Comparison of Marine Sediment Extraction Sites by Means of Shoreface Zonation

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ABSTRACT


Marine sand and gravel resources receive an increasing interest, leading to greater quantities of dredged material. Nevertheless, knowledge concerning negative impacts on adjacent coastal sediment transport systems and the duration necessary for the physical regeneration of extraction sites is scarce. Here we assess time scales of regeneration of three extraction sites situated in the Baltic Sea by investigating sonographic data sets covering several years. We incorporate data from other extraction sites and compare the results by applying a shore-normal zonation of the shoreface. Hence, limiting depths of the upper and lower shorefaces are calculated from wave statistics. From our comparisons we conclude that the time scales of regeneration are most profoundly determined by the position of the extraction site relative to the seaward limit of the shoreface. Locating extraction sites well beyond this limit therefore implies a slow regeneration. In contrast, material extractions on the upper shoreface may exhibit a fast regeneration, but negative impacts on the coastal sediment budget cannot be excluded. Additional factors controlling the velocity of regeneration are the depth of the extraction as well as the character and availability of the potential material for regeneration. As a consequence, there is no “ideal” location for marine sediment extraction. The appropriate place should be a well-balanced compromise allowing fast regeneration together with a minimised impact on the coastal sediment budget.

ADDITIONAL INDEX WORDS: Physical regeneration, time scales, upper and lower shoreface.

INTRODUCTION

Marine sand and gravel extractions increasingly gain significance due to an overall growing demand, supply shortages of land-based aggregates, improved mining technologies and advantages with respect to quality, availability and transport. Nevertheless, disadvantages may arise if mining is conducted too close to the shore as this may have negative influences on the coastal sediment budget (e.g. Nielsen et al., 1991). Based on the concept of equilibrium beach profiles, Otake et al. (2002) analytically show that sand extractions on the upper shoreface inevitably lead to beach erosion. Hilton and Hesp (1996) reason that the weak recovery of the Pakiri-Mangawhai coast (New Zealand) following severe erosion after a major storm event in 1978 was probably the consequence of sand mining well within the shoreface system. Also, modelling studies have shown that impacts of mining on shoreline change are minimised when the extraction site is located below the wave base (Demir et al., 2003). Therefore, it has been advocated to limit extraction to sites in water depths of more than ~20 m (e.g. Van Alphen et al., 1991; Nielsen et al., 1991).

The time scales of the physical regeneration of aggregate extraction sites are not well known today. In the following we assess such time scales of three extraction sites and compare them with extraction sites at locations with different energetic conditions published elsewhere. Doing this, we apply the shore-normal zonation of the shoreface provided by Cowell et al. (1999), allowing an improved comparability of different sites.

According to the concept of Cowell et al. (1999), the shoreface extends from the limit of wave runup on the beach face to the limit of effective influence by gravity waves. The shoreface can be sub-divided into an upper and a lower portion with the morphological changes being greatest in amplitude and frequency on the upper shoreface.

The seaward limit of the upper shoreface is given by the closure depth $h_c$ which marks the limiting water depth down to which significant (i.e. detectable) morphological changes occur during a year with average wave conditions.

Beyond this closure depth lies the lower shoreface, where morphological changes are not detectable during a year with average wave conditions. Detectable morphological changes on the lower shoreface take place on longer time scales, typically in the order of decades to centuries (Stive and De Vriend, 1995). Nevertheless, significant cross-shore sediment transport occurs down to a limiting depth $h_l$ (Hallermeier, 1981).

Both limiting water depths can be calculated by several empirical formulae. Hallermeier (1978) originally defined the closure depth $h_c$ as:

$$h_c = 2.28 \cdot H_{sx} - 68.5 \cdot \left( \frac{H_{sx}^2}{g \cdot T_{sx}^2} \right)$$

(1)

where $H_{sx}$ is the annual significant wave height that is exceeded for 12 hours during a year, $T_{sx}$ is the associated wave period and $g$ is the acceleration due to gravity. Expressed with the more common wave parameters, mean annual significant wave height $H_s$ and its standard deviation $\sigma$, the closure depth reads (Hallermeier, 1981):

$$h_c = 2 \cdot H_s + 11 \cdot \sigma$$

(2)

Equation 1 was re-evaluated by Birkemeier (1985), using a data set of high-precision morphological measurements spanning two years. He found that:

$$h_c = 1.75 \cdot H_{sx} - 57.9 \cdot \left( \frac{H_{sx}^2}{g \cdot T_{sx}^2} \right)$$

(3)
better fits the data than equation 1. BIRKEMEIER (1985) also stated that the simple relationship

$$h_s = 1.57 \cdot H_{xx}$$  \hspace{1cm} (4)

provided an appropriate approximation of the closure depth.

The seaward limit of the lower shoreface given by an empirical formula provided by HALLERMEIER (1981) is expressed as:

$$h_s = \left( H_s - 0.3 \cdot \sigma \right) \cdot T_s \cdot \frac{g}{\sqrt{5 \cdot 10^3 \cdot d}}$$  \hspace{1cm} (5)

where $T_s$ is the mean annual significant wave period and $d$ is the characteristic grain size for the lower shoreface.

We have investigated two research areas with three extraction sites, namely Graal-Müritz 1, Tromper Wiek 1 and Tromper Wiek Ost (Figure 1). All research areas are situated in the southwestern Baltic Sea. Their characteristics are summarised in Table 1.

**METHODS**

The research areas were repeatedly investigated in semi-regular time intervals between March 1999 and September 2001. The seafloor of the extraction sites was mapped with high-resolution sidescan sonar (KLEIN 595). Data were recorded in digital form employing the software package ISIS (Triton Elics Int.). This enabled us to create geo-referenced mosaics of the investigated seafloor. Validation of the sidescan sonar data was achieved by grain size analysis of seafloor sediments and by underwater video surveying. The mosaic files were displayed in geographic information systems like DELPH MAP (Triton Elics Int.) and ARC VIEW (Esri). Repeated data collection of the same areas enabled us to identify changes of the sediment distribution patterns and of the traces of sediment extraction.

The seaward limits of the upper and lower shoreface of the research areas were calculated applying equations 1-5. The necessary annual wave statistics were computed from wind data for Tromper Wiek by M. Larson (cited in Diesing, 2003). In the case of Graal-Müritz, calculated values of $h_s$ and $h_L$ were adopted from Dette et al. (2001).

**RESULTS**

For the Tromper Wiek field site, the following annual wave data were derived for a location at 13 m water depth: $H_s=0.77$ m, $\sigma=0.48$ m, $T_s=3.9$ s, $H_{xx}=3.10$ m and $T_{xx}=7.6$ s (M. Larson, cited in Diesing, 2003). Down to c. 10 m water depth, the seafloor is uniformly covered with marine sands, displaying a median grain size of 113 µm on average. The resulting limiting depths of the upper and lower shoreface are listed in Table 2.

The seafloor of the Graal-Müritz area is dominated by marine fine to medium sands with smaller patches of coarse-grained lag deposits. The marine sands form N-S trending, large to very large dunes (according to the classification of Detlefsen, 1990) with wavelengths of up to 180 m and heights of up to 2.7 m.

Extraction commenced in 1988; since then 1.8 million m$^3$ of sand were extracted by trailer suction dredging (Zeiler et al., 2004). This resulted in relatively shallow (<1 m) furrows of less than 10 m width and several hundreds of metres length (Figure 2a). Repeated sidescan sonar surveys reveal that those furrows re-filled quickly within months (Figure 2b). Therefore, the typical time scales of regeneration lie in the range of months.

The extraction site Tromper Wiek 1 is situated in water depths between 9 and 14 m. Here, the seafloor is covered by sandy gravel forming prominent NE-SW-trending ridges, which are interpreted as the remains of a drowned beach ridge system dating back to the Late Pleistocene (Schwarzer et al., 2000). The sediment is extracted by anchor hopper dredging, which results in the formation of extraction pits, 5 to 50 m in diameter and up to 7 m deep (Figure 2c). After extraction, the material is screened on board, i.e. sediments with grain sizes >2 mm are sorted out and spilt back into the sea. The spilt material settles down in the area of extraction, creating recognisable sediment distribution patterns on the seafloor (Figure 2c). Between 1988...
and 2000, approximately 460,000 m$^3$ of sediment were extracted, of which half of the volume was spilt back into the sea (pers. comm., K. Brauckhoff, Müsing GmbH).

From repeated sidescan sonar surveys it is obvious that the pits do not re-fill completely, but remain relatively stable for at least several years. However, the pattern of spilt sands shows fast changes (Figure 2d). Spilt sands are re-mobilised especially during late winter and early spring, when easterly winds cause high waves within the research area. The re-mobilised spilt sands partly re-fill the pits as could be proved by cores obtained from the seafloor inside the pits. We estimate the appropriate time scales for regeneration to be in the order of years, at least.

The seafloor of the extraction site Tromper Wiek Ost is characterised by marine fine sands in water depths between 14 and 21 m. Sand has been extracted twice: 151,000 m in 1989 and 21 m. Sand has been extracted twice: 151,000 m in 1989 and 104,000 m in 2000 (pers. comm., W. Sorge, Bergamt Stralsund).

The extraction took place by trailer suction dredging in water depths around 20 m. The dredging activities caused relatively shallow (<1 m) furrows of several hundreds of metres length and less than 10 m width. The furrows, which were created in 1989, are still clearly detectable. Therefore, the time scales of regeneration are assessed to be in the order of decades.

### DISCUSSION

The calculated values of the closure depth vary considerably for each location, depending on the formula utilised (Table 2). DIESING (2003) compared calculated values of the closure depth in Tromper Wiek with “tracer stick” measurements (for methodology see SCHWARZER and DIESING, 2001) and computed energy dissipation values. It was found that equations 3 and 4 agreed well with those results, while equations 1 and 2 overpredicted the closure depth. The latter finding is supported by results of GRACIA NICHOLLS et al. (1998) and NICHELLS et al. (1998). We therefore apply the following closure depths: 4.0 m for Graal-Müritz and 4.5 m for Tromper Wiek.

In the following, we compare our results by applying the seafloor zonation and incorporate data from further extraction sites, located in the Baltic Sea some kilometres NE of Graal-Müritz (Wustrow; KRAUSE, 2002), in the North Sea off Sylt Island (Westerland II; ZEILER et al., 2003) and at the east coast of New Zealand’s North Island (Pakiri; HILTON and HESP, 1996). In this way, we combine data from sandy coasts classified as wave dominated (Graal-Müritz, Wustrow and Tromper Wiek) to mixed energy-wave dominated (Westerland and Pakiri), according to the classification of DAVIS and HAYES (1984). Nevertheless, the levels of wave energy input strongly differ between the locations, which results in deviating values of the upper and lower shoreface limiting depths. While for Wustrow, the relatively low values of DETTE et al. (2001) are applicable (table 2), the seaward limits of the upper and lower shoreface lie in 10.1 m and 24.5 m water for Pakiri (HILTON and HESP, 1996). In the case of Westerland, calculated values based on wave data (SCHADE and KOHLHASE, 1991) and sedimentological data (Koster, 1979) are $h=7.5$ m and $h=12-17$m (DIESING, 2003).

Figure 3a displays the shoreface zonation of the research areas and the location of the extraction sites in terms of water depths. Most extraction sites are located near the seaward limit of the shoreface, while the extraction in Pakiri takes place on the upper shoreface. Within Tromper Wiek Ost, sediment is removed from the continental shelf.

To allow for direct comparison, we define a normalised water depth $h/h$, which is calculated by dividing the water depth $h$ of the extraction site by the depth of the seaward limit of the lower shoreface $h$. Normalised water depths <1 indicate that the extraction site is situated on the shoreface, while values >1 are indicative for a location of the extraction site on the continental shelf (Figure 3b).

Further on, we combine normalised water depths with the assessed time scales of regeneration (Figure 3c). It is obvious that increasing values of normalised water depth generally coincide with increasing regeneration times. This means that regeneration times are related to the location of the extraction site relative to the ambient shoreface zonation. Our findings are underpinned by results of VAN DOLAH et al. (1998), cited in WORK et al. (2003), who examined six sediment extraction sites at the coast of South Carolina, USA. They found typical regeneration times within 5 to 12 years, with sites closer to shore exhibiting a shorter regeneration time.

Nevertheless, this relationship is not straightforward. From Figure 3c, it can be estimated that other factors might also play a role. Evidently, Graal-Müritz 1, Wustrow, Tromper Wiek 1 and Westerland II all display a similar normalised water depth around 1, but differ considerably in regeneration time. The regeneration times co-vary with maximum extraction depths (Table 1), thus giving a hint that the depth of extraction is another factor involved in the time scales of regeneration. Shallow extractions therefore favour faster regeneration, while pits several metres deep might not re-fill substantially within years to decades, as in the case of Tromper Wiek 1 and Westerland II (FIGGE et al., 2002; ZEILER et al., 2004).

Finally, the character and the availability of potential sediment for re-filling have to be taken into account. DIESING (2003) showed a selective re-mobilisation of spilt sands in Tromper Wiek 1, where the finer components were transported into the pits while the remaining spilt sands tended to coarsen.
over a 6-months period of observation. This process will slow down regeneration, as the thresholds necessary to re-mobilise the coarsening material will be surpassed less frequently with time. Additionally, the material re-filling the pits is mostly of local origin, with spilt sands dominating over other sources (Diesing, 2003; Zeiler et al., 2003). However the volume of spilt sands is definitely limited to about 50 % of the volume to be re-filled. Other sources must therefore contribute in the future in order to re-fill the pits, but sediment dynamics have been proven to be of low intensity on the lower shoreface and shelf of Tromper Wick (Diesing, 2003). Therefore a limited availability of spilt sands will probably result in prolonged regeneration times.

CONCLUSIONS

We have shown that the concept of shoreface zonation (Cowell et al., 1999) provides a useful tool to compare wave-dominated coasts with differing energetic regimes. From our comparisons we conclude the following: Aggregate extraction seaward of the shoreface implies long time spans of regeneration due to the fact that thresholds of re-mobilisation of the ambient sediment are surpassed only during extreme events, while extractions on the shoreface can be re-generated quite fast. Nevertheless, in the latter case there is a potential of negative effects on the sediment budget (e.g. Hilton and Hesp, 1996; Otay et al., 2002; Demir et al., 2003). As a consequence, there is no "ideal" location for marine sediment extraction. The appropriate place for extraction should be a well-balanced compromise allowing relatively fast regeneration together with a minimised impact on the coastal sediment budget. In order to fulfil those requirements detailed knowledge about sediment budgets, availability and dynamics in the considered area is necessary.

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Figure 3. Comparison of extraction sites incorporating data from HILTON and HESP (1996; Pakiri), KRAUSE (2002; Wustrow) and ZEILER et al. (2004, Westerland): a) Extension of upper shoreface, lower shoreface and continental shelf in terms of water depth. Wave energy input is increasing from left to right. White boxes indicate position of extraction sites. b) Position of extraction sites (white boxes) relative to the distribution of shoreface and continental shelf, displayed in terms of normalised water depth. c) Normalised water depth distribution of shoreface and continental shelf, displayed in terms of normalised water depth. Hatched arrows indicate possibly longer regeneration times, as regeneration was not completed until the end of observation.

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