz and is applicable in shallow water areas with water depths ranging from 0.5 to 500 m. The transducer illuminates a maximum swath on the seabed that is 150° across-track by 1.5° along-track, whereas the swath consists of 101 individual beams (1.5° x 1.5°, beamspacing 1.5°) (Reson, 1999). The surveys of the dumping site were carried out with a swath width of 143° across-track by 1.5° along-track. This setting allowed to cover a seabed area of ~6 times the water depth. The individual survey-tracks had a width of approximately 90 m in which the tracks were slightly overlapping. With a cruising speed of the survey vessel of 7 knots and an update rate of 7.5 pings per second a swath line of depth values could be measured every 38 cm (ConsultING-Team, 1999).

The geographical positions were received via a differential global positioning system (DGPS) associated with several reference stations installed on-shore in the region. Thus, according to the surveying company, a position accuracy of approximately 30 cm were achieved (ConsultING-Team, 1999). To compensate the variations of the ship movements (heave, roll, pitch, yaw) a motion sensor was applied. The sound velocity was measured every hour and the soundings corrected in real-time.

The sounding data were processed with the computation and visualization software Matlab. A regular data grid with a 4 m node spacing in the N-S and E-W direction was defined and the sounding data within each grid cell element were averaged to produce a digital terrain model.

3.3.2 Cross-sections

To investigate the subaqueous dunes, covering the dumping site in the outer Weser Estuary, 7 cross-sections are generated based on bathymetric data of a survey carried out on 30 June 1998. All cross-sections are aligned in a northwest-southeast direction transverse to the existing dunes (Fig. 3.2a, b). The distances between the cross-sections range between 40 and 127 m (Table 1). Cross-sections A, AA, B, and C have a total length of 2,625 m, whereas E, F, and G span a distance of 1,050 m (Table 3.1). To classify the dunes, their shape parameters like dune height (H), wavelength (L), the length of lee (b) and stoss side (a), as well as the distance between water surface and dune trough (D(t)), and water surface and dune crest (D(c)) are measured. Finally, the vertical form index VFI (calculated as L/H (Bucher, 1919)), as a measure for the steepness of a bedform and the symmetry index SI (calculated as a/b (Tanner, 1971)) of the dunes are calculated.

To get information about the morphological change of the dunes caused by the dumping of dredge spoil, 4 cross-sections (A, B, E, and F) are selected to generate time series based on bathymetric data sets of the three successive surveys of the investigated dumping site. The surveys were carried out over a 5 month period (30 June-1 December 1998) of intensive dumping during which ~3 million m³ of sediments were deposited. The comparison of the time series of the cross-sections provides a good possibility to determine a migration trend of the dunes.

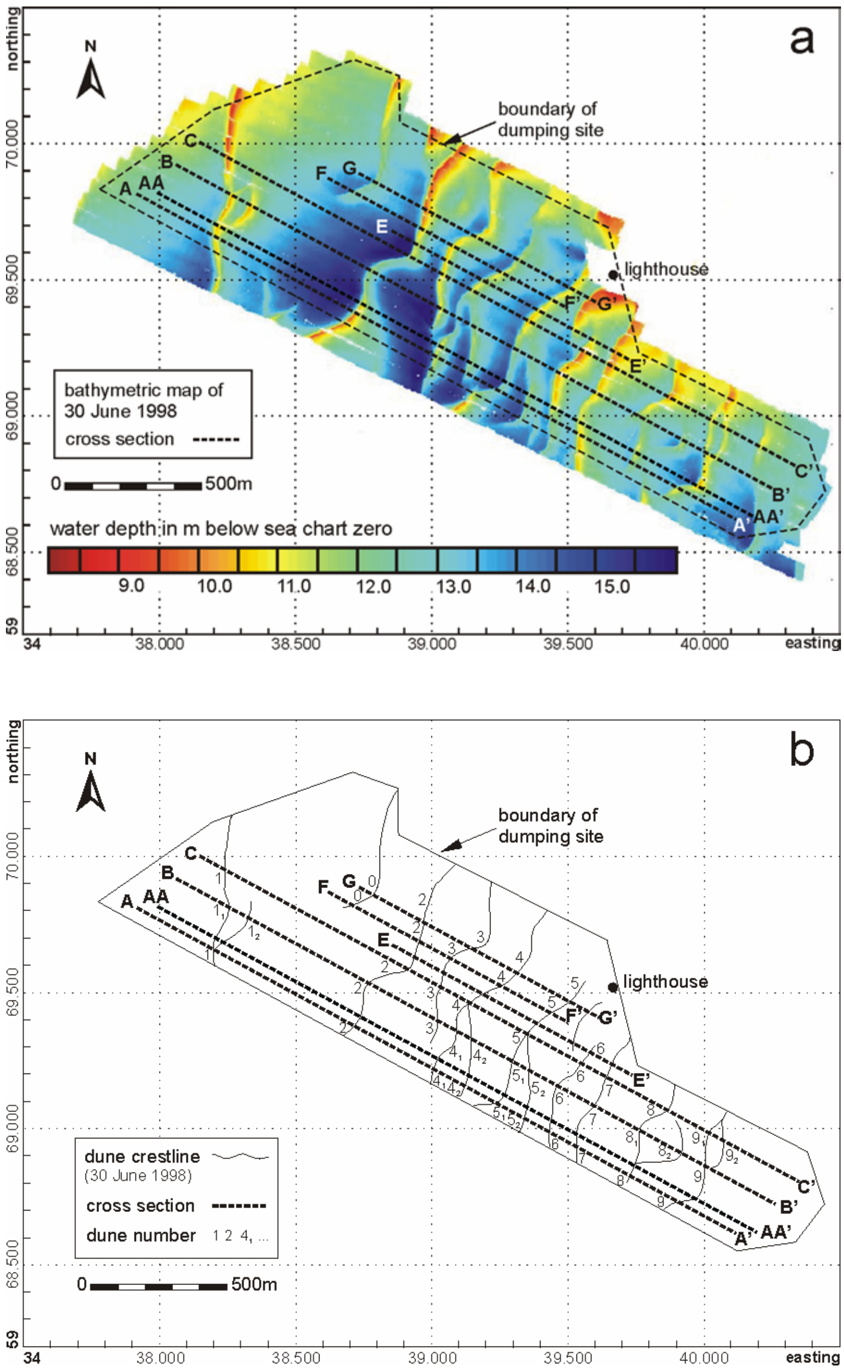

Fig. 3.2a-b (a) Bathymetric map of the investigated dumping site in the outer Weser Estuary (30 June 1998) showing the position of the cross-sections (dotted lines). Water depth values are given in meters below German sea chart datum (low water springs), grid numbers are Gauss-Krueger coordinates. (b) The extent of the dumping site showing the position of the dune crestlines (30 June 1998) and the position of the cross-sections (dotted lines). The investigated dunes are numbered.

Table 3.1 Position of the 7 cross-sections through the dumping site in the outer Weser Estuary, German Bight (coordinates denoted for Gauss-Krueger-Projection).

cross-section	starting point (X)		end point (X')		length (m)	distance to following cross-sections (m)
	northing	easting	northing	easting		
A – A'	5,969,814	3,437,920	5,968,615	3,440,120	2,625	40,0
AA – AA'	5,969,818	3,438,000	5,968,619	3,440,200	2,625	126,7
B – B'	5,969,920	3,438,065	5,968,722	3,440,265	2,625	120,0
C – C'	5,970,000	3,438,150	5,968,802	3,440,350	2,625	53,3
E – E'	5,969,685	3,438,855	5,969,205	3,439,735	1,050	60,0
F – F'	5,969,880	3,438,620	5,969,400	3,439,500	1,050	73,3
G – G'	5,969,910	3,438,710	5,969,430	3,439,590	1,050	-

3.4 Results and Discussion

3.4.1 Morphological dune characteristics

The various morphologies of dunes can be differentiated by descriptors of first, second and third order arranged in decreasing importance (Ashley, 1990). First order descriptors are size (wavelength and height) and plan-form shape (straight or sinusoidal) which are necessary to subdivide dunes into reasonable classes. The superposition of dunes by smaller bedforms (simple or compound) and the sediment type the dunes are composed of are second order characteristics. Furthermore, third order descriptors are useful to describe details of bedform morphology (e.g. symmetry / asymmetry), bedform behavior, and flow characteristics (e.g. migration history of dunes) (Ashley, 1990). For the description of the large-scale dunes investigated in the present study, size and shape as well as third order descriptors were used. According to Ashley (1990), the bedforms covering the seabed of the dumping site in the outer Weser Estuary are classified as very large dunes. The dunes have maximum heights between 2.7 and 6.7 m, whereas the mean heights vary from 1.8 to 5.5 m (Table 3.2). Maximum wavelengths of the individual dunes, measured from trough to trough, range between 159.3 and 407.4 m, whereas their mean wavelengths vary from 119.2 to 242.3 m (Table 3.2). The only exception is represented by dune 1. Its wavelength varies along its span from 510.5 to 797.7 m with a mean wavelength of 623.8 m (Table 3.2). These are significantly higher values compared to the other dunes, hence, pointing to dune 1 as the largest bedform of the entire study area. Furthermore, it is apparent that the size of individual dunes varies markedly along their span. For example, height and wavelength of dune 2 range between 3.0 and 5.9 m and between 118.5 and 407.4 m, respectively. Interestingly, the lowest values appear in the central part of the dune and not at the dune ends (Table 3.2), a morphological characteristic which has been previously described by Fenster et al. (1990).

Table 3.2 Morphological dune parameters for dune 1 to 9 based on bathymetric data of the 30 June 1998 survey. L, b, a, H are denoted in meters, depth values are given in meter below German sea chart datum (low water springs).*

dune	cross-section	L	b	a	H	D (c)	D (tb)	D (ta)	VFI	SI
1	A	545.6	51.6	494.0	5.2	10.6	13.7	15.8	104.9	9.6
	AA	641.2	72.4	568.8	5,2	10.6	13.5	15.8	123.3	7.9
	B	510.5	31.1	479.4	4.7	10.5	12.4	15.2	108.6	15.4
	C	797.7	24.1	773.6	6.7	9.8	12.3	16.5	119.1	32.1
	mean	623.8	44.8	579.0	5.5	10.4	13.0	15.8	114.0	16.2
2	A	407.4	106.8	300.6	5.9	9.8	15.8	15.7	69.1	2.8
	AA	339.4	62.4	277.0	5.1	10.6	15.8	15.7	66.5	4.4
	B	300.6	50.7	245.0	3.9	11.7	15.2	15.6	77.1	4.8
	C	128.5	26.5	102.0	3.3	11.4	16.5	14.7	38.9	3.8
	E	118.5	28.2	90.3	3.0	10.9	16.0	13.9	39.5	3.2
	F	163.0	43.3	119.7	3.6	10.0	14.4	13.6	45.3	2.8
	G	238.7	52.6	186.1	4.3	9.6	14.1	13.9	55.5	3.5
	mean	242.3	52.9	188.7	4.2	10.6	15.4	14.7	56.0	3.6
3	B	107.2	50.8	56.4	3.3	10.8	15.6	14.1	32.5	1.1
	C	142.5	42.9	99.6	3.8	10.5	14.7	14.3	37.5	2.3
	E	169.3	38.2	131.1	3.7	10.5	13.9	14.2	45.8	3.4
	F	215.1	28.2	186.9	3.6	10.7	13.6	14.3	59.8	6.6
	G	200.3	38.7	161.6	2.8	11.2	13.9	14.0	71.5	4.2
	mean	166.9	39.8	127.1	3.4	10.7	14.3	14.2	49.4	3.5
4	A	136.3	28.2	108.1	2.9	12.2	14.9	15.1	47.0	3.8
	AA	161.7	31.5	130.2	3.7	11.6	14.9	15.3	43.7	4.1
	B	181.6	45.7	135.9	2.5	11.9	14.4	14.4	72.6	3.0
	C	243.6	34.4	209.2	2.8	11.3	14.3	14.1	87.0	6.1
	E	218.8	44.2	174.6	2.8	11.5	14.2	14.3	78.1	4.0
	F	200.2	28.7	171.5	2.4	11.5	14.3	13.9	83.4	6.0
	G	147.8	25.3	122.5	2.3	11.5	14.0	13.7	65.7	4.8
	mean	184.3	34.0	150.3	2.8	11.6	14.4	14.4	68.2	4.5
5	A	124.9	39.2	85.7	2.3	11.7	14.5	14.0	54.3	2.2
	AA	98.4	29.3	69.1	1.8	12.0	14.5	13.8	54.7	2.4
	B	82.2	34.4	47.8	1.9	12.4	13.4	14.3	43.3	1.4
	C	199.0	33.5	165.5	3.2	10.5	14.1	13.7	62.2	4.9
	E	193.9	60.9	133.0	2.8	10.7	14.3	13.5	69.3	2.2
	G	86.4	28.4	58.0	1.7	10.9	14.3	12.6	51.5	2.0
	mean	130.8	37.6	93.2	2.3	11.4	14.2	13.6	55.9	2.5
6	A	109.5	19.0	90.5	1.6	11.8	14.0	13.4	68.4	4.8
	AA	109.2	23.1	86.1	2.1	11.2	13.8	13.3	52.0	3.7
	B	121.8	18.8	103.0	1.1	11.2	13.8	13.3	110.7	5.5
	C	159.3	69.0	90.3	2.7	9.8	13.7	12.5	59.0	1.3
	E	96.4	18.9	77.5	1.3	11.3	12.8	12.6	74.2	4.1
	mean	119.2	29.8	89.5	1.8	11.1	13.6	13.0	72.9	3.9
7	A	237.1	30.5	206.6	3.0	10.6	13.4	13.6	79.0	6.8
	AA	254.0	32.4	221.6	2.3	11.2	13.3	13.5	110.4	6.8
	B	165.5	17.3	148.2	2.9	10.5	13.3	13.4	57.1	8.6
	C	263.8	25.7	238.1	2.9	10.0	12.5	12.9	91.0	9.3
	mean	230.1	26.5	203.6	2.8	10.6	13.1	13.4	84.4	7.9
8	A	188.5	21.0	167.5	1.7	11.7	13.6	13.4	110.9	8.0
	AA	266.9	25.5	241.4	4.2	11.4	13.5	15.6	63.6	9.5
	B	219.1	62.1	157.0	1.7	11.8	13.4	13.5	128.9	2.5
	C	196.7	20.7	176.0	2.1	10.3	12-9	12.4	93.7	8.5
	mean	217.8	32.3	185.5	2.4	11.3	13.4	13.7	99.2	7.1
9	AA	257.5	22.4	235.1	4.0	10.5	15.6	14.5	64.4	10.5
	B	186.7	37.0	149.7	2.2	11.1	13.4	13.3	84.9	4.0
	C	147.6	15.7	131.9	2.9	11.1	12.4	13.0	50.9	8.4
	mean	197.3	25.0	172.2	3.0	10.9	13.8	13.6	66.7	7.6

* L = wavelength; b = length of lee side; a = length of stoss side; H = dune height; D(c) = water depth between water surface and crest; D(tb) = water depth between water surface and trough (lee side); D(ta) = water depth between water surface and trough (stoss side); VFI = vertical form index (L/H); SI = symmetry index (a/b)

In plan view, the crestlines of the dunes are slightly (dunes 1 and 7) to strongly (dunes 2, 4, and 5) sinusoidal (3-D plan-form shape) and partly bifurcated. Especially, dunes 4 and 5 show a significant branching in their south-western portion (Fig. 3.2a, b). The vertical form index, VFI, is variable, ranging between 32.5 and 128.9 (Table 3.2). It is obvious that the dunes can be grouped into three distinct classes, according to their VFI. Dunes 2, 3, 4, 5, and 9 have a mean VFI of 49.4 to 68.1. The mean VFI for dunes 6, 7, and 8 ranges from 72.9 to 99.0, and thus indicating that these dunes are significantly flatter than the ones in the first group. In addition, the VFI for every individual dune varies pronounced between a minimum-maximum-range of ~60. Dune 1 is again an exception. With 114.0, this dune shows the highest VFI and is therefore, the flattest dune of the whole study area (Table 3.2).

The symmetry index, SI, of the dunes ranges between 1.1 and 10.5 (respectively 32.1 for dune 1) indicating that all investigated dunes are asymmetric in their cross-sectional profiles. Highest mean SI, and consequently, highest asymmetries are given for dune 1 (SI = 16.2) and dunes 7, 8, and 9 with a range of 7.1 to 7.9 (Table 3.2). The gently rising stoss slope of the dunes is oriented towards the riverine head and the steep lee slope is facing towards the open sea, which is also the direction of the residual tidal flow. The large dunes are therefore be classified as ebb-dominated bedforms. Furthermore, the dunes are orientated transverse to the main tidal direction with the tides penetrating into the estuary from a north-westerly direction.

The investigated very large dunes show a good correlation between wavelength, L, and dune height, H, which is linear in log-log plots. The scatter diagram of these two morphological parameters (Fig. 3.3a) indicates a positive correlation with a calculated correlation coefficient of $r = 0.78$. By comparing this relationship to that proposed by Flemming (1988), which is described by the positive exponential relationship $H = 0.0677L^{0.8098}$, it becomes obvious that the H/L values for the dunes of the investigated dumping site are found below Flemming's mean or equilibrium line (Fig. 3.3a). However, the H/L-relationship described by Flemming (1988) shows a mean global trend, and just serves as a reference against which local trends can be compared (Flemming, 2000). Therefore, the site-specific data set from the dumping site of the outer Weser Estuary cannot be expected to accurately reproduce this global trend, especially as only a limited size range of very large dunes is covered and no smaller bedforms are considered.

The dune dimension, especially of large-scale bedforms, is assumed to be dependent on the water depth (e.g. Allen, 1968). However, more recent studies show that this relationship does not apply in general (Wewetzer and Duck, 1999), indicating that water depth is not a primary factor controlling dune size (Flemming, 2000). Other parameters like sediment grain size and current velocity, which are mostly related to water depth, also influence the dune size (Berné et al., 1993). However, a relationship between dune height and water depth, like reported by Allen (1968), could also be found in our study (Fig. 3.3b). On the associated scatter diagram is shown a good linear correlation (r = 0.77). Nevertheless, this correlation does not fit well to that proposed by Allen (1968), as the trend line for the dunes investigated here is considerably steeper.

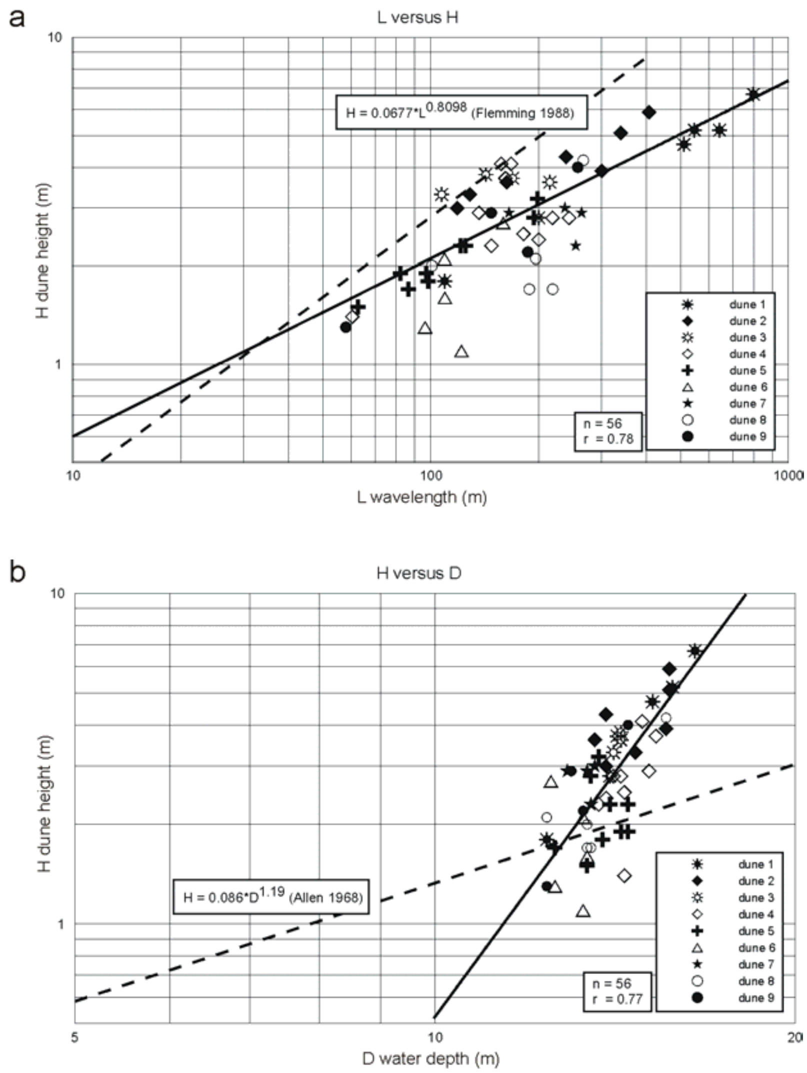

Fig. 3.3a-b (a) Scatter plot of dune wavelength L against dune height H. The data show a good positive correlation with r = 0.78 (bold line). The dashed line marks the H/L relationship presented by Flemming (1988). (b) Scatter plot of water depth D against dune height H. The data show a good positive correlation with r = 0.77 (bold line). The dashed line marks the H/D relationship presented by Allen (1968).

3.4.2 Impact of dumping

3.4.2.1 Shallowing of the seabed

For the 5-month dumping period in 1998 (30 June-1 December), the change of the water depth (minimum, maximum, mean) at the 7 cross-sections as well as for the whole surveyed dumping site is shown in Table 3.3. During this time, ~3 million m^3 of dredge spoil were dumped at the site which resulted in a strong shallowing of the seabed with a decrease in mean water depth of 1.1 m (Wienberg et al., accepted).

In June, the mean water depths for the different cross-sections show that the seabed of the dumping site shallows parallel to the span of the dunes from southwest to northeast, indicating a mean water depth of 13.5 m (all water depth information is given in meters below German sea chart datum, respectively low water springs) for the southernmost cross-section A and 12.7 m for the northernmost cross-section G (Fig. 3.2a, b; Table 3.3). This trend persists during the next five months, despite dumping. In fact, this trend is strengthened. Whereas in June, the seabed shallows on average ~0.8 m from southwest (cross-section A) to northeast (cross-section G), in August and December, the shallowing of the seabed is increased to 1.9 m across the dumping site.

In addition, it is obvious that the decrease in water depth, and therefore the supply of dumped sediments, is strongest in the 62-days time period between 30 June and 30 August, when the decrease in mean water depth ranges between 0.5 m and 1.7 m. Between 30 August and 1 December (time period: 93 days), the decrease in water depth only amounts to 0.2 to 0.5 m (Table 3.3). The same tendency can be observed for the whole dumping site, with a strong decrease of 0.9 m on average between June and August and a slight decrease of 0.2 m between August and December (Table 3.3).

Table 3.3 Change of the water depths along the cross- sections A to G during a 5 month survey period. All water depth values are given in meter below German sea chart datum (low water springs).

cross-section	30 June			30 August			1 December			decrease mean water depth		
	min	max	mean	min	max	mean	min	max	mean	Jun-Aug	Aug-Dec	total
A	9.8	15.8	13.5	9.8	15.8	12.9	9.7	15.5	12.7	0.5	0.3	0.8
AA	10.4	15.8	13.5	10.2	15.7	12.7	10.7	15.6	12.6	0.8	0.2	0.9
B	10.5	15.6	13.1	9.8	15.0	12.2	10.1	14.3	11.9	0.9	0.3	1.2
C	9.8	16.5	12.7	9.3	14.9	11.7	9.4	13.7	11.3	1.1	0.3	1.4
E	10.0	14.4	13.1	9.2	13.5	11.6	9.1	12.8	11.2	1.5	0.4	1.9
F	10.2	16.0	12.8	9.5	14.4	11.2	9.4	13.5	10.7	1.6	0.5	2.1
G	9.6	14.3	12.7	7.8	12.9	11.0	8.1	12.6	10.8	1.7	0.2	1.9
total survey	8.3	17.0	12.5	5.1	16.5	11.6	5.2	16.1	11.4	0.9	0.2	1.1

3.4.2.2 Change of dune morphology

The time-series of cross-sections A, B, E, and F (Fig. 3.4, Table 3.4) provide detailed information about the impact of the dumped dredge spoil on the morpohological characteristics of the investigated dunes, and thus, allow to study the disturbance of a natural morphological system due to an artificial add of sediments.

The impact of the dumped sediments on the dune morphology can be well recognized in the time series of cross-section A (Fig. 3.4a). During the 5-months dumping period, the height, H, of the dunes, especially of those in the eastern section, is strongly decreased by about 0.5-2.0 m (Table 3.4a). This can be attributed to the filling-up of the dune troughs of up to 2.0 m during the entire survey campaign, whereas the crests do not change their vertical position. The distance between crest and water surface, D(c), remains nearly the same, in fact, some dune crests seem to be slightly eroded (e.g. dunes 1, 4_1, and 4_2), resulting in an increased water depth at these points. On the other hand, the wavelength, L, of the dunes shows only small variations. Therefore, the dunes are becoming increasingly flat during the dumping period, which is also reflected in increased values for the vertical form index, VFI (Table 3.4a). Furthermore, the symmetry index, SI, decreases, i.e. the dunes change their shape to a more symmetrical form. The cross-section A, based on bathymetric data of the last survey of the dumping site (1 December), shows that the easternmost dunes (dunes 7, 8, and 9) are completely buried by dumped sediments (Fig. 3.4a).

The time series of cross-section B, which is placed 126 m further north to cross-section A (Table 3.1), displays a similar situation (Fig. 3.4b). Also in this part of the dumping site, the dunes are flattened intensely due to the fact that the wavelengths of the dunes only change around a small factor compared to their height. The dune heights are decreased between 0.5 and 2.2 m (Table 3.4b), primarily caused by the fact that the troughs of the dunes are filled up with dumped sediments, especially during the time period between the first (30 June) and second survey (30 August). Already in this 2-months period, the distance between trough and water surface is decreased by up to 2.2 m. This effect is again most obvious in the eastern part (Fig. 3.4b). Actually, the dunes there (dunes 7, 8, and 9) are more or less buried already by the end of August. The only exception seems to be dune 6 (Fig. 3.4b). While its neighbouring dunes show a completely changed morphological appearance, the shape of dune 6 is clearly silhouetted against the seabed throughout the whole time series, despite dumping. Different from cross-section A, some dune crests of cross-section B show a remarkable rise of up to 1.4 m, although there are also some dunes whose crests are slightly eroded (e.g. dune 1).

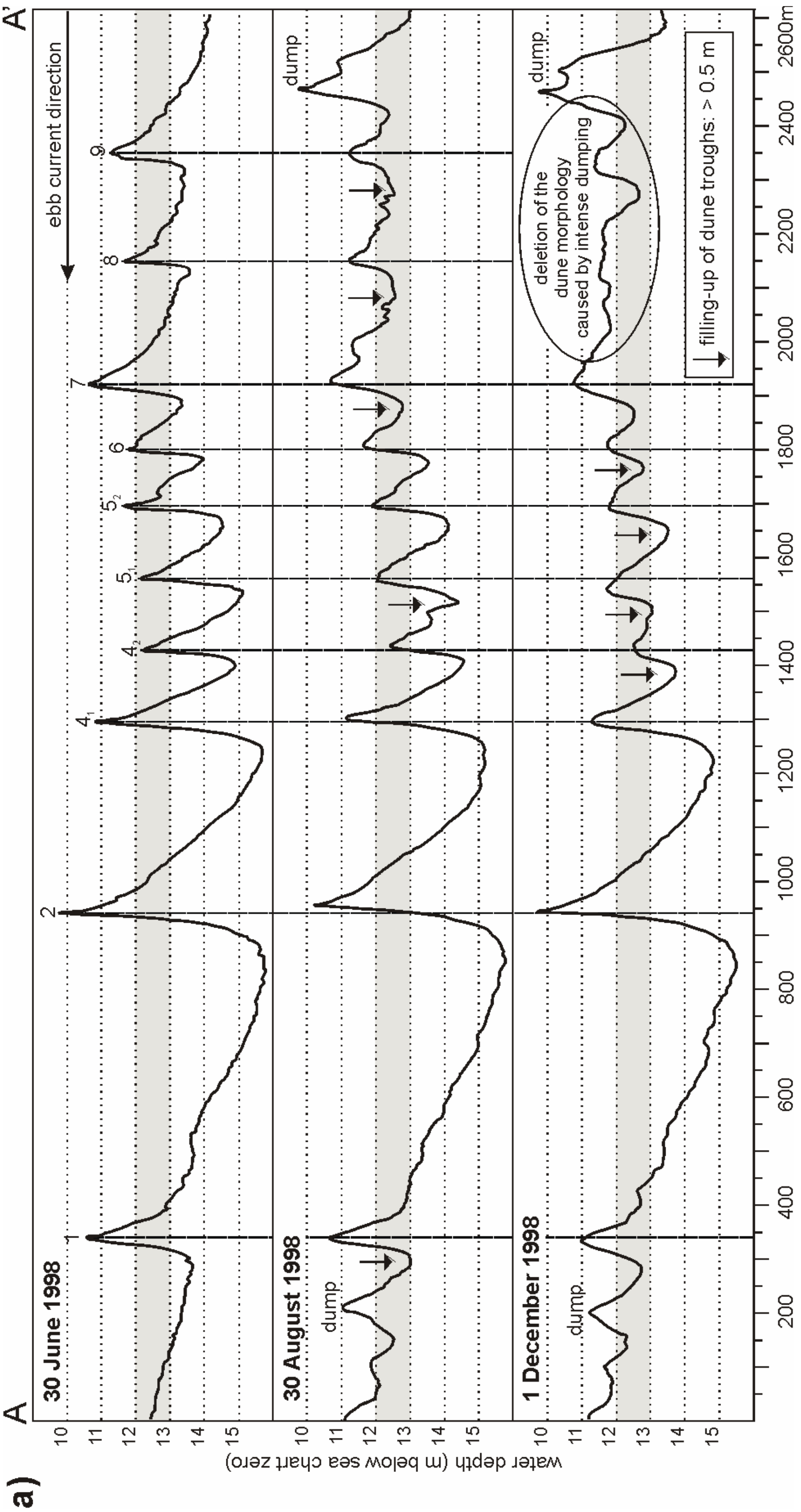

Fig. 3.4a-d Cross-sections through the study area (30 June, 30 August, and 1 Decemeber 1998). (a) cross-section A, (b) cross-section B, (c) cross-section E, and (d) cross-section F. Vertical scale has 63x exaggeration. The position of the cross-sections is indicated in Fig. 3.2.

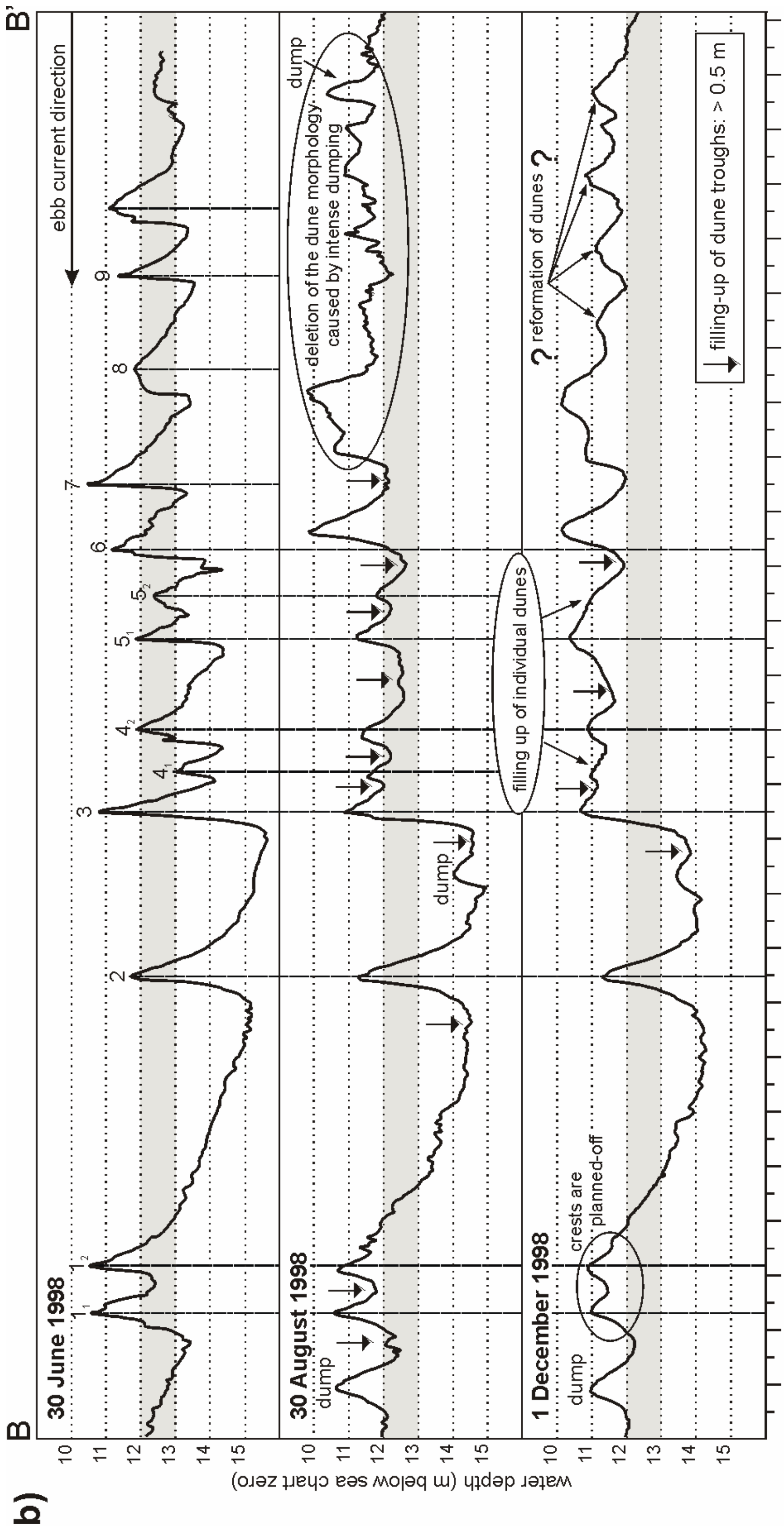

Fig. 3.4 continued.

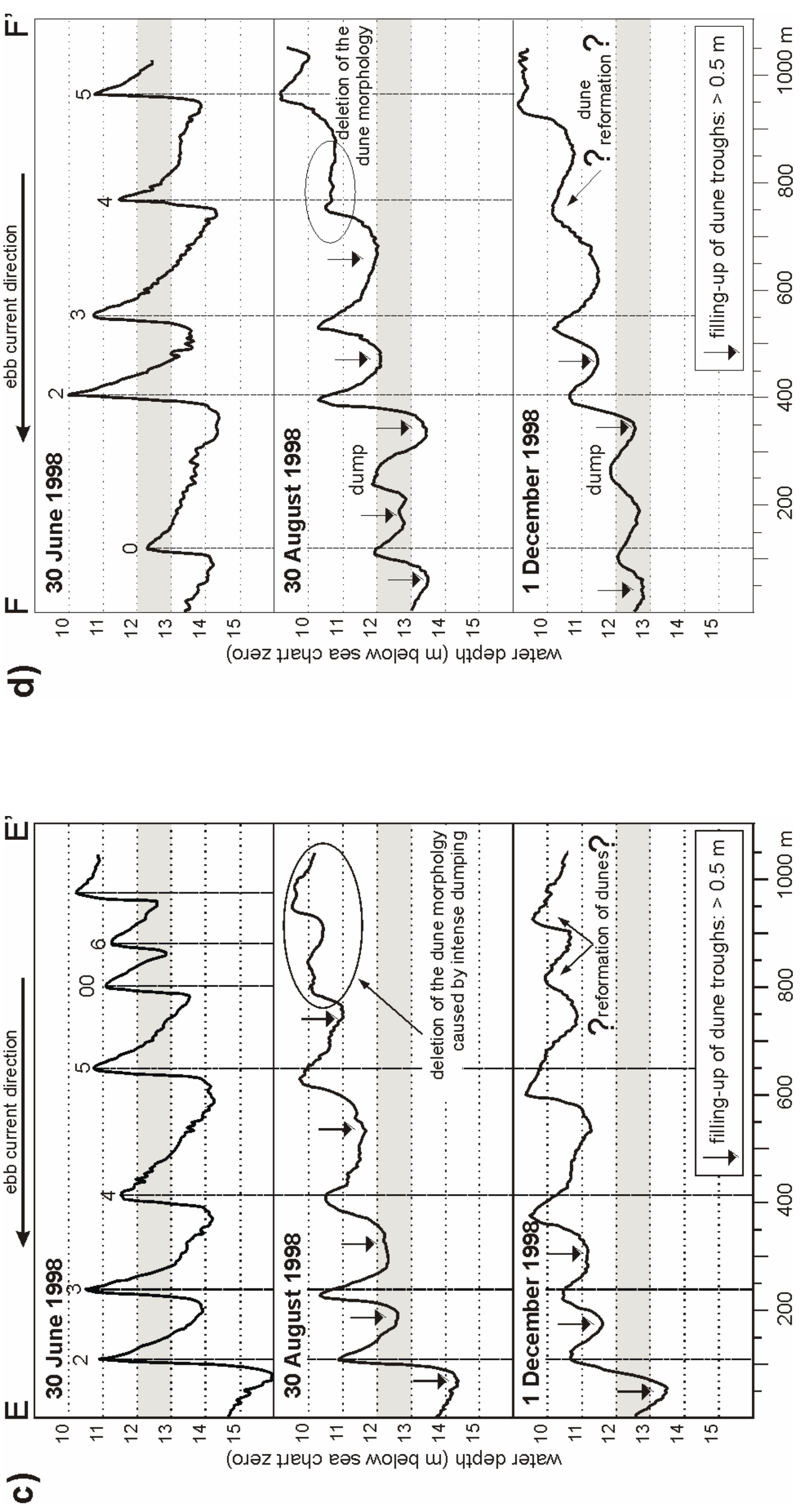

Fig. 3.4 continued.

Table 3.4a-b Change of the morphological dune parameters of dunes 1 to 9 for cross-sections A (a) and B (b) during the 5 month survey campaign (date 1: 30 June, date 2: 30 August, date 3: 1 December 1998) with a multibeam echosounder system. L, b, a, and H are denoted in meters, depth values are given in meter below German sea chart datum (low water springs).

a)

cross-section A

dune	date	L	b	a	H	D (c)	D (tb)	D (ta)	VFI	SI
1	1	545.6	51.6	494.0	5.2	10.6	13.7	15.8	104.9	9.6
	2	561.7	46.7	515.0	5.1	10.7	13.0	15.8	110.1	11.0
	3	565.5	50.6	514.9	4.5	11.0	12.7	15.5	125.7	10.2
2	1	407.4	106.8	300.6	5.9	9.8	15.8	15.7	69.1	2.8
	2	389.0	102.2	286.8	5.0	10.2	15.8	15.2	77.8	2.8
	3	373.9	95.5	278.4	5.1	9.7	15.5	14.8	73.3	2.9
4(1)	1	157.2	53.1	104.1	4.1	10.8	15.7	14.9	38.3	2.0
	2	165.7	59.2	106.5	3.4	11.2	15.2	14.6	48.7	1.8
	3	166.0	73.3	93.3	2.4	11.3	14.8	13.7	69.2	1.3
4(2)	1	136.3	28.2	108.1	2.9	12.2	14.9	15.1	47.0	3.8
	2	108.3	28.0	80.3	2.0	12.4	14.6	14.4	54.2	2.9
	3	116.0	44.3	71.3	0.6	12.5	13.7	13.1	193.3	1.6
5(1)	1	121.1	25.4	95.7	2.3	12.2	15.1	14.5	52.7	3.8
	2	143.6	42.0	101.6	2.1	12.0	14.4	14.1	68.4	2.4
	3	142.8	33.0	109.8	1.8	11.7	13.1	13.5	79.3	3.3
5(2)	1	124.9	39.2	85.7	2.3	11.7	14.5	14.0	54.3	2.2
	2	115.4	35.3	80.1	1.6	11.9	14.1	13.5	72.1	2.3
	3	116.0	41.9	74.1	1.0	11.8	13.5	12.8	116.0	1.8
6	1	109.5	19.0	90.5	1.6	11.8	14.0	13.4	68.4	4.8
	2	103.7	31.9	71.8	1.1	11.7	13.5	12.8	94.3	2.3
	3	102.0	59.2	102.0	0.7	11.8	12.8	12.5	145.7	1.7
7	1	237.1	30.5	206.6	3.0	10.6	13.4	13.6	79.0	6.8
	2	203.0	46.4	156.6	1.9	10.7	12.8	12.6	106.8	3.4
	3	157.6	67.8	89.8	1.0	10.8	12.5	11.8	157.6	1.3
8	1	188.5	21.0	167.5	1.7	11.7	13.6	13.4	146.4	8.0
	2	190.3	67.1	123.2	1.3	11.2	12.6	12.5	110.9	1.8
	3	- dune is totally buried by dumped sediments - - - - - - - - - - - - - - - - - -								

L = wavelength; b = length of lee side; a = length of stoss side; H = dune height; D(c) = depth between water surface and crest; D(tb) = depth between water surface and trough (lee side); D(ta) = depth between water surface and trough (stoss side); VFI = vertical form index (L/H); SI = symmetry index (a/b).

Table 3.4 continued.

b) cross-section B

dune	date	L	b	a	H	D (c)	D (tb)	D (ta)	VFI	SI
1(1)	1	109.3	53.0	56.3	1.8	10.6	13.4	12.4	60.7	1.1
	2	82.2	43.2	39.0	1.2	10.6	12.4	11.8	68.5	0.9
	3	91.4	57.0	34.4	0.4	11.0	12.2	11.4	228.5	0.6
1(2)	1	510.5	31.1	479.4	4.7	10.5	12.4	15.2	108.6	15.4
	2	494.3	38.2	456.1	3.8	10.7	11.8	14.5	130.1	11.9
	3	476.3	42.3	434.0	3.3	10.9	11.4	14.2	144.3	10.3
2	1	300.6	50.7	245.0	3.9	11.7	15.2	15.6	77.1	4.8
	2	347.3	81.9	265.4	3.3	11.3	14.5	14.6	105.2	3.2
	3	327.1	101.2	225.9	2.5	11.3	14.2	13.8	130.8	2.2
3	1	107.2	50.8	56.4	3.3	10.8	15.6	14.1	32.5	1.1
	2	85.4	36.7	48.7	1.1	10.9	14.6	12.0	77.6	1.3
	3	- strongly changed by dumped sediments - - - - - - - - - - - - - - - - - - -								
4(1)	1	60.3	17.2	43.1	1.4	13.0	14.1	14.4	43.1	2.5
	2	55.4	16.1	39.3	0.6	11.6	12.0	12.2	92.3	2.4
	3	- dune is totally buried by dumped sediments - - - - - - - - - - - - - - - - -								
4(2)	1	181.6	45.7	135.9	2.5	11.9	14.4	14.4	72.6	3.0
	2	186.6	32.2	154.0	1.1	11.4	12.2	12.5	169.6	4.8
	3	- strongly changed by dumped sediments - - - - - - - - - - - - - - - - - - -								
5(1)	1	62.7	19.0	43.7	1.5	11.9	14.4	13.4	41.8	2.3
	2	83.9	31.6	52.3	1.0	11.2	12.5	12.2	83.9	1.7
	3	- strongly changed by dumped sediments - - - - - - - - - - - - - - - - - - -								
5(2)	1	82.2	34.4	47.8	1.9	12.4	13.4	14.3	43.3	1.4
	2	81.1	23.2	57.9	0.8	11.8	12.2	12.6	101.4	2.5
	3	- dune is totally buried by dumped sediments - - - - - - - - - - - - - - - - -								
6	1	121.8	36.8	103.0	2.1	11.2	13.8	13.3	58.0	2.8
	2	171.3	57.9	113.4	2.3	9.9	12.6	12.2	74.5	2.0
	3	158.7	63.8	94.9	1.9	10.1	11.9	12.0	83.5	1.5
7	1	165.5	17.3	148.2	2.9	10.5	13.3	13.4	57.1	8.6
	2	- dune is totally buried by dumped sediments - - - - - - - - - - - - - - -								
	3	- dune is totally buried by dumped sediments - - - - - - - - - - - - - - -								
8(1)	1	219.1	62.1	157.0	1.7	11.8	13.4	13.5	128.9	2.5
	2	- dune is totally buried by dumped sediments - - - - - - - - - - - - - - -								
	3	- reformation of dune morphology ?- - - - - - - - - - - - - - - - - -								
8(2)	1	100.7	14.2	86.5	2.0	11.4	13.5	13.4	50.4	6.1
	2	- dune is totally buried by dumped sediments - - - - - - - - - - - - - - -								
	3	- reformation of dune morphology ? - - - - - - - - - - - - - - - - -								
9	1	186.7	37.0	149.7	2.2	11.1	13.4	13.3	84.9	4.0
	2	- dune is totally buried by dumped sediments - - - - - - - - - - - - - - -								
	3	- dune is totally buried by dumped sediments - - - - - - - - - - - - - - -								

L = wavelength; b = length of lee side; a = length of stoss side; H = dune height; D(c) = depth between water surface and crest; D(tb) = depth between water surface and trough (lee side); D(ta) = depth between water surface and trough (stoss side); VFI = vertical form index (L/H); SI = symmetry index (a/b).

Special regard should be paid to the eastern portion of cross-section B based on bathymetric data of the last survey in 1 December 1998. As by the end of August, this zone was characterized by buried dunes, three months later new bedforms seem to reshape (Fig. 3.4b). This process is also be recognized in the time series of cross-sections E and F (Fig. 3.4c, d). Especially for cross-section F (Fig. 3.4c), it is assumed that on the stoss side of the previously buried dune erosion took place. Afterwards, the eroded sediment is further transported to the northwest in the direction of the dominant ebb current and deposited at the lee side.

Reformation of dunes has also been observed in shipping channels of estuaries, where bedforms are quite common (e.g. Redding, 2000; Bartholdy et al., 2002). Large-scale bedforms with their variable heights (trough-crest-trough) constitute a potential navigational hazard. Therefore, in recent years, it was tried by responsible waterway authorities to lower dune heights by removing sediment from the crests and deposit the material in their troughs. However, it has been observed that a rapid re-building of the crests took place in the range of days or even hours, provided that the crests are not lowered by more than 50% of their original height (Redding, 2000).

3.4.3 Migrational trend

In the last few decades there have been many attempts to measure dune migration (e.g. Ludwick, 1972; Langhorne, 1973; Aliotta and Perillo, 1987; Fenster et al., 1990) showing that, in general, the migration rate decreases as bedform height increases. Therefore, small to medium dunes often superimposed on larger bedforms are more dynamic and migrate faster than large to very large dunes. Indeed, large-scale bedforms are in general relatively stable and are only subject to minor changes in morphology (Ashley, 1990; Fenster et al., 1990).

By comparing the bathymetric data sets of successive surveys of the investigated dumping site and by following the position of the crestlines, it is identified that the very large dunes covering the seabed are relatively stable, showing only slight movements (Fig. 3.5). However, because of the supply of the huge amount of dumped sediments (in total: ~3 million m^3), it is difficult to determine an accurate migration rate. Especially, dunes which are situated in the central eastern part of the dumping site are strongly affected by the dumping, resulting in a significant rise of their crests, and consequently, in an artificial shifting of the crestline position (Fig. 3.5).

Therefore, only dunes which can be found in the western part of the site (dunes 1-5) are used to measure a migration rate. The values listed in Table 3.5 indicate that during a time period of

5 months, these dunes show a slight migration trend predominantly towards the open sea, and thus, in the direction of the dominant ebb current. The mean migration rates range from 0.5 to 4.9 m.

It is conspicuous that the migration of a sinusoidal crestline is rather inhomogeneous along their span. For example dune 2, which can be identified on all cross-sections, shows an averaged migration rate of 1.5 m towards the open sea, whereas the values over its span vary between -2.6 m (towards the estuary head) and +6.1 m (towards the open sea) (Table 3.5). Similar observations are reported from the Jade Estuary which is situated west of the Weser Estuary (Ulrich, 1973). The crests of bedforms found in this adjacent region move back and forth with a net forward component in response to the dominant current direction.

Several studies assume that the asymmetry of a dune indicates a net sediment transport in direction of the lee side resulting in a migration of the dune towards this direction (Jones et al., 1965; Langhorne, 1982; McCave and Langhorne, 1982; Twichell, 1983; Aliotta and Perillo, 1987; Harris, 1988). In an ebb-dominated system, this process is mainly driven by the dominant ebb tide, which erodes both the sediments deposited by the preceding flood tide and sediments on the stoss side of a dune, whereas during flood tide no such flank erosion occurs (Langhorne, 1982).

This is also true for the dunes investigated here. The dunes show a distinct asymmetry with the lee slope facing the open sea and the stoss slope facing the riverine head, reflecting the dominance of the ebb tidal current in the Weser Estuary. In Figure 3.6, a difference grid based on bathymetric data sets of the two surveys at the beginning (30 June 1998) and at the end (1 December 1998) of the dumping operation is displayed. Due to the high supply of dumped sediments, almost the whole dumping site is characterized by a strong sediment accumulation of up to 5 m (Wienberg et al., accepted). Nevertheless, small areas of erosion can be clearly recognized. By plotting the position of the crestlines of 30 June on this difference map, it becomes conspicuous that these erosional zones primarily occur on the stoss side of the dunes (e.g. dunes 1, 2, 7, 9) (Fig. 3.6) indicating the sediment transport across an asymmetrical dune. Therefore, these erosional zones can be used as an additional indicator for a slight migration of the subaqueous dunes with erosion at the stoss side and deposition at the lee side.

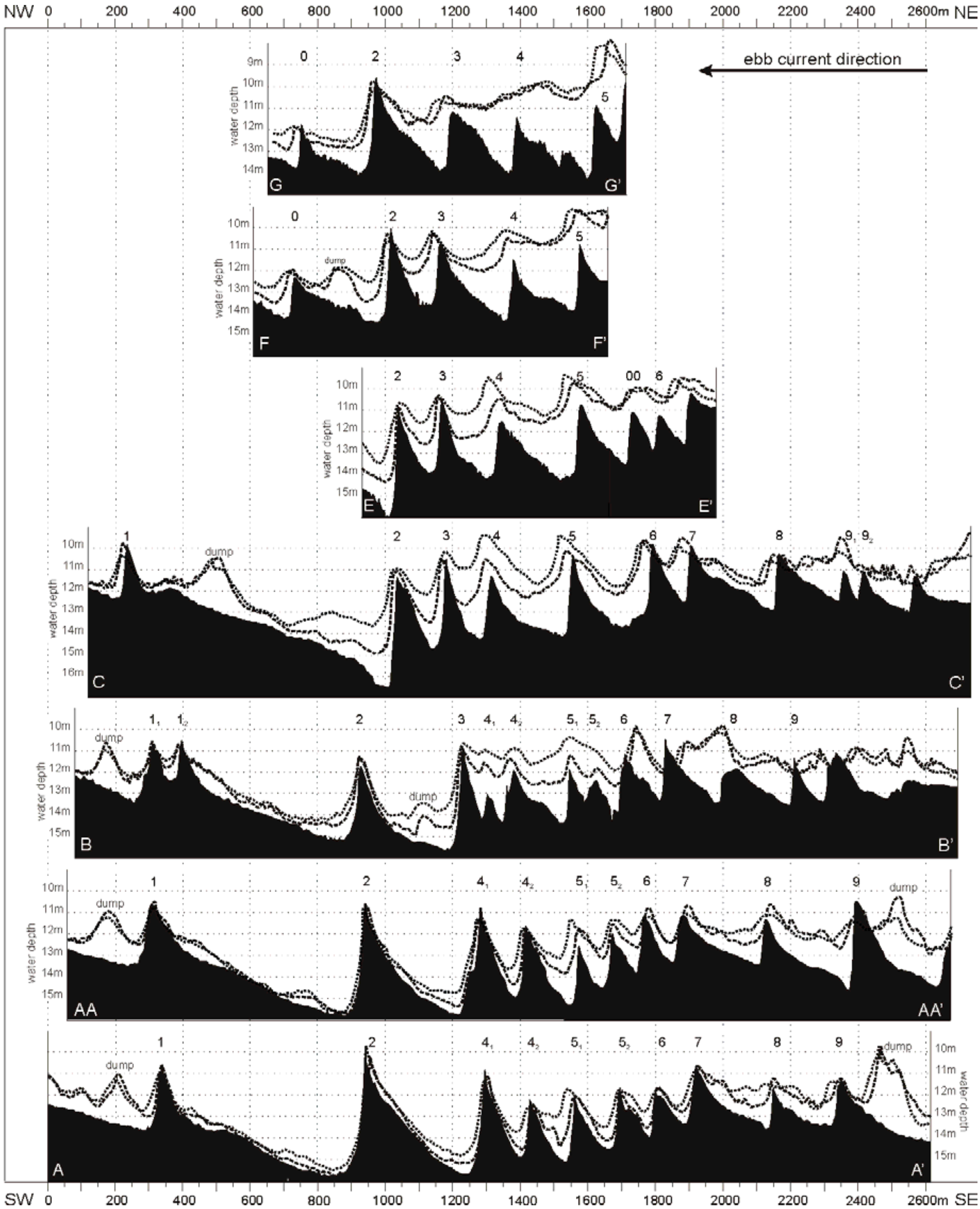

Fig. 3.5 Comparison of the cross-sections through the study area based on three successive bathymetric surveys (black-filled: 30 June, dashed line: 30 August, dotted line: 1 Decemeber 1998). Superelevation of the dunes = x63. The position of the cross-sections is indicated in Fig.3.2.

Table 3.5 Migration trend of dunes situated in the western part of the dumping site. Migration rates are denoted in meters. Migration direction: + = in diretion towards the open sea, - = in direction towards the estuary head; d = dunes are totally buried by dumped sediments.

dune	survey period*	A		AA		B		C	E	F	G	mean migrational rate
1	1-2	+1.7		-8.3		-0.5	+9.7	+11.5	/	/	/	
	2-3	+5.0		+1.9		-3.6	-3.1	+2.1	/	/	/	
	total	+6.7		-6.4		-4.0	+6.6	+13.6	/	/	/	+4.9 m
2	1-2	-14.6		-4.4		+1.5		+0.8	+0.7	+9.4	+10.8	
	2-3	+12.0		+7.8		-0.1		+0.2	-2.5	-3.6	-10.1	
	total	-2.6		+6.1		+1.4		+1.0	-1.8	+5.8	+0.7	+1.5 m
3	1-2	/		/		+1.5		+10.5	d	d	d	
	2-3	/		/		-0.1		-6.6	d	d	d	
	total	/		/		+1.4		+4.0	d	d	d	+2.7 m
4	1-2	-6.5	-8.1	-1.7	-0.3	d	d	d	d	d	d	
	2-3	+6.6	+0.3	+7.8	+3.9	d	d	d	d	d	d	
	total	+0.1	-7.8	+6.1	+3.6	d	d	d	d	d	d	+0.5 m
5	1-2	d	+0.3	d	d	d	d	d	d	/	d	
	2-3	d	+3.3	d	d	d	d	d	d	/	d	
	total	d	+3.6	d	d	d	d	d	d	/	d	+3.6 m

*survey period 1-2: 30 June-30 August 1998 (2-months period); survey period 2-3: 30 August-1 December 1998 (3-months period); total: 30 June-1 December 1998 (5-months period)

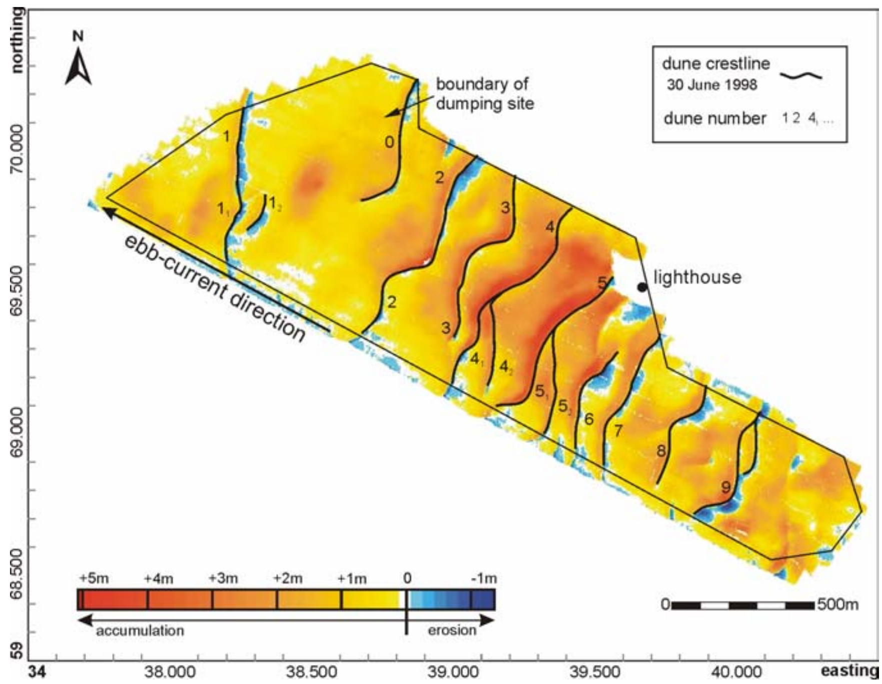

Fig. 3.6 Position of dune crestlines as measured on 30 June 1998 (solid line) plotted on a difference grid generated of two surveys of the entire dumping site which were carried out at the beginning (30 June) and the the end (1 December) of the dumping period.

3.5 Conclusions

Repeated surveys of a dumping site, which is situated in in water depths between 6 and 20 m (below German sea chart datum) at shallow subtidal shoals of the outer Weser Estuary, have revealed that the entire seabed is covered with large-scale bedforms. These bedforms are sinusoidal and asymmetric in shape and partly bifurcated. Due to their heights of up to 6.7 m and wavelengths ranging between 159 and 407 m, they are classified as very large dunes. A good correlation between dune height and wavelength is recognized. Furthermore, the height of the dunes seems to be related and controlled by the water depth which is relatively low with a mean of 12.5 m (below German sea chart datum).

The morphology of the dunes was strongly affected by the dumping of ~3 million m^3 of dredge spoil which were deposited at the dumping site during a 5-month period in 1998. Besides a strong shallowing of the seabed of around 1 m, also the dune size and shape are totally changed. Especially, the dune troughs are strongly filled up, whereas the crests are not much affected. Some dunes, primarily in the eastern and central part of the dumping site, where the biggest amount of dredge spoil was dumped, are completely buried. However, in a time series of cross-sections, it becomes obvious that a reformation of bedforms takes place. Therefore, it is most likely that the investigated dunes try to re-establish a new dynamic equilibrium between the actual controlling factors current velocity and direction, as well as water depth and grain size, resulting in a particular dune size and shape. This equilibrium was intensely disturbed by the artificial supply of sediment and the resulting decrease in water depth.

An accurate migration rate for the 5 months of investigation is hard to determine due to the dumping and the related morphological change of the dunes. Nevertheless, a slight migration trend towards the open sea is recognized by comparing the shifts of the crestline positions obtained from successive bathymetrical surveys. This assumption is further confirmed by the asymmetrical shape of the dunes. The lee slope of the dunes is oriented towards the open sea emphasizing the dominance of the ebb tide in the outer Weser Estuary.

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3.6 Appendix - Morphological dune parameters

L	:	wavelength
b	:	length of lee side
a	:	length of stoss side
H	:	dune height
D(c)	:	water depth between water surface and dune crest
D(tb)	:	water depth between water surface and dune trough, lee side
D(ta)	:	water depth between water surface and dune trough, stoss side
VFI	:	vertival form index
SI	:	symmetry index

Acoustic seabed classification in a dynamic environment (outer Weser Estuary, German Bight) – monitoring of dumping activities

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Abstract

Acoustic seabed classification provides a sophosticated technique to discriminate seabed characteristics and to map its distribution in high spatial and temporal resolution. In the present study the seabed classification system of the Quester Tangent Corporation™ was applied to investigate a 9-km^2 area in water depths between 6 and 20 m (below German sea chart datum). The survey area is situated in the exposed outer Weser Estuary (German Bight) and comprises a section of a continuously dredged shipping channel as well as a part of a dumping site. The acoustic data, collected by means of a singlebeam 200 kHz echosounder combined with a QTC View™ system, were classified into three acoustic classes. These classes were identified as: 1) fine to medium sand with a low content of shell fragments; 2) medium sand with a moderate content of shell fragments; and 3) medium to coarse sand with a high content of shell fragments. The composition of the sediments with varying contents of shell fragments was strongly reflected in the high variance of the acoustic reflectors. Over three acoustic surveys in a period of 18 months, natural and anthropogenic influences on changes in the sediment composition and morphology could be carried out in the outer Weser Estuary. It became apparent that maintenance dredging as well as dumping of dredge spoil constituted a strong impact.

Keywords: acoustic seabed classification, sidescan sonar, sediment samples, bedforms, maintenance dredging, dredge spoil dumping, Weser Estuary

4.1 Introduction

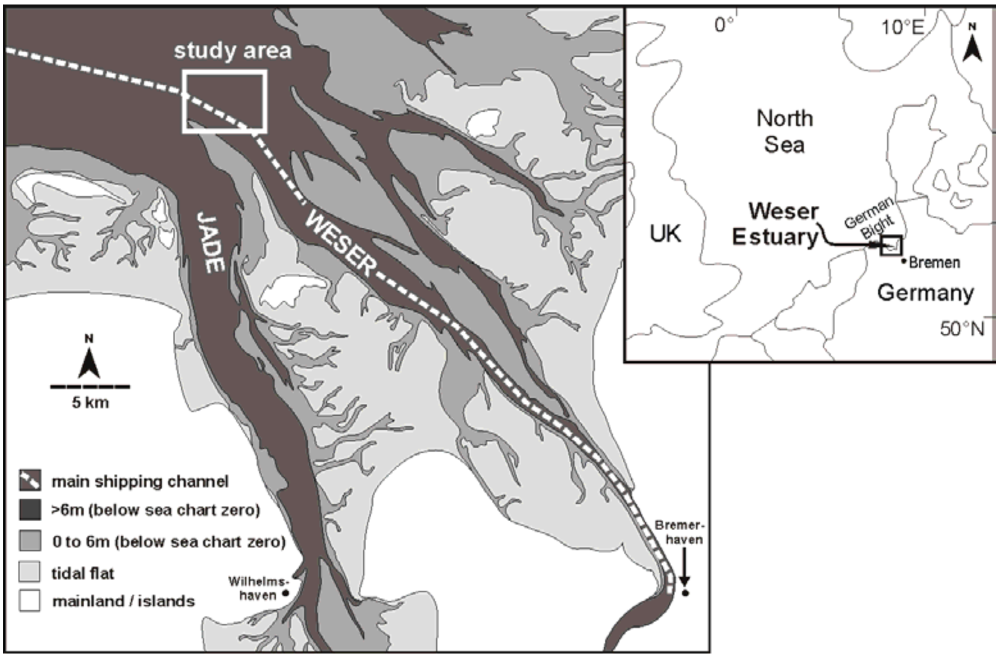
In the last decade, acoustic seabed classification became established as a standard tool in seafloor surveying and underwater remote sensing. Conventional methods to classify the seafloor are in situ sampling of bottom sediments or visual methods such as underwater videos, which are extremly time and cost intensive. Mapping seabed characteristics by remote acoustic sensing methods such as underwater seismic, sidescan sonar, or echosounder-based classification systems are becoming of increasing importance, because they are less expensive and time-consuming and provide a high spatial and temporal resolution (Blondel, 2003; Kenny et al., 2003).

The QTC View™ seabed classification system, used in this study, is one if this new powerful instruments for the discrimination of seabed characteristics. It records the first return signal of the tranmitted pulse of a singlebeam echosounder and processes data to a Geographic Information System (GIS) to map differences in seabed characteristics (Collins et al., 1996). The shape of the amplitude of returning signals includes a number of parameters such as sediment composition, seabed roughness, bedforms such as ripples, and biological components. Several studies have verified the relationship between returning (backscattering) signal and seabed characteristics in coastal environments all over the world (Collins et al., 1996; Hamilton et al., 1999; Preston et al., 2000; Anderson et al., 2001; Ellingsen et al., 2002; von Szalay and McConnaughey, 2002; Freitas et al., 2003).

4.2 Study area

The study site is situated in the exposed outer Weser Estuary (German Bight) (Fig. 4.1). The sedimentological and morphological state of the investigated area changes continuously due to the highly dynamic processes induced by tidal currents and waves resulting in a permanent cycle of sediment erosion, transport and deposition. Inshore, extensive tidal flats line the estuary, followed in water depths between 6 and 20 m (below German sea chart datum) by shallow subtidal shoals. Two tidal channels are developed, which are separated by flow-parallel elongated sand bars. They bend out in a northwestern direction and merge with the westerly shipping channel of the Jade Bay (Fig. 4.1). The western main shipping channel of the outer Weser Estuary has a total length of 60 km and was repeatedly dredged to a present water depth of 14 m (below German sea chart datum) (Wetzel, 1987; Wienberg, 2003).

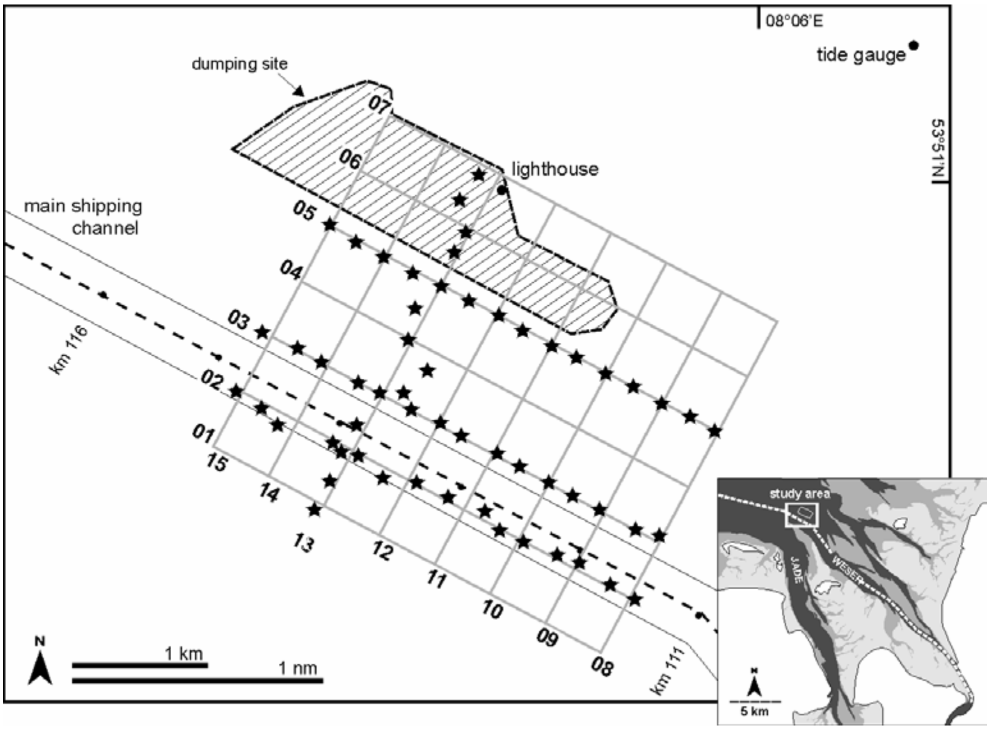
The outer Weser Estuary is strongly exposed to hydrodynamic processes due to the absence of offshore islands at its mouth (Fig. 4.1). The semidiurnal tides penetrate with unhindered energy from a northwestern direction into the estuary, marked by a distinct spring and neap tidal cycle. Due to the slight dominance of the ebb tide in the outer Weser Estuary, the residual sediment transport is directed towards the open sea (Bundesanstalt für Gewässerkunde, 1992; Wasser- und Schiffahrtsamt Bremerhaven, 1996). The tidal range amounts to 2.8 m at the estuary mouth and increases to 4.2 m towards the head. Mean maximum current velocities of 1.0 to 1.3 ms^{-1} are common for the uppermost part of the water column, whereas at the seabed the maximum current velocities are much lower with a mean of 0.7 ms^{-1} (Bundesanstalt für Gewässerkunde, 1992).



4.1 Map of the outer Weser Estuary (German Bight) showing the position of the study area.

The outer Weser Estuary belongs to the innermost part of the German Bight with the highest sediment accumulation of North Sea sands (Zeiler et al., 2000). There, a bedload convergence with a thickness of up to 10 m is caused by longshore sediment transport from west to east along the East-Frisian Islands (Johnson et al., 1982) and from north to south in the offshore area of the North-Frisian Islands (Mittelstaedt et al., 1983). The 10 m isobath of water depth constitutes the offshore extension of this zone. The bottom sediments of the German Bight are a reworked mixture of the Holocene-Pleistocene basement in this area (Figge, 1981; Zeiler et al., 2000). In general, they are mainly composed of fine to medium sand with a silt and clay content of less than 1% (Wetzel, 1987). Only ~10% of the material derived directly from riverine sources, whereas about 90% originated from marine sources (Hoselmann and Streif, 1997).

The 9-km^2 survey area in the outer Weser Estuary comprises a section of the repeatedly dredged main shipping channel as well as a part of a dumping site (Fig. 4.2). The dumping site was used in 1998 for the dumping of ~3 million m^3 sediment in the course of the last deepening of the main shipping channel (Wienberg et al., accepted), and is still in use for the dumping of dredge spoil of maintenance dredging.



4.2 Map of the study area showing the survey grid and the position of the sediment samples (★).

4.3 Methods

4.3.1 Acoustic seabed classification

The acoustic surveys were performed in August 2001, December 2001, and October 2002, aboard the research vessel "Senckenberg", at an average speed of 6 knots (Table 4.1). The survey grid consisted of 15 lines with a spacing of 0.25 nm (Fig. 4.2). Seven lines (lines 1-7) with a length of 1.75 nm were oriented southeast to northwest and run parallel to the main shipping channel. Eight lines (lines 8-15) with a length of 1.5 nm were placed perpendicular to the previous ones. Survey lines 2 and 3 bordered the shipping channel of the outer Weser Estuary, while the western part of lines 6 and 7 as well as the northern part of lines 11-15 covered the dumping site (Fig. 4.2).

The digital part of QTC View^{TM} was combined with the analogue echosounder system Furuno FTC 1000 with a frequency of 200 kHz, a beam angle of 7.4° (6 decibels), a pulse length of 0.5 ms, and a power of 1,000 W. The recorded depth range was limited to 50 m, which allowed an automatic beam angle footprint correction. For example, in water depths of 15 m a footprint of ~1.9 m can be obtained. A Differential Geographic Positioning System (DGPS) Shipemate system was used for positioning.

The acoustic data were analyzed using an unsupervised classification (Collins and McConnaughey, 1998). The QTC View^{TM} system self uses the first returning signal in the echo from the seabed and analyzes the shape of each echo by a series of algorithms. These algorithms characterize in relation to energy and spectral components, yielding 166 descriptors of each echo (Collins et al., 1996; Collins and Lacroix, 1997; Tsemahman et al., 1997). Principal-Component-Analysis (PCA) reduces the large quantity of information to three most useful descriptors, so-called Q-vectors (Q1, Q2, Q3), which prove enough to recognize the different types of seabed. When plotting the points defined by Q1, Q2, and Q3 on a three-axis plot, echoes of similar character form clusters that stand for distinct acoustic classes (Collins et al., 1996; Collins and Lacroix, 1997; Tsemahman et al., 1997).

To determine the range of acoustic variability of the surveyed seabed, the raw data were processed with the post-processing software QTC Impact, which classified the acoustic data by cluster analysis. The final output from QTC Impact was accepted by GIS software packages, from which charts of the bottom relief and acoustic diversity were generated, using the geographical position (given by DGPS), the water depth (recorded by the singlebeam echosounder), and the acoustic classes (identified by the QTC Impact). The result is a georeferenced trackplot classified by sediment type, from which an interpolated map of sediment distribution was generated then. To calibrate and adjust the acoustic signal strength of raw signal of the echosounder, several waveform records (QVW-files) and gain intensity checks were carried out during each survey.

Table 4.1 QTC View^{TM} surveys.

date	time	survey line	raw data records	base gain	pulse rate	pulse length	vessel
06 August 2001	15:53 – 18:17	01-07	2,807	13 dB	low	long	6 kn
13 December 2001	07:26 – 12:21	01-15	5,212	13 dB	low	long	6 kn
23 October 2002	02:15 – 07:28	01-15	5,520	13 dB	low	long	6 kn

4.3.2 Sidescan sonar

To transfer the point-related acoustic classification to a spatial pattern considering the larger morphology, the data were coupled with sidescan sonar records. In August 2001, parallel to the QTC View^{TM} survey, sidescan sonographs were collected along the predefined survey grid (Fig. 4.2). The sidescan sonar survey was performed using a Klein-Digital-Sonar Model 595 dual-channel system (100 kHz, 500 kHz). A swath range of 100 m was adjusted, thereby mapping a 200 m wide strip of the seabed. Vessel speeds were ~4 knots.

4.3.3 Sediment samples

To associate each acoustic class identified by the QTC View^{TM} system with seabed characteristics, groundtruthing was undertaken by sampling 58 bottom sediments using a shipek grab sampler. The sampling positions were placed on survey lines 2, 3, 5, and 13 (Fig. 4.2) with a spacing of approximately 0.125 nm. Subsequently, the sediment samples were analyzed for grain size distribution by the laboratory of the Senckenberg Institute in Wilhelmshaven (Germany).

4.4 Results and Discussion

4.4.1 Acoustic classes and sediment types

For the 9-km^2 study area in the outer Weser Estuary between 2,800 and 5,500 raw data records per survey (August 2001, December 2001, October 2002) were processed. A total of 13,539 acoustic records were catalogued into three acoustic classes (Table 4.2).

Table 4.2 Acoustic classes identified by QTC Impact.

survey	surveyed tracks	raw data records	Class 1 (blue)	Class 2 (red)	Class3 (green)	Class 1 (%)	Class 2 (%)	Class 3 (%)
06 August 2001	01-07	2,807	1,530	636	641	54.5	22.7	22.8
13 December 2001	01-15	5,212	1,669	2,187	1,356	32.0	42.0	26.0
23 October 2002	01-15	5,520	3,044	380	2,096	55.1	6.9	38.0
	∑	13,539	6,243	3,203	4,093	46.1	23.7	30.2

Class 1 was the most frequent acoustic class with a mean of 46.1% of all data records. Class 2 showed a varying frequency during the successive surveys. In August 2001 and October 2002, this class exhibited the smallest amount of raw data records. In December 2001, it was the most frequent class and dominated over class 1 and 3 with 42.0% of raw data records collected during this survey. Class 3 was consistently frequent throughout the entire survey campaign and constituted a mean of 30.2% of all data records (Table 4.2).

The defined acoustic classes reflect the three predominant sediment surface types occurring in the study area (Fig. 4.3a-c), labeled in Table 4.3 as sediment type 1, 2, and 3. The geographical distribution of the defined acoustic classes and the main sediment types indicated a close correspondence between the acoustic patterns and the sedimentary assemblages. Overall, the sediments collected in the study area were mainly composed of fine to coarse sand. The sand fraction (0.063-2.0 mm) of all analyzed sediment samples ranged between 72.84 and 99.48 wt-% (Table 4.3). The silt fraction (<0.063 mm) constituted a minor component and never exceeded values of 3.52 wt-%, while the content of grain size fraction >2 mm ranged from 0.51 to 26.73 wt-%. However, the sediments collected in the study area are more or less highly admixed with shell fragments of different particle sizes (>2 mm, <2 mm). For example, a maximum of up to 35.14 wt-% of shell fragments were recognized for sediment type 3 (Table 4.3). Therefore, a classification of sediment types based on grain size only was somewhat problematic. The content of shell fragments had to be considered as well, in particular with regard to the high variance of the acoustic reflectors produced by these components. This is in agreement with a study of Magorrian et al. (1995), who observed in the Strangford Lough of Northern Ireland that the presence of epifauna and infauna may have an important effect on the backscatter of an acoustic signal.

Table 4.3 Sediment grain size analysis, expressed as percent of total sediment dry weight. The content of shell fragments of the total sediment dry weight is listed separately.

Acoustic class	Sediment type		grain size fraction			content of shell fragments		
			>2 mm	0.063-2.0 mm	<0.063 mm	>2 mm	<2 mm	total
Class 1	Type 1	range	0.51-3.75	96.25-99.48	0.00-0.74	0.00-2.24	1.67-6.28	0.00-8.80
		mean	1.79	98.11	0.10	1.41	4.14	5.55
Class 2	Type 2	range	4.99-14.71	85.01-95.01	0.00-3.52	3.91-11.64	3.15-8.78	8.68-16.01
		mean	7.54	91.55	0.90	6.51	5.83	12.34
Class 3	Type 3	range	7.99-26.73	72.84-92.01	0.00-1.34	9.81-23.72	5.04-11.42	13.31-35.14
		mean	14.65	85.18	0.17	12.19	8.65	20.83

According to this, acoustic class 1, which was predominant in the survey area, corresponds well to sediment type 1. This sediment type is composed of fine to medium sand with a low content of shell fragments (mean: 5.5 wt-%). The sand fraction amounts to a mean of 98.11 wt-% of the total sediment dry weight, whereas the grain size fractions >2 mm and

<0.063 mm are minor constituents. Due to the low content of shell fragments and the small size of these particles, mainly <2 mm, the surface of sediment type 1 appears smoothed and homogeneous (Fig. 4.3a, Table 4.3).

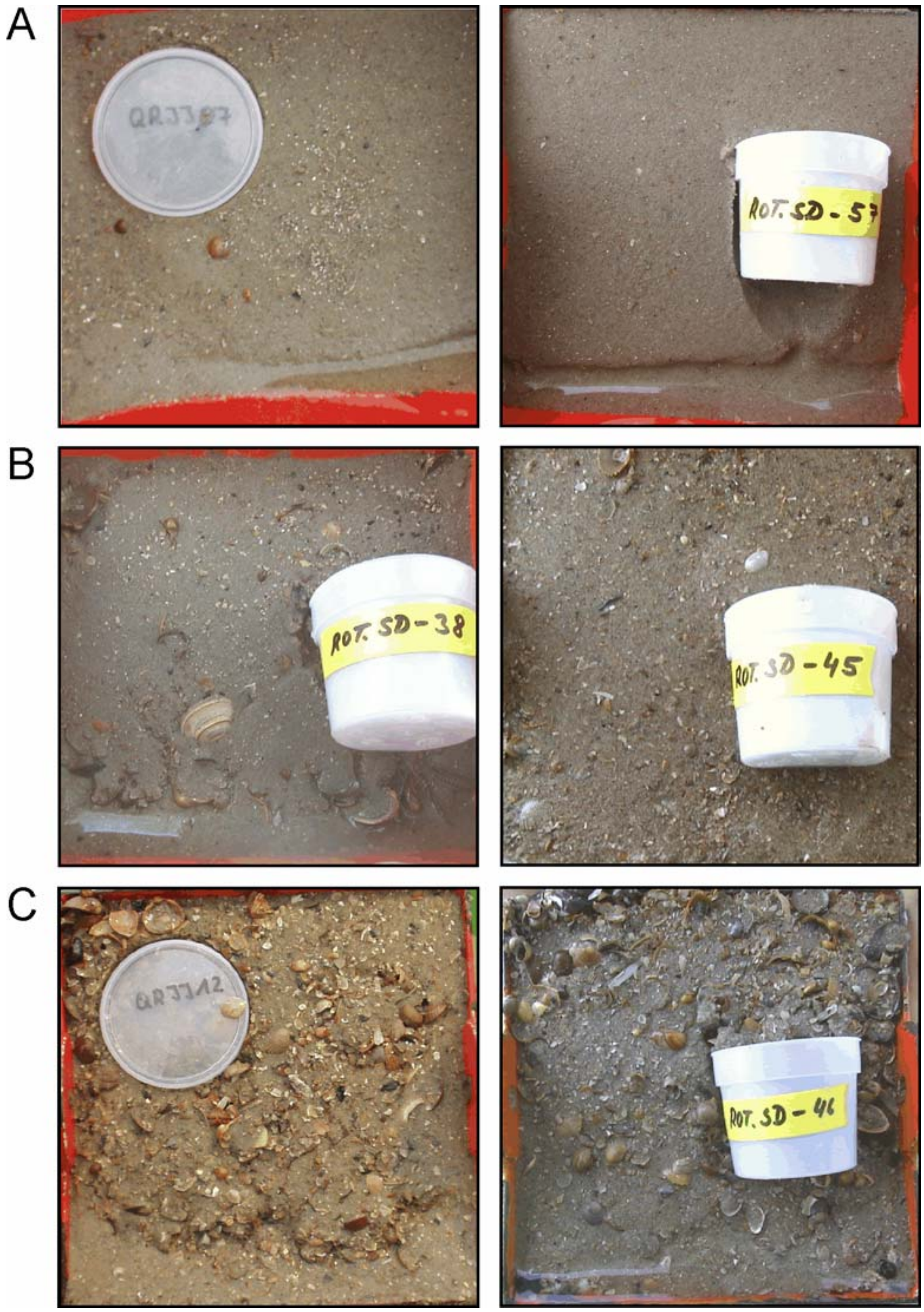


Fig. 4.3a-c Sediment types identified by acoustic classification. A) Acoustic class 1 = Sediment type 1: fine to medium sand with low content of shell fragments; B) Acoustic class 2 = Sediment type 2: medium sand with a moderate content of shell fragments; C) Acoustic class 3 = Sediment type 3: medium to coarse sand with a high content of shell fragments.

Acoustic class 2 corresponds to sediment type 2, which was identified as medium sand with a moderate content of shell fragments (mean: 12.34 wt-%). It describes a transitional sediment type between the sediments identified by the acoustic classes 1 and 3. Sediment type 2 is made up of 91.55 wt-% of sand and 7.54 wt-% of grain size fraction >2 mm. The shell fragments are coarser compared to sediment type 1, because more fragments have sizes >2 mm (Fig. 4.3b, Table 4.3).

Finally, acoustic class 3 corresponds to sediment type 3. This sediment type is composed of medium to coarse sand with a high content of shell fragments (mean: 20.83 wt-%). It shows the lowest content of sand fraction with a mean of 85.18 wt-% and the highest content of grain size fraction >2 mm with a mean of 7.54 wt-%, which is mainly composed of shell fragments. In contrast to sediment type 1, the surface of sediment type 3 appears rough and inhomogeneous due to the high amount of shell fragments (Fig. 4.3c, Table 4.3).

4.4.2 Comparison of sidescan sonar and QTC View™

The analysis of the sidescan sonar records, acquired in August 2001, revealed that the seabed of the entire survey area was inhomogeneous in terms of morphological seabed structures. Regions with three distinct groups of bedforms were differentiated: 1) large subaqueous dunes partly superimposed by ripples; 2) fields of ripples; and 3) regions with no distinct seabed structures. The results of the QTC View™ survey from August 2001 showed that the distribution of the defined acoustic classes, and thus of sediment types, provided a similar image.

Large subaqueous dunes were identified at the dumping site, in the northwest of the survey area, and in the entire zone between dumping site and shipping channel. The dunes have wavelengths ranging from 130 to 420 m and ripples cover the stoss side of several dunes. The results of the acoustic classification traced the typical grain size distribution of subaqueous dunes. The dune crests were dominated by class 3, and thus by medium to coarse sand with a high content of shell fragments. Whereas in the dune troughs, finer sands were found, mainly made up of fine to medium sand with a low content of shell fragments, corresponding to acoustic class 1 (Fig. 4.4).

The seabed of the shipping channel and its margins were characterized by expanded fields of ripples, which had wavelengths ranging from 2.0 to 2.5 m. The acoustic classification showed a strong alternation between the three defined acoustic classes, and thus a highly variable sediment distribution of fine to coarse sand and high to low contents of shell fragments

(Fig. 4.5). The backscatter of the acoustic signal did not only reflect the rapid change of the sediment composition, it also reprints the high frequently morphological variation of the ripples.

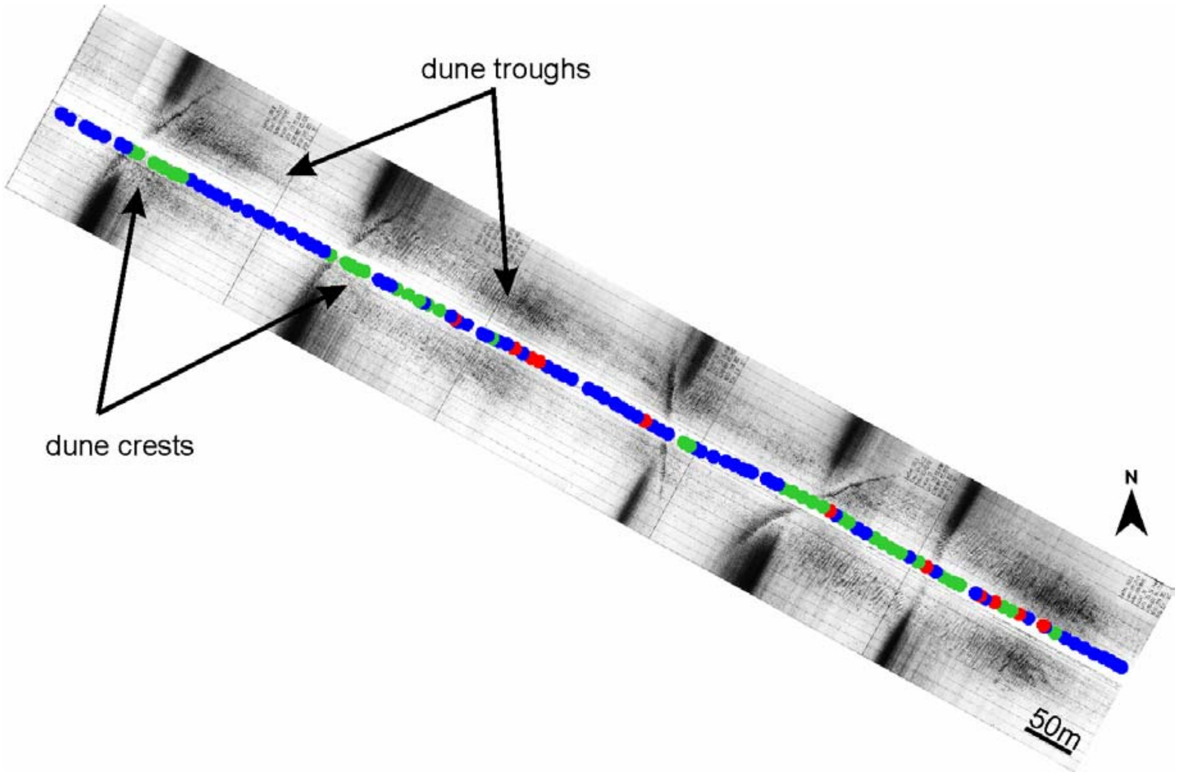


Fig. 4.4 Sidescan sonar record overlayed by acoustic QTC View™ data. Blue = class 1, red = class 2, and green = class 3 (see text for class explanation). The western part of survey line 5 is represented, where large subaqueous dunes are detected. The position of the survey line is indicated in Figure 4.2.

Regions with no distinct seabed structures occurred in the easternmost part of the study area, in the central part of the dumping site, and southerly of the shipping channel. The acoustic classification of these regions showed a relatively homogeneous image. A definite dominance of acoustic class 1 was identified, partly interrupted by a minor constituent of class 2. The corresponding sediment types are types 1 and 2, which stand for fine to medium sand with a low to moderate content of shell fragments.

It is apparent that the acoustic data obtained by the QTC View™ system reflected more than simply the sediment distribution. The seabed morphology also appears to be important. This assumption is confirmed by several studies who stated that beside the sediment texture other aspects such as microtopography, geotechnical parameters (bulk density and porosity), and infaunal composition have to be considered in interpreting acoustic data (Bornhold et al., 1999; Preston et al., 2000). Therefore, a combined application of sidescan sonar and

QTC View™ is very effective to characterize seabed areas in a sedimentological and morphological manner.

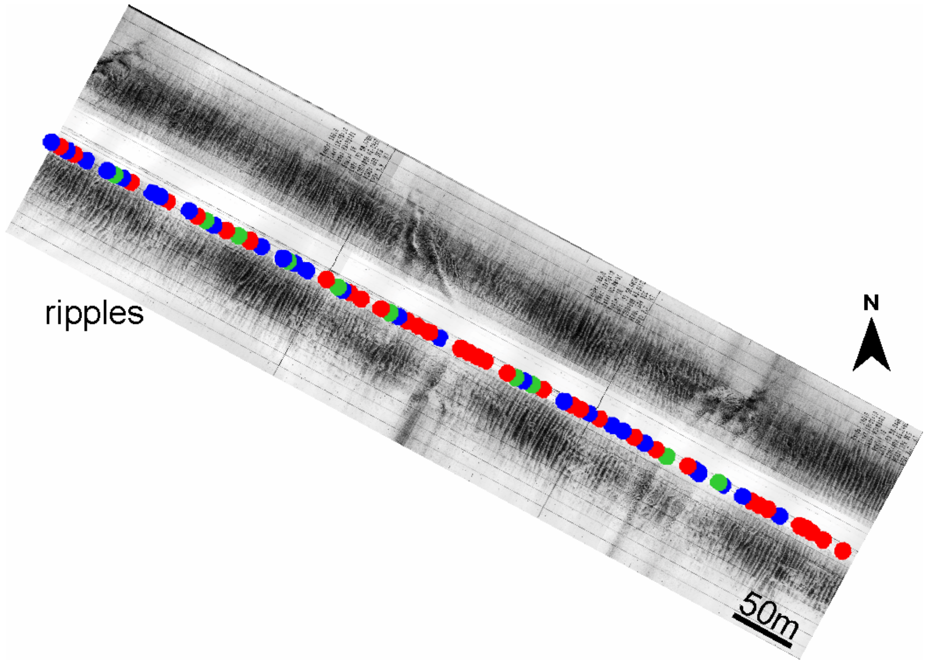


Fig. 4.5 Sidescan sonar record overlayed by by acoustic QTC View™ data. Blue = class 1, red = class 2, and green = class 3 (see text for class explanation). The western part of survey line 3 is represented, where an expanded field of ripples is detected. The position of the survey line is indicated in Figure 4.2.

4.4.3 Time series of successive QTC View™ surveys

In a time series of successive acoustic surveys (August 2001, December 2001, October 2002), variations of the distribution of acoustic classes and, thus, variations of the sediment distribution were obtained. The results of processing the three acoustic data sets are given in Figure 4.6a, b. The data are shown as colour-coded classified points along the vessel track line and interpolated maps.

In August 2001, the distribution of acoustic classes was divided into three zones (Fig. 4.6a, b). In the northern to central part of the survey area, including the dumping site and the area between dumping site and shipping channel, a zone dominated by a sequence of classes 1 and 3 was observed, which was interpreted as a response to the predominant occurrence of large subaqueous dunes. Further to the south, in the range of the shipping channel, a strong alternation of all defined classes was recognized corresponding to the development of ripples. Finally, south of the shipping channel a zone with no distinct bedforms and a smoothed homogeneous surface was associated with a dominance of acoustic class 1.

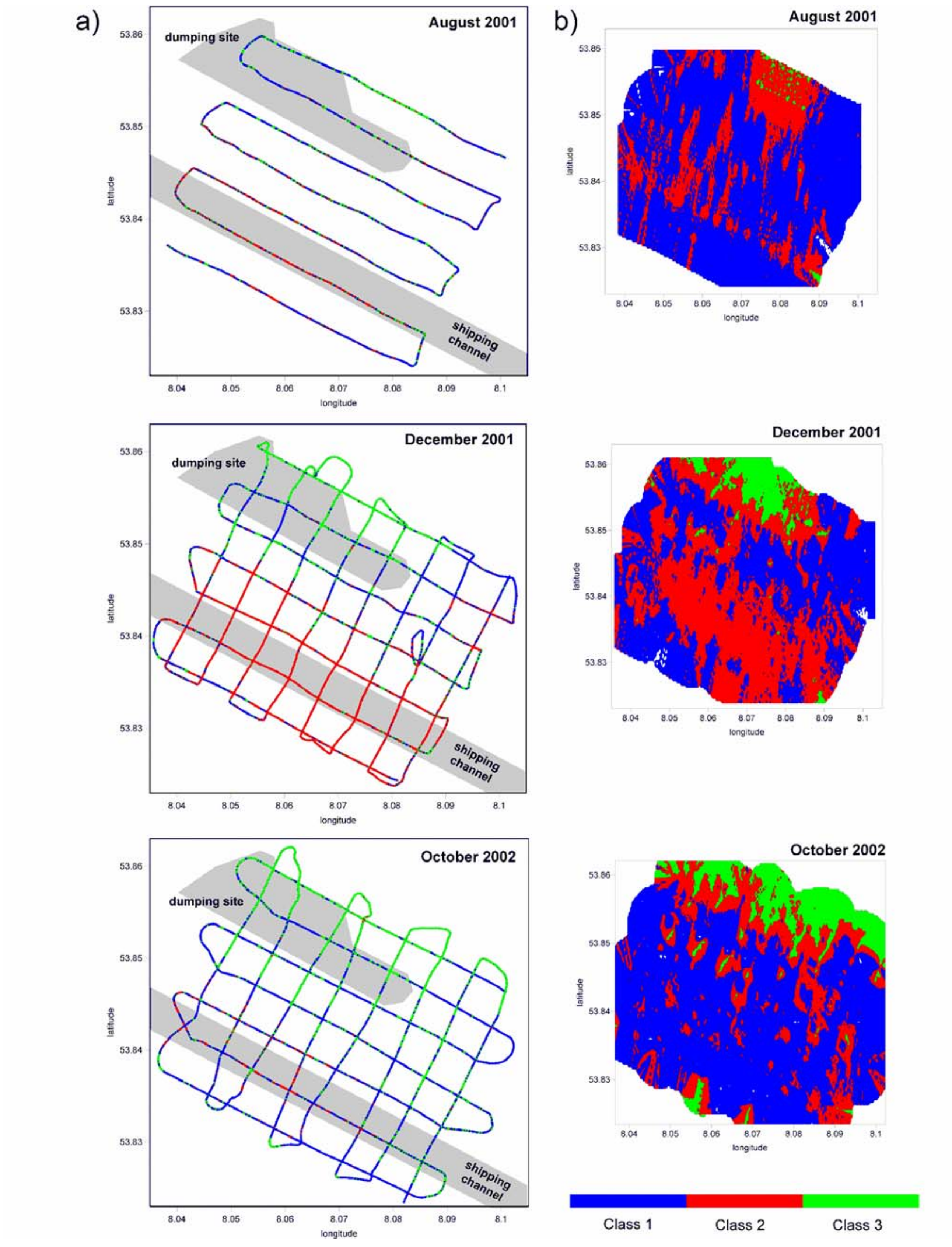


Fig. 4.6a-b Time series of successive acoustic surveys carried out with the QTC View™ system. The acoustic data were acquired in August 2001, December 2001, and October 2002, and were organized into 3 acoustic classes. The data are shown as a) colour-coded classified points along the vessel track line and b) interpolated maps. The positions of the dumping site (top) and the shipping channel (bottom) are marked in grey.

In December 2001, the distribution of the acoustic classes has been partly changed (Fig. 4.6a, b). Especially, the southern part of the survey area showed a completely different image compared to August 2001. The shipping channel, formerly characterized by a highly alternating sequence of classes 1, 2, and 3, which were attributed to the occurrence of numerous ripples, changed to a pronounced dominance of class 2 in December 2001 (Fig. 4.6a, b).

Ripples and subaqueous dunes, as detected on the sidescan sonar records, frequently arise at the seabed of many shipping channels and constitute a potential navigational hazard due to their variable height (trough-crest-trough) (Redding, 2000; Knaapen and Hulscher, 2002). In the outer Weser Estuary, the development of ripples and dunes is a common problem for the local waterway and shipping authority and strong efforts have been made to remove these bedforms by dredging (Wasser- und Schiffahrtsamt Bremerhaven, 1996). The section of the shipping channel surveyed in this study had to be dredged repeatedly as well. From July to September 2001, no dredging occurred in this particular section, whereas in the time span from October to December 2001 the amount of dredged sediment increased. A total of 29,490 m^3 of sediments were removed and subsequently dumped at the surveyed dumping site. Moreover, exactly 2 weeks before the QTC View™ survey was carried out, 12,873 m^3 of sediments were dredged (Wasser- und Schiffahrtsamt Bremerhaven, unpublished data). It is most likely that the dredging operations destroyed the morphology of the ripples and the seabed became smoothed, identified by the dominance of class 2 observed in December 2001 (Fig. 4.6a, b). Scientific publications concerning the application of QTC View™ to monitor effects of dredging are relatively rare. Nevertheless, Maushacke and Collins (2001) showed for the Elbe River that changes of sediment patterns due to dredging operations can be very successfully described with a QTC View™ system. They observed that after using a water injection dredge the sediment distribution changed significantly because silty sediment patches totally disappeared from the dredging area and the seabed became much more homogeneous.

Not even the sedimentological conditions at the seabed of the shipping channel were disturbed by dredging but also the dumping site was affected by the disposal of dredge spoil. While in August 2001 the surveyed part of the dumping site was more or less dominated by acoustic class 1 (fine to medium sand with a low content of shell fragments) and morphologically characterized by large subaqueous dunes, in December 2001 a sedimento-logical change to coarser sediments represented by acoustic classes 2 and 3 was observed (Fig. 4.6a, b). This might be attributed to the relatively great amount of 220,095 m^3 of dredge spoil, which was dumped from October to December 2001, just before the second acoustic survey. Collins and McConnaughey (1998) assumed that acoustic classification can be used to quantify the effects of dredge spoil dumping by tracking the movement of sediment following dumping and characterize the distribution of the dumped sediments. However, due to the fact that the survey area did not completely cover the dumping site, it was not possible to give any statement about the fate of the dumped material.

Ten months later, in October 2002, the seabed in the range of the shipping channel was again characterized by a strong alternation of classes 1, 2, and 3 (Fig. 4.6a, b). Furthermore, south of the shipping channel class 1 was predominant. In October 2002 as well as in the prior months, no significant amounts of sediments were dredged in the surveyed section of the shipping channel. Thus, the sedimentological and morphological conditions in these areas returned to the state found in August 2001. Finally, the seabed at the dumping site was still dominated by acoustic classes 2 and 3, as already recognized for the last survey in December 2001.

4.5 Conclusions

The acoustic data, obtained by the QTC View™ systen, were catalogued into three acoustic classes, which were identified as fine to medium sand, medium sand, and medium to coarse sand admixed with an increasing content of shell fragments. The composition of the sediments with varying contents of shell fragments was strongly reflected in the high variance of the acoustic return signals, which verifies that the presence of epifauna and infauna has an important effect on the backscatter of acoustic signals.

Sidescan sonar records revealed that the seabed morphology of the study area was very inhomogeneous. Regions with no seabed structures, large dunes partly superimposed by ripples, and ripple fields existed in parallel and were associated with the distribution of acoustic classes. Thus, it can be concluded that the acoustic classification was not influenced by the sediment composition only, even more it provided a combined information about sediment distribution and seabed morphology. Theferefore, a combined application of sidescan sonar and QTC View™ constitutes a very effective means to gain a complete image of sedimentological and morphological patterns in a dynamic environment.

The changes in sediment distribution were successfully described by a time series of successive QTC View™ surveys. It was shown that maintenance dredging of the shipping channel and dumping of dredge spoil constituted a strong impact. Ripples developed at the seabed of the shipping channel were removed by dredging and the sediment distribution changed from a very inhomogeneous composite of all three sediment types, respectively acoustic classes, to an expanded dominance of medium sand with a moderate content of shell fragments (class 2). Whereas, the sediment distribution at the dumping site changed because of the dredge spoil dumping from a dominance of fine sands to medium to coarse sands.

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Conclusions and Perspectives

The continuous dredging of shipping channels is a commom problem in most estuaries. Shoals constitute navigational hazards, which have to be removed to guarantee a safe access to the adjacent harbors. Dredging is always associated with the dumping of dredge spoil at declared sites, which are normally located close to the dredged channel. In this context, a main problem is the uncertainty, whether the dumped material remains at the site or is further transported by currents and redistributed in the surrounding estuarine area. In the worst case, the previously dredged channel might be re-infilled. However, knowledge about the fate of dumped sediments and their interaction with the existing morphological and sedimentological conditions is still fragmentary, especially in a dynamic tidally influenced environment. For this reason, in the present thesis, the consequences of dredge spoil dumping were investigated in order to acquire detailed knowledge about morphodynamical processes and seabed characteristics and their change due to the anthropogenic impact (Fig. 5.1).

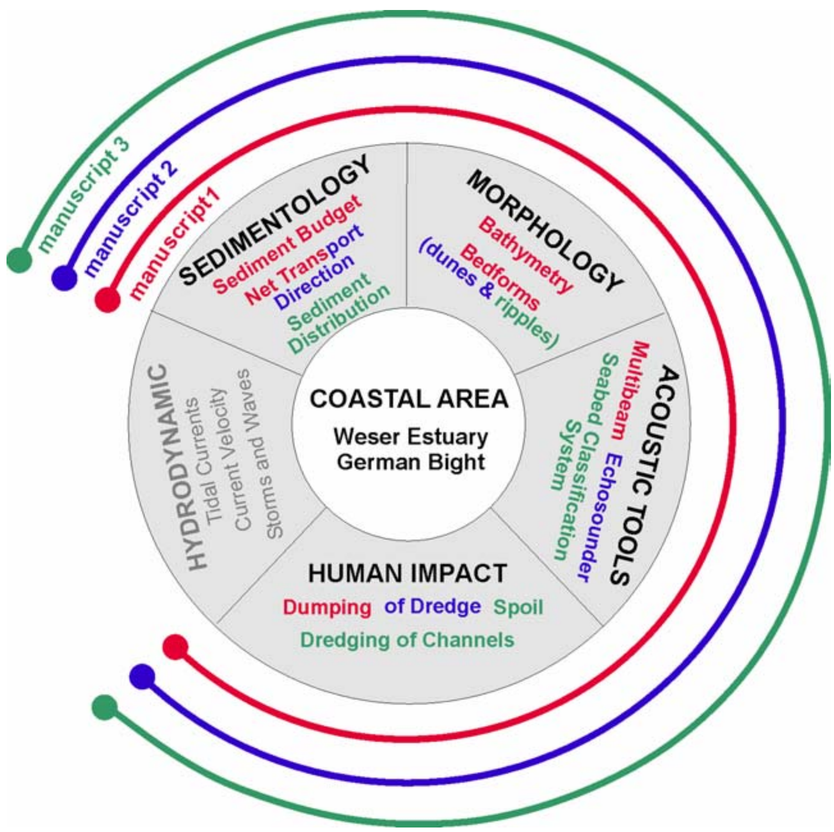


Fig. 5.1 Main objectives of the three manuscripts building the main part of the present thesis.

The study focussed on a specific dumping site in the outer Weser Estuary (German Bight), which was repeatedly surveyed with sophisticated acoustic measuring instruments, namely a shallow-water multibeam echosounder (Reson SeaBat 8101) and a seabed classification system (QTC View^{TM}) (Fig. 5.1).

In 1998, the dumping site was used for the dumping of ~3 million m^3 dredge spoil, which was removed out of the local shipping channel. Data sets of a multibeam echosounder system showed that the dumping caused an abrupt and intensive change of the local seabed. Most conspicuous was the strong shallowing of the seabed by about 1 m due to the huge supply of sediment. The dumped material, which was mainly composed of fine to medium sand, accumulated as clearly silhouetted rises at the seabed.

Nevertheless, a sediment loss of ~0.561 million m^3 within a time period of 5 months was calculated. The outer Weser Estuary is characterized by a slight dominance of the ebb tide in terms of higher current velocities and ebb duration, which results in a residual sediment transport towards the open sea. This predominant sediment transport towards the North Sea thus, in all likelihood explains the sediment loss during the dumping operation.

This assumption was confirmed by very large subaqueous dunes (wavelength: 159-406 m, maximum height: 6.7 m), which covered the entire dumping site. The dunes were asymmetrical in shape with the lee slope facing the open sea, emphasizing the dominance of the ebb tide in the outer Weser Estuary. In addition, the dunes slightly migrated towards the open sea.

The size and the shape of the subaqueous dunes were intensely affected by the dredge spoil dumping. Especially, the dune troughs were strongly filled up and some dunes were even completely buried. However, a time series of cross-sections showed that a reformation of bedforms took place. The dunes started to re-establish a new dynamic equilibrium between the controlling factors current velocity and direction, as well as water depth and grain size, which was intensely disturbed by the artificial supply of sediment and the resulting decrease in water depth.

Surveys with the echosounder-based seabed classification system QTC View^{TM} provided information about the sediment distribution in the surrounding area of the dumping site, including a part of the shipping channel. The sediments in the area were composed of fine to coarse sands, in which the content of shell fragments increased along with the sand fraction. Sidescan sonar records revealed that the dumping sites as well as the southern adjacent area were dominated by large subaqueous dunes with wavelengths between 130 and 420 m, whereas small ripples with wavelengths of 2.0-2.5 m occur in the range of the shipping channel. The sediment distribution was associated with morphological seabed structures occurring in the area. For example, the sediment distribution traced the dune morphology with fine sands and a low content of shell fragments mainly occurring at the dune troughs, whereas coarse sands with a high content of shell fragment appeared at the dune crests. In a time series of successive acoustic surveys, it became apparent that the sediment distribution changed due to maintenance dredging and dumping of dredge spoil.

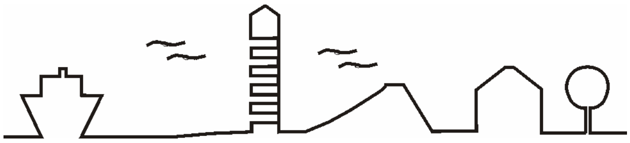
Concluding, the combined application of multibeam echosounder and seabed classification system associated with sidescan sonar records is a promising approach to investigate the consequences of dumping in dynamic coastal seas in detail. These acoustic measuring instruments provide the opportunity to acquire data about variations in seabed morphology, sediment budget, and sediment distribution in high spatial and temporal resolution.

With regard to future intentions as e.g. the installation of offshore windparks in the German Bight (North Sea), the construction of the first German deepwater port in Wilhelmshaven as well as the further deepening of the shipping channels of the Weser and Elbe Rivers associated with dumping of dredge spoil, it is necessary to gain more detailed knowledge about the present morpho-, sediment-, and hydrodynamical state of the affected areas. Otherwise, a reasonable prediction about the consequences of these constructional interferences, especially about any negative effects, cannot be satisfied.

Further studies concerning the investigation of the consequences of a human impact such as the dumping of dredge spoil have to be carried on and extended. For example, to observe the accurate pathways of sediment transport in a dumping area, dumped sediments have to be monitored over a large distance (across the margins of a dumping site) and a long time period. In this context, tracers can be applied to mark sediment particles to accurately monitor the transport.

Moreover, to gain a more complete image of the morphodynamic processes, accompanying measurements concerning the hydrodynamics should be carried out as well. In particular, information about the local hydrodynamic parameters like current velocity and direction has to be considered for further studies. In combination with data received by the presented high-resolution acoustic survey methods, it will help in gaining a more complete image about the morphodynamical processes in an anthropogenically affected area.

Interdisciplinary Graduate Program: ‘Living Environment North Sea Coast’



The present thesis was embedded in an interdisciplinary graduate program with the project title “Living Environment North Sea Coast – Fundamentals for a Sustainable Use”, which was initiated and coordinated by the Department of Geosciences and founded by the University of Bremen.

Eight PhD-students of six different disciplines of natural sciences and humanities (biology, earth sciences, history, law, physics, and psychology) were integrated to this program. The aim was to investigate the interaction between environment and society and to gain knowledge of basic fundamentals, which will enable a more sustainable use of the North Sea coast habitat.

All individual dissertations are linked to the environment of the German North Sea coast and deal with subjects concerning natural processes and their response to the human impact:

- reconstruction of climate variability in the late Holocene (geology: Carolyn Scheurle)
- analysis of ecological sensitivity due to the climate change (biology: Jürgen Meyerdirks)
- monitoring of coastal morphodynamics and their change due to human impact (geology: Claudia Wienberg)
- modelling of a ground water budget in the coastal zone (geology: Tomas Feseker)
- evaluation of satellite pictures to produce topographical maps of tidal flats (physics: Jens Dannenberg)

as well as social questions resulting of the interaction between man and nature:

- investigation of user conflicts and their regulation in the face of past and future port projects (history: Oliver Höpfner)
- analysis of the acceptance of off-shore windparks in different social groups (psychology: Markus Ladineo)
- use of law for the determination and liability of the influx of pollutants (law: Ann-Katrin von der Heide).

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