Environmental Aspects of Aggregate Dredging

Refined source terms for plume dispersion studies

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Report SR 548
March 1999

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Summary

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The UK marine aggregate industry for the recovery of sand and gravel currently extracts an average of 24 million tonnes per annum. The UK Department of Environment, Transport and the Regions has issued guidelines for the environmental assessment of marine aggregate dredging proposals which indicate that the transport and outwash of fine sediment resuspended by dredging activities require consideration.

During aggregate dredging a small proportion (typically a few percent by mass of the overall load) of fine bed material (<63μm) is introduced into the water column and is then dispersed in the form of a plume. HR Wallingford was commissioned by the Department of the Environment to undertake a study to improve the understanding of the processes associated with the release of fine material during aggregate dredging. The knowledge gained from this study will be used to improve predictive capability so that the environmental aspects of future aggregate dredging proposals can be better assessed.

Small amounts of fine material may be put into the water column at several stages during aggregate dredging. These include the disturbance created by the draghead as material is pumped from the bed, the overflow through the spillways when an "all-in" load is being collected and the overflow through the reject chutes and the spillways during dredging for a "screened" load. Additionally some fine material will inevitably be conveyed with the aggregate to the shore and may later be washed or transported back into the marine environment.

The effect of dredging operations on the dispersion of fine material has received greater attention in recent years. These research programmes have included basic research in the UK, Netherlands, USA and Hong Kong. Whilst much of this research is generic, only work in Hong Kong and the UK relates to sand winning and it is only in the UK that research has been undertaken on the extraction of marine gravel sources.

One of the key findings of this recent research, and the starting point for the work described in this report, is the fact that on board observations of the masses of material released from a dredger demonstrate significantly greater amounts of material being lost from the dredger than can be found when monitoring the fluxes of sediment within plumes generated by the dredging operation.

Summary continued

Two hypotheses have been suggested to explain the rapid descent of material from the water column during this dynamic phase of the plume generation. The first is that the rapid descent is due to increased settling velocity caused by the fine material being aggregated together or with coarser material. The second is that it is due to the initial momentum of the discharge and the greater density of the discharged plume than the surrounding water. These two hypotheses have been tested in the course of this study using field experiments and computational modelling of the dynamic phase of the plume behaviour. The results of these investigations identified the initial momentum of the discharge and negative buoyancy as being the most important factors in the initial dispersion phase for the cases tested.

The passive phase of dispersion of plumes arising from dredging activity can be modelled using a spectrum of approaches. Each of the approaches is extremely reliant on the accuracy of the estimate of the amount of material initially entrained into the water column as a result of the dynamic phase of the plume generation and dispersion. The selection of which approach to use is dependent on the circumstances of the study and information desired from the analysis. Three main approaches have been considered in this study, the desk analysis approach, the advection/diffusion model and the process-based model. A comparison of these models has shown that under non-uniform flow conditions or where long term simulation periods (a number of tidal cycles) are required or where resuspension process are important, desk analysis and diffusion/advection models are not reliable predictors of plume behaviour.

A further recent advance has been field measurement campaigns using bed frame instrumentation which has improved our understanding of natural suspended solids concentrations in offshore waters, particularly during relatively rough weather conditions. The data gained from such monitoring has suggested that natural variation of suspended sediment concentrations can be larger than the effects of dredging plumes.

The results of this study have already been used in practice on behalf of the UK aggregate dredging industry with respect to improving the assessment of the environmental impact of aggregate dredging

For further information on this study please contact Dr Mike Dearnaley of the Ports and Estuaries Group at HR Wallingford.

Contents

Contents continued

Tables

Contents continued

Contents continued

Plates

Contents continued

Part 1

INTRODUCTION

PART 1 Introduction

1. INTRODUCTION

1.1 Background

Over the past decade the UK marine aggregate dredging industry for the recovery of sand and gravel currently has extracted an average of 24 million tonnes per annum (Reference 1). Slightly over half of this resource is landed on the south and east coasts representing a third of the UK construction sand and gravel requirements. Marine aggregates are becoming more important because of increasing constraints on land based quarrying and the UK government is promoting the use of the marine resource and expects that by the year 2006 production will have increased to 30 million tonnes.

The UK Department of Environment, Transport and the Regions has issued guidelines for assessing marine aggregate dredging proposals. These indicate that the transport and outwash of fine sediment resuspended by the dredging and the effects of onboard screening and grading require consideration.

The aggregate industry has suffered in the past from poor public perception. Whilst much has been done to allay this concern, aggregate dredging is generally viewed in the same manner as all dredging activities, namely that it is as a dirty operation (Plate 1.1) and environmentally damaging. There is thus a requirement for considerable education of all concerned with respect to the real effects of aggregate dredging activities. During aggregate dredging a significant proportions of the mass dredged is returned to the water column via spillways and reject chutes. Most of this material is in the sand size fraction (0.063mm to 2mm) and only a small proportion (typically a few percent of the overall load) is fine material (<0.063mm). It is the finest material that is most likely to contribute to far-field impacts away from the dredging zone in terms of increases in turbidity and the possibility of blanketing of the seabed.

Fine material resuspended by the dredging activity is dispersed in the form of a plume. Such plumes are advected and dispersed by a number of mechanisms, resulting in increases in suspended sediment concentrations above background levels and deposition on the sea bed. The dispersion of such plumes has been modelled through a variety of approaches but only in recent years has field data become available against which such models have begun to be sensibly tested. The field research has indicated that the initial dynamic phase of dispersion, the behaviour of material discharged from the dredger just after release into the water column, is both complex and of primary importance to the resulting turbidity of the dredging plume.

In 1996 HR Wallingford was commissioned by the Department of the Environment (39/5/103, cc1037) to undertake a study to improve the understanding of the processes associated with the release of fine material during aggregate dredging. The knowledge gained will be used to improve predictions of plume dispersion so that future environmental assessment of aggregate dredging operations can be improved.

1.2 Objectives

The objective of this study is to improve the understanding of and the ability to predict the environmental impact of turbidity generated during aggregate dredging operations. To fulfill this overall objective the following specific aims were identified:

- To obtain and review field measurements of the dispersion of fine material around typical examples of the UK aggregate dredging fleet.

- To obtain field measurements of the settling velocity of the fine material released into the water column during aggregate dredging operations

- To undertake laboratory measurements of the particle size distribution of the material released into the water column during aggregate dredging operations

- To undertake field measurements of the natural suspended sediment concentrations occurring during offshore storm conditions at UK licensed areas.

- To parameterise the physical processes described above for use in predictive studies.

1.3 Structure

This report is divided into four parts. Part 1, comprising Chapters 1 to 4, forms the introduction to the report, explaining the background to the present study in the context of the state of the present aggregate industry. The processes involved in the generation of plumes during dredging are discussed and different predictive approaches for modelling sediment plume dispersion are described. Part 2, comprising Chapters 5 to 7, contains descriptions of a number of field surveys monitoring dredging discharges and associated suspended sediment increases undertaken during dredging operations and discusses the knowledge gained from this data collection. Measurements of background sediment concentrations experienced in the vicinity of some of the UK's dredging sites are also presented. The results of Part 2 lead to the identification of specific mechanisms of preferential settling which are then investigated in more detail in Part 3. These investigations take the form of an experiment to identify the relative importance of aggregation during the initial phase of plume discharge from the dredger (Chapter 8) and numerical modelling carried out to examine the effects of momentum and density-induced settling during this initial phase (Chapter 9). Finally, in Part 4, (Chapter 10), the different approaches to plume dispersion modelling are compared and conclusions drawn about their best use. The conclusions arising from the study are presented in Chapter 11 together with recommendations for further work.

2. AGGREGATE DREDGING IN THE UK

2.1 Background

Marine aggregates are found in many locations around the coastal waters of Great Britain on the Continental Shelf. They make an essential contribution to the national supply of aggregates for the construction industry, which are used in all types of construction. The industry uses modern and sophisticated equipment, which requires multi-million pound investments in ships and wharves, and directly employs about 2,500 people.

2.2 Description of UK aggregate dredging fleet

The UK aggregate industry fleet comprises about 50 vessels, owned by a variety of companies (Reference 2). Most of the fleet dates before 1975 but there are recent additions. The capacity of the vessels varies between 280m^3 and 3000m^3, with only two vessels exceeding this capacity, The Arco Humber (4000m^3) and The Camdijk (5100m^3). The vessels are mostly self-discharging, using shipcranes, pumps, scrapers, bucket wheels and bottom dumps to offload their cargo. Spillways are generally above the water line except for the most modern additions to the fleet.

Aggregate dredging, in particular winning material for beach nourishment often involves vessels from the main Dredging Contractors. The capacity of the contractor fleet vessels varies up to 23,500m^3. Unlike the aggregate industry vessels the contractors vessels are generally characterised by having a central spillway discharging below the keel.

Dredging takes the form of a series of runs back and forth across the area of deposit being worked. Each run leaves a smooth groove in the sea bed a few metres wide, depending upon drag head size, and 20-30cm deep. The dredging vessel moves along the bed trailing the draghead at a speed of 1-3 knots. The dredger may load an "all-in" cargo or a "screened" cargo. An "all-in" cargo is one where there is no additional selective processing of material as it enters the hopper and the material in the hopper will be broadly representative of the particle size distribution of material on the sea bed. A "screened" cargo is one where the material is sorted before it enters the hopper and some of the material is discarded back into the sea. In this case the material in the hopper on completion of the loading will be either finer or coarser than that on the sea bed depending on whether the screening was for sand or gravel, discarding coarser or finer material respectively. Irrespective of whether the load is 'all-in' or 'screened' there will be some overflow of material via spillways in the hopper as the hopper is filled to achieve an economic load. The more modern vessels are able to dredge in up to 50m of water and can load up to 2,500 tonnes/hour from depths of 35m. The larger vessels operated by the Contractors are often equipped with drag arms on both sides of the vessel. Most of the aggregate industries vessels only operate a single drag arm.

3. MECHANISMS FOR ENTRAINMENT OF FINE MATERIAL INTO WATER COLUMN DURING AGGREGATE DREDGING

During aggregate dredging operations material is resuspended into the water column via three main processes:

- Disturbance of seabed by the draghead
- Overflow from the spillways, a process designed to maximise the aggregate load in the hopper
- Losses through reject chutes when material is being screened

The first of these processes is not considered within the scope of this study as the most significant releases of fine sediment into the water column are as a result of overflow and screening losses.

There have been few attempts to quantify the amount of fine material that is lost into the water column during aggregate dredging operations. Typically in the UK a deposit that is a suitable sand or gravel source will contain only a few percent of fine (<0.063mm) material. In contrast in Hong Kong some deposits have been worked as viable sand sources where there have been much higher proportions of fine material.

As a starting point for an assessment of impact it might be assumed that all the fine material encountered by the dredging process is disturbed and released back into the water column to be dispersed in the form of a plume. The following example calculations illustrate this point:

<u>A typical screened cargo in the UK</u>

- cargo load 4000 tonnes
- time to load 4.5 hours
- estimated total amount of material disturbed from bed during loading 12000 tonnes
  (This includes material overflowing from spillways, material rejected by screening process, material disturbed by draghead, as well as the material loaded into the hopper)
- proportion of fines in the bed material 3%

In this case a total of 360 tonnes of fines would have been released into the water column during the loading. If this were at a uniform rate the rate of release of fines would have been about 22kg/s.

<u>A typical 'all in' cargo in the UK</u>

- cargo load 4000 tonnes
- time to load 2.25 hours
- estimated total amount of material disturbed from bed 6000 tonnes
  (including material overflowing from spillways and material disturbed by draghead)
- proportion of fines in the bed material 3%

In this case a total of 180 tonnes of fines would have been released into the water column during the loading. If this were at a uniform rate the rate of release of fines would have been about 22kg/s.

Sand winning in Hong Kong

- cargo load 11500 tonnes
- time to load 1.5 hours
- estimated amount of material disturbed 15000 tonnes
  (including material overflowing from spillways and material disturbed by draghead)
- proportion of fines in the bed material 10%

In this case a total of 1500 tonnes of fines would have been released into the water column during the loading. If this were at a uniform rate the rate of release of fines would have been about 280kg/s.

The results of field investigations in the UK have demonstrated that this assumption is overly conservative. Typically a small fraction (say 0.5 to 1.0%) of fines remains in the load and is transported ashore. Spillway measurements and measurements in the reject chutes from screening have been used to quantify the rates of material lost from the dredger. The most important results however, are those made in the plume of material arising from dredging activity. Measurements of suspended solids concentrations within the plumes clearly demonstrates a significant reduction, perhaps as much as an order of magnitude, of the amount of fine material in the plume compared to that which was released from the spillways and reject chutes.

There are two possible reasons why the amount of fines lost from the dredger is greater than that found within the plumes generated by the dredging operation. Both of these mechanisms occur during an initial stage of plume formation. The plume generation process consists of two phases: a dynamic stage and a passive stage. The dynamic stage occurs rapidly (a matter of a few minutes) so that it is simply not possible or safe to attempt measurements of processes occurring during this stage. All measurements of concentrations within the plume are made once the plume has attained its passive phase.

The two processes that may account for the reduction in fines observed in the passive plume compared to what was lost from the dredger are:

- Some of the fine material discharged into the water through spillways, or as a result of screening is still bound to other larger particles and therefore settles preferentially (at higher settling rates) onto the bed rather than dispersing throughout the water column

- The jet of fine material entering the water column has an initial momentum which enables this body of water to move rapidly downwards, especially where discharge is via the ship hull since under these conditions discharges are correspondingly higher than during overspill. Furthermore because this sediment laden water has a greater density than the underlying water, it accelerates downwards under the influence of gravity. Although mixing occurs between the sediment laden water and the surrounding water, the amount of material left in the water column may be small compared with the material that descends to the bed. The fine material descending to the bed may be resuspended depending upon the local hydrodynamic conditions.

One of the objectives of the present study is to identify the importance of these two processes. As part of the present study HR, in collaboration with various dredging contractors, made in situ measurements of dredging discharges and of increases in suspended sediment concentrations during dredging operations. The results of these field measurements are described in Part 2.

4. METHODS FOR PREDICTION OF PLUME DISPERSION

4.1 Introduction

There are three common methods for considering the dispersion of material resuspended from dredging, each of which involves a different level of analysis:

- A desk analysis involving tidal excursion lengths and residual currents to identify the areas likely to be affected by the plume
- Use of a basic advection/diffusion model to establish an initial estimate of suspended sediment concentration increases and potential deposition
- Full 2D/3D process modelling of sediment transport

Although the choice of approach depends on the nature of the study, these approaches are not exclusive of one another and best practice usually entails an initial appraisal followed by a more in-depth study. The type of results obtained for each of these methods on different dredging operations is considered in Part 4, in Chapter 10.

Although these tools differ as to the level of analysis, the quality of the results determinable by each of the approaches is hugely dependent on the quality of knowledge of the initial conditions, in particular, the mass and rates of input of sediment initially introduced into the water column. In most plume dispersion models this loss of sediment into the water column is described by a "loss rate". To date such loss rates have, where the information is available, been derived by calculating or estimating the mass rate of discharge through the spillways or screening reject chutes and assume that all of this material is entrained into the water column. Unfortunately, as discussed in Chapter 3, this information is usually an overestimate of real "loss rates" as a significant proportion of this material descends rapidly towards the bed. The resulting predictions of suspended sediment concentrations and deposition from process modelling are therefore also over-predictions. However, it should be noted that this shortcoming does not affect the suitability of the process modelling approach, but rather demonstrates the need for more realistic initial conditions for input into these modelling tools. As understanding of the initial conditions of dredging plumes increases, the reliability of the modelling results will correspondingly increase.

Best practice therefore requires acknowledgement of the uncertainty of input rates to the passive stage of the dispersion and the use of a range of input rates to demonstrate the consequences of this uncertainty.

4.2 Desk analysis

Desk analysis of dispersion from aggregate dredging operations involves an initial appraisal of the plume dispersal resulting from dredging. In such a study one might consider the following:

- The type of sediment being dredged
- The system of dredging
- The likely proportion of material that might be lost to the water column
- The magnitude of background suspended sediment concentrations
- The likely settling velocity of the released material
- The speed and direction of currents at the point of dredging
- The tidal excursion (based on the measured speeds)
- The residual movement of the plume (based on the measured speeds)

Mechanisms not considered

- Dispersion of the sediment plume
- Spatial (vertical and horizontal) variation in velocity fields
- The ability of currents to prevent settling and to resuspend sediment

- Vertical turbulence (movement of sediment up and down the water column)
- Variation in concentration through the vertical profile
- Initial density-induced rapid downward movement of the plume

Desk analysis enables the identification of the likely areas that will be affected by the plume, an initial estimate of the amount of material that may be lost into the water column and an upper limit for the deposition of material away from the release point. Much of the work undertaken during desk analysis constitutes a necessary part of the preparation for computational modelling studies.

4.3 Advection/Diffusion modelling - GAUSSIAN

The advection/diffusion modelling method provides an economical means of predicting the dispersion and settling of a plume of suspended cohesive material in a large uniform area. There are a number of simplifying assumptions inherent in such methods but they provide a more accurate numerical estimate of the increases in concentration and of an upper limit for deposition than the desk analysis approach.

One example of this type of approach is the GAUSSIAN model (see Appendix 1). GAUSSIAN represents the processes of advection by currents, settling of the sediment through the water column and the diffusion of suspended material due to the natural turbulence in the flow. The flow within the water area under investigation is assumed to be uniform and uni-directional along a single axis direction. The depth in the area of interest is also assumed to be uniform. Diffusion along and perpendicular to the direction of flow are input parameters, with the former significantly greater than the latter.

The method assumes the initial uniform distribution of released material through the water column of the sediment and models the settling of material on the bed as a steady stream of material under conditions where shear stress is below the threshold for deposition. The method does not allow for the resuspension of sediment from the bed as slack water ends and current speeds pick up. The deposition predicted by the method is thus an upper limit.

Mechanisms not included:

- Spatial (vertical and horizontal) variation in velocity fields (Such variation will increase dispersion)
- Vertical turbulence (movement of sediment up and down the water column)
- Variation in concentration through the vertical profile
- Re-erosion of material from bed
- Initial density-induced rapid downward movement of the plume

4.4 Process modelling - SEDPLUME

2D and 3D process modelling enables a more realistic estimate of the increases in suspended sediment concentration and of deposition than the advection/diffusion model described above. In particular the inclusion of spatial variation in current velocity, and the processes of turbulent diffusion and resuspension of material from the bed can greatly improve the description of plume movement. However, the accuracy of process modelling is hampered by the poor state of knowledge of the initial conditions of the released material, in particular in terms of the amount of sediment lost during the dredging process that is initially released into the water column to be advected and dispersed. This is the subject of ongoing research by a team being lead by HR Wallingford for Dutch Dredging Contractors.

One example of process modelling is the HR SEDPLUME model (explained in detail in Appendix 2). Briefly, the model uses the hydrodynamic output from a flow model and the assumption of a logarithmic velocity profile through the water column, or if required, 3D hydrodynamic output, to track the 3 dimensional movement of sediment particles. Dispersal in the direction of flow is provided by the shear action of differential speeds through the water column while turbulent dispersion is modelled using a random walk technique. The deposition and resuspension of particles are modelled by establishing critical shear stresses for erosion and deposition. Resuspension occurs when the bed shear stress exceeds the critical shear stress for erosion while deposition occurs when the bed shear stress falls below the critical shear stress for deposition.

The SEDPLUME model does not account for the initial rapid movement of the released plume due to its initial momentum and greater density than the underlying fluid. The model uses an initial condition whereby the material is distributed in a gaussian fashion over a specified radius, uniformly distributed throughout the water column or at a specified height above the bed. Where more information about the likely distribution of sediment just after release is known, SEDPLUME will give a more accurate representation of the initial movement of the sediment plume than GAUSSIAN, although it is more common that little is known about the initial circumstances of sediment release.

Assumptions:
Logarithmic velocity profile (when using 2D hydrodynamics)
Depth-averaged suspended sediment concentrations (when using 2D hydrodynamics)

Mechanisms not included:
Initial momentum or density-induced rapid downward movement of the plume

These different predictive methods are compared with respect to different dredging conditions in Chapter 10.

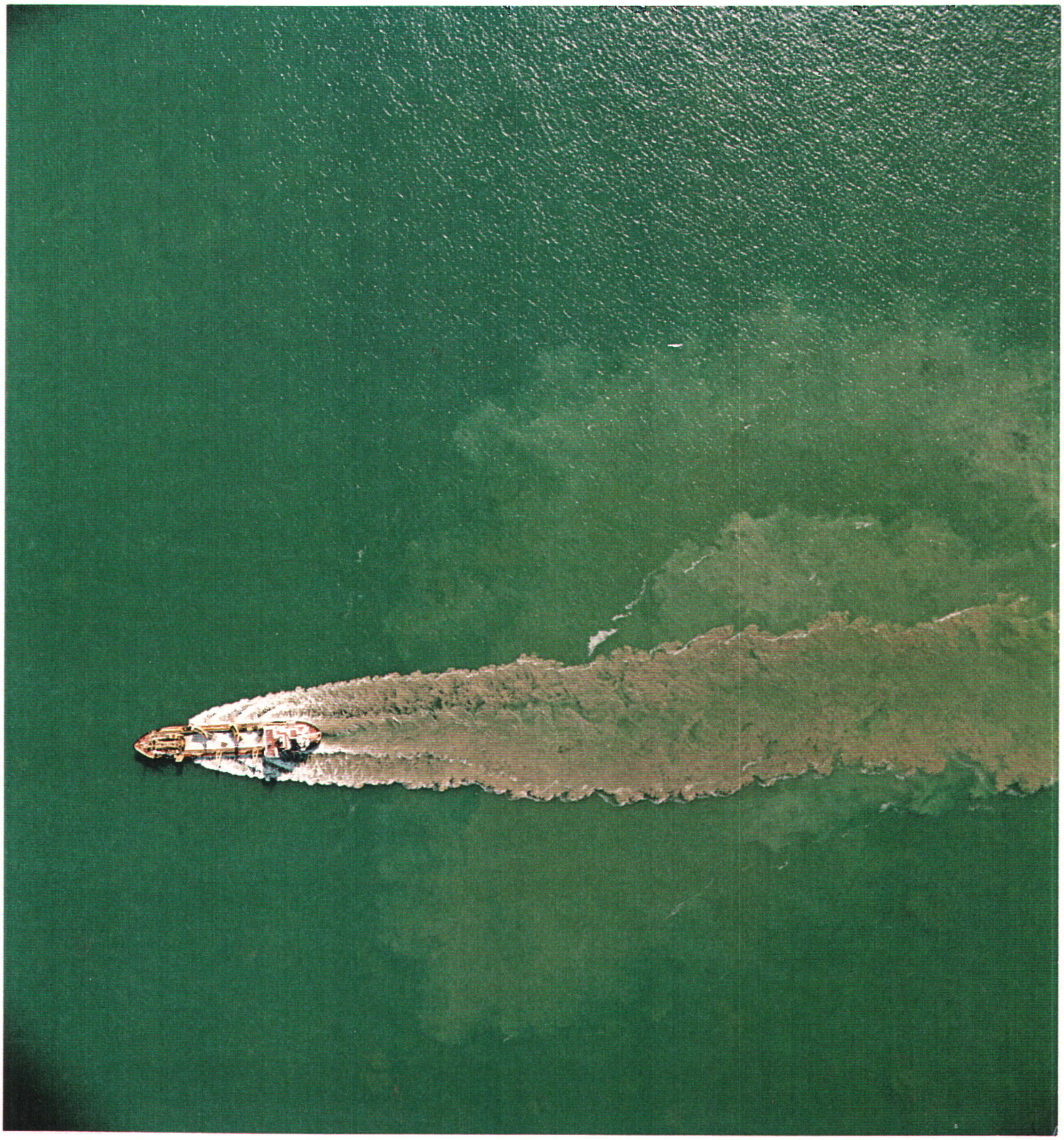

Plate 1.1 **Resuspension of discharged material into water column during dredging operations**

Part 2

FIELD MEASUREMENTS

5. MEASUREMENTS OF SPILLWAY AND REJECT CHUTE LOSSES

5.1 Great Yarmouth/Lowestoft

ARC Marine Ltd have been co-operating with Coastline Surveys and the University of Wales, Cardiff through an ongoing research project to investigate overboard discharges during dredging operations (Reference 3). Samples were taken to measure the quantity of solids being lost from the overflow spillways and reject chute during aggregate dredging 20km off the east coast of the UK between Great Yarmouth and Lowestoft. The bed material at the trial location comprised sandy gravel on or just below the seabed, and screens were used to divert water plus a proportion of material less than 5mm in diameter overboard such that the resulting load was 60% stone and 40% sand.

The proportion of losses for the various size gradings through the spillway and the reject chute are summarised in the following table (see also Reference 4).

Table 2.1 Proportional losses of sediment particle fractions from spillway and reject chute during dredging operations at Great Yarmouth and Lowestoft

Particle Size (mm)	Proportion in discharge (%)	
	Spillway	Reject chute
<0.063	38.0	1.0
0.063-0.125	14.0	0.9
0.125-0.250	5.7	8.9
0.250-0.500	12.9	31.4
0.500-1.000	9.2	27.3
1.000-2.000	3.3	12.0
>2.000	16.9	18.5

The actual quantities of material lost through the spillways or diverted overboard by screening were calculated. This was done using typical performance values for the IHC 700mm cargo pumping system installed onboard an "A" class vessel, together with the concentrations of solids from the samples taken during loading from both the spillways and reject chute.

The average loading time when screening for stone was 4.83 hours, and 12,158 tonnes of dry solids and 33,356 tonnes of water was pumped by the cargo pump. Of this mixture 4,185 tonnes of dry solids was retained in the vessel's cargo hold with 7,235 tonnes of dry solids being diverted overboard via a reject chute from the screening process. A further 750 tonnes of dry solids was lost through the vessel's overflow spillways, giving a total loss of about 66% of the material picked up from the bed. These results are summarised in the following table.

Table 2.2 Sediment losses during dredging operations at Great Yarmouth and Lowestoft

	Dry solids (tonnes)	Water (tonnes)
Quantity pumped	12,200	33,300 - 33,400
Quantity retained	4,200	800 - 900
Quantity rejected via screening	7,200	13,450 - 13550
Quantity lost via spillways	800	21,350 - 21,450
Total Losses	8,000	34,800 - 35,000

Based on this information it can be seen that via the spillways approximately 35kg total of dry solids per m^3 of water is returned to the water column and via the screening chute some 535kg total of dry solids per m^3 of water is returned. The percentage of fines (<0.063mm) released is significantly different between the two inputs with the resultant that over the 5 hour period the average rate of input of fines to the water column is about 20kg/s.

5.2 Hastings

Comparative figures of losses from a hopper estimated by the Dredging Companies were provided as input to a previous HR study of Shingle Bank, Hastings (Reference 4). This operation did not involve screening and so the overall losses were considerably less at about 6% of the material picked up from the bed.

The Hastings study concluded that some 11kg total dry solids per m^3 of overspill passed over the spillways during a 2.5 hour dredging period when a total mass of 4,400 tonnes of dredged material was recovered. Of this total 4,150 tonnes was retained and 250 tonnes was washed out during dredging (130 tonnes of silt/clay and 120 tonnes of sand). The average rate of input of fines to the water column in this case was about 14kg/s. The particle size breakdown of the material lost overboard in the Hastings study is summarised in the following table.

Table 2.3 Proportional losses of sediment particle fractions during dredging operations at Hastings

Particle size (mm)	Proportion in overflow (%)	Maximum mass lost overboard during one hopper load of 4,150t (tonnes)
<0.063	52.3	130.8
0.063-0.125	8.7	21.8
0.125-0.250	18.1	45.3
0.250-0.500	19.0	47.5
0.500-1.000	1.8	4.5
>1.000	0.3	0.8

5.3 Hitchcocks measurements (Reference 5)

Extending the work described in Section 5.1 Hitchcock, using a variety of methods, analysed the discharge (spillway and screening reject chute) loads of a number of dredging cargoes and derived the following representative efficiencies (ie ratio of load retained to quantity of sediment pumped) for ARC Marine "A" class vessels, (Table 2.4).

Table 2.4 Loading efficiencies for ARC Marine "A" class vessels

Cargo Type	Efficiency
No screening (all in)	93%
Screening for sand (stone out)	58%
Screening for stone (sand out)	34%

Hitchcock also used the data to produce representative particle size breakdowns for spillway and reject chute discharge, (Tables 2.5 and 2.6) although these representative values can be the product of considerable variation. Proportions of fine material within the same licensing area were found to vary by up to an order of magnitude.

Table 2.5 Proportions of materials in overspill discharge from two different dredge vessels

Particle size (mm)	Combined cargoes		Sand Cargo Only		Stone cargoes		All-In cargo only	
	"A" class	"S" class	"A" class	"S" class	"A" class	"S" class	"A" class	"S" class
< 0.063	39.3%	22.2%	18.4%	n/a	42.7%	22.7%	n/a	22.0%
0.063-0.125	14.3%	15.3%	5.2%		15.8%	16.9%		12.7%
0.125-0.025	8.2%	34.6%	24.5%		5.4%	35.6%		32.8%
0.025-0.5	14.5%	24.5%	36.8%		10.8%	22.2%		28.3%
0.5-1.0	8.1%	2.4%	9.7%		7.8%	1.9%		3.2%
1.0-2.0	2.8%	0.5%	2.8%		2.8%	0.4%		0.5%
>2.0	12.8%	0.5%	2.6%		14.7%	0.3%		0.5%

Table 2.6 Proportions of materials in reject discharge measured from "A" class dredge vessels

Particle size (mm)	Sand cargo only	Stone cargoes
< 0.063	0.1%	1.0%
0.063-0.125	0.2%	0.9%
0.125-0.025	2.1%	8.9%
0.025-0.5	10.1%	31.4%
0.5-1.0	9.9%	27.3%
1.0-2.0	4.1%	12.9%
>2.0	73.5%	18.5%

5.4 Summary of UK spillway measurements

Based on the spillway measurements that have been made on behalf of the Dredging Companies the following table has been proposed for use.

Table 2.7 Summary of spillway measurement losses

Material size (mm)	Rate* of input to water column (kg/s)
<0.063	14 – 20
0.063-0.125	2 – 10
0.125-0.250	5 – 40
0.250-0.500	5 – 136
0.500-1.000	1 - 118
>1.000	0 - 135

*The lower of the two quoted values applies to the case of loading all-in, the higher value corresponds to the case of screening.

6. PREFERENTIAL SETTLING DUE TO AGGREGATION AND MOMENTUM

6.1 Introduction

There is evidence (see Chapter 3) to suggest that during the initial phase of dispersion aggregation of fine sediment and/or the momentum-induced rapid settling of the material significantly reduces the proportion of sediment initially entrained into the water column. This evidence results from a number of suspended sediment monitoring surveys carried out during dedging operations. The measurements were not all taken during aggregate dredging operations, some of the measurements occurring during maintenance dredging operations in approach channels and berths. However, the conclusions of the studies were the same – that there is rapid descent of material towards the bed during the initial stages of plume generation after release.

In this chapter the evidence from some of these measurement campaigns is presented.

6.2 Measurements for the Owers Bank Study

In 1995 HR Wallingford, Coastline Surveys and the main UK Aggregate Dredging Contractors carried out a dedicated field survey in the English Channel using ADCP and water sampling techniques. This examined suspended solids concentrations in the plumes of material resuspended during dredging as a means of verifying and refining the predictive techniques adopted in earlier environmental assessments of the impact of turbidity generated during dredging. The results of this study are described in Hitchcock (Reference 5), HR Wallingford (Reference 6), and Hitchcock and Dearnaley (Reference 7). The measurements obtained can be summarised as follows:

- Approximately 150 ADCP transects providing through depth current speed and direction and backscatter data.(which can be processed to give additional information regarding suspended sediment concentrations).
- Approximately 150 water samples subsequently analysed for total solids content, sand/silt content and particle size distribution .
- Optical silt monitor output during measurements (approximately 12 hours of output at 2 second intervals).

- Six bed grab samples from one of the vessel tracks.
- Opportune underwater video showing drag head trails along one of the vessel tracks.

The measurements demonstrated that whilst it was possible to track a plume for up to 3.5km from the dredging area (using ADCP monitoring which can detect very small changes in concentration within the water column) the concentrations within the plume had decayed to background levels of less than 10mg/l over a distance of less than 500m. The majority of the material resuspended was sandy but the decay of mud and sand concentrations in the plume was found to occur over similar timescales. The study clearly demonstrated a very rapid reduction in suspended sediment concentrations in the immediate vicinity of the dredger.

The field observations were supported by advection-diffusion plume modelling using the GAUSSIAN model. It was found that only by assuming that 20%-30% of the material released from the dredger via spillways and reject chutes was initially entrained into the water column could the model reproduce observed concentrations close to the dredging point and even then the model over-estimated concentrations at greater distances. These results supported the theory that density and momentum differences between the overflow and water column during the first few minutes of resuspension and/or aggregation of sediment are the most important factors controlling short term resuspension of the dredged material.

6.3 Dredging activities in Hong Kong

Hong Kong has been engaged in a major programme of construction, which includes land reclamation. This has resulted in a need for large quantities of marine sand for fill. There has been an increasing requirement in Hong Kong to undertake Environmental Impact Assessments associated with marine mining. Because of the scale of the operations, this has promoted a number of studies directed at establishing the losses during the dredging operation and the subsequent advection and dispersion of the plumes of fine material so generated.

Specific field measurements have been carried out to examine the resuspension of fine material during dredging, and these have been reported by Whiteside et al (Reference 8). The paper considers the loading of the 8,225m^3 trailer dredger HAM 310 over a period of 90 minutes. It was shown that for a total measured load of 11,500 tonnes the total overflow loss was 3,000 tonnes. The overflow was calculated as the difference between the inflow and the load. It was estimated that approximately 50% of the overflow was of fine particles (<0.063mm). These figures show that approximately 80% of the material dredged was retained and the average rate of overflow of fine material over the 90 minute period was 280kg/s. If an overflow rate of 7m^3/s were assumed then the average concentration of fines in the overflow would be 40kg/m^3, and much of the flow would descend directly to the seabed as a density flow.

Field measurements using ADCP techniques in Hong Kong have investigated the processes occurring during the first few minutes of the plume generation (Reference 9). These showed that the initial processes are likely to be responsible for the loss to the bed of a considerable proportion of the fine material initially released into the water column, (Reference 8).

HR Wallingford (Reference 10) has investigated the processes that may be occurring during this initial phase of the development of a plume. The HR work has been summarised by Whiteside et al (Reference 8). It has been concluded that, for the vessels operating in Hong Kong with a single sub-surface spillway, the initial momentum of the discharge from the vessel is a significant factor, resulting in much of the material descending directly to the seabed. Additionally it has been postulated that the disaggregation of fine muddy material during the dredging process is not complete and that a further significant proportion of the muddy material released into the water column may be in the form of fine clay balls, or adhered to coarser grains. Thus some of the resuspended fine material may settle out of the passive phase of the plume to the bed with settling velocities in excess of that of a natural muddy suspension.

6.4 "S" Factor results

Various literature exists concerning the rate of resuspension associated with different forms of dredging, and this has been reviewed in Reference 11. The resuspension data is often published in the form of so-called "S-factors" (References 6 and 7) which define the amount of sediment, in kg per cubic metre dredged, which is resuspended in the immediate vicinity of the dredger. Using the data from the preceeding sections of this chapter, the following table has been created.

Table 2.8 "S" factors

Dredger type	"S Factor", kg/m^3
Trailer (limited overflow) Maintenance (no overflow)	15 7
Cutter	6
Bucket	15 - 30
Hong Kong aggregates (sand)	500 (total), 250 (silt only)
Hastings aggregates (all-in gravel)	120 (total), 60 (silt only)
Great Yarmouth aggregates (screened gravel)	3,800 (total), 180 (silt only)

The methods for determining the resuspension between the different operations are not consistent. The aggregate dredging figures come from direct sampling of the spillways and might therefore be reduced by up to an order of magnitude based on observational data to give figures consistent with the measures for the capital and maintenance operations.

The table shows that for measurements in the immediate vicinity of a dredger the rate of resuspension derived appear significantly lower than those derived from measuring the losses from the dredger directly. The implication of this is that there must be processes occurring in the immediate vicinity of the dredger, such as the rapid descent to the bed of sediment laden water from the spillways, which may remove significant amounts of resuspended material from the water column. It seems unlikely that an aggregate dredger loading an all-in cargo would resuspend significantly more fine material than a trailer dredger overflowing during maintenance dredging of silt.

These measurements strongly suggest that the processes of aggregation and momentum-induced settling are significant in the initial behaviour of dredging plumes. As described in the introduction it was the implication of this fact that brought about the objective of this study, that these processes should be further investigated. These investigations, described in Part 3, took the form of field measurements of preferential settling (through aggregation) of fine deposits and computational modelling of the initial dispersion of the plume under the effects of momentum and negative buoyancy. The objective of these investigations was to identify the dominant mechanism for preferential settling of fine material.

7. MEASUREMENTS OF BACKGROUND SUSPENDED SEDIMENT CONCENTRATIONS

7.1 Introduction

One of the identified objectives of the study was to take measurements of background suspended sediment concentrations at various dredging locations in the UK to improve the understanding of natural variability of the offshore suspended sediment regime. This knowledge is helpful when considering the context into which predictions of increased suspended sediment concentrations associated with dredging activities can be placed.

When the study was first proposed it was envisaged that these measurements would take place from aggregate dredgers on an opportune basis. Whilst this approach was initially adopted it was considered that without finding a remote method the reliability of such measurements would be questionable. This reliability is an important factor when considering the variety of organisations who would be interested in the data.

During the course of this study the Minipod instrument for near bed measurements has been extensively applied by CEFAS (Centre for Environment, Fisheries and Aquaculture Science), an agency of MAFF (Ministry of Agriculture Fisheries and Foods). Minipods are large (2m in height) self-contained bed frames which can be deployed onto the seabed with sensors attached, enabling readings to be taken over periods of several weeks. This procedure has been used to take background readings at sites off East Anglia and the mouth of the Tees Estuary. The instrumentation has clearly demonstrated the reliability of this technique as a means of quantifying the variability of the near bed suspended sediment regime and of providing the data in terms of waves and currents against which to consider this variability.

7.2 Water sampling in the vicinity of licensed sites

HR Wallingford has a data base of background suspended sediments determined from water samples recorded adjacent to areas of aggregate dredging. These measurements are usually from monitoring as part of dredging licence applications but also come from other sources, notably the NERC North Sea Project undertaken in 1988/89.

- Owers Bank
  Measurements undertaken during the monitoring described in Section 6.2 gave background concentration of 3-23mg/l, with an average of 14mg/l (Reference 5). These samples were obtained during neap tides in the summer period under calm conditions.

- Shingle Bank, Hastings
  Concentrations of 6-8mg/l during storm force 5 winds and 0-12 mg/l during calm conditions were measured in 1993 (Reference 4).

- West of Dowsing
  The NERC North Sea Project 1988-89 monitored background concentrations of 1-35 mg/l off from the Lincolnshire Coast (Reference 12).

- Area 401, Great Yarmouth
  The NERC North Sea Project 1988-89 monitored background concentrations of 2-3 mg/l during Summer conditions and 8-12 mg/l during Winter conditions offshore from Great Yarmouth (Reference 3).

- Area 432, Folkestone
  Recordings over a spring tide cycle on June 1986 from 3 vessels anchored offshore from Shakespeare Cliff, Dover, gave suspended sediment concentrations of 5-7mg/l (Reference 13).

- Area 430, East of Southwold
  The NERC North Sea Project 1988-89 recorded mean monthly offshore concentrations of 1-8mg/l, with nearshore concentrations of 2-16 mg/l (Reference 14).

- Area 372/1, North Nab
  EA measurements at Worthing, Nab Tower and West Princessa Buoy (1992-94) and at Selsy Bill and East Brambles (1992-1996) recorded values of 0-100mg/l (Reference 15).

- Area 433, North Nab
  HR Wallingford undertook a field exercise in January and February 1989 to provide information for studies relating to the proposed second power station at Fawley (Reference 16). Measurements at

Bembridge on the eastern coast of the Isle of Wight recorded concentrations on spring and neap tides ranging from 5-17mg/l with an average value of 13mg/l.

- Rye Bay, Hastings and Harwich
  South Coast Shipping were able to make some opportune measurements of suspended sediment concentrations in severe weather in March 1994 (Reference 17). The measurements were made in three locations – Rye Bay, Hastings Shingle Bank and Cutline, offshore from Harwich Harbour. The measurements varied between 220mg/l and 410 mg/l and the full details of the samples taken are given below in Table 2.9.

Table 2.9 South Coast Shipping Measurements

Location	Sample number	Depth	Wind conditions	Suspended solids content (mg/l)
Hastings Shingle Bank	1	Close to sea bed	SW 6-7	262
	2	Close to sea bed		270
	3	Mid-depth		318
	4	Sea bed		220
Rye Bay	1	Mid-depth	SW 6-7	365
	2	Sea bed		251
Cutline Area B	1	Mid-depth	West 5 (Previous 24 hours West 7)	337
	2	Close to sea bed		375
Cutline Area C	1	Mid-depth	West 5 (Previous 24 hours West 7)	399
	2	Close to sea bed		410
	3	Sea bed		331

These measurements on the whole represent monitoring over short periods where conditions were calm. The main exception to this is the Rye Bay/Harwich/Cutline measurements which recorded background concentrations over a magnitude higher.

7.3 Minipod measurements taken around Roughs Tower

Roughs Tower has been the main disposal site for maintenance dredged material originating from Harwich Harbour and the Stour and Orwell Estuaries. Currently approximately 2.4Million tonnes/annum of sediment are placed at the disposal site (Reference 18) which is approximately 15km SE of Harwich Harbour (Figure 2.1). This sediment is essentially material with a high mud content. The water depth at the site is approximately 14m and conditions at the site are extremely dispersive for this type of material. Video, side-scan sonar measurements and bed sampling have shown little evidence of dredged material remaining at the site some 10 days after placement. As part of the monitoring procedure of the Harwich Approach Channel Deepening Environmental Impact Assessment a Minipod was placed at a location some 5km to the NE of the Roughs over the period 11/11/97 to 14/12/97 (Reference 19). During this time current speeds and direction, water depth, wave heights and turbidity were logged over a 10 minute "burst" at half hour intervals. The period of Minipod placement coincided with the placement of 128,000 TDS (Tonnes Dry Solids) of material over four days (9-12 December) by the W.D. Fairway. Thus the Minipod insuments were able to record the effect of the resulting dispersing sediment plume on turbidity close to the bed. The turbidity measurements were undertaken using two optical sensors, placed at 0.55m and 0.75m above the bed which measured the variation in suspended sediment concentrations in terms of a voltage signal. At the present time these voltage signals have not been calibrated, however the signal is a simple function of the suspended sediment concentration of fine material and therefore the variation in the voltage signal is still extremely informative. Figure 2.2 shows the variation in the sensor voltage over the whole monitoring period. Highlighted are periods of storminess and also the period over which the W.D.Fairway was disposing of maintenance dredged material. The figure shows that the effect of the maintenance placement is less than that caused by the storms of 2m waves on 18-20 November and 3m waves on 17-19 December 1997, which are estimated to have be of the order of 300mg/l. The conclusion to made from these results was that the placement operation did not increase suspended sediment levels more than naturally occurring events at the Minipod location.

7.4 Minipod deployment at the Inner Gabbard

A further Minipod deployment was undertaken to the north of the proposed new disposal site, at the Inner Gabbard some 15km east of the Roughs Tower site, in February of 1997 (Reference 20). Measurements of current speed and direction, water depth, wave height and turbidity were made over the period 20/2/97 to 11/3/97. These measurements coincided with a single trial placement of 8000m^3 of maintenance dredged material at the new placement site on 28 February by the W.D.Gateway. The Minipod was placed 2.5km to the North West of the placement site and experienced a peak in suspended sediment concentrations corrresponding to the placement plume (Figure 2.3). However, suspended sediment concentrations in excess of this placement induced peak were experienced for approximately 12% of the measurement period. The sensor readings are in terms of a voltage output but the results shown in Figure 2.3 are estimated to correspond to mean levels of 50-100mg/l.

7.5 Minipod measurements taken at the Tees maintenance disposal site

Minipods were deployed some 2km NW of the Tees disposal site (see Figure 2.4) over the periods 30/1/96-14/3/96 and 6/12/96-20/1/97 (Reference 21). These Minipods took measurements of current speed and direction, wave height and also of turbidity using an optical sensor. The Tees disposal site is less dispersive than that at the Roughs and evidence of previous placements has been found when the site has been surveyed using sidescan-sonar.

During both Minipod deployments maintenance dredged material was placed on a continual daily basis at the site. Two vessels, the largest with a hopper capacity of 1500m^3, each made up to 4 placements a day. During the Minipod deployments total volumes of 190,000m^3 and 92,500m^3 of dredged material were placed at the site, 80% of which was sand. Parts of the suspended sediment sensor reading time series for the two deployments are shown in Figures 2.5 and 2.6 (in terms of voltages), together with the corresponding wave heights and placement loads. Almost no evidence of increases in suspended sediment concentrations arising from placement was found, the recorded suspended sediment response appearing principally to be due to the variation in wave action. This is in spite of specific placement of material and Minipod in order that any resulting plume would pass by the Minipod.

An important result of the minipod measurements at the Tees site is the effect of storm sequencing on the suspended sediment regime. It took very large storm waves (>4m) to cause the backscatter instrument to go off scale 19/2/96. However, following this large storm a period of calm weather meant that material resuspended settled back to the bed. A subsequent, but smaller, storm (□ 1m waves) on 1/3/96 generated a similar magnitude of increase in suspended sediment in the water column.

7.6 Minipod deployments around Race Bank (Area 107)

The most extensive minipod deployment yet undertaken around a dredging operation was carried out in the vicinity of Race Bank (Reference 22). .Here on one occasion four minipods were deployed specifically to monitor the progress of a plume away from the Area 107 site as it moved towards the sensitive crab fishery on Race Bank. The monitoring clearly demonstrated the progress of the plume, and like the data sets described in Sections 7.3 and 7.4 can be used as the basis of model calibration.

7.7 Conclusions

The measurements of background suspended sediment concentrations undertaken during aggregate dredging activities or from opportune and generally short-term monitoring usually give relatively low background suspended sediment concentrations of the order of 0-30 mg/l. These measurements by their very nature usually apply to non-stormy conditions. However the small number of opportune measurements taken in storm conditions and the use of Minipod deployments which can monitor for periods of 6-8 weeks and capture storm event responses, have shown that background suspended sediment concentrations can naturally increase to levels in excess of those experienced during aggregate dredging operations, although the distance of the Minipod from the source of dredged material has to be taken into account.

As a rule of thumb it might be inferred that suspended sediment concentrations observed under calm conditions could be increased by a factor of between 5 and 10 during storm conditions.

It is recommended that long term deployment of bed mounted instrumentation be used to investigate the natural variability of suspended sediment concentrations offshore. It would be possible to extend the data base of information described above based on other minipod deployments that have been undertaken by CEFAS.

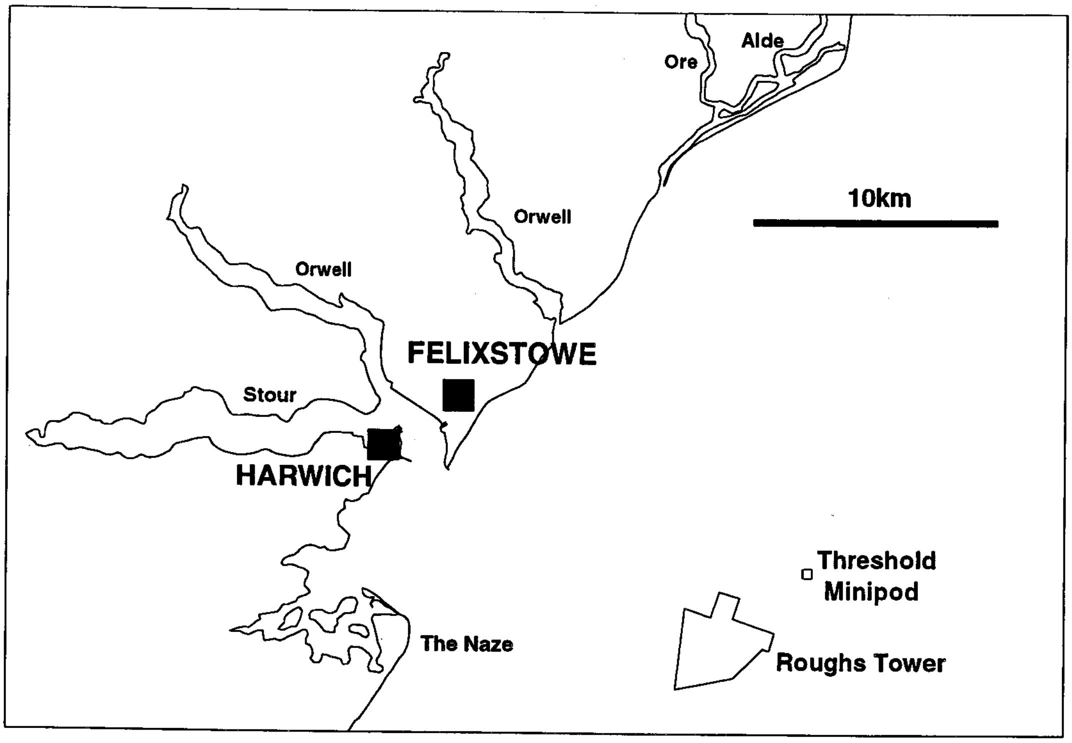

Figure 2.1 **Location of Roughs Tower maintenance material disposal site**

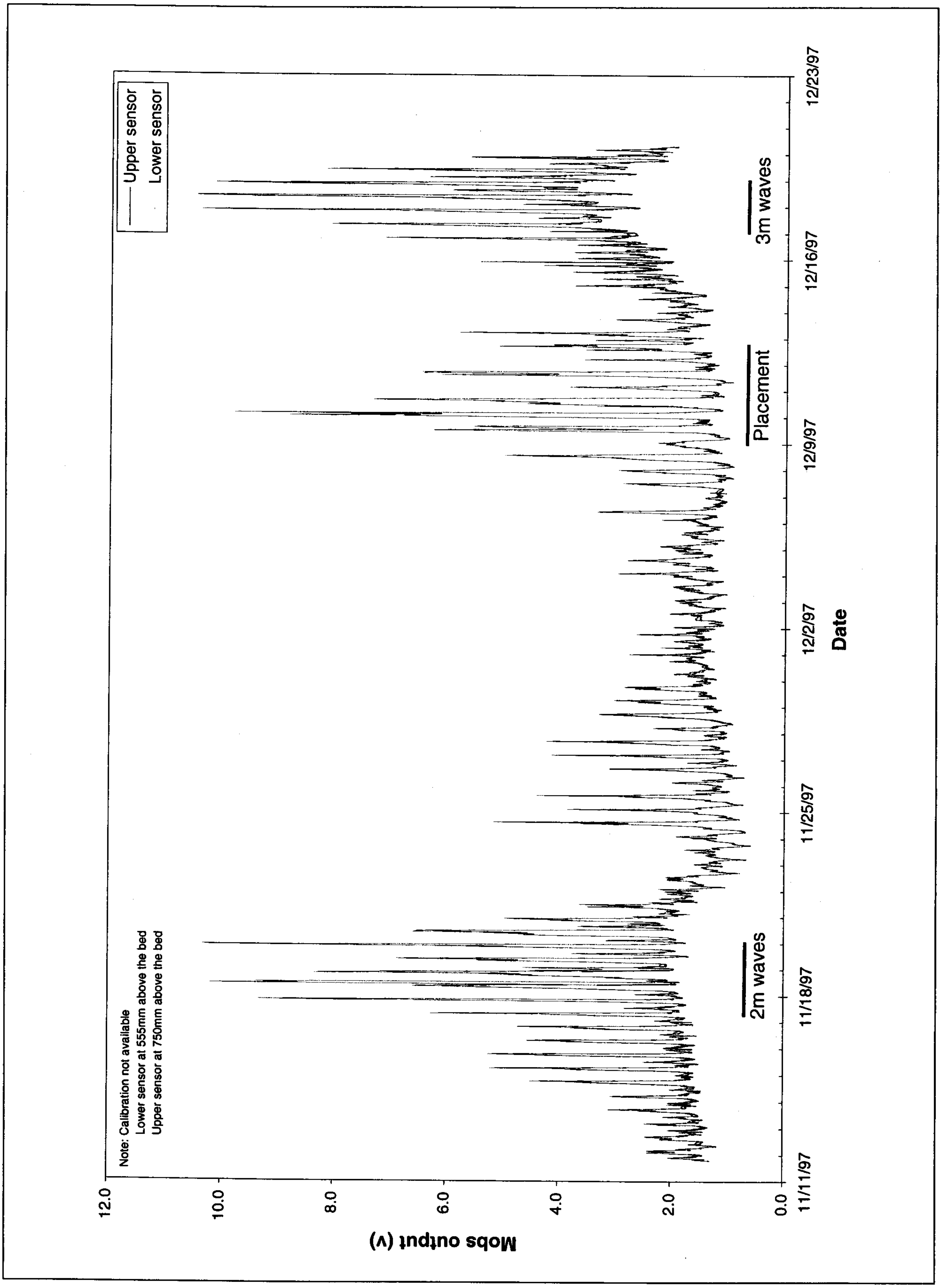

Figure 2.2 **Time series of MOBS suspended sediment sensor output for deployments at Roughs Tower disposal site**

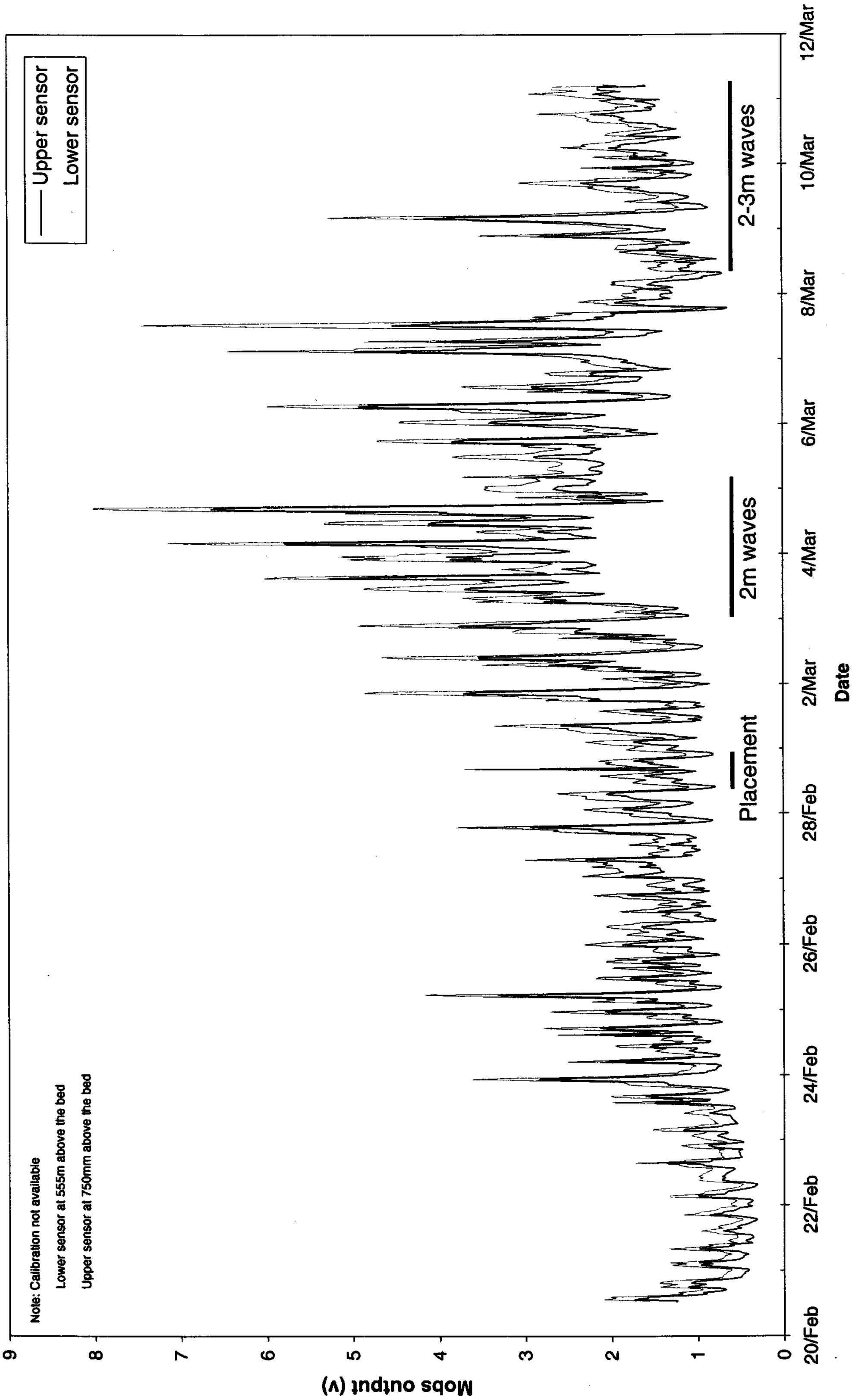

Figure 2.3 **Time series of MOBS suspended sediment sensor output for deployments at proposed new disposal site for Harwich Harbour**

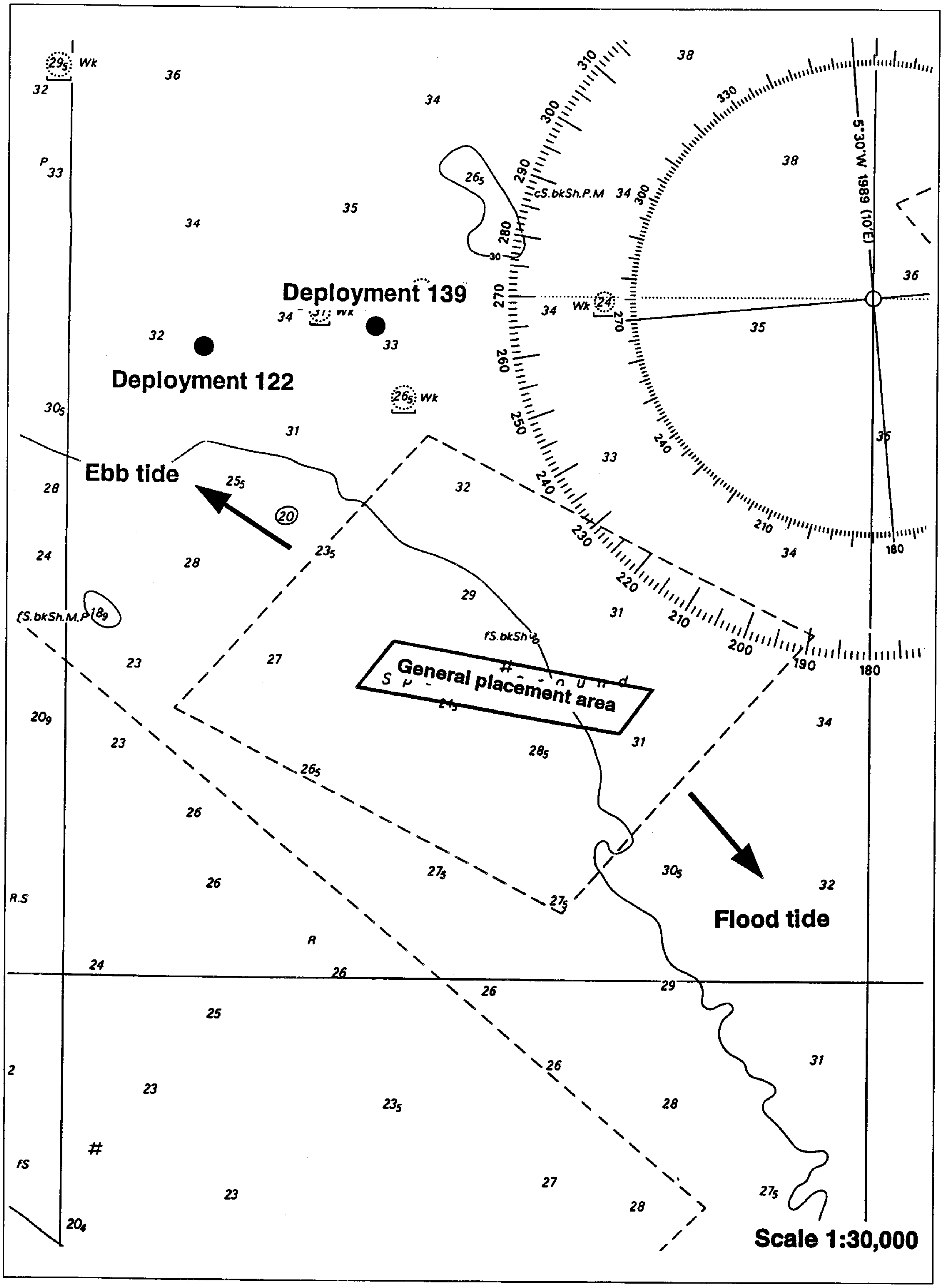

Figure 2.4 Location of Tees maintenance material disposal site

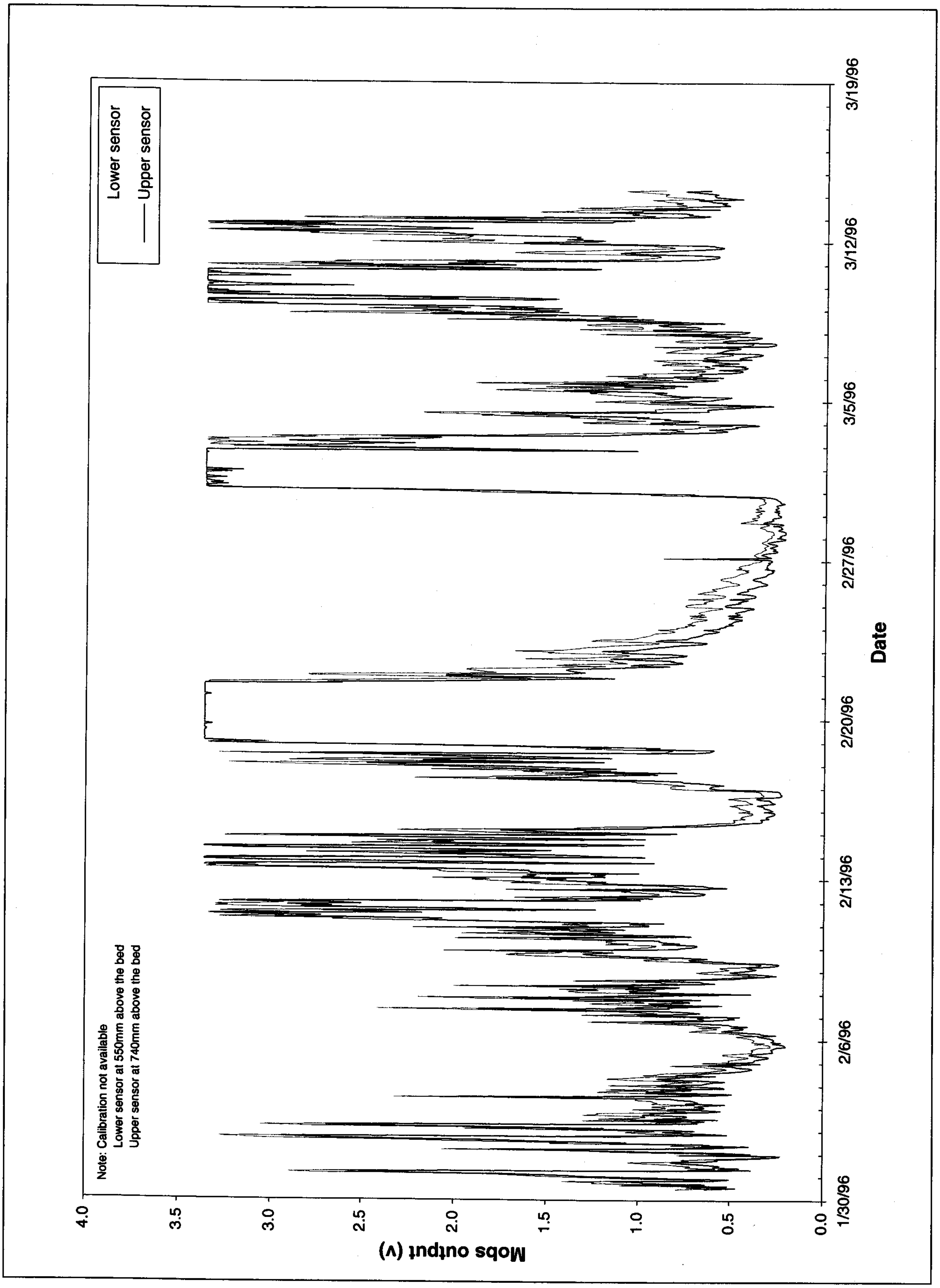

Figure 2.5 **Time series of MOBS suspended sediment sensor output for deployments at Tees disposal site 30/1/96-14/3/96**

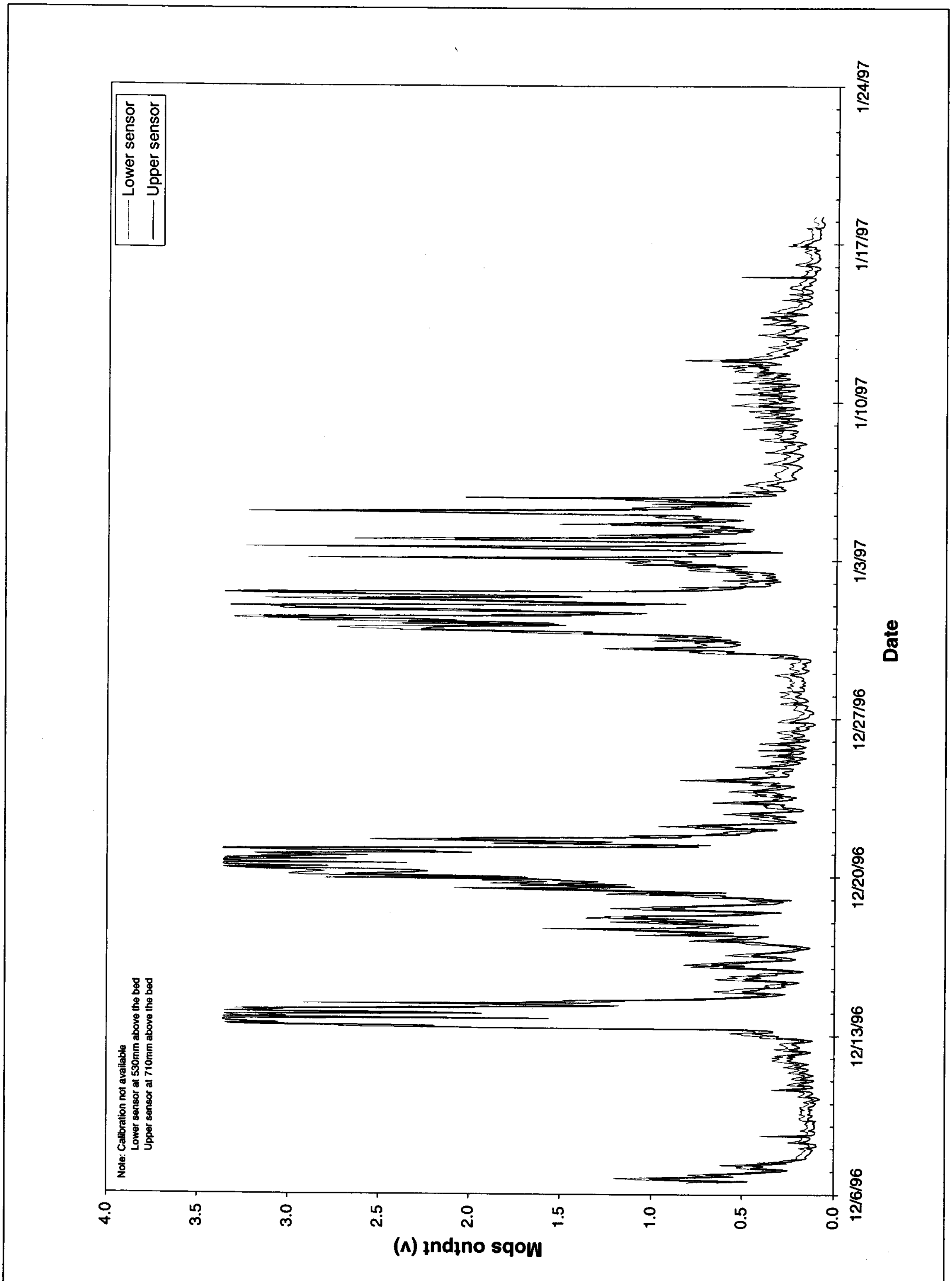

Figure 2.6 **Time series of MOBS suspended sediment sensor output for deployments at Tees disposal site 6/12/96-20/1/97**

Part 3

INVESTIGATION OF INITIAL DISPERSION PROCESSES

8. MEASUREMENTS OF SETTLING VELOCITY OF FINE MATERIAL RELEASED INTO THE WATER COLUMN DURING AGGREGATE DREDGING OPERATIONS

8.1 Objective

It has been observed that there is an initial rapid loss of fine material (<0.063mm) from the plumes generated by dredging operations compared to the mass of fine material lost from the dredger itself (Chapter 5). A possible explanation for this is that some of the fine material lost from the dredger is aggregated either to other fine particles or to coarser particles. The net effect being that the fine material released from the dredger settles through the water column with higher settling velocities than it would otherwise.

To investigate the possibility of preferential settling through this process the method adopted was to take samples from the spillway of a dredger during aggregate dredging and observe, in a controlled experiment, the settling characteristics of the material in the overflow using a specially designed settling column. It is accepted that the nature of the experiment is to some extent artificial, as the settling characteristics of the "captured" sample are determined in the quiescent environment of the column as opposed to the continuously moving turbulent waters of the sea. This could lead to an acceleration of the settlement of fine material, and consequently an overestimate of the settled quantities. However, if the analysis shows that similarly sized fine material within the tube settles at differential rates, this would indicate, at least the likelihood, that aggregation is occurring.

8.2 Test procedure

8.2.1 Description of the column

The settling column, shown in Figure 3.1 and Plate 2, comprised a 1.5m long, 200mm bore Perspex tube. There were five, 10mm bore sampling ports evenly spaced (200mm) between the top and bottom of the tube. These ports enabled samples of water to be simultaneously withdrawn from the column at different levels so that sediment concentration and particle size distribution could be identified throughout the column. In addition to, and 200mm below, these ports there was a 20mm bore drain tap, the purpose of which was to facilitate the draining of the overlying water at the end of the test. Below this tap, in the bottom of the column a cone section reduced the diameter of the column from 200mmm to 60mm. This is the section of the column where settled material collected. A 50mm valve on the bottom of the column allowed the contents of the bottom cone to be completely drained, enabling the settled residue to be obtained and analysed .

8.2.2 Field testing

The HR sampling column tests were carried out on samples taken from the starboard spillways of the Arco Severn during a screened aggregate dredging operation on the Owers Bank on the evening of 27 November 1996. A total of 14 samples were collected from the vessel's spillways, of which 6 were tested on board the Arco Severn at the time of collection, and the remaining 8 in the HR laboratory two days later. In the former case the column was pre-filled with ambient seawater, whilst in the laboratory freshwater was used, allowing the effect of salinity on preferential settling under these conditions to be investigated.

The column was first part filled with sea water, or fresh water in the case of the laboratory measurements, and left to stand for a few minutes to allow any entrained air to disperse. A 10 litre sample of overflow material from the spillway was then gently poured through a coarse (10mm) sieve into the top of the column. After a period of time (5 or 10 minutes) a sample of the water in the column was drawn from each of the 10mm ports into 500ml sample bottles for subsequent laboratory analysis. Each port was flushed out for a few seconds prior to the sample being taken.

Once sampling of the overlying water was complete the column was drained through the 20mm bore drain tap. The remainder of the contents of the column was then drained via the 50mm bottom valve into a 10-litre bucket for subsequent laboratory analysis. Any coarse material retained in the sieve was also added to the contents of the bucket. Typically the total volume of this final sample was about 7 litres.

The column was then cleaned and refilled ready for the next test.

The suspended sediment concentrations within the settling column were to be monitored during the course of the experiments to give information regarding the initial mixing of the sample and further information regarding the settling of suspended material. Unfortunately, the logging apparatus was damaged during the course of testing, and become inoperable.

8.2.3 Laboratory Analysis

The samples from the 7 litre buckets and the 500ml bottles resulting from the column tests were analysed as follows:

Settled material (7 litre buckets)

1. These samples were split at 63μm by wet sieving followed by sieve analysis of the dried sand fraction (>63μm). The test sieves were manufactured to BS410.1986 and the sieving procedure was carried out to the provisions of BS 1796: Part 1:1989.

2. The silt fraction (<63μm) was analysed by laser diffraction over the range 1 to 100μm and the two analyses combined to provide a total percent undersize versus size analysis. (The laser diffraction analyser is calibrated using National Institute for Standards and Technology certified particle size standards).

Suspended material (500ml bottles)

1. The concentration of the sediment in suspension was determined gravimetrically by filtration onto pre-weighed 0.45μm nylon membrane filters after measuring the volume of each sample. The filters were air-dried in order to minimise any alteration of the sediment.

2. The filtered sediment was recovered, deflocculated and analysed by laser diffraction over the size range 1 to 100μm.

8.3 Results

8.3.1 Test results

Table 3.1 shows the results and the range of tests carried out, including the initial column salinity for each test. The results of the experiments show that the preferential settling exhibited in these specific test conditions is unaffected by the presence of salinity. The test results corresponding to 10 minute tests are shown with a shaded background.

Table 3.1 Description of tests and results from settling column experiment

Test No	Mass of material (g)			Mass of fines in suspension (g)		Mass on bed at end of Test (g)		% of fines still in suspension at end of Test	Initial column salinity (mg/l)	Time of test with respect to onset of dredging (hrs: mins)	% fines in sample
	Fine <63μm	Coarse >63μm	Total	5 min	10 min	Fine	Coarse				
1	3.0	3.1	6.1	2.1	-	0.9	3.1	70.0	32	0:02	49
3	11.2	2.8	14.0	8.9	-	2.3	2.8	79.5	32	0:31	80
4	14.3	16.1	30.4	11.1	-	3.2	16.1	77.6	32	0:47	47
5	22.5	23.2	45.7	19.2	17.0	5.5	23.2	75.6	32	1:07	49
6	31.5	31.4	62.9	24.9	-	6.6	31.4	79.0	32	1:28	50
9	9.6	37.4	47.0	7.6	-	2.0	37.4	79.2	32	2:15	20
12	12.7	12.1	24.8	10.1	-	2.6	12.1	79.5	0	4:51	51
13	5.7	4.4	10.1	4.3	4.1	1.6	4.4	71.9	0	5:06	56
14	32.2	71.2	103.4	27.0	22.2	10.0	71.2	68.9	0	5:22	31
15	5.3	34.0	39.3	4.2	-	1.1	34.0	79.2	0	5:40	13
16	44.2	26.7	70.9	36.8	31.1	13.1	26.7	70.4	0	5:53	62
17	50.8	41.0	91.8	40.8	-	10.0	41.0	80.3	0	6:11	55
18	21.4	58.0	79.4	15.9	13.3	5.5	58.0	74.3	0	6:24	27
19	17.6	42.7	60.3	14.1	-	3.5	42.7	80.1	0	6:41	29

From the table it can be seen that Test 14 had the greatest mass of material in the column. In this case the total mass was calculated to be about 100g, of which 32g was fine material. In Test 16 the mass of fine material was about 45g, compared to a total mass of 70g. The least material was present in Test 1 which was collected early in the dredging cycle when less solids were leaving the hopper via the overflow spillways. In this case the total mass was 6g, of which 3g was fine material.

The particle size distributions for the final 7 litre bucket samples show that these contain a large proportion of coarse material which would have fallen to the bottom of the column almost immediately. The largest sieve size on which material was retained was 12.7mm in the case of Test 16. The total mass of material in the column in this test was 40g, and about 12% of this was retained on the largest sieve, equating to a retained mass of 5g. This was probably due to a single pebble or stone. In general the largest sieve size on which material was retained was 2.0mm.

8.3.2 5 and 10 minute particle size distributions

The results of the particle size analyses of the samples in suspension for each of the Tests are shown in graphical form in terms of particle size versus percent of the total mass under that size in Figures 3.2 to 3.20. These demonstrate the way in which the different particle size bands are distributed throughout the depth of the water column.

After a period of undisturbed settling the distribution of material throughout the water column would normally be such that the majority of fine material would be found in the upper portion of the water column. Further down the water column the material found in suspension would be expected to become progressively coarser with some mixing of finer sediment due to flow circulations caused by the coarser particles settling.

The results of the particle size distribution analyses show that, generally, after 5 minutes the water in the column is still well mixed due to vertical circulations set up during the introduction of the spillway sample into the top of the column. The extent of mixing is demonstrated by the similarity of the particle size distribution curves from one sampling port to another. For example, in Test 13 (Figure 3.10), the largest proportion of fine material was found in the sample withdrawn from Port 4, which is some 900mm from the top of the column. In the same test the largest proportion of coarse material was 700mm from the top of the column (Port 3).

Only in Test 1 (Figure 3.2), which had the lowest mass of fine material of all the tests (3.0g), was a more natural size/depth distribution apparent after five minutes. But in this case the variability in the form of the particle size distribution was much greater from one port to another than in any of the subsequent, higher concentration tests.

The analysis suggests that after 10 minutes the circulations in the column have diminished to a level such that gravitational settling is the dominant mechanism. Nearly all of the 10 minute samples show a graded particle size distribution with respect to depth in the water column. For example, Test 16 (Figure 3.16), shows a wide variation in particle size from one sampling port to the next. In this case the largest proportion of fine material is found towards the top of the water column with the majority of the coarser material being found close to the base. The exception was Test 13 (Figure 3.11), which shows that the water column is still mixed. The mass of fine material present in this test was, however, particularly low at 5.7g.

8.3.3 Preferential settling

The settling experiments were designed so that no individual fine particle settling under the forces of gravity and water resistance alone would reach the bottom of the settling tube during the course of the experiment. Therefore any fine sediment found in the 7 litre sample bucket at the end of an experiment had settled preferentially. Because the experiment was conducted in a settling column, and the dredged material was poured into the settling column through a sieve, the scope for the plume of material to move rapidly downwards because of its initial momentum was reduced. The constriction of the settling tube walls also reduced any tendency for a plume of material to move rapidly downwards, either as a result of the initial momentum or because of greater density. Observations of the test showed that the dredged material was reasonably well mixed throughout the top of the water column within a short time. Thus the main process by which any material settled preferentially below an initial mixing depth was due to increased settling velocity caused by aggregation.

The mass of fine material remaining in the column at the end of a test, and the mass that deposited in the 7-litre bucket sample can both be determined from the laboratory analysis (Table 3.2). The test results corresponding to 10 minute tests are shown with a shaded background. The phenomenon of initial mixing at the top of the water column may have reduced the distance that some sediment particles have to fall to reach the bottom of the settling column and therefore over the course of the 10 minute tests it is possible that a small proportion of fine particles may have reached the bottom without preferential settling. The results shown in Table 3.2 have allowed for this possibility by adjusting the results assuming that material was initially well-mixed throughout the top half of the settling tube (results shown in italics). This possibility reduces the amount of preferential settling by a few percent but does not alter the results of Table 3.2 significantly.

Table 3.2 Preferential settling from the settling column experiment

Test No	Column		Bucket	Total	% of total mass to settle preferentially *assuming initial mixing* assuming no mixing
	Conc (mg/l)	Mass (g)	Mass (g)	Mass (g)	
1	57	2.1	0.9	3.0	30
3	235	8.9	2.3	11.2	21
4	294	11.1	3.2	14.3	22
5	450	17.0	5.5	22.5	*21*-24
6	661	24.9	6.6	31.5	21
9	201	7.6	2.0	9.6	21
12	269	10.1	2.6	12.7	20
13	109	4.1	1.6	5.7	*25*-28
14	590	22.2	10.0	32.2	*24*-31
15	111	4.2	1.1	5.3	21
16	826	31.1	13.1	44.2	*23*-30
17	1082	40.8	10.0	50.8	20
18	352	13.3	5.5	18.8	*23*-29
19	373	14.1	3.5	17.6	19
Mean value					*22*-24

The table shows that in the samples tested up to 31% of the fine material settled at a faster rate than may have been expected, with a mean value of 22-24%. The amount of fine material preferentially settling does not appear to correlate with the proportion of fines in the sample, although the mass of fine sediment settling preferentially is directly proportional to the mass of fine sediment in the sample (Figure 3.21). This result implies that the preferential settling of fine particles in the settling column was not dependent on the interaction between finer and coarser particles, but was rather dependent on the mutual interaction, flocculation, of fine particles only.

8.4 Conclusions

Because of the experiment design, the material introduced into the water column rapidly mixed without the momentum or density induced flow that is observed during dredging and so these processes did not apply. It was concluded that the fine material in the water column settled faster because of flocculation. The effect of this process is that this effect causes only a small enhancement of settling of fine material as the proportion of fine material found to be settling preferentially in the experiments was relatively small (19-31%). Since the evidence from observations during dredging is that the vast majority of fine sediment is removed rapidly from the water column, it is to be concluded that aggregation of particles with associated increases in settling velocity is not the dominant process in this removal. This is not to say the effect is insignificant. In particular, dredging operations in circumstances which lead to discharging of clay lumps/balls into the water column would produce a more pronounced effect of preferential settling due to aggregation.

9. COMPUTATIONAL INVESTIGATION INTO THE EFFECT OF MOMENTUM-INDUCED SETTLING

9.1 Background

The other hypothesis concerning the rapid removal of fine sediment released by dredging from the water column is that the process of discharging sediment into the water column, together with the negative buoyancy effect caused by the greater density of the sediment plume, gives a significant downward momentum to the plume, resulting in the rapid descent of material towards the bed. The descent of the plume causes turbulent mixing within the surrounding waters but most of the material arrives at the bed to be dispersed by gravity and currents along the bed as a viscous fluid or alternatively to be resuspended back into the water column as hydrodynamic conditions allow.

To study this effect a series of sensitivity tests was undertaken using a numerical model of the initial phase of plume dispersal developed by the US Environmental Protection Agency (EPA) (Reference 23).

9.2 Description of models and experiments

9.2.1 EPA models

The EPA models were based on equations for the continuity of mass, the continuity of horizontal momentum and the change in vertical momentum due to density differences between the plume and the ambient water. The models employ an entrainment hypothesis, that the rate of inflow of diluting water into the plume (per unit surface area of the plume) is proportional to the local velocity of the plume. The constant of proportionality, was determined by dimensional analysis and experiment. It was assumed that the flow in the plume is fully turbulent. Two models were used – UOUTPLM and UMERGE . The models are briefly described in Appendix 3 and in more detail in Reference 23.

The models computed the average characteristics of the plume and assumed that the plume had an identifiable boundary. This approach simplified the numerical equation solving considerably. In reality however, the variation of both concentration and velocity across the plume becomes approximately gaussian a short time after plume release.

9.2.2 Description of experiments

The models were run for a number of combinations of density of discharge (1026-1160kg/m^3), height of release point above the bed (10-40m), discharge rate (1.25-10.0 m/s) and strength of crossflow (0.0-2.0m/s). In each of the tests the density of sea water was taken as 1025kg/m^3 and the current speed used took into account the motion of the dredger (assumed to be 1m/s) travelling in an orthogonal direction to the specified cross current. Each test stopped when the centre-line of the plume intersected the level of the bed.

9.3 Results of numerical modelling

The results of the dispersion simulations undertaken are listed in Appendix 4 and give rise to the following conclusions:

- The results showed that the centre line of all plumes reached the bed, mostly quite close to the release point. However, in most cases a considerable portion, up to 50%, of the plume never reached the bed. The exceptions to this were denser plumes, released closer to the sea bed, with higher discharges.

- The time taken for the plume to reach the bed varied from a few seconds to a few minutes depending on the input parameters.

- The slowest moving plumes reached the bed at a similar speed to the settling velocity of the coarsest grains in the discharge material, but most of the plumes fell much more quickly than the fastest possible settling velocity so that the speed of the coarsest fraction of material within the plume is not considered to be important in the initial descent of the plume.

- The denser plumes, as expected, reached the bed much more quickly than the less dense plumes and with less dilution.
- The vertical speeds at which the plumes travel indicate that the effect of momentum and/or density on the settling of the plume is much more significant than the effect of aggregation discussed in Chapter 8.
- The dilution of the plume increased with the speed of the dredging vessel and with the height of discharge release above the bed.
- A higher discharge release caused a higher initial jet velocity and lower dilution of the plume.
- The dilution of the plume was much more sensitive to the initial discharge than to the initial density which implies that the initial momentum of the plume is more significant than the density-induced acceleration which the plume experiences.

The gaussian variation of concentration and downward velocity across the plume mean that at the extremities of the plume the descent is not so rapid and the turbulence in the water column may be sufficient to keep sediment particles in suspension, allowing the sediment particles to be entrained into the water column. Without considering turbulent effects at the bed it can be assumed that entrainment will occur as the speeds of the fluid on the extremity of the plume approach those of the settling velocity of fine sediment which is of the order of ~1mm/s. It can be deduced from the results, which showed that the final average vertical speed of the plume was between 0.02m/s and 2m/s that the proportion of material where this may apply is a small fraction of the total mass of the plume hitting the bed.

There are two effects that are not considered by the plume momentum modelling which may have significant effects on plume behaviour:

- The turbulence between the perimeter of the plume and the surrounding water may be damped by the increase in viscosity of high suspended sediment concentrations, leading to less entrainment of sediment into the water column.
- The model does not include the effect of the interaction of the sediment plume with the bed. The impact of the plume on the bed will result in a considerable exchange of momentum which might result in further release of sediment into the water column at the bed.

9.4 Modelling of initial dispersion for different types of aggregate dredging operations

The UMERGE model discussed in Section 9.2 was used to model the dispersion of discharges arising from different dredging operations under conditions representative of those carried out regularly in the UK. The three operations considered were overspill discharge from "all-in" loading, hull discharge from "all-in" loading and reject chute discharge from a screened load.

The parameters used as input for these dispersion simulations were based on observations and field measurements of aggregate dredging operations made by HR and Hitchcock (Reference 5) and were as follows:

Table 3.3 Input parameters for representative plume dispersion simulations

Run number	Discharge type	Height of discharge above sea bed (m)	Discharge rate(m^3/s)	Density of discharge (kg/m^3)	Radius of discharge jet (m)
1	Overspill "all-in"	15	0.33	1035	0.5
2			1.0		
3	Hull "all-in"	7	2.0	1035	1.0
4			6.0		
5	Screening reject chute	15	0.66	1100	0.5
6			2.0		

Current speed (constant through depth) = 0.5m/s
Speed of Dredger = 1m/s
Depth of water = 15m
Draught of dredger = 8m
Sea water density =1025kg/m^3
Pumping rate of dredger = 2.0m^3/s and 6.0m^3/s

Runs 1 and 2 correspond to discharge from a single spillway on a dredger with a total of six spillways while runs 3 and 4 correspond to discharge through the hull from a dredger with a single central spillway. Runs 5 and 6 correspond to the output of the reject chute during sand screening operations.

For the through hull discharge the diameter of the discharge was assumed to be 2m. For the spillways, the discharge was assumed to be cylindrical as it enters the water, with a 1m diameter. For discharges above the water line (overspill and screening chute discharges) the release point was assumed to be at the water surface with the characteristics given in Table 3.3.

The trajectories of the resulting plumes are shown in Figures 3.22 to 3.24. The plumes are tracked in the model until either the plume descends to the bed or the vertical velocity falls below a certain threshold. In reality, however, the turbulence caused by the dredger movement (and in particular, the propeller) will significantly impact upon the plume as the back of the dredger passes by causing more general dispersion through the water column. This would occur after a period of time of the order of 30-60 seconds and would be accompanied by generation of additional turbulence in the water column, not represented by the EPA models. The state of the plumes at 30 seconds and 60 seconds has therefore been marked in the figures to give some idea of how the effects of momentum and density induced settling might contribute to plume dispersion before turbulent dispersion becomes dominant.

In the case of the all-in overspill discharge, after 150m most of the plume is still in suspension for both cases of pumping rate (Figure 3.22). After 60 seconds the plume is all still in suspension for both cases. This contrasts strongly with the results of all-in through hull discharge (Figure 3.23) where most of the plume hits the bed within 35m (2m^3/s pumping rate) and 5m (6m^3/s pumping rate) and within a period of less than 30 seconds. The reason for this is principally due to the release of the discharge much nearer the sea bed but can also be partly attributed to the increase in momentum of the plume.

The screened load reject chute discharge (Figure 3.24) came somewhere between the previous two results with half of the discharged material reaching the sea bed within 100m of the release point for the 2m^3/s pumping rate and within 40m for the 6m^3/s pumping rate. For this case however, there is a marked difference regarding the proportion of material reaching the bed after 30 seconds with the plume still totally in suspension for the 2m^3/s pumping rate while the 6m^3/s pumping rate causes a 50% reduction in suspended material over this time period.

The proportion of material still remaining in suspension after 60 seconds for each case can be estimated assuming that there is a gaussian variation of suspended sediment concentration over the plume with the limits of the plume as calculated by UMERGE representing two standard deviations from the plume centre. The proportion of sediment left in suspension after 60 seconds (or less in the case of briefer simulations) is given in Table 3.4.

Table 3.4 Proportion of plume left in suspension after 60 seconds

Run	Discharge type	Proportion of plume left in suspension after 60 seconds (%)
1	Overspill all-in	100
2		100
3	Hull all-in	40
4		40
5	Screening reject chute	80
6		30

These results indicate that for typical aggregate dredging operations the main control over the amount of material reaching the bed within the first minute is the height of release above the bed with discharge rate, and to a lesser extent density, having some effect. (Note that the proportion of material reaching the bed is much less sensitive to discharge rate than distance travelled by the plume or time taken to reach the bed). In terms of dredging practice the main control on resuspension is then whether the discharge is via the hull or over the ship side, with the pumping rate of the dredger and the type of operation (all-in or screening) being of secondary importance. Spillway discharge appears to cause considerably more resuspension into the water column than does hull discharge, with screened load discharges varying between these two extremes. The higher density of screened loads appears to allow more variation in the proportion of material resuspended than all-in loads.

9.5 Conclusions

The computational modelling tests described above show that the effects of initial momentum and negative buoyancy are more significant than aggregation in determining the initial dispersion of discharges from dredging operations. The speed at which plumes descend under the influences of initial momentum and negative buoyancy varies with the type of aggregate dredging operation but can be orders of magnitude higher than the settling velocity of individual sediment particle grains. This effect appears to be more significant than the effect of aggregation/flocculation investigated in Chapter 8. However, the amount of material resuspended is more dependent on whether central hull or shipside discharge is used, with discharge rate being a secondary factor.

As discussed in Chapter 3, the estimation of the mass of fine material resuspended into the water column as a result of dredging operations was previously undertaken by assuming that all of the fines pumped into the dredger are resuspended into the water column. More recently such estimates have been shown to be conservative, and estimates have improved following measurements of discharges made from spillways and reject chutes and as a result the estimates of fine material resuspended into the water column have reduced in magnitude. The investigations of Chapters 8 and 9, supported by the field observations described in Chapter 6, have shown that the effects of aggregation, initial momentum and density prevent a significant proportion of such discharges from being resuspended into the water column suggesting further revision of the method of estimation of the mass of fine material forming the plume during dredging operations is required. Although there are limitations to the experiments undertaken within this study, it is possible to use their results to provide an improved estimate of fine material resuspension, until such time as the initial phase of plume dispersion is better understood and described.

It is recommended that the rate of discharge of fine material be calculated either from direct measurements, or in the absence of these, average tables such as those presented in Chapter 5. Once the discharge rate has been established then Table 3.5 can be used to estimate the proportion of this fine material that will be resuspended into the water column. Representative estimates are given for each type of dredging operation.

Table 3.5 Estimates of proportion of discharge of fine material resuspended into water column

Operation type	Overspill all-in	Hull discharge all-in	Screening for sand
Proportion resuspended	75%	30%	25%-60%

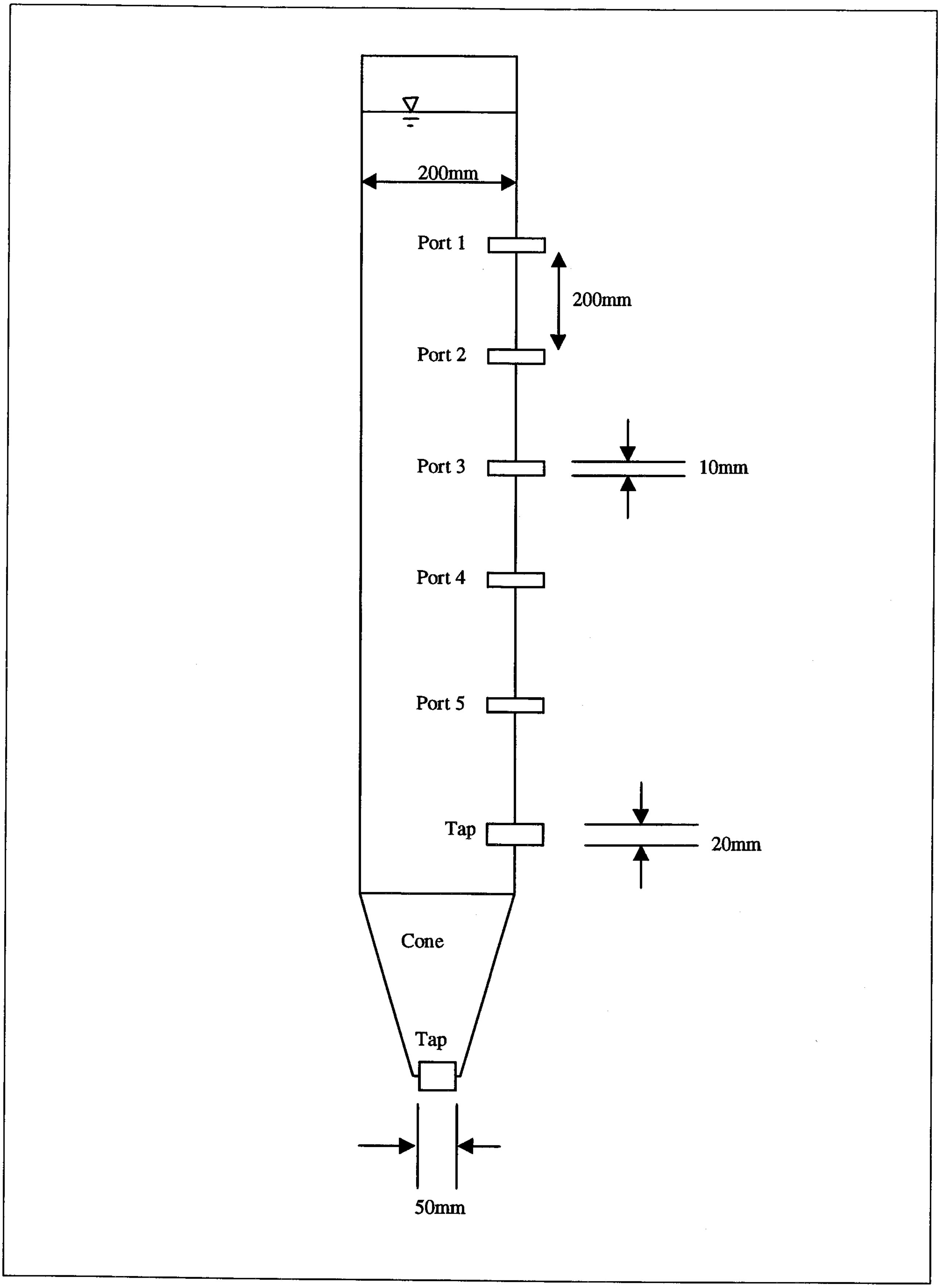

Figure 3.1 **Settling column specifications**

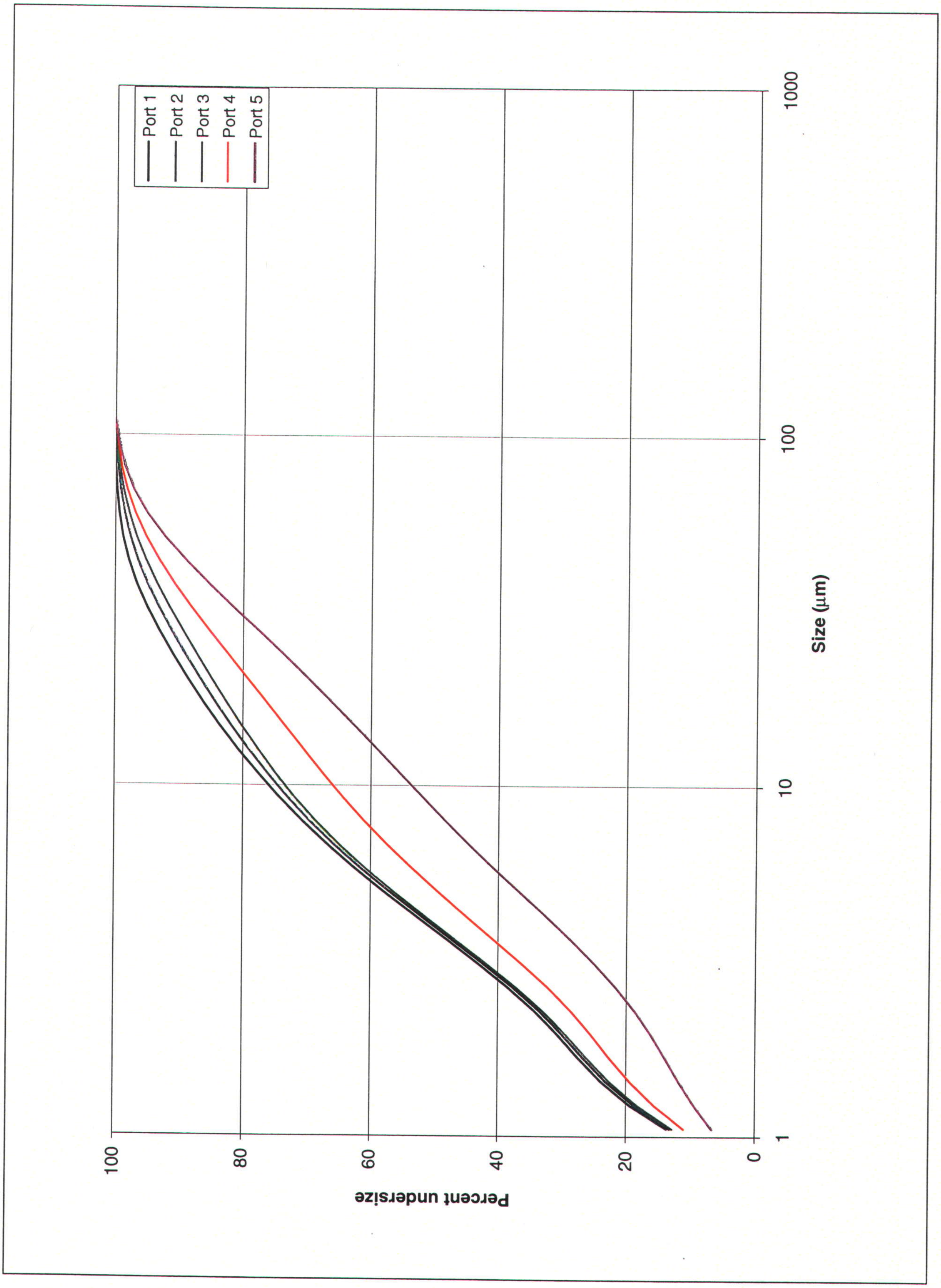

Figure 3.2 **Tube 1 : Particle size analysis of samples withdrawn after 5 minutes**

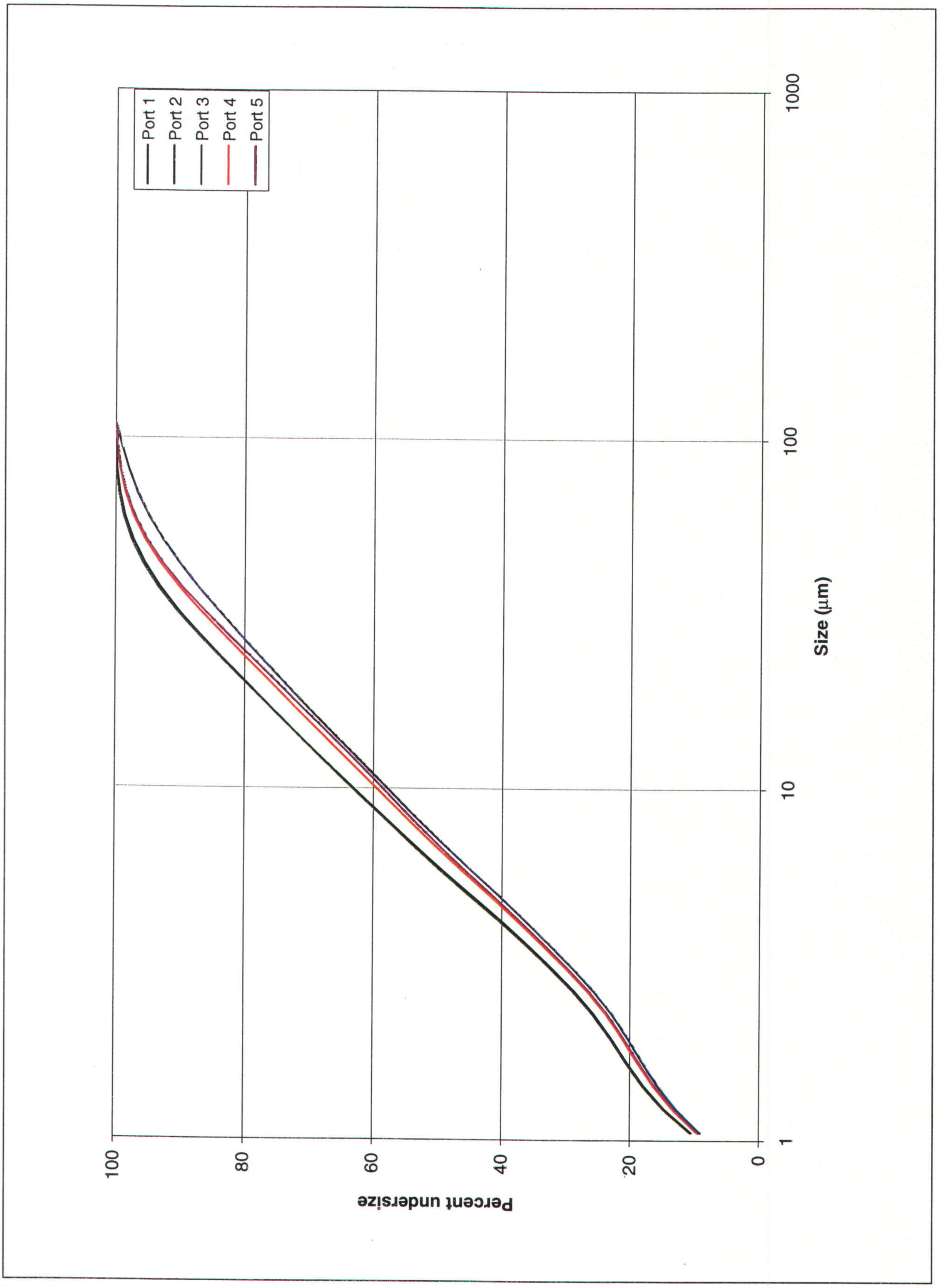

Figure 3.3 **Tube 3 : Particle size analysis of samples withdrawn after 5 minutes**

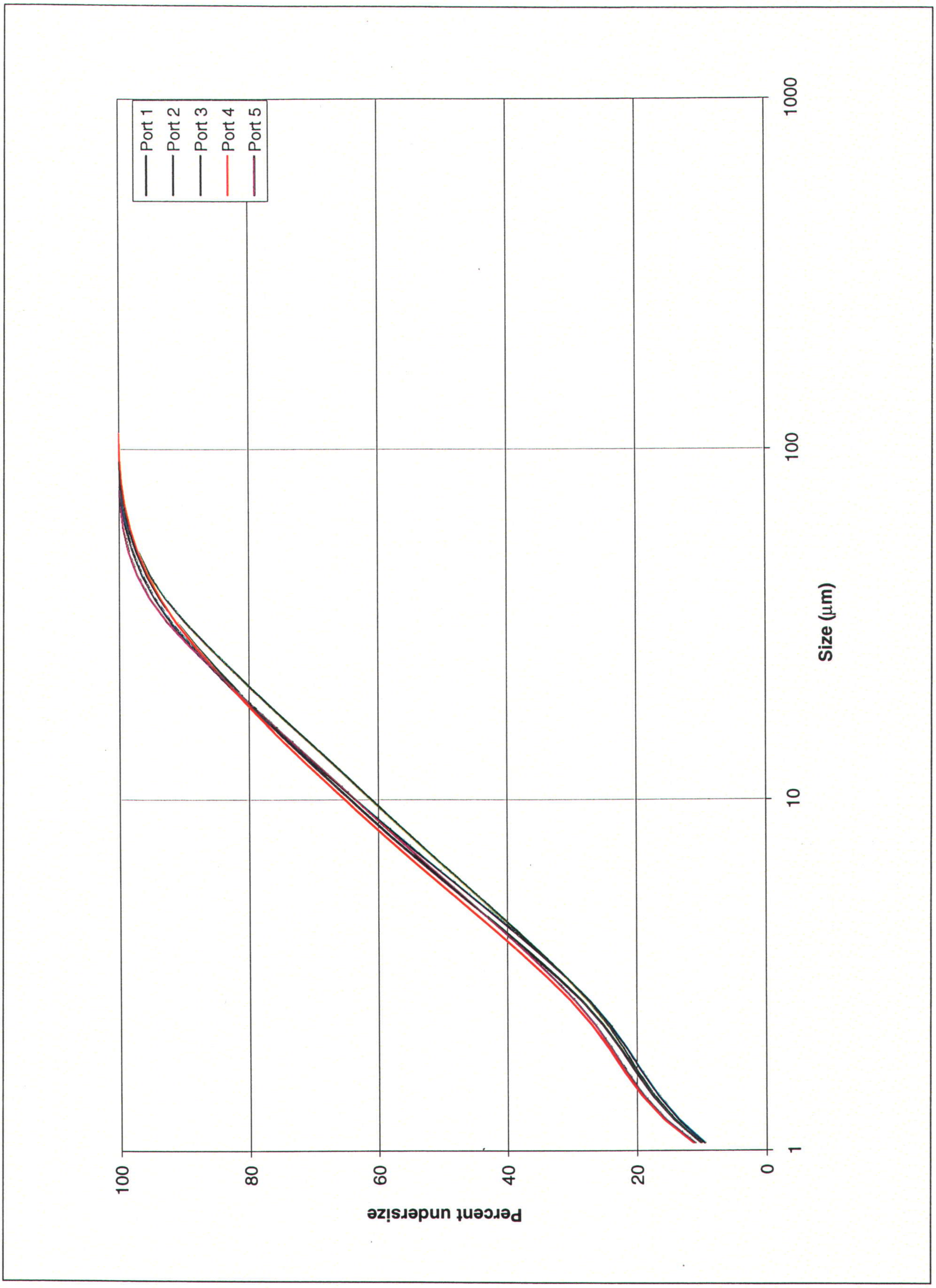

Figure 3.4 **Tube 4 : Particle size analysis of samples withdrawn after 5 minutes**

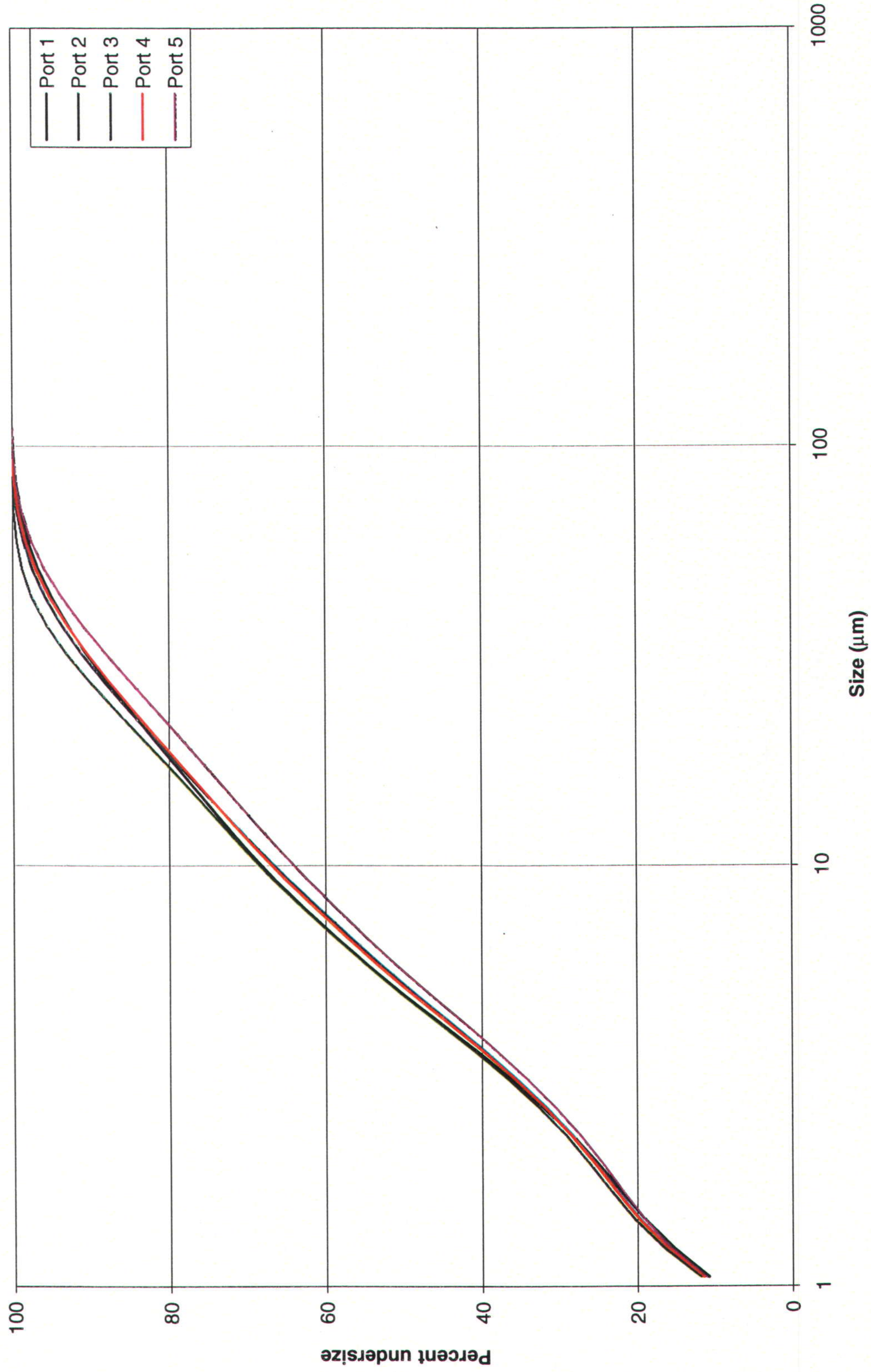

Figure 3.5 Tube 5 : Particle size analysis of samples withdrawn after 5 minutes

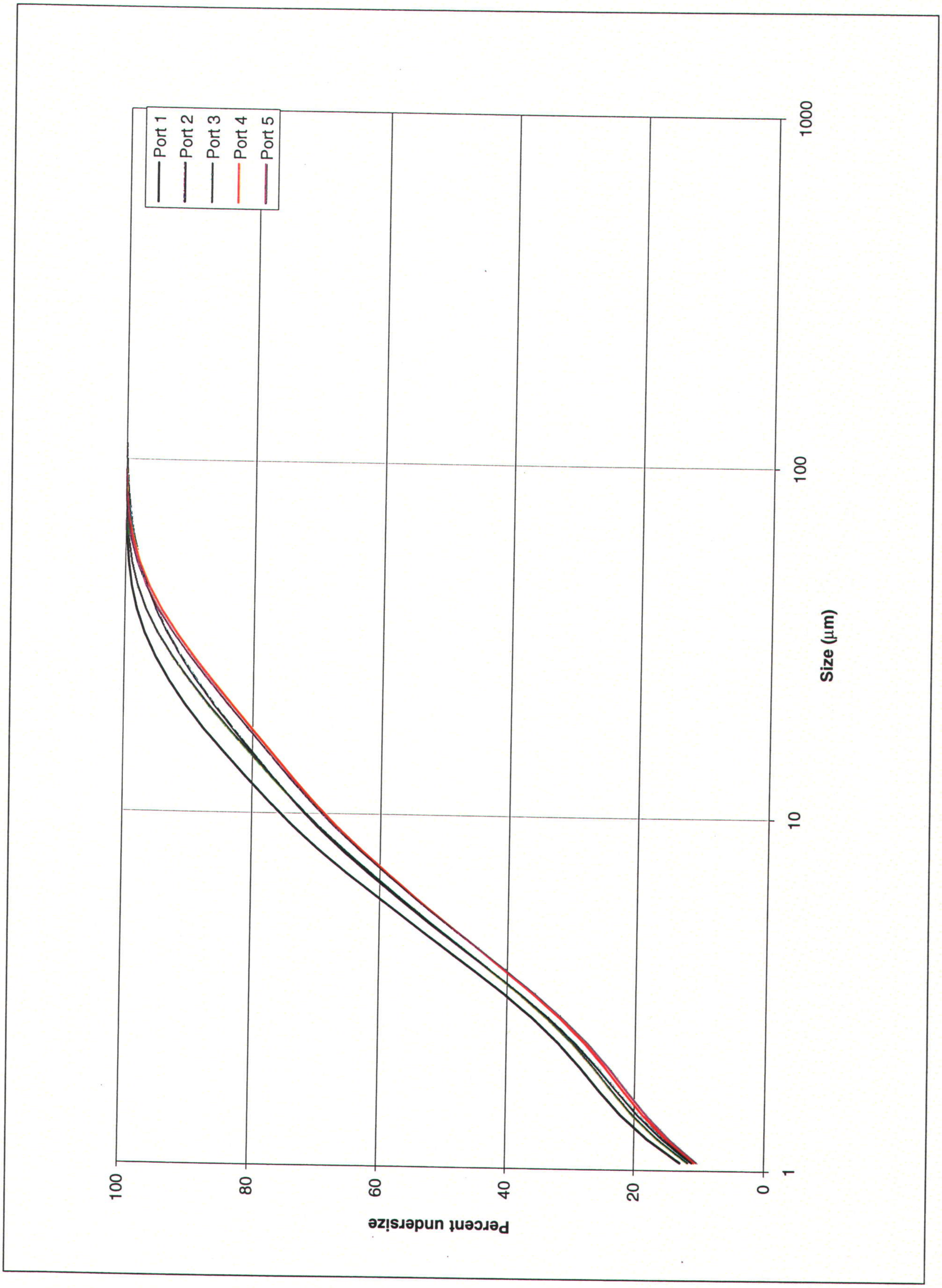

Figure 3.6 **Tube 5 : Particle size analysis of samples withdrawn after 10 minutes**

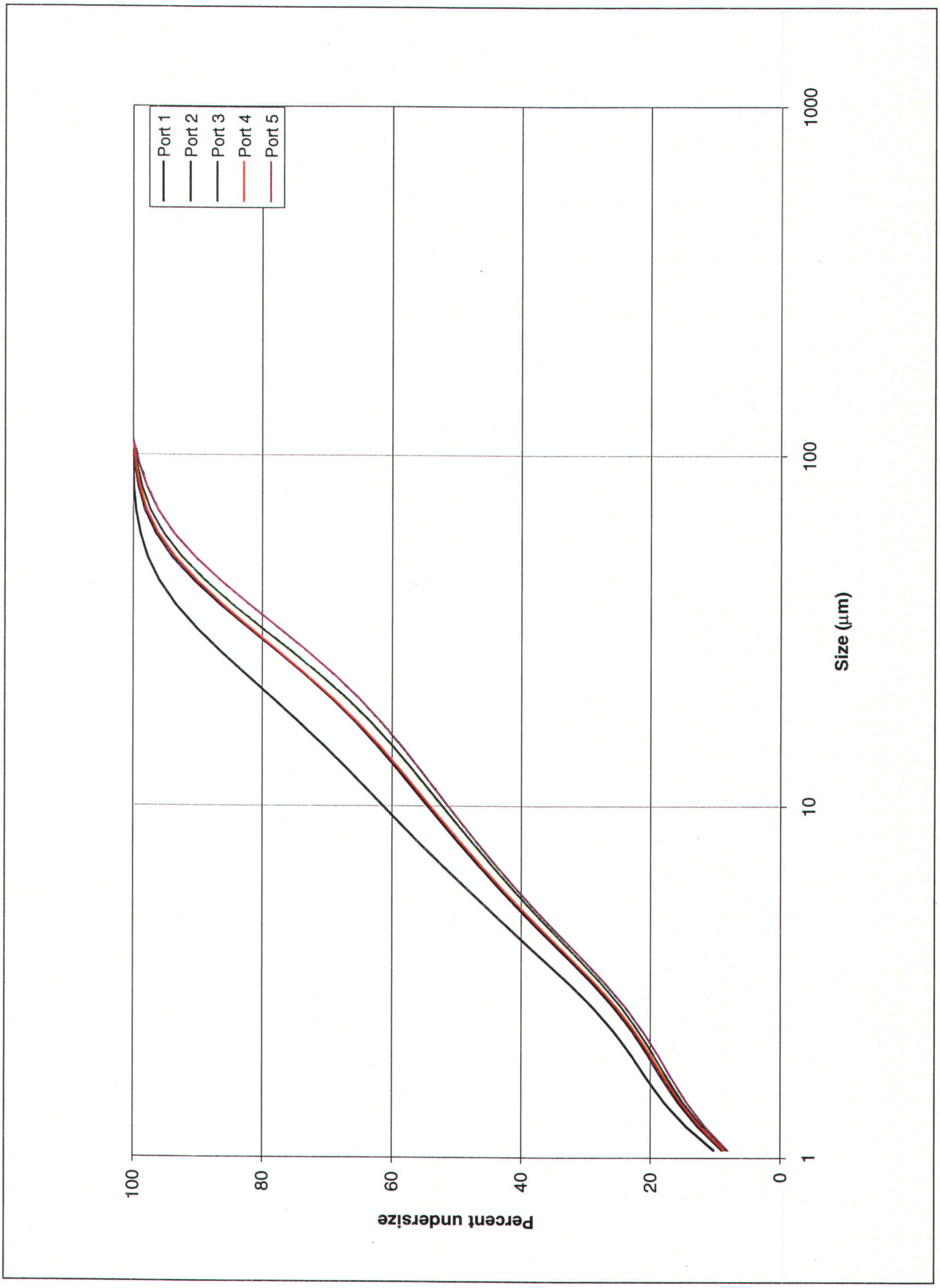

Figure 3.7 **Tube 6 : Particle size analysis of samples withdrawn after 5 minutes**

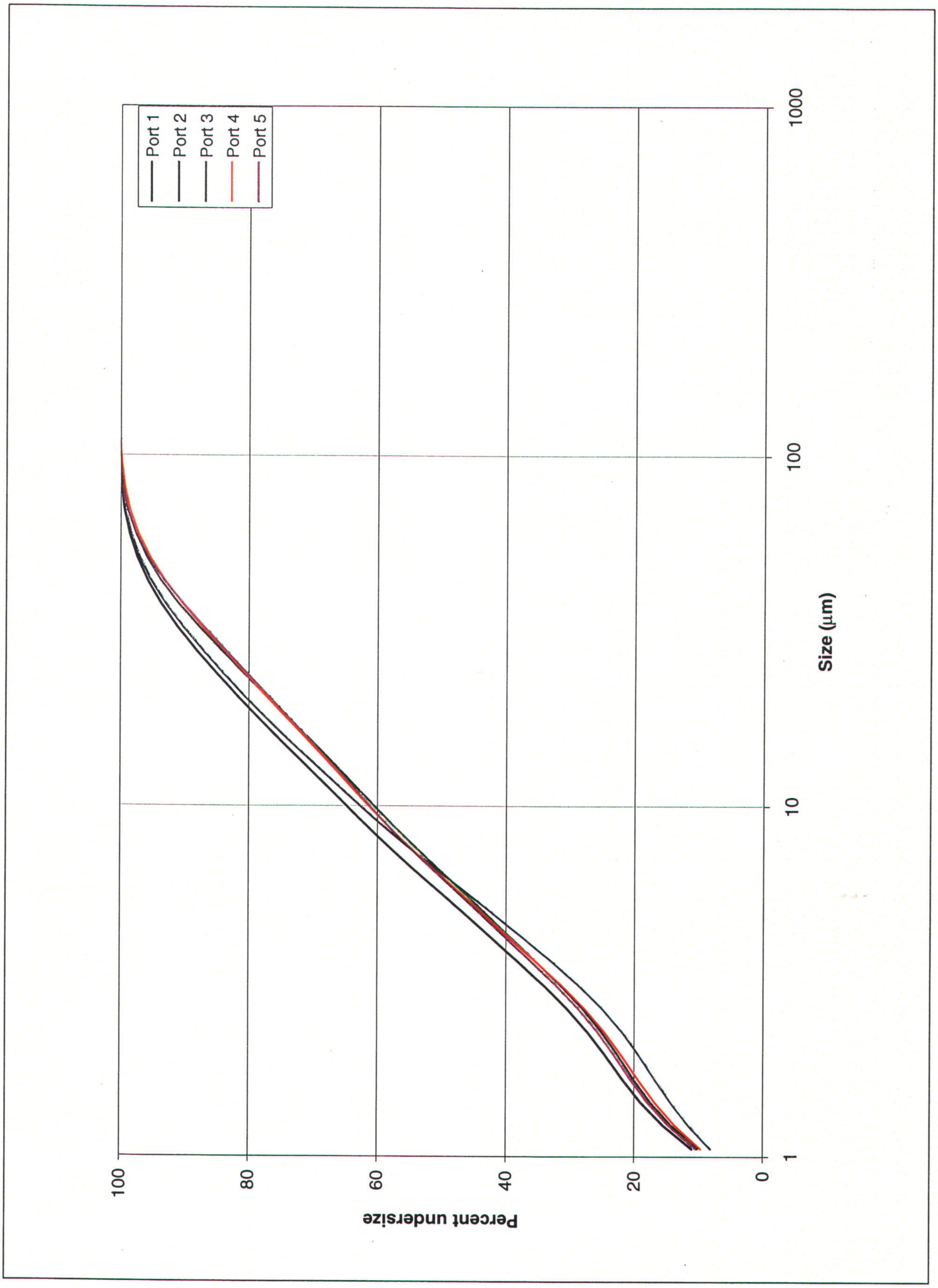

Figure 3.8 **Tube 9 : Particle size analysis of samples withdrawn after 5 minutes**

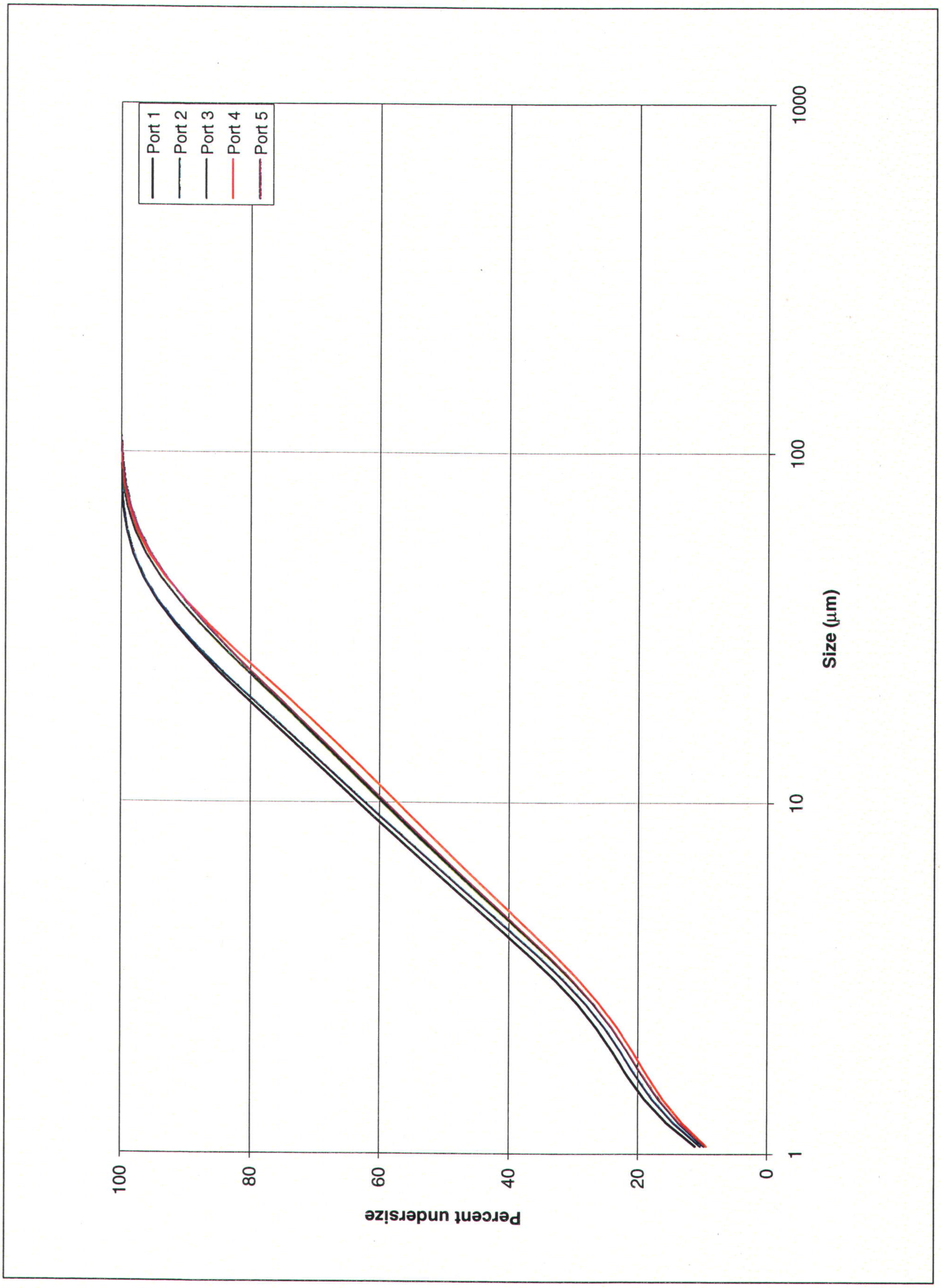

Figure 3.9 **Tube 12 : Particle size analysis of samples withdrawn after 5 minutes**

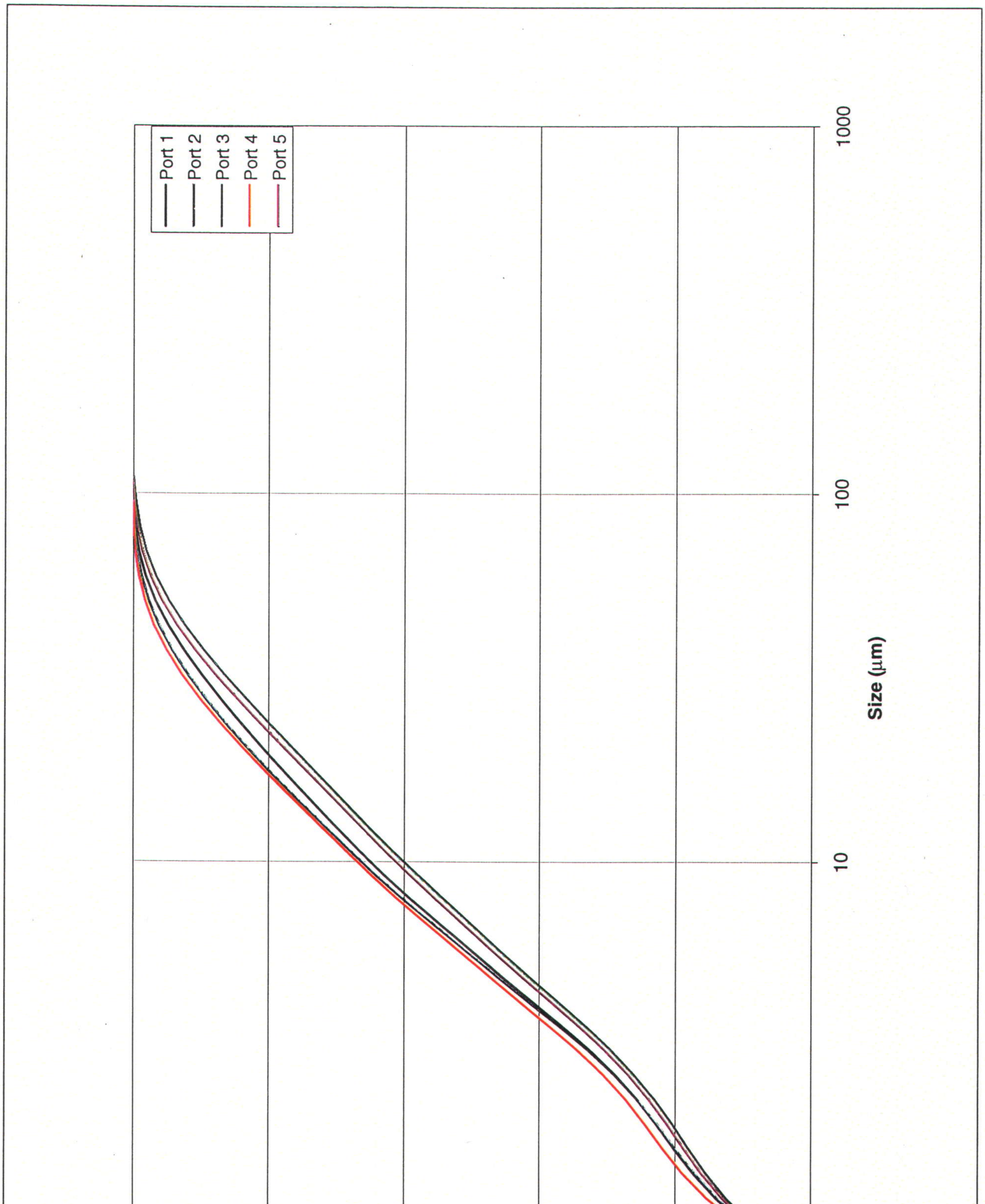

Figure 3.10 **Tube 13 : Particle size analysis of samples withdrawn after 5 minutes**

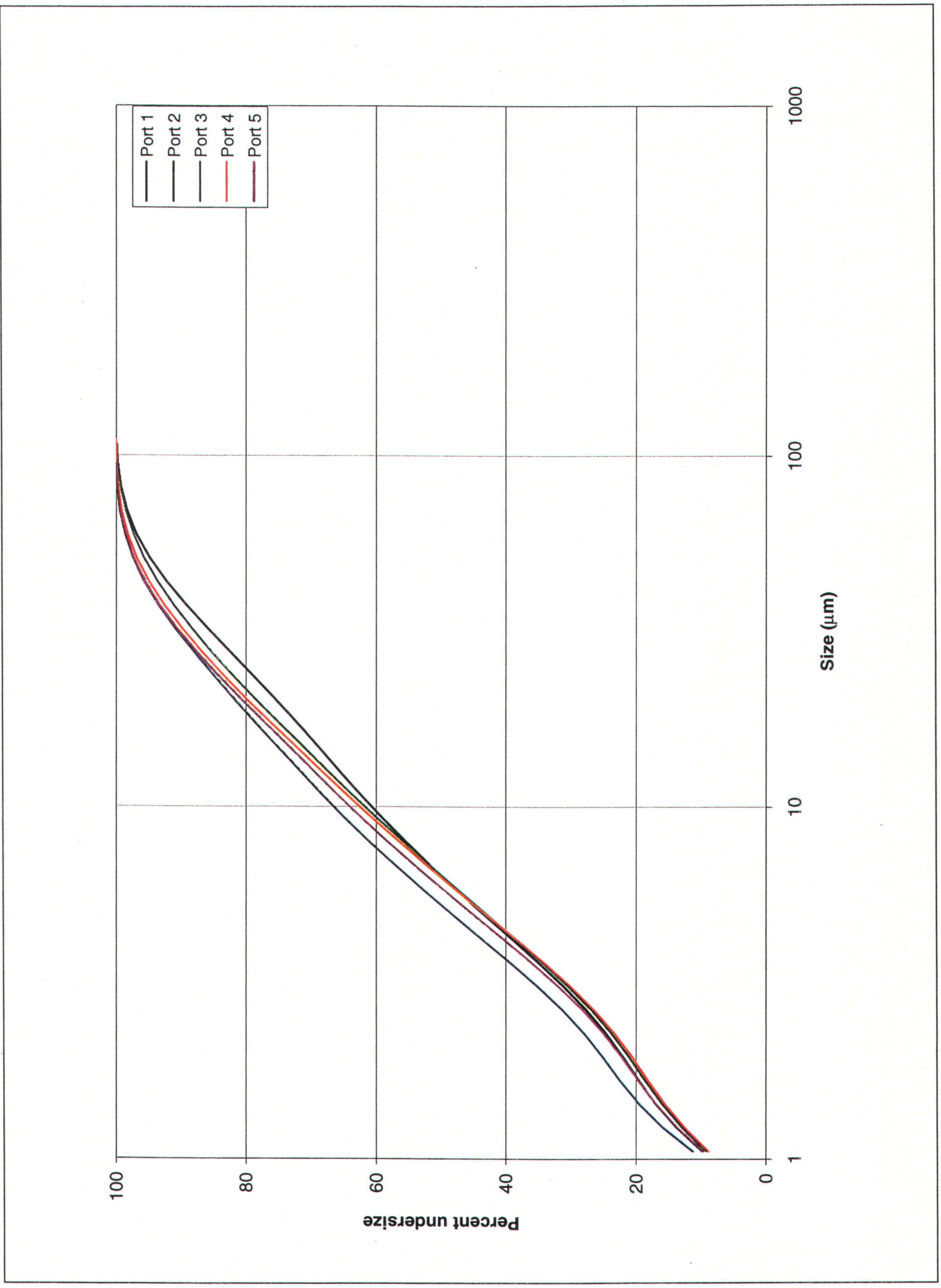

Figure 3.11 Tube 13 : Particle size analysis of samples withdrawn after 10 minutes

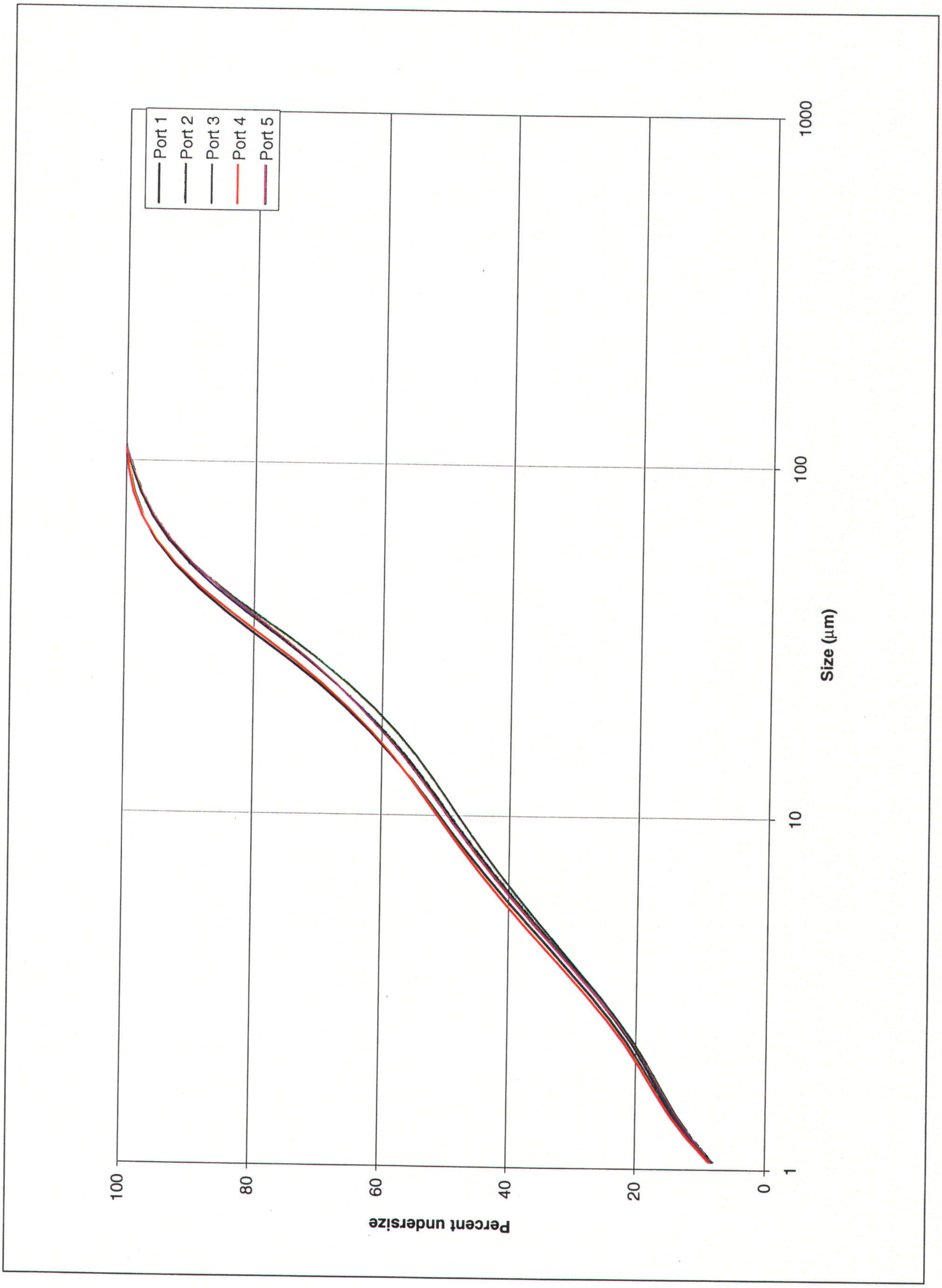

Figure 3.12 **Tube 14 : Particle size analysis of samples withdrawn after 5 minutes**

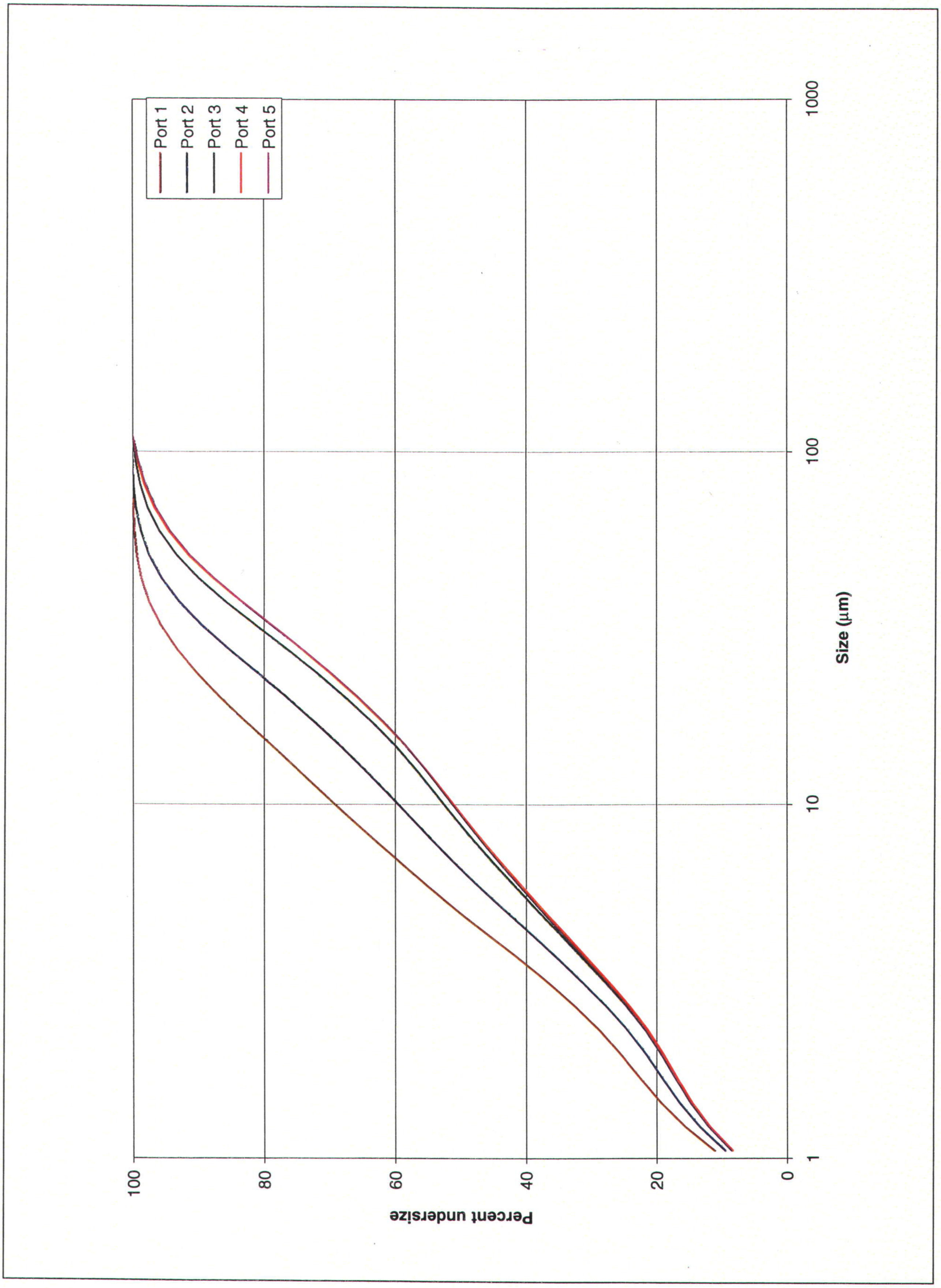

Figure 3.13 Tube 14 : Particle size analysis of samples withdrawn after 10 minutes

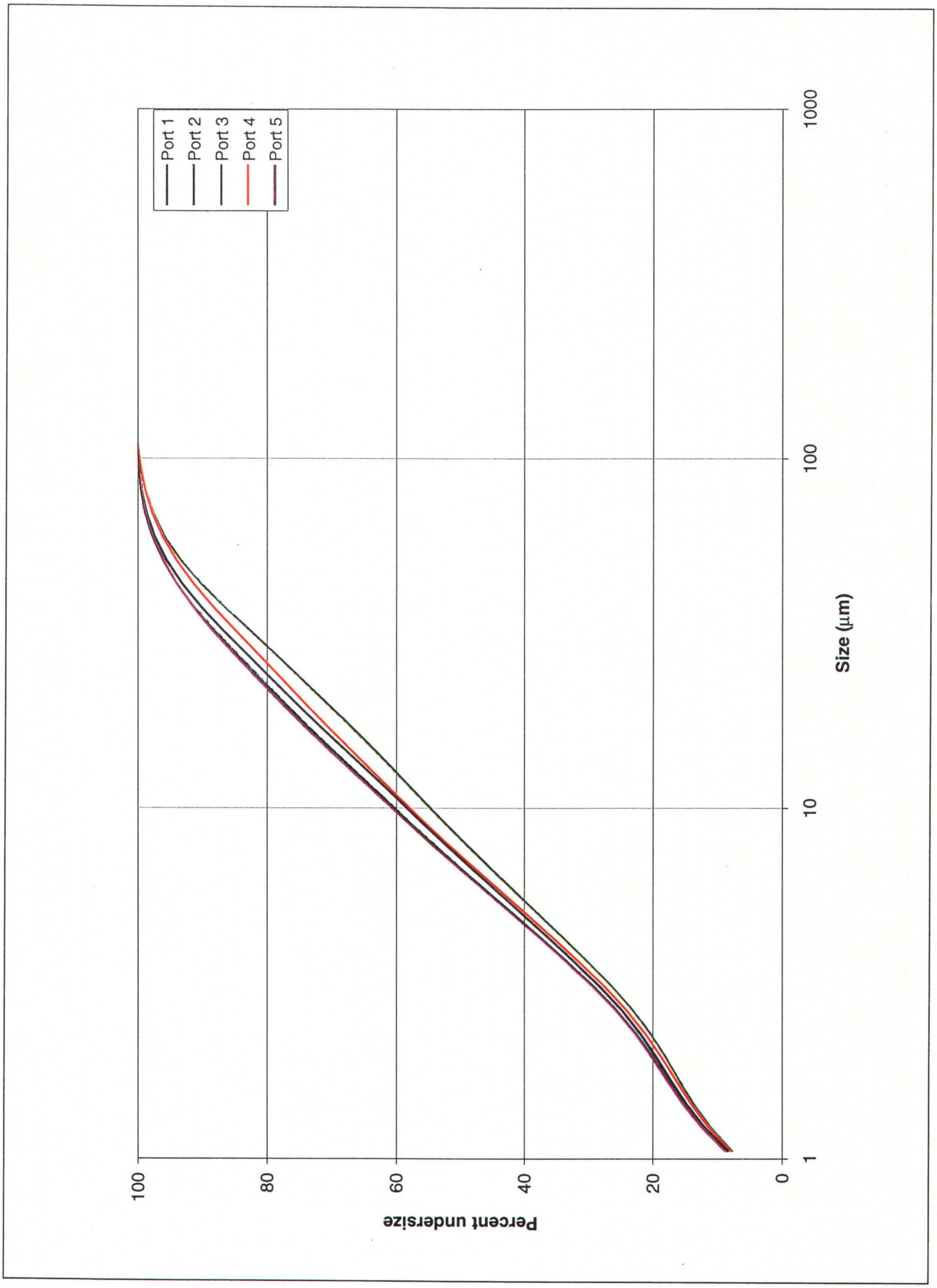

Figure 3.14 Tube 15 : Particle size analysis of samples withdrawn after 5 minutes

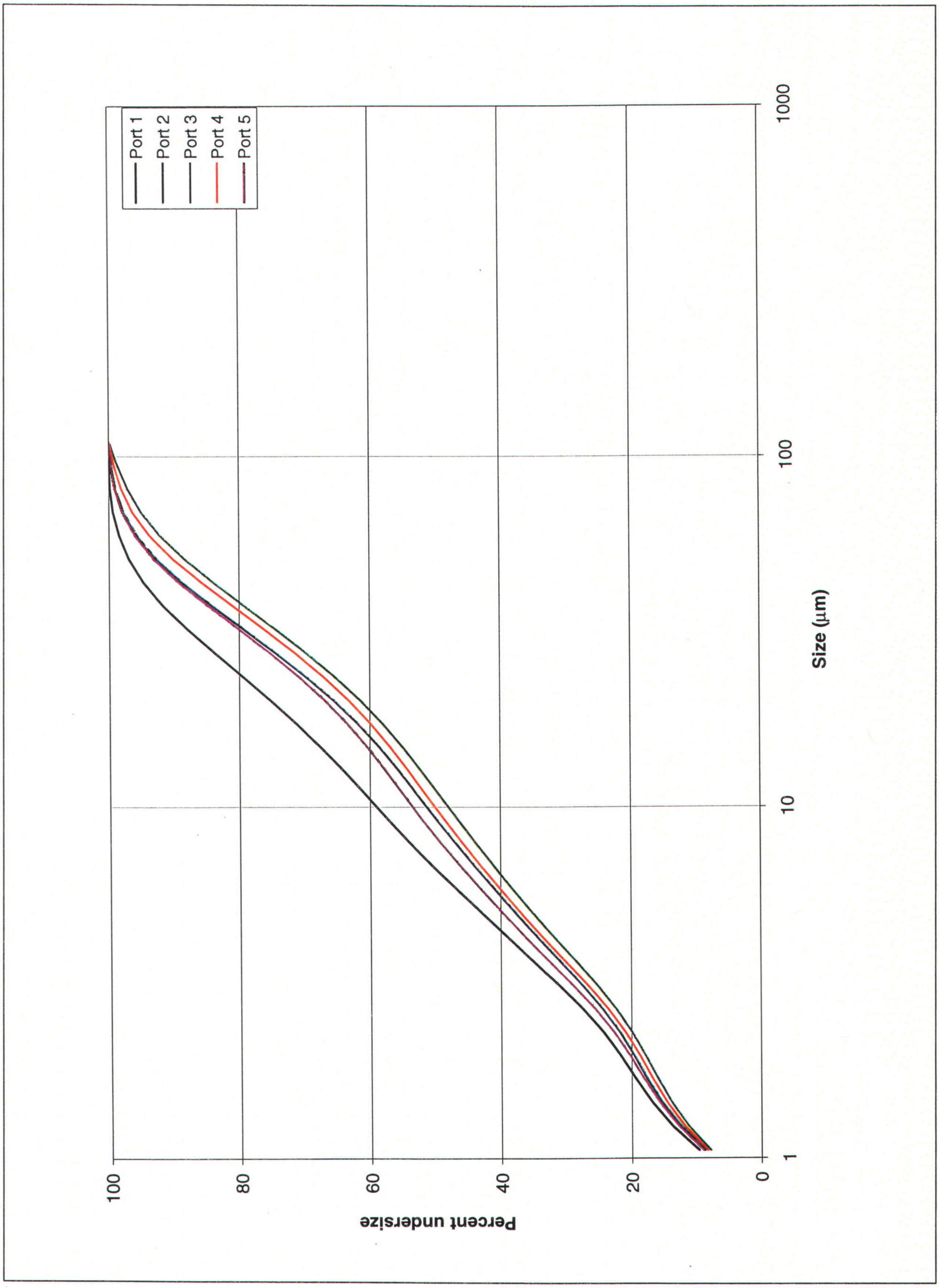

Figure 3.15 Tube 16 : Particle size analysis of samples withdrawn after 5 minutes

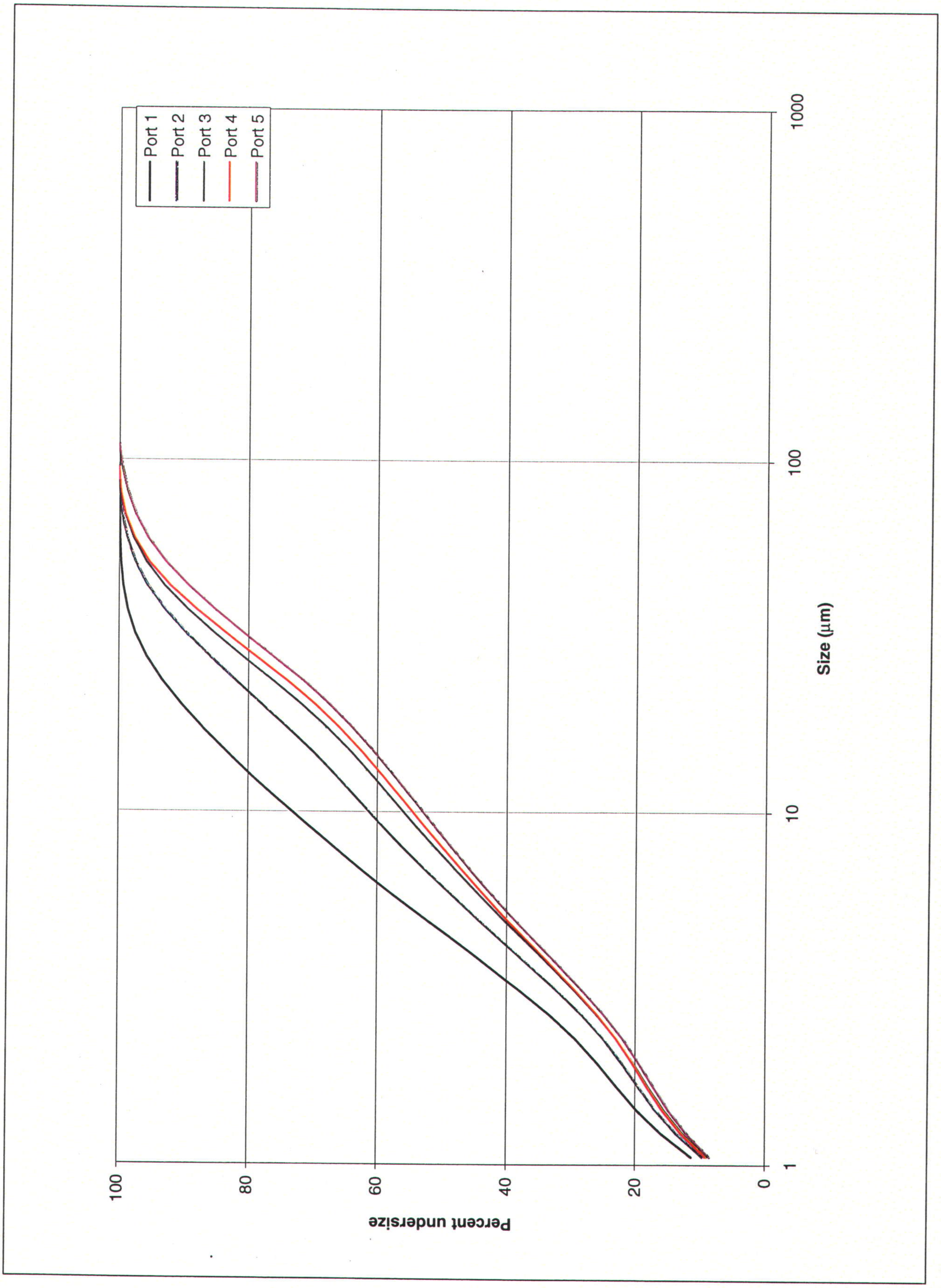

Figure 3.16 **Tube 16 : Particle size analysis of samples withdrawn after 10 minutes**

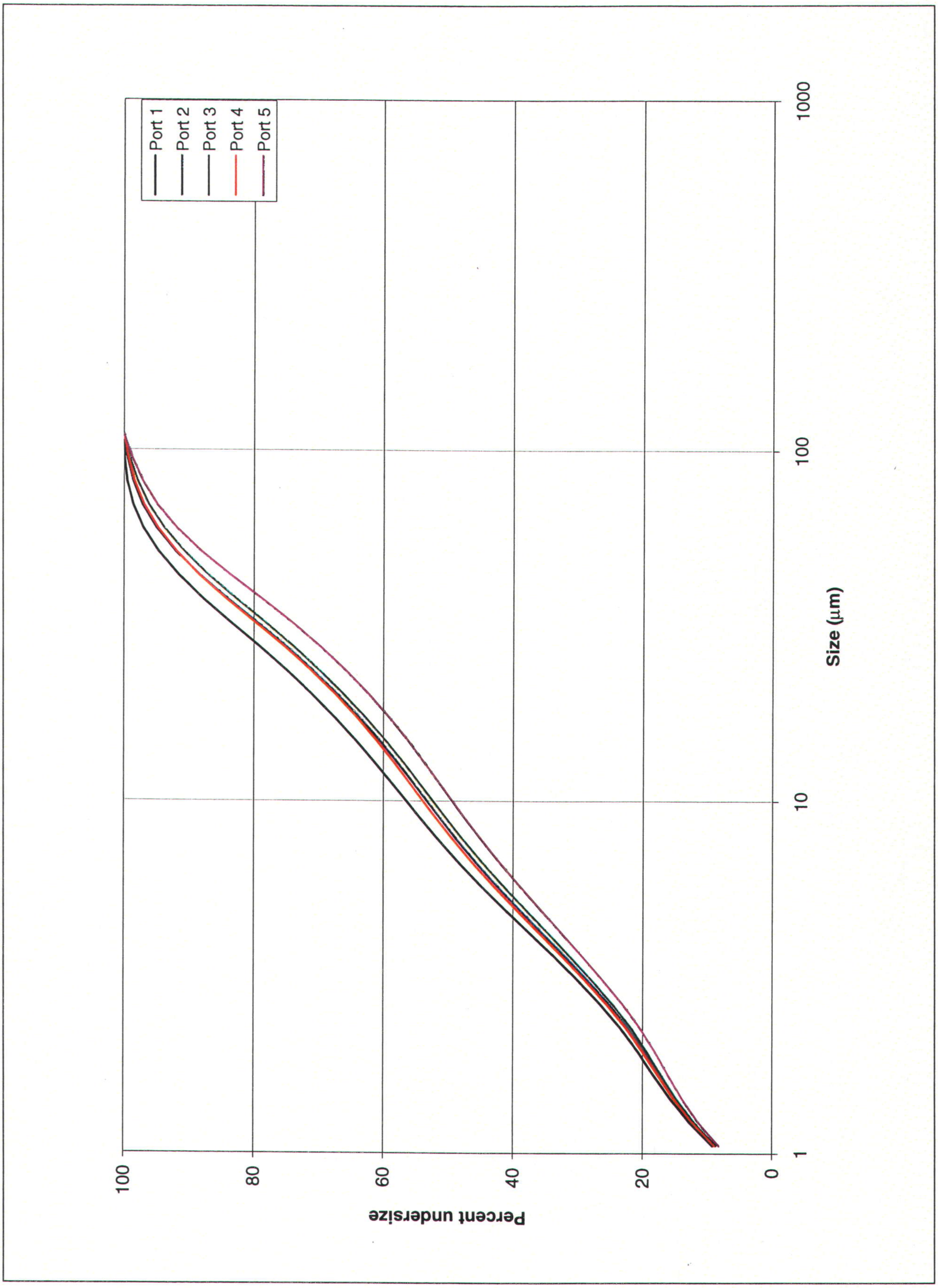

Figure 3.17 Tube 17 : Particle size analysis of samples withdrawn after 5 minutes

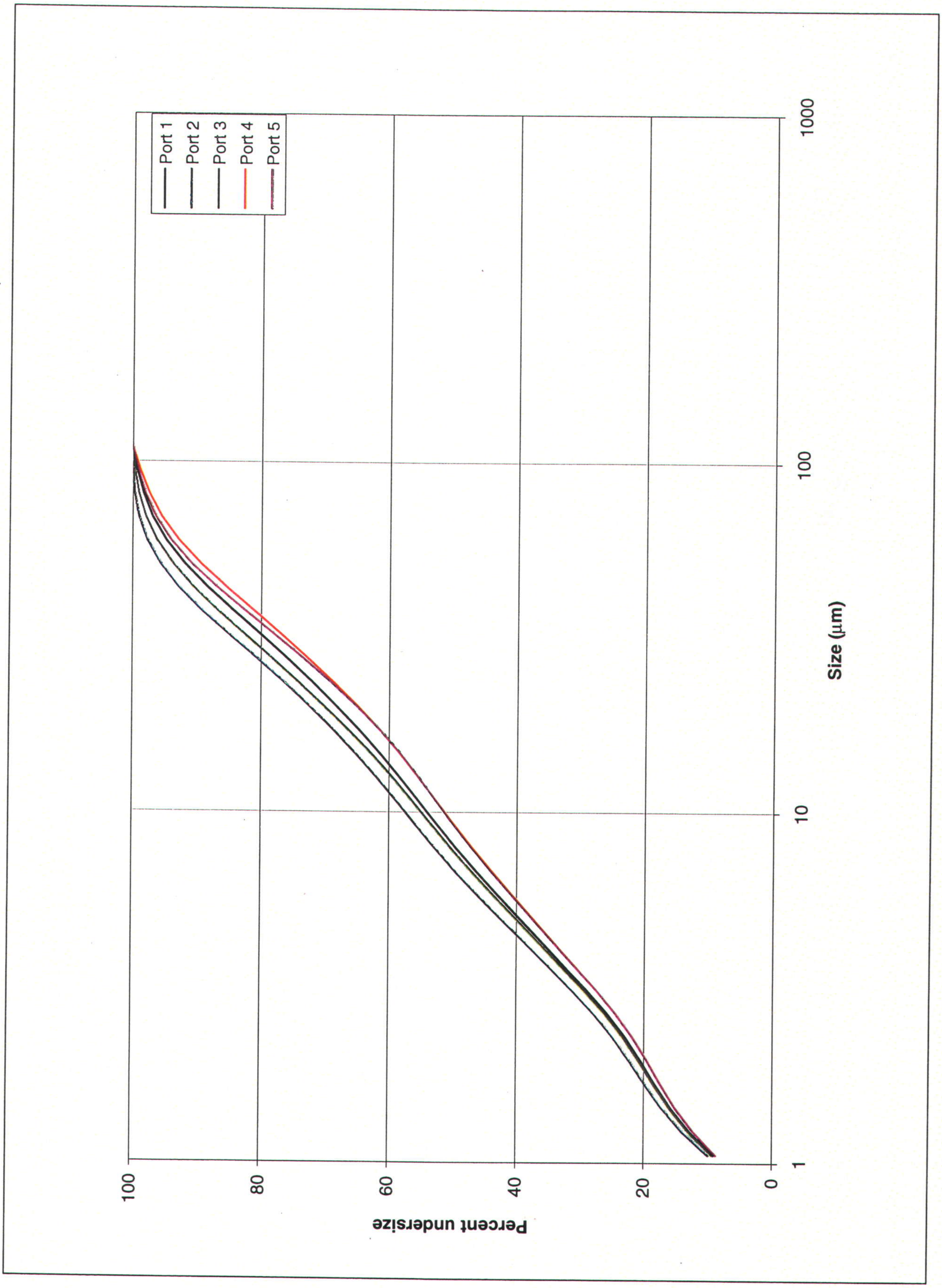

Figure 3.18 **Tube 18 : Particle size analysis of samples withdrawn after 5 minutes**

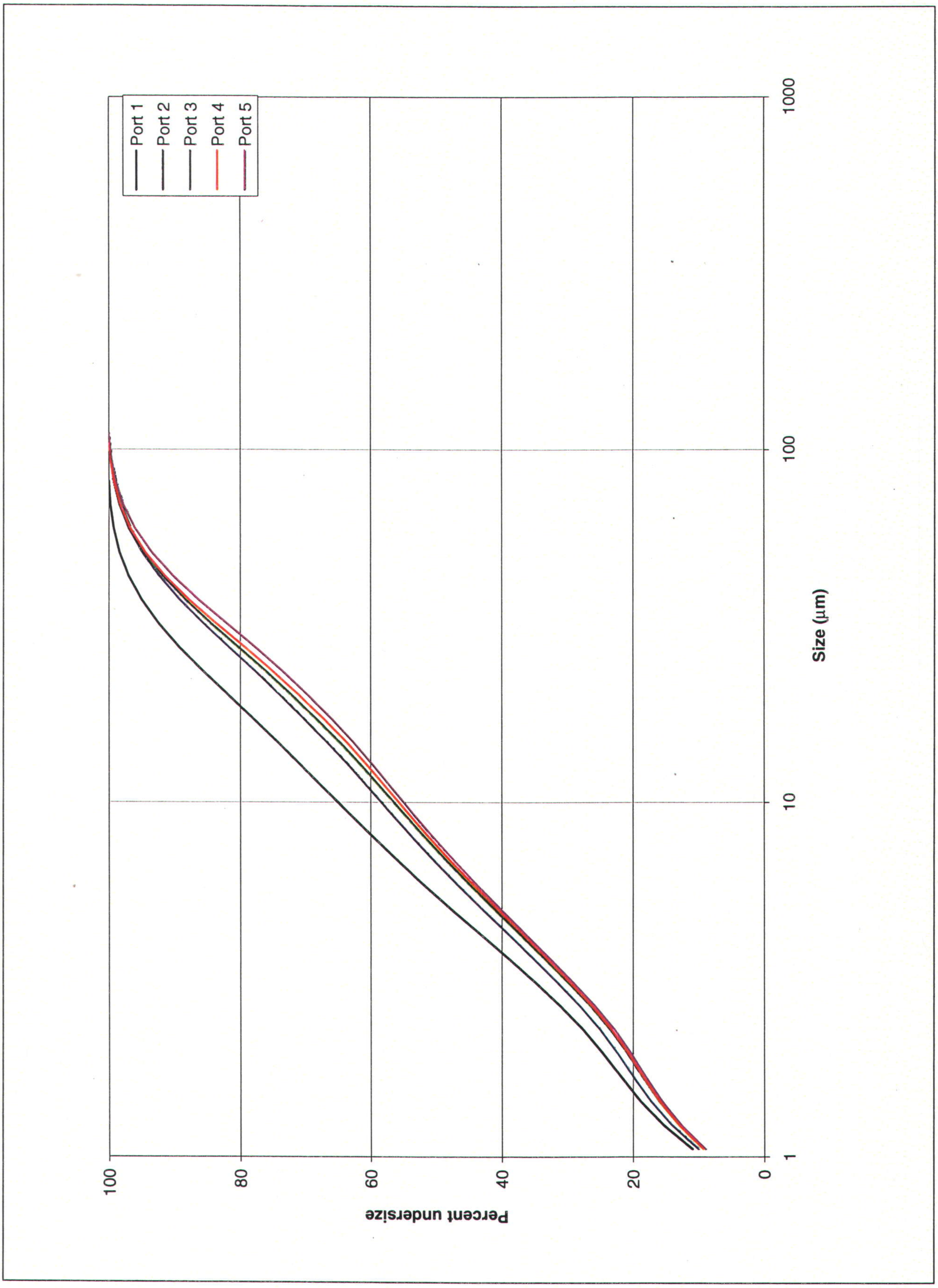

Figure 3.19 **Tube 18 : Particle size analysis of samples withdrawn after 10 minutes**

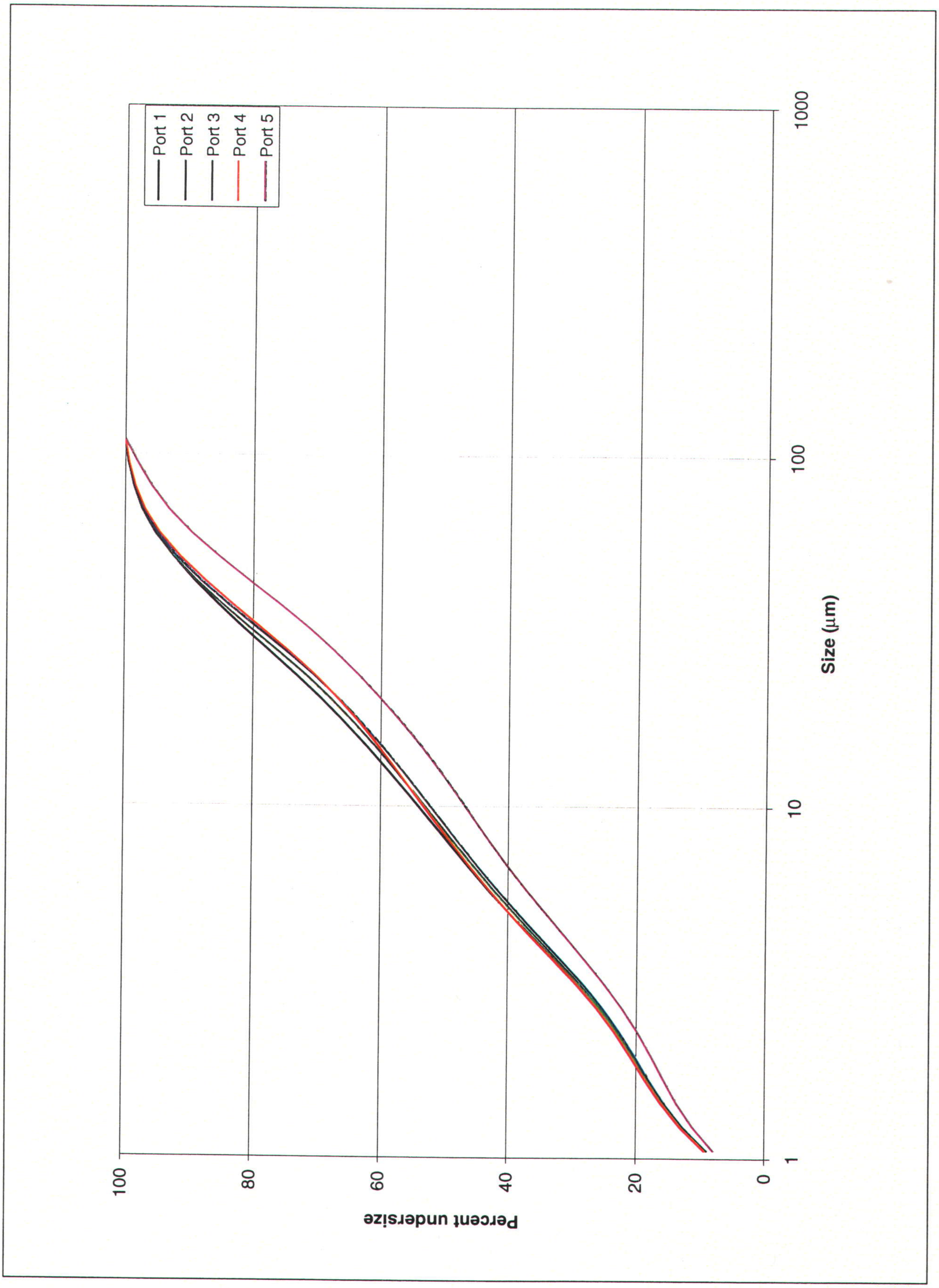

Figure 3.20 Tube 19 : Particle size analysis of samples withdrawn after 5 minutes

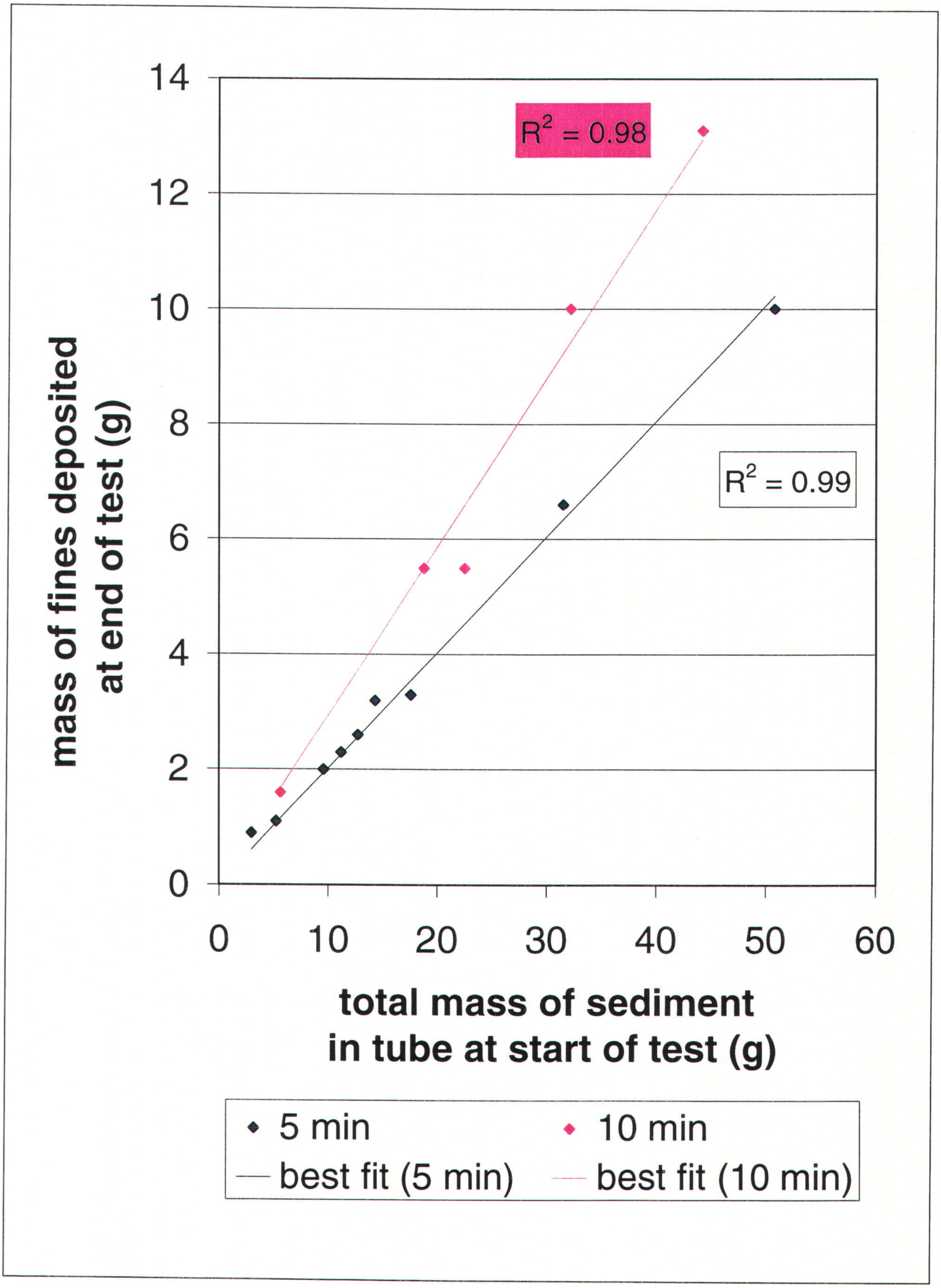

Figure 3.21 **Correlation between mass of fine material in test sample and fine material observed to settle preferentially**

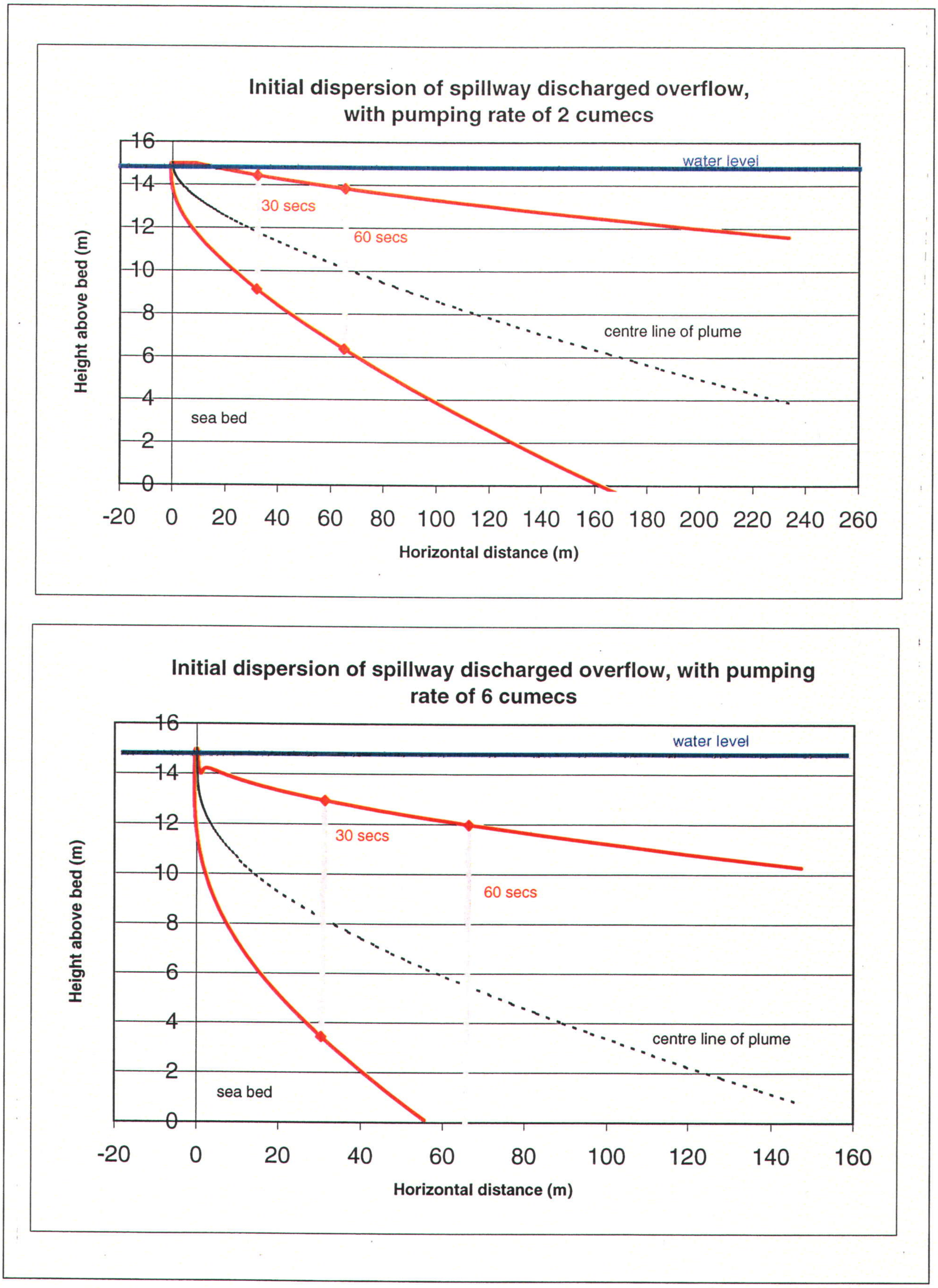

Figure 3.22 Modelling of initial dispersion of spillway discharged overflow

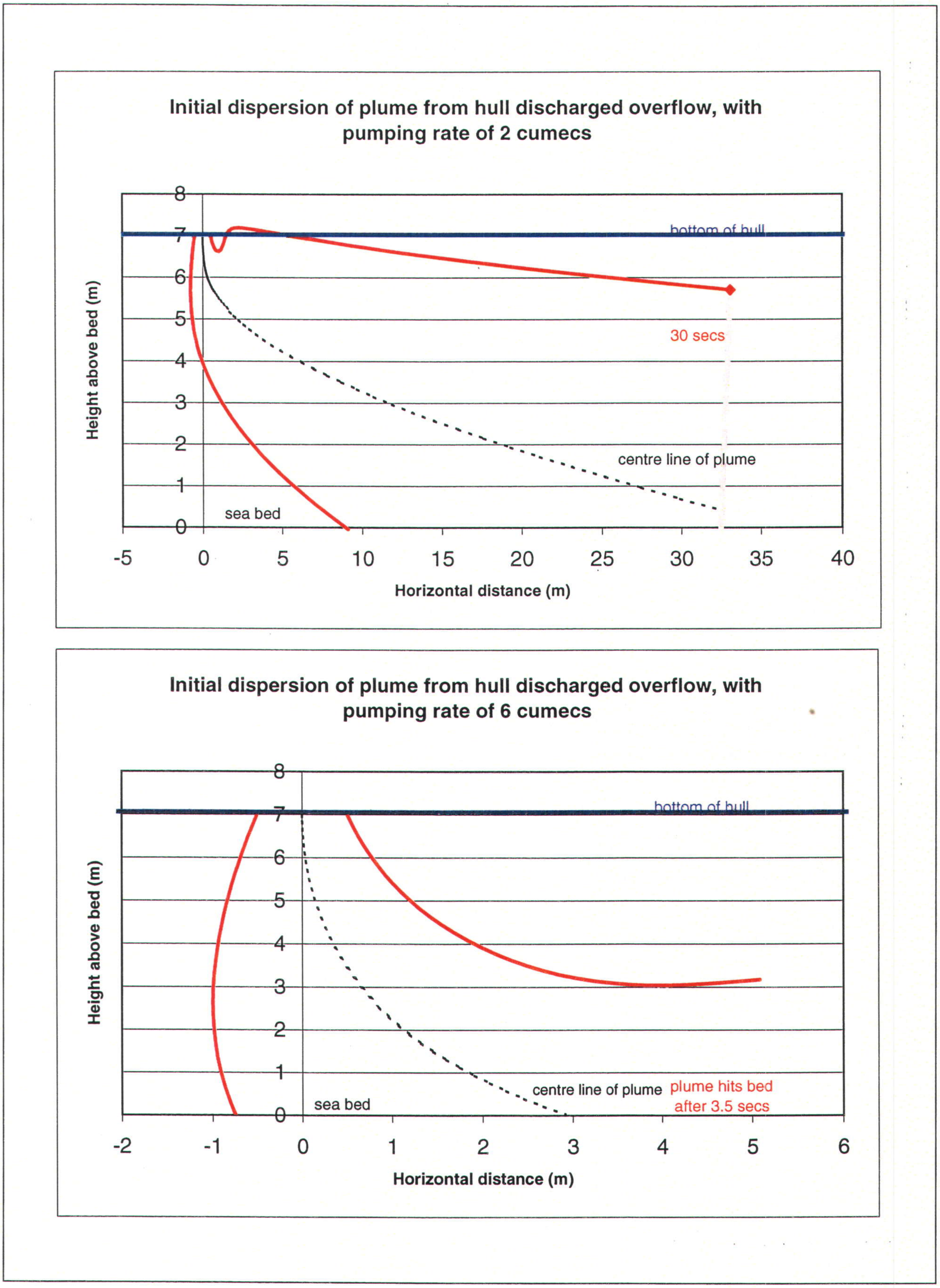

Figure 3.23 Modelling of initial dispersion of hull discharged overflow

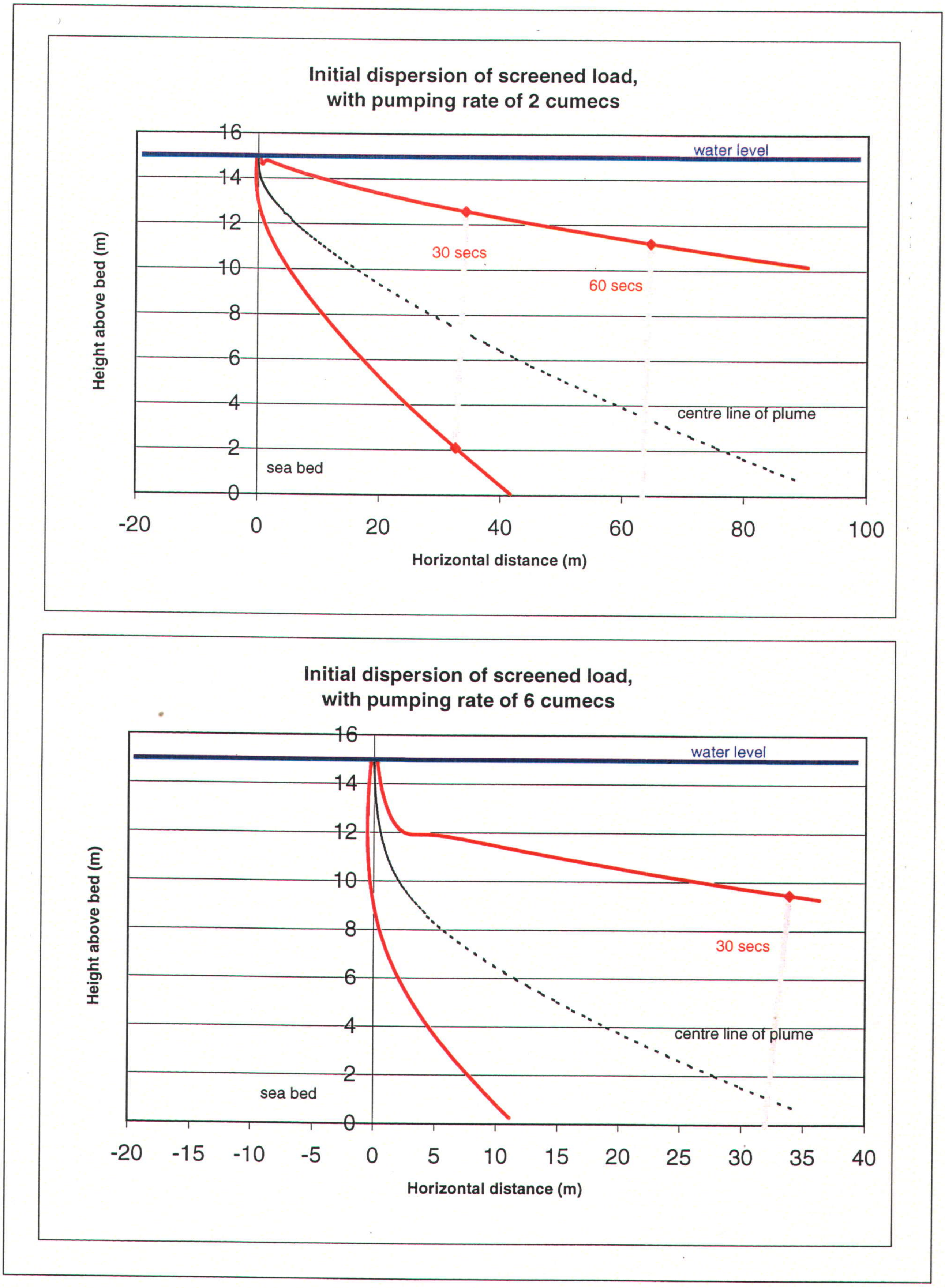

Figure 3.24 Modelling of initial dispersion of reject chute discharge from a screened load

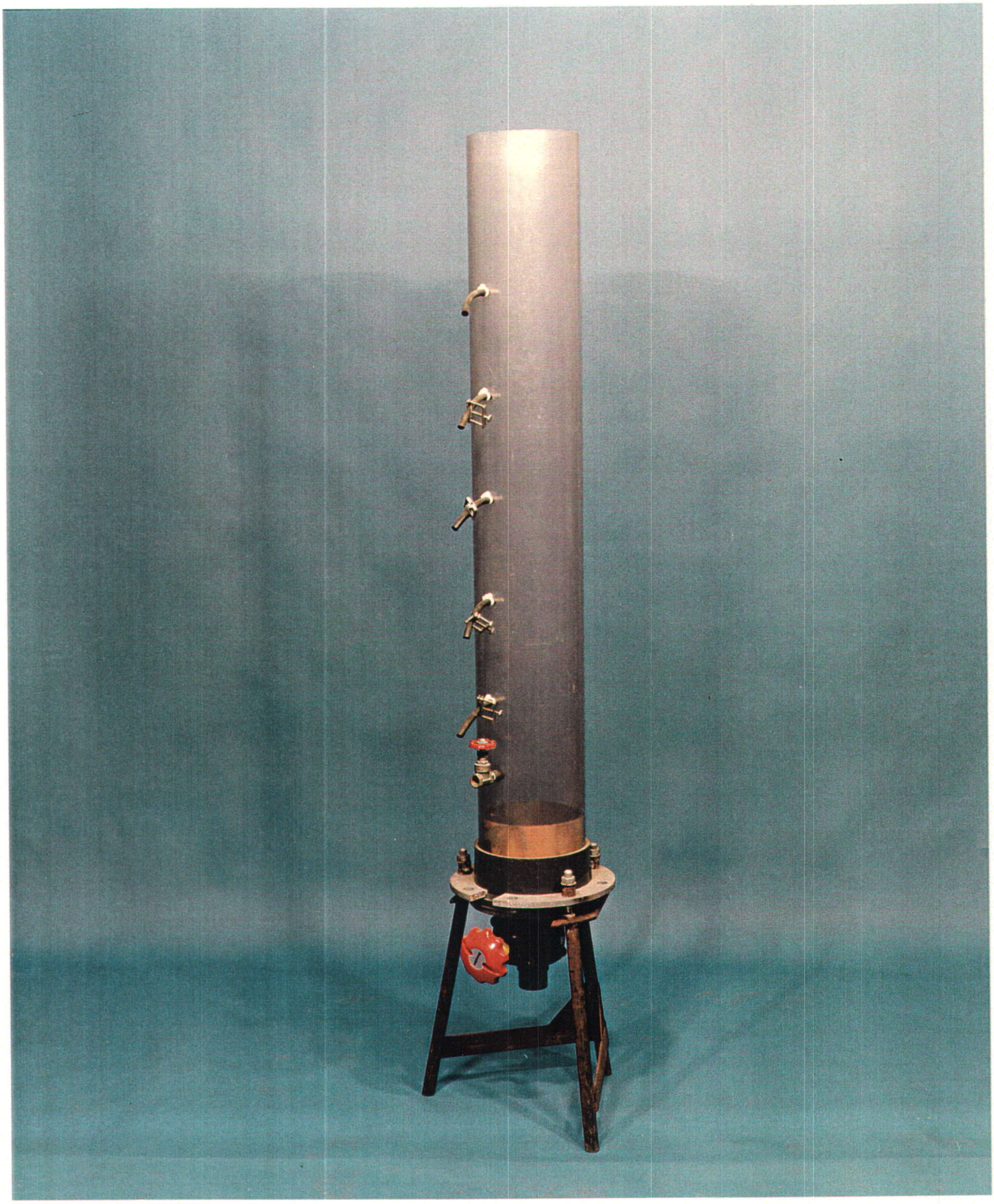

Plate 3.1 Settling column used in field testing

Part 4

USE OF PREDICTIVE APPROACHES

10. A COMPARISON OF PREDICTIVE APPROACHES

10.1 Methodology

The three methods, the desk analysis approach, with GAUSSIAN and SEDPLUME representing the advection/diffusion and process-based approaches, were compared using two different dredging scenarios. The first is release from a position on the south east coast of the UK where flow conditions are reasonably unidirectional. In this case release is continual over five tides. The second is release from a position in Hong Kong waters where the channel geometry is complex thereby producing complicated current flow structures. In this case release is continual over the first tide. These two cases were selected because HR has well established flow models of these areas. In both cases continual release was modelled as this is the simplest method to determine the areal extent of the footprint of dredging operations.

In both cases the following arbitrary, but representative, parameters were used:

Diffusion coefficient	$D=0.3m^2/s$
settling velocity	$W_s=1x10^{-3}m/s$
loss rate of fine sediment	$\partial m/\partial t=10$ kg/s
critical shear stress for re-erosion	$\tau_e=0.5$ N/m^2
critical shear stress for deposition	$\tau_d=0.1$ N/m^2
erosion rate (SEDPLUME)	M=0.0005 ms
dry density of settled sediment	$\rho_d=500$ kg/m^3

10.2 Results for uniform flow conditions – Offshore from Harwich Harbour

The movement of sediment in approximately uniform flow conditions was represented by release at a position some 15km south east of the mouths of the Stour and Orwell estuaries (see Figure 4.1). The release was modelled as continual over five (repeating) mean spring tides, starting at HW, and the resultant movement of the plume was modelled using the GAUSSIAN and SEDPLUME models.

The peak mean spring current (depth-averaged) speeds at the (hypothetical) release point vary from 1.0m/s on the flood tide to 1.2m/s on the ebb tide with the flood and ebb tidal excursion lengths being 15km and 17.5km respectively, implying that the deposition footprint could be up to 32.5km long. The width of the deposition footprint depends on the initial plume movement after release which is unknown. The movement of material is along the SW/NE axis, parallel to the coastline. The depth of water at the site is 14m.

Figures 4.2 and 4.3 show the plume after 0.5 tides as calculated by the GAUSSIAN and SEDPLUME models. The plumes extend some 17km (GAUSSIAN) and 14.5km (SEDPLUME) on the initial ebb tide. The results are similar except for the different distance travelled by the plumes, and at the north extremity of the plume where the SEDPLUME model predicts concentrations above background in excess of 5mg/l while the GAUSSIAN model only predicts concentrations just above 2mg/l. The deposition after 0.5 tides for the GAUSSIAN and SEDPLUME results are shown in Figures 4.4 and 4.5. Again the deposition footprints are similar except for their respective lengths. The SEDPLUME model predicts a footprint of the order of the tidal excursion while the GAUSSIAN method predicts a slightly longer footprint. The GAUSSIAN result shows greater deposition towards the release point and less deposition towards the northern extremity of the plume. The differences between the GAUSSIAN and SEDPLUME results are principally caused by deposition occurring during the initial slack time of the model run, which is resuspended in the SEDPLUME model but which is not resuspended in the GAUSSIAN model. This initial deposition in the GAUSSIAN model reduces the amount of sediment which is available to travel northwards on the ebb tide. Note also that SEDPLUME predicts that all of the sediment deposited is resuspended on the following tide, unlike the GAUSSIAN model which assumes permanent deposition.

Figures 4.6 and 4.7 show the plume after 1 tide. The results of the two models match less well than previously with the GAUSSIAN plume concentration falling below 1mg/l above background some 6km SW of the release point while the SEDPLUME plume extends for 15km SW of the release point with concentrations above background in excess of 5mg/l. Again the reason for this is the resuspension of deposited material in SEDPLUME which is not resuspended in GAUSSIAN. The effect is larger than previously because material has been able to deposit during the LW slack as well as the initial HW slack. The deposition after 1 tide for the GAUSSIAN and SEDPLUME results are shown in Figures 4.8 and 4.9 The footprints are different primarily because the GAUSSIAN model does not resuspend the material deposited previously at LW. The GAUSSIAN footprint extends some 35km long by 1.5km wide, roughly centred on the release point. This compares reasonably with the tidal excursion, the process of dispersion allowing some extra length.

The GAUSSIAN model assumes a steady fall of sediment at a predetermined rate as long as speeds are below a preset threshold. The model does not allow for resuspension of this material. This type of situation represents quiescent conditions where current speeds are too low to resuspend deposited sediment, which is not the case in the example quoted above, or alternatively, represents locally quiescent conditions where bed geometry provides protection from resuspension. The GAUSSIAN model could therefore be seen as a worst case scenario which predicts the maximum deposition possible at any point, although its prediction of the deposition footprint will be unrealistically high as a whole, unless current speeds at the point of interest are very low. The SEDPLUME model is able to represent the effect of resuspension and therefore the prediction of the deposition footprint is more accurate than that of GAUSSIAN. However, model and survey resolution of bathymetry means that locally sheltered areas are unlikely to be represented within the model. A worst case scenario is therefore worked out in a similar manner by assuming that all deposited sediment remains settled.

The difference in the treatment of deposition has a large effect on the dispersion of the sediment plume. The longer term dispersion of the plume is a combination of the advection of material with the current, the diffusion of material caused by turbulence and differential current speeds through the water column, and the loss of sediment deposited on the bed. Essentially the more deposition predicted by a method, the smaller the magnitude of longer-term suspended sediment concentrations above background levels. GAUSSIAN therefore does not give an accurate or worst case for suspended sediment concentration increases in the long term, unlike SEDPLUME which is a more useful tool for longer term dispersion.

10.3 Affect of lagrangian residuals

The longer term dispersion of sediment plumes, even in apparently unidirectional circumstances, can lead to inaccuracies in the modelling of plume advection. The example used above in Section 10.2 shows that for short term dispersion it is the treatment of deposition and resuspension that governs the accuracy of prediction, with the advection of the plume apparently well represented in both models. However, over a longer period of time, the lagrangian nature of suspended sediment transport becomes more important. The differences in advection between the models in Section 10.2 were small. As the dispersion continues however, the small differences arising from the non-uniformity of the current patterns has a significant effect on the movement of the plume. Figure 4.10 shows the state of the SEDPLUME plume after 4.5 tides together with the 1mg/l envelope of the GAUSSIAN plume. It can be seen that the plume as modelled by SEDPLUME affects areas as much as 5km to the east of the release point. This knowledge is important for an environmental impact assessment. This effect is even greater where flow is not uni-directional as in the following example.

10.4 Non-unidirectional flow – Hong Kong Harbour

This simulation presents a difficult test for the GAUSSIAN model because the geometric shape of the coastline, which is not represented in GAUSSIAN has a large effect on current patterns and therefore sediment dispersion. In particular the flow patterns vary considerably over the area of plume dispersion. This movement of sediment in non-unidirectional flow conditions was represented by release at a position located between Ma Wan and Tsing Yi Islands (see Figure 4.11). The GAUSSIAN and SEDPLUME models simulated continual release over the first diurnal tide, starting at LLW and continued to track the resulting sediment plumes over the second tide. The tide used was a spring tide under low freshwater flow conditions which essentially constitutes well-mixed conditions.

The diurnal tide used is composed of two flood tides of 6 and 7 hours duration, with a short ebb tide of 3 hours and a long ebb tide of 9 hours. The peak mean spring current (depth-averaged) speeds at the (hypothetical) release point vary from 0.5m/s on the flood tides to 0.1 and1.2m/s on the shorter and longer ebb tides respectively. The longest flood and ebb tidal excursion lengths are 4km and 11km respectively. The movement of material is along the SW/NE axis, parallel to the coastline. If an estimate of the likely width of the plume is 200m then the deposition footprint could be 15km long and 200m wide. The depth of water at the dredging area is 35m.

Figures 4.12 and 4.13 show the plume after 0.5 tides (12.5 hours) as calculated by the GAUSSIAN and SEDPLUME models. It can be seen that at this point in the simulation the GAUSSIAN model has reproduced the behaviour of the plume reasonably near the release point. However SEDPLUME shows that at t=0.5 tides there are two plumes, material previously moved westward and deposited earlier in the simulation having been resuspended and carried further westward. The distance travelled by these plumes approximately corresponds to one and two flood tidal excursions.

Figures 4.14 and 4.15 show the plume after 1.0 tides (25 hours) as calculated by the GAUSSIAN and SEDPLUME models. The effect of resuspension of material is now very significant with the GAUSSIAN model predicting suspended sediment concentrations near to the placement, while the SEDPLUME model predicts an extensive distribution of the sediment plume.

Figures 4.16 and 4.17 show the predicted deposition resulting from the plume at the end of the simulation, after 2.0 tides (50 hours). The results show that the GAUSSIAN simulation is unable to reproduce anything like the distribution of the SEDPLUME results.

Sections 10.2 and 10.3 discuss the how the GAUSSIAN method, which is based on uniform flow conditions and proscribes resuspension, results in much higher deposition near the release point, and consequently lower concentrations away from the release point. Furthermore, the impact of mild non-uniformity of flow conditions over long dispersion times has been demonstrated. In this section it has been shown that the effect of significantly non-uniform flow conditions exacerbates this trend in GAUSSIAN results, compromising the accuracy of GAUSSIAN predictions except in areas local to the release point. The GAUSSIAN method is no longer able to simulate a worst case scenario for deposition since any locations which are sheltered and therefore prone to deposition cannot be reproduced in the GAUSSIAN model.

10.5 Other considerations

The dispersion of material can occur in different ways of which the most common are small-scale temporal variation of currents (turbulent dispersion) and spatial variation in currents. The latter occurs both in a horizontal sense, as in Section 10.4, or in a vertical sense. The variation of current speed through the water column is approximately logarithmic which results in dispersion as flow near the surface flow is faster than flow near the bed. This type of dispersion is referred to as shear dispersion and is a much larger effect than turbulent dispersion. This type of dispersion must be approximated by a diffusion coefficient in GAUSSIAN, whereas SEDPLUME can reproduce the shear effect.

Further non-uniformity in flow conditions can occur as a result of salinity-induced density gradients in an estuary, or as a result of wind action, which produce opposing residual currents near the bed and near the surface of the water column. Sediment near the bed will have a residual tendency to travel in one direction until turbulence carries this sediment into the upper water column whereupon the sediment will have a residual tendency to travel in the other direction. The overall residual tendency of a plume is thus dependent on the proportion of material in the upper and lower parts of the water column. This type of information can only be deduced if flow conditions are allowed to vary through the vertical profile, and for accurate plume modelling under these conditions 3D hydrodynamic input is required.

10.6 Conclusions of comparison of different approaches to plume dispersion prediction

1. An initial scoping exercise must be carried out as part of any environmental assessment procedure. A desk assessment of the potential initial pattern of dispersion should be incorporated in this exercise. The scoping exercise should identify whether further modelling (GAUSSIAN or SEDPLUME) is required.

2. In situations of spatially uniform flow conditions and where there are no flow effects resulting from the geometry of the sea bed, GAUSSIAN provides an economic and computationally efficient method of calculating upper limits for deposition.

3. The accuracy of the GAUSSIAN prediction improves as flow conditions approach those where deposition is continuous.

4. The accuracy of the GAUSSIAN prediction deteriorates as the time of simulation increases.

5. Where flow conditions are not spatially uniform, where dispersion over long time periods is required, where geometry interferes with flow patterns, where an accurate prediction of suspended sediment concentrations is required, or where resuspension of material is likely to be significant, the GAUSSIAN method cannot describe plume dispersion. In this case process modelling (such as SEDPLUME) is a more suitable option.

11. CONCLUSIONS AND RECOMMENDATIONS

As a result of the improvement in the understanding of the processes involved in release of fine material during dredging operations, the method of estimation of the mass of fine material resuspended into the water column as a result of dredging operations has changed. Previous to this study conservative estimates were calculated based on the proportion of fine material in the in situ material and the total amount of material pumped into the dredger. Field measurements, including those undertaken as part of this study, of dredging discharges have enabled a greater understanding of the content of discharges into the sea with subsequent downward revision of estimates of the mass of fine material resuspended into the water column. Since the commissioning of this study a great deal of research into the plumes caused by aggregate dredging has been undertaken. Much of this research has taken the form of field monitoring of sediment discharges and suspended sediment increases caused by dredging operations. The information derived from these measurements has led to a greater understanding of the types of processes that occur during the initial dynamic phase of dispersion. In particular, this has led to the conclusion that during the dynamic phase of dispersion there is rapid movement of a large proportion of discharged material towards the bed and that as a result the proportion of fine sediment initially resuspended into the water column is further significantly reduced.

Two possible causes of this rapid descent were identified – increased settling velocity caused by aggregation released particles and rapid settling of particles caused by the initial momentum of discharge and negative buoyancy. These processes of momentum/density-induced and aggregation-induced removal of fines from the water column have been investigated and it is clear that the momentum-induced settling is the more significant process of the two. This process appears to considerably reduce the proportion of sediment entrained into the water column and therefore to reduce the concentration of dredging-induced plumes.

A spectrum of tools is currently available for modelling plume dispersion but such modelling is open to uncertainty due to the poor understanding of the initial plume behaviour, which as has been demonstrated above, is momentum/density dominated. The quality of dredging plume dispersion modelling would be improved most, therefore, by improving understanding of this momentum/density-induced settling.

Although the basic structure of these processes can be represented in a model, as described in Chapter 9, there are a number of crucial areas where the processes are badly described, notably:

- The magnitude of (and factors controlling) the mixing between the plume and the surrounding water.

- The impact of turbulence on the plume descent, in particular how the damping effect of higher concentrations on turbulence affects the entrainment of material into the water column.

- The effect of the impact of the plume onto the bed in resuspending sediment into the water column.

Further research into plumes caused by aggregate dredging should be targetted towards investigating the process of rapid settling caused by the initial momentum of discharge from the dredger and the affect of negative buoyancy. Such research should bear in mind the need to address the poor state of knowledge of the specific areas listed above and should be structured in such a manner as to provide input to the type of approaches to dispersion prediction outlined in Chapter 4. In particular, the proportion of material entrained into the water column is of paramount importance.

This study has shown that further revision of the method of estimation of the mass of fine material resupended during dredging operations is required. Although there are limitations to the experiments undertaken within this study, it is possible to use their results to provide an improved estimate of fine material resuspension, until such time as the initial phase of plume dispersion is better understood and described. The table below can be used to estimate the proportion of fine material that will be resuspended into the water column compared to the mass of fine material discharged from the dredger. Representative estimates are given for each type of dredging operation.

Operation type	Overspill all-in	Hull discharge all-in	Screening for sand
Proportion resuspended	75%	30%	25%-60%

Recent advances in methods of long-term monitoring of suspended sediment concentrations have enabled suspended sediment signatures over periods of several months to be recorded enabling both the effect of storm events and of dredging/placement operations on suspended sediment increases to be compared. As a broad rule of thumb it is reasonable to assume that in UK coastal waters suspended sediment concentrations may increase above background levels by a factor of between at least 5 and 10 during storm conditions.

Where such data is available the effect of dredging/placement has been shown to be less than the natural variation. Such results could lead to a reassessment of the hitherto supposed "dirty" effects of aggregate dredging and it is recommended that more long-term monitoring be undertaken towards this goal.

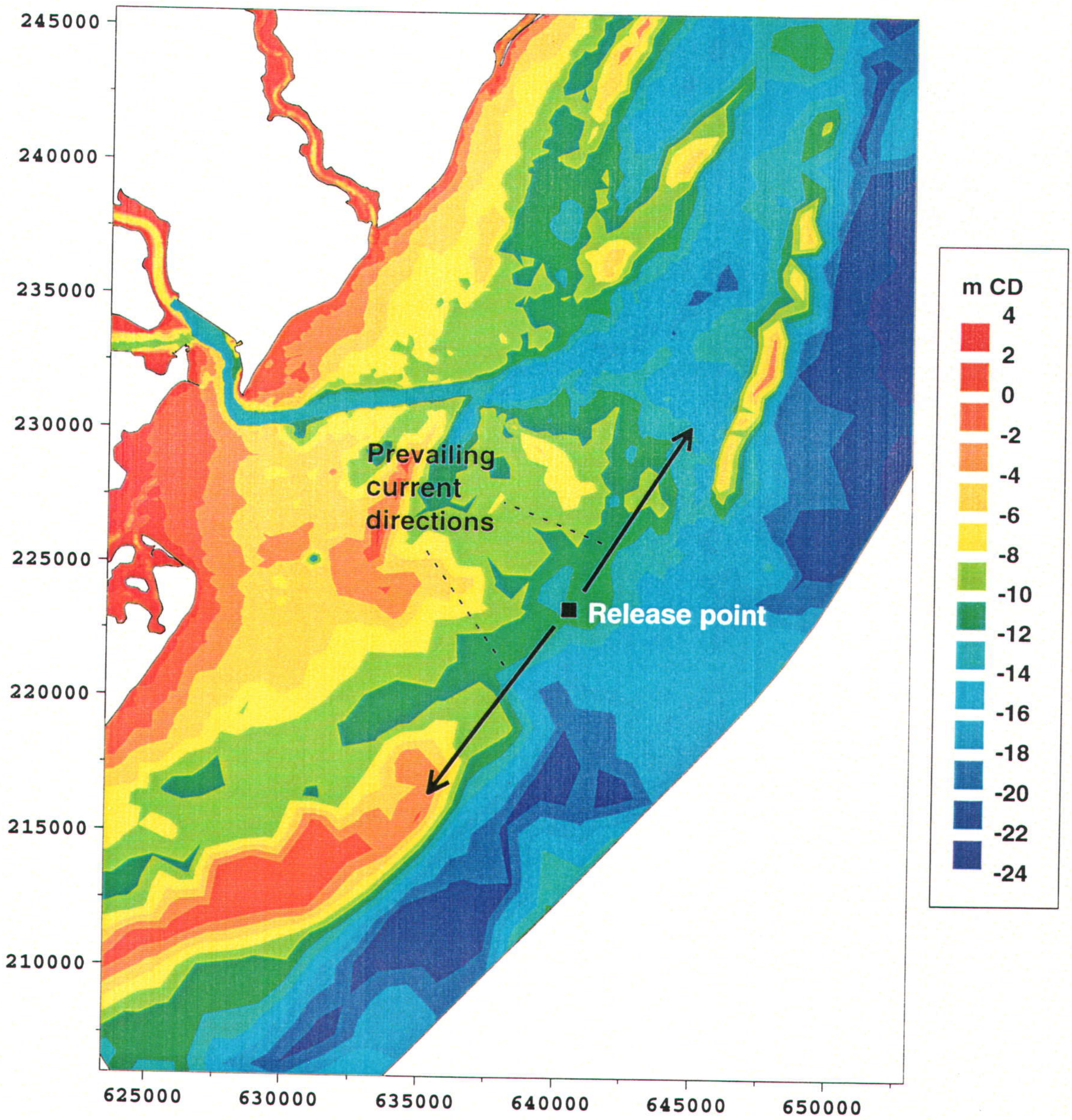

Figure 4.1 Location of simulated dredging offshore from Harwich

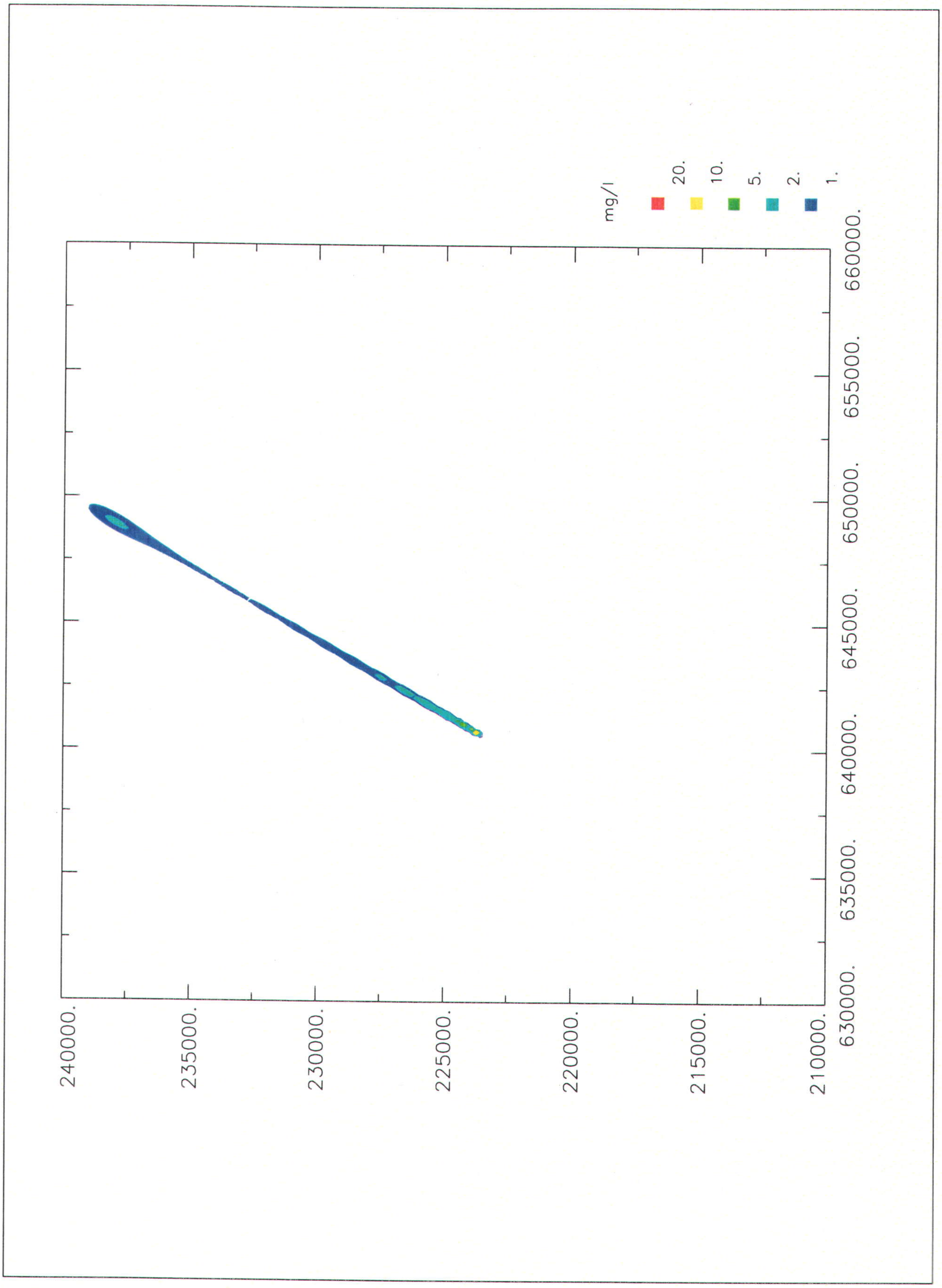

Figure 4.2 **Extent of plume after 0.5 tides as calculated by the GAUSSIAN model**

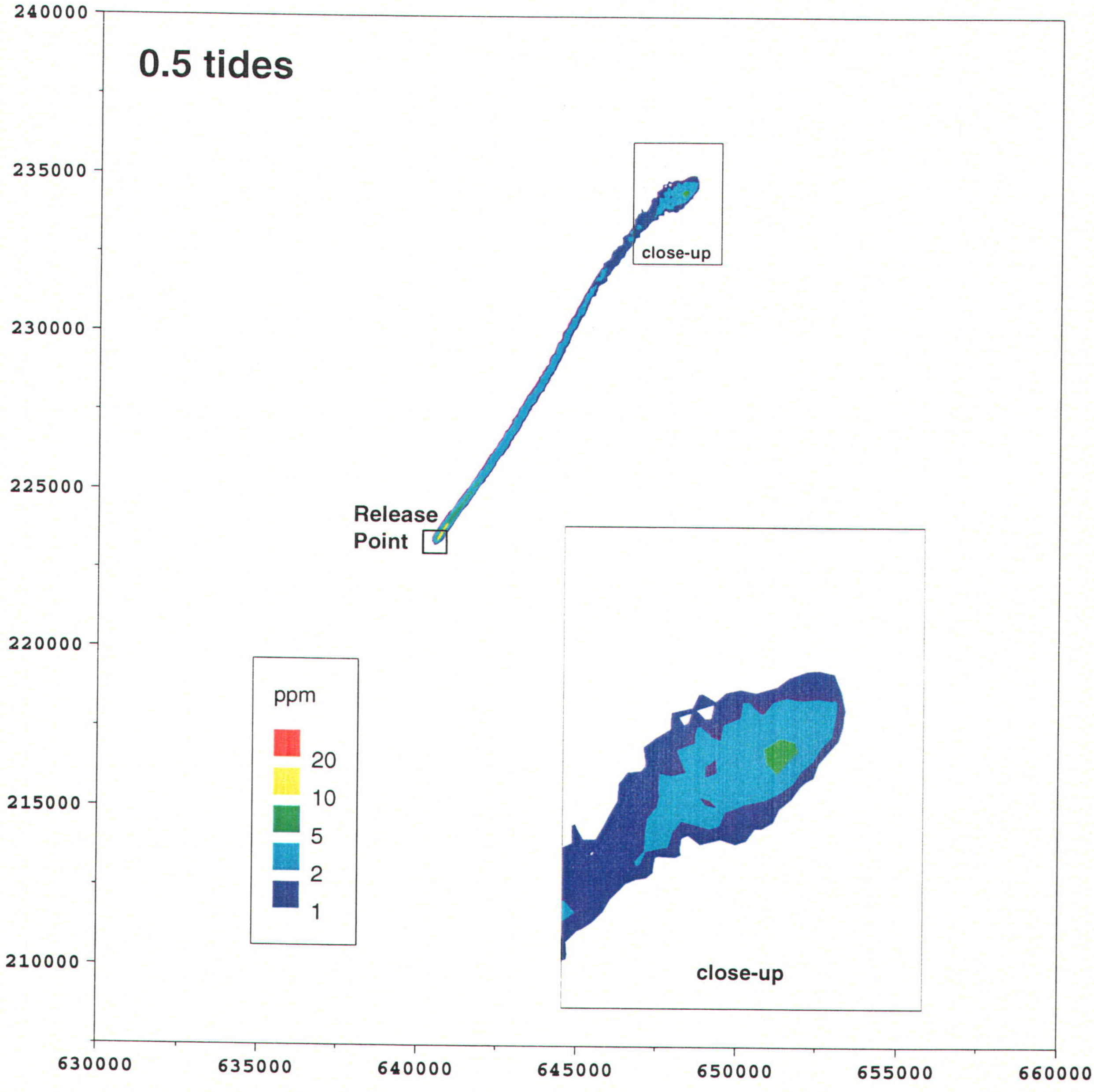

Figure 4.3 Extent of plume after 0.5 tides as calculated by the SEDPLUME model

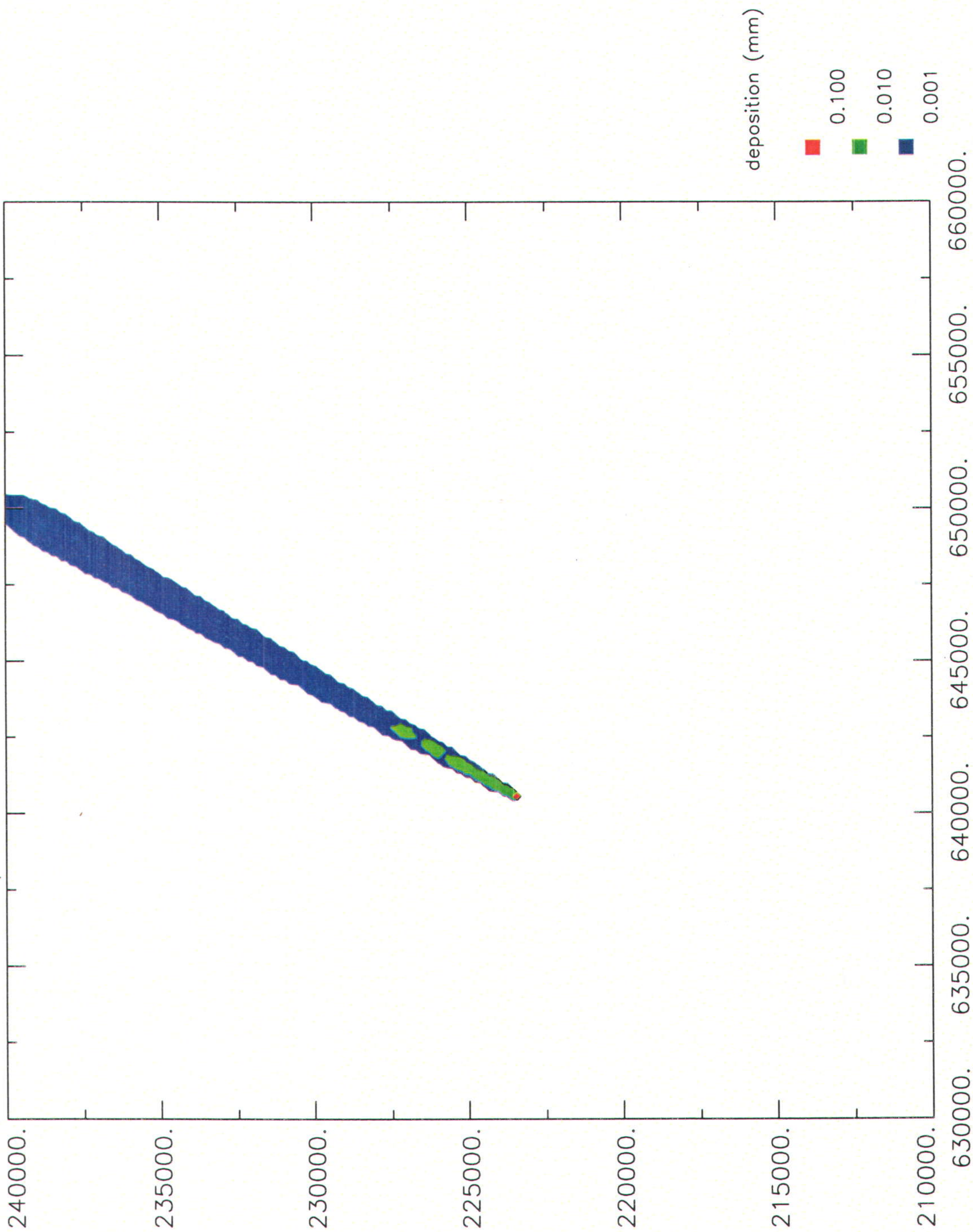

Figure 4.4 Deposition after 0.5 tides as calculated by the GAUSSIAN model

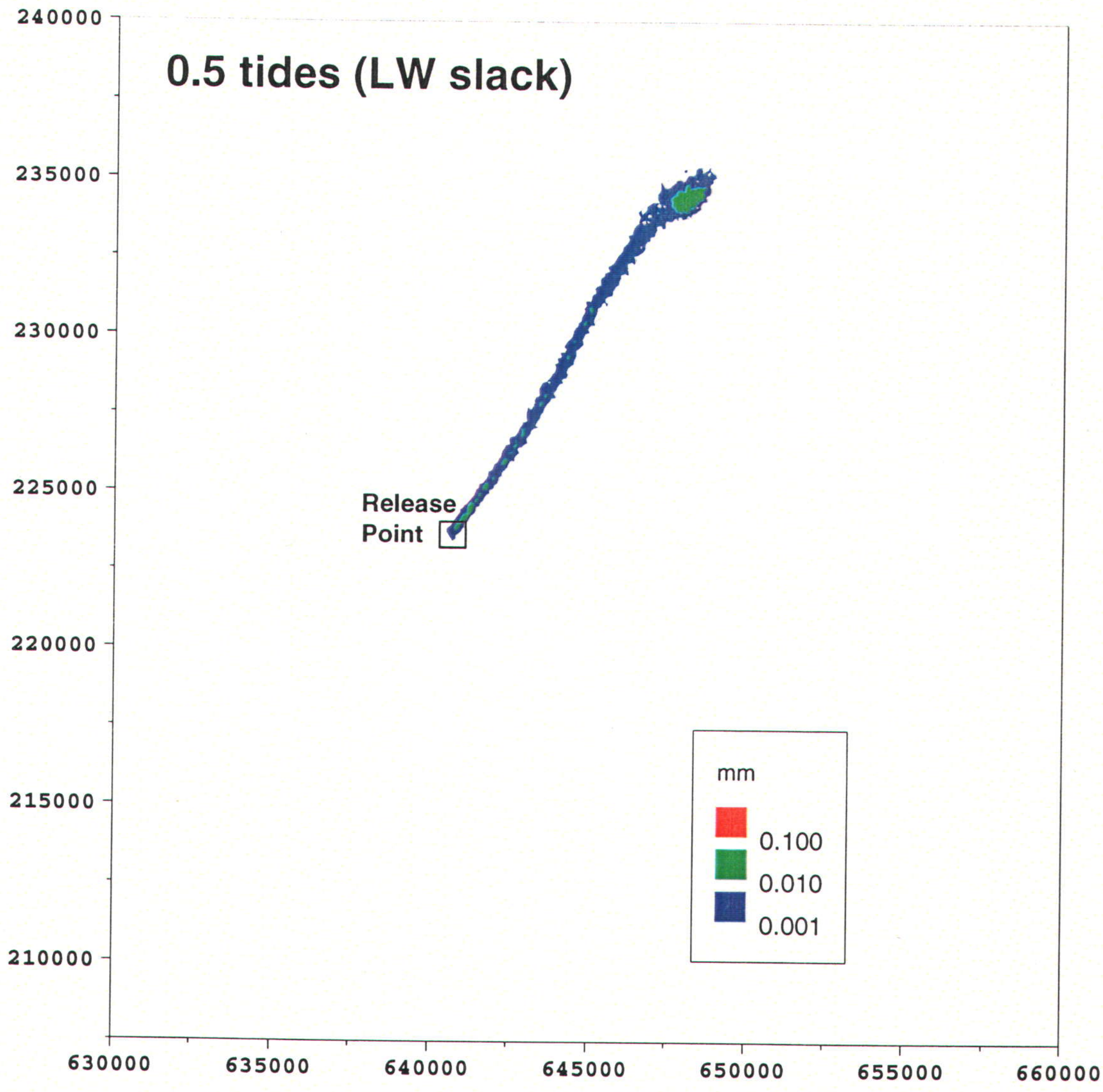

Figure 4.5 **Deposition after 0.5 tides as calculated by the SEDPLUME model**

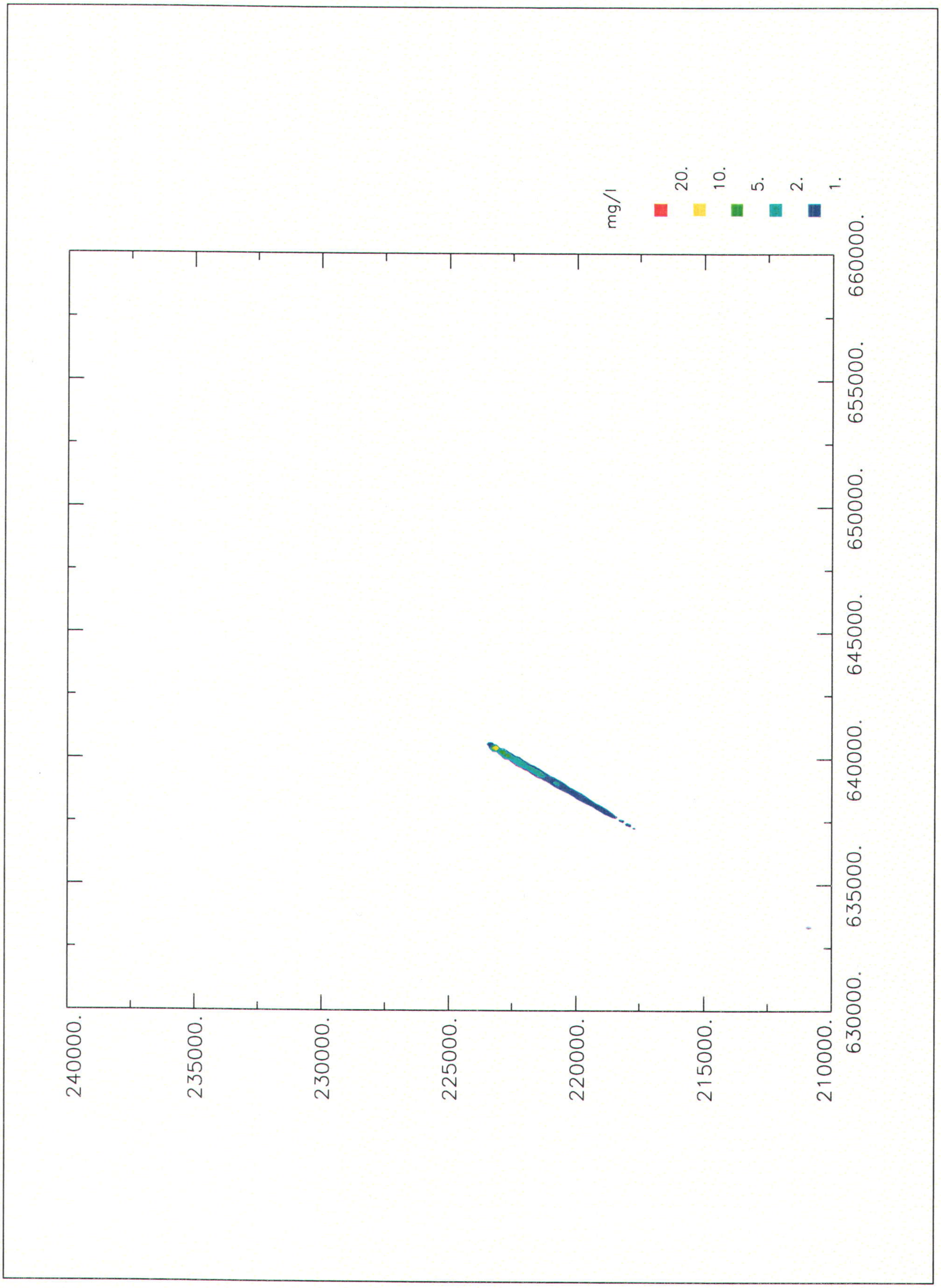

Figure 4.6 **Extent of plume after 1 tide as calculated by the GAUSSIAN model**

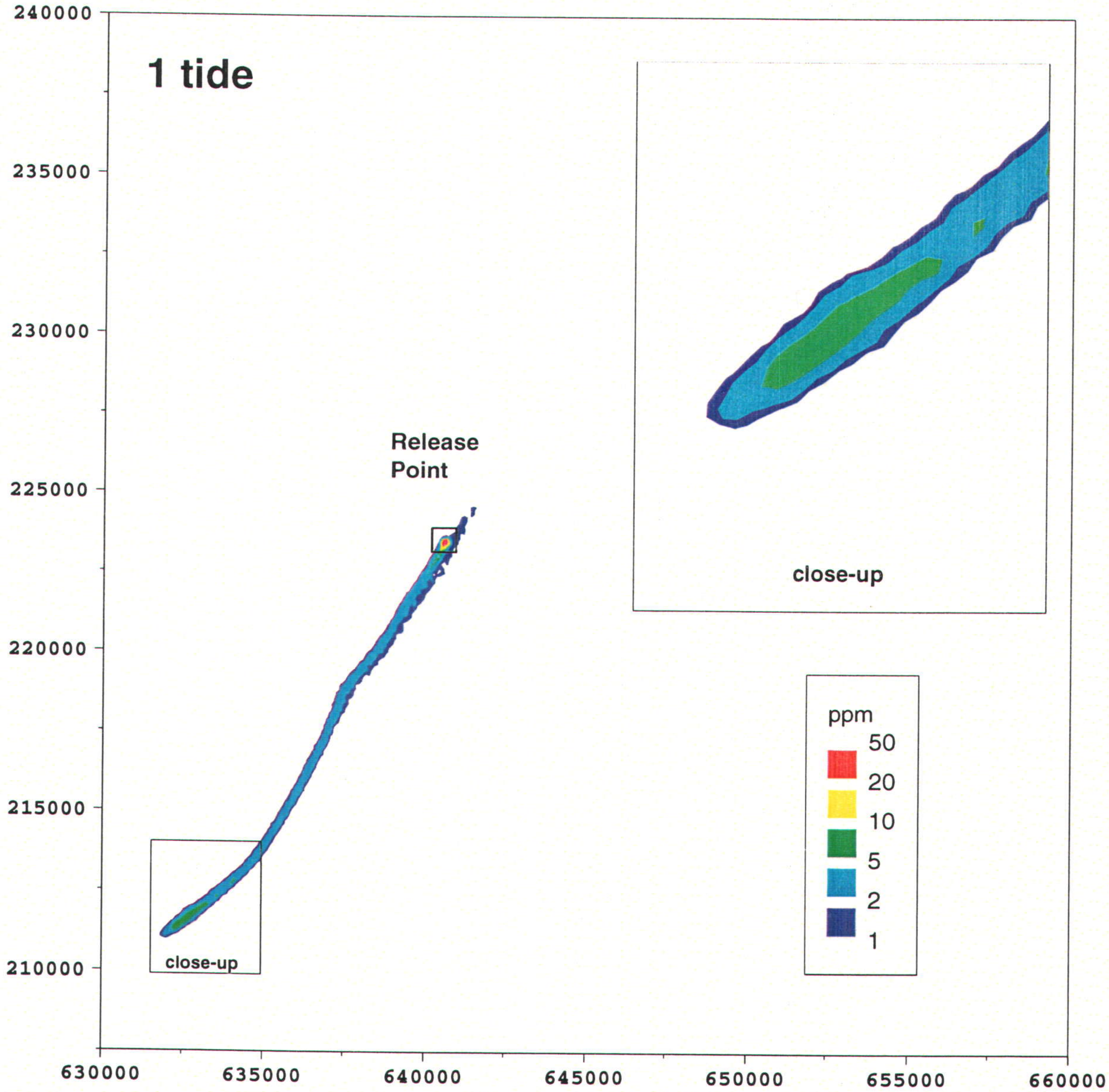

Figure 4.7 **Extent of plume after 1 tide as calculated by the SEDPLUME model**

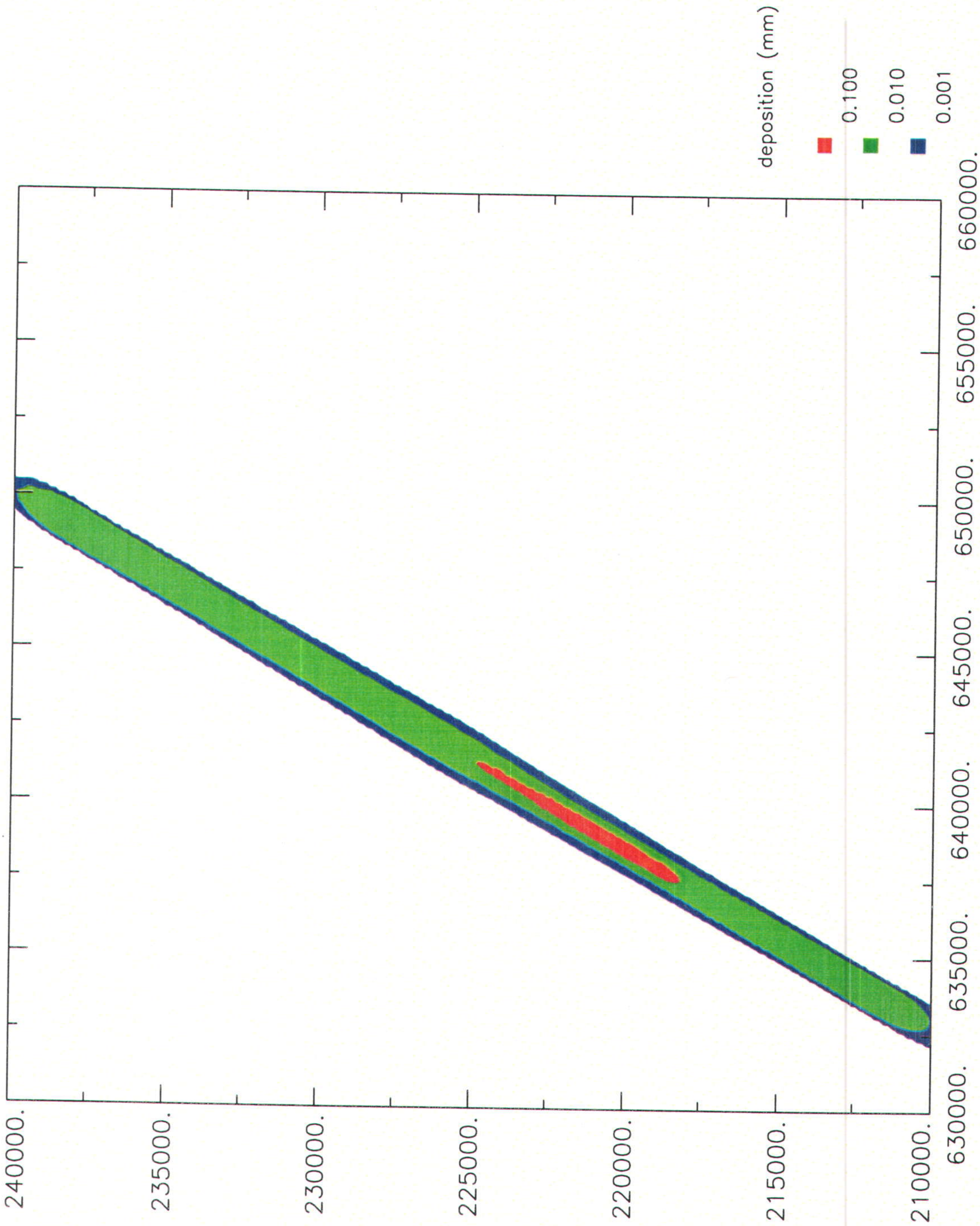

Figure 4.8 Deposition after 1 tide as calculated by the GAUSSIAN model

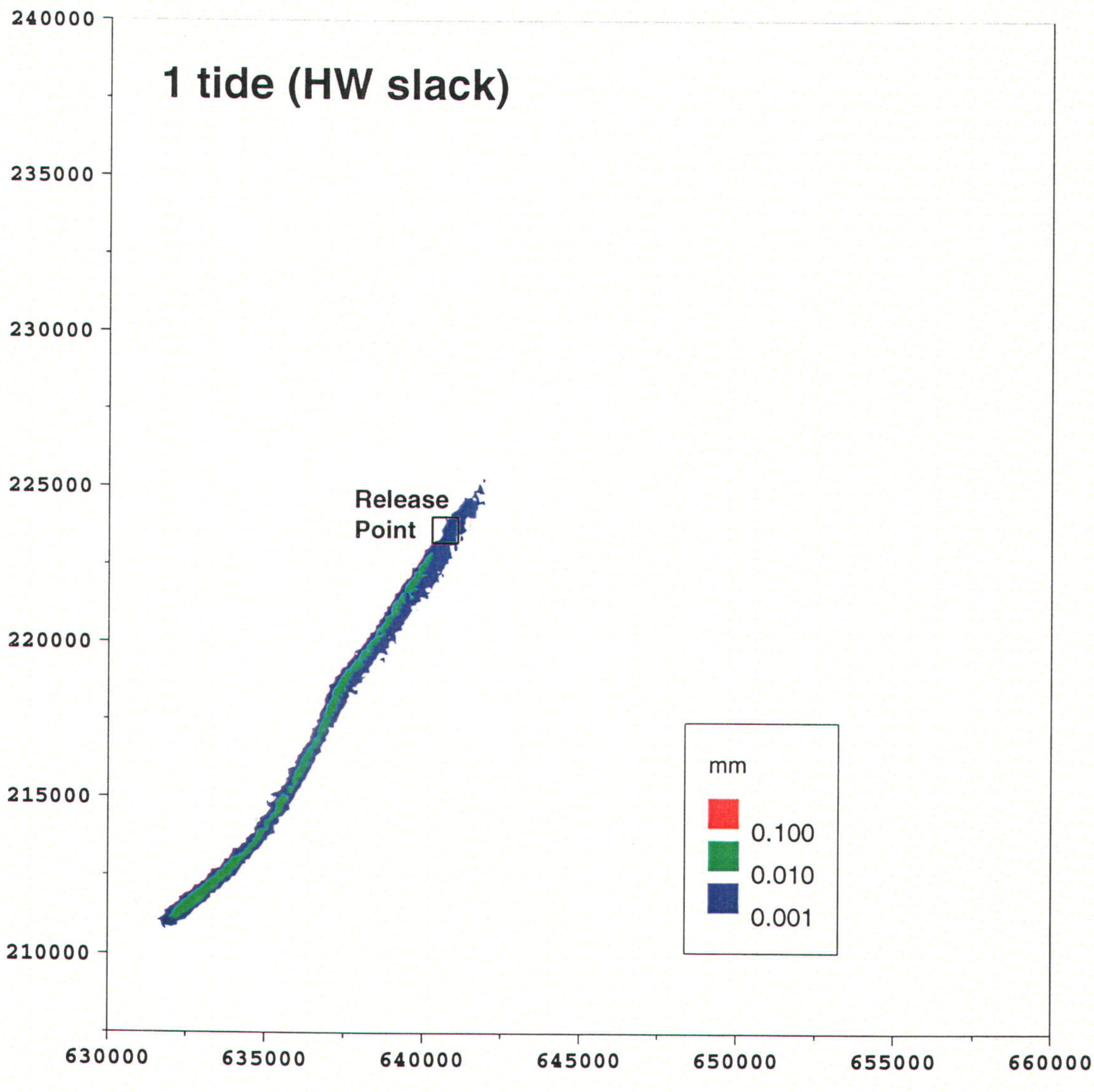

Figure 4.9 **Deposition after 1 tide as calculated by the SEDPLUME model**

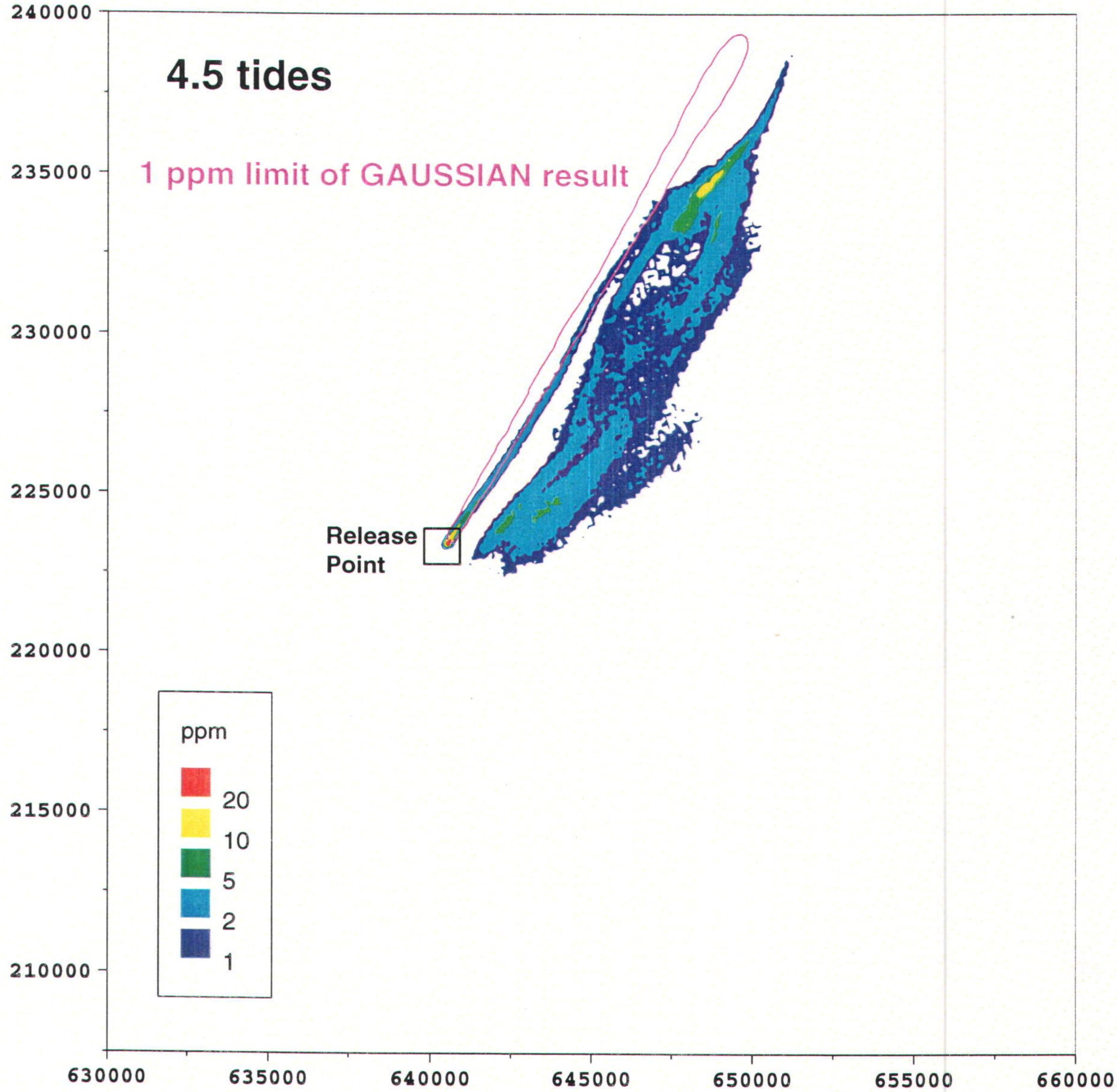

Figure 4.10 **Extent of SEDPLUME and GAUSSIAN plumes after 4.5 tides**

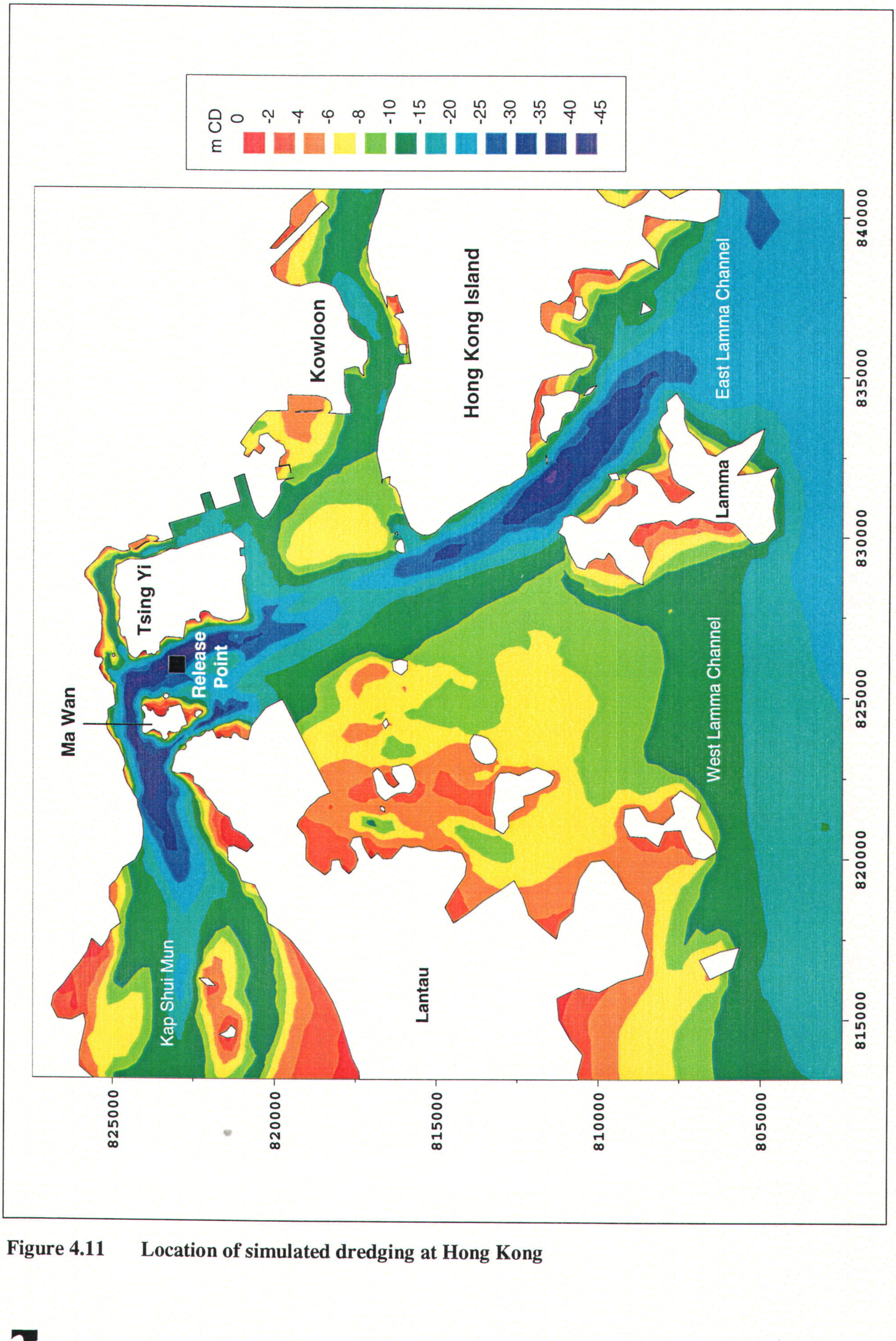

Figure 4.11 Location of simulated dredging at Hong Kong

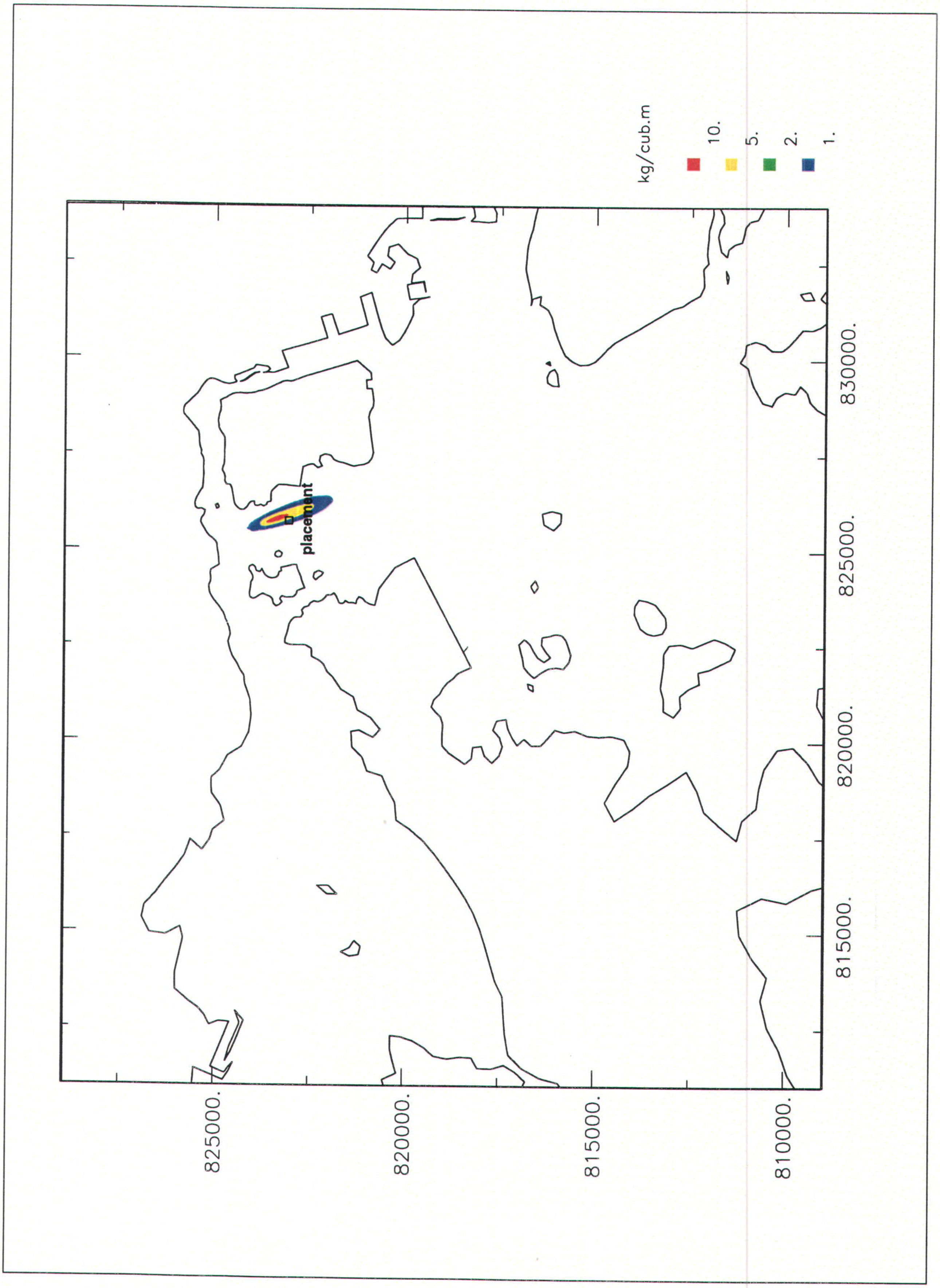

Figure 4.12 **Extent of plume after 0.5 tides as calculated by the GAUSSIAN model (Hong Kong)**

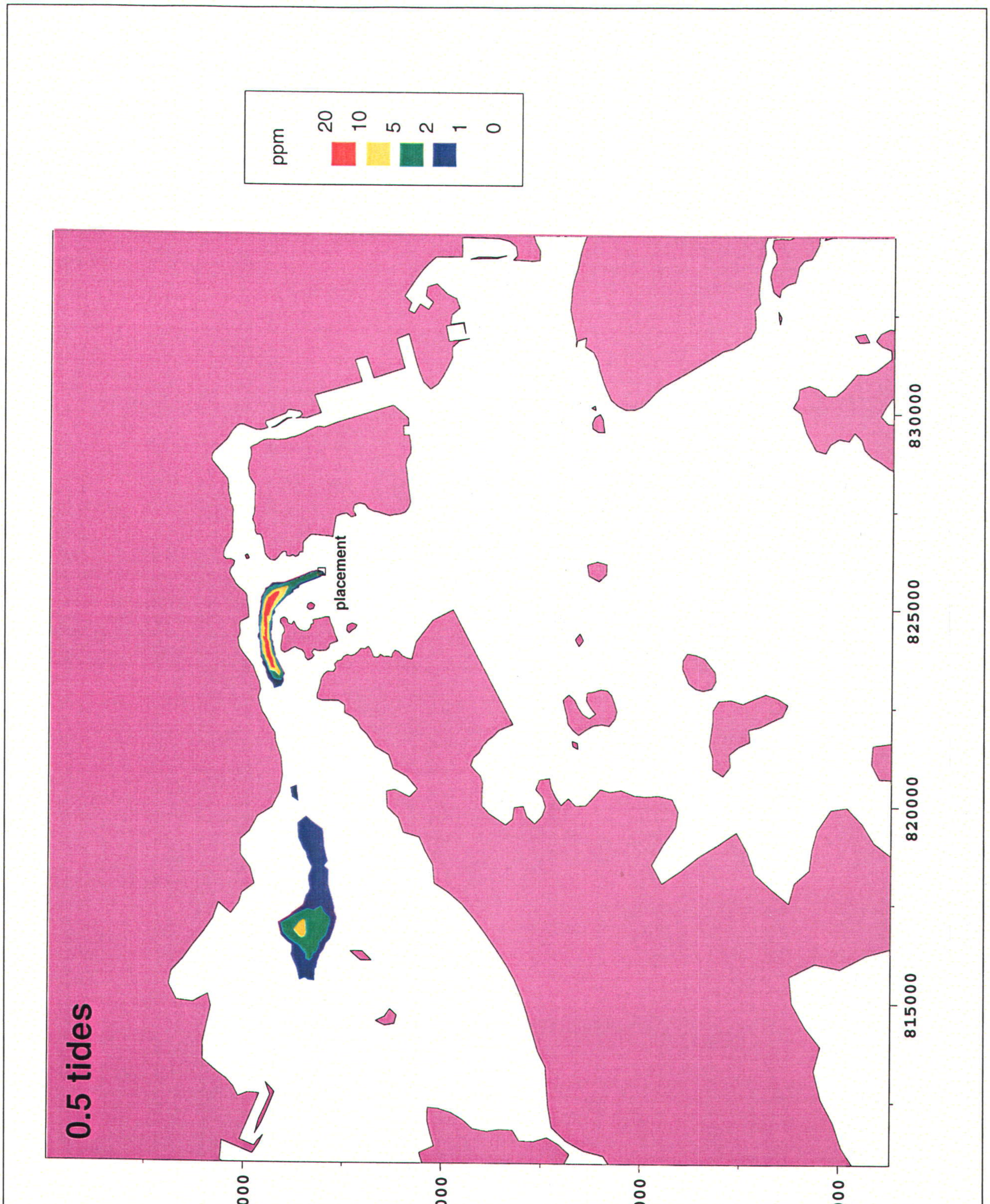

Figure 4.13 **Extent of plume after 0.5 tides as calculated by the SEDPLUME model (Hong Kong)**

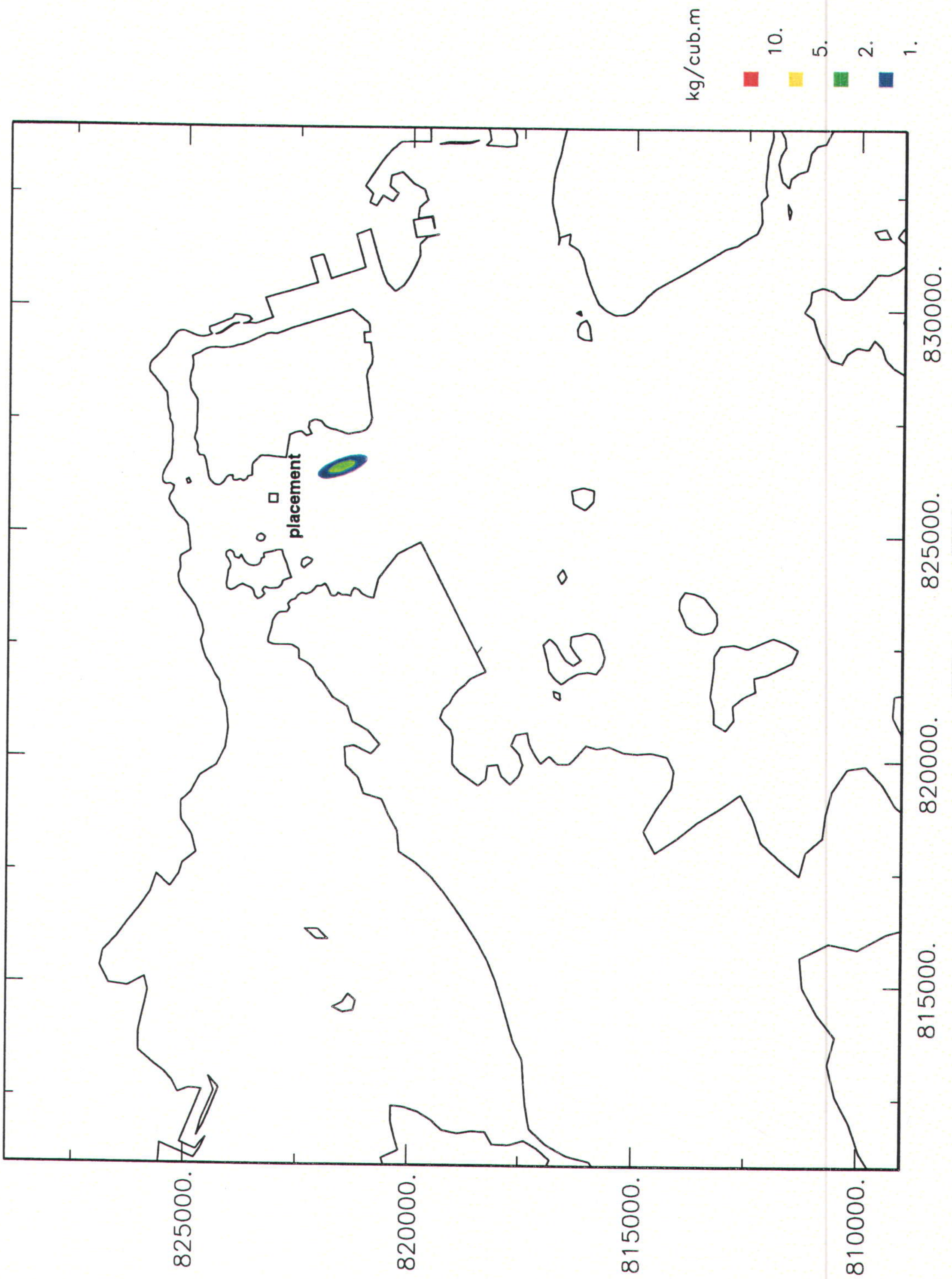

Figure 4.14 Extent of plume after 1 tide as calculated by the GAUSSIAN model (Hong Kong)

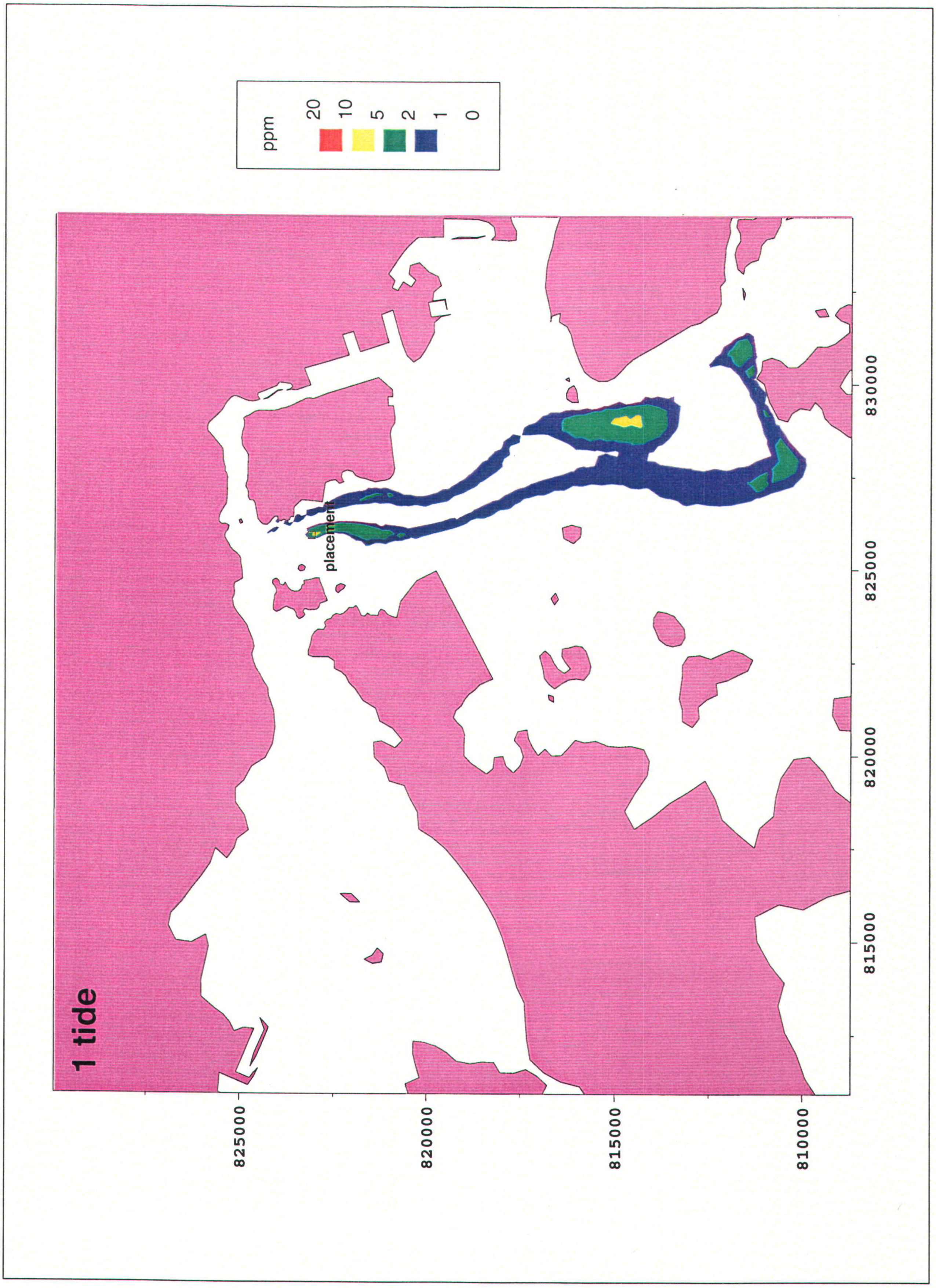

Figure 4.15 **Extent of plume after 1 tide as calculated by the SEDPLUME model (Hong Kong)**

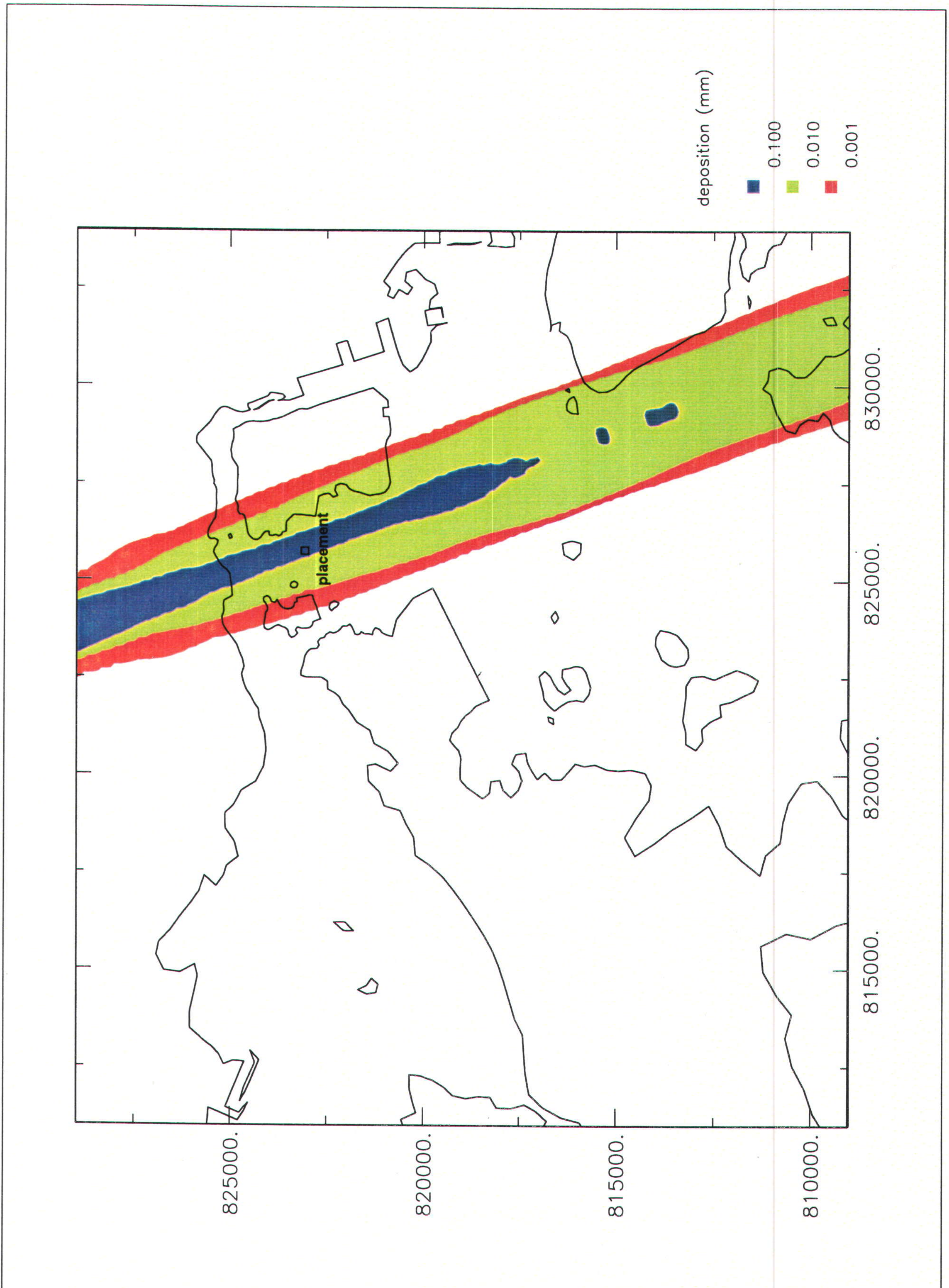

Figure 4.16 Deposition after 2 tides as calculated by the GAUSSIAN model (Hong Kong)

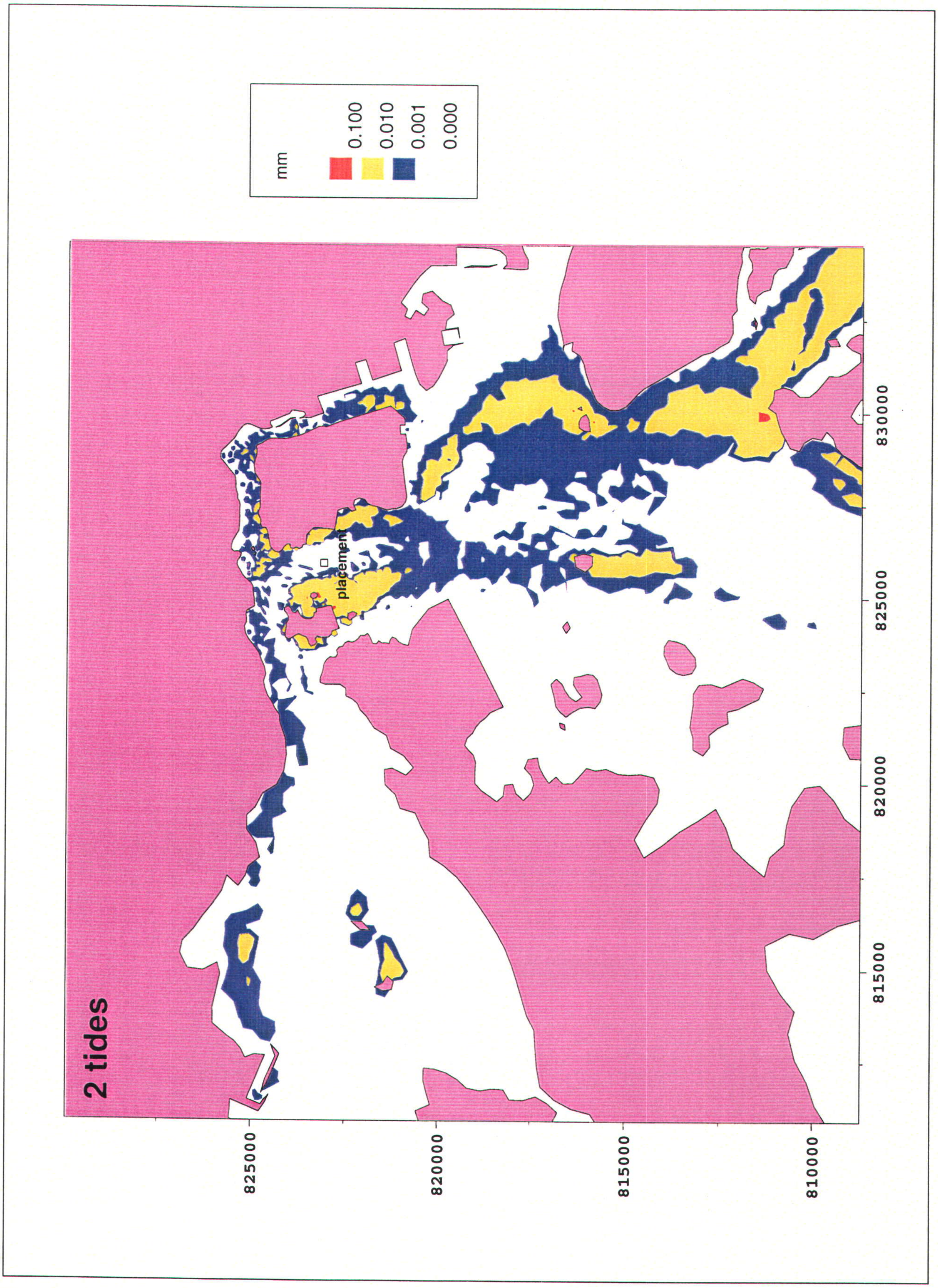

Figure 4.17 **Deposition after 2 tides as calculated by the SEDPLUME model (Hong Kong)**

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Appendices

Appendix 1

Description of Gaussian model

Appendix 1 GAUSSIAN Technical Description

GAUSSIAN represents the processes of advection by currents, settling of the sediment through the water column and the diffusion of suspended material due to the natural turbulence in the flow. The flow within the area under investigation is assumed to be uniform and uni-directional along a single axis direction. The depth in the area of interest is also assumed to be uniform. Diffusion along and perpendicular to the direction of flow are input parameters, with the former significantly greater than the latter.

These simplifying assumptions reduce the diffusion equation to,

$$\frac{\partial c}{\partial t}+\frac{\partial (uc)}{\partial t}-D_x\frac{\partial^2 c}{\partial x^2}-D_y\frac{\partial^2 c}{\partial y^2}+\frac{W_s}{h}c=0$$

where c is the suspended sediment concentration,
c is the concentration increase,
t is the time after release,
x and y are the coordinates along and perpendicular to the direction of flow,
D_x and D_y are the diffusion coefficients in the x and y directions,
W_s is the settling velocity,
h is the water depth.

The solution for an instantaneous release of a slug of material into the water is as follows:

$$C(x,t)=\frac{M}{4\pi ht\sqrt{D_xD_y}}\exp\left(-\frac{(x-\xi)^2}{4D_xt}-\frac{y^2}{4D_yt}-\frac{W_s}{h}t\right)$$

where $\xi = \int_0^t u dt$.

The method of Carslaw and Jaeger (Reference 1) can be used to solve the problem for time varying release. This comprises the addition of a number of such solutions for placement at small discrete time intervals resulting in a computational solution, C′, for the required release pattern.

$$C'(x,t)\approx\sum_{x1}^{x2}\sum_{t1}^{t2}f(C,x_1,x_2,t_1,t_2)\partial t\partial x$$

where $f(C,x_1,x_2,t_1,t_2)=C(x,t)$ $\quad x_1<x<x_2,\ t_1<t<t_2$

$= 0$ $\quad$ otherwise

The GAUSSIAN method assumes the initial uniform distribution of released material through the water column of the sediment and models the settling of material on the bed as a steady stream of material under conditions where shear stress is below the threshold for deposition. The method does not allow for the resuspension of sediment from the bed as slack water ends and current speeds pick up. The deposition predicted by the method is thus an upper limit.

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Appendix 2

Description of SEDPLUME model

Appendix 2 SEDPLUME-3D Technical Description

Flow in a coastal region consists of large-scale tidal motion, wind-driven currents and small-scale turbulent eddies. In order to model the dispersal of suspended mud in such a region, the effects of these flows on suspended mud plumes must be simulated. The random walk dispersal model, SEDPLUME-3D, represents turbulent diffusion as random displacements from the purely advective motion described by the turbulent mean velocities computed by the three dimensional free surface flow model, TELEMAC-3D.

Representation of mud disturbance

In SEDPLUME-3D, the release of suspended mud in coastal waters is represented as a regular or intermittent discharge of discrete particles. Particles are released throughout a model run to simulate continuous mud disturbance or for part of the run to simulate mud disturbance over an interval during the tidal cycle, for instance to represent the resuspension of fine sediment during dredging operations. At specified sites a number of particles are released in each model time-step and, in order to simulate the release of suspended mud, the total mud released at each site during a given time interval is divided equally between the released particles. Particles can be released either at the precise coordinates of the specified sites, or distributed randomly, centred on the specified release sites. The particles can be released at the surface or evenly distributed through the water column. This allows the representation of the initial spreading of plumes of material released by a dredger, for example, but SEDPLUME-3D results are generally fairly insensitive to the specified initial spreading radius.

Large scale advection

TELEMAC-3D simulates tidal flows in coastal waters, including the effects of any thermal or saline stratification and any three dimensional structure induced by bed friction or wind stress. Three components of current speed are calculated at a number of points through the depth and these values are interpolated to establish the precise current at the position of each SEDPLUME particle. Each particle is then advected by the local flow conditions. Because the three dimensional structure of the flow is calculated by TELEMAC-3D, effects such as shear dispersion of plumes are automatically represented.

Turbulent diffusion

In order to simulate the effects of turbulent eddies on suspended mud plumes in coastal waters, particles in SEDPLUME-3D are subjected to random displacements in addition to the ordered movements which represent advection by mean currents. The motion of simulated plumes is, therefore, a random walk, being the resultant of ordered and random movements. Provided the lengths of the turbulent displacements are correctly chosen, the random step procedure is analogous to the use of turbulent diffusivity in depth-averaged mud transport models. This is discussed in more detail below.

(a) Lateral diffusion

The horizontal random movement of each particle during a time-step of SEDPLUME-RW consists of a displacement derived from the parameters of the simulation. The displacement of the particle in each of the orthogonal horizontal directions is calculated from a Gaussian distribution, with zero mean and a variance determined from the specified lateral diffusivity. The relationship between the standard deviation of the displacement, the time-step and the diffusivity is defined in Reference 1 as:

$$\frac{\Delta^2}{\Delta t} = 2D \qquad 1$$

where

Δ	= standard deviation of the turbulent lateral displacement (m)
Δt	= time-step (s)
D	= lateral diffusivity (m^2s^{-1}).

In a SEDPLUME-3D simulation, a lateral diffusivity is specified, which the model reduces to a turbulent displacement using Equation (1). No directional bias is required for the turbulent movements, as the effects of shear diffusion are effectively included through the calculated depth structure in the mean current profile.

(b) Vertical diffusion

Whilst lateral movements associated with turbulent eddies are satisfactorily represented by the specification of a constant diffusivity, vertical turbulent motions can vary significantly horizontally and over the water depth, so that vertical diffusivities must be computed from the characteristics of the mean flow field, rather than specified as constants. In neutral conditions, the vertical diffusivity, K_z, is given by:

$$K_z = 0.16\, h^2 \left(1 - \frac{h}{d}\right) \frac{\partial u}{\partial z} \qquad 2$$

where

h	= height of particle above the bed
d	= water depth
0.16	= (von Karman constant)^2
u	= current speed
z	= vertical coordinate

The value of the vertical diffusivity is calculated at each particle position, then a vertical turbulent displacement is derived for each particle from its K_z value using an equation analogous to (1) for the lateral turbulent displacement.

If the water density varies in the vertical, then stable stratification can occur, whereby the turbulence is damped by buoyancy effects. In this case the mixing length as adapted by a function of the Richardson number, based on field measurements (Reference 2).

(c) Drift velocities

A particle undergoes a random walk as follows:

$$x^n = x^{n-1} + A(x^{n-1}, t^{n-1})\Delta t + B(x^{n-1}, t^{n-1})\sqrt{\Delta t}\; \xi^n \qquad 3$$

where x^n is the position of the particle at time t^n, A is the advection velocity at timestep $n-1$ and B is a matrix giving the diffusivity. ξ is a vector of three random numbers, each drawn from a normal distribution with unit variance and zero mean. In the case of SEDPLUME-3D, B is diagonal, with the first two entries equal to $\sqrt{(2D)}$ (as introduced in the previous section) and the third diagonal entry being equal to the local value of $\sqrt{(2K_z)}$.

The movement of a particle undergoing a random walk as described in equation (3) can be described by the Fokker-Planck equation in the limit of a very large number of particles and a very short timestep, where we introduce subscripts *i,j* and *k* running over the three coordinate directions:

$$\frac{\partial f}{\partial t}+\frac{\partial}{\partial x_i}(A_i f)=\frac{\partial^2}{\partial x_i \partial x_j}(\frac{1}{2}B_{ik}B_{jk}f) \qquad 4$$

The probability density function $f(x,t|x_0,t_0)$ is the probability of a particle which starts at position x_0 at time t_0 being at position x at time t.

Equation (4) can be compared with the advection-diffusion equation for the concentration of a pollutant, c:

$$\frac{\partial c}{\partial t}+\frac{\partial}{\partial x_i}(u_i c)=\frac{\partial}{\partial x_i}(K_{ik}\frac{\partial}{\partial x_k}c) \qquad 5$$

where K_{ik} is the eddy diffusion matrix, diagonal in our case but not necessarily so. Thus identifying f with c, we can see that the two equations are equivalent provided that we take the advection velocity as:

$$A_i=u_i+\frac{\partial}{\partial x_k}K_{ik} \qquad 6$$

In the case of SEDPLUME-3D, the diffusivity varies only in the vertical and is constant in the horizontal, so the horizontal advection velocity is simply the flow velocity (assuming that the relatively small effects of changing water depth can be neglected). However, when considering the movement of particles in the vertical it is important to include the gradient of the diffusivity (often referred to as a drift velocity) in the advection step. If this term is omitted then particles tend to accumulate in regions of low diffusivity, which in our case means at the surface and at the bed.

This subject is discussed in considerably more detail in References 3,4,5 and 6.

Sedimentation processes

(a) Settling

In SEDPLUME-RW, the settling velocity (w_s) of suspended mud is assumed to be related to the mud concentration (c) through an equation of the form:

$$w_s=\max(w_{\min},Pc^Q) \qquad 7$$

where w_{min}, P and Q are empirical constants. Having computed a suspended mud concentration field, as described subsequently in this section, a settling velocity can be computed in each output grid cell from Equation (7) and used to derive a downward displacement for each particle during each time-step of a model simulation. This displacement is added vectorially to the other computed ordered and random particle displacements. Note that there is a specified minimum value of w_s. This results in settling velocities being constant at low suspended mud concentrations, as indicated by recent research at HR. (Reference 7).

(b) Deposition

SEDPLUME-3D computes bed shear stresses from the input tidal flow fields using the rough turbulent, based on a bed roughness length input by the user. If the effects of storm waves on mud deposition and erosion at the sea bed are to be included in a model simulation, a bed shear stress associated with wave orbital motions, computed from the results of mathematical wave model simulations, is added to that resulting from the simulated tidal currents (Reference 8). Where the computed bed stress, τ_b, falls below a specified critical value, τ_d, and the water is sufficiently deep, then deposition is assumed to occur. Mud deposition is represented in SEDPLUME-3D by particles approaching the sea bed becoming inactive when τ_b is below τ_d. Whilst active particles in the water column contribute to the computed suspended mud concentration field, as described subsequently in this appendix, inactive particles contribute to the mud deposit field.

In shallow areas, where tidal currents are sufficiently weak to allow mud accretion, normal wave action can prevent mud deposition. This effect is included empirically in SEDPLUME-3D, by specifying a minimum water depth below which deposition does not occur.

(c) Erosion

The erosion of mud deposits from the sea bed is represented in SEDPLUME-3D by inactive particles returning to the water column (becoming active) when τ_b exceeds a specified erosional shear strength, τ_e. The number of particles which become re-suspended in each cell of the output grid in each time-step of a simulation is determined by the equation:

$$\text{Erosion Rate} = M(\tau_b - \tau_e) \qquad \mathbf{8}$$

where M is an empirical erosion constant.

Computation of suspended mud concentrations

In SEDPLUME-3D, suspended mud concentrations are computed on a multi-layer square grid designed to resolve the essential features of relatively small-scale plumes. The layers of the output grid are separated by the element planes of the TELEMAC-3D grid, so that if there are N planes in the TELEMAC-3D mesh, there are N-1 layers in the SEDPLUME-3D output grid. In each SEDPLUME-3D grid cell a concentration is derived by dividing the total suspended mud represented by all the active particles in that cell by the volume of the cell.

Computation of mud deposit distributions

SEDPLUME-3D computes mud deposit distributions by summing the mass of mud represented by the inactive particles in each cell of the output grid, and assuming that the resulting mass is evenly distributed over the cell area.

The model is usually used to simulate the dispersal of mud released by dredging-related activity in one of the following three ways:

(a) Dredging in shallow areas releases small quantities of mud into the water column close to the sea bed.

(b) When dredging for marine fill, the coarse sediment content of dredged material may be increased by over-filling of the receiving barge; with coarse material settling rapidly in the barge and the fine mud component remaining in suspension and re-entering the water column.

(c) The disposal of dredged spoil in deep water results in a dense column of sediment descending rapidly to the sea bed. Entrainment of water into this column results in some of the fine mud component entering the water column.

The model is most suited to simulating detailed distributions of suspended mud and mud deposits near areas of dredging-related activity over a few tidal cycles. The far-field effects of dredging-related activity can be simulated using other models in use at HR Wallingford.

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Appendix 3

Description of EPA plume dispersion models UOUTPLM and UMERGE

Appendix 3 Description of EPA plume dispersion models

UMERGE

Theoretical development

The computer model UOUTPLM (References 1 and 2) considers a single plume element. By following the element as it gains mass due to ambient fluid entrainment, the characteristics of a continuous plume in a flowing ambient are described. The original cooling tower plume model has been adapted for marine discharges (Reference 3). Density (or temperature and salinity) and velocity are assumed to be average properties of the element. The sums of plume element and entrained mass, horizontal momentum, and energy are conserved. An equation relating temperature, salinity, and density (Reference 4) is used to calculate the density of the ambient and the plume element at each time step.

Entrainment brings ambient mass (plus momentum, temperature, and salinity) into the plume element. Entrainment is assumed to consist of either of two mechanisms. One mechanism, sometimes called forced entrainment, is due to the impingement of current on the plume. It is the mass flux through the boundary area of the plume element projected on a plane normal to the current. The element is usually a section of a bent cone. Therefore, the projected area formulation contains a cylindrical term, a growth term, and a curvature term as described in Reference 5. The second mechanism is aspiration entrainment (i.e., the Taylor entrainment hypothesis discussed in Reference 6) which captures 0.1 times the product of the external area of the plume element and its shear velocity. Total entrainment is taken to be the larger of these two mechanisms.

Model Description

In the computer program, the entrained mass is added to the element's mass to become the new mass. The new temperature and salinity of the element are the averages of the old values and the entrained ambient values weighted by their relative masses. The horizontal velocity is found in the same way, thus conserving horizontal momentum. The vertical velocity depends on buoyant force as well. The new density, and thus buoyancy, creates a vertical acceleration on the plume segment. Since the element is considered to be one of a train, each following the preceding element, drag is assumed to be negligible. The segment length is changed in proportion to the total velocity to conserve mass and pollutant. The radius is changed to correspond to the new mass and density. Dilution is calculated by comparing the initial volume to that of the element. The program terminates execution when the vertical velocity reaches zero, the surface is reached, or length scales or execution step limits are reached whichever occurs first.

UMERGE

Theoretical Development

The model UMERGE analyzes a positively buoyant discharge by tracing a plume element through the course of its trajectory and dilution. Conditional controls, rather than conceptual limitations, prevent analysis of negatively buoyant discharges. UMERGE is a two-dimensional model which accounts for adjacent plume interference and which accepts arbitrary current speed variations with depth. Diffuser ports are assumed to be equally spaced and may be oriented at any camon elevation angle. The current is assumed to be normal to the diffuser axis and the discharge velocity vector is assumed to be in the plane formed by the current direction and the vertical axis.

The basic plume equations are summarized as follows

1. dm/dt = entrainment (Taylor hypothesis + forced continuity)

2. d(mu)/dt = u_O(dm/dt) (conservation of horizontal momentum)

3. d(mv)/dt = (□□/□)mg (vertical momentum)

4. d(mT)/dt = T_O((tn/dt) (conservation of temperature)

5. d(mS)/dt = S_O(dm/dt) (conservation of salinity)

6. □h/(u^2+v^2)1/2 = □hi/$(u_i^2+v_i^2)^{1/2}$ = constant

Where

i = initial conditions

o= ambient conditions.

Equation (6) transforms the integral flux plume equations to their Lagrangian counterparts . Also required is an equation for density as a function of temperature and salinity (Reference 4). The equations are integrated with respect to time.

Forced and aspiration entrainment (The Taylor hypothesis, see Reference 6) are handled in much the same way as in UOUTPLM. However, rather than considering the larger of the two components as being the operative mechanism, they are considered additive, based on superimposed flow fields. In the absence of a current, entrainment is due solely to aspiration. At moderate current levels, entrainment is from both mechanisms but aspiration is somewhat reduced in the lee of the plume. In the presence of higher currents, entrainment is largely forced (References 5 and 7).

The merging equations are based on purely geometric considerations. The mass of overlapping portions of adjacent plumes is redistributed by increasing the normal dimensions of the plumes, and entrainment is adjusted accordingly.

Assumptions inherent in the model formulation include:

Exchange between adjacent plumes does not change the average properties of a plume element (mirror imaging) but does affect the plume radius.

- The model calculates average plume properties.
- The ambient fluid is largely undisturbed by the presence of the plume.
- No net pressure forces are exerted on the plume by the anbient and adjacent plume elements exert no net force on each other.
- Energy and salinity are conserved.
- Specific heat is considered to be constant over the range of temperatures observed in the system.
- In addition to entrainment by aspiration, all fluid on the projected area of the plume is entrained
- Current direction is assumed to be normal to the diffuser axis

The plume boundary encloses all the plume mass.

Model Description

Entrainment is considered as the mass flowing through the projected pllzne area plus the aspirated quantity. While the concept is simple, the computation for the projected plume area is complex and the reader is referred to Frick (Reference 5) for further development. The changes in mass (□m) and time (□t) are scaled internally by the model, allowing for a variable time step. This feature shortens execution time, important when using microcomputers or when using the program to optimize a design. The new plume element average horizontal velocity, temperature, and salinity are calculated using weighted averages of both the element and entrained masses. In calculating the vertical velocity, the effect of buoyancy is taken into account.

The subsequent position of the plume element is found by multiplying the new element velocity by the time increment and adding to the previous coordinates. The length of the plume element changes during each time increment due to the velocity gradient between the two faces of the element. Elongation, or contraction, can be estimated by comparing the element velocities between iterations. The effect of merging is estimated by distributing the overlapping mass to other portions of the plume, calculating the resulting changes in the element radius, and by adjusting entrainment terms. Once all plume properties have been calculated for a given time step, the iteration process begins anew until the vertical velocity becomes negative (maximum rise), the surface is reached, or the maximum number of specified iterations is exceeded.

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Appendix 4

Results of numerical modelling of initial plume dispersion

Appendix 4 Results of numerical modelling of initial plume dispersion

Table A4-1 EPA dispersion model input parameters

Run No	Model	Ht of source above bed	Current speed	Plume density	Stratified flow ?	Discharge Angle	Discharge rate
1	UOUTPLM	20	0.00	1026	no	90	10
2	UOUTPLM	20	0.00	1030	no	90	10
3	UOUTPLM	20	0.00	1040	no	90	10
4	UOUTPLM	20	0.00	1080	no	90	10
5	UOUTPLM	20	0.00	1160	no	90	10
6	UOUTPLM	20	0.40	1040	no	90	10
7	UOUTPLM	20	0.65	1026	no	90	10
8	UOUTPLM	20	0.65	1040	no	90	10
9	UOUTPLM	20	0.65	1080	no	90	10
10	UOUTPLM	20	0.65	1160	no	90	10
11	UOUTPLM	20	1.10	1030	no	90	10
12	UOUTPLM	20	1.10	1040	no	90	10
13	UOUTPLM	20	1.10	1080	no	90	10
14	UOUTPLM	20	1.10	1160	no	90	10
15	UOUTPLM	20	1.50	1040	no	90	10
16	UOUTPLM	10	1.10	1080	no	90	10
17	UOUTPLM	10	0.65	1080	no	90	10
18	UOUTPLM	30	1.10	1080	no	90	10
19	UOUTPLM	30	0.65	1080	no	90	10
20	UOUTPLM	40	1.10	1080	no	90	10
21	UOUTPLM	40	0.65	1080	no	90	10
22	UOUTPLM	20	1.10	1080	no	90	5
23	UOUTPLM	40	0.65	1040	yes	90	10
24	UOUTPLM	40	0.65	1040	no	90	10
25	UOUTPLM	30	0.65	1040	no	90	10
26	UOUTPLM	30	0.65	1040	no	75	10
27	UOUTPLM	30	0.65	1040	no	60	10
28	UMERGE	20	0.65	1026	no	90	10
29	UMERGE	20	0.65	1040	no	90	10
30	UMERGE	20	0.65	1080	no	90	10
31	UMERGE	20	0.65	1160	no	90	10
32	UMERGE	20	1.10	1026	no	90	10
33	UMERGE	20	1.10	1160	no	90	10
34	UMERGE	20	0.00	1080	no	90	10
35	UMERGE	40	1.10	1080	no	90	10
36	UMERGE	12	1.10	1160	no	90	10
37	UMERGE	12	1.10	1026	no	90	10
38	UMERGE	12	0.65	1026	no	90	10
39	UMERGE	24	0.65	1026	no	90	10
40	UMERGE	36	0.65	1026	no	90	10
41	UMERGE	24	1.10	1026	no	90	10
42	UMERGE	36	1.10	1026	no	90	10
43	UMERGE	12	0.65	1160	no	90	10
44	UMERGE	24	0.65	1160	no	90	10
45	UMERGE	36	0.65	1160	no	90	10
46	UMERGE	20	1.00	1160	no	90	1.25
47	UMERGE	20	2.00	1160	no	90	1.25
48	UMERGE	20	1.10	1139	no	90	10
49	UMERGE	20	1.10	1139	no	90	5

Table A4-2 EPA dispersion model results

Run No	Final horiz displ.	Final dilution	Final velocity		Final plume		Time of impact (s)
			horizontal	Vertical	radius	Diameter	
1	0.00	4.28	0.00	0.56	4.75	-	-
2	0.00	4.52	0.00	0.72	4.20	-	-
3	0.00	4.94	0.00	0.97	3.59	-	-
4	0.00	5.91	0.00	1.43	3.47	-	-
5	0.00	6.93	0.00	2.00	2.83	-	-
6	3.93	6.74	0.33	0.77	4.61	-	-
7	48.02	42.24	0.63	0.09	12.65	-	-
8	17.45	28.21	0.62	0.30	10.16	-	-
9	7.12	11.23	0.59	0.90	5.63	-	-
10	3.95	7.25	0.57	1.81	3.44	-	-
11	104.34	79.12	1.08	0.11	13.65	-	-
12	68.37	74.52	1.08	0.18	13.52	-	-
13	28.87	57.96	1.08	0.39	10.92	-	-
14	15.04	34.59	1.07	0.73	8.29	-	-
15	117.01	107.10	1.48	0.15	13.80	-	-
16	10.26	17.27	1.03	0.52	6.47	-	-
17	1.97	4.03	0.49	1.31	2.95	-	-
18	70.16	124.54	1.09	0.29	18.47	-	-
19	13.49	25.51	0.62	0.69	8.56	-	-
20	92.84	217.75	1.09	0.27	22.01	-	-
21	23.77	49.80	0.64	0.54	12.80	-	-
22	60.05	132.90	1.09	0.24	13.13	-	-
23	66.76	115.15	0.64	0.19	20.58	-	-
24	65.94	114.60	0.64	0.19	20.56	-	-
25	48.51	63.76	0.64	0.21	17.25	-	-
26	39.47	59.72	0.65	0.24	14.34	-	-
27	44.28	56.15	0.66	0.24	14.22	-	-
28	78.12	47.70	0.64	0.07	-	30.21	128.44
29	27.28	36.58	0.63	0.25	-	25.72	47.29
30	11.08	20.08	0.62	0.63	-	16.85	20.95
31	6.27	14.05	0.61	1.20	-	11.35	12.48
32	233.59	87.43	1.09	0.05	-	31.85	219.98
33	22.07	47.55	1.08	0.59	-	21.95	22.43
34	0.00	5.91	0.00	1.41	-	7.18	11.90
35	114.17	239.16	1.09	0.24	-	50.64	107.33
36	9.40	18.27	1.05	0.79	-	13.17	10.55
37	23.92	38.71	1.07	0.07	-	21.02	76.23
38	23.92	20.48	0.62	0.12	-	20.30	42.35
39	121.03	65.25	0.64	0.06	-	35.48	195.67
40	267.89	133.71	0.64	0.05	-	50.96	424.05
41	330.91	118.65	1.09	0.04	-	37.08	309.33
42	680.84	239.32	1.09	0.03	-	52.56	629.33
43	2.84	6.65	0.56	1.49	-	7.27	6.67
44	8.63	19.12	0.62	1.08	-	13.95	16.31
45	16.04	41.07	0.64	0.86	-	21.64	28.09
46	171.52	596.05	0.99	0.10	-	35.26	173.15
47	489.99	1202.33	2.00	0.07	-	35.39	246.24
48	24.63	51.38	1.08	0.53	-	22.91	24.88
49	38.83	109.29	1.09	0.35	-	24.28	37.56