



**Hydraulics Research**  
Wallingford

HEAVY METAL TRANSPORT AND DISPERSAL BY  
MAINTENANCE DREDGING: A study of the Tees

E A Delo, BSc. PhD, CEng, MICE, MIWEM  
T N Burt, BSc

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Registered Office: **Hydraulics Research Limited,**  
Wallingford, Oxfordshire OX10 8BA.  
Telephone: 0491 35381. Telex: 848552

CONTRACT

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## ABSTRACT

Metal pollutants, which may occur naturally or be anthropogenic, enter an estuary in both dissolved and particulate form mainly through the river input at the tidal limits, freshwater run off and outfalls discharging from the banks. Dredging operations are carried out in a number of British estuaries and rivers. Sediments from areas of intense shipping and industrial activity tend to have higher metal concentrations than those from less active areas. There is growing concern that the disposal of contaminated dredged material at sea may have a harmful effect on the marine environment. One area of particular concern is whether sediment-attached metals desorb in a fully saline environment.

There is clearly a need for an improved understanding of the transport processes involved in open-water disposal of dredged material. For instance, the estuarine contaminants are typically bound to the fine grained fractions of the solid phase of sediment and accordingly the development of techniques to predict the movement of these particles will be beneficial in assessing the suitability of a disposal site.

The Department of the Environment has commissioned Hydraulics Research to study the estuarine transmission of heavy metal pollutants in an attempt to determine the extent to which they are accumulated within an estuary or passed out to sea and the factors affecting their transmission. This report is one of a series covering several aspects of this investigation.

Analysis of the heavy metals copper, zinc, lead, iron, manganese and cobalt has been undertaken on samples obtained from the dredged length of the River Tees, the Tees Inner Disposal Site and around the Disposal Site. The average concentrations of the six heavy metals (total sediment) on the annual quantity of 1.6M m<sup>3</sup> of dredged material disposed of at the site were estimated to be copper - 138mg/kg, zinc - 143mg/kg, lead - 177mg/kg, iron - 34500mg/kg, manganese - 460mg/kg and cobalt - 12mg/kg. The average concentration of silt (i.e. less than 63µm in size) of the dredged material was estimated to be 70%.

The concentrations of heavy metals (total sediment) on the bed sediments within the disposal site were found to be lower relative to the estimated average for the dredged material, copper - 20%, zinc - 55%, lead - 33%, iron - 44%, manganese - 55% and cobalt - 33%. The average silt content within the disposal site was found to be approximately 20%.

Analysis of the size grading of samples taken within and around the disposal site revealed a net sand transport direction to the south-east, i.e. along the coastline and parallel to the bathymetry. This was supported by continuous recording current meter data. The average concentrations of heavy metals (total sediment) in four compass directions around the disposal site were found to be generally higher in the south-east and north-west regions compared to the disposal site. The average silt content in these directions was also higher at approximately 30%. Although, the average silt content in the north-east region was also 30% the average metal concentrations were lower than the disposal site. Differences in the inter-relationships between manganese and some of the other metals and the silt content were found for the samples taken within the disposal site compared to those taken in the regions around the site.



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## 1 INTRODUCTION

Metal pollutants, which may occur naturally or be anthropogenic, enter an estuary in both dissolved and particulate form mainly through the river input at the tidal limits, freshwater run off and outfalls discharging from the banks. Dredging operations are carried out in a number of British estuaries and rivers. Sediments from areas of intense shipping and industrial activity tend to have higher metal concentrations than those from less active areas. There is a growing concern that the disposal of contaminated dredged material at sea may have a harmful effect on the marine environment. One area of particular concern is whether sediment-attached metals desorb in a fully saline environment. The United Kingdom has obligations, under international agreements to control marine pollution resulting from deposit at sea of dredged material. The Food and Environmental Protection Act (Part II) 1985 and through it, the Oslo and London Dumping Conventions will continue to have an increasing impact on the dredging contractors on the UK.

The national and international concern for environmental and fisheries protection is focused on two aspects of the disposal to sea of dredged material. Firstly, the disposal of large quantities of solid materials will cause a significant change in the sediment nature and quality in the vicinity of the disposal site. In some instances the local sea bed life could be totally destroyed. Secondly, accretion of suspended material in estuaries scavenges toxic contaminants from river water. These contaminants may be remobilised by dredging and disposal and in effect 'released' from the estuarine mud at the disposal site.

There is clearly a need for an improved understanding of the transport processes involved in open-water disposal of dredged material. For instance, the estuarine contaminants are typically bound to the fine grained fractions of the solid phase of sediment and accordingly the development of techniques to predict the movement of these particles will be beneficial in assessing the suitability of a disposal site.

The Department of the Environment (DoE) has commissioned Hydraulics Research (HR) to study the estuarine transmission of heavy metal pollutants in an attempt to determine the extent to which they are accumulated within an estuary or passed out to sea and the factors affecting their transmission. This report is one of a series covering several aspects of this investigation.

Previous research by HR into the estuarine transmission of heavy metals includes extensive field studies in two contrasting estuaries-; that of the River Parrett in Somerset (Ref 1) and that of the River Conwy in North Wales (Ref 2). A literature review of contemporary research work was also carried out (Ref 3). During 1981 HR carried out a pilot study in the estuary of the River Tees followed by three further field studies of the estuary and disposal site during 1985 and 1986. These studies are briefly outlined below;

- March 1981 - A pilot study identifying the distribution of silt ( $< 63\mu\text{m}$ ) along the estuary and the concentrations of heavy metals on the silt (Ref 4)
  
- June 1985 - A study of sediment and attached metals dredged from the estuary. The behaviour of the dredgings on disposal and the spatial

distribution of sediment attached metals (on the silt fraction) at the disposal site (Ref 5)

March 1986 - A data-collection exercise to establish sediment grain size distribution and attached metals concentrations along the estuary at the disposal site and surrounding the disposal site

September 1986 - A study to investigate the metal concentrations on the total sediment, plus an exercise monitoring the bed immediately before and after a disposal exercise to determine short term physical and chemical changes (Ref 6)

The importance of dredging in the sediment cycle of the River Tees and the high metal concentrations on bed sediments rendered it a suitable estuary in which to carry out such a field study. This report presents and compares the data collected by HR, from the estuary and disposal site during these field studies. It also presents a literature review of relevant research work, and presents the results of a short-term dispersal study, a sediment transport study and an appraisal of the apparent inter-relationships between the different metals.

Based on these preliminary investigations an initial assessment is made of the fate of sediments and attached metals dredged from the River Tees and disposed of at the THPA disposal site. Finally, is an endeavour to find definite answers to some of the unresolved issues, recommendations are made for the

development of these studies in the on-going HR research program investigating the consequences of dredged material and attached heavy metals disposed of in tidal waters.

## 2 LITERATURE REVIEW

### 2.1 Characteristics of metals in Tees Estuary/Bay

(a) Murray L A & Norton M G - The composition of dredged spoils dumped at sea from England and Wales (Ref 7)

(i) Following the analysis of 'material' dredged from some 130 sites around the coast of England and Wales it was found that the highest concentrations of trace metals were generally encountered in dredgings from areas of intense shipping activity and heavy industry such as the Tees, Tyne and Mersey estuaries.

(ii) The concentrations of metals on sediments dredged from the River Tees and at Hartlepool are given in Table 1.

(iii) Very significant elevations of mercury (Hg), chromium (Cr) and zinc (Zn) were found in the River Tees, also elevations of copper, lead and cadmium but not of nickel (Ni).

(iv) Anti-fouling and primers which are rich in copper (Cu), zinc (Zn) and lead (Pb) can lead to elevated concentrations of these metals in local sediments.

(b) Taylor D - The effect of discharges from three industrialised estuaries on the distribution of heavy metals in the coastal sediments of the North Sea (Ref 8)

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- (i) The distribution of 11 heavy metals in coastal sediments along the NE coast of England was studied in an attempt to assess the environmental impact of industrial wastes discharged into the highly developed estuaries of the Tyne, Tees and Humber.
- (ii) Previous hydrographic studies of the Tees Bay area indicated that the outflowing water of the Tees estuary exerts its maximum effect on the sediments in the vicinity of the 10 fathom (~ 20m) contour line. All the sites selected for study were centred on this line.
- (iii) Grab samples were taken at 14 sites along this stretch of coast and analysed for metals concentrations and particle size. The results of samples taken from the vicinity of the Tees, along with those from an uncontaminated site are given in Table 1. Only Cu, Mn and Zn were found at elevated levels in the study area.
- (iv) If the estuarine outflows were the major source of trace metals in the inshore sediments it could be expected that concentrations of the industrially important metals such as Cd, Cu, Pb and Hg would be highest in the vicinity of the estuary mouths with a gradual decline in concentration with distance. A profile of

heavy metal distribution on the inshore sediments (~ 20m contour) of the NE coast shows that this distribution may exist in the vicinity of the Tyne and Wear estuaries but not in the Tees area.

(v) In the Tees area all the metal concentrations (except Hg) increase with distance from the estuary mouth reaching a maximum approximately 30km along the coast to the south at Runswick Bay. There is no significant anthropogenic input into the coastal zone here but there is a major geological difference between this region and the rest of the study area in that the local Jurassic rock is considerably richer in metal bearing minerals than the adjacent rocks to the SE and NW.

(vi) The author concludes that the local geology of the area may be a more significant factor than the industrial input in determining the metal content of marine sediments.

## 2.2 Behaviour of dredged material disposed at sea

(a) Joyce J - On the behaviour of dumped dredger spoil (Ref 9)

(i) Observations at dredger disposal sites off Lowestoft indicated that fine particulate material dispensed from a dredger consists of 2 phases, one solid and the other semi-fluid.

- (ii) The author postulates that the dredged mud, combined with seawater and agitated by the dredging process, could form into these two distinct fractions within the hopper of the dredger. The solid fraction is formed from the lumps of consolidated mud dredged from the lower layers of bed sediment and the semi-fluid fraction is formed from the upper layers of unconsolidated mud mixed with water that has entered the storage hoppers during the dredging process.
- (iii) SCUBA divers observed pebble-like lumps of mud up to 10cm in diameter in the vicinity of one disposal site. There is also evidence that they occur as far as 2km seawards of the disposal site. Sediment core samples also showed mud lumps buried in the sand, in some cases 40cm below the sediment surface.
- (iv) An echo-sounder was mounted in a research vessel positioned 50m downstream of the dredger and switched on as disposal commenced. The resultant trace indicated that after some 3-4 minutes a turbid cloud reached from the seabed to within 6m of the surface and took about 1 minute to pass beneath the ship, giving an approximate descent rate of 3cm/s. The cloud remained a discernible feature for some 500m.
- (v) This dual phase nature of material dispensed at sea has been noted by other workers, including HR who observed twin

phase behaviour in sludge disposed in Liverpool Bay in 1971.

- (vi) The author summarises that once introduced into the marine environment the 2 phases behave differently. The solid phase falls directly to the bed where it forms a persistent deposit with a localised effect (although 2km is hardly localised and being buried is not a persistent surface bed feature - KAT comment) while the semi-fluid phase is carried by the prevailing currents in the form of a turbid cloud.

(b) Herbich J B - Dredging equipment and the effect of dredging on the environment (Ref 10)

- (i) The author refers to the findings of Holliday et al (1978) which indicated that dredged material disposed in open water varies from taking minutes to hours to be deposited at the bottom.
- (ii) Discharge of coarse material will initially be accelerated due to gravity and will reach terminal velocity in constant density ocean water.
- (iii) The velocity rate for fine materials will also reach the terminal velocity but it may decrease due to the entrainment of ambient water.
- (iv) In very deep water the particles will segregate with the larger particles settling faster and the smaller particles settling at a slower rate.

(v) The terminal velocity will be effected by the density changes in the water column, by the currents and to some extent by the storm waves in the upper part of the water column.

(c) Herbich J B - The Center for Dredging Studies at Texas A & M University (Ref 11)

(i) In a paper outlining the formation, history and activities of the Centre, the author outlines a field study of the disposal of dredged material.

(ii) A field study revealed that immediately after deposition over 40% of the dredged material (based on original in situ volume) left the designated disposal area and spread out over the bay floor as a mud-density flow. Eventually dredged material covered an area about 3 times larger than that of the original designated disposal area. (Bassi D E and Basco D R, 1974).

### 2.3 Desorption of metals from sediments in fully saline water

(a) Murray L A & Norton M G - The composition of dredged spoils dumped at sea from England and Wales (Ref 7)

(i) There have been several investigations studying the release of metals into the water column from sediments immersed in seawater. They indicate that while

initial release of trace elements into the water column has been demonstrated in laboratory experiments this appears to be temporary.

(ii) The results of 3 different studies referred to by the authors suggest, in turn, that:

- any temporary release of mercury (Hg) from the sediments into the surrounding water is followed by readsorption onto suspended clays, by precipitation and then by scavenging by iron (Fe) released from the sediments,
- only very low levels of metals are released to the water column on resuspension of sediments,
- only manganese (Mn) is released in significant amounts from dredged sediments, the other metals being rapidly readsorbed onto the particulate material or released either in small amounts or not at all.

(iii) Thus the authors conclude that the majority of the metals in disposed dredged material are likely to remain with the particulate material, and that significant adverse effects on water quality at the disposal site are unlikely either during or after dumping.

(b) Hoff J T, Thompson J A J & Wong C S - Heavy metal balance from mine tailings into seawater - A laboratory study (Ref 12)

- (i) A laboratory experiment was conducted to observe the release or removal of dissolved metals in sea water to which various amounts of mine tailings were added. Analysis for concentrations of Fe, Mn, Cu, Zn, Ni, Cd and Pb was carried out.
  
- (ii) The following results relate to the tests with the highest initial mine tailings concentration (1000 mgkg<sup>-1</sup>) but similar trends were observed at lower concentrations. All of the metals (except Cd) exhibited changes in their dissolved concentration after the addition of mine tailings. Iron (Fe), copper (Cu) and lead (Pb) attained high peak concentrations after 3 hours then decreased to initial (Fe, Cu) or lower (Pb) values after one month. Mn and Ni concentrations increased slowly during the observation period and remained elevated at termination. The concentration of Zn gradually declined from its initial value and Cd concentration did not change.
  
- (iii) The increases in dissolved metal concentrations are attributed to chemical interaction between the mine tailings and seawater. Drawing on the studies of other research workers the authors identify some of the mechanisms which may occur in this instance:

- when mine tailings are diluted with seawater electrostatically bound metal ions are exchanged with Ca and Mg ions,
- it has been shown that Co and Cu ions bound to clay surfaces are released to a rather small extent in seawater because the ions are tightly held by surface complexation,
- the ion exchange capacity of mine tailings would be expected to be less than that of clay,
- sulphide minerals such as Galena (Pb), Pyrite (Fe), Chalcopyrite (Cu) and Sphalerite (Zn) are essentially insoluble in water but are thermodynamically unstable with respect to oxidation - various ions could catalyse the oxidation of metal sulphides but the reaction in seawater has received little (if any) research,
- suspended sediments promote the precipitation of iron from sea water,
- iron hydroxide is known to be an efficient scavenger of trace metals from sea water.

(iv) In this study the release of metals appears to be dependent upon mine tailings

concentration but the removal of metals is not.

(v) Parameters such as salinity, oxygen content, pH values and organic complexing agents may well vary between estuary and ocean sites and such changes may have a remobilising effect on heavy metals. For example, during dredging oxygen content does not remain stable within the sediment and when dredged material is dumped at sea it is generally introduced into an environment that has a higher oxygen and salt content.

(vi) The authors refer to Chen who (under unstated experimental conditions) found that, with the exception of Cr, all metals were released in the sediment-water interface. In comparison with background sea water values Cd, Mn, Ni and Zn were significantly released; Cu, Fe and Pb were only moderately released.

(c) Calmano W, Wellershaus S & Forstner U - Dredging of contaminated sediments in the Weser Estuary : Chemical forms of some heavy metals (Ref 13)

(i) Concentration and chemical forms of metals in bottom sediments and dredged mud of the Weser Estuary were studied.

(ii) Two groups of metals are identified; those with a relatively high potential of mobilisation such as Cd, Zn, Mn and Ni, and those that are strongly bound on particles such as Cr, Cu, Pb and Fe.

- (iii) The dissolution rates of metals in artificial seawater over 96h were investigated. Results showed that Mn was significantly released (25%), Pb, Cd and Zn were released to only a very small extent and no dissolution effects were observed for Ni, Cr and Fe.
- (iv) During a dumping event the authors observed the behaviour of metals sorbed to the dredged material; there was no measurable increase in the heavy metal concentrations in solution.
- (v) The uptake of metals in aquatic environments is not a simple function of total metal concentrations, the prediction of toxicity on organisms requires the understanding of physical, chemical and biotic process.

#### 2.4 Influence of sediment grain size

- (a) Murray L A & Norton M G - The composition of dredged spoils dumped at sea from England and Wales (Ref 7)

- (i) The potential of metals to become associated with sediments is generally believed to be related to the available surface area of the sediment particles, thus differences in particle-size distribution in different samples may account for some variability in metal concentrations.

(ii) Recent MAFF studies have shown that the fine ( $< 90\mu\text{m}$ ) sediment fraction contained metal concentrations in excess of those presented in Table 1 (i.e. marine sediments unaffected by waste disposal) only when anthropogenic sources of those metals could be identified (e.g., disposal/discharge of effluent).

(b) Kiff - Personal communication

(i) Plots of heavy metal concentration against particle size may be an indicator of the origins of the metal. In very general terms high concentrations in the silt ( $< 60\mu\text{m}$ ) fraction support the theory of adsorption from solution whereas high concentrations in the sand fraction ( $> 60\mu\text{m}$ ) implies naturally occurring minerals (which could dissolve and be adsorbed onto the fines).

### **3 METAL CONCENTRATIONS IN RIVER SEDIMENTS**

#### **3.1 Scope of surveys**

Heavy metals enter the Tees estuary, both in dissolved and particulate form, at the tidal limit and via the various tributaries and numerous industrial and domestic outfalls. The distribution of the outfalls discharging into the Tees has previously been discussed (Ref 4). It is evident that with such a dense distribution of outfalls (~90) and the intense level of shipping activity, heavy metal concentrations (particularly on the fine sediment) are likely to be significantly greater than those found in an industrially less active estuary.

The river bed sediments were sampled using a grab along the entire tidal length of the Tees in March 1981 and along the lower 14km of the river in March 1986 (see Fig 3).

The thirty-one samples obtained in March 1981 were analysed for particle size distribution and the concentration of six selected heavy metals - copper zinc, lead, iron, manganese and cobalt - on the silt fraction (ie <63 $\mu$ m fraction) of each sample. Likewise, in 1986 the fifty-three samples were analysed for concentration of the same six heavy metals but on the total sample rather than the silt fraction. The percentage of silt in each sample was also determined. In addition, ten of the fifty-three samples were analysed to measure the concentration of the six heavy metals on the silt fraction of the sample.

Each sample was identified by a number and a chainage from an assumed measuring line across the mouth of the river. Furthermore, samples which were within a designated hydrographic survey area of the Tees and Hartlepool Port Authority were also identified by the appropriate chart number (see Fig 3).

### 3.2 Longitudinal distribution

The percentage of silt, median particle size ( $D_{50}$ ) and concentration of metals are given in Table 2 (1981 samples) and Table 3 (1986 samples). These figures were processed to give the mean values of the percentage silt and metal concentrations in each of the chart areas 0 to 9 which cover the lower 14km of the river. This was done because dredging of the river does not take place above chainage 14km. The results are presented in Tables 6 and 7 respectively

for the 1981 and 1986 samples and are shown diagrammatically in Figures 3 to 9.

The longitudinal distribution of the percentage of silt in the river (Fig 3) indicates that along the length of the river within chart numbers 1 to 8 the silt content is between 60% to 90% by weight. At the mouth of the river (i.e. chart number 9) and at the upstream limit of dredging (ie chart number 0) the silt content is lower at approximately 25% and 35% respectively.

The concentration of copper, averaged within each of the nine chart areas, on the 1981 samples (silt fraction analysis) and the 1986 samples (total fraction analysis) are shown in Figure 4. The concentration of copper is generally greater on the silt fraction of the samples than the total sample, although the reverse is evident for chart numbers 1 and 2, with little difference between the concentrations for chart number 4. In terms of total sample concentration of copper, the trend is an increase from the river mouth (chart number 9) to a reasonably constant value in the river covered by chart numbers 6 to 4, followed by a steady decline to a low value at the upstream dredging limit. For the silt fraction concentration of copper the pattern is broadly similar, except that the concentration from the mouth (chart number 0) to well upstream in the river at chart number 3 is approximately constant. A sharp decrease in the concentration of copper on the silt fraction of the river bed sediment is observed from chart number 3 to chart number 0.

The longitudinal distribution of zinc is depicted in Figure 5. The concentration of zinc on the total sample rises steadily from just over 100mg/kg at the

river mouth to approximately 700mg/kg at chart number 6. Further upstream, within chart numbers 5 to 1 the concentration remains around 600mg/kg before falling to 400mg/kg at the dredging limit. The concentration of zinc on the silt fraction is sharply greater within chart numbers 9 to 3 during which the concentration gradually rises (except for chart number 3) from a little under 800mg/kg at the mouth of the river to over 1200mg/kg at chart number 3. Interestingly the concentration then falls rather suddenly to approximately 200mg/kg which is well below the concentration of the comparative total sample analyses.

Lead concentrations on the total sample and the silt fraction illustrate contrary trends along the dredged length of river (Fig 6). For chart numbers 9 to 1 the concentration of lead on the total samples progressively increases from approximately 50mg/kg at the river mouth to 450mg/kg at chart number 1. On the other hand, the concentration on the silt fraction reduces from close to 850mg/kg at the river mouth to 100mg/kg at chart number 1.

The concentration of iron on the total sample (Fig 7) gradually increases from approximately 27000mg/kg at the river mouth to 55000mg/kg at chart number 5, whereafter, it drops to around 35000mg/kg within chart numbers 4 to 1 and then reduces further to 25000mg/kg at chart number 0. In terms of concentration of iron on the silt fraction, the pattern is one of a reasonably constant concentration of approximately 40000mg/kg throughout the dredged length of the river, except for chart numbers 5, 4 and 3 within which the concentration is between 55000 to 60000mg/kg.

Manganese concentrations are shown in Figure 8 to be generally greater on the silt fraction than on the

total sample, with the exceptions of chart numbers 7 and 6. The concentration of manganese on the total sample increases from below 400mg/kg at the rivermouth to a peak of over 900mg/kg within chart number 6, following which there is steady decline (except for chart number 1) in concentration to below 300mg/kg by chart number 0. Manganese on the silt fraction shows a peak of approximately 1250mg/kg within chart number 3 with concentrations downstream reducing to below 500mg/kg and upstream reducing to below 600mg/kg.

Cobalt concentrations on the total sample (Fig 9) are seen to generally fluctuate between 10 and 18 mg/kg along the dredged length of the river, except within chart number 5 where the concentration peaks sharply at 27mg/kg. With respect to cobalt on the silt fraction it is evident that there is no clear pattern along the river. The concentration of cobalt varies between 18 and 24mg/kg within the dredged length of the river.

### 3.3 Influence of particle size

The degree of correlation between the concentration of each metal and the percentage of silt was calculated and is shown in Tables 4 and 5 for the 1981 and 1986 samples respectively. There is little correlation between metal concentration on the silt fraction and the percentage of silt (Table 4). Only copper exhibits a significant correlation (>90%) with the percentage of silt. On the other hand, there is a considerable degree of correlation between the metal concentration on the total sample and the percentage silt (Table 5). Except for cobalt, which does not correlate with the percentage silt at a significance level of greater than >90%, the other five metals all show a significance of correlation greater than 99%. Although not tabulated the correlation between the

metal concentration on the silt fraction and the median particle diameter was not significant at the 90% confidence level for any of the six metals.

These results clearly indicate the affinity of the metals for the small size fractions within the sediment. Accordingly, when the total sample was analysed the concentration of metal was found to be significantly dependent on the silt content. By analysing only the silt fraction, however, this dependence is significantly reduced.

This phenomena is further illustrated by calculating the proportion of the total metal on a sample which is on the silt fraction. A plot of this proportion against percentage silt content is shown in Figure 10. The data points in figure 10 are from samples taken within the dredged river, disposal site and around the outside of the disposal site. The results of each of the six metals were averaged to give a single value of the proportion of the total metal which was attached to the silt fraction. For a silt content of 20% by weight it is seen (Fig 10) that about 40% of the total metal is attached to that silt. With a silt content of 60% this proportion is almost 90%.

### 3.4 Correlation between metals

The metal concentrations on the silt fraction of the sixteen samples taken within the dredged length of the river in 1981 were processed to determine the linear regression coefficient of each pair of metals with respect to a linear correlation (Table 4). The results indicate that the concentration of all six metals were significantly inter-related (at least 90% confidence), with the three exceptions of copper-cobalt, lead-manganese and lead-cobalt.

A similar procedure was undertaken for the fifty-three samples collected in 1986 and analysed for metal concentrations on the total sediment (Table 5). The level of significance of the correlation between the metals may be seen to be generally much higher (>99.9%) than for the silt fraction samples. The metals not giving a significant correlation between one another include the three pairs identified from the 1981 samples, ie copper-cobalt, lead-manganese and lead-cobalt with the additional pair of lead-iron.

#### **4 RIVER DREDGING**

##### **4.1 Quantity and distribution**

The River Tees has a tidal length of some 32km and is subject to intense shipping and industrial activity. The lower 14km of the estuary, and a navigation channel extending into Tees Bay, is subject to maintenance dredging by the Tees and Hartlepool Port Authority (THPA). The subsequent dredged material is disposed of at the Inner Disposal Site in Tees Bay (Fig 2).

The Tees and Hartlepool Port Authority (THPA) currently operate two trailing suction hopper dredgers, 'Cleveland County' and 'Hoertness' and one grab hopper dredger, 'Seal Sands'. Both maintenance and capital works dredging operations are carried out by the THPA. Maintenance dredging is carried out along the lower estuary and approach channel in Tees Bay (Fig 2) and also at Hartlepool. The resultant dredged material is disposed of exclusively at the Inner Disposal Site which is under the jurisdiction of the THPA. Dredged material from capital works operations is disposed of at the Outer Disposal Site in Tees Bay but these operations are not the subject of this study.

On average an annual total of 1.6 million in-situ cubic metres of material is dredged during maintenance dredging. All the chart areas except chart number 0 undergo maintenance dredging. Annual dredged quantities from each chart area for the years 1981-1985 inclusive are given in Table 6. The actual quantities vary from year to year but the general pattern is similar, i.e. areas heavily dredged one year tend to be most years and similarly for areas which are lightly dredged.

The average dredged quantity for each chart number for the years 1981-1985 are summarised in the histogram presented in Figure 11. The area within chart number 9 for example, contributes over 20% of the total dredged quantity while, in contrast, the area covered by chart number 5 contributes only 4%.

#### 4.2 Silt content

A weighted average of the silt content may also be derived by combining the average silt content within each chart number with the respective dredged quantity. Table 7 gives the results of analyses by THPA and Hydraulic Research of the silt content in chart numbers 0 to 13 together with the weighted averages. Overall it may be concluded that approximately 70% of all material dredged comprises silt, ie 70% of the dredged material has a particle diameter of less than 0.063mm.

#### 4.3 Metal concentrations

To estimate the average concentration of each of the six metals on the dredgings it is necessary to combine the concentrations on the total sediment as measured within chart numbers 0 to 9 (Table 3) and an estimate

of the concentration of metals on the sediment outside the river on the approach channel (Table 1) covered by chart numbers 10 to 13, with the averaged dredged quantities given in Table 6. This yields a weighted average for each metal which are presented in Table 8. The respective concentrations are copper - 138mg/kg, zinc - 143mg/kg, lead - 177mg/kg, iron - 34450mg/kg, manganese - 460mg/kg and cobalt - 12mg/kg.

The total weight of metal dredged from the river may also be calculated for an assumed dry density of dredged material of 400kg/m<sup>3</sup>. This gives the following approximate values in tonnes per year: copper - 100, zinc - 200, lead - 100, iron - 20 000, manganese - 300, and cobalt - 8. However, not all of this is anthropogenic in its source and a varying but considerable proportion of each metal is due to naturally occurring sources.

## **5 METAL CONCENTRATIONS ON BED SEDIMENTS AT DISPOSAL SITE**

### **5.1 Scope of surveys**

The Inner Disposal Site (Fig 2) has been used for the past fifteen years by THPA for the disposal of material dredged from the River Tees during maintenance dredging operations. This disposal site is 2.5km by 2.0km in size and approximately 8km offshore in a water depth of between 25m and 35m. The bed sediments within the disposal site were grab sampled on a 0.5km grid in June 1985 and March 1986. The bed sediments surrounding the site were also grab sampled on a 1km grid during the March 1986 survey. The location of the bed samples for the two surveys together with the bathymetry of the area are shown in Figure 12.

To aid the interpretation of the results of the silt content and heavy metals analysis the samples surrounding the disposal site were grouped according to their compass direction from the site. The four regions surrounding the site (Figure 12) extended approximately 2.5km from the boundary of the site, except for the south-west area region which extended only 1.5km. These regions were identified as the north-east, south-east, south-west and north-west.

The samples obtained were analysed to determine their silt content, i.e. the proportion of the total sample by weight that was smaller in size than 63 microns, and concentrations of six heavy metals, i.e. copper, zinc, lead, iron, manganese and cobalt. The metals analysis was carried out on the silt fraction of the samples obtained in June 1985 and on the total sample for those acquired in March 1986.

## 5.2 Silt content

The silt content of the samples taken within the disposal site and the surrounding regions are presented for the March 1986 survey in Table 9 and for the June 1985 survey in Table 12. There is a great variability in the silt content of the bed sediments. For example, from the March 1986 survey results (Table 9) the minimum silt content within the disposal site is just above 1% and the maximum is approximately 60%. Similar differences in the bed sediments may also be observed for the four surrounding areas (Table 9).

Nevertheless, an attempt was made to identify general trends in the silt content of the bed sediments by calculating the average silt content for each of the five regions at the disposal site, i.e. within the boundaries of the disposal site, and the four quadrants to the north-east, south-east, south-west

and north-west respectively. These data are presented together with the average silt content of the dredged material in the first three columns of Table 10 and as a histogram in Figure 13.

In comparison to the silt content of the dredged material (approximately 70%), the disposal site and the surrounding areas have much lower silt contents. The disposal site was also found to have a lower average silt content than three of the four surrounding regions. The 1985 and 1986 surveys of the disposal site resulted in average silt contents of 24% and 15% respectively. Outside the disposal site boundaries, the average silt content was found to be 32% in the north-east region, 30% south-east, 7% south-west and 28% north-west.

These results would tend to suggest that dredged material disposed of at this site does not accumulate on the bed within the site. It must therefore be transported out of the site. This could occur partly during the disposal process itself and later due to the effects of tidal currents, wave action and gravity. Further discussion of the various processes involved in the disposal of dredged material and its subsequent movement is given in the following chapter.

### 5.3 Metal concentrations

The results of the analysis of metal on the 78 samples (Fig 12) taken in March 1986 are given in Table 9 and are grouped according to their regional location. The average concentration of the metals in each region are given in Table 10. Although all the samples from the 1986 survey were analysed for heavy metals on the total sediment, some 18 samples were also analysed to determine the concentration of metals on the silt fraction. These results are given in Table 11. A

similar silt fraction analysis was also performed on the samples taken within the disposal site in June 1985 for which the results are presented in Table 12.

Comparing the average concentrations of metals within the disposal site in Tables 10 and 12 it is clear that the concentrations are much higher on the silt fraction compared to the total sediment. This affinity for the smaller size particles has already been highlighted in the discussion of the concentrations of metals in the river (section 3.4) and was summarised in Figure 10. For example, the average concentration of copper on the total sediment was  $42\text{mgkg}^{-1}$  as against  $182\text{mgkg}^{-1}$  on the silt fraction. The other five metals gave similar differences.

The average concentrations of metals within each region are shown graphically for the six metals - copper, zinc, lead, iron, manganese and cobalt - in Figures 14 to 19 respectively. Also depicted on each of the graphs is the estimated average concentration of metals on the dredged material (section 4.3).

For the metals copper, zinc and lead there was found to be a distinct difference between the concentration of metal on the dredgings and that on the sediment within and around the disposal site. The concentrations of these metals on the bed sediments were less than half of those on the dredgings. However, for the metals iron, in particular manganese, and cobalt the differences were less marked.

Turning to the relative concentrations of the metals in each of the regions, it was found that the trend in the results was one of slightly higher concentrations in the south-east and north-west regions, lower concentrations in the south-west and much the same in

the north-east region compared with the disposal site. These findings are similar to that for the silt content (Fig 13) except that the north-east was found to have slightly more silt on average than the disposal site.

#### 5.4 Correlation between metals

As a way of evaluating statistically the inter-relationships between the concentrations of the six metals and the silt content, an independent linear regression was performed on pairs of results. The coefficients resulting from this analysis were then identified by degree of significance, i.e. more than 10%, less than 10%, less than 1% and less than 0.1% (i.e. very highly significant).

Results of the correlation analysis of the concentration of metals on the samples collected in March 1986 from within the disposal site are presented in Table 13. Looking first at the relationship between the concentrations of metals and the silt content it was found, as expected, that there was a high degree of correlation. This implied that as the silt content increased so too did the concentrations of metals, thus again supporting the well established evidence of the affinity of metals for the fine grained sediments. There was also a strong inter-dependency between the concentrations of each of the six metals which was shown by the generally high (1% or 0.1%) levels of significance.

Statistical analysis of the concentrations of metals on the bed sediments taken in March 1986 from outside the disposal site are given in Table 14. The results show a very strong inter-dependency between the concentrations of five of the metals and the silt

content. The one metal which was different was manganese, which was found not to correlate with either copper, zinc, lead or silt content.

Similar statistical analyses were conducted for the June 1985 samples acquired from within the disposal site and analysed for metals concentrations on the silt fraction (Table 15). As expected, none of the metals correlated with the silt content. There was, though, a strong degree of correlation between most of the pairs of metals.

However, the metals analysis conducted on the silt fraction of the samples taken from outside the disposal site obtained in March 1986, gave somewhat different correlations than those from within the disposal site (Table 16). No correlation was evident between cobalt and any of the other metals, and between iron and any of the other metals, except manganese. There was also no correlation found between manganese and zinc, and manganese and lead. Nevertheless, as expected, little correlation was again found between any of the metals and the silt content.

## **6 DISCUSSION OF THE DISPERSAL OF DREDGED MATERIAL**

### **6.1 Introduction**

There are a number of processes by which dredged material disposed of at an open-water disposal site may be dispersed. During the disposal operation itself, it has been observed that (Ref 6) a cloud of slowly settling fine particles is formed comprising probably less than 1% of the dredged material. This

cloud can be advected out of the disposal site area by tidal currents.

Most of the material, however, plunges to the bed and spreads in a manner akin to that of a density current driven by its inertia from the fall through the water column, hydrostatic water surface slope force and by the presence of local bed gradients. Entrainment of material from the water/dredged material interface could also occur if the differential velocity was sufficiently high. The initial spreading of the dredged material would tend to cease after 5 to 10 minutes with the material spread thinly over an area of a few hundred metres in diameter. Consolidation of the stationary dense fluid would tend to take place and the dredged material would be susceptible to re-suspension by, or entrainment into, the moving overlying water column. Further bulk flow of the dredged material in the form of a density current could also occur dependent on hydrodynamic, bathymetric and sediment conditions.

As the dredged material disperses it becomes mixed with the natural bed sediments of the area and its particle size distribution will change. This mixture of the dredged material with the natural bed sediments will be increasingly more pronounced away from the disposal site and away from the dominant direction of transport. Heavy metal contaminants adsorbed onto the surface of the dredged material will, if not desorbed from the sediments, move with the dredged material. From the literature (section 2.3) it was indicated that most of the metals initially adsorbed onto the dredged material will predominantly remain on the particulate material. The one notable exception was manganese which was found to release significant amounts (up to 25%) when discharged into a saline environment.

## 6.2 Sediment transport paths

The existing sand transport regime of the Tees Inner Disposal Site was analysed for this study by Dr P McLaren using the size grading of the sand fraction of the samples taken in September 1986. The report on this work is given in full in Appendix A.

In summary, the findings were that the sands are being actively transported in a net south-east direction approximately parallel to the bathymetry and that the gravel-sized material was taking part in the present transport regime. The silt fraction of the dredged material currently being disposed of at the site was not considered to be incorporated into the existing transport regime but appeared to be rapidly removed from the vicinity of the disposal site.

It is interesting to compare the finding of a net south-east transport direction for the sands with the progressive vector plots of a recording current meter deployed in the disposal site during April 1986. The results are presented in a field exercise report (Ref 6) and show a net drift to the south-east in the tidal current at 1m above the bed. This tends to support the conclusion of the sediment transport study.

The general pattern of the proportion of silt in the bed sediments within and around the disposal site was presented above in section 5.2. It was found that the disposal site itself had an average silt content of approximately 20% compared with a value of approximately 30% in the three surrounding regions to the north-west, north-east and south-east. The south-west region had a much lower average silt content of less than 10%. From the view point of transport of the silt material disposed of within the

site, it is difficult to conclude much other than the net direction of transport is not to the south-west. This certainly is not in contradiction with either the current meter observations or the analytic work.

### 6.3 Metal transport

The results of the analysis of heavy metals in terms of the average concentration on the total sediment within the disposal site and the four surrounding regions give support to the dominance of the north-west/south-east transport directions. For the metals copper (Fig 14), zinc (Fig 15) and lead (Fig 16) the average metal concentrations in the south-east and north-west regions were significantly higher than either the north-east or south-west. The pattern was less clear for the metals iron (Fig 17), manganese (Fig 18) and cobalt (Fig 19). In relation to the concentrations in the disposal site itself it may be seen that the north-west and south-west regions had generally slightly higher concentrations, except for copper, which were a little lower.

The differences between the estimated concentration on the dredged material and that within the disposal site has been shown to be more marked for the metals zinc, copper and lead and to a lesser extent cobalt, than the metals iron and manganese. This is indicative of a relatively high naturally occurring level of iron and manganese in the river and in Tees Bay compared to the metals input from anthropogenic sources.

However, it should be appreciated that the concentrations of metals on the total sediment sample ought to be assessed in the context of the silt content of the sediment. It is well recognised that heavy metals have an affinity for the smaller particle

sizes (section 2.4). Accordingly, it is to be expected that other things being equal the concentration of heavy metal on sediment will be positively correlated to its silt content. This was in fact shown to be the case for the March 1986 samples taken within and around the disposal site (section 5.4).

This being so, it may now be seen that the generally higher concentrations of heavy metals found in the south-east and north-west regions compared to the disposal site can be related to the higher silt content of those sediments. An exception to this does occur for copper (Fig 14) which has slightly lower concentrations of metals in all surrounding regions. A further very interesting point is the lower concentrations of copper, zinc and lead in the north-east region compared to the disposal site even though the average silt content is higher at 30% compared to 20%. This would tend to suggest that transport to the north-east (i.e. seawards) is not as strong with respect to the heavy metals as for transport along the north-west/south-east corridor (i.e. parallel to the coast and bathymetry).

With respect to the linear regression analyses on the concentrations of heavy metals and the silt content (section 5.4) the results showed significant differences for one metal. The metal manganese was found not to correlate with either copper, zinc, lead or silt content on the samples taken outside the disposal site, but it was found to correlate with all other metals and silt content within the disposal site. It is interesting that these differences should occur on the one metal which has been found by other researchers to have a high mobility potential. However, at this stage it is not possible to draw any firm conclusions from this finding.

## 7 CONCLUSIONS AND RECOMMENDATIONS

### 7.1 Conclusions

- 1 Analysis of the heavy metals copper, zinc, lead, iron, manganese and cobalt has been undertaken on samples obtained from the dredged length of the River Tees, the Tees Inner Disposal Site and around the Disposal Site.
- 2 The average concentrations of the six heavy metals (total sediment) on the annual quantity of 1.6M m<sup>3</sup> of dredged material disposed of at the site were estimated to be copper - 138mg/kg, zinc - 143mg/kg, lead - 177mg/kg, iron - 34500mg/kg, manganese - 460mg/kg and cobalt - 12mg/kg.
- 3 The average concentration of silt (i.e. less than 63µm in size) of the dredged material was estimated to be 70%.
- 4 The concentrations of heavy metals (total sediment) on the bed sediments within the disposal site were found to be lower relative to the estimated average for the dredged material, copper - 20%, zinc - 55%, lead - 33%, iron - 44%, manganese - 55% and cobalt - 33%.
- 5 The average silt content within the disposal site was found to be approximately 20%.
- 6 Analysis of the size grading of samples taken within and around the disposal site revealed a net sand transport direction to the south-east, i.e. along the coastline and parallel to the bathymetry. This was supported by continuous recording current meter data.

- 7 The average concentrations of heavy metals (total sediment) in four compass directions around the disposal site were found to be generally higher in the south-east and north-west regions compared to the disposal site. The average silt content in these directions was also higher at approximately 30%. Although, the average silt content in the north-east region was also 30% the average metal concentrations were lower than the disposal site.
- 8 Differences in the inter-relationships between manganese and some of the other metals and the silt content were found for the samples taken within the disposal site compared to those taken in the regions around the site.

## 7.2 Recommendations

- 1 It is recommended that in future work the spatial scope of the bed sampling survey of the disposal site area is increased to approximately 10km by 10km grid and orientated to the north-east/south-west direction. Analysis of the heavy metals should be conducted on three size fractions, e.g. 0-20 $\mu$ m, 20-63 $\mu$ m and 63-90 $\mu$ m.
- 2 A further sampling exercise should be conducted of the bed sediments in the dredged length of the River Tees with the analysis of heavy metals being conducted on three size fractions used for the analysis of the disposal site samples.

## 8 ACKNOWLEDGEMENTS

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**TABLES.**



TABLE 1

## Heavy metal concentrations and sediment properties in the Tees Estuary/Bay area and some comparisons

Source (Author)	Sample	No. of samples	Cd	C	Co	Cu	Pb	Mn	Hg	Ni	Ag	V	Zn	% silt (clay)
Murray & Norton	R. Tees	13	3.6 (0.2- 13.0)	493 (13.0- 1500)	-	234 (22.0- 700)	325 (50- 850)	-	7.02 (0.5- 20.0)	40.0 (20.0- 65.0)	-	-	766 (72- 3000)	-
	Hartlepool	1	< 0.2	42.0	-	56.0	95.0	-	0.80	40.0	-	-	120	-
Taylor	N. Hartlepool	8	0.2 (0.2- 0.2)	7.3 (5.9- 8.8)	5.9 (5.0- 7.2)	9.8 (5.9- 18.9)	47.5 (43.1- 51.7)	170.0 (149.0- 189.4)	0.05 (0.04- 0.10)	11.4 (10.4- 13.3)	0.9 (0.9- 0.9)	21.2 (18.6- 25.2)	66.7 (61.5- 74.5)	4.39 (1.56- 10.38)
	Longsacar	7	0.2 (0.2- 0.2)	7.9 (7.4- 9.0)	6.6 (5.9- 6.9)	7.5 (5.2- 13.3)	48.0 (44.1- 56.9)	171.4 (108.8- 198.8)	0.05 (0.04- 0.09)	9.0 (8.4- 9.7)	0.9 (0.9- 0.9)	19.7 (12.8- 25.0)	57.7 (44.8- 63.8)	2.79 (1.58- 4.08)
	Teesmouth	8	0.2 (0.2- 0.2)	6.9 (5.7- 8.5)	5.6 (4.2- 6.8)	9.7 (7.3- 15.7)	35.9 (28.7- 40.3)	170.0 (92.7- 283.0)	0.08 (0.04- 0.26)	7.4 (7.1- 8.4)	0.9 (0.9- 0.9)	16.0 (11.9- 18.8)	53.3 (31.0- 90.4)	1.30 (0.2- 3.17)
	Redcar	9	0.2 (0.2- 0.2)	7.5 (5.9- 8.8)	4.7 (4.2- 5.0)	3.9 (2.9- 6.0)	42.0 (26.0- 81.6)	153.7 (121.0- 189.4)	0.41 (0.15- 0.95)	7.6 (7.1- 8.6)	0.9 (0.9- 0.9)	21.4 (18.3- 25.2)	51.6 (42.7- 66.3)	2.69 (0.19- 9.38)
	Torbay (uncontaminated)	41	0.37 (0.2- 0.7)	9.9 (5.8- 17.2)	6.6 (4.6- 14.0)	4.2 (2.6- 7.6)	31.2 (21.3- 65.7)	128.3 (81.2- 265.9)	0.07 (0.02- 0.33)	7.2 (4.2- 15.0)	-	-	24.8 (17.2- 42.0)	-
Murray & Norton	'Background'*	?	< 0.2	17-50	-	5-18	10-90	-	0.04- 0.13	30-45	-	-	30-115	-

\* Range of metal concentrations found in silt-clays (< 90µm) in marine sediments unaffected by waste disposal, presented by Murray & Norton based on data from Eagle et al 1978 and R S Nunny, pers. comm.

TABLE 2 SILT CONTENT AND CONCENTRATIONS OF SIX HEAVY METALS  
ON THE SILT FRACTION OF BED SEDIMENTS IN THE  
DREDGED RIVER TEES MARCH 1981

CHART NUMBER	No of samples	%silt	Cu (mg/kg)	Zn (mg/kg)	Pb (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Co (mg/kg)
9	2	12	255	789	854	44367	594	21
8	1	81	265	860	530	41550	515	18
7	1	90	258	720	580	39900	480	20
6	2	61	289	990	550	41100	620	23
5	1	74	298	1015	431	57500	910	21
4	2	85	248	1110	346	58000	980	23
3	1	72	289	1225	350	59500	1270	27
2	1	61	148	440	171	38700	740	24
1	2	88	92	182	94	33400	570	23
0	3	40	83	202	106	35700	565	20

TABLE 3 SILT CONTENT AND CONCENTRATIONS OF SIX HEAVY METALS  
ON BED SEDIMENTS IN THE RIVER TEES MARCH 1986

CHART NUMBER	No of samples	%silt	Cu (mg/kg)	Zn (mg/kg)	Pb (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Co (mg/kg)
0	4	20	63	408	259	24175	286	10
1	6	86	186	580	450	38667	528	15
2	6	76	196	590	386	38667	390	11
3	5	71	173	628	378	35610	467	10
4	5	67	254	588	263	40920	490	12
5	5	61	223	564	239	54580	682	27
6	6	70	258	705	273	50033	918	15
7	5	85	202	472	167	47460	702	18
8	6	81	212	182	101	39133	500	16
9	5	36	54	105	53	27560	382	11

TABLE 4 INDEPENDENT LINEAR REGRESSION COEFFICIENTS FOR SILT CONTENT AND CONCENTRATIONS OF SIX HEAVY METALS ON THE SILT FRACTION OF BED SEDIMENTS IN THE DREDGED RIVER TEES 1981

	Cu	Zn	Pb	Fe	Mn	Co	%silt
Cu	1.00	0.90	0.50	0.64	0.45	0.14	0.44
Zn	0.90	1.00	0.59	0.86	0.68	0.43	0.21
Pb	0.50	0.59	1.00	0.46	0.09	0.20	-0.29
Fe	0.64	0.86	0.46	1.00	0.85	0.56	-0.02
Mn	0.45	0.68	0.09	0.85	1.00	0.76	0.05
Co	0.14	0.43	0.20	0.56	0.76	1.00	-0.22
%silt	0.44	0.21	-0.29	-0.02	0.05	-0.22	1.00

Number of data points = 16  
 Average % silt = 62.1  
 Degrees of freedom = 14  
 Correlation coefficient 0.426 0.623 0.742  
 Levels of significance 0.100 0.010 0.001

	Cu	Zn	Pb	Fe	Mn	Co	%silt
Cu		0.1	10.0	1.0	10.0	0.0	10.0
Zn			10.0	0.1	1.0	10.0	0.0
Pb				10.0	0.0	0.0	0.0
Fe					0.1	10.0	0.0
Mn						0.1	0.0
Co							0.0
%silt							

TABLE 5 INDEPENDENT LINEAR REGRESSION COEFFICIENTS FOR SILT  
 CONTENT AND CONCENTRATIONS OF SIX HEAVY METALS ON  
 BED SEDIMENTS IN THE DREDGED RIVER TEES MARCH 1986

	Cu	Zn	Pb	Fe	Mn	Co	%silt
Cu	1.00	0.81	0.57	0.54	0.44	0.18	0.54
Zn	0.81	1.00	0.76	0.63	0.57	0.31	0.40
Pb	0.57	0.76	1.00	0.22	0.19	-0.03	0.41
Fe	0.54	0.63	0.22	1.00	0.85	0.82	0.39
Mn	0.44	0.57	0.19	0.85	1.00	0.59	0.36
Co	0.18	0.31	-0.03	0.82	0.59	1.00	0.06
%silt	0.54	0.40	0.41	0.39	0.36	0.06	1.00

Number of data points = 53  
 Average % silt = 67.2  
 Degrees of freedom = 51  
 Levels of significance 0.100 0.010 0.001  
 Correlation Coefficient 0.229 0.351 0.440

	Cu	Zn	Pb	Fe	Mn	Co	%silt
Cu		0.1	0.1	0.1	1.0	0.0	0.1
Zn			0.1	0.1	0.1	10.0	1.0
Pb				0.0	0.0	0.0	1.0
Fe					0.1	0.1	1.0
Mn						0.1	1.0
Co							0.0
%silt							

TABLE 6 DREDGED IN-SITU QUANTITIES 1981-1985

CHART NUMBER	YEAR					AVERAGE
	1981	1982	1983	1984	1985	
QUANTITIES IN 1000'S INSITU M <sup>3</sup>						
13	0	0	0	0	0	13
12	62	34	44	46	31	43
11	184	177	208	274	234	215
10	117	78	96	74	182	109
9	142	133	138	92	190	139
8	55	76	75	27	65	60
7	127	81	124	76	41	90
6	166	139	213	126	88	146
5	188	156	172	124	137	155
4	226	320	377	329	451	341
3	160	113	106	134	125	128
2	160	84	83	72	98	99
1	69	41	45	41	55	50
0	0	0	0	0	0	0
TOTAL	1656	1434	1682	1414	1698	1590

TABLE 7 ESTIMATION OF THE AVERAGE SILT CONTENT OF DREDGED MATERIAL FROM THE RIVER TEES

CHART NUMBER	THPA	% SILT CONTENT		AVERAGE	ANNUAL DREDGING QUANTITY (1000' s m <sup>3</sup> )
		HR 1981	HR 1986		
0	-	91	20	56	- .
1	80	26	86	64	43
2	82	86	76	81	215
3	84	90	71	82	109
4	80	61	67	69	139
5	76	78	61	72	60
6	84	93	70	82	90
7	80	76	85	80	146
8	87	74	81	81	155
9	80	90	36	69	341
10	32	32	-	32	128
11	38	90	-	64	99
12	54	81	-	68	50
13	30	13	-	22	13
WEIGHTED AVERAGE	74	76	53	71	1588

TABLE 8 ESTIMATION OF THE AVERAGE CONCENTRATIONS OF SIX HEAVY METALS ON THE DREDGED MATERIAL FROM THE RIVER TEES

CHART NUMBER	METAL CONCENTRATION						ANNUAL DREDGING (1000's m <sup>3</sup> )
	Cu	Zn	Pb	Fe	Mn	Co	
	(mg/kg)						
0	63	408	259	24175	286	10	-
1	186	580	450	38667	528	15	43
2	196	590	386	38667	390	11	215
3	173	628	378	35610	467	10	109
4	254	588	263	40920	490	12	139
5	223	564	239	54580	682	27	60
6	258	705	273	50033	918	15	90
7	202	472	167	47460	702	18	146
8	212	182	101	39133	500	16	155
9	54	105	53	27560	382	11	341
10*	15	90	40	20000	280	6.8	128
11*	15	90	40	20000	280	6.8	99
12*	15	90	40	20000	280	6.8	50
13*	15	90	40	20000	280	6.8	13
WEIGHTED AVERAGE	142	352	182	34960	466	12	Total 1588

\* Metal concentrations estimated from Table 2

TABLE 9 SILT CONTENT AND CONCENTRATIONS AT THE TEES INNER DISPOSAL SITE MARCH 1986

SAMPLE NUMBER	SECTOR	% SILT	Cu (mg/kg)	Zn (mg/kg)	Pb (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Co (mg/kg)
25A	SITE	6.91	15	57	20	13700	231	4
20	SITE	9.65	24	82	33	19000	220	6
27	SITE	18.12	28	93	50	22000	300	6
22	SITE	1.63	13	62	22	9700	221	4
16	SITE	4.89	28	88	35	15100	221	3
25	SITE	17.21	21	81	33	16900	250	6
32	SITE	10.51	15	72	35	25100	350	5
17	SITE	29.29	43	141	61	22900	320	8
8	SITE	59.95	390	750	154	38100	1110	15
12	SITE	3.73	20	76	29	14100	260	3
21	SITE	6.64	22	78	31	18400	231	5
7	SITE	3.25	16	61	27	13500	218	3
30	SITE	19.93	20	79	44	27000	310	6
18	SITE	51.21	20	68	16	32100	440	13
11	SITE	4.54	16	49	20	11900	232	2
26	SITE	2.67	12	63	23	22000	260	5
13	SITE	19.70	31	103	45	32500	320	5
6	SITE	2.40	15	59	22	12950	226	4
55	SW	20.52	33	159	66	30700	1530	8
24	SW	7.13	15	76	26	16500	280	6
42	SW	15.67	19	79	45	19600	260	6
39	SW	2.71	10	75	37	16000	310	4
29	SW	0.81	10	70	23	19000	290	6
41	SW	3.06	11	83	41	19800	310	5
15	SW	1.75	8	43	16	11500	250	2
1	SW	2.32	11	57	19	12600	259	1
38	SW	4.31	12	97	35	32600	360	5
10	SW	1.69	13	52	21	12000	220	3
86	SW	18.58	18	106	37	22500	360	7
60	SE	25.42	48	163	79	28100	390	8
84	SE	40.29	51	169	86	26800	330	10
91	SE	50.17	51	159	86	24500	300	10
90	SE	19.50	25	118	43	22400	290	7
85	SE	31.64	28	127	60	24500	330	8
82	SE	38.11	28	116	50	21200	550	6
81	SE	40.71	42	149	81	24900	290	9
34	SE	0.82	10	68	28	17100	390	5
35	SE	1.52	11	113	43	29200	390	6
61	SE	35.53	41	144	68	27700	370	8
94	SE	68.12	52	138	80	30500	360	11
93	SE	41.51	42	124	63	25500	320	9
36	SE	5.67	14	92	21	32700	1190	8
92	SE	15.54	26	128	61	24000	350	8

TABLE 9 CONTINUED

SAMPLE NUMBER	SECTOR	% SILT	Cu (mg/kg)	Zn (mg/kg)	Pb (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Co (mg/kg)
53	NW	45.11	38	109	57	28900	340	9
56	NW	17.36	33	109	47	18100	250	8
68	NW	41.78	36	137	57	28300	830	7
64	NW	35.76	34	128	64	30400	360	7
50	NW	13.52	28	113	54	24900	330	7
63	NW	70.64	55	159	92	31000	370	10
65	NW	72.39	53	156	91	35150	415	11
49	NW	0.35	6	42	18	13100	214	4
47	NW	19.28	29	104	58	20700	330	7
77	NW	15.51	18	95	37	18000	360	6
54	NW	23.80	53	143	90	27700	390	10
57	NW	17.00	20	95	31	24700	470	8
48	NW	43.33	54	126	97	23800	350	10
4	NW	18.47	35	110	47	18800	270	6
69	NW	66.46	50	138	87	37200	480	9
45	NW	1.59	17	61	24	16700	540	6
51	NW	2.74	11	72	27	12300	205	4
73	NW	61.32	47	148	78	32800	350	9
2	NW	13.87	43	128	64	17700	247	6
14	NE	7.26	34	76	20	26300	640	6
70	NE	0.83	6	38	14	17200	290	1
78	NE	94.10	29	88	20	51400	400	19
9	NE	42.51	51	176	85	30400	410	6
72	NE	32.02	20	63	19	30000	650	8
71	NE	32.43	26	85	42	23300	320	6
58	NE	51.20	32	98	58	20900	310	7
79	NE	25.37	21	87	45	23900	290	6
33	NE	4.37	8	56	26	13900	226	5
28	NE	14.25	20	89	27	19200	350	7
74	NE	32.38	21	76	9	36100	700	10
76	NE	25.04	14	81	36	19800	224	6
75	NE	7.38	16	60	6	34600	670	12
5	NE	60.72	48	136	82	32900	380	9
23	NE	2.69	9	43	15	16400	218	3
66	NE	39.12	26	94	45	24300	290	8

TABLE 10 AVERAGE SILT CONTENT AND CONCENTRATIONS OF SIX HEAVY METALS ON THE SILT OF BED SEDIMENTS WITHIN AND SURROUNDING THE TEES INNER DISPOSAL SITE

SECTOR	No OF SAMPLES	% SILT	Cu	Zn	Pb	Fe	Mn	Co
SITE	18	15.1	42	115	39	20300	318	5.7
NE	17	32.0	26	88	38	26800	399	7.6
SE	14	29.6	34	129	61	25600	418	8.1
SW	11	7.1	15	82	33	19300	403	4.8
NW	18	28.2	34	112	57	23600	371	7.4

TABLE 11 AVERAGE SILT CONTENT AND CONCENTRATION OF SIX HEAVY METALS ON THE SILT FRACTION OF BED SEDIMENTS WITHIN AND SURROUNDING THE TEES INNER DISPOSAL SITE MARCH 1986

Grab No	% SILT	Cu	Zn	Pb	Fe	Mn	Co
6	3	131	261	156	55000	720	16
7	6	214	497	251	56700	660	18
8	56	174	398	211	44800	530	18
11	7	175	312	146	45800	570	18
12	22	180	412	278	46430	510	16
13	26	329	419	245	47600	720	20
16	23	255	840	345	61000	930	20
17	30	303	890	536	58000	700	17
18	49	39	108	47	43750	432	15
20	22	221	504	280	44200	474	15
21	34	192	520	279	50800	720	19
22	8	112	335	208	44160	482	15
25	23	192	474	260	34300	493	13
26	29	252	850	354	71900	990	16
27	22	125	292	191	38250	408	14
30	17	107	310	174	50000	530	13
32	4	91	260	129	41800	610	11
Mean	22	182	452	241	49088	616	16

TABLE 12 SILT CONTENT AND CONCENTRATIONS OF SIX METALS ON THE SILT OF BED SEDIMENTS WITHIN THE TEES INNER DISPOSAL SITE JUNE 1985

Grab No	%silt	Cu	Zn	Pb	Fe	Mn	Co
6	3	131	261	156	55000	720	16
7	6	214	497	251	56700	660	18
8	56	174	398	211	44800	530	18
11	7	175	312	146	45800	570	18
12	22	180	412	278	46430	510	16
13	26	329	419	245	47600	720	20
16	23	255	840	345	61000	930	20
17	30	303	890	536	58000	700	17
18	49	39	108	47	43750	432	15
20	22	221	504	280	44200	474	15
21	34	192	520	279	50800	720	19
22	8	112	335	208	44160	482	15
25	23	192	474	260	34300	493	13
26	29	252	850	354	71900	990	16
27	22	125	292	191	38250	408	14
30	17	107	310	174	50000	530	13
32	4	91	260	129	41800	610	11
Mean	22	182	452	241	49088	616	16

TABLE 13 INDEPENDENT LINEAR REGRESSION COEFFICIENT FOR SILT CONTENT AND CONCENTRATIONS OF SIX HEAVY METALS ON BED SEDIMENTS WITHIN THE TEES INNER DISPOSAL SITE MARCH 1986

	Cu	Zn	Pb	Fe	Mn	Co	%silt
Cu	1.00	1.00	0.95	0.58	0.96	0.71	0.70
Zn	1.00	1.00	0.96	0.60	0.96	0.72	0.71
Pb	0.95	0.96	1.00	0.64	0.91	0.68	0.69
Fe	0.58	0.60	0.64	1.00	0.73	0.81	0.84
Mn	0.96	0.96	0.91	0.73	1.00	0.83	0.83
Co	0.71	0.72	0.68	0.81	0.83	1.00	0.96
%silt	0.70	0.71	0.69	0.84	0.83	0.96	1.00

Number of data points = 18  
 Average % silt = 15.1  
 Degrees of freedom = 16  
 Levels of significance 0.100 0.010 0.001  
 Correlation coefficient 0.400 0.590 0.708

	Cu	Zn	Pb	Fe	Mn	Co	%silt
Cu		0.1	0.1	10.0	0.1	1.0	1.0
Zn			0.1	1.0	0.1	0.1	1.0
Pb				1.0	0.1	1.0	1.0
Fe					0.1	0.1	0.1
Mn						0.1	0.1
Co							0.1
%silt							

TABLE 14 INDEPENDENT LINEAR REGRESSION COEFFICIENT FOR SILT CONTENT AND CONCENTRATIONS OF SIX HEAVY METALS ON BED SEDIMENTS SURROUNDING THE TEES INNER DISPOSAL SITE MARCH 1986

	Cu	Zn	Pb	Fe	Mn	Co	%silt
Cu	1.00	0.87	0.90	0.52	0.07	0.60	0.77
Zn	0.87	1.00	0.91	0.51	0.18	0.52	0.63
Pb	0.90	0.91	1.00	0.35	-0.03	0.42	0.65
Fe	0.52	0.51	0.35	1.00	0.44	0.82	0.70
Mn	0.07	0.18	-0.03	0.44	1.00	0.24	0.04
Co	0.60	0.52	0.42	0.82	0.24	1.00	0.75
%silt	0.77	0.63	0.65	0.70	0.04	0.75	1.00

Number of data points = 60  
 Average % silt = 25.8  
 Degrees of freedom = 58  
 Levels of significance 0.100 0.010 0.001  
 Correlation coefficient 0.215 0.331 0.415

	Cu	Zn	Pb	Fe	Mn	Co	%silt
Cu		0.1	0.1	0.1	0.0	0.1	0.1
Zn			0.1	0.1	0.0	0.1	0.1
Pb				1.0	0.0	0.1	0.1
Fe					0.1	0.1	0.1
Mn						10.0	0.0
Co							0.1
%silt							

TABLE 15 INDEPENDENT LINEAR REGRESSION COEFFICIENT FOR SILT CONTENT AND CONCENTRATIONS OF SIX HEAVY METALS ON BED SEDIMENTS WITHIN THE TEES INNER DISPOSAL SITE JUNE 1985

	Cu	Zn	Pb	Fe	Mn	Co	%silt
Cu	1.00	0.79	0.80	0.47	0.59	0.64	0.10
Zn	0.79	1.00	0.93	0.70	0.72	0.42	0.14
Pb	0.80	0.93	1.00	0.53	0.51	0.36	0.12
Fe	0.47	0.70	0.53	1.00	0.87	0.46	-0.02
Mn	0.59	0.72	0.51	0.87	1.00	0.51	-0.06
Co	0.64	0.42	0.36	0.46	0.51	1.00	0.27
%silt	0.10	0.14	0.12	-0.02	-0.06	0.27	1.00

Number of data points = 17  
 Average % silt = 22.3  
 Degrees of freedom = 15  
 Levels of significance 0.100 0.010 0.001  
 Correlation coefficient 0.412 0.606 0.725

	Cu	Zn	Pb	Fe	Mn	Co	%silt
Cu		0.1	0.1	10.0	10.0	1.0	0.0
Zn			0.1	1.0	1.0	10.0	0.0
Pb				10.0	10.0	0.0	0.0
Fe					0.1	10.0	0.0
Mn						10.0	0.0
Co							0.0
%silt							

TABLE 16 INDEPENDENT LINEAR REGRESSION COEFFICIENT FOR SILT CONTENT AND CONCENTRATIONS OF SIX HEAVY METALS ON BED SEDIMENTS WITHIN THE TEES INNER DISPOSAL SITE MARCH 1986

	Cu	Zn	Pb	Fe	Mn	Co	%silt
Cu	1.00	0.78	0.55	0.22	0.44	-0.08	-0.38
Zn	0.78	1.00	0.76	0.01	0.03	0.07	-0.13
Pb	0.55	0.76	1.00	-0.35	-0.16	0.13	.00
Fe	0.22	0.01	-0.35	1.00	0.62	0.19	-0.18
Mn	0.44	0.03	-0.16	0.62	1.00	0.12	-0.48
Co	-0.08	0.07	0.13	0.19	0.12	1.00	0.23
%silt	-0.38	-0.13	.00	-0.18	-0.48	0.23	1.00

Number of data points = 18  
 Average % silt = 24.6  
 Degrees of freedom = 16  
 Levels of significance 0.100 0.010 0.001  
 Correlation coefficient 0.400 0.590 0.708

	Cu	Zn	Pb	Fe	Mn	Co	%silt
Cu		0.1	10.0	0.0	10.0	0.0	0.0
Zn			0.1	0.0	0.0	0.0	0.0
Pb				0.0	0.0	0.0	0.0
Fe					1.0	0.0	0.0
Mn						0.0	-10.0
Co							0.0
%silt							



FIGURES.



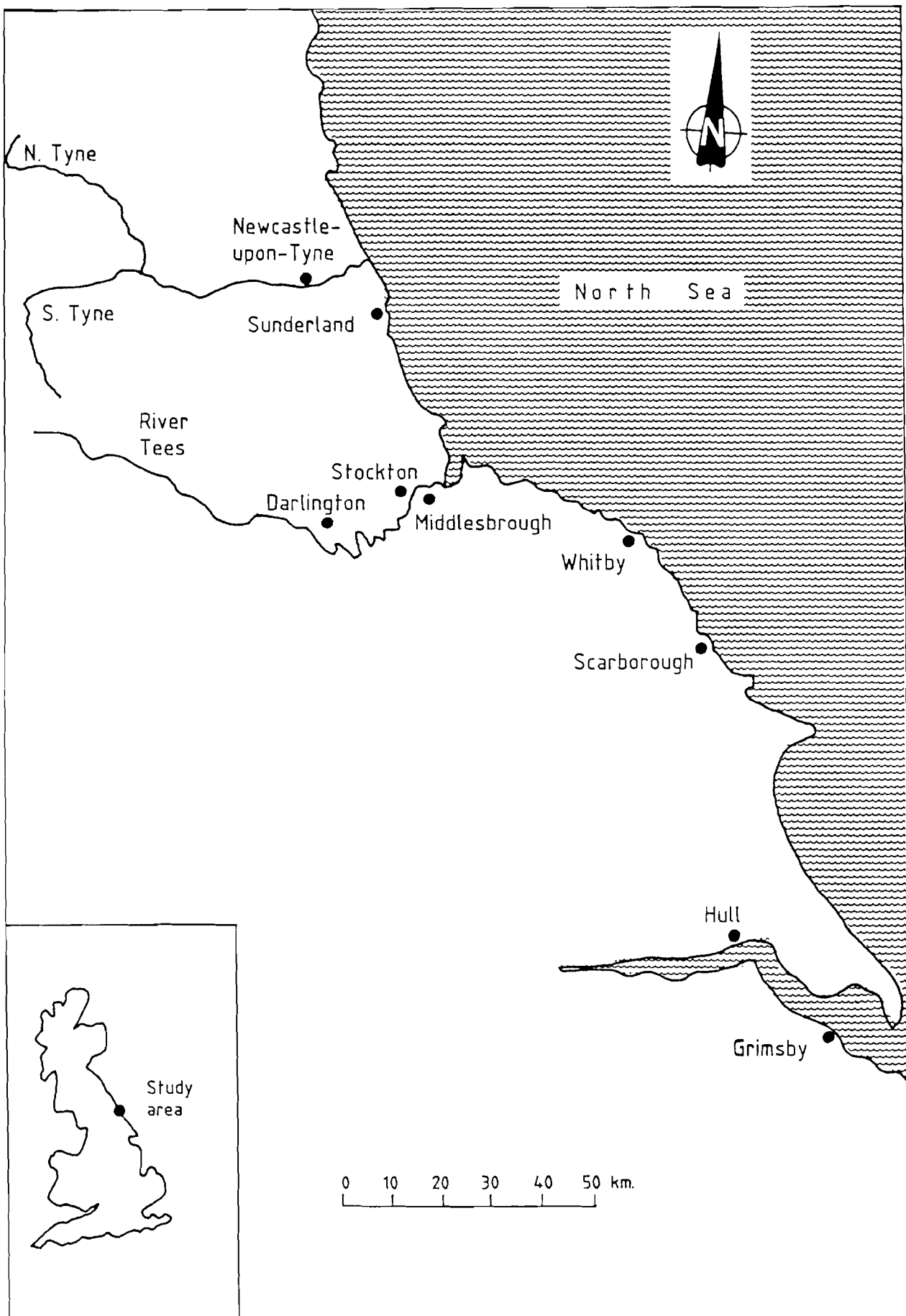


Fig 1 Location map of River Tees

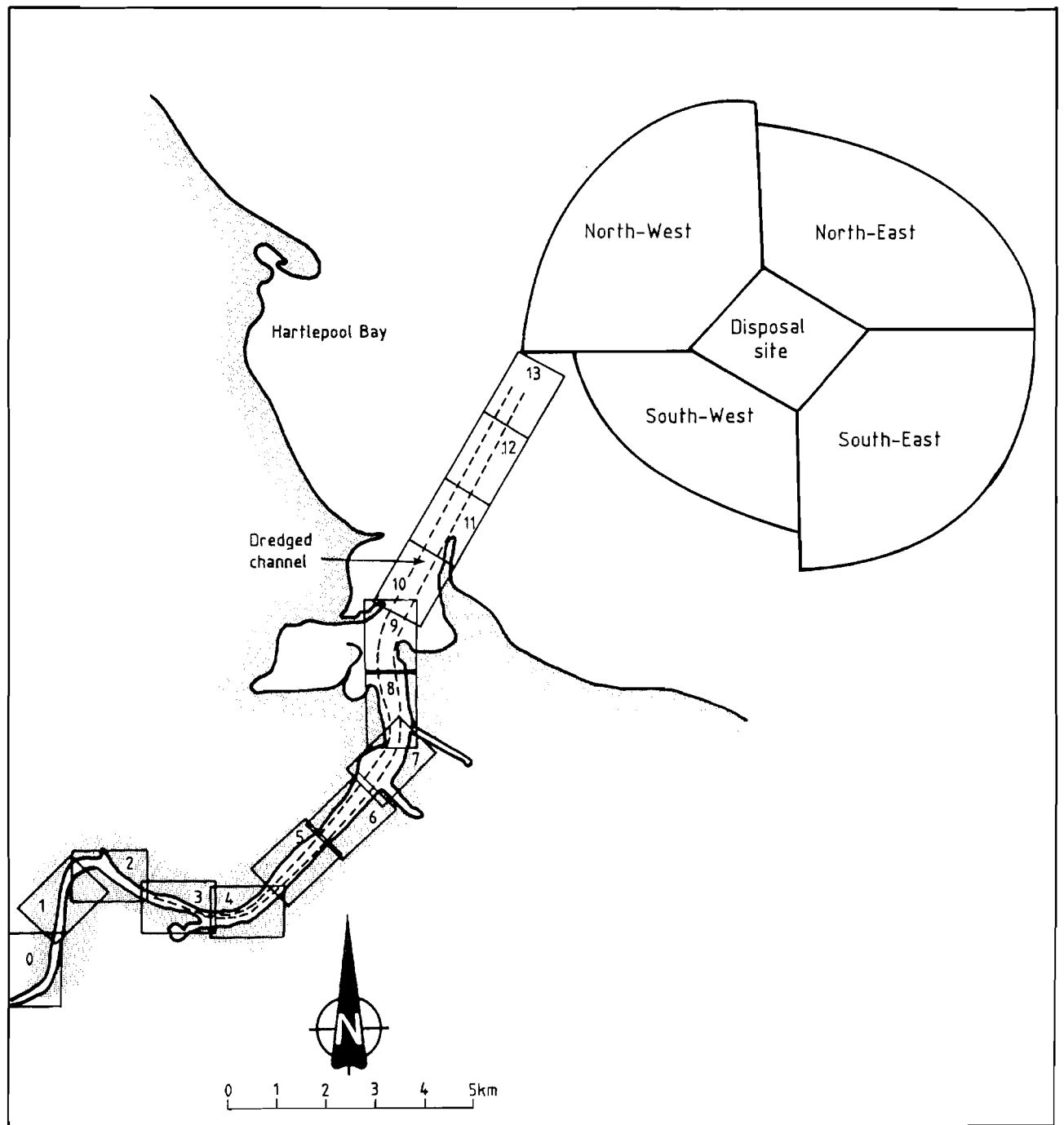


Fig 2 Location map of Inner Disposal Site



Fig 3 Distribution of silt content of bed sediments in the dredged River Tees

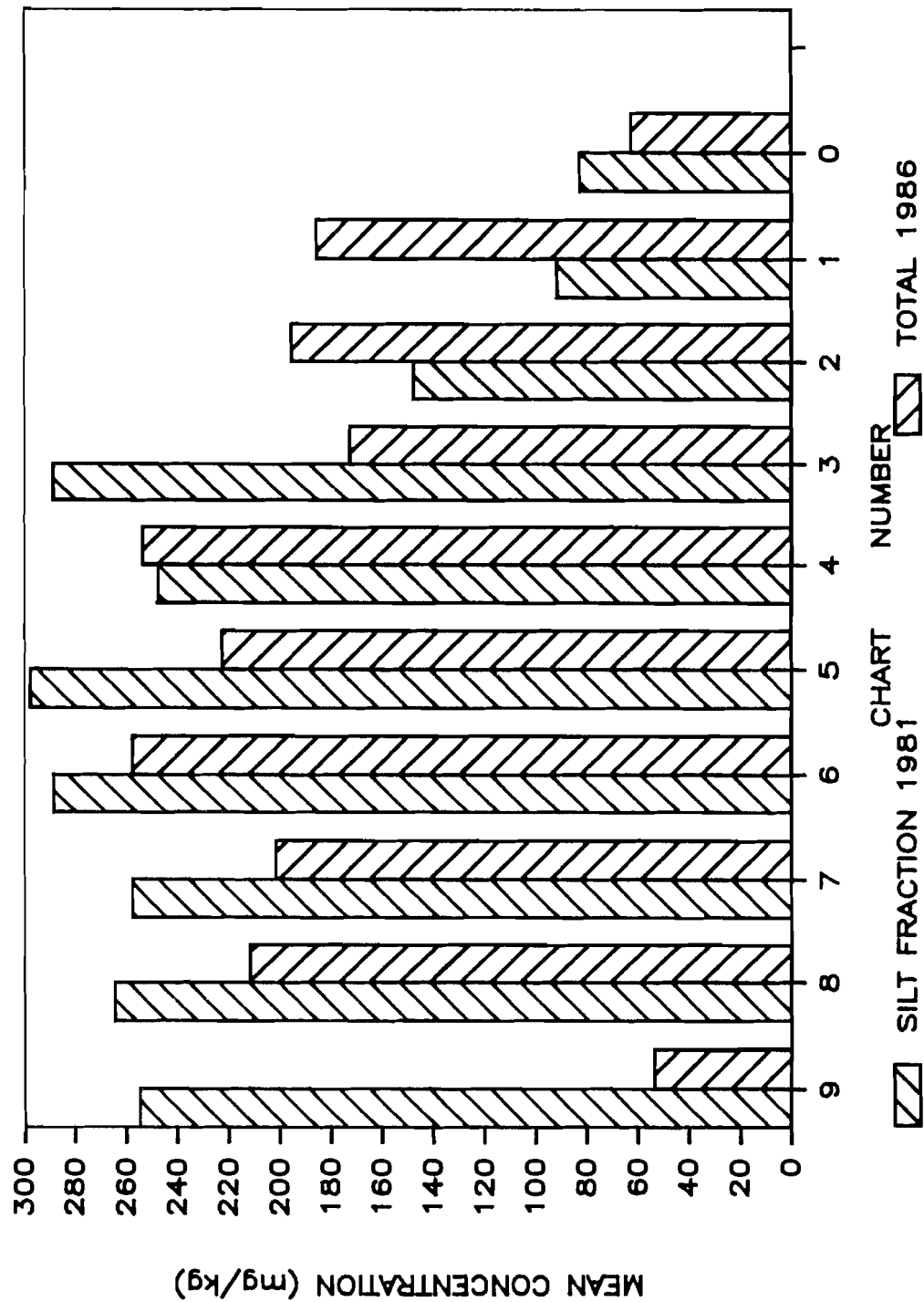


Fig 4 Distribution of copper on bed sediments in the dredged River Tees

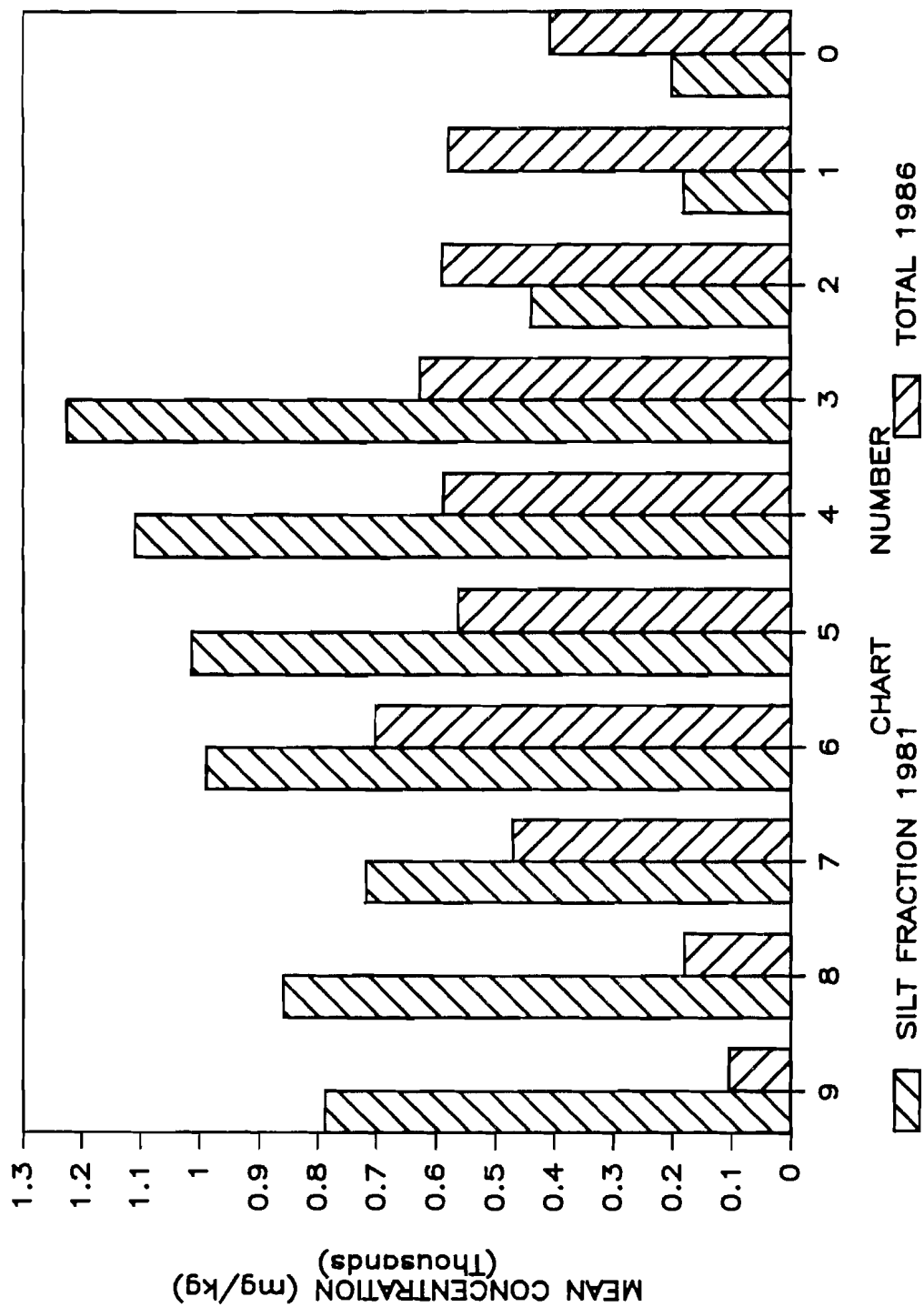


Fig 5 Distribution of zinc on bed sediments in the dredged River Tees

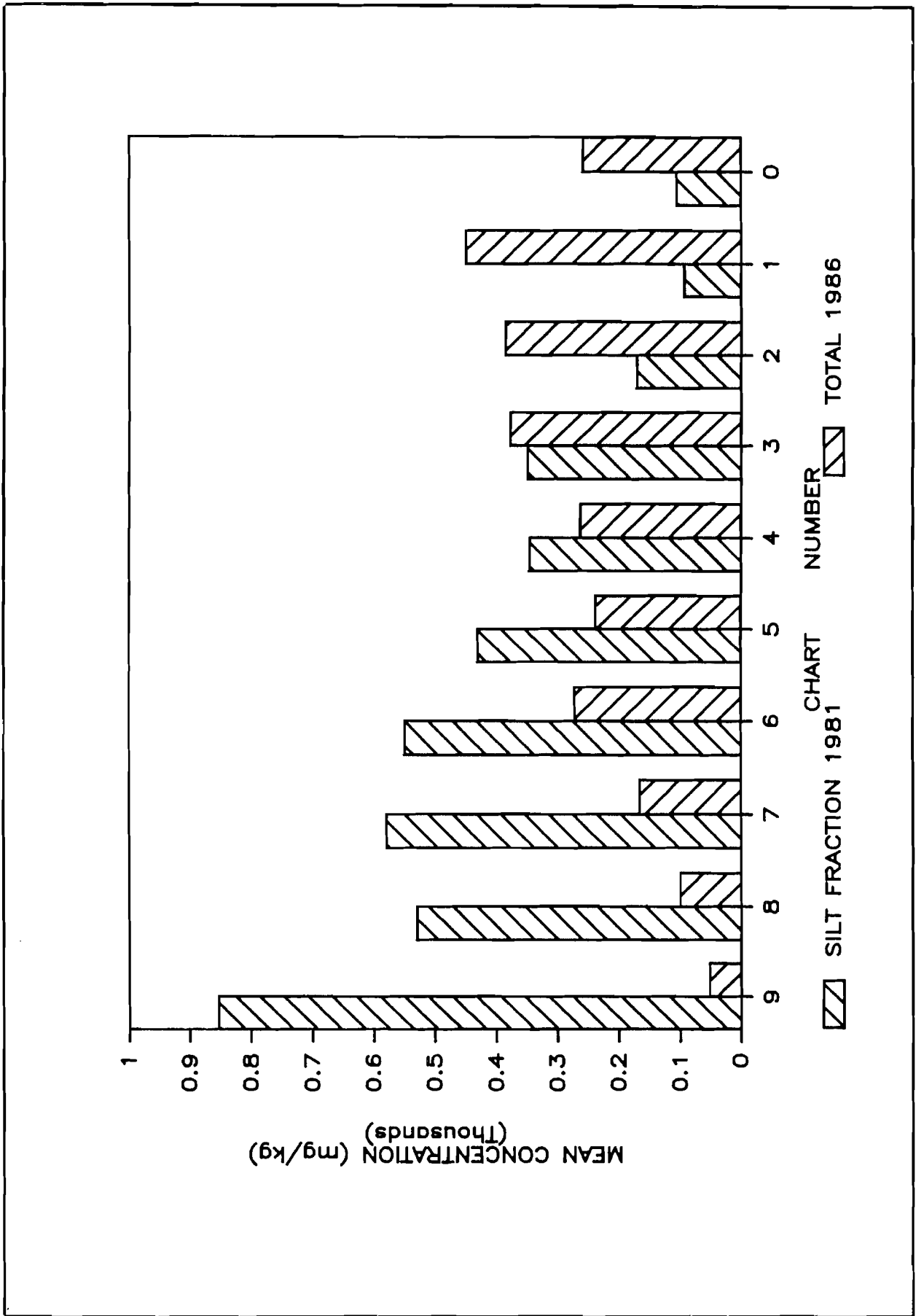


Fig 6 Distribution of lead on bed sediments in the dredged River Tees

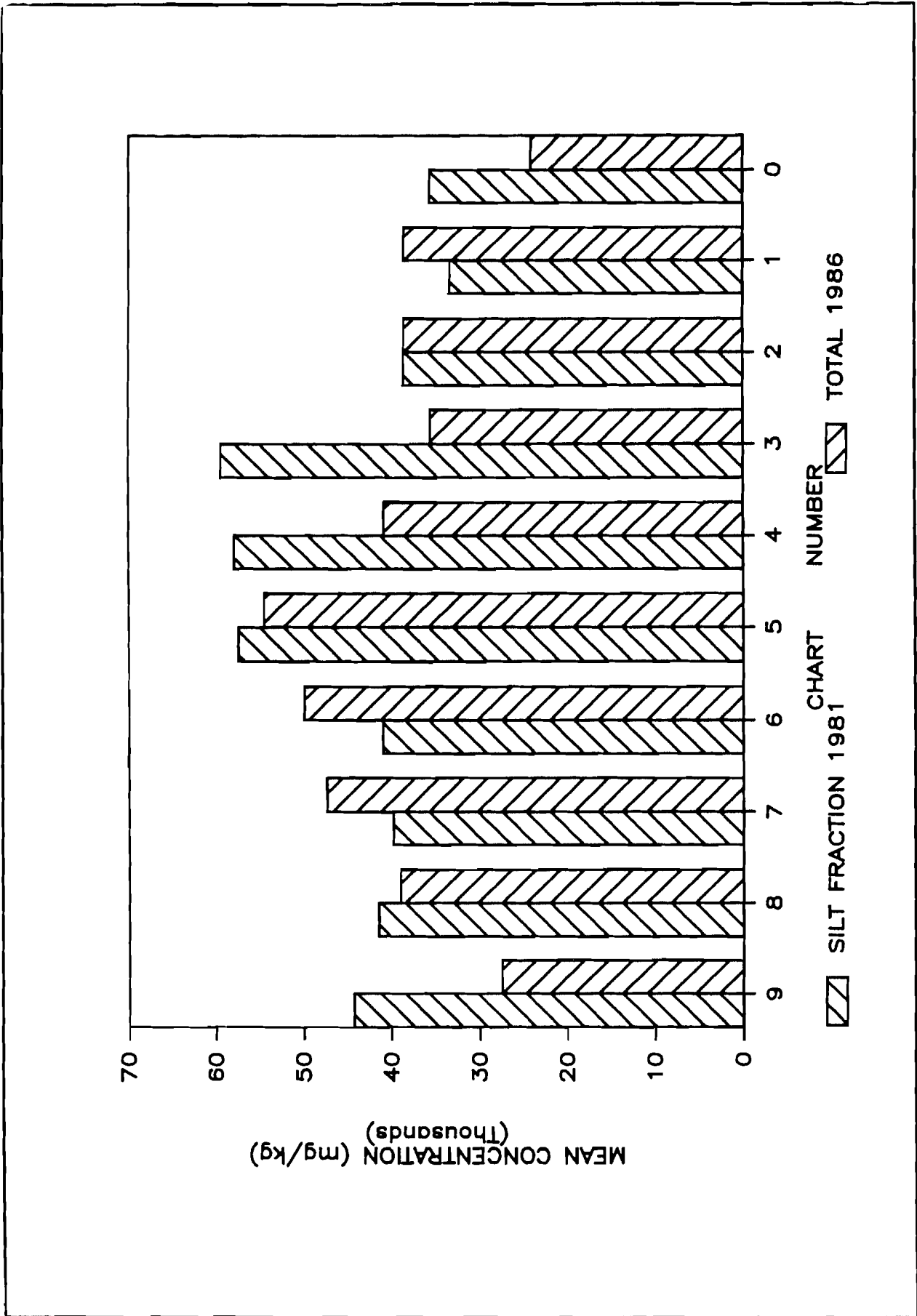


Fig 7 Distribution of iron on bed sediments in the dredged River Tees

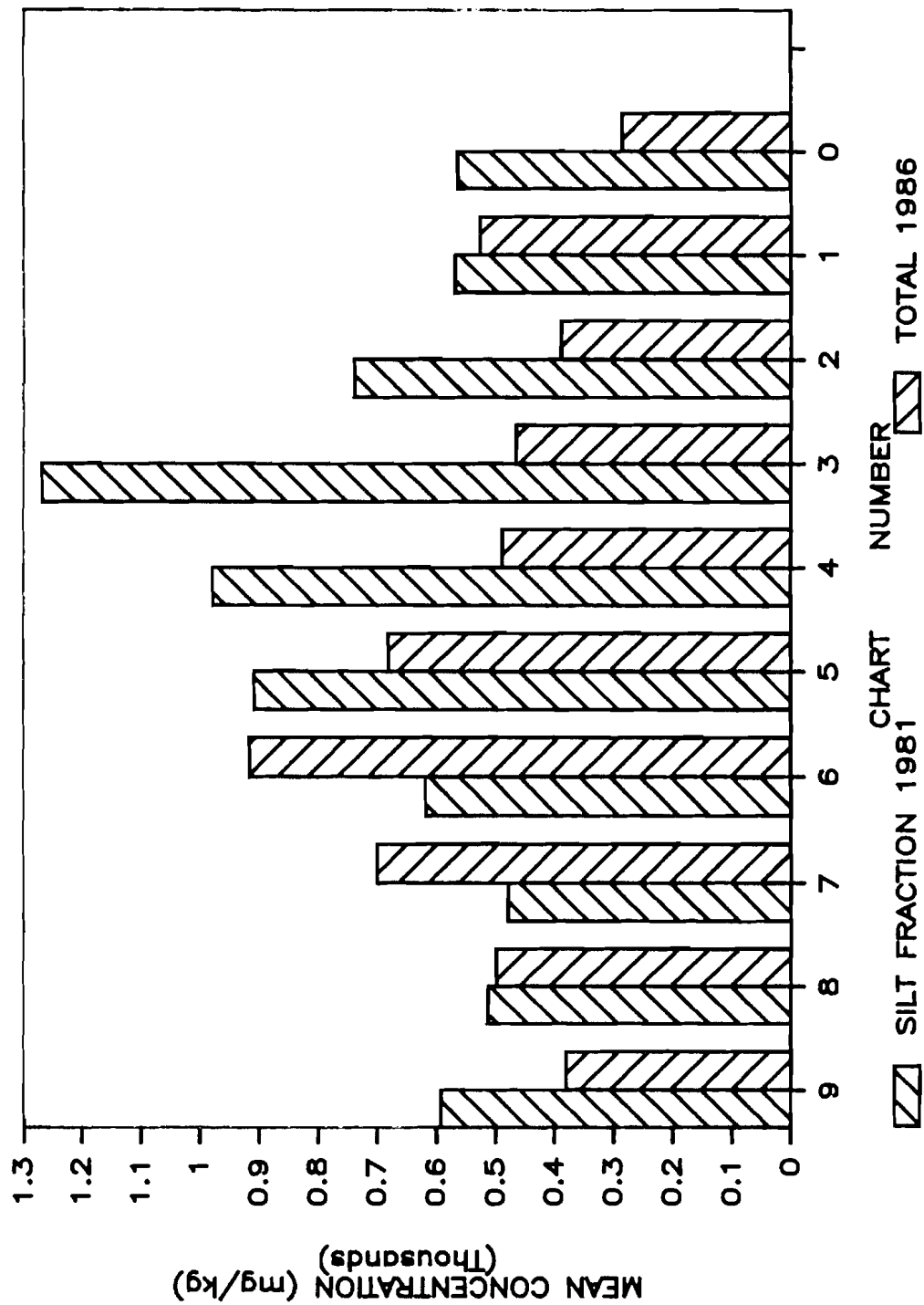


Fig 8 Distribution of manganese on bed sediments in the dredged River Tees

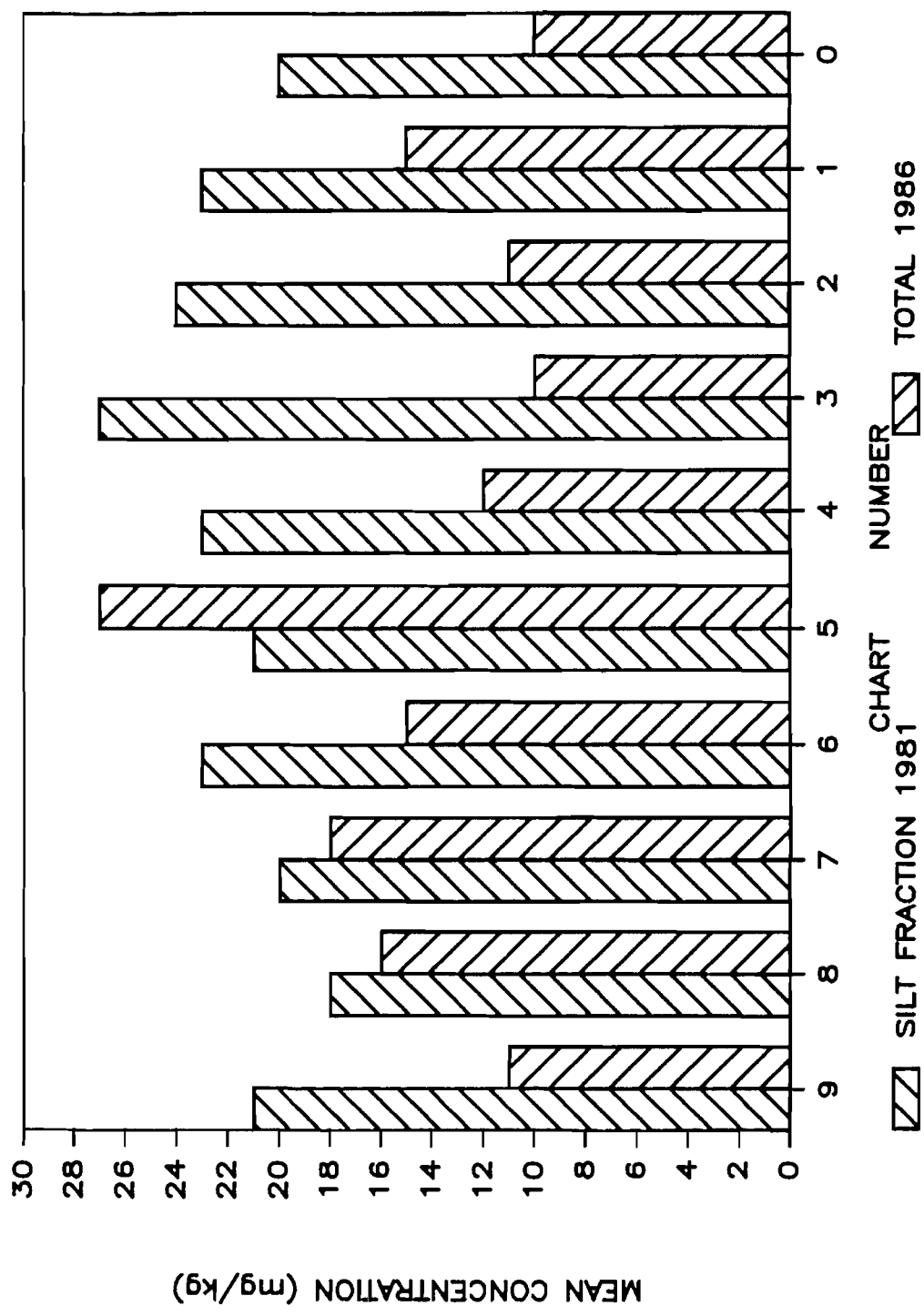


Fig 9 Distribution of cobalt on bed sediments in the dredged River Tees

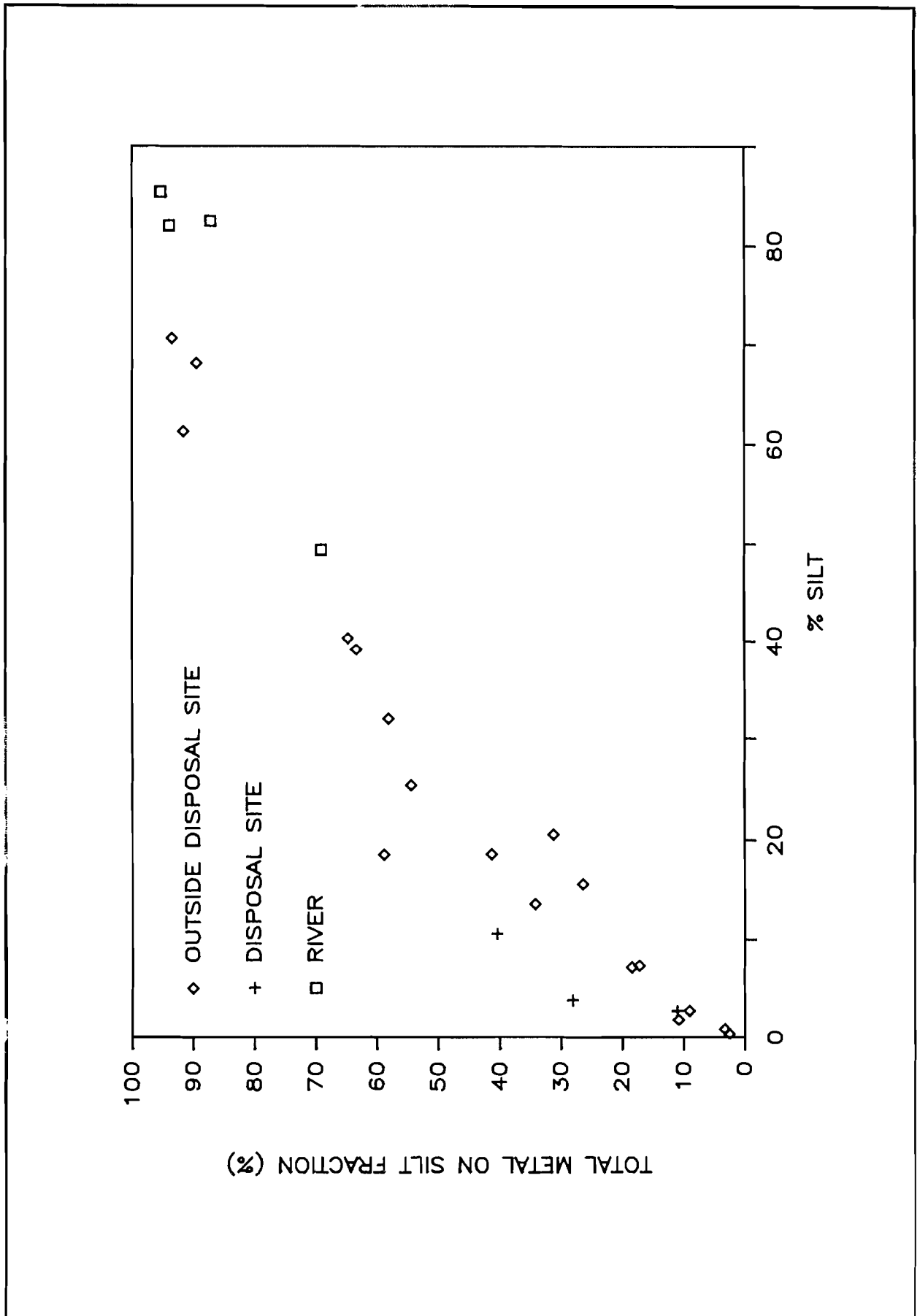


Fig 10 Proportion of metals on silt fraction in sediments

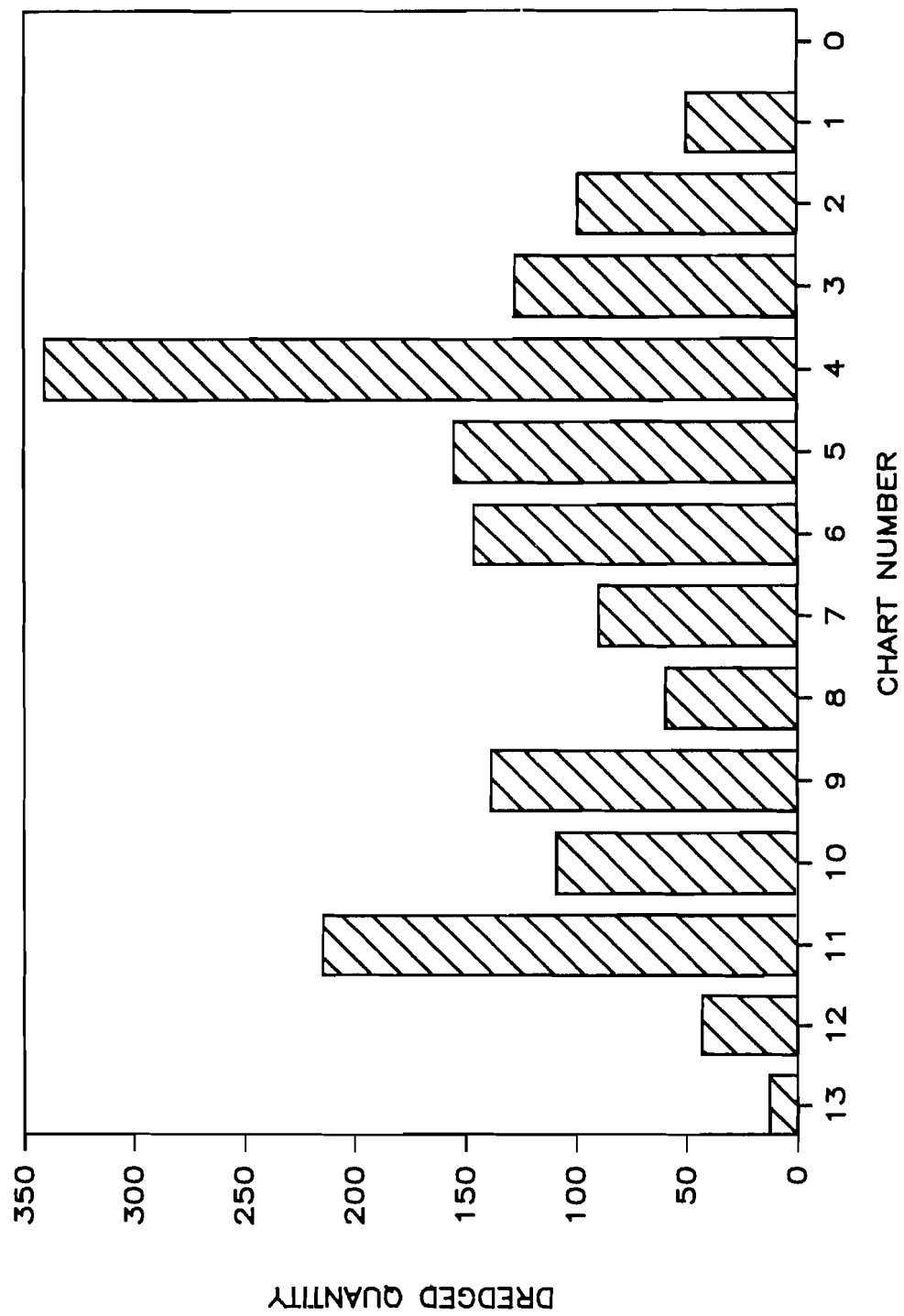


Fig 11 Distribution of dredged quantities from River Tees

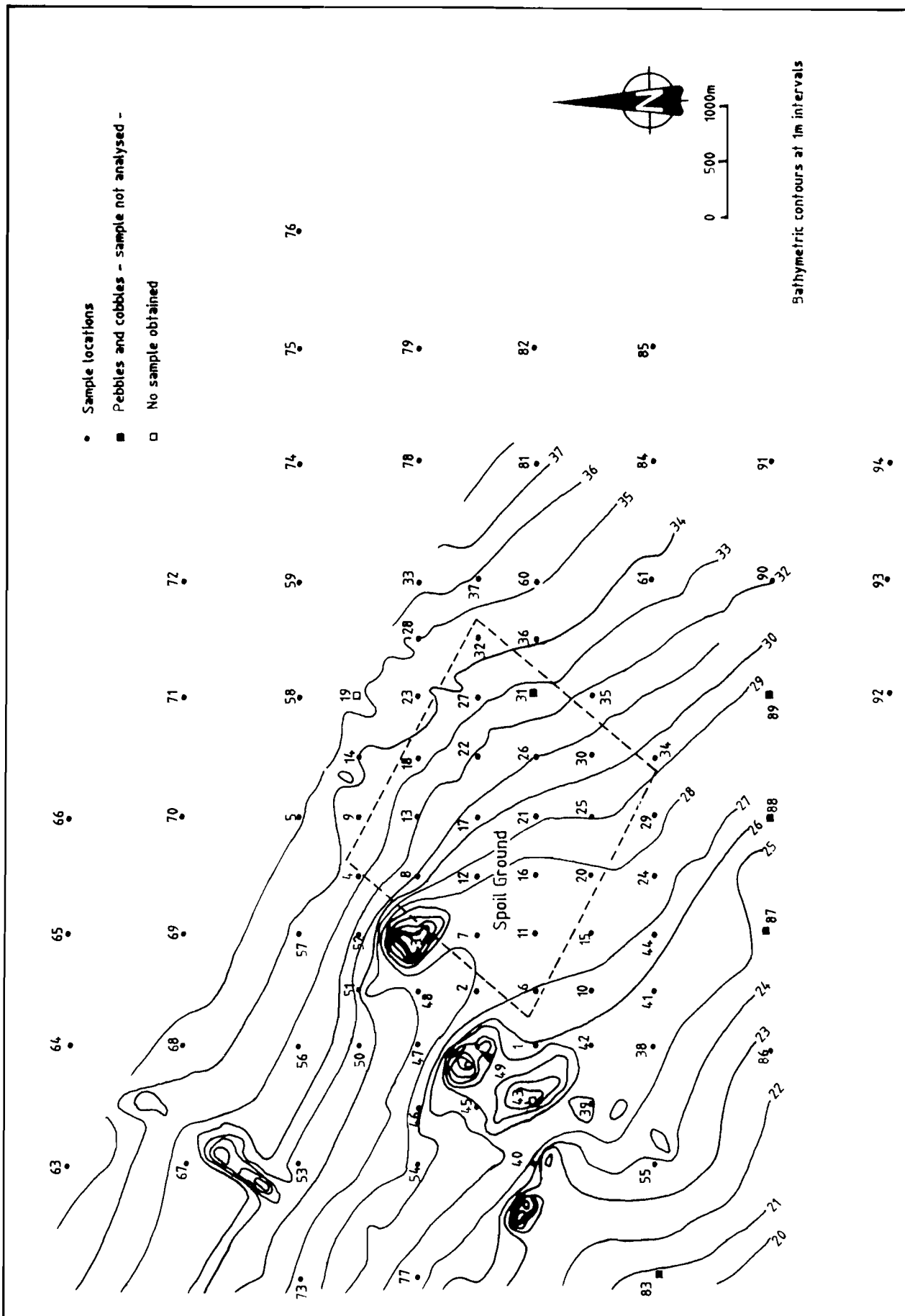


Fig 12 Detailed bathymetry and location of grab samples of bed sediments obtained at the Tees Inner Disposal Site during the June 1985 and March 1986 surveys (McLanen)

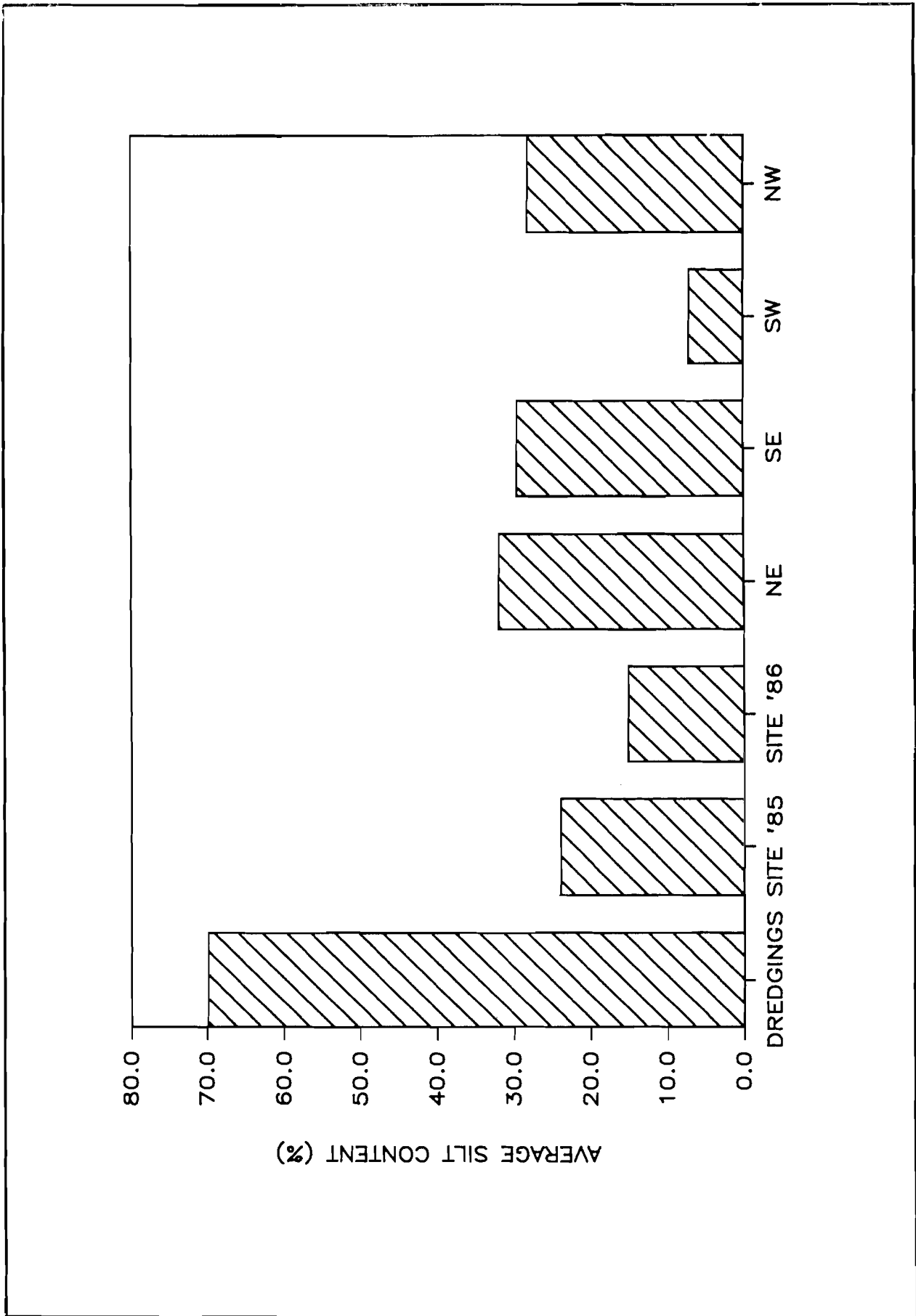


Fig 13 Distribution by region of silt content of bed sediments at the Tees Inner Disposal Site

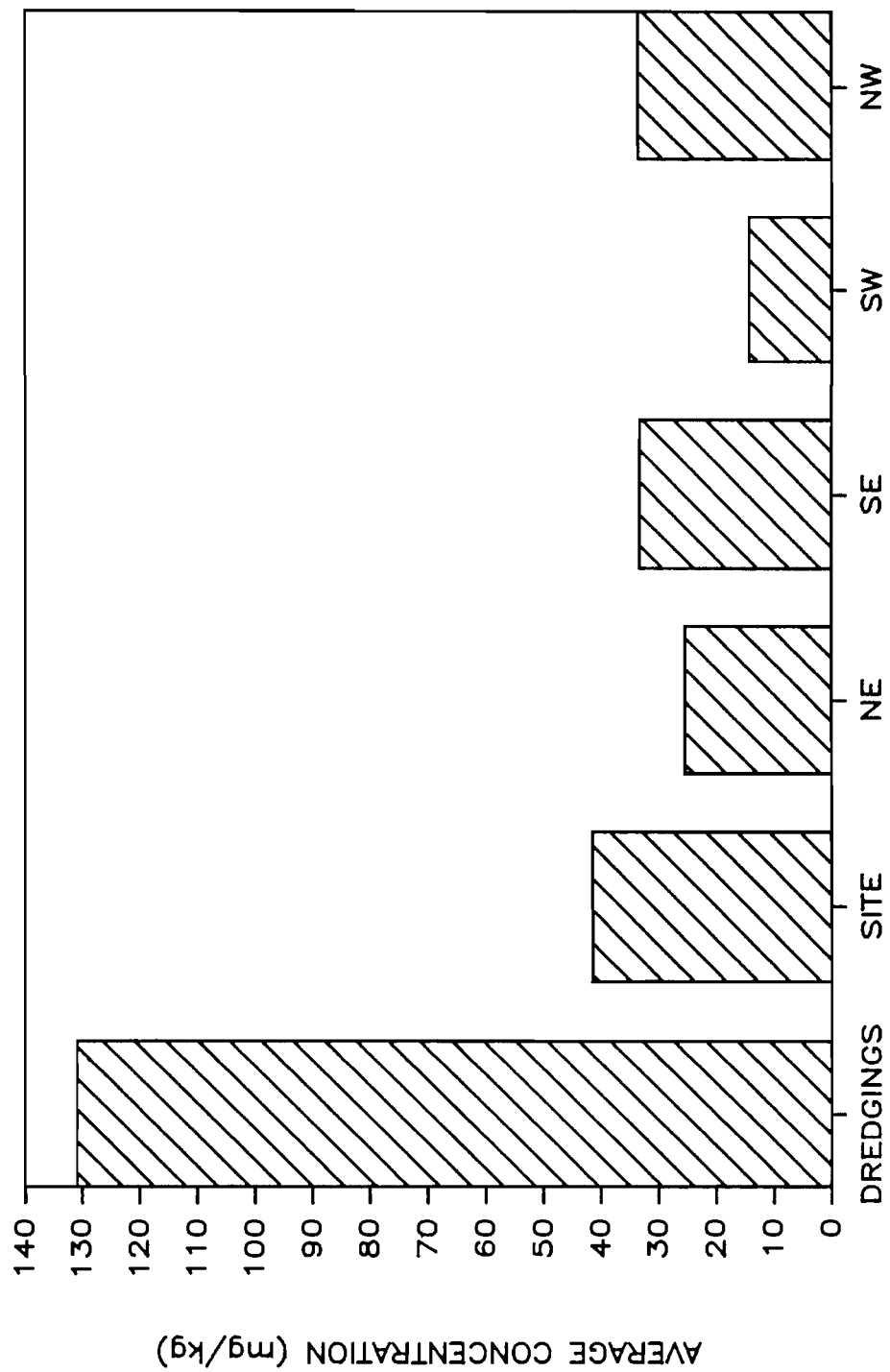


Fig 14 Distribution by region of copper on bed sediments at the Tees Inner Disposal Site

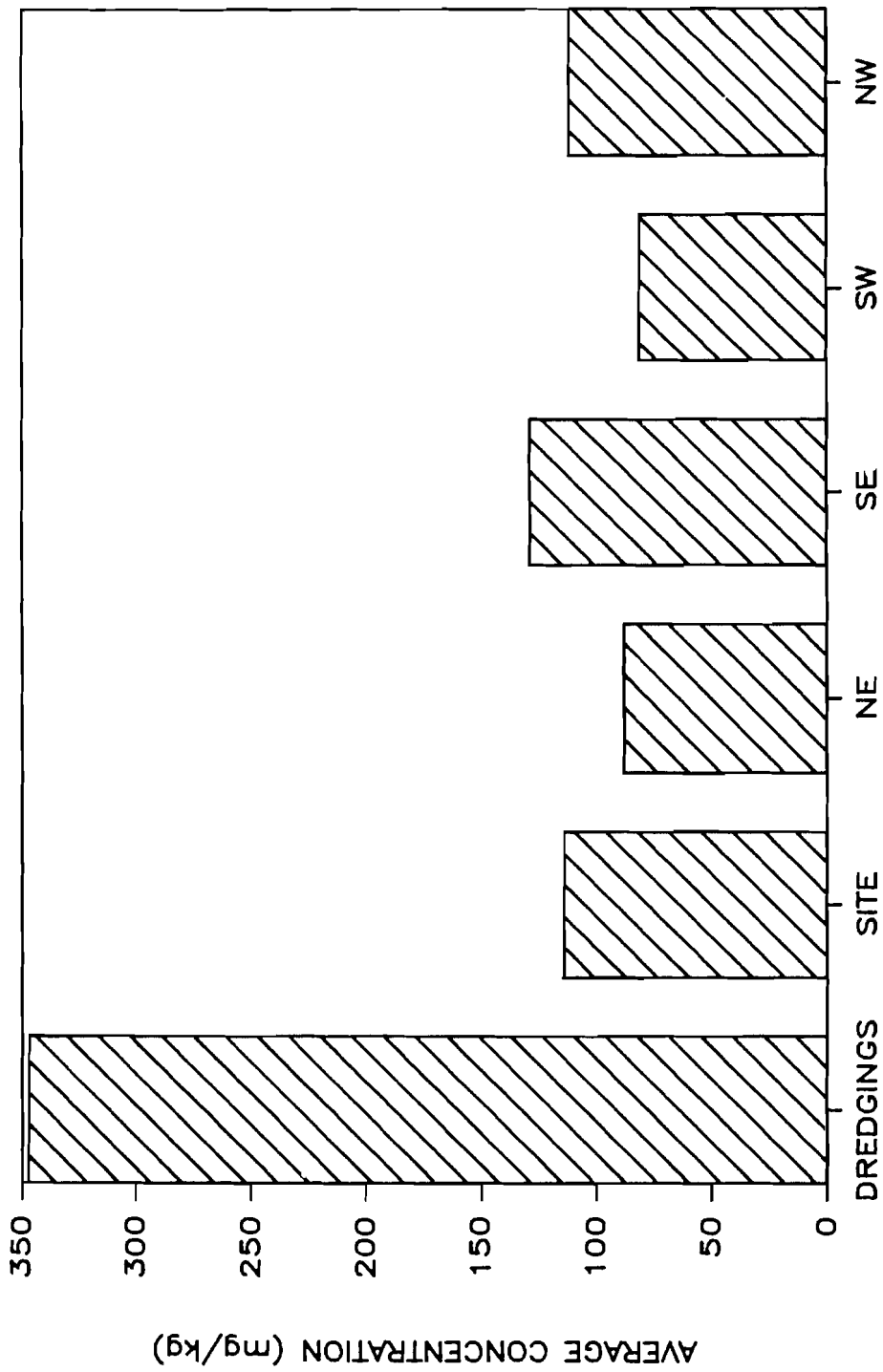
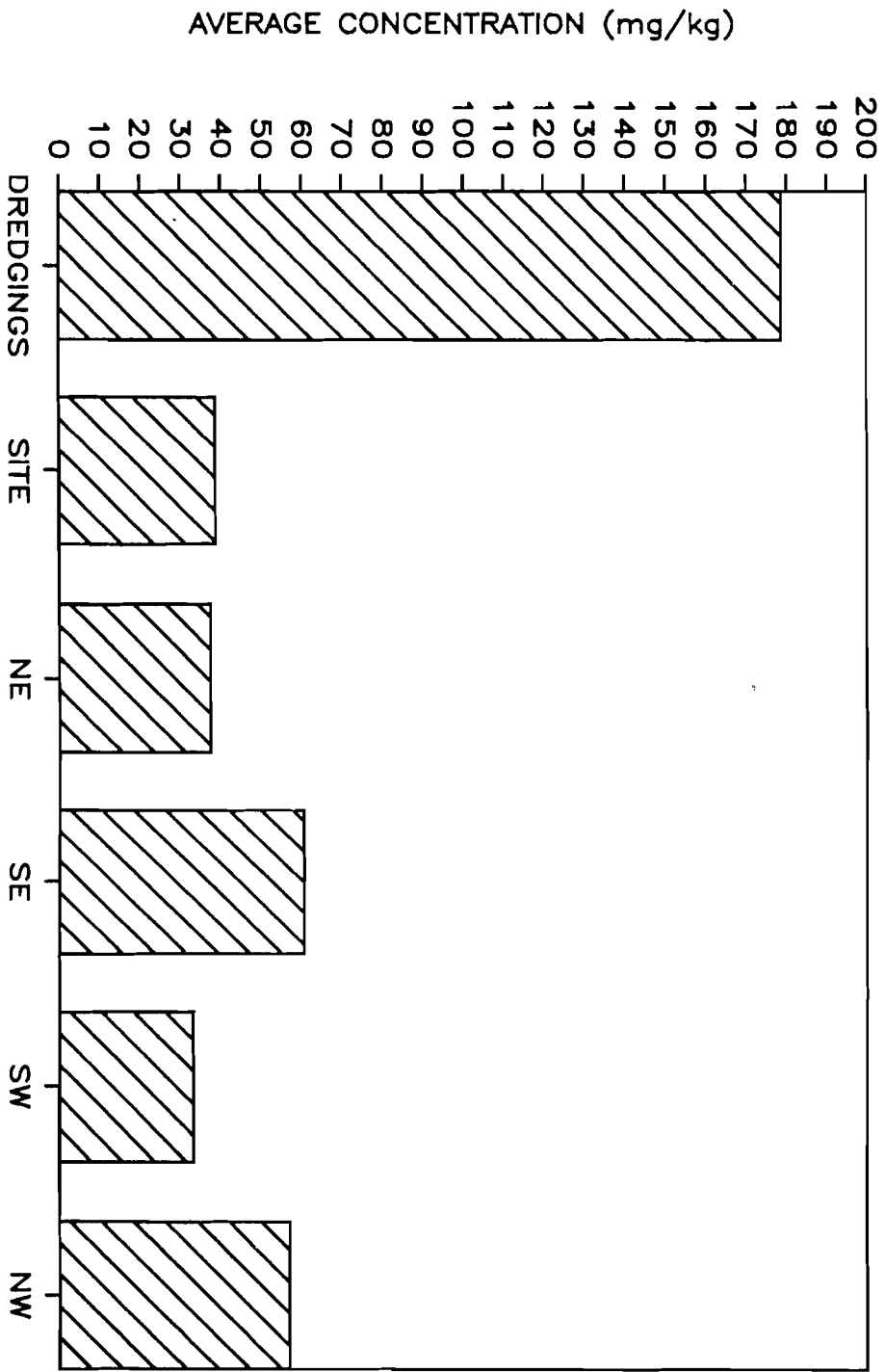


Fig 15 Distribution by region of zinc on bed sediments at the Tees Inner Disposal Site

Fig 16 Distribution by region of lead on bed sediments at the Tees Inner Disposal Site



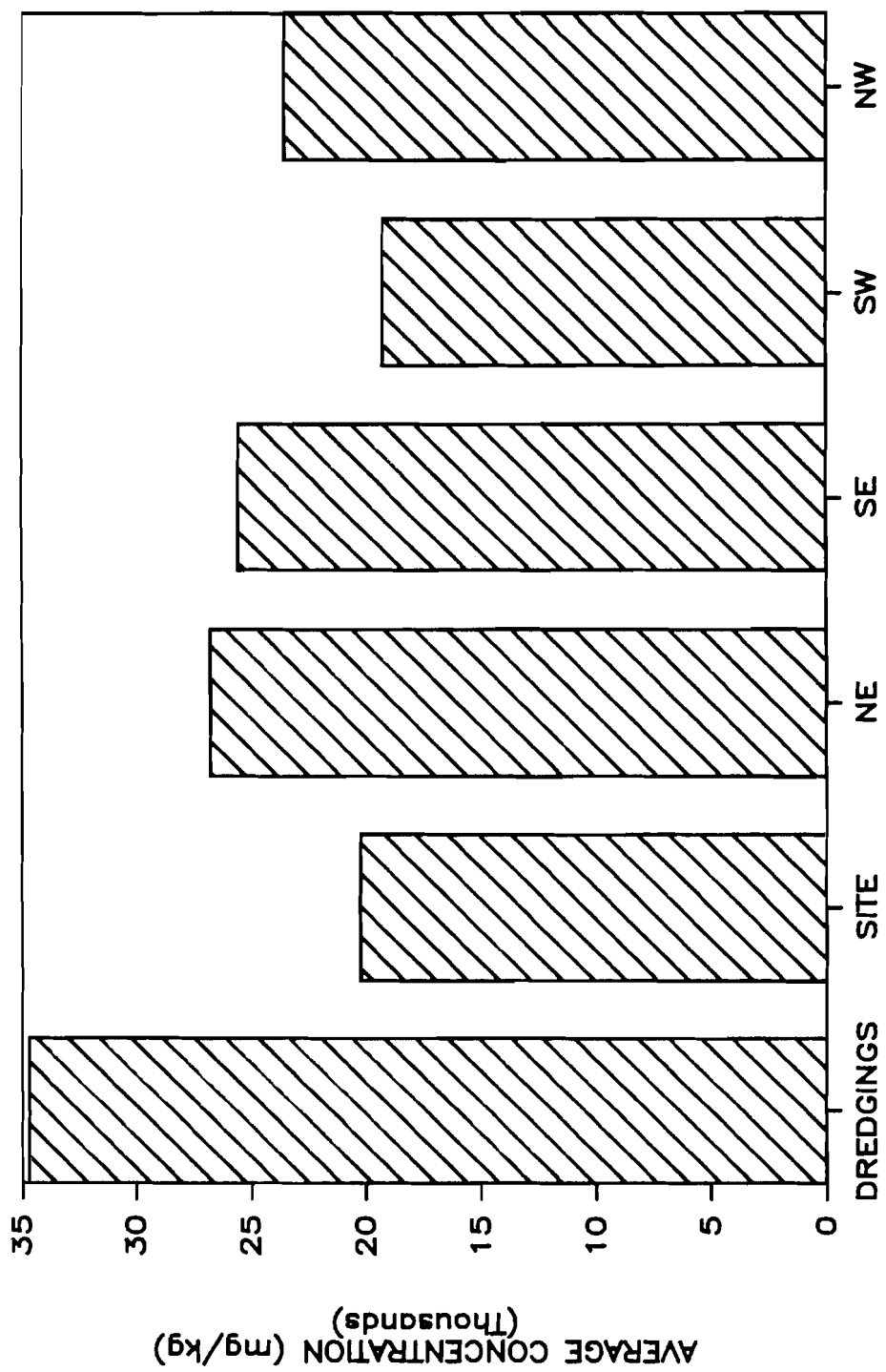


Fig 17 Distribution by region of iron on bed sediments at the Tees Inner Disposal Site

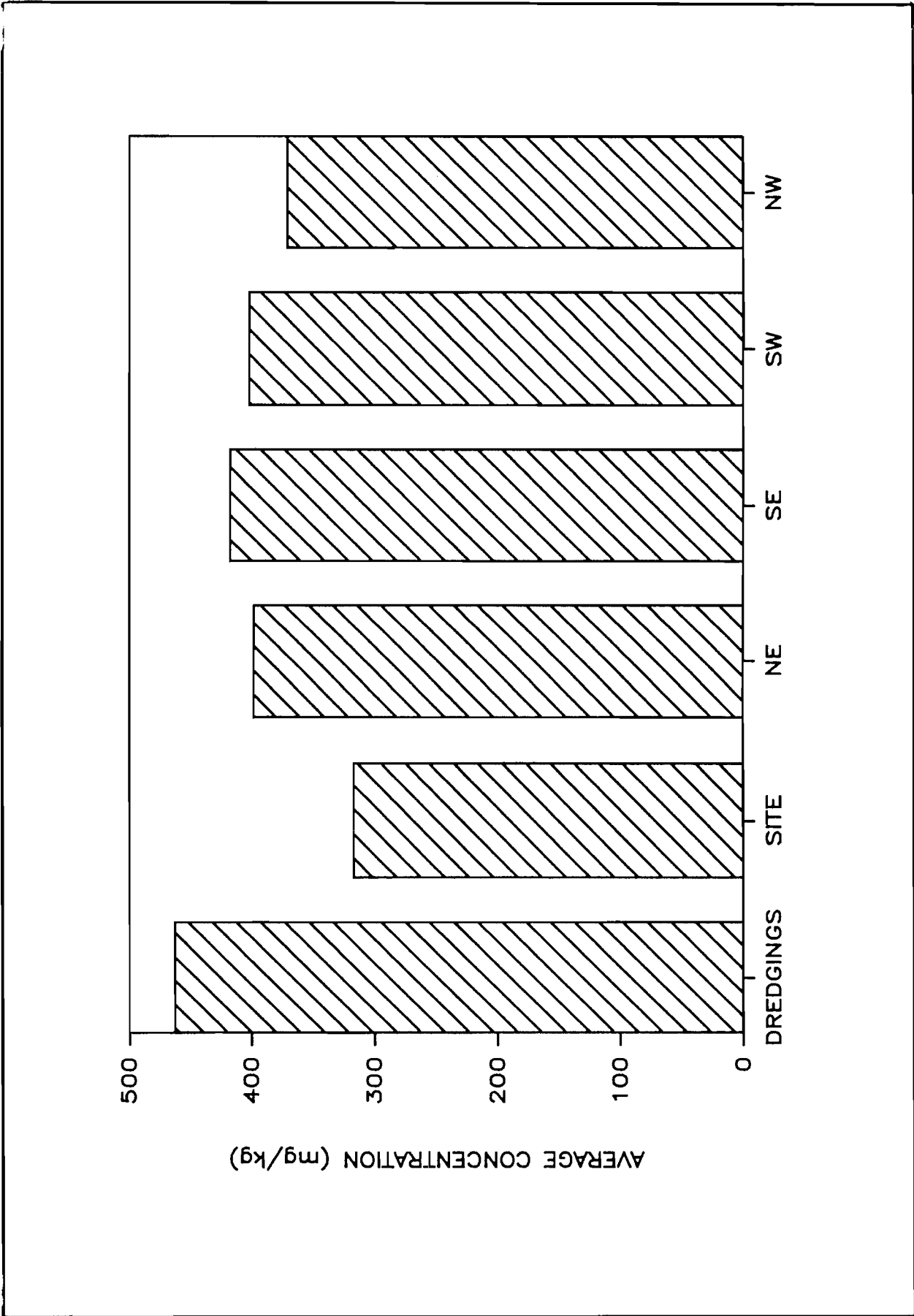


Fig 18 Distribution by region of manganese on bed sediments at the Tees Inner Disposal Site

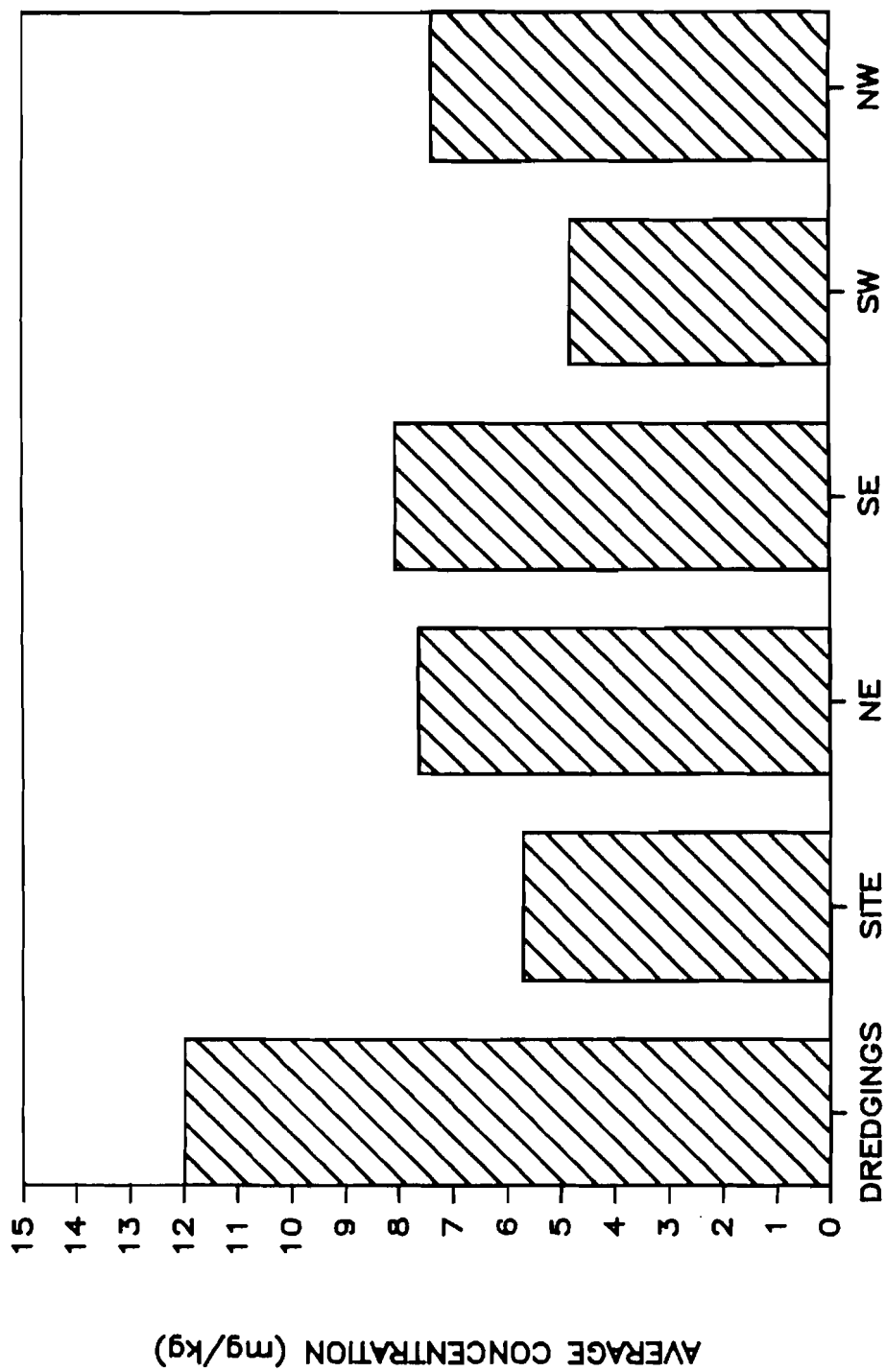


Fig 19 Distribution by region of cobalt on bed sediments at the Tees Inner Disposal Site



APPENDIX.



THE SEDIMENT TRANSPORT REGIME AT THE TEES  
ESTUARY OFFSHORE SPOIL GROUND

A report for:

Hydraulics Research Ltd.,  
Wallingford

by

Patrick McLaren  
GeoSea Consulting  
Cambridge

January, 1987



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## 1.0 INTRODUCTION

### 1.1 Background

Hydraulics Research Ltd., as part of a program to monitor the Tees Estuary spoil ground (Fig.1), collected 85 sediment grab samples from both the spoil ground itself as well as from its immediate vicinity (Fig.2). The samples were collected in March 1986 and were accurately surveyed on a 500m grid.

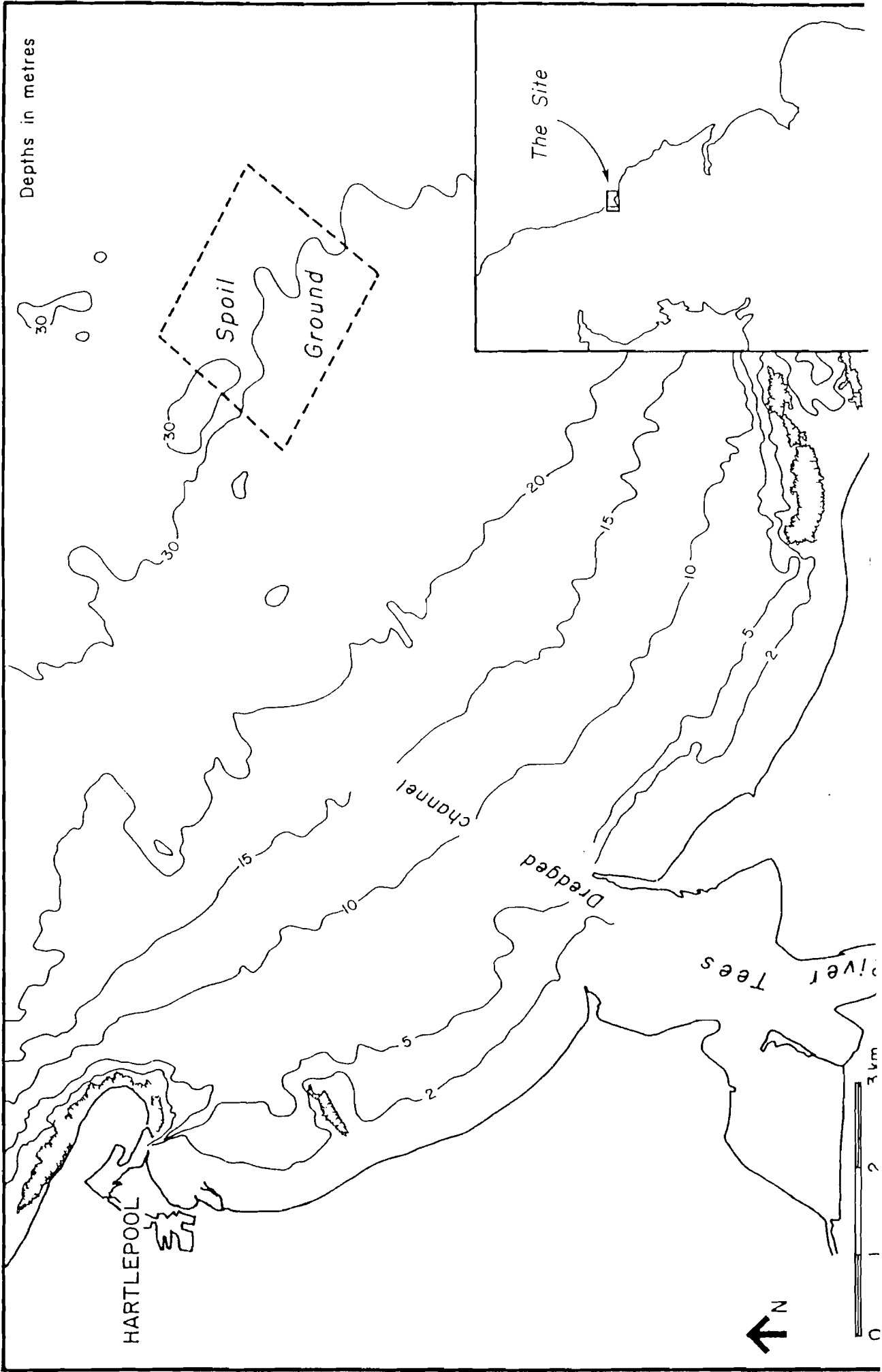
The purpose of this report is to utilize the grain-size distributions from the 85 grab samples in order to assess

- (i) the present patterns of sediment transport at the spoil ground
- (ii) the probable stability of the disposed material and
- (iii) the probability of each particular size of material being transported beyond the designated dumpsite.

### 1.2 Method

The technique to derive the existing sediment transport regime utilizes the relative changes in grain-size distributions of the sediments themselves (McLaren and Bowles, 1985). The derived patterns of transport are, in effect, an integration of all processes responsible for the erosion, transport and deposition of bottom sediments over the period of time represented by the actual samples. In addition, the analysis provides the relative probability of any particular size of material being transported. Details of the theory are provided in Appendix I; however the approach is summarized here.

Suppose two sediment samples ( $D_1$  and  $D_2$ ) are taken sequentially in a known transport direction (for example, from a river bed where



Depths in metres

The Site

Spoil Ground

channel

Dredged

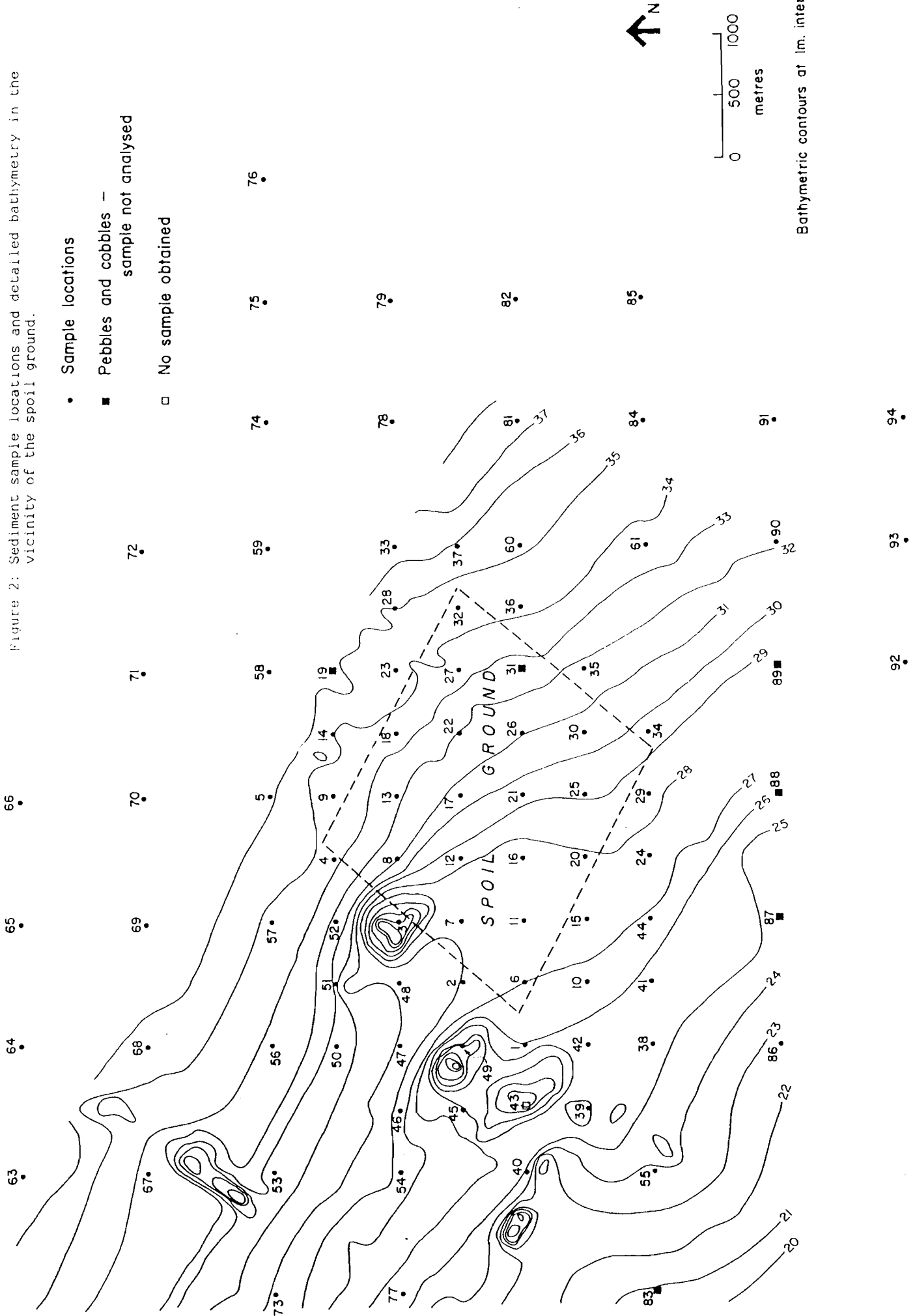
river Tees

HARTLEPOOL

N

0 1 2 3 km

Figure 2: Sediment sample locations and detailed bathymetry in the vicinity of the spoil ground.



$D_1$  is the up-current sample. In a perfect world, theory shows that the sediment distribution of  $D_2$  may become coarser or finer than  $D_1$ , but if it becomes coarser, the skewness of the distribution must become more positive. Conversely, if  $D_2$  is finer than  $D_1$ , the skewness must become more negative. The sorting will become better (ie. the value for variance will become less) in both cases. If either of these two trends is observed, we can infer that sediment transport is occurring from  $D_1$  to  $D_2$ ; if the trend is different from the two acceptable trends, for example if  $D_2$  is finer, better sorted and more positively skewed than  $D_1$ , the trend is unacceptable and we cannot suppose that transport between the two samples has taken place.

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

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

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

In reality, changes following the above two trends are seldom observed in a sequence of samples, even when the transport direction is clearly known. This is due to complicating factors such as variation in the grain-size distributions of the source material, local and temporal variability in the  $X(s)$  function and a variety of sediment sampling difficulties (ie. sample doesn't adequately describe the deposit: it's taken too deeply, not deep enough etc.). However, a trend is easily determined when a statistical approach is

used whereby all possible pairs contained in a sample sequence are examined. When one of the trends exceeds random probability within the sample sequence, we can infer the direction of transport and calculate  $X(s)$ .

To analyze for sediment transport directions over 2-dimensions, a grid of samples is required. Each sample is analyzed for the complete grain-size distribution and these are entered into a micro-computer equipped with appropriate software to calculate statistically acceptable trends for all sample sequences and the corresponding transport ( $X(s)$ ) functions.

### 1.3 Data Base

A total of 95 grab samples were attempted; however 10 of these were either unsuccessful or yielded pebbles and cobbles of varying size and number and were not analyzed (Fig.2). Grain-size distributions were obtained from standard seive and pipette analytical techniques and the size analyses ranged from -5.0 phi (pebbles) to 9.0 phi (clay). The data were presented as weight per cent at 0.5 phi class intervals (a total of 29 intervals). All analyzed samples contained sand; 68% contained a significant gravel content and 55% a significant mud (silt and clay) content.

## 2.0 PHYSICAL SETTING

### 2.1 Waves

The Tees Estuary spoil ground is located about 9km northeast of the harbour entrance. It covers 3.6km and ranges in water depth from 27m at its western corner to nearly 35m at its eastern corner (Fig.2). At these water depths, significant peak orbital

velocities of 30cm/sec will be exceeded for 1% of the time or for about 3 or 4 days per year (Draper, 1967)\*. Such velocities easily exceed the thresholds required to initiate the movement of coarse sand (0.5 phi) for wave periods of 10 seconds and of very coarse sand (-0.5 phi) for wave periods of 1 second (Komar and Miller, 1975). The spoil ground is, therefore, within a wave climate capable of initiating the transport of the existing sediments.

## 2.2 Tides

Mean spring tidal amplitude at the Tees entrance is 4.3m. According to Huntley (1980) the maximum tidal stream amplitudes at average spring tides is about 75 cm/sec. Maximum velocities are achieved in a southeast direction parallel to the coast.

## 2.3 Storm Surges

Numerical modelling studies on storm surge prediction indicate that wind generated currents are invariably parallel to the coast adjacent to the Tees Estuary. Similar to the tidal stream, southeast currents tend to be dominant achieving velocities of 50 to 75 cm/sec (Flather and Davies, 1978).

## 2.4 Geology

The spoil ground is located on Triassic New Red Sandstone (Brown, 1981). On land both faults and Tertiary dykes strike northeast, a direction corresponding with several of the bathymetric highs shown in Figure 2. These highs are up to six metres

-----

\* These figures are for the nearest wave station for which data has been analyzed. (Smith's Knoll light vessel off the east coast of Norfolk).

long. They are most likely basaltic dykes or barytized faults, both of which are more resistant to erosion than the country rock. The inability for the grab-sampler to obtain a sample at location 43 (Fig.2) further suggests the presence of bedrock.

During the last glaciation ice completely covered this part of the North Sea shelf, with the result that little sediment was ever deposited in this area (Jansen, et al, 1979). On surficial sediment maps of the North Sea, the region of the spoil site has been identified as either pre-Quaternary outcrop or hard rock (Dingle, 1970; Caston, 1979). Nevertheless, the grab samples indicate that there is at least a veneer of unconsolidated sediments; the high and random gravel content of which suggests that bedrock is not far below the surface.

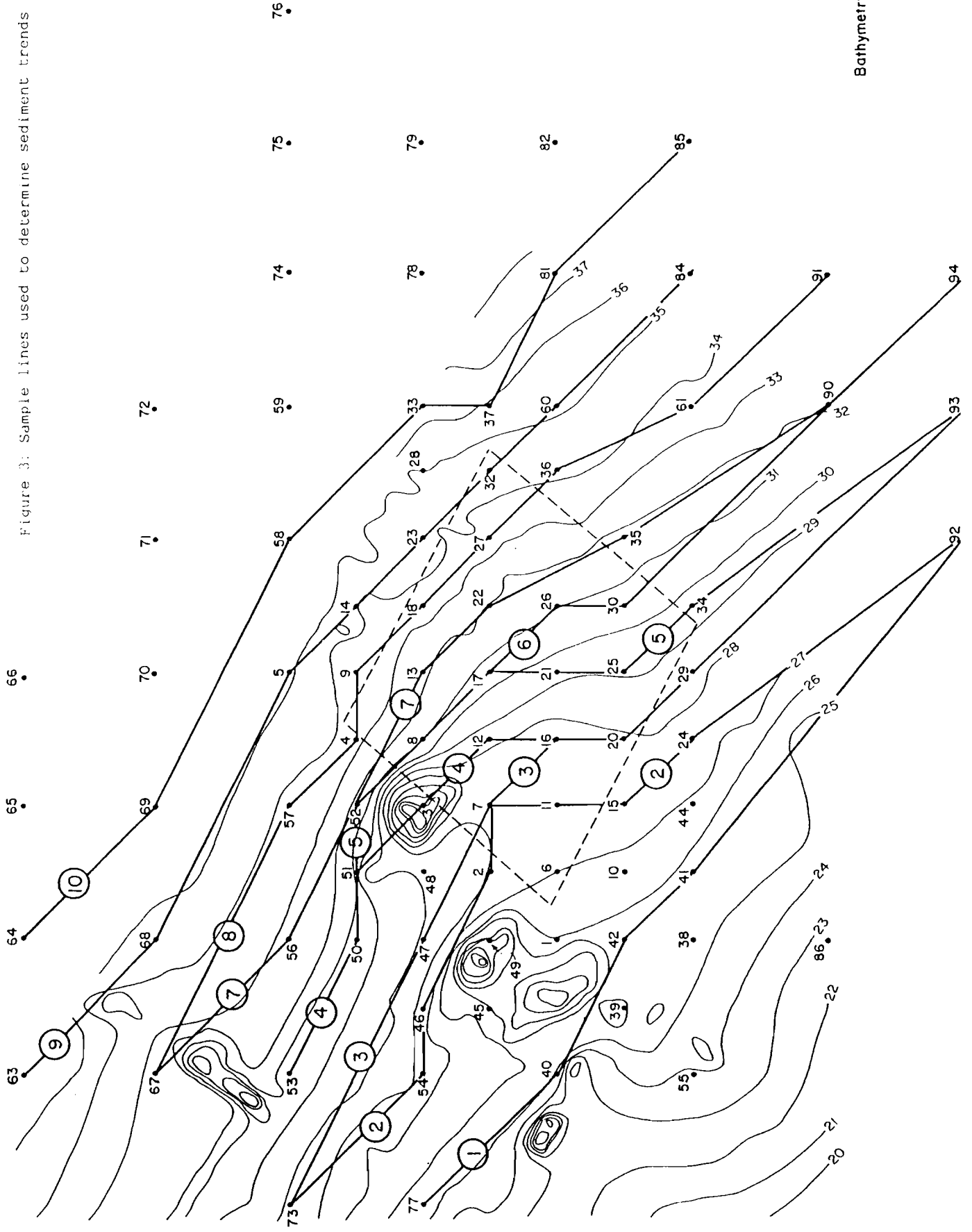
Within the region surrounding the spoil site sand waves have been observed (Stride, 1973) and, based on bedform morphology, net sediment transport is postulated to be southeast, parallel to the coast (Banner, 1979).

### 3.0 PRESENT PATTERNS OF SEDIMENTATION

More than 80 various sequences of samples were tested for transport direction of which 10 are selected to demonstrate the pertinent findings (Fig.3). The results of the trend analysis for each line are presented in Table 1, and derived transport patterns are illustrated in Figure 4. These findings are summarized as follows:

- (1) All transport directions shown in Figure 4 were derived for the sand portion of the grain-size distributions only (-0.5 phi to 4.5 phi).
- (2) No consistent results were achieved using either complete distributions or other portions of the distributions.

Figure 3: Sample lines used to determine sediment trends (see Table 1)



Bathymetric contours at 1m. intervals

TABLE 1

Sediment trend statistics for each of the lines shown in Figure 3

Definitions:

- (i)  $R^2$  = multiple correlation coefficient among the mean, sorting and skewness of each sample in the line. This is a relative indication of how well the samples are related by transport.
- (ii) Case B: Sediments becoming finer, better sorted and more negatively skewed in the direction of transport.
- (iii) Case C: Sediments becoming coarser, better sorted and more positively skewed in the direction of transport.
- (iv) N = number of possible pairs in the line of samples.
- (v) x = number of pairs making a particular trend in a specific direction.
- (vi) Z = Z-score statistic: \*\* are those trends significant at the 99% level. \* are those trends significant at the 95% level.

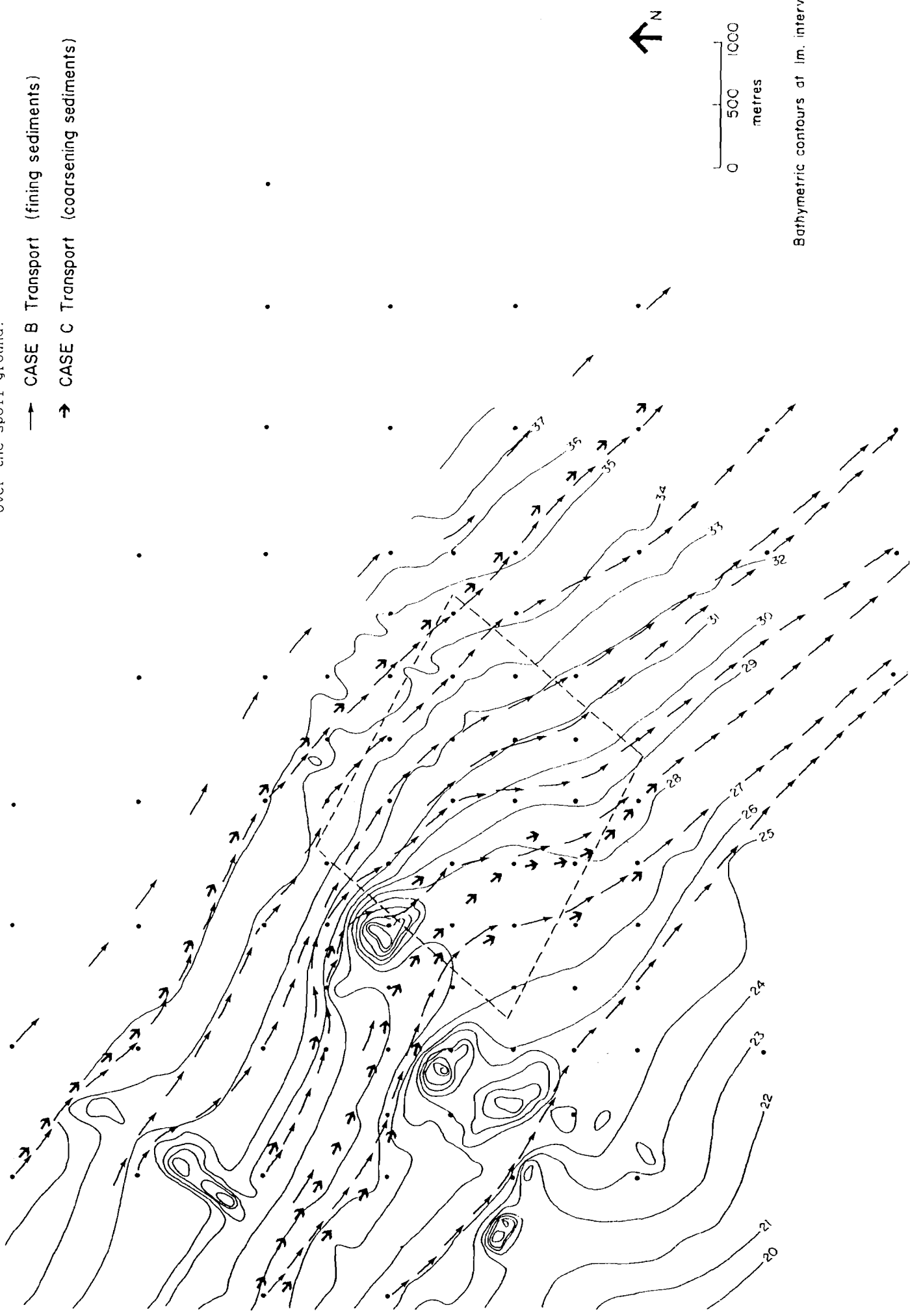
TABLE 1

Line	Case	$R^2$	Direction	N	x	Z
1	B	0.93	NW	10	1	-0.24
			SE	10	5	3.59 **
	C		NW	10	1	-0.24
			SE	10	1	-0.24
2	B	0.76	NW	36	5	0.25
			SE	36	13	4.28 **
	C		NW	36	5	0.25
			SE	36	8	1.76 *
3	B	0.70	NW	28	2	-0.85
			SE	28	7	2.00 *
	C		NW	28	1	-1.43
			SE	28	13	5.43 **
4	B	0.70	NW	36	4	-0.25
			SE	36	12	3.78 **
	C		NW	36	3	-0.76
			SE	36	8	1.76 *
5	B	0.23	NW	45	4	-0.73
			SE	45	15	4.23 **
	C		NW	45	5	-0.28
			SE	45	7	0.62
6	B	0.44	NW	45	3	-1.18
			SE	45	19	6.03 **
	C		NW	45	6	0.17
			SE	45	6	0.17
7	B	0.86	NW	28	1	-1.43
			SE	28	16	7.14 **
	C		NW	28	3	-0.29
			SE	28	5	0.86

TABLE 1 Contd.

Line	Case	$R^2$	Direction	N	x	Z
8	B	0.82	NW	36	7	1.26
			SE	36	21	8.32 **
	C	NW	36	4	-0.25	
		SE	36	0	-2.27	
9	B	0.85	NW	28	6	1.43
			SE	28	8	2.57 **
	C	NW	28	1	-1.43	
		SE	28	10	3.71 **	
10	B	0.95	NW	21	4	0.91
			SE	21	6	2.23 *
	C	NW	21	1	-1.07	
		SE	21	5	1.57	

Figure 4: Summary of the net sediment transport directions over the spoil ground.



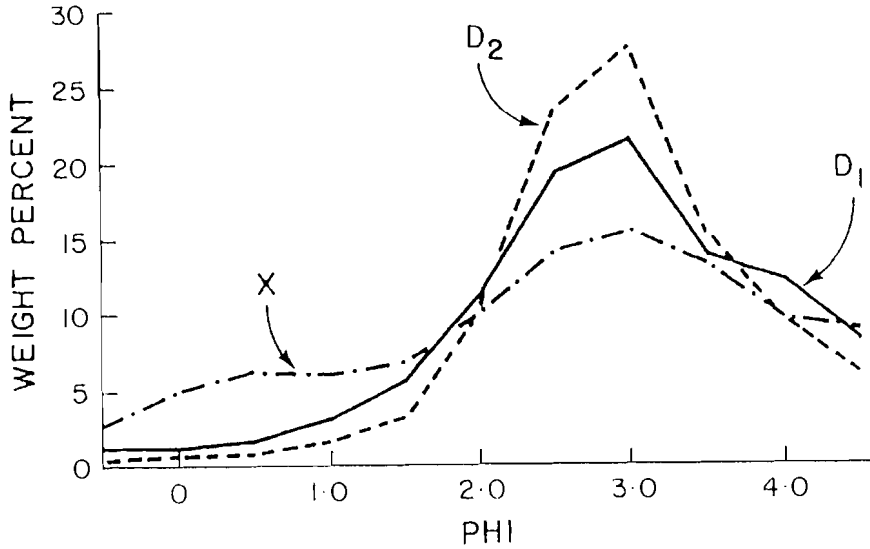
- CASE B Transport (fining sediments)
- - - CASE C Transport (coarsening sediments)

Bathymetric contours at 1m. intervals

- (3) No consistent results were found in directions normal to the bathymetry. Net transport either up or down slope does not appear to be occurring.
- (4) For sand-size sediment, all transport trends are approximately parallel to the bathymetry in the southeast direction (Table 1, Fig.4).
- (5) The  $R^2$  values which provide an indication of how well the sediments are related by transport are exceptionally high for these lines on either side of the spoil site ( $R^2 = 0.93$ , Line 1 and  $0.95$ , Line 10). The values decrease progressively as the lines cross over the centre of the spoilsite, the lowest value being for Line 5 where  $R^2 = 0.23$  (Table 1). The values generally increase again beyond Line 5, the highest values being achieved beyond the spoil ground.
- (6) Eight of the 10 lines show Case B transport (ie. the sediments are becoming finer, better sorted and more negatively skewed in the direction of transport) at the 99% level (Table 1). The remaining two (Lines 3 and 10) are significant at the 95% level. The mode of the X-distribution represents the size with the greatest probability of transport, which is 3.0 phi at water depths above 30m and 3.5 phi (very fine sand) at water depths below 30m (compare the  $D_1$ ,  $D_2$  and X distributions for Lines 1 and 8, Fig.5).
- (7) Four lines indicate high energy, Case C transport (Table 1). With the exception of Line 9, these lines are concentrated in the vicinity of the bathymetric

(a) LINE 1  
CASE B

	MEAN	So	Sk
D <sub>1</sub>	2.83	1.05	-0.33
D <sub>2</sub>	2.92	0.85	-0.49
X	2.48	1.36	-0.44



(b) LINE 8  
CASE B

	MEAN	So	Sk
D <sub>1</sub>	2.40	1.16	-0.58
D <sub>2</sub>	2.93	0.85	-0.75
X	3.01	1.19	-0.91

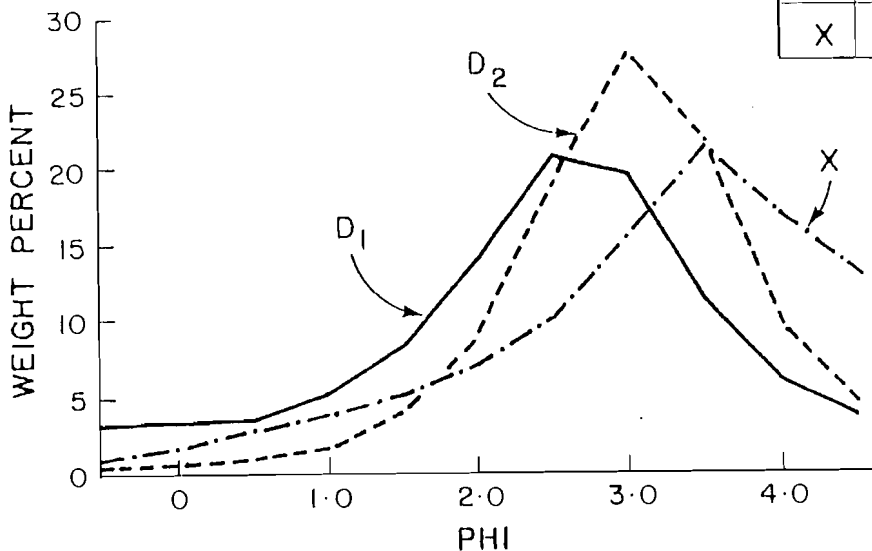


Figure 5: Sediment distributions of the average up-current samples (D<sub>1</sub>) and the average down-current samples (D<sub>2</sub>) for those samples producing Case B trends. Figure 5(a) is for Line 1 which is above 30m water depth. Figure 5(b) is below 30m water depth. The resultant X-distributions define the relative probability of each size being eroded, transported and deposited.

highs (Fig.4). In all the lines exhibiting Case C transport, the mode of X is 2.00 phi (medium sand; Fig.6).

#### 4.0 DISCUSSION

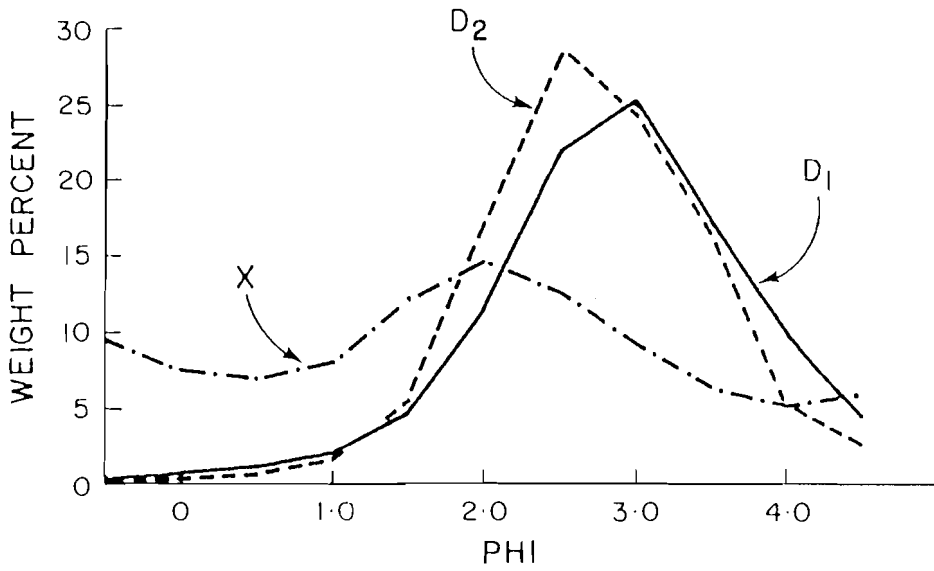
The southeast net transport directions shown in Figure 4 appear to agree well with known processes. The wave climate is sufficient to initiate particle motion for sand size material for at least one per cent of the time and tidal currents and storm surge modelling both favour southeast as the dominant direction.

Another important indication that transport is occurring in this direction is seen in the detailed bathymetry of the northeast trending highs (Fig.2). Along the southeast margin of each bathymetric high, there is a "tail" pointing towards the southeast suggesting that these may be deposits that are trapped in the lee of the bedrock knobs. Samples 3 and 49 both fall on one of these "tails" of sediment (Fig.2). Sample 3 is within a metre of the top of the high and contains 77% gravel suggesting that bedrock is very near the surface. Sample 49 is more than 3 metres from the top of the high, contains neither gravel nor mud, and is an exceptionally well sorted, fine sand. Sediment is clearly thick enough to obscure the high gravel content immediately overlying the bedrock.

Gravel occurs randomly over the area and concentrations making up more than 50% of the sample are found at all depths (Fig.7). This reflects the thinness of the present sediment cover and it is probable that little or no gravel is taking part in the transport regime. The fact that transport directions could not be determined when gravel was included in the distributions further supports this conclusion.

(a) LINE 3  
CASE C

	MEAN	S <sub>0</sub>	S <sub>k</sub>
D <sub>1</sub>	2.83	0.89	-0.5
D <sub>2</sub>	2.65	0.80	-0.3
X	1.88	1.43	-0.0



(b) LINE 9  
CASE C

	MEAN	S <sub>0</sub>	S <sub>k</sub>
D <sub>1</sub>	2.91	1.17	-0.8
D <sub>2</sub>	2.61	0.87	-0.0
X	2.13	1.07	0.0

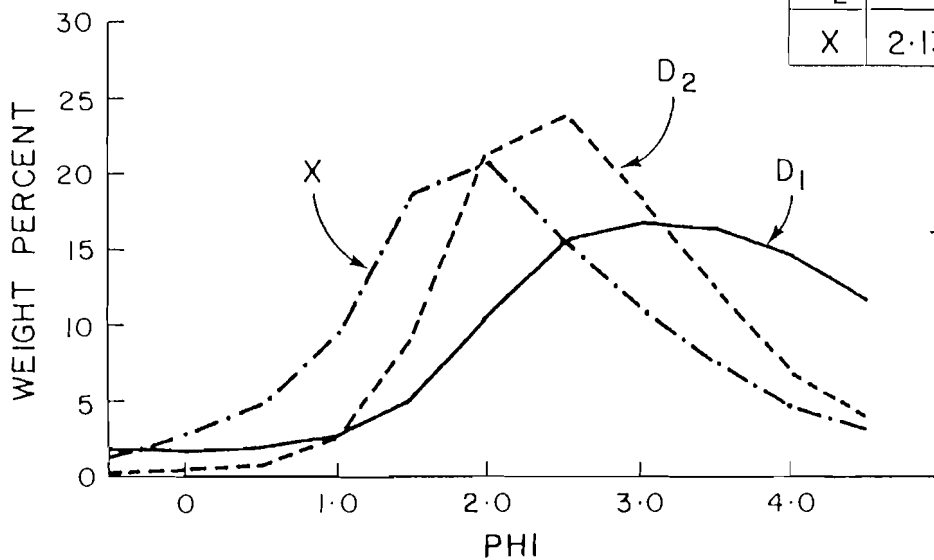
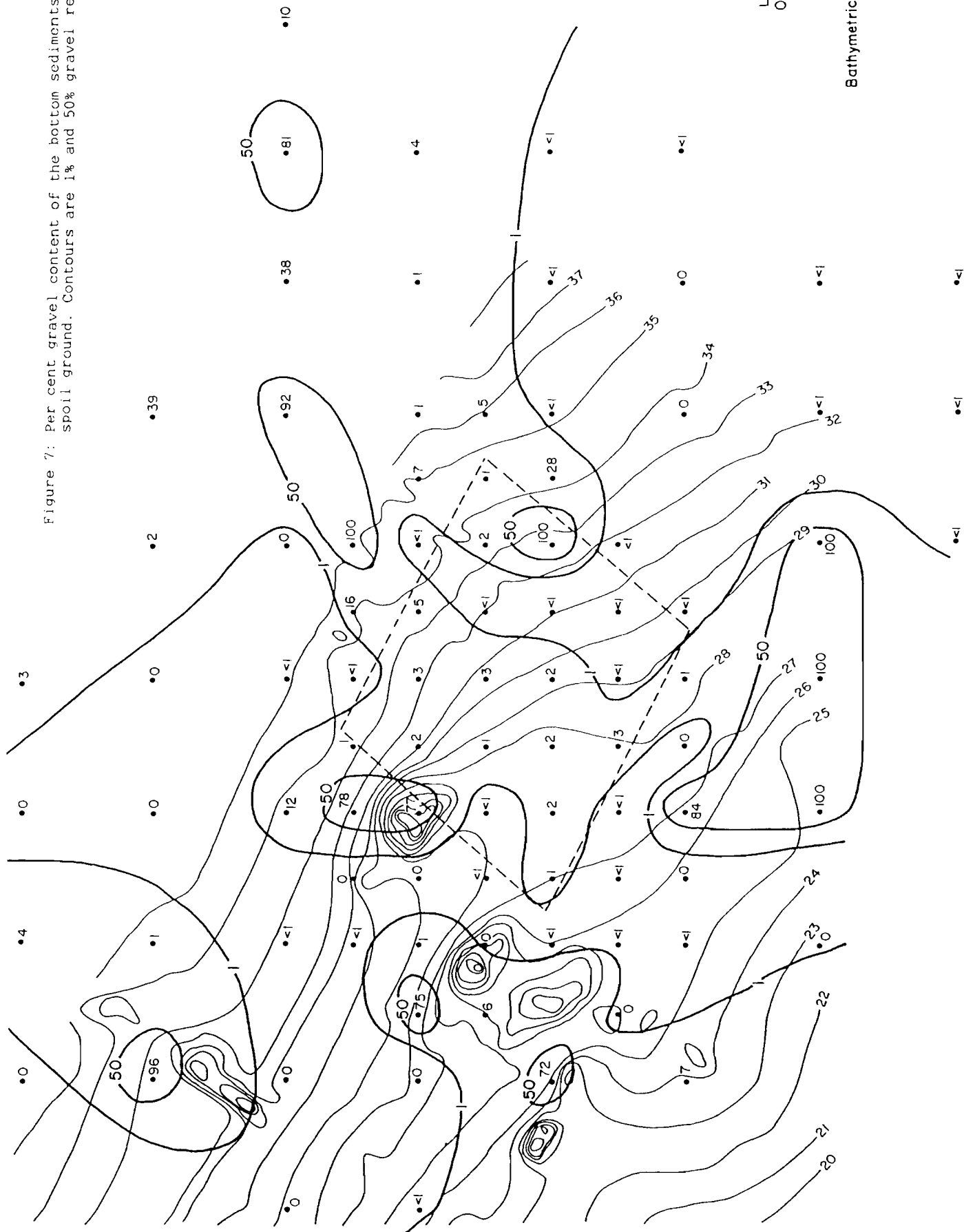


Figure 6: Sediment distributions of the average up-current samples (D<sub>1</sub>) and the average down-current samples (D<sub>2</sub>) for those samples producing Case C trends. See the caption to Figure for complete explanation.

Figure 7: Per cent gravel content of the bottom sediments over the spoil ground. Contours are 1% and 50% gravel respectively.



Bathymetric contours at 1m. intervals

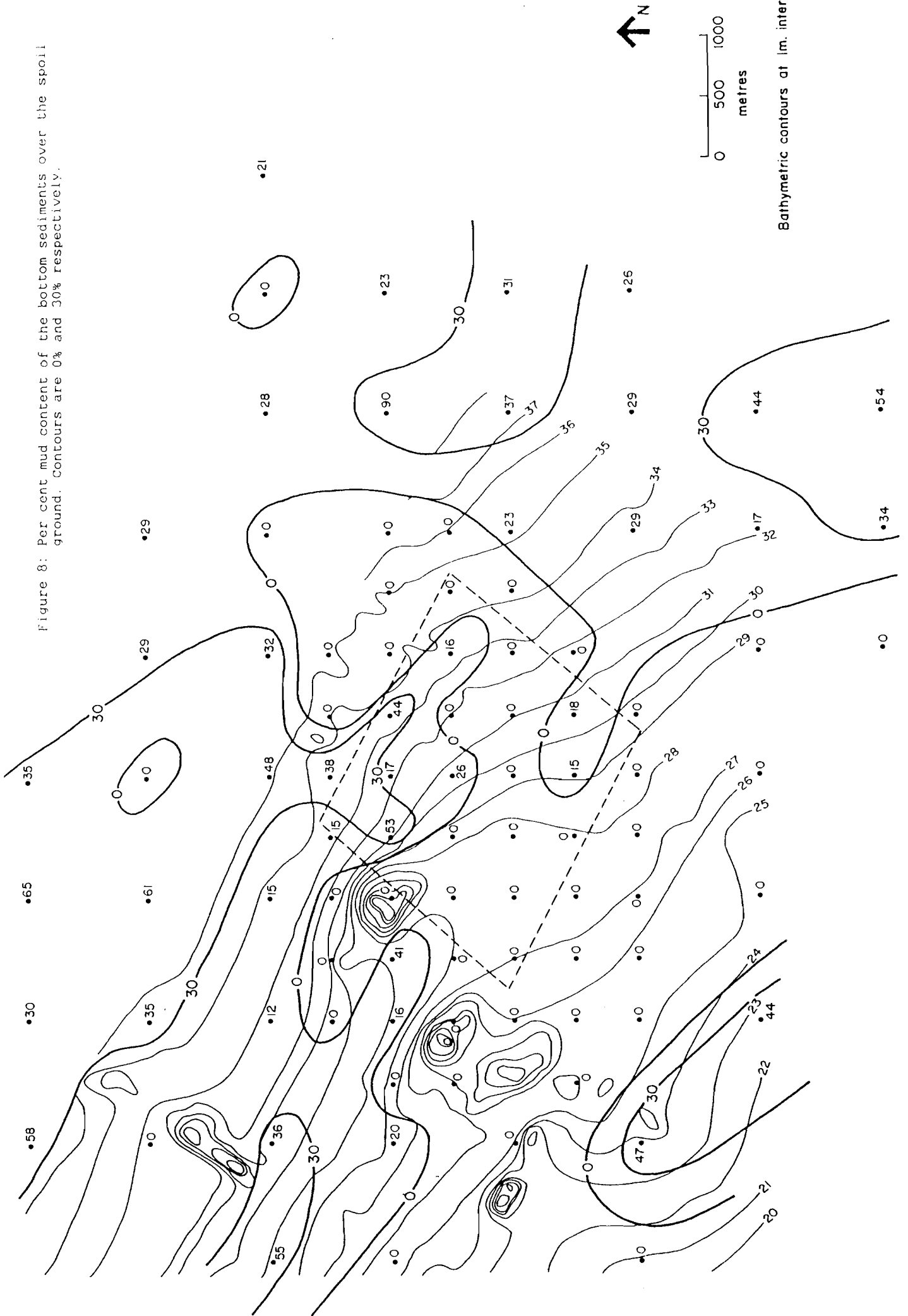
On the other hand, the mud content contained in the samples also appears to be extraneous to the present transport regime. Trends could not be determined with the mud content included in the size distributions. Figure 8 shows that concentrations of mud are also essentially random throughout the sediments and do not favour a particular depth or location. It is noteworthy that well over half of the ground itself contains no mud in its sediments (Fig.8).

Over the past 5 years the average composition of sediment dumped at the spoil ground is 28% sand and 72% mud (Hydraulics Research Ltd., pers. comm.). It must therefore be concluded that the muds are not becoming incorporated into the transport regime of the existing sediments and that they are being swept clear of the spoil ground altogether, undoubtedly to the southeast. It is possible that much of the dumped mud never reaches the bottom at this location, and its transport and deposition must be looked for elsewhere.

The trends show that active transport is occurring for the sand-size sediments, although the high gravel contents indicate a relatively sediment-starved environment. The  $R^2$  values for the lines outside the borders of the spoil ground are extremely high. The sudden drop in the  $R^2$  values for the lines crossing the spoil ground is due to the dumping of a new population of sand. The fact that trends are still observed for these lines indicates that the dumped sands are becoming incorporated into the natural deposits and being transported to the southeast.

The relatively high gravel content in the sediments throughout the area is a reflection of the proximity to bedrock and suggests a relatively sediment starved environment. The model did not determine

Figure 8: Per cent mud content of the bottom sediments over the spoil ground. Contours are 0% and 30% respectively.



any areas specific to a lag development suggesting winnowing and erosion; it is therefore concluded that this portion of the shelf is in dynamic equilibrium.

Most of the trends are Case B indicating a "low energy" transport environment with respect to the available size-distributions. The presence of several "high energy" transport lines (Case C) suggest coarser sediments in the direction of transport. The presence of Case C trends between the bedrock highs are due to a concentration of currents through the intervening "passes".

## 5.0 CONCLUSIONS

- (1) The spoil ground is located on an area of thin sedimentary cover consisting predominantly of sand with a random gravel content reflecting the close proximity to bedrock.
- (2) These sands are being actively transported in a net southeast direction approximately parallel to the bathymetry. Sand accumulates in the "lee" of bedrock highs producing "tails" in the southeast direction.
- (3) The prevailing or common "low-energy" processes transport very fine sand (3.0 phi and 3.5 phi, above and below 30m water depth respectively) the most easily.
- (4) High energy transport does occur, during which medium sand (2.0 phi) has the highest probability of being transported. High energy transport is most common in the valleys between bathymetric highs where currents are concentrated.
- (5) Gravel-sized material is not taking part in the present transport regime.

- (6) The sand portion (28%) of material presently being dumped at the spoil ground is incorporated into the existing sand transport regime and being removed towards the southeast.
- (7) The mud content (72%) of material being dumped is not incorporated into the existing transport regime and appears to be rapidly removed from the vicinity of the spoil ground. Present concentrations of mud taken in the sampling program probably reflect local accumulations that have occurred soon after a dumping event. They are overlying the sand and gravel and it can be expected that they will be rapidly removed towards the southeast.

#### 6.0 RECOMMENDATIONS

- (1) From the above it is clear that spoil from the Tees Estuary is not being contained within the boundaries of the designated spoil ground. If this is its purpose, the site should be abandoned.
- (2) For future monitoring programs, re-arrange the sampling grid so that the lines are parallel to and perpendicular to the bathymetry. This will maximize the information on sediment movement.
- (3) A reconnaissance sub-bottom profiling survey should be undertaken to the southeast to determine the locality of mud deposition derived from the spoil ground. Areas that are suspected to be receiving this mud should be sampled to confirm the sediment transport paths from the dumpsite. Until the location of this mud deposition is known, adverse affects of the spoil on the environment cannot be determined.

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### 8.0 ACKNOWLEDGEMENTS

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APPENDIX I

Sediment Transport Model

## APPENDIX I

## SEDIMENT TRANSPORT MODEL

The following is a brief review of the transport model, a detailed analysis of which is contained in McLaren and Bowles (1985).

## CASE A (Development of a lag deposit)

Consider a sedimentary deposit which has a grain-size distribution denoted by the function  $g(s)$  (Figure A-1), where "s" is grain size in phi units. If eroded, the sediment that goes into transport has a new distribution,  $r(s)$ , which is derived from  $g(s)$  according to the function  $t(s)$  so that:

$$r(s_i) = kg(s_i)t(s_i) \dots \dots \dots (1)$$

or

$$t(s_i) = \frac{r(s_i)}{kg(s_i)}$$

where  $g(s_i)$  and  $r(s_i)$  define the proportion of the sediment in the  $i^{\text{th}}$  grain-size class interval for each of the sediment distributions.

$k$  is a scaling factor that normalizes  $r(s)$  so that:

$$\sum_{i=1}^N r(s_i) = 1$$

thus:  $k = \frac{1}{\sum_{i=1}^N g(s_i)t(s_i)}$

With the removal of  $r(s)$  from  $g(s)$  the remaining sediment (a lag) has a new distribution denoted by  $d(s)$  (Figure A-1) where:

$$d(s_i) = k'g(s_i)(1-t(s_i))$$

or

$$t'(s_i) = \frac{d(s_i)}{k'g(s_i)} \text{ where } t'(s_i) = 1-t(s_i) \text{ and}$$

$$k' = \frac{1}{\sum_{i=1}^N g(s_i)(1-t(s_i))}$$

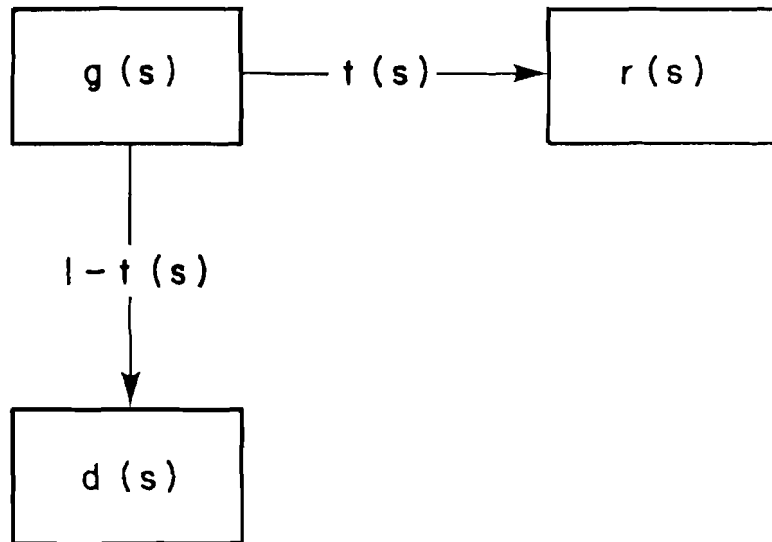


Figure A-1 : Sediment transport model to develop a lag deposit  
(see Appendix I for definition of terms).

The function,  $t(s)$ , is defined as a sediment transfer function and is described in exactly the same manner as a grain-size distribution function. It may be thought of as a function that incorporates all sedimentary and dynamic processes that result in initial movement and transport of particular grain sizes during a unit of time.

Data from flume experiments show that the distributions of transfer functions change from having a highly negative skewness to being nearly symmetrical (although still negatively skewed) as the energy of the eroding/transporting process increases. These two extremes in shape are termed low energy and high energy transfer functions respectively (Figure A-2). The shape of  $t(s)$  is also dependent, not only on changing energy levels of the process involved in erosion and transport, but also on the initial distribution of  $g(s)$  (Figure A-1). The coarser  $g(s)$  is, the less likely it is to be acted upon by a high energy transfer function. Conversely, the finer  $g(s)$  is, the easier it becomes for a high energy transfer function to operate on it. In other words, the same process may be represented by a high energy transfer function when acting on fine sediments, and by a low energy transfer function when acting on coarse sediments. The terms, high and low energy are, therefore, relative to the distribution of  $g(s)$ .

The fact that  $t(s)$  appears to be mainly always a negatively skewed function results in  $r(s)$ , the sediment in transport, always becoming finer and more negatively skewed than  $g(s)$  (Figure A-1). The function  $1-t(s)$  is, therefore, positively skewed, with the result that  $d(s)$ , the lag remaining after  $r(s)$  has been removed, will always be coarser and more positively skewed than the original source sediment.

If  $t(s)$  is applied to  $g(s)$  an infinite number of times (i.e. "n" times), then the variance of both  $g(s)$  and  $d(s)$  will approach zero (i.e. sorting will become better). However, depending on the initial

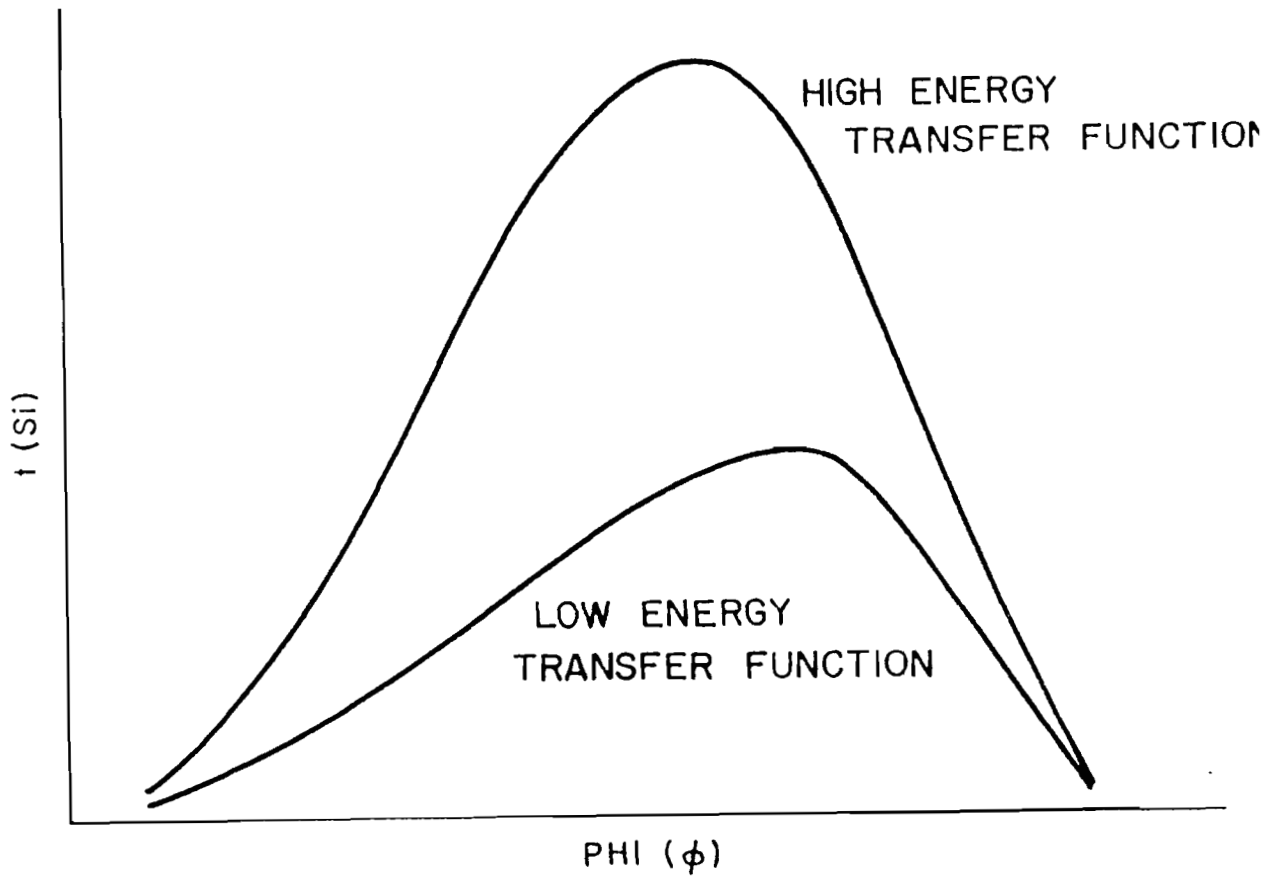


Figure A-2 : Diagram showing the extremes in shape of transfer functions ( $t(s)$ ).

distribution of  $g(s)$ , it is possible for variance to become greater before eventually decreasing. Because the phi scale produces approximately Gaussian or normal distributions which are symmetrical, it is probable that an increasing variance will rarely be observed.

Given two sediments,  $d_1(s)$  and  $d_2(s)$ , and  $d_2(s)$  is coarser, better sorted and more positively skewed than  $d_1(s)$ , it may be possible to conclude that  $d_2(s)$  is a lag of  $d_1(s)$  and that the two distributions were originally similar (Case A; Table A-1).

CASE B (sediments becoming finer in the direction of transport)

Consider a sequence of deposits ( $d_1(s), d_2(s), d_3(s), \dots$ ) that follows the direction of the sediment in transport (Figure A-3). Each deposit is derived from its corresponding sediment in transport, and according to the "3-box" model shown in Figure A-1, each  $d_n(s)$  can be considered a lag of each  $r_n(s)$ . Thus  $d_n(s)$  will be coarser, better sorted and more positively skewed than  $r_n(s)$ . Similarly, each  $r_n(s)$  is acted upon by its corresponding  $t_n(s)$  with the result that the sediment in transport becomes progressively finer, better sorted and more negatively skewed.

Any two sequential deposits (e.g.  $d_1(s)$  and  $d_2(s)$ ) may be related to each other by a function  $X(s)$  so that:

$$d_2(s) = kd_1(s)X(s) \text{ where } k = \frac{1}{\sum_{i=1}^N d_1(s_i)X(s_i)} \quad \text{(in order to normalize } d(s))$$

or 
$$X(s) = \frac{d_2(s)}{kd_1(s)} \dots \dots \dots (2)$$

As illustrated in Figure A-3,  $d_2(s)$  can also be related to  $d_1(s)$  by:

$$\begin{aligned} d_2(s) &= \frac{kd_1(s)t_1(s)(1-t_2(s))}{1-t_1(s)} \\ &= kd_1(s)X(s) \end{aligned}$$

where 
$$X(s) = \frac{t_1(s)(1-t_2(s))}{1-t_1(s)} \dots \dots \dots (3)$$

TABLE A-1: Summary of the interpretations with respect to sediment transport trends when one deposit is compared to another.

CASE	RELATIVE CHANGE IN GRAIN-SIZE DISTRIBUTION BETWEEN DEPOSIT $d_2$ AND DEPOSIT $d_1$	INTERPRETATION
A	coarser better sorted more positively skewed	$d_2$ is a lag of $d_1$ (No direction of transport can be determined)
B	finer better sorted more negatively skewed	(i) The direction of transport is from $d_1$ to $d_2$ (ii) The energy regime is decreasing in the direction of transport (iii) $t_1$ and $t_2$ are low energy transfer functions (Figure A-5)
C	coarser better sorted more positively skewed	(i) The direction of transport is from $d_1$ to $d_2$ (ii) the energy regime is decreasing in the direction of transport (iii) $t_1$ is a high energy transfer function (Figure A-5) (iv) $t_2$ is a high or low energy transfer function

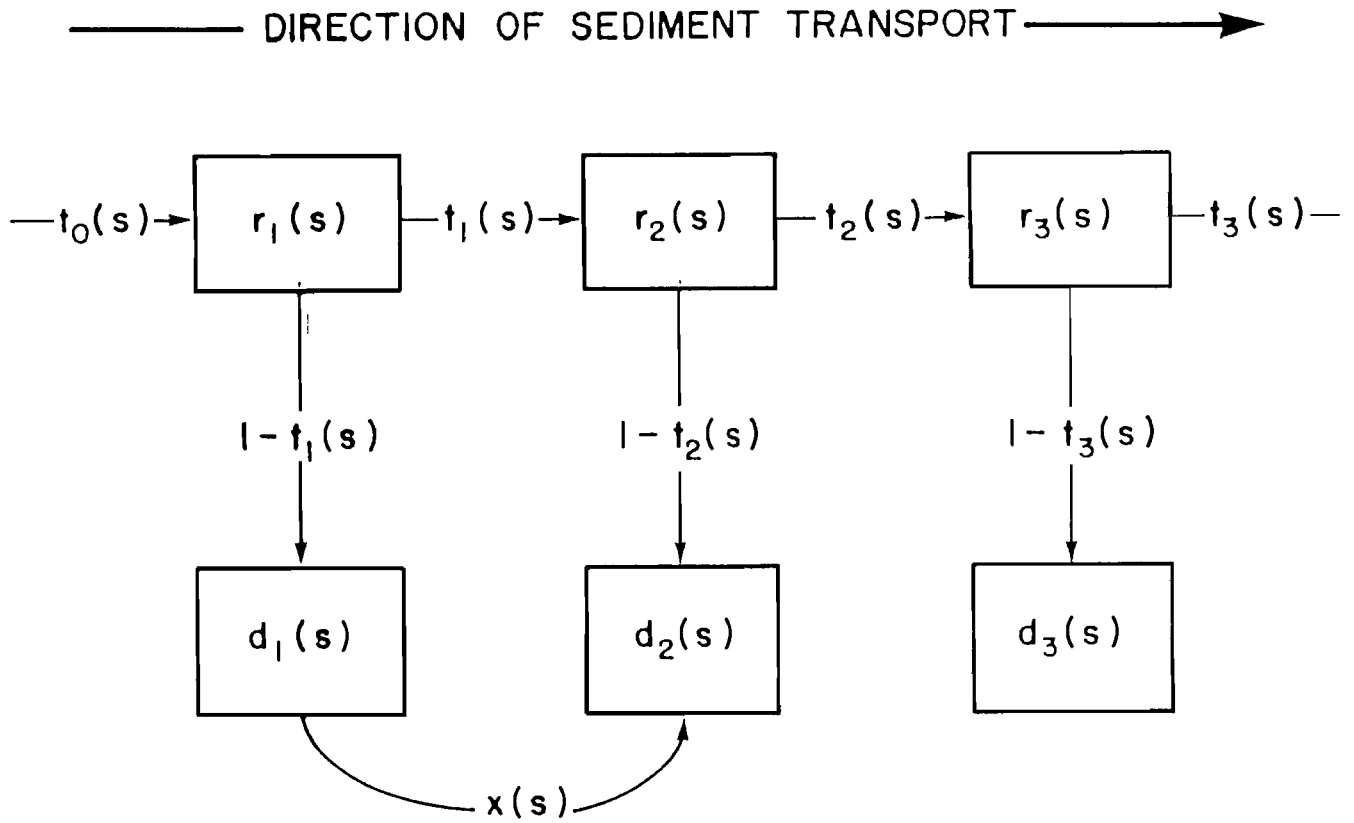


Figure A-3 : Sediment transport model relating deposits in the direction of transport (see Appendix I for definition of terms).

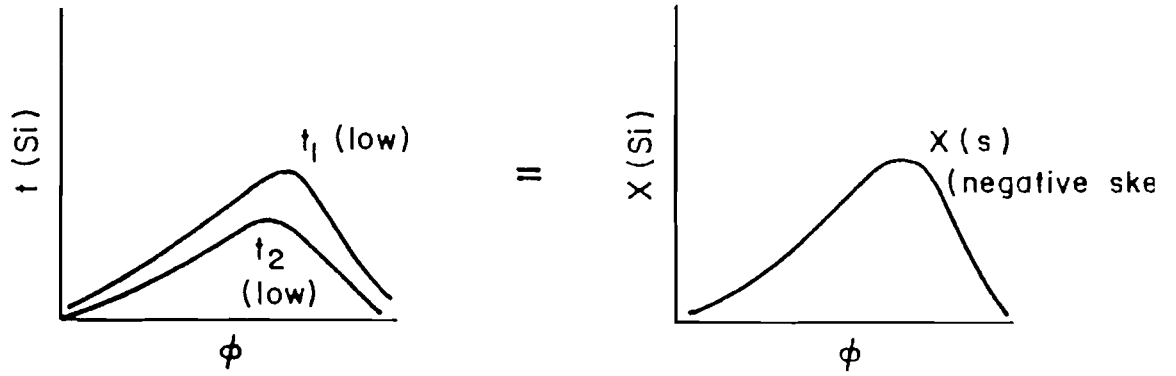
The function  $X(s)$  combines the effects of two transfer functions  $t_1(s)$  and  $t_2(s)$  (equation 3). It may also be considered as a transfer function in that it provides the statistical relationship between the two deposits and it incorporates all of the processes responsible for sediment erosion, transport and deposition over the period of time represented by the samples. The deposit  $d_2(s)$  will, therefore, change relative to  $d_1(s)$  in accordance to the shape of  $X(s)$  which, in turn, is derived from the combination of  $t_1(s)$  and  $t_2(s)$  as expressed in equation 3. It is important to note that  $X(s)$  can be derived from the deposits themselves (equation 2) and it provides the relative probability of any particular sized grain being moved.

Using empirically derived  $t(s)$  functions it can be shown that when energy is decreasing in the direction of transport (i.e.  $t_2(s) < t_1(s)$ ) and both are low energy functions (Figure A-4), then  $X(s)$  is always a negatively skewed distribution. This will result in  $d_2(s)$  becoming finer, better sorted and more negatively skewed than  $d_1(s)$ . Therefore, given two sediments,  $d_1(s)$  and  $d_2(s)$  and  $d_2(s)$  is finer, better sorted and more negatively skewed than  $d_1(s)$ , it may be possible to conclude that the direction of sediment transport is from  $d_1$  to  $d_2$  (Table A-1).

#### CASE C (Sediments becoming coarser in the direction of transport)

In the event that  $t_1(s)$  is a high energy function (Figure A-2), and  $t_2(s) < t_1(s)$  (i.e. energy is decreasing in the direction of transport), the result of equation 3 will produce a positively skewed  $X(s)$  distribution (Figure A-4). Therefore,  $d_2(s)$  will become coarser, better sorted and more positively skewed than  $d_1(s)$  in the direction of transport, and should this relationship be observed, it may be possible to conclude that the direction of sediment transport is from  $d_1$  to  $d_2$  (Table A-1).

CASE B:  $t_2 < t_1$ ; both low energy functions



CASE C:  $t_2 < t_1$ ;  $t_1$  is a high energy function;  $t_2$  is high or low

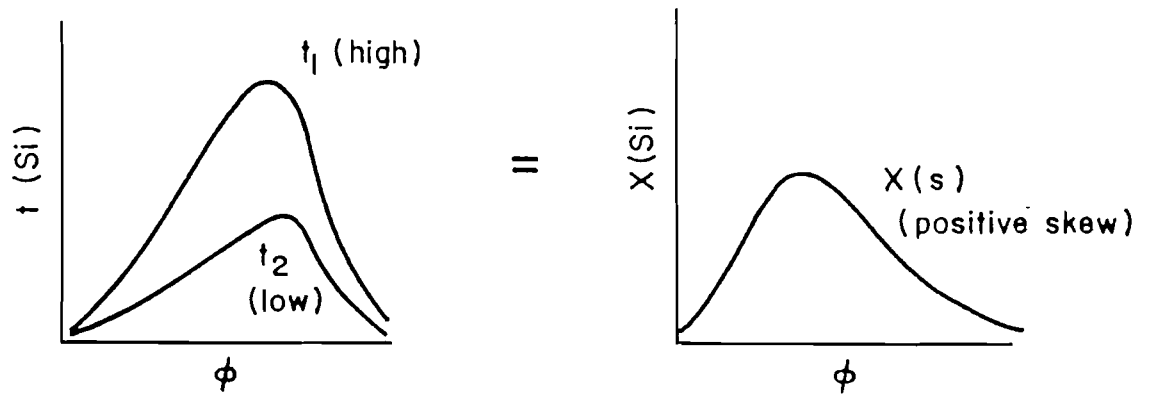


Figure A-4 : Summary diagram of  $t_1$  and  $t_2$  and corresponding  $X$ -distributions (equation 3) for Cases B and C (Table A-1).

It is interesting to note that sediments cannot become coarser forever because, with coarsening, it becomes less and less likely that the transport processes will maintain high energy characteristics. As the deposits become coarser, the transfer function describing the processes will revert to a low energy function with the result that the sediment must become finer again.

Cases A and C produce identical grain-size changes between  $d_1$  and  $d_2$  (Table A-1). Generally, however, the geological interpretation of the environments being sampled will clearly differentiate between the two Cases.

#### METHOD TO DETERMINE TRANSPORT DIRECTION FROM GRAIN-SIZE DISTRIBUTIONS

Clearly the model presented above does not result in perfect sequential changes of grain-size distributions in the direction of sediment transport, although numerous authors have recognized general changes in specific parameters (e.g. mean grain size or sorting). The model demands specific changes in all three parameters (mean, sorting and skewness) to suggest a transport direction. Given such complicating factors as variability in "original source", probable local and temporal variability in the transfer functions, and variable time intervals represented by the samples themselves, it is not surprising that sequential changes in grain-size distributions are seldom recognized.

One approach that appears to be successful in recognizing trends is a simple statistical method whereby the Case (Table A-1) is determined among all possible pairs in a sample sequence. Given a sequence of "n" samples, there are  $\frac{n^2 - n}{2}$  directionally-orientated pairs that may exhibit a transport trend in one direction, and an equal number of pairs in the opposite direction. When any two samples are compared with respect to their mean size, sorting and skewness, 8 possible trends exist; compared to  $d_1$ ,  $d_2$

may be: (i) finer (F), better sorted (B) and more negatively skewed (-); (ii) coarser (C), more poorly sorted (P) and more positively skewed (+); (iii) C, B, -; (iv) F, P, -; (v) C, P, -; (vi) F, B, +; (vii) C, B, +; or (viii) F, P, +. Of these trends, only two are of interest, namely F, B, - (Case B) and C, B, + (Case A or C), for which there is a 1/8 probability of either occurring at random ( $p = 0.125$ ). To determine if the number of occurrences that a particular Case exceeds the random probability of 0.125 the following two hypotheses are tested:

$H_0$  :  $p < 0.125$  and there is no preferred direction; and

$H_1$  :  $p > 0.125$  and transport is occurring in a preferred direction.

Using the Z-score (Spiegel, 1961) in a one-tailed test,  $H_1$  is accepted if:

$$Z = \frac{x - Np}{\sqrt{Npq}} > 1.645 \text{ (0.05 level of significance)..... (4)}$$

or  $> 2.33$  (0.01 level of significance)

where:  $x$  = observed number of pairs representing a particular Case in one of the two opposing directions;

$N$  = total number of possible unidirectional pairs.

( $N = n^2 - n$  where  $n$  = number of samples in the sequence);

$p = 0.125$ ; and

$q = 1.0 - p = 0.875$

The Z-statistic is considered valid for  $N > 30$  (i.e. a large sample). Thus, for this application, a suite of 8 or 9 samples is the minimum required to evaluate adequately a transport direction (i.e.  $\frac{9^2 - 9}{2} = 36$ , the total possible pairs in one direction).

