I.O.S.

# SIZEWELL-DUNWICH BANKS FIELD STUDY

## TOPIC REPORT: 7

# FINAL REPORT
# A STUDY OF NEARSHORE SEDIMENT TRANSPORT PROCESSES

B. J. LEES

REPORT 146
1983

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF OCEANOGRAPHIC SCIENCES

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*When citing this document in a bibliography the reference should be given as*

LEES, B.J. 1983 Sizewell-Dunwich Banks
Field Study, Topic Report: 7.
Final Report. A study of nearshore
sediment transport processes.
*Institute of Oceanographic Sciences,*
*Report*, No. 146, [45pp.]

INSTITUTE OF OCEANOGRAPHIC SCIENCES

TAUNTON

# SIZEWELL-DUNWICH BANKS FIELD STUDY

## TOPIC REPORT:7

## Final Report
## A study of nearshore sediment transport processes

by

B.J. Lees

I.O.S. Report No. 146

1983

*This project was supported financially by the Department of the Environment*

CONTENTS

## SUMMARY

This is the final report in a series concerning the Sizewell-Dunwich Field Study. Besides summarising the significant results of the earlier reports, it attempts to show how various aspects of the work are drawn together into a final, multi-disciplinary whole. The study is examined in a regional context and also in the wider one of general scientific and coastal engineering applications.

The data base for these wide-ranging conclusions comprises the results of geophysical and coring surveys, 23,766 hours of useful current meter data from 23 stations, wave measurements from 5 stations, 3 of them through a 4 year period, sediment transport measurements of both suspended and bedload, and over a year of monthly beach profile measurements.

The regional work has increased the understanding of nearshore dynamic processes involved in the inception, growth and maintenance of an offshore sandbank. The history of the bank is described from its initial stages as two separate banks during the early part of the last century, to their elongation and amalgamation and the resulting bank's movement westwards closer to the shore. The pattern of coastal erosion has left a slight headland at Thorpe Ness and it is shown that even a small headland such as this may modify the tidal flow. A mechanism would then exist to initiate and maintain a sandbank associated with the headland. Although the growth of the bank is in the opposite direction to the bedload transport residuals, a consideration of suspended sediment transport processes shows that they may be responsible. The documented shoreward movement of the banks, on the other hand, is likely to be related to wave activity.

Important points of wider relevance include firstly demonstrating the necessity of choosing the correct bedload transport equation to apply in a particular situation, reinforcing results from work carried out earlier in Swansea Bay. Secondly it is shown that in the Sizewell-Dunwich Bank area the suspended sediment transport rate varies as the friction velocity to the power 2.8. Furthermore it is seen that the nearbed velocity profile hardly deviates from the Karman-Prandtl logarithmic profile, in spite of the high concentration of suspended sediment. The relationship between the eddy diffusivity of suspended sand particles and the eddy viscosity of the fluid has been defined. The sheltering effect of the elongated bank on a shoreline formerly suffering severe erosion is demonstrated both empirically and theoretically. Further support is given to theories of bank maintenance involving vorticity and advective effects in the residual currents. Finally, the success of a relatively inexpensive method, using fluorescent tracer, of measuring bedload transport rates and directions is noted.

# SIZEWELL-DUNWICH FIELD STUDY FINAL REPORT : A STUDY OF NEARSHORE SEDIMENT TRANSPORT PROCESSES

## 1 INTRODUCTION

This is the final report in a series of seven Topic Reports concerning the Sizewell-Dunwich Field Study. Besides summarising the important conclusions of the earlier reports, it attempts to draw them together as a unified whole, and highlight the particular aspects which are of wider scientific and practical interest.

For further details of the individual aspects summarised below, reference may be made to the separate Topic Reports, which are listed in Appendix A.

The work began in 1975 in the Sizewell-Dunwich Banks area off Suffolk, East Anglia (Figure 1) as a regional multi-disciplinary study to evaluate the relationship between an offshore bank and the shoreline. It was also envisaged as an attempt to understand the mechanism by which banks are formed, and the way in which some banks reach overall stability and others do not.

The project developed through 1976 in response to the interest taken by the Department of the Environment as an examination of a relatively simple and stable offshore sandbank, with the short term aim of resolving its sediment transport system. The long term objective was to use the understanding gained for predictive purposes. Part of this aim was to be able to provide useful information to those concerned with environmental problems such as the effects of offshore dredging, costal erosion and the design of sea defences. Closely allied with the work in the early stages was a project to construct a finite-difference numerical model, firstly of the water flow, and later with the intention of incorporating sediment transport terms and equations. The Sizewell-Dunwich Banks with their fairly simple geometric form were to be used as a prototype for the validation of the model, and hence initially, data acquisition was considerably influenced by the model's requirements.

As the project developed further, from 1977 onwards, there was a change of emphasis away from the regional aspect towards problem solving of a more general nature. The Institute of Oceanographic Sciences had been working since April 1974 on a question related to coastal erosion in Swansea Bay, South Wales, a project also largely funded by the Department of the Environment. In addition to comprising a study of the immediate area and its specific problems, this work was seen in the wider context of the general interrelation of the coastline and the offshore zone. (Swansea Bay (Sker) Project series of Topic Reports, Appendix B). In particular, as the Swansea Bay and Sizewell-Dunwich projects progressed, it became apparent that the two widely contrasting coastal areas should be used to enhance the broader goal. Sediment transport studies became increasingly important because of the need to compare measured with predicted rates of transport under different conditions of bathymetry, shoreline geometry, tidal regime and wave climate. Further factors requiring investigation have included assessing the influence of meteorological forcing on currents and therefore on sediment transport, and the effect of waves in shallow water areas.

## 2 RESEARCH PROGRAMME

The measurements began with a sedimentological survey, using sidescan sonar, and boomer and pinger continuous seismic profiling equipment. These data were calibrated with grab samples, box and vibrocores. The survey was undertaken in winter (February, Figure 2a) and was partially repeated in the summer (August, Figure 2b) to identify differences which could be due to different meteorological conditions and associated parameters. A bathymetric survey, to be used in wave refraction computations, was also part of this programme.

An analysis of the tidal dynamics of the area was undertaken. The data base was provided by records mainly from Plessey MO21 self-recording current meters. Current meter stations were selected for short term (2 month) moorings, with good data being obtained from 22 locations, and with one long term mooring providing data over a period of 2¼ years. Tidal elevations were obtained from the Institute of Oceanographic Sciences' (IOS)(Bidston) tide gauge at Lowestoft, with supplementary data from the CEGB gauge at Sizewell, although the latter was in place for one week only. IOS (Taunton) data were also available from three seabed pressure transducers, at Southwold, Dunwich and Aldeburgh, which were set to record continuously for a two week period in order to provide tidal height correction data for the bathymetric survey. Velocity profiles were measured by various methods, enabling predictions to be made of bedload sediment transport rates and directions from the mid-water current meter data.

A comprehensive set of wave measurements is also available, from the three frequency modulated pressure transducers already mentioned, which were on site for 4¼ years. Further data came from two Waverider buoys located one on each side of the Dunwich Bank, specifically to measure wave height attenuation by the bank.

Progress towards the understanding of ongoing sediment transport processes has been achieved by measuring both bedload and suspended load in the field. It has been possible to calibrate various commonly used bedload sediment transport equations using a fluorescent tracer technique. Suspended sediment concentration and velocity profiles were measured with a pumped sampling rig. Understanding the relationship of the bank to the shoreline has also been an integral part of the study, and therefore beach profiles at approximately 1 km spacing were surveyed at monthly intervals for over a year. The development and maintenance of the bank has been further understood by reference to its evolution as shown in hydrographic surveys carried out during the past century. Assessment of their accuracy and that of other relevant historical documents has been part of the work.

## 3 RESULTS IN A REGIONAL CONTEXT

### 3.1 General topography

The coastline in the study area curves inland very gently from a slight headland or ness at Southwold in the N to a similar, but more prominent feature at Thorpe Ness in the S (Figure 1). A small river, the Blyth, flows into the sea immediately S of Southwold. Offshore there is a gently sloping platform reaching a mean depth of 15 m below Chart Datum approximately 4 km offshore. Lying on this platform is a linear sandbank with its long axis parallel to the coastline and about 2 km from it. There is a central col separating the Dunwich Bank to the N from the Sizewell Bank to the S. The two together are approximately 11 km long and 1 km wide, with mean slopes of 1 in 60 to the W, and 1 in 200 to the E. Inshore from the bank is a channel, again elongated parallel to the coastline and reaching a mean depth of just over 9 m below Chart Datum. There is a 6 m to 8 m deep channel between Thorpe Ness and the southern end of the Sizewell Bank.

## 3.2 Geology : sedimentary sequence and Quaternary history

The coastline, which forms the western boundary of the research area, is composed mainly of relatively unconsolidated rocks of the Norwich Crag Series, of preglacial Pleistocene age (Funnell and West, 1977). The only pre-Quaternary rock identified offshore is the Pliocene Coralline Crag, a ridge of shelly, iron-stained sand outcropping in the SW of the area as an ENE-WSW continuation of Thorpe Ness (Figure 2a).

Schematic sections, one parallel to the shore and two normal to it comprise Figure 3, clarifying the interrelationships of the Quaternary sediments. The sections show the shelly clays, sands and gravels of the Norwich Crag Series lying unconformably against the Coralline Crag ridge and underlying the Holocene sediments covering the remainder of the study area. The erosion surface of these beds dips to the E, but there is no evidence for the direction of dip within the Crag strata. Both the Crags have been identified by their macrofossil content.

The recognition of the alluvium from its microfossil content as being probably of Holocene age, together with the infilling and burial of channels SE of Southwold, is evidence of a post Pleistocene marine transgression. The erosion of the Norwich Crag Series referred to above could have occurred at least partially during this transgression. However Carr and Baker (1968) and Carr (1971) who worked in the Orford and Shingle Street area immediately S of Aldeburgh, considered that the evidence there indicated a Pleistocene planation of a similar surface. The buried channels, mentioned above, could have been initiated during the late Pleistocene. Alluvial clay has been recognised onshore (Figure 2a) and it is reasonable to suppose that it is part of the same deposit as that offshore and that the transgression reached inland to where the present deposits of alluvium are found. As far as the author is aware, there has been no investigation of these clays for dating, either from peat horizons, or microfossil content, but they may be similar to estuarine clays both to the N and S of the area. Carr and Baker (1968) gave radiocarbon dates of 8460 ± 145 y BP and 3460 ± 100 y BP for peat samples occurring within estuarine clays in the Orford area. This is of the same order as evidence given by Coles and Funnell (1981) for two marine incursions, c 7500 y BP and c 2000 y BP in the Broadland valley of east Norfolk.

At the time of the transgression, the relatively resistant Minsmere and Dunwich cliffs extended further E than now, so separating the two river valleys which suffered incursion from the sea.

Following a relative lowering of sea-level, the sea withdrew to at least a shoreline near the present coastline in the S, and probably further E in the N, allowing the river Blyth to form several estuarine channels. Perhaps these were superimposed on the earlier drainage pattern postulated above. This could account for geophysical evidence which shows two channels lying closely together (Lees, 1980). The mineral vivianite, a hydrated iron phosphate, identified in the alluvium 2 km SSE of Southwold, is often associated with clays deposited in estuarine channels because a source of phosphate is provided by fossil bones and shells (Read, 1972). Also flowing into what was the same broad estuary would be rivers from the Walberswick and the present Minsmere Nature Reserve areas. There were probably sand and gravel ridges further offshore, perhaps forming a barrier beach.

A relative sea-level rise then resulted in an advance of the sea, probably carrying material from the ridges shorewards. This infilled the estuarine channels and may have provided a source of material for the formation of sand and shingle ridges across the valleys, ie the beach ridge at Walberswick, the sand and shingle barrier ridge immediately N of Dunwich, and the ridges and subsequent sand dunes dividing the Minsmere Nature Reserve and the Sizewell power station property from the sea.

During the time of transgression, because of the unconsolidated nature of the land, coastal erosion continued and is continuing intermittently.

### 3.3 Historical changes in the coastline and offshore banks

Documentary evidence is available in the form of legal records and court rolls from the seventh century AD, but it concentrates on the former city of Dunwich. From 1836 onwards there is a greater number of specific measurements at points along the coast. They highlight firstly the variability of erosion over time, which ranges from zero to 18.3 m $yr^{-1}$, and secondly the often simultaneous erosive events at different sites in the Aldeburgh to Easton Bavents area (Figure 1).

The hydrographic charts cover the period 1824 - 1965. They show initially two small banks, opposite Sizewell and Dunwich respectively. The Sizewell Bank grew northwards and the Dunwich Bank declined until it was incorporated into the elongating Sizewell Bank, about 1921/2. Between 1824 and 1965 this northerly progression averaged 49 m $yr^{-1}$. The Sizewell-Dunwich system also moved landwards with a maximum rate of 10.7 m $yr^{-1}$ between 1867 and 1965. Thus in 1965 the banks were only two thirds of the distance they had been from the coast near Minsmere in 1867 (Figure 4).

Calculations suggest that the volume of sediment lost from the coast between Easton Bavents and Thorpe Ness during the century prior to 1965 is similar to that gained by the offshore banks. However, it would be too simplistic to argue for a simple transference of material between the two. Some of the complexities involved will be discussed below.

### 3.4 Tidal currents : observed and residual circulations

The tidal movements and residual circulation depend on the astronomical tides. The principal lunar, or $M_2$ tide enters the North Sea from the Atlantic and propagates southwards as a progressive wave. It becomes modified in various ways due to the shape and structure of the North Sea itself and the more local perturbations of the coastline and seabed in the area under consideration. At Sizewell-Dunwich these effects can be represented by describing the tide as a combination of progressive and standing wave oscillations, and harmonic constituents of astronomic and shallow water origins.

The current meter data have confirmed that the tidal currents are essentially rectilinear, with ellipticities of the order of 5% and less, and with mid-water tidal stream maxima in the order of 1.00 m $s^{-1}$.

The residual flow pattern in the area is complex (Figure 5) although there is evidence of an anticlockwise eddy in the mean circulation, which is situated over the Sizewell Bank. Mean current residuals of up to 0.13 m $s^{-1}$ occur inshore from the Sizewell Bank. These are largely due to the eddy formed north of Thorpe Ness, causing the southerly current to flow for approximately 7 hours during each tidal cycle. A similar phenomenon is shown more markedly in Start Bay, Devon (Pingree and Maddock, 1979) where Start Point, a more prominent headland than Thorpe Ness, affects the flow in such a way that the inshore current flows southwards for 10 hours per tidal cycle.

The tidal residuals also show a complex variety of flow directions at the northern end of the Dunwich Bank, near Southwold, although existing data are not clearly indicative of an eddy there.

The eddy patterns in the flow may have developed during the retreat of the Dunwich and Minsmere coastline through erosion, leaving the relatively consolidated Coralline Crag of Thorpe Ness more prominent. Heathershaw and Hammond (1980) refer to various workers in rivers and the sea who have shown that such eddies can form on either side of a promontory. The eddies may rotate in a clockwise or anticlockwise direction, depending on which side they occur. The subsequent growth of the banks indicates there was a plentiful sediment supply. A major source would be from the soft cliffs already mentioned.

Current measurements from a long term current meter mooring have confirmed that the residual circulation is also influenced by meteorological forcing. During stormy periods good correlations are shown between the alongshore components of the residual flow and the wind stress. Work is in progress to evaluate this phenomenon further.

Density currents are not considered to be significant in the Sizewell-Dunwich area because the freshwater input is minimal.

## 3.5 Sediment transport

Velocity profile measurements have enabled sediment transport predictions to be made from the midwater current meter readings. Comparisons with the results from a fluorescent tracer experiment have shown that of 5 widely used sediment transport formulae, Yalin's (1963) equation gives the closest agreement with observed values at Sizewell-Dunwich. The expression predicts rates which vary typically from 0.003 g $cm^{-1}$ $s^{-1}$ offshore to 0.069 g $cm^{-1}$ $s^{-1}$ inshore. The increased rates nearshore may be partly due to the increased effects of waves on tidal residuals and sediment transport in shallow water.

A schematic representation of the sediment transport paths is shown in Figure 6. An apparent bedload parting seaward of Dunwich may be compared with the bedload parting further offshore which has been identified by Stride (1973) from sedimentological data. The latter feature appears to be related to the presence of the amphidromic point in the southern Bight of the North Sea and is also revealed in bed shear stress distributions from a numerical model of the tidal circulation in this area (Pingree and Griffiths, 1979).

This study shows that the predicted directions of net bedload transport are opposite to the direction of the banks' trend from their point of attachment to the coast. Only in the area north of the bedload parting is the direction of predicted net bedload movement similar to the trend of the banks, which Carr (1979) has shown have extended in a northerly direction. An explanation for this behaviour will be offered below when suspended sediment transport is discussed.

The southerly residuals suggest the possibility of sediment transfer from the banks to the shore at Thorpe Ness, a hypothesis strongly supported by Robinson (1980). A contrary view is held by McCave (1978) and for an analysis of these opposing ideas, reference may be made to Carr (1981). The last author, partly on grounds of the availability of specific sediment sizes, tends towards the view of McCave, that sediment moves from Thorpe Ness to the offshore bank. Evidence for the removal of sediment from the foreshore at Thorpe Ness during stormy weather, as suggested by McCave (1978), and its replacement in calmer times, is provided by Blackley (1979). He describes the development and landward migration of intertidal bars at Thorpe Ness after storms, which may provide the necessary mechanism. It is not known what proportion of the eroded sediment is subsequently replaced. Any transfer of sediment between the ness and the bank is likely to be reduced by the strong flushing action to the SE between the two. If sand moves from the ness to the bank, sand deposition might be expected in the direction of the flushing. A southerly tongue to the Sizewell Bank is recorded as having been present earlier this century and may be a frequently occurring short lived feature (Carr, 1979).

An explanation for the apparent contradiction between bedload measurements and predictions indicating transport to the S, and the trend and elongation of the banks northwards from the coastline, is offered by considering suspended sediment transport processes. The suspended mode is dominant over that of the bedload by at least 2 orders of magnitude. At spring tides the net, depth-integrated suspended sediment transport rate, based on near bottom velocity and concentration profile measurements, was as much as 5.66 g $cm^{-1}$ $s^{-1}$. The neap rate, however, is likely to be only one fifth of this. The available evidence from 5 stations where suspended sediment transport rates were estimated, (Figure 1) shows an overall transport rate to the N.

### 3.6 Wave climate

Observed wave data demonstrate that under most circumstances there is little difference in the energy reaching the coastline S of, opposite to or N of the Sizewell-Dunwich Banks. However, under severe storm conditions large waves break on the banks so that there is then a substantial difference between offshore and inshore wave height, thus demonstrating the sheltering effect of the banks. The critical wave height above which the attenuation takes effect is in the region of 2.46 m at high water, and 2.07 m at low water.

Wave refraction, ray tracking and wave energy programs demonstrate a marked wave focussing effect along the shoreline, particularly in the Sizewell- Thorpe Ness region, for waves approaching from $30^o$, the direction of maximum fetch. When the wave approach is normal to the banks, refraction is minor, with energy being fairly uniformly distributed alongshore.

The interactions between wave and tidal currents are still poorly understood and the prediction, using existing theories of sediment transport under a combination of the two can be grossly in error. In particular, none of the sediment transport equations mentioned above accounts intrinsically for the effects of waves. In this study the approach used has been that due to Bijker (1967) who developed an expression for the enhancement of the bed shear stress due to wave activity. Figure 7a shows how the enhancement under typical significant wave heights affect the actual transport rates, using Yalin's equation. Even moderate wave conditions ($H_s$ = 1 m, period = 6 s) in 12 m water would increase transport rates by a factor of about 2 at peak tidal flows, and by more with decreasing flow speed. Figure 7b shows exceedance curves for wave induced and tidally induced currents for the Sizewell-Dunwich area, showing the likelihood of the above effects.

It should be remembered that although wave activity may enhance the bed shear stress, once the particles are in suspension they are moved mainly by tidal currents. However, a net movement of sediment in the direction of wave propagation may occur in shallow water as a result of wave particle orbits being not quite closed. It has been calculated that during periods of prevailing wave activity from the NE this would give a shoreward drift at the base of the water column of 0.35 m $s^{-1}$, of the same order of magnitude as the tidal residuals. Historical and fluorescent tracer evidence does point to a westward movement of the bank during stormy conditions. The latter data in particular indicate that wave action may have been responsible for this shoreward movement.

### 3.7 Beach changes

After 12 months (1978/1979) losses were concentrated over the 7 northern sections which extended from Sizewell to Southwold. Gains were confined to the southern sections ie Aldeburgh, and Thorpe Ness to Sizewell, and to the section furthest N. Maximum sectional gains or losses in volume over the 15 month period, equivalent to an increase in height of 0.52 m and a fall of 0.37 m, were at Sizewell (gain) and Minsmere Cliffs (loss). The greatest volume changes occurred at the Thorpe Ness section. When all 10 sections were taken together there appeared to be no obvious trend in volume change during the summer, but over the winter accretion was dominant.

The wind pattern for the survey period followed that of previous years with a dominant NE wind direction. Mean winter wind speeds were higher than in typical years, averaging some 6.8 m $s^{-1}$.

Over the year 1978/1979 the mean summer significant wave height ($\overline{H}_s$), measured by the inshore frequency modulated pressure transducer at Dunwich (Figure 1), was 0.34 m compared with a mean winter value of 0.61 m. In December 1978, 40% of waves measured had a significant wave height in excess of 1 m.

There is a clear relationship between the total volumes, for all sections, of beach material moved and $\overline{H}_s$ (Figure 8). The greatest volume change occurred in February 1979, which coincided with a period of strong northeasterly winds and associated high waves. It is interesting to note that there is no correlation between erosion or accretion values separately and $\overline{H}_s$.

The formation and migration of the intertidal bars at Thorpe Ness mentioned above provides a mechanism for the particularly large changes at this section.

## 4 REGIONAL CONCLUSIONS

Measurements of bedload and suspended load sediment transport rates, together with records from a network of current meter stations, have indicated some processes which may be involved in the inception, growth and maintenance of an offshore sandbank.

Five sediment transport equations, three relating to bedload only, and two to total load, have been calibrated for this particular area. Yalin's (1963) bedload relationship gave the best estimates. It was therefore used in conjunction with the current meter data to predict the overall bedload transport circulation pattern. The data demonstrate that the main transport is to the S, although the banks trend northwards from the coastline and have elongated in the same direction.

An explanation for this apparent contradiction is offered by considering suspended sediment transport processes. The suspended mode is dominant over that of the bedload by two orders of magnitude and the available evidence, albeit limited, shows an overall transport to the N.

The evolution of Thorpe Ness, resulting in a small promontory, and the coastal recession S of Southwold, could have set up tidal residual eddies which were then responsible for the inception of the Sizewell-Dunwich Banks. Historical data show the presence of two small banks opposite Sizewell and Dunwich (south of Southwold) in 1824 (Carr, 1979). Work by Pingree and Maddock (1979) at Start Bay, Devon, has shown how vorticity and advective effects in the tidal currents can maintain such structures.

Historical and fluorescent tracer evidence point to a slow westward mass movement of the banks during stormy conditions. The latter data in particular indicate wave action to be responsible. However it is not clear why the Sizewell tidal residual eddy still forms in its original location, now slightly seaward of the bank.

The fact that long term erosion has become considerably reduced at Dunwich has been shown to be due to the elongation of the banks, giving them a protective rôle under extreme conditions. The sand and shingle barrier at Walberswick, further N, is under increasing attack during storms. As the very slow (in civil engineering terms) relative rise of mean sea-level continues, the frequency of it being breached must increase. At Sizewell the presence of the bank offshore, and the wide, duned foreshore give the area reasonable protection.

## 5 CONCLUSIONS OF WIDER SCIENTIFIC INTEREST AND ENGINEERING APPLICATION

### 5.1 Applicability of commonly used sediment transport equations.

The ultimate aim of much work on sediment transport is to understand the processes involved well enough to be able to predict accurate rates and directions from the minimum data possible. To this end various sediment transport equations have been developed, but almost entirely in flumes and rivers. The present project has provided a much-needed input by calibrating 5 such expressions in the sea, continuing the work of Gadd et al (1978) in the New York Bight, and Heathershaw et al (1981) in Swansea Bay, South Wales. The latter group of workers found that Bagnold's (1963) approach, when modified to remove its dependence on the excess shear stress (Gadd et al, 1978) gave the best estimates. In contrast this expression was found to overpredict by 2 orders of magnitude in Sizewell-Dunwich and the equation giving the best results was that due to Yalin (1963) (Figure 9). Bagnold's (1963), Einstein's (1950) and Yalin's (1963) expressions were used by Gadd et al (1978) in the New York Bight. They found that Bagnold's (1963) equation gave transport rates 1 order of magnitude greater than that of Yalin (1963). Gadd et al used radioisotope tracer experiments carried out nearby (Lavell et al, 1977) as a rough check on the validity of the formulae employed. The tracer experiments were of short duration (13 and 9 days) and may well have had insufficient time for the marked sand to have reached equilibrium with the background material. Their results of the comparisons with the 3 different formulae are inconclusive, and have been used as guides to orders of magnitude only.

Amongst the difficulties encountered when attempting to apply these relationships to real situations in the sea is the specification of values for the various parameters. This problem is discussed in detail by Heathershaw (1981) showing how each of the 5 equations under consideration is sensitive to various parameters such as water depth, mean particle size, and roughness length ($Z_0$).

Swansea Bay and Sizewell-Dunwich differ from one another in coastal geometry, fresh water and sediment input, mean grain size of mobile material, tidal range, fetch characteristics and tidal dynamics. One result of this is that in Swansea Bay the dominant mode of sand transport is by bedload rather than suspended load, whereas the opposite is true in Sizewell-Dunwich, with suspended load transport exceeding bedload by 2 orders of magnitude.

It is clear that any one or more of the above characteristics may effectively determine the most suitable expression to use. Consequently, rather than base predictions on a knowledge of the mean grain size of the substrate and the water flow behaviour alone, it is better to calibrate possible transport equations in the field in order to choose the one which is the most appropriate. It may also be noted that because of the non-linear relationship between tidal currents and bedload sediment transport, the predicted directions of sediment movement do not necessarily coincide with residual tidal current directions.

A particularly important point to remember when measuring bedload transport using tracers is to allow adequate time for the tracer to reach equilibrium with the background sediment. Failure to do this could result in overprediction of transport rates.

### 5.2 The relationship of suspended sediment transport to friction velocity.

Prediction of suspended sediment transport rates and directions is far more difficult, largely due to the difficulty of sampling under severe environmental conditions and to the extreme non-linearity of their relationship to water velocities.

Suspended sediment transport ($q_{ss}$) is dynamically related to the friction velocity ($U_*$) to a power which may be greater than unity, times the excess shear stress. The excess shear stress is directly proportional to the friction velocity squared, which means that $q_{ss}$ is proportional to $U_*^{n+2}$, where n = 1 at least. Bagnold (1963) and Yalin (1972) both suggested that the rates vary as $U_*^3$, but more recent work by Dyer (1980) indicates that in certain cases $q_{ss}$ varies as $U_*$ to a power between four and seven. Analysis of the relevant Sizewell-Dunwich data shows that in this particular area $q_{ss}$ varies typically as $U_*^{2.8}$, which is only slightly less than $U_*^3$ (Figure 10). Again, predictions should be based on field measurements since there is no clear general relationship.

### 5.3 Roughness lengths and the modification of the logarithmic velocity profile.

A parameterisation of the seabed roughness is required in sediment transport equations in order to calculate the bed shear stress and hence the transport rates and directions. There is a paucity of data from the British continental shelf referring to this roughness and the boundary layer velocity measurements in the Sizewell-Dunwich area have contributed to our knowledge in this field. Roughness length ($Z_0$) values have been calculated from velocity measurements for sandy to clayey substrates. The optimum values appear to be 0.0008 m for a clay substrate, 0.0039 m for the sand, silt and clay admixtures, 0.0029 m for fine sand and 0.0083 m for medium sand. Both sand grades are likely to be rippled. The unexpectedly high value for the admixtures is almost certainly due to the presence of a high density of the tube worm Owenia fusiformis. The top of the tube and the feeding parts of the animal project slightly from the seabed, giving additional roughness.

One perhaps surprising discovery has been the behaviour of the very high concentrations of suspended sediment, up to 1.892 g $l^{-1}$ of mainly very fine to fine sand (10 cm above the seabed) and a mean depth concentration of silt and clay in 10 m water of 0.230 g $l^{-1}$. These suspensions do not appear to modify the velocity profiles significantly from the logarithmic structure, at least in the bottom 2 m. This may be because the mainly sand suspension comprises discrete particles. In contrast, in Swansea Bay, where the velocity profiles are significantly modified, the suspended sediment is predominantly silt and clay. Nevertheless, the precaution was taken of only using the profiles which fitted the Karman-Prandtl equation above a 99% significance level, to calculate the roughness lengths.

### 5.4 Calculation of transport rates of separate grain sizes

A further problem in the prediction of suspended sediment transport rates is that engendered by the differential transport of different grain sizes. Progress has been made in developing techniques for the analysis of suspended sediment transport data with regard to the different size fractions.

A factor of proportionality ($\beta$) can be defined relating the eddy diffusivity of the sediment to the eddy viscosity of the surrounding fluid. This factor has been calculated from the slopes of the regression lines obtained by fitting the velocity and concentration profiles to the Karman-Prandtl and

Rouse equations respectively. Although many workers find such a factor to be less than one, in general $\beta > 1$ in Sizewell-Dunwich (Figure 11). Whereas it is not difficult to envisage 'damping' effects which high concentrations of suspended sediment may have on the near-bed velocity profile, a particle accelerating effect is more difficult to explain. Jobson and Sayre (1970) suggest that the diffusion of larger sediment particles, at least up to the medium sand range, is enhanced by centrifugal force arising from the curvature of fluid particle path lines, particularly in flows with strong vortex activity. Wave effects are not likely to play a major part in this instance as significant wave heights and wave periods were small at the time of the experiments.

Suspension of sediments is further complicated by the hysteresis effect, where there is a time lag between a change in velocity and that in the actual suspension or deposition of particles (Thorn, 1975). It is clear that measurements of sand concentration at a specific site will include material advected into the area by tidal currents and that not all sediment will be locally derived.

### 5.5 Wave attenuation by an offshore bank

The sheltering effect of an offshore bank sub-parallel to a neighbouring coastline is well known, and has been used in coastal protection work by the construction of artificial underwater banks (CERC, 1973). The placing of two Waverider buoys, one each side of the Dunwich Bank (Figure 1) has not only highlighted this protective capability by demonstrating that high waves break on the bank, but has also shown that the effect can be predicted theoretically.

The offshore Waverider buoy was installed in approximately 16 m of water, and the inshore one in approximately 11 m. Simultaneous records were obtained for periods between November 1978 and May 1979. Negligible attenuation was shown for the small waves, but as the offshore height ($H_{so}$) increased, the inshore significant wave height ($H_{si}$) did not increase above about 3 m. These data were reported by Carr et al (1982) and the plot they gave of measured inshore wave height against offshore wave height was sufficiently striking to warrant further work (Tucker et al, in press). These authors show that the critical wave height, at which such breaking occurs, varies between 2.46 m (high water) and 2.07 m (low water) for this area. The mean depth of water over the bank at high water is 5.1 m, and is 3.9 m at low water.

The expression

$$H_{si}^2 = \beta_w^2 H_{so}^2 \left[ 1 - \exp\left( - \frac{2H_c^2}{H_{so}^2} \right) \right] \qquad (1)$$

represents the relationships, where $\beta_w$ is the ratio $\frac{H_{si}}{H_{so}}$ for small waves (= 0.974) and $H_c$ is the critical height. Figure 12 shows the plot of all inshore and offshore data together with the statistically fitted curve.

### 5.6 Formation and maintenance of a sandbank in the lee of a headland

Many banks appear to be tied to headlands, but it is not clear how large a headland has to be to produce the flow effects leading to the generation of a bank. Many attempts at modelling the residual currents resulting from flow past a headland have been made (eg Tee, 1976; Maddock and Pingree, 1978). Tee (1976) in particular demonstrated the importance of the advective terms in his numerical model based on the solution of the two dimensional non-linear shallow water equation. Such effects are clearly seen in the neighbourhood of Portland Bill, Dorset, U.K.; Sker Point, Swansea Bay, South Wales (Heathershaw and Hammond, 1980) and to lesser extent in Start Bay, Devon, U.K. Thorpe Ness, despite its very limited topographic effect, is yet one more area underlining the importance of vorticity and advective effects.

### 5.7 Measurement of bedload transport in the field

There is only a limited number of techniques available for the measurement of bedload transport. This study has added a method previously restricted to the beach and nearshore zone, to those available for the measurement of offshore bedload transport. It has been shown that quantitative results for transport rates and directions can be relatively easily obtained using a fluorescent tracer. This has advantages of considerably reduced cost and the absence of potential health hazards over the more commonly employed radioactive tracers.

In the Sizewell-Dunwich area it was possible to measure the tracer dispersion for seven and a half months, a useful attribute, as offshore injected material typically appears to take 10 to 20 days to attain equilibrium with the indigenous sediment (Heathershaw and Carr, 1977). Bedload sediment transport calculations also require a knowledge of the depth to which the labelled material has become buried. This is straightforward to measure for fluorescent tracer by using coring techniques.

## 6 GENERAL CONCLUSIONS

The multidisciplinary study of the Sizewell-Dunwich Banks area is the second such project commissioned by the Department of the Environment and undertaken by the Institute of Oceanographic Sciences (Taunton). An important part of the Final Report for the earlier Swansea Bay study is a comprehensive discussion of methodology and analytical techniques, emphasising their strengths and weaknesses. The conclusions resulting from the discussion are also highly relevant to the Sizewell-Dunwich work and therefore the summarising tables are included in this report (Tables 1 - 3).

In Sizewell-Dunwich as well as Swansea Bay there has been an attempt to assess as many of the physical factors involved as possible, and to look at their overall importance in terms of the sediment budget of the particular area. As a result further understanding of the processes involved in the formation and development of an offshore bank have been achieved and the important rôle of the bank in protecting the adjacent coastline determined. However, more specific results, having implications for studies in other areas, have also been obtained.

Of particular interest are :

1 The necessity of choosing the correct sediment transport formula to apply in a particular situation.

2 The variation of the suspended sediment transport rate as the friction velocity to the power 2.8.

3 The occurrence of logarithmic near-bottom velocity profiles, in spite of the high concentration of suspended sediment. This is probably because the suspension is mainly very fine sand, ie discrete particles, unlike Swansea Bay, where the suspended solids are largely clay-sized.

4 The ratio of the eddy diffusivity of suspended grains to the eddy viscosity of the fluid, which was found to be greater than one. This means that the sediment particles, mainly of very fine sand, actually diffuse faster than the particles of containing fluid. The whole process does take place, of course, in turbulent conditions.

5 The demonstration of wave height attenuation by a bank above an $H_s$ critical for specific water depths, and in particular the ability to predict this theoretically.

6 Further support for theories of sandbank formation and maintenance in the lee of a headland, due to vorticity and advective effects in the currents.

7 The justification for using relatively inexpensive and harmless fluorescently labelled tracer for bedload sediment transport measurements.

The study has shown that there is still a need for further understanding of large and small scale sediment transport processes. In particular the mechanisms affecting suspended sediment transport are not well understood. Here prediction is difficult at present with comprehensive measurements of velocities and concentrations still being necessary. Probably one of the most important points to emerge from the research is that the careful and accurate field measurement of parameters is shown to be an essential part of any predictive work. Although general conclusions can be drawn, details of particular processes are all too often site-specific.

## 7 ACKNOWLEDGEMENTS

I would like to acknowledge the support and cooperation of my colleagues at the Institute of Oceanographic Sciences, Taunton. This work was supported financially by the Department of the Environment.

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# LIST OF TABLES

The following tables are taken from Heathershaw, Carr and Blackley (1981): Swansea Bay (Sker) Project, Topic Report: 8. Final Report: Coastal erosion and nearshore sedimentation processes.

TABLE 1 SUMMARY OF METHODS USED IN ASSESSING LONGER TERM CHANGES IN THE COASTLINE

| Subject Area | Method | Optimum Period | Applicability | | Advantages | Disadvantages |
|---|---|---|---|---|---|---|
| A. Geomorphology including Sedimentology, Biology and Archaeology | 1) Assessment of form of feature (eg ridge alignment; volume of sand dunes) | Last 2000 years | | Only on accreting coasts | Macro-scale (cf spot values of A2 and A3 | Only indicates net accretional events in evolutionary sequence |
| | 2) Absolute dating | Varies depending upon isotope (4 x 10 yrs with $^{14}$C) | Requires suitable sediment or material (eg peat, shells, bones, charcoal) | | Precise date<br>May enable long-term sequence to be established | Limited suitable material and conditions eg cohesive sediments and reducing environment. Both A2 and A3 can be extended substantially over geological timescale |
| | 3) Relative dating (eg pollen, microfossils, varves) | Last 10,000 years | | | | |
| B. Documentary | Written records | Since ~ 1100 AD | Widespread but very uneven coverage. Most valuable when concerned with specific local estate or town records | | | Interpretation subjective. Earlier records usually for state or ecclesiastical taxation purposes or legal agreements. Later ones topographical description but frequently derived from earlier (out-dated) sources |
| | Maps and charts | Since ~ 1800 AD. Some useful large-scale estate maps and plans used in litigation prior to this but most small scale and inaccurate | Widespread but very uneven coverage. ⑲ particularly useful because of overlap of hydrographic and topographic surveys of coastline by official bodies (H.D. and O.S.). Also charts of many minor ports no longer viable, and tithe maps | | Enables relatively accurate measured comparisons | Conditions may not be representative at time of survey. Some traces of bad survey occur and may not be detected. Partial revisions often ambiguous. Date of publication ≠ date of survey.<br>Changes in criteria (eg tide level definitions) over time may hamper comparability. Tide levels, especially low water, often inaccurate or generalised on land surveys prior to aerial photography. Thereafter high and low water lines frequently not contemporary with each other. |
| C. Aerial Photography | Qualitative interpretation from obliques. Possible quantitative interpretation from verticals | Post 1945. Occasional inter-war and wartime records | Useful potential sources for photogrammetry | | Enables simultaneous coverage of areas of interest, possibly in relation to critical event (eg 1953 East Coast Floods) | Problems of providing control on existing sorties and on shorelines generally. Much of 'vertical' photography available suffers from tilt; presence of cloud; has been taken at unsuitable tide state; or is too small scale. |

TABLE 2 SUMMARY OF GEOPHYSICAL AND SEDIMENTOLOGICAL TECHNIQUES FOR DETERMINING SEDIMENT TRANSPORT RATES AND DIRECTIONS

| Subject Area | Method | Nature of data obtained | | Advantages | Reservations and Comments | | |
|---|---|---|---|---|---|---|---|
| A Geophysics | 1) Continous seismic profiling | Details of bedrock surface and volume of unconsolidated sediments. Some indication of type of superficial material | | Relatively rapid areal coverage and initial interpretation on site | CSP restricted to adequate water depth. May not penetrate sea-bed depending on sediment type. A1 and 2 need repeated surveys to establish trends. Refraction seismograph and georesistivity may be appropriate onshore | | Movement is sum of processes. Not possible to differentiate between bed-load and suspended load except through biassing tracer particle size |
| | 2) Echo-sounding | | | | | | |
| | 3) Sidescan sonar | Alignment of sand waves, megaripples, etc. Qualitative only | | | Without closely repeated surveys over time it is not clear how much the observed forms depend on the state of tide (flood or ebb), spring-neap cycle, or wave | | |
| B Sedimentology | 1) Particle size analysis | Spatial trends in mean size, sorting, etc. Qualitative only | | Fairly rapid method of analysis | Many of the analytical techniques only applicable to sand grade and assume log-normal distribution. Assumption of fining of particle size with distance transported from source. Accuracy dependent upon sampling techniques (ie relatively undisturbed cores v. grab samples); sieving intervals, etc. Site (as Swansea Bay) may not have wide enough size range present. Grain-size parameters are discussed in Folk (1966) | | |
| | 2) Tracer experiments<br>a) Fluorescent labelling | Mainly applied to beach studies | Both B2a and B2b are frequently qualitative but quantitative results possible | Cheap. Relatively simple to sample. Substantial quantities can be labelled | Full analysis not practical in field and maximum travel may not be detected. Mainly coated sand; some simulated pebbles | Response not necessarily that of indigenous material. Excess travel at beginning of experiment because tracer not in equilibrium with environment. Experimental period may not provide representative conditions | |
| | b) Radioactive isotopes labelling (usually) of simulated sediment | Mainly applied offshore | | Detection in field hence spread of tracer is known | Mainly 'sand' grades simulated although mud and pebbles have been labelled | | |
| | c) Geological tracers - diagnostic geological types | Qualitative | | Unlikely to attract public attention and interference | Tracer needs to have same specific gravity; roundness and abrasion characteristics to indigenous. Mainly applicable to pebbles and cobbles | | |
| | d) Dyed and 'painted' sediment | Mainly qualitative | | Cheap. Relatively simple to sample. Substantial quantities can be labelled | | | |

TABLE 3a SUMMARY OF METHODS FOR PREDICTING SEDIMENT TRANSPORT RATES BASED UPON HYDRAULIC DATA

| Subject Area - Prediction | | | | |
|---|---|---|---|---|
| Method | Nature of data obtained | Advantages | Disadvantages | References |
| 1. Offshore areas (tidal currents): | | | | |
| a) Bedload prediction from: | | | | |
| current measured at one height above sea-bed | Sediment transport rates and directions usually over many tidal cycles | Uses conventional recording current meter techniques, gives good long term estimate of net sediment transport | Choice of appropriate sediment transport formula is not clear, problems in relating bed shear stress to near bottom current due to uncertainty in form of velocity profile. Difficult to account for effects of waves. Seabed roughness not usually known | Gadd et al, 1978;<br>Heathershaw and Hammond, 1979 |
| or | | | | |
| near bottom velocity profile measurements | Sediment transport rates and directions over 1-2 tidal cycles | Gives detailed information on transport processes over tidal cycle, measurement usually made when surface waves are not present. Gives estimate of seabed roughness ( $Z_o$) and information on near bottom velocity profiles | Requires specialist equipment operated from ship, only gives estimate of net sediment movement over 1-2 tidal cycles | |
| b) Suspended load prediction from: | | | | |
| current and concentration measured at one height above sea-bed | Sediment transport rates and directions over many tidal cycles | Can be done with conventional recording current meter techniques and say an optical device for measuring suspended sediment concentration | The forms of the velocity and concentration profiles are assumed and extrapolated over entire flow depth. Need to know the sea-bed roughness | Heathershaw and Hammond, 1979;<br>Dyer, 1980 |
| or | | | | |
| near bottom velocity and concentration profile measurements | Sediment transport rates and directions over 1-2 tidal cycles | Gives detailed information on velocity and concentration profiles over the tidal cycle. Can provide grain size information on suspensions. Gives information on sea-bed roughness | Requires specialist equipment; usually, only sequential sampling at various levels in the bottom boundary layer is possible | |
| 2. Beach (waves): | | | | |
| a) Littoral drift calculation from: | | | | |
| direction of wave approach and wave height and period measurements | Longshore sediment drift rate within the surf zone | If wave height, period and direction are known, method is relatively simple to apply | Precise determination of wave direction is difficult and many require sophisticated equipment and data analysis techniques | |

TABLE 3b SUMMARY OF METHODS FOR MEASURING SEDIMENT TRANSPORT RATES

| Subject Area - Measurement | | | | |
|---|---|---|---|---|
| Method | Nature of data obtained | Advantages | Disadvantages | References |
| 1. Bedload: | | | | General: Graf, 1971;<br>Vanoni, 1975;<br>McCave, 1979 |
| a) Box- or basket-type sampler | Amount of sediment retained in a pervious basket or box | Simple, direct measurements | Require calibration in flumes to determine efficiency; interfere with flow; of no use when bedforms are present; mainly used in rivers | |
| b) Pan- or tray-type sample | Amount of sediment retained in an open pan | | | |
| c) Pit-type sampler | Amount of sediment retained in a pit or depression in the channel bottom | | | |
| d) Acoustic: | | | | |
| Self-generated noise | Acoustic noise of particle collisions | Does not disturb flow at point of measurement, fast time response, continuous record, could be used under waves | Indirect sampling; still at development stage; qualitative data only | Specific:<br>Salkield, 1978 |
| Doppler frequency shift | Particle velocity in saltation layer | | | |
| Back scattered energy | Particle concentrations in saltation layer | | | |
| Bedform migration rates | Rate of movement of bedform | Comparatively simple, continuous record possible | Of no use on plane beds and requires theoretical relation between bedload transport rate and bedform migration rate | |
| Acoustic pebbles | Rates and direction of movement of pebble size material | Gives information on displacements of individual particles | Pebble size particles only | Dorey, et al, 1975 |
| 2. Suspended load: | | | | General: Graf, 1971;<br>Vanoni, 1975;<br>McCave, 1979 |
| a) Bottles and traps: | | | | |
| NIO, Van Dorn, Niskin | Instantaneous sample of water and sediment in 1-30 l range | Simple | Insufficient sediment for grain size analysis; do not align with flow | Specific:<br>McCave, 1979;<br>McCave, 1973;<br>Vanoni, 1975 |
| Delft | Trapped sediment only | Simple | Requires additional flow measurement for concentrations; particle size 50$\mu$m only | |
| Neyrpic, US DH-59 or US P-61 river samplers | Depth or point integrated samples of water and sediment up to 1 l | Samples at stream velocity, aligned with flow | Used mostly in rivers | |
| b) Pumped sampling:<br>Filtering and weighing | Filtered sediment $>40\mu$m and water samples for $<40\mu$m, quantity of fluid | High volume samples yielding sufficient amounts of sediment for grain size analysis | Problems with representativeness of sample and material settling out in pump hoses; does not sample at stream velocity; cannot be used under waves | Crickmore & Aked, 1975;<br>Heathershaw & Hammond, 1979; Bennett, 1978 |
| c) Optical devices:<br>Transmission, scattering and occultation | Concentration of material in suspension | Short time response, continuous record, used extensively in the sea, can be used under waves | Require calibration with in-situ sediments; fouling of optics; complications with small particle sizes | Soulsby,1977;Shepherd, 1978;Lesht,1979;Butman & Folger,1979;Lavelle et al,1978;Cacchione & Drake,1978 |
| d) Acoustic:<br>Scattering techniques | Concentration | Short time response, continuous record, can be used under waves | Still at development stage | Soulsby, 1977 |
| e) Electro-mechanical:<br>Piezo-electric or capacitive | Number of sediment particle impacts in known cross sectional area | Short time response, continuous record | Still at development stage, requires additional flow measurement for concentration, cannot be used under waves | Soulsby, 1977 |
| f) Nuclear:<br>Gamma-ray densitometry (back scatter or transmission) | Density | Short time response, continuous record | Requires careful calibration, really only useful for dense suspensions | Parker, et al, 1975 |

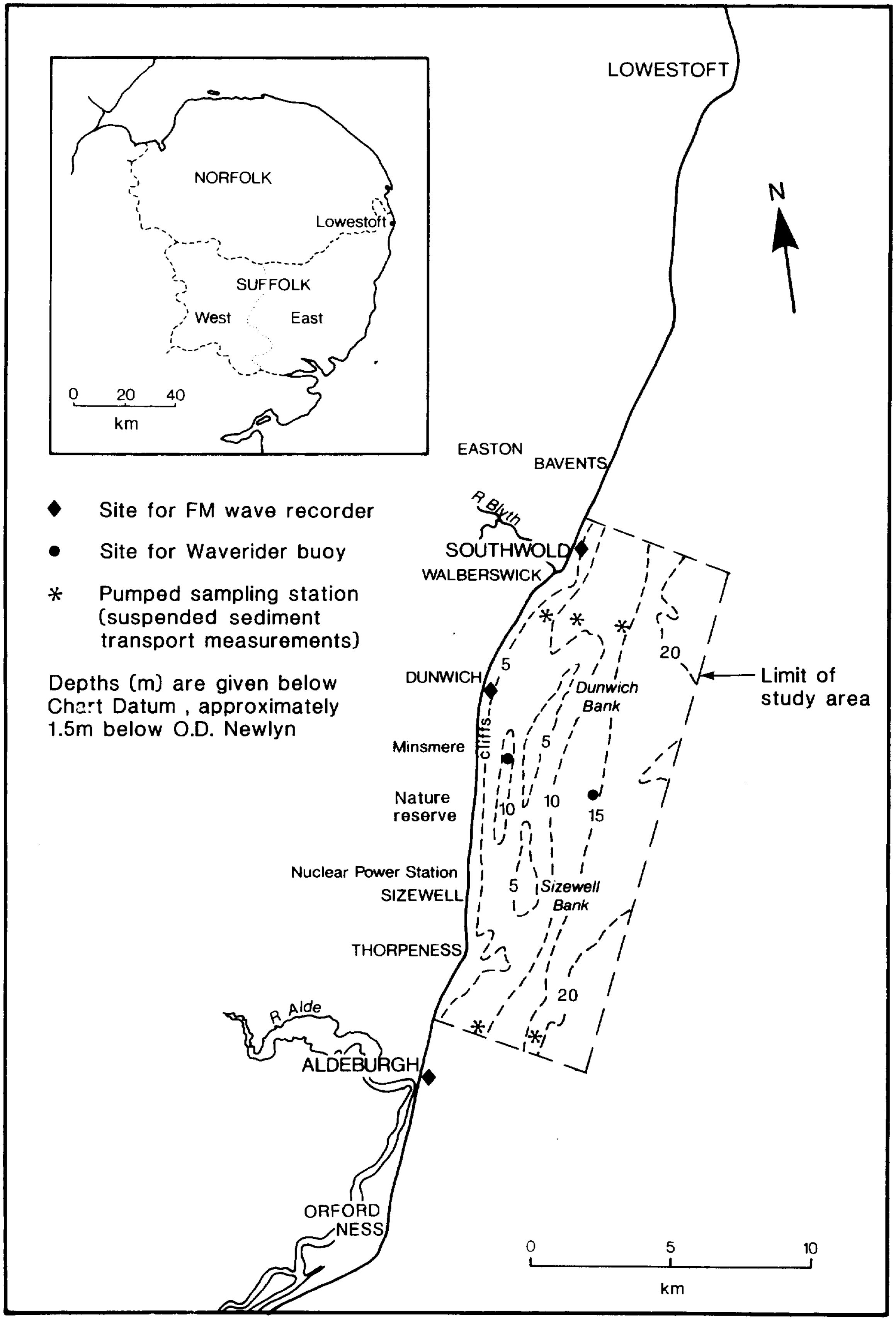


Fig.1 Location Map.

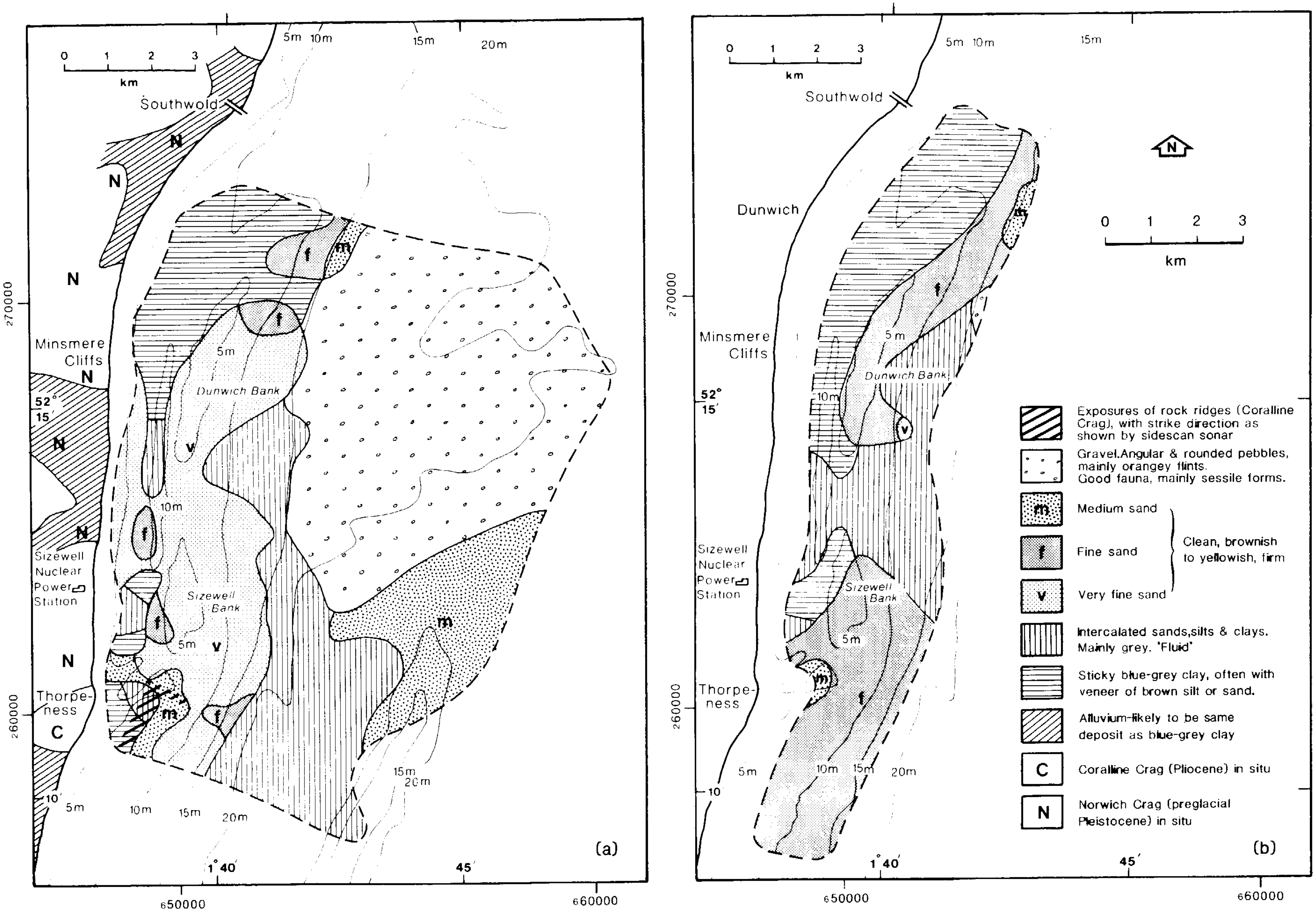


Fig.2 Sediment distribution a) Winter (February/April) b) Summer (August).

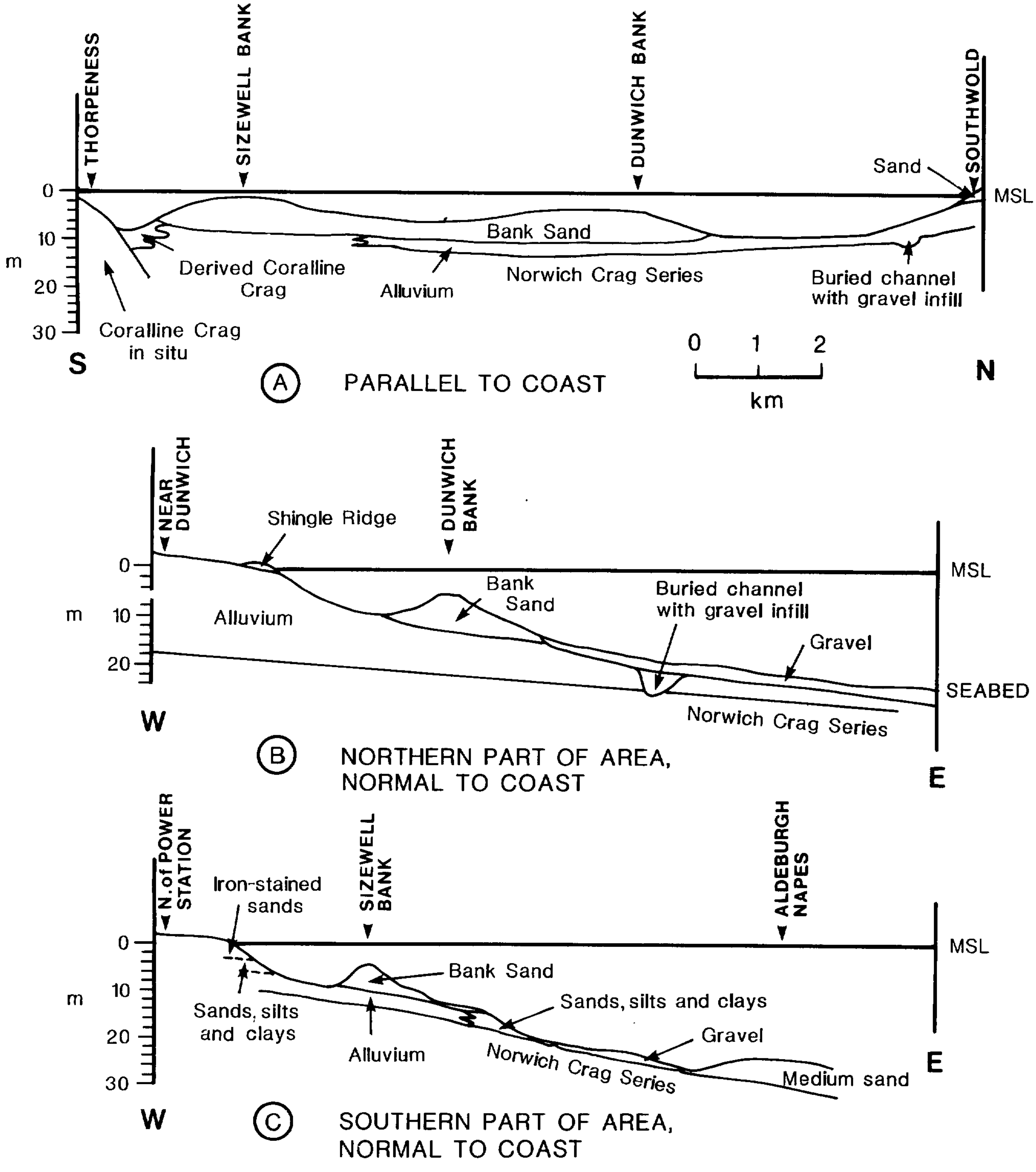


Fig.3 Schematic sections of the seabed to show the superficial geological structure of the area.

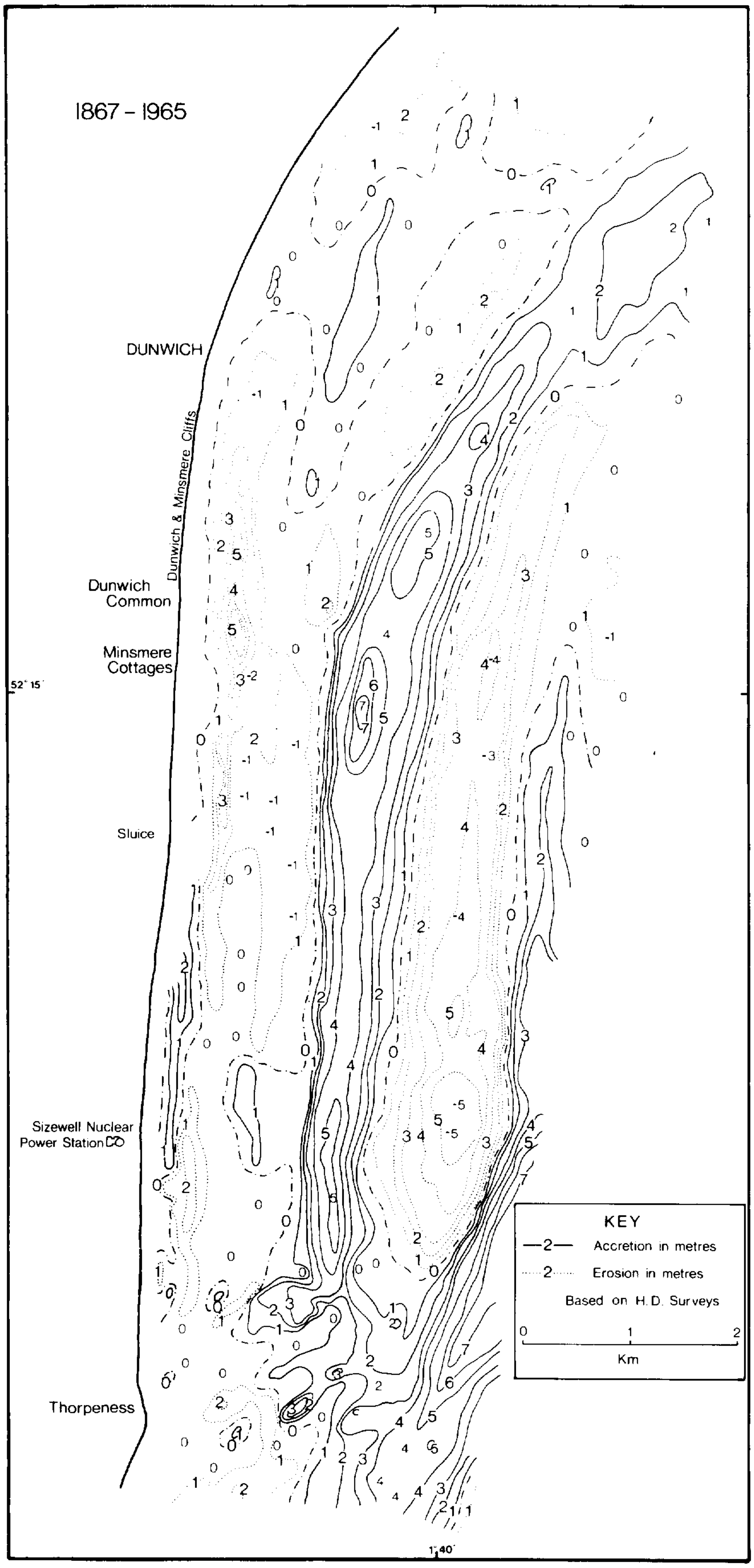


Fig.4 Isopleths of erosion and accretion from 1867 to 1965.

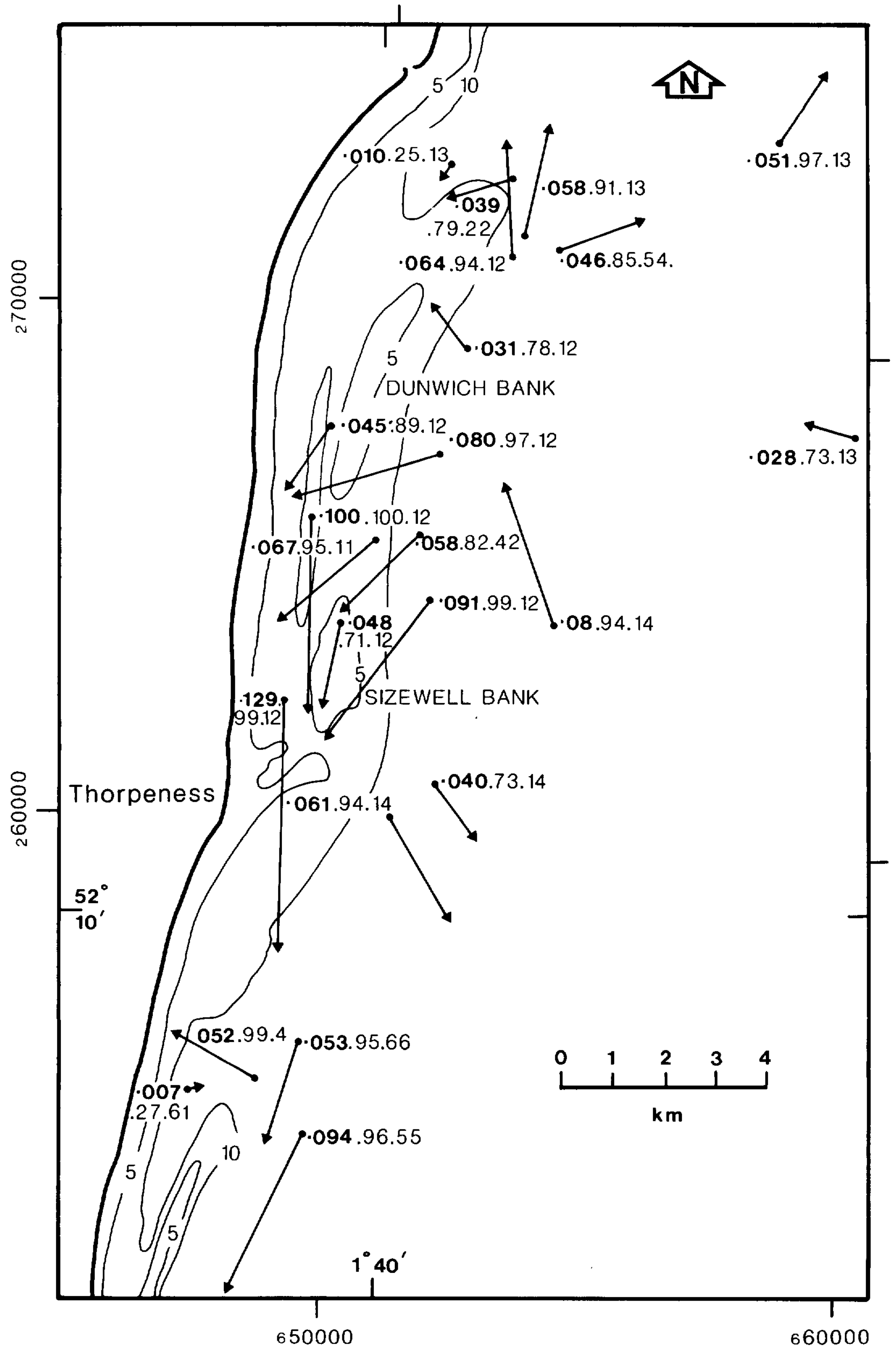


Fig.5 Summary of mid-depth tidally induced residuals. Residual flow data have been presented in the manner suggested by Ramster et al (1978) and each set of figures shows: the residual flow speed in m $s^{-1}$; the steadiness factor as a percentage; the length of the record in days (in that order).
NB: These data are not synoptic.

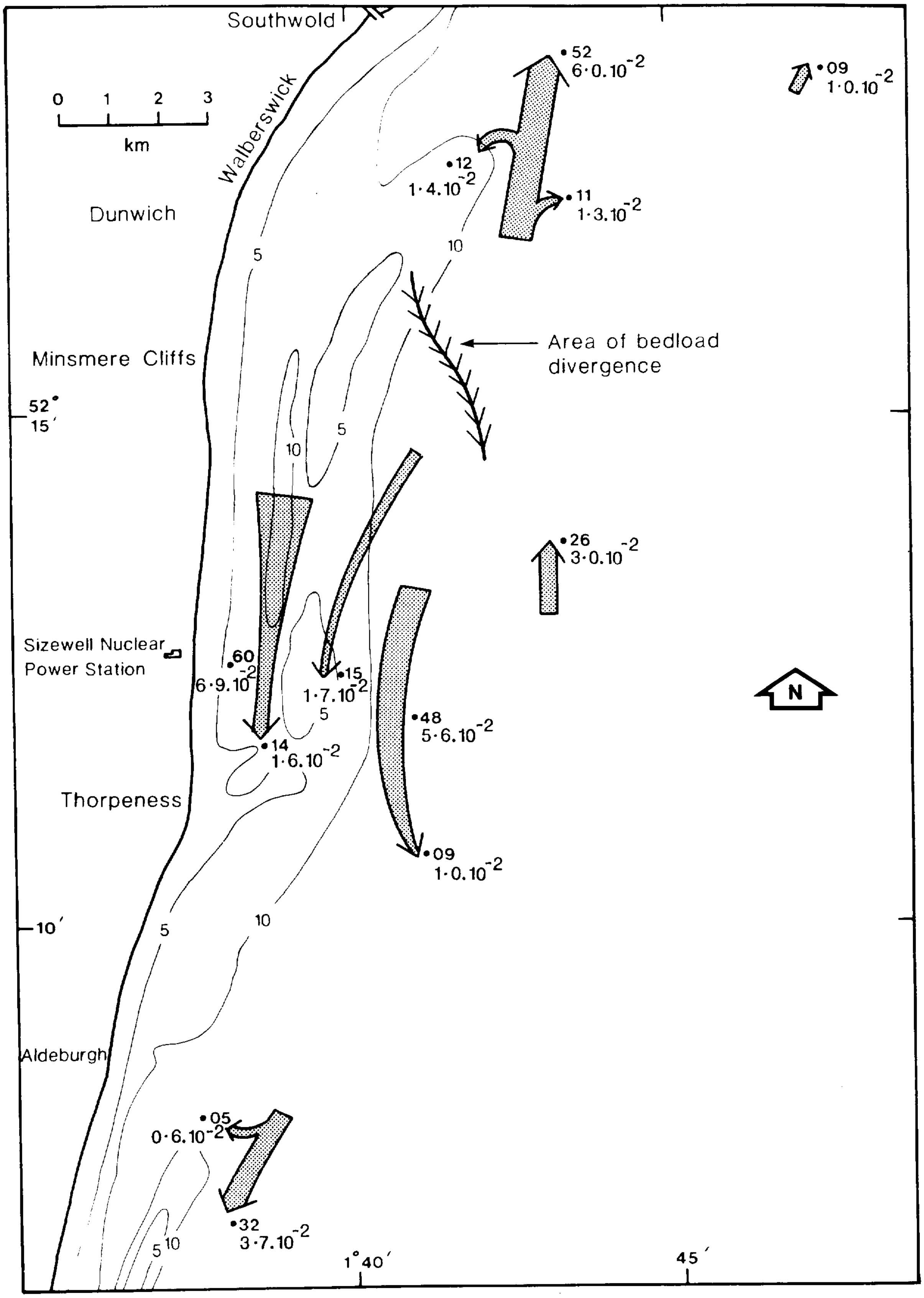


Fig.6 Schematic summary of bedload sediment transport paths. Numbers are sediment transport rates in g cm$^{-1}$s$^{-1}$, and tonnes m$^{-1}$ day$^{-1}$ respectively.

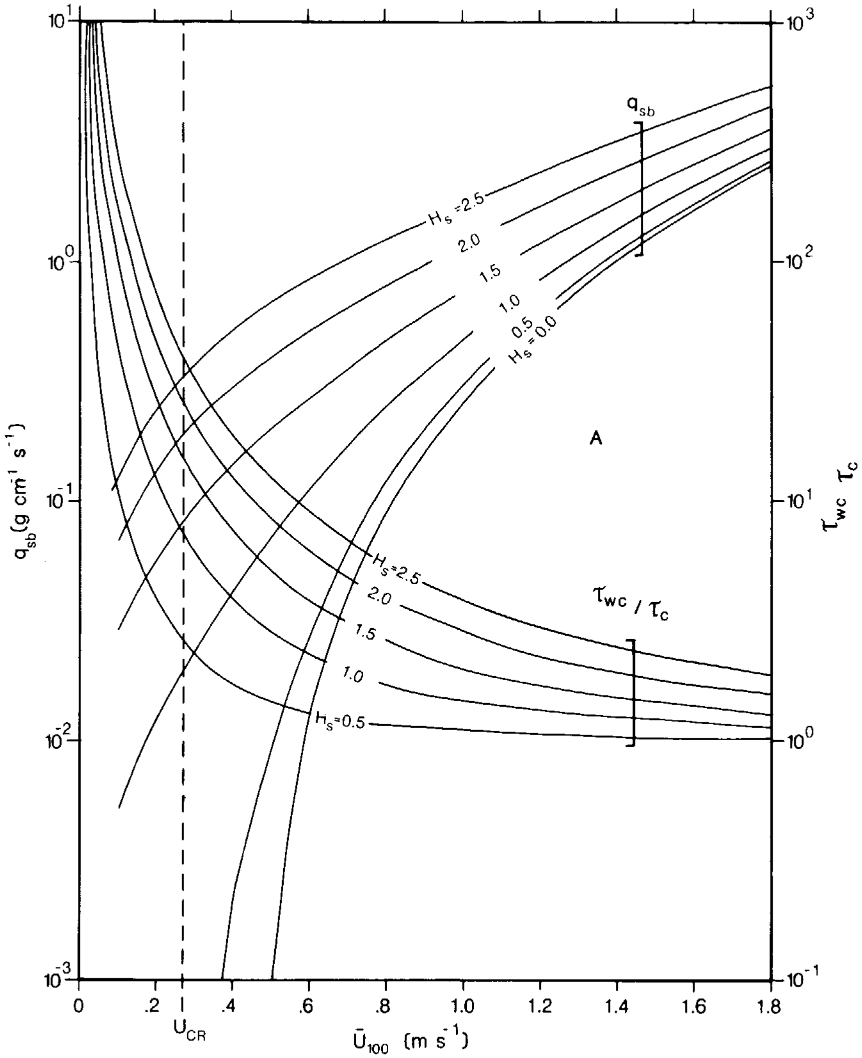
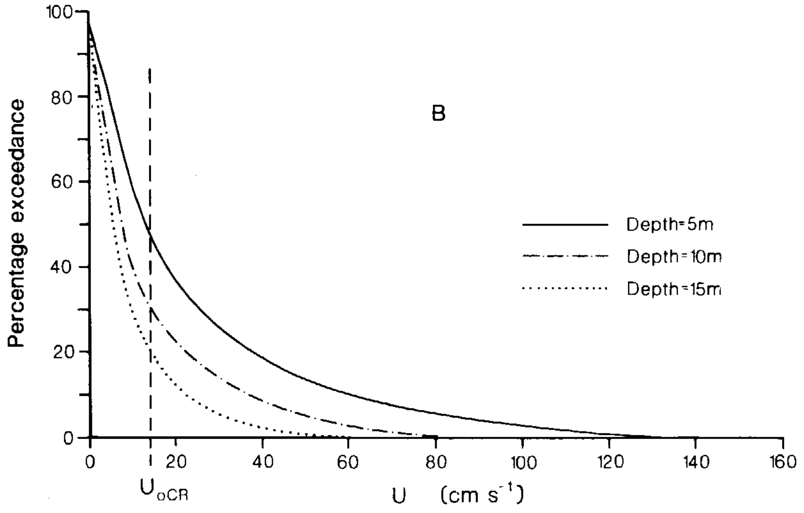
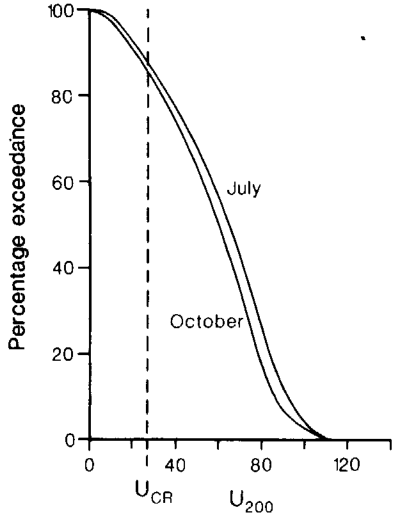


Fig.7 A. Effect of waves on sediment transport. Bijker's (1967) magnification factor $\tau_{wc}/\tau_c$ illustrating effect of increasing wave height (H) on bedload transport rates ($q_{sb}$), as function of current at height of 100 cm above seabed ($U_{100}$). NB These calculations have been carried out for a wave of 6s period and water depth of 12 m, with roughness length of .05 cm, typical for fine sand.





B. Wave induced current exceedance curves, based on 1 year's wave measurements made offshore from Southwold. $U_{OCR}$ is indicated and has been calculated from equation (14).

C. Percentage exceedance curves for tidally induced currents, using 1 month's data in each case.

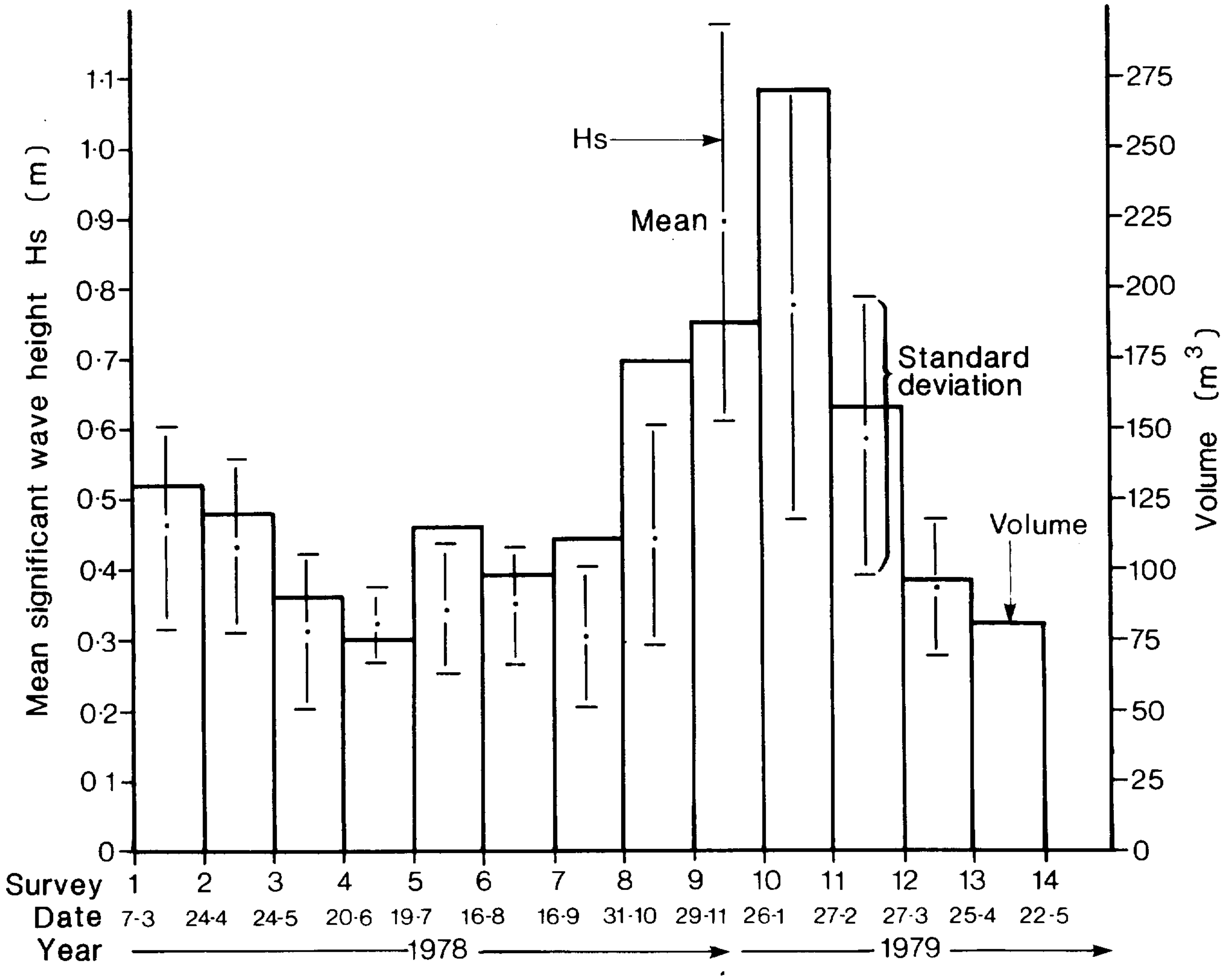


Fig.8 Comparison between total monthly volume of beach material moved in cubic metres and mean monthly significant wave height ($\bar{H}_s$) at Dunwich. Standard deviations for $H_s$ are also shown.

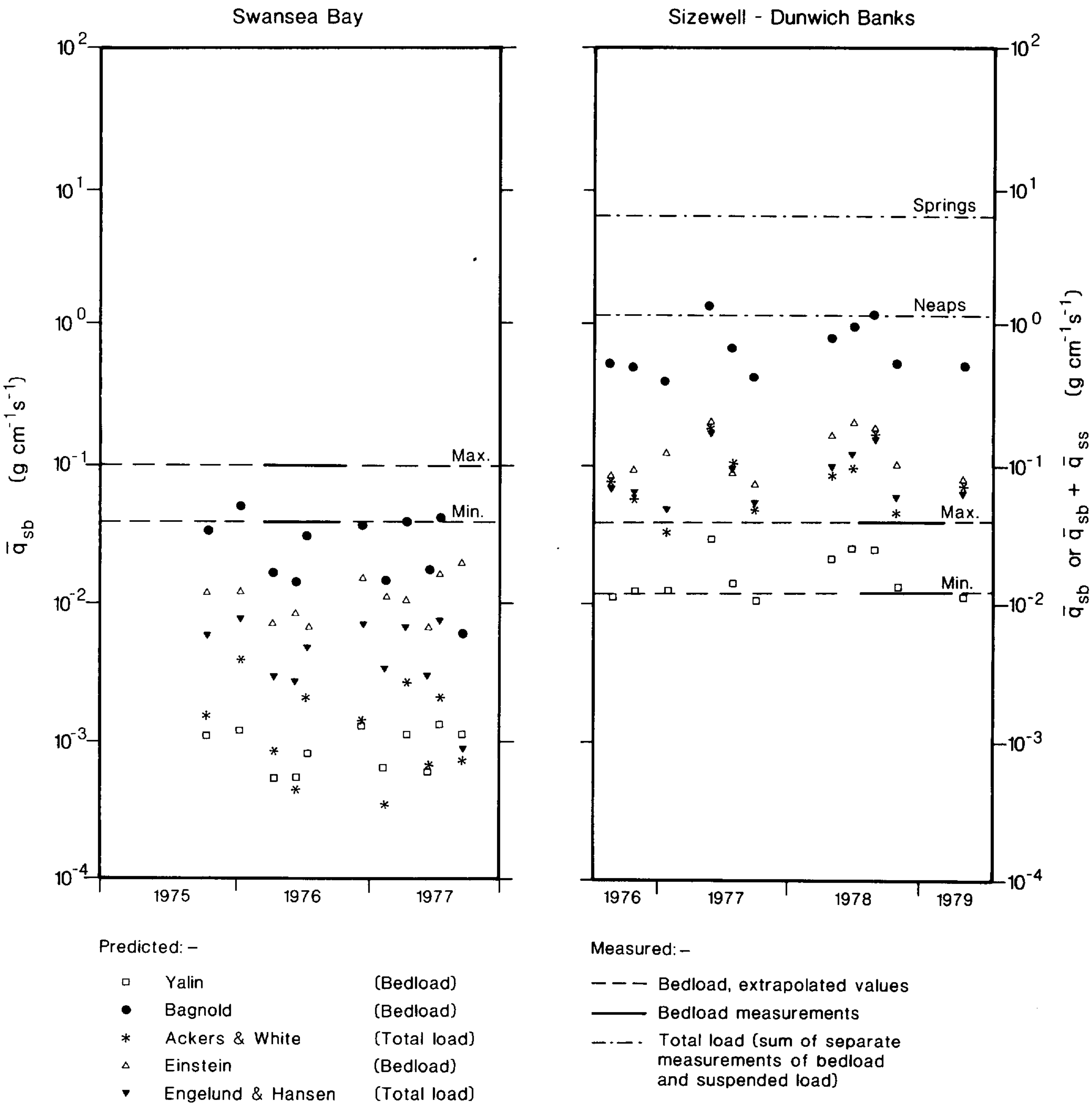


Fig.9 Comparisons of measured and predicted net transport rates ($\overline{q_{sb}}$).

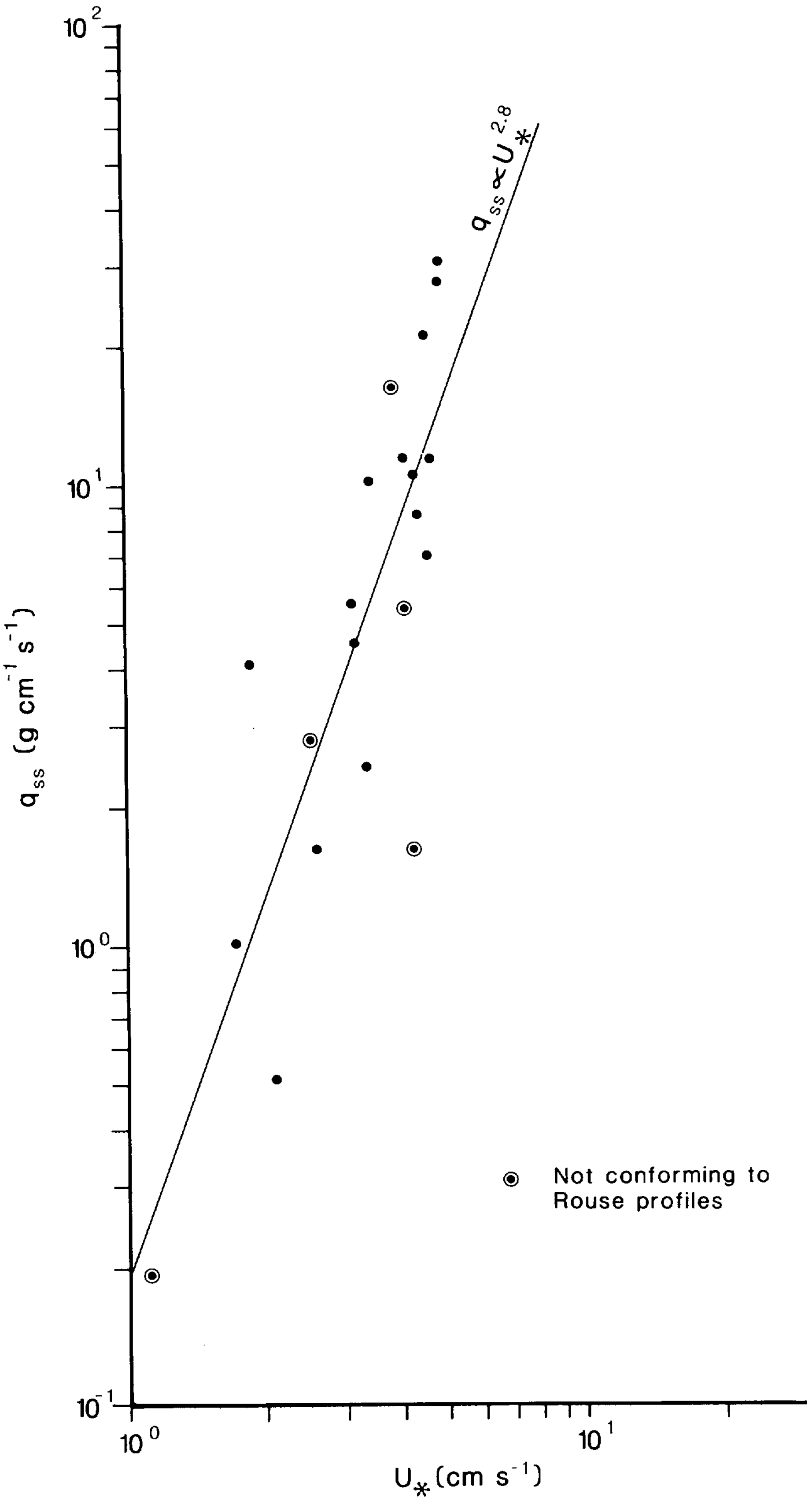


Fig.10 Variation of total suspended sediment transport rate ($q_{ss}$) with friction velocity ($U_*$). Linear regression analysis shows $q_{ss}$ α $U_*^{2.8}$

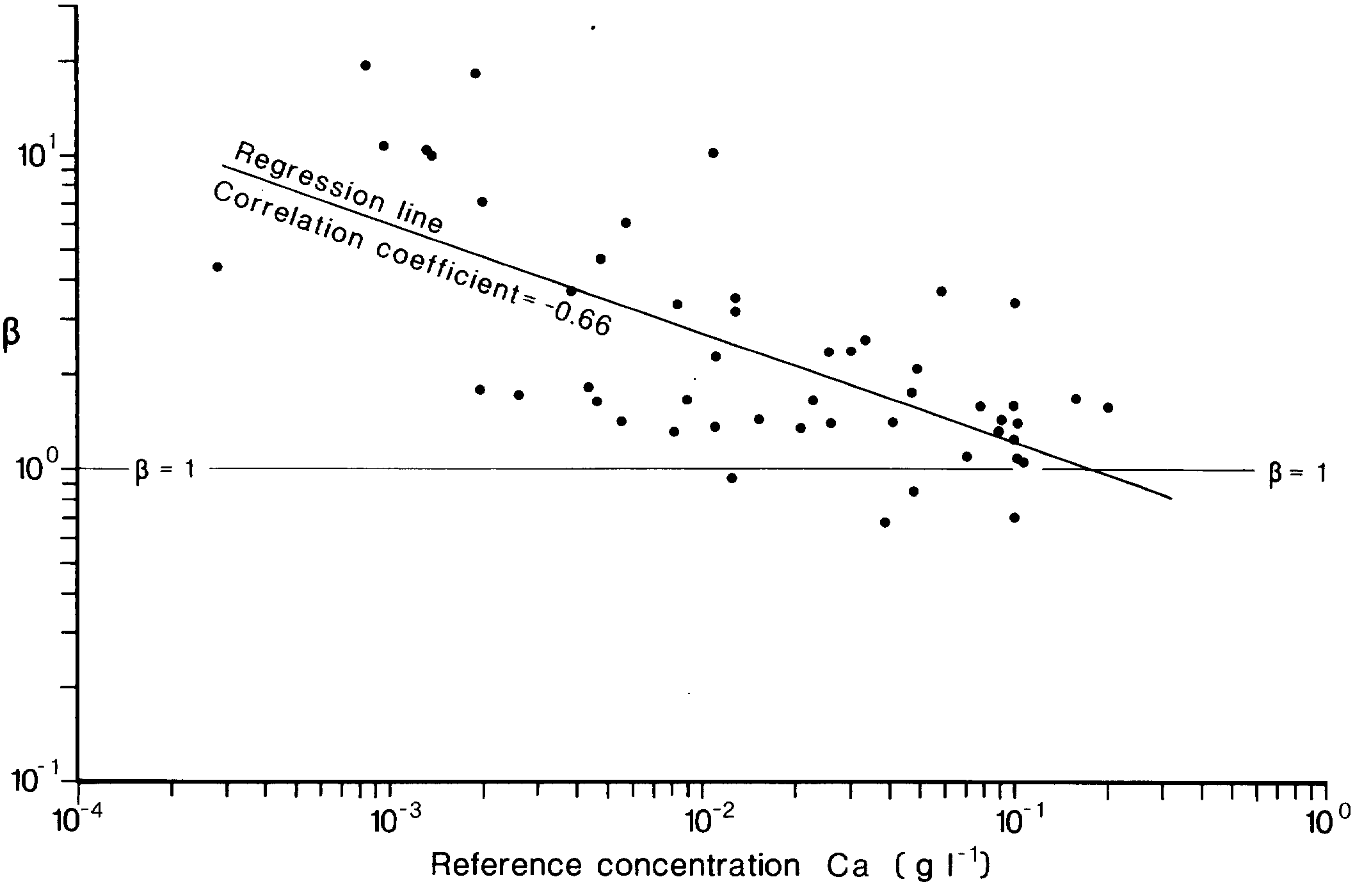


Fig. 11 Values of β, where the eddy viscosity of the fluid equals β times the eddy diffusivity of the suspended particles, plotted against the reference concentration ie that at a level 1 m above the seabed.

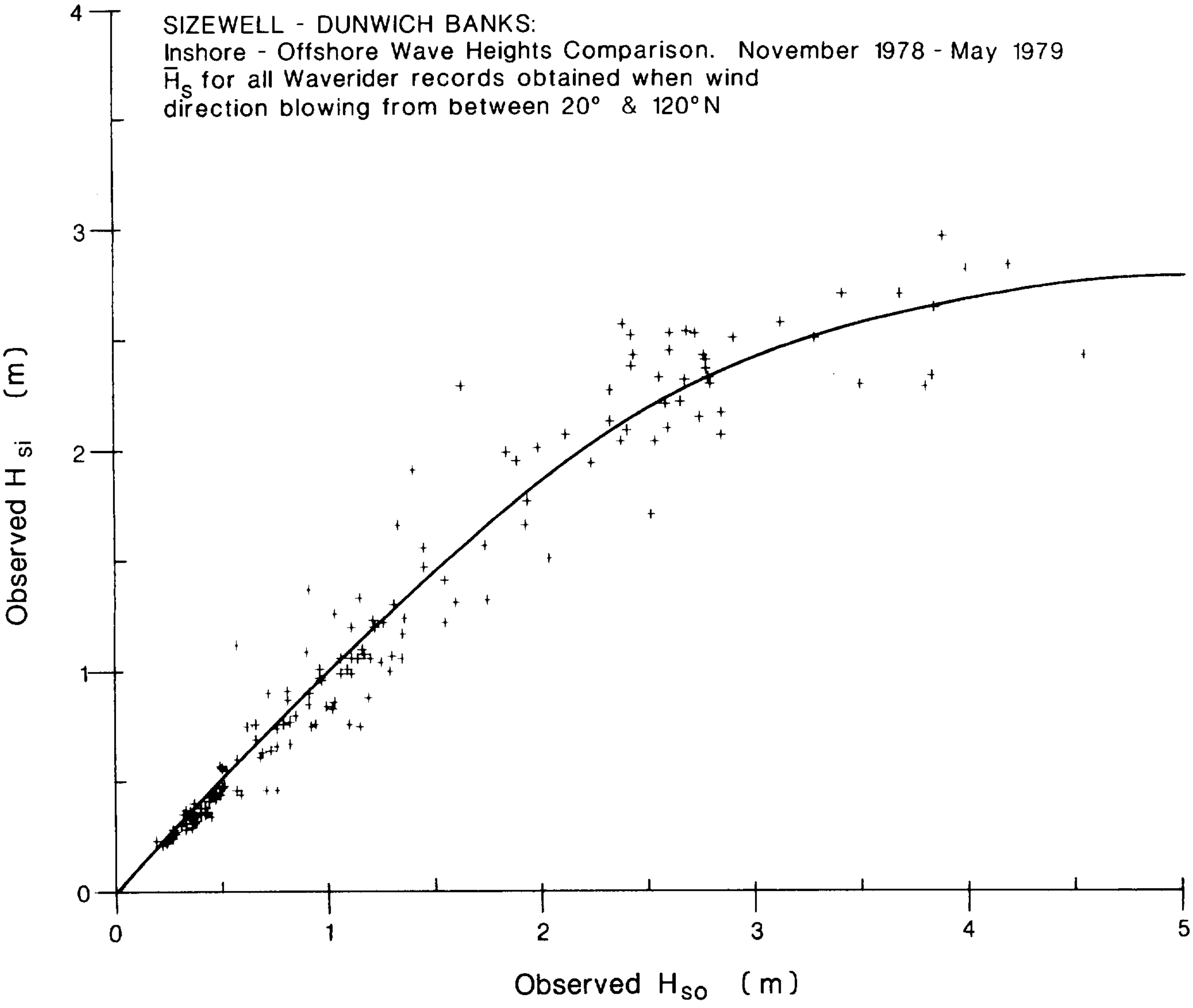


Fig.12 Significant wave heights for the inshore Waverider buoy plotted against those for the offshore buoy. The fitted curve has the equation

$$H_{si}^2 = \beta_w^2 H_{so}^2 \left[1 - \exp\left(-\frac{2H_c^2}{H_{so}^2}\right)\right]$$

For further explanation see text.

APPENDIX A

List of IOS Topic Reports describing the Sizewell-Dunwich work

1 Sizewell-Dunwich Banks Field Study: a) Introduction
b) Geological Background No 88, 1980

2 Sizewell-Dunwich Banks Field Study: Long-term changes in the coastline and offshore banks. No 89, 1979

3 Sizewell-Dunwich Banks Field Study: Beach changes between Aldeburgh and Southwold March 1978 to May 1979 No 90, 1979

4 Sizewell-Dunwich Banks Field Study: Tidal currents: Observed tidal and residual circulations. No 104, 1980

5 Sizewell-Dunwich Banks Field Study: Offshore sediment movement and its relation to observed tidal current and wave data. No 123, 1981

6 Sizewell-Dunwich Banks Field Study: Wave data: observed and computed climates. No 128, 1981

7 Sizewell-Dunwich Banks Field Study: Final report: a study of nearshore sediment transport processes No 146, 1982

# APPENDIX B

## List of IOS Topic Reports describing work in Swansea Bay

| | | | |
|---|---|---|---|
| 1 | Swansea Bay: | (a) Introduction<br>(b) Long-term changes of the coastline | No 42, 1977 |
| 2 | Swansea Bay: | Evidence of beach stability: Photogrammetric and topographic measurements | No 51, 1977 |
| 3 | Swansea Bay: | Geophysical interpretation and sediment characteristics of the offshore and foreshore areas | No 60, 1978 |
| 4 | Swansea Bay: | Tidal currents: observed tidal and residual circulations and their response to meteorological conditions | No 92, 1979 |
| 5 | Swansea Bay: | Wave data: observed and computed wave climate | No 99, 1980 |
| 6 | Swansea Bay: | Offshore sediment movement and its relation to observed tidal current and wave data | No 93, 1979 |
| 7 | Swansea Bay: | Foreshore sediment movement and its relation to observed tidal current and wave climate | No 98, 1980 |
| 7a | Swansea Bay: | Beach fluorescent tracer experiments | No 105, 1981* |
| 8 | Swansea Bay: | Final Report: a study of foreshore and offshore sedimentation processes | No 118, 1981 |

*Additional to original Topic Report series.

## APPENDIX C

List of published research papers to July 1982, using Sizewell-Dunwich data

1 A new technique for injecting fluorescent sand tracer in sediment transport experiments in a shallow water marine environment. B J Lees. Marine Geology, 33, M95-M98, (1979).

2 Evidence for the sediment circulation along the coast of East Anglia. A P Carr. Marine Geology, 40, M9-M22, (1981).

3 Sediment transport measurements in the Sizewell-Dunwich Banks area, East Anglia, UK. B J Lees. Special Publication of the International Association of Sedimentologists, 5, 269-281, (1981).

4 Spatial and seasonal aspects of beach stability. A P Carr, M W L Blackley and H L King. Earth Surface Processes and Landforms, 7, 267-282, (1982).

5 Quaternary sedimentation in the Sizewell-Dunwich Banks area, Suffolk. B J Lees. Bulletin of the Geological Society of Norfolk (in press).

6 Relationship between eddy viscosity of seawater and eddy diffusivity of suspended particles. B J Lees. Geo-Marine Letters (in press).

7 The effect of an offshore bank in attenuating waves. M J Tucker, A P Carr and E G Pitt. Coastal Engineering (in press).