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Assessment of the Effects of Marine Aggregate Extraction on the Coastline: an Example from the German Baltic Sea Coast

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ABSTRACT

The German Baltic Sea coast between Warnemünde and Darss is rapidly eroding. In this area, extensive sand extraction takes place at water depths of 8-13 m, for both local beach nourishment and industrial use. Sand resources in the area are restricted to a layer of <2 m of Holocene sand, whilst contemporary input of sand is limited to erosion of the cliff sections. To investigate if sand extraction in this area has any effect on the coastline, bathymetric data from two particular time periods were compared, as well as the location of the coastline over 5 different years, ranging from 1953-2002. Waves and wave-induced sediment transport were simulated using the integrated coastal zone model, Sistema de Modelado Costero (SMC). Results indicate some primary areas of concern: small changes in bathymetry of approximately 10% are sufficient to cause significant modifications in sediment transport potential at the coast; and, thus, alternations in the patterns of erosion and accretion. Sediment transport by both wave action and currents, induced by the inflow of North Sea water, is in a NE direction towards Darss. Here, deposition takes place in a National Park, where dredging is prohibited. There is very little input of sediment in the system. Any sand that is removed by marine aggregate extraction, for industrial use, will have a negative effect on the total sediment budget at the shoreline.

ADDITIONAL INDEX WORDS: *dredging, sediment transport, integrated coastal zone model, Sistema de Modelado Costero (SMC), differential bathymetry, beach erosion.*

INTRODUCTION

Sand is extracted from the seabed for many uses, including the construction industry and beach nourishment. In response to increasing demand, more marine sand is extracted from the inner continental shelf (<60 m water depth) in Europe, every year. As such, concerns have been raised about the adverse effects on the coastal system, including ecology, the seabed and the adjacent shoreline. For example, the results of a questionnaire sent to local residents in South Wales, have shown that a vast majority believes that marine aggregate (MA) extraction is responsible for the increased rates of beach erosion at local beaches (Simons and Hollingham, 2001).

There are different ways in which offshore MA extraction may cause changes to the coastline. For example, Brampton and Evans (1998) identify 5 effects: (a) beach draw-down; (b) modifications to tidal currents; (c) changes in sediment transport; (d) variations in nearshore wave conditions; and (e) a reduction in shelter provided to the coastline. Many of these effects are interrelated (as discussed below). Nairn *et al.* (2004) suggest that shoreline changes occur in two ways: (i) an extraction site interrupts or modifies the sediment supply pathways to the coast, reducing the sediment budget at the shoreline; or (ii) modifications in wave transformation patterns change the character of the waves reaching the coast, altering sediment transport and, eventually, changing erosional and accretional patterns. The study of coastal impact of dredging is not straightforward and, as such, many different approaches have been adopted.

Extensive MA extraction takes place in the Baltic Sea, in the area between Warnemünde and Darss (Figure 1), for both beach nourishment purposes and industrial use (Krause, 1998). Two of the offshore extraction sites are located close to the coast, i.e. Graal Müritz and Wustrow; they are located in water depths of 8-12 and 11-13 m, respectively (Figures 1 and 2). Wave conditions and wave-induced sediment transport within the area of these extraction sites are investigated here, to assess if the dredging may impact upon the coast. Offshore bathymetry and the location of coastlines, over a number of years, were compared to study patterns of erosion and accretion. Waves (in the absence of tides) and sediment transport were modelled using Sistema de Modelado Costero (SMC), an integrated coastal zone model.

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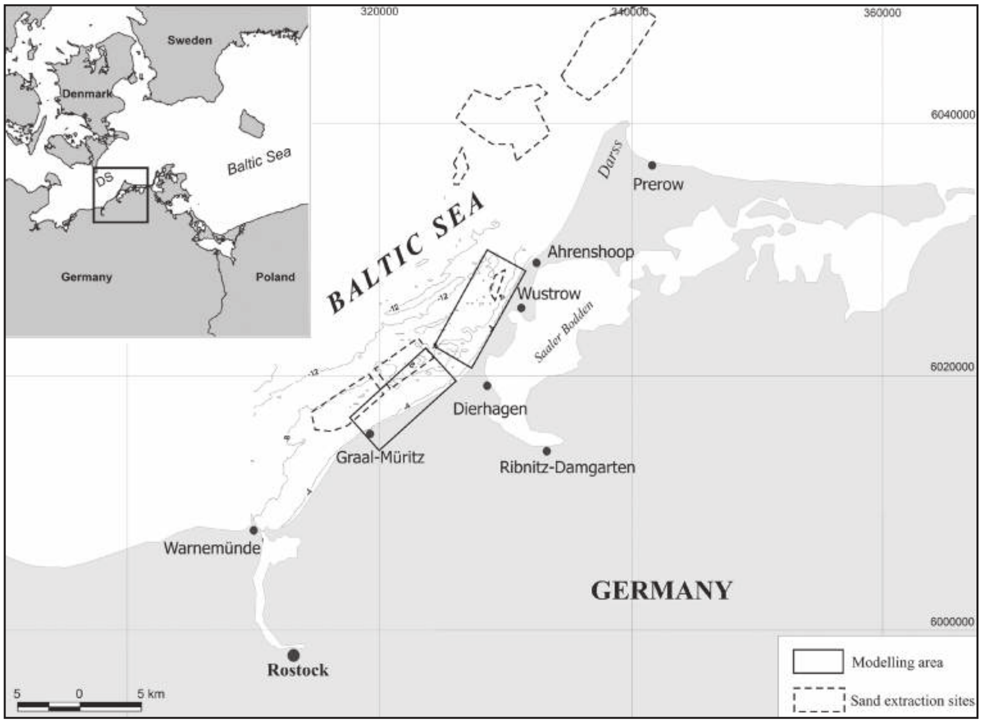

Figure 1. Location map, showing the major towns, extraction sites Graal Müritz and Wustrow, and the fine grids used for modelling. DS = Darss Sill.

EFFECTS OF MA EXTRACTION ON THE COASTLINE

Effects on Coastal Sediment Budget

The most direct effect of MA extraction on the coastline is beach draw-down; this may occur when material is extracted from within the active beach profile. Beach sand or gravel, transported seawards during storm events, remains trapped in the depression. It will not return to the upper beach during calm conditions, thus resulting in a net loss of beach material (Brampton and Evans, 1998). Beach draw-down was the cause of the destruction of the coastal village of Hallsands, Devon (UK), in 1917, where between 1897 and 1902 some 382,000 m^3 of gravel was extracted from the foreshore (Pearce, 1996; Simons and Hollingham, 2001).

Reduction in the sediment budget at the shoreline may occur also due to modification or interruption of the sediment supply pathways, towards the coast. Such a reduction may occur in two ways: dredging may remove sediment that would normally supply the beach; or an extraction site may trap sediment, which would otherwise have been transported towards the coast. The latter process is suggested to be the reason for the weak recovery of the Pakiri-Mangawhai coast in New Zealand, following storms in 1978. Although extraction in this area takes place within the surf zone, it has been impossible to prove a cause-effect relationship between sand extraction and backshore stability (Hilton and Hesp, 1996). Anctil and Ouellet (1990) have calculated littoral drift changes for three dredging scenarios in Quebec (Canada) and found that only excavation at the sea bed of 2 m or more in depth had a significant impact on sediment transport. These investigations have concluded that the coastal impact can be limited, by gradually changing the bathymetry, leaving the system sufficient time to adjust. This outcome is achievable by preventing multiple dredging over the same area.

Effects on Waves and Currents

Modification of the bathymetry may alter nearshore wave conditions, by changing the wave refraction patterns; hence, the wave direction, or the total wave energy, reaching the coast. Since breaking waves are generally considered to be the dominant factor affecting the coast, Maa, Hobbs, and Hardaway (2001); Maa *et al.* (2004) have used the change in breaking wave height to assess the coastal impact of changing wave transformation, caused by extraction. Even though the local wave height between the extraction site and the coast can increase by as much as two-fold, the change in the breaking wave height is less significant, as most of the wave energy is dissipated before the waves reach the shore (Byrnes *et al.,* 2004a; Maa *et al.,* 2004). However, in areas with a steep shoreface, the wave energy does not dissipate significantly and, instead, increases considerably upon reaching the coast (Byrnes *et al.,* 2004b). For example, at Grand Isle, Louisiana (USA), two large salients and areas of increased erosion developed shoreward of an offshore extraction site that was situated some 800 m offshore, in a water depth of 4.6 m (Bender and Dean, 2003). The extraction pit affected the wave propagation pattern, which, in turn, caused changes in erosion and accretion at the coast.

Maa and Hobbs (1998) have examined longshore sediment transport, using breaking wave conditions, calculated from modelled wave transformation processes. The model results

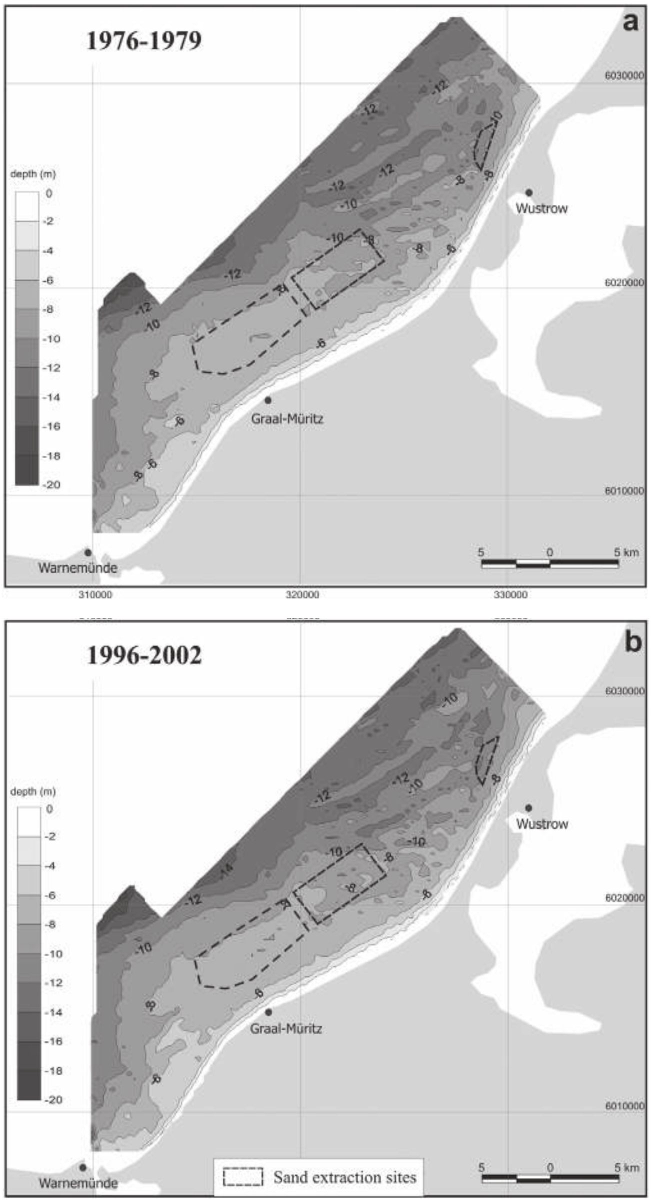

Figure 2. Bathymetry of (a) 1976-1979 and (b) 1998-2002, with the extraction sites indicated.

showed considerable natural wave energy convergence, which could be responsible for severe beach erosion over the same area. However, the dredging effects on wave transformation and longshore sediment transport were found to be insignificant. KELLEY, RAMSEY, and BYRNES (2004) developed a new approach for evaluating the coastal impact of an extraction site, incorporating natural spatial and temporal variability in the wave climate, as the basis for determining the level of significance. A coast with a natural high variety of wave conditions and, consequently, sediment transport will be less sensitive to wave modifications caused by dredging, than a coast with a limited range of wave conditions.

Wave conditions at the shoreline may change also as a result of dredging of nearshore sandbanks, reducing the shelter provided to the coastline. The disappearance, or lowering, of the bank will change the wave patterns between the bank and the coast; this, in turn, will cause changes in sediment transport and, hence, erosion and accretion patterns at the shoreline (HAYES and NAIRN, 2004). An example is the 1996 beach nourishment project undertaken in Martin County, Florida (USA), where sand was extracted from a shoal located some 910 m offshore, in a water depth of 12.8 m. By lowering the shoal height, the coast was exposed to increased wave action, resulting in localised erosion (BENDER and DEAN, 2003). Similarly, sand extraction from a large shore-parallel shoal, located 10 km offshore of the coast of Louisiana, USA, would increase erosion and overwash on the adjacent shoreline (SUTER, MOSSA, and PENLAND, 1989).

The effects on tidal currents are, typically, limited and very localised. For example, MAA *et al.* (2004) modelled the influence of dredging of two shoals offshore of Maryland and Delaware (USA), on the tidal currents. The results showed only small changes in the maximum near-bed tidal current velocity at the shoals, indicating only a negligible impact. Elsewhere, BYRNES *et al.* (2004a) found that, whilst the extraction at sites offshore from Alabama (USA) could produce a localised effect on the currents, there was no impact upon the prevailing or ambient flow characteristics.

SITE DESCRIPTION

The German Baltic Sea coast is a micro-tidal area, with a negligible tidal range. The study area is situated between Warnemünde and Ahrenshoop (Figure 1). The shoreline in this area consists of narrow beaches, with dunes and cliffs of Pleistocene deposits (LAMPE, 2002). The main source of sediment in the coastal zone is retreating cliff sections. Sediment input from rivers is negligible. The slow-flowing Warnow River drains into the Baltic Sea at Warnemünde, but its sediment discharge consists mainly of suspended fines. The coastal zone here is experiencing long-term erosion, with an average coastal retreat varying from 30-70 m/100 years, over the last 160 years (JANKE and LAMPE, 1998). In order to maintain the beaches, sand has been extracted offshore for beach nourishment projects, since 1968. Besides beach and dune nourishment, a wide range of shore protection structures have been installed, e.g. groynes, breakwaters and dykes, to reduce coastal erosion. In this study, two sediment extraction sites are considered, which are located close to the coast: Graal-Müritz and Wustrow (Figure 1).

The offshore area is characterised by the Darss Sill (Figure 1). Approximately 73 % of the water exchange between the Baltic Sea and the North Sea is through this relatively shallow, narrow strait. The seafloor consists of glacial till, overlain by a thin layer (<30 cm) of lag deposits which, in turn, is covered, over a small part of the area, by Holocene marine sand (LEMKE *et al.,* 1994). In the area of Graal-Müritz, the overlying marine sand has a maximum thickness of 1.1 m (DIESING, 2003). NNW-SSE oriented sandwaves, with heights of up to 2.7 m and a wavelength of approximately 180 m, are present in this area. Within their troughs, coarse lag sediments are exposed (DIESING, 2003). The extraction site of Graal-Müritz is located some 2.5-5.5 km offshore, within a water depth of

8-12 m. Extraction at this site has taken place since 1988 (Diesing, 2003). The Wustrow extraction site is located about 1 km off the coast, near Wustrow, in a water depth of 11-13 m. Sand has been extracted here, for beach nourishment projects, since 1997. The mean thickness of the overlying marine sand, in this area, is 1.9 m (Krause, 2002). For extraction at both sites, a trailer suction hopper dredger is used; this creates shallow (ca. 0.5 m deep) furrows on the seafloor, which have widths of 3-10 m and lengths of up to 1 km (Diesing, 2003; Manso *et al.,* this volume).

The bathymetry of the extended offshore area (Warnemünde to Ahrenshoop) shows that the nearshore zone (<10 m water depth) becomes narrower towards the north (Figure 2). Whilst the 10 m depth contour is located approximately 10 km offshore of Graal-Müritz, it is only 2.5 km away from the coast at Wustrow. Large offshore sandbanks are present within this area, oriented obliquely to the coast (Figure 2).

METHODOLOGY AND DATA

Bathymetric Data

Bathymetry relating to two different time periods was compared: 1976-1979 (before dredging) and 1996-2002 (after dredging). The data were obtained from the BSH (Bundesamt für Seeschifffahrt und Hydrographie = Federal Maritime and Hydrographic Agency), Germany. It was necessary to use data sets derived from multiple surveys, undertaken over several years, because no survey covered the complete area, within any particular year. The horizontal error of the older data set is about 20 m + 5% of the depth; for the recent data set, it is about 5 m + 5% of the depth. The vertical error is highly dependent upon water depth; it ranges from 0.50-0.56 m and 1.00-1.10 m for the new and old bathymetry data sets, respectively (IHO, 1998; MONK, 2005 pers. comm.).

Aerial Photographs

In order to compare the location of the coastline, over time, aerial photos were used. Sets of photos from 4 different years (1953, 1980, 1994 and 1998), together with a set of orthophotos (2002), were obtained from the Landesvermessungsamt, Mecklenburg-Vorpommern, Germany (Table 1). The aerial photos were scanned and rectified, using the orthophotos (with a resolution of 8 dm) and the software ER-Mapper 6.4. The rectification error was maintained at less than 1 m, for most of the photos. However, for some of the photos, especially the older ones, this was not possible; as such, the error could extend up to 2 m. When taking into account the resolution of the orthophotos of 8 dm, together with the size of the pixels of the scanned aerial photos of about 1.5 m, the maximum total error may have been about 4 m. Following rectification, mosaics were created and the coastlines from different years were digitised and compiled in a GIS database (ArcView).

Wave and Sediment Transport Modelling

In this study, the software Sistema de Modelado Costero (SMC), translated as Coastal Modelling System, has been used to simulate wave propagation, as well as the currents induced and sediment transport in the coastal area of Graal-Müritz and Wustrow. SMC was developed by the Coastal Engineering and Oceanography Group (G.I.O.C., 2002), of the University of Cantabria, in collaboration with the Coastal and Environmental Department of the Spanish Government. SMC includes different modules and numerical implementation, to assist in coastal dynamics studies; it utilises the parabolic solution of the mild-slope equations (Kirby and Dalrymple, 1983), for wave propagation. The software allows the simulation of monochromatic or spectral waves from deep waters, to the coast. In each case, wave-induced currents and potential sediment transport can be obtained. Sediment transport is computed from the previously obtained wave and current fields, using the formulae of Bailard (1981) and Soulsby (1997). Both methods compute the total sediment transport, taking into account bed load and suspended load transport.

Table 1. *Year, number and scale of the aerial photographs used to study coastline changes.*

Date	Number of aerial photographs	Scale
1953	9	1:22000
1988	16	1:18000
1994	20	1:12500
1998	23	1:12500
2002	47 (ortho-photos)	pixel size: 8 dm

Two areas were selected for modelling: Graal-Müritz and Wustrow. For both areas, two coarse offshore grids (300 x 300 m) were established for the different wave directions, each with a fine grid (15 x 30 m) attached, for the nearshore area. Monochromatic waves were used in the model.

Wave Climate

The NNW-WNW-facing coast, between Warnemünde and Ahrenshoop, is a fetch-limited coastline and is sheltered from waves coming from the Baltic Sea, to the east (Figure 1). A continuous five-year record (1998-2002) of directional wave data, measured every hour, was available from a measuring station located close to Ahrenshoop. Over this period, the dominant wave direction was from W-WNW, with more than 65 % of all waves originating from this direction (Figure 3 and Table 2). Large storm waves originate, typically, from a WNW direction.

Table 2. *Proportion of all waves with Hs >0.2 m in different directions.*

Direction	N	NNW	NW	WNW	W	WSW
Percentage	9.95	8.42	4.99	23.70	41.60	8.97

For the wave modelling, five “wave cases” were selected, corresponding to two different directions. The most common wave condition is represented by a significant wave height (Hs) of 0.68 m, a period (Tm) of 4.64 s and a direction (Dir) of 276°. Within this context, long period swell waves in this area have a direction of 347°, a wave height of 0.31 m and a period of 6.09 s. For completeness, locally-generated wind waves from this direction were also simulated; these have a wave height of 0.56 m and a period of 4.44 s. Furthermore, an average yearly storm wave (Hs 1.29 m, Tm 5.77 s, Dir 276°) and the average 5-yearly storm wave (Hs 1.40 m, Tm 6.00 s, Dir 276°) were modelled (Table 3). Because most sediment transport takes place during storm conditions, the results of the latter will be discussed in detail.

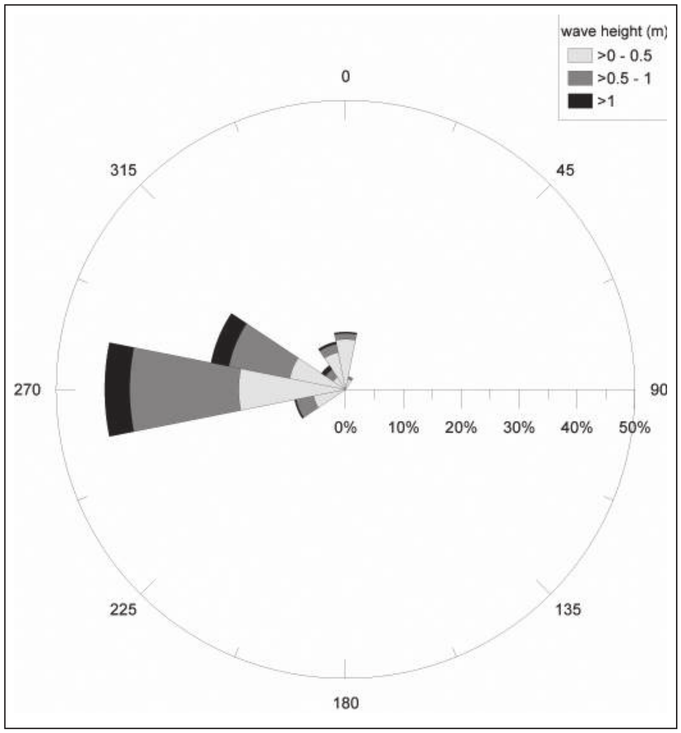

Figure 3. Distribution of wave directions and wave height, from measurements obtained at the StAUN Messnetz station at Ahrenshoop, for the period 1998-2002.

Table 3. *Parameters of the modelled wave conditions (significant wave height, mean period and wave direction).*

Wave cases	Hs (m)	Tm (s)	Dir (°)
Local waves 1	0.68	4.64	276
Local waves 2	0.56	4.44	347
Swell	0.31	6.09	347
Storm (1y)	1.29	5.77	276
Storm (5y)	1.40	6.00	276

RESULTS

Bathymetry

Bathymetric changes between 1976-1979 and 1996-2002 are subtle (Figure 4) and, in general, lie within the range of the maximum vertical error of the bathymetry (around ± 1 m). The highest rate of seabed erosion (4.5 m, in ca. 20 years) can be found in a small area close to the extraction site of Wustrow. The broad shallow zone (<10 m), offshore of Graal-Müritz is stable, typically showing no change. In general, accretion takes place in the coastal zone close to the Wustrow coast; erosion occurs in the offshore area to the NE of Graal-Müritz (Figure 4).

Coastline

The location of the coastline has fluctuated considerably between 1953 and 2002. Comparing the 1953 and 2002 coastlines, two areas of maximum erosion (of up to 3 m per year) can be identified: the coast to the south of Graal Müritz, and the Darss area (Figure 5). However, a maximum accretion of 3-5 m per year takes place at the northerly tip of the Darss Peninsula, immediately to the north of the rapidly-eroding Darss coast (Figure 6). In general, the coastline from the south of Graal-Müritz to Dierhagen is mainly erosional, except for a small section of prograding coastline, lying close to the town of Graal-Müritz. This accretional zone is located in an area where repeated beach nourishment has been undertaken (MBLU, 1995). The coast from Dierhagen to Wustrow has experienced, overall, a small amount of accretion; whilst, from the north of Wustrow up to Darss, an overall erosional trend was observed.

The extensive coastal protection works, including groynes, breakwaters and beach nourishment projects, make it difficult to distinguish (from the aerial photographs) the natural trend in shoreline evolution. For example, the two large accretional peaks near Wustrow and Ahrenshoop (Figure 5) are associated with the breakwater construction in 1985 and 1986, respectively. Subsequently, considerable accretion has taken place on the lee side of these breakwaters.

Wave and sediment transport modelling

The results of the simulation of WNW storm waves show that they focus upon particular areas of the coastline, as a result of the offshore bathymetry. The subtle differences between the old and new bathymetry cause also small changes in the nearshore wave conditions (Figure 7). Within the Graal-Müritz area, the offshore wave height has increased; however, most of the energy dissipates before the waves reach the shore (Figure 7). The changes in the Wustrow area are most

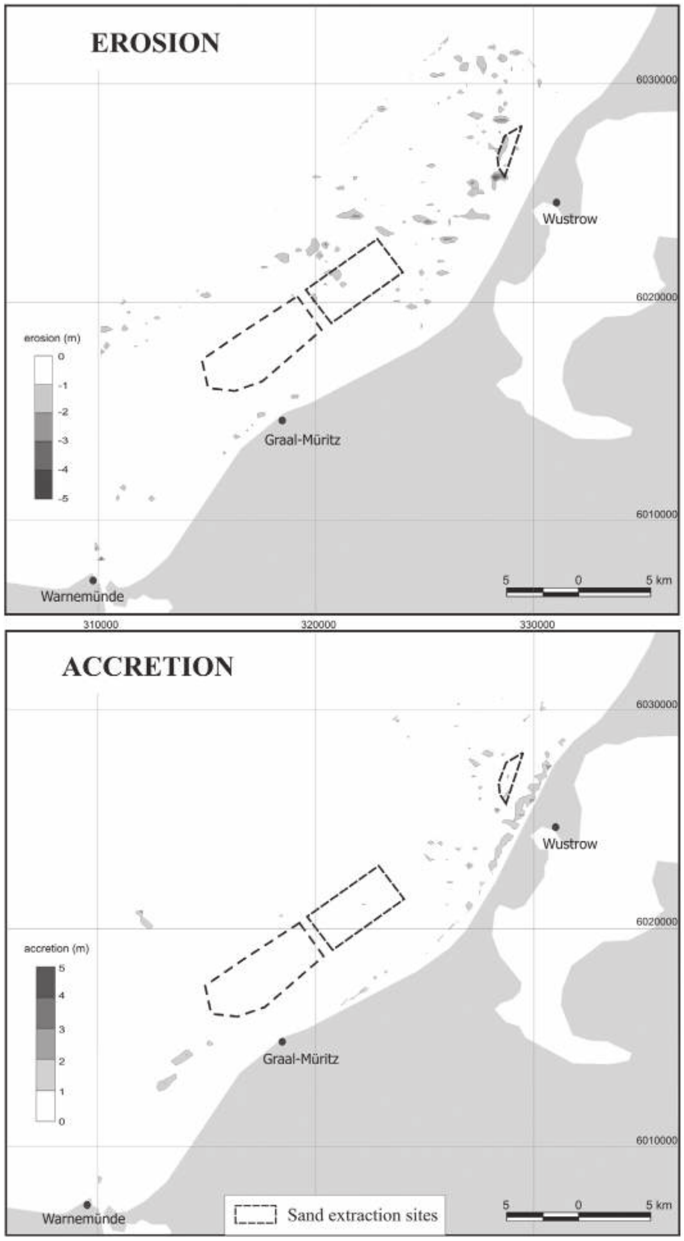

Figure 4. Comparison of the bathymetry of 1976-1979 and 1998-2002, showing areas of erosion and accretion. Corresponding to a maximum vertical error of ca. 1 m, the changes from 1 m and more are indicated. The largest erosion of almost 5 m is found directly to the SW of the Wustrow extraction site.

pronounced at the extraction site, where wave heights have increased.

Most sediment transport takes place during storm conditions. The simulation of WNW storm waves shows sediment transport mainly at bathymetric depths down to 2-3 m and not beyond the 4 m depth contour. The direction of wave-induced sediment transport, for waves coming from a 276° direction, is towards the NE. However, the modelled waves, with a direction of 347°, generate sediment transport in a SW direction. Since the prevailing wave direction is from the W and WNW (Figure 3 and Table 2), the dominant sediment transport direction is towards the NE.

The calculations of sediment transport potential for the modelled storm waves show distinct peaks along the coast, in the Wustrow area. These peaks are located generally within the same area for the pre- and post-dredging bathymetries. However, there is an increase in transport potential in the area located landward of the extraction site, in the post-dredging scenario. Comparison of the transport potential, for the old and new bathymetry in the Graal-Müritz area, shows a very distinct peak of 58 $m^3/h/m$ during the period of 1976-

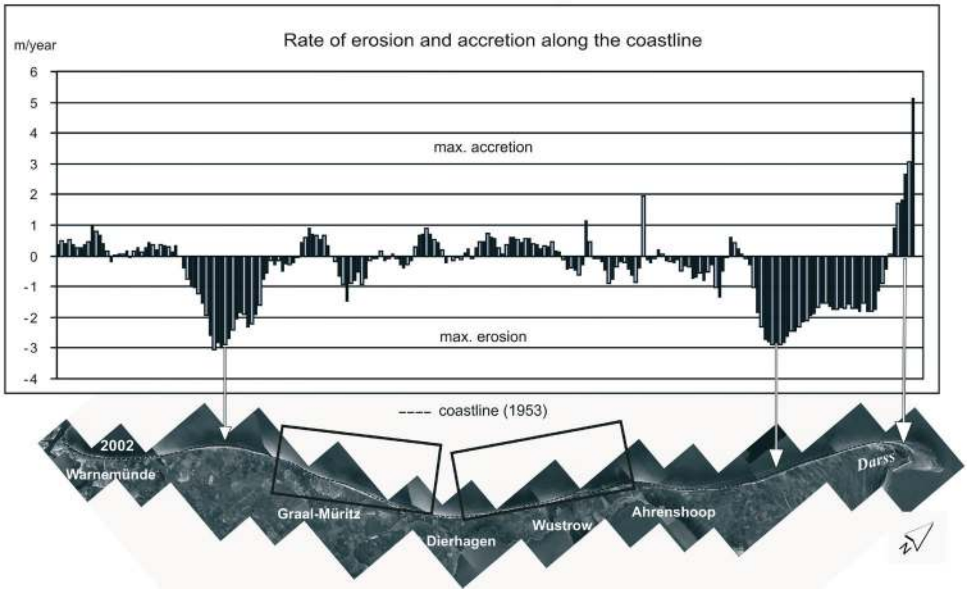

Figure 5. A rotated mosaic of aerial photographs of the 2002 coastline, from Warnemünde in the South to the Darss Peninsula in the North. The mouth of the Warnow River can be seen in the South, close to Warnemünde.The two rectangles indicate the modelling grids. The graph shows the average rate of erosion and accretion (m/year) along the coastline, between 1953 and 2002.

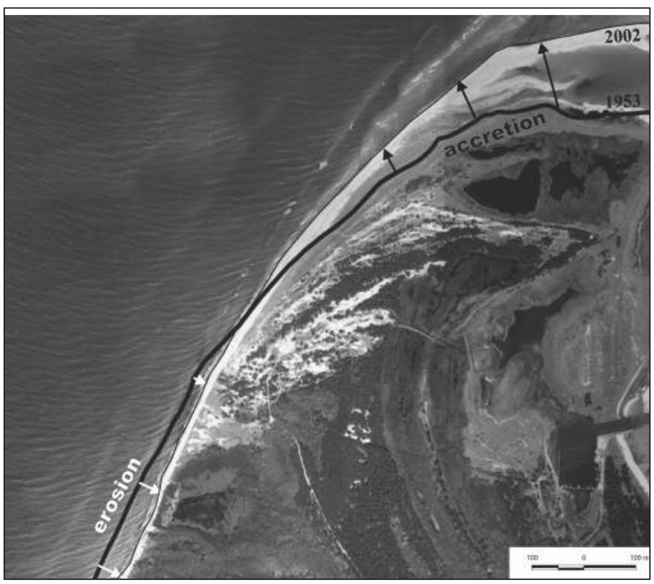

Figure 6. Aerial photograph of 2002, focusing in upon the northern part of the Darss Peninsula. The coastlines from 2002 and 1953 are shown, indicating clearly a change from erosion in the south to accretion in the north.

1979, which has disappeared almost entirely in 1996-2002 (Figure 8). The analysis of the coastline locations indicates that, between 1953 and 1988, this area was eroding rapidly, even though beach nourishment was undertaken here (MBLU, 1995). Erosion rates have decreased over the period extending from 1988 to 2002 (Figure 8).

DISCUSSION

Offshore sediment extraction may affect the coastline in different ways. It may interrupt or modify coastal sediment supply, or alter sediment transport rates and pathways, as a result of changing waves or currents. In the micro-tidal German Baltic Sea, the effect of MA extraction on tidal currents can be neglected. Furthermore, dredging takes place well beyond the active beach profile. Sand extraction in this area does not remove nearshore sandbanks and, hence, will not cause any reduction in the shelter provided to the coastline. As such, extraction in this area may affect nearshore wave conditions and associated sediment transport and the total sediment budget at the shoreline; these factors need to be assessed.

Wave modelling has shown that, even though the changes in bathymetry observed over a period of 20 years are subtle, they have resulted in modifications to the waves. Consequently, alterations have taken place in the sediment transport at the coast (Figure 8). The largest change in transport potential is identified as lying between Graal-Müritz and Dierhagen, where a decrease from 58 m^3/h in 1976-1979, to approximately 20 m^3/h in 1996-2002, was found. Overall, the sediment transport potential is higher for the Wustrow area, than for the Graal-Müritz area; this corresponds to the findings of WEILBEER and ZIELKE (1999). Their investigations conclude that the steeper bathymetry, to the north, causes more wave energy to reach the coast; this, in turn, results in a higher transport potential.

The results of the modelling show that the extraction sites lie outside the area of wave-induced sediment transport; this is consistent with the results of DIESING *et al.* (2006), who calculated that the closure depth for this area is 4 m. Detectable morphological changes over longer timescales (decades to centuries), occur down to a limiting depth

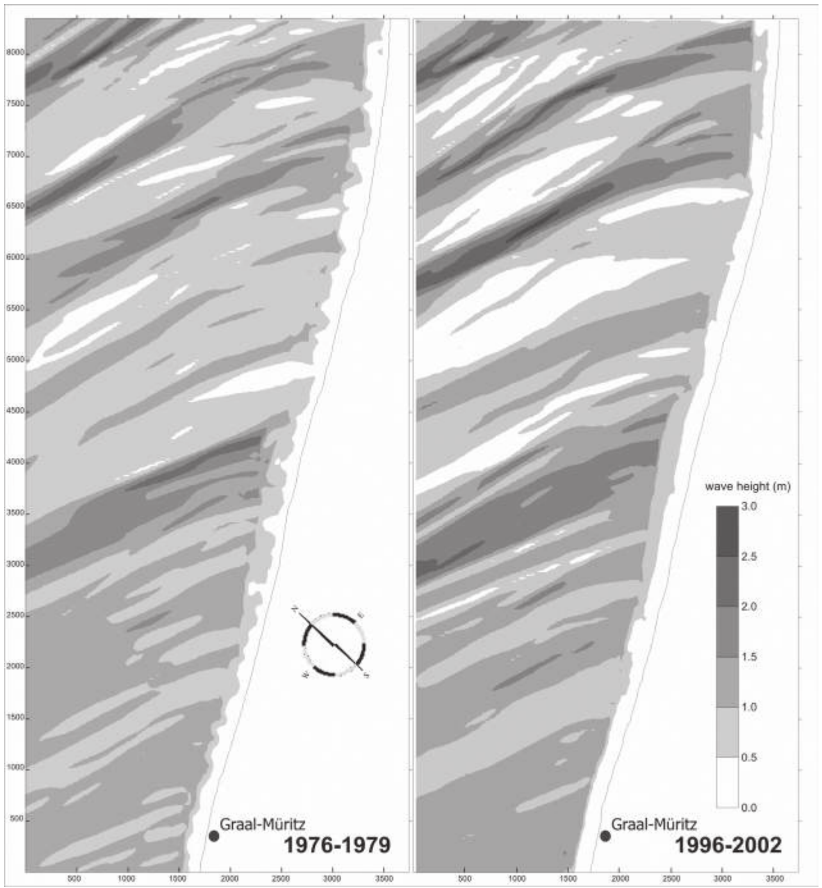

Figure 7. Wave heights for the modelled 5-yearly storm (Hs 1.40 m, Tm 6.00 s, Dir 276°) in the Graal-Müritz area: (a) modelled wave heights for the 1976-1979 bathymetry; and (b) modelled wave heights for the 1998-2002 bathymetry. Note the areas of wave focussing in the north and centre of the coastline. For the location of the modelling area, see Figures 1.and 5.

of h_i = 10 m (Diesing *et al.,* 2006). However, short-term changes and, therefore, sediment transport, were shown to occur down to depths of 8-13 m, as observed from repeated side-scan sonar surveys, following dredging. The dredged furrows at Graal Müritz were almost completely refilled after 6 months (Diesing, 2003); those at Wustrow showed considerable infilling, after 10 months (Krause, 2002). Interestingly, the bedforms offshore from Wustrow are located also in water depths lying beyond those associated with wave-induced sediment transport. According to Lemke *et al.* (1994), these bedforms are the result of currents generated by the inflow of saline bottom water from the North Sea. Bedform changes that have been observed indicate flow velocities of 70-100 cm/s; these only seldomly occur, typically on time-scales of months-years (Lemke *et al.,* 1994). These NE-flowing currents cause the transport of sediments in offshore areas beyond the zone of wave-induced transport. Thus, both the dominant directions of wave-induced sediment transport and the current-induced sediment transport are in a NE direction. Such transport moves sediment out of the area, to Darss, where it is deposited, accumulating along the Darss Peninsula. Long-term accretion in this area is indicated also by a sequence of Holocene beach ridges (Lampe, 2002), running parallel to the present-day coastline (Figure 6). The Darss area is a National Park, where extraction activities are prohibited.

Overall, the coast from Warnemünde to Darss has only a limited amount of marine sand resources: the cover of Holocene sand is thin (Diesing, 2003; Krause, 2002), whilst there is little contemporary input from the rivers. The main sediment source is erosion of retreating cliff sections (Hoffmann and Lampe, 2007). An increase in storminess in the Baltic Sea area, as reported by Kont *et al.* (2005), together with a rise in sea level will result in an increase in cliff erosion; hence, increase the supply of sediment to the coastal zone (Hoffmann and Lampe, 2007). At the same time, it will lead also to an increase in beach erosion and sediment transport, by wave action. Extraction of sediment for local beach nourishment may bring offshore sand into the zone of wave-dominated sediment transport, where it will be transported towards the northeast. Extraction of sediment for industrial use will leave the system completely.

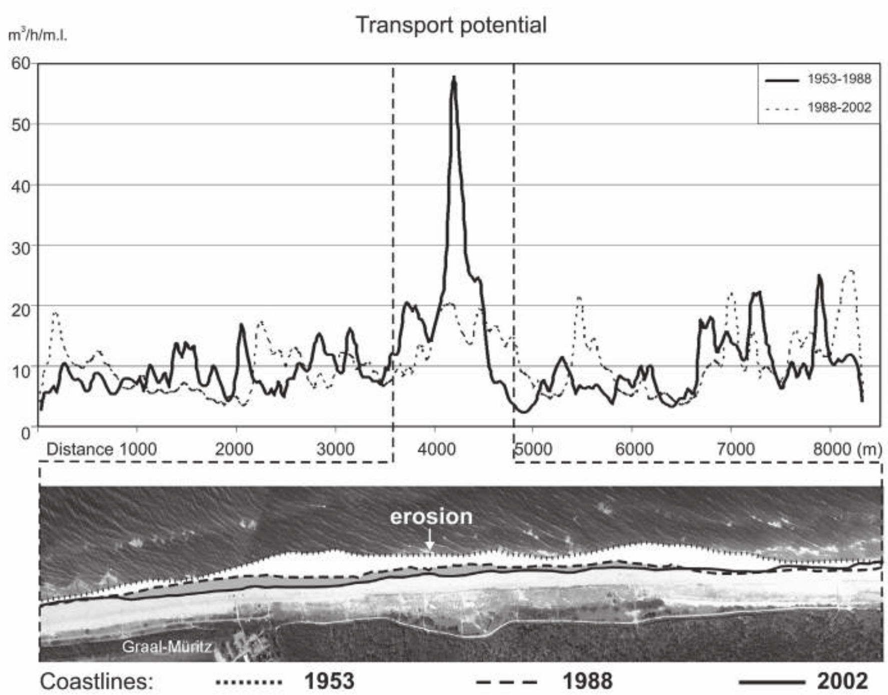

Figure 8. Sediment transport potential calculated by SMT for the coast from Warnemünde to the Darss Peninsula. Note the large peak in transport potential for the old bathymetry, which has now completely disappeared. The aerial photograph shows the location of the peak in sediment transport potential along the coastline between Graal Müritz to Dierhagen (the area between the dotted lines in the graph). Also indicated are the coastlines of 2002, 1988 and 1953.

CONCLUSIONS

Few examples exist of direct coastal erosion caused by marine sand extraction; these relate to the removal of sand from the upper shoreface. In the Baltic Sea, dredging takes place well beyond the depth of wave action, i.e. in water depths of 8-13 m. No direct relationship was found between changes in bathymetry and those at the coastline. It is suggested that the coastal changes result mainly from extensive coastal protection works carried out in the area. Therefore, it is difficult to assess the effects of dredging on the coastline in the area of Warnemünde to Darss. However the present study has indicated a few points of concern, as outlined below.

- Only very small changes in bathymetry (1-2 m) are sufficient to cause significant modifications in sediment transport potential at the coast and, thus, alternations in the patterns of erosion and accretion. Therefore, care should be taken that extraction does not cause lasting changes in the bathymetry.
- Overall, the coast from Warnemünde to Darss is an eroding coast. Sediment is transported in a NE direction by both wave action and currents, induced by the inflow of North Sea water. Such material is deposited in the Darss area, in a National Park, where dredging is prohibited.
- There is very little input of sediment into the system. The main source of sediment is material eroded from cliff sections. Any sand that is removed by MA extraction, for industrial use, will have a negative effect on the total sediment budget at the shoreline.

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