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SWANSEA BAY (SKER) PROJECT
TOPIC REPORT: 8

A D HEATHERSHAW, A P CARR AND M W L BLACKLEY

Final Report:
Coastal erosion and nearshore sedimentation processes

REPORT NO 118

1981

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF
OCEANOGRAPHIC
SCIENCES

INSTITUTE OF OCEANOGRAPHIC SCIENCES

Wormley, Godalming,
Surrey GU8 5UB
(042-879-4141)

(Director: Dr. A. S. Laughton, FRS)

Bidston Observatory,
Birkenhead,
Merseyside L43 7RA
(051-653-8633)
(Assistant Director: Dr. D. E. Cartwright)

Crossway,
Taunton,
Somerset TA1 2DW
(0823-86211)
(Assistant Director: M. J. Tucker)

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FINAL REPORT

COASTAL EROSION AND NEARSHORE SEDIMENTATION PROCESSES

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This project was supported financially by the
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Institute of Oceanographic Sciences
Crossway
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Somerset

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PREFACE TO FINAL REPORT

Although, since its inception, the objectives of the Swansea Bay (Sker) project have included the study of specific local problems, the primary purpose has been to recognise and investigate aspects of wider scientific relevance. In particular, there has been an attempt to determine those areas of research in nearshore sedimentation processes which have a direct bearing on coastal erosion and coastal zone management and to assess the extent to which further research is required therein.

This dual purpose is reflected in the final report.

SUMMARY

This is the final report in a series describing the results of a research project to study the sedimentation regime in Swansea Bay in relation to the erosion of sand on the foreshore. Previous reports have treated various aspects in detail: this one attempts to give a broad overview and to draw conclusions of wider relevance. Thus the report falls into two parts, the first dealing with purely regional aspects of the sediment circulation pattern and budget in Swansea Bay, and the second concerned with those aspects of the study which are of more general scientific interest and relevance to the coastal engineering community and which have a bearing on coastal erosion processes in general.

Although brief summaries of the reports describing specific aspects of the areal study are included here reference should be made to the appropriate report (see Appendix A) for further details, if required.

It has not been possible in this study to identify a definite single cause for the erosion of the foreshore on the E side of Swansea Bay but there is evidence from photogrammetric measurements to show that the rate of loss of sand corresponds closely to the rate of removal by sand winning.

The evidence from a substantial body of data, and from theory, is that the replenishment by natural processes of material lost from the beach is likely to occur only over a long period of time. Evidence points to the sedimentary system in the Bay being virtually closed and the beach being in a state of quasi-equilibrium with the prevailing wave climate. Supply of appropriate grades of material to the beach from offshore is limited while alongshore movements of sediment appear to be weak and variable in direction. The presence of fine cohesive sediment offshore and the effects of the breakwater and dredged approach channel at Port Talbot cannot be entirely discounted in further preventing offshore sand reaching the eastern shore of Swansea Bay.

The second part of the report examines the techniques used during the research in Swansea Bay and their applicability to similar problems in other locations. It identifies those conceptual areas where further research is required to improve our understanding of sediment transport processes and, thereby, our ability to predict sediment movement. Existing methods of prediction are largely empirical and the various methods that are available require field calibration. The Swansea Bay study has highlighted a pressing need for improved

1 INTRODUCTION

1.1 General comments

This report summarises the results of 5 years of research by the Institute of Oceanographic Sciences (IOS) into large scale sediment transport processes in the Swansea Bay area of the Bristol Channel. However, the report goes beyond the purely regional aspects and examines these data in a broader context. It seeks to identify areas where improvement in our understanding of fundamental processes is needed in order to make accurate large scale predictions of sediment movement possible.

Interest in sediment movement on the continental shelf and in the nearshore zone stems largely from the need for civil engineers to predict the results of man-made change. Such change may occur as a result of the placement of engineering structures on the sea-bed, through the construction of new harbours, or by the removal of sediments for industrial use or to improve navigation. Dramatic changes may also occur during periods of severe storm activity and lead to coastal erosion and flooding.

Sediment transport processes are by no means uniquely physical, and there is strong evidence (eg McCave, 1976) to suggest that biological processes may be significant in causing sediment particle exchange within the sea-bed and that chemical processes influence particle size distributions by flocculation. In relating present day trends to those which occur on the longer time scale, there is also a need for geological interpretation. Research programmes in this country and abroad (eg Sternberg, 1979) reflect strongly the need for a multidisciplinary approach to the sediment transport problem.

The predictive capability required by engineers is similarly reflected in research programmes, proposed (eg McDowell et al, 1980a, b) or already in progress, which contain a large element of computer modelling.

instruments and methods for measuring sediment transport rates in the field particularly under adverse, but critical environmental conditions. This applies equally for both waves and tidal currents, and for offshore and foreshore sites.

of the foreshore and the sea-bed conditions is necessary....before long-term conclusions can be reached". Therefore: "The Coast Protection Authority shall undertake or cause to be undertaken a detailed study of the evolving beach conditions, the offshore sea-bed conditions and the potential sediment budget available for beach replenishment".

1.3 Objects of research

The objectives of the research project in Swansea Bay can therefore be outlined as follows:

1.3.1 Of local importance

1.3.1.1 To try to assess the causes of erosion along the eastern foreshore and the proportionate responsibility of the potential factors. These are land reclamation near Swansea, together with natural accretion on the N side of the Bay; construction of training walls along the Neath estuary; the possible interruption of longshore sediment transport due to the building of the Port Talbot tidal harbour and the effect of the dredged approach channel there; extraction of sand and gravel from the foreshore and offshore banks; and the inhibiting effect on coarse sediment bed-load transport of both silt spoil deposited in the bay and the presence of naturally-occurring fine-grained sediment there.

1.3.1.2 To calculate the amount of sediment reaching the beach from offshore, its particle size range, and the variability in volume dependent upon prevailing physical conditions. It was anticipated that in the specific context of Swansea Bay this particular problem might be solvable only qualitatively because of the environmental variability and conflicting evidence.

1.3.2 Wider objectives

These two questions have wider spatial relevance but the Institute's main concern, reflected in the financial support provided by central government (DOE) can be outlined as follows:

1.3.2.1 To identify, and where possible isolate, the processes responsible for erosion, accretion and transport of sediment; to assess their relative importance with a view to concentrating upon the most critical aspects. To

In the UK there have been few regional scale sediment transport studies in which the full range of physical processes has been examined over representative time scales. The IOS study in Swansea Bay has gone some way towards filling this gap in our knowledge, but at the same time has identified those areas where further research is needed. Some associated work was carried out by the Department of Oceanography, University College of Swansea, under contract to IOS. This has been reported in Ferentinos and Collins (1978), and is referred to as appropriate in the present report.

1.2 Terms of Reference

Early in 1973 Glamorgan County Council, as it then was, approached the former Unit of Coastal Sedimentation (UCS) regarding erosion problems along the foreshore of the E part of Swansea Bay, notably on Morfa Mawr and Kenfig Beaches. (Figures 1 and 2 show the principal places referred to in the text.) This approach was formalised in a letter dated 12 June 1973. Subsequently it was agreed that the Institute of Oceanographic Sciences (IOS) Taunton Laboratory (into which the UCS had by then been incorporated) would write a preliminary report for the Council suggesting work which needed to be undertaken to assess the reality and extent of the erosion and its possible cause(s), the report being without a guarantee that IOS could undertake the work.

IOS later decided that many of the aspects of the problem were of widespread interest and applicability and that the subject would be suitable for a type study. Furthermore this study could be fitted into the organisation's overall research programme. Because of its broad relevance the Department of the Environment (DOE) agreed that the project should be included in their programme of commissioned work.

There are thus two levels at which the study may be viewed, that of the immediate area and its specific problems, and in the wider context of the interrelation between coastline and offshore in general.

In December 1973 a Public Inquiry was held by the Welsh Office into the Borough of Port Talbot Coast Protection Order 1973 and the same authority's Interim Coast Protection Order. These Orders had had the effect of prohibiting the extraction of beach material from the foreshore at least in the short term. While upholding the Orders the Inspector wrote that: " A detailed study desk study concentrated on the documentary records. Having established that the problem was a genuine one the research programme then developed a two-pronged attack.

The first objective was to describe the bathymetry (Figure 2) and superficial geology and sediments (Figure 3) of the area using geological, geophysical and other surveying techniques. The coastline and offshore are intimately related so that both had to be included. These results then formed the background for the planning of a series of field measurements (Figure 4) to study the processes at work. Wave data were gathered, both the incident waves well offshore using a Waverider buoy, and the direction and height of waves nearshore using a radar and seabed pressure recorder. Currents were measured mainly by self-contained recording current meters at a number of sites and depths and at representative periods during the summer and winter together with one longer term installation. Sediment transport was measured by pumped sampling giving short-term results, and by tracer methods, both on the beach and offshore, providing longer-term averages. Regular beach surveys followed the response of the beach to the varying weather conditions during the seasons.

All aspects of the research programme interacted, and for the beach processes especially, synoptic studies were made of the wave and current input together with the response of the sediment.

IOS commenced the research on Swansea Bay in mid-1974 and the field work was completed by 1977, since which time the processing of the data and writing of the Topic Reports has continued. Topic Reports 1 to 7 (and 7a) describe particular aspects of the study in detail (see Appendix A for a list of these). This is the final report and gives an overview of the whole project. It starts by describing in this section the results as they specifically apply to Swansea Bay. It then discusses in section 3 their broader relevance, and the applicability of the techniques used to other sites. Finally in section 4 unresolved problems are identified together with their implications.

2.2 Past changes in the coastline and offshore

2.2.1 Historical and geomorphological

The dune systems along the E side of the Bay (Figure 1) do not exceed 6000 years in age. At their maximum extent, before extraction by man, they probably determine the nature of sediment circulation cells; the extent to which they are self-contained, and the effect of particle size upon this.

1.3.2.2 To develop and evaluate methods and techniques for the study of the coastline and the offshore zone and determine the most useful (ie least ambiguous) forms of analysis.

1.3.2.3 To attempt quantification of the various processes with the aim of producing a realistic sediment budget.

1.3.2.4 To understand the overall system sufficiently well to allow prediction of the effects of altering various conditions and parameters.

1.3.2.5 Where these goals prove impossible, to identify the precise difficulties in order that research may be directed towards their solution.

These broad objectives are both ambitious and long-term. The results of the Swansea Bay project can only be regarded as an initial step towards their solution.

2 SWANSEA BAY: A REGIONAL STUDY

2.1 Programme of research

The Swansea Bay study has incorporated three different but complementary approaches. These are the examination of historical and other records; the acquisition of data from field equipment and experimentation and, finally, the interpretation and synthesis of the information so acquired in order to try and establish causes. There is thus a systematic progression from description to interpretation, the latter in as quantifiable a way as possible but largely using existing methods. (It is the task of another team in the Sedimentation Group of the Institute of Oceanographic Sciences to undertake basic research into detailed transport mechanisms and to develop new analytical methods.)

In the specific Swansea Bay context there was prime need to confirm the reality of the problem of coastal erosion and to see, if it existed on a significant scale, to what extent it was of recent origin. Hence the initial

Material removed during the construction of Port Talbot tidal harbour ranged between pebbles and silt in size. Capital dredging for the harbour totalled 11.2 x 10^6 tonnes. Estimated maintenance dredging for Port Talbot and Swansea Bay between 1960 and 1976 has been comparable in volume of sediment involved. This material was deposited in or adjacent to the Bay.

Full details of the above work may be found in Topic Report 1 (see Appendix A).

2.3 Superficial geology and sedimentology of the area

Grab sampling, box-coring and vibrocoring techniques were used in conjunction with geophysical methods in order to determine whether there were suitable deposits of sand to feed the beach from offshore. The continuous seismic profiling (CSP) records provided valuable information on the subsurface geology and the thickness of the Pleistocene and Holocene sediments including both the modern sandbanks (Figure 2) and the large expanse of fine sediment situated in the middle of the research area (Figure 3). The sandbanks were shown to be between 8 m and 12 m thick while the mid-bay fine sediment was up to 0.8 m thick. This latter area of silt and clay was already in existence at least before 1859, but the subsequent dumping of large quantities of dredged spoil appears to have added considerably to its thickness.

Sandwave fields and megaripples were detected in some areas, their orientation giving an indication of the direction of movement of the sediment. In the case of South Kenfig Patches, this was found to be southeasterly on the northern side and northwesterly on the southern side.

It was concluded that, particularly in the case of Morfa Beach, there was little offshore material comparable with that of the adjacent shoreline. Examination of the beach material itself showed that the finest sand occurred at low water mark while along the beaches it became marginally finer towards the centre of Aberafan Beach and in the areas around the River Kenfig and Sker Point further south. However trends were weak both spatially and temporally and standard analytical techniques proved relatively unrewarding.

Full details of the above work may be found in Topic Report 3 (see Appendix A).

contained about 1.2 x 10^8 tonnes of sand, most likely derived from earlier dunes located further seaward rather than directly from the sea-bed.

The historical evidence from about 1100 AD onwards emphasises the long-term variability of this area of coast both in the context of flooding and reclamation of the marshes and in the instability of the sand dune systems.

Maps, dating between the 1840's and early 1960's indicate that since the mid-nineteenth century there have been two main areas of change, that around the R Neath and that close to Port Talbot. Each site has been associated with civil engineering works; the Neath with a training wall built in the 1870's and the Port Talbot docks with a series of breakwaters begun in 1865 and extended several times thereafter. While there has been a general tendency for the low water mark to recede slowly landward there have been local areas of accretion of which Crymlyn Burrows (Figure 1) is the most important.

The documentary evidence provided by hydrographic charts suggests that although the offshore banks have progressively changed their relative positions between 1859 and 1974 there have been no significant changes in their volumes during this period.

2.2.2 Extraction and dredging

Following a Public Inquiry in 1973 the Inspector recommended that research be undertaken into the cause of erosion along the E foreshore of Swansea Bay and the relation of beach material and offshore sediment supply there. Meanwhile no further extraction from the inter-tidal zone was to be permitted.

Between 1970 and 1976 an average of just over 4 x 10^5 tonnes of marine dredged sand and gravel was unloaded at Swansea and Briton Ferry each year, mostly derived from Nash Bank. This compares with an annual average of 1.15 x 10^5 tonnes removed from the E foreshore of Swansea Bay over the period 1970-73. Calculations, based on figures from the whole foreshore extraction period (approximately 1934-73) suggest a lowering of the beach by up to 0.25 m, assuming uninterrupted longshore interchange between Port Talbot and Sker Point, uniform distribution across the beach, and no gain or loss offshore.

Sand-winning from the dunes is of longer standing. It has been of a similar order of magnitude to that of the foreshore.

the transitory development of an inter-tidal drainage channel close to the section line although there may also have been some losses offshore through southerly littoral drift in the area, and second order effects reflecting adjustment to earlier extraction to the N. The re-surveying of the beach profiles in October 1977, showed the effects of summer accretion around the River Kenfig, and erosion on Margam Beach near a new pipeline. Otherwise previous trends continued.

Full details of the above work may be found in Topic Report 2 (see Appendix A).

2.5 Foreshore sediment movements

To help assess the mechanism and magnitude of onshore-offshore and longshore transport two experiments were carried out on Morfa Mawr beach (Figure 4). These tracer experiments revealed no preferential direction of sand movement in the short term (ie over one or two tidal cycles) and virtually none over the six months period between the two tracer experiments.

Calculations show that typical ocean waves, of 8 seconds period, from the sector 220° to 270° are refracted so that the local angle of incidence is small (generally < ±3°). The beach is therefore in plan equilibrium with the prevailing wave climate (see section 2.6).

The standing wave tide in this locality gives rise to tidal currents (see section 2.7) which sweep over the beach face and extend inshore nearly as far as the edge of the surf zone. Although these currents are capable of mobilising a large amount of sediment, their action is more or less symmetrical so that net sediment movements are negligible.

Thus both waves and tidal currents act in such a manner as to exclude any predominant direction of sediment movement along the beach, in particular that of the eastern coastline, although further offshore and to the N and S of Morfa beach, current measurements indicate weak alongshore movements of sediment (see sections 2.7 and 2.8). Furthermore, it must be remembered that the actual amount of sand cover on the beach is often very thin (Blackley, 1978).

Further details of the above work may be found in Topic Reports 7 and 7a (see Appendix A).

2.4 Measurements of beach changes

Recent map evidence, based on photogrammetry by IOS from aerial surveys carried out on behalf of the British Transport Docks Board, is restricted to the beach S of the Port Talbot tidal harbour. It shows that peat and clay exposures increased between 1968 and 1970 and again between 1970 and 1975, although some areas (just south of the tidal harbour and around the River Kenfig) remained free throughout. In the central area of Kenfig Beach patches of cobbles became far more conspicuous. Little movement of the contours was detected on Margam Beach between 1968 and 1970. During the same period on Kenfig Beach, however, the contour spacing near low water mark was reduced indicating a steepening of the beach there. Both beaches tended to erode between 1970 and 1975 but this was concentrated at mid-tide level.

Beach sections were surveyed along 11 lines, between the River Neath and Sker Point (see Figure 4), every month between September/October 1975 and April/May 1977 with a further survey in October 1977, ie after 2 complete years. These showed that, not only the lowest but also most of the highest profiles occurred during the winter months. In general most of the overall change from month to month was accounted for by movement of material over the upper beach face. The lower beach tended to follow the erosional or accretional pattern of the upper beach but to a lesser extent. Data recorded from one section showed that there was a close correlation between the packing density of the sand and the beach height changes.

Volume change calculations showed that although some individual sections underwent relatively large gains or losses of material from month to month, the net imbalance over the whole shoreline was small. Similarly, comparisons between Autumn 1975 and Autumn 1977 data for all the beaches along the E shoreline of Swansea Bay taken together showed no significant net change in volume of sediment present.

Initially it was thought that the stability of the beaches decreased from N to S (see TR2) but subsequently it was found that maximum changes in beach elevation were closely correlated with the spatial distribution of wave energy (see TR5 and section 2.6 of this report). Nevertheless net losses over both the 18 month and 2 year periods were recorded from the most southerly section, that at Sker Point on Kenfig Beach. It is considered that this result is primarily due to

Full details of the above work may be found in Topic Report 5 (see Appendix A).

2.7 Tidal currents and residual circulations

Tidal currents were measured over extended summer and winter periods in order to determine the extent to which they were capable of moving sediment along the sea-bed and in suspension. The sites selected are indicated in Figure 4.

Observations of tidal and residual currents in Swansea Bay show that the area exhibits a diverse range of flow features. Foremost amongst these are the pronounced changes in the strength of the tidal currents in both the alongshore and onshore-offshore directions (Figure 6). These variations, and interactions between semi-diurnal and quarter-diurnal currents in the lunar tides, play a significant role in determining the sediment circulation pattern in the area. Furthermore, the area is characterized by an order of magnitude variation in tidal mixing and sediment transport over the Neap-Spring cycle (Figure 7). The N of the Bay is an area of low tidal energy and therefore likely to be an area of net fine sediment deposition.

Residual current observations (Figure 8) confirm the presence of a large clockwise eddy situated over the Scarweather Sands and associated with this, the presence of convergent flow near the sea-bed and divergent flow at mid-depth on the flanks of the sandbank. The area to the S of Port Talbot appears to be an area of divergence in the mean tidal circulation. These features are illustrated schematically in Figure 9.

The measured phases of the currents and elevations indicate a standing wave type tidal oscillation within the Bay with the tidal currents reaching their maximum strength at more or less the same time over the area as a whole.

Both theory and observation suggest that the circulation in the Bay is likely to be influenced by meteorological forcing, particularly during periods of storm surge activity (Figure 10). The response is complex but the results indicate that wind driven currents into or out of the Bay may be the most likely mechanism affecting the residual circulation. In particular during a storm surge strong offshore winds would appear to have the greatest effect on the residual circulation. During these periods residual currents may reach speeds of about 10 cm s^{-1} which is about five times the value during quiescent flow conditions. During

2.6 Wave climate and predicted beach stability

As noted in section 2.5 wave data have been used to determine the wave climate of the area and to investigate alongshore variations in wave energy and their relation to the equilibrium of the beach on the E side of the Bay. An example of the wave climate data is shown in Figure 5.

Wave refraction studies have shown that the offshore banks (Figure 2), especially the Scarweather Sands, but also the White Oyster Ledge, are capable of bringing about wave energy focussing. For waves in the SW sector these effects are particularly pronounced in the region of Sker Point leading to departures from normal wave incidence at the coast. However, further N, extending up to the Neath estuary, wave crests are aligned parallel to the shoreline. The calculations have been verified by radar measurements of wave approach angle over a period of 1 year (Heathershaw et al, 1980) at Port Talbot. These field data failed to show any significant number of large waves arriving at the beach at an oblique angle.

The data suggest that along the eastern shoreline of Swansea Bay variation in beach height and longshore transport of sediment (littoral drift) are related to differences in wave energy. Despite some differences between observed and predicted wave climates, the results show that:

(a) where the direction of wave approach at the coast is normal to the beach, ie the beach is in plan equilibrium, there is a significant correlation between wave energy and beach height variability, increasing energy being associated with greater variability. Here most of the wave energy goes into producing 'up-beach' or 'down-beach' movements of sediment;

(b) where the direction of wave approach at the coast is not normal, more of the available energy goes into producing a littoral drift. This may partially account for the net losses of sand from the beach at Sker Point recorded during the period 1975-1977 (see section 2.4).

Calculations of the fetch characteristics at Port Talbot confirm that the wave climate in Swansea Bay is dominated to a large extent by its open fetch to the N Atlantic. The calculations show that due to the angular spreading of wave energy the range of fetch-limited directions is smaller than that based on geometric fetch considerations alone and that seas arriving from directions between 180° and 300° are limited solely by the duration of the wind.

Predicted bedload transport paths (Figure 12) give general agreement with geophysical evidence and indicate a westward movement of sediment close to the coast S of Porthcawl, and across the southern extremity of the Bay through the sand bank system comprising the Scarweather Sands and possibly Nash Bank, towards the Gower coast and westward through the Helwick Bank. This is illustrated schematically in Figure 13. The potential net rates of movement of material in this area are of the order of 2×10^{-1} gm cm^{-1} s^{-1}, that is about 2 tonnes m^{-1} day^{-1}. Moving inshore there is a general decrease in transport, reflecting the diminishing tidal energy until in the vicinity of Port Talbot and the River Neath transport rates two orders of magnitude lower and equal to about .02 tonnes m^{-1} day^{-1} are observed. The area immediately offshore of Morfa Beach appears to be a stagnation point in the pattern of net sediment movements with negligible longshore transport of sand size material (see Figures 12 and 13).

The differences in predicted transport rates suggest that the Bay is effectively by-passed by the offshore westward movement of sediment. In fact the only predicted movements of sand size material into the Bay from the W occur in the vicinity of Mumbles Head and at the western extremity of the Scarweather Sands, the latter probably being associated with bank-forming processes. However, weak transport of sediment from the W may be inferred in the vicinity of Port Talbot and Morfa Beach where a divergence in the predicted sediment circulation pattern (Figures 12 and 13) may imply a shoreward movement of sand size material. However this feature has not been observed. The observed transport pattern suggests that if movement of material into the Bay does occur it can only do so by a transfer of material from the W flowing stream in the area between Mumbles Head and the S extremity of the White Oyster Ledge. The interpretation of predicted sediment transport paths is in general agreement with the conjectural sediment circulation patterns given by Ferentinos and Collins (1978) and Collins et al (1979), except that transport into the Bay by tidal currents alone seems improbable. It is possible that a wave-induced transport, particularly during periods of strong SW winds, is the most likely mechanism although we have no direct evidence of its occurrence. However, against this hypothesis must be balanced the finding that wave-induced mass transport effects in the area are small and of the order of 2 cm s^{-1} at the bed and that the tracer studies did not indicate any significant shoreward movement of material even over long periods of time when appreciable wave activity is known to have occurred.

quiescent periods residual tidal elevations (observed tide minus predicted tide) show the expected inverse correlation with atmospheric pressure ("inverted barometer effect") with the tides being over or under estimated by up to .2m.

In the shallow area to the N of the Bay, salinity and temperature data made available by the Welsh Water Authority indicate that the freshwater discharges from the rivers Neath, Tawe and Afan significantly modify the seawater density giving rise to density currents of the order of 1-2 cm s^{-1} which are comparable with, if not greater than, the tidal residuals. It is not improbable that in the N of the Bay, the mean circulation is entirely controlled by the density field. Overall the characteristics, particularly of the residual circulation, are of spatial, temporal and secular variability. Nevertheless, as noted in section 2.5, for the Morfa Beach area the tidal currents are typically parallel to the shore and symmetrical in action. As a result there is normally no net longshore sediment transport. However, further offshore, asymmetry of the tidal currents does lead to weak alongshore movements of water and sediment to the N and S of Morfa Beach.

Full details of the above work may be found in Topic Report 4 (see Appendix A).

2.8 Offshore sediment movement and transport paths

2.8.1 Bedload transport

Bedload transport rates have been predicted using a modified form of Bagnold's (1963) formula. Comparisons with radioactive tracer estimates (Figure 11), based on 2 experiments carried out at representative sites offshore (Figure 4), have shown that this formula gives the best predictions (within a factor of 0.5 - 2) of the observed transport rates. Although the potential net transport rates predicted by the various formulae examined may vary by as much as two orders of magnitude, they all predict similar directions of sediment movement.

The observed sediment distribution, transport rates and circulation pattern reflect strongly the tidal dynamics of the area (see Topic Report 4). The area immediately offshore of Port Talbot is one of low tidal energy and therefore likely to be an area of net deposition for fine sediments. The areas further offshore and alongshore towards the S exhibit stronger tidal currents and therefore increasing sediment mobility.

works such as the approach jetties to the now disused Port Talbot docks. However, there is little or no evidence to show that, in spite of its size, the tidal harbour, constructed between 1968 and 1970, has had any substantial effect on the adjacent beaches. These aspects are considered in greater detail in Topic Report (TR) 1.

Comparisons of photogrammetric surveys based on air photographs taken in 1968 and 1975 indicate an average net fall in beach level for Morfa Mawr and Kenfig of 0.4 m ± 0.29 m. This compares with an estimated average fall of 0.10 m which would be anticipated from the known volumes extracted from the foreshore during that time (see TR2). The latter figure assumes no supply of sand onto the beaches from offshore or longshore. Regular topographic surveys of the beach between October 1975 and October 1977 indicated that during the post extraction period there was little net overall volume change. Taking Aberafan, Margam (Morfa) and Kenfig beaches together the calculated change was a loss of 0.014 m, a value smaller than the attainable accuracy of the profiles themselves (see TR2).

The assumption of minimal longshore transport along most of the shoreline between the R Neath and Sker Point is firmly based. Except for small, locally-generated, seas, waves approach most of the shoreline with normal incidence (see TR5). Thus sediment transport is mainly normal to the beach. Furthermore, currents associated with the standing wave tide in this area are relatively small (TR7) in the Swansea Bay context and their action is more or less symmetrical giving rise to only small tidal residuals and weak alongshore movements of sediment, relative to the high transport rates predicted offshore.

These conclusions were confirmed by both the tide by tide and 6 month net transport measurements for fluorescent tracer sand experiments on Morfa Beach (see TR7 and 7a).

There are some areas offshore in Swansea Bay which have a similar mean sediment size to the sand comprising the eastern beaches (see TR3). However, these bank deposits appear to have no direct link with the coast and the areas closest to Morfa Beach consist mainly of coarse glacial material in the N Kenfig Patches or fine cohesive sediment off Port Talbot. The latter may be partly a response to the one-time deposition of locally generated dredging spoil and partly to the lower current velocities both there and around the Neath estuary (see TR4).
Over the period 1859-1974 the Hugo and Scarweather banks have been realigned and

Despite the presence of the W flowing sand stream close to the Gower coast, we should not discount the possibility, as suggested by Collins et al (1979), of an easterly littoral transport close inshore, probably induced by wave activity in this area.

2.8.2 Suspended load transport

Observed and predicted transport rates indicate that for sand size material of the type found on the foreshore on the E side of the Bay, bed load is likely to be the dominant mode of transport. However it is necessary to look at this process against a background of high concentrations of fine particulate material. Although the mean particle size of the suspension is typically about 70 µm, with a settling velocity of .32 cm s^{-1}, the finer particulate matter will have considerably lower settling velocities and we would thus anticipate little variation in the concentrations over the tidal cycle. In fact a depth mean concentration of the order of 90 mg l^{-1} would appear to be present for most of the time as 'washload'. Suspended sediment measurements have not indicated any systematic variation of depth mean concentration in moving from the weaker near-shore tidal flows to the higher energy environment further offshore. However, the work described in Topic Report 6 shows that these concentrations may be sufficiently high to modify current velocity profiles near the sea-bed and that hydraulic parameters derived from conventional velocity profiles may be incorrectly estimated.

2.8.3 Sea-bed roughness

The roughness of the sea-bed has been found to vary over the tidal cycle in a more complex manner than can be explained by present theories and this fact has a bearing on the accuracy of the sediment transport calculations. Nevertheless it can be stated with a fair degree of certainty that sand comparable to that of Morfa Mawr and Kenfig Beaches does not reach those sites from offshore in significant quantities.

2.9 Swansea Bay study: Conclusions

The following section is a summary of the main conclusions from the Swansea Bay study.

Both the historical and cartographic evidence suggest that at least since the 12th Century there has been a very slow, long term tendency for erosion of the coastline along the E side of Swansea Bay. This area includes the Morfa Mawr and Kenfig Beaches which were the subject of the 1973 Public Inquiry into the prohibition of extraction of sand and gravel from the intertidal zone. Erosion rates appear to have been greater in the neighbourhood of early civil engineering wave induced transport during particularly severe storms.

(b) while there is some tendency to wastage of the Morfa and Kenfig beaches through natural processes, this is not very substantial. The prime cause for the lowering of the beaches in the period up to 1973 was the human removal of sand from the inter-tidal zone.

3 GENERAL IMPLICATIONS

3.1 General comments

The results in section 2 indicate the complexity of the processes which influence the supply of sediment to, and the movement of material on, a beach and in the near-shore zone generally. They indicate that to isolate the most important processes and to quantify and predict their effects requires a quantitative understanding of the sediment circulation over a wide area. This can only be obtained by a strategy of investigation involving techniques from several disciplines. Those techniques available at the present time have limitations and are not generally able to give either the quantity or quality of information which could be desired, particularly when financial constraints are taken into account. However, knowing what tools are available, and their strength and weaknesses, can go a long way to making the problems of coastal engineering amenable to research with limited financial resources.

In the study of Swansea Bay the research strategy was to examine historical documents and records and to determine the long term trends in the development of the coastline. This was followed by detailed measurements to describe and then quantify the sediment distribution and circulation, together with measurement of the relevant hydraulic parameters. Subsequently, these results were interpreted within a theoretical framework based on conclusions derived from work elsewhere in order to try to obtain a consistent, qualitative, overall view of the patterns of sediment movement.

This sequence is one that should be appropriate to many coastal engineering problems. Consequently it is necessary to examine the various techniques that were applied to Swansea Bay, to discuss the circumstances under which they can be applied elsewhere, the potential errors involved, and to point out the outstanding problems displaced broadly towards the S in accordance with the net tidal flow; they have remained at a similar distance from the shore and of a similar volume (see TR1).

The tidal current data for the Bay show spatial, temporal and secular variability. Thus the main tidal stream bypasses the Bay, while in the NE density currents due to the freshwater discharges from the rivers Neath and Tawe are of the same magnitude or larger than the tidal residuals. There is an order of magnitude difference in tidal mixing between neap and spring tides. Meteorological forcing is also important with residual currents generated under storm conditions being typically some 5 times larger than those during quiescent flow conditions (see TR4).

Sediment transport is largely through bedload. The calculated bedload sediment transport rates closely reflect the tidal current pattern. Although estimates of the potential rates of movement of sediment varied considerably all the formulae used for the calculations predicted the same directions of movement (TR6) and agree with the geophysical evidence (see TR3). The principal feature of the sediment circulation pattern is the predicted westward flow of sand which effectively bypasses the Bay itself. Only near Mumbles, White Oyster Ledge, and at the western end of the Scarweather Sands is there any predicted inflow of sand attributable to tidal currents alone. Although this may happen elsewhere in conjunction with waves, waves generally seem only to lower the threshold at which transport may take place. However, it is possible that large waves generated by storms may induce a steady shoreward movement of sediment although such events will be comparatively rare.

The high (up to 90 mg l^{-1}) depth mean concentrations of fine suspended material do not seem to show any systematic tidal variation. Their principal effect may be interpreted as modifying the current velocity profile near the bed, and this, coupled with problems in determining sea-bed roughness may result in some inaccuracy in the estimates of the various hydraulic parameters. Nevertheless, in general, it can be said that sand does not reach Morfa Mawr or Kenfig Beaches from offshore in any significant quantities.

It is therefore concluded that:

(a) there is no effective replacement mechanism for sand permanently removed from the beaches along the eastern side of Swansea Bay except perhaps for some

Since the Second World War accurate dating has become possible through the calculation of decay times of natural (and man-made) radioactive isotopes incorporated in geological deposits when they were laid down. Because 'half-life' varies with the particular element it may be possible to obtain precise dates ranging from a few to many millions of years. Carbon-14 (^{14}C), covering the period to approximately 40,000 years ago, is particularly valuable in this context, especially since salt marsh peat, and suitable shell deposits, occur frequently. However, none of these techniques must be used uncritically. For example, peat and shells must be uncontaminated, in situ and in the case of the former the relationship between the plant species' growth zone and high water mark must be known. More recently Lead-210 (^{210}Pb) - Polonium-210 (^{210}Po) dating has been found particularly suitable for dating marine sediments over periods of approximately 100 years.

3.2.3 Historical evidence

Similar reservations over techniques and interpretation are required in the analysis of documentary evidence. Although old maps and charts are generally more objective than written records, early survey methods were often very primitive. Thus, apart from occasional large-scale estate plans, land and marine surveys are rarely precise enough for quantitative analysis until about 1800 AD. Even thereafter, in spite of the growing number of Ordnance Survey maps and Admiralty hydrographic charts, problems still arise. Although these may include occasional traces of bad survey it is more important to recognise the inherent limitations of plotting accuracy and partial revision. (Partial revision may, however, help establish the accuracy of the initial survey.) Other points that must be considered include changes in surveying techniques, for example from lead-lines and sextant angles to echosounding and micro-wave position-fixing. New techniques do not necessarily produce greater accuracy. Thus photogrammetry from aerial survey is quicker than conventional ground survey but may be less accurate, except in the case of low water marks where time is of the essence. Comparisons of high and low water marks on successive surveys may be unsatisfactory because of initial error, eg the surveyed tides did not follow prediction, and because of the Ordnance Survey's changing criteria over time. Tide marks frequently do not conform to any physical manifestation on the ground. For example, the high water mark along part of the coastline of Bridgwater Bay on the S side of the Bristol Channel meanders over the broad inter-tidal salt marsh rather than corresponding with either the seaward edge or the storm beach to landward.

which need independent research in order to make improved techniques and predictions possible in the future.

Some of the techniques included in the discussion which follows, are additional to those employed in the Swansea Bay study.

3.2 Coastal stability over the long term

3.2.1 General

Site investigations are necessarily short-term relative to the frequency of extreme meteorological events and especially in the context of a geological time scale. However, in many cases the sediment movements which occur during extreme events (eg storms) are the ones of main practical importance. Thus the site investigation data must usually be placed in a long-term context and the difficulties of doing this are often underestimated.

Experience at Swansea Bay and elsewhere suggests that documentary records may be of value back to the 12-16th century depending upon the site. Prior to that time geomorphological and, occasionally, archaeological evidence are of value particularly on an accreting coastline where dateable deposits occur.

3.2.2 Dating of deposits

Although it may be possible to deduce past trends through, for example, the alignment of sand dunes and shingle ridges, the most valuable information is gained by dating techniques. At Swansea these enabled estimation of the age of the sand dune systems along the E shore of the Bay and, because their volume could be calculated, their average long-term rate of accretion. Dating methods include micropalaeontology, pollen analysis, magnetic fabric analysis, and the use of radioisotopes. Changes of environment, as between estuary and open sea, or over time may be reflected in the variations in species of micro-fossils and pollen grains. Both are especially well preserved in cohesive sediments. It is frequently possible to provide a reasonably precise chronological framework from such data. Another more recent and still experimental approach is to compare the history of the earth's magnetic variation with the remnant magnetism in borehole samples of interest. With appropriate grades of sediment this may provide reasonably precise dating within any 400 year cycle.

3.3.1 Geophysical methods

Geophysical methods of survey offshore fall into 2 categories, sidescan sonar and continuous seismic profiling. With the former it is possible to obtain an oblique view of the bedforms and other structures on the sea floor. These include sand waves and megaripples, the alignment of which can reflect the dominant processes operating on the sea-bed. Both the effects of tidal currents and waves may be shown. Repeated surveys may be necessary to elucidate the relative importance of each.

Providing water depth is sufficient, CSP is especially useful in indicating the thickness of offshore banks above bedrock and hence the likely volume of sediment contained therein.

3.3.2 Sedimentological methods

The mean sand particle size along the E shore of Swansea Bay showed little variation, although there was a slight fining down beach towards low water mark. Sedimentologists have frequently taken fining of non-cohesive sediment as an indication of direction of longshore or offshore transport. Thus the results at Swansea Bay could help confirm the results described in Sections 2.6 and 2.8 or merely reflect the narrow range of particle sizes present on the beach. Direction of fining may, however, become reversed from time to time as observed on the pebble beach at Slapton, Devon (Gleason, et al, 1975).

Bi-modal distributions are thought to reflect different sources of material or the influence of more than one hydraulic process on the sediment.

More elaborate forms of statistical analysis of sand and coarser grades of sediment are frequently undertaken. These include an assessment of 'sorting' ie variance; skewness; and peakedness or kurtosis, for all of which there is a range of criteria and formulae (Folk, 1966). Results may be considered as indicating a response to source and origin of material; distance transported; and stability of the beach. Although not considered appropriate in Swansea Bay it may be worthwhile carrying out this type of analysis in site investigations elsewhere.

Using criteria such as bedform distribution and asymmetry together with an assumption of fining down transport paths, it may be possible to derive a large

A useful, and frequently neglected, data source are the maps and plans produced for the Tithe Commissioners mainly during the mid-nineteenth century. However yet again these vary in scale of survey, format, accuracy and coverage and must be treated circumspectly.

Regarding the length of records, Carr (1980) has stated: "Long-term records have the effect of averaging the changes that have occurred over the corresponding timespan. They may well include the effects of extreme events but are not explicit in so doing. Thus they represent the sum but not the range of conditions that have been experienced and may partially reflect factors and circumstances that have been superseded. The progressive extension of breakwaters at the entrance to (the now disused) Port Talbot Docks in Swansea Bay appears to have had a corresponding effect on the foreshore. Calculations based solely on maps and plans pre- and post-dating the series of engineering works would be interpreted as showing a linear response and thus fail to reflect the present day dynamic equilibrium. Short-term records and experiments <u>may</u> show a new or recent trend at variance with earlier conditions and thus be valid and significant. For construction works of limited duration, it may be that these types of data and extrapolations based upon them are what are required although it is unlikely that, in a geomorphological sense, a representative range of conditions is met. It must be emphasised, however, that even analyses based on surveys spaced a long time apart do not guarantee that extremes have been experienced in the meantime or that the conditions when the data were acquired were representative."

In the case of Swansea Bay, the aerial survey covering the period 1968-75 appears to reflect the same changes as are shown by a comparison of the cartographic data between the 1840's and 1960's but the monthly surveys during 1975-77 do not.

Methodology for determining changes in the coastline over an extended timescale are tabulated in the summary given in Table 1.

3.3 Geology and sedimentology

Geophysical and sedimentological techniques may prove valuable in the context of coastal erosion and accretion and these are discussed below.

This problem is discussed in full below and detailed discussion in parentheses and inset from the main text may be omitted without any loss of continuity. A summary of techniques for predicting and measuring sediment transport rates is given in Table 3.

3.4.1 Tidal currents

3.4.1.1 Bed load prediction

Prediction of sediment movement on a regional scale requires relating sediment transport and hydraulic parameters measured at a few points and for limited periods, and extrapolating these relationships over the area as a whole. This therefore involves the selection of a suitable sediment transport formula. In practical terms the engineer is faced with the difficult task of choosing from the many formulae which are available (eg Yalin, 1972, lists 6, Vanoni, 1975, gives 13 and Graf, 1971, describes 5) only one which will give the best predictions. However, the choice of a suitable sediment transport formula for use in the marine environment is by no means clear for the following reasons:
(a) none has been developed specifically for use in the sea under oscillatory tidal currents
(b) most are based on observations in steady unidirectional flows in rivers or flumes and
(c) none can intrinsically account for the effects of waves.

Recent and comprehensive comparisons of sediment transport formulae include those by White (1972), Ackers and White (1973), White et al (1975, 1978), Flemming and Hunt (1976), Swart (1976) and Graaff and Overeem (1979). Ackers and White (1973) examined 15 sediment transport formulae and on the basis of comparisons with some 1000 observations developed a total load formula. This formula was examined independently by Swart (1976) and Flemming and Hunt (1976) who concluded that the Ackers and White formula gave the best agreement with observation.

However, Ackers and White's formula has not, as far as we can determine, been used previously for predicting sediment transport rates under more or less open sea conditions and appears to have been limited to the comparatively shallow nearshore zone. The only detailed comparisons of measured and predicted transport rates on the shelf that we are aware of are those due to Gadd et al (1978) who compared transport rates derived from radioactive tracer experiments scale sediment circulation pattern. This can indicate sources, sinks and the predominant transport paths, but how much sediment moves and when it is moved can only be found by direct measurement.

Methods for determining direction and quantity of sediment transport by geophysical and sedimentological techniques are summarised in Table 2.

3.4 Prediction and measurement of sediment transport

Present understanding of sediment transport processes in the sea is so limited that any attempt to determine regional sediment circulation patterns in relation to coastal erosion problems, must contain a large element of uncertainty particularly in terms of the quantities involved.

Numerical modelling techniques for predicting sediment movement, while having made considerable progress in recent years (eg see McDowell et al, 1980a, b, Fanos, 1979, Flemming, 1977) do not yet offer a complete solution to these problems because the biggest unknown is the accuracy of whatever sediment equation is used. Most models require extensive calibration against field data and are confined to a fairly narrow coastal zone (of the order of 10 km and less).

There is however much that can be achieved by observation, and experience has shown that careful and systematic measurements may not only provide a coherent and meaningful pattern of sediment circulation on a regional scale, but also improve our understanding of sediment transport processes. These observations can also give reasonable estimates of the sediment budget for an area. Nevertheless, measurements of this nature are costly and progress towards numerical modelling techniques for predicting sediment movement is both a natural and a desirable step.

However, sediment movement is often governed to a large extent by wind or wave induced effects which are basically random in their nature, and it is often the more extreme events which are important. Furthermore, even the regular periodic motions of the tides contain turbulent or irregular motions in the currents near the sea-bed which are directly capable of influencing sediment movement. Thus, even when the processes are fully understood it may only be possible to predict the sediment movements within fairly broad confidence limits.

ρ_s the sediment density

ρ the fluid density

The roughness length z_0 is not usually explicit in a formula but enters into the prediction because it is necessary to relate τ or u_* to the flow at a particular level above the sea-bed. This is usually achieved by assuming that the velocity profile is logarithmic and of the form

$$U = \frac{u_*}{K} \ln \frac{z}{z_0} \qquad (1)$$

where U is now the current at height z and K is von Karman's constant, usually taken as 0.4 in suspension free flows. Dependent upon the choice of formula it may also be necessary to specify a critical bed shear stress or friction velocity, τ_{cr} or u_{*cr}. Assuming that ρ_s, ρ, z_0 and τ_{cr} (or u_{*cr}) are known and remain constant with time, the simplest formulae (eg Bagnold, 1963) only require specification of the tidally varying quantity u_* whereas the more sophisticated techniques (eg Ackers and White, 1973) also require the depth mean flow ($\overline{U}$) and the total flow depth (h) to be specified over the tidal cycle. In many cases, $\overline{U}$ will not be known, since its determination requires total depth velocity profile measurements, and in offshore areas difficulty may occur in combining tidal variations in h with those which occur in u_* determined from current measurements. Further complications may arise because in practice z_0 is not constant over the tidal cycle (see Heathershaw and Hammond, 1979 , Heathershaw, 1981, Dyer, 1980) and also because there is considerable uncertainty surrounding the threshold of sediment movement in tidal currents (see Dyer, 1980; Langhorne, 1980). Estimates of τ_{cr} are usually based upon Shields' on the NE seaboard of the United States with those predicted by Bagnold's (1963), Einstein's (1950) and Yalin's (1963) sediment transport formulae.

For the Swansea Bay study, and on the basis of evidence presented by Swart (1976), Flemming and Hunt (1976) and Gadd et al (1978), the 5 formulae listed in Table 4 were chosen for evaluation. Full details of the formulae are given in Heathershaw and Hammond (1979).

The results of our comparisons are shown in Figure 11 where the predicted tidally averaged rates have been compared with those measured during 2 radioactive tracer experiments. The only formula to give consistently good agreement at both locations was the modified form of Bagnold's (1963) equation. Ackers and White's (1973) formula only gave good agreement at the shallower of the two sites examined. However it should be noted that some of the variability in the predicted net transport rates may also be due to seasonal changes in the tidal current regime and wave climate (see Heathershaw and Hammond, 1979 and Heathershaw et al, 1981).

The principal difficulty in applying these formulae in a real situation, where the flow regime and sediment characteristics may be diverse, is the difficulty in specifying values for the various parameters. For example, some formulae require detailed information on bedform roughness, which, over a large area of sea-bed, may simply not be known or which cannot realistically be generalised.

> (Most modern sediment transport prediction schemes, deterministic or probabilistic, express the sediment transport rate as some general function of a number of parameters which may include:
>
> τ the bed shear stress ($\tau = \rho u_*^2$ where u_* is the friction velocity)
>
> τ_{cr} the critical shear stress for sediment movement
>
> $\bar{u}$ the depth mean flow
>
> h the flow depth
>
> z_0 the sea bed roughness

dependence may be explicit or implicit dependent upon the choice of formula.

A consistent feature of all these calculations (Figures 15 and 16) is that Bagnold's (1963) modified formula exhibits the least sensitivity to changes in particle size and roughness length. While depth dependence is not particularly critical (Figure 14) the choice of formula may be influenced by flow regime, Ackers and White's and Engelund and Hansen's formulae showing orders of magnitude difference at high and low current speeds.

While Bagnold's modified formula appears to have been most successful in predicting sediment transport rates under predominantly tidal currents offshore, for calculations of sediment movement on the foreshore on the E side of Swansea Bay, IOS used Ackers and White's (1973) formula (Wilkinson, 1980). However, because no comparisons with measured transport rates were possible in this instance, we are unable to comment on its suitability for this particular environment.

3.4.1.2 Suspended load predictions

It is not possible, at present, to predict suspended sediment transport rates from a knowledge of the near bottom velocity field and the sediment characteristics alone. This stems principally from the need to parameterise suspended sediment concentrations in terms of a reference concentration for which actual measurement is required. As in the case of bed-load transport, prediction of suspended sediment transport is complicated by its high power law dependence on the friction velocity.

(The solution of the steady state diffusion equations gives the mass concentration at a height z above the sea-bed, $C(z)$, in terms of a reference concentration $C(a)$ measured at some height a. The resultant vertical distribution, known as the Rouse concentration profile, is of the form

$$\frac{C(z)}{C(a)} = \left(\frac{h-z}{h-a}\cdot\frac{a}{z}\right)^{\frac{w_s}{\kappa u_*}} \qquad (2)$$

where h is the flow depth and w_s the settling velocity. However, various attempts have been made to overcome the problems of measuring $C(a)$

> (1936) curve and steady flow data, and do not take into account the effect of ripples on the sea-bed.
>
> The non-linear nature of the sediment transport process means that any uncertainty in u_* may lead to considerable uncertainty in predicting transport rates. For example if the bed load transport q_{sb} is proportional to u_*^3 then a 10% error in u_* leads to a 30% error in q_{sb}. At lower transport rates for which $q_{sb} \propto u_*^5$ the errors are likely to be even greater. When these difficulties are compounded by any uncertainty in the other quantities ($\bar{U}$, h , τ_{cr} and z_c , see later) it is clear that the different formulae may give widely differing estimates of the rate of sediment movement. In practice a lot of the uncertainty in u_* is due to uncertainty in z_c.)

Furthermore it can be shown (see above) that due to the highly non-linear nature of the sediment transport processes small errors in the measurement of the near bed currents, and hence the friction velocity (u_*), may lead to large errors in the predicted sediment transport rates. However, the results shown in Figures 14-16 suggest that there may also be systematic differences between the various formulae as a result of their sensitivity to changes in depth (h), roughness length(z_c) and particle diameter (d).

Figures 14, 15 and 16 show predicted bedload (q_{sb}) or total load (q_{st}) transport rates for those formulae showing the greatest and the least sensitivity to changes in depth (h), roughness length (z_c) and particle diameter.

It should be noted that only two formulae have depth dependence and that this is both explicit and implicit in the case of Ackers and White's (1973) formula but only explicit in the case of Engelund and Hansen's (1967) formula. None of the formulae is explicitly dependent on roughness length since z_0 only enters into the calculations through the requirement to relate the friction velocity u_* or bed shear stress τ to a near-bed current measurement (U_{100}). Grain size

To obtain suspended sediment transport rates it is necessary to numerically integrate the produce of Equations (1) and (2) over the entire flow depth, that is

$$q_{ss} = \int_{z_0}^{h} C(z) . \frac{u_*}{\kappa} \ln \frac{z}{z_0} . dz \qquad (6)$$

where z_0 is the measured roughness length and h the total flow depth. The validity of the logarithmic velocity profile over the entire flow is largely untested. However, since the bulk of the sand-size material in suspension is likely to be concentrated near the bed these errors are likely to be small. Alternative procedures would involve concentration and velocity profile measurements over the entire flow depth.

Similarly to bed load predictions, any uncertainty in u_* may lead to large errors in suspended sediment transport rate due to its high power law dependence. Again, the uncertainty in u_* occurs mostly as a result of uncertainty in z_c .)

In practical terms the approach adopted by IOS to determining suspended sediment transport rates and employing theoretical forms for the near bed velocity and concentration profiles (see above), is, with the exception of determining a reference concentration, a relatively simple scheme to operate. However, the velocity and concentration profiles given in Equation (1) and (2) may not have general applicability and in fact in the Swansea Bay study logarithmic velocity profiles and Rouse concentration profiles were only found to apply, separately, for just under 50% of the time.

In many engineering applications where it may not be necessary to distinguish between bed-load, and suspended load it may be simpler to use a total load formula (eg Ackers and White, 1973, Engelund and Hansen, 1967) which to some extent overcomes the difficulties due to reference concentration.

by relating it to a near bed concentration, usually taken at the junction between the bed load and the suspended load. Thus Smith (1977) and Smith and McLean (1977) have suggested that the reference concentration may be expressed as

$$C(a) = C(0)\gamma_0 S/(1+\gamma_0 S) \qquad (3)$$

where S is the normalised excess shear stress given by

$$S = (\tau - \tau_{cr})/\tau_{cr} \qquad (4)$$

and γ_0 is an empirically determined constant of order 10^{-3}, provided that a is taken as approximately equal to z_0. $C(0)$ is, notionally, at least, the maximum permissible concentration at the bed and for large excess shear stresses, ie $S \to \infty$, $C(a) \to C(0)$. For low excess shear stresses Smith (1977) has shown that

$$C(a) = \gamma_1 \rho_s S \qquad (5)$$

for $a \simeq z_0$. For material having a grain size of 180 μm Smith and McLean (1977) have found $\gamma_0 = 2.4 \times 10^{-3}$ and $\gamma_1 = 1.24 \times 10^{-3}$. However Dyer (1980) measuring on a rippled sand bed having a mean grain size of 250 μm has found a value of γ_1 , of about 3×10^{-5} which is very nearly 2 orders of magnitude lower than the value given by Smith and McLean (1977). Although a combination of Equations (2) and (3) would remove the requirement for a reference concentration measurement, there is considerable uncertainty surrounding the empirical constants γ_0 and γ_1, and we are thus still very dependent on the Rouse concentration profile (Equation 2).

the bed shear stress and l is the mixing length given by $l = \kappa z$ for small values of z. Thus, according to Bijker's theory, enhancement of the bed shear stress is given by,

$$\frac{\tau_{wc}}{\tau_c} = 1 + \frac{1}{2}\left(\xi \frac{u_o}{\bar{U}}\right)^2 \qquad (8)$$

where τ_{wc} is now the resultant bed shear stress due to currents and waves, averaged over a wave period, τ_c is the bed shear stress due to currents alone, ξ is given by $\xi = p \ln[(h/z_0) - 1]$, h is the mean depth, p is an empirically determined constant, which Bijker (1967) found equal to 0.45, and $\bar{U}$ is the steady depth mean current.

The components of τ_{wc} parallel to and at right angles to the current can be calculated using Bijker's method so that in principle the angle between τ_{wc} and τ_c is known for any combination of wave height, wave period and direction of wave propagation relative to the current. In practice however, the direction of wave approach relative to currents in coastal waters is difficult to estimate and Bijker's method involves numerical evaluation of sets of elliptic integrals corresponding to each direction. For simplicity therefore, Equation 8, which is independent of wave direction, has been used to quantify the effects of waves on sediment transport.

To obtain an upper limit to the enhancement of the bed shear stress by waves, it is necessary to evaluate Equation (8) for typical and extreme conditions.)

In the Swansea Bay study, Heathershaw and Hammond (1979) found that Bijker's (1967) method gave large increases in predicted sediment transport rates for

3.4.2 Waves

The successful prediction of sediment transport under waves and more importantly under combinations of waves and currents, presents one of the major areas of difficulty in sediment transport research. A review of the literature on this subject has been given by Davies and Wilkinson (1977).

The theory of wave/tidal current interaction is still poorly understood in this context although recent theoretical developments go some way to improving our understanding of the physical processes involved. For example Grant and Madsen (1979) present an analytical theory for combined wave and current interaction which utilizes a combined wave-current friction factor and a time invariant eddy viscosity model to effect turbulent closure of the equations of motion.

Present approaches are largely empirical, for example Owen and Thorn (1979) employ an experimentally determined sand flux mulitiplier to account for the effects of waves, and it is likely to be some time before theories are available which are capable of dealing with the wide range of conditions encountered on the continental shelf.

One approach which has been widely used (eg Swart, 1976, Fanos, 1979, Graaff and Overeem, 1979) is that developed by Bijker(1967) which, although semi-empirical, does attempt to deal with the physical interaction of the waves and the currents.

(The theory consists of making a vector addition of the orbital velocity (u_0) of the wave and the velocity due to the tidal current alone, at a height above the sea-bed equivalent to the thickness of the viscous sublayer. The resultant velocity is converted to a bed shear stress using Prandtl mixing length theory in which the bed shear stress is given by

$$\tau = \rho l^2 \left[\frac{\partial \bar{u}(z)}{\partial z}\right]^2_{z \to 0} \qquad (7)$$

where $u(z)$ is the combined velocity at a height z above the bed, ρ is the density, τ is

(Such effects have been shown to give (see Taylor and Dyer (1977)) modified velocity profiles similar in form to those found in the atmospheric boundary layer. That is

$$u = \frac{u_*}{\kappa}\left(\ln\frac{z+z_0}{z_0} + \frac{\beta z}{L}\right) \qquad (9)$$

where β is an empirically determined constant, which from atmospheric boundary layer experiments has a value of 4.7 ± .5 and L is the Monin-Obukhov length. In fact Taylor and Dyer were able to show (using the results of Barenblatt (1953, 1955)) that Equation (9) could be expressed in terms of the suspended sediment concentrations and settling velocity (w_s) as

$$u = \frac{u_*}{\kappa}\left[\zeta + \frac{1}{B}\ln\left\{1 + \frac{AB}{1-B}\cdot\left(e^{(1-B)\zeta} - 1\right)\right\}\right] \qquad (10)$$

where

$$\zeta = \ln\frac{z+z_0}{z_0} \qquad (11)$$

and A and B are given by

$$A = \frac{\beta w_s \kappa g \sigma C_0}{u_*^3} z_0 \quad \text{and} \quad B = \frac{w_s}{\kappa u_*} \qquad (12)$$

where C_0 is now the surface concentration of sediment and $\sigma = (\rho_s - \rho)/\rho$ where ρ_s is the sediment density.)

Heathershaw and Hammond (1979) found that by taking the effects of suspended sediment into account and fitting velocity profiles of the form given in Equation (10) to the data, it was possible to obtain lower and perhaps more realistic values of the roughness length (z_0). However, it was felt that further examination of the theory and the data was necessary before this result could be applied generally.

3.4.4 Measuring techniques

The Swansea Bay study has illustrated that there is a considerable spread in the tidally averaged transport rates predicted by the various sediment transport theories (see Section 3.4.1 and Figures 11, 14, 15 and 16).

even moderate wave conditions. For example Figure 17 indicates that for a wave height (H) of 1 m and a near bottom current (u_{100}) of 50 cm s^{-1}, bed load transport rates (q_{sb}) predicted by Bagnold's (1963) equation will be increased by a factor of about 5, with the effect becoming more pronounced as the steady current decreases in strength.

It should be noted that Bijker's approach may be applied to any combination of waves and currents from the shallow water outside the breaker zone on beaches to the deeper predominantly tidal flows offshore. Furthermore it may be used with any of the formulae described previously (Section 3.4.1.1) and with many others (see Swart (1976), Graaff and Overeem (1979)).

In order to calculate sediment transport due to waves alone on the beach on the E side of Swansea Bay, the energy flux method (Komar, (1976))was used . Wilkinson (1980) was thus able to show that wave induced transport alone was in general less than that due to tidal currents.

3.4.3 Velocity profiles

A central difficulty in calculating sediment transport rates from near-bottom current measurements lies in the determination of the bed shear stress. This is due to the uncertain form of the near-bottom velocity profile. For convenience in Swansea Bay it was assumed that this was logarithmic and of the form given in Equation (1), ie

$$u = \frac{u_*}{\kappa} \ln \frac{z}{z_0}$$

However, measurements have shown that this expression may not apply at all times and furthermore where velocity profile measurements are not available the roughness length (z_0) will have to be estimated from a knowledge of the sediment characteristics alone. Thus lack of precise information on the vertical distribution of currents and the roughness length may introduce errors into friction velocity (u_*) estimates and the calculated sediment transport rates.

The Swansea Bay measurements showed that near-bottom velocity profiles deviated consistently from the logarithmic form (Equation 1) to give a concave downward shape which could be attributed to suspension induced density stratification effects.

Further aspects of sediment transport sensors are discussed later in this report.

4 OUTSTANDING SCIENTIFIC PROBLEMS AND THEIR IMPLICATIONS FOR COAST EROSION AND PROTECTION

4.1 Sediment transport processes

The work in Swansea Bay has highlighted a number of areas where better understanding of sediment transport and fluid dynamical processes is required to improve our ability to make predictions of sediment movement on the large scale. These are:

(a) The need for reliable information on roughness length(z_0) values associated with different substrates and the way in which these vary over the tidal cycle. (There is a paucity of data relating to z_0 values in the shelf seas around the British Isles);

(b) The need for improved understanding of the way in which suspended sediment modifies near-bottom velocity profiles (see Equation 10). Further research here might be extended to include the accelerative and decelerative effects on velocity profiles which have been described recently by Soulsby and Dyer (1980);

(c) The need for improved methods of parameterising the reference concentration and its variation over the tidal cycle. Ideally a means of predicting suspended sediment transport is required which is independent of the need to measure reference concentration;

(d) The development of sediment transport theories which can take into account the combined effects of waves and currents.

4.2 Coast erosion/protection

Several aspects of the Swansea Bay study have implications for coast erosion and protection and may warrant further study. These are:

(a) Sandbanks: The study identified the important role played by secondary currents in maintaining sandbanks in equilibrium in tidal flows off headlands and other irregularities in coastal geometry (Heathershaw and Hammond, (1980)). In view of the importance of such features to the sediment budget of an area and their role in protecting adjacent coastlines from wave attack, a fuller understanding of the processes maintaining sandbanks is required.

Although these formulae employed empirical constants determined in river and flume experiments final predictions of the sediment circulation pattern were only possible by making comparisons of the various predictions with sediment transport rates measured in the sea using radioactive tracer techniques. To re-calibrate these formulae for marine use would require detailed investigations of the within tide variations of sediment transport and this is not possible with tracer techniques which, in this case, give only tidally averaged estimates.

There is thus a pressing need for instruments and techniques with which to make such detailed measurements over the tidal cycle.

The work in Swansea Bay (Heathershaw and Carr (1977), Heathershaw and Hammond (1979)) has shown that with care radioactive tracer techniques may be used to estimate net movements of sediment, principally as bed-load, under tidal currents. However, the results also show that the time taken for tracer to come into equilibrium with the sea-bed is perhaps longer, typically 10-20 days, than was previously realised. Interpretation of tracer dispersion patterns over shorter periods than this would lead to exaggerated transport rates.

Measurements of sediment movement on the foreshore in Swansea Bay (Wilkinson (1980), Blackley (1981)) with fluorescent tracer showed that the directions of sediment movement could be determined with some precision although there was uncertainty concerning the actual amounts. Interestingly these measurements (Blackley (1981)), showed grain size selective transport similar to that reported by Komar (1977) and a similar but briefer delay to the offshore radioactive material in the tracer coming into equilibrium with its surroundings.

Suspended sediment measurements using pumped sampling techniques (Heathershaw and Hammond, (1979)) were successful in determining general levels of suspended sediment concentration in Swansea Bay. However, the lack of simultaneous sampling at all levels complicated interpretation of these results in terms of accepted suspended sediment distributions (eg the Rouse concentration profile, Equation 2). To some extent this difficulty may have been due to the bulk of the suspended-load being made up of fine particulate material ($< 40\ \mu m$). Use of the equipment elsewhere (Lees (1980) where the suspension comprises coarser material),has shown that sequential sampling may not be a serious problem under these circumstances.

scale, detailed observations of the processes governing sediment movement and the movement itself require a new generation of sediment transport sensors which are capable of resolving changes over smaller space and time scales. The difficulty of relating these "point" observations to the larger scale processes will remain and it seems likely that sediment transport processes will only be fully understood by studying them at both large and small scales.

In a recent review Salkield (1978) has considered bed load samplers in two groups, those which sample directly (ie sediment traps) and those which sample indirectly. Among the latter Salkield has listed acoustic methods which include:

(1) "Self generated noise" probes in which particle collision energy is measured;

(2) Acoustic techniques in which the doppler frequency shift and attenuation of backscattered energy is related to particle velocity and concentration in the saltation layer;

(3) Echo sounder techniques to measure bedform migration rates.

While these techniques offer the greatest hope for improving our understanding of sediment transport processes, none has been developed to that stage where completely reliable measurements are at present possible.

Techniques for measuring concentrations are somewhat limited, particularly in tidal currents under open sea conditions. Pumped sampling equipment has been widely used (Crickmore and Aked, 1975; Heathershaw and Hammond, 1979) and this has the advantage of being able to recover suspended sediment samples for grain size determinations. However, attempts to correlate turbulent velocity and concentration fluctuations will require sensors which have a much shorter time response than those of the pumped sampling techniques which, typically, average concentration over periods of up to 5 minutes. The most promising fast response techniques under development at the moment appear to be acoustic probes (Salkield, 1978) and impact sensors (Soulsby, 1977) although optical devices are being increasingly used (Lavelle et al, 1978; Shepherd, 1978). However, many of these sensors still require in-situ calibration with other more conventional techniques.

In our opinion high priority should be given to the development of these

In particular, for sandbanks associated with headlands the vorticity arguments which have been put forward by Pingree (1978) and Pingree and Maddock (1979) require further investigation. It is further required to determine whether similar processes are responsible for maintaining those sandbanks which form offshore and which are not necessarily associated with headlands;

(b) Beaches: Several aspects of the beach studies in Swansea Bay require further investigation. Heathershaw et al (1981) showed that on beaches with high tidal ranges and low slopes, the mechanical properties of the beach sediments may be influenced to a large extent by the probability of exposure of various sections of the beach face to wave activity. Furthermore the response of the beach water table to the tides and the way in which this is modified by land water drainage may play an important role in determining the erosion potential of sediments on beaches.

The beach in Swansea Bay, and for that matter other beaches in the UK (Carr et al, (1981)) appears to be atypical in as much that it does not follow the usual seasonal pattern of winter drawdown of sediment from the intertidal zone with a build-up during the summer months. Although there is evidence to suggest that beach height variability is greatest during the winter months and that for beaches which are in plan equilibrium, variability is well correlated with alongshore variations in wave energy, the general applicability of this result remains untested.

4.3 Sensors for measuring sediment transport

Techniques for measuring bed-load and suspended load transport rates have already been described in an earlier section (3.3.4). In particular tracer techniques were widely used to select an appropriate sediment transport formula for use offshore and for determining sediment movements on the foreshore.

However, while this technique is of great value in providing estimates of sediment movement which are representative of processes acting on the larger

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new sensors in order to improve the understanding of fundamental sediment transport processes. Such developments would also enable sediment transport data to be obtained under more extreme conditions than are presently practicable.

5 CONCLUSIONS

There have been few co-ordinated attempts to determine the role of the various physical factors in relation to coastal erosion problems and furthermore there is a danger that those experiments which have been carried out are not representative of the larger scale and longer term processes influencing the supply of sediment to a particular area.

The Swansea Bay study has shown that it is possible, with existing techniques, to make regional scale predictions of sediment transport which overcome some of these problems. However, such predictions have only been possible with

(a) certain assumptions relating to the theory of sediment transport processes, and

(b) by extensive comparisons of measured and predicted sediment transport rates from various formulae.

The study has identified the need for improved understanding of both small and large scale sediment transport processes and suggests that despite a very high degree of sophistication, current engineering practice may present a somewhat oversimplified view of the processes which occur in nature.

In our opinion therefore there is a pressing need for further research into the detailed processes of sediment movement on the sea-bed and to improve our overall predictive capability. However, such work should seek to incorporate the results of the detailed short-term small scale process studies into the framework of the larger scale and longer term processes.

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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) Continuous 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 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 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 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. 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.

[illegible] SUMMARY OF METHODS FOR MEASURING SEDIMENT TRANSPORT RATES

	Subject Area - Measurement			
Method	Nature of data obtained	Advantages	Disadvantages	References
1. Bedload:				
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	General: Graf, 1971; Vanoni, 1975; McCave, 1979
b) Pan- or tray-type sampler	Amount of sediment retained in an open pan			
c) Pit-type sampler	Amount of sediment retained in a pit or depression in thd 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: 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: a) Bottles and traps:				General: Graf, 1971; Vanoni, 1975; McCave, 1979
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: McCave, 1979; McCave, 1973; Vanoni, 1975
Delft	Trapped sediment only	Simple	Requires additional flow measurement for concentrations; particle size 50 μm 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: Filtering and weighing	Filtered sediment >40 μm and water samples for <40 μm, 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 and Aked, 1975; Heathershaw and Hammond, 1979 ; Bennett, 1978
c) Optical devices: 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 and Folger, 1979; Lavelle et al, 1978; Cacchione and Drake, 1978
d) Acoustic: Scattering techniques	Concentration	Short time response, continuous record, can be used under waves	Still at development stage	Soulsby, 1977
e) Electro-mechanical: 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: 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

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

		Subject Area - Prediction		
Method	Nature of data obtained	Advantage	Disadvantage	Reference
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; 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 sea-bed 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 ; 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	

APPENDIX A

List of IOS Topic Reports describing work in Swansea Bay

1.	Swansea Bay:	(a) Introduction (a) 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

TABLE 4

Sediment transport formulae used in comparisons of observed and predicted sediment transport rates in Swansea Bay. Full details of the formulae are given in Heathershaw and Hammond (1979)

Originators		Date	Type	Mode
Bagnold	(a)	1963	Deterministic	Bed load
Yalin	(a)	1963	Deterministic	Bed load
Einstein	(a)	1950	Stochastic	Bed load
Ackers and White	(b), (c)	1973	Deterministic	Total load
Engelund and Hansen	(b), (c)	1967	Deterministic	Total load

Used recently by (a) Gadd et al 1978
(b) Swart 1976
(c) Flemming and Hunt 1976

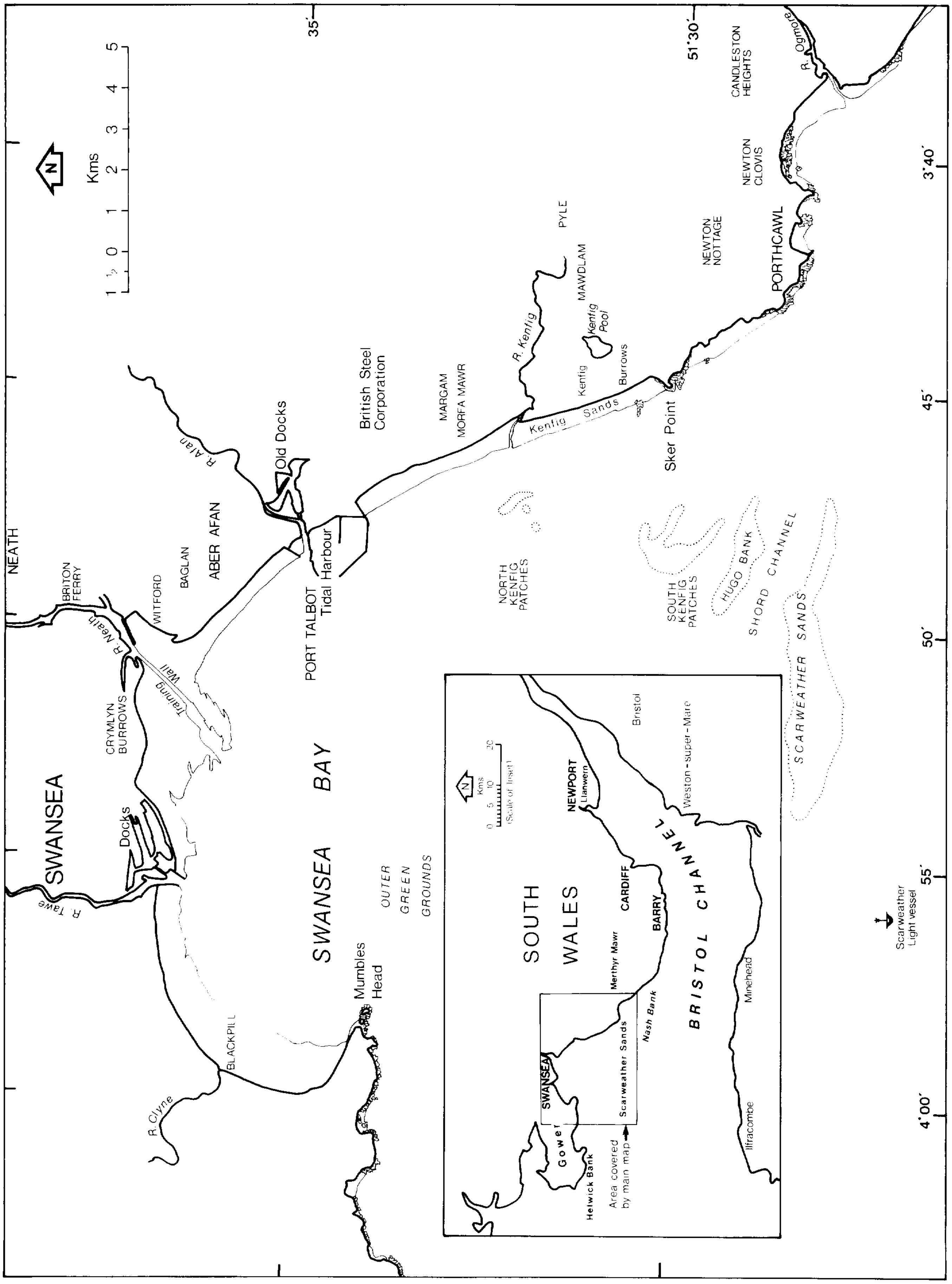


Figure 1 Location Map

APPENDIX B

List of published research papers, as at December 1980, incorporating data obtained as a result of the Swansea Bay project.

1. Measurements of sediment transport rates using radioactive tracers, by A D Heathershaw and A P Carr. ASCE Proceedings Coastal Sediments '77 (1977) 399-417.

2. The significance of cartographic sources in determining coastal change by A P Carr. In: Cullingford D A, Davidson D A and Lewin J (Eds). Timescales in Geomorphology, John Wiley and Sons Ltd (1980), 69-78.

3. Wave direction estimates in coastal waters using radar, by A D Heathershaw, M W L Blackley and P J Hardcastle. Coastal Engineering, 3, (1980) 249-267.

4. (a) Changes in Historical Time, by A P Carr and M W L Blackley;

   (b) Tidal currents and residual circulation in the Swansea Bay area of the Bristol Channel, by A D Heathershaw and F D C Hammond;

   (c) Waves, Currents and Littoral Drift, by R H Wilkinson;

   (d) Transport and deposition of non-cohesive sediments in Swansea Bay, by A D Heathershaw and F D C Hammond;

   (e) Swansea Bay: Beaches and supralittoral deposits, by M W L Blackley and A P Carr;

   In: Collins M B, Banner F T, Tyler P A, Wakefield S J and James A E (Eds), Industrialised Embayments and their Environmental Problems, Pergamon Press (1980), pp 616.

5. Secondary circulations near sand banks and in coastal embayments, by A D Heathershaw, and F D C Hammond. Deutsche Hydrographische Zeitschrift, 33,(1980),135-151.

6. The tidal region of the Bristol Channel: a numerical modelling approach, by A Owen, Geophysical Journal Royal Astronomical Society, 62, (1980), 59-75.

7. A three-dimensional model of the Bristol Channel, by A Owen, Journal of Physical Oceanography, 10, (1981), 1290-1302.

8. Tidal variations in the compaction of beach sediments, by A D Heathershaw, A P Carr, M W L Blackley and C F Wooldridge. Marine Geology (in press).

9. Spatial and seasonal aspects of beach stability, by A P Carr, M W L Blackley and H L King. Earth Surface Processes and Landforms (in press).

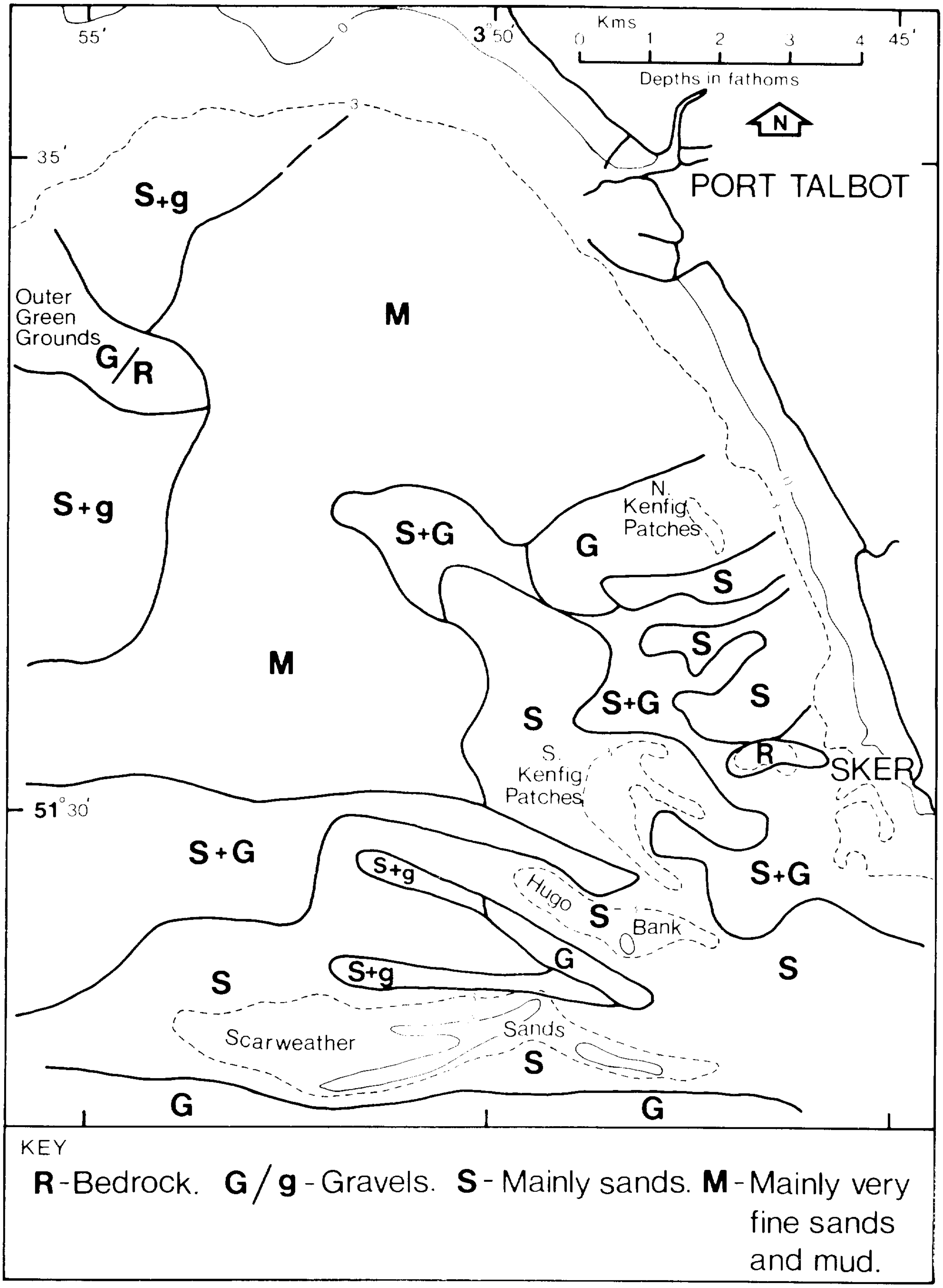


Figure 3 Sediment distribution

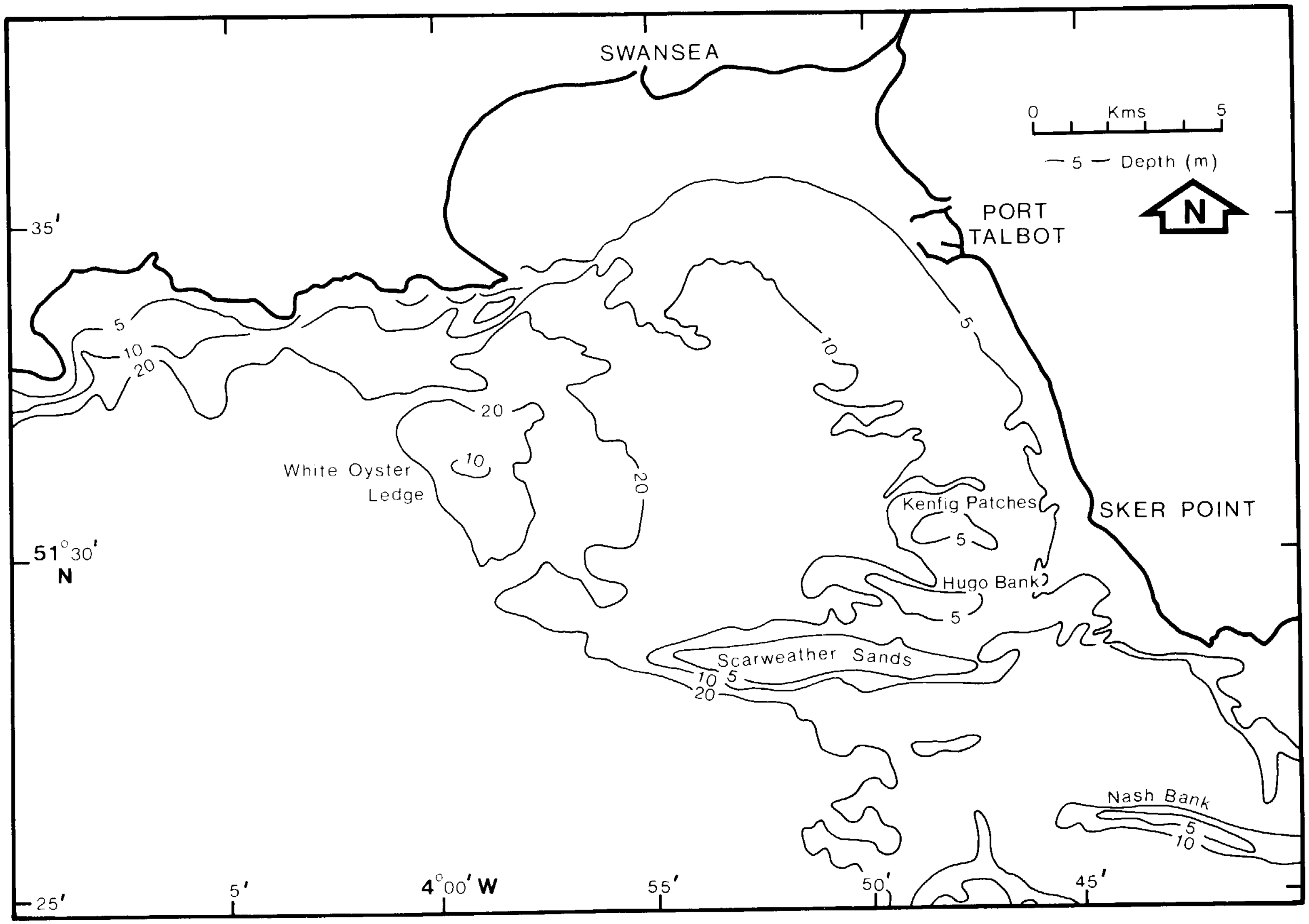


Figure 2 Bathymetry of area

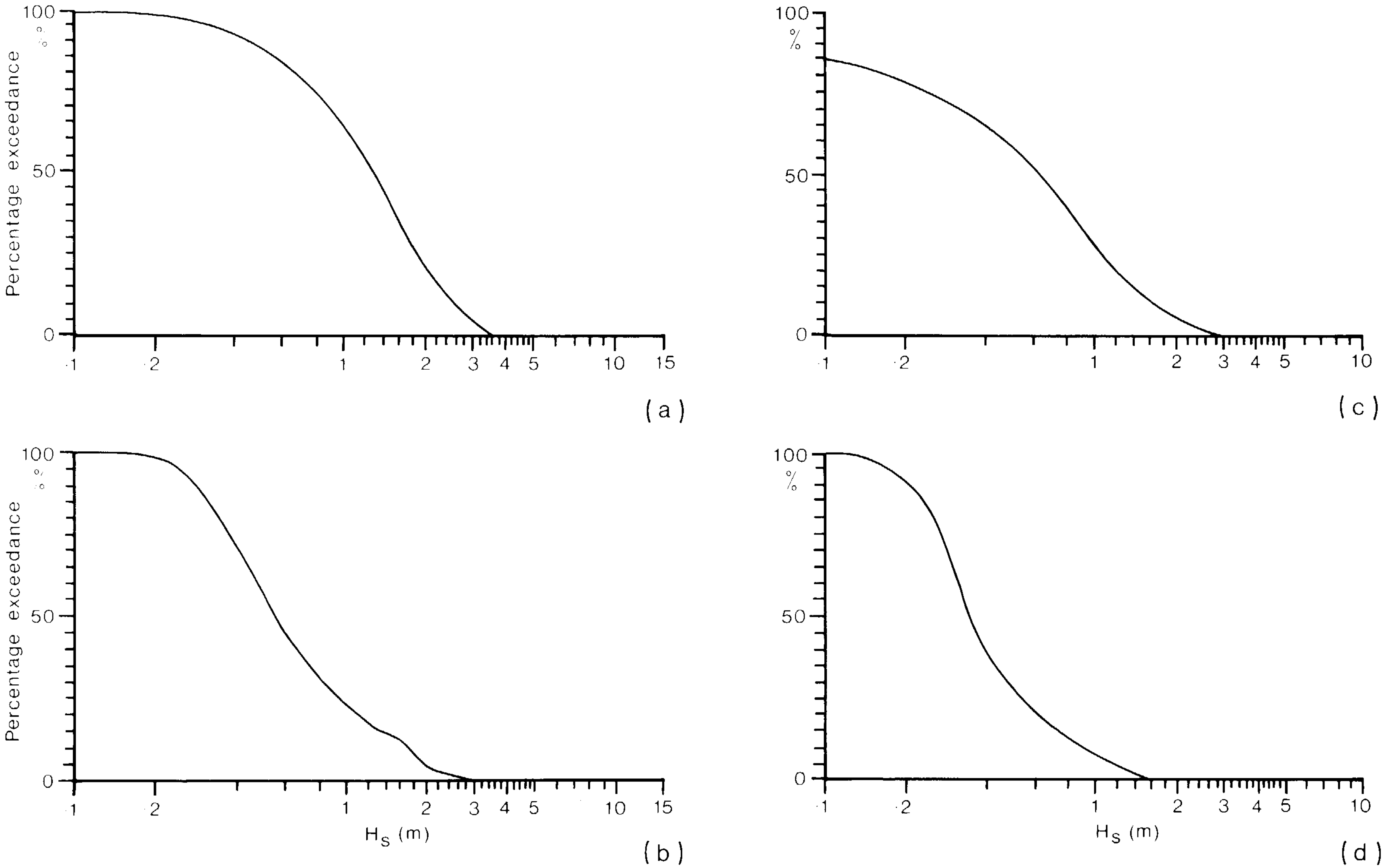


Figure 5 Wave climate: Winter (a) and Summer (b) wave height (H_s) exceedance curves for for waves measured at the Scarweather Light Vessel during the periods December 1976-February 1977 and June-August 1977 respectively. Also shown are Winter (c) and Summer (d) wave height exceedance curves for Port Talbot measured during the periods December 1975-February 1976 and June-August 1977 respectively.

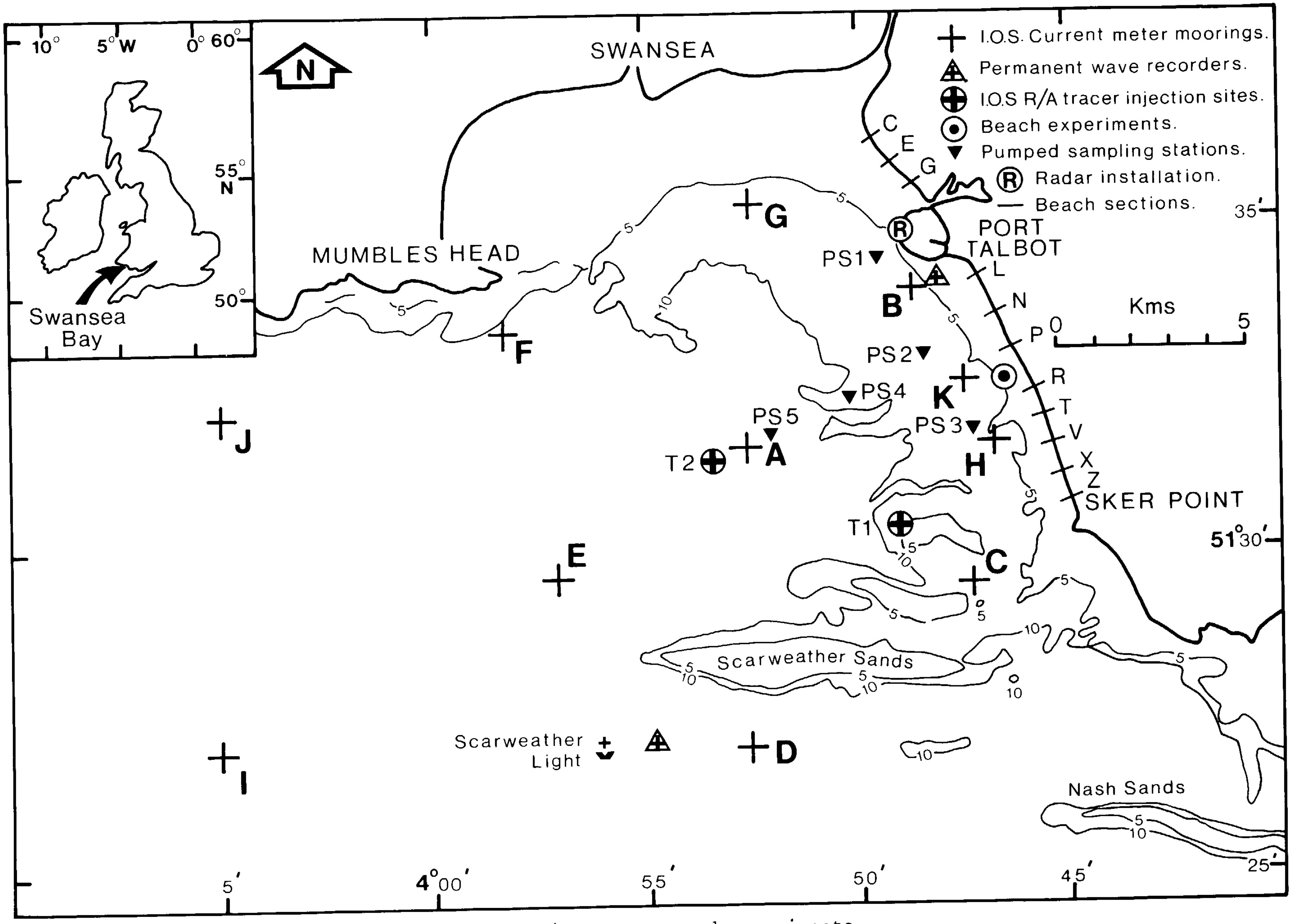


Figure 4   Location of instruments and experiments

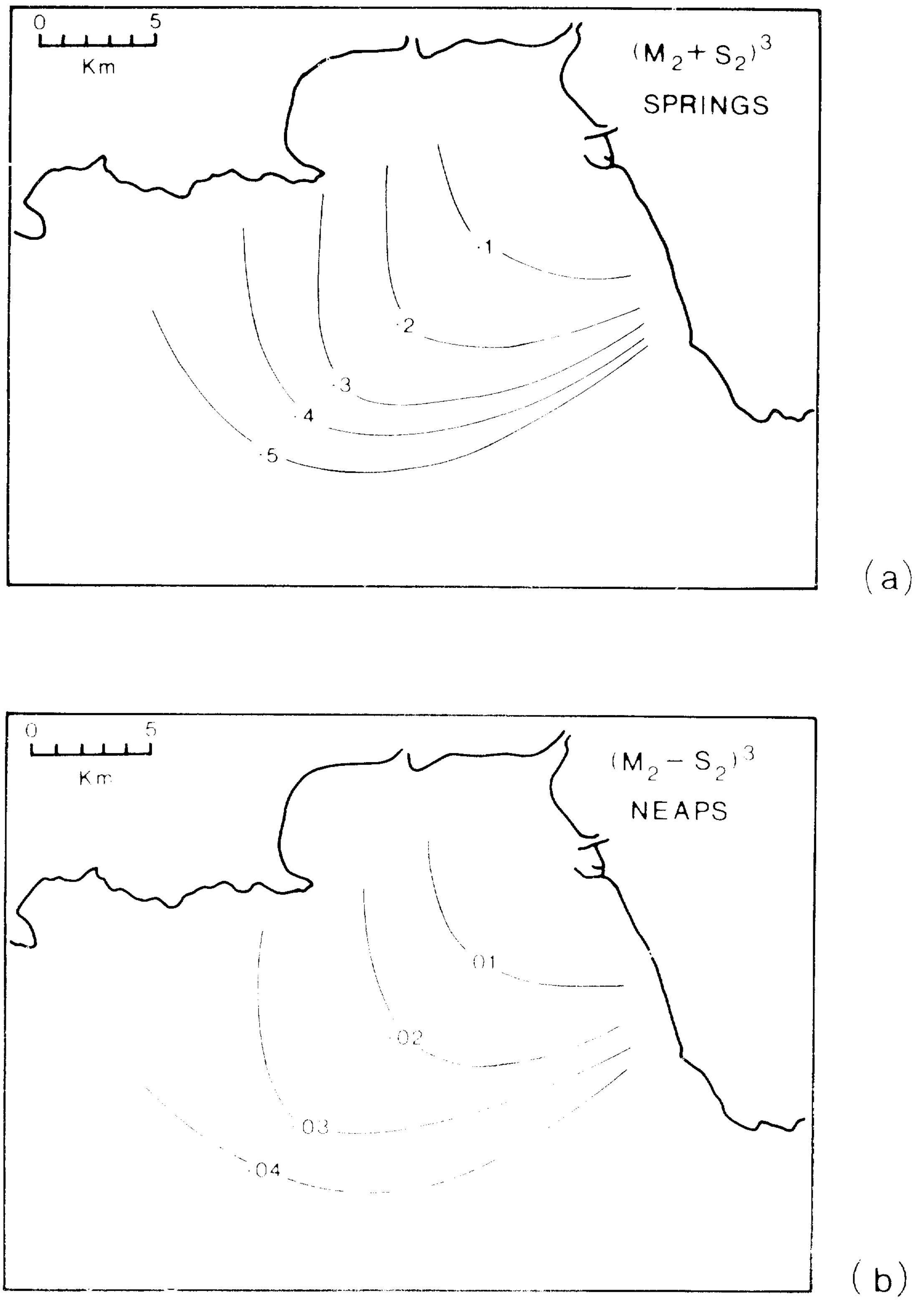
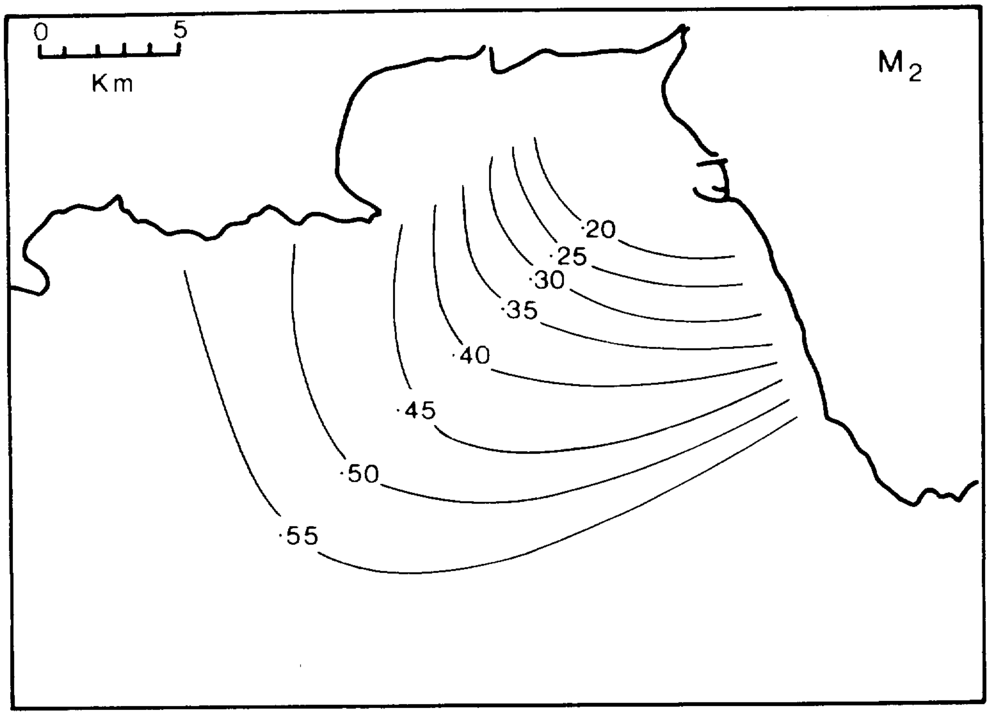
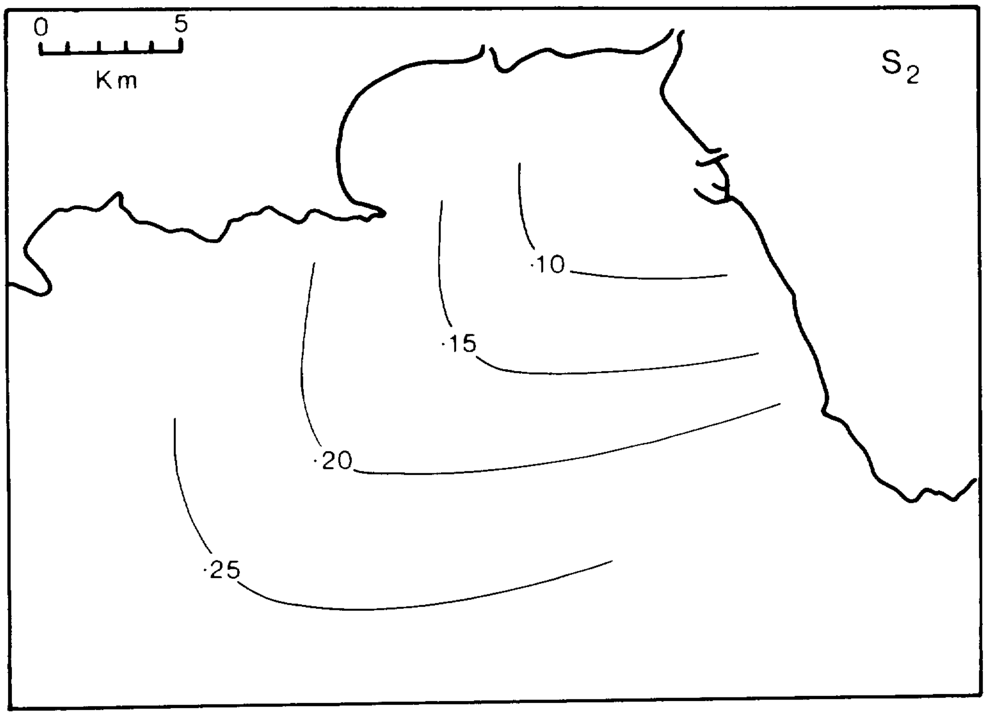


Figure 7 Distribution of [illegible] (b) current amplitudes cubed, [illegible].



(a)



(b)

Figure 6 Tidal stream amplitudes for measured near-bottom currents in Swansea Bay. Current amplitudes shown in ms^{-1}.

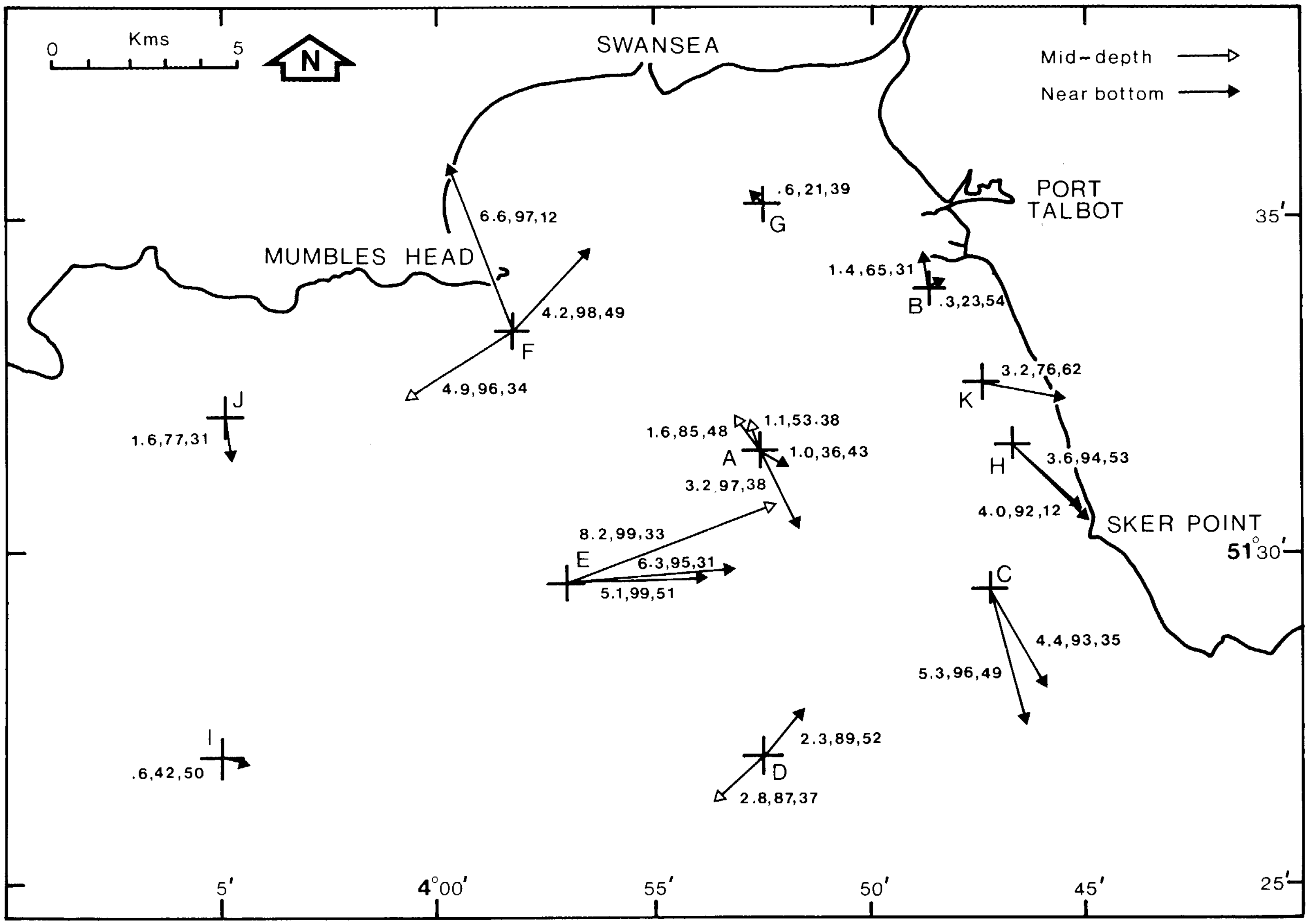


Figure 8 Summary of measured tidally induced residuals at mid-depth and near-bottom. The numbers indicate residual flow speed in cm s^{-1}, the steadiness factor as a percentage and the length of the record in days.

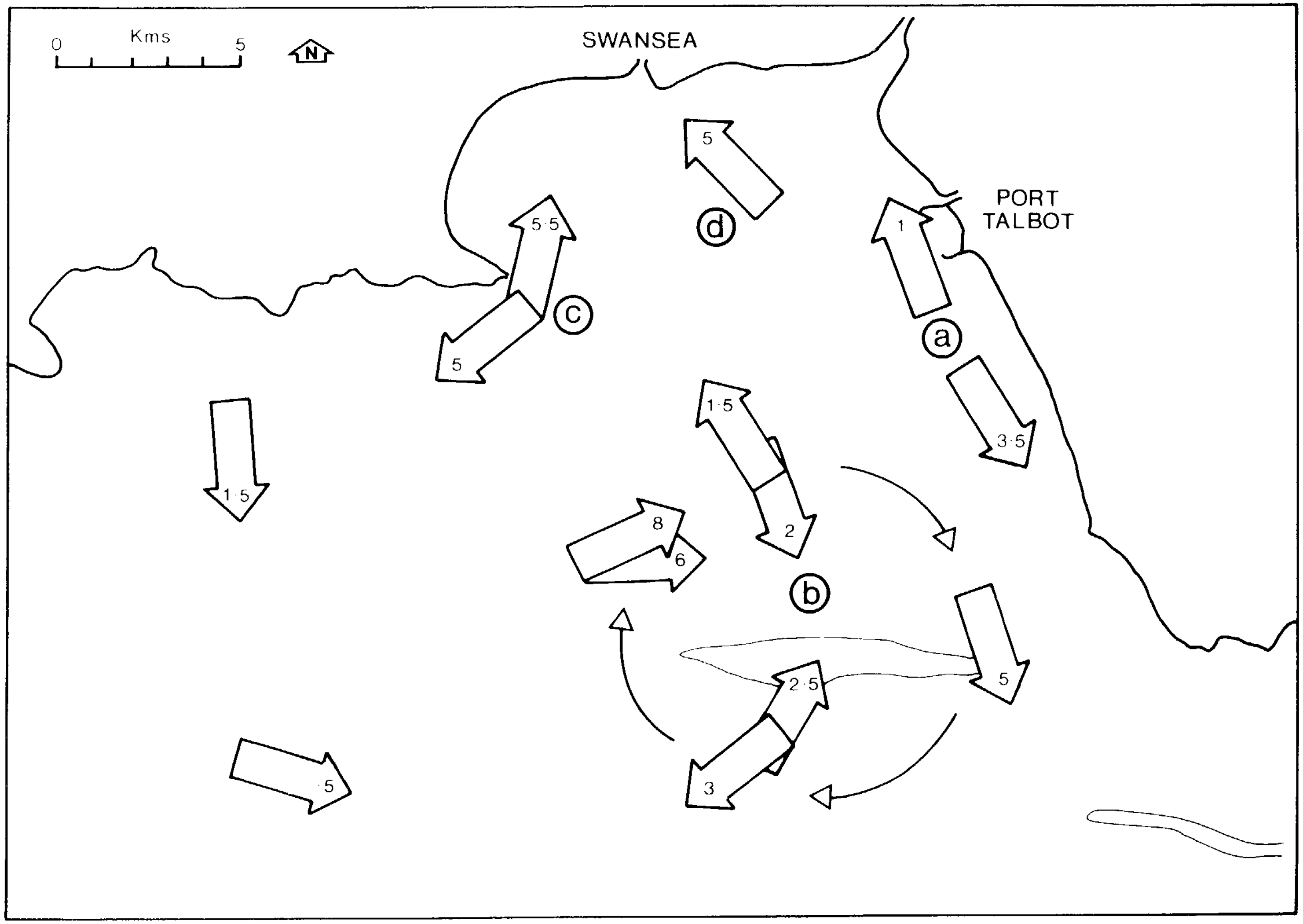


Figure 9 A schematic summary of the mean tidal or residual circulation in Swansea Bay showing (a) an area of divergence to the S of Port Talbot; (b) an area of possible upwelling in a clockwise eddy over the Scarweather Sands; (c) an area of mean flow reversal off Mumbles Head; (d) an area SW of the River Neath where the mean circulation may be influenced by density currents. Upper arrows are mid-depth measurements otherwise arrows indicate near-bottom flow speeds in cm s^{-1}.

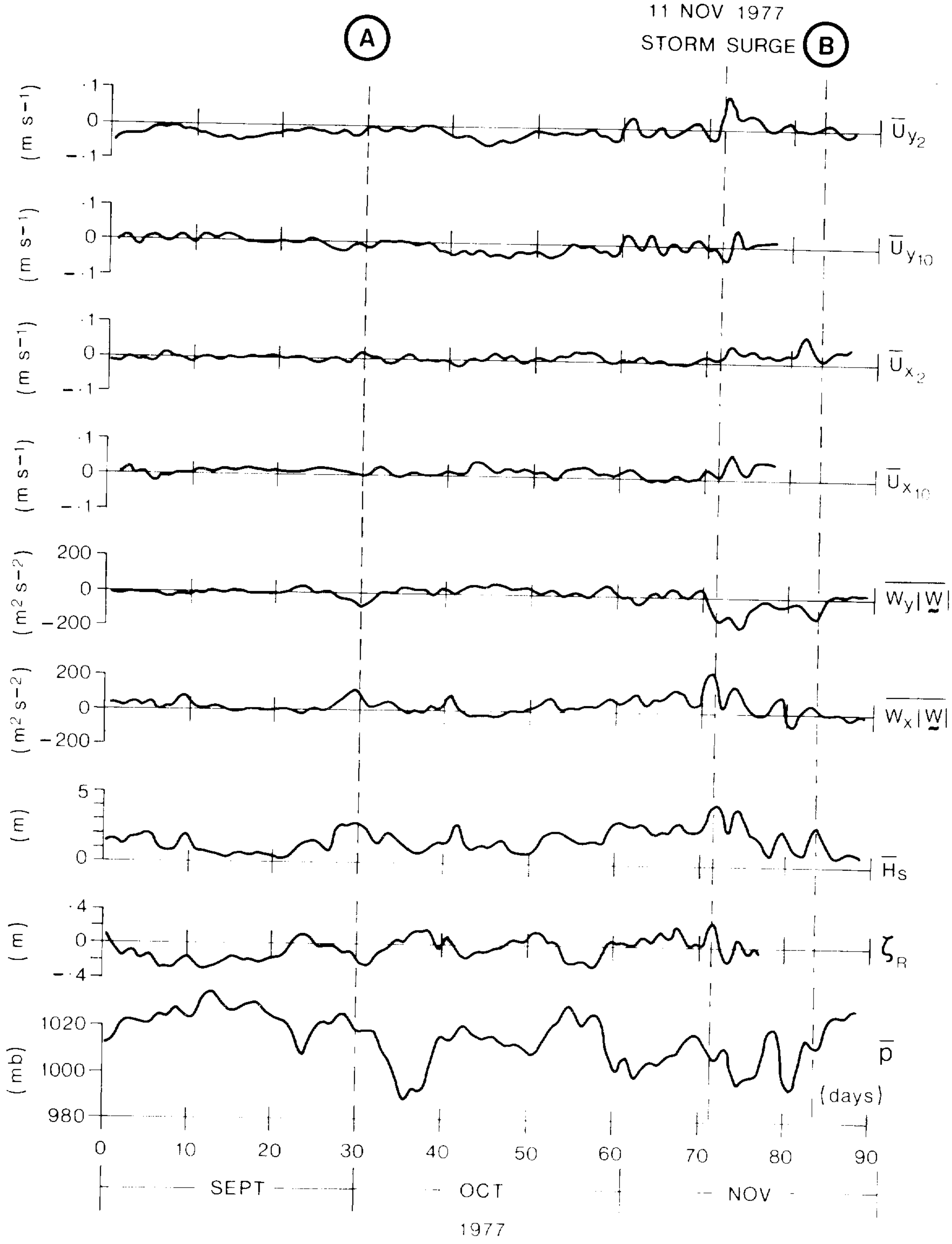


Figure 10 Data set illustrating meteorological forcing. This figure shows daily means of the NE (x) and NW (y) components of the residual flow $\bar{U}$ at heights of 2 m and 10 m above the sea-bed, the NE and NW components of the wind stress as $w_x|w|$ and $w_y|w|$, wave height H_s, observed minus predicted tide $\bar{\zeta}_R$, and atmospheric pressure $\bar{p}$. The storm surge of 11 November 1977 is indicated and A and B denote high wind stress events associated with low residual flows.

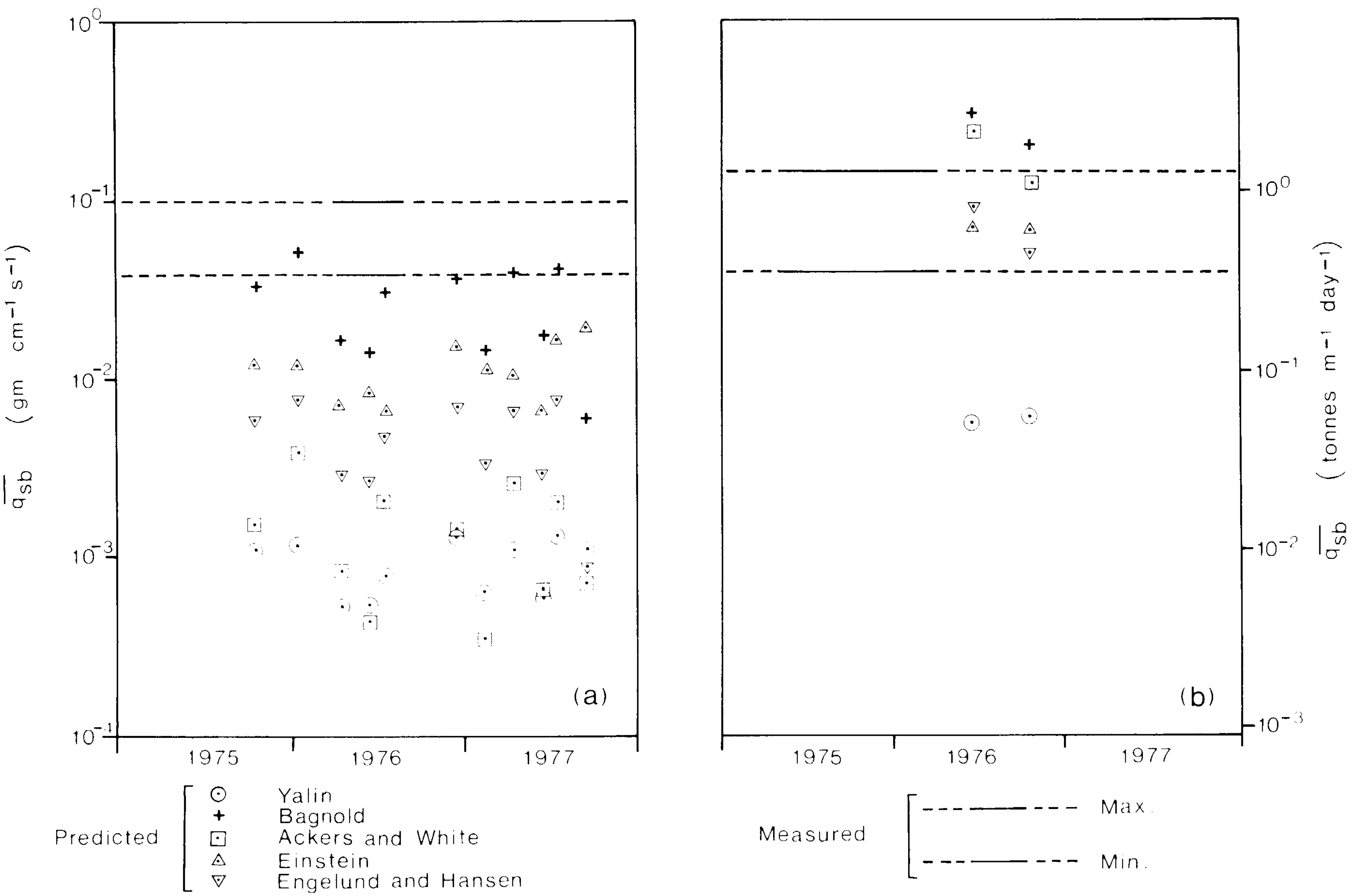


Figure 11 Comparisons of measured and predicted net bedload transport rates ($\bar{q}_{sb}$) from various equations. The maximum and minimum rates are derived from radioactive tracer experiments.

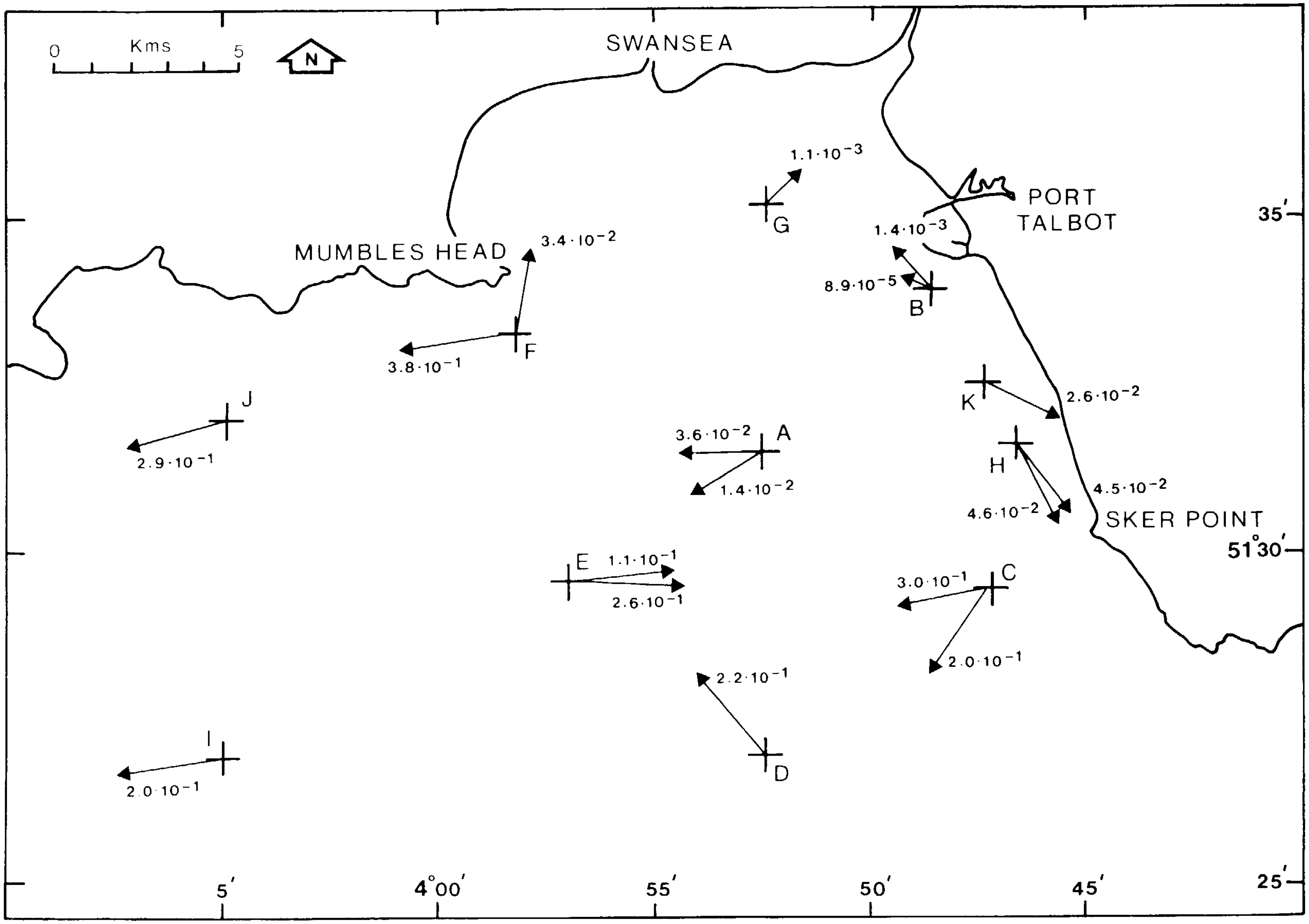


Figure 12 Summary of net tidal movements of sediment showing predicted bedload transport rates ($\bar{q}_{sb}$) and directions for the area calculated using a modified form of Bagnold's (1963) equation. Transport rates are given in gm cm^{-1} s^{-1}. Two arrows are shown where it has been possible to indicate Summer and Winter variations.

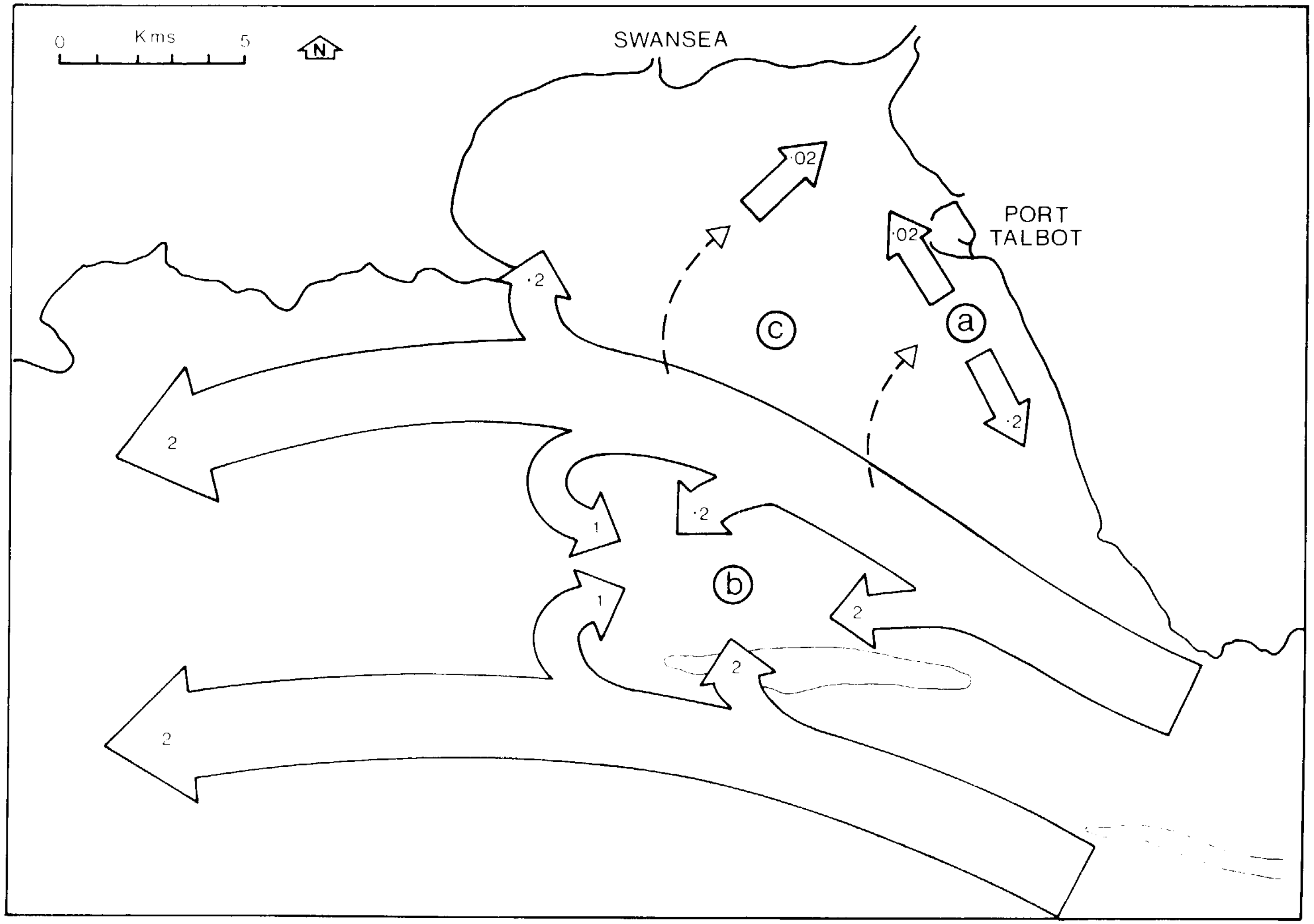


Figure 13 A schematic summary of sediment transport paths in the Swansea Bay area based upon predictions from near-bottom current measurements and the orientation of bedforms given by Collins et al (1979). The figure shows a two order of magnitude variation in bed-load transport rates from about 2 tonnes m^{-1} day^{-1} (figures in arrowheads) in the offshore areas to about .02 tonnes m^{-1} day^{-1} in the vicinity of Port Talbot and Swansea. Important features are (a) the area of bedload parting to the S of Port Talbot and (b) the area of bedload convergence in the vicinity of the Scarweather Sands. The broken arrows (c) indicate a possible wave induced transport.

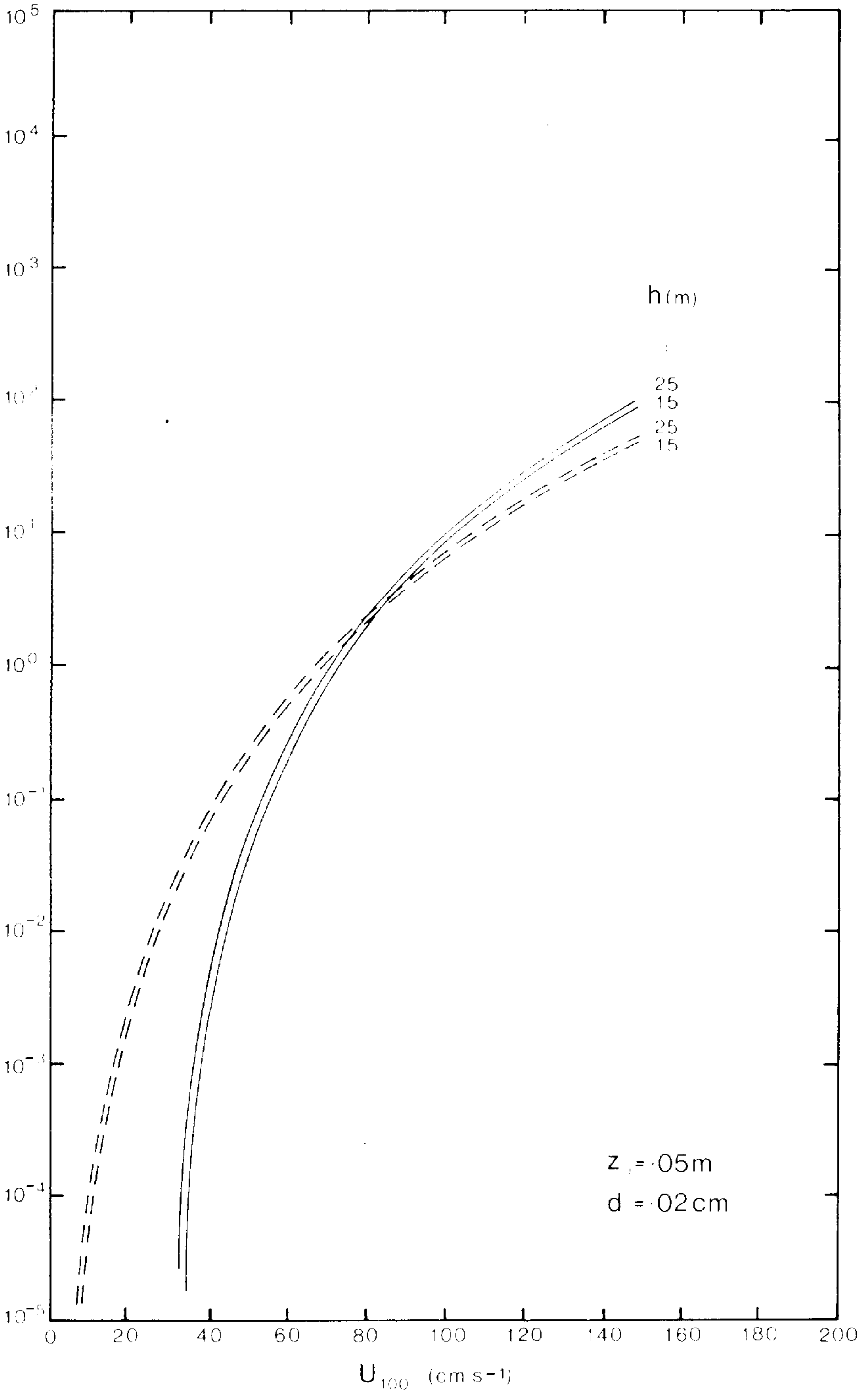


Figure 14 Sediment transport and changes in flow depth: Predicted transport rates from Engelund and Hansen's (1967) (broken curve) and Ackers and White's (1973) (solid curve) equations for the same roughness length (z_0 = .05 cm) and particle size (d = .02 cm) but for different water depths, h = 15 m and h = 25 m. Predicted rates are shown as a function of the near-bed current U_{100} .

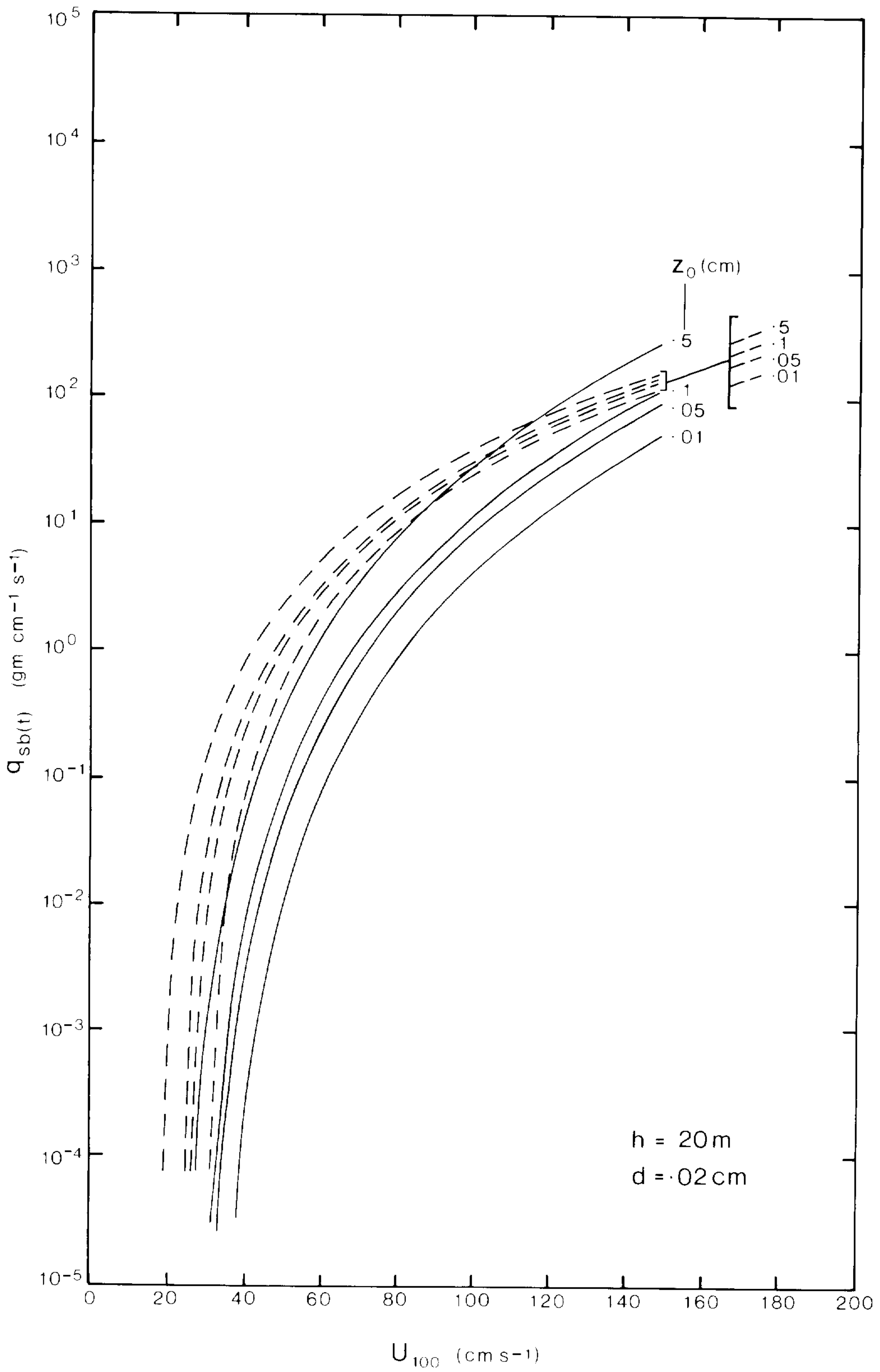


Figure 15 Sediment transport and changes in sea-bed roughness: Predicted transport rates from Bagnold's (1963) (broken curve) and Ackers and White's (1973) (solid curve) equations for the same water depth (h = 20 m) and particle size (d = .02 cm) but for different roughness length values, z = .01, .05, .1 and .5 cm. Predicted rates are shown as a function of the near-bed current U_{100}

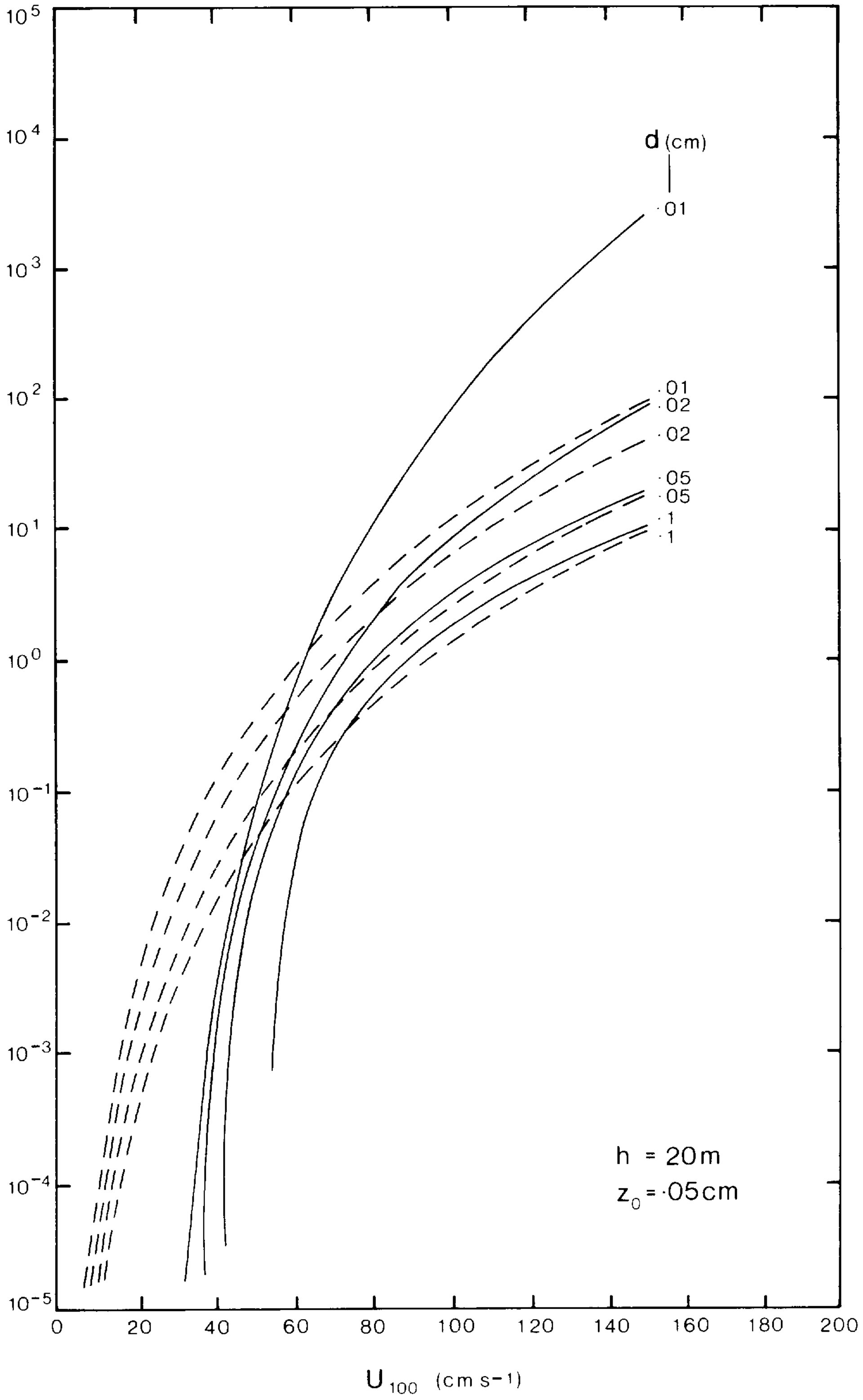


Figure 16 Sediment transport and changes in particle size: Predicted transport rates from Engelund and Hansen's (1967) (broken curve) and Ackers and White's (1973) (solid curve) equations for the same water depth (h = 20 m) and roughness length (z_o = .05 cm) but for different particle sizes, d = .01, .02, .05 and .1 cm. Predicted rates are shown as a function of the near-bed current U_{100} .

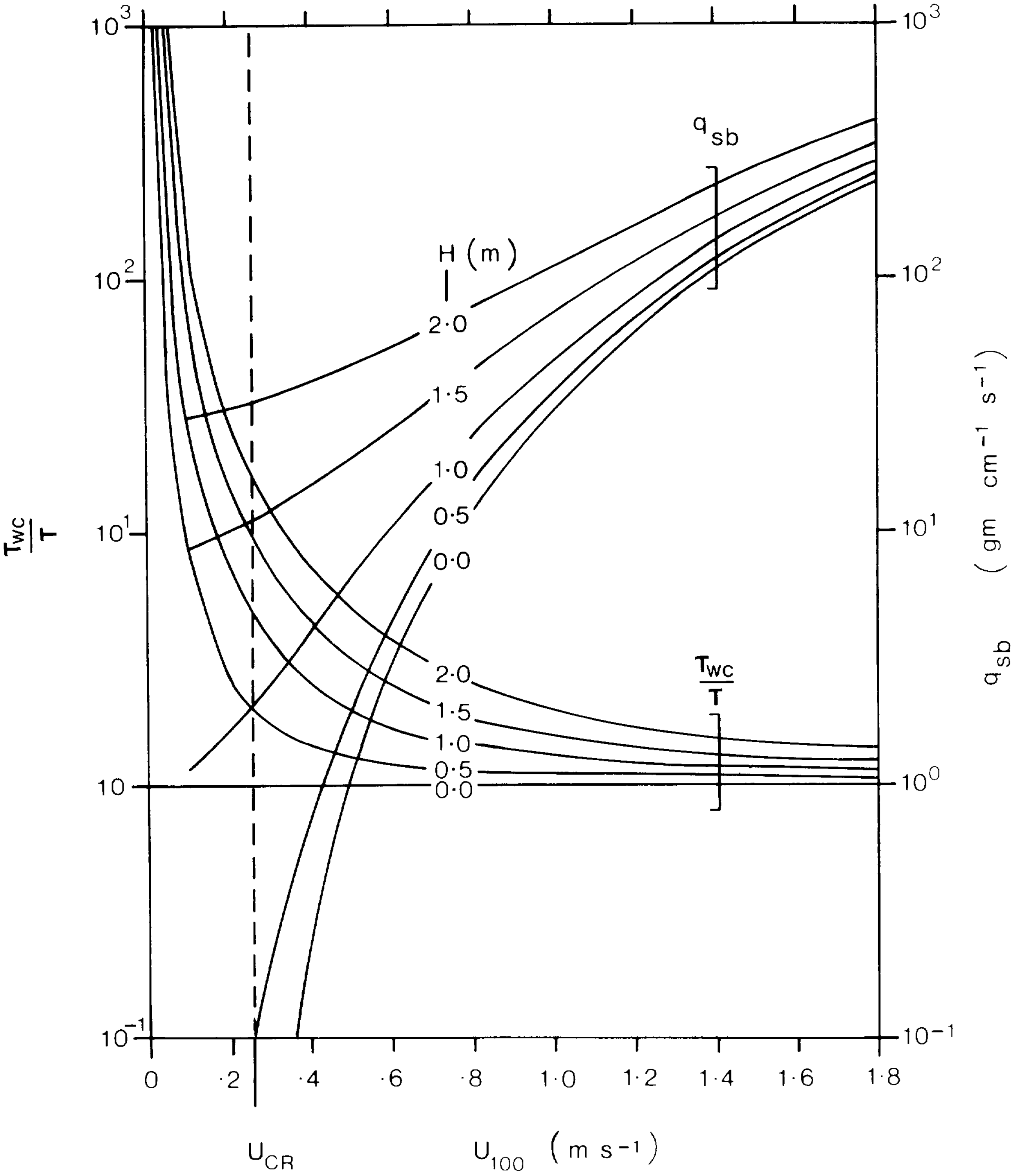


Figure 17 Sediment transport under waves and currents: The ratio of the bed shear stress due to waves and currents (τ_{wc}) to the bed shear stress due to currents alone (τ) calculated using Bijker's (1967) equation. The effect of increasing wave height (H) on bedload transport rates (q_{sb}) is illustrated using Bagnold's (1963) equation in terms of the near-bed current U_{100} . U_{CR} is the steady current threshold.