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Sediment Transport Studies in the Tidal Basins of the Dutch Waddenzee

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With 5 Text-Figures

Key words: Grain size texture, sediment trend analysis, sediment transport paths, GIS, tidal basin, Wadden Sea.

Abstract

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In January 1991 GeoSea produced its first report for the Rijksinstituut voor Kust en Zee, Haren, which presented the results of a Sediment Trend Analysis (STA™) for the Eems/Dollard Estuary. An STA is a technique pioneered by GeoSea which uses the relative changes in the grain-size distributions of bottom sediments to develop patterns of net sediment transport. In addition, the technique defines the dynamic behaviour of bottom sediments with respect to erosion, deposition and dynamic equilibrium. The data base is comprised of the complete grain-size distributions from sediment grab samples that are collected over a predetermined grid which is typically at a 500 m spacing.

Since the completion of the Eems/Dollard study (680 samples), an STA has been undertaken more or less annually in each of the Dutch Waddenzee tidal basins: Vliestroom (1,500 samples) 1992; Marsdiep (2,000 samples) 1994; Friesche Zeegat (850 samples) 1995; Borndiep (1,200 samples) 1996 and the Lauwers/Schild (1,100 samples) completed in 1997. Two smaller projects were also undertaken. One looked in detail at the Dollard (1992) and another at the NOURTEC beach nourishment site on Terschelling as part of the Borndiep project (1995). The last time a grain-size data set on a regional scale was collected took place during the 1950's and covered only the intertidal areas.

The STA for each tidal basin produced broadly similar results. Offshore from the barrier islands, sediment transport parallels the shoreline in a north-east and east direction. At each tidal inlet this regime is interrupted by the dynamics associated with its corresponding tidal basin. Over the ebb-tidal deltas there are typically complex transport gyres that originate in the deepest portion of the channel separating the barrier islands. Inside the tidal basins transport is generally landward from the deeps and the sediment trends follow the dendritic network of channels with net accretion over the extensive intertidal flats. Fine sediments, often showing bimodal distributions, identified the wantijs or tidal null points that separate the tidal basins from each other.

The distributions of the sediments and the interpretative findings of the STA's may be used for many coastal management considerations such as: (i) the best locations for dredged material disposal sites; (ii) optimum channel alignment to minimise dredging; (iii) understanding the effects of coastal structures; and (iv) determining the dispersal of contaminants contained in the sediments. In addition, the Rijksinstituut voor Kust en Zee use the textural data for correlation with numerical models and for generating GIS-derived bottom sediment maps.

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Introduction

In 1989, GeoSea Consulting had undertaken two Sediment Trend Analyses (STA™) for RIKZ Den Haag in the Rotterdam approaches with particular regard to the disposal of dredge material at the Looswaal Noord site and the influence of this activity on beach processes north of the Rotterdam entrance. The sampling required for the STA's provided a detailed inventory of the sediment types (collected on a grid with 500 m spacing). The STA itself provided an understanding of the net sediment transport pathways together with a discussion of the probable processes and their effects on the dumpsite and adjacent shoreline. As a result of the findings of these studies, the Rijksinstituut voor Kust en Zee (RIKZ) asked GeoSea to undertake an STA in the Eems/Dollard Estuary as part of an overall project designed to assess the effects of dredging and disposal activities. Since that time studies have been carried out in all of the tidal basins of the Dutch Waddenzee providing a database containing the sediment distributions at some 6,000 locations as well as maps showing the net sediment transport pathways.

Materials and Methods

Sample Collection

The logistical support required for the sample collection was provided by the fleet of RIKZ research vessels. A sample grid was based upon a 1 km spacing in the offshore, but was reduced to 500 m and even 250 m in the tidal inlets, over the principle bathymetric features and in areas of particular concern such as disposal and beach nourishment sites, and areas requiring significant maintenance dredging. Samples were collected using a Van Veen type grab which typically collected the top 10–15 cm. Indertidal samples were sometimes collected by hand at low water using a two man all-terrain vehicle, and beach samples were taken along the midtide line using a Land Rover. Positioning was achieved by Syledis and differential GPS. In each case a sample of about 100 g was collected and bagged in numbered, self-seal bags.

Grain Size Analysis

All samples were analysed with a Malvern laser particle sizer to determine the grain-size distribution of sediments within the range of -0.5 phi (1.41 mm) to 10.5 phi (1 μ). This technique has two major advantages. Firstly, it is rapid and thus allows the analysis of large numbers of samples. Secondly, it provides a technique that gives a full distribution of the sand and fine sediment size ranges without merging data from different methodologies. The only exception to this is for sediments containing gravel (>0 phi; 1 mm) which are first sieved at 0.5 phi intervals. Sieve data are merged with the laser distributions using a reproportioning algorithm developed by GeoSea. Since STA looks at relative changes in the grain-size distributions a constancy of analytical method is essential.

Well mixed samples are introduced into the Malvern through a water bath which incorporates both mechanical and ultrasonic dispersion prior to passing the dispersed sediment through a laser beam. Mechanical and ultrasonic dispersion has the ability to break apart aggregates thereby altering the size distribution of the original deposit. GeoSea has conducted experiments on this phenomenon and has found that mild ultrasonic dispersion is insufficient to alter the trend statistics. The intensity of the resultant diffraction pattern is measured on a diode and converted to a grain-size distribution. In practice, lenses of different focal lengths are used to measure the sand and mud (silt and clay) sediment fractions and the overlap areas of the separate measurements are compared and used to reproportion the Malvern results into a single distribution. Three separate measurements are made on each sample and are averaged to provide the final distribution. Completed distributions are then compiled into an ASCII format database which, together with a digitised version of the sample location map and bathymetry, are imported into proprietary software designed to carry out an STA.

Sediment Trend Analysis (STA)

The theory behind an STA was first published by McLaren & Bowles (1985). Since that time the theory and practice has been refined and developed based upon GeoSea's experience of applying the technique to a wide variety of sedimentary environments. The following is a brief description of the theory.

The technique to determine the sediment transport regime utilises the relative changes in grain-size distributions of the bottom sediments. The derived patterns of transport are, in effect, an integration of all processes responsible for the transport and deposition of the bottom sediments. The latter may be considered as a facies that is defined by its grain-size distribution. There is **no direct time connotation,** nor does the depth to which the sample was taken contain any significance (provided, of course, that the sample does, in fact, accurately represent the facies). For example, D_1 may be a sample of a facies that represents an accumulation over several tidal cycles, and D_2 represents several years of deposition. The trend analysis simply provides the sedimentological relationship between the two. It is unable to determine the rate of deposition at either locality, but frequently the derived patterns of transport do provide an indication of the probable processes that are responsible in producing the observed sediment types.

Suppose two sediment samples (D_1 and D_2) are taken sequentially in a known transport direction (for example from a river bed where D_1 is the up-current sample and D_2 is the down-current sample). The theory shows that the sediment distribution of D_2 may become finer (Case B) or coarser (Case C) than D_1; if it becomes finer, the skewness of the distribution must become more negative.

Conversely, if D_2 is coarser than D_1, the skewness must become more positive. The sorting will become better (i.e., the value for variance will become less) for both Case B and C. If either of these two trends is observed, we can infer that sediment transport is occurring from D_1 to D_2. If the trend is different from the two acceptable trends (e.g. if D_2 is finer, better sorted and more positively skewed than D_1), the trend is unacceptable and we cannot suppose that transport between the two samples has taken place.

In the above example, where we are already sure of the transport direction, $D_2(s)$ can be related to $D_1(s)$ by a function X(s) where 's' is the grain size. The distribution of X(s) may be determined by:

$$X(s) = D_2(s)/D_1(s)$$

X(s) provides the statistical relationship between the two deposits and its distribution defines the relative probability of each particular grain size being eroded, transported and deposited from D_1 to D_2.

Interpretation of the X-Distribution

Empirical examination of X-distributions from a large number of different environments has shown that four basic shapes are most common when compared to the D_1 and D_2 distributions. These are as follows:

(1) Dynamic Equilibrium: The shape of the X-distribution closely resembles the D_1 and D_2 distributions. The relative probability of grains being transported, therefore, is a similar distribution to the actual deposits. This suggests that the probability of finding a particular grain in the deposit is equal to the probability of its transport and redeposition (i.e., there is a grain by grain replacement along the transport path). The bed is neither accreting nor eroding and is, therefore, in dynamic equilibrium.

(2) Net Accretion: The shapes of the three distributions are similar, but the mode of X is finer than the modes of D_1 and D_2. Sediment must fine in the direction of transport; however, more fine grains are deposited along the transport path than are eroded, with the result that the bed, though mobile, is accreting.

(3) Net Erosion: Again the shapes of the three distributions are similar, but the mode of X is coarser than the D_1 and D_2 modes. Sediment coarsens along the transport path, more grains are eroded than deposited, and the bed is undergoing net erosion.

(4) Total Deposition: Regardless of the shapes of D_1 and D_2, the X-distribution more or less increases monotonically over the complete size range of the deposits. Sediment must fine in the direction of transport; however, the bed is no longer mobile. Rather, it is accreting under a "rain" of sediment that fines with distance from source. Once deposited, there is no further transport.

Recently, a fifth form of the X-distribution has been discovered. Occurring only in extremely fine sediments when the mean grain-size is very fine silt or clay, the X-distribution may be essentially horizontal. Such sediments are usually found far from their source and the horizontal nature of the X-distribution suggests that their deposition is no longer related strictly to size-sorting. In other words, there is now an equal probability of all sizes to be deposited. This form of the X-distribution was first observed in the muddy deposits of a British Columbia fjord and is described in McLaren et al. (1993).

Interpretation of a Trend

In reality, a perfect sequence of progressive changes in grain-size distributions is seldom observed in a line of samples, even when the transport direction is clearly known. This is due to complicating factors such as variation in the grain-size distributions of source material, local and temporal variability in the X(s) function, and a variety of sediment sampling difficulties (i.e., the sample doesn't adequately describe the deposit; it's taken too deeply or, alternatively, not deep enough etc.).

Initially, a trend is easily determined using a statistical approach whereby, instead of searching for "perfect" changes in a sample sequence, all possible pairs contained in the sequence are assessed for possible transport direction. When one of the trends exceeds random probabiltiy within the sample sequence, we infer the direction of transport and calculate X(s).

Despite the initial use of a statistical test, various other qualitative assessments must be made in the final acceptance or rejection of a trend. Included is an evaluation of R^2, a multiple correlation coefficient defining the relationship among the mean, sorting and skewness in the sample sequence. If a given sample sequence follows a transport path perfectly, R^2 will approach 1.0 (i.e., the sediments are perfectly "transport-related"). A low R^2 may occur, even when a trend is statistically acceptable. This situation may arise for a number of reasons: (i) sediments on a presumed transport path are, in reality, from different facies, and valid trend statistics occurred accidentally; (ii) the sediments are from a single facies, but the chosen sequence is only a poor approximation of the actual transport path, and (iii) extraneous sediments have been introduced into the natural transport regime, as in the case of dredged material disposal. R^2, therefore, is assessed qualitatively, and when low, statistically accepted trends must be treated with caution.

To analyse for sediment transport directions over two dimensions, a grid of samples is required. Each sample is analysed for its complete grain-size distribution and these are entered into a computer equipped with appropriate software to "explore" for statistically acceptable trends. The technique to explore for transport pathways is initially undertaken randomly (e.g., lines of samples running east-west or north-south across the study area).

The term "random" is used loosely in that it is not strictly possible to remove the element of human decision-making entirely. The important aspect of the initial search for sediment trends is that it is undertaken with no preconceived concept of transport directions. It is, however, assumed that there will be a net sediment transport pattern and that changes in the grain-size distributions throughout the study area will not be random. The derivation of the final patterns may be likened to communication theory which, in the case of extremely noisy signals, requires the "discovery" of a "message" as the proof that the message does indeed exist.

As familiarity with the data increases, exploration becomes less and less random until a single and final coherent pattern of transport is obtained. On completion of an interpretation, each transport line may then be used to derive a corresponding X(s) function from which the behaviour of the bed material on the transport path is inferred.

At present, the approach of obtaining the final derivation of the net sediment transport pathways relies on assessing and reomoving "noise" qualitatively. The GeoSea trend programming is specifically designed to do this in that all sample distributions may be readily compared with one another (and excessively noisy distributions discarded), the best sediment types can be determined for the analysis, and the relationships among all the sample pairs may be assessed. Because we are unable to know the exact nature of the "noise" that we may be confronted with, it is difficult at this stage to devise a quantitative technique to eliminate it. To do so is the subject of much on-going research, not only by GeoSea, but at various universities.

GIS and Modelling Applications in Support of Coastal Management

Over the past six years the RIKZ has developed a number of Geographic Information System applications. As a result, data derived from the different STA's enable comparisons with modelling and tracer experiment studies, survey data, wave and tidal current information, photographic surveys and environmental inventory data. The underlying philosophy developed by the RIKZ suggests that enlightened management of such a complex environment requires information derived from as many sources as possible. A management tool (GIS) that is able to examine specific data individually, makes correlation among many diverse data types and whose sources can be updated easily with new or revised information, is of great use.

In particular, a GIS application called SEDIMAP allows for the easy elaboration and presentation of the GeoSea grain-size data in response to requests concerned with channel alignments and deepening, sand extraction from the foreshore for beach nourishment, the optimal location of disposal sites for dredged material and a number of environmental impact studies. Examples of the output from this application are shown in Figs. 1–3.

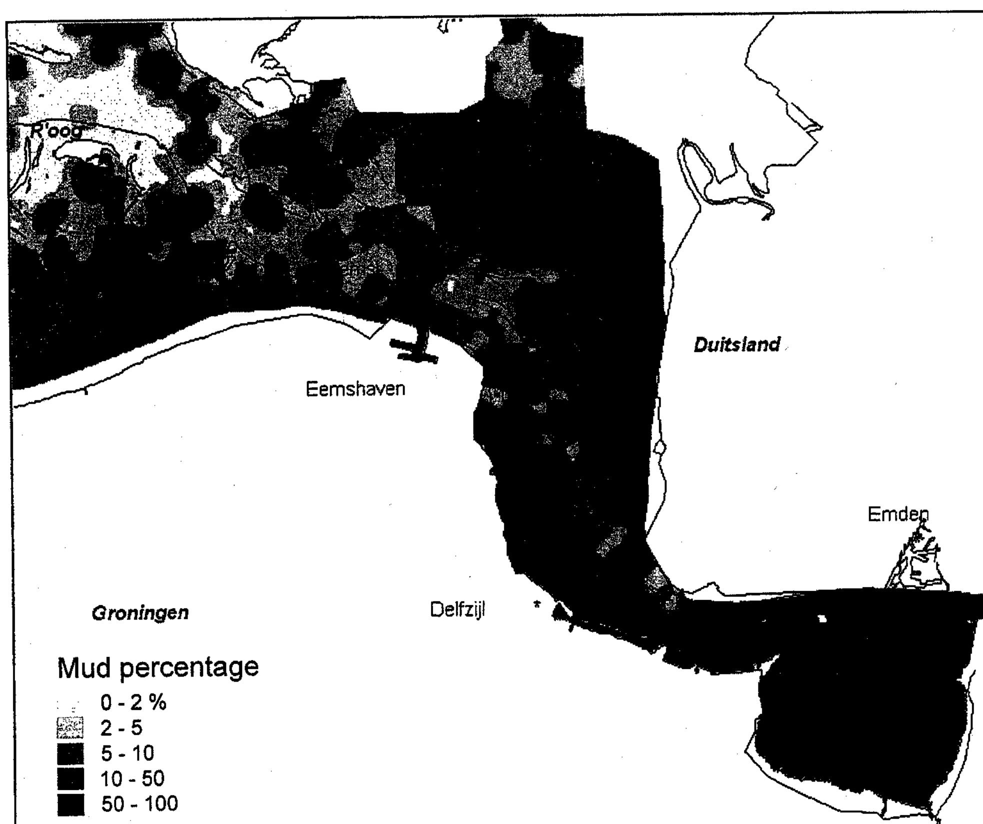
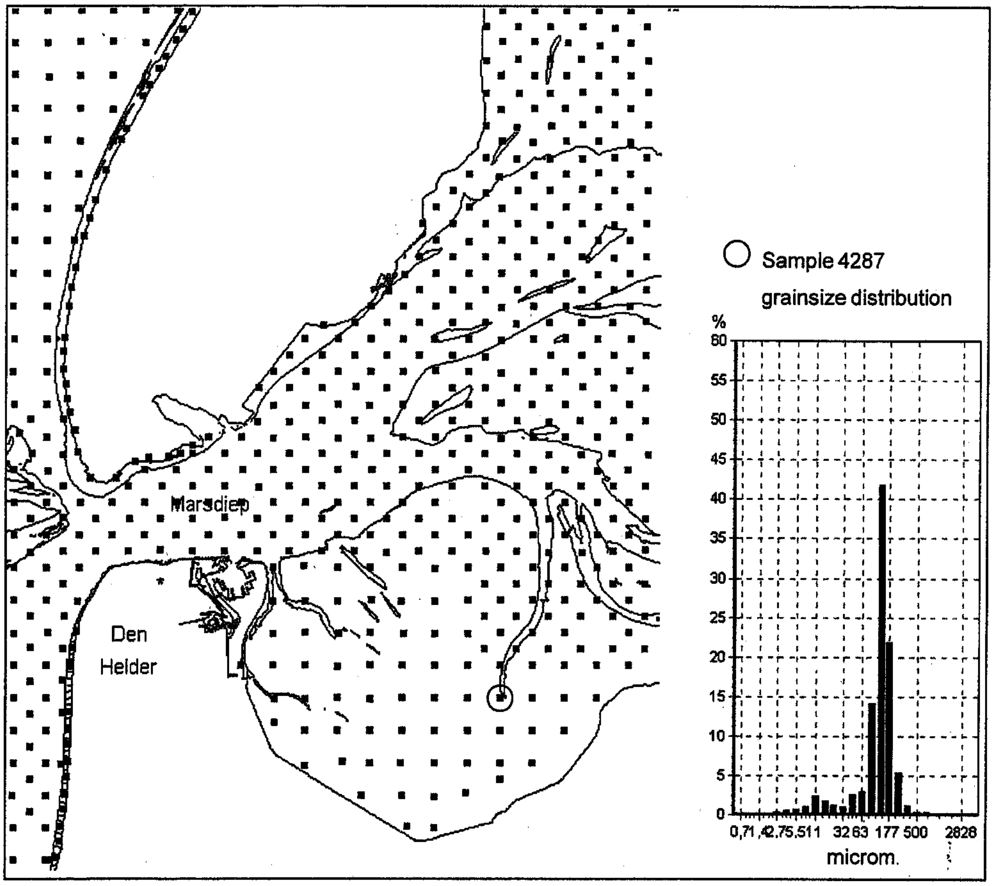


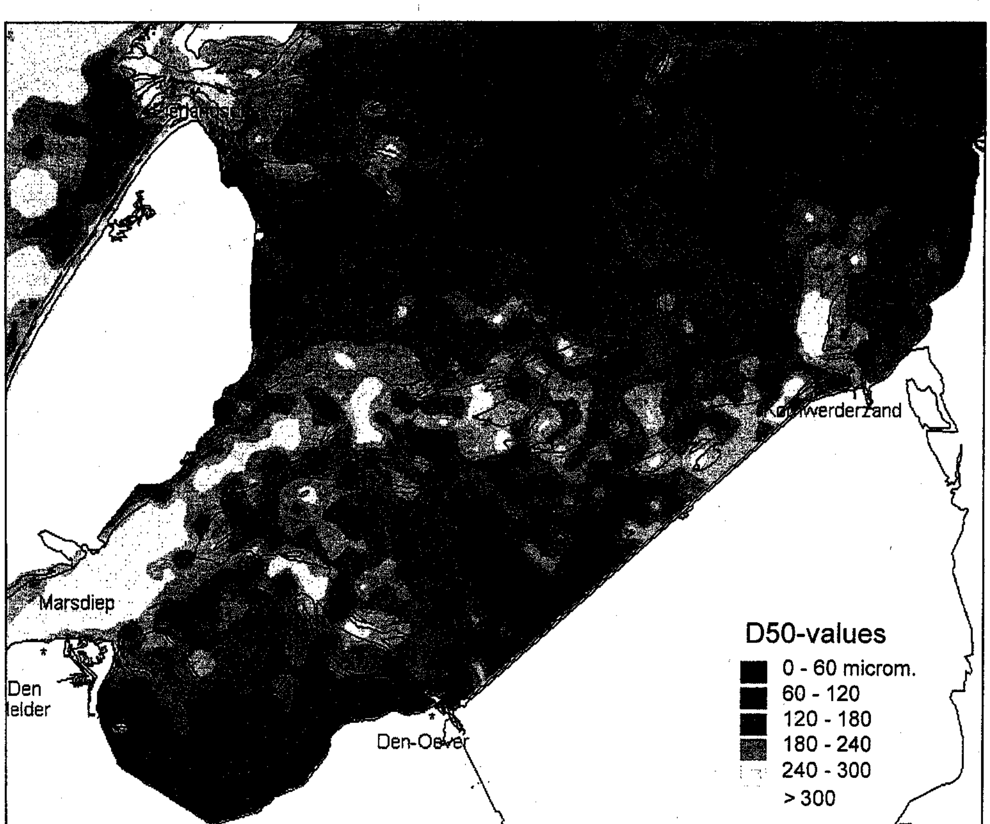
Fig. 1. SEDIMAP output showing the mud percentages of samples from the Eems/Dollard Estuary, Dutch Waddenzee.

▶

Fig. 2. SEDIMAP output showing the sample points and the location and grain-size distribution of a particular sample from the Balgzand area in the Eems/Dollard Estuary.

Fig. 3. SEDIMAP output showing the D50 values of samples from the Marsdiep and Vliestroom tidal basins in the Eems/Dollard Estuary.


Marsdiep
Den
Helder
Sample 4287
grainsize distribution
%
microm.


Kornwerderzand
Marsdiep
Den
Helder
Den-Oever
D50-values
0 - 60 microm.
60 - 120
120 - 180
180 - 240
240 - 300
> 300

Results

The Eems/Dollard Estuary (1991/92)

This data set consisted of about 670 samples which were grouped into three facies: sand, bimodal and muddy sediments. The net transport patterns for each were determined.

In the outer estuary a complicated pattern of ebb and flood transport pathways emerged. Many of the shoals acted as boundaries between these regimes and the study allowed for the definition of a better alignment of the shipping channel to make full use of the ebb transport of sediment thereby reducing the requirements for maintenance dredging.

The entrance to the Eems River revealed the interesting phenomenon of sand and bimodal sediments being transported seawards by the ebb tide while the muddy sediments are transported and deposited in an upstream direction. This was confirmed in the later study on the tidal reaches of the river carried out for BAW Hamburg and is attributed to tidal asymmetry and the cohesive properties of the fine sediments.

A number of the dredge material disposal sites were also examined to determine if their location was optimal for the resuspension and redeposition of the dredged material.

The Vliestroom Tidal Basin (1992)

About 1,500 samples were collected and analysed for this study. The area was predominantly sand and sandy mud; however, some lines of fine sediments were also tested near the Port of Harlingen and along the Afsluitdijk. The sampling grid did not extend far enough offshore to allow the definition of the eastward longshore transport in the North Sea, but the trends did reveal complex gyres of sand transport to the east and west of the tidal entrance defining the ebb-tidal delta. It appeared that the deep channel within the entrance acts as a reservoir for sediment which is periodically replenished by storm events, from which sand is removed by the ebb and flood tidal currents. If sand is moved into the basin then it tends to follow a dendritic pattern of accretionary transport and is deposited onto the intertidal flats.

An exception to this was found south-west of the Island of Terschelling where a complex pattern of ebb and flood transport regimes was discovered. It coincides with an area known to have dangerous shoaling conditions for shipping to the island. A new route for the shipping channel paralleling transport pathways was recommended, thereby ensuring minimal dredging and disturbance to the environment.

A continuous longshore transport on the seaward facing beaches of the islands of Terschelling and Vlieland was not detectable. Instead there appeared to be a relationship with offshore sediments and a transport parting zone associated with the offshore gyres.

The Marsdiep/Engelsmangat Tidal Basins (1994)

This study was based upon approximately 2,000 samples and revealed a very similar regime to that of the Vliestroom. Again it appeared that the tidal entrance itself is acting as a reservoir for sand deposited during storm events and redistributed from there by the flood and ebb tidal currents. Complex gyres of transport were found to the east and west of the entrance over a well defined ebb-tidal delta and in this study the sampling grid went far enough offshore to reveal the dominant north/north-east transport of sand in the North Sea.

Also, in common with the islands of Terschelling and Vlieland, beach transport on Texel and to the south of Den Helder revealed transport parting zones influenced by the offshore gyres rather than clear longshore drift.

Finally, a north-easterly transport pathway of muddy sediments from within the Marsdiep basin along the Afsluitdijk and into the port of Harlingen was discovered.

The Friesche Zeegat Tidal Basin (1995)

This study was based upon the analysis of 850 sediment samples with sandy sediment being the principal facies. In this area the dominant eastward transport of sand in the North Sea appears to be deflected by the dynamics associated with the Eems Estuary to create two distinct regimes. The first originates in the north-west and impinges on the eastern end of Ameland and the second originates in the north-east and impinges on the western end of Schiermonikoog. These two regimes converge over the shoals making up the Engelsmanplaat and probably account for the more muddy sediments found in this area. Some of the trend lines revealed equilibrium and erosional transport in these offshore regimes.

The two offshore regimes are directed into the tidal entrance and, although there does appear to be a parting zone where material is either moved into the basin or taken to the offshore, the ebb tidal delta in this area is not as clearly defined compared to the previous tidal inlets. The material which does move into the basin clearly follows accretionary transport paths in the channels and is deposited over the intertidal flats.

The Borndiep Tdial Basin (1996)

This study, based upon the collection and analysis of some 1200 samples, allowed the clarification of some of the details of the offshore regime revealed in the Friesche Zeegat study the previous year. The study also included the analysis of 115 samples collected as part of the Dutch NOURTEC beach transport programme, a detailed analysis of the beach, surf-zone and nearshore processes on the Island of Terschelling.

As in the previous studies, the north-east transport of sand in the North Sea was revealed on the outer edges of the sampling area. However, as seen in the Friesche Zeegat study, this regime appeared to be increasingly influenced by the transport dynamics of the eastern tidal entrances and by that of the Eems Estuary. The presence of the gyre systems on either side of the tidal entrance was confirmed, the gyre to the east evidently causing erosion on the western end of the island of Ameland and the Bornrif sand bank. This is thought to be caused by a decreasing sediment supply and is consistent with retreating shoreline profiles on the island. Erosional characteristics in a gyre to the west of the Borndiep and to the east of the Vliestroom were also discovered.

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The Lauwers/Schild Tidal Basin (1997)

The study of the final tidal basin, the Lauwers/Schild area immediately west of the Eems Estuary, was completed in June 1997. Based upon a database of 1,100 samples collected during May/June 1996, the results complete the "gap" between the Friesche Zeegat and the Eems Estuary and the trends correlate very well with the earlier studies.

The STA revealed the easterly transport regime in the offshore is increasingly modified by the dynamics of the Eems Estuary. Sediments typically enter the north side of the main tidal channels and return in a westerly direction on their southern sides. In the nearshore zone these trends curve to the south-west and approach the island of Schiermonnikoog at an oblique angle. Ebb tidal deltas are essentially absent and this may be due to the increasing influence of the estuary or to a decrease in the tidal volumes entering the basins. Inside the basins the transport regime remains identical to all the previous studies with flood-dominated, accretionary transport paths following the main channels and spreading over the intertidal flats in a dendritic pattern.

Discussion

A knowledge of sediment texture and sediment transport pathways was recognised by the RIKZ as being an essential component for the management of the Waddenzee environment. Both have a bearing on all aspects of coastal management, from beach nourishment, channel alignments, dredging and disposal activities, contaminant transport and habitat enhancement and conservation.

The Dutch Waddenzee, in common with the Wadden areas of Germany and Denmark, is recognised as an area of extreme ecological importance for fish, bird and marine mammal populations. It is also an area of intense and conflicting human activities encompassing industry on the one hand and fishing and recreational use on the other. Combined with a highly complex natural environment that constantly changes under the driving wind, tidal and current forces, effective management must utilise a large and diverse data base that is rapidly accessible and easily interpreted.

These studies have provided one aspect of the required information, namely a sediment inventory of the entire Waddenzee area together with an understanding of net sediment transport directions and dynamic behaviour.

This information allows comparison with other research being undertaken by the RIKZ and is easily incorporated into a GIS information system. A summary map indicating the regional transport pathways for sandy sediments revealed by these studies is shown in Fig. 4 with a detail figure presented as Fig. 5.

On the whole there appears to be a north-eastward transport of sand in the North Sea and this is widely supported in the literature (Eisma 1980; Misdorp et al. 1990). This transport regime appears to become increasingly deflected and dissipated towards the east, possibly due to the dynamics associated with the Eems Estuary. The characteristics of transport in the vicinity of the tidal entrances themselves appeared similar in nearly all cases with complex gyres of transport on either side of the ebb tidal deltas, some of which are causing erosion of the nearby islands, notably Ameland and Terschelling. This erosion may be the result of a decreasing supply of the North Sea offshore sands, and thus there is a deficiency of new sediments in the Borndiep and Friesche Zeegat entrances. The presence of transport gyres at the entrances to the tidal inlets has also been intimated in the literature, both from morphological studies (Dijkema et al. 1980; Postma 1981; Ehlers 1988; Misdorp et. al. 1989) and from modelling studies (Bilse 1991).

All of the beaches on the islands and on the mainland coast south of Den Helder, appear to be influenced by these gyres and exhibit parting zones at some point along their length. The NOURTEC study also revealed that longshore transport may be too simple a scenario for transport on these beaches and that a strong offshore tendency is also likely. The deeps within the tidal entrances typically contain a sediment parting zone from which material is moved by both ebb and flood tidal currents. It is suggested that such parting zones are recharged periodically by storm events. Once inside a tidal basin sediments typically follow the dendritic channel networks and onto the intertidal flats in an accretionary transport regime.

In conclusion, the results of six years of work can now be combined to give a sediment inventory readily accessible through GIS applications. The sediment trend analysis of GeoSea, carried out on a large sample set from the Dutch Waddenzee allows comparison with other RIKZ research and forms the basis for assessing the likely processes that influence sediment transport. Such information enhances the ability of the RIKZ to make rational decisions in their ongoing coastal and marine management of this vitally important natural environment.

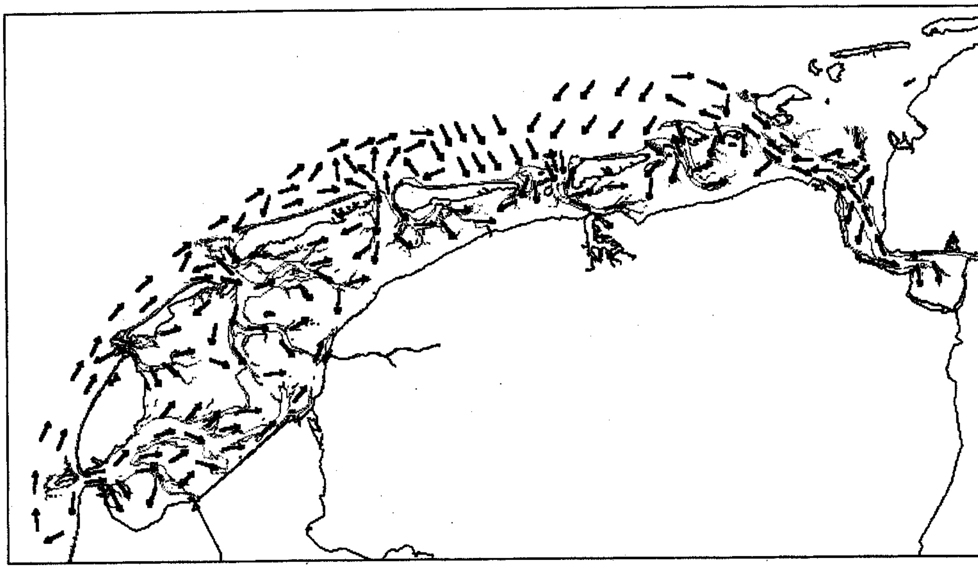

Fig. 4. Summary of net sand transport directions derived from statistical analyses carried out in the Dutch Waddenzee.

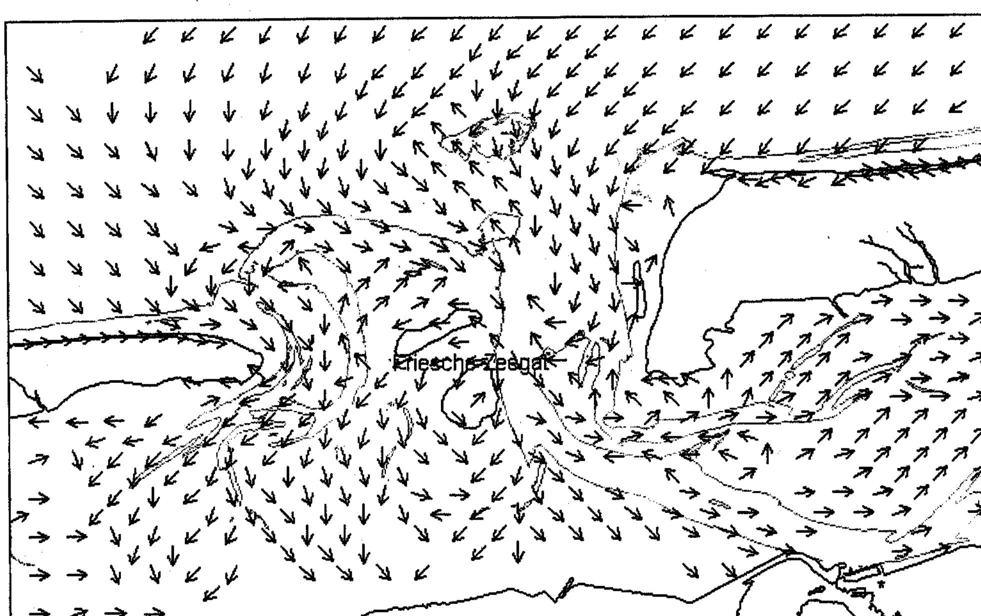

Fig. 5. Detail of net sand transport directions derived from statistical analyses carried out in the Dutch Waddenzee.

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