A HEURISTIC APPROACH TO THE EVALUATION OF SEAFLOOR BATHYMETRIC CHANGES : A CASE STUDY OF DUNDEE HARBOUR, EASTERN SCOTLAND

Harun Shah bin Mat Zin

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This thesis is submitted to the Department of Geology in the University of St Andrews for the Degree of Doctor of Philosophy

(May, 1996)

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DECLARATION

(i) I, HARUN SHAH MAT ZIN, hereby certify that this thesis, which is approximately 45,000 words in length, has been written by me, that it is the record of work carried out by me and that it has not been submitted in any previous application for a higher degree.

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PRESENTATIONS AND PUBLICATIONS

(1) **Title:** Methods of Gridding Bathymetric Data for the Study of Seafloor Topographic Changes.

Conference: Hydro'94 - The Ninth Biennial International Symposium of the Hydrographic Society, 13 - 15 September, 1994.

Venue: Aberdeen Exhibition & Conference Centre, Aberdeen, Scotland.

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(2) **Title:** A Methodology for Evaluation of Seafloor Sediment Deposition and Erosion in Harbour areas.

Conference: The Fourteenth World Dredging Congress, 14 - 17 November, 1995.

Venue: Amsterdam RAI Exhibition Centre, Amsterdam, The Netherlands.

Publication: Proceedings of the 14th World Dredging Congress, Vol.2, pp669 - 684.

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COL - Collocation
MCS - Minimum curvature spline
IDWM - Inverse distance weighting method
LSQ - Least squares

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ABSTRACT

The phenomena of seabed bathymetric changes in Dundee harbour, eastern Scotland have been investigated, by use of archive bathymetric data. The bathymetric data were available from the Dundee Port Authority, from its past annual harbour maintenance programmes during the period of 1989 to 1993.

Archive bathymetric data are seen as under-utilised, after being used for their intended purposes. A methodology was therefore developed to use sequential bathymetric data to estimate the deposition and erosion of sediment over a period of time. This is in the form of a systematic procedure of processing for comparison of data from different dates. The comparison or differencing of bathymetric data in their original form cannot be directly applied. This would require each data point to be located at spatially common positions (i.e. grid points) and could be achieved only through interpolation. A procedure known as 'gridding' is instead used to prepare depths at the spatially fixed points or nodes.

Six different methods of interpolation have been examined and trial computations using a common data subset for each individual method conducted. The results of the interpolation were often substantially different from one method to another. A technique known as the Blending Interpolation Technique is proposed to overcome the uncertainty in depth interpolation. Computer programs were specifically written for this study and for the visualisation of the phenomena of deposition and erosion, use was made of the available UNIRAS software package.

The methodology and procedures of this study are not only applicable for an estuarine harbour environment, but are also equally applicable to any areas such as large

reservoirs, lakes or coastal ports and harbours, that are continuously affected by the phenomena of sedimentation and erosion, where their estimation and quantification are of critical importance.

This study, however, has demonstrated the usefulness of the Blending Interpolation Technique which is seen as a future tool to detect, monitor and quantify seabed changes, in particular where bathymetric data of the same area are available from different dates. It also serves to prolong the usefulness of archive bathymetric data kept for an area.

CHAPTER 1

INTRODUCTION

1.1 GENERAL STATEMENT

Many rivers and estuaries provide sites for ports and harbours. Such locations are often more favourable than open coastal areas because of the degree of shelter and protection they afford against strong winds and waves. However, whilst riverine and estuarine harbours may have the advantage of shelter, such harbours are often subject to the adverse influences of strong currents, freshets and floods.

In addition to these adverse influences, the consequences of any interference to the boundary conditions and geometry of any part of a harbour area will be to modify the innate instability of the floor of the harbour area and its surrounding. This is sometimes referred to as a process of re-establishing the 'regime' or equilibrium. The continuing phenomena of river and seabed changes may be slow and negligible, but sometimes they can be dramatically rapid, so as to cause concern to navigation safety which may lead to a costly compensatory dredging programme or may even lead to failure of harbour structures due to scouring at the foundations.

In the event that the natural or 'regime' state governing a hydrodynamic system is extensively modified, heavy or rapid siltation and scouring problems are likely to occur. For example, as in the case of an estuarine harbour area, whenever the natural water depths are modified by dredging, either to create deeper berths or to increase the area of deep water, siltation and erosion will be induced. This is because greater volumes of water will enter the dredged area and the immediate consequence will be changes in the water and sediment circulation patterns. Similarly, the construction of various structures such as wharves and jetties within an existing harbour area, without due consideration being given to any possible consequences to changes of bottom topography, may aggravate the natural, slow siltation processes into widespread, rapid deposition and erosion.

O'Connor (1983) provides some examples of the possible changes that might be expected as a result of engineering activities in estuarine and coastal situations. Most common engineering activities are the construction of dam, barrage, dock entrance and jetty, dredging and training wall. For instance, construction of dam across a river feeding the estuary will regulate the freshwater flows and at the same time increases siltation rates elsewhere in the estuary. During flood tide, sediment is brought into the estuary and as it flows further along the estuary the transport rate will be reduced as less water is now required to fill up the inter-tidal volume. On the ebb-tide, velocities are lower than previously and thus less time is available to move sediment. The net result will be progressive siltation until a new equilibrium is reached.

Extensive deposition and erosion of bed sediments within existing harbour areas can cause serious problems for port and harbour management. To the authorities concerned precautionary steps have to be taken to ensure that the effects of these processes are regularly checked and, where possible, they are continuously monitored and the dimensions of resulting changes as depositional and erosional sites precisely established. Continuous monitoring is necessary to minimise the chances of the depositional sites and scour zones becoming permanently localised, so resulting in serious damage to structures or dangers to navigation.

At present, most of the studies of harbour sedimentation and erosion are focused on forecasting and predicting the outcome of an event by means of modelling techniques (e.g. Abbot, 1976; Reinalda, 1977; Thorn, 1987; Falconer, 1983). Before any development or modification to an existing harbour area is made, it is likely that modelling will precede the construction works. Modelling is based on either numerical or physical data and supplemented by field measurements. In reality, however, within most models there are factors which may not be valid for the area in question. Furthermore, the complexities of many harbour areas are such that they are impossible to model without excessive simplification. Although the methods of modelling have been widely accepted by practitioners, to some extent the results of such works can still fall short of the expected (Thorn, 1982). For example, results from modelling may give only limited insight into seabed changes which can be inadequate for accurate quantification and areal estimation of sediment deposition or assessment of dredging works done. Deficiency in models, however, is often linked to their inability to estimate and pin-point sediment deposition or erosion sites to the required degree of accuracy.

In consequence, port and harbour authorities continue to base their judgements and decision making on *in situ* field measurements derived principally from bathymetric surveys. Although the acquisition of bathymetric data is always seen as tedious and costly, such surveys are considered important and provide fundamental information which should be obtained regularly. Therefore, in this regard bathymetric surveys can be considered as a primary source of information leading to a better description and estimation of the sediment deposition and erosion in harbour areas. Comparison of sequential bathymetric data with a view to guiding port and harbour authorities on quantifying and estimating of such phenomena will form the main subject of this thesis.

1.2 BACKGROUND OF RESEARCH

In the study of riverine and estuarine harbour environments, field measurements often form a basis for engineers or scientists to produce a detailed description of the sedimentation phenomena in an area. Various kinds of *in situ* field measurements may be carried out, either for the task itself or to provide supplementary information. For example, Cooper (1987) outlined a range of field measurement techniques often used to improve the efficiency of maintenance dredging works. These are classified as 'routine' and 'specialist' measurements. Routine measurements include depth, position and bed density, whilst specialist measurements include wave height, current velocity, sediment transport and soil properties.

Routine measurements in the form of bathymetric surveys are common in relation to the study of bottom topography by port and harbour authorities. In most major ports and harbours bathymetric surveys are carried out regularly, ranging in frequency from fortnightly to annually. Surveys may be restricted to specific areas such as a quay, wharf, jetty or navigation channel, or may cover the whole of a harbour area. The latter is the case for the Dundee harbour area of eastern Scotland. Although many ports and harbours have been frequently charted, information on bathymetric changes is often by no means readily obtained. Sometimes the surveys were not sufficiently comprehensive and, in many cases, the data are poorly collated.

In most cases no attempt has been made to analyse and document changes in the bottom topography of the area covered by the surveys. However, the authorities can obtain significant additional information on seabed changes of harbour areas by taking full advantage of the bathymetric data which were retained but were often forgotten. Whilst there have been attempts to do this, these have largely failed owing to the absence of a suitable methodology and proper computer software to handle bathymetric data. This has led the author to instigate a study to establish a methodology to effectively evaluate changes in seafloor topography using such archive bathymetric data.

An overall research scenario pertaining to this study is depicted in Figure 1.1. Within a harbour area developed in an estuary, there are four concerns with respect to sediment

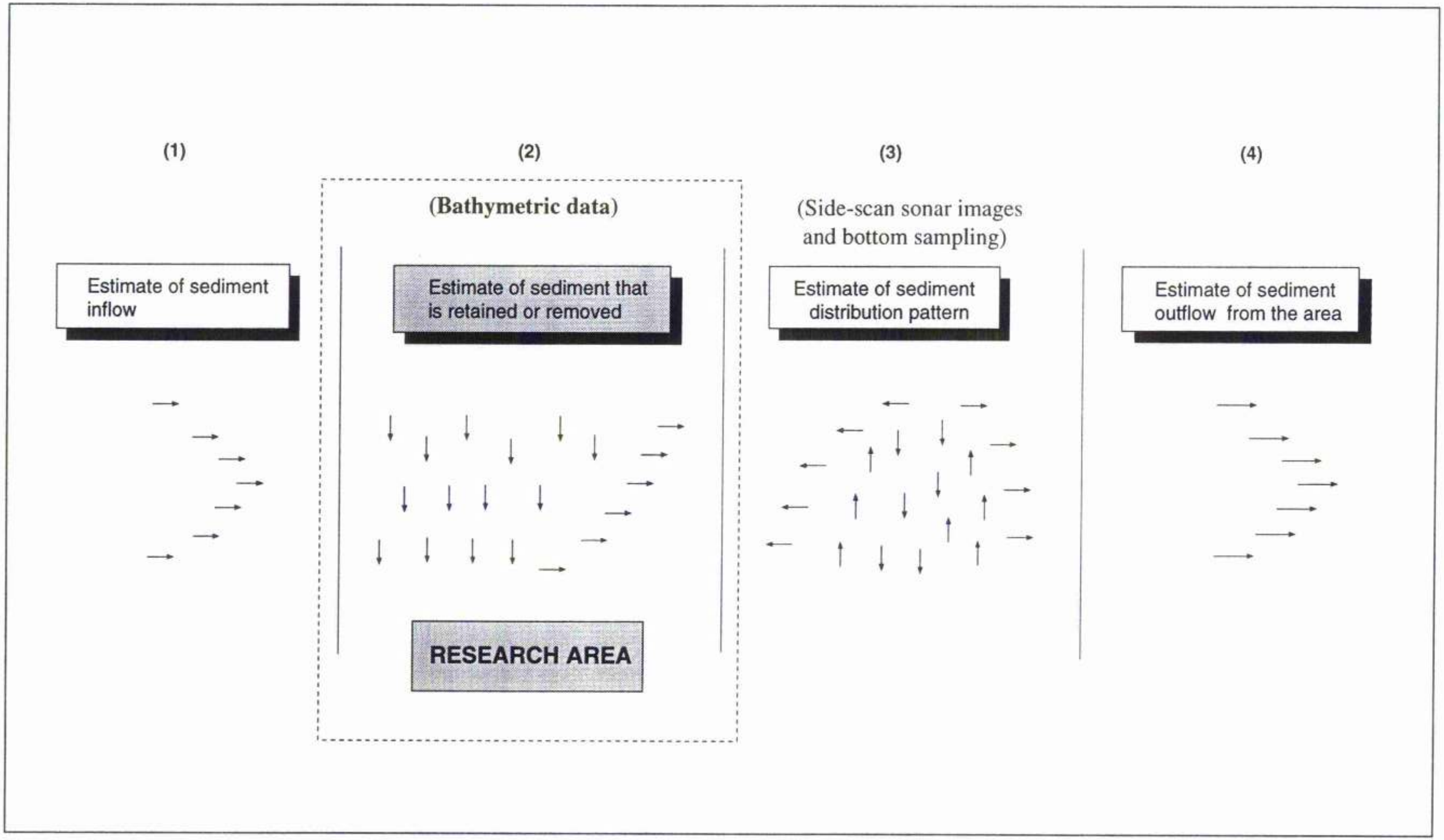


Figure 1.1. Diagrammatic representation of an investigation of seafloor sediment movement, deposition and erosion.

movement, deposition and erosion. These are (1) Estimation of sediment inflow into an area. This can be sediment flux evaluated by measuring the sediment discharge rate, i.e. the product of the flow rate and the suspended and bedload sediment concentration over a period of time; (2) Estimation of the quantity of sediment that is retained or removed out of an area. This requires either modelling or field measurements, or a combination of both. Modelling provides an insight or a first estimation as to the amount of sedimentation and its impact. Field measurements provide better accuracy in terms of the areal extent and quantity of sediment deposition and erosion since the bathymetric data used are acquired directly on site at specific times. Direct comparison of depths determined at various times enables the assessment of bathymetric changes within the area; (3) Sediment textural and distribution patterns can be studied by taking bottom samples and acoustic imaging using side-scan sonar; and (4) Estimation of sediment outflow can be evaluated in a similar manner to the inflow.

In an attempt to study changes in bottom topography by whatever approach, one must also be aware of the complexities of the bed surfaces being investigated. The seabed or river bed may undergo changes in either horizontal (x,y) or vertical (z) directions. The rate of change may vary from seconds to decades with magnitudes ranging from negligible (millimetres level) to very significant (sub-metres level).

In order to facilitate the definition, size or magnitude of changes, it is necessary to classify the magnitude of the changes into three distinct categories: micro-structure level (< 0.3 metre), meso-structure level (0.3 - 1.0 metre) and macro-structure level changes (> 1 metre). It is least difficult to study surface changes at either the meso-scale or the macro-scale level because the magnitude of changes at these levels can be accurately measured by any depth measuring equipment such as an echo-sounder. However, if one tries to investigate changes at the micro-structure level, then a problem of accuracy is anticipated. One obvious reason is that the magnitudes of micro-structure level changes often fall just within the detection limit of most depth measuring devices. Yet sometimes, it is still important to determine changes in depth to that level of accuracy and demand availability of very high precision depth measuring equipment such as digital echo-sounder and electronic position fixing systems to ensure that accurate data from the identical site are being compared.

As will be discussed in detail later in the following Chapters, if the seabed is composed of soft material (e.g. fluid mud), it will be difficult to measure depth. Obviously, this is because the returned signal from bottom is weak and there is a need to define the exact bottom.

As a result of the complexities and the processes that induced them, the detection and estimation of changes in seafloor topography may not always be straightforward and this poses a challenge to engineers and scientists working in such environments.

1.3 OBJECTIVE AND SCOPE

The focus of attention in this thesis will be on the development of a methodology for accurate estimation of areal extent, rates and quantities of sediment retained or lost from a harbour area. A methodology which is based on 'heuristic' approach is introduced, and investigation on the phenomenon of seafloor sediment deposition and erosion will be carried out in the Dundee harbour area, eastern Scotland. The study involves the use of archive bathymetric data acquired during the period 1989 to 1993, which have been made available by the Dundee Port Authority. Development of suitable algorithms and computer programs forms the bulk of the work undertaken. It is intended to lead to the development of a standard procedure which will enable reliable quantification and description of the phenomena occurring during any given period of study. The aim is to provide a reference technique for port and harbour authorities to assess the stability of individual areas of their harbour floors.

1.4 THESIS LAYOUT

In accordance with the above aim and objective, Chapter 2 presents an overview and discussion of the estuarine environment of the Tay and the physical processes acting within its waters. It aims to enumerate and link the possible cause-and-effect relationships involved in the phenomena of sediment deposition and erosion.

Chapter 3 provides an account of the terminology, methods of acquisition and processing of bathymetric data and includes discussion of the limitations and problems associated with the acquisition and processing of such data.

A close examination of the available bathymetric data for the Dundee harbour area suggests that comparison of the data from the various surveys cannot be performed directly. This is because, despite the fact that same area has been repeatedly surveyed the individual depth measurements are at different spatial positions. An intermediate process is therefore proposed, i.e. the 'gridding process' carried out to allocate data to common spatial positions. Thus, Chapter 4 involves a discussion of the possible methods of gridding the bathymetric data. A selection of methods to grid data, with examples of computational procedures of each individual method, is also presented.

A technique, which is based on a blending approach, and a depth selection strategy to select a representative depth value for the various interpolated depths, is proposed as a best possible solution. Chapter 5 details the description and the uses of UNIRAS computer software subroutines and presents a computer program known as Blending Interpolation Technique (BIT) which was written for this purpose.

Chapter 6 presents data from the Dundee harbour area to portray seabed changes between 1989 and 1993. Data for the periods; 1989-90, 1990-91, 1991-92, and 1992-93, have been processed using the Blending Interpolation Technique. Results are displayed in tabular, graphical and pictorial forms. An analysis of changes occurring during each time interval is presented, leading towards a concluding description and estimation of seafloor sediment deposition and erosion in the area.

Finally, Chapter 7 contains a summary and overall discussion of the study, and concludes with suggestions as to some potential applications and future work.

CHAPTER 2

PHYSICAL PROCESSES AND CHARACTERISTICS OF THE TAY ESTUARINE ENVIRONMENTS

2.1 INTRODUCTORY REMARKS

This chapter provides an overview and discussion of those related topics which are significant to the study of seabed changes, with particular reference to the estuarine environment of the Tay. It aims to enumerate and possibly inter-link the various physical processes known to operate in the Tay Estuary and whose interactions will induce the phenomena of sediment deposition and erosion.

Since the phenomena of deposition and erosion are site specific, an attempt later in this thesis to evaluate them will require locational justification. Thus, a suitable location within the estuary which requires special attention is a harbour area. It is essential, therefore, at the outset, to describe the Tay Estuary as a whole, including its physical setting, the associated water motions, the sediment sources and their distributions. This is especially important in order to establish understanding of the cause-and-effect relationships and the influences of one reach of the estuary upon another.

Of specific interest will be the lower middle reach, which is of commercially strategic importance especially the northern shore, along which the commercial harbour of Dundee is situated. The seabed of the Dundee harbour area will be subject to a detailed study, as the locality in which evaluation for deposition and erosion will be carried out.

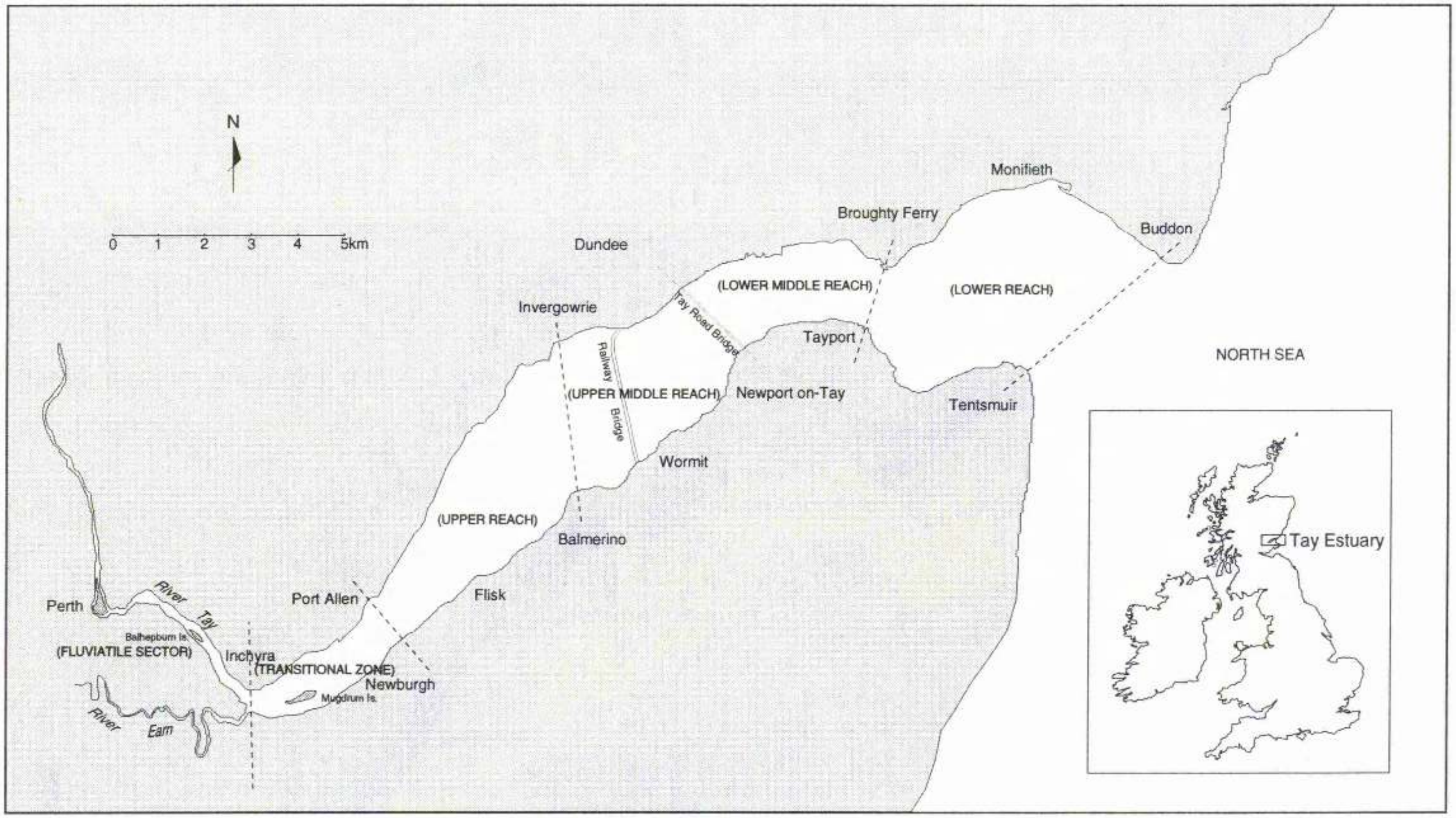


Figure 2.1. Subdivision of the Tay Estuary into the upper, upper middle, lower middle and lower reaches.

2.2 PHYSICAL SETTING OF THE TAY ESTUARY

A geological account of the estuarine development and sediment distribution in the Tay has been given by McManus (1972). Geographically, the Tay Estuary is situated in the eastern part of Scotland (Figure 2.1). It was formed from drowned river valleys which flooded as sea level rose during glacial retreat. The estuary receives freshwater input from a 6500 km^2 catchment area, and periodic incursion of salt water from the North Sea. The River Tay begins at the eastern end of Loch Tay and meets the River Earn at a confluence above Newburgh before ending its 73 km journey to the open North Sea at Monifieth Bay. These two main rivers; the Tay and Earn, are the principal drainage channels which contribute fresh water inflows into the estuary at a daily average rate of 167 and 31 cumecs respectively (Pontin and Reid, 1975). Although there are small streams flowing directly into the estuary below the Tay-Earn confluence, their contributions to the total flows can be considered as negligibly small.

Looking into a more detailed context of the estuary, the landward limit of the Tay estuarine zone may literally begin at the uppermost limit of tidal intrusion. However, exact definition of the location of this uppermost limit of tidal intrusion is often confused with the limit of elevated water. Thus, the so-called 'tidal' effect is in fact the impact of buffering of river water on the intruding saltwater and not the limit of salt water intrusion. The actual estuarine head may be far below the extreme limit of the elevated water. During periods of moderate river discharge the tidal water elevation can be detected as far upstream as the mouth of the River Almond, located about 3 km above Perth and, in the case of Earn, about 4 km above Bridge of Earn.

Buller et al. (1971) and McManus (1972), however, provide a rather different location for the limit of the Tay estuarine zone. They practically defined the uppermost limit of the estuary as beginning at the confluence of the Rivers Tay and Earn, stretching seaward to a limit taken by a line drawn from Buddon Ness and Tentsmuir Point. Thus, these two extreme ends will provide a proper delimitation of the Tay Estuary, sometimes referred to as the 'estuary proper'.

Beginning at the uppermost section of the River Tay; between Perth and Balhepburn Island is known as the fluviatile sector, which varies between aggradation and degradation following artificial deepening in the mid-nineteenth century. Based on a survey chart produced for Perth harbour between 1986 to 1990 by the Tay Estuary Research Centre (McManus, 1993), the bottom topography of the fluviatile sector consists of an irregular series of deeps and shallows varying in depth from 1 to 3 m. However, from Balhepburn to Inchyra the bottom begins to level out and deepening again towards the Tay-Earn confluence. Beyond this point is where the estuary is physically defined and can be subdivided into four distinctive parts; the upper, upper middle, lower middle and lower reaches.

2.2.1 **Upper estuary**

The upper reach of the Tay Estuary, occupies the area between the Tay-Earn confluence and Balmerino. Between the confluence and Port Allen, bifurcation of waters occur to north and south of Mugdrum Island and this is a transitional zone between the fluviatile sector described above and the so-called estuary proper. This zone is largely one of erosion, characterised by the water cutting into clays and the bed is composed of boulders and pebbles, upon which fine flocculant muds will settle during still stand periods at high and low tide. The northern shore of the reach consists of a classic estuarine succession with marshes at or above high water. The mud-flat area decreases in height towards the southerly channel with sands in increasing proportions. In the main channel coarser sands migrate seawards along the channel bed and margins, often forming dune features.

2.2.2 **Upper middle estuary**

The upper middle reach occupies the area between Balmerino and the Tay Road Bridge. The reach is typified by the unstable migrating shoals of the Middle and Birkhill Banks.

2.2.3 **Lower middle estuary**

The lower middle reach starts from the Tay Road Bridge to a line drawn from Broughty Ferry Castle to Tayport. The estuary begins to narrow down to the east of Dundee and continues to narrow until at Tayport where it widens out to the North sea. Within the reach there contains sand waves form the Newcombe shoal. On the northern shore of this reach between Dundee and Broughty Ferry stands the Dundee harbour area. To the east, on the southern shore of lower middle estuary, is the Tayport harbour. Sands dominate the main channel with finer silts shoreward to each side (see Figure 2.9).

2.2.4 **Lower estuary**

The lower reach of the estuary, occupies the area from Broughty Ferry seawards and has a relatively stable channel. Along the channel are clays with boulders and also pebbles elsewhere. On the northern part, the Lady Bank is just off Monifieth, from where beaches and sand dunes extend to Buddon Ness. On the southern shore, sands extend to Tentsmuir Point. Shallow banks of the Gaa and Abertay Sands run seawards to north and south of the main channel to link across the bar which acts as a partial protecting barrier for the seaward end of the estuary channel from the wave activity of the North Sea.

Various research activities ranging from engineering to environmental aspects, have concentrated on studies which are associated and applicable only to each and individual reach. For example, Alizai and McManus (1980) concentrated their effort on estimating the rate of sediment being trapped within plant stems in the reed-lined coast of the upper estuary and produced an estimated figure for that area as 195 tonnes per year.

The existence of morphological features such as mud-flats, inter-tidal flats, sand banks, large and small scale ripples, and migratory channels in the upper and upper middle reaches are indications that the areas are undergoing some form of continuing changes. These may be considered very drastic from an engineering point of view. A study by Buller and McManus (1971), of the gross inter-comparison of bathymetric charts, covering the areas between 1816 and 1963, showed that the upper and upper middle reaches comprise both stable and unstable areas. The migration of sand banks and channels, if unchecked over a long period, may pose uncertainty for navigation in the area.

Similarly, in the lower reaches of the estuary right out to the open North Sea, many research workers have contributed towards the general understanding of the estuary. Charlton (1980), for example, investigated the exchange rate or flushing capability of the outer Tay Estuary using simple mathematical models, where the results showed that the exchange rate varies from 40% for a 2.5 m tide to almost 60% for 4 m tide, decreasing to between 50 - 55% for 5 m tide. The decrease in the exchange rate for the 5 m tide is explained by the greater volume of water flowing southwards over the Abertay Sands. The asymmetry of ebb and flood flow in the area, contributes to the high flushing rate through the estuary. Other studies reported have included those of the salinity distribution by Williams and West (1975), mathematical tidal modelling by Williams and Nassehi (1980), and applications of remote sensing techniques by Cracknell et al. (1987).

The seabed surrounding the Dundee harbour is also subject to changes related to the dynamic nature of the physical processes acting in the estuary. Therefore, the usefulness and benefit of all research undertaken, especially in the close proximity of the harbour areas, should be of interest to the port authority.

2.3 WATER CIRCULATION PATTERN

Within the Tay Estuary, the interaction of the river discharge with tidal water results in patterns of water circulation which play a major role in determining the deposition and erosion of the transported sediments. It is therefore necessary to describe the water movements within the estuary.

2.3.1 Tides and tidal level

For the Tay Estuary in general, the tidal characteristic of the area is of semi-diurnal type, with twice daily rise and fall of the tide and a tidal range of between 2.2m and 5m, during neap and spring tides, respectively. During flood tides, high water occurs first at the mouth of the estuary and progresses into the estuary with a speed roughly proportional to the square root of water depth. Distortion of the tidal range occurs as the tidal waves enters the estuary and is primarily controlled by three factors; (1) the variation of the cross-sectional area of each reach; (2) the rise and fall of the channel bed; (3) the fresh water inflow from the rivers.

Charlton et al. (1975) noted that, as the tide progresses upstream, it passes through the narrow constriction between Broughty Ferry and Tayport. Along this constriction, although the width of the channel is minimal, the cross-sectional area is found to be at its maximum. The increase in tidal range which begins upstream of Tayport (Figure 2.2) is induced by the reduction of the cross-sectional area and width of the channel. At and above Flisk there is a reduction in tidal range and at the same time an increase in mean

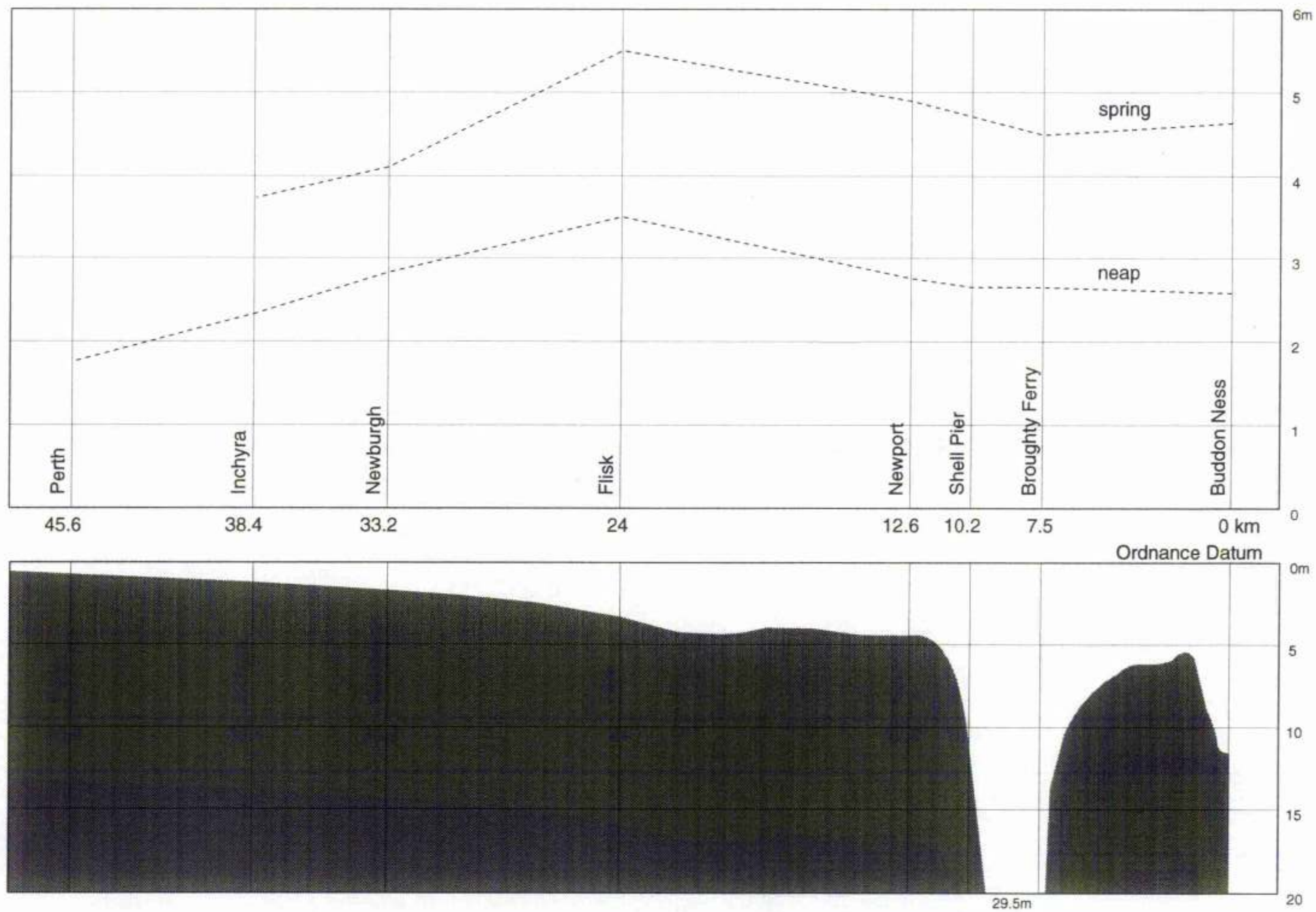


Figure 2.2. Tidal ranges (top) and longitudinal profile (bottom) along the Tay Estuary (after Charlton et al., 1975).

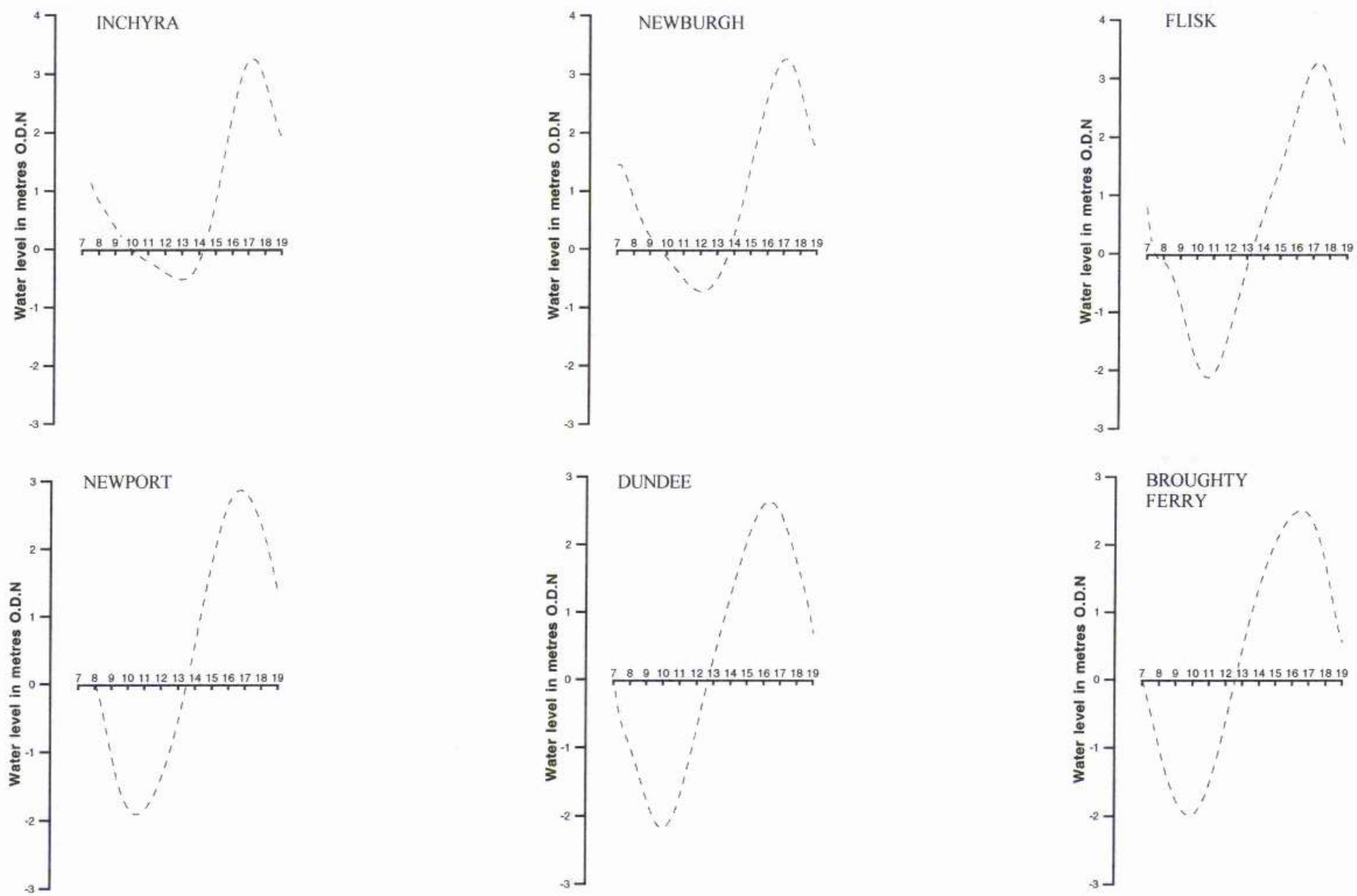


Figure 2.3. Tidal curves observed during spring tide at various sites along the Tay Estuary (after Buller et al., 1972).

water level due to a rise in bed elevation in the area (Figure 2.3). The tidal delay experienced between the two end limits of the estuary is of approximately 2 hours (Gunn and Yenigun, 1987).

The predictions of the times and heights of high and low water for the Port of Dundee are based on the analysis of the harmonic tidal constituents at Aberdeen, the nearest so-called standard port. The tidal constituents are derived from tidal records longer than the required period of 19.8 yrs (to include the influence of astronomical tides). This provides an accurate estimation of the lowest astronomical tide (LAT), i.e. a value which is crucial for the establishment of the Chart Datum level of an area.

2.3.2 **Tidal motion**

The tidal motion that influences the Tay Estuary is attributable to an amphidromic point situated about 60km off the southern Norwegian coast, as described by Proudman and Doodson (1924). During the flood tide, the south-westwards migrating tidal waves traverse across the mouth of the Tay Estuary, overspilling the Gaa Sands before branching into the main Tay channel and into St Andrews Bay (Figure 2.4). The south moving flood tides in St Andrews Bay then move in a clockwise direction forming a large eddy. It continues by spilling over the Abertay Sands and joins the main channel on its journey into the estuary. The flood flow travels through the narrow constriction between Tayport and Broughty Ferry, passing through the deepest part of the estuary (charted depth of 29.5m), concentrated mainly on the southern side. The flow then widens out and passes over Newcombe shoal. This is evidenced by standing undular waves west of the shoal. The flow is fairly evenly distributed between the channels as it passes between the bridges. As it reaches to the west of the Railway Bridge, it branches out into the southern and Kingoodie channels. Along Kingoodie channel, the flow

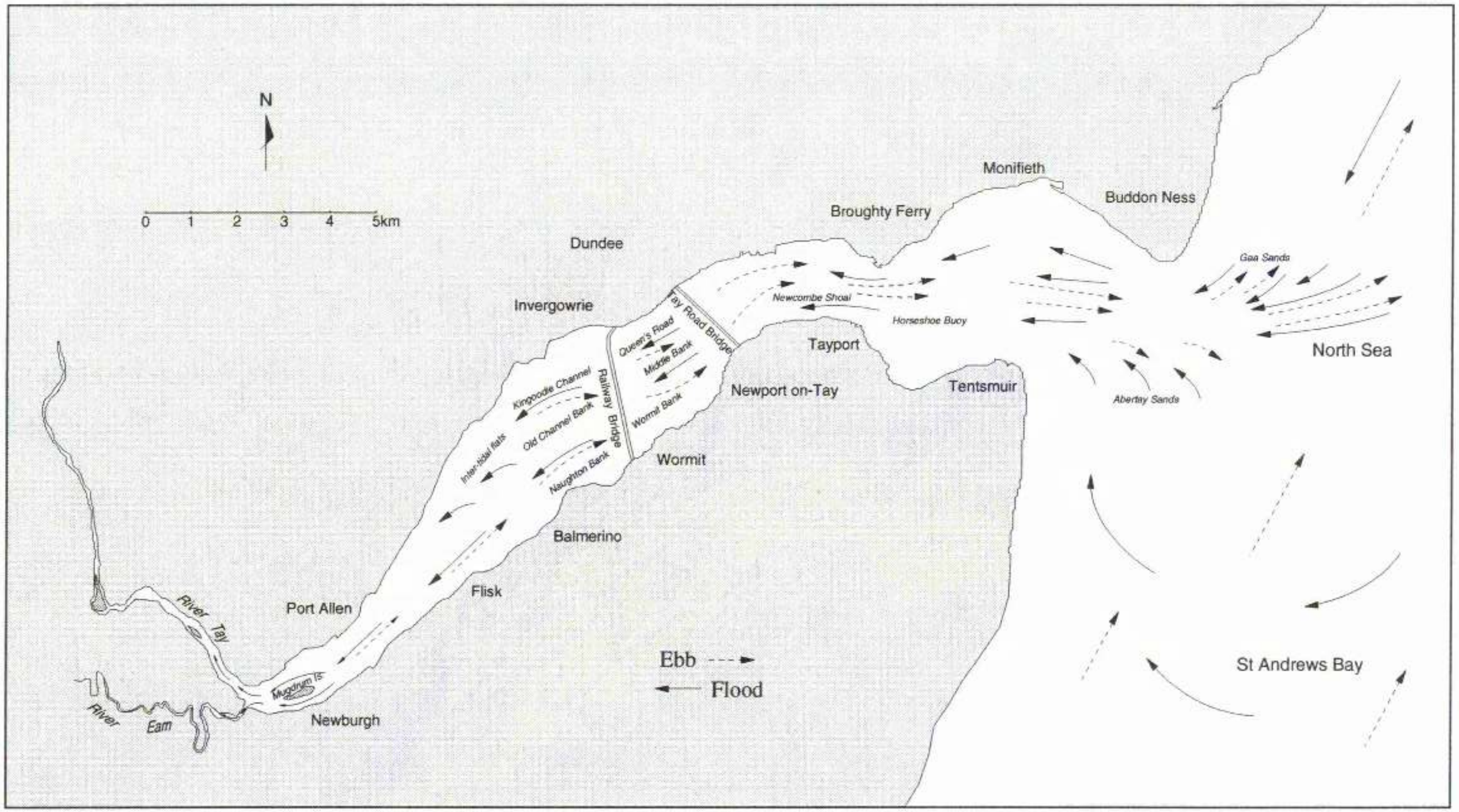


Figure 2.4. Water movements in the Tay Estuary during flood and ebb flows (after Charlton et al., 1975).

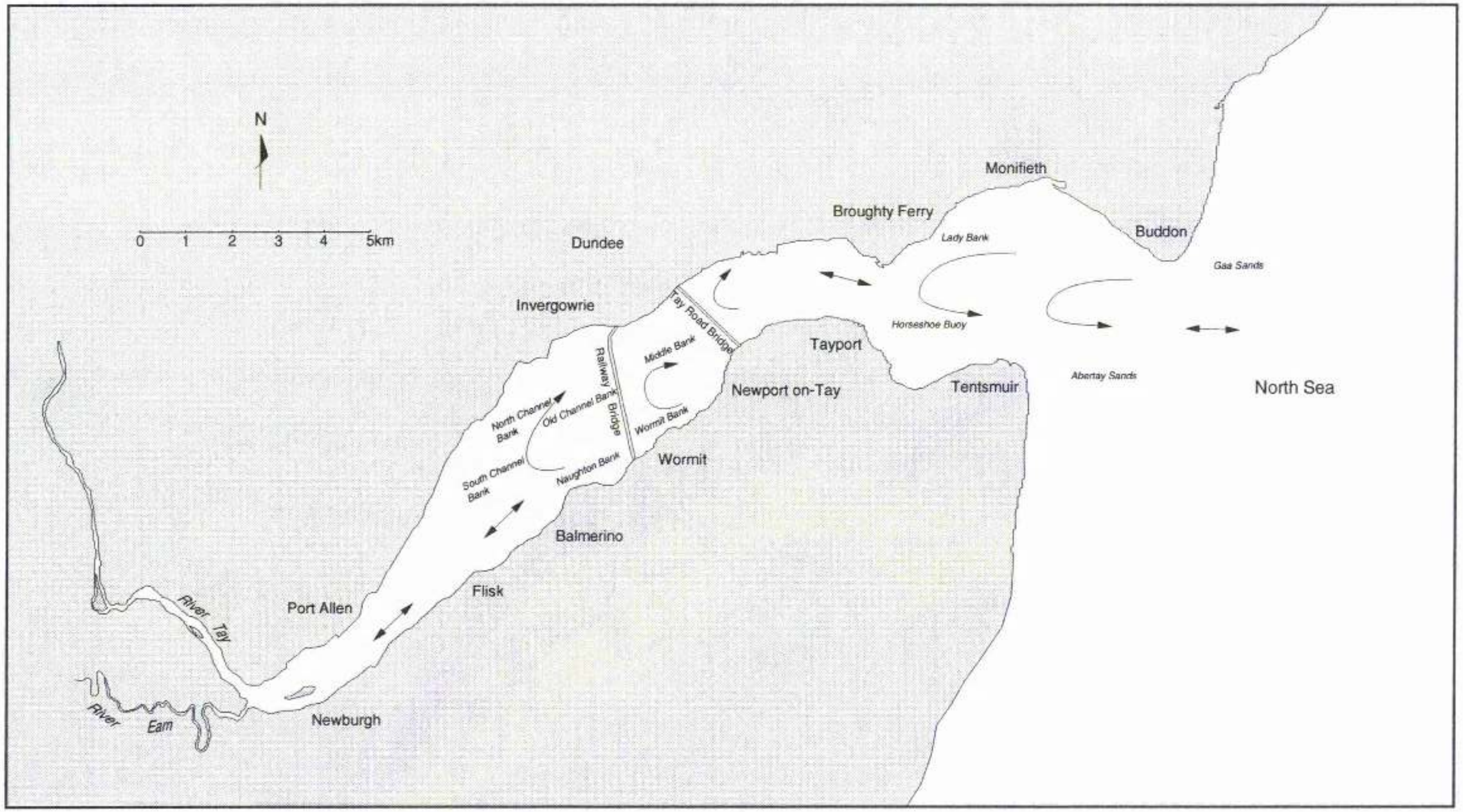


Figure 2.5. Eddy circulations occur in the Tay Estuary as the high tide begins to ebb (after Charlton et al., 1975).

spreads over the inter-tidal flats on the north side between the Railway Bridge and Newburgh. The flow from the south channel also spreads over the flats to the north. The final stage of the journey along the estuary is around Mugdrum Island and pushes upstream into the Tay and Earn river channels.

As the tide recedes, complex imbalances gradually build up throughout the estuary between residual dynamic energy in the main channel and opposing surface gradients resulting from tidal wave movement. As a result, there will be a series of major rotational eddy lenses developed at various locations, which normally last between 30 and 45 minutes before the full opposing tidal current becomes dominant (Figure 2.5).

The ebb flow draining off the flats tends to concentrate in the main channel, being stronger in the main southerly channel west of the Railway Bridge. Between the bridges, the main flow swings towards the south bank of Newport and heads through the Road Bridge in a more northerly direction towards Dundee and Broughty Ferry. The main flow travelling through the narrows between Tayport and Broughty Ferry tends to the north side and then back into the main channel off Monifieth Bay. A proportion of the flows spill over the Abertay and Gaa Sands and finally join the North Sea. The general water movement across the mouth during the ebb flow is in a northerly direction.

2.4 SOURCES OF SEDIMENT

Sediments entering the Tay Estuary may be derived either from a single source or from a combination of any of the following sources: fluvial, marine and marginal. However, a more detailed picture of sediment sources within the Tay Estuary is illustrated in Figure 2.6.

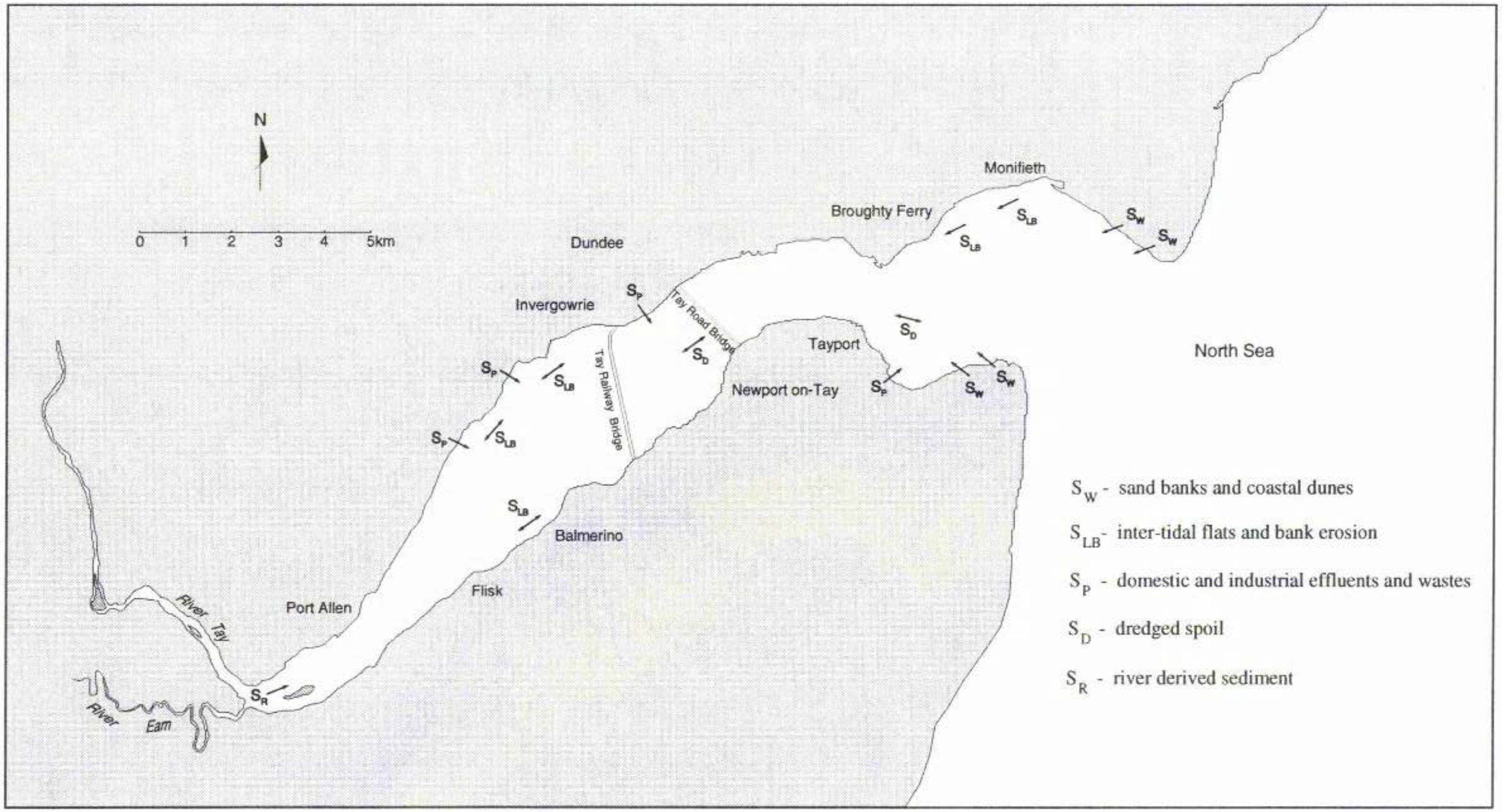


Figure 2.6. Sources and inferred directions of sediment into the Tay Estuary.

2.4.1 **Fluvial input** - (S_R)

Fluvial input of sediment into an estuary can be associated with river discharge. A study by Pontin and Reid (1975), based on the records of the years 1958 - 72, on freshwater input suggest that the Earn contributes approximately 16% and the Tay 84% of the total inflow. The daily average of suspended load carried by the Rivers Almond, Earn and Tay accounted for as much as 1.1, 11.5 and 90.8 tonnes/day respectively. However, the amount may increase to a total of 133.5 tonnes/day in winter and substantially decline to about 54.3 tonnes/day in summer.

2.4.2 **Marine input** - (S_W)

Marine sediment derived from the North Sea may enter the estuary by the agencies of wind generated waves and tidal currents. Strong wind blowing over the sand dunes at the mouth of the estuary may move particles into the main channel which enter the estuary by tidal currents. The effect of waves from the North Sea is largely filtered by sand bars at the entrance.

2.4.3 **Marginal input** (S_{LB}, S_P , S_D)

The sources of marginal input (S_{LB}) of sediments into the estuary are local erosion of cliffs, banks and shores. However, the quantity is negligible as only 8% out of the 40km shoreline shows active erosion (Al-Jabbari et al., 1980). To seaward of the Railway Bridge the input of material may come from industrial and municipal waste discharged (S_P) into the estuary (Reeves, 1994). These include crude sewage discharges via short outfalls from Invergowrie, Dundee, Monifieth and Newport/Wormit. Perhaps, some of the sediment (S_D) could be derived within the estuary itself, for instance, from resident estuarine sediment as in the case of dumped spoil from designated dumping sites (see

Table 6.1). The prevailing south-westerly winds may generate waves of up to 1 m in height within the estuary itself (McManus, 1968). Obviously, these can resuspend bed sediment in shallow areas, such as inter-tidal flats and sand banks.

2.5 DESCRIPTION OF SEDIMENT TYPES AND DISTRIBUTION

The sediments present in the Tay Estuary range from pebbles to very fine colloidal materials in suspension. The sediment load transported by the two rivers, the Tay and the Earn, consists of solid material and material in solution. On entering the estuary, the fluvially derived materials are eventually spread over the sandbanks and tidal flats from which the silt and mud fractions will be carried progressively down stream, where they accumulate and, in some cases, may create temporary or permanent deposition sites.

2.5.1 Classification of sediment type

Sediment is classified according to its particle size and there are many sediment classification systems available with slightly different scales expressed in either imperial or metric units. Wentworth (1922) advocated a metric scale and Krumbein (1934) introduced a logarithmic scale known as the Phi (Φ) scale which simply expressed the particle size as $\Phi = -\log_2 d$ (mm). Table 2.1 provides an example of the classification of sediment according to PIANC - the Permanent International Association of Navigation Congress which is meant for dredging (Oosterbaan, 1973). It contains six consecutive size classes: boulders, cobbles, gravel, sand, silt and clay. Clay has strong cohesive and plasticity properties while sand and coarser sediments are non-cohesive. Silt is the transistion between clay and sand, and is rarely found in isolation. Above the particle size of 2mm are gravels, which can be recognised in 3 grades: coarse, medium and fine. Cobbles and boulders are easily identifiable by visual examination and measurement. The size dividing cobbles from gravel is 64mm, 2mm between gravel and sand and 0.062mm between sand and silt.

Table 2.1. Sediment classification according to PIANC (Oosterbaan, 1973)

Sediment type		*Range of size (mm)*
Boulders	-	> 200
Cobbles	-	60 - 200
Gravels	Coarse	20 - 60
	Medium	6 - 20
	Fine	2 - 6
Sands	Coarse	0.6 - 2
	Medium	0.2 - 0.6
	Fine	0.06 - 0.2
Silts	Coarse	0.02 - 0.06
	Medium	0.006 - 0.02
	Fine	0.002 - 0.006
Clays	-	< 0.002

With regard to the sediment types and their distributions in the Tay Estuary, it is reasonable to believe that they have not changed to any great extent over the few last decades (McManus, per. comm.). The results obtained by previous workers are still considered as providing a good preliminary approach to the understanding of sediment types and distributions. The descriptions presented below will follow those of the previous workers to provide a macroscopic view of the sediment distributions and description.

Extensive sediment sampling which has involved analysis of over 2000 underwater and beach samples from throughout the entire estuary has been undertaken by Tay Estuary Research Centre groups between the years 1964 and 1978. Out of these, approximately 300 samples were used to describe the sediment types and distribution of the upper and upper-middle reaches of the Tay (Buller and McManus, 1975) and 1000 samples for the lower and outer reaches (McManus et al., 1980).

Table 2.2. Textural nomenclature for Tay sediments. (After Buller and McManus, 1975)

Doeglas (Md)	Phi (Md)	Wentworth (equivalent)	Q_1MdQ_3	Descriptions
5	4 - 5	Silt	-	-
4	3 - 4	Very fine sand	345	Poorly sorted very fine sand
			344	Well sorted very fine sand
3		Fine sand	334	
				Well sorted fine sand
			333	
			233	
				Well sorted medium to fine sand
2	1 - 2	Medium sand	222	
			124	
				Variably sorted coarse to medium sand
1	0 - 1	Coarse sand	111	
-1	-1 - 0	Very coarse sand		

Based on these samples, the above researchers constructed facies maps for the reaches based on the distribution of the sediment types grouped according to grain sizes in the form of Q_1MdQ_3 indices (Doeglas, 1971), with slight modification in the form of a system of textural nomenclature with an indication of sorting (Table 2.2). The parameter Q_1 is the value of the first quartile (25th percentile) of the grain size cumulative frequency curve, Md is the value of the 50th percentile, and Q_3 is the 75th percentile. For example, a sample with an index of 345 has a median of 4, which indicates 'very fine sand', and a quartile difference of 2 integer units which means 'poorly sorted' very fine sand. In a similar way, a sample with quartile difference of 0 and 1 represents a 'well sorted' sediment.

2.5.2 **Sediments of the upper and upper middle reaches**

The seabed materials of the upper and upper middle reaches of the estuary range from poorly sorted very fine sands to pebbles (Figure 2.7). The descriptions begin at the confluence of the Tay and Earn, where it appears that a band of variably sorted coarse to medium sand extends from the mouth of the River Earn towards the northern shore just north of Mugdrum Island, forming the floor of minor channels which encircle Kerewhip Island and finally joins the main channel east of Port Allen. The bed materials of the main channel in this area are mainly of boulders, pebbles and the Arctic Errol clay.

Inter-tidal flats dominate the section between Errol and Kingoodie. The inter-tidal flats descend gently towards the southern shore and consist of upper and lower flats. Above the flats are marshes colonised by *Phragmites*, growing on organic rich sediments, of dark coloured silts and clays. The upper flats are composed of poorly sorted very fine sand to well sorted fine sands. The lower flats, however, consist entirely of well sorted fine sand.

The main channel progresses close to the southern shore between Port Allen and Balmerino (Figure 2.8). The bathymetry of this area is characterised by elongated hollows and intervening saddles. The types of sediment and their distributions generally follow the bathymetric pattern. Between Birkhill and Balmerino, the main channel is lined with boulders, pebbles, compacted peats, and black and red consolidated clays.

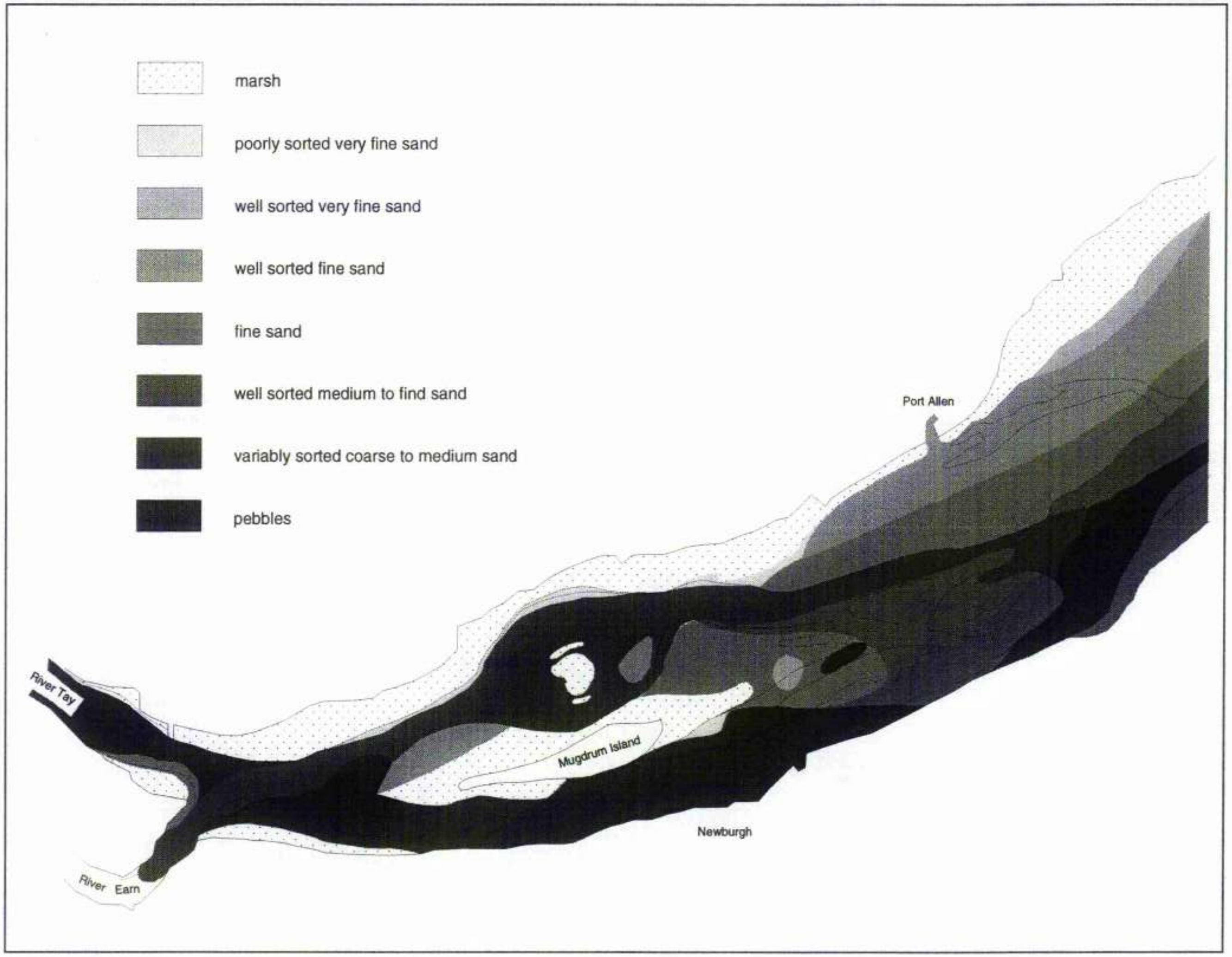


Figure 2.7. Sediment types and distribution of the upper reaches of the Tay Estuary (after Buller and McManus, 1975).

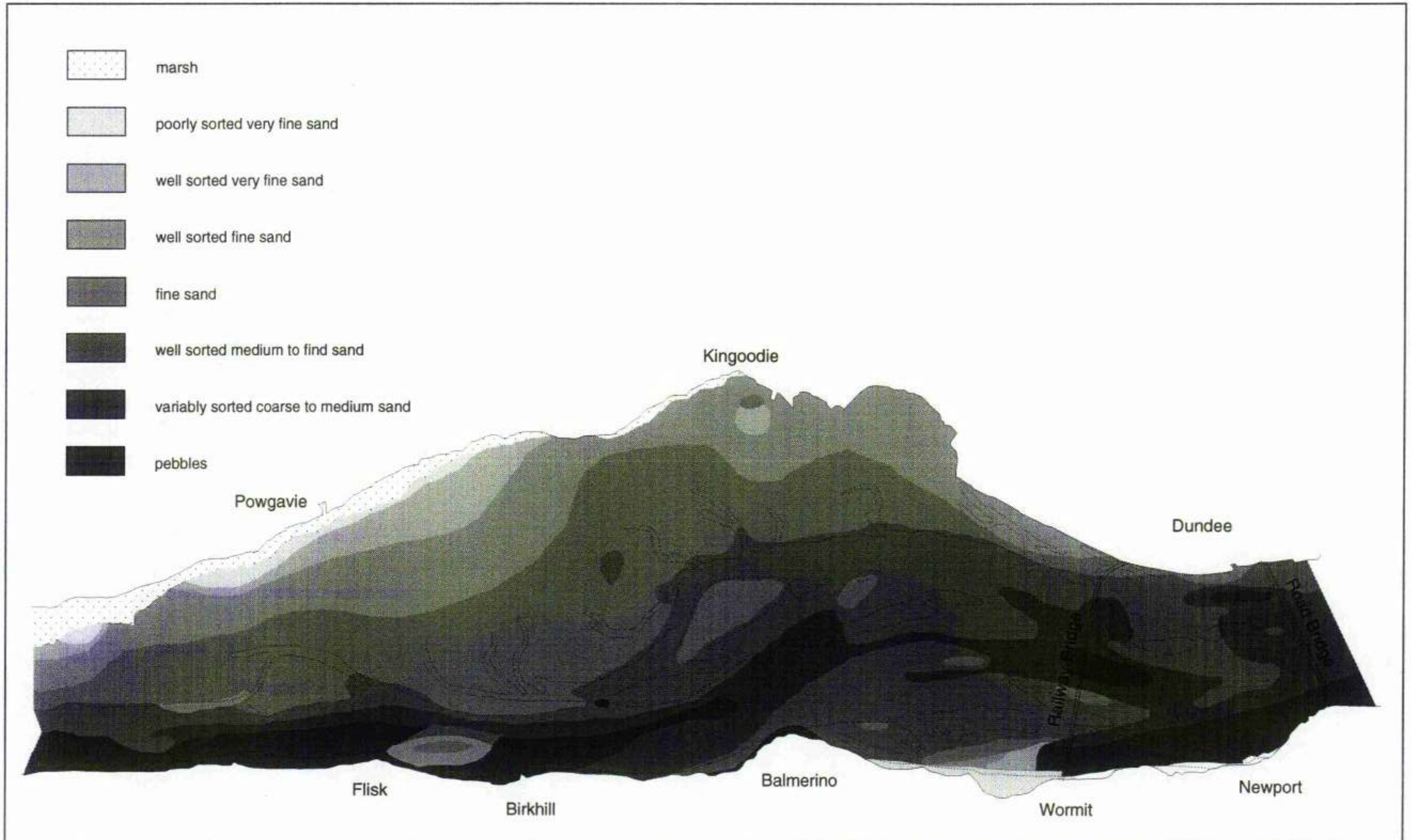


Figure 2.8. Sediment types and distribution of the upper and upper middle reaches of the Tay Estuary (after Buller and McManus, 1975).

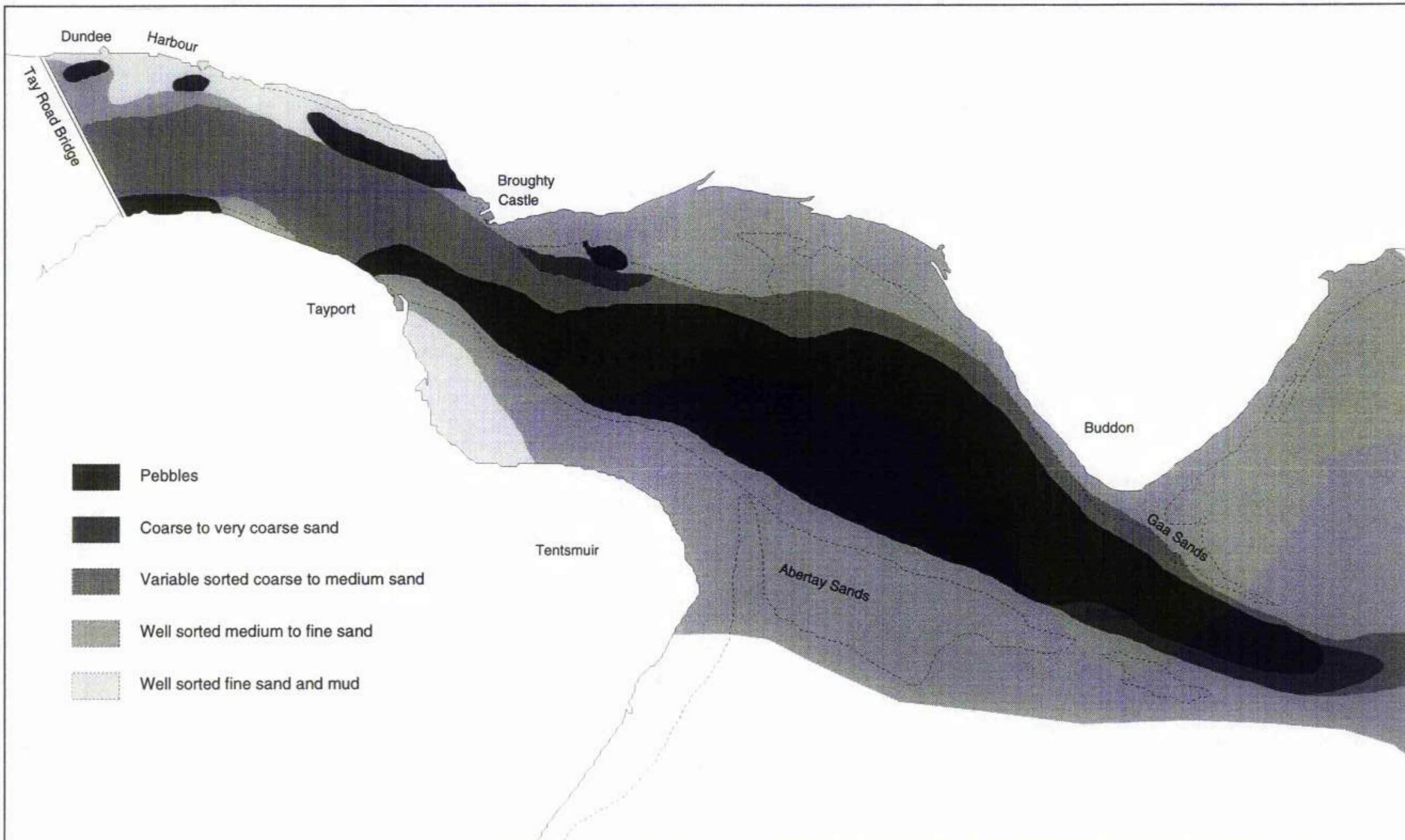


Figure 2.9. Sediment types and distribution in the lower middle and lower reaches of the Tay estuary (after McManus et al., 1980).

Between Balmerino and the Road Bridge is an area of complex bathymetry. The main channel curves gently towards the north of the Old Channel Bank and close to the Naughton and Wormit banks in the south, before passing underneath the Railway Bridge. Approximately beneath the Railway Bridge is the confluence of the main and Kingoodie channels. The bed is often irregularly over-deepened by scouring around the bridge piers, as shown from side-scan sonar surveys by Duck and Dow (1994). To the west of the Naughton channel is the Wormit channel which acts as the main channel north of Tayport. Between the bridges Middle Bank acts as a divider between the main channel and Queen's Road Channel. This area has been extremely unstable especially between Balmerino and the Railway Bridge (Buller and McManus, 1971). A pattern of coarse to medium sands occurs southwest of the Old Channel Bank and the southerly narrow zone begins to widen towards the confluence of the Kingoodie and main channels.

2.5.3 **Sediments of the lower and outer reaches**

On the northern shore between the Road bridge and Broughty Ferry, the estuarine bed is floored by silty sands to muddy deposits. The protruding andesitic rock masses of Beacon and Fowler rocks are lined with gravels and also recur off Broughty Ferry. Towards the beach near Broughty Ferry, the area is covered by pebbles and boulders that originated from cliffs of andesitic lava and volcaniclastic sediments (Figure 2.9).

On the southern shore, eastwards of the Road Bridge, irregular patches of sands and gravels are found which may be derived from erosional ridges and submarine ledges. The Newcombe shoal is formed of sandwaves and dunes of coarse to fine gravel and it is surrounded by fine sand and silts. The channel floor is, in general, largely of coarse and medium sand formed into dunes. The tidal flats between Tayport and Tentsmuir are floored by rippled sands, ranging from well sorted fine sand and mud in the west, to well sorted medium to fine sand in the east.

The embayment between Broughty Ferry, Monifieth and Buddon Ness (Monifieth Bay) is covered with patchy assemblages of sediments, pebbles, sands, and mussels. The Abertay and Gaa Sands form the borders of the main channel and are of medium to fine sand. The channel shallows as the two spit complexes join to form the bar.

2.6 SUMMARY & SYNTHESIS

The Tay Estuary has been generalised as a partially mixed estuary by Williams and West (1975), although it may change to well mixed estuarine characteristics in the event of high river discharge. The mixing of fresh and salt waters, in combination with the various physical and chemical processes, gives rise to complex sedimentological and biological environments. Within the estuary there exist imbalances and instabilities affecting the estuary floor which require continuous investigation, especially in areas such as the harbour. Changes which occur on the estuary bed are mainly attributable to two factors: natural processes and human intervention in the environment.

2.6.1 Natural instability

As the whole water mass in the estuary moves up and down according to the tidal periodicity, there exists a friction between the water and the bed. This results in turbulence which attacks fresh-salt water interface and this not only mixes water at the surface but also mixes fresher water downwards (Dyer, 1994). This causes a longitudinal gradient in salinity, diminishing towards the head of the estuary, both in the surface and bottom water layers.

A zone of high suspended sediment concentration, referred to as a turbidity maximum, develops at the head of the salt intrusion. It is a distintive feature of partially and well mixed estuaries. It is a combined effect of fresh and salt water mixing and, tidal and river discharge. Suspended sediment concentrations found in this zone will be higher than those up or further down the estuary.

Dobereiner (1982) has studied the turbidity maximum in the Tay Estuary and pointed out that suspended sediment concentrations of around 10 mg/l are normal under average tidal and river discharge conditions. However, the location of turbidity maximum may change with different river discharges and tidal ranges. During high river discharge (of 280 cumecs) at normal spring high tide (5.0m), the turbidity maximum (of about 35 mg/l) was found to be located between the Tay-Earn confluence and Balmerino. During the associated low tide, higher maximum concentrations (up to 84 mg/l) occur 1km west of the Railway Bridge. The peak concentration during high tide occurs in waters with 0-6‰ salinity while during low tide in waters with 0-8‰ salinity. Observations made during the highest spring tide (5.7m) with river discharge at slightly above the daily average ($210m^3s^{-1}$), revealed that values of suspended sediment concentrations, were similar to those measured with $280m^3s^{-1}$ river discharge, but peak values rose to 170mg/l and 220mg/l at low and high tides, respectively. The turbidity peaks occurred in salinities of between 0 to 5‰ at high water, and between 0 to 8‰ at low water. As before, the formation of the turbidity maximum is greater at low tide than at high tide.

Thus the effects of tides play an important role in the formation of the turbidity maximum. Perhaps, it is interesting to note that the location of turbidity maximum peak during the lowest spring tide occurred within the Dundee harbour area. Other observations made at low tide during high river flows ($370m^3s^{-1}$) showed the peak was situated between the Railway and Road Bridges. As river discharge decreases the peak moves landwards.

The formation of the various features found in the upper and upper middle parts of the estuary may be regarded as temporary storage sites for net and oscillatory sediment movements. At high tide, the intertidal flats are covered by a shallow layer of water. As the tide recedes, fine sediments on the upper tidal flats are brought into suspension by weak tidal flows. This situation can be severe, if superimposed by wind induced waves (Weir and McManus, 1987). The water passes over the lower tidal flats as the ebb continues and drains until the upper tidal flats are dry. As it flows, it erodes the banks of drainage runnels introducing dense clouds of fine grains into suspension. The suspensions are drained into the surface and mid-depth waters of the main channel as plumes. The turbid waters then continue downstream until ponded by the next incoming tides from the sea, while the upper estuarine water is still weakly ebbing. This creates a zone of high suspended sediment concentrations. The situation will later reverse during the flood tide as the tidal wave progresses upstream. As the volume of tidal water increases it is progressively diluted and disperses the concentrations throughout the entire cross-sectional area. These processes of aggradation and degradation generate the various bedforms found in the estuary.

During floods and freshets, the zone of turbidity maximum can migrate further downstream or even out of the estuary. The suspended materials may be transported or deposited all along the floor including the seafloor of the Dundee harbour area and along the adjacent main navigation channels. This can be inferred from the evidence of continuous dredging of the main channel by the Dundee Port Authority in between the Road Bridge and Broughty Ferry.

2.6.2 **Man-induced changes**

In addition to natural changes, the activities of man characterise the Tay Estuary, either within or near the Dundee harbour area, in the form of pollution, dredging and dumping of spoils. Dredging involves not only mass transfer of sediment but, at the same time, alters the shape of the estuary floor. Davies (1978) examines the situation of maintenance dredging in an estuarine environment and the possible impact of dredging is upon estuarine circulation.

Overdeepening may result in greater penetration of salt water and the transfer of the turbidity maxima to other parts of the estuary. Dredging may also act as a means of sediment sorting, with finer fractions being left behind through overspilling. This residual sediment takes the form of dense mud suspensions that can pose a problem in indentifying the actual bed level during bathymetric surveying. The substitution of fine for coarse fraction sediments may also provide a different channel equilibrium depth, possibly at a higher level than the original.

Within the middle and lower estuary there are three spoil dumping sites; one is close to Middle Bank just west of the Tay Road Bridge, the second is north east of Newcombe Shoal, and the third is on the western part of Lady Bank. The harmful effect of spoil dumping in the vicinity of an area is often dictated by its time-scale response and remains unknown unless some form of monitoring or investigation is initiated.

'Traps' to sediment motion within the Tay-Earn system have caused substantial quantities of sediment to be deposited in lochs since the last glaciation ceased (Al-Ansari, 1976; Al-Jabbari, 1978; Al-Kazwini, 1981). The material has failed, therefore, to reach the estuary or the North Sea. The effect of hydro-electric schemes: the Tummel Valley and Breadalbane schemes, on flood control is acknowledged but, at the same time, trapping of sediment has also occured. In the lower courses of the major tributaries to the Isla and Earn Rivers in Strathmore and Strathearn, vertical and lateral accretion occur in their extensive floodplains.

It is interesting to note that the mineralogy of the sediments found along the River Earn is almost identical to that of the upper middle estuary (Mishra, 1969) and this brings forward an hypothesis that the Earn supplies most of the present day sands to the estuary, whereas the Tay probably supplies the greatest quantities of suspended sediment. Added to this, is another interesting finding by Al-Dabbas and McManus (1987) who suggest that North Sea derived sands have entered the estuary and accumulated on the upper estuarine tidal flats. It would be no suprise if some of these sediments contributed to the deposits found in the Dundee harbour area, a factor which merits investigation.

CHAPTER 3

BATHYMETRIC DATA SAMPLING AND ACQUISITION

3.1 INTRODUCTION

Mapping of the seabed topography in strategic areas such as in ports and harbours requires accurate and efficient data acquisition. Such surveys may be both expensive and time consuming, and this is especially so if the area has a shallow depth and if small changes in depth are critical. For some ports and harbours, the port authority has the responsibility for surveying and charting the area. The data are normally made available to the Hydrographic Office (HO) for the production of new charts or the updating of old charts and nautical publications. In the conduct of such surveys, it may be necessary to follow certain guidelines or conform to standards as specified by regulating bodies such as the Royal Institution of Chartered Surveyors (RICS, 1983; 1984) or, alternatively, to internationally accepted standards as set out by the International Hydrographic Organisation (IHO)/International Federation of Surveyors (FIG, 1994). The rationale in following these recognised guidelines or standards is to ensure uniformity, systematic and professional conduct of the task, in order to guarantee the reliability of the gathered data. Bathymetric surveys not conducted in accordance to guidelines or standards may be unsuitable or unfit for port and harbour applications. There are considerable risks and financial consequences associated with inaccurate or incomplete surveys which can prove to be even more expensive if a survey has to be repeated.

This chapter will examine both theoretical and practical considerations of sampling and acquisition of bathymetric data and, aims to provide an appreciation and assessment of its merits and limitations. This is especially important when one intends to use such data for accurate evaluation of seabed bathymetric changes. The account of the terminology, methods of acquisition, use of automated survey systems for speed and efficiency of data acquisition, and the attainable accuracy of data are all put into perspective to assess the suitability of a newly gathered, or already available, data set for the study of seabed changes.

In simple terms, bathymetric surveying is a methodical sampling of the underwater topography or relief of an area of seabed by carrying out simultaneous measurements of depth (z) and position (x,y). The generic term seabed topography or relief is used throughout this thesis to refer to the bottom of a tidal river, estuary or sea. The task of measuring seabed topography therefore entails not only measurements of depth and position of the survey vessel (known as sounding), but also the recording of tide levels.

Water depth is defined as the vertical distance between the surface and the seabed. In tidal waters the level of the water surface fluctuates according to the rise and fall of the tides. In this situation it is necessary to reduce the measured depth to a fixed reference plane known as a sounding datum, which can be defined as any arbitrary plane. Depth is reduced to a sounding datum by subtracting tidal height. For specific applications, such as for navigation purposes, a well defined datum known as Chart Datum is adopted. The definitions of Chart Datum and other reference levels and that of seabed will be addressed later in this chapter.

3.2 DEPTH MEASUREMENT AND ACCURACY

In moden bathymetric surveying, depths are normally measured by specialised equipment known as echo-sounders which may either be of analogue or digital type, or a combination of both. It is important to be aware of the capability of a modern hydrographic echo-sounder, as commonly used for bathymetric surveying, in order to assess its measuring accuracy.

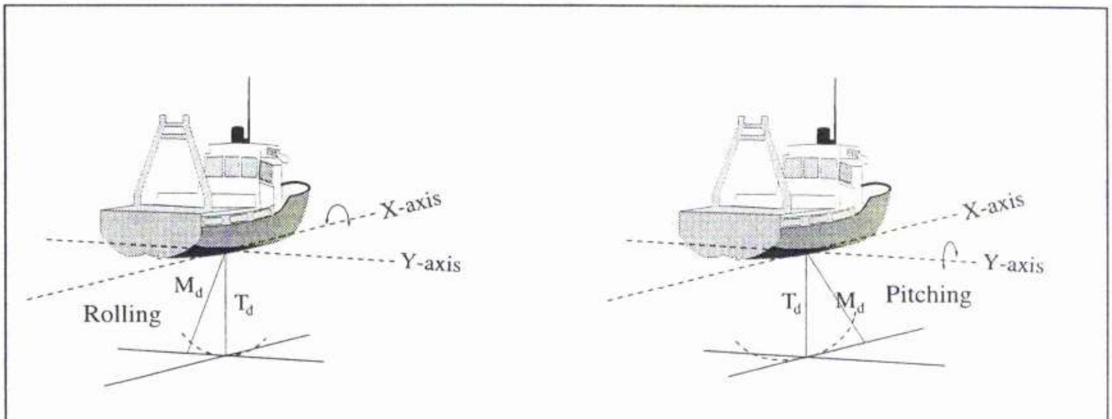


Figure 3.1. Vessel attitudes showing (a) rolling, (b) pitching and (c) heaving.

The theory and principles of depth measurement have been described in many textbooks on surveying and hydrography (e.g. Ingham, 1992; Milne, 1980; Clark, 1974). The concept of an echo-sounder is based on electrical energy being converted to acoustic energy which is transmitted and received via a transducer. The time (t) taken for the acoustic pulse to travel to and from the seabed (the two-way travel time) is measured and if the velocity of propagation in the medium (c) is known then the depth T_d can be calculated as $\frac{ct}{2}$ and displayed in either numerical form or graphically as an echogram.

3.2.1 **Unresolved factors**

Despite advances in technology there are factors that remain unresolved pertaining to achieving accurate depth measurement. Even today's modern hydrographic echo-sounders are influenced by the combination of operating from a moving survey vessel and the effect of sea state. These factors will be discussed under the following headings:

(i) uncertainty in vertical depth due to vessel motion

(ii) masking of seabed anomaly by instrument resolution

(iii) depth sampling accuracy

(iv) others (such as calibration, squat etc.)

The uncertainty in vertical depth due to vessel motion is related to the attitude of the transducer that transmits and receives the acoustic signal and which is normally attached to the side of the hull or underneath the vessel. As the vessel moves, it may subject to rolling, pitching and to some extent heaving, as survey work does not always take place in calm water. Under these conditions the transducer will no longer be directed vertical to the seabed. As illustrated in Figure 3.1(a), rolling occurs perpendicular to the vessel track causing the transducer to swing to the left and right causing the slant-depth (M_d) to be measured instead of the true depth (T_d). On the other hand, pitching is a movement along the y-axis, increasing from zero at the centre of gravity to a maximum at the bow and stern (Figure 3.1b). The whole vessel may also move vertically in response to wave motion, especially in the presence of long period sea swell, and this gives rise to heave (Figure 3.1c). The combination of roll, pitch and heave causes the seabed to appear 'wavy' and 'jagged' on a echogram and this can easily be mistaken for sand waves. It is often difficult to detect the effects of roll, pitch and heave in the survey records. However, echograms revealing the presence of a systematic rise and fall of the seabed may provide an indication of vessel movement.

An explicit means to minimise the effects of vessel motion on survey data is by using a heave compensator and inertial measurement unit (IMU). These devices use accelerometers to sense the vertical and lateral movements and correct the seabed level on echograms for these effects. A mathematical treatment of such sensors is considered in detailed by Luscombe (1994).

Table 3.1. Diameters (m) of insonified areas covered by the various beamwidths at varying depths

Beam width	5m	10m	15m	20m	25m	30m
2°	0.174	0.349	0.523	0.698	0.873	1.047
4°	0.349	0.698	1.047	1.397	1.746	2.095
6°	0.524	1.048	1.572	2.096	2.620	3.144
8°	0.699	1.399	2.098	2.797	3.496	4.196
10°	0.875	1.750	2.625	3.500	4.374	5.249
12°	1.051	2.102	3.153	4.204	5.255	6.306

Although modern digital echo-sounders operate in conjunction with a heave compensator or inertial measurement unit to minimise the effects of roll/pitch and heave, it may still not be simple and straight forward to achieve high accuracy depth measurements. During transmission, the sonar energy will be concentrated into a beam which is transmitted in the form of a cone (Figure 3.2a). The shape and size of the cone will depend on the water depth and transducer beamwidth used (Table 3.1).

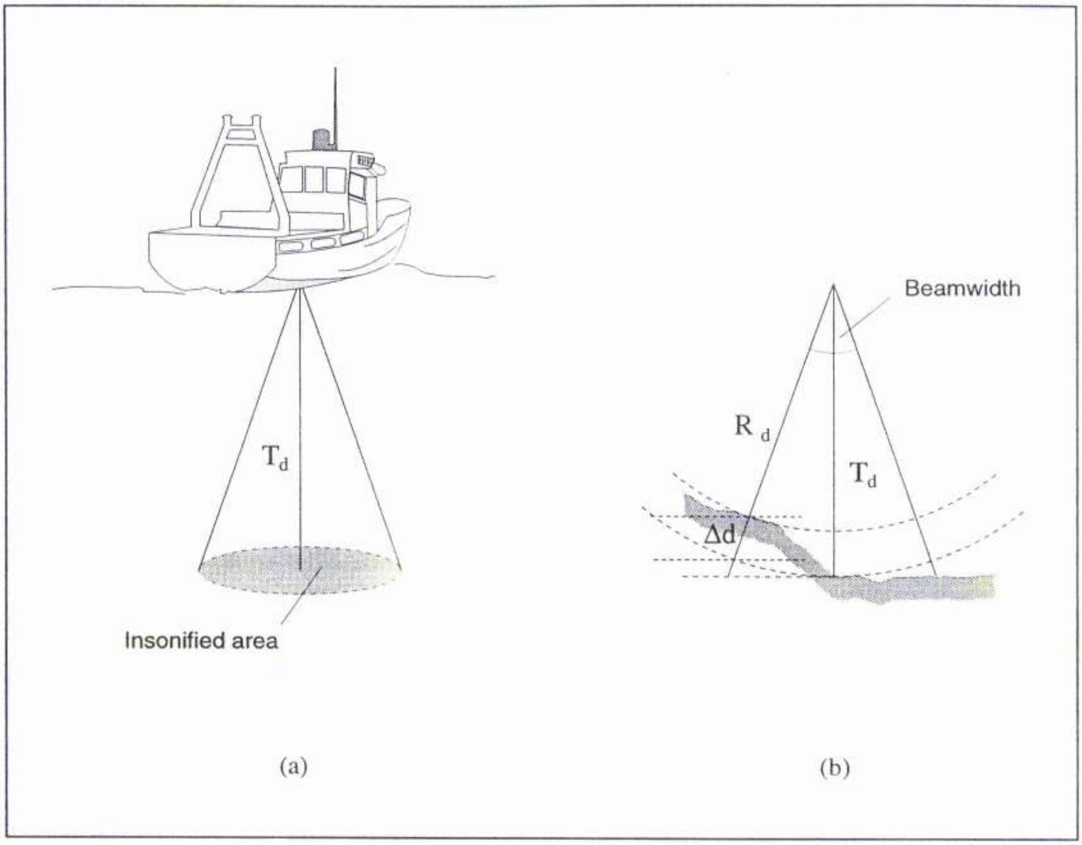


Figure 3.2 (a) Footprint or insonified area covered by sonar beam and (b) a simple error geometry showing the effect of first return signal from seabed.

Most survey echo-sounders operate at a frequency of between 30 and 200kHz with a beamwidth selected between 7° and 12°. The wider the beamwidth the larger will be the footprint or insonified area (Table 3.1). A wide beamwidth may result in uncertainty by the masking of seabed anomalies. This can be explained by the fact that the first signal returned from the seabed will be recorded as the depth and it is always the case that the first signal returned will be via the shortest path taken. As shown in Figure 3.2(b) the slant path (R_d) is recorded instead of the direct path (T_d) which is the true depth, thus causing a small error in the measured depth (Δd). The masking of seabed anomalies is primarily as a result of the generalisation of depth by the cone and the greater the beam width the larger will be the discrepancy. Consequently, over an undulating surface, a slightly shallower depth is often recorded (Figure 3.3).

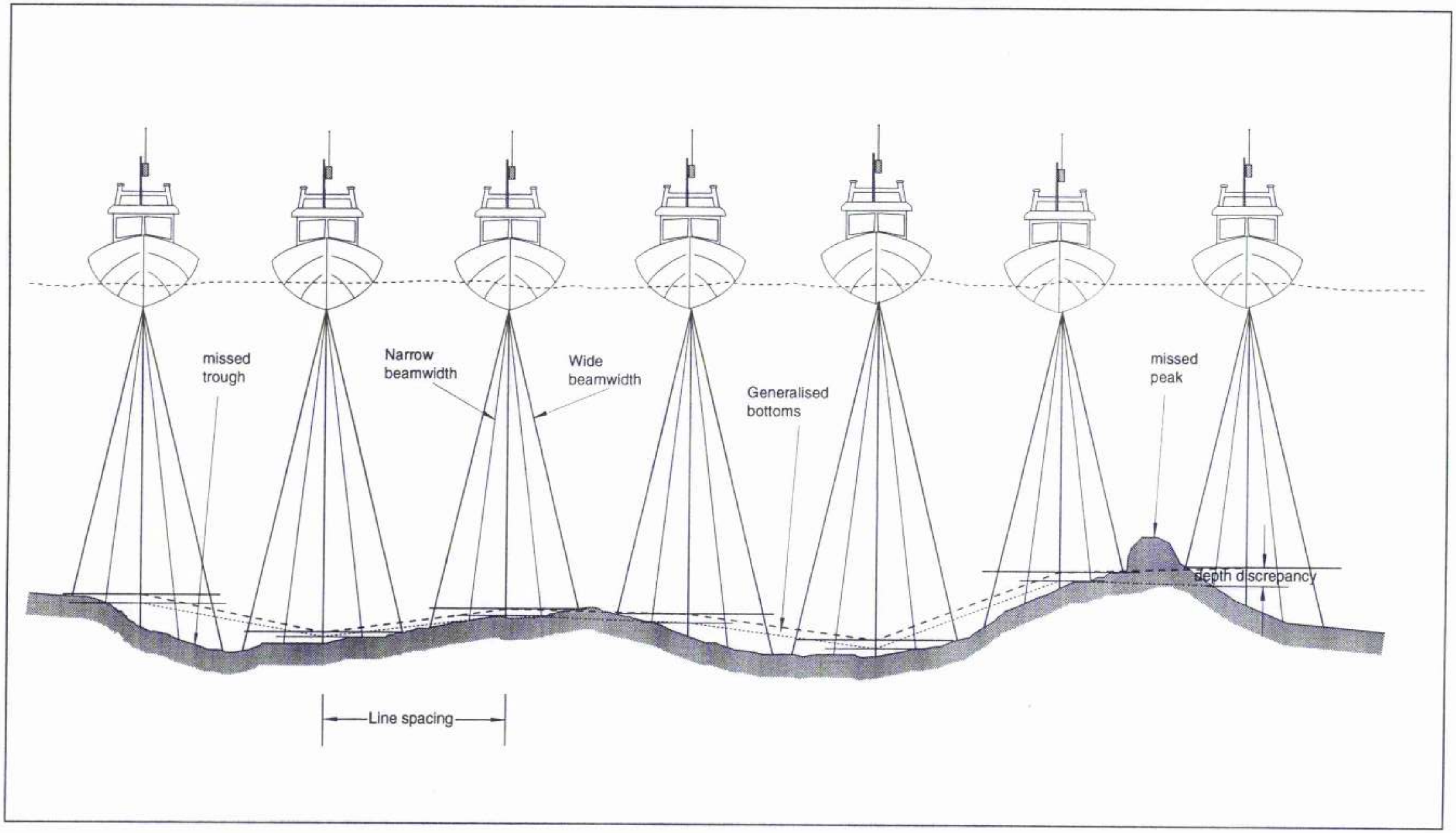


Figure 3.3. Generalisation of bottom profiles due to beamwidth.

A modern digital echo-sounder permits a higher depth sampling rate per second. Although this significantly improves the depth sampling accuracy, it poses the problem of choosing which single depth should represent the group of depths taken in the period of one second, commensurate with chart scale. For example, a sampling rate of 10 depths per second at a vessel speed of 4 knots (which is approximately 2 metres per second) will permit the echo-sounder to sample at least 5 depths per metre travelled. If the plotting scale of the chart is 1:1250 then there will be 1.25 X 5, or at least 6, depths logged for every millimetre of the chart. If say, the depth figure to be shown on the chart is 3mm in size, with free spacing around it of 0.5mm, every depth figure printed on the chart will representing 4 X 6 = 24 measured depths. This is a typical example of the problem of depth sampling using a modern digital echo-sounder when trying to reduce uncertainty and improve accuracy by sampling more depths.

A micro-processor is often incorporated within the echo-sounder to automatically perform the depth selection. However, for much better and accurate results, raw data should be logged while surveying and later a post-processing procedure is undertaken to select depths for ultimate display or output. The method of automated depth selection can vary from simple averaging to a very sophisticated method such as one described by Brouwer (1976). His method ensures a measured depth is only selected in its real position and no averaging or mean value is used.

Another possible method, but less rigorous, is by matching depth and position through time-tagging. During logging, every depth (z) and position (x,y) is separately time-tagged to the nearest 0.01 sec. Later, at the post processing stage, a simple post-processing computer program is used to match the depths with their corresponding positions based on time-tagging as a reference. Obviously, storing the abundant data in this format is an advantage for future use.

A further factor to be considered, is the variation in sound velocity due to differing salinity layers in the survey area. This, however, can be readily overcome through proper and regular calibration of the echo-sounder especially before, during and after a day's work.

A phenomenon, often ignored during a bathymetric survey, is the effect of vessel squat. When the vessel moves through water it pushes water ahead and this volume of water must then be compensated by water returning down at the sides of the vessel and under the keel (Barrass, 1979). This causes a drop in pressure, resulting in a slight reduction in the draught of the vessel from the waterline of its static position. The effect of squat may vary according to the amount of load of the survey vessel. Notably, during the start of a survey, the vessel's fuel tank is filled up with fuel but may be half full or near empty towards the end of the day's work. Although the size of squat depends on the vessel's size, shape and the load it carries, it has to be seriously considered if high accuracy depth measurements are expected. Detailed theory and investigation on ship squat is given in Barrass (1979) and the example of its effect on a ship when navigating over a muddy seabed is discussed by Vantorre and Coen (1989).

3.2.2 **Overall depth accuracy consideration**

Having discussed the attitudes of the transducer due to the motions of the survey vessel and the effect of the generalisation of seabed by the cone effect, it is worth considering next the net error one would anticipate in a depth measurement. The tolerance of depth measurement specified by international bodies such as the IHO/FIG, is 1% of depth greater than 30m and 30cm for less than 30m (IHO, 1987). Manufacturers of modern hydrographic echo-sounders usually supply technical information on the capability and accuracy of depth measuring of their equipment. According to an evaluation carried out by the British Port Federation (1987), on average the accuracy quoted by most manufacturers falls between 1 and 10cm in under 30m of water. Adding the effects of rolling, pitching and, to some extent, heaving together with the type of bottom material, it is reasonable to estimate that under normal circumstances, the expected accuracy of depth measurement will be between 20 and 30cm in under 30m of water. Higher standards of depth accuracy, of course, can be achieved if the position and attitude of the vessel can be resolved with a high degree of precision.

3.3 DETERMINATION OF POSITION AND ACCURACY

In parallel with the ever increasing demands for accurate depth measurement, there is also a similar demand for better positioning accuracy. This is the case, in particular for port and harbour surveys, where positioning accuracy of the sub-metre level is demanded. The use of automated land or satellite based systems for positioning has becoming ever increasing to meet the various stringent demands.

3.3.1 Land based positioning system

A land based system which is commonly used in port and harbour surveys is based on the range/bearing method. The system configuration for the range/bearing method may operate under any of three groups: manual, semi- and fully-automated range/bearing systems. A fully automated system consists of a distance measuring device using infra-red light or laser and a radiotelemetry unit placed at an onshore station. A passive reflector, portable computer (plus data acquisition and processing software), echo-sounder and a radiotelemetry unit are all installed on board the survey vessel (Figure 3.4a). The electronic distance measuring equipment (EDM) is interfaced with the radiotelemetry unit for the transfer of positional data to the computer on board the survey vessel. For example, the Geodimeter Model 140T, developed by a Swedish firm, Geotronics, is capable of self-tracking the reflector fixed to the survey vessel after it is

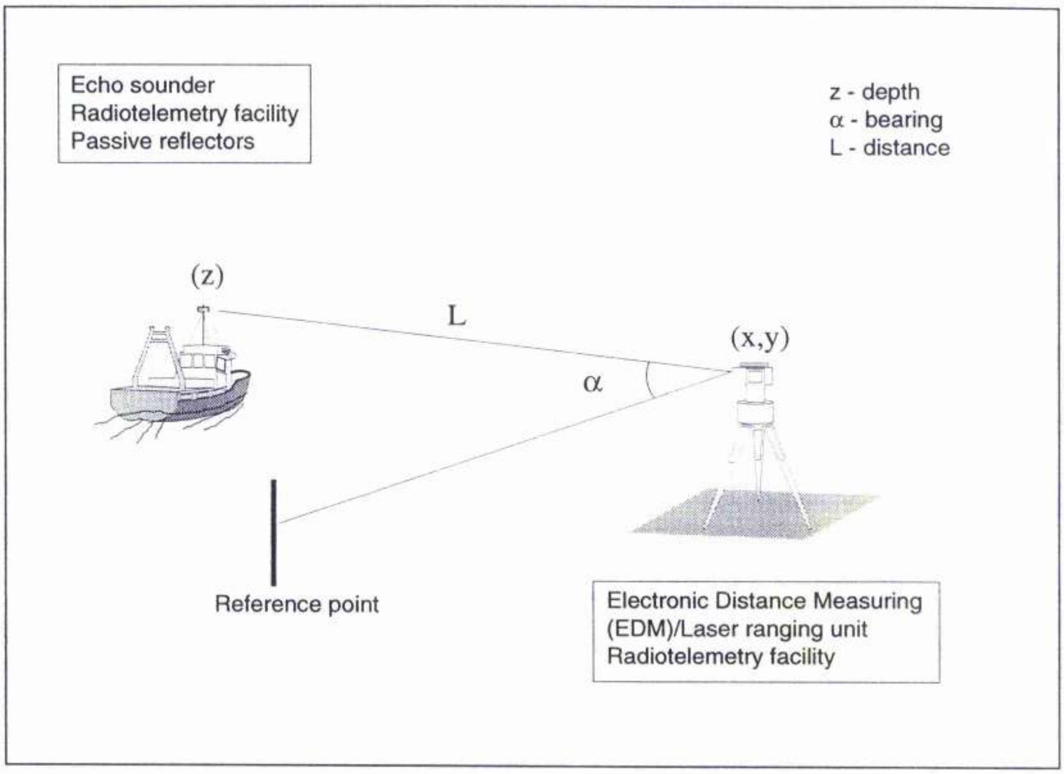


Figure 3.4(a) A range/bearing system configuration

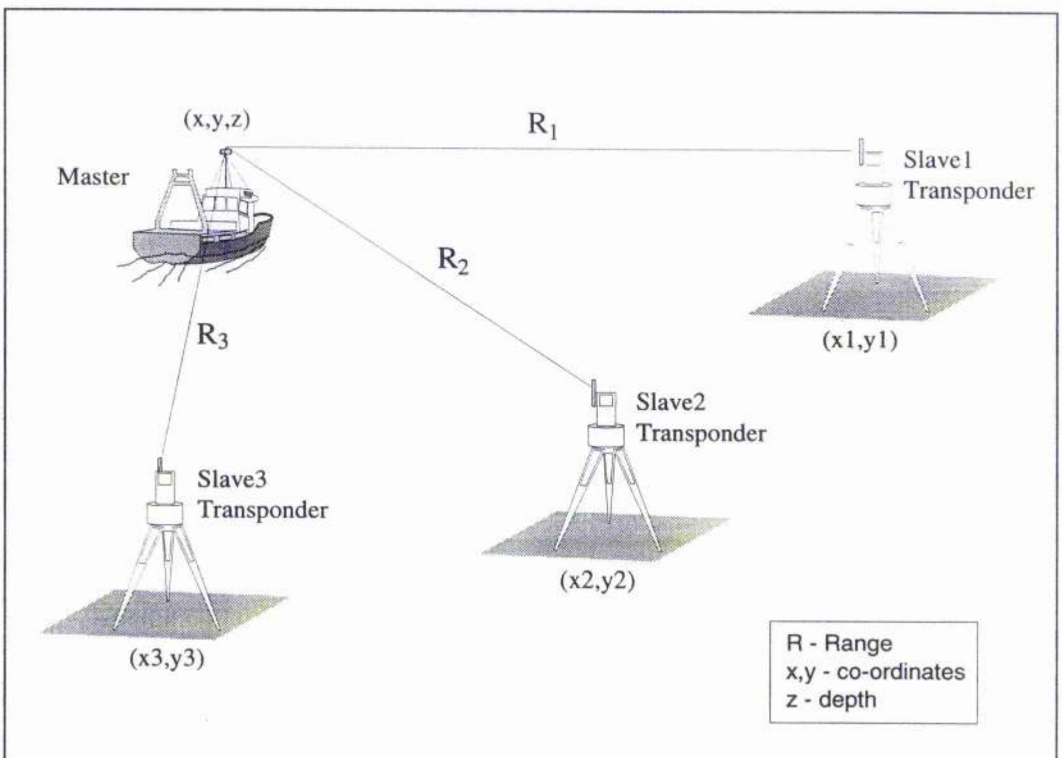


Figure 3.4(b) A range/range system configuration

locked on to and continuously measuring and transmitting the positional parameters of the vessel via the radiotelemetry link. In this way, the computer on board can display in real time the position of the vessel with respect to the pre-determined survey-lines. This will provide invaluable assistance for the helmsman to steer the vessel on the pre-determined courses for precise coverage of the survey area. In this way, there will be independent control of equipment both on shore and at sea. Another example is the use of a laser range bearing unit such as the Atlas Polarfix system whose dynamic accuracy is claimed to be about 0.2m per km of measured range over distances of up to 7km (Wentzell, 1987). For a semi-automated system, manual tracking by shore-based personnel using conventional electronic digital distance measuring equipment, instead of an automatic tracking type of EDM, is typical. Positional data of the survey vessel are transmitted from on shore to the survey vessel via radiotelemetry in a similar way to that of the fully automated system.

In manual range/bearing systems, however, data cannot or will not be transferred in real time to the computer on board. Therefore, co-ordination between personnel on shore and at sea is important. The shore-based personnel, with the positional data obtained, will be able to 'con' or direct the survey vessel to either 'left' or 'right' guiding the helmsman to steer on-line by the use of radio communication. Data recording on shore and on board are carried out separately and this, of course, requires highly experienced and well organised personnel.

Another form of land based system is the range/range system, which operates using microwaves. This system provides continuous positioning thus obviating the need for shore-based personnel to track the survey vessel. A range/range system configuration comprises a master and slave/remote units. The slave/remote units are positioned at known stations on shore and the master is on board the survey vessel. The master unit operates by simultaneously and continuously interrogating all the slave/remote units and each slave/remote unit will respond to the interrogation using individual identifiable codes, each unique to the individual unit. The master unit is then able to identify the individual ranges and the intersection of the position lines will be determined as the 'fix' or position of the survey vessel. At least two ranges or position lines are required to compute the vessel's position. For better accuracy, three or more slave/remote unit should be deployed over the survey area. An example of the range/range configuration is shown in schematic form in Figure 3.4(b). The system comprises transponders positioned at known shore stations with the digital distance measuring unit (DDMU) set on board the survey vessel. A micro-processor in the DDMU will compute ranges and co-ordinates of the vessel. A track guidance facility incorporated in the DDMU will display the position of the vessel with respect to the survey lines and off-track information. The helmsman then uses the information to help steer the vessel along the track lines.

In a fully automated system, a computer (plus hydrographic software) and data logger are housed into a single 'blackbox' unit where measurements coming from various sensors are integrated. Within this so-called 'blackbox' unit, rigorous processing of data using specialised software for the computation of fixes, prediction of position ahead by Kalman Filtering (Cross, 1990) and real time data visualisation are all made possible.

A common problem facing the users of range/range systems is the loss of signal, though the vessel is still within the line-of-sight of the shore stations, due to multipath or the 'range-hole' effect. The multipath effect is the phenomenon by which the received signal is composed of both direct transmission and reflection from the surface of the sea (Laurila, 1983). At a certain distance range the reflected wave will be 180° out of phase with the direct wave and thus this causes a partial cancellation of the transmission. Achievable accuracy using the range/range system is between 1 and 3m.

3.3.2 **Satellite based positioning system**

Sometimes it may not be possible to use conventional range/range or range/bearing systems effectively, for example in congested harbour areas where there are multiple ship movements that may complicate positioning of the survey vessel. An option is to use a Satellite based system such as the Differential Global Positioning System (DGPS).

Satellite based positioning means the determination of the absolute and relative co-ordinates of points on land or at sea by processing measurements to and from artificial earth satellites. Nowadays, satellite based positioning systems are increasingly being used, especially with the introduction of portable types of Differential Global Positioning System (DGPS). Figure 3.5 is a simple schematic diagram of a DGPS configuration, which comprises of a mobile unit and a stationary reference station. At both locations are GPS receivers that carry out pseudo-ranging or phase measurement. Pseudo-ranging is the term used when a satellite transmits a signal at known time and the time it reaches a receiver is measured. Phase measurement, however, is concerned with the phase of a signal received from a satellite combined with a knowledge of the total number of complete cycles between the satellite and receiver, thus leading to a distance computation (Langley, 1993). The reference receiver, in addition, computes pseudo-range corrections for all the available satellites and sends the corrections from the reference station to the mobile station via radio communication (V.H.F or U.H.F). In this way real time co-ordinates of the mobile station can be determined to a very precise level (to sub-metre level).

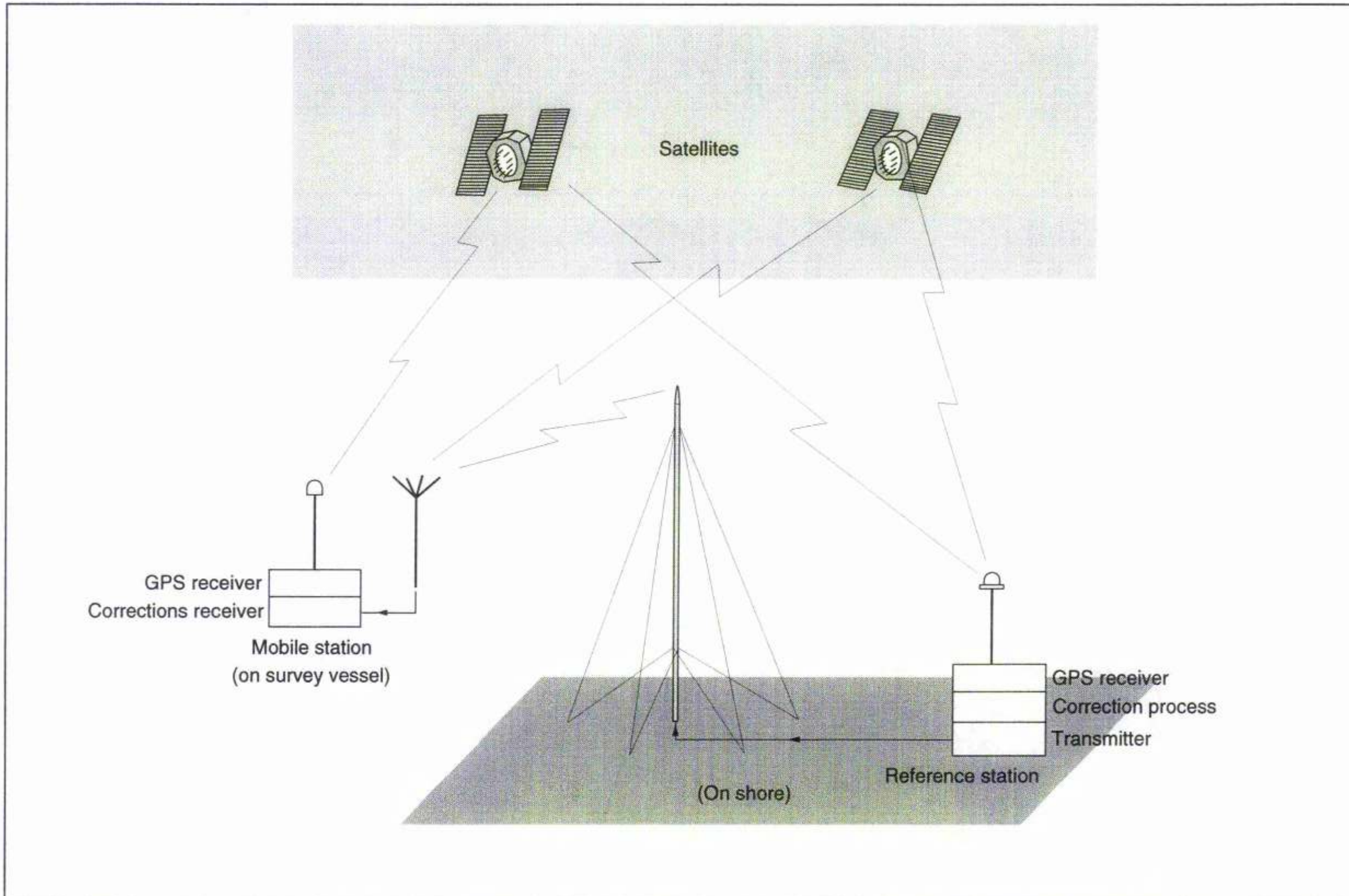


Figure 3.5 A simple Differential Global Positioning System configuration.

Examples of DGPS models commonly used in hydrography are Sercel, Trimble and Magnavox systems. The detailed theory and principle of GPS/DGPS systems can be found in various sources on satellite positioning (Neil and Robert, 1994; Leick, 1995).

3.4 TIDAL OBSERVATION

As the survey vessel moves up and down with the rise and fall of the tides, it is necessary to carry out tidal observation during the survey. In manual operation, an observer is required to read the tide level at regular intervals, for example at every 30 minutes. The accuracy of reading is to within 10cm.

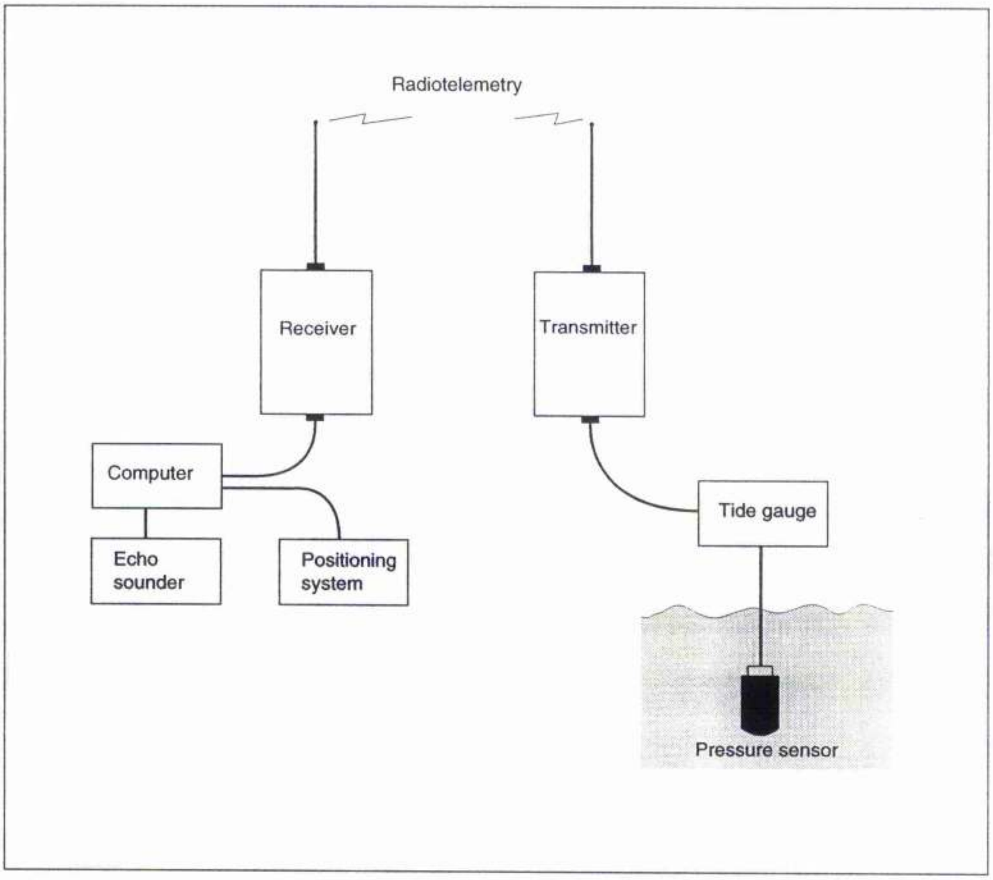


Figure 3.6. A schematic diagram of an automated survey system incorporating a radio tide gauge

The use of an automated radio tide gauge, however, will enable continuous recording of tidal heights at high resolution (to the nearest centimetre) and enable real time access to tidal data by radiotelemetry link to the computer on board the survey vessel. Figure 3.6 is an illustration of an automated survey system incorporating a radio tide gauge.

3.5 THE REFERENCE PLANE

Tidal datums are fundamental bases to which not only soundings can be reduced, but they are also needed for the depiction of shorelines on charts. There are various definitions of water level and these are depicted in Figure 3.7. Detailed description of each level can be found in Hicks (1986). However, most important of all are the reference planes that are used as bases for bathymetric data: Chart Datum and Mean Sea Level. These will be described in the following sections:

3.5.1 Chart Datum

All depth information shown in navigation charts are referred to Chart Datum. A Chart Datum for an area is taken as the lowest water level ever observed over the area so that there will rarely be less water than is shown on the chart. All depths that refer to Chart Datum are known as charted depths. They can be either positive or negative. Positive values indicate that there is water overlying the bed, while negative values represented by a 'bar' on top or below the depth figure, are drying heights. This important depth symbol is useful in navigation, especially to determine enough under-keel clearance and to avoid hazardous grounding of ships.

The predicted tidal heights shown in Tide Tables are also referred to Chart Datum and this makes it possible to estimate at any time the instantaneous water depth of a point

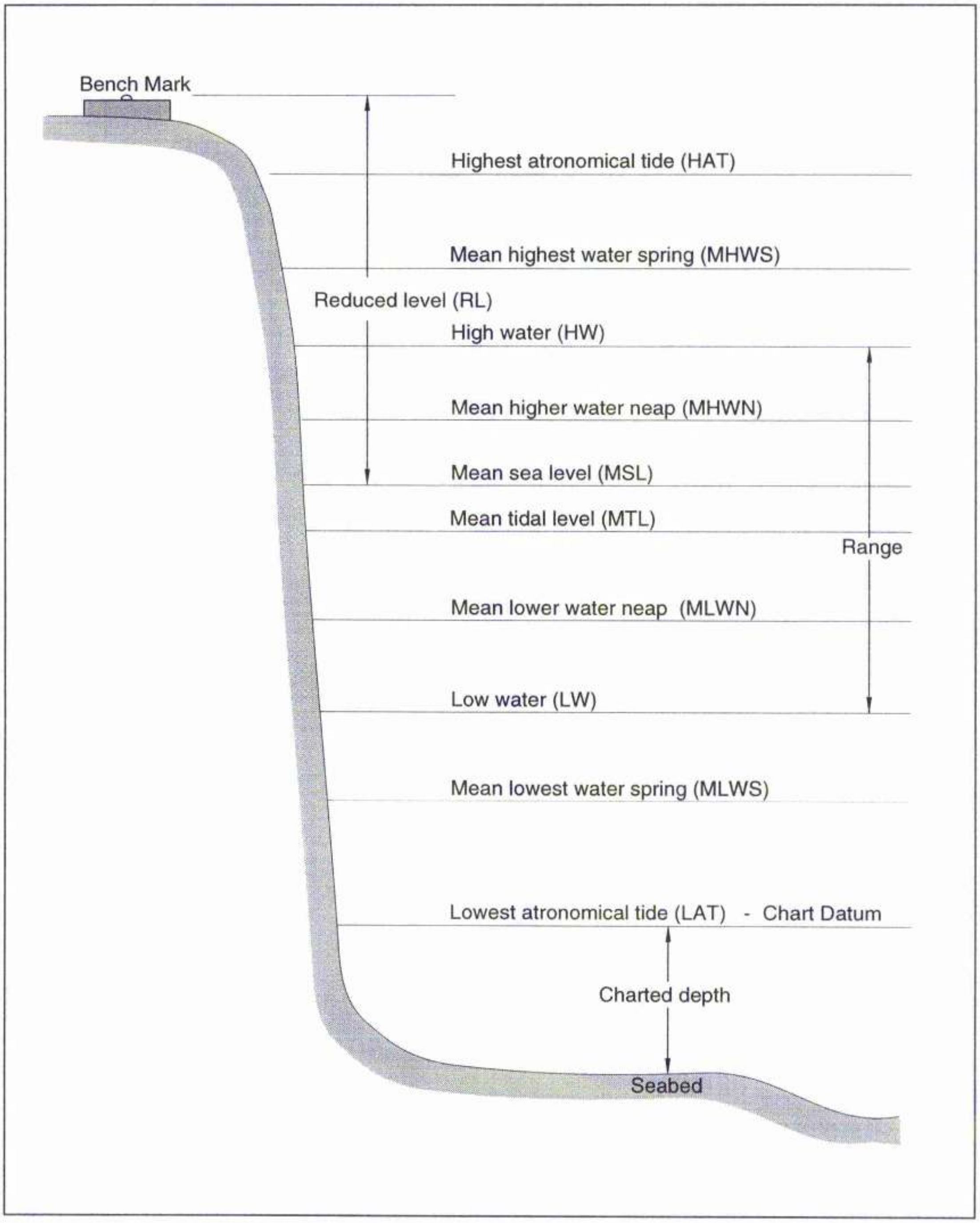


Figure 3.7 Relationships between the various water levels

in the charted area. Information on predicted tides are shown in Tide Tables. Those of the United Kingdom, for example, are published by the British Admiralty/Hydrographic Office (HO) and calculated at the Institute of Oceanographic Sciences Office (Bidston).

Over a long and narrow estuary, like the Tay Estuary, several Chart Datums that vary in steps have to be established to accommodate the longitudinal gradient of water level. According to the information shown on the chart of the upper Tay Estuary, published by the Tay Estuary Research Centre (1988), beginning at Dundee harbour the Chart Datum of the area is 2.90m below O.D. and this gradually decreases westwards to Perth harbour where the value of Chart Datum coincides with Ordnance Datum (Table 3.2).

Table 3.2. Chart Datum values and tidal information along the Tay Estuary.

Place	Distance (m) below O.D	Tidal delay	Tidal Amplitude (m)
Dundee harbour	2.90	0^h 00^m	5.0
Flisk Point	2.32	0^h 20^m	5.4
Newburgh Quay	1.00	0^h 30^m	4.2
Inchyra Pier	0.50	0^h 40^m	3.8
Perth harbour	0.00	0^h 50^m	3.6
Bridge of Earn	0.00	1^h 15^m	2.5

3.5.2 **Mean Sea Level**

The value of Chart Datum for an area may remain fixed for an indefinite period, as long as it is deemed fit to express the water depth of the area relative to it. However, it might not be suitable as a reference level for engineering applications, such as numerical modelling, construction of marine structures and land reclamation works. This is because sea level may change over a period of years and, to accommodate these changes, M.S.L is used instead. M.S.L can be specified as: monthly mean sea level and yearly mean sea level, which are the arithmetic means of monthly and yearly heights, respectively.

From a scientific point of view, M.S.L is a value that denotes a level of an equipotential surface (Heiskanen and Moritz, 1967; Bomford, 1980). Heights on dry land are expressed in units above mean sea level. One apparent disadvantage of referring depth to mean sea level is that one needs to manipulate the depth before adding the tidal value to obtain the instantaneous depth at a point.

3.6 **DEFINITION OF SEABED**

In areas where the seabed material is mainly composed of consolidated silt, clay, sand or harder materials then the definition of the bed may not be very subjective and can be literally taken at the interface between water and sediment. In such situations, the depth measured with an echo-sounder will explicitly define the bed level. However, a common occurrence, especially found in heavily silted areas of harbours or navigation channels, where the seabed is predominantly composed of very soft material (e.g. fluid mud), the question of where is the true bed poses a problem. Silt, with a wet density of $1200kg/m^3$, may contain as much as 85% by volume of water and 15% by volume of dry sediment (Nederlof and Bochove, 1981). In consequence the signal of an echo-sounder may not detect a sharp boundary between water and sediment.

The reflection of acoustic waves is determined by the reflection coefficient (R) between two layers (water and sediment) encountered by the waves as they hit the seabed and can be expressed as:

$$R = \frac{I_2 - I_1}{I_2 + I_1} \tag{3.1}$$

where subscripts 1 and 2 denote the upper (water) and lower (seabed) layers respectively, and $I = (\rho c)$ the acoustic impendance, which is dependent upon velocity (c) and medium density (ρ) (Wood, 1963). The greater the contrast between the value of acoustic impedance between two layers, the greater will be the value of R and the clearer will be the seabed shown on the echo gram. Urick (1983) further illustrates that the directional patterns of reflection from the bottom also depend on the different conditions of roughness and impedance contrast (Figure 3.8).

On smooth and rough seabeds of high impedance contrast, only a small amount of the emitted sound enters the bottom. Over a rough bottom of high impedance contrast, in particular, there can be a high level of scattering, possibly resulting in only a small amount of the signal being returned - Figures 3.8(a) & 3.8(b). In a low impedance contrast situation, both smooth and rough surfaces will absorb more sound energy into the bottom and therefore a considerably lower signal is returned - Figures 3.8(c) & 3.8(d). For real seabed situations, however, (b) and (c) occur more commonly than (a) and (d), where (b) may be representative of a rough sand/gravel bottom whilst (c) is typical of a soft muddy bottom.

With regard to the transmitted pulses from an echo-sounder, at high frequency (>200kHz) the signal will be reflected from the first density interface encountered, be it water/fluid mud or water/rock. In the fluid mud situation, difficulty in establishing the actual level is apparent since the fluid mud may be several metres in thickness. Fluid mud, with typically high water content, will obviously result in only slight contrast in the acoustic impedance with water and will be a weak reflector. On the other hand, if a low frequency (e.g. 33kHz) sound source is used, the depth shown may be greater than the acceptable depth due to penetration into overlying soft layers. The problem of establishing the density and thickness of the overlying layer has to be solved. This gives rise to the need for a different definition of seabed: the nautical bottom.

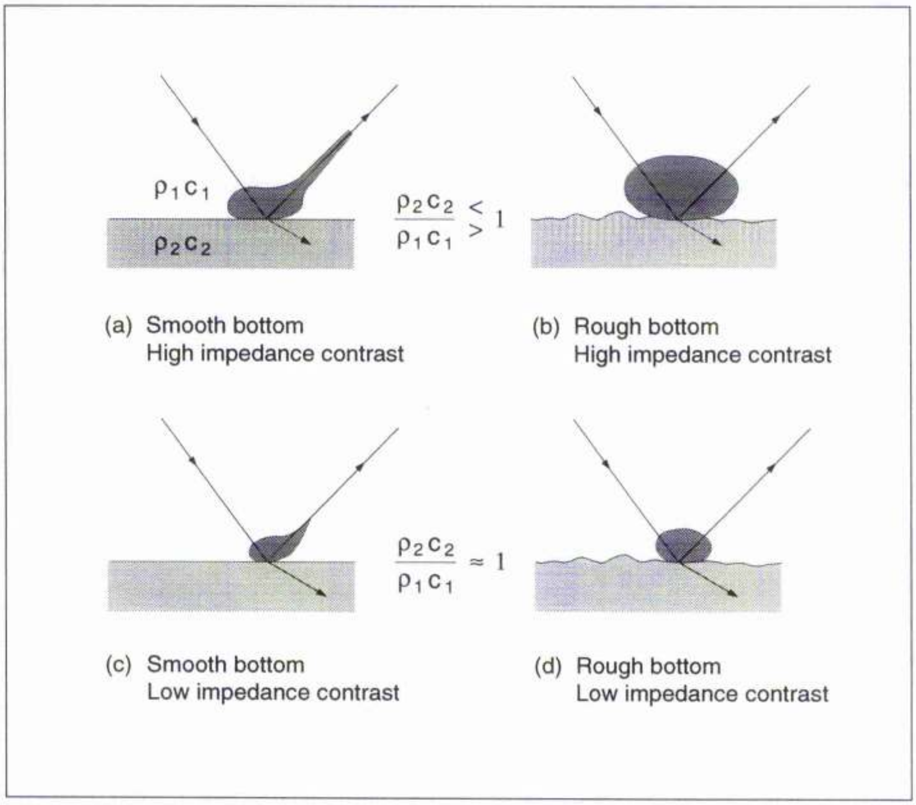


Figure 3.8 Reflections of the return of signal from seabed depend on the roughness and impedance contrast (ρc) (after Urick, 1983).

3.6.1 **Nautical bottom**

The exact definition of 'seabed' over a very soft bottom of suspended and unconsolidated material is difficult to determine and it has to be further defined by another term called the 'nautical bottom'. The idea of nautical bottom is related to ship navigating over soft, fluid mud where dredging is uneconomical to carry out as the material has a very low shear strength. The nautical bottom is thus defined as a level of undetermined density, above which a ship having the keel clearance laid down for the area concerned can safely manoeuvre.

3.6.2 **Nautical depth**

Nautical depth is complementary to that of the nautical bottom and is the distance between Chart Datum and the nautical bottom. The definition of nautical depth is based on the following criteria:

(i) The ship's hull must not suffer any damage even if its draft were to reach the full nautical depth. In practice, a vessel needs an under keel clearance of at least 10% of its draft.

(ii) Navigation response of the vessel must not be adversely effected.

The terminology, nautical depth and nautical bottom, obviously have implications on bathymetric surveying as there is uncertainty in determining the exact level of a very soft seabed. In general, it has been accepted by many that the nautical depth above a soft bottom may fall between the bed as defined by the 210kHz echo-sounder and that of the 1200kg/m^3 density horizon. This will be close enough to the depth value obtained using a dual frequency echo-sounder of 33kHz and 210kHz. Any apparent change in the seabed composition can be detected by a large difference in depth values displayed by the individual frequencies.

3.7 **LINE SPACING**

Spacing of survey lines will determine the thoroughness of a seabed survey. The closer the line spacing, the more accurately the actual topography of the seabed will be recorded. Considerable attention has been given to determine the relationship between line spacing and survey accuracy. Cloet (1976) tried to establish a measure of possible survey error due to line spacing, by choosing close line surveys known as saturation surveys taken at 13.5m. He later simulated the survey using wider line spacings, selecting sounding lines at 30, 60 and 100m apart. He concluded that the depth error increases by approximately 0.1m for every 10m increase in line spacing above 30m. Bouwmeester and Heemink (1993) considered a similar problem using a geostatistical approach and their findings were in close agreement with Cloet (1976). However, both attempts focused mainly on determing the peak levels of sand waves whereas in port and harbour situations, the problem is more intricate i.e. determination of the detailed topography of the seabed including the 'deep' and the 'shallow' water areas. In other words, use of a closer line spacing is desirable (5 - 10m).

3.8 SYNTHESIS AND DISCUSSION

Information on seabed bathymetric changes in the form of rate and quantity, are often required for port and harbour management. These can be obtained by the comparison of sequential bathymetric data, i.e. by comparing depth values (Z_i - Z_{i-1} = ΔZ_i) of different dates, measured over the same points on the seabed and subsequently deducing the annual rate of change ($cm.yr^{-1}$) and quantity (m^3) from the differences (ΔZ_i). The reliability of such hard facts obtained will depend on how accurately the measured quantity Z_i was measured or derived. One may also realise that the quantity ΔZ_i can be very sensitive to errors found in the quantity Z.

All possible errors contributing to the degradation of the value Z have been addressed above, i.e. the effects of vessel motion (roll, pitch and heave) and limitations in the echo-sounder measurement (due to beamwidth and type of seabed material). Where conventional, manual methods have been used for positioning a survey vessel and acquisition of depths, it is sometimes impossible to directly compare the bathymetric data obtained. Uncertainty in the position where a depth was actually measured and its true value are always questioned. However, present day technology for positioning and sounding, where the use of automation has become a standard contractual term of a survey project, the uncertainty in position and depth has been minimised. The use of automated depth and positioning systems mean that a greater amount of data than necessary can be collected in their real positions. Besides providing a fast and reliable data acquisition, the data are also subject to more rigorous processing before a result is produced. What is left to decide is purely practical: (1) How frequently is a survey needed? (2) What is the threshold level of change detection? (3) What is the optimum line spacing ?

To answer these hypothetical questions, one has to consider the long term objective of the use of the bathymetric data. So far, bathymetric data are considered as having short lives. In other words, after they have been used for producing charts or in calculations they are of no future use. They will become obsolete with time as the seabed they once represented changes and no longer retains the characteristics and spatial patterns of the time of survey.

The question of how frequently a survey is needed is rather site-specific. Assuming that the change of seabed is a slow, continuous one, with major changes occuring only due to floods or dredging works, it will be reasonable to carry out a new survey as soon as possible after the event. Under normal circumstances, once a year will be likely.

On the question of the detection of threshold limit of change, one has to consider the measuring resolution of all equipment used and the sea conditions during the survey. Assuming that, during a survey, an automated survey system incorporating a radio tide gauge was used and the survey was conducted in calm weather, an estimate of the change detection threshold value is estimated based on the measurement resolution of each item of equipment (Table 3.3).

Table 3.3. Example of estimation of change detection threshold value

Depth measurement	± 10 cm
Tidal recording	± 5 cm
Heave/roll/pitch	± 15 cm
Squat	± 5 cm
Calibration	± 5 cm
Detection threshold:	± 40 cm

Assuming that the ± sign in the figures represents a 50% probability, it is reasonable to estimate that it is possible to detect any change that is not less than 20cm (or 50% of 40cm). Below the threshold limit of 20cm, the actual value of ΔZ_i may indeed be a 'noise' value.

On the choice of the size of line spacing, a common practice is to adopt a 'heuristic' approach. This is based on the fact that port and harbour authorities do not take any chance of missing any 'shallow' that might endanger shipping and as well not to miss any 'deep' in order to optimise the cost of dredging. This is especially crucial in unsurveyed waters or in areas where changes in seabed bathymetry vary dramatically. For an unsurveyed area, in particular, an initial sounding-line spacing of 5 or 10m is not uncommon. Hitherto such areas may need to be covered only by larger line spacing of say 10 to 25m, to match the intended scale of a chart (selected at 1:10,000 to 1:25,000 or smaller).

One may also notice that, even though the sounding lines are designed to be parallel, under the real working environment this is seldom achieved. Strong currents, winds and frequent obstructions to navigation may cause the survey vessel to zig-zag close to the pre-determined course. This will be acceptable as long as the prescribed minimum line-spacing is maintained. However, for subsequent comparison of any two sets of data, there will be a need for a procedure known as 'gridding'. The justification and procedures for gridding will be discussed in Chapter 4.

CHAPTER 4

METHODS OF GRIDDING BATHYMETRIC DATA

4.1 INTRODUCTION

The estimation of magnitude, quantity and extent of seabed changes in area can be accurately determined by comparing bathymetric data from different dates. The conventional way of comparing the data is by means of cross-sectional plots drawn at regular fixed intervals or in the form of contour plans or charts. Thus the changes are revealed by either superimposing the plots or by manual comparison of the charts by 'eyeballing.' This task can become very complicated and is prohibitively time-consuming when a large data set or area is involved. Obviously, the apparent disadvantage of both methods is that only a small area can be selected at one time during each evaluation and, as such, it is sometimes impractical to visualise the change phenomena as a whole or to detect changes at fine structure level.

Thus, the use of digital data with an additional method called 'gridding'; a process whereby a reasonably accurate interpolation of known irregularly scattered depths to spatially fixed grid points, can lead to a more objective step towards providing a continuous representation of seafloor topography in the form of single image. Again, it is important to reiterate that gridding will only be justified in situations where an area has been considered to be fully surveyed and the seabed topography is fully developed by sufficient depth coverage.

The use of cross-section or contouring techniques to show changes in seabed topography is no longer considered as sufficient to fully portray changes to a fine detail level. This is because both methods are either discrete or have too much generalisation in their presentation. Figure 4.1 is an illustration in which two sets of profile line data are compared to reveal changes. One can note that although the difference between the two data sets is apparent, information is shown only along the specific line. To study changes covering large areas requires comparison of a number of such sections and this of course is difficult.

Although cross-sectional plot methods have been widely used, they do not reveal detailed changes in seabed topography, because the information on the seabed is concentrated only along the cross-sectional lines. Even with data at closely spaced lines it may still become impractical, though possible, to draw cross-sections at a very close interval of say less than 10 metres. For example, in a typical harbour area of size 0.5km in width by 2.0km in length, one may end up with large numbers of drawings to evaluate if cross-sections at spacings of less than 10 metres are used.

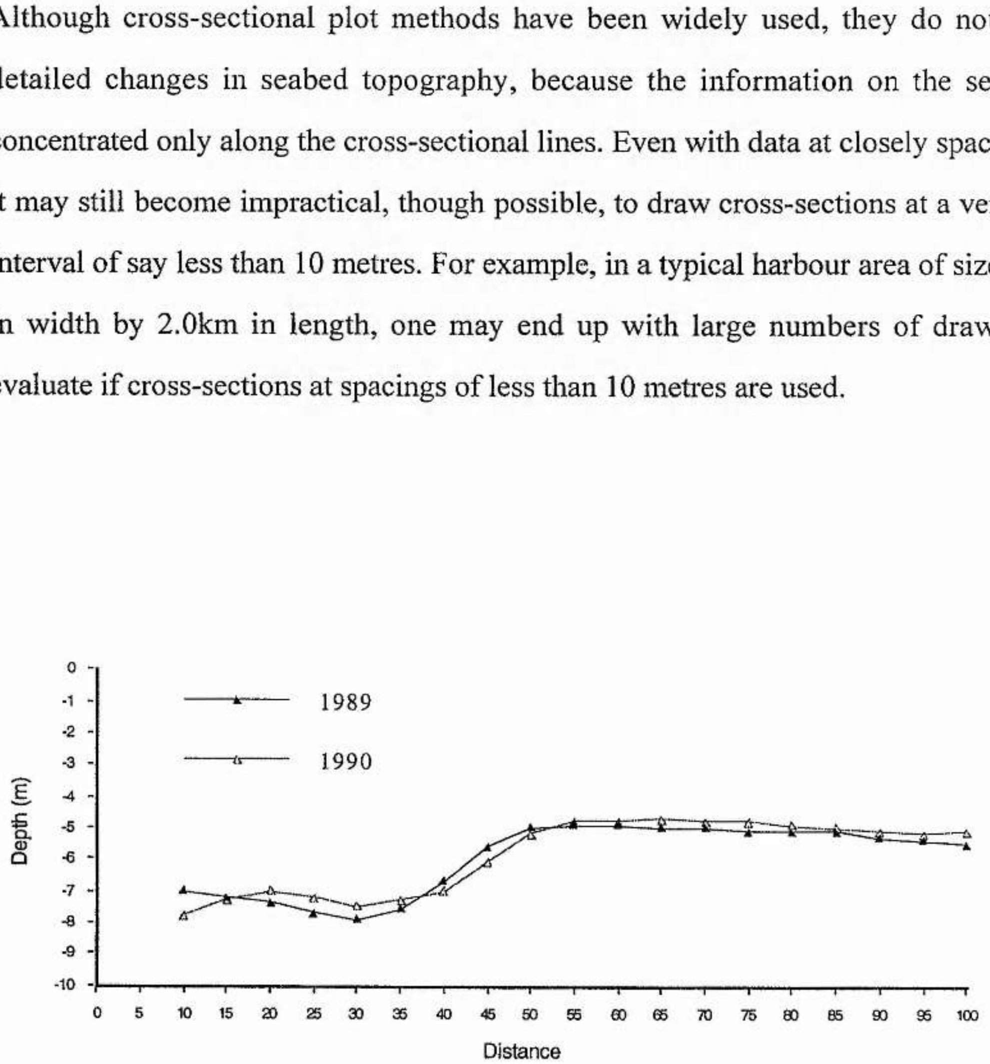


Figure 4.1. Superimposing the data of two bathymetric survey lines/ cross-sections obtained during different years.

As an alternative, contour charts or maps may be used to represent the bathymetric data. However, comparison of charts by 'eyeballing' has its limitations if the position of water depths shown on the charts are irregularly scattered. It can be difficult to detect changes visually especially if the magnitudes of such changes are small (at micro-structure level of < 0.3 metres) and they are located at various scattered locations.

Direct comparison between two charts can be made easier only if the depths are located at mesh intersections or at grid nodes. Usually bathymetric data are sampled along tracks with minimum intervals between the tracks in order to record significant seabed features. However, the individual depth data points often do not coincide precisely with the intended tracks or mesh intersections.

As a result, proper re-arrangement of the sampled data is required, so that direct comparison of water depths is possible. One possible way of doing this is by re-arranging the irregularly scattered depth data points into spatially fixed positions along a line or in grid form through interpolation. Figures 4.2(a) & 4.2(b) show examples of irregular data being transformed into gridded patterns and Figures 4.3(a) & 4.3(b) show information in the form of deposition and erosion respectively obtained by direct comparison between the two gridded data sets.

In bathymetric surveying, it is not ethically acceptable to the profession to represent incomplete survey by filling up the missing data points by interpolating them from neighbouring measured data points. To allow this means would encourage or sometimes lead to undesirable 'extrapolation' of data for the sake of making a survey look like a complete job. Furthermore, the task is considered ambiguous, laborious and time consuming and can be an error-prone process if carried out by an operator inexperienced with the interpolation procedures.

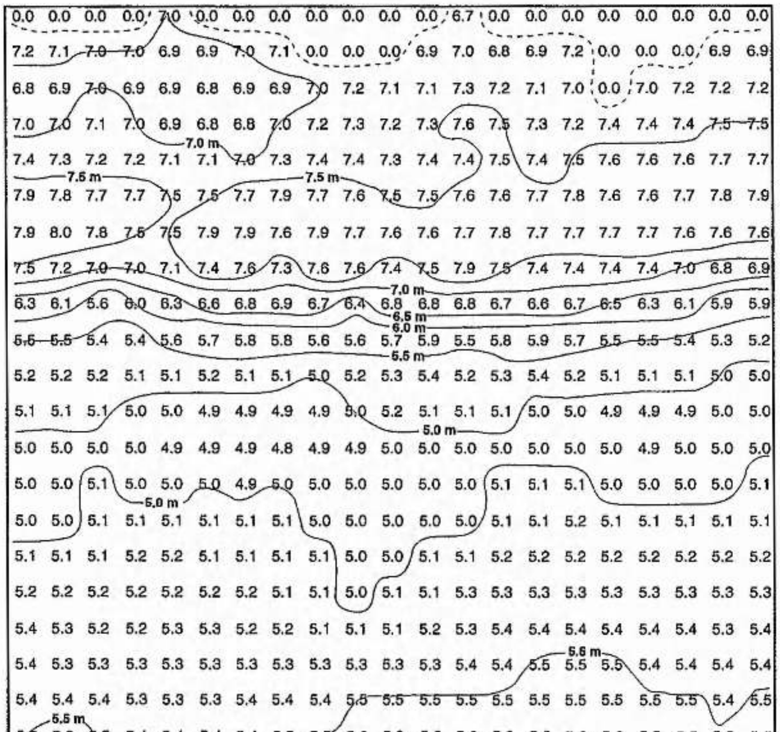


Figure 4.2(a) Example of gridded data - B0989 (see page 126).

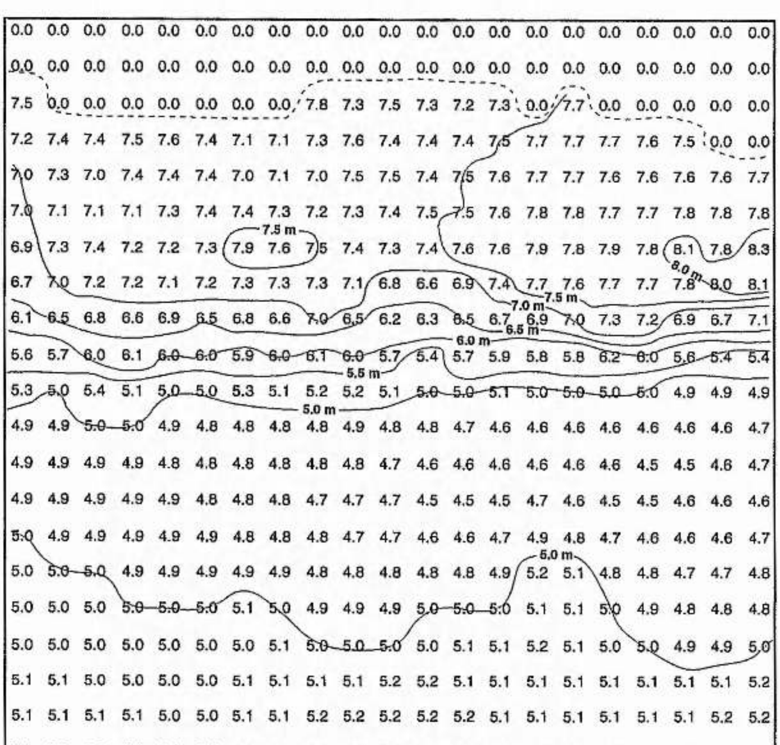


Figure 4.2(b) Example of gridded data - B0990.

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.8**	**0.1**	**0.3**	**0.2**	0.0	**0.1**	0.0	**0.6**	0.0	0.0	0.0	0.0	0.0
0.2	**0.4**	**0.2**	**0.5**	**0.7**	**0.6**	**0.3**	**0.1**	**0.1**	**0.3**	**0.2**	**0.1**	0.2	**0.1**	**0.4**	**0.5**	**0.3**	**0.2**	**0.1**	0.0	0.0
0.4	0.0	0.2	**0.2**	**0.2**	**0.3**	0.0	0.2	0.4	**0.1**	**0.1**	0.0	**0.1**	**0.1**	**0.3**	**0.3**	0.0	0.0	0.0	0.1	0.0
0.9	0.7	0.6	0.6	0.1	0.1	0.2	0.6	0.5	0.3	0.1	0.0	0.1	0.0	**0.1**	0.0	**0.1**	**0.1**	0.0	0.0	0.1
1.2	0.7	0.4	0.3	0.3	0.6	0.0	0.0	0.4	0.3	0.3	0.2	0.1	0.2	**0.1**	**0.1**	**0.2**	**0.2**	**0.5**	**0.2**	**0.6**
0.8	0.2	**0.2**	**0.2**	0.0	0.3	0.4	0.0	0.2	0.5	0.6	0.9	1.0	0.1	**0.3**	**0.2**	**0.3**	**0.3**	**0.8**	**1.2**	**1.2**
0.3	**0.4**	**1.2**	**0.6**	**0.6**	0.1	0.0	0.2	**0.3**	**0.1**	0.5	0.5	0.3	0.0	**0.3**	**0.3**	**0.8**	**0.9**	**0.8**	**0.8**	**1.2**
0.1	**0.3**	**0.6**	**0.7**	**0.4**	**0.3**	**0.1**	**0.2**	**0.5**	**0.5**	0.0	0.4	**0.2**	**0.1**	0.0	**0.1**	**0.7**	**0.5**	**0.1**	**0.1**	**0.3**
0.1	0.2	**0.2**	0.0	0.1	0.1	**0.2**	0.0	**0.2**	0.0	0.1	0.4	0.2	0.2	0.4	0.1	0.1	0.1	0.2	0.1	0.1
0.1	0.2	0.0	0.0	0.2	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.4	0.2
0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.4
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.4	0.4	0.4
0.0	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.3	0.5	0.5	0.5	0.5	0.4
0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.0	0.1	0.4	0.5	0.5	0.5	0.4
0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.2	0.3	0.2	0.1	0.2	0.4	0.4	0.4	0.5	0.4
0.3	0.3	0.2	0.2	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.2	0.3	0.4	0.4	0.4	0.4	0.4
0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.3	0.2
0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.4	0.4	0.3	0.3
0.4	0.4	0.3	0.3	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.6	0.5	0.4	0.3	0.2

Figure 4.3(a) Location of erosion sites.

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.8**	**0.1**	**0.3**	**0.2**	0.0	**0.1**	0.0	**0.6**	0.0	0.0	0.0	0.0	0.0
0.2	**0.4**	**0.2**	**0.5**	**0.7**	**0.5**	**0.3**	**0.1**	**0.1**	**0.3**	**0.2**	**0.1**	0.2	**0.1**	**0.4**	**0.5**	**0.3**	**0.2**	**0.1**	0.0	0.0
0.4	0.0	0.2	**0.2**	**0.2**	**0.3**	0.0	0.2	0.4	**0.1**	**0.1**	0.0	**0.1**	**0.1**	**0.3**	**0.3**	0.0	0.0	0.0	0.1	0.0
0.9	0.7	0.6	0.6	0.1	0.1	0.2	0.6	0.5	0.3	0.1	0.0	0.1	0.0	**0.1**	0.0	**0.1**	**0.1**	0.0	0.0	0.1
1.2	0.7	0.4	0.3	0.3	0.6	0.0	0.0	0.4	0.3	0.3	0.2	0.1	0.2	**0.1**	**0.1**	**0.2**	**0.2**	**0.5**	**0.2**	**0.6**
0.8	0.2	0.2	0.2	0.0	0.3	0.4	0.0	0.2	0.5	0.6	0.9	1.0	0.1	**0.3**	**0.2**	**0.3**	**0.3**	**0.8**	**1.2**	**1.2**
0.3	**0.4**	**1.2**	**0.6**	**0.6**	0.1	0.0	0.2	**0.3**	**0.1**	0.5	0.5	0.3	0.0	**0.3**	**0.3**	**0.8**	**0.9**	**0.8**	**0.8**	**1.2**
0.1	**0.3**	**0.6**	**0.7**	**0.4**	**0.3**	**0.1**	**0.2**	**0.5**	**0.5**	0.0	0.4	**0.2**	**0.1**	0.0	**0.1**	**0.7**	**0.5**	**0.1**	**0.1**	**0.3**
0.1	0.2	**0.2**	0.0	0.1	0.1	**0.2**	0.0	**0.2**	0.0	0.1	0.4	0.2	0.2	0.4	0.1	0.1	0.1	0.2	0.1	0.1
0.1	0.2	0.0	0.0	0.2	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.4	0.2
0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.4
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.4	0.4	0.4
0.0	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.3	0.5	0.5	0.5	0.5	0.4
0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.0	0.1	0.4	0.5	0.5	0.5	0.4
0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.2	0.3	0.2	0.1	0.2	0.4	0.4	0.4	0.5	0.4
0.3	0.3	0.2	0.2	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.2	0.3	0.4	0.4	0.4	0.4	0.4
0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.3	0.2
0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.4	0.4	0.3	0.3
0.4	0.4	0.3	0.3	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.6	0.5	0.4	0.3	0.2

Figure 4.3(b) Location of deposition sites.

However, it is believed that the interpolation of depths from irregularly scattered to a gridded form to achieve the necessary comparison between two sets of bathymetric data might be acceptable with the use of properly designed computer algorithms. The procedures will require the introduction of interpolation technique. Under these circumstances agreement on the method to be used to permit interpolation is essential. In this work it is suggested that the manipulation of digital data should be achieved using a method called 'gridding.' By this process, a reasonably accurate interpolation of depths are used to generate depths determined at irregularly spaced points at spatially fixed grid points. This may permit objective provision of the repeated representation of seafloor topography in the form of single image.

4.2 **GRIDDING**

The term 'gridding' as used here pertains to a computer-aided, mathematical technique for interpolating depths at any required points. During the gridding process the area or domain under investigation has to be first subdivided into sub-domains, commonly in the form of square grids. Each square grid is made up of four corners known as nodes. The entire mosaic-like pattern resembles a mesh which covers and statistically represents the domain or area. Other forms of sub-domain used are rectangular, hexagonal or triangular (Kennie and Petrie, 1990).

In theory, a simple condition commonly imposed on depth interpolation will be:

$$| Z_{interpolated} - Z_{measured} | = \text{minimum} \tag{4.1}$$

which means that the absolute difference between the measured and interpolated depths should be determined as small as possible (say, to 0.1m). The above condition is however, seldom known or met for all interpolation points because they can never always coincide with every measured point. This can be explained by the fact that in practice, for economical reason, a sounding line during a bathymetric survey will never be run or surveyed more than once, unless it is not satisfactorily run (off track situation) when a re-run of the line will be made. Perhaps, depths can never be exactly determined along the required lines as it is difficult to keep the survey vessel exactly on pre-surveyed line. In other words, in most cases there will be no repeated measurements over a single measured point on the seabed to permit one to assess the minimum condition of expression (4.1). If the measured point coincides with the required interpolation point then, of course, no interpolation will be needed for that point.

4.3 **DEPTH INTERPOLATION AND PROBLEMS**

In the past, when computers were not widely used as a tool to process bathymetric data, interpolating depths at spatially fixed points was not considered as an appropriate method to represent the bathymetry of a seafloor. The locations where depths were measured were shown exactly in the final bathymetric chart representation. As a result of the diversity in their uses, the demands for better and appropriate bathymetric data representation have increased and therefore the data representations have to be systematic and easy to use.

Bathymetric data are no longer seen to be confined to chart making or simply for the estimation of volumes of material to be removed or excavated during dredging. Such data may also be used for scientific applications such as the analysis of the spatial distribution of seafloor sediment deposition and erosion in an area during a period of years. This application can be useful as a supplement to modelling works for the area.

Gridding is therefore designed to estimate depths at undetermined points between survey lines. The accuracy of the estimated depths will depend on the accuracy and distribution of the measured depths, the interpolation algorithm used and the computing time afforded. Before going into detailed descriptions of each of the selected interpolation methods used under the proposed technique, it is important to stress that results obtained after the gridding process will not yield more accurate depths than those acquired by direct measurement.

There are a number of computation methods which have been successfully applied to seafloor mapping or similar applications. For example, the work of Chiles and Chauvet (1975) used the kriging method for cartography of the seafloor, Claussen and Kruse (1988) used polynomial equations in the DTM-Program TASH for bathymetric mapping application and others used simple or weighted averaging.

In bathymetric data interpolation, a common uncertainty one has to confront when choosing an interpolation method is whether the method will take up either one of the following three possible values; shoalest/shallowest depth, greatest depth or average depth. It will be evident in the following sections that between the interpolation methods there will no identical answer and as a result there will always be the three possibilities. The physical nature of the seabed that remains hidden underwater makes it impossible to ever know for certain whether what is being obtained from an interpolation is actually shallowest, greatest or average depth of all possible interpolated depths, without recourse to comparing results from various types of algorithm or formulae during the interpolation.

4.3.1 **Shoalest or Shallowest depth**

It should be emphasised that all depths shown on a bathymetric chart are indeed the shoalest or shallowest depths. No doubt a chart will also show areas of 'deep' water but the water depths in such 'deep' zones are also reported in terms of the minimum depth not the maximum depth at the location of the measured point. This has been explained earlier in Chapter 3, where the limitation lies in the principle of echo-sounding, which has, in fact, a tendency towards measuring the shallowest depth, the one of interest to navigators.

In depth interpolation, however, the selection of an interpolation method is critical, for example, where a chosen method might indeed give a shallowest depth when the true depth is greater, then possibly too great sediment deposition may be indicated and, as a result, false changes can be portrayed.

4.3.2 **Greatest depth**

The greatest depth is of concern, for example, in marine construction works where the emphasis is on the greatest rather than the shallowest depth. This is because the wrong choice of depth may result in an increase in the quantities of construction materials needed and in the time of construction.

On the other hand, if one is to interpolate a greater depth when the true depth is in fact less then possibly, there will be an unnecessary increase in cost and also a safety risk because the true depth of the area is, in fact, less than the stated depth. An easy way to avoid the complication is to take the average depth of the two extreme values.

4.3.3 **Average depth**

The problem of selecting correct depth actually exists at the recording stage where a dual frequency echo-sounder is used. The fact that the 210kHz frequency will display a slightly shallower depth than the 33kHz frequency poses an uncertainty in depth definition especially over an unconsolidated, muddy seabed. Although a simple and quick solution to the problem is to take the mean or average between the two depths, the uncertainty remains unresolved especially when a dispute results from of an incorrect choice. Thus, in depth interpolation one has to be very careful when average depth is to be used.

4.4 THE CHOICE OF METHODS

Several methods of interpolation have been published in the literature. An excellent review of these and references on related topics is provided by Watson (1992) and a specific review by Schut (1976) details applications for digital terrain modelling. Although there are many available methods (e.g. of Akima, 1978), their applications are strictly related to a triangular cell or triangulation approach and not a point by point basis as desired in bathymetric mapping.

In general the choice of method is determined such that it can be easily implemented using computers. Importantly, it should work even under the minimum number of possible data points of 1, and to the maximum number of say 50 (depending on the size of memory of available computer). This is because, in gridding of bathymetric data, it is important that closest neighbouring data points are assigned greater significance than the more distant ones.

During the gridding process each and every node is visited in succession (sometimes referred to as point-wise interpolation) and each node is therefore assumed to be governed by a region or area of influence, where any data points that fall within the region or area are taken as predictors of the interpolation point.

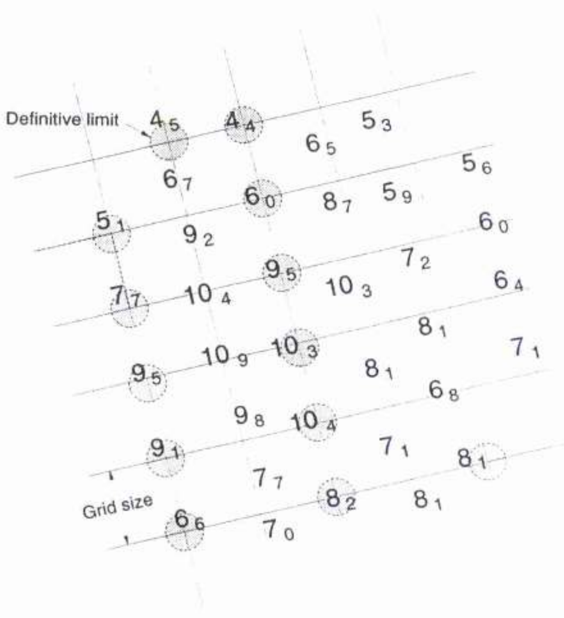
In the selection of interpolation methods, one also has to be certain that they will cover the possible maximum and minimum values, i.e. the range of shallowest and greatest depths. Some of the methods selected here are similar in several respects to those described by Braile (1978), except that the implementations are rather different to suit this particular application. So, on this basis, a total of six suitably different methods of interpolation have been identified, and these are described below.

4.5 SINGLE CLOSEST NEIGHBOUR POINT - (SCNP)

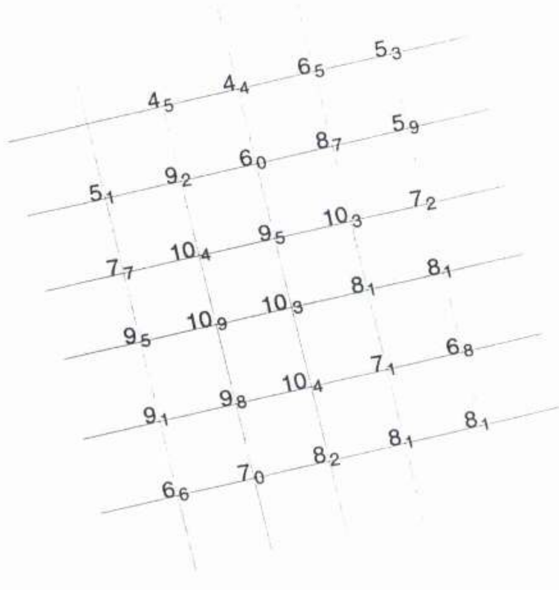
This method is the simplest form of interpolation which involves a minimum amount of computation. At each grid location a finite definitive limit is set whereby, during each search for data points, any single data point that falls within this limit will automatically be assigned as an interpolated depth value for the node.

The definitive limit can be of any arbitrary value taken, for example, a value of 0.25 x grid size. If a 5 metres grid size is chosen then the definitive limit will be 1.25 metres. That is to say, any data point that falls within 1.25 metres from the interpolation point will be selected (Figure 4.4a). Note that any depth figure found within the shaded circles will be taken as the depth located at the centre of the circle. The process is repeated for each and every node point in the grid. This method may indeed be a best method in achieving accurate result because the actual measured depth is actually being used with no interpolation needed. But, however, it is still of limited use. It is only by chance that the SCNP method works for all interpolations. So, this method cannot, by itself, be used to achieve the gridding of the entire area of interest.

The application of a similar method is termed 'pigeon-holed' by Kielland (1983). Instead of using the definitive limit as a criterion for selection of a depth for the grid point, a data point that falls within a square grid is used, whereby looking at the real position of the data, each depth will be 'pigeon-holed' into its respective closest matrix position (Figure 4.4b).



(a) Example of grid point interpolations by SCNP method.
Shaded circles define the definitive limits.



(b) Diagram showing depths after pigeon-holed to their respective grid points

Figure 4.4

4.6 SIMPLE LINEAR INTERPOLATION METHOD - (SLIM)

4.6.1 The geometrical concept

This is a three-stage process in which first, the selection of the data points is required. Next, the Z-values at the intersections of a horizontal or vertical line that passes through the node and the boundaries are calculated, and then, in a similar way, the Z-value at node point is calculated. Regarding configurations of data points, there are two typical cases.

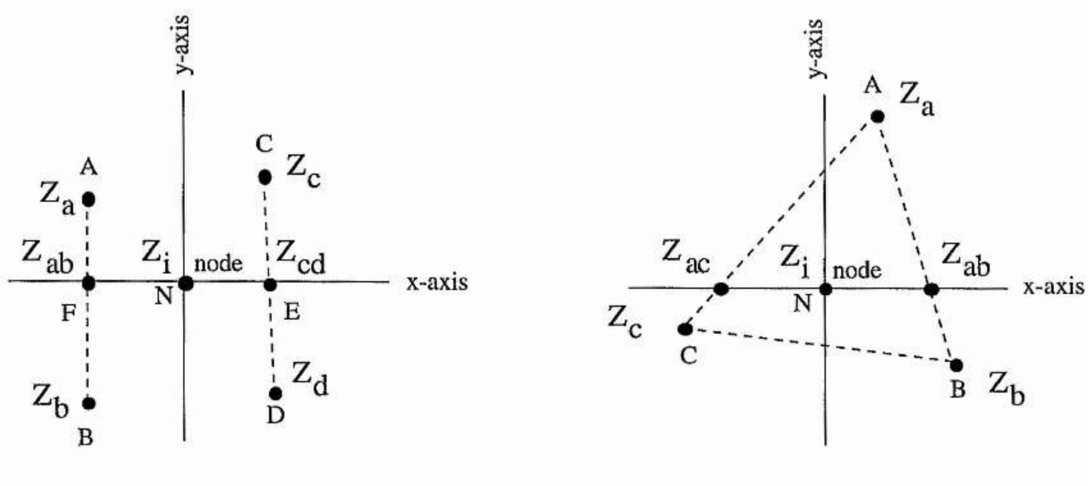


Figure 4.5. Geometry of Simple Linear Interpolation Method showing arrangements with three and four data points (for details see page 78).

One is known as common neighbour and the other as quadrant neighbour (see Figure 5.5). The arrangement of data points under this method has to be in quadrant neighbour configuration and at least three quadrants are required. This method is based on the principle of linear surface geometry and is compatible with the along-line sampling technique of bathymetric survey. Figure 4.5 shows the arrangement of the data points as required under this method. Two pairs of data points (Z_a, Z_b) and (Z_c, Z_d) lie on the two adjacent survey lines respectively, where each data point represents a quadrant. The intermediate points (Z_{cd} and Z_{ab}) between the respective pairs have be determined using the following mathematical relationships:

$$Z_{cd} = \frac{Z_d \, CE + Z_c \, DE}{CD} \tag{4.2}$$

$$Z_{ab} = \frac{Z_b \, AF + Z_a \, FB}{AB} \tag{4.3}$$

$$Z_i = \frac{Z_{cd} \, FN + Z_{ab} \, NE}{FE} \tag{4.4}$$

Once the intermediate points are determined the depth Z_i at the node point N can be similarly obtained. This method requires the grid points to be surrounded by at least three to four data points and this restriction provides some azimuth control which will significantly improve the interpolated value.

4.6.2 **Interpolation defect**

A trial computation performed using this method has revealed that this method suffers from a computational defect which may contribute to a false depth estimate. This is illustrated in the example shown in Figure 4.6. Under SLIM the location of the two intermediate points can be determined either along the x or y axis. If the interpolation is done along a constant y then the interpolated depth Z_i will be 8.995 metres. On the other hand, if it is done along a constant x the value of Z_i will be 9.603. This difference of 0.608 metres in depth may be significant from the point of view of detecting changes in bathymetry.

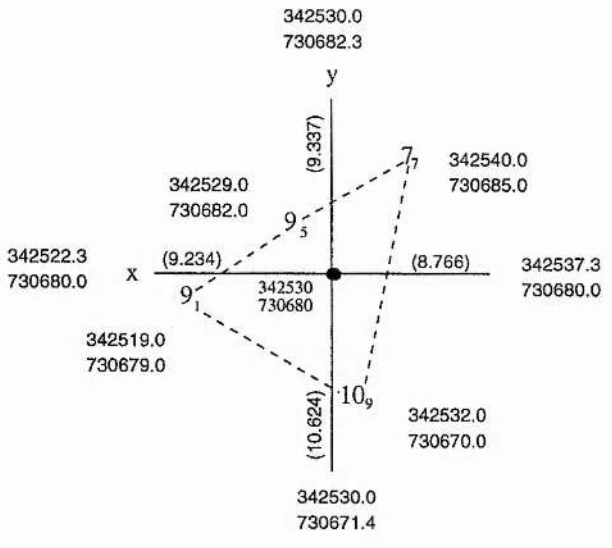


Figure 4.6

Hypothetical data subset. Depth interpolated along y-axis can be different from depth interpolated along x-axis. Figures in bracket denote interpolated depths.

It is difficult to know along which axis should an interpolation be carried out. However, this computational ambiguity happens only by chance, especially when any three data points lie on the same line (collinearity situation) which is common in bathymetric data distribution.

4.7 INVERSE DISTANCE WEIGHTING METHOD - (IDWM)

Another method of transforming irregularly scattered to gridded data is by the method of inverse distance weighting. The different between the IDWM from the above two methods is on the selection of data points. The SCNP uses only a single closest data point within a definitive limit while the SLIM uses selective points representing quadrants. The method of inverse distance however, makes use of all the data points that fall within the region or area of influence. This can be expressed as:

$$Z_{intpl} = \frac{\Sigma(w_i Z_i)}{\Sigma w_i} \qquad (4.5)$$

In Equation (4.5), the interpolated value (Z_{intpl}) is computed as a weighted average of the values at the data points. The weight attached to a data point is a function of the distance from the points of interpolation to the data point and it is taken as inversely proportional to its distance from the point of interpolation ($w_i = \frac{1}{d^n}$ where n is the power used, typically 0.5 to 2). This results in the interpolated value being determined independently from every data point.

Table 4.1 shows a numerical example of this method. In the first step of the interpolation, for each and every node, it is required to determine a set of data points known as a data subset. The respective distance between each data point and the node is then computed.

The weight of the individual data point is taken as the square of its inverse distance divided by the total of all the squares of inverse distances. This is sometimes called normalisation and it is carried out to make the total influence equal to unity. If this is not done, the total influence will be open ended. The interpolated value (Z_{intpl}) is then determined by the summation of the influence w_iZ_i; weight multiplied by depth.

Table 4.1. Numerical example of interpolation by the Inverse Distance Weighting Method using common neighbour data

Depth value (Z_i)	Distance from node(m)	Square of Inv.dist	Corrected weight	w_iZ_i
10.3	9.192	0.011835	0.125463	1.292
10.3	5.701	0.030768	0.326163	3.359
9.5	5.701	0.030768	0.326163	3.099
10.9	9.925	0.010152	0.107616	1.173
10.4	9.618	0.010810	0.114595	1.192
		Σ	1.000000	Z_{intpl}: 10.115

Table 4.2. Numerical example of interpolation by the Inverse Distance Weighting Method using quadrant neighbour data

Depth value (Z_i)	Distance from node(m)	Square of Inv.dist	Corrected weight	w_iZ_i
10.9	9.925	0.010152	0.123058	1.341
10.4	9.618	0.010810	0.131033	1.363
10.3	5.701	0.030768	0.372954	3.841
9.5	5.701	0.030768	0.372954	3.543
		Σ	1.000000	Z_{intpl}: 10.088

There are two alternatives to determine a data subset for an interpolation point. A common neighbour refers to data points that fall within a prescribed distance. A quadrant neighbour requires a selection of data points, where each quadrant will be represented by a single data point closest to the node. One would therefore expect different results if the configuration of the data subset is changed from common to quadrant neighbours (Table 4.2). Although, in this example, the difference in the interpolated depths shown in Tables 4.1 and 4.2 is small, in other instances it can be unacceptably large (> 0.1m).

4.7.1 **Choice of weight**

A weight is assigned to each data point to determine the individual influence and is dependant on the distance of the data points from the node whose value is to be estimated. The farther a data point is from the node, the less will be its influence and the closer a data point is to the node, the greater will be its influence. This is equivalent to a decay function. A sharp decrease of the weighting at small distances from the node point produces a representation of the surface that fits well at the data points.

Figures 4.7(a) to 4.7(d) show the effect of varying exponential power of the inverse distance. For the exponential power of two there is a sharp drop in weight at about 3 metres from the centre levelling off to infinity at zero value. For an exponential power of one the sharp drop also occurs somewhere near the 3 metre distance but there is a gradual level off maintaining its value between 0.3 to 0.05. As the exponential power decreases the sharp drop off reduces in range and the level off becomes gradually slow.

In most applications, the inverse distance squared is used as a weighting function and the choice of exponential power of two is most commonly used because it produces a sharp decrease in influence as the data is farther away from the interpolation point. The weight will approach a value of one if the distance between the interpolation point and the node approaches 1 metre.

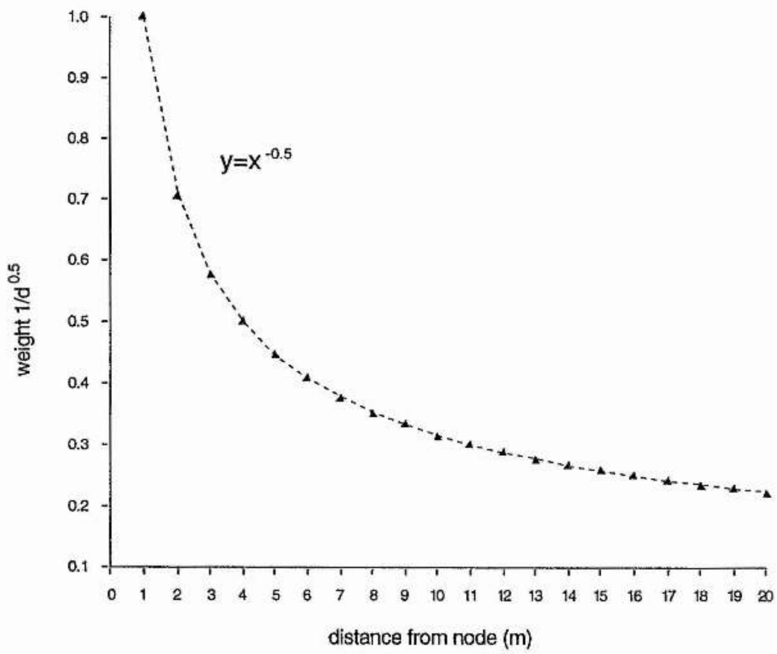


Figure 4.7 (a) Graph showing weight as inversely proportional to the power of 0.5

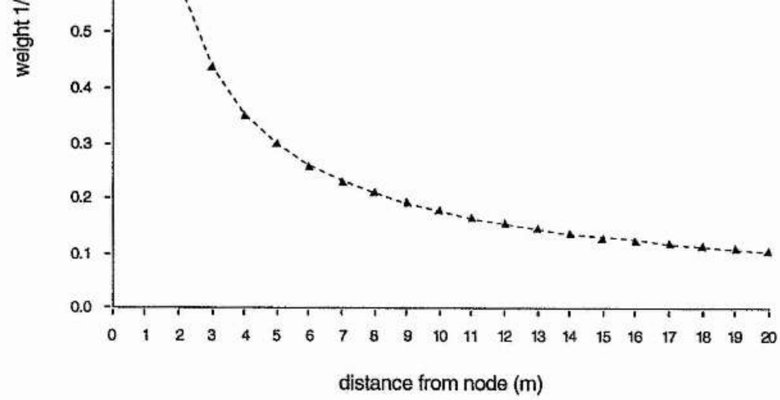


Figure 4.7 (b) Graph showing weight as inversely proportional to the power of 0.75

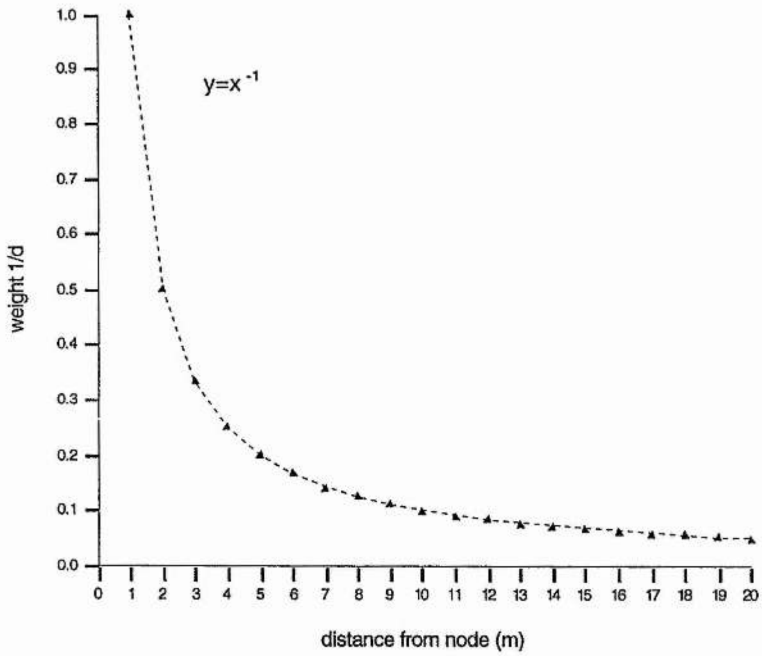


Figure 4.7 (c) Graph showing weight as inversely proportional to the power of 1.0

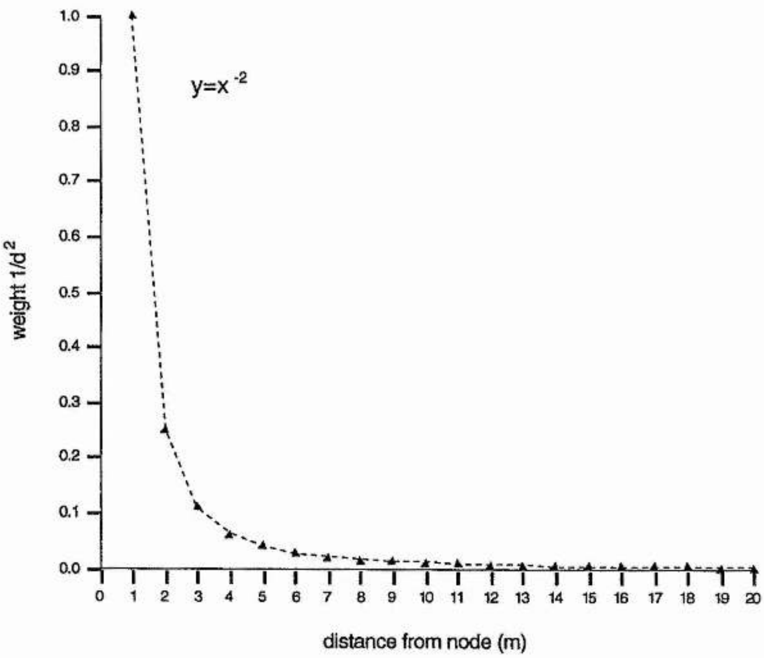


Figure 4.7 (d) Graph showing weight as inversely proportional to the power of 2.0

Coincidentally, as the data point approaches the node point (i.e. less than 1 metre) the influence will be void and the SCNP method will take over the function of IDWM. This is compatible with bathymetric data as one places more confidence in the nearest data point than one further away.

4.7.2 **Choice of radius**

It is also possible to produce differing results using IDWM, in particular as there are no clear guidelines on the choice of the length of the search radius. Obviously, if one were to select an inappropriate radius it would affect the result of an interpolation. To obtain an optimum number of data points it is recommended by the author that the search radius of between 1 and 2 sounding spacings is used as too many data points will unjustifiably increase the computation.

4.7.3 **Effect of varying search radius**

The apparent defects of this method lie in the uncertainty of selecting the search area size and that the interpolated value can be perturbed unduly by isolated aberrant data values (Henley, 1984). Table 4.3 shows the effect of varying the length of the search radius where interpolated depths can change significantly. There is a marked difference between the depth values of the search radii of 10 and 24 metres under common neighbour, respectively. This suggests that it may not necessarily be a true assumption that the greater the number of data points the more accurate will be the interpolated depth. This contributes to a different of 0.538 metres which may results in an ambiguity in the detection of bathymetric changes. It may also contain strong biases if the data points are not evenly distributed (Lord and Wilson, 1984).

Results obtained under quadrant neighbour configuration however, only show a slight difference in values between the minimum and maximum radii (Table 4.3). Although the difference is negligibly small in this example it can sometimes be unacceptably large in some cases.

Table 4.3 The effect of varying the radius on the interpolated depths(m)

Radius(m)	r=10	r=11	r=13	r=15	r=16	r=17	r=18	r=20	r=24
No.of points	3	4	5	6	9	11	12	13	20
IDWM - Cnbr	10.086	10.108	10.108	10.085	9.909	9.889	9.889	9.972	9.548
IDWM - Qnbr	10.043	10.073	10.073	10.073	10.073	10.073	10.073	10.073	10.073

The three methods mentioned above are based on a linear relationship between the point of interpolation and data points, or sometimes referred to as distance-based methods. An entirely different approach to interpolation is by means of a mathematical surface to fit in between data points. This method is free from those defects found in the distance-based methods, but it also has a defect in itself.

$$f(x,y) = \Sigma(a_i f_i) \tag{4.6}$$

A mathematical surface is a combination of elemental surfaces known as basis functions, which are expressed in co-ordinates of location. For example, in Equation 4.6, each term ($a_i f_i$) can be thought of as a surface in its own right ranging from horizontal to slanting and curved surfaces.

One important consideration under this method is the choice of surface which is to be computed for the data points. Polynomials are often used to fit a surface between data points. For example, it is possible to fit up to a fifth-order polynomial surface to six data points. The data subset for each grid point is searched in the usual way and used to calculate the local mathematical surface surrounding the grid point.

The combination of such surfaces for a given data set or subset can be obtained by solving a set of simultaneous equations. This requires the unknowns (a_i), which form a set of coefficients, to be solved simultaneously by forming a set of normal equations.

The depth value at any required point can therefore be determined by substituting back the determined coefficient values with the co-ordinates of the point (x,y) into Equation 4.6. The search area is then moved successively over the entire area and the computation of the local mathematical surface is repeated until the gridding process is complete.

Another important consideration is the choice of the function f_i. There are various ways of defining this function. One is by choosing a monotonically decreasing function of distance which results in a continuous surface.

The methods of fitting a mathematical surface to a data set are commonly referred to as Fitted Function Methods (FFMs) (Watson, 1992). Under FFMs there are three variants: a mathematical surface is made to fit exactly between data points; a surface which is a smooth surface and fits between the data points; and a surface which is fitted to a set of data points that minimises the sum of squares of residuals. A method under each variant will be dealt with separately in the following sections.

4.8 **METHOD OF COLLOCATION** - COL

The method of collocation contains a surface that is forced to fit exactly through all the data points found in a subset chosen for the interpolation. In other words, the Z of the mathematical surface of the seabed coincides with the Z of the measured seabed surface. The underlying theory and discussion leading to this method can be found in Lancaster and Salkauskas (1986).

4.8.1 **The concept of surface fitting**

Given a set of data points (as in this case the depths of seabed and their positions), which are systematically distributed over an area, find the equation of a surface that can fit exactly through all the data points and that provides a logical interpolation at any intermediate points. The surface fitting concept using polynomials performed in the conventional way can lead to erroneous results. Thus, it has been improved by use of a mathematical model such as that presented below:

4.8.2 **Mathematical model**

$$Z(x,y) = a_1\Delta(p_n - p_1) + a_2\Delta(p_n - p_2) + a_3\Delta(p_n - p_3) + \ldots\ldots\ a_i\Delta(p_n - p_i) \qquad (4.7)$$

where

$Z(x,y)$	depth at interpolation point
a_i	coefficients
$\Delta(p_n - p_i)$	basis function
p_n	interpolation point
p_i	data points

The above mathematical model consists of an independent variable, Z (in this case the depth of seabed), the coefficients a_i as the unknown, and the basis functions as the predictors. For each measured depth the corresponding equation is formed. The unknown coefficients are determined by simultaneous solution of the normal equations.

4.8.3 **Normal equations**

$$\begin{vmatrix} e_1 & \Delta(p_1-p_2) & \Delta(p_1-p_3) & \Delta(p_1-p_4) \\ \Delta(p_2-p_1) & e_2 & \Delta(p_2-p_3) & \Delta(p_2-p_4) \\ \Delta(p_3-p_1) & \Delta(p_3-p_2) & e_3 & \Delta(p_3-p_4) \\ \Delta(p_4-p_1) & \Delta(p_4-p_2) & \Delta(p_4-p_3) & e_4 \end{vmatrix} \begin{vmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{vmatrix} = \begin{vmatrix} Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \end{vmatrix}$$

The simultaneous linear equations shown above are in matrix form for a combination of four data points. Any number of points can be used by expanding the number of rows or column in a similar manner.

The unknowns, a_i in the above normal equations, can be solved by standard numerical methods. The interpolated depth for the interpolation point can therefore be obtained by substituting its co-ordinates and the solved coefficients into equation (4.7).

4.8.4 **Basis function**

The important function $\Delta(p_i - p_j)$ used in the normal equations is known as a basis function. It is used as a prediction function for separate geometric surfaces where each surface is a surface of revolution centred at one of the data points. Arthur (1965) suggests a decay-type function which has a maximum value of one at zero distance and is positive for all distances less than an arbitrary constant limit, e (Figure 4.8). The value for e is taken as the maximum distance separating data points. The effect can be seen as a radially symmetric kernel of influence around each data point. Schut (1974) lists and describes several other kernel functions that may be used for the basis function. Mason (1984) uses power functions.

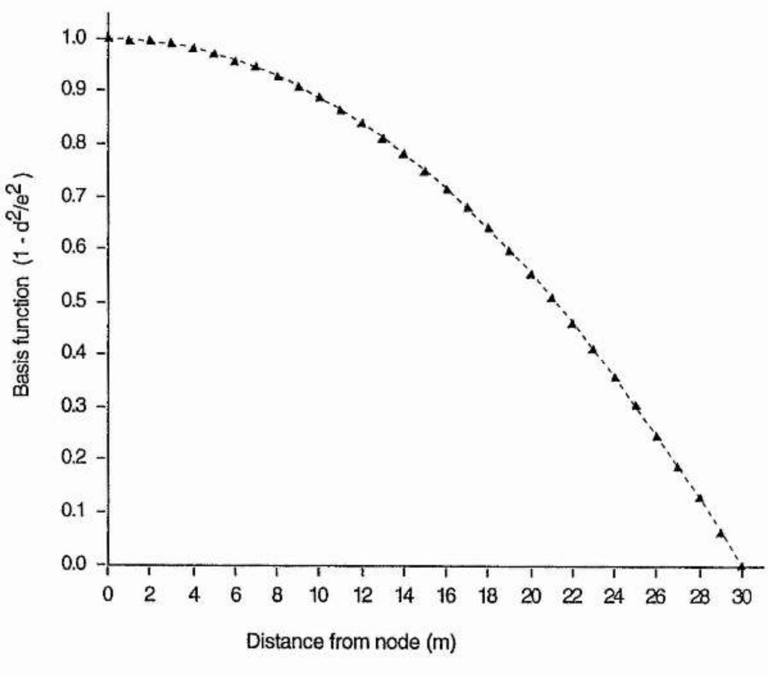


Figure 4.8. Arthur's (1965) basis function.

Hardy (1971) has given his interpretation of the method of surface fitting as a summation of the mathematical surfaces as defined by a basis function, where the value of a combined surface at a point of interpolation is the interpolated value.

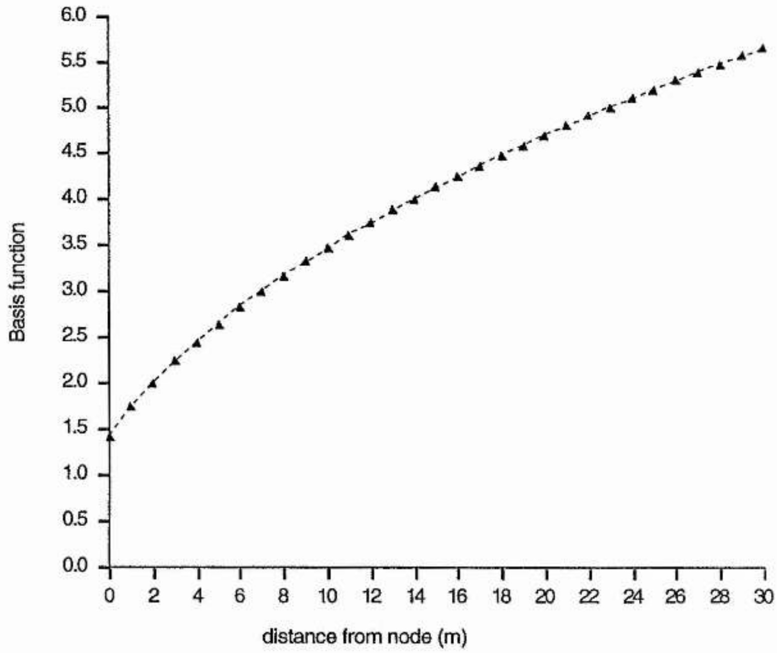


Figure 4.9. Hardy's (1977) basis function.

The basis function used by (Hardy, 1977), as shown in equation (4.8), is in the form of an hyperboloid (Figure 4.9).

$$\Delta(p_i - p_j) = [(p_{ix} - p_{jx})^2 + (p_{iy} - p_{jy})^2 + e_j^2]^{1/2} \qquad (4.8)$$

Expression (4.8) acts to increase the relative influence of the data as the distance (p_i - p_j) becomes larger, i.e. like a inverted decay function. The arbitrary constants, e_j, are used to avoid sharp 'peaks' and 'pits' at data points. The value can be arbitrary but is usually taken as a small percentage of the average distance between the node and all the data points in a subset.

A shortcoming of the method of collocation can be seen in that, for most cases, the interpolated depths are slightly shallower in comparison with the depths obtained by other methods. There is no means of checking the reliability of the resulting mathematical surface under this method and the subsequent interpolated value using the mathematical surface will remain ambiguous.

4.9 **MINIMUM CURVATURE SPLINE** - MCS

Instead of forcing a surface linearly through all the data points, the method of minimum curvature spline uses a surface with a smooth curve to fit between the data points.

4.9.1 **The spline concept**

A 'spline' is an instrument used by draughtsmen to join points on a curve. It may be bent to pass through the data points resulting in a smooth curve. If there is a systematic trend in the data the resulting smooth curve will cause wild oscillation between the data points resulting in extreme 'high' and 'low'. To reduce these unwanted oscillations, first a linear trend in the data has to be established by using a low order polynomial. The distortions can be reduced by fitting the residuals with a minimum curvature surface and adding it to the polynomial surface. The difficulty in achieving reliable results using this method is to find a good fit or to maintain minimum oscillation, if there are fewer data points available that can fit the computation of a surface.

The detailed concept and explanation of spline interpolation is given by Chapra and Canale (1987). Meinguet (1979, 1983) gives details of the mathematical theory underlying the minimum curvature surface. Harder and Desmarias (1972) introduced MCS originally for the interpolation of wing deflections in aircraft design. Minimum curvature splines are also discussed by Dyn and Levin (1982), Cheney (1986) and Wahba (1981, 1986).

However, the relevant mathematical treatment relating to surface fitting can be simplified through a mathematical model as presented below:

4.9.2 **Mathematical model**

$$Z(x,y) = b_0 + b_1x + b_2y + a_1\Delta(p_n - p_1) + a_2\Delta(p_n - p_2) + ... \ a_i\Delta(p_n - p_i) \qquad (4.9)$$

In the above equation, the first three terms are a low order polynomial which represent horizontal and tilted planes along the x and y axes. The rest of the terms of the equation build the minimum curvature surface. This is in accordance with Schut (1976) where a systematic trend in the data can be simultaneously determined and expressed as a low order polynomial. By fitting the residuals with a minimum curvature surface and adding it to the polynomial surface, the distortion can be reduced.

4.9.3 **Normal equations**

$$\begin{vmatrix} 1 & x_1 & y_1 & 0 & \Delta(p_1\text{-}p_2) & \Delta(p_1\text{-}p_2) & \Delta(p_1\text{-}p_2) \\ 1 & x_2 & y_3 & \Delta(p_1\text{-}p_2) & 0 & \Delta(p_1\text{-}p_2) & \Delta(p_1\text{-}p_2) \\ 1 & x_3 & y_4 & \Delta(p_1\text{-}p_2) & \Delta(p_1\text{-}p_2) & 0 & \Delta(p_1\text{-}p_2) \\ 1 & x_4 & y_4 & \Delta(p_1\text{-}p_2) & \Delta(p_1\text{-}p_2) & \Delta(p_1\text{-}p_2) & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & x_1 & x_1 & x_1 & x_1 \\ 0 & 0 & 0 & y_1 & y_1 & y_1 & y_1 \end{vmatrix} \begin{vmatrix} b_0 \\ b_1 \\ b_2 \\ a_1 \\ a_2 \\ a_3 \\ a_4 \end{vmatrix} = \begin{vmatrix} Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ 0 \\ 0 \\ 0 \end{vmatrix}$$

The normal equations presented above are meant for four data points. In the system of equations, the first four equations are associated with the combination of a low order polynomial with the minimum curvature surface.

The fifth equation in the system, is the summation of the coefficients which is equal to zero, as a requisite for a continuous first derivative. The sixth and seventh equations are conditions for exact fit between the data points.

4.9.4 **Basis function**

The basis function used is that advocated by Franke (1982) and is in the form of $\Delta(p_i - p_j) = d^2 \log d$, where d is the distance between two data points, p_i and p_j. The shape of the function resembles an hyperboloid with a monotonic increase in values as the distances increases from the centre (Figure 4.10).

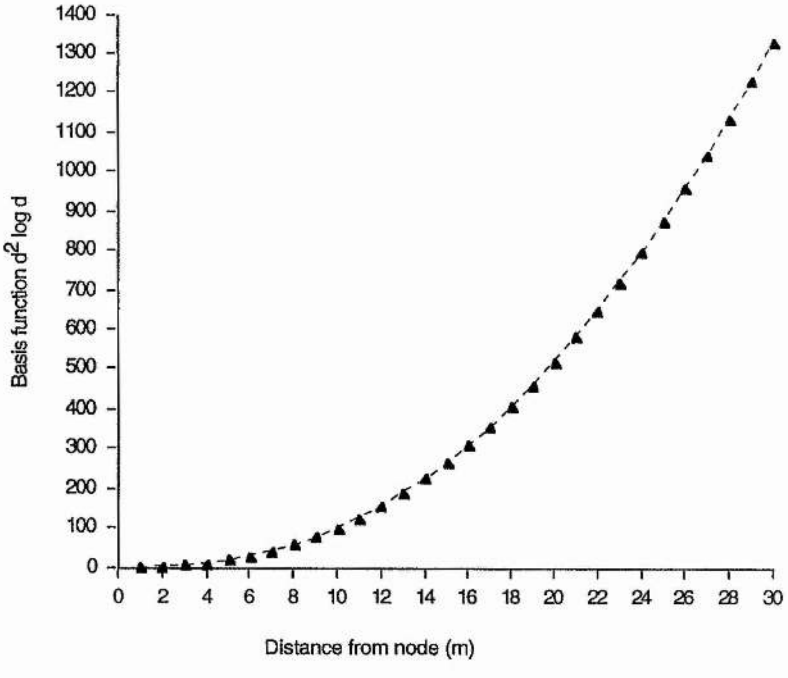


Figure 4.10. Franke's (1982) basis function in the form of an hyperboloid shape.

4.10 **METHOD OF LEAST SQUARES** - LSQ

The method of least squares, however, is based on a criterion whereby a surface is fitted to a set of data points by the use of a polynomial, such as linear, cubic or quadratic equations, that minimises the sum of the squares of the residuals.

4.10.1 **The concept**

Since the values of measured depths Z_i (i=1,2...n data points) in the mathematical models inevitably contain measurement errors, the need to make such a surface to pass exactly through all the data points is not appropriate. A method of least squares will approximately adjust a surface to fit to the set of data as closely as possible and at the same time minimise the sum of the squared residuals. This can be expressed as:

$$\varnothing_i = \Sigma[\, Z_{comp.} - Z_{meas.}]^2 \qquad (4.10)$$

where $\varnothing_i$ is a minimising function.

The underlying theory of the principle of least squares is found elsewhere, e.g. Cross (1990), Mikhail and Gracie (1981). A more rigorous method is provided by Ayeni (1979), where an optimum least squares interpolation can be achieved by using a stepwise regression. Stepwise regression is a statistical method for selecting the most significant independent variables from a given set of variables to be included in the 'best' regression equation. In the context of seafloor topographic mapping, the independent variable, Z, represents depth and the independent variables, x and y, are functions of a location corresponding to each depth.

The so-called optimum least squares interpolation includes only the significant terms in the equation to be included in the regression model. This involves adding and deleting a term until, at the end, only the most significant terms which make the greatest improvement to the goodness of fit are included in the model.

Thus, the derived coefficients of the interpolation formula are more stable and less sensitive to small data sets and observational errors present in the data. Although this method is technically sound, its exclusion in the methods of selection is mainly because it is lengthy and involves complicated procedures.

Claussen and Kruse (1988) used four mathematical functions (see Table 4.5) and applied them by partitioning the search area around the grid point into eight octants and choosing a certain number of closest points of each octant. With a small data subset the partitioning into octants may be applicable and the configuration will in itself become a common neighbour.

The computations may begin first with the elliptical surface. The standard deviation derived from the difference between the data points and the corresponding points on the computed surface will provide residuals. If the residuals are, in general, in excessive of the prescribed accuracy, then the interpolation will proceed with the next mathematical function, and so on.

A trial computation based on the four mathematical functions; elliptical, hyperbolic, oblique and plane equations using a small number of data points suggests that there is not much improvement in the interpolated value although there are slight changes in the residuals (Table 4.5). This is the reason why the method proposed by Ayeni (1979) is not included in the choice of methods. Perhaps, with a small number of data points (e.g. with less than 20) there is no significant difference in the outputs of the various equations.

Table 4.5. Computation by least squares method using the four different mathematical functions

Depth	(Elliptical)		(Hyperbolic)		(Oblique)		(Plane)	
meas.	comp.	resd.	comp.	resd.	comp.	resd.	comp.	resd.
10.9	10.730	0.169	10.733	0.167	10.707	0.192	10.289	0.620
10.4	10.209	0.190	10.207	0.193	10.219	0.181	10.280	0.120
10.3	10.584	- 0.284	10.582	- 0.282	10.607	- 0.307	10.280	0.200
9.5	9.923	- 0.423	9.924	- 0.424	9.926	- 0.426	10.280	- 0.780
10.3	9.953	0.347	9.953	0.347	9.941	0.359	10.280	- 0.020

meas. - measured depth
comp. - computed depth
resd. - residual

(Elliptical surface): $Z(x, y) = a_0 + a_1 x + a_2 y + a_3 xy + a_4 x^2 + a_5 y^2$

(Hyberbolic surface): $Z(x, y) = a_0 + a_1 x + a_2 y + a_3 xy$

(Oblique plane): $Z(x, y) = a_0 + a_1 x + a_2 y$

(Horizontal plane): $Z(x, y) = a_0$

4.10.2 **Mathematical model**

In bathymetric data interpolation essentially requires a simple and straight forward method; lengthy procedures are unaffordable from a computing point of view. Thus, only the basic principle of least squares is used here and a brief outline is provided merely as a precursor to the description of the method to be followed.

The choice of the mathematical model can be selected from a list of monomials that represent a plane to a much more complex surface. However, the mathematical model adopted for this application is in the form of second order polynomial equation:

$$f(x, y) = a_0 + a_1x + a_2y + a_3xy + a_4x^2 + a_5y^2 \qquad (4.11)$$

A derivation is provided here as a brief outline on the procedure involved. To minimise the function $\O_i$, a partial derivative is taken with respect to each unknown, i.e. with respect to each coefficient, and equated to zero. As an example the partial derivative with respect to a_0 is given as:

$$\O_i = \Sigma[\, a_0 + a_1x + a_2y + a_3xy + a_4x^2 + a_5y^2 - Z_{meas.}]^2$$

$$\frac{\partial \O}{\partial a_0} = 2\Sigma\left(a_0 + a_1x + a_2y + a_3xy + a_4x^2 + a_5y^2 - Z_{meas.}\right) = 0$$

$$2Z_{meas.} = 2\Sigma\left(a_0 + a_1x + a_2y + a_3xy + a_4x^2 + a_5y^2 \right)$$

$$Z_{meas.} = a_0\,(N) + a_1(\Sigma x) + a_2(\Sigma y) + a_3(\Sigma xy) + a_4(\Sigma x^2) + a_5(\Sigma y^2) \qquad (4.12)$$

The derivation above is for only one equation and the rest of the equations are obtained in a similar manner to the steps leading to equation (4.12). These lead to the formation of normal equations.

4.10.3 **Normal equations**

$$\begin{vmatrix} n & \Sigma x & \Sigma y & \Sigma xy & \Sigma x^2 & \Sigma y^2 \\ \Sigma x & \Sigma x^2 & \Sigma xy & \Sigma x^2y & \Sigma x^3 & \Sigma xy^2 \\ \Sigma y & \Sigma xy & \Sigma y^2 & \Sigma xy^2 & \Sigma x^2y & \Sigma y^3 \\ \Sigma xy & \Sigma x^2y & \Sigma xy^2 & \Sigma x^2y^2 & \Sigma x^3y & \Sigma xy^3 \\ \Sigma x^2 & \Sigma x^3 & \Sigma x^2y & \Sigma x^3y & \Sigma x^4 & \Sigma x^2y^2 \\ \Sigma y^2 & \Sigma xy^2 & \Sigma y^3 & \Sigma xy^3 & \Sigma x^2y^2 & \Sigma y^4 \end{vmatrix} \begin{vmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{vmatrix} = \begin{vmatrix} \Sigma Z_{meas} \\ \Sigma xZ_{meas} \\ \Sigma yZ_{meas} \\ \Sigma xyZ_{meas} \\ \Sigma x^2Z_{meas} \\ \Sigma y^2Z_{meas} \end{vmatrix}$$

The above system of normal equations always has a unique solution that determines a minimum $\O_i$. To evaluate, for interpolation accuracy, each and every selected data point used in the computation is re-interpolated back into Equation (4.11) using the solved coefficients to determine their corresponding computed value. A comparison between the observed and the computed data will provide the residuals.

However, a shortcoming in this method is that it is difficult to find a good fit between the observed and the computed values especially where the data points are very unevenly distributed, erratic, or with very large depth differences.

4.11 SUMMARY AND DISCUSSION

The basic problem of obtaining information on seabed changes by comparison between bathymetric data is having to re-arrange the data into a common suitable format. One way of doing this is by using a cross-sectional plot. However, this method may not fully represent the topography because it concentrates only on information along the cross-sectional line. To capture sufficient information means closer cross-sections are required. However, cross-section intervals of less than 10 metres are not practical because these involve too many drawings or cross-sections to evaluate.

As an alternative to the cross-sectional method, manual inspection by 'eye-balling' of charts or maps proves impractical especially if large data sets or areas are involved. The technique of 'eye-balling' is also complicated if the size and magnitude of change is small and irregularly scattered. One possible solution is to grid the bathymetric data at spatially fixed points. The most common form is that of a square grid.

Results from interpolation can be very subjective, if the magnitude of change sought is of the same order as the micro-structure level. The differences between the various interpolated values are often about the same magnitude as the size of the bathymetric change. Six distinct interpolation methods have been identified and their suitability for this application discussed. Inter-comparison between the results requires a selection of one single value to determine the value for the node.

The first method identified is based on a single closest data point to the node that falls within the definitive limit in the search area. It is a method where a value, if qualified, is 'pigeon-holed' into the nearest matrix. If the definitive limit is kept small, then this method will become the most ideal form of interpolation because it involves only the minimum amount of computation. However, this method seldom works for the entire data set unless there is always a data point close to every grid point.

Table 4.6. Data set for trial computation (see page 103)

	Node:	X 342537.5 Y 730662.5
X	Y	Z
342524	730668	9.8
342532	730670	10.9
342540	730672	10.4
342548	730674	9.2
342522	730658	10.4
342532	730661	10.3
342543	730663	9.5
342553	730666	6.0
342530	730650	9.9
342541	730653	10.3
342553	730656	8.7
342536	730643	8.1
342545	730645	7.2
342529	730682	9.5
342540	730685	7.7
342516	730666	7.7
342556	730676	6.7
342561	730658	6.5
342527	730641	6.8
342554	730648	5.9

The second method is the IDWM which requires that all data points found within the range of the interpolation point are used in the computation. This method is based on a weighted average where each individual data point is a predictor to the interpolation point. By summing of the influence of each data point the interpolated value is obtained. However, this method has a prominent disadvantage in that it fails to avoid the 'shadowing' of the influence of a data point by a nearer one in the same direction.

The interpolated value is sensitive to the distance and location of data points. This method cannot infer an interpolated value that is higher or lower than the maximum and minimum values of the data subset.

As an alternative to using all the data points (common neighbourhood) only a few selected data points which represent a quadrant are used. With four quadrants this method works quite satisfactorily but the interpolated value can be perturbed unduly if one of the preferential data points is an aberrant value. This is, however, opposed to the original idea of IDWM which is based on common neighbour configuration.

The simple linear interpolation method, however, is designed to use quadrant neighbour data in its computation. Using simple linear geometry this method interpolates linearly between two adjacent survey lines. The problem with this method is that, the interpolated values obtained along the x and y axes are different.

The three methods discussed above can be categorised as distance-based methods. Linear distances are used in their computations. However, instead of using linear distance relationships, methods based on a mathematical surface may be considered in the list of selected methods of interpolation. These methods fall under the category of fitted function methods.

There are three variants under this category: (i) a surface is made to fit linearly and exact through all the data points; (ii) a smooth surface is fitted exactly between the data points; and (iii) a surface that satisfies the minimum sum of residuals.

In the so-called Fitted Function Methods, the parameters of an analytical bivariate function that represents the data have to be determined. This is done by forming a set of equations which are different from the conventional way.

A trial computation using each selected method was performed for a node based on a common data set as shown in Table 4.6. In addition, the radius of search was incrementally increased in steps from 10 to 24 metres to study the variations in the results. The results are tabulated in Table 4.7.

Of specific interest is the result obtained by the method of least squares (Table 4.5), where the choice of monomials is insignificant. Using a small size of data subset does not significantly change the interpolated value.

The results from the trial computations suggest that all the methods produce a wide range of values which in some cases are unreasonably large. The obvious effect of the wrong choice of search radius will be an increase in the number of data points and this inevitably increases the amount of computation.

Table 4.7. The effect of varying search radius length (r) on interpolated depths.

Radius	r=10	r=11	r=13	r=15	r=16	r=17	r=18	r=20	r=24
No.of points	3	4	5	6	9	11	12	13	20
IDWM - Cnbr	10.086	10.108	10.108	10.085	9.909	9.889	9.889	9.972	9.548
IDWM - Qnbr	10.043	10.073	10.073	10.073	10.073	10.073	10.073	10.073	10.072
SLIM - Qnbr	10.200	10.238	10.238	10.238	10.238	10.238	10.238	10.238	10.238
COL - Cnbr	9.157	9.431	9.431	10.105	10.435	10.365	10.365	10.330	10.154
LSQ - Cnbr	9.936	10.263	10.263	10.197	9.576	9.558	9.558	9.718	10.263
MCS - Cnbr	9.936	9.942	9.942	10.107	9.942	10.258	10.258	10.300	-

Cnbr - Common neighbour
Qnbr - Quadrant neighbour

In bathymetric mapping having an unnecessarily large number of data points in a computation does not significantly improve the results, indeed it may sometimes worsen it. Basically, in an interpolation, a minimum number of three data points will produce a result. However, if four data points are available each of which represents a quadrant, then this will provide a reasonable azimuthal consideration.

It is also found that a search radius of between 1 and 2 times the sounding line spacing is capable of providing a minimum to an optimum number of data points to qualify for interpolation. A radius length of beyond twice that of the sounding spacing can become unacceptable as this will increase the number of data points and, at the same time, will not improve the interpolated value. Therefore, one has to be critical in selecting the minimum and maximum size of the search radius.

One must also be aware that, if the gridded values of a data set are ambiguous, then the subsequent changes determined by taking the difference between any two gridded data sets will produce a false estimate of change. The selected method, however, still cannot qualify unless it is implemented in a consistent way using a well defined data subset. Thus, a technique based on a blending approach is herein adopted to minimise the effect of interpolation ambiguity resulting from the inconsistency in the procedure of interpolation by each method. The technique known as the Blending Interpolation Technique (BIT) is designed to implement the above methods, incorporating additional features into a single system. This technique will be discussed in Chapter 5.

CHAPTER 5

PROPOSED TECHNIQUE AND PROGRAMMING APPLICATIONS

5.1 INTRODUCTORY REMARKS

A variety of interpolation methods, namely SCNP, IDWM, SLIM, COL, MCS and LSQ, have been introduced and discussed in some detail in Chapter 4. The ultimate goal of depth interpolations here is to obtain optimum depths representation at grid nodes, so as to discretise the seabed topography into a regular grid form. As previously noted, interpolated depths obtained by SCNP can be considered as optimum because they are close to the measured values and therefore require no further attention. However, results from trial computations conducted for the rest of the methods have disclosed that there can be significant differences between their values. If the differences are small (say < 0.2 metres) it is unlikely that there will be any significant problem over which depth to select. However, if the differences are significantly large then they raise problems over how to determine which of the five depth values is the most probable.

Judging on the theoretical basis and the mathematical structure on which each of the five methods was built, there can be no doubt that the methods were all suitable for use in interpolation of depth at an undetermined location. However, this is not always the case the trial computations revealed that within and between the methods there are sometimes unacceptably large differences (> 0.5 metres), which may not have been recognised if just one method had been used. However, if the five depth values are combined, they can form an ideal set for comparison, from which a judicious selection of a single depth value for a grid node can be made.

The differences between the interpolated depths also pose a question of whether the use of a single interpolation method, as commonly found in many forms of commercial software, to grid the entire bathymetric data set of an area, is valid. Inevitably, if significant differences that exist in gridded data are not minimised then subsequent use of such data might lead to either grossly inaccurate or unrepresentative results.

One possible reason that can account for the large difference in the results between the methods can be attributed to indiscriminate use of the methods without realising their limitations or ill-defined use of data points while interpolating. It will be helpful therefore, if there are clear guidelines to indicate which interpolation methods seem to work 'best' under certain circumstances. However, systematic guidelines and procedures, especially on performing depth interpolation for comparison of seabed topography, are either unavailable or unsatisfactory. Although many attempts have been made to address interpolation problems (e.g. Sallaway, 1981; Casey and Monahan, 1986; Eddy and Looney, 1993) all have been related to contouring or other issues, not to the gridding of bathymetric data.

Lam (1983) reviewed methods for spatial interpolation and arrived at two general conclusions: (1) no one method may be singled out as the 'best'; and (2) the selection of an appropriate method depends on the type of data, degree of accuracy desired, and amount of computation afforded.

The fact that there is no single 'best' method, has again been confirmed by the results of the trial computation shown in Table 4.7. Even by a slight increase or reduction in the length of the search radius, one can expect a significant change in the interpolated depth value. In other words, a method may work quite well for one data set but not necessarily perform as well on another. The choice of a method is commonly attached to the user accuracy requirements, data density and uniformity, and also to how the methods are to be programmed if storage and processing speed are the main considerations. But, even when seeking a decision on which method is the 'best' for an application, there is no clear and definite answer. Faced with this complication, it was recognised that there is a need to formulate a computational strategy which could minimise the differences so as to lead to more consistent results.

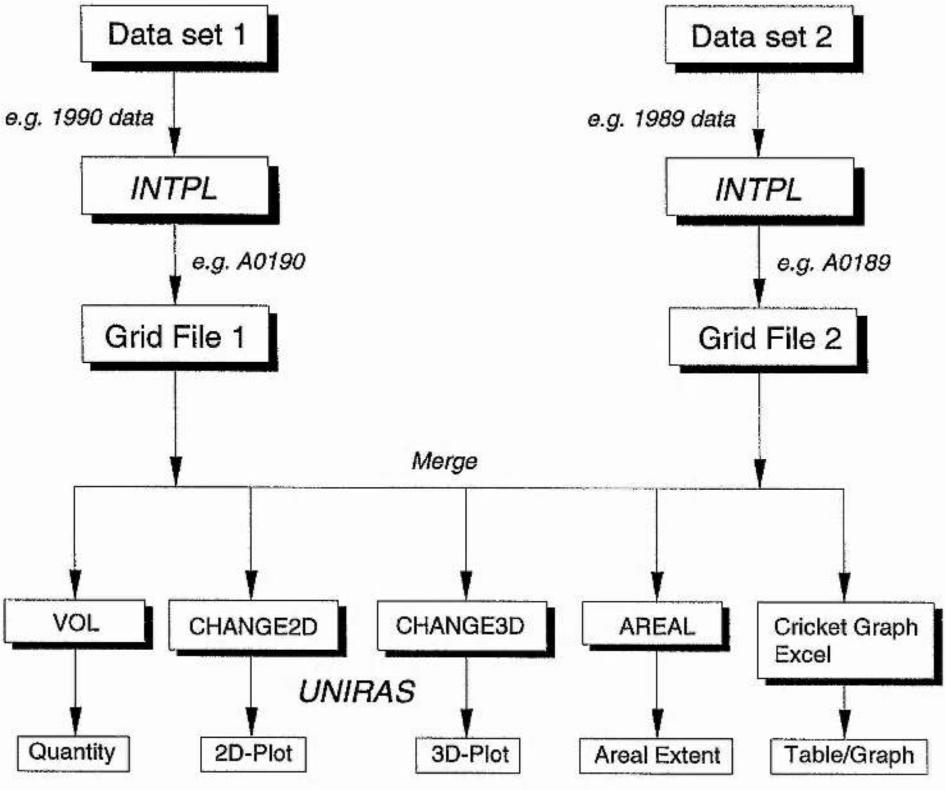


Figure 5.1. The BIT modules (see page 108).

It is therefore intended in this chapter to proposed a technique that serves as a possible solution to the problem of gridding of bathymetric data, and is called the *Blending Interpolation Technique*. It is designed to provide a systematic procedure for objective gridding and to extend the display of results. It incorporates software including a computer program *INTPL,* which is specifically written for this purpose. The outputs are in the form of gridded data which can be fed into UNIRAS routines, to further demonstrate the extension of the technique. This chapter provides the detailed description and the implementation of such a technique.

5.2 BLENDING INTERPOLATION TECHNIQUE - (BIT)

The Blending Interpolation Technique is based on a modular concept formulated to use all the six selected methods by incorporating them into a single computer program called *INTPL*. Some additional features (such as: (1) grid orientation; (2) data points configuration and arrangement and (3) depth selection strategy) are introduced by blending them together to arrive at a more objective approach towards depth interpolation at the grid nodes. By possessing these blended characteristics and incorporating the above mentioned additional features within the program, it will justify an assumption that the interpolated values thus derived are the representatives of all possible depth values that an interpolation may take. It will also provide the extreme possible values which form the maximum and the minimum.

BIT has the facility of a user-application program capable of being designed, with some modification, where necessary, to host graphic subroutines. A schematic diagram (Figure 5.1) lists the various modules that compose BIT.

Given two sets of data designated as Data Set 1 and 2 respectively, they are individually gridded into 2 separate Grid Files by *INTPL.* These two files are then merged together into a single file by the user-application program *CHANGE2D* as a differential file or by some other user-own application programs as listed, to display for example a 2D/3D-plot. Alternatively, the information resulting from a merged file can be manipulated to obtained the various other outputs such as volume, area, graph and table.

This example of a modular computing environment is not peculiar in a situation, for instance, where there is no suitable software to perform a specialist task such as an investigation of seafloor topographic changes. For example, Laughlin et al. (1993) demonstrate an approach to the analysis of spatial data not performed within a single program, but in three separate software/hardware environments. The development of BIT for such a study using bathymetric data is also stimulated by the ideas presented by Moritz and Randall (1995) in their simulation program ODAMS on the quantitative assessment of open water disposal activities. Tipper (1976) provides a discussion and example on how sediment deposition and erosion surfaces can be represented.

5.3 COMPUTATIONAL STRATEGY

The core of BIT lies in the computer program *INTPL*. To justify the computational aspects of this computer program, the following criteria are used as a basis of its operation:

(1) Interpolation procedures for a node must be based on a common data subset, which contains a set of nearest data points to be used in all the methods. This will place an emphasis more on local rather than global isotropic. In other words, it gives priority to local details.

(2) The interpolated value has to be within a small tolerance limit set above the maximum and below the minimum values of the data subset. This is to accommodate possible interpolated values that might exceed the maximum and minimum values of the data points and at the same time to avoid excessive 'peaks' and 'pits'.

(3) As there is no one method of interpolation that can work independently as a singled out 'best' method, a comparative approach is inevitable and therefore has to be adopted. This will be accomplished by the procedure of depth selection strategy in which a selection of a single depth value is obtained.

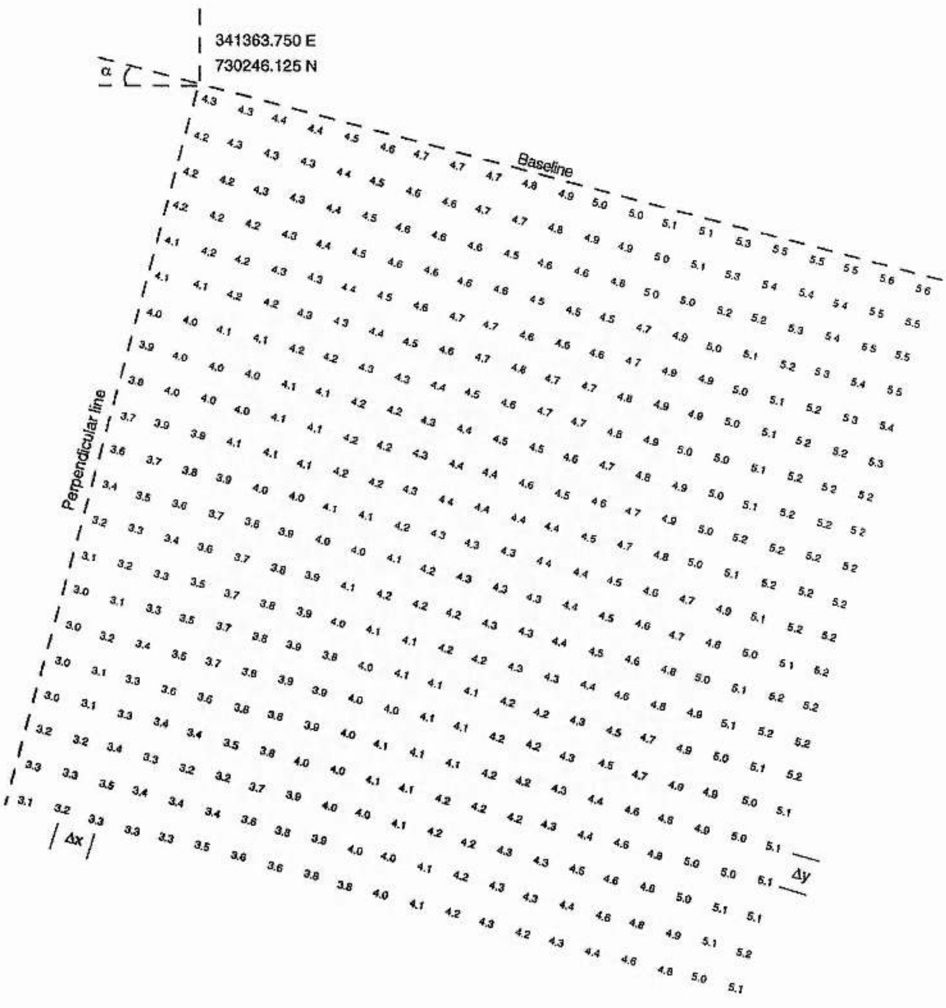


Figure 5.2. A graphical explanation of the parameters; rotation angle (α), baseline, perpendicular line and upper left co-ordinates.

5.3.1 **Grid generation and orientation**

The term 'gridding', as defined in Section 4.2, requires that the area under investigation has to be first subdivided into smaller domains each known as a 'grid', which is a representation of a network of nodes. Grid generation for an area is accomplished by specifying five parameters: an origin (x,y co-ordinates); base-line; perpendicular-line; x and y spacing; and its orientation.

The origin is taken as the upper left most corner of the grid and is defined by its co-ordinates. If unrotated, a base-line usually trends parallel to the x-axis and is defined by its length whilst the perpendicular-line trends at right angled to the base-line. The Δx and Δy spacings will determine the number and the size of spacings of nodes within grid. A combination of these five parameters constitutes a block. Figure 5.2 is a graphical illustration of a block as defined by the parameters.

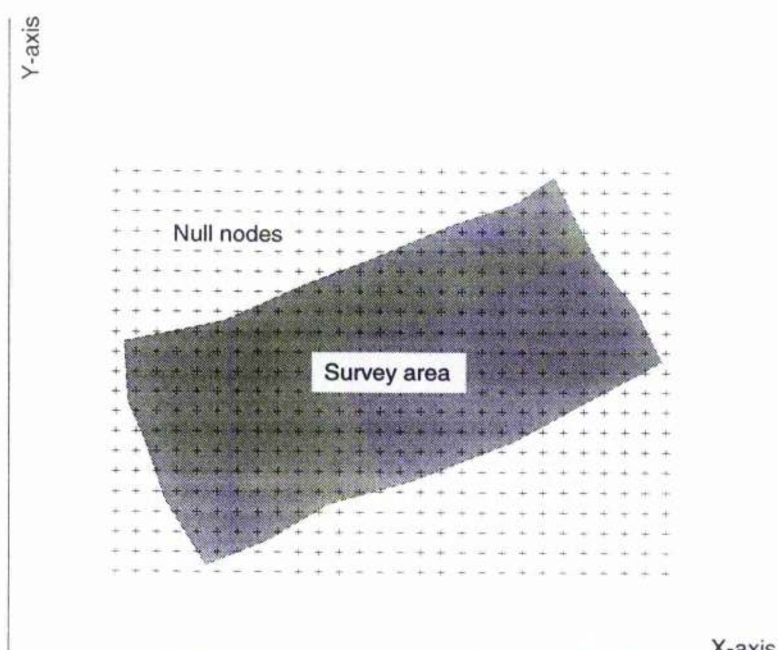


Figure 5.3. An area overlay with a normal grid

The limits of the grid are designed to encompass only the area covered by the data (dark patches as shown in Figures 5.3 & 5.4). The initial arrangement is normally done in a north-south and east-west direction as illustrated in Figure 5.3. However, such an arrangement will include a significant numbers of undesirable nodes, which are external to the boundary of the data points. These undesirable nodes are called 'null' nodes because they are not surrounded by data points. These redundant node points will not be considered; because in such cases interpolations cannot take place.

The inclusion of the null nodes will not only increase the unnecessary computational work but also introduces extra data storage. Thus, orientation of the grids is necessary to reduce the numbers of redundant nodes and, at the same time, to fit the area into a smaller map area as depicted in Figure 5.4.

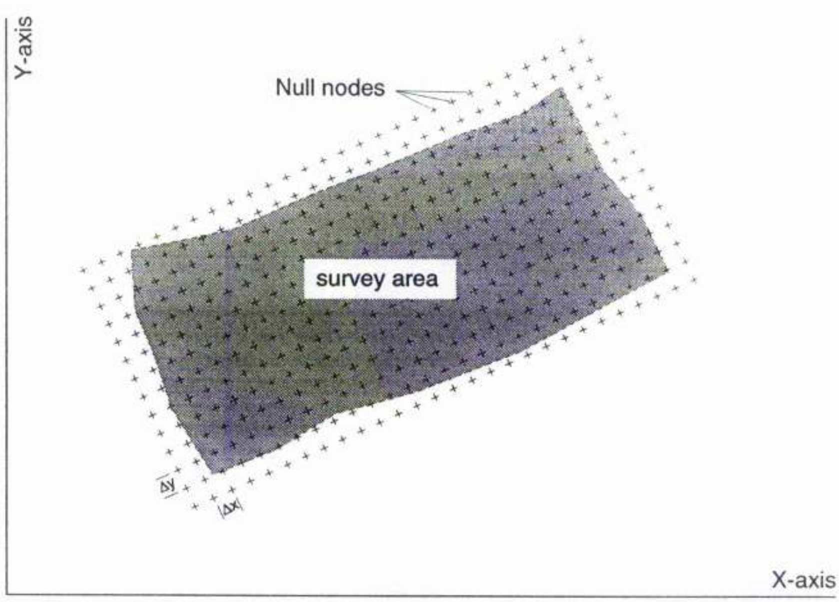


Figure 5.4. An illustration of a rotated grid. Δx and Δy are grid spacing along axes x and y respectively.

5.3.2 **Boundary of data subset**

In the field of computational geometry (Preparata and Shamos, 1990), an efficient and popular way of bounding a set of data points is by using a convex hull. It has been subject to a variety of investigations mainly to define an efficient way to determine and handle the convex hull of a data set (e.g. Graham,1972; Jarvis,1973; Eddy, 1977a; Green and Silverman, 1978). Basically, there are three distinct ways to define the boundary of a data subset namely: a Common boundary; Convex hull boundary; Natural neighbour boundary.

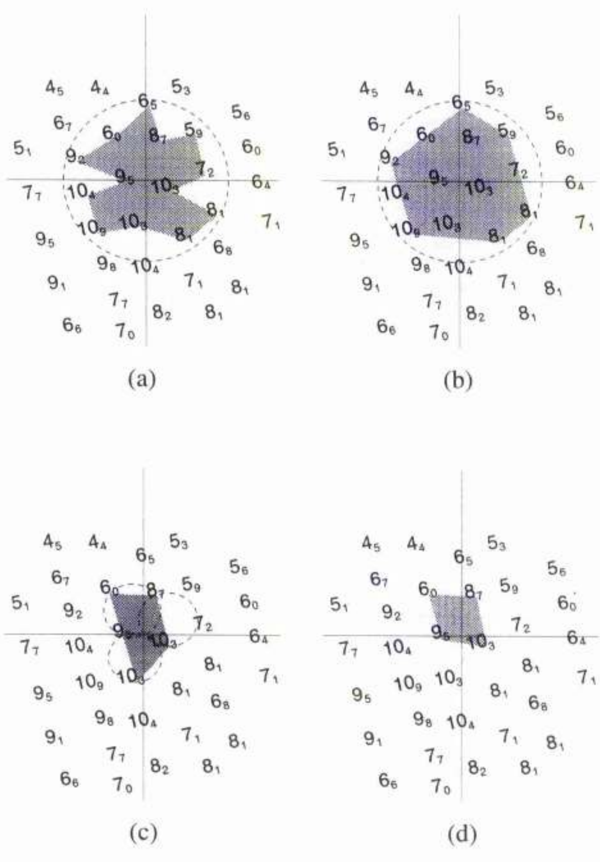


Figure 5.5. Four different possible boundaries for data subset. (a) Common boundary, (b) Convex hull boundary, (c) Natural neighbour boundary and (d) Quadrant neighbour boundary.

A common boundary for a data subset (Figure 5.5a) is arbitrarily defined as a polygon that joins all the data points in a subset and there will be no data point found within its boundary. However, a common boundary may result in a number of ways that the polygon can be constructed. Thus, a preferable type of boundary is introduced, i.e. a convex hull boundary.

A simple definition for a convex-hull configuration is provided by Watson (1992), where a convex hull is a region enclosed by a connected set of straight line segments around the perimeter; none of the lines can be extended between any of the data points because each data point lies either on one of these bounding line segments, or to only one side of each such line, i.e. the boundary of the convex hull has no indentations - Figure 5.5(b).

A more specialised form of boundary which is commonly used in spatial data analysis is a natural neighbour boundary (Figure 5.5c). The natural neighbour boundary of a node is established by circles that pass through the node and three or more data points such that no data point lies inside any of these circles (Watson, 1985). Ambiguity sometimes exists if data points are close to a straight line or collinear. Nevertheless, the natural neighbour boundary will not be considered because the objective of interpolation here does not warrant the use of such a specialised boundary.

The use of a convex hull as a boundary for a data subset however, is important in particular to determine whether an interpolation situation exists. It is used as a criterion to distinguish whether it is interpolation or extrapolation. For example, if a node position falls on or within the convex hull boundary of the data subset, then the subsequent calculation is simply an interpolation. However, if a node position falls outside the convex hull of the data subset then obviously it is an extrapolation, and it can be eliminated from further consideration.

A convex hull boundary has been used in conjunction with the proposed method of SLIM. Under SLIM, only the closest data points are used, i.e. those belonging to the quadrant neighbour points. Quadrant neighbour points comprise data points each representing a quadrant that is the closest to the node (Figure 5.5d). A quadrant neighbour boundary therefore forms the shape of a triangle if only three data points are available, or a rectangular shape if there are four data points.

The method of determining the convex hull as used here is due to Eddy (1977a). The convex hull algorithm was represented in two subroutines called *SPLIT* and *CONVEX* (Eddy, 1977b).

```
SUBROUTINE SPLIT (N,X,M,IN,II,JJ,S,IABV,NA,MAXA,IBEL,NB,MAXB)
```

The subroutine *SPLIT* consists of 7 inputs and 6 outputs where the inputs are:

N - total number of data points in a set

X(2,N) - (x & y) co-ordinates of the data with 2 rows and N columns

M - number of points input as data subset

IN(M) - subscripts for array X of the points in the input subset

II - subscript or array X of one point on the partitioning line

JJ - subscript for array X of another point on the partitioning line

S - switch to determine output

and the outputs are:

IABV(M) - subscript for array X of the points above the partitioning line

NA - number of elements in IABV
MAXA - subscript for array X of point furthest above the line which is set to zero if NA is zero

IBEL(M) - subscript for array X of the points below the partitioning line

NB - number of elements in IBEL

MAXB - subscript for array X of point furthest below the line which is set to zero if NA is zero

The subroutine *CONVEX* consists of 4 inputs, 2 work areas designated by parameters (IA,IB), and 3 outputs.

```
SUBROUTINE CONVEX (N,X,M,IN,IA,IB,IH,NH,IL)
```

where,

IA(M) - subscript for left son subsets

IB(M) - subscript for right son subsets

IH(M) - subscript for array X of the vertices of the convex hull

NH - number of elements in array IH and IL

IL(M) - a linked list giving in order in a counter clockwise direction the elements of array IH

The subroutine *SPLIT* requires the input of a data subset as array X, which contains M data points. It will then partition the array with respect to a particular line, forming two arrays of points (IABV and IABL). These two arrays are referred to as the 'above' and 'below' arrays respectively. Successive calls to *SPLIT* by *CONVEX* will then form the convex-hull of the data subset.

5.3.3 **Point containment test - (PCT)**

A crucial stage before an interpolation, is to carry out a so-called 'point containment test' to determine whether a node point falls within, or outside, the convex hull of its selected data points. To do this, simple mathematical testing is required. Having formed the boundaries of the data subset by constructing its convex hull, a horizontal ray (or horizontal line) is taken to pass through the node point and the x co-ordinate of the point of intersection between the ray and the convex hull boundaries are worked out. Only the x co-ordinate needs to be determined as the y co-ordinate always remains constant (Figure 5.6).

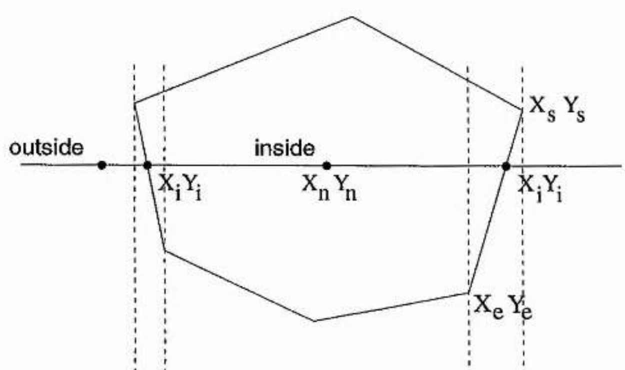


Figure 5.6. Graphical illustration of a point containment test

Every boundary of the convex hull is searched for intersection (see page 243). Each time an intersection is found, a check is made to find if the x co-ordinate of the intersection falls within the values of the x co-ordinates of the two end-points of the edge (X_s and X_e respectively). If it is so, then a count is made. After going through all the edges then a decision made is based on the number of counts. If there are 2 counts then the node points will definitely fall within the convex hull. If only one count is made then the node point falls on the boundary. If none, it definitely falls outside the convex hull. Similar approaches to the above method are also described in Bowyer and Woodwark, (1983) and Laurini and Thompson, (1992).

5.4 **Depth selection strategy - (DSS)**

A decision to proceed with an interpolation will be made only if a node falls inside or on the boundary of its data subset. Tables 5.1 and 5.2 were samples of results of interpolation extracted from the gridded files of the computer program *INTPL* for the 1989 and 1990 data respectively. In general, the results obtained are reasonably close to one another except in some cases where the effect of low and high depth values are apparent (those shown with an asterisk). The results also provide an impression of the problem one might confront if a single method is used to grid the whole data set. Even if there is a small difference between the results one may be faced with a dilemma of which one to choose from. This may become extremely confusing if the difference is between 0.3 and 0.5 metres, in particular if micro-scale level changes (≤ 0.3m) are to be considered in the study of seabed changes. If an interpolated value belongs to a group having deviations of this size, it would not be accepted as a mean of taking a practical decision.

A simple guideline is set whereby all interpolated depths having deviations which exceed 1 metre or more could possibly be due to errors in the data. A query on the interpolation and the data therefore has to be made, which may require a separate individual interpolation. However, interpolated depths with deviations which are equal to or less than 0.5 metres can easily be evaluated. Thus a selection approach has to be adopted through the so-called 'depth selection strategy', or DSS, to judicious selection of a single value from a group of interpolated depths.

Table 5.1. Example of interpolated depth values for 1989 data.

X	*Y*	*SCNP*	*SLIM*	*IDWM*	*COL*	*MCS*	*LSQ*	*BIT*
342458.438	730612.500	0.000	6.822	6.876	0.000	6.869	6.885	6.869
342463.375	730613.250	0.000	6.940	6.979	7.041	7.033	6.852	6.940
342468.312	730614.000	0.000	6.932	6.966	6.929	6.973	6.842	6.929
342473.281	730614.688	0.000	6.851	6.918*	6.610*	6.782	6.917	6.782
342478.219	730615.438	0.000	6.779	6.709	6.657	6.765	6.790	6.709
342483.156	730616.188	0.000	6.673	6.675	6.570	6.699	6.617	6.617
342488.125	730616.875	6.400	0.000	0.000	0.000	0.000	0.000	6.400
342493.062	730617.625	0.000	6.522	6.507	0.000	6.402	6.655	6.522
342498.000	730618.375	0.000	6.476	6.487	6.453	0.000	6.470	6.470
342502.938	730619.062	6.500	6.500	6.500	6.500	6.500	6.500	6.500
342507.906	730619.812	0.000	6.515	6.510	0.000	0.000	6.544	6.515
342512.844	730620.562	0.000	6.461	6.496	6.474	6.533	6.444	6.496
342517.781	730621.250	0.000	6.419	6.428	0.000	6.425	6.408	6.419
342522.750	730622.000	0.000	6.283	6.280	6.103	6.278	6.290	6.278
342527.688	730622.750	0.000	6.171	6.129	6.104	6.112	6.219	6.171
342532.625	730623.438	0.000	6.069	6.077	5.913	6.033	6.113	6.033
342537.562	730624.188	0.000	5.988	5.972	0.000	5.982	6.047	5.988
342542.531	730624.938	0.000	6.007	6.025	0.000	5.967	6.037	6.007
342547.469	730625.625	0.000	5.991	6.054	6.013	6.012	6.043	6.013
342552.406	730626.375	0.000	5.953	5.992	6.011	5.994	5.934	5.992
342557.375	730627.125	5.800	0.000	0.000	0.000	0.000	0.000	5.800
342457.719	730617.438	0.000	7.053	7.001	6.867	6.961	7.062	6.961
342462.656	730618.188	0.000	7.132	7.091	0.000	7.099	7.089	7.099
342467.594	730618.938	0.000	7.266	7.123	7.197	7.168	7.122	7.197
342472.562	730619.625	0.000	7.190	7.115	7.233	7.217	7.136	7.190
342477.500	730620.375	0.000	7.323	7.442*	7.412	7.411	7.071*	7.323
342482.438	730621.125	0.000	7.183	7.203*	6.791*	7.181	7.143	7.143
342487.406	730621.812	0.000	6.990	6.973	6.811	6.927	6.949	6.927
342492.344	730622.562	0.000	6.756	6.719	6.670	6.784	6.728	6.728
342497.281	730623.312	0.000	6.640	6.531	6.525	6.541	6.757	6.640
342502.219	730624.000	6.500	6.500	6.500	6.500	6.500	6.500	6.500
342507.188	730624.750	0.000	6.465	6.454	6.369	6.493	6.408	6.408

Table 5.2. Example of interpolated depth values for 1990 data.

X	*Y*	*SCNP*	*SLIM*	*IDWM*	*COL*	*MCS*	*LSQ*	*BIT*
342458.438	730612.500	0.000	6.755	6.764	0.000	6.776	6.774	6.764
342463.375	730613.250	0.000	6.272*	6.844	6.858*	6.849	6.390	6.390
342468.312	730614.000	0.000	6.189	6.128	5.718*	6.204*	6.197	6.128
342473.281	730614.688	0.000	6.435	5.887	5.669	5.716	6.352	5.887
342478.219	730615.438	0.000	6.648	6.633	6.676	6.692	6.482	6.633
342483.156	730616.188	0.000	7.220*	7.189	0.000	0.000	6.617*	7.189
342488.125	730616.875	0.000	6.741	6.650	6.630	6.644	6.724	6.650
342493.062	730617.625	6.200	0.000	0.000	0.000	0.000	0.000	6.200
342498.000	730618.375	0.000	6.426	6.417	6.476	6.434	6.421	6.434
342502.938	730619.062	0.000	6.415	6.379	6.451	6.456	6.317	6.379
342507.906	730619.812	0.000	6.273	6.272	6.103*	6.224	6.430*	6.272
342512.844	730620.562	0.000	6.298	6.311	6.103*	6.231	6.439*	6.298
342517.781	730621.250	0.000	6.399	6.460	6.319	6.395	6.393	6.393
342522.750	730622.000	0.000	6.551	6.590	6.490	6.613	6.642	6.551
342527.688	730622.750	0.000	6.909	6.873	6.798	6.935	7.046	6.909
342532.625	730623.438	0.000	6.949	6.849	6.173*	6.853	6.955*	6.849
342537.562	730624.188	0.000	6.451	6.403	0.000	6.363	6.451	6.403
342542.531	730624.938	0.000	6.115	6.090	0.000	6.118	6.098	6.098
342547.469	730625.625	0.000	6.099	6.101	0.000	6.098	6.087	6.098
342552.406	730626.375	0.000	6.083	6.127	0.000	5.896*	6.343*	6.127
342557.375	730627.125	0.000	6.150	6.193*	5.793*	6.055	6.301	6.055
342457.719	730617.438	0.000	6.785	6.788	0.000	6.790	6.790	6.788
342462.656	730618.188	0.000	6.839	6.784	6.898	0.000	6.660	6.784
342467.594	730618.938	0.000	6.461	6.458	5.838*	6.495	6.509*	6.458
342472.562	730619.625	0.000	6.242	6.232	6.144*	6.199	6.738*	6.242
342477.500	730620.375	0.000	6.843	6.958	6.605	6.818	6.839	6.818
342482.438	730621.125	7.300	0.000	0.000	0.000	0.000	0.000	7.300
342487.406	730621.812	0.000	6.892	6.800	6.933	7.034	6.638	6.800
342492.344	730622.562	0.000	6.581	6.589	6.575	6.566	6.674	6.589
342497.281	730623.312	0.000	6.518	6.533	6.449	6.517	6.464	6.517
342502.219	730624.000	0.000	6.445	6.452	6.512	6.497	6.391	6.452
342507.188	730624.750	0.000	6.361	6.397	6.231	6.342	6.405	6.342

The operation of DSS in essence involves comparisons between all the computed depths. First it is required to find the shallowest and the greatest depth among the interpolated values. Next, an average between these two extreme depths is taken and this in turn is compared with each and every interpolated depth. A closest depth to the average is selected as a final interpolated depth. In this way the final interpolated value falls within the range of the computed depth values (Figure 5.7). The argument of not selecting the average depth is purely a matter of choice but, under DSS, selecting a depth which is derived straight from a formula rather than by a normal averaging will inspire more confidence in the interpolated value.

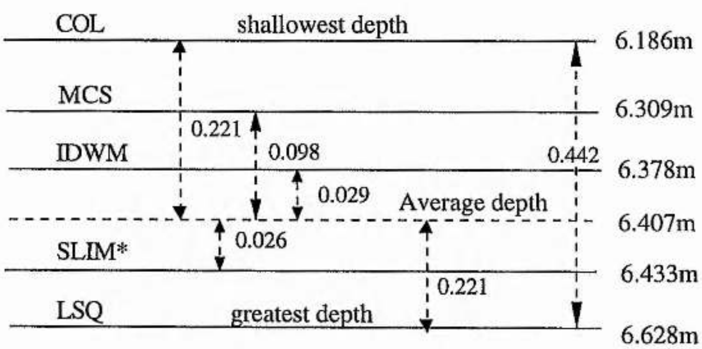


Figure 5.7. Depth Selection Strategy: the final depth is provided by SLIM. (Figure not to scale)

COL - Collocation
MCS - Minimum curvature spline
IDWM - Inverse distance weighting method
SLIM - Simple linear interpolation method
LSQ - Least squares

5.5 The developed software

In the following sections the various computer programs that form the BIT are described and presented:

5.5.1 *INTPL*

The characteristic of the interpolation program *INTPL* is based on a common notion of integrating the various interpolation methods discussed earlier into a single system. Within the program, features such as grid orientation, convex hull, point containment test and, most importantly, the decision of a final depth selection by DSS will justify the computational aspect of the technique.

The following is a brief outline of the steps involved in *INTPL* which form the framework of the computer programming:

Step 1: *Grid design*

The technique begins by designing a network of node points (grid) to represent the area. In order that as many nodes as possible are used to encompass an area, or to make the grid normal to the shoreline, rotation of the grid is usually necessary. Grid rotation is sometimes required to fit an area into a smaller map area. If the grid is not rotated, more redundant grid points (null grid) may be included (see Figures 5.3 & 5.4).

Step 2: *Define search area for a node*

This involves assigning a search radius which is literally taken to be the minimum value of sounding spacing and extends to a maximum of up to twice that of sounding spacing at the maximum search limit. Beyond the maximum limit too many data points will be captured that would cause unnecessary extra computations.

Step 3: *Determination of a single closest neighbour point (SCNP)*

This stage is to take advantage of any single data point found during a search for a data subset that happens to fall within a definitive limit. If a data point is found, then the current search will be abandoned and the program will proceed with the search of a data subset for the next node.

Step 4: *Formation of a data subset*

If no data point qualifies under the SCNP method, then the search continues until the end of the data file. All data points that fall within the search area will be grouped as a data subset for a node.

If no data points are found then the search radius is increased by 25% of the initial search radius and a new search for further neighbouring points is repeated, until the end of the data file. If the number of data points found is less then 3, the radius is again increased by another 25% and so on, and it will only cease searching when it reaches a 50% increase. If there are still no data points found then it is assumed that the node is a null node (node that falls outside the entire data set) and the depth value will be set either to zero or any desired value.

If more than three data points are found then the program will proceed with the so-called point containment test (PCT), to test if an interpolation will be necessary. If a node fails the point containment test, the search radius will be increased by another 50%. This in total makes the maximum search radius up to twice that of the sounding spacing.

Step 5: *Computation by IDWM*

If a node passes the point containment test, then the program will commence with the interpolation by IDWM.

Step 6: *Computation by COL, MCS and LSQ*

The computation will then continue with the method of surface fitting.

Step 7: *Computation by SLIM*

Next, the data subset will be sorted according to the quadrant neighbour points and computation by SLIM follows. This will complete the computational stages.

Step 8: *Depth selection strategy*

At this stage there will be five interpolated depths available to choose from and this final part of the program will therefore be a selection of a single value from these five possible depths through the so-called depth selection strategy, as previously illustrated in Figure 5.7.

INTPL is coded in FORTRAN, and is intended for use on a workstation or on a 386/486 personal computer with a DOS operating system. A total of thirteen subroutines are incorporated into *INTPL*, six of which are borrowed subroutines.

Detailed procedures on the various steps found in *INTPL* are summarised in a flow-chart as shown in Figure 5.8.

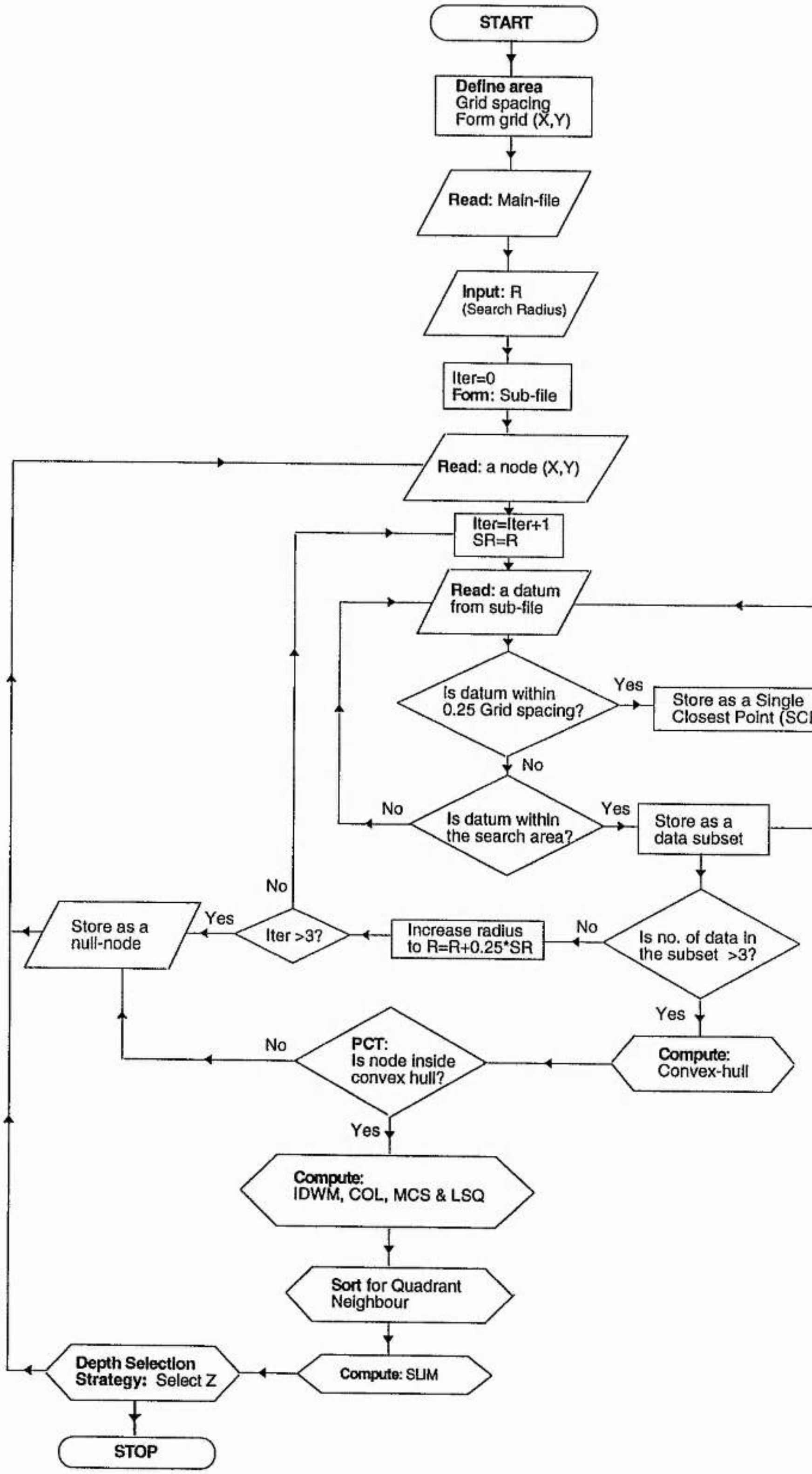


Figure 5.8. Flow-chart for *INTPL*

Specifically written for the program are: (1) *MAXMIN* - to determine maximum and minimum values; (2) *GRID* - to generate grid; (3) *COORD* - to calculate the co-ordinates for a given bearing and distance; (4) *NEAR* - to determine a nearest point to the node; (5) *PCTEST* - to test whether a point lies inside, or outside a polygon; (6) *ROTATE* - to rotate a grid; and (7) *COLTEST* - to test for collinearity between a node and data points.

Four of the subroutines (*DECOMP, SOLVE, MULTI, INVERS*) are for the solution of normal equations and these are published numerical subroutines which can be found in most textbooks on numerical analysis (e.g. Gerald and Wheatley 1994; Hostetter et al. 1991; Lindfield and Penny, 1989). The remaining two subroutines; *SPLIT* and *CONVEX*, have been described earlier.

5.5.2 *CHANGE2D*

This computer program performs change detection between 2 sets of gridded data files of different dates. Each file has a standard reference given as a file name, for example A0189 and A0190. The letter 'A' stands for area A and is followed by four digit numbers in which the first two digits are the block number, i.e. '01' for block number 1, and the last two digits denote the year of the data. Having a standard file name reduces confusion over the identity of each and individual gridded data file.

The program is also capable of outputting a separate file for deposition and erosion sites respectively. The differences between the two files are obtained by subtracting the past date file from the later date file. Differences with a negative sign will indicate deposition values whilst those with positive signs indicate erosion. No changes are indicated by a zero value. To extract the depositional sites, the corresponding depths from the past date data having positive signs are made equal to the value of the present date depths, i.e. as if no changes in depths have occurred. A similar method is applied to extract the erosional sites.

5.5.3 *VOL*

In reality the program *VOL* actually calculates the 'depth volume' on a regular grid, i.e. the volume of the water column between Chart Datum and the seabed. Given two sets of gridded data files, the program first determines the depth volume of each individual file and later subtracts one volume from another, to reveal any volumetric changes between the two surfaces in units of cubic metres.

In practice, after a survey cross-sections were usually drawn at certain intervals ranging from 5 to 50 metres or even greater depending on the applications and intended purposes. The volumes are then calculated using either the Trapezoidal, Simpson's 1/3 rule, or Simpson's 3/8 rule based on these cross-sectional areas (Uren and Price, 1984). Other formulae, such as the cubic spline volume formula presented by Chen and Lin (1991), can also be used but will not be discussed here.

However, a simple and efficient method to compute volume can be obtained by taking the horizontal plan area multiplied by the average depths of the four corners of each square grid. As an example of a calculation of depth volume, using a 5 metre square, the depth volume of the square area at the bottom left of Figure 5.2 occupied by the nine contiguous gridded depths can be obtained as in Table 5.3.

The example, as provided in Table 5.3, also illustrates how an organised procedure can be designed to compute the depth volume. Column 1 contains the reference for the individual grid node. Column 2 shows depths below Chart Datum. In Column 3 are the numbers that represent how many times the depth has occupied the corresponding square and, finally, in Column 4 are the cross-products between Columns 2 and 3. The volume of the water column between Chart Datum and the seabed is therefore obtained by taking the plan area of a square multiplied by the sum of the cross-products and dividing by 4.

Table 5.3. Volumetric calculation using square grid

Grid ref.	Depth (m)	No.of squares occupied (n)	(n) x Depth
Z_{11}	3.1	1	3.1
Z_{12}	3.2	2	6.4
Z_{13}	3.3	1	3.1
Z_{21}	3.3	2	6.6
Z_{22}	3.3	4	13.2
Z_{23}	3.5	2	7.0
Z_{31}	3.2	1	6.4
Z_{32}	3.2	2	6.4
Z_{33}	3.4	1	3.4

Total: 52.4

Volume = (5)(5)[52.4]/4 =327.5 cubic metres.

The total volume of the whole block can also be obtained by extending a similar calculation procedure to include the rest of the depths. The smaller the grid spacing, the greater will be the confidence placed in the calculated volumes.

The computational procedures as shown in Table 5.3 can, however, be further simplified by representing them using mathematical expressions 5.1(a) - 5.1(d). For m rows and n columns of gridded data, the contributions of the depths to the total volume are expressed as:

For 1 square grid: $Z_{11} + Z_{1n} + Z_{m1} + Z_{mn}$ (5.1a)

For 2 squares grid: $2\sum_{i=2}^{m-1}[Z_{i1}+Z_{in}] + 2\sum_{j=2}^{n-1}[Z_{1j}+Z_{mj}]$ (5.1b)

For 4 squares grid: $4\sum_{i=2}^{m-1}\sum_{j=2}^{n-1}Z_{ij}$ (5.1c)

Volume = [(1a)+(1b)+(1c)]/4 (5.1d)

The mathematical expressions listed above are specifically designed for computer programming. Direct computation of volumes leading to quantitative estimates of deposition and erosion can therefore be easily accomplished with a computer.

5.5.4 *AREAL*

The areal extent of deposition and erosion sites is conventionally expressed in units of square metres. This is only appropriate if the size and shape of each site can be clearly determined and delineated. However, as the sites, in most cases, comprise a myriad of individual cluster sites, it will be difficult and tedious to work out the size and shape of each individual site as expressed in unit area of square metres. This can be especially difficult if there are too many very small individual clusters of such sites.

A meaningful way to express the areal extent of deposition and erosion is therefore achieved by quoting them according to the number of nodes they occupy. The separation of no change, depositional and erosional nodes into individual files thus makes this technique more efficient in describing areal extent of the individual change phenomena. By counting the respective nodes according to their signs and expressing them as percentages of the whole block, the three different areal extents can be estimated.

Table 5.4. Example of statistical indications of deposition and erosion derived for Block B13-1990/91

	Deposition	*Erosion*
Mean	: -0.889	0.561
Median	: -0.398	0.281
Standard Deviation	: 0.158	0.637
Variance	: 2.092	0.406
Range	: -2.093	3.357
Minimum	: -0.001	0.001
Maximum	: 6.628	3.358
Count	: 7441	1308

5.5.5 *Statistical indication*

Other flexibility of using gridded data is the determination of a simple statistical indication of deposition and erosion, e.g. using Cricket Graph III program. Figures 5.9(a) & 5.9(b) are examples of histogram plots built from such data. The outputs from the program *VOL* (e.g. volumes) and *CHANGE2D* (e.g. maximum and minimum change values) can also be compiled into a spreadsheet program (e.g. Excel) and the command 'Descriptive Statistics' can be used to obtain the required information as in the example

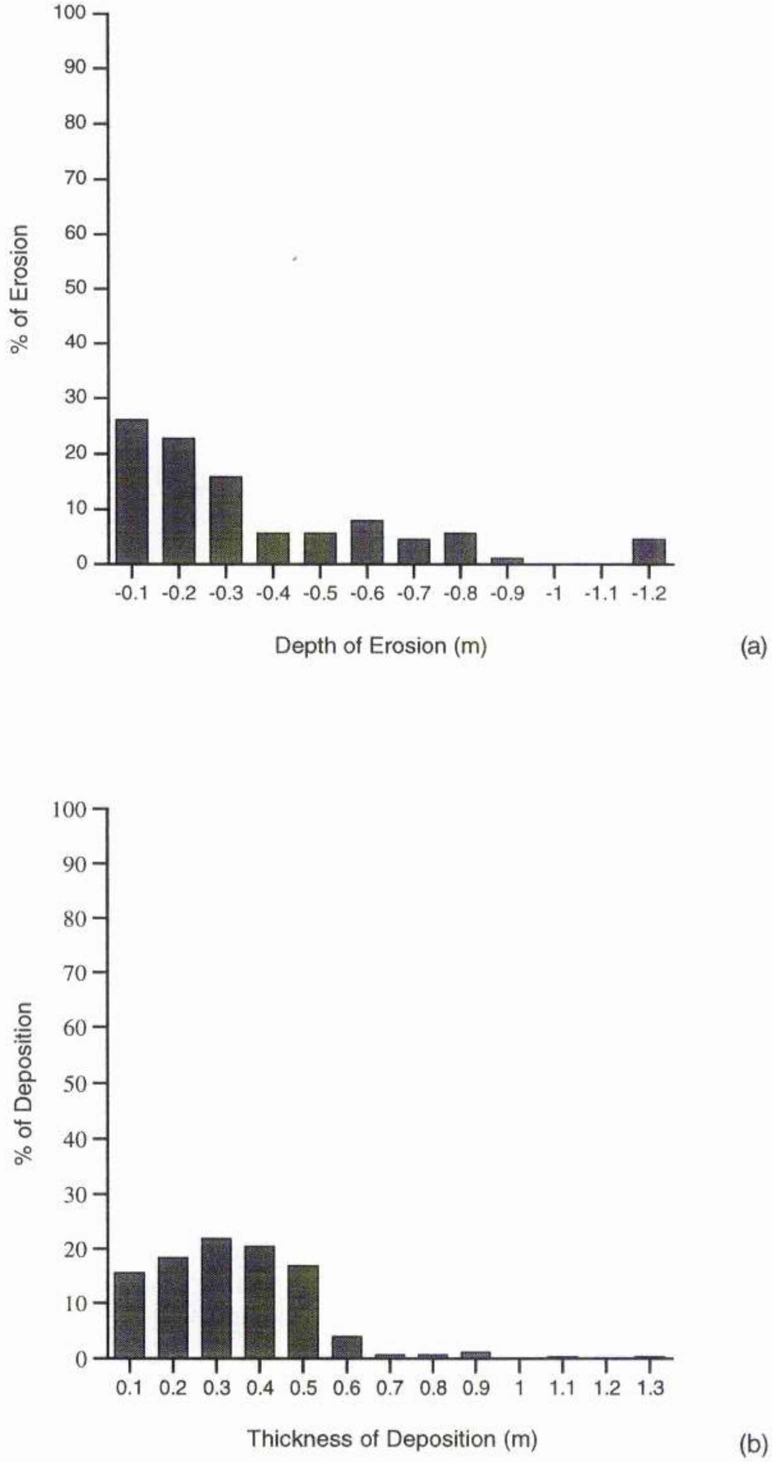


Figure 5.9. Histogram plots for gridded data of Block 13, area B for the period 1990/91: (a) erosion (b) deposition

provided in Table 5.4. The procedure can be repeated for all blocks forming an area for estimation of the overall rates and extents of sedimentation and erosion. Note that there is a significant difference between the mean and median values of deposition and erosion.

5.5.6 *Data input*

Appendices A to D are the working examples of the program *INTPL, CHANGE3D, VOL* and *AREA,* respectively. The descriptions provided are intended for all programs in BIT that were specifically installed and compiled in workstations at St Andrews University.

5.6 **UNIRAS software package**

In the following sections a brief introduction is given on UNIRAS software package. UNIRAS is an acronym for Universal Raster system and is a comprehensive software package designed for graphical display of data. There are two ways to use this package, either by the interactive programs (e.g. UNIGRAPH and UNIMAP) or through user-application programs which incorporate the various FORTRAN routines (Fundamental Graphics Library and Application Graphics Library).

Initially, it was planned to use the interactive programs found in the UNIRAS software package for the graphical display of the data. However, as it was found that the interactive programs have limitations in handling bathymetric data for the intended purpose, in particular, on the available interpolation routines, there is a limited option to choose from other than those embedded within the program. Also there are limitations on the display of data in the user-required form. Thus, user-application programs were separately written to incorporate the various UNIRAS subroutines to perform the task at hand.

5.6.1 *Programming structure*

UNIRAS routines have been designed for display of graphics. The 480 routines available for use are fully documented in IUCC (1989). Appendix C is an example of how a selection of UNIRAS routines can be incorporated into a user-application program. Fundamental routines are used in conjunction with other UNIRAS routines to produce graphics. An ouput program has to start with the GOPEN routine, must always be called before using any other UNIRAS routines, and must end with a call to the GCLOSE routine.

The connection between UNIRAS and the output device is handled by a Driver. The Driver acts as an interface between UNIRAS software and the graphics hardware device. Drivers are essentially subroutines that convert the output graphics primitive (picture) into the appropriate language to drive the hardware device.

At St Andrews University in particular, UNIRAS software has been installed in the Sun workstations and can only work using OpenWindows. The appropriate device driver is a multidriver type MX11. The GROUTE routine must be called to select a target graphics device, or a dummy device. For example the following commands are typed in when using a PostScript driver: 'GROUTE> select mpost;exit'. This will produce a PostScript file called POST in the working directory. Other alternatives to 'mpost' are 'hcposta4' for the colour A4 size plot and 'hcposteps' for an encapsulated colour PostScript file which allows it to be imported into another package, e.g. word processing package - Word. Once created the PostScript file can be submitted to a printer for hardcopy.

5.7 **Data rendering and presentation**

The eventual output of the technique BIT is in the form of gridded files, differential files and 2D-plot. Relevant to this work are the 2D/3D-plots that will be discussed in the following sections.

5.7.1 *Procedure for 2D-plot*

The output from program *CHANGE2D* is a 2D-plot showing the plan position of the individual sites of deposition and erosion. The sequence of inputs to *CHANGE2D* begins when the program prompts for input of filename of a gridded data file (see Appendix B-2). The later date file is entered as, e.g. A1391, followed by the file for the previous survey, A1390. Then there will be two options displayed: enter '1' to calculate and display deepening/erosion and '2' for shoaling/deposition.

Once a choice is entered the program will automatically create an output file according to the selection. For example, if an option '1' is input, then the output file created will be E:B13-9091. The letter 'E' stands for erosion, 'B' for area B, the number '13' refers to block number 13 of area B, and the first two and the last two digits indicate the period between the two dates, 1990 and 1991. The program next scans through the input data files and informs the number of nodes found in each file. The number of nodes in both input files should be equal, if not the program will stop because of incompatibility.

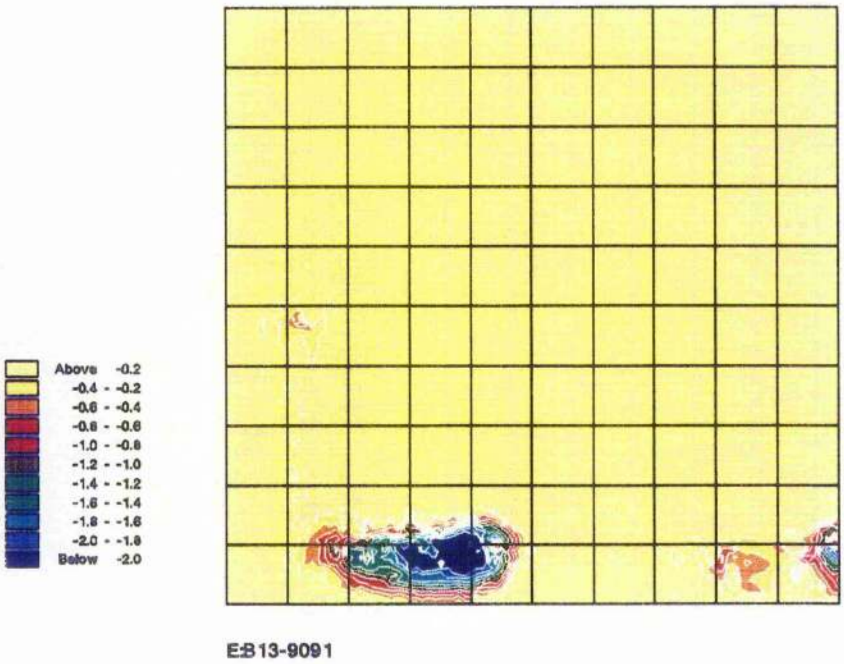
For consistency in the outputs, the sequence of all file inputs must strictly follow the prompt command. One is only interested to assess the current situation and, as such, the differences having positive signs signify erosion and negative signs deposition. While comparing the two data sets, sometimes one may come across a situation where one of the gridded points has a zero depth value and the corresponding point in the other file is not zero. If one simply subtracts the two files then the magnitude of change is unrealistic and incorrect. When this situation is encountered, the program will consider the difference as void and converts the difference to zero as if the values of the two gridded points are equal. In other words, at that point there is no change experienced in the seabed.

As pointed out in Chapter 3, the accuracy of a depth measurement using an echo-sounder is accurate to within 0.1 to 0.3 metres. This uncertainty in depth value can increase if the seabed is composed of low density materials (e.g. soft mud, silt) as this may lead to a poor signal being returned to the echo-sounder. It is therefore reasonable to place an estimate of a threshold limit for change detection at 0.2 metres, i.e. any difference in depths of less than 0.2 metres will be ignored. Therefore, the minimum value shown in the scale legend for the 2D/3D plots is 0.2 metres.

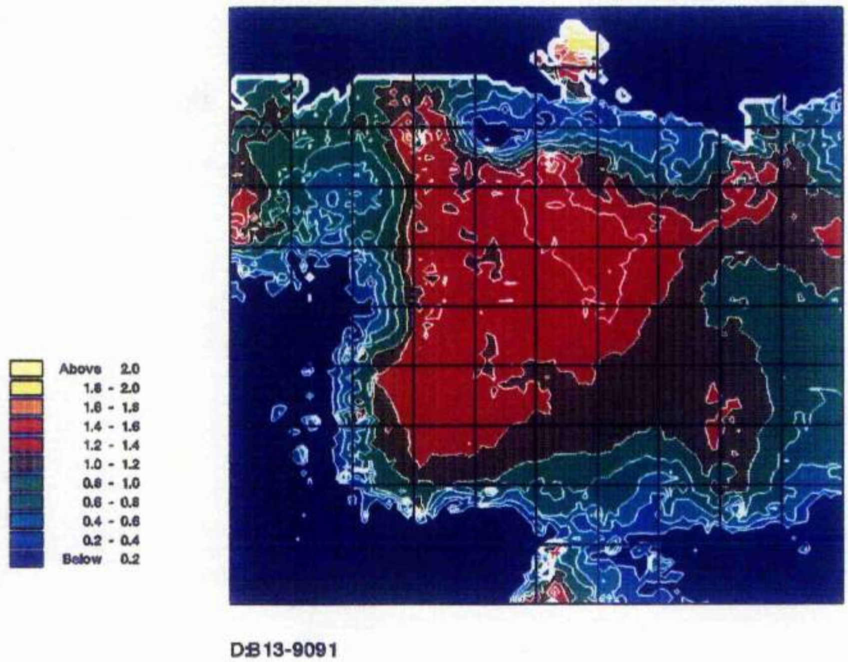
Having determined the depth differences for all the nodes, the program will resume with its plotting. Examples of 2D-plots are shown in Figure 5.10 which are based on the setting shown in the example provided in Appendix B-2. These examples represent deposition and erosion sites in Block 13 of area B between the period 1990-91.

5.7.2 *Procedure for 3D-plot*

To obtain a 3D-plot draped with deposition or erosion sites, one can use the program *CHANGE3D* - (see Figure 5.11). This program is used only to visualise an area in a perspective view. The procedures involved in creating a 3D-plot are similar to those of a 2D-plot.

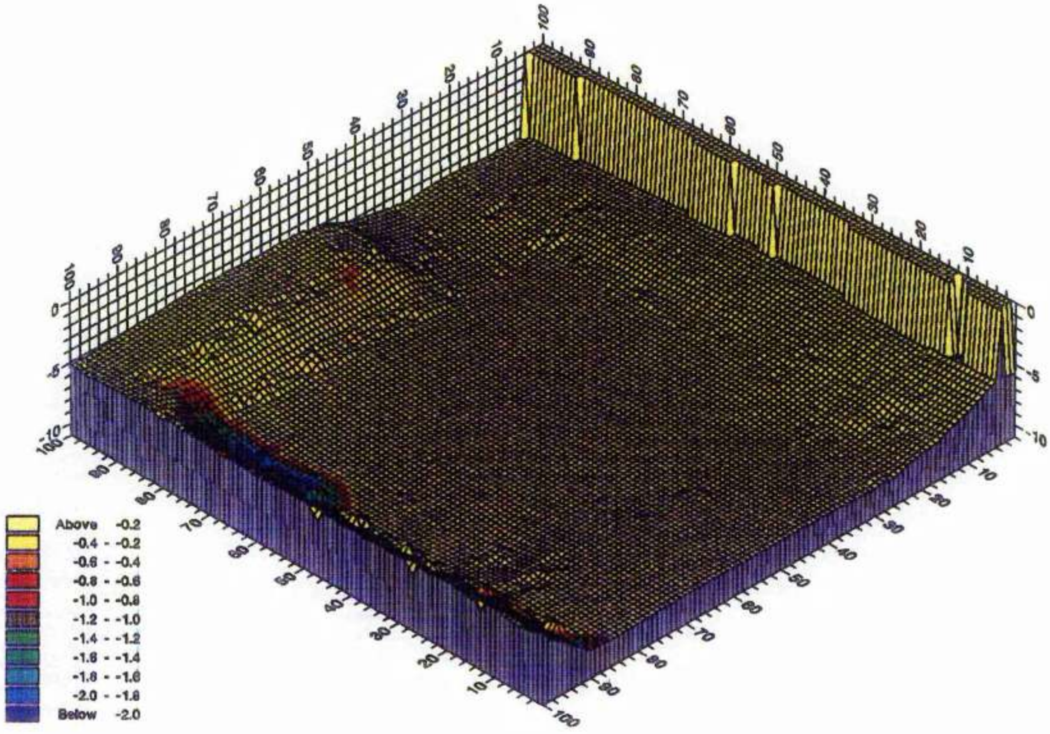


(a)

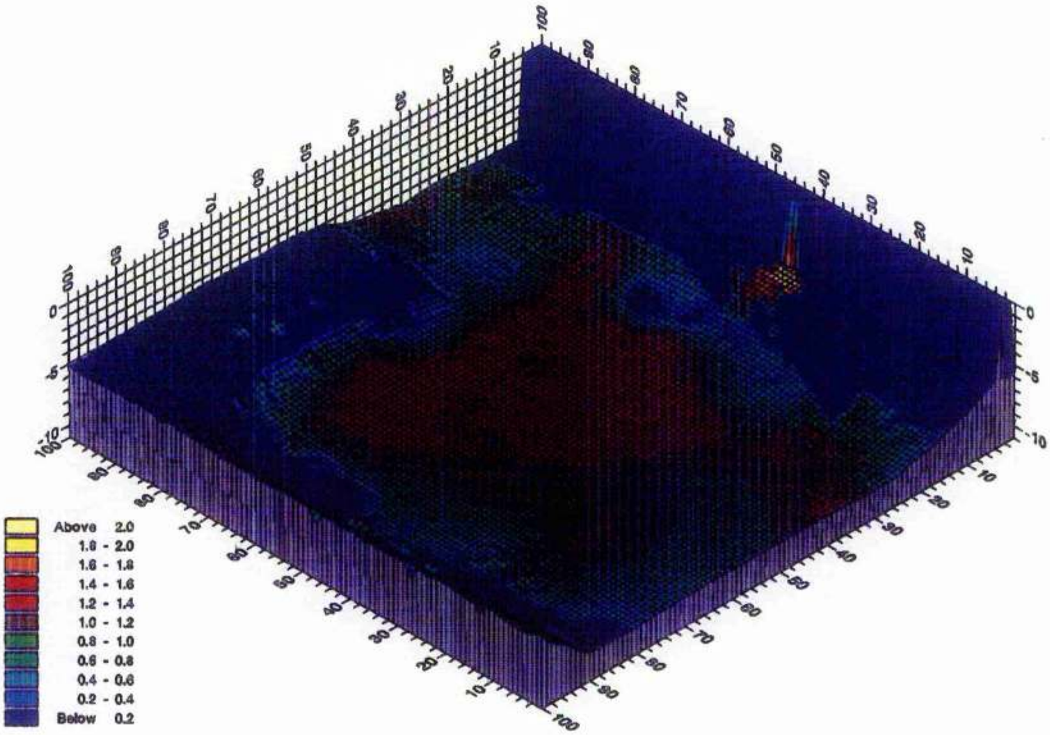


(b)

Figure 5.10. 2D-plots for (a) erosion (b) deposition



(a)



(b)

Figure 5.11. 3D-plots for (a) erosion (b) deposition

5.8 Summary and discussion

In general, interpolation of depth values using a single method can produced false results that could lead to inaccurate or misleading accounts of developments in studies of seafloor sediment deposition and erosion. This has been discussed and examined by using numerical examples. The accuracy of an interpolation is governed by the data density and sampling resolution. By no means can interpolation of depths give greater accuracy to the 'computed seabed' than the 'measured seabed' itself.

Trial computations based on the five selected methods have shown that the differences between the interpolated values can be unacceptably large and may exceed the values of the defined micro-scale change level (< 0.3 metres). However, by integrating the results of the six methods into a single program a rational set of interpolated depth values may be provided that span the shallowest and greatest possible depths. During a selection for a single depth value, one could simply take the average of the shallowest and the greatest depths to come to a fast and mentally straightforward answer. However, the validity of such a method can be disputed as the derived value is subject to ambiguity in the sense that it is not generated by means of a proper mathematical technique. A proper selection is therefore justified only through the so-called depth selection strategy. This is achieved by taking the average of the shallowest and greatest depths and, in turn, comparing this with the individual interpolated depth obtained by the five methods. A value closest to the average will be selected as the final interpolated depth value.

The efficacy of the Blending Interpolation Technique lies in the fact that it provides a platform for the blending together of all six suitably qualified methods of interpolation into a single hybrid system of interpolation. Performing as individuals, no one interpolation method can qualify as a single 'best' interpolation method.

Besides being an interpolation routine, BIT can also be embedded with other routines for the display of results. For example, the UNIRAS software package, which is available at the University of St Andrews, has been used as a display or graphical tool within BIT. Of particular interest is the 2D-plot routine developed for the display of seafloor sediment deposition and erosion sites. A 'real world' application of BIT will be demonstrated in Chapter 6.

CHAPTER 6

DEPOSITION AND EROSION IN HARBOUR AREAS: A CASE STUDY

6.1 INTRODUCTION

Being a typical riverine and estuarine harbour where some forms of modification of the natural water depth have been made, it is likely that the seabed of Dundee harbour will experience the phenomena of sedimentation and erosion. A fundamental problem facing the port authority from time to time is to determine and monitor precisely the effects of such phenomena in the harbour area. The verification of the extent of such phenomena in practice is determined by regular bathymetric surveys.

In other U.K ports, for example in the Port of London, bathymetric surveys are required more frequently than once a year to assist in dredging works. Regular maintenance dredging in the River Thames for instance, requires approximately 300,000m^3 of sediment to be removed annually. Other ports (e.g. Port of Aberdeen), may need a survey once every year and to cover only a certain area of the harbour, whilst some parts require surveys only if there is a demonstrated need.

Despite the high cost involved in conducting a bathymetric survey (often representing a significant proportion of the costs of the annual maintenance of the harbour) the port authority still has to rely on this empirical method in deciding whether or not an area is safe for navigation or whether sufficient material has been removed from the area. Thus, the conduct of regular bathymetric surveys becomes mandatory for assessment of the impact of sedimentation and erosion of the seabed in an area.

Siltation affecting the area of Dundee harbour is dominated by natural deposition of suspended materials, whilst erosion is due to the scouring or removal of the loose seabed sediment. Their causes, in general, may be partly the consequence of past dredging activities, construction works, or partly from natural flood events that occur within or the harbour area. As in the case of Dundee harbour, over the last decade bathymetric surveys have been conducted almost every year, these covered a large portion of the harbour area. The availability of these continuous, sequential bathymetric data sets for the harbour area in particular, has provided a unique opportunity for the implementation of the proposed methodology and technique of evaluation as already discussed in Chapters 4 and 5, in a real harbour environment.

This chapter therefore provides a practical example of the application of the proposed methodology and aims to illustrate how to exploit the full potential of the vast amount of information contained in the bathymetric data. This application could also prolong the usefulness of such data by transforming them into useful information, for example, the estimation and quantification of the extent of deposition and erosion of the seafloor sediments over specific time periods.

6.2 THE STUDY AREA - Dundee harbour area

The selected area of study for this thesis lies within the area of Dundee harbour which is situated on the northern shore of the lower middle reach of the Tay Estuary (Figure 6.1). Its geographic position is on the concave side of a bend of the narrow constriction which provides water passage from the upper reaches to the North Sea. It may also potentially form a trap either to sediments washed downstream by ebb-currents or upstream by flood currents. Within the constriction lie two key locations which are of concern to the port authority: the areas of Dundee harbour and the main navigation channel. Although, only the area that encompasses the former will be considered in this study the problems of sedimentation and erosion in the latter may be quite similar to those of the former.

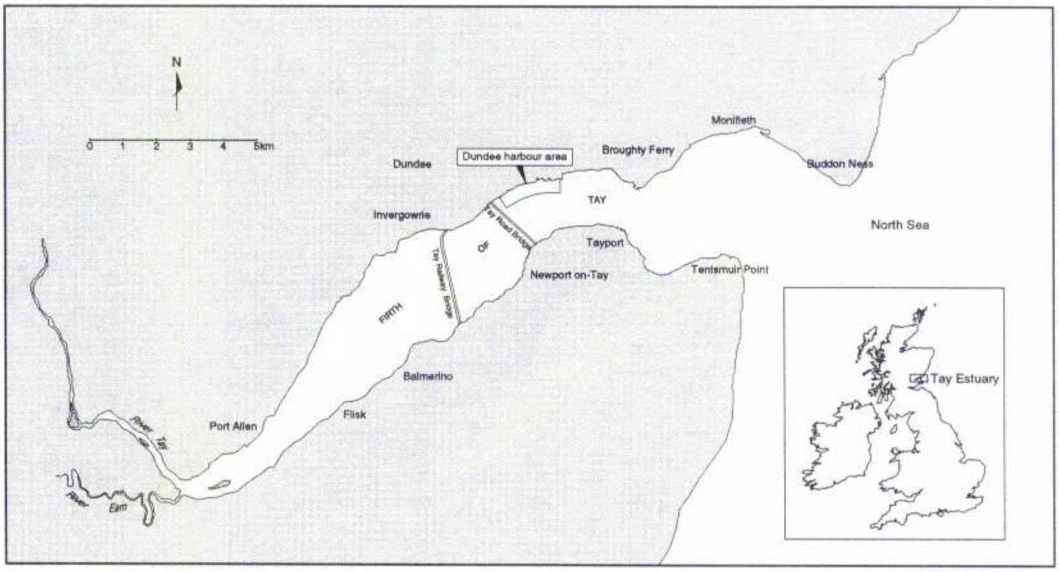


Figure 6.1. A location plan showing the Dundee harbour area with respect to the Tay Estuary.

6.2.1 **The related problems**

According to a study by Charlton et al., (1975), the areas upstream of Dundee receive around 152 x 10^6 and 272 x $10^6 m^3$ of saltwater on neap and spring tides, respectively. On an average day, as much as 3.4 x $10^6 m^3$ of fresh water may enter the estuary from the river system transporting on average 1.65 x 10^6 tonnes of materials annually (Al-Jabbari, et al., 1980). A large proportion, well over 90%, of the are carried in the form of suspended load (Al-Ansari and McManus, 1979).

The mixing of fresh and salt waters within estuaries is believed to result in flocculation of the cohesive materials carried in suspension (Postma, 1967; Dyer, 1972). The flocs may settle on the estuary bed under suitable conditions of tide, currents and waves. De-flocculation may occur as the particles are brought back into fresh water by estuarine circulation due to wave or current action. Indeed, flocculation and de-flocculation are far from being exclusively the result of mixing of the fresh/salt water, but also as a combining process of organic binding (Dyer, 1994), aided by physical motion of the water body (Sinawi, 1996).

The complex combinations of the physical and chemical processes within the estuary have produced characteristic forms of bed roughness, especially in the upper part of the estuary. Much of the materials being brought into the estuary by the river system becomes temporarily trapped on extensive mud and sandflats found within the upper reaches (McManus and Alizai, 1987). Some of the sediment may find its way into the navigation channel, leading to the need for intermittent dredging of the navigation channel by the port authority. Perhaps, it is reasonable to speculate that some of the fluvially sourced sediment may enter and cause deposition on the floor of Dundee harbour.

Table 6.1. Disposal of dredge spoil in the Firth of Tay (wet tonnage) between 1989-1993. (Courtesy of Scottish Office, Agriculture and Fisheries Department)

Year	Middle Bank	Newcome Buoy	Horseshoe Buoy	Tay Bridge
1989	39,514	0	0	5,400
1990	0	0	0	0
1991	0	0	0	360
1992	0	9,429	7,863	8,784
1993	50,883	24,320	0	4,714

It has been estimated in the past, that over 24,000 in situ tonnes of silt and clay were removed annually through selective dredging from the areas of Dundee harbour and the main navigation channel (Finney, 1987). According to a reliable observer (who wishes to remain anonymous), at one time in the mid-1980s, during capital dredging within the harbour area, dredged materials were loaded into a 2,000 m^3 load capacity hopper and as many as 17 loads per day of dredged materials were dumped at the designated dumping site of Middle Bank. This exercise lasted for about 2 weeks. This amounts to a total volume of approximately 476 x $10^3 m^3$ of dredge spoils having been dumped at the site. However, documented amounts (Table 6.1), obtained from the Scottish Office, Agriculture and Fisheries Department, show that in more recent years far less than the observed values were removed.

In principle, there are three ways to estimate the quantities of sediment on the seabed: (1) according to the amount of sediment removed in situ (m^3); (2) hemisphere and settling/centrifuge method; (3) the amount of sediment in the means of transport (in hoppers or barges). For scientists or harbour engineers who are concerned with evaluating aspects of sedimentation and erosion, it is the dimension of space (depth and volume) which is important and not the mass of the load.

Apparently, the first method is efficient when applied to seabed material of harder soil types such as sand, gravel and rock. Depths can be easily measured with an echo-sounder over consolidated materials because there is a distinct boundary at the water-sediment interface. However, over a bed of fine sand and clay or fine particles which settle slowly when disturbed, especially during dredging, there is no distinct boundary between the actual surface to be measured and the water with which it is mixed. This calls for the use of second and third methods.

In the second method, the quantity of sediment can only be estimated after it has been removed or dredged and has been being placed in a hopper or barge. The 'hemisphere and settling/centrifuge method' is therefore applied. It is based on the fact that material placed in the hopper or barge will settle in two layers; the mixed upper layer and the settled bottom layer. The half-ball; a hemisphere of density 1.2 kg/m^3, when lowered into the material will stop sinking on the surface of the settled material of similar density. The settled part is measured first and 1 dm^3 samples of the mixture are taken at various spots and then centrifuged for ten minutes at the speed of 1500 rev/min. after which the amount of sediment is determined. From the sediment percentage, the silt content of the fluid load is derived and added to the quantity previously measured by the half-ball.

In the third method of estimating quantity, Rokosh (1989) proposed a weight measurement method in 'tonnes of dry matter' as represented below:

$$TDM = \frac{\rho_N - \rho_W}{\rho_M - \rho_W} \times \rho_M \times V_T \tag{6.1}$$

where,

TDM	total mass of dry load
ρ_N	the average density of the wet load (mixture)
V_T	the total volume of load
ρ_M	the density of particles in the load
ρ_W	the density of interstitial water

However, the method of TDM represented by expression (6.1) suffers from a drawback whereby the evaluation of the variables ρ_M and ρ_W requires precision laboratory support and, furthermore, TDM is in tonnes and does not give an insight into the in situ volume of sediment removed (Chandramohan, 1995).

With regard to the quantities expressed in wet tonnage, as listed in Table 6.1, it is basically a measure of water displacement of the hopper or barge used. The draught of the hopper or barge is measured for example by pressure transducers which are attached to the underside of the vessel. At least two of the devices are required, one at the bow and the other at the stern. After the pressures have been converted into units of length, e.g. in centimetres, the corresponding weight of the vessel can be determined from the displacement table appropriate for the vessel. By first measuring the weight of the empty vessel and then again with hopper filled and subsequently determining the difference, the so-called wet load can be calculated.

It is difficult to verify or attempt to compare the documented and the observed quantities of sediment dumped in the Tay Estuary due to the difference in the units used (m^3 versus wet tonnage, respectively). But the information in Table 6.1, however, does provide an important indication of dredging activities in the area of Dundee harbour.

Around and in close proximity to the harbour area, the evidence of morphological features such as mud flats, sand banks and migratory channels indicates that the seabed of the area can be relatively unstable. In the past their development, migration and destruction have been studied by various workers; Buller and McManus, (1971) made a comparative study of bathymetric charts (1816-1963) and grossly delineated the area into 'stable' and 'unstable'; Dobereiner (1982) and Dobereiner and McManus, (1983) carried out water sampling and current measurements to study areas of high suspended sediment concentration (or turbidity maxima) and their migration, the deposition of fine particles and water circulation patterns in the estuary.

Important events have also been reported in the upper reaches of the Tay Estuary, when various major flooding incidents occurred since 1837 in the Tay and Earn catchments. According to a study by Gilvear (1993) and Gilvear et al. (1994), the most recent of these, the February 1990 and the January 1993 floods caused extensive embankment breaches leading to inundation of the river flood plains. Former areas of braiding which were isolated from the main channel by flood embankments are vulnerable to erosion during the flood events. Following these flood events, McInally et al. (1994) carried out a study on flood mitigation measures for the area using a one-dimensional hydraulic model to provide comprehensive information on which to assess flood defence requirements and options.

Nevertheless, floods may induce extensive movement of sediment within the estuary and the net effect is to cause a significant amount of sediment to be entrained and distributed throughout the estuary. The sediment movement and distribution could certainly reach Dundee harbour and further downstream as far as the open North Sea. Several questions are therefore raised - (i) What effect does flooding have on specific strategic areas such as harbours along the estuary? (ii) How much sediment is washed into and out of the area? (iii) Where does bed change actually occur? and (iv) What are the likely quantities involved?

It is difficult to answer the above questions in response to a single flood. This is because the long term impact of such floods on the areas downstream cannot necessarily be detected over a short period of time following their occurrences. The suspended sediments may in fact come from within the estuary itself having undergone various cycles of deposition and erosion before re-entering the harbour areas. Some of the sediments, mainly those composed of silt and clay, that are washed into the lower reaches of the estuary could possibly be those previously settled on the bed of the harbour areas which have been re-eroded, re-entrained and washed upstream by waves and currents. In one instance, over a relatively short period of time (within 1 year), the rates of siltation and scouring observed in a dredged channel in the proximity of Dundee harbour to have reached values of 1 metre and between 0.5 to 0.8 metres respectively, as reported in a study on siltation in the approach channel of Tayport harbour (TERC, 1976).

The mobile nature of the seabed sediments makes it complicated to estimate their quantity and distribution by size in an area. Before the sediment is finally transported away from the harbour area or flushed out of the estuary, it will remain in the transitory state between deposition and erosion. Indeed, the processes leading to deposition and erosion (i.e. flocculation, settling, deposition, consolidation and re-erosion) involve the response of the whole estuary rather than just a particular area. The cycle of erosion and deposition is ephemeral yet continuous, so that it is justifiable to evaluate only the net impact of the annual changes within the area. This is because the impact of an extreme, short-term event can be more severe than the average and slow, long-term impact. For example, a flood may cause more sedimentation or erosion to occur in the harbour than would take place over a number of years under normal conditions.

The use of mathematical or physical models to assess and predict siltation and erosion in estuaries has been widely reported and well documented. Odd (1981), provides a useful discussion of the predictive ability of one-dimensional numerical models and lists the main factors affecting accuracy and their predictive ability. The mathematical model should not be seen merely as a replacement of the physical model, but rather a complement to it (Abbott, 1976). Fisher et al. (1979) review the types of river and estuary models available, what they achieve and how to choose the most appropriate model for any specific purpose. Thorn (1982) pointed out that whether a mathematical or physical model is used to make a prediction or simulation, one may only get a qualitative answer near to the truth and one will be unlikely to achieve anything near real quantitative accuracy. In this regard, the quantification and estimation of the amount of sediment lost or gained as required in harbour maintenance programmes, cannot be determined by modelling alone. There is still no real substitute for expert field measurements such as bathymetric surveys, as modelling works cannot provide the accuracy of volumetric changes nor areal estimations sufficiently reliable to satisfy a port authority.

In line with the above discussions, an attempt is therefore made in this study to evaluate the phenomena of deposition and erosion of the seabed sediment based on the archive of bathymetric data from the harbour area. This study serves as an extension of use of bathymetric data rather than a substitution for modelling works. The evaluation focuses on quantifying and estimating the net annual seafloor sediment deposition or erosion within the harbour area. In particular, the method is capable of pin-pointing the potential depositional and erosional sites, their patterns of spatial distribution, estimation of quantities, the percentage of area occupied and, finally, the likely annual rates of accumulation and scouring during the study period. The proposed methodology is useful in providing a first step towards a scientific understanding and also as a reference for management and improving design efficiency of any subsequent or future maintenance dredging works to be undertaken in the area.

6.2.2 **Schematisation of the study area**

Practically, if conclusive results are to be attained, the evaluation process must cover the entire harbour area. However, as sequential bathymetric data for the whole harbour area are often incomplete or unlikely to be available, only a representative portion of the entire harbour area that were satisfactorily covered by surveys are used to represent the harbour. The limit of this representative area of the harbour encompasses the critical areas that are operationally important, such as areas along wharves and jetties.

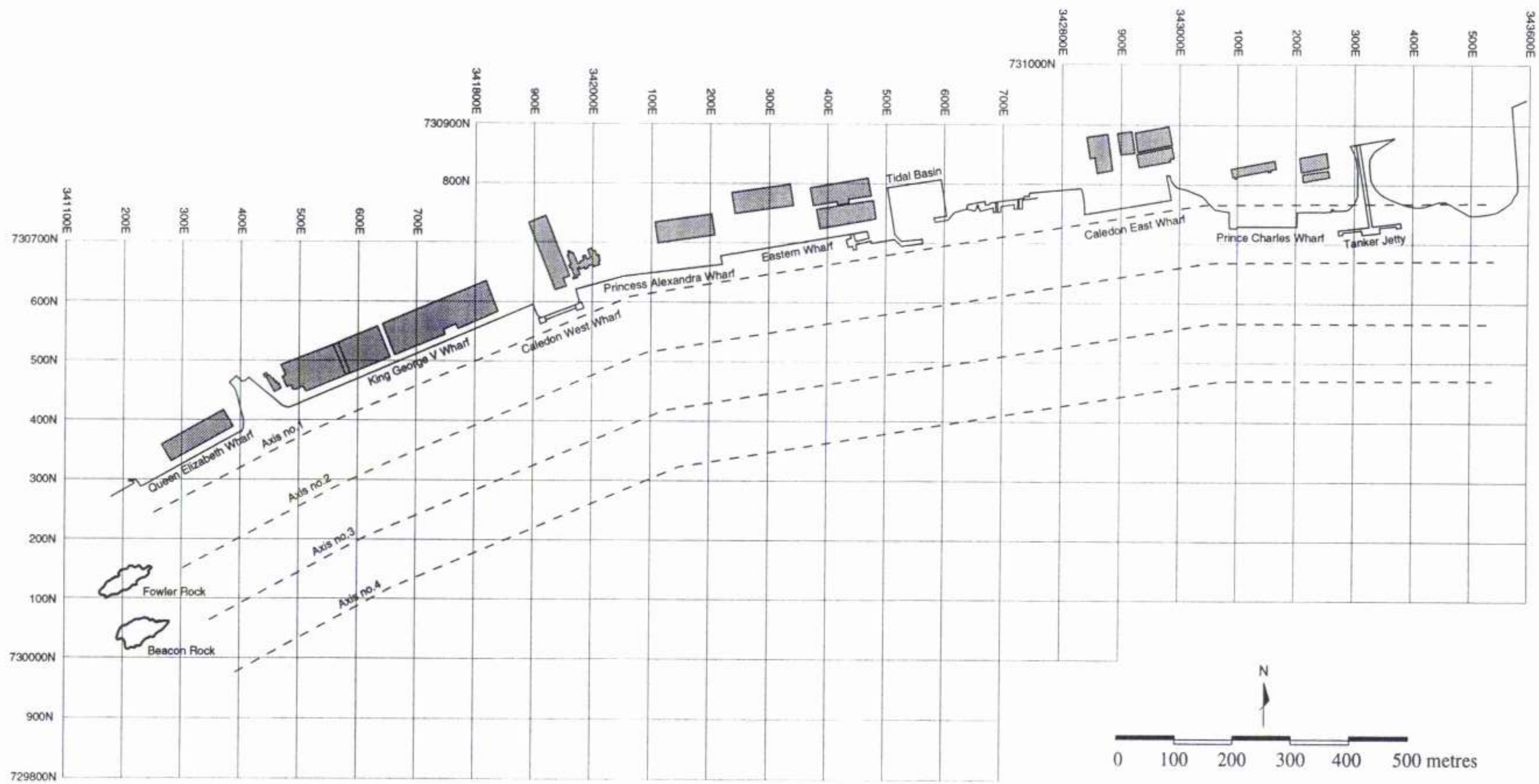


Figure 6.2. A plan view of the Dundee harbour area superimposed with a normal grid

It will therefore be convenient first to define the limit of this representative area of the Dundee harbour. The limit for this so-called Dundee harbour area is arbitrarily defined as stretching about 2.4km in length from Queen Elizabeth Wharf to the Tanker Jetty in Broughty Ferry and extending to about 400m offshore in width (Figure 6.2).

Float tracking measurements have shown that the dominant ebb-flow in the area is near parallel to the shore (Craig and Adams, 1970). Other investigations, including the use of mathematical models, also produced similar results (Gunn et al., 1987; Gunn and Yenigun, 1987). It will be natural therefore, to design the evaluation axes for such phenomena either longitudinally or laterally across the area. Perhaps, it will also be more meaningful to follow the river flow-line. In the case of the Dundee harbour area, the flow-lines are very nearly parallel to the wharves.

In order that a systematic and detailed investigation of the deposition and erosion of sediment can be carried out, the harbour area has to be schematised into smaller sub-areas. Each sub-area is designed to accommodate and closely follow the wharves. Whenever the orientation of the wharf changes the orientation of the corresponding sub-area will also change, and a new sub-area is formed. The area examined therefore comprises 5 sub-areas, namely: Queen Elizabeth Wharf (Area A), King George V/Caledon West Wharf (Area B), Princess Alexandra /Eastern Wharf (Area C), Tidal Basin/Caledon East Wharf (Area D) and, finally, Prince Charles Wharf/Tanker Jetty (Area E).

Each sub-area is chosen to conveniently accommodate the wharves and to fit exactly the number of blocks needed for each area (Figure 6.3), as opposed to the normal north-south grid pattern as depicted in Figure 6.2, in which some blocks only partially fit into the area. The width of 400m was selected on the assumption that, beyond this zone, the phenomena can be linked to the adjacent navigation channel which, of course can be investigated independently in a similar way.

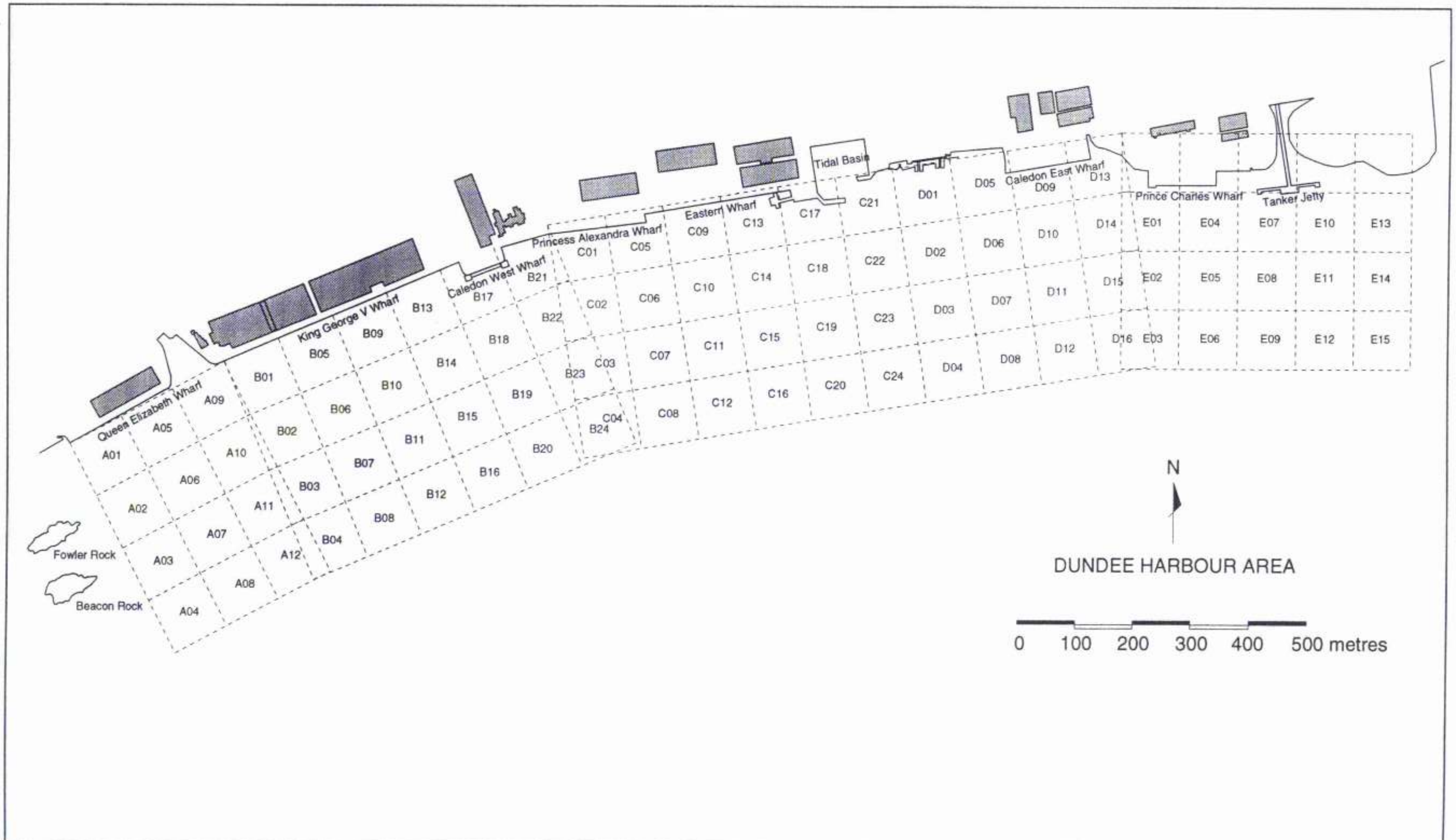


Figure 6.3. Schematisation of the Dundee harbour area into 5 sub-areas and 96 blocks

Each sub-area is then further sub-divided into blocks of size 100 x 100m and this dimension provides a reasonable number of nodes. For example, if a 1 m grid is used then in a block there will be 10,201 nodes (which approximately corresponds to 71Kbytes of computer space). A reference is assigned to each block as depicted in Figure 6.3. Blocks are designed not only to assist in the calculations of volume change and areal extent which may be applicable in dredging works, but also as an area referenced to individual locations.

Having defined the size and the partitioning of the harbour area, if cross-sections are drawn across it at 25m spacing, then a total of 96 cross-sections is required. Under the proposed schematisation, there will be 96 blocks which is exactly the same number as cross-sections. However, a cross-sectional drawing shows less information than a block because it can show only information along the cross-sectional line. An advantage of using blocks lies in the fact that information in a block can be presented either in 2 or 3-dimensions.

6.3 BATHYMETRIC DATA

The data obtained for Dundee harbour were from previous bathymetric surveys kept in the form of hard copy format, plotted at a scale 1:1250. In order for the data to be processed by the developed computer program (*INTPL*), this required that all depths from the related part of the chart are converted into digital form, through the process of digitisation and manual keying of the depths through the keyboard. This is a very tedious and time consuming job and it presents a major problem in data conversion. However, if during the survey the data had been stored in digital format, then this problem of course could have been alleviated. However, as the proposed method of evaluation involves the recovery and use of past date data (i.e. archive data), inevitably this problem cannot be totally avoided. Furthermore, the port authority is interested only in a ready processed and presentable format. Data in digital form can be of little use if there is no clear objective in their applications. Thus, in most cases, only data in hard copy are available and the problem of a need to digitise remains. It is therefore important that, in future, the port authority should store digital data along with the hard copy charts.

Over the last 10 years, the Dundee Port Authority has carried out maintenance programmes of its harbour area which include hydrographic surveys. They are for the purpose of checking navigation depths and verifying the need of any requirement for maintenance dredging in any part of the area. All the surveys were carried out at 10m sounding spacing with depths plotted every 10m apart. The directions of the survey lines vary from normal to parallel with the shore line configuration. Some of the sounding lines, however, were run in arbitrary directions. Most importantly, the depth reference datum adopted for each survey was in common, i.e. based on the level of the lowest astronomical tide (LAT) of the harbour area, which is defined as 2.9m below Ordnance Datum, Newlyn (O.D.). The co-ordinate system used in all the charts was also in common, i.e. based on the Ordnance Survey National Grid of Great Britain. Having in common the reference systems for co-ordinates and depths for all data, they become useful, enabling manipulations to be made with few complications for the study.

A brief description of the data for each year is given below in order to explore the sources, references and the nature of the data.

6.3.1 The available data

Bathymetric data from annual surveys conducted in the years 1985, 1988, 1989, 1990, 1991, 1992 and 1993, covering the study area, were obtained from the Dundee Port Authority. Data prior to these dates are sketchy and incomplete and were kept on microfilm at reduced scale. After a preliminary inspection and visual analysis of these data, it was decided to exclude the 1985 and 1988 data because they were inconsistent in terms of scale, depth coverage and line-spacing in comparison with the other data. The exclusion of the 1985 and 1988 data left only 5 data sets for subsequent processing.

(i) Bathymetric data of 1989

The bathymetric survey for July 1989, were presented in 5 drawings, referenced as Drg. No. DHA-02-sheets 1 to 5. The plotting scale for all the drawings is 1:1250. The spacing of depths is generally 10m apart. Depths were taken along arcs of concentric circles with radius being incremented at every 10m as line spacing. As the length of the radii is large, the arc of each concentric circle appears to be nearly a straight line. The sounding directions are not normal to the wharf front, but inclined approximately between 30° - 60°. There are large gaps in the data from some areas especially near Caledon West Wharf and from Eastern Wharf to Tanker Jetty, where there are no depths shown. This is probably due to the presence of ships at berth during the time of survey. In general, the area which covered about 97% of the whole Dundee harbour area, was satisfactorily surveyed and suitable for analysis.

(ii) Bathymetric data of 1990

The August 1990 survey was represented in 4 drawings referenced as HS 152 to 155 - 1 to 4/90. The depth data are everywhere 10m apart with sounding lines made normal to the wharf front. Most areas along the wharves were fully covered by soundings except near Prince Charles Wharf where an oil rig was present at the time of the surveys, leaving a large gap unsurveyed. Gaps were also found between sounding lines near Queen Elizabeth Wharf. An overall estimate of depth coverage for that year was about 99%.

(iii) Bathymetric data of 1991

The August 1991 survey also comprises 4 drawings referenced as HS 142 - 1 to 4/91. Line spacing was maintained at 10m apart and the direction of sounding was perpendicular to the wharf front. Soundings along the wharf front were almost complete. However, a few gaps existed between sounding lines especially along those facing the entrance to Camperdown Dock and to the east of the Tidal Basin. Depth coverage for the whole area was about 98%, with a large gap unsurveyed towards the offshore limit off the Tanker Jetty.

(iv) Bathymetric data of 1992

For the October 1992 survey, the sounding-line directions were longitudinal to the area and arranged at an angle of 60° to 70° to the wharf front. Although the depth-spacing was uniform along the lines, the line-spacings varied between 10 and 12m. Gaps along the wharf front were minimal and the total depth coverage was estimated to be 97%. The six relevant drawings are Drg. No.3 - 1 to 6.

(v) Bathymetric data of 1993

There is a marked difference in the sounding pattern for the July 1993 survey. Sounding direction was almost perpendicular to the wharf front with depths neatly spaced at 5m along track. Line spacing was still 10m. This closer depth spacing along- track introduced extraneous data and the coverage was almost nearly 100%. Reference numbers for the six drawings are given as S 221 to 226/93.

Samples of hardcopy extracts of each individual charts can be seen in Appendix E.

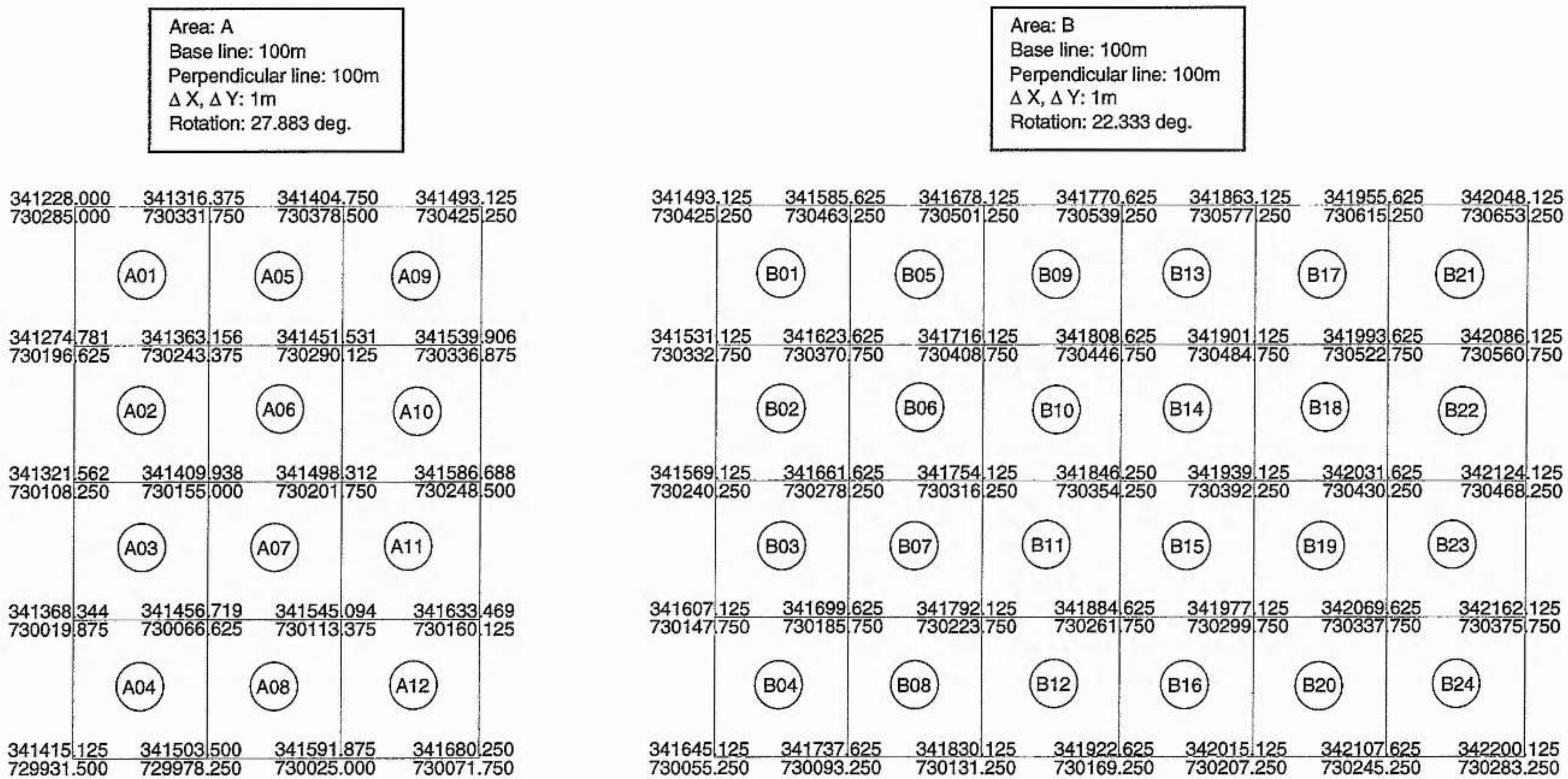


Figure 6.4. Examples of tabulation for block parameters of areas A and B (see page 158).

6.4 DATA ORGANISATION

Having defined the size of each block as 100 x 100m, for each year in total there will be 91 gridded data files representing the harbour area. There will be 12 files for area A, 24 for areas B and C respectively, 16 for area D and 15 for area E. In view of the considerable amount of data involved, either as raw or gridded data, this means that a consistent strategy for data management was required.

The strategy for data management primarily involves organising the reference and location of all the blocks. It is important that the parameters: the upper left co-ordinates; baseline; perpendicular line; grid spacing and grid rotation, used for the creation of each block remain as a set of constants. Of critical importance, within each sub-area, the blocks should not overlap. Figure 6.4 is an example of how the parameters of every block are tabulated. Such a guide is extremely important to assist future queries on gridding, to avoid confusion or mistaken identity of each individual block. In this way, the information shown in Figure 6.4 also readily provides a list of co-ordinates of every corner of every block, to assist if there is a need to locate the exact position and limit of a particular block. This is important in the event of subsequent work or detailed field investigation that requires the retrieval of data for a set of blocks of a particular area.

6.4.1 Separation of deposition and erosion sites

Once gridding is performed for each and every block from different dates, then differencing follows. Differencing is a process to subtract blocks from different dates of the same spatial location. Differencing between the corresponding blocks will produce three groups of numbers, i.e. positive for 'erosion', negative for 'deposition' and zero for 'no-change'.

Before one may proceed with the determination of volume or area for deposition and erosion for each individual block, a separation between depositional and erosional sites has to be achieved. As an illustration, consider an example of a dredging situation (Figure 6.5), in which one normally determines how much a depth value deviates from the design level (usually taken as either a plane or a slant surface). Any value that is above this plane or level is considered as a 'high-spot' or 'under-dredged' and the volumes of materials are usually calculated with reference to this plane. If, however, one is required to determine the difference between 2 non-planar surfaces, as in the case of surfaces of two sets of annual surveys, then this can pose a problem.

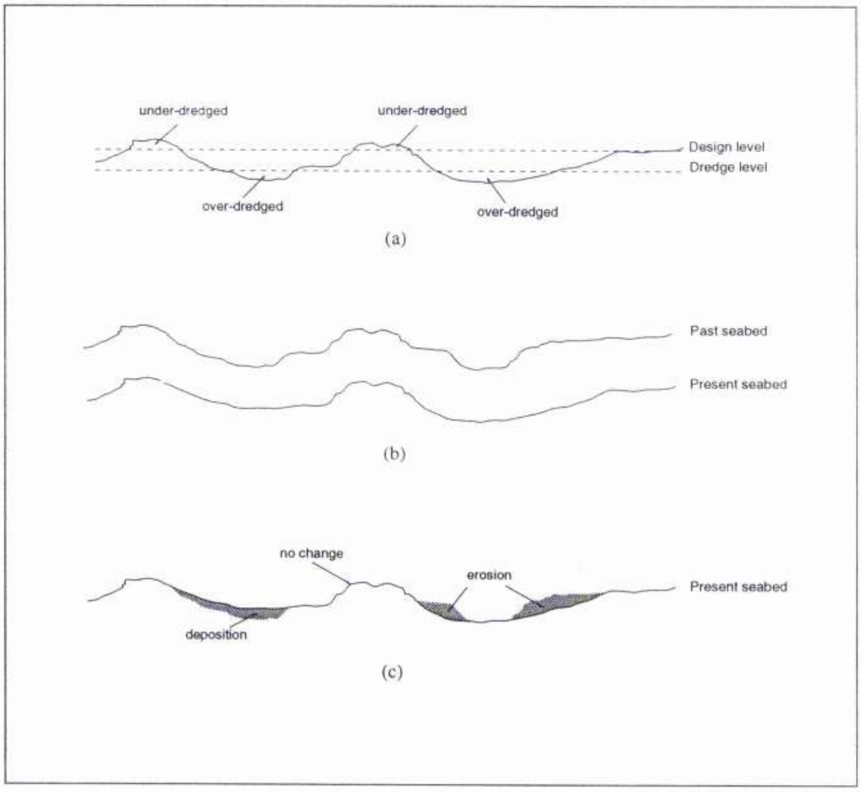


Figure 6.5. Hypothetical seabed conditions. (a) Under-dredged and over-dredged situation (b) Past and present seabeds (c) Deposition and erosion

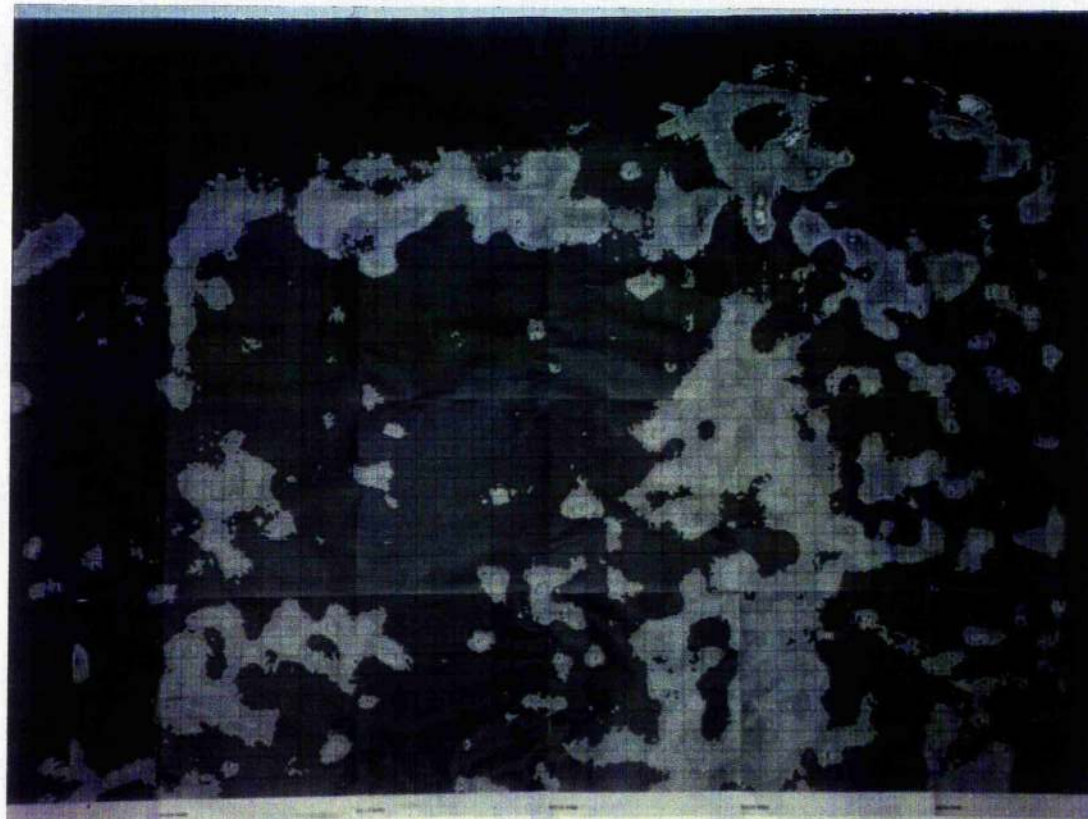


Figure 6.6. A seabed mosaic of area C for the period 1989/90 which comprises of 24 contiguous blocks, each block is outlined by creases in the mosaic. Lighter patches signify areas of deposition.

This problem is commonly found in dredging works where dredging is usually carried out to slightly below the required level to satisfy the terms of contract. This often results in undulating surfaces as shown in Figure 6.5(a). After some time, as a result of either natural deposition or erosion, the seabed surfaces may appear as in Figure 6.5(b). If the two surveys were then compared the difficulty is simply how to separate the depositional and erosional sites - Figure 6.5(c).

A practical way is to adopt the surface of the later date of a period as a reference surface and differences are obtained by subtracting the earlier ($Data_{i-1}$) from the more recent data ($Data_i$). The differences with negative values will indicate deposition, positive will show erosion and no changes are indicated by a zero value. To extract depositional sites for instance, the depths from the past date having positive differences are made equal to the value of the present date depths, i.e. as if no changes in depths have occurred. A similar method is applied to extract the erosional sites. In this way separate files for deposition and erosion are formed respectively, and used in the subsequent processing.

6.4.2 **Formation of Mosaics**

Once separate files for deposition and erosion sites have been created, it will be much easier to produce outputs for each, either in pictorial, tabular or graphical forms. In this evaluation process, only 2-D plots have been used to show depositional and erosional sites. For each sub-area, mosaics for deposition and erosion sites are formed by joining all the contiguous blocks. Figure 6.6 is an example of a mosaic which was produced for the period 1989/90 showing the depositional sites for area C.

Table 6.2. Computed volumes of deposition and erosion in the Dundee harbour area (m^3)

Block	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Area												*1989/90*												
A	2164.769	2368.520	3161.531	1166.340	2630.812	3369.102	1236.172	1335.833	6591.695	2735.484	566.109	940.930												
	1328.703	147.062	69.863	65.371	378.984	156.188	959.180	646.336	1480.109	163.414	2142.344	982.664												
B	1152.172	632.188	665.406	639.695	3390.289	1816.995	1500.438	2204.914	3587.102	3111.055	856.031	1969.633	332.562	992.281	554.305	766.188	0.621	101.773	239.031	1000.211	0.000	1482.140	1045.648	2013.016
	4027.578	642.430	1118.555	1168.273	2268.195	222.305	515.297	269.297	1560.406	57.297	728.086	345.656	44670.102	1947.102	1404.969	990.594	39475.594	23784.945	2039.586	620.453	47093.648	13823.461	613.594	169.258
C	0.312	2333.078	1350.336	1116.566	893.578	2522.008	2724.961	3866.250	1598.109	1822.758	1483.367	1959.078	2231.805	2955.398	3451.516	3845.188	2242.344	4141.164	4487.773	4243.195	1442.844	1914.883	1883.633	2049.938
	40045.055	2368.422	435.469	82.648	15459.211	432.008	135.641	57.484	21167.930	861.352	405.602	135.258	7689.102	899.180	130.328	51.953	11076.172	568.719	23.352	26.875	726.223	2697.125	1863.594	2360.102
D	155.561	1701.430	504.219	503.875	934.482	3289.320	1214.719	575.844	2753.953	3987.756	502.828	3830.234	656.240	1690.977	665.109	1960.516								
	33.731	3358.000	4911.953	3587.320	92.225	385.391	933.273	3416.125	5.664	243.562	2750.864	536.812	98.137	841.680	7252.328	2324.688								
E	553.140	621.258	1767.582	8.038	674.094	3254.438	63.969	1975.641	6732.391	148.199	3131.100	1708.547	359.387	1505.594	0.000									
	176.746	6668.531	2002.453	778.634	4057.125	1168.797	916.736	4030.344	214.312	1741.422	4465.594	316.922	1956.453	1802.609	0.000									
												1990/91												
A	2954.156	3245.137	2060.465	9.878	4003.990	4298.609	5565.344	922.729	9297.125	6714.484	6683.727	2695.035												
	340.172	10.098	68.727	0.000	58.984	100.773	38.367	0.000	138.930	0.000	10.453	3.500												
B	9560.117	5097.797	4891.969	2479.863	7550.219	3445.195	3286.484	2038.258	7800.812	2424.914	2399.086	2158.164	13110.891	4109.562	3094.188	4003.797	11701.305	7296.641	5028.047	4311.883	14472.830	7161.297	4197.414	4043.560
	0.000	0.000	20.510	121.908	225.086	0.539	53.711	434.422	140.297	59.484	110.719	301.797	1442.200	69.727	62.002	49.445	359.555	266.409	61.141	80.203	3.578	303.477	65.125	68.104
C	10741.883	2800.953	4044.009	2161.297	7132.150	2868.836	2549.602	1964.617	7000.422	4935.500	4547.030	4423.375	4242.016	4585.523	2600.300	2777.125	3051.953	7229.023	1403.852	995.812	8293.352	6803.992	5010.409	5631.055
	186.672	415.195	103.281	31.094	615.492	163.562	275.992	311.461	374.336	36.305	32.383	2.633	1433.406	403.445	149.039	264.211	1042.617	884.492	597.258	1019.898	561.875	195.352	45.906	376.680
D	1485.020	6900.758	9310.305	6334.031	3363.426	2043.820	3020.008	4521.719	2526.352	1746.297	4196.008	2540.203	2471.875	3491.734	7217.582	5098.031								
	50.306	210.570	48.758	208.125	357.961	572.742	196.672	656.125	708.047	425.750	431.133	897.000	141.242	208.562	642.047	385.531								
E	1606.668	7909.570	5876.719	1505.164	3707.328	4873.336	3770.664	3344.766	1842.227	4351.605	5125.547	481.186	4470.062	2753.695	0.000									
	127.730	355.391	241.578	2614.648	633.406	30.305	228.211	279.766	0.523	22.805	9.766	0.000	134.859	48.059	0.000									
												1991/92												
A	649.453	17.287	148.047	0.000	2189.344	25.742	45.867	0.005	1012.570	0.000	34.867	8.422												
	2014.038	2537.982	1523.479	11.898	4376.789	6403.320	4172.414	993.193	4310.531	8310.750	5059.773	3200.203												
B	2431.430	0.164	4.352	3.148	2618.936	0.000	911.852	8.133	875.803	4.188	0.016	8.992	8321.945	31.156	0.010	8.092	2619.680	260.922	0.570	7.633	1833.453	198.875	0.000	7.328
	1469.094	6957.977	6627.320	4153.820	2039.742	7214.023	7810.156	5673.586	3461.480	7337.786	7407.312	6414.320	2154.422	9088.008	6788.359	6643.977	1252.477	7251.031	7759.180	6014.797	1409.664	7556.023	8171.836	6233.211
C	1346.930	16.186	0.000	5.352	850.305	0.250	0.000	26.445	1395.195	0.586	0.000	0.000	772.242	22.891	0.000	0.000	394.039	59.781	14.898	2.383	307.742	20.773	32.688	1.852
	3562.055	6729.344	7954.852	6294.850	4129.422	6405.734	7313.711	5020.922	6643.258	7434.156	7253.555	5819.891	5344.125	6785.430	5944.672	5513.109	5185.688	5899.883	4042.930	4819.695	3921.523	5540.859	4845.750	6011.930
D	365.707	96.641	7.469	22.750	918.250	21.672	24.875	25.453	1315.867	1.594	21.656	2.922	2767.297	102.711	159.625	0.000								
	3547.625	4523.305	5434.031	6181.328	3129.056	4198.117	4984.922	7530.422	4152.812	4872.273	6250.750	9903.828	2562.996	3167.125	7008.586	11126.891								
E	100.961	14.609	0.000	750.825	31.641	5.518	20.547	6.953	0.000	28.766	2.781	0.000	41.297	796.008	0.000									
	7751.817	9292.648	9926.453	5075.469	6454.734	6661.117	5059.227	7784.078	3377.940	5807.625	10111.016	695.827	5290.211	5433.977	0.000									
												1992/93												
A	8383.625	1566.012	919.481	3432.152	7817.350	2202.828	1171.852	4290.280	10130.422	6091.734	2938.508	3614.172												
	2902.016	32.020	570.633	5.055	141.989	132.859	580.930	19.367	67.969	0.172	203.133	120.852												
B	8383.625	5953.852	6451.703	3097.422	5822.070	6222.141	3672.445	2672.773	4755.785	3834.953	3806.836	2638.000	6612.977	4978.281	3205.695	1964.406	2275.320	4453.719	3298.680	1996.719	1845.492	2563.727	2923.070	1938.180
	2902.016	0.006	162.031	88.664	239.582	3.242	1123.602	195.523	31.266	198.141	51.906	195.797	2705.133	163.445	3.914	332.891	3782.484	973.469	5.852	89.531	5005.852	758.227	4.109	88.727
C	1525.680	2258.203	3104.188	2353.109	2747.398	2221.664	2670.062	2050.008	3908.922	2921.984	3221.547	2373.375	3174.906	3517.055	3677.409	2916.828	1759.781	3474.477	3383.711	3584.398	3315.520	3752.398	3105.500	3113.352
	7249.469	392.195	4.906	85.436	5145.688	148.992	10.469	102.484	1693.941	134.031	4.266	45.125	1333.117	109.633	36.789	68.773	2543.031	129.055	15.797	5.773	882.958	28.094	81.734	75.203
D	1994.922	3005.938	2206.680	3808.891	1586.016	3288.906	2193.227	4832.578	1906.531	2383.820	1992.367	5233.891	1811.777	1160.250	828.005	5794.891								
	798.078	74.830	88.531	71.211	1999.031	64.266	189.297	53.031	1703.203	42.547	296.617	10.922	3188.578	713.180	364.984	3.031								
E	2720.352	2167.734	5988.859	2545.797	3344.516	4915.908	1943.812	3843.906	3109.305	2486.875	5166.234	1809.883	1811.680	3579.484	89.398									
	1225.208	910.062	4.047	2531.969	200.047	358.828	485.602	237.453	254.156	62.578	191.734	569.352	110.234	1973.453	397.580									

Note: Top value denotes deposition and bottom value for erosion

6.5 VOLUMETRIC ESTIMATION

Using the separate file for deposition or erosion, one could also work out the quantity of the material found or removed out of the area. Table 6.2 is a compilation of volumes of deposition and erosion calculated for the individual blocks in the 'Dundee harbour area'. Tables 6.3 and 6.4 provide a summary of the overall quantities of deposition and erosion for each area for different periods respectively.

Table 6.3. Volumes of sediment deposition (m^3).

Area	1989/90	1990/91	1991/92	1992/93
A	28,267	48,361	4,130	52,358
B	30,274	138,227	20,177	94,567
C	56,560	105,917	5,271	70,429
D	24,927	66,265	5,875	43,828
E	22,503	51,689	1,800	45,524
Total:	162,531	410,459	37,253	306,706

Table 6.4. Volumes of sediment erosion (m^3).

Area	1989/90	1990/91	1991/92	1992/93
A	8,740	770	43,815	4,777
B	189,357	4,466	136,689	19,105
C	109,699	10,203	138,517	20,266
D	30,772	6,141	88,532	9,651
E	30,596	4,727	89,712	9,516
Total:	369,164	26,307	497,265	63,315

Table 6.5. Statistical information on deposition, erosion and no change of area A for the period 1989/1990 (see page 165)

				Deposition (metres)		**Erosion (metres)**	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
A01	52.49	36.08	11.43	0.3	0.1	0.1	0.5*
A02	74.70	10.75	14.55	0.3	0.1	0.0	0.1
A03	73.05	5.63	21.32	0.3	0.1	0.0	0.1
A04	51.27	7.99	40.74	0.1	0.0	0.1	0.2
A05	60.74	17.95	21.31	0.3	0.1	0.0	0.1
A06	84.58	10.75	4.67	0.4	0.1	0.1	0.2
A07	58.12	41.64	0.24	0.1	0.0	0.1	0.6*
A08	62.15	37.58	0.26	0.2	0.0	0.0	0.1
A09	71.05	21.61	7.34	1.1*	0.1	0.1	1.2*
A10	85.96	13.66	0.38	0.3	0.0	0.1	0.3
A11	32.31	67.39	0.30	0.1	0.0	0.1	0.2
A12	49.57	50.18	0.25	0.1	0.0	0.1	0.2
Mean	63.00	26.77	10.23	0.23	0.05	0.07	0.17

Note: Values shown with an asterisk are excluded from computation of the mean value

6.6 AREAL ESTIMATION

The areal extent of deposition, erosion and no change within the study area have also been determined. However, only values for area A for each period are presented as examples. These are found in columns 2, 3 and 4 of Tables 6.5 and 6.6 respectively. Under each column of every Table is the mean value for that column. The tabulations for all the other blocks of the harbour area are presented as Appendix D.

6.7 STATISTICAL RECORD

Apart from the estimation of volume and areal extent, it may sometimes be useful to compile indication on the statistics of areal extent and rates of deposition and erosion, for example, in generating long term statistical records which may form part of an engineering investigation of the harbour area.

6.7.1 Depositional and erosional values

Again, by referring to Table 6.5, in columns 5 and 8 for example, are the corresponding maximum and minimum values for the deposition and erosion within the individual blocks during the period 1989/90. The derivations of these maximum and minimum values are obtained from the gridded file and are far from straightforward. This is because the presence of any aberrant or perturbed values may influence the spread in the value between maximum and minimum.

A more detailed approach is required for the determination of the actual maximum and minimum values of deposition and erosion. The approach is by examining the cumulative frequency of the occurrences using various class values. First, it is necessary to group the depositional or erosional values according to their respective class intervals as depicted in Figure 6.7. By selecting only those class values considered as significant class values, i.e. those > 5% that form a cluster of at least 70% of their occurrences, then, the selection of maximum and minimum values of the cluster will identify the maximum and minimum values of deposition or erosion, respectively. In this way, the inclusion of any single large or small values may be avoided from the selection of the minimum and maximum values of deposition and erosion. A simple example of the situation can be illustrated using Figure 6.7, where the class values of 0.1 and 1.5m are selected, instead of 0.1 and 2.1m, to represent the minimum and maximum value respectively.

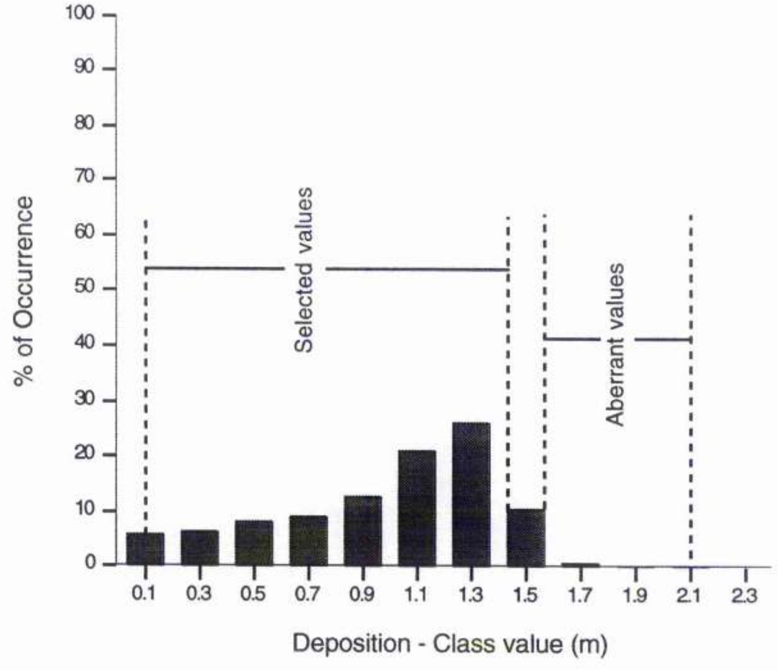


Figure 6.7. A histogram plot showing the presence of aberrant and perturbed values.

Table 6.6. Calculated values of deposition and erosion rates (see page 168)

	1989/90		1990/91		1991/92		1992/93	
Area	Dep.(m)	Ero.(m)	Dep.(m)	Ero.(m)	Dep.(m)	Ero.(m)	Dep.(m)	Ero.(m)
A	0.05 - 0.23	0.07 - 0.17	0.06 - 0.43	0.00 - 0.06	0.00 - 0.08	0.06 - 0.49	0.07 - 0.33	0.00 - 0.16
B	0.07 - 0.29	0.09 - 0.24	0.09 - 0.47	0.02 - 0.19	0.00 - 0.03	0.14 - 0.60	0.11 - 0.41	0.03 - 0.11
C	0.01 - 0.40	0.05 - 0.23	0.09 - 0.43	0.04 - 0.17	0.02 - 0.08	0.10 - 0.67	0.10 - 0.41	0.03 - 0.11
D	0.10 - 0.45	0.06 - 0.21	0.10 - 0.68	0.08 - 0.30	0.02 - 0.08	0.11 - 0.69	0.10 - 0.46	0.06 - 0.22
E	0.08 - 0.46	0.09 - 0.66	0.10 - 0.75	0.06 - 0.24	0.02 - 0.09	0.09 - 0.79	0.09 - 0.49	0.07 - 0.27
Average	0.22	0.24	0.32	0.15	0.04	0.47	0.26	0.13

6.7.2 **Annual rate of erosion**

Having determined the maximum and minimum significant erosional values for every block, an overall estimate of the annual rate of erosion can then be worked out. The sediment erosional rates are often based on broad averaging between the determined maximum and minimum values. This is simply done by taking the average of maximum and minimum values without considering the influence or effect of the single aberrant or perturbed value present.

For example, to illustrate the problem of having aberrant or perturbed values, consider the information as shown in column 8 of Table 6.5. If one takes a straight forward derivation of a single value to represent an overall rate just by simply taking the gross average of all values shown in the column, then one derives an erosional value of 0.32m. Indeed, there are values in that column (those shown with an asterisk) which cannot be considered as due to natural erosion, but rather as man-induced change (e.g. dredging). Again, by excluding these unrepresentative values from the calculation, the probable natural erosional rate will then be reduced to 0.17m, which is about 50% lower than the value inferred through broad averaging. Obviously, some judgement and careful analysis are therefore required before any single value is derived from a set of values. It is important that this single aberrant or perturbed value be identified and discarded from the set, if not it will lead to either over or underestimation of the overall rate value of deposition and erosion.

Based on the compiled values shown in Table 6.6, after taking into consideration all possible effects of aberrant and perturbed values, it is suggested that an overall value for the annual rate of sediment erosion during the period 1989 to 1993 is $25 cm.yr^{-1}$.

6.7.3 **Annual rate of deposition**

Similarly, an overall estimate for the annual depositional rate value can be derived by filtering all possible values known to be caused by man-induced changes, such as depositional values in dredged areas. Thus, an overall value for the annual rate of deposition is around $21 cm.yr^{-1}$.

6.8 ANALYSIS OF RESULTS

Rigorous processing of the yearly data has led to the recognition of some important and interesting patterns of spatial distributions, quantities, and rates of seafloor sediment deposition and erosion in the Dundee harbour area. To ease the description and analysis of the results, graphical, pictorial and tabular forms are used for presentation.

6.8.1 **Deposition during the period 1989 - 1993**

(i) Period 1989/90 - (Figure 6.8)

For the period 1989/90, the depositional pattern for the whole harbour area is rather patchy in nature. In area A, the most affected parts are located along the Queen Elizabeth wharf (A01, A05 & A09) spreading offshore towards adjacent areas (A02, A03, A06 and A10). Elsewhere in the area are mainly small isolated deposition spots. It is estimated that between 5 and 23cm of sediment accumulated in the area due to natural deposition, which is on average about $14 cm.yr^{-1}$. During this period there were also some dredging activities especially in areas close to the wharf. These areas were dredged to between 0.5 and 1.2m deeper than the previous depths. As a result, around 0.4 to 1.1m of sediment accumulated in some parts of the dredged areas, as indicated by the bathymetric survey data of the following year. Statistics also indicate that deposition occurred in 63% of the area while in 10% of the area there was no change.

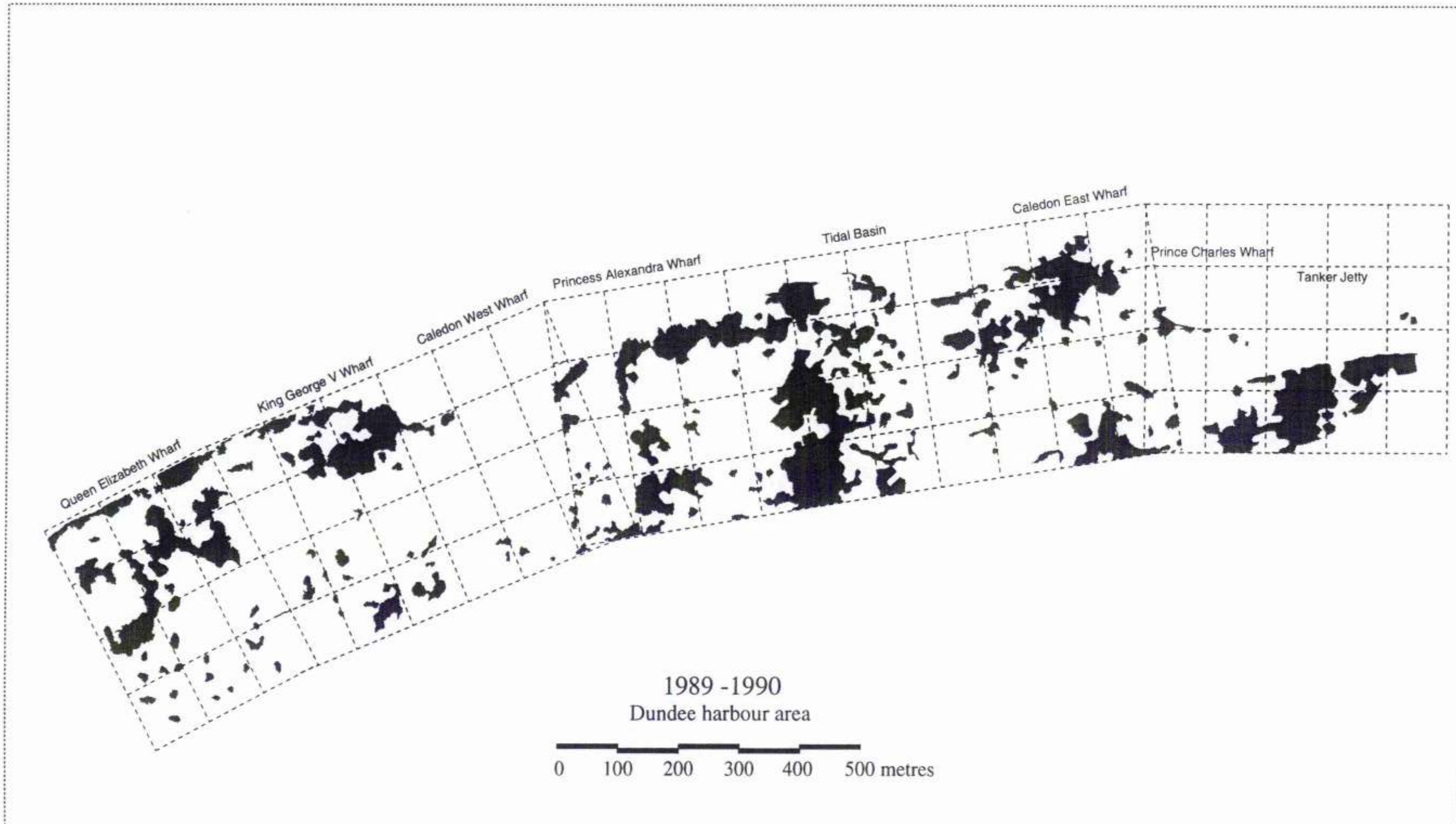


Figure 6.8. Locations of seafloor sediment deposition sites for the period1989/90. Dark patches signify areas of deposition.

Areas along King George V Wharf (B01, B05 & B09) were silted by about 40cm and the rest of the areas showed scattered areas of deposition of 0.1 to 0.3m. Man-induced changes in the form of dredging were prominent especially along the wharf. These areas were dredged to -9.5m (LAT) which involved removing between 0.5 and 4.5m of the seabed. The accumulation rate for area B is between 7 and 29cm (which is about same as the erosion rate of 9 - 24 cm).

In area C, however, there is a marked pattern to the deposition, i.e. linear clusters of sediment deposition both along and across the flow-lines. A depositional zone 50m wide and 100m offshore extends from C02 eastwards for 500m to C21. Lateral deposition is concentrated in blocks C15,C16,C19 & C20 and decreases into C23 & C24. This includes a dredged area perpendicular to the Tidal Basin. The estimated average deposition in area C is around 21cm.

Deposition in area D occurred as clusters found 50-200m off the wharf. Another cluster was found in D12 and the rest of area D comprised of isolated spots. About 38% of area D is affected by deposition averaging 28cm in thickness.

There is insufficient data coverage for area E during the 1990 survey. As a result, no complete account of deposition is available for this area. However, the thickness of deposition in places where data are available has been worked out to be approximately 46cm.

(ii) Period 1990/91- (Figure 6.9)

During the period 1990/91 there was a remarkable increase in the areas and thickness of sediment deposition sites which covered most parts of the harbour area especially in areas close to the wharf. The lateral trend has become a prominent pattern, showing a

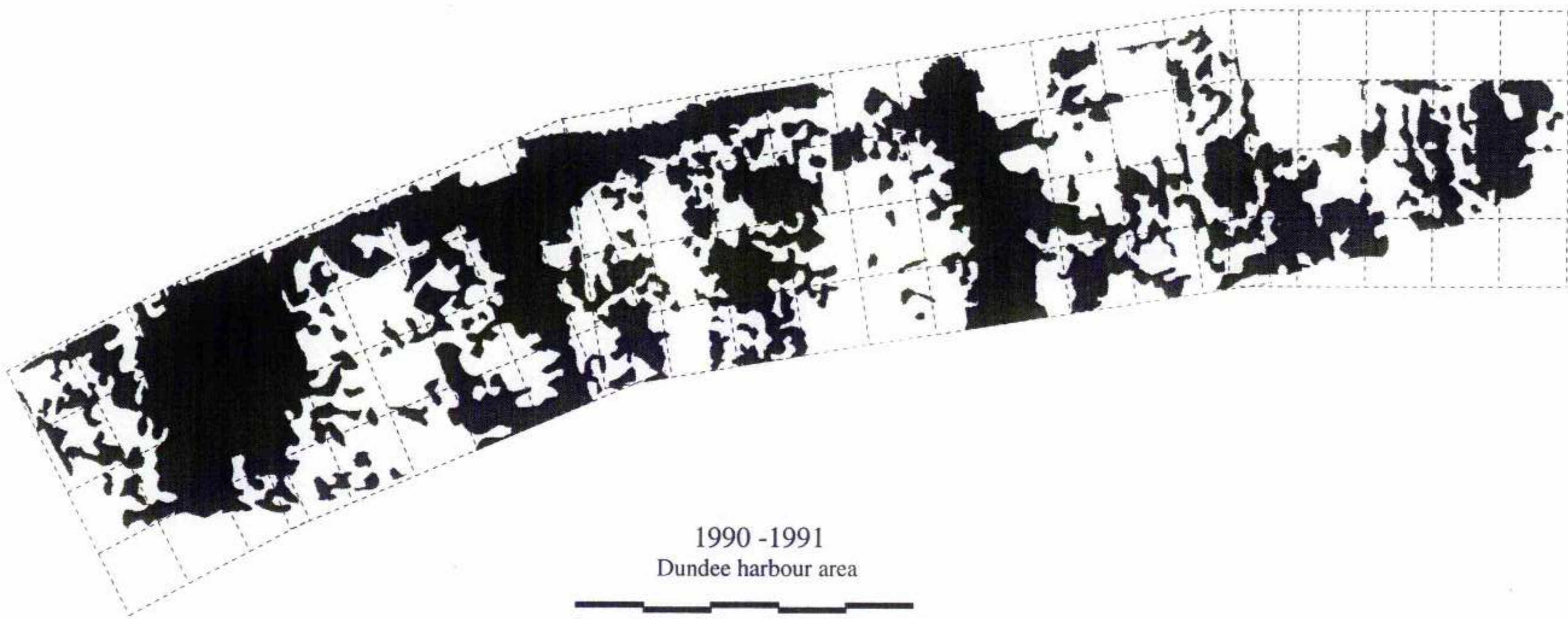


Figure 6.9. Locations of seafloor sediment deposition sites for the period1990/91.
Dark patches signify areas of deposition.

dominant north-south pattern of belts of sediment deposition. In area A in particular, the deposition of between 6 and 43cm covering 69% of the area. In some parts, there is heavy deposition with as much as 70cm, detected.

In area B, infilling of the dredged areas has become a prominent pattern of deposition. In the dredged areas enhanced deposition by as much as 1.6m is detected. Deposition varies from 9cm to 47cm with concentration along the dredged areas.

In area C, there exhibits a rather interesting pattern. In 1989, the dredger began dredging near C24 and proceeded towards the Tidal Basin before changing its course to parallel the wharf at C22. During the following period (1990/91) sediment began to accumulate in the dredged areas as shown by patterns similar to those of previous dredged areas. This is supported by the fact that deposition was heavy in disturbed areas. As much as 1.2m of sediment accumulated in the dredged areas. Within the dredged areas along the wharf, it is estimated that 0.6 to 1.5m of sediment had accumulated. At the same time, inevitably some slope erosion developed in the dredged areas. Though difficult to pin-point exactly but analysis using 3D-plot will indicate its occurrence (see Figures 5.10a and 5.11a). Those erosional values caused by slope erosion have to be excluded in the determination of annual erosional rate, because they do not represent the type of natural seabed erosion. For example (see Tables 6.5.9 on Statistical information in Appendix D), at C13 it is believed that the erosional value of 0.8m is caused by slope erosion and also at C18 and C19. Thus, by excluding these values, as pointed out in Section 6.7.1, an erosion rate of 0.17m is obtained. On the other hand, if they were included in the average, then a slightly different value is reached (0.21m).

The deposition in area D is a continuation of that in area C. On the western limit the accumulation of sediments is concentrated along the dredged areas, while on the eastern side and the rest of the area, deposition is a progressive development of the previous

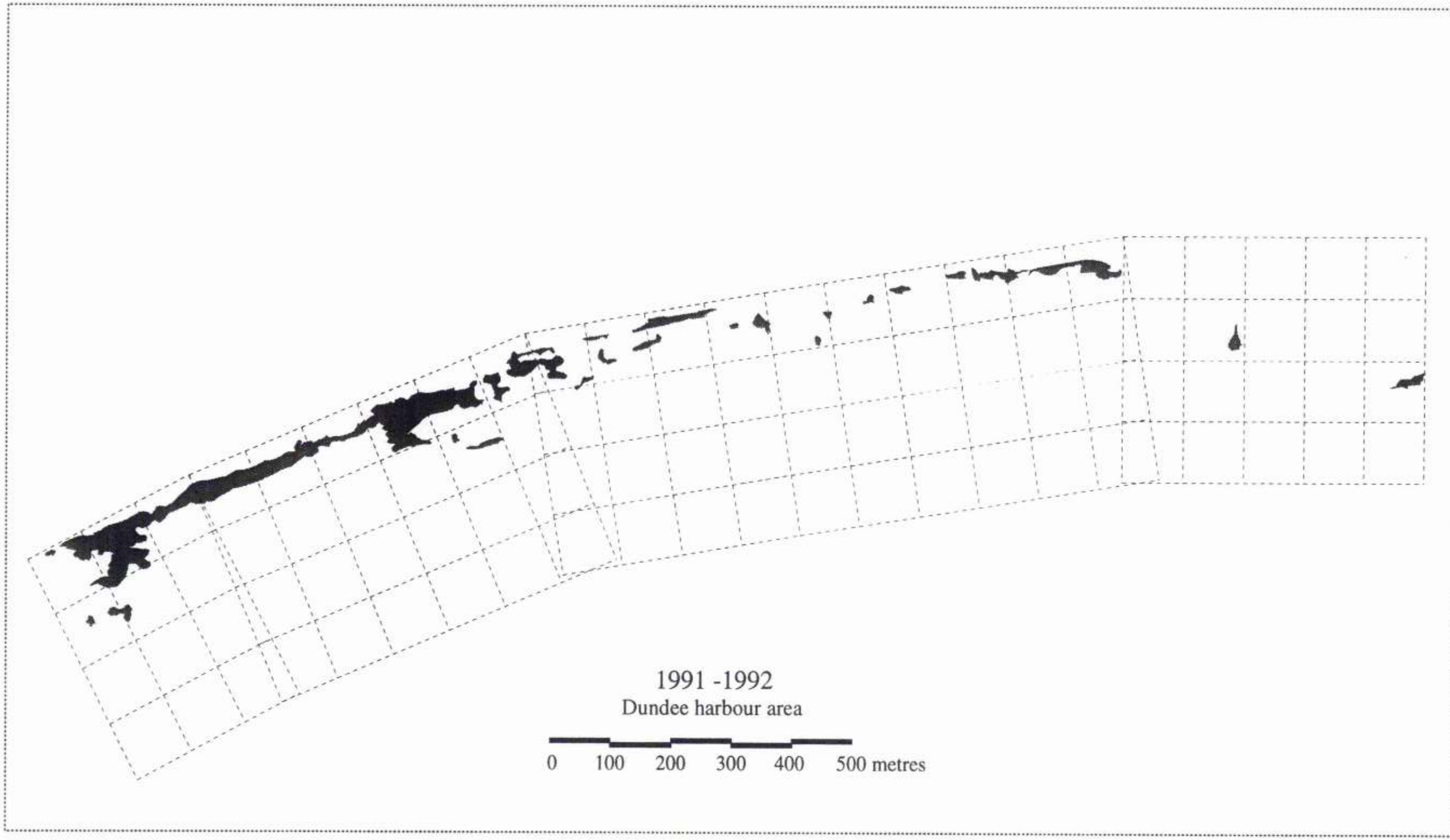


Figure 6.10. Locations of seafloor sediment deposition sites for the period1991/92.
Dark patches signify areas of deposition.

deposition sites. Deposition which occurred in 70% of the area reached as much as 39cm (excluding that in the dredged areas).

Similarly, for area E, more deposition is found, although in only 58% of the area. The depositional value is estimated to be between 0.6 and 1.1m.

(iii) Period 1991/92 - (Figure 6.10)

The port's expansion programme for the year 1992 involved dredging of the entire harbour area. Some parts of the harbour were dredged to -9.5 metre depth (LAT) to accommodate bigger ships. As a result, the 1991/92 data show far less deposition than for the preceding period. However, deposition still occurred at a remarkably high rate, although it was confined to a linear strip parallel to the wharf line and up to 100m offshore.

In area A, deposition which occurred in 6% of the area reached a maximum thickness of 0.8m. In other parts, negligible depth changes suggest deposition of less than 10cm. In erosional areas the floor dropped by about 8cm.

A similar pattern is found in areas B, C and D. In general, about 0.5m of sediment accumulated along the deposition line with slightly higher values at B13 where up to 1.3m was detected. For the rest of the area, the deposition value was negligible (less than 10cm). By not including deposition in the dredged areas, the deposition rate for this period is estimated to be 2cm.

Deposition in area C was less than 10% and slightly scattered, though still close to the wharf. The depositional value was between 2 and 8cm which gives an averaged value of 5cm.

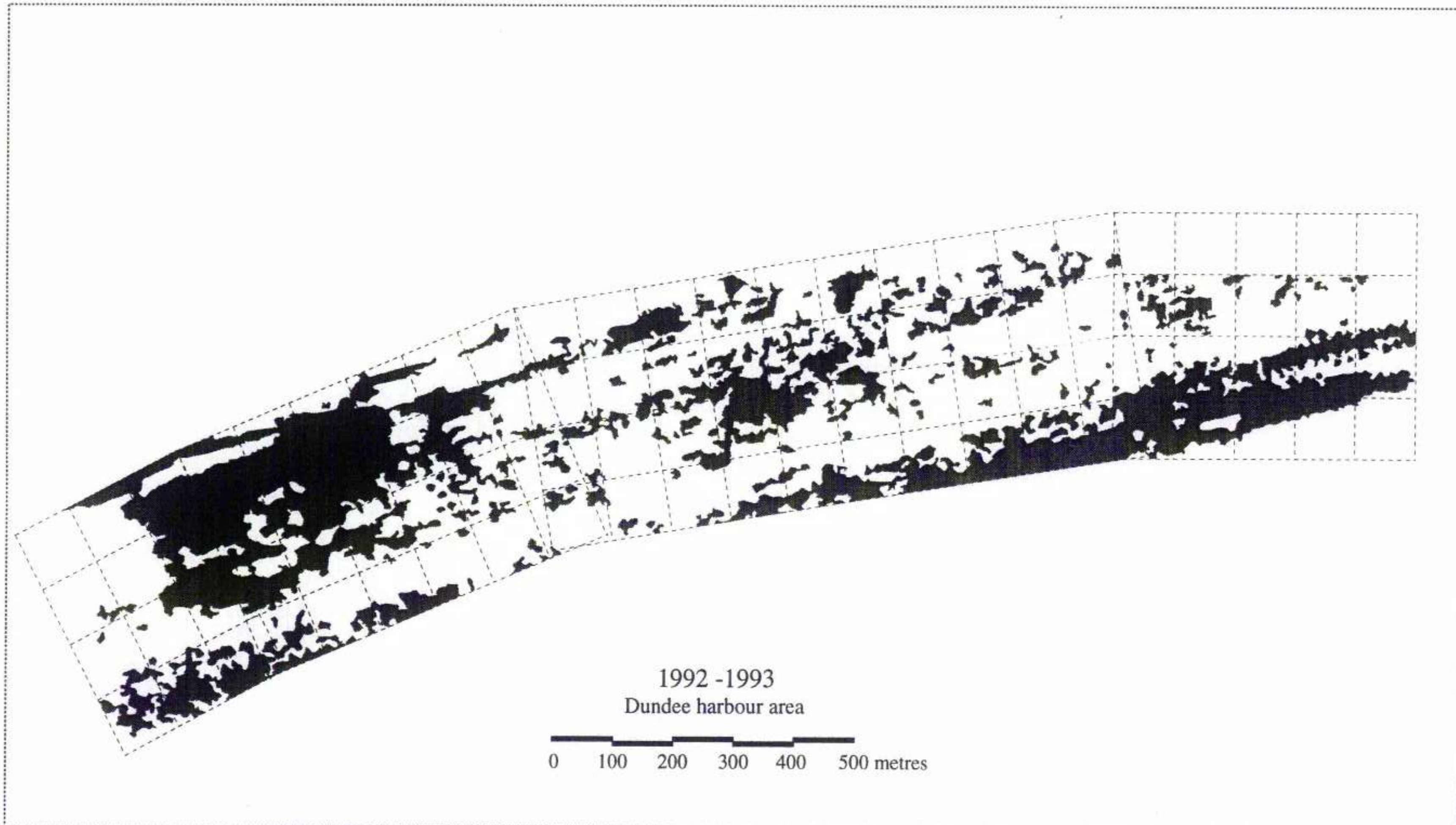


Figure 6.11. Locations of seafloor sediment deposition sites for the period1992/93. Dark patches signify areas of deposition.

The deposition in area D was similar to that of area C, where accumulation was concentrated along the wharf. It is estimated that between 0.3 and 0.8m of sediments accumulated close to the wharf. However, the calculated value of natural deposition for the area was substantially lower between 2 and 8cm.

Deposition found in area E was negligibly low (about 2%). Deposition was between 2 and 9cm.

(iv) Period 1992/93 - (Figure 6.11)

During the period 1992/93 the harbour area was affected by a strong build up of sediments. The sediment patterns closely followed the flow-line direction.

In area A the accumulation of sediment was heavy along the wharf, and in blocks bordering area B. Along the wharf, deposition was between 0.4 and 0.9m whilst in other parts of the area the deposition averaged 0.33m.

The flow-line pattern of deposition continued in area B where a significant amount of sediment accumulated as a large patch. The estimated, averaged value of deposition was 41cm. In areas, particularly along the wharf, between 0.5 to 1.3m of sediment accumulated.

The accumulation formed smaller clusters as it entered area C. The deposition in the area was 13 cm with accumulation along the wharf slightly higher (50cm). The rest of the area contained small patches of deposition sites with a prominent linear pattern emerging from the south-western corner and continuing into areas D and E. In areas D and E, the deposition rate was about the same as in area C.

6.8.2 **Erosion during the period 1989-1993**

Erosion on the bed of the harbour area is caused by either natural or man-induced activities. Natural erosion is mainly associated with the action of waves and tidal currents on the loose seabed sediment flooring the area. Man-induced erosion, however, is in the form of dredging works, designed to provide adequate depth for navigation.

During the year 1989, the area around Caledon West Wharf was dredged to -9.5m (LAT), lowering the bed to an average of about 4.5m greater than the previous depth of 5.0m (LAT). In areas close to Princess Alexandra and Eastern Wharves (Figure 6.12), the depths of 8.0m (LAT) were reached by removing 2 to 3m of the seabed sediment. A small area (around block C17) was also deepened to provide adequate depth for the launching of a life boat at all states of tide. In addition, sectors within blocks C22 - C24 and D2 - D4 perpendicular to the Tidal Basin were also dredged. Other areas dredged extended from Caledon East Wharf to the down stream limit of the harbour area with concentrations 200 - 250m offshore in area E.

During the period 1990/91 the pattern of erosion essentially comprised isolated spots coincident with previous erosion sites (Figure 6.13). However, in 1992, intensive dredging works were undertaken that involved almost the whole harbour area (Figure 6.14). In some places the area was dredged to a maximum of 5m depth (LAT) and to even deeper in other parts. This almost destroyed the continuity of the previous record of deposition built up in the area.

Finally, the 1992/93 period showed a rather different pattern, in which deposition was concentrated mostly along the wharves (Figure 6.15). These patterns may have been due to the stirring of the seabed by ships during berthing at the wharves. There are also a few sites where there is emerging evidence of a gradual increase in erosion as in areas A and E.

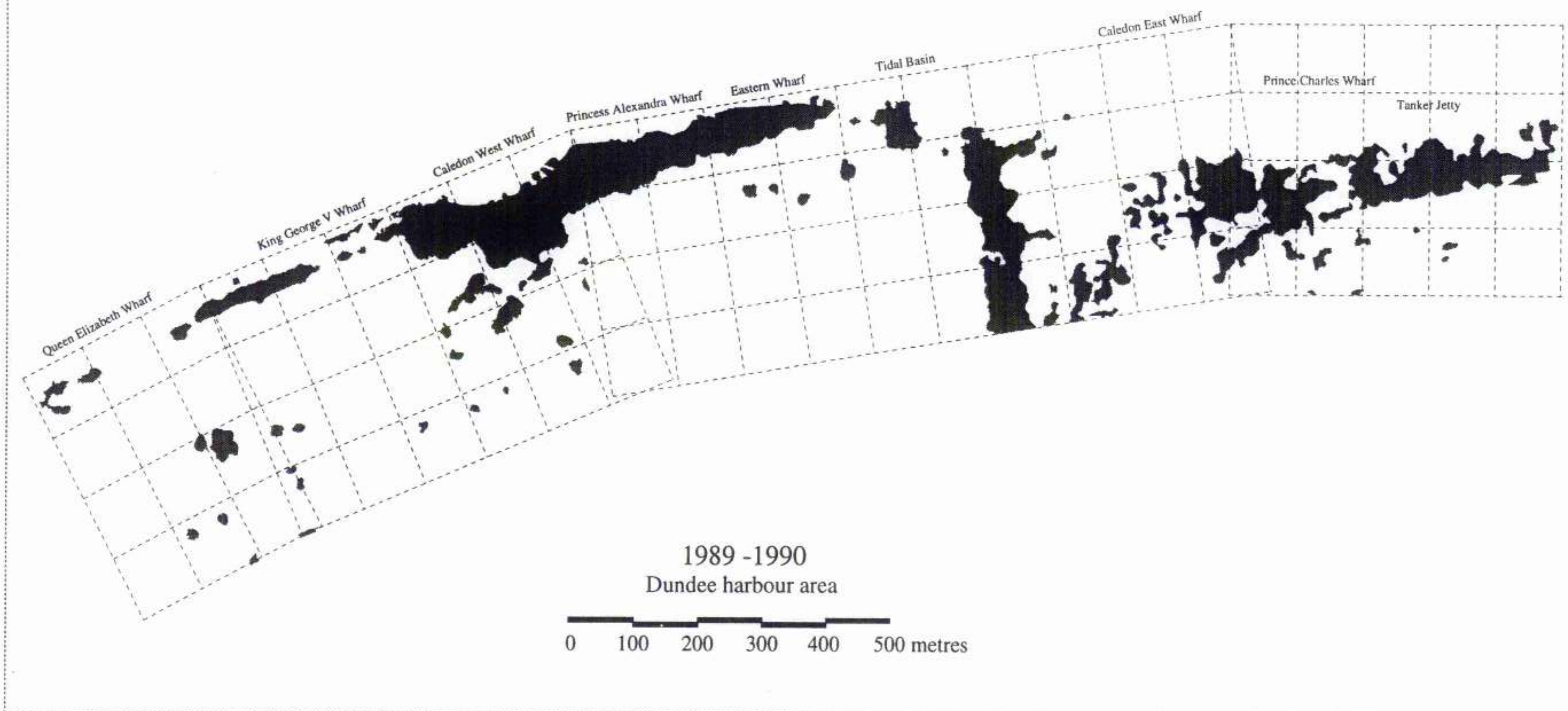


Figure 6.12. Locations of seafloor sediment erosion sites for the period1989/90.
Dark patches signify areas of erosion.

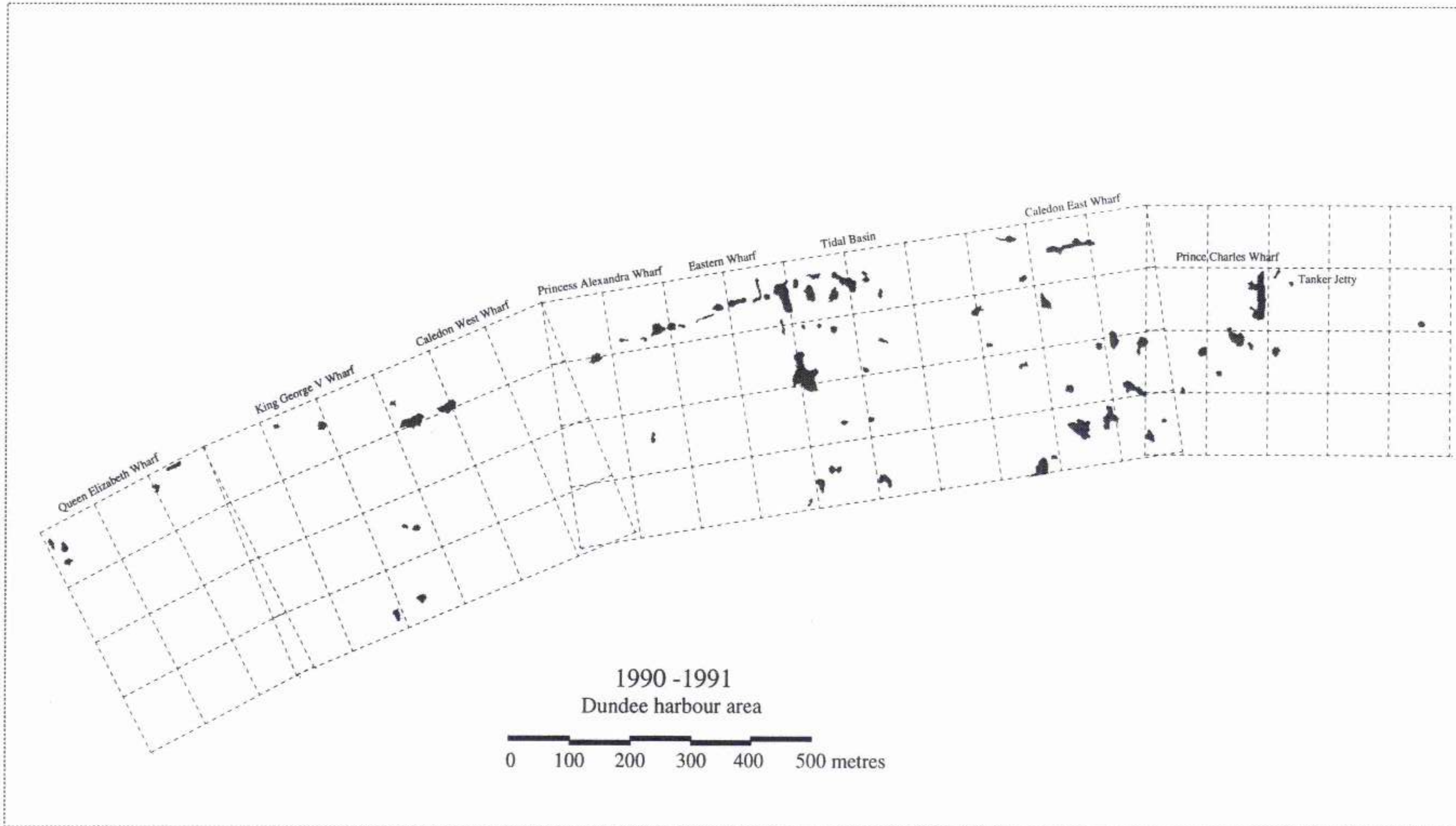


Figure 6.13. Locations of seafloor sediment erosion sites for the period1990/91.
Dark patches signify areas of erosion.

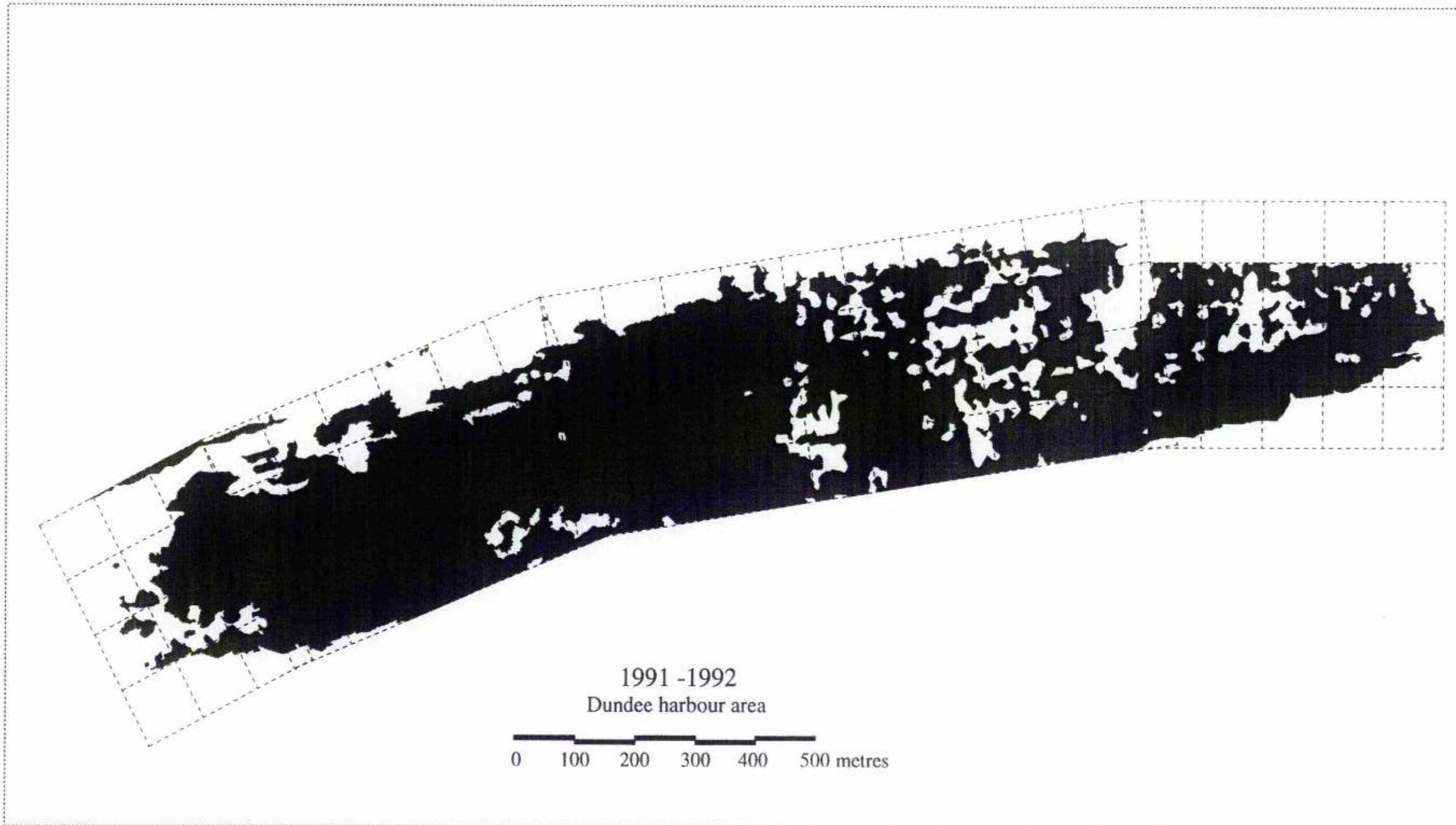


Figure 6.14. Locations of seafloor sediment erosion sites for the period1991/92. Dark patches signify areas of erosion.

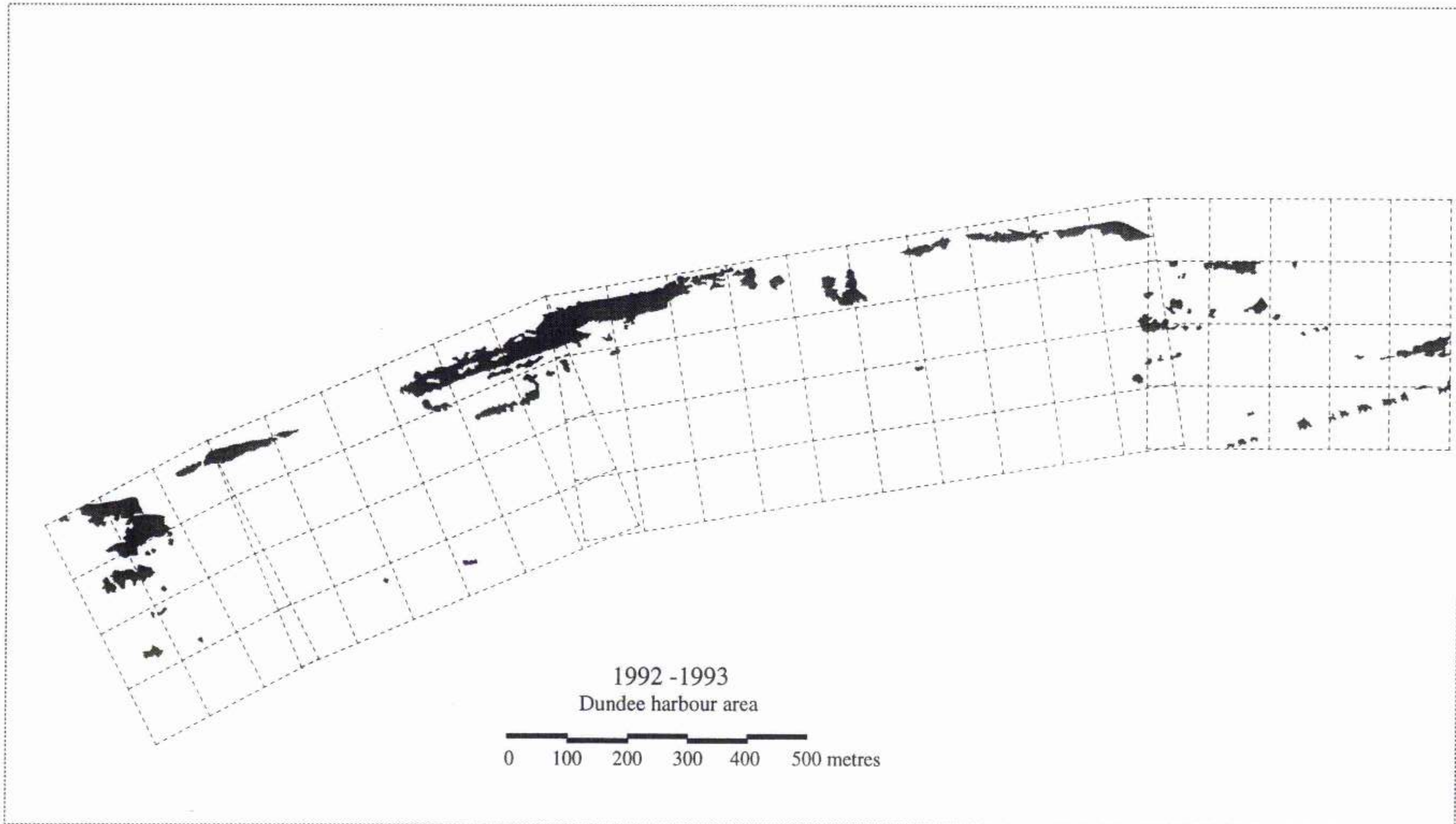


Figure 6.15. Locations of seafloor sediment erosion sites for the period1992/93.
Dark patches signify areas of erosion.

6.8.3 Evaluation along four longitudinal axes

To further demonstrate the differences recognised, between each period of surveying the harbour area is represented by four longitudinal axes, each of which axis passes through every block longitudinally (see Figure 6.2). Bar charts have been constructed showing the blocks as horizontal axes and the volumes of change calculated for the respective blocks along the vertical axes, as shown in Figures 6.16 to 6.19. These figures are complementary to Figures 6.8 to 6.15. Interpretations of changes can either be provided across or along the axes. The differences between the sets of figures above is that the latter represent information in quantitative form while the former provide it in pictorial form.

Table 6.7. Sediment budget for 1989 - 1993

Period	*Net gain (m^3)*	*Net loss (m^3)*
1989/90	-	207,433
1990/91	384,152	-
1991/92	-	360,012
1992/93	243,391	-
	627,543	567,445
	567,445	
Total gain:	60,098 m^3	

6.8.4 Sediment budget

The sediment budget for the harbour area over the periods 1989 - 1993 was estimated on the basis of the computed quantities of deposition and erosion obtained. The results are listed in Table 6.7.

1989/90 **1990/91**

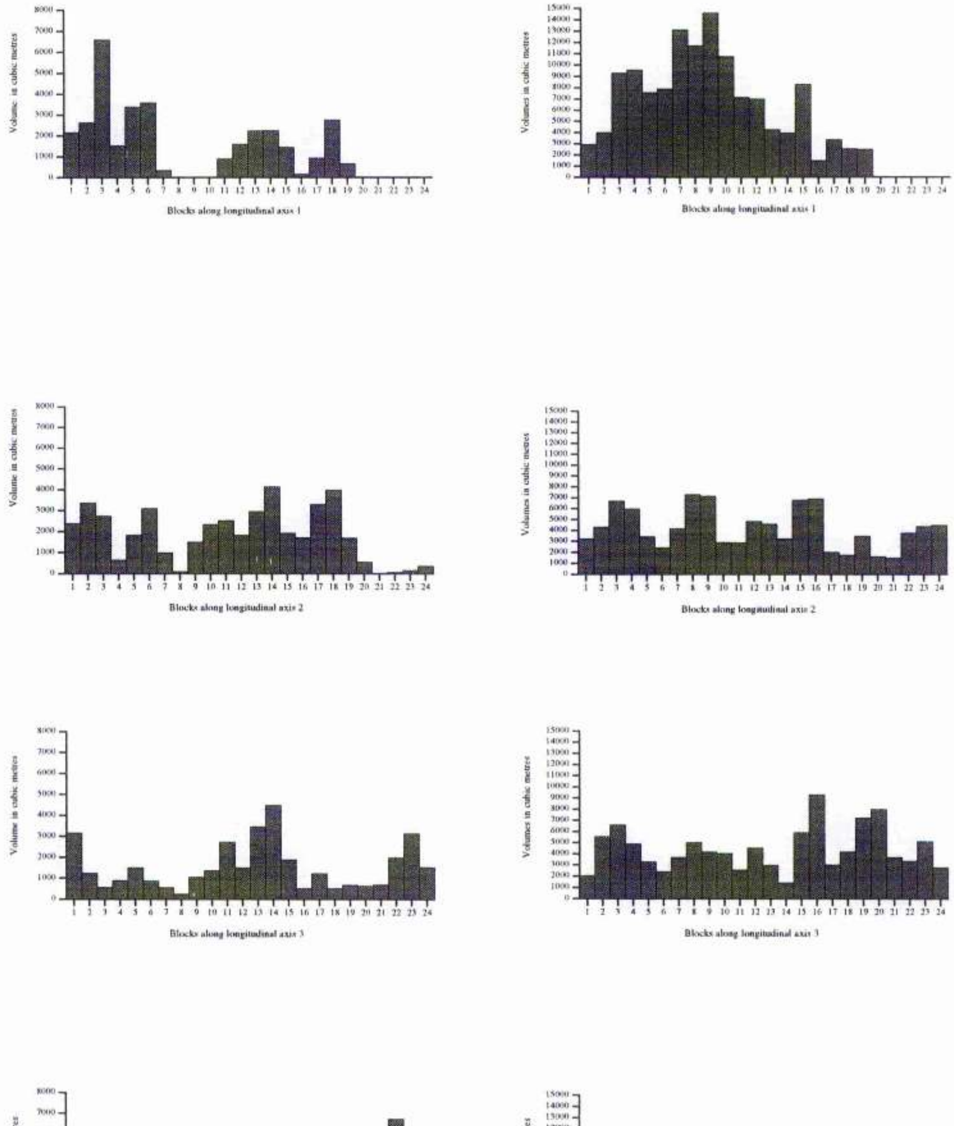


Figure 6.16. Bar charts representing volumes of deposition along the 4 respective axes (Periods 1989/90 & 1990/91).

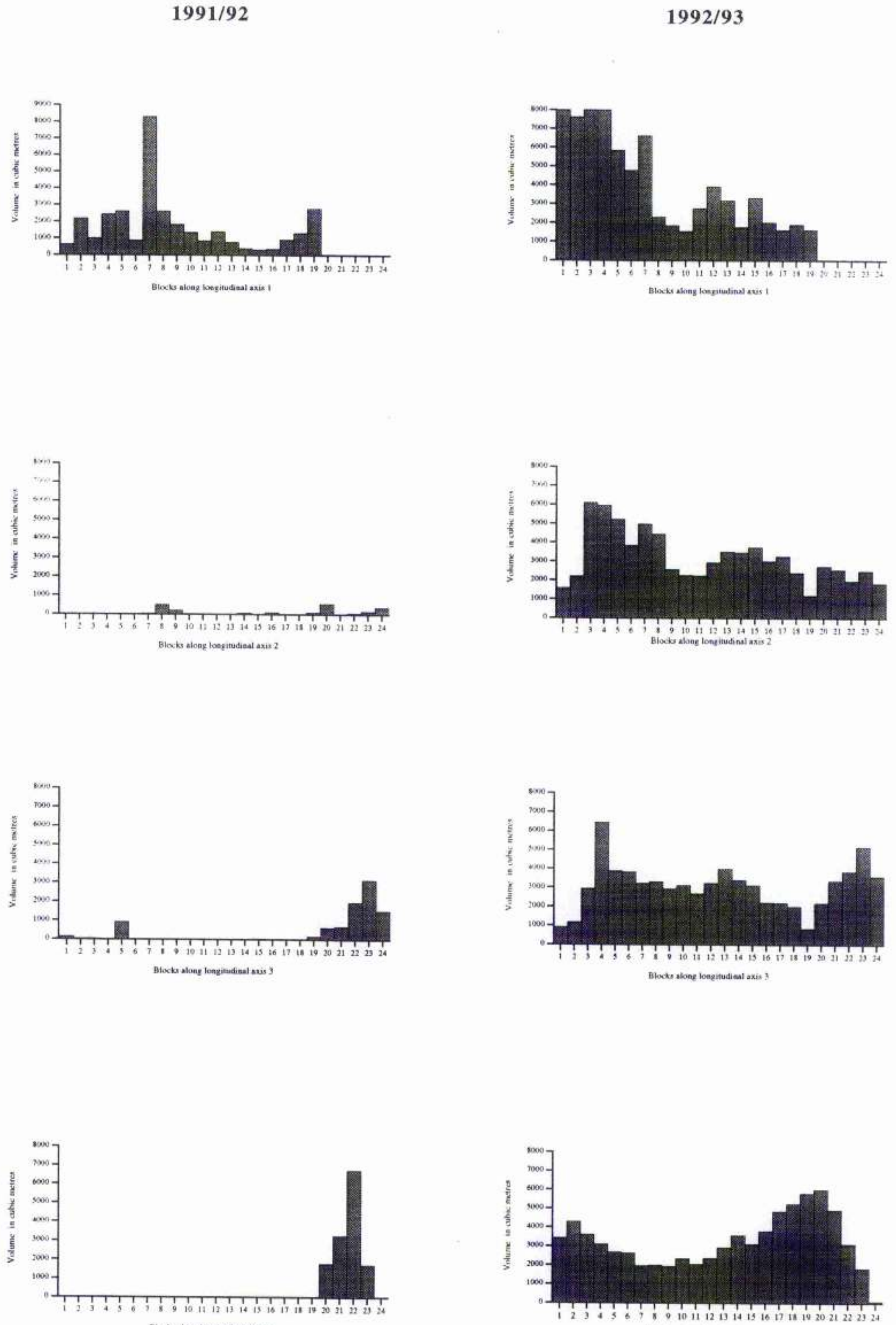


Figure 6.17. Bar charts representing volumes of deposition along the 4 respective axes (Periods 1991/92 & 1992/93).

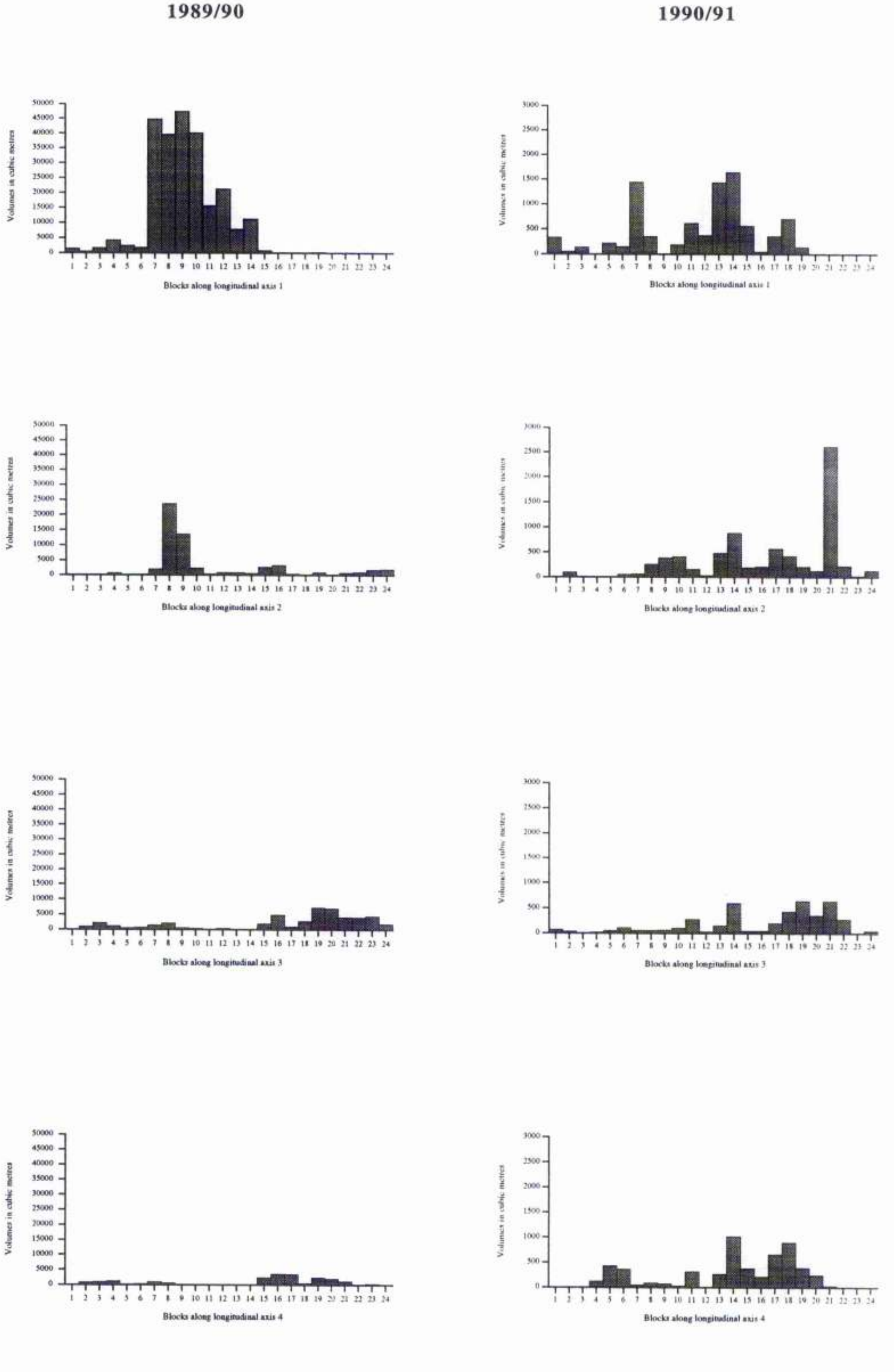


Figure 6.18. Bar charts representing volumes of erosion along the 4 respective axes (Periods 1989/90 & 1990/91).

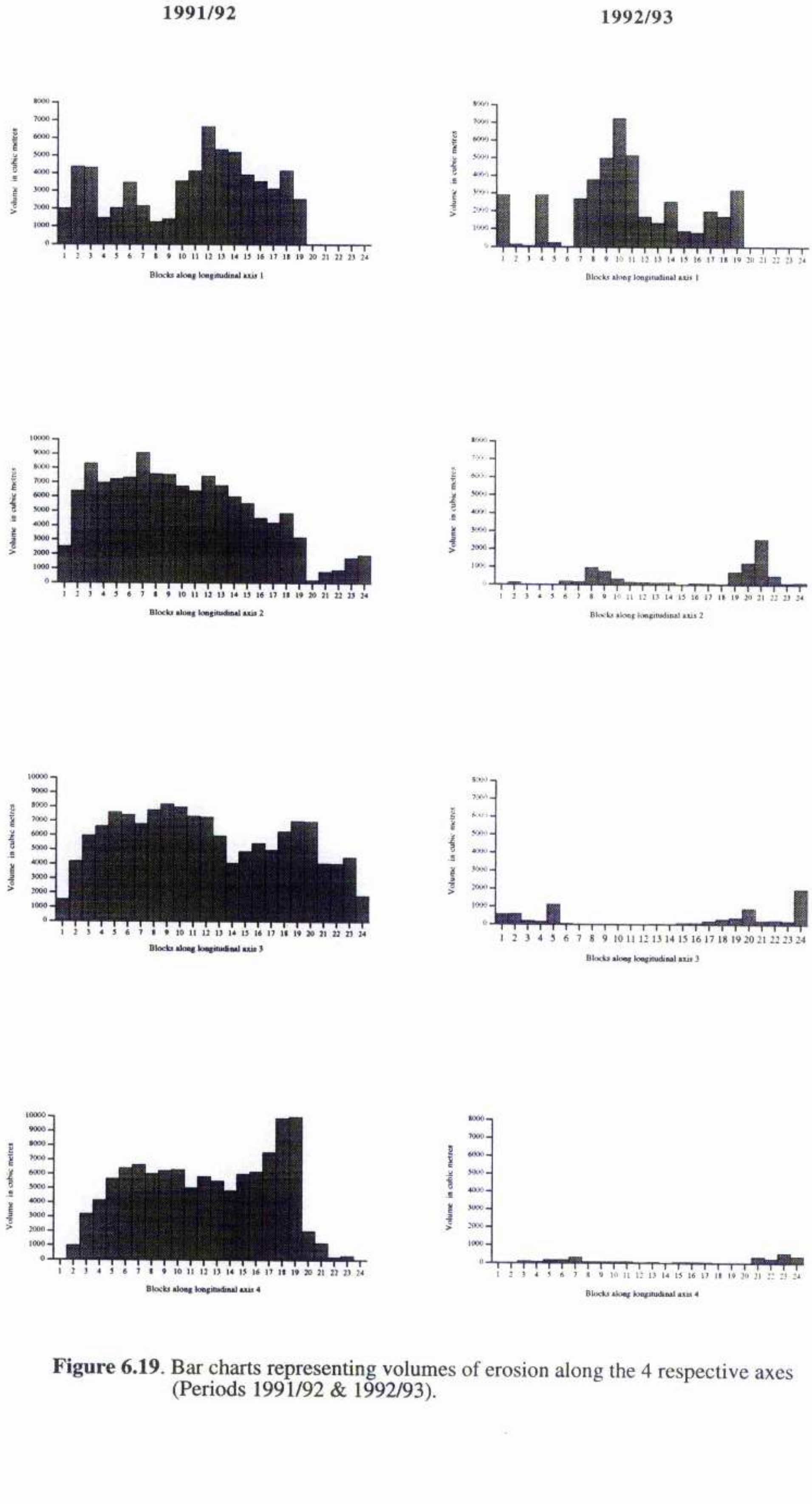


Figure 6.19. Bar charts representing volumes of erosion along the 4 respective axes (Periods 1991/92 & 1992/93).

The figures reveal that there was a gross deposition of sediment of 60 x 10^3m^3 between the years 1989 and 1993. This gain in sediment might possibly be attributed to the two major flood events of 1990 and 1993. It can be estimated that the average annual sediment deposition rate was not less than 15 x 10^3m^3 in the Dundee harbour area, which is equivalent to a gross deposition of about 16 $cm.yr^{-1}$.

6.9 SUMMARY AND DISCUSSION

A case study of seafloor sediment deposition and erosion has been presented for the Dundee harbour area. Archive bathymetric data from the years 1989 to 1993 were used, in conjunction with the proposed methodology as discussed in earlier Chapters. The technique of comparisons of these data has provided useful information leading to the estimation of quantities, areal extents and net rates of sedimentation and erosion in the harbour.

In general, there is no indication to suggest that there exist sites with particular stable patterns of deposition or erosion dominating Dundee harbour. During the years 1989 and 1993, various parts of the harbour area were dredged and unfortunately, in most cases, the time of data collection followed dredging operations. This provides a gap during which proper evaluation of the status of natural deposition and erosion in the area can be performed satisfactorily. For proper implementation of the evaluation strategy, the collection of data must be carried out before any changes to seabed topography are made by dredging.

There is primary evidence to suggest that the occurrence of major floods in the catchment influenced the sedimentation pattern in the Dundee harbour area. The seabed of the area is predominantly of silt and clay, and alterations to the natural depths enhanced the slow natural deposition into a sudden rapid infilling of the disturbed areas during and the following flood events.

The port authority must be aware of the impact of major flood events in the area. Such events may appear operationally insignificant in the short term, but slow, progressive natural accumulations, added by a sudden major flood, can be serious, if totally neglected.

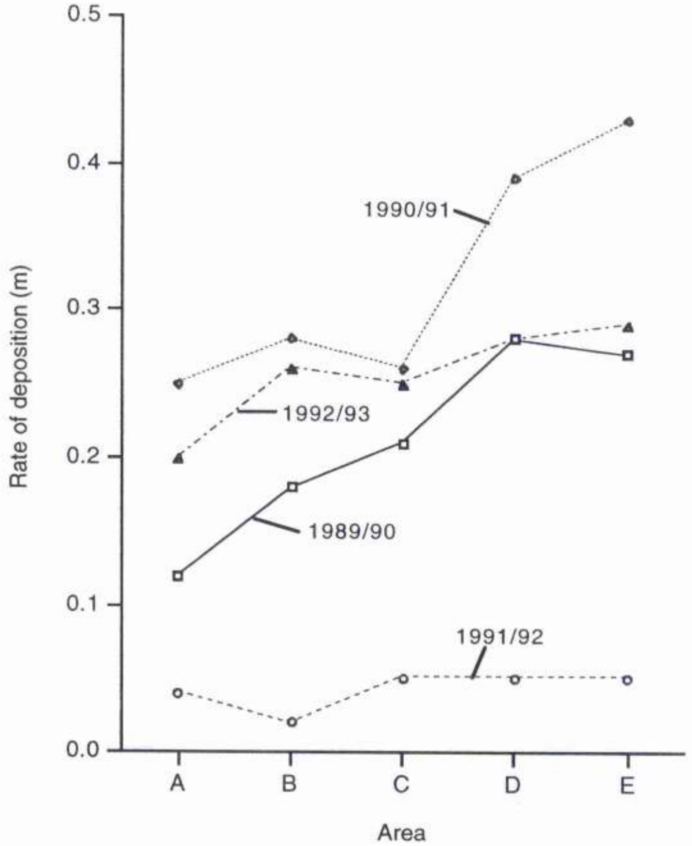


Figure 6.20. Trend in net depositional rates for the 5 sub-areas of the Dundee harbour area.

Some ideas on sediment deposition and erosion rates for the Dundee harbour area have also been presented from the analysis of the five years of sequential data. During the period 1991/92, a period where there was no major flooding, the average deposition rate was as low as 6cm. However, during periods that contain a major flood, the rate of deposition was slightly higher. Specifically this study has unravelled the impact of the two recent major flood events of February, 1990 and January, 1993. The evidence of an increase in the average deposition rate from 4 cm to a figure between 22 and 32 cm is an indication of the impact (Table 6.6). During the periods 1989/90 and 1990/91, there was an increase in the deposition rate. However, there was a sharp decrease as the deposition plummeted to a lowest value of 4cm during 1991/92, before increasing to 26cm during 1992/93 (Figure 6.20). The systematic rise and fall of the deposition rates coincided with the occurrences of the February, 1990 and January, 1993 flood events.

However, the findings of this study should be treated with some caution in the sense that, if predictive results are anticipated, then analysis of data from many more years of recording (possibly 10 -15 years) are required.

The idea of evaluating seabed topography as presented in this Chapter, could also provide guidance to port and harbour authorities on the procedures for using archived bathymetric data to document the impacts of natural and man-induced changes within its harbour areas.

Rennis (1993) discussed the setting up of environmental management systems in ports and harbours, for environmental concerns are now playing a larger role in port policies and management decisions. Although the certification of the new British Environmental Standard, BS 7750, which provides guidelines for implementing and enforcing an environmental management system, is unlikely to become statutory, it will benefit the authorities by helping them to operate voluntarily with an awareness of the water-related impacts. It is beyond the scope of this study to stress the necessary procedures of BS 7750. However, ideas presented from this study, may perhaps, assist in the recognition of the phenomena in the field and help port authorities to implement the environmental management system in the future. In general, the evaluation approach, as described in this Chapter, may provide a baseline for future and long term studies of erosion and sedimentation in harbours.

CHAPTER 7

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

This thesis has examined the phenomena of seafloor bathymetric changes to estimate and quantify the deposition and erosion of sediment in a harbour environment of the Tay Estuary. The use of bathymetric data has been applied in the evaluation of the phenomena and the Dundee harbour area was chosen as a study area. The scope of the work was directed towards the development of a technique and procedure for estimating and quantifying the rate and extent of the phenomena, using archive bathymetric data available for the area.

The overall evaluation work, however, was based on a heuristic type of approach, whereby the phenomena have to be first understood from their cause-and-effect relationships, and later the resulting changes of seafloor bathymetry will be determined by evaluating their past and present situations. This is possible only if sequential data are available from detailed and repeated bathymetric surveying of the same area. Several major topics were addressed and discussed, including the various water-related physical processes, whose interactions induce changes in the estuary, methods of sampling and the acquisition of bathymetric data, the gridding of the available data, and the proposed technique and procedures of evaluation.

Chapter 2 explicitly discussed the various physical processes occurring within the water column of the Tay estuarine environment. To facilitate the discussion, the physical setting of the estuary was divided into four distinct reaches, namely: upper, upper middle, lower middle and lower reaches. The physical processes discussed are mainly related to water circulation patterns attributed to freshwater inflow and saltwater intrusion into the estuary. Although many of the physical processes that occur in the Tay Estuary have been known and studied for many years, their impact on the estuary itself are still far from being fully established. For example, within the upper middle reach, there exist sand banks and inter-tidal flats forming accumulation sites for sediment brought in either by the rivers or sea. Consequently, they could also become sources of sediment supply themselves to strategically located areas such as Dundee harbour, which is situated downstream. How much and where sediment is being deposited or scoured is of concern especially to the Dundee Port Authority. Such information on deposition and erosion is of value in the preparation for the annual port and harbour maintenance programme.

It was also considered necessary to address the method of sampling and acquisition of bathymetric data in Chapter 3. This is to provide insight on depth and position measurement accuracy, before gaining access to the data especially during the evaluation stage. In determining the suitability of a data set for the purpose of evaluating seafloor bathymetric changes, two main criteria were identified. First, the accuracy with which depths have been determined is critical. This is because any significant errors, in excess of a depth threshold limit, that exist in any two measured depths used in a comparison of data, will be propagated into the difference which will then subsequently be used as a measure of bathymetric change. In an area of soft bottom, in particular, it is prudent to use a dual frequency echo-sounder as this will provide an indication of bottom sediment density. A typical frequency of 210kHz will reveal the surface of fluid mud whilst the 33kHz frequency will penetrate into the unconsolidated bottom. It is then a matter of choice as to which depth, or an average, is used in the subsequent data analysis. A second criterion is related to sounding spacing. Obviously, the use of a sounding spacing of 10m or less will inspire more confidence in the determination of bottom topography than a 25m spacing. Some might argue that the former will involve as much as double the amount of work than is required by the latter. Nevertheless, if one has the clear objective of using the data in the future, as described in this thesis, then the data acquired at such a close line spacing will obviously 'pay for itself'. Moreover, carrying out a bathymetric survey at a closer line-spacing than normally required (say at 5 - 10m) must be accompanied by a reliable positioning system such as the Differential Global Positioning System or an automated range/bearing system as described in Chapter 3. This will reduce errors in positioning of the survey vessel, thus providing highly accurate bathymetric data.

In Chapter 4, the question of comparing two sets of data from the same area, but where the depths were not in identical spatial positions, poses a problem. It was considered necessary to have these data gridded through interpolation, before the process of differencing is possible. There are numerous methods of data interpolation, ranging from simple linear interpolation to highly sophisticated surface fitting techniques. A study conducted has identified suitable algorithms and methods for interpolating depths at grid nodes. In general, two groups of interpolation methods are suitable for depth interpolation: linear and surface interpolation methods. Within the linear interpolation group, three simple methods are available: Single Closest Neighbour Point (SCNP), Simple Linear Interpolation Method (SLIM) and Inverse Distance Weighting Method (SLIM). For surface interpolation however, there are three variants: the methods of Collocation (COL), Minimum Curvature Spline (MCS) and Least Squares (LSQ). Their selections were justified based on the sound mathematical principles upon which they were derived.

A trial computation was also conducted on all these methods, using identical data subsets (see Table 4.6). It was revealed, surprisingly, that in most cases, the results of the interpolation are substantially different. None of these methods, however, can operate individually because the result of interpolation under each individual method may vary significantly according to the number and the configuration of the data points used. It is then very difficult to rely on a single method in depth interpolation and it was decided to use all the six methods blended into a single technique. There is also a need for consistent and systematic ways of computing and this was achieved by the development of the so-called Blending Interpolation Technique (BIT).

Incorporated into BIT is a procedure of selecting the data configuration, such as the common and quadrant neighbours. This is to suit the individual computational requirement of each method. A selection of a single value from the six interpolated depth values is performed by a procedure called Depth Selection Strategy (DSS). In this way, the value of a selected single depth from a set of depth interpolated values will inspire more confidence, as it is determined from a range of possible values after undergoing the systematic screening procedures of BIT.

The implementation of the Blending Interpolation Technique was described and discussed in Chapter 5. The emphasis here centred on implementing such a technique into computer programming and several computer routines were developed such as *INTPL*, *CHANGE2D*, *VOL* and *AREAL*. Each computer routine is designed to perform a different task. For example, *INTPL* is used to interpolate depths at grid points whilst the others are used for the graphical and numerical display of results.

In Chapter 6, the application of the proposed technique of BIT in the real harbour environment was demonstrated. This was carried out using sequential bathymetric data from the Dundee harbour area acquired between 1989 and 1993. In extending the technique further, visualisation of the results of bathymetric changes are presented in 2-D form using the UNIRAS computer software package. Two major flood events of February, 1990 and January, 1993 have contributed significantly to sedimentation and erosion of the seafloor of the Dundee harbour area. The port authority should therefore be aware of the possible future occurrence of similar floods and their impacts on the harbour area.

With regard to future works arising from this study, it is felt that any such works should be directed towards a more fully automated and systematic data sampling and acquisition technique so as to obtain more reliable results. This would involve the use of automated survey systems in the data collection and creation of a data base for the study of seabed bathymetry. It would also be useful, perhaps, in the future if the Dundee Port Authority insists on acquiring bathymetric data using a sounding interval, of not greater than the present 10 - 12.5m intervals, as the data will 'pay for itself'. Retention of raw data in digital format, in particular, should be encouraged as this would mean much more data, but, at the same time a much higher accuracy of bathymetric change detection will be achieved.

During the development of the software for the BIT, the speed of computation or computer time was not taken into consideration. If proper algorithms can be designed in the programming steps, such as the use of computational geometry, this should significantly improve the efficiency of the developed computer programs.

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APPENDIX A

(Examples of computation by COL, MCS & LSQ)

APPENDIX A-1

Example of computation by the method of Collocation

pur4% **col**

No.of data: 11128

Enter node value X & Y:

342537.5 730662.5

Enter search radius:

12

No.of points in subset: 5

Constant E: 15.0804
A: 15.0804
A: 18.9307
A: 18.4357
A: 24.5199
A: 24.2100

Constant E: 11.3703
A: 16.1318
A: 11.3703
A: 15.8604
A: 14.7647
A: 17.6973

Constant E: 10.9797
A: 15.2647
A: 15.5828
A: 10.9797
A: 17.1281
A: 14.2675

Constant E: 12.5667
A: 23.0592
A: 15.7046
A: 18.1862
A: 12.5667
A: 15.0979

Constant E: 12.4950
A: 22.6899
A: 18.4400
A: 15.4639
A: 15.0382
A: 12.4950

No.of data= 5 Declared array= 40

Matrix A

15.0804	16.1318	15.2647	23.0592	22.6899
18.9307	11.3703	15.5828	15.7046	18.4400
18.4357	15.8604	10.9797	18.1862	15.4639
24.5199	14.7647	17.1281	12.5667	15.0382
24.2100	17.6973	14.2675	15.0979	12.4950

MATRIX COEFF.

0.310780
-7.59935E-02
2.81040E-02
0.120812
0.159736

Sum of Coefficients: 0.543439

C(X-P):	17.8147
C(X-P):	12.6791
C(X-P):	12.2569
C(X-P):	16.1179
C(X-P):	16.1027

Interpolated Z= 9.43682

APPENDIX A-2

Example of computation by the method of Minimum Curvature Spline

pur4% **mcs**

No. of data: 11128

Enter node values: X & Y

342537.5 730662.5

Enter Search radius:

12

DATA

342541.	730654.	10.3
342532.	730661.	10.3
342543.	730664.	9.5
342531.	730670.	10.9
342539.	730672.	10.4

No. of data within the radius: 5

Do you wish to increase Radius?: Y/N

n

N3= 8 NP= 100

Matrix A

1.00000	342541.	730654.	0.000	319.188	265.543	1107.160	1055.050
1.00000	342532.	730661.	319.188	0.000	293.828	198.954	479.495
1.00000	342543.	730664.	265.543	293.828	0.000	445.198	183.403
1.00000	342531.	730670.	1107.160	198.954	445.198	0.000	148.761
1.00000	342539.	730672.	1055.050	479.495	183.403	148.761	0.000
0.	0.	0.	1.000	1.000	1.000	1.000	1.000
0.	0.	0.	342541.000	342532.000	342543.000	342531.000	342539.000
0.	0.	0.	730654.000	730661.000	730664.000	730670.000	730672.000

MATRIX COEFF.

18304.2
-6.61315E-02
5.96322E-03
3.40987E-03
-2.66533E-03
-4.30228E-03
1.17960E-03
2.37814E-03

Sum of coefficients: 2.32831E-10

Dist:	9.48400	C(P-X):	202.344
Dist:	5.61048	C(P-X):	54.2873
Dist:	5.44764	C(P-X):	50.3075
Dist:	10.09273	C(P-X):	235.489
Dist:	10.15740	C(P-X):	239.176

Interpolated Z= 9.92590

APPENDIX A-3

Example of computation by the method of Least Squares

pur4% **lsq**

No.of data: 11128

Enter node value X & Y:

342537.5 730662.5

Enter search radius:

12

No.of points in subset: 5

1. Elliptic Surface
2. Hyperbolic Surface
3. Oblique plane
4. Horizontal plane

Enter type of surface:
1

MATRIX A

5.00	2686.12	3321.56	1.78438E+06	1.44316E+06	2.20678E+06
2686.12	1.44316E+06	1.78438E+06	9.58666E+08	7.75422E+08	1.18548E+09
3321.56	1.78438E+06	2.20678E+06	1.18548E+09	9.58666E+08	1.46630E+09
1.78438E+06	9.58666E+08	1.18548E+09	6.36889E+11	5.15086E+11	7.87676E+11
1.44316E+06	7.75422E+08	9.58666E+08	5.15086E+11	4.16671E+11	6.36889E+11
2.20678E+06	1.18548E+09	1.46630E+09	7.87676E+11	6.36889E+11	9.74383E+11

COEFF.MATRIX

1239.96
-1.61432
-2.35480
-6.54686E-04
1.84434E-03
2.04642E-03

Interpolated Z= 10.106

1	Z:	10.3	10.046	Resd:	0.254
2	Z:	10.3	10.506	Resd:	-0.205
3	Z:	9.5	9.822	Resd:	-0.322
4	Z:	10.9	10.790	Resd:	0.110
5	Z:	10.4	10.237	Resd:	0.163

pur4% **lsq**

No.of data: 11128

Enter node value X & Y:

342537.5 730662.5

Enter search radius:

12

No.of points in subset: 5

1. Elliptic Surface
2. Hyperbolic Surface
3. Oblique plane
4. Horizontal plane

Enter type of surface:

2

MATRIX A

5.00	2686.12	3321.56	1.78438E+06
2686.12	1.44316E+06	1.78438E+06	9.58666E+08
3321.56	1.78438E+06	2.20678E+06	1.18548E+09
1.78438E+06	9.58666E+08	1.18548E+09	6.36889E+11

COEFF.MATRIX

69.0483
-0.118583
-3.34247E-02
7.60536E-05

Interpolated Z= 10.248

1	Z:	10.3	9.952	Resd:	0.348025
2	Z:	10.3	10.607	Resd:	-0.306548
3	Z:	9.5	9.905	Resd:	-0.404783
4	Z:	10.9	10.734	Resd:	0.166166
5	Z:	10.4	10.203	Resd:	0.197163

pur4% **lsq**

No.of data: 11128

Enter node value X & Y:

342537.5 730662.5

Enter search radius:

12

No.of points in subset: 5

1. Elliptic Surface
2. Hyperbolic Surface
3. Oblique plane
4. Horizontal plane

Enter type of surface:

3

<u>MATRIX A</u>

5.00	2686.12	3321.56
2686.12	1.44316E+06	1.78438E+06
3321.56	1.78438E+06	2.20678E+06

<u>COEFF.MATRIX</u>

41.6970
-6.79039E-02
7.62101E-03

Interpolated Z= 10.248

1	Z:	10.3	9.953	Resd:	0.347177
2	Z:	10.3	10.603	Resd:	-0.303185
3	Z:	9.5	9.905	Resd:	-0.405048
4	Z:	10.9	10.736	Resd:	0.163828
5	Z:	10.4	10.203	Resd:	0.197231

pur4% **lsq**

No.of data: 11128

Enter node value X & Y:

342537.5 730662.5

Enter search radius:

12

No.of points in subset: 5

1. Elliptic Surface
2. Hyperbolic Surface
3. Oblique plane
4. Horizontal plane

Enter type of surface:

4

MATRIX A

5.00000

COEFF.MATRIX

10.28000

Interpolated Z= 10.28000

1	Z:	10.3	10.280	Resd:	1.99995E-02
2	Z:	10.3	10.280	Resd:	1.99995E-02
3	Z:	9.5	10.280	Resd:	-0.780001
4	Z:	10.9	10.280	Resd:	0.619999
5	Z:	10.4	10.280	Resd:	0.119999

APPENDIX B

(Data input and working example of computer programs)

APPENDIX B-1

Data input and working example of INTPL

pur1% **intpl**

Enter Data File: (< 15 Characters)

bathy90.dat

Enter Output File: (< 15 Characters)

C1790

NO. OF DATA POINTS: 12692

Max.X:	343520. Max. Y:	730781.
Min. X:	341234. Min. Y:	729892.

Input Upper Left Coords(m): X & Y

342443.875 730711.500

Input Baseline(m):

100

Input Perpendicular Line(m):

100

Input Rotation Angle(in Degrees):

(Angle +ve above and -ve below horizontal line)

8.383

Corner points

LL:342458.469	730612.562
UL:342443.875	730711.500
UR:342542.812	730726.062
LR:342557.406	730627.125

Enter X spacing:

5

Enter Y spacing:

5

Length X: 100.0000 Length Y: 100.0000

NXI= 21 NYI= 21

Enter search Radius:

12

No. of data in sub-file: 209

Gridding begins now...please wait!

No.of Nodes: 441

No.of empty nodes: 117

No.of interpolated nodes: 324

APPENDIX B-2

Data input and working example of CHANGE2D

pur1% **change2d**

****

Enter PAST/PREVIOUS date filename:

e.g: A0190

A - Area

01 - Block

90 - Year

****

B1391

Enter CURRENT/LATTER date filename:

B1390

****

Enter choice no: 1. Display Deepening/Erosion

2. Display Shoaling/Deposition

****

1

Deposition file : E:B13-9091

Change output file: C:B13-9091

Number of nodes stored in 1st input-file : 10201

Number of nodes stored in 2nd input-file : 10201

Min Depth: 0. Max Depth: 9.9

Minimum Erosion : 0.
Maximum Erosion : - 4.936

Plotting now in progress ....

GROUTE> **select mpost;exit**

pur1% **lpr -Plw POST**

Note: Characters in bold are inputs

APPENDIX B-3

Data input and working example of CHANGE3D

```
pur1% change3d
  ***********************************************
  Enter CURRENT/LATTER date filename:
  e.g: A0190
     A - Area
       01 - Block
         90 - Year
  ***********************************************
B1391
  Enter PAST/PREVIOUS date filename:
B1390
  *******************************************************

  Enter choice no: 1. Display Deepening/Erosion
                   2. Display Shoaling/Deposition

  *******************************************************
2
Deposition file     : D:B13-9091
Change output file: C:B13-9091
Number of nodes stored in 2nd input-file :  10201
Number of nodes stored in 1st input-file  :  10201
Shallowest depth :   4.532
Greatest depth    :   9.365
                      -------
Depth Range       :   4.833
Enter new range:
10
Maximum Deposition:   2.093
Minimum Deposition :  0.201
                      -------
Plotting now in progress ........
GROUTE> select mpost;exit
pur1% lpr -Plw POST
```

Note: Characters in bold are inputs

APPENDIX B-4

Data input and working example of AREAL

```
pur1% areal
Input CURRENT/LATTER filename:
B1391
NO.DATA IN SET2:  10201
Input PAST/PREVIOUS filename:
B1390
NO.DATA IN SET1:  10201
 No.of deposition pts:  7441
 No.of erosion pts   :  1308
 No.of no change pts :  1452
                    TOTAL:  10201
 No.of data pts     : 10201

        Percentage area of deposition   :    72.94
        Percentage area of erosion      :    12.82
        Percentage area of no change    :    14.23
        Total Per centage                    :       100.00

        Maximum deposition value        :    2.093 metres
        Minimum deposition value        :    0.001 metres

Minimum erosion value    :      -0.001 metres
Maximum erosion value    :      -3.358 metres
```

APPENDIX B-5

Data input and working example of VOL

pur1% **vol**

Input CURRENT/LATTER filename:

B1391

NO.DATA IN SET2: 10201

M: 101 N: 101

Input PAST/PREVIOUS filename:

B1390

NO.DATA IN SET1: 10201

M: 101 N: 101

Enter Computation Choice No:

1 - for Deposition

2 - for Erosion

1

Computed Volume 1: 72862.547 cu.metres

Computed Volume 2: 66303.836 cu.metres

Vol.of Deposition: 13116.891 cu.metres

pur1% **vol**

Input CURRENT/LATTER filename:

B1391

NO.DATA IN SET2: 10201

M: 101 N: 101

Input PAST/PREVIOUS filename:

B1390

NO.DATA IN SET1: 10201

M: 101 N: 101

Enter Computation Choice No:

1 - for Deposition

2 - for Erosion

2

Computed Volume 1 : 72862.547 cu.metres

Computed Volume 2 : 73583.719 cu.metres

Vol.of Erosion : 1442.266 cu.metres

APPENDIX C

(Computer programs)

APPENDIX C-1

Computer program INTPL.FOR

```
C
C     BLENDING INTERPOLATION TECHNIQUE (BIT)
C
C
C     DECLARATION STATEMENTS.
C
      PARAMETER(NPTS=25000,NSF=5000,NO=80,CONST=3.141592654/180.0)
      PARAMETER(NZCL=20,NGRID=5000)
C
      REAL X(NPTS),Y(NPTS),Z(NPTS),ZSEL(6),ZCOM(6),ZDIFF(6),
     * XNBR(NO),YNBR(NO),ZNBR(NO),ZINT(2),XINT(4),XND(NPTS),YND(NPTS),
     * XCOR(4),YCOR(4),GRDX(NPTS),GRDY(NPTS),XSF(NSF),YSF(NSF),
     * ZSF(NSF)
C
      REAL XE(NPTS),YN(NPTS),CORRZ(NO),DINV(NO),
     * XQDT(NO),YQDT(NO),ZQDT(NO),ARRY(2,NO),XDS(NO),YDS(NO),ZDS(NO),
     * XCLT(10),YCLT(10)
C
      INTEGER INDX(NO),IWK(NO),IN(NO),INL(NO),INH(NO)
C
      REAL*8 A1(NO,NO),RHS(NO),COEFF(1,NO),XLSQ(NO),YLSQ(NO),
     * A3(NO,NO),ZLSQ(NO),A2(NO,NO),F(NO,1),B(NO,1),
     * XMCS(NO),YMCS(NO),ZMCS(NO),XUSE(NO),YUSE(NO),ZUSE(NO)
C
      REAL*8 XCOLL(NO),YCOLL(NO),ZCOLL(NO),XDIFF(NO),YDIFF(NO),
     * CZZ(NO),ZTMP(NO),E(NO)
C
      REAL*8 INC1,INC2,DIS,DIST,DX,DY,RESUM,DELX,DELY,DPP,
     * ZMCSI,ZLSQI,ZCOLLI,AVERD,CVZ,CSUM,CLENG,D,DSUM,
     * SUMC,SUMX,SUMY,SUMXY,SUM,SUMXX,SUMYY,SUMZ,RES,RESQ,AVRES
C
      INTEGER CSCLEN(3),IPLANE(3),LENGTH(6)
C
      REAL XEST(NPTS),YEST(NPTS),ZEST(NPTS),
     * XU(NPTS),YU(NPTS),ZU(NPTS),CLASS(NZCL)

      REAL XQ1(NO),YQ1(NO),ZQ1(NO),XQ2(NO),YQ2(NO),ZQ2(NO),
     * XQ3(NO),YQ3(NO),ZQ3(NO),XQ4(NO),YQ4(NO),ZQ4(NO)
      CHARACTER TXTSTR(6)*1,CSCTXT(3)*5,ANS*3,VIEW*3,DATAFILE*15,
     * OUTFILE*15
      EXTERNAL BOX2MM
      DATA IPLANE /3,3,1/,LENGTH/6*-1/,CSCLEN/3*-2/
      DATA TXTSTR /6*' '/
      DATA CSCTXT /'Below','Above','     '/
      DATA IWK /80*0/
C
      OPEN(9,FILE='node.out',STATUS='OLD')
      OPEN(4,FILE='subfile.out',STATUS='OLD')
C     OPEN(10,FILE='DSS.out',STATUS='OLD')
```

```
C
C       INPUT DATA FILE
C
        WRITE(*,*) 'Enter Data File: (< 15 Characters )'
        READ(*,*) DATAFILE
        OPEN(7,FILE=DATAFILE,STATUS='UNKNOWN')
C
C       OUPUT FILE
C
        WRITE(*,*) 'Enter Output File: (< 15 Characters )'
        READ(*,*) OUTFILE
        OPEN(8,FILE=OUTFILE,STATUS='UNKNOWN')
C
C       COUNTING NO. OF DATA IN MAIN FILE
C
        ICOUNT=0
  10    READ(7,*,END=20)XVAL,YVAL,ZVAL
         ICOUNT=ICOUNT+1
        IC=ICOUNT
        X(IC)=XVAL
        Y(IC)=YVAL
        Z(IC)=ZVAL
        XE(IC)=X(IC)
        YN(IC)=Y(IC)
        GOTO 10
  20    PRINT*,'NO. OF DATA POINTS: ',IC
C
C       FIND MAX.& MIN X,Y,Z VALUES IN THE MAIN FILE
C
 2100   CALL MAXMIN(IC,X,Y,Z,XMIN,XMAX,YMIN,YMAX,ZMIN,ZMAX)
        WRITE(*,*) 'Max.X:',XMAX,' Max. Y:',YMAX
        WRITE(*,*) 'Min.X:',XMIN,' Min. Y:',YMIN
C
C       DEFINE LIMIT OF WORKING AREA
C
        WRITE(*,*) 'Input Upper Left Coords(m): X & Y'
        READ(*,*)XUL,YUL
        XCOR(2)=XUL
        YCOR(2)=YUL
        WRITE(*,*) 'Input Baseline(m): '
        READ(*,*)BLINE
        WRITE(*,*) 'Input Perpendicular Line(m): '
        READ(*,*)PLINE
        WRITE(*,*) 'Input Rotation Angle(in Degrees): '
        WRITE(*,*) '(Angle +ve above and -ve below horizontal line)'
        READ(*,*)THETA
        ANG=THETA*CONST
C
C       WRITE(8,*)ANG
C
        ROTANG=-ANG
        BBRG=(90.0-THETA)*CONST
        CALL COORD(BBRG,XCOR(2),YCOR(2),BLINE,XCOR(3),YCOR(3))
        PBRG=BBRG+(90.0*CONST)
        CALL COORD(PBRG,XCOR(3),YCOR(3),PLINE,XCOR(4),YCOR(4))
        CALL COORD(PBRG,XCOR(2),YCOR(2),PLINE,XCOR(1),YCOR(1))
        write(*,*)'Corner points'
```

```
      write(*,21)xcor(1),ycor(1)
      write(*,22)xcor(2),ycor(2)
      write(*,23)xcor(3),ycor(3)
      write(*,24)xcor(4),ycor(4)
 21   FORMAT('LL:',F10.3,3X,F10.3)
 22   FORMAT('UL:',F10.3,3X,F10.3)
 23   FORMAT('UR:',F10.3,3X,F10.3)
 24   FORMAT('LR:',F10.3,3X,F10.3)
C
C     TO FORM GRID NODES
C
      WRITE(*,'(A\)') ' Enter X spacing: '
      READ(*,*)SX
      WRITE(*,'(A\)') ' Enter Y spacing: '
      READ(*,*)SY
      WRITE(8,*)SX,SY
C
      NXI=1+IFIX(BLINE/SX)
      NYI=1+IFIX(PLINE/SY)
      WRITE(8,*)NXI,NYI
      write(*,*) 'Length X: ',BLINE,' Length Y: ',PLINE
      NXY=NXI*NYI
C
      CALL ROTATE(ROTANG,4,XCOR,YCOR)
      CALL GRID(XCOR(1),YCOR(1),SX,SY,NXI,NYI,NXY,GRDX,GRDY)
C
      WRITE(*,*) 'NXI= ',NXI,' NYI= ',NYI
      DO 40 KM=1,NXY
      WRITE(9,39)KM,GRDX(KM),GRDY(KM)
 39   FORMAT(I5,2X,F10.3,2X,F10.3)
 40   CONTINUE
C
C     INPUT SEARCH RADIUS
C
      WRITE(*,*) ' Enter search Radius: '
      READ(*,*)RADIUS
      SRADIUS=RADIUS
C
C     FORMATION OF SUB-FILE
C
      CALL ROTATE(ROTANG,IC,XE,YN)
      XLMN=XCOR(2)-2.5*SRADIUS
      XLMX=XCOR(3)+2.5*SRADIUS
      YLMN=YCOR(1)-2.5*SRADIUS
      YLMX=YCOR(2)+2.5*SRADIUS
C
      ISF=0
      DO 41 I=1,IC
      IF(((XE(I).GE.XLMN).AND.(XE(I).LE.XLMX)).AND.
     *  ((YN(I).GE.YLMN).AND.(YN(I).LE.YLMX))) THEN
      ISF=ISF+1
      WRITE(4,38)ISF,XE(I),YN(I),Z(I)
 38   FORMAT(I5,2X,F10.3,2X,F10.3,2X,F6.3)
      ENDIF
 41   CONTINUE
      WRITE(*,*) 'No. of data in sub-file: ',ISF
C
```

```
C
C        START GRIDDING
C
         WRITE(*,*) ' Gridding begins now...please wait!'
C
         NNODE=0
         REWIND(9)
   60    READ(9,*,END=50)NN,GX,GY
         NNODE=NNODE+1
         ND=NNODE
         XND(ND)=GX
         YND(ND)=GY
         GOTO 60
   50    WRITE(*,*) ' No.of Nodes: ',ND
         CALL ROTATE(-ROTANG,ND,XND,YND)
C
C        DEFINE DATA SUBSETS USING RADIUS
C
         REWIND(4)
         ISC=0
   71    READ(4,*,END=72)NS,XSUB,YSUB,ZSUB
         ISC=ISC+1
         XSF(ISC)=XSUB
         YSF(ISC)=YSUB
         ZSF(ISC)=ZSUB
         GOTO 71
   72    CALL ROTATE(-ROTANG,ISC,XSF,YSF)
C
         NULL=0
         DO 70 LN=1,ND
         XNODE=XND(LN)
         YNODE=YND(LN)
C
         NCOUNT=0
         ITER=0
         ITER1=0
  100    SBRADS=SRADIUS
C
         DO 80 IS=1,ISC
         DX=XSF(IS)-XND(LN)
         DY=YSF(IS)-YND(LN)
         DIS=SQRT(DX*DX+DY*DY)
C
C        DETECT THE CLOSEST POINT TO A  NODE (SCNP)
C
         IF(DIS.LE.0.25*SX) THEN
         ZIDWM=0.0
         ZSLIM=0.0
         ZCOLLI=0.0
         ZMCSI=0.0
         ZLSQI=0.0
C
         ZNEAR=ZSF(IS)
         ZBIT=ZNEAR
         GOTO 220
         ENDIF
C
```

```
C
C       DETERMINE DATA SUBSET FOR A  NODE
C
        IF(DIS.LE.SBRADS) THEN
        NCOUNT=NCOUNT+1
        NC=NCOUNT
        XUSE(NC)=XSF(IS)
        YUSE(NC)=YSF(IS)
        ZUSE(NC)=ZSF(IS)
        ARRY(1,NC)=XSF(IS)
        ARRY(2,NC)=YSF(IS)
        ENDIF
  80    CONTINUE

C
C       IF NO DATA FOUND INCREASE SEARCH RADIUS BY 25%. AFTER 2
C       ITERATIONS, IF STILL NO DATA FOUND THEN ASSUME NODE FALLS
C       OUTSIDE DATA AREA AND CONTINUE WITH THE NEXT NODE
C
        IF(NCOUNT.LT.3) THEN
        NCOUNT=0
        ITER=ITER+1
        SRADIUS=SBRADS+(RADIUS/4.0)
        IF(ITER.GT.2) GOTO 90
        GOTO 100
        ENDIF
C
  90    IF(NCOUNT.LT.3) THEN
        NULL=NULL+1
        ZSLIM=0.0
        ZIDWM=0.0
        ZLSQI=0.0
        ZCOLLI=0.0
        ZMCSI=0.0
        ZNEAR=0.0
        ZBIT=0.0
        GOTO 220
        ENDIF
C
C       IF NCOUNT=3 : COLLINEARITY TEST
C
        ITEST=1
        IF(NCOUNT.GE.3) THEN
        DO 79 I=1,NC
        XDS(I)=XUSE(I)
        YDS(I)=YUSE(I)
        ZDS(I)=ZUSE(I)
  79    CONTINUE
C
        CALL COLTEST(NCOUNT,XDS,YDS,ICLT)
        ITEST=ICLT
        IF(ITEST.EQ.-1) THEN
        ITER1=ITER1+1
        SRADIUS=SBRADS+(RADIUS/4.0)
        IF(ITER1.GT.2) GOTO 190
C
```

```
C
C       INITIALISE  NCOUNT
C
        NCOUNT=0
        GOTO 100
        ENDIF
        ENDIF
C
C       TEST NODE FALLS  INSIDE OR OUTSIDE DATA  AREA
C
        CALL PCTEST(NC,ARRY,XND(LN),YND(LN),KCODE)
        IF(KCODE.EQ.1.OR.KCODE.EQ.0) THEN
        DO 81 I=1,NC
        XDS(I)=XUSE(I)
        YDS(I)=YUSE(I)
        ZDS(I)=ZUSE(I)
 81     CONTINUE
        CALL MAXMIN(NC,XDS,YDS,ZDS,XDMN,XDMX,YDMN,YDMX,ZSHAL,ZDEEP)
C
C       IF FLAT NO INTERPOLATION NECESSARY
C
        IF(ZSHAL.EQ.ZDEEP) THEN
        ZNEAR=ZDEEP
        ZSLIM=ZDEEP
        ZIDWM=ZDEEP
        ZCOLLI=ZDEEP
        ZMCSI=ZDEEP
        ZLSQI=ZDEEP
        ZBIT=ZDEEP
        GOTO 220
        ENDIF
        GOTO 190
        ENDIF
C
C       INCREASE SEARCH RADIUS BY ANOTHER 25%.
        STOP AFTER 2 ITERATIONS
C
        IF(KCODE.EQ.-1.AND.NCOUNT.GE.3) THEN
        NCOUNT=0
        ITER1=ITER1+1
        SRADIUS=SBRADS+(RADIUS/4.0)
        IF(ITER1.GT.2) GOTO 91
        GOTO 100
        ENDIF
C
C       EMPTY NODE
C
 91     NULL=NULL+1
        ZSLIM=0.0
        ZIDWM=0.0
        ZLSQI=0.0
        ZCOLLI=0.0
        ZMCSI=0.0
        ZNEAR=0.0
        ZBIT=0.0
        GOTO 220
```

```
C
C     CALCULATION OF INVERSE DISTANCE WEIGHTING
C
C     COMPUTE INVERSE DISTANCE
C
 190  ZNEAR=0.0
      SUM=0.0
      DO 140 LL=1,NC
      DNX=XUSE(LL)-XND(LN)
      DNY=YUSE(LL)-YND(LN)
      DISN=SQRT(DNX*DNX+DNY*DNY)
      DINV(LL)=1.0/(DISN*DISN)
      SUM=SUM+DINV(LL)
 140  CONTINUE
C
C     CALCULATE CORRECTED WEIGHT EQUAL TO UNITY
C
      SUMWT=0.0
      DO 150 JI=1,NC
      CORRZ(JI)=DINV(JI)/SUM
      SUMWT=SUMWT+CORRZ(JI)
 150  CONTINUE
C
C     TO CALCULATE THE WEIGHTED MEAN OF Z
C
      ZWT=0.0
      DO 160 JJ=1,NC
      ZWT=ZWT+CORRZ(JJ)*ZUSE(JJ)
 160  CONTINUE
      ZIDWM=ZWT

C
C     IF COL.TEST FAILS ONLY COMPUTE IDWM AND RETURN
C
      IF(NC.EQ.3.AND.ITEST.EQ.-1) THEN
      ZNEAR=0.0
      ZSLIM=0.0
      ZCOLLI=0.0
      ZMCSI=0.0
      ZLSQI=0.0
      ZBIT=ZIDWM
      GOTO 220
      ENDIF
C
C     TO TEST IF 4 OR MORE POINTS ARE COLLINEAR
C
      IF(NCOUNT.GT.3.AND.KCODE.EQ.0) THEN
      NTEST=0
      NTIME=NCOUNT-2
      DO 161 I=1,NTIME
      XCLT(I)=XUSE(I)
      YCLT(I)=YUSE(I)
      XCLT(I+1)=XUSE(I+1)
      YCLT(I+1)=YUSE(I+1)
      XCLT(I+2)=XUSE(I+2)
      YCLT(I+2)=YUSE(I+2)
```

```
      CALL COLTEST (3,XCLT,YCLT,ICLT)
      IF(ICLT.EQ.-1) NTEST=NTEST+1
 161  CONTINUE
      IF(NTEST.EQ.NTIME) THEN
      ZNEAR=0.0
      ZSLIM=0.0
      ZCOLLI=0.0
      ZMCSI=0.0
      ZLSQI=0.0
      ZBIT=ZIDWM
      GOTO 220
      NDIF
      ENDIF
C
C     INTERPOLATION BY MINIMUM CURVATURE SPLINE
C
      DO 5000 I=1,NC
      XMCS(I)=XUSE(I)
      YMCS(I)=YUSE(I)
      ZMCS(I)=ZUSE(I)
 5000 CONTINUE
C
      DO 5100 J=1,NC
      A1(J,1)=1.0D0
      A1(J,2)=XMCS(J)
      A1(J,3)=YMCS(J)
      DO 5200 K=1,NC
      DX=XMCS(J)-XMCS(K)
      DY=YMCS(J)-YMCS(K)
      DIS=DSQRT(DX*DX+DY*DY)
      IF(DIS.EQ.0.0) THEN
      CVZ=0.0D0
      ELSE
      CVZ=(DIS*DIS)*DLOG(DIS)
      ENDIF
      A1(J,K+3)=CVZ
5200  CONTINUE
5100  CONTINUE
C
      DO 5300 I=1,3
      A1(I+NC,1)=0.0D0
      A1(I+NC,2)=0.0D0
      A1(I+NC,3)=0.0D0
5300  CONTINUE
      DO 5400 K=1,NC
      A1(NC+1,K+3)=1.0D0
      A1(NC+2,K+3)=XMCS(K)
      A1(NC+3,K+3)=YMCS(K)
5400  CONTINUE
      ZMCS(NC+1)=0.0D0
      ZMCS(NC+2)=0.0D0
      ZMCS(NC+3)=0.0D0
      NCP3=NC+3
      CALL DECOMP(NO,NCP3,A1,INDX,D)
      CALL SOLVE(NO,NCP3,A1,INDX,ZMCS)
      CSUM=0.0D0
```

```
      DO 5600 J=1,NCP3
      COEFF(1,J)=ZMCS(J)
      IF(J.GE.4) CSUM=CSUM+COEFF(1,J)
5600  CONTINUE
C
      F(1,1)=1.0D0
      F(2,1)=XNODE
      F(3,1)=YNODE
      DO 5700 J=1,NC
      DELX=XMCS(J)-XNODE
      DELY=YMCS(J)-YNODE
      DIST=DSQRT(DELX*DELX+DELY*DELY)
      IF(DIST.EQ.0.0) THEN
      CLENG=0.0D0
      ELSE
      CLENG=(DIST*DIST)*DLOG(DIST)
      ENDIF
      F(J+3,1)=CLENG
5700  CONTINUE
      CALL MULTI(COEFF,F,ZMCSI,1,NC+3,1)
      IF(ZMCSI.GT.ZDEEP.OR.ZMCSI.LT.ZSHAL) ZMCSI=0.0
C
C     INTERPOLATION BY METHOD OF COLLOCATION
C
      DO 6000 I=1,NC
      XCOLL(I)=XUSE(I)
      YCOLL(I)=YUSE(I)
      ZCOLL(I)=ZUSE(I)
      ZTMP(I)=ZUSE(I)
6000  CONTINUE
C
      DO 6100 I=1,NC
      LCOUNT=0
      DSUM=0.0D0
      DO 6200 J=1,NC
      XDIFF(J)=XCOLL(J)-XCOLL(I)
      YDIFF(J)=YCOLL(J)-YCOLL(I)
C
      IF(ABS(XDIFF(J)).EQ.0.0.AND.ABS(YDIFF(J)).EQ.0.0) THEN
      LCOUNT=LCOUNT+1
      GOTO 6200
      ENDIF
      DPP=DSQRT(XDIFF(J)*XDIFF(J)+YDIFF(J)*YDIFF(J))
      DSUM=DSUM+DPP
6200  CONTINUE
      AVERD=DSUM/(NC-LCOUNT)


C
C     CONSTANT E
C
      E(I)=AVERD
C
      DO 6300 K=1,NC
      CZZ(K)=DSQRT(((XDIFF(K)*XDIFF(K))+(YDIFF(K)*YDIFF(K)))+
     *(E(I)*E(I)))
```

```
      A2(K,I)=CZZ(K)
 6300 CONTINUE
 6100 CONTINUE
      CALL DECOMP(NO,NC,A2,INDX,D)
      CALL SOLVE(NO,NC,A2,INDX,ZTMP)
C
      CSUM=0.0D0
      DO 6500 J=1,NC
      COEFF(1,J)=ZTMP(J)
      CSUM=CSUM+COEFF(1,J)
 6500 CONTINUE
C
C     INTERPOLATION OF DEPTH AT NODE POINT
C
      DO 6700 J=1,NC
      DELX=XNODE-XCOLL(J)
      DELY=YNODE-YCOLL(J)
      F(J,1)=DSQRT((DELX*DELX+DELY*DELY)+(E(J)*E(J)))
 6700 CONTINUE
C
      CALL MULTI(COEFF,F,ZCOLLI,1,NC,1)
      IF(ZCOLLI.GT.ZDEEP.OR.ZCOLLI.LT.ZSHAL) ZCOLLI=0.0
C
C     INTERPOLATION BY LEAST SQUARES
C
      DO 2300 I=1,NC
      XLSQ(I)=XUSE(I)
      YLSQ(I)=YUSE(I)
      ZLSQ(I)=ZUSE(I)
 2300 CONTINUE
C
C     WRITE(*,*) '     1. Elliptic Surface '
C     WRITE(*,*) '     2. Hyperbolic Surface '
C     WRITE(*,*) '     3. Oblique plane '
C     WRITE(*,*) '     4. Horizontal plane '
C     WRITE(*,*) '       ----------------- '
C     WRITE(*,'(A\)') ' Enter type of surface: '
C
      IF(NC.GE.6) ISURF=1
      IF(NC.EQ.4.OR.NC.EQ.5) ISURF=2
      IF(NC.EQ.3) ISURF=3
      IF(ISURF.EQ.1) NOU=6
      IF(ISURF.EQ.2) NOU=4
      IF(ISURF.EQ.3) NOU=3
      IF(ISURF.EQ.4) NOU=1
C
      F(1,1)=1.0D0
      F(2,1)=XNODE
      F(3,1)=YNODE
      F(4,1)=F(2,1)*F(3,1)
      F(5,1)=F(2,1)*F(2,1)
      F(6,1)=F(3,1)*F(3,1)
C
      DO 3300 I=1,NOU
C
      INC1=1.0D0
      INC2=1.0D0
```

```
      SUMC=0.0D0
      DO 2400 M=1,NC
      IF(I.EQ.2) INC2=XLSQ(M)
      IF(I.EQ.3) INC2=YLSQ(M)
      IF(I.EQ.4) INC2=XLSQ(M)*YLSQ(M)
      IF(I.EQ.5) INC2=XLSQ(M)*XLSQ(M)
      IF(I.EQ.6) INC2=YLSQ(M)*YLSQ(M)
      SUMC=SUMC+(INC1*INC2)
2400  CONTINUE
      A3(I,1)=SUMC
C
      SUMX=0.0D0
      INC2=1.0D0
      DO 2500 M=1,NC
      IF(I.EQ.2) INC2=XLSQ(M)
      IF(I.EQ.3) INC2=YLSQ(M)
      IF(I.EQ.4) INC2=XLSQ(M)*YLSQ(M)
      IF(I.EQ.5) INC2=XLSQ(M)*XLSQ(M)
      IF(I.EQ.6) INC2=YLSQ(M)*YLSQ(M)
      SUMX=SUMX+XLSQ(M)*INC2
2500  CONTINUE
      A3(I,2)=SUMX
C
      SUMY=0.0D0
      INC2=1.0D0
      DO 2600 M=1,NC
      IF(I.EQ.2) INC2=XLSQ(M)
      IF(I.EQ.3) INC2=YLSQ(M)
      IF(I.EQ.4) INC2=XLSQ(M)*YLSQ(M)
      IF(I.EQ.5) INC2=XLSQ(M)*XLSQ(M)
      IF(I.EQ.6) INC2=YLSQ(M)*YLSQ(M)
      SUMY=SUMY+YLSQ(M)*INC2
2600  CONTINUE
      A3(I,3)=SUMY
C
      SUMXY=0.0
      INC2=1.0
      DO 2700 M=1,NC
      IF(I.EQ.2) INC2=XLSQ(M)
      IF(I.EQ.3) INC2=YLSQ(M)
      IF(I.EQ.4) INC2=XLSQ(M)*YLSQ(M)
      IF(I.EQ.5) INC2=XLSQ(M)*XLSQ(M)
      IF(I.EQ.6) INC2=YLSQ(M)*YLSQ(M)
      SUMXY=SUMXY+XLSQ(M)*YLSQ(M)*INC2
2700  CONTINUE
      A3(I,4)=SUMXY
C
      SUMXX=0.0D0
      INC2=1.0D0
      DO 2800 M=1,NC
      IF(I.EQ.2) INC2=XLSQ(M)
      IF(I.EQ.3) INC2=YLSQ(M)
      F(I.EQ.4) INC2=XLSQ(M)*YLSQ(M)
      IF(I.EQ.5) INC2=XLSQ(M)*XLSQ(M)
      IF(I.EQ.6) INC2=YLSQ(M)*YLSQ(M)
      SUMXX=SUMXX+XLSQ(M)*XLSQ(M)*INC2
2800  CONTINUE
```

```
      A3(I,5)=SUMXX
C
      SUMYY=0.0D0
      INC2=1.0D0
      DO 2900 M=1,NC
      IF(I.EQ.2) INC2=XLSQ(M)
      IF(I.EQ.3) INC2=YLSQ(M)
      IF(I.EQ.4) INC2=XLSQ(M)*YLSQ(M)
      IF(I.EQ.5) INC2=XLSQ(M)*XLSQ(M)
      IF(I.EQ.6) INC2=YLSQ(M)*YLSQ(M)
      SUMYY=SUMYY+YLSQ(M)*YLSQ(M)*INC2
 2900 CONTINUE
      A3(I,6)=SUMYY

C
C     FORMATION OF RHS
C
      SUMZ=0.0D0
      DO 3000 M=1,NC
      IF(I.EQ.1) INC2=ZLSQ(M)
      IF(I.EQ.2) INC2=XLSQ(M)*ZLSQ(M)
      IF(I.EQ.3) INC2=YLSQ(M)*ZLSQ(M)
      IF(I.EQ.4) INC2=XLSQ(M)*YLSQ(M)*ZLSQ(M)
      IF(I.EQ.5) INC2=XLSQ(M)*XLSQ(M)*ZLSQ(M)
      IF(I.EQ.6) INC2=YLSQ(M)*YLSQ(M)*ZLSQ(M)
      SUMZ=SUMZ+INC2
 3000 CONTINUE
      RHS(I)=SUMZ
 3300 CONTINUE
C
      CALL DECOMP(NO,NOU,A3,INDX,D)
      CALL SOLVE(NO,NOU,A3,INDX,RHS)
C
C
      DO 4800 J=1,NOU
      COEFF(1,J)=RHS(J)
 4800 CONTINUE
C
C     INTERPOLATION OF DEPTH AT NODE POINT
C
      CALL MULTI(COEFF,F,ZLSQI,1,NOU,1)
      IF(ZLSQI.GT.ZDEEP.OR.ZLSQI.LT.ZSHAL) ZLSQI=0.0
C
      RESUM=0.0D0
      DO 3100 J=1,NC
      B(1,1)=1.0D0
      B(2,1)=XLSQ(J)
      B(3,1)=YLSQ(J)
      B(4,1)=B(2,1)*B(3,1)
      B(5,1)=B(2,1)*B(2,1)
      B(6,1)=B(3,1)*B(3,1)
      CALL MULTI(COEFF,B,ZC,1,NOU,1)
      RES=ZLSQ(J)-ZC
      RESQ=RES*RES
      RESUM=RESUM+RESQ
 3100 CONTINUE
      AVRES=DSQRT(RESUM/NC)
```

```
C
C     SORT QUADRANT NEIGHBOUR
C
      IF(NC.EQ.3) THEN
      NTOT=3
      DO 121 I=1,NTOT
      ARRY(1,I)=XUSE(I)
      ARRY(2,I)=YUSE(I)
 121  CONTINUE
      GOTO 175
      ENDIF
C
      I1=0
      I2=0
      I3=0
      I4=0
      DO 120 IQ=1,NC
      DELTX=XUSE(IQ)-XND(LN)
      DELTY=YUSE(IQ)-YND(LN)
C
C     SEARCH FIRST QUADRANT
C
      IF(DELTX.GE.0.0.AND.DELTY.GE.0.0) THEN
      I1=I1+1
      XQ1(I1)=XUSE(IQ)
      YQ1(I1)=YUSE(IQ)
      ZQ1(I1)=ZUSE(IQ)
      GOTO 120
      ENDIF
C
C     SEARCH SECOND QUADRANT
C
      IF(DELTX.GE.0.0.AND.DELTY.LT.0.0) THEN
      I2=I2+1
      XQ2(I2)=XUSE(IQ)
      YQ2(I2)=YUSE(IQ)
      ZQ2(I2)=ZUSE(IQ)
      GOTO 120
      ENDIF
C
C     SEARCH THIRD QUADRANT
C
      IF(DELTX.LT.0.0.AND.DELTY.LE.0.0) THEN
      I3=I3+1
      XQ3(I3)=XUSE(IQ)
      YQ3(I3)=YUSE(IQ)
      ZQ3(I3)=ZUSE(IQ)
      GOTO 120
      ENDIF
C
C     SEARCH FOURTH QUADRANT
C
      IF(DELTX.LT.0.0.AND.DELTY.GT.0.0) THEN
      I4=I4+1
      XQ4(I4)=XUSE(IQ)
      YQ4(I4)=YUSE(IQ)
      ZQ4(I4)=ZUSE(IQ)
```

```
      ENDIF
 120  CONTINUE
C
C     SELECT A DATUM FOR EACH QUADRANT
C
      NTOT=0
      IF(I1.GT.0) THEN
      NTOT=NTOT+1
      CALL NEAR(I1,XQ1,YQ1,ZQ1,XNODE,YNODE,XQDT(NTOT),
     *     YQDT(NTOT),ZQDT(NTOT))
      ENDIF
C
      IF(I2.GT.0) THEN
      NTOT=NTOT+1
      CALL NEAR(I2,XQ2,YQ2,ZQ2,XNODE,YNODE,XQDT(NTOT),
     *     YQDT(NTOT),ZQDT(NTOT))
      ENDIF
C
      IF(I3.GT.0) THEN
      NTOT=NTOT+1
      CALL NEAR(I3,XQ3,YQ3,ZQ3,XNODE,YNODE,XQDT(NTOT),
     *     YQDT(NTOT),ZQDT(NTOT))
      ENDIF
C
      IF(I4.GT.0) THEN
      NTOT=NTOT+1
      CALL NEAR(I4,XQ4,YQ4,ZQ4,XNODE,YNODE,XQDT(NTOT),
     *     YQDT(NTOT),ZQDT(NTOT))
      ENDIF
C
      DO 200 I=1,NTOT
      ARRY(1,I)=XQDT(I)
      ARRY(2,I)=YQDT(I)
 200  CONTINUE
C
C     IF NC=4, PCTEST-OK, BUT NTOT.LT.3
C
      IF(NC.GE.4.AND.NTOT.LT.3) THEN
      NTOT=NC
      DO 201 I=1,NC
      ARRY(1,I)=XUSE(I)
      ARRY(2,I)=YUSE(I)
 201  CONTINUE
      GOTO 175
      ENDIF

C
C     IF QUADRANT NEIGHBOURS=3
C
      IF(NC.GE.4.AND.NTOT.EQ.3) THEN
      CALL COLTEST(NTOT,XQDT,YQDT,ICLT)
      ITEST=ICLT
      IF(ITEST.EQ.-1) THEN
      ZSLIM=0.0
      GOTO 210
```

```
      ENDIF
C
      CALL PCTEST(NTOT,ARRY,XNODE,YNODE,JCODE)
      IF(JCODE.EQ.1.OR.JCODE.EQ.0) GOTO 175
C
      IF(JCODE.EQ.-1) THEN
      ZSLIM=0.0
      GOTO 210
      ENDIF
      ENDIF
C
C     CALCULATION BY SIMPLE LINEAR INTERPOLATION METHOD (SLIM)
C
C     SORTING BOUNDARY IN COUNTERCLOCKWISE
C
 175  N1=NTOT+1
      DO 2 I=1,NTOT
      J=N1-I
   2 I N(J)=I
C
      DO 1400 IM=3,NTOT
      CALL CONVEX(NTOT,ARRY,IM,IN,IWK,IWK(NC+1),INH,IHULL,INL)
      IK=INL(1)
      DO 6 I=1,IHULL
      J=INH(IK)
      XNBR(I)=ARRY(1,J)
      YNBR(I)=ARRY(2,J)
   6 I K=INL(IK)
      XNBR(IHULL+1)=XNBR(1)
      YNBR(IHULL+1)=YNBR(1)
1400  CONTINUE
C
C     SORT X,Y FOR Z
C
      DO 300 I=1,IHULL+1
      DO 400 J=1,NCOUNT
      IF(XUSE(J).EQ.XNBR(I).AND.YUSE(J).EQ.YNBR(I)) THEN
      ZNBR(I)=ZUSE(J)
      ENDIF
 400  CONTINUE
 300  CONTINUE
      NTOT=IHULL
C
C     SIMPLE LINEAR INTERPOLATION METHOD
C
 130  ICOUNT=0
      YINT=YNODE
      DO 170 I=1,NTOT
      J=I+1
      XSTART=XNBR(J)
      YSTART=YNBR(J)
      ZSTART=ZNBR(J)
      XEND=XNBR(I)
      YEND=YNBR(I)
      ZEND=ZNBR(I)
      IF(YNODE.LT.YEND.AND.YNODE.GE.YSTART) THEN
```

```
      ICOUNT=ICOUNT+1
      GOTO 180
      ENDIF
      IF(YNODE.GE.YEND.AND.YNODE.LT.YSTART) THEN
      ICOUNT=ICOUNT+1
      GOTO 180
      ENDIF
      GOTO 170
 180  T=(YNODE-YEND)/(YSTART-YEND)
      XINT(ICOUNT)=(XSTART-XEND)*T+XEND
      DLX=XSTART-XEND
      DLY=YSTART-YEND
      DLENG=SQRT(DLX*DLX+DLY*DLY)
      DXI=XINT(ICOUNT)-XEND
      DYI=YINT-YEND
      DLINT=SQRT(DXI*DXI+DYI*DYI)
      ZINT(ICOUNT)=(ZSTART*DLINT+ZEND*(DLENG-DLINT))/DLENG
 170  CONTINUE
C
      DTINT=XINT(1)-XINT(2)
      IF(DTINT.EQ.0.0) THEN
      ZSLIM=0.0
      GOTO 210
      ENDIF
C
      DSINT=XNODE-XINT(2)
      ZSLIM=(ZINT(1)*DSINT+ZINT(2)*(DTINT-DSINT))/DTINT
      IF(ZSLIM.GT.ZDEEP.OR.ZSLIM.LT.ZSHAL) ZSLIM=0.0
C
C     DEPTH SELECTION STRATEGY
C
210   ZCOM(1)=ZNEAR
      ZCOM(2)=ZIDWM
      ZCOM(3)=ZSLIM
      ZCOM(4)=ZCOLLI
      ZCOM(5)=ZMCSI
      ZCOM(6)=ZLSQI
C
      IZT=0
      DO 211 I=1,6
      IF(ZCOM(I).EQ.0.0) GOTO 211
      IZT=IZT+1
      ZSEL(IZT)=ZCOM(I)
 211  CONTINUE
C
      IF(IZT.EQ.1) THEN
      ZBIT=ZSEL(IZT)
      GOTO 220
      ENDIF
C
      ZBIG=ZSEL(1)
      DO 212 I=2,IZT
      IF(ZSEL(I).GE.ZBIG) ZBIG=ZSEL(I)
 212  CONTINUE
C
      ZSMALL=ZSEL(1)
      DO 213 J=2,IZT
```

```
      IF(ZSEL(J).LE.ZSMALL) ZSMALL=ZSEL(J)
 213  CONTINUE
C
      ZAVG=(ZBIG+ZSMALL)/2.0
C
      DO 214 K=1,IZT
 214  ZDIFF(K)=ABS(ZSEL(K)-ZAVG)
C
      ZBIT=ZSEL(1)
      ZDMN=ABS(ZSEL(1)-ZAVG)
      DO 215 L=2,IZT
      ZDIF=ABS(ZSEL(L)-ZAVG)
      IF(ZDIF.LT.ZDMN) THEN
      ZDMN=ZDIF
      ZBIT=ZSEL(L)
      ENDIF
 215  CONTINUE
C
 220  WRITE(8,4000)ZBIT
      SRADIUS=RADIUS
  70  CONTINUE
4000  FORMAT(F6.3)
      NOD=ND-NULL
      CLOSE(7)
      CLOSE(9,STATUS='KEEP')
      CLOSE(8,STATUS='KEEP')
      CLOSE(4,STATUS='KEEP')
      STOP
      END
C
      SUBROUTINE MAXMIN(N,X,Y,Z,XMN,XMX,YMN,YMX,ZMN,ZMX)
C
C     This subroutine computes maximum and minimum
C     value for input data
C
      REAL X(N),Y(N),Z(N)
      XMX=X(1)
      YMX=Y(1)
      ZMX=Z(1)
C
      DO 10 I=2,N
      IF(X(I).GT.XMX) XMX=X(I)
      IF(Y(I).GT.YMX) YMX=Y(I)
      IF(Z(I).GT.ZMX) ZMX=Z(I)
  10  CONTINUE
C
      XMN=X(1)
      YMN=Y(1)
      ZMN=Z(1)
      DO 20 J=2,N
      IF(X(J).LT.XMN) XMN=X(J)
      IF(Y(J).LT.YMN) YMN=Y(J)
      IF(Z(J).LT.ZMN) ZMN=Z(J)
  20  CONTINUE
      RETURN
      END
C
```

```
C
      SUBROUTINE GRID(XO,YO,XI,YI,NXI,NYI,NXY,XGRDX,YGRDY)
C
C     This subroutine constructs a rotated NXI x NYI nodes
C
      REAL XGRDX(NXY),YGRDY(NXY)
      K=0
      DO 10 I=1,NYI
      DO 20 J=1,NXI
      K=K+1
      L=K
      YGRDY(L)=YO+(I-1)*YI
      XGRDX(L)=XO+(J-1)*XI
 20   CONTINUE
      K=L
 10   CONTINUE
      RETURN
      END
C
      SUBROUTINE COORD(BRG,XCR,YCR,DIST,XCO,YCO)
C
      XDEP=DIST*SIN(BRG)
      YLAT=DIST*COS(BRG)
      XCO=XCR+XDEP
      YCO=YCR+YLAT
      RETURN
      END
C
      SUBROUTINE NEAR(N,XQ,YQ,ZQ,XNDE,YNDE,XNEAR,YNEAR,ZNEAR)
C
      REAL XQ(N),YQ(N),ZQ(N)
      XNEAR=XQ(1)
      YNEAR=YQ(1)
      ZNEAR=ZQ(1)
      IF(N.EQ.1) RETURN
      DNEAR=SQRT((XQ(1)-XNDE)**2+(YQ(1)-YNDE)**2)
      DO 10 I=2,N
      DIST=SQRT((XQ(I)-XNDE)**2+(YQ(I)-YNDE)**2)
      IF(DIST.LT.DNEAR) THEN
      DNEAR=DIST
      XNEAR=XQ(I)
      YNEAR=YQ(I)
      ZNEAR=ZQ(I)
      ENDIF
 10   CONTINUE
      RETURN
      END
C
      SUBROUTINE SPLIT(N,X,M,IN,II,JJ,S,IABV,NA,MAXA,IBEL,
     *NB,MAXB). (Refer to Eddy, 1977b)
C
      SUBROUTINE CONVEX(N,X,M,IN,IA,IB,IH,NH,IL).
      (Refer to Eddy, 1977b)
C
```

```
C
C     SUBROUTINE PCTEST(N,XX,XNODE,YNODE,KCODE)
C
C     THIS IS A POINT CONTAINMENT TEST SUBROUTINE
C
C
      DIMENSION XX(2,N),IN(25),IL(25),IH(25),
     *          X(25),Y(25),XINT(4)
      INTEGER IWORK(50)
      DATA IWORK/50*0/
C
      N1=N+1
      DO 2 I=1,N
      J=N1-I
  2 I N(J)=I
C
      DO 10 M=3,N
      CALL CONVEX(N,XX,M,IN,IWORK,IWORK(N+1),IH,NHULL,IL)
      IK=IL(1)
      DO 6 I=1,NHULL
      J=IH(IK)
      X(I)=XX(1,J)
      Y(I)=XX(2,J)
  6 I K=IL(IK)
      X(NHULL+1)=X(1)
      Y(NHULL+1)=Y(1)
 10   CONTINUE
C
C     POINT CONTAINMENT TEST
C
      ICOUNT=0
      DO 11 I=1,NHULL
      J=I+1
      XSTART=X(I)
      YSTART=Y(I)
      XEND=X(J)
      YEND=Y(J)
      YINT=YNODE
C
C     ONLY RELATED EDGES ARE SELECTED
C
C     NODE FALLS ON HORIZONTAL BOUNDARY (KCODE=0)
C
      IF(YNODE.EQ.YSTART.AND.YNODE.EQ.YEND) THEN
      KCODE=0
      RETURN
      ENDIF
C
      IF(YNODE.GE.YSTART.AND.YNODE.LT.YEND) THEN
      ICOUNT=ICOUNT+1
      GOTO 14
      ENDIF
      IF(YNODE.LE.YSTART.AND.YNODE.GT.YEND) THEN
      ICOUNT=ICOUNT+1
      GOTO 14
      ENDIF
      GOTO 11
C
```

```
C     COMPUTES X INTERSECT
C
 14   T=(YNODE-YEND)/(YSTART-YEND)
      XINT(ICOUNT)=(XSTART-XEND)*T+XEND
C
C     NODE COINCIDES WITH VERTEX
C
      IF(XINT(ICOUNT).EQ.XNODE) THEN
      KCODE=0
      RETURN
      ENDIF
 11   CONTINUE
C
C     IF NO INTERSECT - NODE FALLS OUTSIDE HULL
C
      IF(ICOUNT.EQ.0) THEN
      KCODE=-1
      RETURN
      ENDIF
C
C     IF ONLY 1 INTERSECT - OUTSIDE BOUNDARY
C
      IF(ICOUNT.EQ.1) THEN
      KCODE=-1
      RETURN
      ENDIF
C
      DO 100 I=1,ICOUNT
      IF(XINT(I).EQ.XINT(I+1)) GOTO 100
      IF((XNODE.LT.XINT(I)).AND.(XNODE.GT.XINT(I+1))) THEN
      KCODE=1
      RETURN
      ENDIF
      IF((XNODE.GT.XINT(I)).AND.(XNODE.LT.XINT(I+1))) THEN
      KCODE=1
      ELSE
      KCODE=-1
      RETURN
      ENDIF
 100  CONTINUE
      RETURN
      END
C
      SUBROUTINE ROTATE(ANGLE,N,XEAST,YNORTH)
C
C     This subroutine is used to rotate X & Y
C     into a new coord.system
C
      REAL XEAST(N),YNORTH(N)
      U=COS(ANGLE)
      V=SIN(ANGLE)
      DO 10 I=1,N
      TX=XEAST(I)*U-YNORTH(I)*V
      YNORTH(I)=XEAST(I)*V+YNORTH(I)*U
      XEAST(I)=TX
 10   CONTINUE
      RETURN
```

```
      END
C
      SUBROUTINE DECOMP(NDIM,N,A,IPVT,DET)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION A(NDIM,N)
      INTEGER IPVT(N)
      DET=1.0D0
      IPVT(N)=1
      IF(N.EQ.1) GO TO 70
      NM1=N-1
      DO 60 K=1,NM1
      KP1=K+1
      M=K
      DO 10 I=KP1,N
 10   IF(DABS(A(I,K)).GT.DABS(A(M,K))) M=I
      IPVT(K)=M
      IF(M.NE.K) IPVT(N)=-IPVT(N)
      P=A(M,K)
      A(M,K)=A(K,K)
      A(K,K)=P
      DET=DET*P
      IF(P.EQ.0.0D0) GO TO 60
 20   DO 30 I=KP1,N
 30   A(I,K)=-A(I,K)/P
      DO 50 J=KP1,N
      T=A(M,J)
      A(M,J)=A(K,J)
      A(K,J)=T
      IF(T.EQ.0.0D0) GO TO 50
      DO 40 I=KP1,N
      A(I,J)=A(I,J)+A(I,K)*T
 40   CONTINUE
 50   CONTINUE
 60   CONTINUE
 70   DET=DET*A(N,N)*DFLOAT(IPVT(N))
      RETURN
      END
C
      SUBROUTINE SOLVE(NDIM,N,A,IPVT,B)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION A(NDIM,N),B(N),IPVT(N)
      IF(N.EQ.1) GO TO 30
      NM1=N-1
      DO 10 K=1,NM1
      KP1=K+1
      M=IPVT(K)
      S=B(M)
      B(M)=B(K)
      B(K)=S
      DO 10 I=KP1,N
 10   B(I)=B(I)+A(I,K)*S
      DO 20 KB=1,NM1
      KM1=N-KB
      K=KM1+1
      B(K)=B(K)/A(K,K)
```

```
      S=-B(K)
      DO 20 I=1,KM1
 20   B(I)=B(I)+A(I,K)*S
 30   B(1)=B(1)/A(1,1)
      RETURN
      END
C     SUBROUTINE MULTI(A,B,C,IA,JA,JB)
C
      REAL*8 A(IA,JA),B(JA,JB),C(IA,JB)
      DO 10 I=1,IA
      DO 20 J=1,JB
      C(I,J)=0.0D0
      DO 30 K=1,JA
      C(I,J)=C(I,J)+A(I,K)*B(K,J)
 30   CONTINUE
 20   CONTINUE
 10   CONTINUE
      RETURN
      END
C
      SUBROUTINE INVERS(A,AA,N,NN)
C
      REAL A(NN,NN),AA(NN,NN)
      DO 10 I=1,NN
      DO 20 J=1,NN
      AA(I,J)=0.0
 20   CONTINUE
      AA(I,I)=1.0
 10   CONTINUE
      DET=1.0
      DO 30 I=1,N
      DIV=A(I,I)
      DET=DET*DIV
      DO 40 J=1,N
      IF(DIV.EQ.0.0) GOTO 40
      A(I,J)=A(I,J)/DIV
      AA(I,J)=AA(I,J)/DIV
 40   CONTINUE
      DO 50 J=1,N
      IF(I-J) 1,50,1
 1    RATIO=A(J,I)
      DO 60 KK=1,N
      A(J,KK)=A(J,KK)-RATIO*A(I,KK)
      AA(J,KK)=AA(J,KK)-RATIO*AA(I,KK)
 60   CONTINUE
 50   CONTINUE
 30   CONTINUE
      RETURN
      END
C
      SUBROUTINE COLTEST(N,X,Y,ICLT)
C
C     IF NCOUNT is EQ.3 test for Collinearity
C
      REAL X(N),Y(N)
      XLFT=X(1)
      YLFT=Y(1)
```

```
      XRGT=X(3)
      YRGT=Y(3)
      KC=1
    1 DXRL=XRGT-XLFT
      DYRL=YRGT-YLFT
      JC=KC
      KC=JC+1
      XMDL=X(KC)
      YMDL=Y(KC)
C
      IF(KC.EQ.4) THEN
      XMDL=X(1)
      YMDL=Y(1)
      ENDIF
      DXML=XMDL-XLFT
      DYML=YMDL-YLFT
      CRPROD=(DXRL*DYML)-(DXML*DYRL)
C
C     IF COLLINEAR SET ICLT=-1
C
      IF(CRPROD.GT.-2.0.AND.CRPROD.LT.2.0) THEN
      ICLT=-1
      RETURN
      ENDIF
C
      XLFT=X(KC)
      YLFT=Y(KC)
      XRGT=X(JC)
      YRGT=Y(JC)
C
      IF(KC.EQ.4) THEN
      ICLT=1
      RETURN
      ENDIF
      GOTO 1
      END
```

APPENDIX C-2

Computer program CHANGE2D.FOR

```
C
C       BLENDING INTERPOLATION TECHNIQUE (BIT)
C
C       This program plots 2D image of Seafloor topographic changes
C       using output files from INTPL.FOR
C
C       DECLARATION STATEMENTS.
C
        PARAMETER(NPTS=11000,NDCL=10,NECL=10,IUNDEF=9999,
     *  RUNDEF=999.999)
C
        INTEGER CSCLEN(3),IPLANE(3),LENGTH(6)
        integer lenar1(4)
        character*1 txtar1(4),ARE1,ARE2
C
        REAL ZSET1(NPTS),ZSET2(NPTS),DCLASS(2),ECLASS(2),
     *  ZDIFF(NPTS),ZDEP(NPTS),ZERO(NPTS),CCOL(NDCL)
C
        CHARACTER TXTSTR(6)*1,CSCTXT(3)*5,FNAME1*10,FNAME2*10
        CHARACTER RESQ*3,CFILE*9,DFILE*10,EFILE*10
        EXTERNAL BOX2MM
        DATA IPLANE /3,3,1/,LENGTH/6*-1/,CSCLEN/3*-2/
        DATA TXTSTR /6*' '/
        DATA CSCTXT /'Below','Above','     '/
        DATA DBL,NTICK /10.0,9 /
        DATA CFILE /'         '/
        DATA DFILE /'          '/
        DATA EFILE /'          '/
        data lenar1 /4*0 /
        data txtar1 /4*' '/
C
        OPEN(11,FILE='FWORK2',STATUS='OLD')
        OPEN(10,FILE='FWORK1',STATUS='OLD')
C
        WRITE(*,*) '  Enter PAST/PREVIOUS date filename: '
        WRITE(*,*) '  e.g: A0190                         '
        WRITE(*,*) '     A - Area                        '
        WRITE(*,*) '      01 - Block                     '
        WRITE(*,*) '       90 - Year                     '
C
        READ(*,*)FNAME1
        WRITE(10,*)FNAME1
        OPEN(7,FILE=FNAME1,STATUS='UNKNOWN')
C
        WRITE(*,*) 'Enter CURRENT/LATTER date filename: '
        READ(*,*)FNAME2
        WRITE(10,*)FNAME2
        OPEN(8,FILE=FNAME2,STATUS='UNKNOWN')
C
```

```
1600 write(*,*) '   Enter choice no: 1. Display Deepening/Erosion                     '
     write(*,*) '                                                                    '
     write(*,*) '                           2. Display Shoaling/Deposition           '
     write(*,*) '                                                                    '
C
     READ(*,*)mdispL
     REWIND(10)
     READ(10,1601)ARE1,BLK1,IYR1
     READ(10,1601)ARE2,BLK2,IYR2
1601 FORMAT(A,A2,I2)
C
C    To create Erosion output file
C
     WRITE(11,1605)'E',':',ARE2,BLK2,'-',IYR1,IYR2
1605 FORMAT(A,A,A,A2,A,I2,I2)
C
C    To create Deposition output file
C
     WRITE(11,1606)'D',':',ARE2,BLK2,'-',IYR1,IYR2
1606 FORMAT(A,A,A,A2,A,I2,I2)
C
C    To create Change.out file
C
     WRITE(11,3)'C',ARE2,BLK2,'-',IYR1,IYR2
   3 FORMAT(A,A,A2,A,I2,I2)
C
     REWIND(11)
     READ(11,1604)EFILE
     READ(11,1604)DFILE
     READ(11,1607)CFILE
1604 FORMAT(A10)
1607 FORMAT(A9)
C
     OPEN(9,FILE=CFILE,STATUS='UNKNOWN')
C
     IF(MDISPL.EQ.1) WRITE(*,*) 'Erosion file: ',EFILE
     IF(MDISPL.EQ.2) WRITE(*,*) 'Deposition file: ',DFILE
     WRITE(*,*)'Change output file: ',CFILE
     IND=0
     REWIND(7)
     READ(7,*)ANG
     READ(7,*)SX,SY
     READ(7,*)XNI,YNI
1000 READ(7,*,END=1100)ZBIT
     IND=IND+1
     zset1(ind)=ZBIT
     ID=IND
     GOTO 1000
1100 WRITE(*,*) 'Number of nodes stored in 1st input-file: ',ID
C
     IND=0
     REWIND(8)
     READ(8,*)ANG
     READ(8,*)SX,SY
     READ(8,*)XNI,YNI
     NXI=INT(XNI)
     NYI=INT(YNI)
1200 READ(8,*,END=1300)ZBIT
```

```
      IND=IND+1
      zset2(ind)=ZBIT
      ID=IND
      GOTO 1200
 1300 WRITE(*,*) 'Number of nodes stored in 2nd input-file: ',ID
C
      DO 1400 I=1,ID
      ZDIFF(I)=ZSET2(I)-ZSET1(I)
      IF(ZSET1(I).EQ.0.0.OR.ZSET2(I).EQ.0.0) ZDIFF(I)=0.0
      WRITE(9,*)ZDIFF(I)
 1400 CONTINUE
C
C     To determine depth range
C
      CALL MAXMIN(ID,ZSET2,ZUMN,ZUMX)
      WRITE(*,*) 'Min Depth:',ZUMN,' Max Depth:',ZUMX
C
C     PLOTTING USING UNIRAS
C
      WRITE(*,*) 'Plotting now in progress ........'
      CALL GROUTE ('    ')
      CALL RDEFON('SWIM',1)
      CALL GOPEN
      CALL GRPSIZ(XSIZE,YSIZE)
      write(*,*)XSIZE,YSIZE
      CALL GVPORT(0.25*XSIZE,0.1*YSIZE,0.8*XSIZE,0.8*YSIZE)
      CALL GVPROJ(2)
      ZLIM=INT(ZUMX)+1.0
      CALL GLIMIT(0.,XNI,0.,YNI,0.,0.)
      CALL GSCALE
      CALL GWBOX(1.0,1.0,0.25)
C
C     SET LEGEND BOX LIMIT
C
C     PRESENT MINUS PAST
C     -VE DEPOSITION
C     +VE EROSION
C
C
      IF(MDISPL.EQ.1) THEN
      DO 1500 I=1,ID
      ZERO(I)=0.0
      IF(ZDIFF(I).GT.0.2) ZERO(I)=-ZDIFF(I)
 1500 CONTINUE
      CALL MAXMIN(ID,ZERO,ZEMN,ZEMX)
      WRITE(*,*) 'Minimum Erosion  : ',ZEMX
      WRITE(*,*) 'Maximum Erosion  : ',ZEMN
C
      CMIN=-2.0
      STEP=0.2
      ECLASS(1)=CMIN
      ECLASS(2)=STEP
      CALL RCLASS(ECLASS,NECL,5)
      ENDIF
C
      IF(MDISPL.EQ.2) THEN
      DO 1520 I=1,ID
      ZDEP(I)=0.0
```

```
      IF(ZDIFF(I).LT.-0.2) ZDEP(I)=-ZDIFF(I)
1520  CONTINUE
      CALL MAXMIN(ID,ZDEP,ZDMN,ZDMX)
      WRITE(*,*) 'Maximum Deposition: ',ZDMX
      WRITE(*,*) 'Minimum Deposition: ',ZDMN
C
C     Any deposition less than 0.2m  is ignored
C
      CMIN=0.2
      STEP=0.2
      DCLASS(1)=CMIN
      DCLASS(2)=STEP
      CALL RCLASS(DCLASS,NDCL,5)
      ENDIF
C
      TXTHGT=0.025*MIN(XSIZE,YSIZE)
      CALL RAXTEF(4,'SWIM',1)
      CALL RAXLFO(0,0,IUNDEF,IUNDEF)
C
C     Set the x and y axes
C
      CALL RAXBTI(IUNDEF,RUNDEF,RUNDEF,DBL)
      CALL RAXSTI(NTICK)
      CALL RAXDIS(3,1,IUNDEF)
      CALL GCONLI(1,0.,0,10.,10.,-0.25,1)
      CALL GCONWI(-0.1,1)
      CALL GCONCO(CCOL,1)
      IF(MDISPL.EQ.1) THEN
      CALL GCNR2S(ZERO,NXI,NYI)
      CALL GCNR2V(ZERO,NXI,NYI)
      ENDIF
c
      IF(MDISPL.EQ.2) THEN
      CALL GCNR2S(ZDEP,NXI,NYI)
      CALL GCNR2V(ZDEP,NXI,NYI)
      ENDIF
      CALL GSCAMM
      CALL GCLOPT(CSCLEN,CSCTXT,0.85*TXTHGT,1,0.,1)
      CALL GCOSCL(10.,25.)
      CALL RTXJUS(0,1)
      CALL RTXHEI(3.)
      IF(MDISPL.EQ.1) CALL RTX(12,EFILE,0.25*xsize,0.03*ysize)
      IF(MDISPL.EQ.2) CALL RTX(12,DFILE,0.25*xsize,0.03*ysize)
C
      WRITE(*,*) 'Do you want to quit? (y/n)'
      READ(*,*)RESQ
      IF(RESQ.EQ.'N'.OR.RESQ.EQ.'n') THEN
      GOTO 1600
      ENDIF
      IF(RESQ.EQ.'Y'.OR.RESQ.EQ.'y') THEN
      WRITE(*,*) 'Press-CRTL-Z to exit ......'
      ENDIF
      CALL GCLOSE
      CLOSE(7)
      CLOSE(9,STATUS='KEEP')
      CLOSE(8,STATUS='KEEP')
      CLOSE(10)
      CLOSE(11)
```

```
      STOP
      END
C
      SUBROUTINE MAXMIN(N,Z,ZMN,ZMX)
C
C     This subroutine computes maximum and minimum
C     value for input data
C
      REAL Z(N)
      ZMX=Z(1)
C
      DO 10 I=2,N
      IF(Z(I).GT.ZMX) ZMX=Z(I)
 10   CONTINUE
C
      ZMN=Z(1)
      DO 20 J=2,N
      IF(Z(J).LT.ZMN) ZMN=Z(J)
 20   CONTINUE
      RETURN
      END
C
      SUBROUTINE ROTATE(ANGLE,N,XEAST,YNORTH)
C
C     This subroutine is used to rotate X & Y
C     into a new coord.system
C
      REAL XEAST(N),YNORTH(N)
      U=COS(ANGLE)
      V=SIN(ANGLE)
      DO 10 I=1,N
      TX=XEAST(I)*U-YNORTH(I)*V
      YNORTH(I)=XEAST(I)*V+YNORTH(I)*U
      XEAST(I)=TX
 10   CONTINUE
      RETURN
      END
```

APPENDIX C-3

Computer program CHANGE3D.FOR

```
C
C      BLENDING INTERPOLATION TECHNIQUE (BIT)
C
C
C      DECLARATION STATEMENTS.
C
       PARAMETER(NPTS=11000,NDCL=10,NECL=10,IUNDEF=9999,
     * RUNDEF=999.999)
       PARAMETER(NZCL=20,NGRID=5000)
       CHARACTER TXTSTR(6)*1,CSCTXT(3)*5,ANS*3,FNAME1*10,ARE1*1,
     * ARE2*1,
     * FNAME2*10,CFILE*10,DFILE*10,EFILE*10,BLK1*2,BLK2*2

       INTEGER CSCLEN(3),IPLANE(3),LENGTH(6),IWK(80)
       REAL ZSET2(NPTS),ZSET1(NPTS),ZDIFF(NPTS),ZSURF(NPTS),
     * ZERO(NPTS),ECLASS(2),DCLASS(2),ZDEP(NPTS),ZCHG(NPTS)
       EXTERNAL BOX2MM
       DATA IPLANE /3,3,1/,LENGTH/6*-1/,CSCLEN/3*-2/
       DATA TXTSTR /6*' '/
       DATA CFILE /'          '/
       DATA DFILE /'          '/
       DATA EFILE /'          '/

       DATA CSCTXT /'Below','Above','     '/
       DATA IWK /80*0/
C
       OPEN(11,FILE='FWORK2',STATUS='OLD')
       OPEN(10,FILE='FWORK1',STATUS='OLD')
C
       WRITE(*,*) '  Enter CURRENT/LATTER date filename:                    '
       WRITE(*,*) '  e.g: A0190                                             '
       WRITE(*,*) '     A - Area                                            '
       WRITE(*,*) '       01 - Block                                        '
       WRITE(*,*) '         90 - Year                                       '
C
       READ(*,*)FNAME2
       WRITE(10,*)FNAME2
       OPEN(7,FILE=FNAME2,STATUS='UNKNOWN')
C
       WRITE(*,*) '  Enter PAST/PREVIOUS date filename: '
       READ(*,*)FNAME1
       WRITE(10,*)FNAME1
       OPEN(8,FILE=FNAME1,STATUS='UNKNOWN')
C
 2100  write(*,*) '              Enter choice no: 1. Display Deepening/Erosion    '
       write(*,*) '                                                               '
       write(*,*) '                               2. Display Shoaling/Deposition  '
       write(*,*) '                                                               '
C
       READ(*,*)mdispL
       REWIND(10)
       READ(10,1601)ARE2,BLK2,IYR2
```

```
      READ(10,1601)ARE1,BLK1,IYR1
 1601 FORMAT(A,A2,I2)
C
C     To create Erosion output file
C
      WRITE(11,1606)'E',':',ARE2,BLK2,'-',IYR1,IYR2
C
C     To create Deposition output file
C
      WRITE(11,1606)'D',':',ARE2,BLK2,'-',IYR1,IYR2
 1606 FORMAT(A,A,A,A2,A,I2,I2)
C
C     To create Change.out file
C
      WRITE(11,3)'C',':',ARE2,BLK2,'-',IYR1,IYR2
    3 FORMAT(A,A,A,A2,A,I2,I2)
C
      REWIND(11)
      READ(11,1604)EFILE
      READ(11,1604)DFILE
      READ(11,1604)CFILE
 1604 FORMAT(A10)
      OPEN(9,FILE=CFILE,STATUS='UNKNOWN')
C
      IF(MDISPL.EQ.1) WRITE(*,*) 'Erosion file: ',EFILE
      IF(MDISPL.EQ.2) WRITE(*,*) 'Deposition file: ',DFILE
      WRITE(*,*)'Change output file: ',CFILE
      IND=0
      REWIND(7)
      READ(7,*)ANG
      READ(7,*)SX,SY
      READ(7,*)XNI,YNI
 1000 READ(7,*,END=1100)ZBIT
      IND=IND+1
      ZSET2(IND)=ZBIT
      ID=IND
      GOTO 1000
 1100 WRITE(*,*) 'Number of nodes stored in 2nd input-file: ',ID
C
      IND=0
      REWIND(8)
      READ(8,*)ANG
      READ(8,*)SX,SY
      READ(8,*)XNI,YNI
      NXI=INT(XNI)
      NYI=INT(YNI)
 1200 READ(8,*,END=1300)ZBIT
      IND=IND+1
      ZSET1(IND)=ZBIT
      ID=IND
      GOTO 1200
 1300 WRITE(*,*) 'Number of nodes stored in 1st input-file: ',ID
C
      DO 1400 I=1,ID
      ZSURF(I)=-ZSET2(I)
      ZDIFF(I)=ZSET2(I)-ZSET1(I)
      IF(ZSET1(I).EQ.0.0.OR.ZSET2(I).EQ.0.0) ZDIFF(I)=0.0
      WRITE(9,*)ZDIFF(I)
```

```
 1400   CONTINUE
C
C       TO DETERMINE DEPTH RANGE
C
        CALL MAXMIN(ID,ZSET2,ZDMN,ZDMX)
        WRITE(*,*) 'Shallowest depth: ',ZDMN
        WRITE(*,*) 'Greatest depth  : ',ZDMX
        RANGE=ZDMX-ZDMN
        WRITE(*,*) '  Depth Range: ',RANGE
        WRITE(*,*) 'Enter new range: '
        READ(*,*)ZRANGE
        ZAXIS=-ZRANGE
C
        IF(MDISPL.EQ.1) THEN
        DO 1500 I=1,ID
        ZERO(I)=0.0
        IF(ZDIFF(I).GT.0.0) ZERO(I)=-ZDIFF(I)
        ZCHG(I)=-ZERO(I)
 1500   CONTINUE
        CALL MAXMIN(ID,ZCHG,ZEMN,ZEMX)
        WRITE(*,*) 'Minimum Erosion   : ',ZEMN
        WRITE(*,*) 'Maximum Erosion   : ',ZEMX
        ENDIF
C
        IF(MDISPL.EQ.2) THEN
        DO 1520 I=1,ID
        IF(ZDIFF(I).LT.0.0) ZDEP(I)=-ZDIFF(I)
 1520   CONTINUE
        DO 1530 I=1,ID
        ZCHG(I)=0.0
        IF(ZDEP(I).GE.0.2) ZCHG(I)=ZDEP(I)
 1530   CONTINUE
        CALL MAXMIN(ID,ZCHG,ZDMN,ZDMX)
        WRITE(*,*) 'Maximum Deposition: ',ZDMX
        WRITE(*,*) 'Minimum Deposition: ',ZDMN
        ENDIF
C
C       PLOTTING USING UNIRAS
C
        WRITE(*,*) 'Plotting now in progress ........'
        CALL GROUTE(' ')
        CALL RDEFON('SWIM',1)
        CALL GOPEN
        CALL GRPSIZ(XSIZE,YSIZE)
        CALL GVPORT(0.1*XSIZE,0.09*YSIZE,0.9*XSIZE,0.9*YSIZE)
        CALL GVPROJ(2)
        CALL GLIMIT(100.,NXI,100.,NYI,ZAXIS,0.)
        CALL GSCALE
        CALL GWBOX(1.0,1.0,0.25)
        CALL GVUANG(315.,35.,35.)
C
        IF(MDISPL.EQ.1) THEN
        CMIN=-2.0
        STEP=0.2
        ECLASS(1)=CMIN
        ECLASS(2)=STEP
        CALL RCLASS(ECLASS,NECL,5)
        ENDIF
```

```
C
C       Any deposition less than 0.2m is ignored
C
        IF(MDISPL.EQ.2) THEN
        CMIN=0.2
        STEP=0.2
        DCLASS(1)=CMIN
        DCLASS(2)=STEP
        CALL RCLASS(DCLASS,NDCL,5)
        ENDIF
C
        TXTHGT=0.025*MIN(XSIZE,YSIZE)
        CALL RAXDIS(7,1,0)
        CALL RAXIS3(0,TXTHGT,IPLANE,LENGTH,TXTSTR)
        CALL GCONLI(3,-1.,1,1.,1.,-1.,1)
        IF(MDISPL.EQ.1) CALL GCONR4(ZSURF,ZERO,NXI,NYI)
        IF(MDISPL.EQ.2) CALL GCONR4(ZSURF,ZCHG,NXI,NYI)
        CALL GSCAMM
        CALL GCLOPT(CSCLEN,CSCTXT,0.85*TXTHGT,1,0.,1)
        CALL GCOSCL(10.,15.)
        CALL RTXJUS(1,1)
        CALL RTXHEI(4.0)
        CALL RTX(-2,'        ',0.2*XSIZE,0.05*YSIZE)
C
        WRITE(*,*) 'Do you want another plot? ......(Y/N): '
        READ(*,*)ANS
        IF(ANS.EQ.'Y'.OR.ANS.EQ.'y') GOTO 2100
        CALL GCLOSE
C
        CLOSE(7)
        CLOSE(10)
        CLOSE(11)
        CLOSE(9,STATUS='KEEP')
        CLOSE(8,STATUS='KEEP')
        CLOSE(4,STATUS='KEEP')
        STOP
        END
C
        SUBROUTINE MAXMIN(N,Z,ZMN,ZMX)
C
C       This subroutine computes maximum and minimum
C       value for input data
C
        REAL Z(N),ZGT0(11000)
C
        ZMX=Z(1)
        DO 10 I=2,N
        IF(Z(I).GT.ZMX) ZMX=Z(I)
  10    CONTINUE
C
        L=N
        LL=0
        DO 2 I=1,N
        IF(Z(I).EQ.0.0) THEN
        L=L-1
        GOTO 2
        ENDIF
        LL=LL+1
```

```
      ZGT0(LL)=Z(I)
    2 CONTINUE
C
      ZMN=ZGT0(1)
      DO 20 J=2,L
      IF(ZGT0(J).LT.ZMN)ZMN=ZGT0(J)
   20 CONTINUE
      RETURN
      END
```

APPENDIX C-4

Computer program AREAL

```
C
      Program AREAL
C
C     This program works out the percentage of erosion
C     or deposition of an area.
C
      PARAMETER (NPTS=15000)
      CHARACTER*15 FNAME2,FNAME1
      REAL*8 ZDEP(NPTS),ZERO(NPTS),ZSAME(NPTS),D1(NPTS),
     *D2(NPTS),ZCHG(NPTS),DEPTH2(NPTS),DEPTH1(NPTS)
C
C     INPUT DATA FOR SURFACE 2
C
      WRITE(*,*) 'Input CURRENT/LATTER filename: '
      READ(*,*)FNAME2
      OPEN(8,FILE=FNAME2,STATUS='UNKNOWN')
      ICOUNT=0
      READ(8,*)ANG
      READ(8,*)SX,SY
      READ(8,*)M,N
 101  READ(8,*,END=100)ZVALUE
      LCOUNT=LCOUNT+1
      LC=LCOUNT
      DEPTH2 (LCOUNT)=ZVALUE
      GOTO 101
 100  WRITE(*,*)'NO.DATA IN SET2: ',LCOUNT
C
C     INPUT DATA FOR SURFACE 1
C
      WRITE(*,*) 'Input PAST/PREVIOUS filename: '
      READ(*,*)FNAME1
      OPEN(9,FILE=FNAME1,STATUS='UNKNOWN')
      JCOUNT=0
      READ(9,*)ANG
      READ(9,*)SX,SY
      READ(9,*)M,N
 103  READ(9,*,END=102)ZVALUE
      JCOUNT=JCOUNT+1
      JC=JCOUNT
      DEPTH1(JCOUNT)=ZVALUE
      GOTO 103
 102  WRITE(*,*)'NO.DATA IN SET1: ',JCOUNT
C
C     COMPARE FOR EMPTY NODES
C
      DO 104 I=1,LC
      D1(I)=DEPTH1(I)
      IF(DEPTH2(I).EQ.0.0D0) D1(I)=0.0D0
 104  CONTINUE
      DO 105 I=1,LC
      D2(I)=DEPTH2(I)
      IF(D1(I).EQ.0.0D0) D2(I)=0.0D0
```

```
 105    CONTINUE
C
C       SEPARATE 2 SURFACES
C
        OPEN(4,FILE='DIFF.OUT',STATUS='OLD')
        DO 110 I=1,JCOUNT
        ZCHG(I)=D2(I)-D1(I)
        WRITE(4,*)ZCHG(I)
 110    CONTINUE
C
        IC=0
        JC=0
        KC=0
        ICOUNT=0
        JCOUNT=0
        KCOUNT=0
        DO 107 I=1,LCOUNT
        IF(ZCHG(I).LT.0.0D0) THEN
        ICOUNT=ICOUNT+1
        IC=ICOUNT
        ZDEP(IC)=ZCHG(I)
        ENDIF
C
        IF(ZCHG(I).GT.0.0D0) THEN
        JCOUNT=JCOUNT+1
        JC=JCOUNT
        ZERO(JC)=ZCHG(I)
        ENDIF
C
        IF(ZCHG(I).EQ.0.0D0) THEN
        KCOUNT=KCOUNT+1
        KC=KCOUNT
        ZSAME(KC)=ZCHG(I)
        ENDIF
 107    CONTINUE
        PRINT*,' No.of deposition pts:',IC
        PRINT*,' No.of erosion pts   :',JC
        PRINT*,' No.of no change pts :',KC
        ITOT=IC+JC+KC
        PRINT*,'              TOTAL:',ITOT
        PRINT*,' No.of data pts      :',LC
        WRITE(*,*)
        AREAD=IC/DFLOAT(LC)*100.0
        WRITE(*,120)AREAD
        AREAE=JC/DFLOAT(LC)*100.0
        WRITE(*,121)AREAE
        AREA0=KC/DFLOAT(LC)*100.0
        WRITE(*,122)AREA0
        TOT=AREAD+AREAE+AREA0
        WRITE(*,123)TOT
 120    FORMAT(1X,' Percentage area of deposition:',1X,F6.2,'%')
 121    FORMAT(1X,' Percentage area of erosion   :',1X,F6.2,'%')
 122    FORMAT(1X,' Percentage area of no change :',1X,F6.2,'%')
 123    FORMAT(1X,'             Total Percentage:',1X,F6.2,'%')
        WRITE(*,*)
        CALL MAXMIN(IC,ZDEP,ZDMX,ZDMN)
        WRITE(*,124)-ZDMX
 124    FORMAT(1X,' Maximum deposition value:',F6.3,' metres')
```

```
      WRITE(*,125)-ZDMN
 125  FORMAT(1X,' Minimum deposition value:',F6.3,' metres')
      CALL MAXMIN(JC,ZERO,ZEMN,ZEMX)
      WRITE(*,126)-ZEMN
 126  FORMAT(1X,' Minimum erosion value   :',F6.3,' metres')
      WRITE(*,127)-ZEMX
 127  FORMAT(1X,' Maximum erosion value   :',F6.3,' metres')
      close(8)
      close(9)
      STOP
      END
C
   SUBROUTINE MAXMIN(N,Z,ZMN,ZMX)
C
      REAL*8 Z(N)
      ZMX=Z(1)
      DO 10 I=2,N
      IF(ZMX.EQ.0.0D0) THEN
      ZMX=Z(I)
      GOTO 10
      ENDIF
      IF(Z(I).EQ.0.0D0) GOTO 10
      IF(Z(I).GT.ZMX) ZMX=Z(I)
  10  CONTINUE
      ZMN=Z(1)
      DO 20 I=2,N
      IF(ZMN.EQ.0.0D0) THEN
      ZMN=Z(I)
      GOTO 20
      ENDIF
      IF(Z(I).EQ.0.0D0) GOTO 20
      IF(Z(I).LT.ZMN) ZMN=Z(I)
  20  CONTINUE
      RETURN
      END
```

APPENDIX C-5

Computer program VOL

```
C
      Program VOLUME
C
      PARAMETER (MAX=200)
      CHARACTER*15 FNAME2,FNAME1
      REAL*8  D1(MAX,MAX),SURF1(MAX*MAX),SURF2(MAX*MAX),SURF(MAX*MAX)
     * D2(MAX,MAX),ZCHG(MAX*MAX),DEPTH2(MAX*MAX),DEPTH1(MAX*MAX)
C
C     INPUT  SURFACE  2
C
      WRITE(*,*) 'Input 2nd filename: '
      READ(*,*)FNAME2
      OPEN(8,FILE=FNAME2,STATUS='UNKNOWN')
      ICOUNT=0
      READ(8,*)ANG
      READ(8,*)SX,SY
      READ(8,*)M,N
101   READ(8,*,END=100)ZBIT
      ICOUNT=ICOUNT+1
      DEPTH2(ICOUNT)=ZBIT
      GOTO 101
100   WRITE(*,*)'NO.DATA IN SET2:',ICOUNT
C
C     INPUT  SURFACE  1
C
      WRITE(*,*) 'Input 1st filename: '
      READ(*,*)FNAME1
      OPEN(9,FILE=FNAME1,STATUS='UNKNOWN')
C
      JCOUNT=0
      READ(9,*)ANG
      READ(9,*)SX,SY
      READ(9,*)M,N
103   READ(9,*,END=102)ZBIT
      JCOUNT=JCOUNT+1
      DEPTH1(JCOUNT)=ZBIT
      GOTO 103
102   WRITE(*,*)'NO.DATA IN SET1: ',JCOUNT
C
      WRITE(*,*)'Enter Computation Choice No: '
      WRITE(*,*)'      1 - for Deposition      '
      WRITE(*,*)'      2 - for Erosion         '
      WRITE(*,*)'         -----------------    '
      READ(*,*)NCHOIC
C
```

```
C
C      COMPUTE VOLUME SURFACE 1
C
       K=0
       DO 104 I=1,M
       DO 105 J=1,N
       K=K+1
       D1(I,J)=DEPTH1(K)
       IF(DEPTH2(K).EQ.0.0D0) D1(I,J)=0.0D0
       SURF1(K)=D1(I,J)
105    CONTINUE
104    CONTINUE
       print 15,'Computed Volume 1:',VOL1(D1,MAX,M,N,SX,SY),' cu.metres'
C
C      COMPUTE VOLUME SURFACE 2
C
       DO 106 I=1,JCOUNT
       SURF(I)=DEPTH2(I)
       IF(SURF1(I).EQ.0.0D0) SURF(I)=0.0D0
       SURF2(I)=SURF(I)
106    CONTINUE
C
       DO 110 I=1,JCOUNT
       ZCHG(I)=SURF2(I)-SURF1(I)
110    CONTINUE
C
       L=0
       DO 107 I=1,M
       DO 108 J=1,N
       L=L+1
       D2(I,J)=SURF2(L)
C
       IF(NCHOIC.EQ.1) THEN
       IF(ZCHG(L).GT.0.0D0) D2(I,J)=SURF1(L)
       ENDIF
C
       IF(NCHOIC.EQ.2) THEN
       IF(ZCHG(L).LT.0.0D0) D2(I,J)=SURF1(L)
       ENDIF
108    CONTINUE
107    CONTINUE
       print 15,'Computed Volume 2:',VOL2(D2,MAX,M,N,SX,SY),' cu.metres'
C
       VCHG=VOL2(D2,MAX,M,N,SX,SY)-VOL1(D1,MAX,M,N,SX,SY)
       IF(NCHOIC.EQ.1) THEN
       print 15,'Vol.of Deposition:',ABS(VCHG)        ,' cu.metres'
       ENDIF
       IF(NCHOIC.EQ.2) THEN
       print 15,'Vol.of Erosion    :',VCHG            ,' cu.metres'
       ENDIF
15     format(A,F10.3,A)
       close(8)
       close(9)
       STOP
```

```
      END
C
      REAL FUNCTION VOL2(H,MAX,M,N,SX,SY)
C
      real*8  H(MAX,MAX)
      DATA  V1,V2,V4/3*0.0/
      V1=H(1,1)+H(1,N)+H(M,1)+H(M,N)
      DO 10 I=2,M-1
      V2=V2+2*(H(I,1)+H(I,N))
10    CONTINUE
      DO 20 J=2,N-1
      V2=V2+2*(H(1,J)+H(M,J))
20    CONTINUE
      DO 30 I=2,M-1
      DO 40 J=2,N-1
      V4=V4+4*H(I,J)
      40  CONTINUE
30    CONTINUE
      VOL2=SX*SY*(V1+V2+V4)/4.0
      RETURN
      END
C
      REAL FUNCTION VOL1(H,MAX,M,N,SX,SY)
C
      real*8  H(MAX,MAX)
      DATA  V1,V2,V4/3*0.0D0/
      V1=H(1,1)+H(1,N)+H(M,1)+H(M,N)
      DO 10 I=2,M-1
      V2=V2+2*(H(I,1)+H(I,N))
10    CONTINUE
      DO 20 J=2,N-1
      V2=V2+2*(H(1,J)+H(M,J))
20    CONTINUE
      DO 30 I=2,M-1
      DO 40 J=2,N-1
      V4=V4+4*H(I,J)
40    CONTINUE
30    CONTINUE
      VOL1=SX*SY*(V1+V2+V4)/4.0
      RETURN
      END
```

APPENDIX D

(Tables 6.5.1 - 6.5.19)

Table 6.5.1. Statistical information on deposition, erosion no-change for the period 1990/91 (Area A)

				Deposition (m)		**Erosion (m)**	
Block	*%Deposition*	*%Erosion*	*%No Change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
A01	77.36	12.78	9.86	0.3	0.1	0.1	0.4
A02	84.56	1.58	13.86	0.3	0.0	0.0	0.1
A03	57.37	6.46	36.17	0.2	0.0	0.0	0.1
A04	0.11	0.00	99.89	0.4	0.0	0.0	0.0
A05	77.10	1.69	21.21	0.4	0.0	0.0	0.1
A06	88.39	6.94	4.67	0.5	0.1	0.0	0.1
A07	96.03	3.56	0.41	0.7	0.1	0.0	0.1
A08	14.69	0.00	85.31	0.2	0.0	0.0	0.0
A09	85.90	3.52	10.58	0.6	0.0	0.0	0.3
A10	92.64	0.00	7.36	0.6	0.2	0.0	0.0
A11	95.23	1.29	3.48	0.7	0.1	0.0	0.1
A12	55.53	0.64	43.83	0.3	0.1	0.0	0.1
Mean	68.74	3.21	28.05	0.43	0.06	0.00	0.12

Table 6.5.2. Statistical information on deposition, erosion no-change for period 1991/92 (Area A)

				Deposition (m)		Erosion (m)	
Block	*% Deposition*	*% Erosion*	*% No Change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
A01	15.78	33.50	50.72	0.2	0.1	0.1	0.6
A02	1.69	47.86	50.46	0.2	0.0	0.0	0.2
A03	10.37	41.70	47.93	0.1	0.0	0.0	0.1
A04	0.00	0.11	99.89	0.0	0.0	0.1	0.5
A05	28.83	66.62	4.55	0.8*	0.1	0.0	0.5
A06	2.27	97.70	0.03	0.1	0.0	0.1	0.7
A07	5.41	93.33	1.25	0.1	0.0	0.1	0.7
A08	0.01	14.68	85.31	0.0	0.0	0.0	0.2
A09	21.40	71.52	7.08	0.7*	0.1	0.1	0.5
A10	0.00	92.76	7.24	0.0	0.0	0.0	0.5
A11	2.91	91.79	5.30	0.2	0.1	0.0	0.7
A12	1.29	54.85	43.86	0.1	0.0	0.0	0.3
Mean	6.33	58.87	33.63	0.08	0.05	0.04	0.46

Note: Values shown with an asterisk are excluded from computation of the mean value

Table 6.5.3. Statistical information on deposition, erosion no-change for the period 1992/93 (Area A)

				Deposition (m)		**Erosion (m)**	
Block	*% Deposition*	*%Erosion*	*% No Change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
A01	40.75	9.16	50.09	0.4*	0.1*	0.0	0.4
A02	45.80	3.67	50.53	0.2	0.1	0.0	0.1
A03	35.21	27.53	37.26	0.2	0.1	0.0	0.1
A04	83.83	0.78	15.38	0.3	0.1	0.0	0.1
A05	88.75	6.81	4.44	0.8*	0.2*	0.0	0.1
A06	86.90	7.40	5.70	0.3	0.1	0.0	0.2
A07	57.54	41.37	1.09	0.1	0.0	0.0	0.1
A08	98.14	1.70	0.17	0.5	0.1	0.0	0.1
A09	94.58	1.72	3.71	0.9*	0.3*	0.1	0.5
A10	99.96	0.04	0.00	0.6	0.2	0.0	0.0
A11	81.82	16.11	2.08	0.4	0.1	0.0	0.1
A12	88.21	11.62	0.18	0.4	0.1	0.0	0.1
Mean	75.12	10.66	14.22	0.44	0.13	0.00	0.16

Note: Values shown with an asterisk are excluded from computation of the mean value

Table 6.5.4 . Statistical information on deposition, erosion no-change for 1989/90 (Area B)

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
B01	36.02	56.03	7.95	0.3*	0.1	0.1	0.8*
B02	47.60	51.90	0.50	0.1	0.0	0.1	0.2
B03	43.37	56.39	0.25	0.2	0.0	0.1	0.2
B04	36.12	60.62	0.25	0.2	0.0	0.0	0.3
B05	65.84	26.06	8.11	0.3*	0.1	0.1	0.6*
B06	78.57	21.09	0.34	0.2	0.1	0.0	0.1
B07	69.77	30.06	0.18	0.3	0.1	0.1	0.2
B08	75.95	23.76	0.28	0.3	0.1	0.1	0.2
B09	64.30	25.10	10.61	0.5*	0.1	0.1	0.6*
B10	91.88	7.74	0.37	0.5*	0.1	0.1	0.2
B11	52.12	47.51	0.36	0.3	0.1	0.2	0.3
B12	75.25	24.48	0.27	0.3	0.1	0.1	0.5*
B13	7.67	75.37	16.96	0.4*	0.1	0.1	0.3
B14	39.57	60.22	0.21	0.3	0.1	0.1	0.3
B15	40.92	58.54	0.54	0.2	0.1	0.1	0.3
B16	45.37	54.38	0.25	0.3	0.1	0.1	5.0*
B17	0.03	46.99	52.99	0.0	0.0	3.5*	0.2
B18	1.06	10.55	88.39	0.0	0.0	0.1	0.3
B19	89.65	10.29	0.06	0.4	0.1	0.1	0.1
B20	9.56	3.04	87.40	0.1	0.0	0.0	4.6*
B21	0.00	59.10	40.88	0.0	0.0	3.5*	0.6
B22	42.93	56.85	0.23	0.6	0.1	0.1	0.3
B23	58.85	40.74	0.41	0.4	0.1	0.1	0.2
B24	81.28	18.36	0.36	0.3	0.1	0.1	0.2
Mean	48.07	36.09	15.72	0.29	0.07	0.09	0.24

Table 6.5.5. Statistical Information on deposition, erosion no change for the period 1990/1991 (Area B).

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
B01	92.26	0.00	7.74	0.8*	0.2*	0.0	0.0
B02	100.00	0.00	0.00	0.5	0.1	0.0	0.0
B03	97.15	2.78	0.07	0.5	0.1	0.0	0.1
B04	69.56	10.76	19.67	0.4	0.1	0.0	0.1
B05	86.07	5.91	8.02	0.5*	0.1	0.0	0.1
B06	98.94	1.02	0.04	0.4	0.1	0.0	0.0
B07	95.24	4.71	0.06	0.4	0.1	0.0	0.1
B08	68.30	22.18	9.52	0.4	0.1	0.1	0.2
B09	83.02	6.36	10.62	1.1*	0.1*	0.1	0.2
B10	93.59	6.31	0.10	0.4	0.1	0.0	0.1
B11	89.38	10.48	0.14	0.3	0.1	0.0	0.1
B12	79.32	20.43	0.25	0.4	0.1	0.0	0.2
B13	72.94	12.82	14.23	1.6*	0.1*	0.1	0.5
B14	98.50	1.49	0.01	0.4	0.1	0.0	0.1
B15	94.82	5.09	0.09	0.4	0.1	0.0	0.2
B16	96.39	3.54	0.07	0.6	0.1	0.0	0.1
B17	63.89	3.98	32.13	1.2*	0.7*	0.1	0.2
B18	93.65	6.25	0.10	1.2*	0.1*	0.1	0.2
B19	94.95	4.98	0.07	0.0	0.0	0.0	0.0
B20	92.02	7.90	0.08	0.4	0.1	0.0	0.0
B21	71.08	7.59	21.33	1.1*	0.1*	0.0	0.4
B22	86.67	13.18	0.16	1.1	0.1*	0.1	0.4
B23	96.11	3.85	0.04	0.4	0.1	0.0	0.1
B24	95.57	4.36	0.07	0.5	0.1	0.0	0.1
Mean	74.13	5.92	19.95	0.47	0.09	0.02	0.19

Note: Values shown with an asterisk are excluded from computation of the mean value

Table 6.5.6. Statistical information on deposition, erosion and no change for the period 1991/92 (Area B)

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
B01	41.42	46.56	12.02	0.5*	0.1	0.1	0.3
B02	0.09	99.91	0.00	0.0	0.0	0.2	0.6
B03	0.57	94.40	5.03	0.1	0.0	0.1	0.5
B04	0.74	79.76	19.51	0.0	0.0	0.1	0.6
B05	25.58	50.41	24.02	0.5*	0.1	0.1	0.3
B06	0.00	100.00	0.00	0.0	0.0	0.2	0.6
B07	0.00	97.13	2.87	0.0	0.0	0.2	0.5
B08	0.98	89.66	9.36	0.0	0.0	0.2	0.6
B09	22.94	50.81	26.25	0.8*	0.1	0.2	0.5
B10	0.07	99.93	0	0.0	0.0	0.2	0.7
B11	0.00	100.00	0.00	0.0	0.0	0.2	0.6
B12	1.32	98.67	0.01	0.0	0.0	0.2	0.6
B13	63.7	23.45	12.85	1.5*	0.1	0.1	0.8
B14	0.62	99.38	0.00	0.0	0.0	0.1	0.9
B15	0.02	99.98	0.00	0.0	0.0	0.1	0.6
B16	1.05	98.93	0.02	0.0	0.0	0.1	0.8
B17	46.07	23.42	30.51	0.6*	0.1	0.1	0.3
B18	7.58	92.38	0.04	0.2	0.1	0.1	0.7
B19	0.16	99.84	0.00	0.0	0.0	0.2	0.6
B20	0.94	99.02	0.04	0.1	0.0	0.1	0.6
B21	45.54	26.22	28.23	0.4*	0.1	0.1	0.8
B22	4.34	95.63	0.03	0.2	0.0	0.1	0.7
B23	0.00	100.00	0	0.0	0.0	0.2	0.6
B24	1.59	98.36	0.05	0.1	0.0	0.1	0.6
Mean	11.06	81.83	7.12	0.03	0	0.14	0.60

Note: Values shown with an asterisk are excluded from computation of the mean value.

Table 6.5.7. Statistical information on deposition, erosion no change for the period 1992/93 (Area B)

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
B01	81.95	6.09	11.96	0.7*	0.2*	0.4*	0.4*
B02	100.00	0.00	0.00	0.5	0.2	0.0	0.0
B03	90.42	4.50	5.08	0.4	0.1	0.1	0.1
B04	89.19	10.03	0.78	0.4	0.1	0.1	0.1
B05	74.80	0.10	25.11	0.5*	0.2*	0.1	0.1
B06	100.00	0.00	0.00	0.5	0.2	0.0	0.0
B07	95.99	0.95	3.06	0.4	0.1	0.0	0.0
B08	88.32	11.44	0.24	0.4	0.1	0.3	0.3
B09	64.78	1.24	33.99	0.4*	0.1*	0.1	0.1
B10	96.72	2.25	1.03	0.5	0.1	0.1	0.1
B11	98.56	1.41	0.03	0.4	0.1	0.1	0.1
B12	85.19	14.53	0.28	0.4	0.1	0.1	0.1
B13	57.56	30.04	12.40	1.3*	0.1*	0.9*	0.9*
B14	93.54	6.43	0.03	0.5	0.1	0.2	0.2
B15	99.34	0.63	0.03	0.4	0.1	0.0	0.0
B16	78.73	21.01	0.26	0.3	0.1	0.1	0.1
B17	29.24	41.29	29.47	0.9*	0.1*	1.2*	1.2*
B18	86.53	13.41	0.06	0.7	0.1	0.5*	0.5*
B19	98.74	1.20	0.07	0.4	0.1	0.1	0.1
B20	78.79	10.11	11.11	0.3	0.1	0.2	0.2
B21	18.63	53.32	28.06	1.0*	0.1*	1.1*	1.1*
B22	71.80	18.39	9.81	0.3	0.1	0.4	0.4
B23	95.69	0.88	3.43	0.3	0.1	0.1	0.1
B24	88.25	9.89	1.86	0.3	0.1	0.1	0.1
Mean	81.78	10.80	7.42	0.41	0.11	0.03	0.11

Figure 6.5.8. Statistical information on deposition, erosion no change for the period 1989/90 (Area C)

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
C01	0.03	72.93	27.04	0.1	0.0	0.9*	4.3*
C02	68.78	31.04	0.19	0.7	0.1	0.1	0.3*
C03	64.05	35.65	0.29	0.4	0.1	0.1	0.2
C04	38.54	8.49	2.52	0.2	0.0	0.0	0.1
C05	18.61	59.02	22.37	0.3	0.1	0.1*	2.0*
C06	73.17	26.62	0.21	0.4	0.1	0.1	0.3
C07	88.23	11.54	0.24	0.4	0.1	0.0	0.2
C08	94.60	5.33	0.07	0.4	0.1	0.0	0.2
C09	29.60	60.07	10.33	0.4	0.1	0.1*	2.5*
C10	61.76	37.95	0.29	0.5	0.1	0.1	0.4
C11	69.32	30.37	0.31	0.4	0.1	0.1	0.2
C12	84.32	15.39	0.29	0.3	0.1	0.1	0.3
C13	46.99	33.85	19.16	0.4*	0.1	0.1*	2.1*
C14	73.74	25.99	0.27	0.6*	0.1	0.1	0.5
C15	89.37	10.53	0.10	0.4*	0.1	0.0	0.1
C16	94.47	5.51	0.02	0.5*	0.1	0.0	0.1
C17	30.71	30.80	38.49	0.4*	0.1	0.1*	2.0*
C18	85.09	14.80	0.11	0.7*	0.1	0.1	0.4
C19	96.60	3.38	0.02	0.5*	0.1	0.0	0.1
C20	98.32	1.64	0.03	0.5*	0.1	0.0	0.1
C21	24.41	11.30	64.29	0.2	0.1	0.0	0.1
C22	52.81	46.35	0.84	0.3	0.1	0.1*	0.7*
C23	64.07	35.88	0.05	0.3	0.1	0.1*	0.7*
C24	59.85	40.04	0.12	0.5	0.1	0.1*	0.6*
Mean	65.39	27.28	9.91	0.40	0.01	0.05	0.23

Table 6.5.9. Statistical information on deposition, erosion no change for period 1990/1991 (Area C).

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
C01	71.46	2.73	25.81	1.5*	0.1	0.0	0.1
C02	82.17	17.61	0.23	0.5	0.1	0.0	0.3
C03	94.80	5.18	0.02	0.4	0.1	0.0	0.2
C04	45.52	1.57	52.91	0.1	0.0	0.0	0.1
C05	69.64	8.29	22.07	0.6*	0.1	0.1	0.3
C06	84.16	15.64	0.21	0.4	0.1	0.0	0.1
C07	83.51	16.22	0.26	0.3	0.1	0.0	0.1
C08	75.14	24.61	0.25	0.4	0.1	0.1	0.2
C09	79.77	10.66	9.58	0.9*	0.1	0.0	0.1
C10	97.66	2.33	0.01	0.6	0.1	0.1	0.2
C11	97.46	2.48	0.06	0.5	0.1	0.0	0.1
C12	99.57	0.41	0.02	0.4	0.1	0.0	0.1
C13	63.81	24.73	11.46	1.1*	0.1	0.1*	0.8*
C14	84.40	15.49	0.11	0.6	0.1	0.1	0.3
C15	88.09	11.69	0.23	0.4	0.1	0.0	0.1
C16	81.57	18.21	0.22	0.4	0.1	0.1	0.2
C17	45.44	23.75	30.81	0.6*	0.1	0.1	0.2
C18	71.56	28.24	0.20	0.6	0.1	0.1	0.3*
C19	65.46	34.16	0.37	0.6	0.1	0.1	0.5
C20	25.33	31.74	42.93	0.2	0.1	0.0	0.1
C21	71.87	7.71	20.42	1.2*	0.1	0.0	0.1
C22	88.77	10.65	0.59	1.1*	0.1	0.1	0.2
C23	93.75	4.05	2.21	1.0*	0.1	0.0	0.1
C24	77.54	20.15	2.30	1.0*	0.1	0.1	0.3
Mean	76.60	14.10	9.30	0.43	0.09	0.04	0.17

Figure 6.5.10. Statistical information on deposition, erosion no change for the period 1991/92 (Area C).

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
C01	30.62	47.49	21.59	0.1	0.0	0.0	0.2
C02	84.68	15.07	0.25	0.0	0.0	0.1	0.6
C03	0.00	100.00	0.00	0.0	0.0	0.2	0.6
C04	1.24	98.74	0.03	0.1	0.0	0.1	0.6
C05	31.19	49.82	18.99	0.3	0.1	0.1	0.4
C06	0.06	99.94	0.00	0.0	0.0	0.1	0.7
C07	0.00	100.00	0.00	0.0	0.0	0.1	0.6
C08	1.74	98.26	0.01	0.1	0.0	0.1	0.5
C09	26.72	65.78	7.50	0.3	0.1	0.1	1.7
C10	0.09	99.91	0.00	0.0	0.0	0.1	0.6
C11	0.00	100.00	0.00	0.0	0.0	0.1	0.5
C12	0.00	100.00	0.00	0.0	0.0	0.1	0.6
C13	13.59	75.07	11.34	0.4	0.1	0.1	0.9
C14	1.29	98.68	0.03	0.0	0.0	0.2	0.7
C15	0.00	100.00	0.00	0.0	0.0	0.1	0.6
C16	0.00	100.00	0.00	0.0	0.0	0.1	0.6
C17	7.67	53.98	38.36	0.3	0.1	0.1	1.3
C18	2.32	97.65	0.03	0.0	0.0	0.1	0.7
C19	2.21	97.76	0.04	0.1	0.0	0.1	0.5
C20	0.71	99.24	0.06	0.0	0.0	0.1	0.5
C21	11.03	59.25	29.72	0.1	0.0	0.1	0.7
C22	1.74	97.72	0.54	0.0	0.0	0.1	0.7
C23	2.14	95.71	2.16	0.1	0.0	0.1	0.6
C24	0.42	97.42	2.16	0.0	0.0	0.1	0.6
Mean	9.14	85.31	5.53	0.08	0.02	0.10	0.67

Figure 6.5.11. Statistical information on deposition, erosion no change for the period 1992/93 (Area C).

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
C01	23.18	55.86	20.96	0.8*	0.1	0.1	1.2*
C02	84.68	15.07	0.25	0.4	0.1	0.1	0.3
C03	98.52	1.43	0.05	0.4	0.1	0.0	0.1
C04	90.66	9.20	0.15	0.3	0.1	0.0	0.1
C05	38.19	43.60	18.20	0.6*	0.1	0.1	1.0*
C06	86.43	13.33	0.24	0.3	0.1	0.1	0.2
C07	93.64	1.88	4.48	0.3	0.1	0.0	0.1
C08	84.46	10.87	4.67	0.3	0.1	0.0	0.1
C09	58.18	22.94	18.88	0.4*	0.1	0.1	0.6*
C10	91.50	8.06	0.44	0.4	0.1	0.1	0.2
C11	98.06	0.82	1.12	0.4	0.1	0.0	0.0
C12	89.33	5.30	5.36	0.3	0.1	0.0	0.1
C13	68.25	20.85	10.90	0.5*	0.1	0.1	0.7*
C14	92.95	6.95	0.10	0.4	0.1	0.0	0.1
C15	96.37	3.57	0.06	0.4	0.1	0.0	0.1
C16	90.84	9.04	0.12	0.4	0.1	0.0	0.1
C17	35.57	26.80	37.63	0.3*	0.1	0.1	1.3*
C18	87.18	6.15	6.68	0.4	0.1	0.0	0.1
C19	97.20	2.73	0.08	0.5	0.1	0.0	0.0
C20	98.69	1.24	0.07	0.4	0.1	0.0	0.1
C21	55.80	13.23	30.97	0.4*	0.1	0.0	0.1
C22	95.57	3.24	1.19	0.5	0.1	0.0	0.1
C23	95.95	3.99	0.06	0.4	0.1	0.0	0.1
C24	92.43	7.10	0.47	0.4	0.1	0.0	0.1
Mean	80.98	12.22	6.80	0.41	0.10	0.03	0.11

Table 6.5.12. Statistical information on deposition, erosion and no change for the period 1989/1990 (Area D)

				Deposition (m)		**Erosion (m)**	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
D01	3.07	1.08	95.85	0.5	0.1	0.1	0.3
D02	40.75	55.42	3.83	0.5	0.1	0.1	0.7*
D03	19.21	77.36	3.42	0.4	0.1	0.1	0.9*
D04	22.18	70.45	7.36	0.3	0.1	0.1	0.7*
D05	19.52	4.10	76.38	0.3	0.1	0.1	0.3
D06	79.69	14.88	5.43	0.5	0.1	0.1	0.3
D07	46.26	44.31	9.43	0.4	0.1	0.1	0.3
D08	23.03	73.06	3.91	0.4	0.1	0.1	0.7*
D09	43.90	0.46	55.64	0.4	0.1	0.0	0.0
D10	88.48	11.11	0.41	0.7	0.1	0.0	0.1
D11	23.12	75.74	1.15	0.3	0.1	0.1	0.5*
D12	71.52	27.71	0.76	0.6	0.1	0.1	0.3
D13	20.54	3.46	76.00	0.4	0.1	0.0	0.1
D14	49.40	25.92	24.68	0.4	0.1	0.0	0.5*
D15	14.28	84.18	1.54	0.5	0.1	0.1	0.9*
D16	46.02	53.83	0.15	0.7	0.1	0.1	0.6*
Mean	38.19	38.94	22.87	0.45	0.10	0.06	0.21

Table 6.5.13. Statistical information on deposition, erosion and no change for the period1990/91 (Area D)

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
D01	12.90	3.72	83.38	0.7*	0.1	0.1	0.2
D02	85.03	12.75	2.22	0.9*	0.1	0.0	0.1
D03	92.89	3.70	3.41	1.2*	0.1	0.0	0.1
D04	80.65	12.05	7.30	0.9*	0.1	0.1	0.4
D05	55.70	12.10	32.20	0.8	0.1	0.1	0.3
D06	61.98	32.51	5.51	0.8	0.1	0.1	0.3
D07	78.67	11.98	9.35	0.5	0.1	0.1	0.2
D08	75.80	20.39	3.81	0.8	0.1	0.1	0.5
D09	55.26	15.68	29.06	0.5	0.1	0.1	0.6
D10	76.70	22.84	0.46	0.4	0.1	0.1	0.3
D11	83.80	15.16	1.05	0.5	0.1	0.1	0.3
D12	67.47	31.81	0.72	0.5	0.1	0.1	0.4
D13	49.51	4.19	46.30	0.6	0.1	0.0	0.2
D14	89.90	9.96	0.14	0.5	0.1	0.0	0.2
D15	83.87	16.03	0.10	0.9*	0.1	0.1	0.5
D16	74.73	17.28	7.99	1.0*	0.1	0.1	0.3
Mean	70.30	15.13	14.56	0.68	0.10	0.08	0.30

Table 6.5.14. Statistical information on deposition, erosion no change for the period 1991/1992 (Area D).

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
D01	13.38	73.54	13.08	0.3*	0.1	0.1	0.5
D02	3.72	96.26	0.03	0.2	0.0	0.1	0.5
D03	0.90	99.10	0.00	0.0	0.0	0.1	0.6
D04	2.85	97.04	0.11	0.1	0.0	0.2	0.6
D05	12.89	67.66	19.45	0.4*	0.0	0.1	0.6
D06	3.56	96.30	0.14	0.1	0.0	0.1	0.5
D07	2.28	97.69	0.03	0.1	0.0	0.1	0.5
D08	2.41	97.57	0.02	0.0	0.0	0.1	0.8
D09	14.42	57.18	28.40	0.5*	0.1	0.1	0.5
D10	0.24	99.76	0.00	0.0	0.0	0.0	0.5
D11	1.48	98.52	0.00	0.1	0.0	0.1	0.6
D12	0.28	99.70	0.02	0.0	0.0	0.1	1.0
D13	17.15	42.75	40.10	0.8*	0.1*	0.1	1.0
D14	8.91	90.91	0.18	0.2	0.1	0.1	0.5
D15	9.44	90.46	0.10	0.2	0.1	0.1	1.0
D16	0.00	92.19	7.81	0.0	0.0	0.2	1.3
Mean	5.87	87.29	6.84	0.08	0.02	0.11	0.69

Table 6.5.15. Statistical information on deposition, erosion no change for the period 1992/1993 (Area D).

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
D01	63.31	24.22	12.47	0.4	0.1	0.1	0.5*
D02	94.54	5.36	0.10	0.4	0.1	0.1	0.2
D03	89.97	9.76	0.26	0.3	0.1	0.1	0.2
D04	92.65	7.18	0.18	0.4	0.1	0.0	0.4
D05	57.62	21.68	20.69	0.4	0.1	0.1	0.9*
D06	94.85	5.06	0.09	0.4	0.1	0.1	0.2
D07	83.45	16.29	0.25	0.3	0.1	0.1	0.2
D08	94.13	3.34	2.53	0.5	0.1	0.0	0.1
D09	56.28	15.57	28.15	0.4	0.1	0.1	0.6*
D10	91.31	6.17	2.52	0.4	0.1	0.0	0.1
D11	78.16	21.61	0.24	0.3	0.1	0.1	0.3
D12	98.20	1.35	0.45	0.5	0.1	0.0	0.1
D13	39.50	19.23	41.27	0.4	0.1	0.0	0.9*
D14	60.21	39.30	0.49	0.3	0.1	0.1	0.4
D15	50.44	41.44	8.13	0.4	0.1	0.1	0.4
D16	99.61	0.39	0.00	0.7	0.1	0.0	0.0
Mean	77.76	14.87	7.36	0.41	0.10	0.06	0.22

Table 6.5.16. Statistical information on deposition, erosion and no change for the period 1989/1990 (Area E).

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
E01	9.36	5.04	85.60	0.6	0.1	0.1	0.6
E02	14.69	83.16	2.15	0.3	0.1	0.1	0.7
E02	50.24	49.53	0.23	0.5	0.1	0.1	0.6
E04	0.25	6.57	93.19	0.2	0.0	0.2	1.8
E05	23.77	75.40	0.82	0.4	0.1	0.1	0.8
E06	67.37	31.78	0.85	0.8	0.0	0.1	0.4
E07	4.05	24.20	71.75	0.2	0.1	0.1	0.5
E08	35.72	64.21	0.07	0.5	0.1	0.1	0.7
E09	77.13	8.55	14.32	1.2	0.1	0.1	0.2
E10	9.49	33.98	56.53	0.1	0.1	0.1	0.7
E11	47.84	50.31	1.85	0.7	0.0	0.1	1.0
E12	24.00	8.26	67.74	0.4	0.1	0.1	0.9
E13	13.00	30.72	56.28	0.4	0.1	0.1	0.9
E14	17.15	25.00	57.86	0.6	0.1	0.0	0.1
E15	0.00	0.00	100.00	0.0	0.1	0.0	0.0
Mean	26.27	33.11	40.62	0.46	0.08	0.09	0.66

Table 6.5.17. Statistical information on deposition, erosion for the period 1990/1991 (Area E).

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
E01	40.15	4.09	55.76	0.6	0.1	0.1	0.2
E02	91.53	8.03	0.44	1.0	0.1	0.1	0.2
E02	75.20	9.66	15.150	1.1	0.1	0.1	0.4
E04	15.68	15.92	68.40	0.6	0.1	0.1	0.4
E05	77.66	22.14	0.21	0.8	0.1	0.1	0.4
E06	60.42	2.68	36.91	1.0	0.1	0.0	0.1
E07	87.80	12.14	0.07	0.6	0.1	0.1	0.3
E08	87.20	12.05	0.75	0.6	0.1	0.1	0.2
E09	29.40	0.26	70.34	0.0*	0.0*	0.0	0.0
E10	97.59	2.38	0.03	0.6	0.1	0.0	0.1
E11	93.13	2.04	4.83	0.6	0.1	0.0	0.1
E12	5.50	0.00	94.50	0.0*	0.0*	0.0	0.0
E13	74.04	6.36	19.60	0.7	0.1	0.0	0.2
E14	35.65	2.69	61.66	0.1*	0.0	0.0	0.4
E15	0.00	0.00	100.00	0.0*	0.0*	0.0	0.0
Mean	58.06	6.70	35.24	0.96	0.10	0.06	0.20

Table 6.5.18. Statistical information on deposition, erosion no change for the period 1991/92 (Area E).

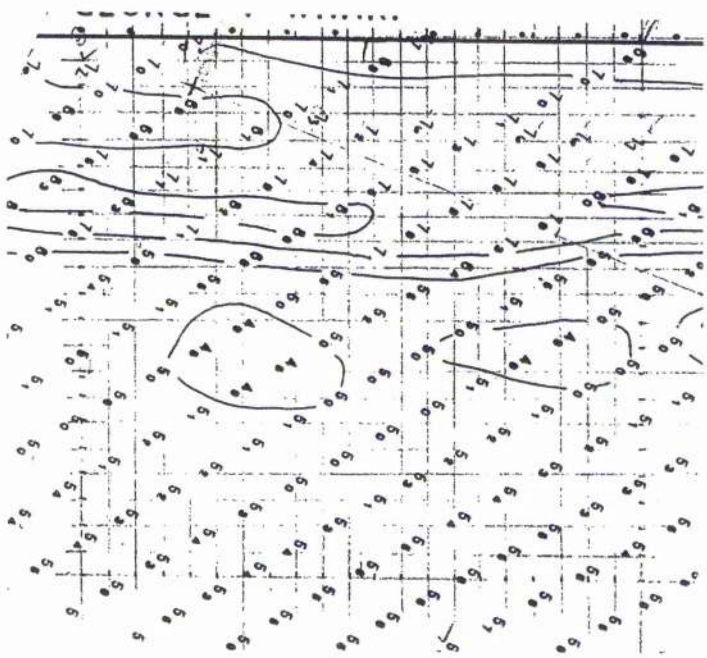
				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
E01	4.66	94.41	0.93	0.2	0.1	0.1	1.2
E02	1.22	98.75	0.04	0.1	0.0	0.1	0.9
E02	0.00	84.95	15.05	0.0	0.0	0.1	1.3
E04	13.69	85.59	0.72	0.4	0.1	0.1	1.1
E05	2.71	97.26	0.04	0.1	0.0	0.1	0.6
E06	0.60	62.84	36.57	0.0	0.0	0.1	0.9
E07	1.64	98.25	0.12	0.1	0.0	0.1	0.5
E08	0.89	98.26	0.84	0.1	0.0	0.1	0.7
E09	0.00	29.34	70.66	0.0	0.0	0.0	0.0
E10	0.83	99.17	0.00	0.0	0.0	0.1	0.6
E11	0.40	94.28	5.31	0.1	0.0	0.1	1.0
E12	0.00	4.94	95.06	0.0	0.0	0.0	0.0
E13	3.42	71.36	25.22	0.2	0.1	0.1	1.2
E14	8.26	44.70	47.03	0.0	0.0	0.1	1.1
E15	0.00	0.00	100.00	0.0	0.0	0.0	0.0
Mean	2.55	70.94	26.51	0.09	0.02	0.09	0.79

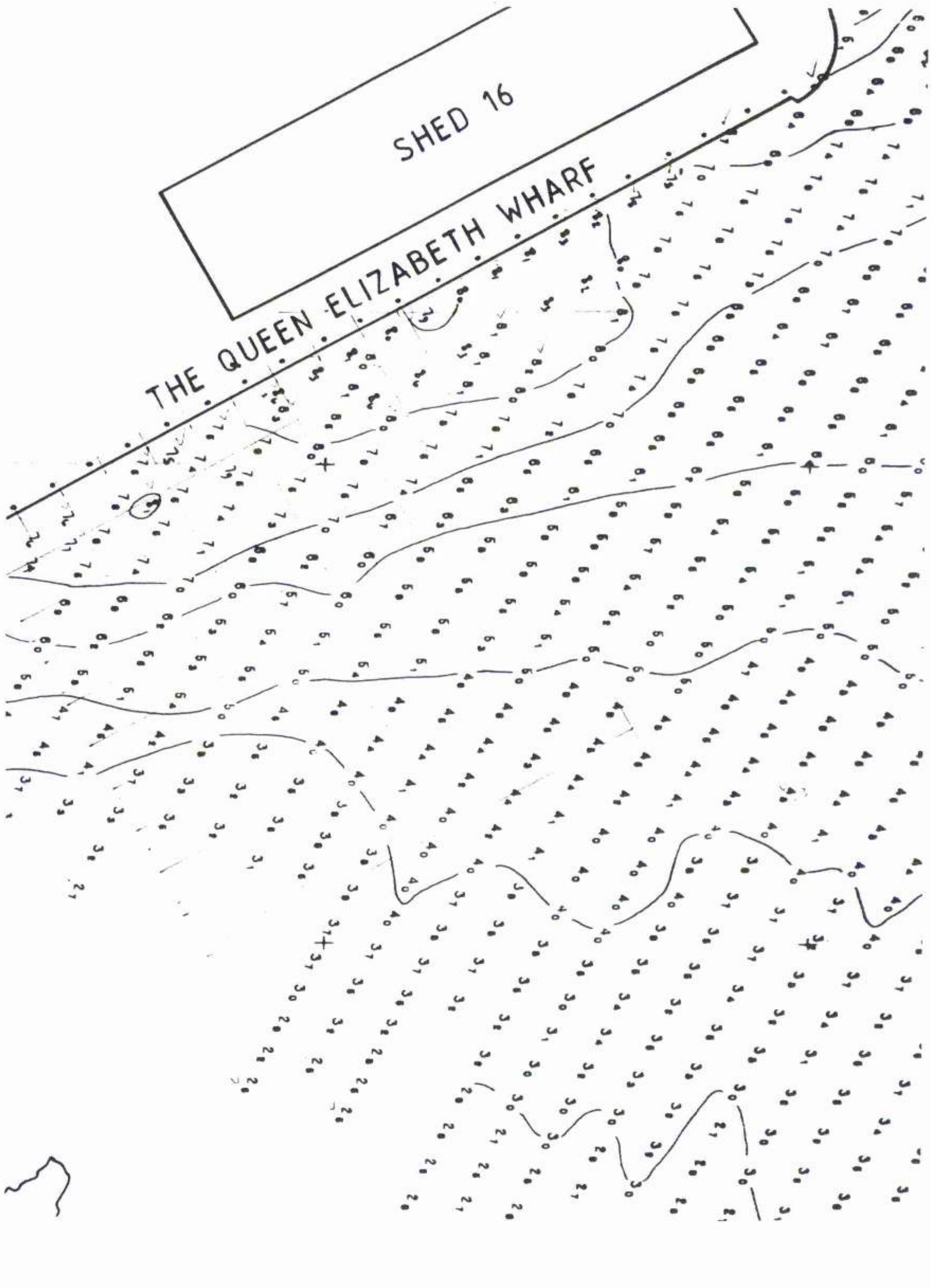
Table 6.5.19. Statistical information on deposition, erosion no change for the period 1992/93 (Area E).

				Deposition (m)		Erosion (m)	
Block	*%Deposition*	*%Erosion*	*%No change*	*Maximum*	*Minimum*	*Minimum*	*Maximum*
E01	61.21	36.38	2.41	0.7	0.1	0.4	0.4
E02	63.33	36.44	0.24	0.5	0.1	0.4	0.4
E03	98.80	0.35	0.84	0.6	0.0	0.1	0.1
E04	63.29	35.91	0.80	0.6	0.1	0.7	0.7
E05	85.25	14.61	0.15	0.5	0.1	0.2	0.2
E06	77.61	10.46	11.93	0.7	0.1	0.2	0.2
E07	71.63	27.98	0.39	0.3	0.1	0.3	0.3
E08	84.68	14.90	0.42	0.5	0.1	0.3	0.3
E09	52.76	4.64	42.60	0.5	0.1	0.3	0.3
E10	89.94	9.83	0.23	0.4	0.0	0.1	0.1
E11	90.39	8.76	0.84	0.6	0.1	0.2	0.2
E12	25.55	6.79	67.66	0.1	0.0	0.1	0.1
E13	61.09	13.44	25.47	0.6	0.0	0.1	0.1
E14	68.06	26.39	5.55	0.6	0.1	0.6	0.6
E15	2.77	5.20	92.03	0.1	0.0	0.1	0.1
Mean	66.42	16.81	16.77	0.49	0.07	0.27	0.27

APPENDIX E

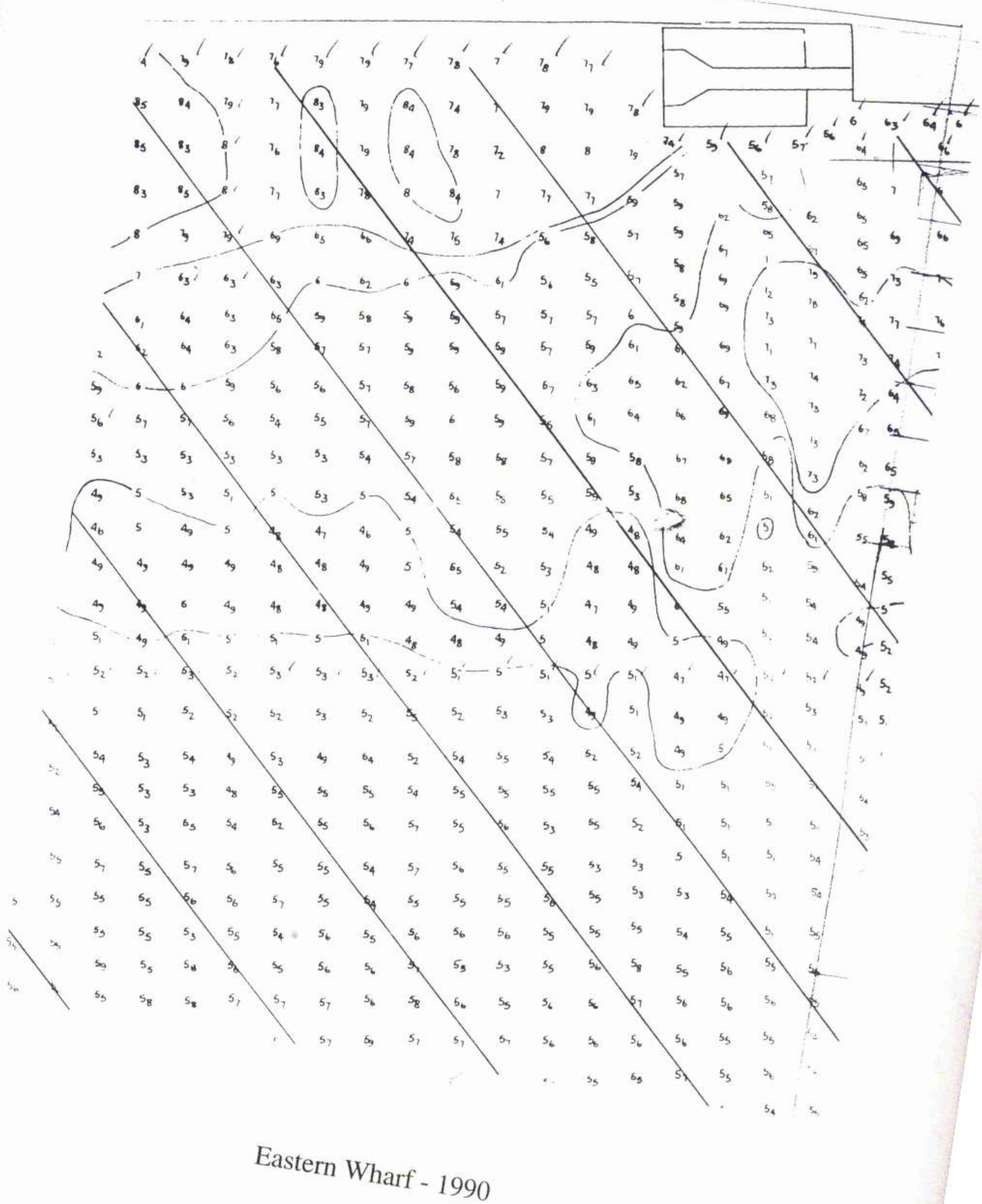
(Hardcopy samples of bathymetric data)



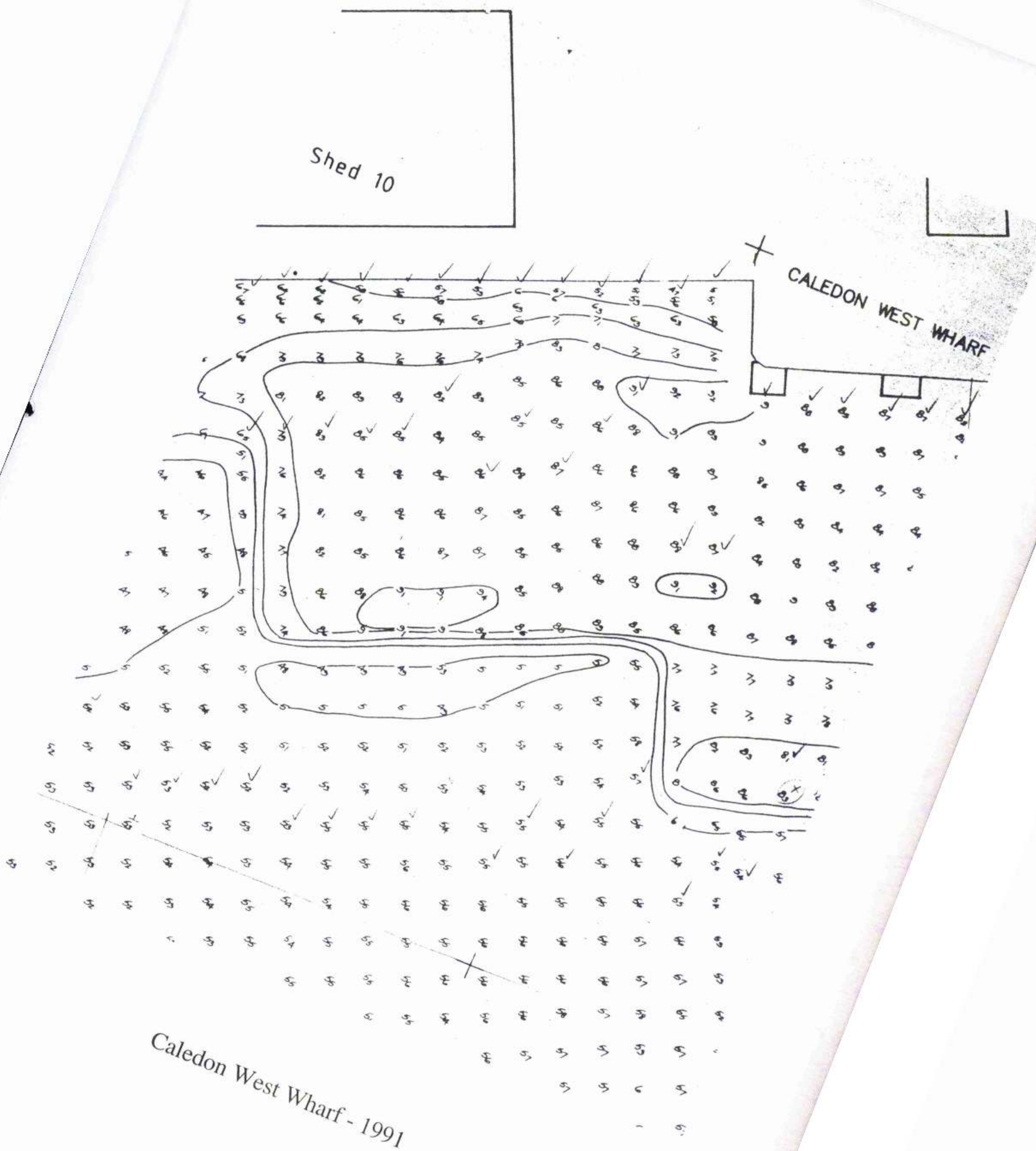


Queen Elizabeth Wharf - 1989

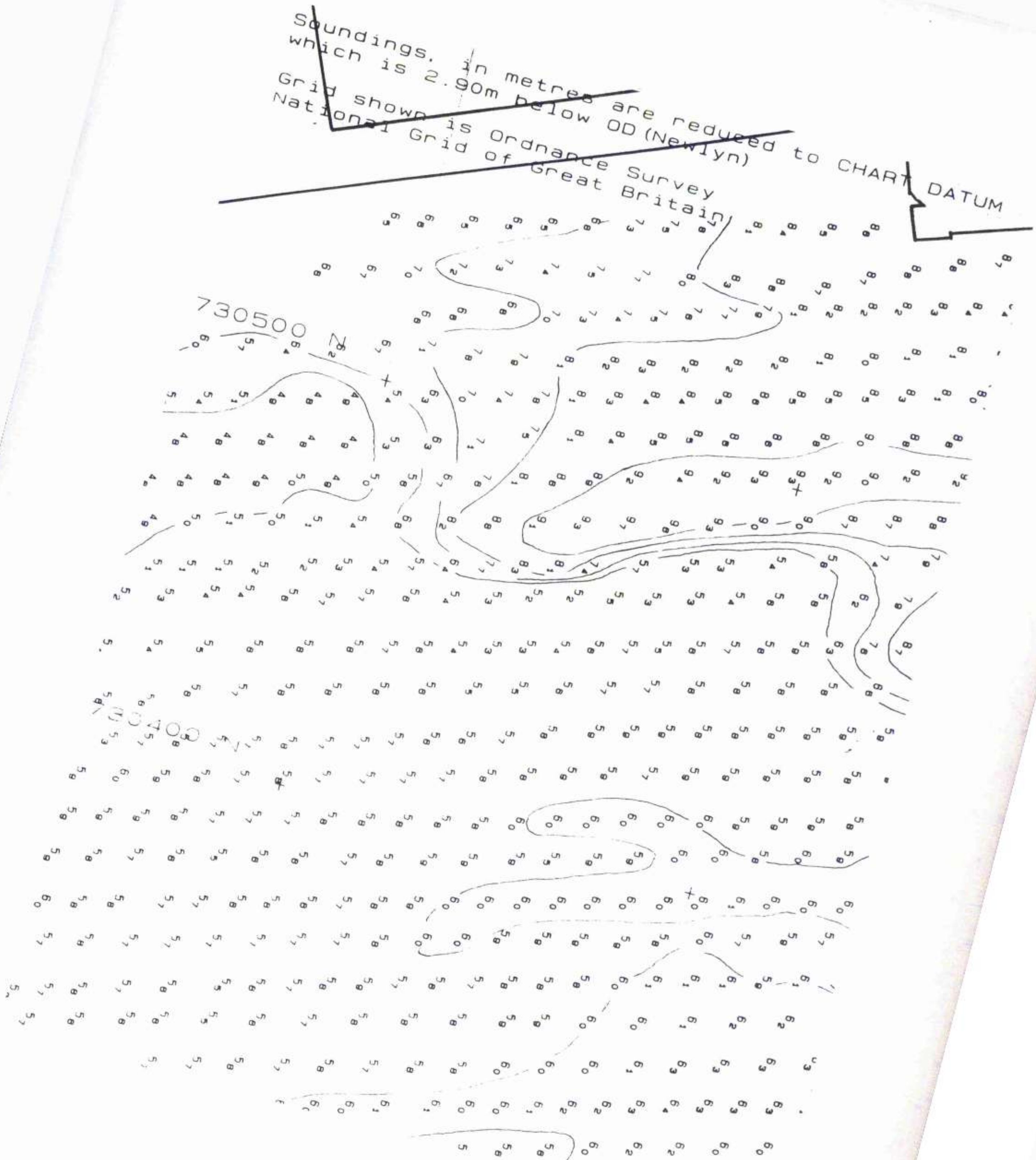
EASTERN WHARF



Eastern Wharf - 1990



Caledon West Wharf - 1991



Caledon West Wharf - 1992

Tidal Basin - 1993