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LAND RECLAMATION AS A CAUSE OF FINE-GRAINED SEDIMENT DEPLETION IN BACKBARRIER TIDAL FLATS (SOUTHERN NORTH SEA)

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KEYWORDS: Sediment depletion; tidal flats; land reclamation; Wadden Sea.

ABSTRACT

Grain size distribution patterns along the East Frisian coast (German Wadden Sea) were evaluated with the aim of identifying potential effects of man-made structures (*e.g.* dikes) on the textural composition and sediment budget of the area. It was found that the distribution of various grain size fractions and settling velocities revealed a well-defined cross-shore energy gradient. Adjacent to the mainland dike the sediment is dominated by the 3.0-3.5 phi sand fraction (>70% by weight). In comparison to the sedimentary sequences normally observed in unobstructed backbarrier depositional environments, the sediments along the land-ward margin are in this case conspicuously depleted in grain sizes <3.5 phi, the corresponding size fractions contributing <20% by weight. This suggests that the dike interrupts the normal energy gradient, thereby inhibiting the deposition of sediments with settling velocities <0.5 cm s^{-1}. This interpretation is confirmed when comparing individual cross-shore transects. The shorter the transect between the barrier island shore and the dike, the greater the fine sediment depletion. Since many faunal assemblages are grain-size specific, it is further suggested that the backbarrier ecosystem must have undergone significant modifications as a result of the substantial reduction in mud flats since the onset of dike construction some 1000 years BP. It is predicted that in the wake of the persisting and possibly accelerating sealevel rise this process of fine sediment depletion will continue and also affect progressively coarser sediments.

INTRODUCTION

It has long been recognized that the interference of man with nature often has detrimental side effects. In the coastal zone such interferences usually affect the local hydrology and this commonly triggers morphological adaptation processes. Along the East Frisian barrier island coast many morphological stability problems can be linked to manned changes in the tidal prism (*e.g.* WALTHER, 1972; LUCK, 1975, 1976; FITZGERALD *et al.*, 1984; FLEMMING, 1991; FLEMMING and DAVIS, 1994).

Although numerous studies dealing with the effects of man-made structures on the hydrology and morphology of local coastal systems have been undertaken (*e.g.* RENGER and PARTENSCKY, 1974; RENGER, 1976; REINECK and SIEFERT, 1980; DIECKMANN, 1985; LOUTERS *et al.*, 1991), their effects on sediment texture and grain size distribution patterns have not been investigated in any detail.

Barrier island depositional sequences commonly commence with a tide-dominated lower shoreface on the seaward side, followed shorewards by a wave-dominated upper shoreface, a barred surf zone and ebb-delta complex, a barrier beach, supratidal flats, aeolian dunes, overwash fans, backbarrier sand flats and channel systems, mixed flats, mud flats and finally extensive salt marshes (*e.g.* REINECK and SINGH, 1973). On the basis of their mud content, German tidal flats have been

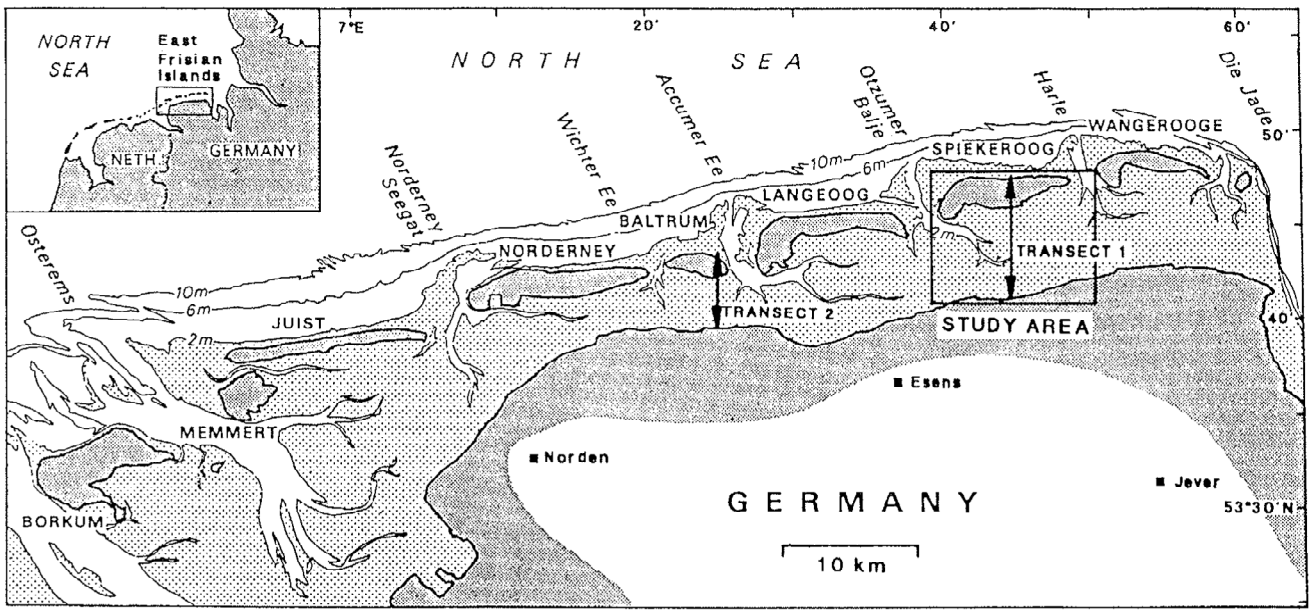


Fig. 1. Map of the East Frisian Wadden Sea showing the study areas and the position of the transects discussed in the text. Tidal flats are stippled.

divided into three major depositional units, *i.e.* sand flats comprising 5-10% mud, mixed flats with 5-50% mud, and mud flats characterized by mud contents >50% (SINDOWSKI, 1973; REINECK and SIEFERT, 1980). The three depositional units form coast-parallel belts, with the muddy facies being situated closest to the shore (REINECK *et al.*, 1986). This spatial arrangement of shoreward-fining depositional units, reflecting a coast-perpendicular energy gradient, has been the subject of numerous studies (*e.g.* HÄNTZSCHEL, 1955; VAN STRAATEN and KUENEN, 1957; VAN STRAATEN, 1961; POSTMA, 1961; EVANS, 1965; REINECK, 1967, 1972; REINECK *et al.*, 1986). None of these studies, however, addresses the significant changes that must have occurred in both the sedimentary regime and the associated fauna in response to land reclamation and dike construction.

In contrast to natural backbarrier environments, the hydrology and morphology of the Wadden Sea has been substantially modified by progressive land reclamation and dike construction over the past 1000 years. Thus, the area of the Wadden Sea as a whole has been greatly reduced, while the width of the backbarrier tidal flats has become considerably narrower in most places. In the present study the effects of these physical interferences on grain size texture, sediment distribution and depositional sequence are investigated and evaluated relative to the energy gradient in the German Wadden Sea.

MATERIALS AND METHODS

The study area is situated along the barrier island coast of Germany near the East Frisian island of Spiekeroog (southern North Sea; Fig. 1). For the purpose of this study some 1200 samples, collected on a dense grid (*ca.* 280 x 280 m) covering almost a complete tidal catchment (Fig. 2), were evaluated. Sample positions were fixed by means of a portable DECCA Navigator which was calibrated before each sampling campaign. In addition, a set of similarly spaced samples was taken for comparative purposes along a north-south transect in the backbarrier tidal flats of the island of Baltrum, where the distance between the island beach and the mainland dike is considerably shorter (Fig. 1).

The samples were processed according to standard laboratory procedures (*e.g.* CARVER, 1971). After desalination the mud content was determined by wet sieving, while splits of the remaining sand fraction were run through an automatically recording settling tube system with a resolution of 0.02 phi (BREZINA, 1979). Settling velocities are presented at a standardized temperature of 24°C or in form of equivalent settling diameters based on a glass sphere standard.

In the course of this study a major discrepancy between the settling tube and the corresponding sieve results became evident. In particular, a significant difference was observed in the relative proportions of the individual very fine sand fractions

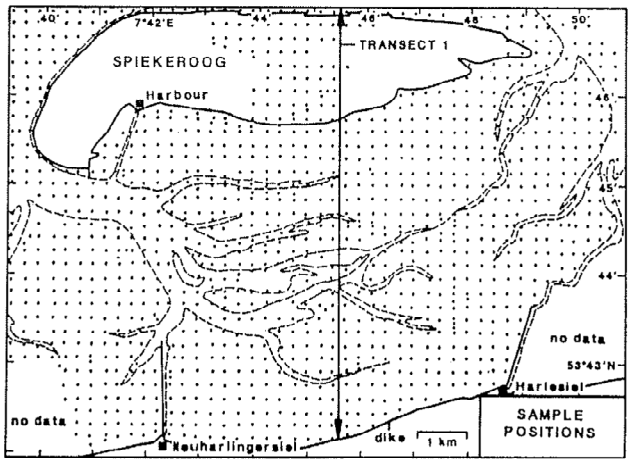


Fig. 2. Physiography, sample grid and position of Transect 1 of the main study area.

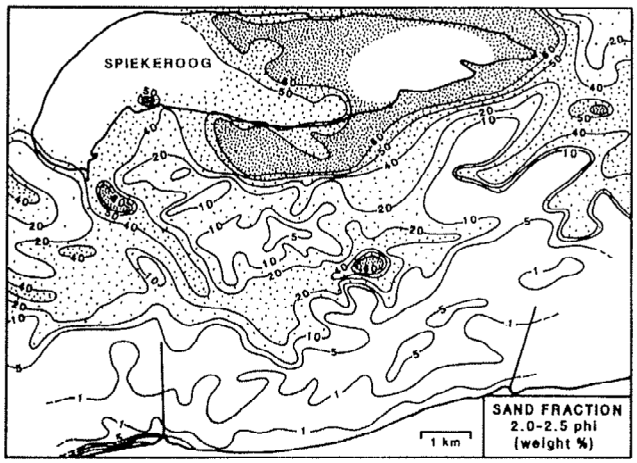


Fig. 3. Distribution pattern of the coarser fine sand fraction (2.0-2.5 phi or 0.250-0.177 mm).

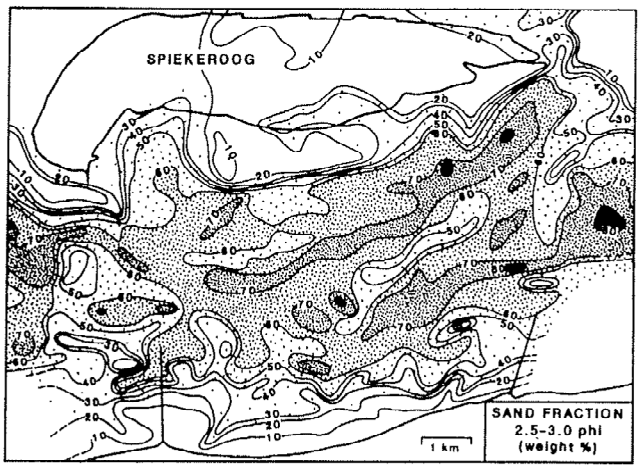


Fig. 4. Distribution pattern of the finer fine sand fraction (2.5-3.0 phi or 0.177-0.125 mm).

recorded by the two analytical methods. The settling tube registered a marked reduction in the contribution of the 3.5-4.0 phi fraction, this trend not being reflected in the sieve data. Since the settling tube data are used to corroborate the sediment depletion hypothesis presented in this paper, a careful error assessment was carried out to ensure that the settling tube data were reliable. Analytical errors can occur if the settling tube is wrongly calibrated and/or if density currents develop during the settling process due to overloading with sediment (*e.g.* BREZINA, 1979), all other effects being negligible by comparison (*e.g.* FLEMMING and THUM, 1978). Calibration errors were discounted after cross-checks were made with glass sphere standards (FLEMMING and ZIEGLER, 1995). With respect to density currents, a slight effect of settling convection was observed with sample splits >1 g. This error, however, accounted for 5% of the observed deviation at the most. On the basis of these error assessments it was concluded that the settling tube results were accurate and that the observed discrepancy between the two methods reflects a hydraulic incompatibility of the sieve data.

For the purpose of this study, grain size distributions are illustrated by the spatial patterns produced by individual 0.5 phi size fractions.

RESULTS

At the seaward margin of the study area, the coarsest sand fraction (coarser fine sand: 2.0-2.5 phi or 0.250-0.177 mm) occupies most of the barrier island, the adjacent backbarrier salt marshes and upper intertidal flats, as well as a number of small patches situated to the south of the western island head and in the central tidal flats (Fig. 3).

The next finer fraction (finer fine sand: 2.5-3.0 phi or 0.177-0.125 mm) covers most of the central tidal flats, reaching concentration levels of more than 80% by weight in places (Fig. 4). A few narrow belts of limited extent, incorporating either slightly finer or slightly coarser material, interrupt the pattern. Such localities indicate the influence of mussel beds or channel margin deposits, respectively.

The shoreward margin of the backbarrier tidal flats, immediately to the north of the mainland dike, is dominated by the coarser very fine sand fraction (3.0-3.5 phi or 0.125-0.088 mm), reaching concentration levels >70% by weight (Fig. 5).

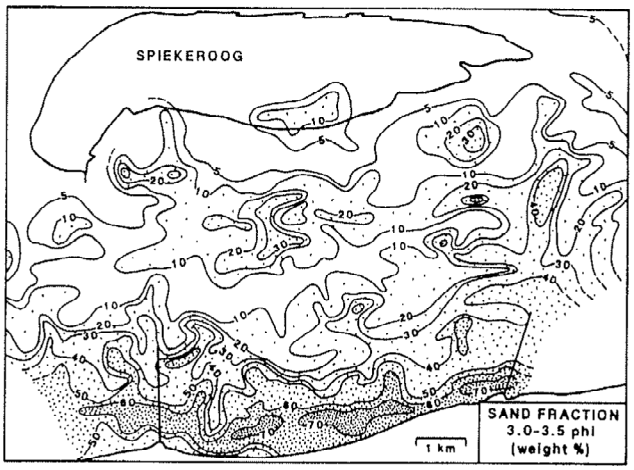


Fig. 5. Distribution pattern of the coarser very fine sand fraction (3.0-3.5 phi or 0.125-0.088 mm).

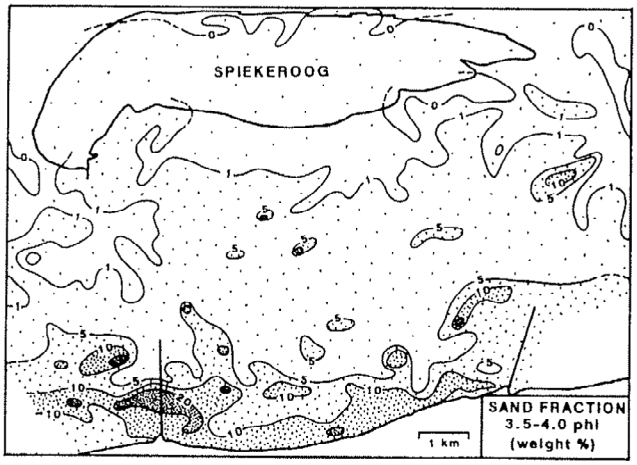


Fig. 6. Distribution pattern of the finer very fine sand fraction (3.5-4.0 phi or 0.088-0.063 mm).

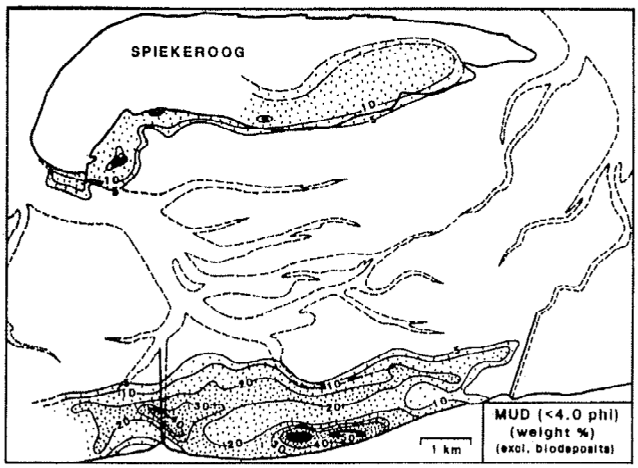


Fig. 7. Distribution pattern of non-biogenic mud deposits (all grain sizes >4.0 phi or <0.063 mm).

In contrast to the 3.0-3.5 phi fraction, the finer very fine sand fraction (3.5-4.0 phi or 0.088-0.063 mm), while occupying almost the same corridor as the coarser very fine sand fraction, contributes barely more than 10% by weight to the total sand fraction over most of the area (Fig. 6). Values reaching up to 20% are restricted to a few small patches.

The mud fraction (all grain sizes <4.0 phi or <0.063 mm) shows a similar distribution pattern as those of the very fine sand fractions, the concentration of mud being higher adjacent to the mainland dike. In addition, it contributes minor quantities to the sediments of the salt marshes situated in the shelter of Spiekeroog Island (Fig. 7). Mud concentrations >30% occur in two small areas, one of which is situated in the south-central part of the mud reach, the other in the vicinity of the approach channel to Neuharlingersiel harbour. It should be noted that the mud fraction attains significantly higher concentration levels than the finest very fine sand fraction, although neither reach values comparable to the other size fractions. The disaggregated muds were not further analyzed as it would have been impossible to determine the true equivalent settling diameters of the original aggregates.

DISCUSSION

All of the 0.5-phi size fractions show coast-parallel distribution patterns, the coarsest sediments being concentrated on the seaward, the finest on the landward side. The only significant deviation from this pattern is observed in the deeply scoured inlets west and east of Spiekeroog Island, where the sediments are dominated by coarse lag deposits (FLEMMING *et al.*, 1992). The progressively shoreward-fining sequence can be viewed synoptically in a composite sediment facies map, on which the 50% concentration contours of the individual size fractions have been superimposed (Fig. 8). In addition, a cross-shore selection of grain size frequency distributions, illustrating the shoreward-fining trend, is also shown in this figure. The bimodality of some of the size frequency distributions demonstrate that the sediment is not only subject to progressive size sorting, but that mixing between different hydraulic populations also occurs. In effect, this means that the sediments of the region comprise two or more hydraulic populations, each being progressively size sorted in the course of landward transport and each overlapping with the next finer population before dropping out.

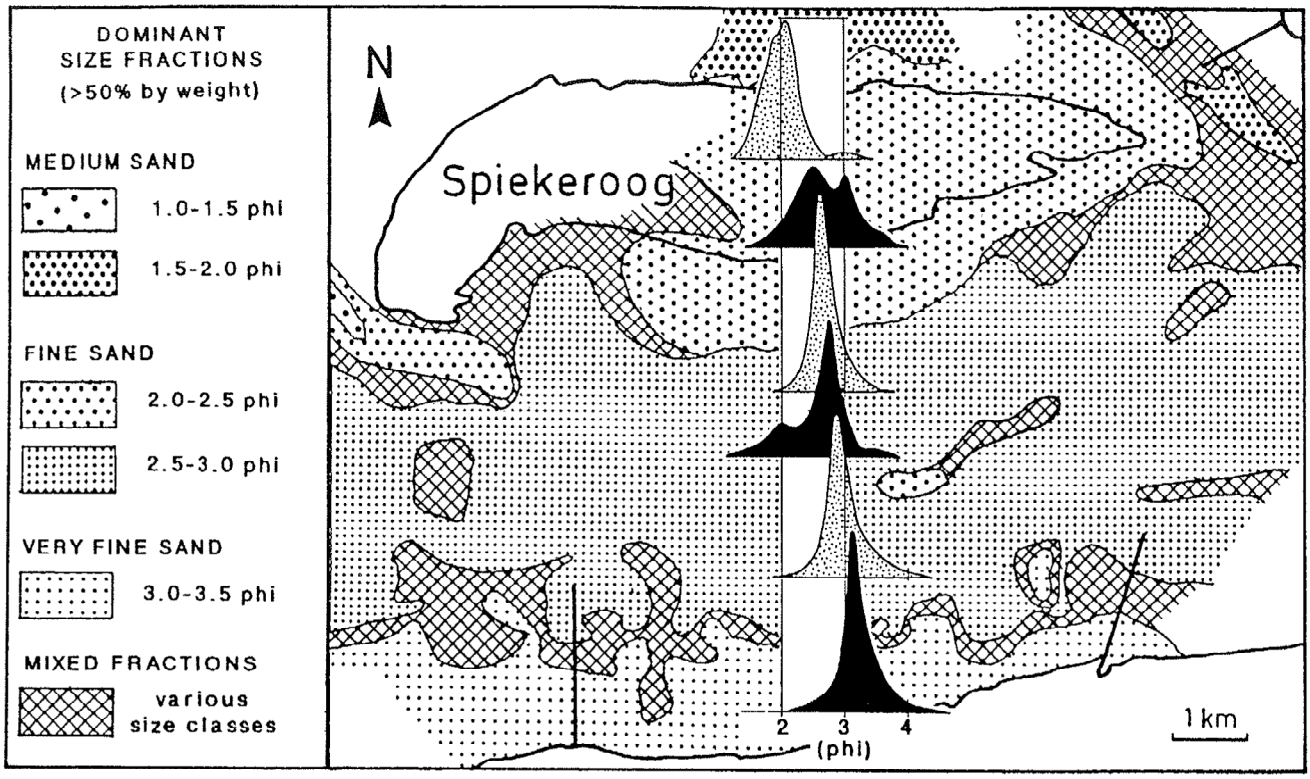


Fig. 8. Synoptic view of the distribution pattern of dominant size fractions in the study area and selected size frequency distribution curves (black and stippled) along Transect 1 (for location see Fig. 1).

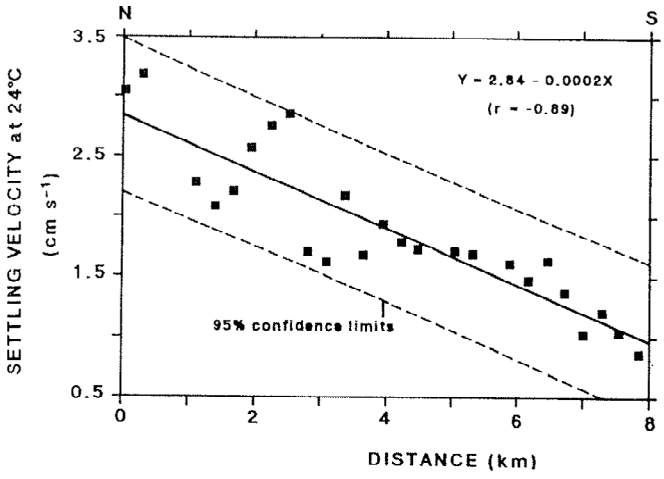


Fig. 9. Settling velocities in cm s^{-1} (at 24°C) of backbarrier sands as a function of cross-shore distance (0 km = barrier island beach). Data from Transect 1 (see Fig. 1).

The shoreward-fining trend clearly reflects a decreasing energy gradient. This is perhaps even better illustrated by a progressive decline in mean settling velocities along the gradient (Fig. 9). Beginning at the island beach, the mean settling velocity of the sediment steadily decreases from around 3 cm s^{-1} to about 0.5 cm s^{-1} (at 24°C), *i.e.* by a factor of 6, when extrapolating the regression line of Fig. 9 towards the mainland dike. The highly significant correlation between settling velocity and cross-shore distance ($r = -0.89$) demonstrates the extremely sensitive response of the sediments to the energy-controlled sorting process.

As pointed out above, the nearshore muds and finer very fine sands not only occupy the same depositional zone as the coarser very fine sands, but are in addition strongly depleted (see Figs. 5, 6 and 7). To explain this one must assume that the size spectrum of suspended matter in the water column includes aggregates with settling velocities equivalent to that of the very fine sand (*i.e.* 0.5-1.0 cm s^{-1} at 24°C). The mud and finer very fine sands, however, hardly contribute more than 20% by weight to the total sediment when viewed on a regional scale. This can only mean that the energy levels adjacent to the mainland dike are too high to allow the deposition of suspended sediments with effective settling velocities below about 0.5 cm s-1. This value compares favourably with settling velocities of larger flocs and aggregates reported in the literature: 0.01-0.65 cm s^{-1} (OWEN, 1971); 0.07-0.55 cm s^{-1} (STERNBERG *et al.*, 1986); 0.02-0.57 cm s^{-1} (KINEKE *et al.*, 1989); 0.1-0.5 cm s^{-1} (VAN LEUSSEN and CORNELISSE, 1992), as summarized in NICHOLS and BIGGS (1985) and EISMA

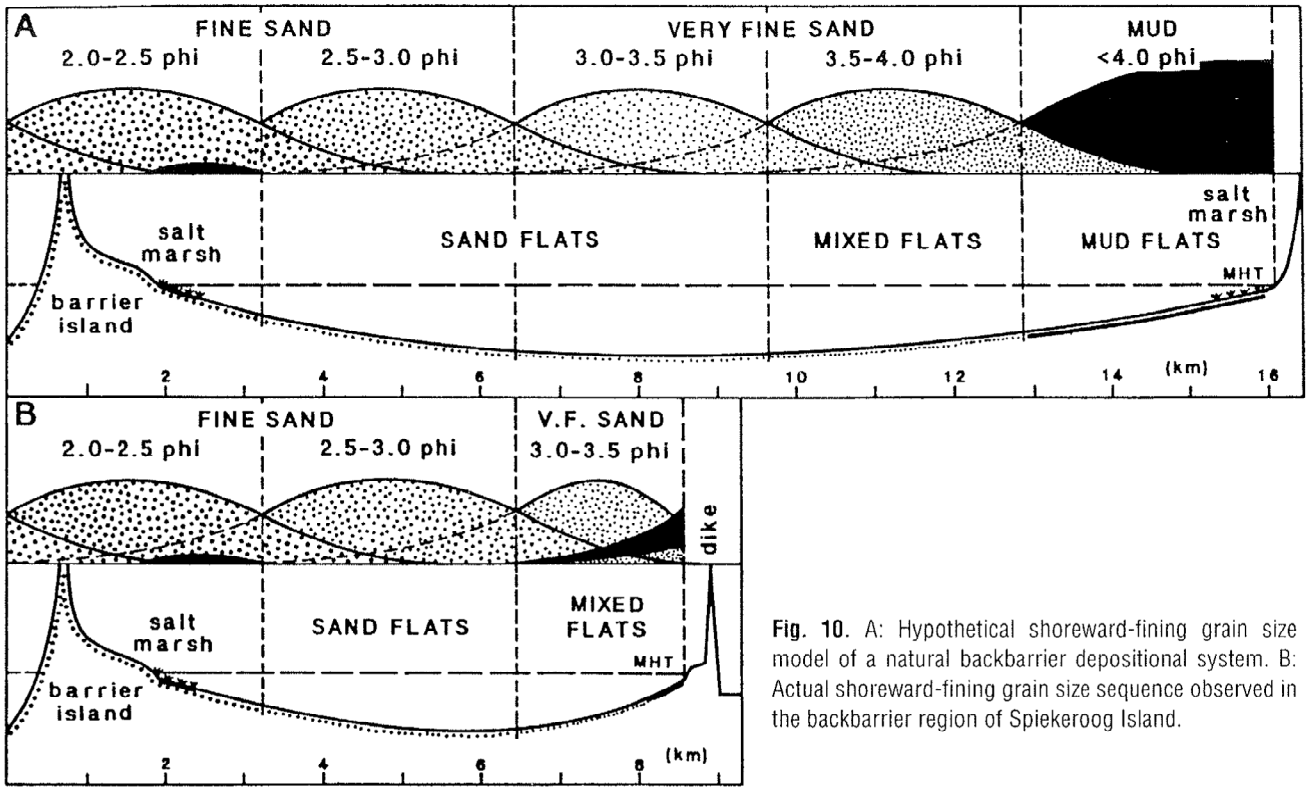


Fig. 10. A: Hypothetical shoreward-fining grain size model of a natural backbarrier depositional system. B: Actual shoreward-fining grain size sequence observed in the backbarrier region of Spiekeroog Island.

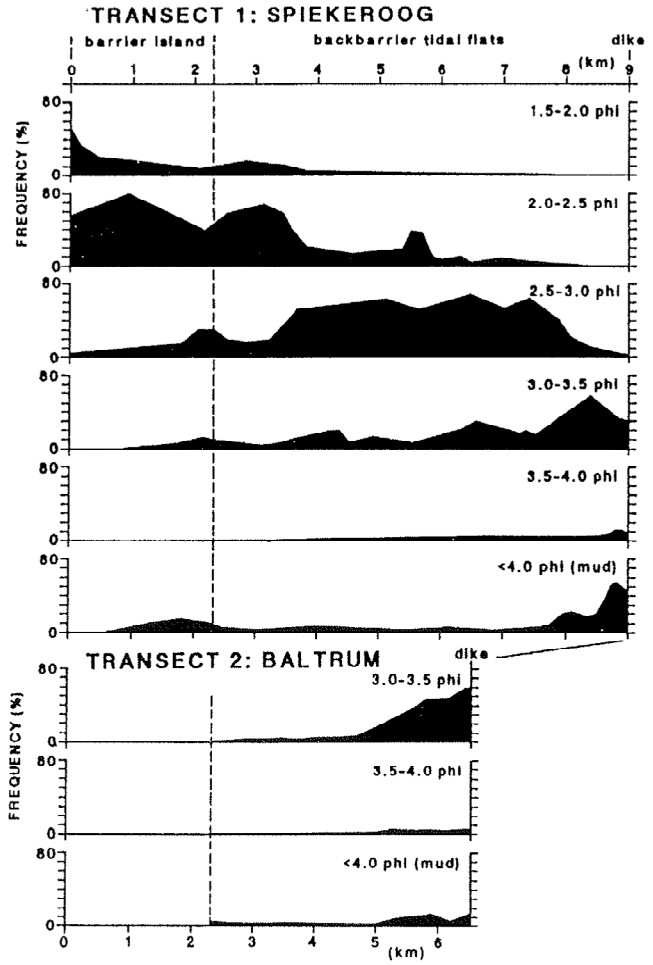


Fig. 11. Comparison of cross-shore grain size trends as a function of transect length along Transect 1 (Spiekeroog) and Transect 2 (Baltrum) (see fig. 1).

(1993). The postulated model of fine sediment depletion is thus corroborated by particle settling behaviour observed elsewhere. In the present case, the critical settling velocities evidently reflect the coarser part of the aggregate size spectrum which is hydraulically equivalent to the coarser very fine sands (3.0-3.5 phi or 0.125-0.088 mm).

The progressive shoreward elimination of the finest sediments in the backbarrier environment of the Wadden Sea contrasts sharply with sediment gradients commonly observed in similar environments elsewhere (*e.g.* KELLERHALS and MURRAY, 1969; SWIFT, 1975; HAYES, 1975, 1979; McCANN, 1979; KRAFT, 1971; KRAFT *et al.*, 1973, 1979; KRAFT and JOHN, 1979). From this it may be construed that without the mainland dikes the Wadden Sea too would have shown a normal energy gradient associated with progressive shoreward-fining sediments, culminating in thick mud and salt marsh deposits along the mainland coast. A hypothetical cross-section, in which the observed shoreward-fining sand belts are extended to include the finer sediment fractions, is shown in Fig. 10A. For comparison, the actual situation in the Spiekeroog tidal flats is shown in Fig. 10B. It illustrates how the finer sediment fractions have been eliminated by land reclamation and dike construction. Borehole data from the reclaimed land behind the dikes confirm that the finer sediments were originally indeed part of the de-

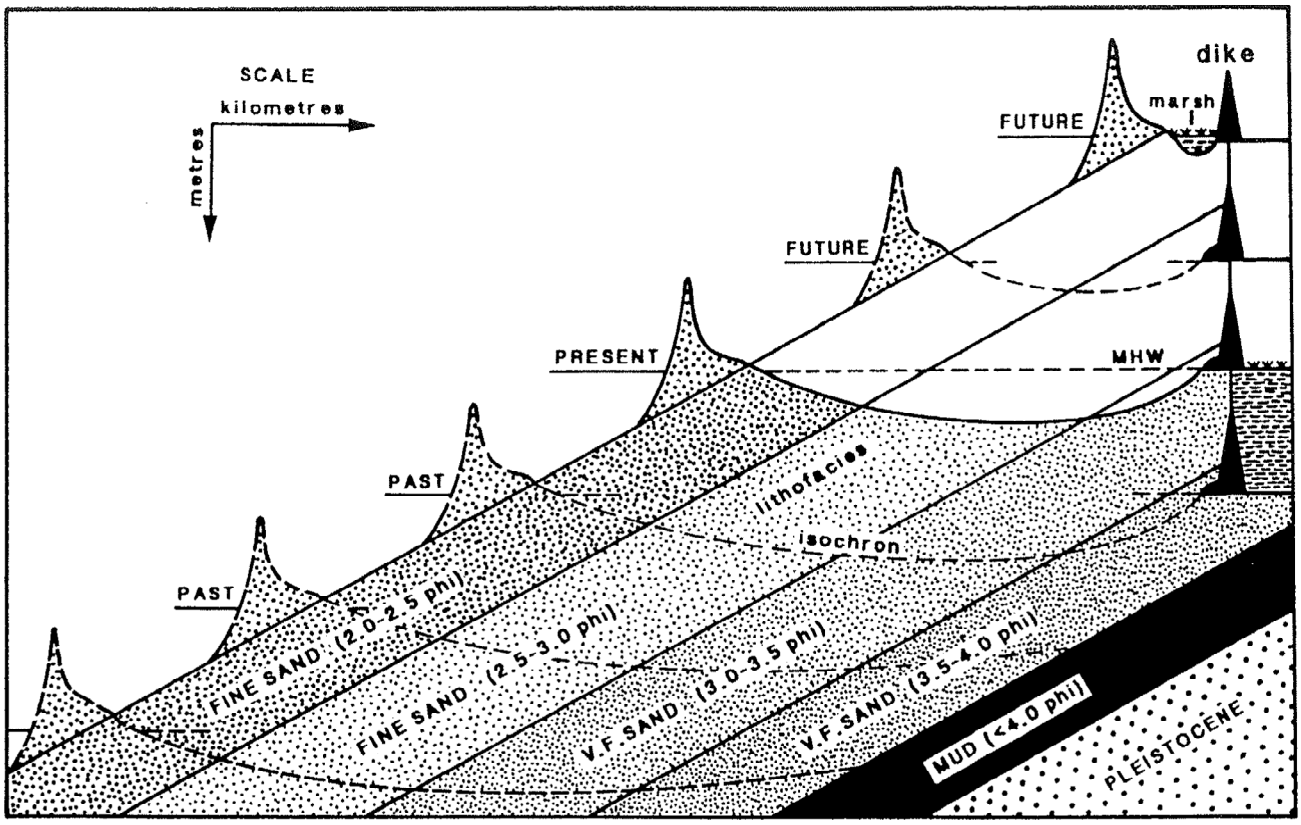


Fig. 12. Strongly simplified lithostratigraphic cross-section of a transgressive barrier island depositional system with and without a mainland dike.

positional sequence (*e.g.* ZAGWIJN, 1986; SINDOWSKI, 1973; STREIF, 1990). Furthermore, the dramatic reduction of mud flats to as little as 25% of their original area must have affected the structure of the Wadden Sea ecosystem, in particular with respect to the role of mud-dwelling organisms.

The size sorting model illustrated in Fig. 10 would imply that in cases where the backbarrier tidal flats are narrower than those behind Spiekeroog Island, the proposed sediment depletion process should have reached an even more advanced stage. That this is indeed the case is clearly demonstrated in Fig. 11, where a transect across the Spiekeroog tidal flats is compared with a transect across the Baltrum tidal flats, the latter being 2.5 km shorter. Whereas the coarser very fine sand fraction (3.0-3.5 phi or 0.125-0.088 mm) still dominates the environment, both the finer very fine sand and the mud fractions are further reduced, now barely contributing 10% to the total.

Finally, the late Holocene evolution of the barrier island coast along the southern North Sea can be viewed in form of a schematic transgressive lithostratigraphic cross-section (Fig. 12). Not only the pre-dike and modern lithofacies associations are shown, but also their future development in the course of the persisting and possibly accelerating sea-level rise, as would be predicted by the sediment depletion model presented in this paper. It is emphasized that the diagram is strongly simplified in order to specifically highlight the basic principle of the model.

CONCLUSIONS

Land reclamation and dike construction along the mainland coast have produced a steeper than normal energy gradient along the shoreward margin of the Wadden Sea. The resulting energy barrier substantially inhibits or prevents the deposition of sediments with settling velocities <0.5 cm s^{-1}, corresponding to equivalent settling diameters of 3.5 phi (0.088 mm) and finer.

The muds associated with the 3.0-3.5 phi sand fraction represent that part of the aggregate size spectrum that is hydraulically equivalent to the co-deposited sands.

The dramatic reduction of mud flats in the course of the past 1000 years has greatly reduced

the space available to mud-living organisms. As a result, the relative contribution of the mud fauna to the Wadden Sea ecosystem must have changed substantially over this period.

In the wake of continued and possibly accelerated sea-level rise and the resulting landward migration of the barrier island chain, it is predicted that the process of progressive fine sediment depletion in the Wadden Sea will continue.

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