Resuspension of bed material by dredging

An intercomparison of different dredging techniques

Volume 1: Main Report

M P Dearnaley
N G Feates
T N Burt
M N H Waller

Report SR 461
February 1996

CONSTRUCTION SPONSORSHIP DIRECTORATE
Department of the Environment

HR Wallingford

Resuspension of bed material by dredging

Putting different dredging technologies in perspective

Volume 1: Main Report

M P Dearnaley
N G Feates
T N Burt
M N H Waller

Report SR 461
February 1996

HR Wallingford

Address and Registered Office: **HR Wallingford Ltd.** Howbery Park, Wallingford, Oxon OX10 8BA
Tel: + 44 (0)1491 835381 Fax: + 44 (0)1491 832233

Registered in England No. 2562099. HR Wallingford is a wholly owned subsidiary of HR Wallingford Group Ltd.

Contract

The work described in this report was funded by the Department of the Environment Construction Directorate (DoE) under research contract PECD 7/6/296 "Intercomparison of dredging techniques". The DoE nominated officer for this contract was Mr P B Woodhead and HR Wallingford's nominated officer was Dr W R White. The report is published on behalf of DoE but any opinions expressed are not necessarily those of the funding department. The research described in this report was carried out in the Ports and Estuaries Group at HR Wallingford which is managed by Dr J V Smallman. The HR job number was DBS 39.

Prepared by Nigel Feates (name) Scientist (Job title)

Approved by M. P. Dearnaley Principal Scientist

Date 15/7/96.

Summary

Resuspension of bed material by dredging
Putting different dredging technologies in perspective

M P Dearnaley
N G Feates
T N Burt
M N H Waller

Report SR 461
February 1996

In recent years there has been increased public concern for the environment and man's impact upon it. The increased awareness has led to a growing volume of legislation relating to environmental issues. Dredging activities are no exception. This means that the dredging and construction industries require more information about the environmental effects of dredging. In 1993 HR Wallingford were commissioned by the Department of the Environment to undertake a study with the aim of providing guidance on the likely increases in suspended solids concentrations associated with different dredging operations.

Dredging consists of three distinct phases: extraction, transport and placement. There may be release of sediment into the water column associated with any of these phases. The release may be an immediate phenomena such as the plumes associated with hopper overflow during extraction or hopper discharge during placement. The resuspension may be a long term phenomena linked with resuspension of natural forces from areas impacted by the dredging activity, such as resuspension of dredged material placed at offshore disposal site.

In this report the different dredging techniques commonly applied in the UK are described, along with the associated processes by which resuspension of bed material can occur. The techniques available for measuring the resuspension of bed material are briefly described along with some comment upon monitoring strategies. A review of previously reported quantification of the increases of suspended sediment concentrations associated with dredging activity is provided. Further detail is given of recent field studies by HR and others during the period of this study is also provided. Some consideration of the differences between short and long term resuspension is discussed. In a discussion section some of the assumptions and uncertainties in predictive modelling of resuspension by dredging operations is considered. Finally, guidelines on estimation of resuspension rates, short term impacts, monitoring and predictive modelling are provided.

Contents

Page

Title page
Contract
Summary
Contents

Volume 1

1 **Introduction** 1
- 1.1 Background 1
- 1.2 Objectives 2
- 1.3 Structure of report 3

2 **The resuspension of bed material by different dredging activities** 3
- 2.1 Introduction 3
- 2.2 Grab Dredgers 3
- 2.3 Bucket Ladder Dredgers 4
- 2.4 Trailing Suction Hopper Dredgers 5
- 2.5 Cutter Suction dredgers 7
- 2.6 Special purpose dredgers - 'environmental dredging' 8
  - *2.6.1 Auger dredgers* 8
  - *2.6.2 Dustpan dredger* 8
  - *2.6.3 Scoop/Sweep dredger* 8
  - *2.6.4 Disc Bottom Cutterhead Dredgers* 8
  - *2.6.5 Horizontal profiling grabs* 9
  - *2.6.6 Pneuma Pump* 9
- 2.7 Special purpose dredgers - 'low cost maintenance dredgers' 9
  - *2.7.1 Agitation dredging* 9
  - *2.7.2 Water injection dredging* 10
  - *2.7.3 Ploughing* 10
  - *2.7.4 Harrowing* 10
- 2.8 Hard rock dredging 10
- 2.9 Resuspension generated by the hopper or barge 10
- 2.10 Placement and discharge 11
  - *2.10.1 Discharge into the water column* 11
  - *2.10.2 Temporary storage of material* 11
  - *2.10.3 Reclamation and nourishment* 12
  - *2.10.4 Pipeline transport* 12
  - *2.10.5 Offshore placement at disposal sites* 12

3 **Techniques available for measuring the resuspension of suspended solids by dredging activity** 12
- 3.1 Introduction 12
- 3.2 Turbidity and suspended solids concentration 13
- 3.3 Natural variability of suspended solids concentrations 13

Contents *continued*

3.4 Determination of suspended solids concentration 13
3.4.1 Gravimetric analysis 13
3.4.2 Particle size determination 14
3.4.3 Water sampling 14
3.5 Turbidity measurements 14
3.6 Acoustic techniques 15
3.7 Other remote techniques 16
3.7.1 Side scan sonar records 16
3.7.2 Aerial photographs 16
3.7.3 Satellite images 16
3.7.4 Specialist bed frames 16
3.8 Monitoring strategies 16

4 Review of published information 18
4.1 Introduction 18
4.2 Guidelines 18
4.2.1 Resuspension and productivity 18
4.2.2 Other factors affecting resuspension 18
4.3 Grab dredges 19
4.4 Bucket ladder dredge 20
4.5 Trailing suction hopper dredges 20
4.6 Cutter suction dredge 21
4.7 Special purpose dredgers - 'environmental dredgers' 22
4.7.1 Auger dredgers 22
4.7.2 Dustpan dredger 22
4.7.3 Scoop dredger 22
4.7.4 Disc bottom cutterhead dredger 23
4.7.5 Horizontal profiling grabs 23
4.7.6 Pneuma Pump 23
4.8 Special purpose dredgers - 'low cost maintenance dredgers' 23
4.8.1 Agitation dredgers 23
4.8.2 Water injection dredging 23
4.8.3 Ploughing 23
4.8.4 Harrowing 24
4.9 Hard rock dredging 24
4.10 Resuspension by hopper or barge 24
4.11 Placement and discharge 25
4.11.1 Discharge into the water column 25
4.11.2 Temporary storage of material 25
4.11.3 Reclamation and nourishment 25
4.11.4 Pipeline transport 25
4.11.5 Offshore placement at licensed disposal sites 26

5 Recent field studies 27
5.1 Introduction 27
5.2 Plume Measurement System of the USACE Dredging Research Programme 28
5.3 Channel deepening to Londonderry, Lough Foyle 29
5.4 Agitation dredging at Sheerness 31

Contents continued

5.5 Construction of pipeline trench, South Coast of England 32
5.6 Maintenance dredging on the River Tees 32
5.7 Measurements of resuspension rates during UK aggregate dredging operations 33
5.8 Dredging activities in Hong Kong 34
5.9 Monitoring associated with the Oresund Link 35

6 The long term impact of dredging activities on suspended sediment concentrations 35
6.1 Introduction 35
6.2 Impacts associated with capital dredging 36
6.2.1 Changes to hydrodynamics 36
6.2.2 Slumping 36
6.2.3 Increased requirement for maintenance 36
6.2.4 Increases in resuspension and erosion by shipping 36
6.3 Impacts common to all types of dredging 37
6.3.1 Changes to the surface of the bed 37
6.3.2 Fluidisation of the sea bed 37
6.4 Agitation dredging 37
6.5 Long term impacts associated with placement 38
6.5.1 Offshore disposal 38
6.5.2 Monitoring placement at offshore sites 39
6.5.3 Backfilling borrow pits 39
6.5.4 Beneficial use of dredged material 40

7 Uncertainties and assumptions to be made in modelling the resuspension of material associated with dredging activity 40
7.1 Introduction 40
7.2 Release rate of material from the dredging activity 41
7.3 Initial mixing of released material 42
7.4 Settling velocity of resuspended material 42
7.5 Erosion properties of placed material 43
7.6 Consolidation of placed material 43
7.7 Fluidisation of bed material 44
7.8 Hydrodynamic conditions at the site of interest 44

8 Guidelines on resuspension of material by dredging activities 44
8.1 General comment 44
8.2 Resuspension processes 45
8.2.1 Timescales 45
8.2.2 Immediate processes 45
8.2.3 Short term processes 46
8.2.4 Longer term processes 46
8.3 Guidance on monitoring 47
8.4 Guidance on predictive modelling 48

Contents continued

9	**Conclusions**	48
10	**Acknowledgements**	48
11	**References**	49

Tables

Table 1 Indicative values for the mass of sediment resuspended per m^3 dredged (from Kirby and Land, 1991)
Table 2 Measurements of resuspension around a grab dredge
Table 3 Typical sediment disturbances around a clamshell dredge at Almeda Naval Air Station
Table 4 Measurements of resuspension around a bucket ladder dredger
Table 5 Measurements of resuspension around a trailing suction hopper dredge
Table 6 Typical sediment disturbances around a trailing hopper dredge
Table 7 Measurements of resuspension around a cutterhead dredge
Table 8 Maximum plume concentrations measured during 'hard-rock' dredging within 1ft of water surface
Table 9 Fate of dredged material during open water disposal

Plates

Plate 1 Visual impact of dredging operations
Plate 2 Grab dredger operating in Lough Foyle, Northern Ireland
Plate 3 Bucket/trailing suction and grab dredgers operating in The Yemen
Plate 4 Trailing suction hopper dredger 'Geopotes 14' operating in the English Channel
Plate 5 Trailing suction dredger 'Arco Severn' operating in the English Channel
Plate 6 Cutter suction dredger 'Orion' operating in the English Channel
Plate 7 Agitation dredging in the Bristol Channel
Plate 8 Suction/agitation dredger 'Agem One' operating at Sheerness
Plate 9 Auger dredger operating in Poole Harbour
Plate 10 Other small suction dredgers
Plate 11 Plough 'Norma' operating in Lough Foyle, Northern Ireland
Plate 12 Overflow from the aggregate dredger 'Arco Severn' operating in the English Channel

Volume 2

Appendices

Appendix 1 Channel deepening to Londonderry, Lough Foyle
Appendix 2 Maintenance dredging on the River Tees

1 Introduction

1.1 Background

In recent years there has been increased public concern for the environment and man's impact upon it. This increased awareness has led to a growing volume of legislation relating to environmental issues. Dredging activities are no exception. This means that the dredging and construction industries require more information about the environmental effects of dredging. In the public perception dredging is considered to be a dirty operation (Plate 1) and consequently environmentally very damaging. There is thus a requirement for considerable education of all concerned with respect to the real effects of dredging activities. In 1993 HR Wallingford were commissioned by the Department of the Environment (PECD 7/6/296) to undertake a study with the aim of providing guidance on the likely increases in suspended solids concentrations associated with different dredging operations.

The magnitude of dredging operations in UK waters is large. There are currently more than 100 dredgers operated by UK ports and dredging companies (Dredging and Port Construction, 1995). Based on available figures the annual tonnage of maintenance dredging is in excess of 33 million tonnes (MAFF, 1995). The majority of this material is placed at offshore sites licensed by the Ministry of Agriculture, Fisheries and Food Directorate of Fisheries Research (MAFF DFR). In 1989 21 million tonnes of marine aggregates were landed in Great Britain, supplying 18% of the sand and gravel requirements of the construction industry (BMAPA, 1994). Capital dredging associated with port and other developments varies from year to year but between 1985 and 1992 average about 8 million tonnes per year (MAFF, 1995). These statistics illustrate that there is significant dredging activity occurring in UK waters.

Dredging inevitably resuspends some bed material into the water column. The environmental impact (both short and long term) of resuspension by dredging operations can comprise:

- a reduction in water translucency and hence in photosynthesis;
- interference with the respiration of fish and other marine life;
- the excessive availability of nutrients;
- the physical and chemical changes in the local environment;
- the aesthetically displeasing effects of the turbid appearance of the water;
- the burial of bottom life which cannot withstand this;

and if the material resuspended is contaminated:

- the migration of (contaminated) sediment from the dredging area;
- the absorption of toxics by marine organisms which can then be harmful to man when such contaminated seafood is consumed;
- the exchange of contaminants between the sediments (brought into suspension) and the water.

These same impacts can also be associated with the resuspension of bed material by natural phenomena such as storms and floods as well as other anthropogenic activities such as vessel movement and fishing. However, the negative impacts associated with dredging should be balanced against the impact of the removal of the (contaminated) material from the dredging area.

The dredging process consists of three distinct phases: extraction, transport and placement. There may be release of sediment into the water column associated with any of these phases. The release may be an immediate phenomena such as the plumes associated with hopper overflow during extraction or hopper discharge during placement. The resuspension may be a long term phenomena linked with resuspension of material by natural forces from areas impacted by the dredging activity, such as resuspension of dredged material placed at an offshore disposal site. There may even be losses due to spillage from a hopper on route to the discharge point.

Research is beginning to be undertaken to quantify some of the impacts of dredging on resuspension of bed material. Most of this research, has, to date, been aimed at addressing the immediate impacts (hours to days) associated with the dredging process rather than longer term effects which may occur after the dredging activity has been completed. This research is driven largely by the concerns over the environmental impact of dredging operations, but also by a separate economic motive of continually optimising the dredging required for safe operation of the world's ports. Advances in dredging plant efficiency are often accompanied by reductions in the resuspension of bed material.

Suspended and resuspended material can be a major problem when it concerns polluted sediments, in areas where the pollution sources are already under control. Suspended material originating from clean sediments require another strategy. Contaminated material in continuously polluting environments also need a different approach. To emphasise this aspect clear reference must be made to background or existing conditions, both regarding resuspension and 'degree of contamination'.

This study is principally concerned with the immediate effect of dredging on resuspension of bed material into the water column. However, within this report the possible long term impact of resuspension associated with dredging activity and the approaches to predictive modelling of the short and long term impacts of dredging are also addressed.

1.2 Objectives

The objectives of this study are:

i) To collect, collate and review accessible research and data on resuspension associated with dredging activity, and

ii) To undertake opportune field measurements on and around dredgers in partnership with members of the dredging industry to contribute to the available information on resuspension associated with dredging activity.

1.3 Structure of report

This report is in nine chapters. In Chapter 2 different dredging techniques and the processes by which associated resuspension can arise are described. The techniques available for measuring the resuspension of bed material associated with dredging activities are described in Chapter 3. A review of previously reported quantification of the increases in suspended sediment concentrations associated with dredging activity is provided in Chapter 4. Field studies undertaken by HR and others during the period of this study are described in Chapter 5. In Chapter 6 consideration is given to some of the longer term impacts of dredging activity. In Chapter 7 a discussion of the uncertainties and assumptions to be made in modelling the impact of dredging activity on suspended solids concentration is provided. Guidelines and conclusions arising from this study are presented respectively in Chapters 8 and 9.

2 *The resuspension of bed material by different dredging activities*

2.1 Introduction

In this chapter different dredging technologies and the associated processes by which resuspension of bed material may arise are briefly reviewed. The review is based upon widely reported phenomena and is intended to provide a general background to the mechanisms of immediate or short term resuspension of bed material by dredging activities. Phenomena associated with particular plant or instrumentation are generally commercially confidential to the industry. Further details of some of the reported studies associated with particular dredging plant are provided in Chapters 4 and 5. For a discussion of the longer term impacts on resuspension of bed material by dredging activities the reader is directed to Chapter 6.

2.2 Grab Dredgers

A grab or clamshell dredger (Plate 2) is a mechanical device operated by a crane and is capable of excavating material at near in situ densities. Sediment resuspension is generated in the following stages of the process:

- While the grab is falling through the water column, the sediment from the previous cycle, which has adhered to the grab, is washed off, also entrapped air will escape from the lowering grab, causing resuspension and aerosols.

- The return flow around the descending grab and its impact on the bottom causes resuspension.

- Pulling out of the already closed grab (possibly tightened by suction) can cause resuspension. In gas rich sediments, such disturbance of the bed enhances resuspension.

- Overflow from an overfull grab spills sediment while it is being raised. A badly closing grab, possibly caused by an obstruction trapped between the shells, also leaks during this stage. Sediment adhering to the outside of the grab is washed off.

- When the grab surfaces, sediment laden water may drain from it.

- The disturbance of sediment may cause the release of gas which is present in it, thus causing enhanced resuspension.

Sediment resuspension can, however, be controlled, often at the expense of productivity. The following measures are the most widely used methods for reducing resuspension:

- The use of a water tight grab. This type of grab is closed from above by rubber flaps or steel plates. This reduces the release of the fines-water mixture when lifted through and above the water.

- The use of a hydraulic grab, which enables the controlling and the monitoring of the opening and closing actions of the grab. If the closure is prevented by an obstruction this can be dropped just above the bottom and the grab process can be re-started.

- The use of a silt screen. A curtain of cloth is suspended from a floating framework down to the bed. This cloth must be permeable to water but not to silt. By this means the area in which the resuspension occurs is isolated from the surrounding water. When the area within the silt screen has been dredged to the required depth, the suspended sediment will settle locally. Considerable attention must be paid to the movement of the screen as careless handling of the screen may completely negate the advantages of its use. The use of silt screens is limited to areas where the ambient currents and wave conditions are low. The aesthetical effect can be reduced by silt screens that have a free opening to the bottom. The suspension of higher concentrations remains below the lower end of the screen.

- Limiting the swinging of the grab over open water. During the time that the grab is swinging across open water between the dredging point and the disposal barge, soil can leak out into the open water.

- Limiting the practice of smoothing the excavated area by dragging the bucket along the bottom.

2.3 Bucket Ladder Dredgers

A bucket ladder dredge consists of a number of buckets linked together in an endless chain which is driven around a rigid movable support called a ladder (see for example, Plate 3). The lower portion of the chain digs into the bed, enabling each bucket to dig up sediment at the bed, to carry it up the ladder and to discharge it into a chute at the top. Material is resuspended during the following stages of the dredging process:

- While the buckets are descending, sediment which has adhered to the bucket can be washed off into suspension.

- Air is carried in the upturned bucket as it is submerged. Most of this air is released only when the bucket is tilted, close to the bottom, possibly loosening soft sediment. This air also causes mixing throughout the vertical and an upward transport of the material resuspended near the bed.

- Overfull buckets may lose sediment during their ascent. This sediment is lost through the entire water column.

- Leakage from chutes which are not in use is an important source of resuspension.

- The disturbance of sediment may cause the release of gas which is present in it, thus causing enhanced resuspension.

While dredging in sensitive areas, a careful operator can reduce resuspension by a bucket dredge by means of the following methods:

- Careful management of the relevant processes. This involves optimising the degree of filling of the buckets, the amount of slack in the bucket chain, controlling the swing, the advance, the number of buckets per minute and the bank height.

- Good maintenance of the discharge chutes also limits the amount of leakage. To prevent such leakage from causing turbidity, an empty barge can be kept alongside under the chute.

- The installation of splash screens at the end of the chutes enables the dredged material to fall into the barge without causing any splash-over of dredged material.

- Extraction of air from the buckets as they descend through the water column can also remove a source of turbidity. Small holes are normally made in the bottom of the bucket to release air on the way down when hitting the water (this also promotes the release of sticky material from the overtopping bucket).

- By creating a 'tunnel' around the 'upgoing' part of the ladder loaded buckets travel in an enclosed surrounding: this prevents the currents washing the fine soil away, and if any material still washes or falls off the bucket it stays within the 'tunnel' where it flows as a dense mixture back to the bottom.

- The use of silt curtains. This is a completely different application to that for grab dredgers (see Section 2.2) and is hardly practical unless a full dock or basin can be closed off.

2.4 Trailing Suction Hopper Dredgers

Trailing suction hopper dredging is undertaken by seagoing vessels that trail a hydraulic suction pipe (dragarm) and draghead for removal of bottom sediments (Plates 4 and 5). Bed sediments are excavated and pumped through the dragarm into hoppers located in the vessel hull. The loading operation, with few exceptions, requires overflow to achieve a material density within the hopper to satisfy economic requirements. This overflow may be through a central discharge chute in the ships hull or via deck level spillways. Resuspension occurs by the following mechanisms during the excavation process with a trailing suction hopper dredge operation:

- The trailing involves the movement of suction pipes and suction heads through the water at velocities of the order of 1-2m/s. This may cause resuspension close to the bed.

- When a jet installation is used, the jet water might spread sediment outside the "reach" of the suction-intake forces if not optimally directed into the suction mouth.

- When the keel clearance is low, the return flow under and along the dredger is a possible source of resuspension.

- Propeller wash may cause erosion especially during the manoeuvring of the dredger.

- Lean mixture is sometimes discharged overboard.

- The hopper may overflow during the loading process. The Department of Transport enforce loadline regulations stipulating spillway requirements which are particularly onerous for sand and gravel dredging.

- The disturbance of the bed sediments can cause the release of gas from the soil enhancing resuspension. This effect is less under the suction head as most of the gas is taken up with the mixture.

- Owing to blockages of the suction head by coarse rubbish and/or sediment it may be necessary to empty the suction pipe several times during a dredging cycle. During the emptying of the suction pipe the mixture from it may flow in to the surface water.

- The disturbance of sediment may cause the release of gas which is present in it, thus causing enhanced resuspension.

- There may be leakage from the hopper itself.

The resuspension caused by a suction hopper dredger can, however, be reduced by the following considerations:

- Trailing velocity, position of the suction mouth and the discharge of the pump must be optimised with respect to each other. The continuous improvements in automation, control and the suction head positioning have afforded considerable economic and environmental advantages.

- Any reduction in the intake of water by the suction head means a more dense pay load and thus reduces the need for overflowing. This can be achieved by directing the flow lines of the suction stream to the actual point of excavation, thus making better use of the erosive capacities of the flow of water into the suction head.

- Under certain circumstances, the return flow method offers a possible improvement for the trailing suction hopper dredging process (van Doorn, 1988). With this method, the water in the hopper which would otherwise be discharged overboard or transported to the disposal site is returned to the suction head to contribute once again to the erosive flow. This limits the total intake of water and increases the pay load.

- A lot of material from the overflow is suspended to the surface because of the presence of air in the overflow mixture. A lot of this air can already be taken out onboard by installation of a properly designed and adjustable overflow system. As a density flow, without air, the overflow mixture finds a quicker way back to the bottom.

2.5 Cutter Suction dredgers

The Cutter Suction dredger (Plate 6) has two main components; the cutterhead and the dredging pump. The cutterhead which is situated at the head of the suction pipe, is used to agitate soft materials or to cut harder materials in order that they may be in a suitable state for removal by hydraulic means. The dredging pump creates a vacuum in the suction pipe and draws the solids up the pipe and through the pump. The solids are then discharged by being pumped through a pipeline. The cutter suction dredger and trailing suction hopper dredger have completely different modes of operation and consequently different sources. Compared to Section 2.4, a cutter suction dredger has no overflow, does not sail with low keel clearances or highly turbulent propeller, has no lean mixture overboard nor leaking hopper. The following sediment resuspension mechanisms are caused by the rotating cutterhead.

- The rotation of the cutter head exerts centrifugal forces onto the cut material which is then thrown out of "reach" of the suction-intake forces.

- When the excavation production (the product of cut height, cut length and swing or trail speed) exceeds the suction capacity of the pump system, excess material will be released into the surroundings.

- The disturbance of sediment may cause the release of gas which is present in it, thus causing enhanced resuspension.

- Mechanical mixing by the rotating cutterhead also contributes towards sediment resuspension.

The resuspension caused by a cutter suction dredger can, however, be reduced by the following considerations:

- Cutter speed, swing velocity and suction discharge must be optimised with respect to each other. The continuous improvements in automation, control and the cutter suction head positioning have afforded considerable economic and environmental advantages.

- A moveable shield around and above a cutter head or suction head reduces the escape of suspended material into the surrounding water column.

- Optimisation of the design of the cutter head with respect to the material being dredged to improve the direction of the material toward the suction intake.

- The use of silt curtains (see Section 2.3).

2.6 Special purpose dredgers - 'environmental dredging'

This group of special purpose dredgers focus on operating with least resuspension of material.

2.6.1 Auger dredgers

This is a small suction dredger which collects the bed material by means of a suction head which contains two horizontal augers that draw the material towards the suction head (Plate 9). From there the material the material passes through the dredging pump to the discharge pipeline. Some auger dredgers are claimed to be able to pump at near insitu densities (Plate 9). The auger dredger like the dustpan dredger (see Section 2.6.4) can only operate in soft materials. A major source of resuspension is associated with priming and repriming of the pump and in manoeuvring the dredger over shallow areas of soft material.

2.6.2 Dustpan dredger

The dustpan dredger consists essentially of a suction pump which draws in a mixture of water and dredged materials through the suction head, which is lowered by winches to the bed (Plate 10). The suction head is usually about as wide as the hull of the dredger and is fitted with high velocity water jets for agitating and mixing the bed material. After sucking the mixture to the surface the dredger pumps it to a disposal area through a floating pipeline. The dustpan dredge is only used in soft material and is commonly used in the UK to remove fresh deposits from capital works prior to the placement of pipelines and tunnel elements. Resuspension processes associated with the dustpan operation are a combination of some of those associated with the other suction dredgers (see Sections 2.4, 2.5 and 2.6.3). Very large dustpan dredgers are used on the major inland waterways of both North and South America.

2.6.3 Scoop/Sweep dredger

The Flemish policy to improve water and bed material quality of the Scheldt Estuary has necessitated recent review of the strategy for maintaining access towards the Kallo Lock. As result a new type of dredge head without rotating cutting devices has been designed (Standaert et al, 1993). The head is a two sided, which is necessary to allow dredging in two opposite swing-directions. The head scrapes material from the bottom into the suction head of the dredger.

2.6.4 Disc Bottom Cutterhead Dredgers

Development by Boskalis has lead to the design of a special cutter suction dredger for use in the removal of thin layers of polluted mud. For this type of dredging it is important to avoid resuspension and spill of any material being dredged. It is also important for the dredging method to be accurate and selective. This helps to reduce costs of treatment, transport or containment of the dredged material. Finally it is important to be able to dredge at a high solids/water ratio so that the volume of material is minimised.

With the disc bottom cutterhead dredger the soil is cut by means of a box shaped cutter with a flat closed bottom and vertical axis of rotation. A suction mouth, for removal of material, is situated inside the cutter. A screen prevent the exchange of cut material with the surroundings. Both the soil input as solid and the soil throughput are measured so that the suction flow rate can be automatically adjusted to the amount of soil being cut. Mud layers with variable thicknesses in the range 0.2m and 0.5m have been dredged.

2.6.5 Horizontal profiling grabs

The horizontal profiling grab is another tool developed by Boskalis for the removal of polluted bed material. The grab is specially developed to deliver an almost horizontal closing movement when used on a hydraulic crane. The maximum opening is approximately 80% wider than the normal hydraulic grab. In this way it is possible to dredge thinner layers. The grab is fitted with a signal on full closure to prevent spills when the grab is not fully closed.

2.6.6 Pneuma Pump

The Pneuma pump is a static submerged dredge unit. It is comprised of three cylinders with adjoining shovels. Attached to the top of the cylinders are three compresses air supply/exhaust pipes which lead to a distributor unit and compressor. A pipeline is attached to the cylinders for the transportation of material. The Pneuma system is based on hydrostatic pump principles.

2.7 Special purpose dredgers - 'low cost maintenance dredgers'

This group of dredgers operate by the principle of resuspension of bed material.

2.7.1 Agitation dredging

Agitation dredging (Plates 7 and 8) can be defined as the removal of bottom material from a selected area by using equipment to raise it temporarily in the water column and natural processes (currents or bedslope) to carry it away (Richardson, 1984).

In most cases agitation dredging techniques are employed because of the apparent low cost and the flexibility of the operation. Agitation dredging techniques may be applied both to capital and maintenance operations. Agitation techniques are used for both large and small dredging operations. In an agitation dredging operation resuspension will occur dependent upon the type of plant used as described in the preceding sections of this chapter. However, resuspension associated with the type of plant are usually minimal compared to the resuspension associated with the direct discharge of all the dredged material into the surrounding waters.

When considering the option for use of agitation dredging techniques the impact of the direct discharge of all the dredged material into the water column compared to the natural loads of sediment in suspension at the site and the natural variability of these loads should be considered. In many cases agitation dredging can be demonstrated to be an environmentally sound, economical dredging strategy.

Sidecasting and other surface dispersion techniques generate a near surface plume, typically this plume is highly aerated and has a high density and momentum compared to the water body into which it is discharged. Inevitably much of the dispersed material will return to the sea bed in the form of a dispersing dense plume.

2.7.2 *Water injection dredging*

Water injection dredging is a particular form of hydraulic agitation dredging where the material removed from the area of interest is not discharged through a pump. The technique aims to generate a near bed low density suspension by discharging a low pressure, high volume vertical jet of water onto the silt. Because of the low pressure the bed material is not jetted away and the water is injected into the bed layer effectively fluidising the bed. The suspension, typically with bulk densities in the range 1,070kg/m^3 to 1,090kg/m^3, is then transported away from the dredging site under the influence of gravitational, hydrostatic and frictional forces.

Water injection dredging is only suitable for removal of silts and fine sands. At present water injection dredging is one form of agitation dredging that does not require a formal MAFF permission. However, water injection dredging is normally undertaken with full MAFF knowledge (Fairgreive, 1996).

2.7.3 *Ploughing*

Ploughing and harrowing techniques employ mechanical agitation of the bed by a suitable vessel, often a tug, towing a specially designed unit along the bed (Plate 11). Ploughing is often employed in conjunction with both maintenance and capital dredging operations. One use of the plough is to move bulk quantities of bed material which would be inaccessible to the larger plant into a position where the material can be removed. The alternative use of ploughing is to level off the sea bed in an area where dredging by larger plant has been undertaken. Some resuspension is inevitable with plough operation. The resuspension is associated both with the impact of the plough on the bed and also the manoeuvring of the towing vessel.

2.7.4 *Harrowing*

Harrowing aims to resuspend material by direct agitation from a towed unit. A highly manoeuvrable towing vessel is desirable so that almost continual agitation of the bed in a particular area can be achieved. Harrowing is undertaken in locations and at times when near bed tidal currents will be sufficient to advect resuspended material away from the area of concern. Harrowing of both muddy and fine sandy beds has been undertaken.

2.8 Hard rock dredging

Hard rock dredging is now largely undertaken using explosives. The explosives are placed in boreholes drilled vertically into the rock being blasted. The work is usually carried out from a floating jack-up pontoon. After blasting the rock is removed by bucket, grab or cutter suction dredgers. Considerable resuspension can be associated with hard rock dredging.

2.9 Resuspension generated by the hopper or barge

If neither sidecasting nor transportation of dredged material through pipelines is practised, the dredged material can be either transported within the hopper itself in the case of hopper dredgers or by a separate barge. In either case, the following sources of resuspension may occur.

- When overflowing from the barge or hopper is carried out, fine material is washed out with the overflow water. The overflow takes the form of a dense plume with a momentum dependent upon the discharge rate and direction. Very dense and high momentum discharges may rapidly sink to the sea bed. Less dense low momentum discharges may mix rapidly with the surface waters. The mixing is enhanced by the propulsion and movement of the vessel.

- When the suction flow is of a low solids content, it is often decided, on the basis of productivity, to pump the lean mixture overboard instead of into the hopper, so as to avoid diluting the load. This method releases solids into the upper part of the water column.

- When loading a barge, material might splash over the sides especially when big lumps are released from the chute of a bucket ladder dredge or from the bucket of a grab.

- Inside a barge loaded with soils and sailing to the unloading location, wave action might develop because of the movements of the barge itself. Thin mixture might, therefore, spill overboard.

- Obviously, leakage of sediment through bottom doors or other hull openings is a major potential source of release into the water column.

Most of these sources of release of solids into the water column can be reduced by careful management, but this is usually accompanied by a reduction in productivity or an increase in the number of necessary trips to the disposal site.

Mining for sands and gravels is a particular case where overflow is necessary (Plate 12). Screening, whereby the relative proportion of either sand or gravel is increased by preferential sieving, is often also undertaken causing a resuspension of fine and coarser material.

2.10 Placement and discharge

2.10.1 Discharge into the water column

Some techniques for placing dredged material have been referred to in the preceding sections of this chapter. Resuspension associated with direct discharge into the water column (agitation dredging or overflow) is largely related to the fate of the density plume(s) generated by the discharge. If the density plume has a sufficient density contrast and initial momentum compared to the surrounding water column, the majority of the material in the plume may impact on the bed with little bulking and relatively low losses. The impact of the plume on the bed may be sufficient to resuspend material either from the bed or from the descending plume. If the plume is only slightly denser than the surrounding water and the release rate is low the material within the release plume may become mixed throughout the water column so that the processes of settlement of individual particles from the plume becomes the mechanism whereby material descends to the bed. Consequently very much more material will be resuspended into the water column in this manner.

2.10.2 Temporary storage of material

Sometimes during trenching operations it is necessary to temporarily store excavated material prior to backfilling. This may be achieved by discharging through a near bed diffuser directly from the pipeline (see Plate 6). If the discharge rate and density are sufficiently high then the majority of the material dredged can be satisfactorily returned to the bed and the short term resuspension minimised. However, long term resuspension will be controlled by the natural hydrodynamic conditions at the site. Large tidal currents and storm waves may resuspend material from the temporary storage area.

2.10.3 Reclamation and nourishment

More traditional methods of placement are direct pumping via pipeline or, when it is possible to manoeuvre a vessel to a suitable location near the reclamation or nourishment area direct discharge sometimes called 'rainbowing'. For these methods of placement losses associated with placement can be minimised by use of appropriate control structures such as bunds, weirs and settling basins. In the absence of such structures around the works then both short term and long term losses may be significant, but always less than under sections 2.10.1 and 2.10.5.

2.10.4 Pipeline transport

Occasionally losses occur when a floating pipeline becomes blocked and has to be repaired. However, such losses can be considered insignificant unless the material being transported is highly contaminated.

2.10.5 Offshore placement at disposal sites

Most of the material that is dredged annually in the UK is placed at offshore sites around the coast. The depth of placement preferably takes place at depths below navigational depths. Natural resuspension might lead to more maintenance dredging were the material to be placed at higher levels. There are about 150 such sites in use in any one year. The use of these sites is licensed and enforced by the Ministry of Agriculture, Fisheries and Food Directorate of Fisheries Research. The placement operation at such a site is typically a very rapid affair lasting less than five minutes. The hopper or barge is opened and the solids/water mixture contained therein slides out of the vessel and falls to the bed. The descent is similar to that described above for direct discharge, only in this instance the density is generally higher. In water depths of less than about 50m it is considered that the majority of the material placed falls directly onto the bed. Immediate resuspension occurs in a small surface plume and potentially in a near bed impact plume. In water depths greater than about 50m it is considered that total entrainment of the material within the plume occurs and the material is all resuspended into the water column to settle as individual particles and lumps under the prevailing currents at the site. Further discussion of longer term processes that may occur at disposal site are discussed in Chapter 6.

3 Techniques available for measuring the resuspension of suspended solids by dredging activity

3.1 Introduction

All dredging results in the resuspension of some material into the water column. Quantification of the levels of resuspension associated with different dredging technologies and operating scenarios is an important aspect of considering the environmental and economic acceptability of a particular project. From the review in Chapter 2 it can be seen that there are numerous possible sources of resuspension for different dredging activities. There are enormous practical limitations in directly measuring the resuspension associated with the different processes. However, it is possible in some instances to directly measure the gross increases in suspended sediment concentrations associated with a particular type of dredging operation. In this chapter the options for direct measurement of the resuspension of bed material by dredging activities are briefly described. The descriptions are aimed at outlining the different techniques and differences between the techniques rather than describing commercially available instruments.

It should be noted that all of the techniques described in this chapter can equally be applied to measuring the background concentrations and the variability of the suspended sediment concentrations that are naturally in suspension.

3.2 Turbidity and suspended solids concentration

Turbidity and suspended solids concentration are different. Turbidity refers to the ability of a liquid to transmit light. The suspended solids concentration is the mass of solids in a given volume of fluid. Turbidity can be used to give an indication of the relative amount of suspended sediment present at a given site. It cannot however be consistently correlated with the weight concentration of suspended matter because of the optical importance of suspended sediment size, shape and refractive index. Both increases in turbidity and suspended solids have environmental impacts most of which are related.

Most remote measuring techniques do not directly measure suspended solids concentrations and require suitable calibration data to establish the relationship between the measured parameter and suspended solids concentration. This calibration procedure is not straightforward and the importance of calibrating against in-situ suspensions cannot be over-emphasised.

3.3 Natural variability of suspended solids concentrations

Resuspension of bed material during dredging must be examined within the context of natural background suspended solids concentrations and of incidental occurrences of high concentrations such as during storms, periods of high river discharge or such as the disturbance caused by ship propellers when the water depth is limited. It is even considered that fishing activities can contribute significantly to the resuspension of material into the water column from the sea bed (Herbich, 1992 and Section 9.21).

The analysis of long term records of suspended sediment concentrations, derived from turbidity measurements, and correlation with such parameters as tidal range, freshwater flow, wind/wave activity and dredging activity has been the subject of recent research at HR Wallingford (Stevenson, 1992) and requires a long term data base from which to determine the existing natural relationships at a site prior to dredging activity. In general it is considered that at least a 3 month period of record is required in order to determine the relationship between tidal range and suspended sediment concentration. The more random nature of wave activity and high freshwater flows can require much longer data sets (of the order of 12 months) from which to establish sensible relationships.

3.4 Determination of suspended solids concentration

3.4.1 Gravimetric analysis

Analysis of discrete samples is the only method for directly determining the concentrations and composition of material in suspension. The method generates large volumes and masses of samples and transportation can prove costly. Samples need to be kept cool and dark in order to avoid organic growth prior to analysis. Filtration in the field can be used to overcome some of these problems but the entire operation then becomes very labour intensive.

Whilst there are many standards and approved methodologies for analysis of suspended solids concentrations it should be noted that there are still inherent inaccuracies in the analysis technique. A good laboratory should be able to reliably and repeatedly measure suspended solids concentrations to an accuracy which is orders of magnitude greater than the natural variability of the suspended sediment concentration at a site. Gravimetric analysis of suspended sediment concentrations of a large number of samples can prove costly.

3.4.2 Particle size determination
In some instances it is of use to examine the composition of material in suspension. A number of techniques exist for such analysis and the most commonly used is now laser diffraction analysis using laboratory based instruments. Here it is usual to determine the size distribution of disaggregated samples of the material in suspension. Typically a sample of about 100mg is required for analysis.

3.4.3 Water sampling
Methods whereby water samples can be obtained for subsequent analysis vary from the insertion of a suitably sized bucket below a deck level spillway (Plate 12) to the use of remotely triggered sampling devices suspended on a suitably weighted line from a survey vessel. It is not the intention within this report to review the different instruments currently available for obtaining water samples.

Small water samples can be obtained quickly and are generally easier to transport. However, when low concentrations of suspended solids are experienced, or if determination of particle size distribution of the suspension is required, larger samples are necessary. Pumped sampling enables a large discrete sample to be obtained albeit over a relatively long period of time. Pumped sampling enables a sufficiently large volume of water to be obtained so that both determination of suspended solids concentration and particle size distributions of low concentration samples can be undertaken (typically requiring 2 to 10 litres). A drawback with pumped sampling is the time taken to obtain one sample. To obtain a discrete sample from a given depth, the water already within the pipeline has to be flushed out (perhaps a duration of one minute) and then the sample has to be obtained (perhaps a duration of up to one minute). The survey vessel will inevitably move during the sampling period. Another drawback with pumped sampling is that when sand is present in suspension, particularly coarse sand, the gravitational settling of the sand during the ascent up the pipe may be significant effectively producing lower sand concentrations that reality. A further problem can be caused by the misalignment of the pump intake and the flow direction. A number of authors have described the various means whereby pumped sampling will lead to an underestimation of the suspended solids concentration (eg. Nelson and Benedict, 1951 and Crickmore and Aked, 1975).

3.5 Turbidity measurements
In order to obtain long term records of suspended sediment concentration a number of indirect measurement techniques have evolved. By far the most common method of determining suspended sediment concentration records is the optical silt monitor. These sensors are based on the photo extinction principal whereby the suspended solids concentration in the water is measured as a function of its turbidity. A photocell within the sensor records the amount of light transmitted as a voltage or current. The measurement will be affected

by small air bubbles in the water column (HR Wallingford, 1996) and by other factors such as humic acid from peaty soils (HR Wallingford, 1992b).

The relationship between the recorded signal and the nominal suspended solids concentration is established by calibration against a range of standard Formazin turbidity solutions or laboratory prepared silt solutions using local material. The relationship between Formazin and natural solids concentrations is determined by sampling insitu at the monitoring site. This calibration is a function of the shape, mineralogy and size distribution of the suspended particles and so may be subject to temporal variations.

It is known that pumped sampling breaks up naturally occurring flocs and accordingly increases the number of particles in suspension increasing turbidity (Stevenson, 1992). It is generally considered important to obtain a calibration factor from undisturbed in-situ samples. Collection of bed samples for later resuspension in the laboratory will not necessarily provide the correct calibration factor. However, this approach is useful when the full range of naturally occurring concentrations cannot be obtained by sampling, ie during storm conditions. This holds for the calibration of other indirect measurement techniques.

Turbidity can also be measured using infra red sensors, which are generally considered superior especially when working in relatively clear waters where the effects of sunlight can be important.

Instruments are also available that measure turbidity by backscatter rather than by light attenuation.

3.6 Acoustic techniques

Much fundamental research has been undertaken into the field of using acoustic measuring techniques for non-intrusively measuring the suspended sediment concentration in the water column (eg Thorne et al, 1991 and 1993). The method of measurement is very dependent upon concentration and grain size. Initial development concentrated on measuring near bed sand transport. However, the theory and analysis techniques have developed and now the instruments are routinely used for examining concentrations of both mud and sand in suspension.

A more recent development has been to use the backscatter signal from vessel mounted (or fixed) Acoustic Doppler Current Profilers (ADCP) as a measure of the suspended solids concentration. The use of an ADCP in this fashion is a complex one and pioneering work has been undertaken by Dredging Research Ltd working in conjunction with EGS on behalf of the Hong Kong Government (Land et al, 1994). The developments by Dredging Research Ltd are now packaged as the SEDIVIEW system which is commercially available (Dredging Research, 1995). Other workers have developed slightly different analysis techniques (eg. Weiergang, 1995 and USACE, 1992).

3.7 Other remote techniques

3.7.1 Side scan sonar records

Side scan sonar has been used on a number of occasions to look at the dynamic phase of the disposal operation (see for example Kirby and Land, 1991). Such records are able to show the advancing density current created by the impact of the placed material on the sea bed.

3.7.2 Aerial photographs

Aerial photographs such as that shown in Plate 1 can provide a useful record of a dredging activity. However, care should be taken when quantifying the processes occurring. Small changes in suspended solids concentration and possible surface effects can create significant boundaries to the naked eye.

3.7.3 Satellite images

Satellite images can now be produced at sufficient resolution to identify the wakes of individual vessels. A recent study has demonstrated the use of enhanced satellite images to illustrate the contrasting natural turbidity regime which exists around Hong Kong (Whiteside et al, 1995).

3.7.4 Specialist bed frames

Over recent years MAFF DFR have undertaken a number of deployments of specialist bed frames around the UK. These frames have been able to record simultaneous data on the hydrodynamic regime and on the suspended sediment concentrations. The frames that are deployed by MAFF DFR have been developed in conjunction with Cambridge University and are now deployed as a routine matter of course and with high data recovery. Three different types of frames are routinely used. These are referred to as the Tetrapod, Quadrapod and Minipod. The three bed frames are described in a recent paper by Rees (1995). The instruments carry electromagnetic current meters, pressure sensors, miniature optical backscatter sensors, acoustic backscatter sensors and specially developed water sampling apparatus in addition to auxiliary sensors for measuring roll pitch, compass orientation and temperature.

The minipod frames are now being deployed around offshore disposal sites as part of a MAFF DFR funded study of the properties of dredged material that is being undertaken by HR.

3.8 Monitoring strategies

In general the monitoring associated with a dredging exercise is aimed at quantifying the magnitude of any increases in suspended sediment concentrations above natural levels. The natural level of suspended sediment concentration can be affected by the tidal range, wave activity and freshwater flow. Biological activity can be also an important consideration in some cases. On a rather shorter time scale (immediate) the passage of vessels and fishing activity can often cause significant increases in suspended sediment concentrations.

When making measurements of the short term resuspension of bed material around a dredging activity, it is reasonable to make background measurements of suspended solids concentrations, turbidity or backscatter in adjacent waters before and during the dredging operation commences or begins to affect the area of interest. When considering the longer term impacts of the dredging operation measurements before, during and after the period of dredging activity are required. If long term measurements are required then remote measurements will almost definitely have to be made. At present the most cost effective measurements are made by installing turbidity meters at sites in the vicinity of the dredging activity and any areas of particular concern. Bed mounted instruments may be required where no suitable fixed structures are available. In some instances deployment of suites of instruments such as the MAFF DFR Minipods (Section 3.7.4) provide a means whereby information concerning the hydrodynamic regime and the suspended sediments concentrations can be related. In any case during the period of a deployment it is necessary to obtain information on fluvial discharges and wind activity in the region of the measurements so that the effects of natural variability can be accounted for in the data record.

An important consideration for any environmental monitoring is the sampling frequency. During a field measurement exercise in the River Thames using optical silt monitors (HR Wallingford, 1974) it was found that the instantaneous output from the transmissometers varied on average by 22% compared with the mean for a series of twenty, three second measurements. This variation increased significantly for higher concentrations (greater than 1,000ppm) (Stevenson, 1992). This demonstrated that an instantaneous reading could be significantly different from a smoothed average value such as obtained by pumped sampling and emphasised the need for frequent sampling.

When only short term measurements are being made with remote instruments, it is important that the sampling frequency is as high as is practical so as to enable identification of any structure in the variability of the recorded data. When long term measurements are being made the storage capacity of the data loggers will become important. In practice readings every 10-15 minutes, either instantaneous or averaged have been found sufficient to allow the effect of tidal fluctuations to be determined. Other fluctuations such as those due to wave activity and variations in freshwater flow can also be detected at this sampling frequency.

Sampling techniques such as viewing the backscatter from the ADCP, enable an instantaneous output to be viewed during the sampling period. These are a vital part of the suite of monitoring techniques to be used during short term measurements. They enable flexibility to be retained within the monitoring programme as decisions based on real time measurements can be made and, if appropriate, modifications to the monitoring undertaken.

All sampling requires a finite time for the sample to be obtained. The most useful sampling of the resuspension of material associated with dynamic dredging operations is that which can be considered to occur instantaneously, compared to the timescale of the variability associated with the dredging operation. Obtaining a remotely triggered sample, which takes of the order of seconds to fill, and the response time of transmissometers, which also have a finite response time, are generally considered to provide instantaneous measures of the suspended sediment concentration and turbidity at fixed points in space and time. The use of pump sampling for larger volume water samples cannot be so considered.

Any water samples undertaken during a monitoring campaign around a dredging activity need to be accompanied by a careful record of position, depth, time, position with respect to the dredging activity and information on the dredging activity.

4 Review of published information

4.1 Introduction

Over the years numerous measurements of the resuspension of material associated with dredging have been made. The measurements have tended to be site specific and have, on a number of occasions been summarised in the form of general guidelines and rules of thumb. In this chapter a summary of the available published data is provided. This chapter largely reviews data that was published before 1992. Further detail of more recent measurements are provided in Chapter 5. This chapter is structured in the same way as Chapter 2 with the exception of an additional section (Section 4.2) which reviews the guidelines available at the onset of this study.

4.2 Guidelines

4.2.1 Resuspension and productivity

In determining and comparing the effect of different dredging methods on the environment, it is not sufficient to have an estimate of the rate of release of sediment into the water column or the maximum observed suspended sediment concentration in the vicinity of the dredging operation. The productivity of the method is also a significant factor, since this determines the length of time for which the dredging needs to be carried out. A factor which takes this into account is the mass of sediment resuspended per m^3 of dredged material. Blokland and van Raalte (1988) describes a systematic method for determining the quantity of sediment released in kg per cubic metre dredged, which is lost in the immediate vicinity of the dredger. This is the so called "S-factor" and can be applied to a number of different dredging methods. Further use of the "S-factor" was made by Kirby and Land (1991) and the table from their paper is reproduced in Table 1.

The concept of the Turbidity Generating Unit (TGU) has been proposed by the Japanese Environmental Protection Division (Volbeda, 1983 and Nakai, 1978). This is the weight of matter brought into suspension in order to produce $1m^3$ of dredged material under standard current conditions. Example TGU values given for clay are $84kg/m^3$ for a grab dredge, $35kg/m^3$ for a cutter dredge and $25kg/m^3$ for a trailing dredge. These values are, however, significantly larger than the "S-factors" suggested by Blokland (1986). This is probably because they have been given for very fine bed material.

4.2.2 Other factors affecting resuspension

The general guidance above must be applied carefully. There are a large number of factors which affect the resuspension of bed material during dredging besides the method of dredging. These include the following:

i) The soil characteristics (including grain size distribution, density, shear strength, compaction, organic matter content and mineralogical composition)

ii) The gas content of the bed material. Escaping gas contributes to resuspension in two ways: silt particles are resuspended by adhering to the bubbles and the rising bubbles increase the vertical mixing of sediment within the water column.

iii) The salinity of the water column. This may influence the levels of resuspension in two ways. Salinity increases the flocculation (particularly in the zone between fresh and slightly saline waters) and hence the settling velocities of cohesive suspended material (see further discussion in Section 7.4); variations in salinity can create stratified layers and density currents which can affect spreading and mixing of the resuspended material and even hinder the settling of resuspended material.

iv) Water temperature. Settling velocity is dependent upon the viscosity of the water. Fine material will settle about twice as quickly in water at 20°C as at 0°C (assuming Stoke's settling)

v) Movement of the water column. Currents, especially near the bottom, even if relatively small, can greatly extend the horizontal spreading of plumes of resuspended material. A positive aspect of the currents is that they reduce the maximum levels of resuspension since the resuspended material is mixed into a larger volume of water. Typically, in tidal waters, for the same dredging operation resuspended sediment concentrations will be about two times higher on neap tides than on spring tide because of the advection by the tidal currents.

vi) Movement of the dredger with respect to the water column. Static dredging operation are affected as described in v) above. With mobile operations it is the relative speed of the dredger to the water column that is important. A trailer suction hopper dredge works efficiently at a certain speed over the seabed. If this speed is two knots and there is one knot tidal current the relative speed of the dredger to the water column, assuming that dredging is parallel to the tidal currents will be one knot with the tidal current and three knots against the current. The initial dispersion of the resuspended material will thus be about three times greater in one direction than the other.

4.3 Grab dredges

Measurements taken during grab dredger operation have been described at Merwedehaven and at Hollandsche IJssel by Pennekamp and Quaak (1990), at Zierikzee by Pennekamp et al (1991), at Black Rock Harbour and at Duwamish Waterway by USACE (1988a), and also at Calumet River by USACE (1988b). The measurements are summarised in Table 2.

The levels of resuspension of up to 105ppm measured at Zierikzee should be viewed in the context of the resuspension caused by navigational traffic which gave rise to peak suspended sediment concentrations of 150 to 200ppm.

The measurements at Black Rock Harbour show a significantly higher level of resuspension than any of the other observations. This is probably due to the bed consisting of a far finer sediment than in any of the other cases. None of the other examples in Table 2 show concentration increases over 140ppm. They therefore fit within the range of 25-300ppm increase described in Section 4.2.1, with the exception of the measurements in the second column. These were taken at Hollandsche IJssel for a watertight grab with a silt screen. Here the measured concentration increase was only 20ppm.

The measurements at Hollandsche IJssel illustrate the benefits of the turbidity reduction measures, since the increase in concentrations is almost halved for a watertight grab and it is reduced by a factor of five with the implementation of a silt screen (Table 2).

More extensive measurements were made at Almeda Naval Air Station in an 8m channel (Sustar et al, 1976). Typical values have been extracted from the study and are given in Table 3 for various positions within the plume. In this example, the concentrations appear to be greatest close to mid-depth rather than close to the bed as has been suggested in some reports.

Monitoring of the operation of the Cable Arm 100E bucket has been described by Buchberger (1993). The bucket, which uses a system of cables rather than fixed arms to control the operation has proved to generate only very low resuspension (reported as 4.5 NTU) which was estimated to be between 10 and 20 times lower than conventional bucket system.

4.4 Bucket ladder dredge

Barnard (1978) described a typical bucket dredge operation as producing a downstream plume of resuspended material extending some 300m at the surface and 500m near the bottom. In the immediate vicinity of the operation near surface concentrations were describing as generally being less than 500ppm, rapidly decreasing with distance. Average water column concentrations were reported to be generally less than 100ppm. The near bottom plume is expected to be higher (Lunz et al, 1984)

Very few measurements of resuspension associated with bucket ladder dredge operations have been reported. One such set of measurements reported by Gemeentewerken Rotterdam (1988) is reproduced in Table 4.

4.5 Trailing suction hopper dredges

The measurements around an operating suction hopper dredge shown in Table 4 were taken from Blokland (1986) and Blokland et al (1986).

There can be significant variation in the vertical profile of resuspended sediment in the vicinity of a trailer dredger. The concentrations at the surface are generally reported as being significantly lower than those near the bed. The comments in Section 4.2.1 and the measurements at Gray's Harbour, Washington (Table 5) support this strong differential between the induced concentrations close to the bed and those at the surface.

Suspended sediment plumes created by a hopper/dragarm dredge at Gray's Harbour, Washington, were measured by sample boats anchored behind the passing dredge. Increases in suspended sediment concentrations were limited to the proximity of the bed for the case with no overflow. In the case of dredging with overflow from the hopper, the plume created behind the hopper was reported to rapidly settle to the lower portions of the water column.

Table 6 shows measured concentrations along the centreline of the path of a trailing suction dredger with overflow (Sustar et al, 1976). Higher levels, over 5,000ppm, can be observed adjacent to the dredger, but such concentrations reduce rapidly to give the values shown in Table 6. The duration of these concentrations is typically less than 15 minutes when the salinity is above 1ppt. However, under turbulent conditions or periods of very low salinity, they may persist for an hour or more.

The wide range of measurements shown in Table 5 make it difficult to suggest likely values for trailing suction dredge induced concentration disturbances. This implies that the uncertainties in the concentrations are probably due to external factors such as the currents, the hopper travelling speed, the water depth, influencing the distribution of the suspended sediment throughout the water column, rather than large variations in the total quantities of sediment resuspended.

4.6 Cutter suction dredge

The complex nature of the flows around a cutterhead dredge and the factors contributing to resuspension of bed material have been investigated by a number of researchers (for example Brahme et al, 1986 and Andrassay and Herbich, 1988). These studies indicate that the resuspension of sediment generally increases with the cutter speed or the swing velocity, while an increase in the suction discharge reduces the level of resuspension. Huston and Huston (1976) describes a general increase in resuspension with cutterhead rpm. It is, however, described as an inconsistent increase, probably because of the complications due to turbulence generated at the cutterhead.

Several researchers have also pointed out that the direction of swing has an effect on sediment resuspension. This effect is probably due to whether the cutter is over-cutting or under-cutting the material (Andrassay and Herbich, 1988).

The effect of thickness of cut has also been investigated by a number of researchers. Nakai (1978) states that the resuspended sediment levels increase with the thickness of cut. However, Hayes et al (1986), Herbich and de Vries (1986) and McLellan et al (1986) imply that the least resuspension occurs when the thickness of cut is approximately equal to the diameter of the cutterhead and that shallower cuts may actually increase the sediment resuspension due to the increased area of the cutter which is exposed, hence throwing sediment beyond the intake pipe.

The dredging angle, defined as the angle between the dredge ladder and the vertical, has been found to have an influence on the resuspension of sediment (Huston and Huston (1986) and Herbich and de Vries (1986). This angle controls the distance between the bed surface and the mouth of the suction inlet. The more the angle of the dredging ladder approaches the vertical, the greater the distance between the sediment and the suction inlet. This results in the sediment experiencing a smaller suction head, thus allowing more sediment to escape into suspension.

These 'scientific laboratory tests' on ladder angle are a very late confirmation of standard practical knowledge of dredging operations. However, the much more complex aspects of resuspension in real dredging can hardly be modelled in the laboratory. Therefore caution should be applied when considering laboratory and field experiences in the literature.

The shape of the cutterhead and the rate angle of the cutter's teeth or blades have also been identified as having an influence on suspended sediment levels (McLellan et al, 1986).

Some measurements taken during the operation of a cutterhead dredge are described by USACE (1988a and 1988b). These are summarised in Table 6.

In Section 4.2.1 it is suggested that the concentrations generated by a cutterhead dredge are extremely sensitive to the distance from the cutterhead. This distance is not given for the measurements in Table 7, making it difficult to draw any conclusions from them. However, it should be noted that making measurements very close to any dredging operation is particularly difficult, and dangerous, from a logistical point of view.

Measurements made using both a clamshell dredge and a cutterhead dredge in similar sediments at the Calumet project have shown considerably higher levels of turbidity generated from the clamshell (see Tables 2 and 7).

Sustar et al (1976) note that the cutterhead dredge resuspends the least amount of solids in the water column per unit volume dredged, less even than the trailing suction hopper dredge without overflow.

During the construction of Sydney Airport's new runway cutter suction dredgers were used to reclaim an area of 170 hectares with 15 million m^3 of sand dredged from Botany Bay (Herbet et al, 1995). Strict constraints concerning the levels of resuspension of dredged material were placed on the operation. These were limiting the level of suspended sediment concentration to 20mg/l during dry conditions and to no more than 20mg/l above background levels after wet weather conditions. To meet this constraint the dredging Contractor installed a silt screen some 4.8km in length. This screen was purchased from Japan at a cost of $5 million.

4.7 Special purpose dredgers - 'environmental dredgers'

4.7.1 Auger dredgers

Auger dredgers used in the UK are generally small. As a consequence resuspension by the dredging action is usually very small. However, manoeuvring of the dredger in shallow water and priming and repriming of the pumps probably contribute more to resuspension than the dredging.

Auger dredgers are often employed for remedial work, carefully removing localised sources of contaminated material. Reinking (1993) describes studies that were undertaken as a preliminary to removal 10,000m^3 of heavily contaminated sediment from the sea harbour channel in Delfzijl. In order to demonstrate the technical feasibility of employing the environmentally friendly auger HAM 254 a full scale trial was undertaken on site and monitored by Delft Hydraulics. The outcome of the monitoring was the establishment of an "S-factor" of 0.1 to 0.4kg/m^3. Resuspended solids were observed to be limited to a maximum of 1.5m above the bottom.

4.7.2 Dustpan dredger

Similarly to the Auger dredgers resuspension as a result of the dredging is likely to be small compared to other associated effects.

No reported measurements of resuspension were available.

4.7.3 Scoop dredger

Resuspension by the scoop dredger has been reported by Standaert et al (1993). A monitoring programme was carried out to determine immediate and medium term (48 hour) resuspension. During the measurements background suspended solids concentrations were about 20mg/l at the surface and 40mg/l near bed. The influence of the dredging operation could not be detected at a distance of 50m from the dredger. Within 5 to 10m of the scoop head resuspension of 2 to 5mg/l above background levels was reported. It was also noted during the monitoring that resuspension by passage of a large gas tanker raised concentrations to 70mg/l near the bed.

4.7.4 Disc bottom cutterhead dredger

Mud layers with variable thicknesses in the range 0.2m and 0.5m have been dredged. Hardly any resuspension and spill of dredged material has been recorded during employment of this dredger. A bulking factor of less than 1.4 has been realised with this technique.

4.7.5 Horizontal profiling grabs

No reported measurements of resuspension were available.

4.7.6 Pneuma Pump

Monitoring reported by Buchberger (1993) demonstrates that the Pneuma system can operate with only very small levels of resuspension. However, when the pump was clogged with debris resuspension levels 18mg/l above a background of 10mg/l were observed.

4.8 Special purpose dredgers - 'low cost maintenance dredgers'

4.8.1 Agitation dredgers

Few measurements have been reported around dredging operations where agitation methods are employed. This is largely because in the past sites where such dredging is undertaken have not been subject to particular environmental sensitivities. Monitoring, if considered, would largely be on the basis of investigating the efficiency of the operation. However, since the efficiency, measured in financial terms, was largely a major saving compared with other more traditional measures further investigation was usually unwarranted. For example, the change in dredging policy at the Port of Bristol from the use of trailer dredgers placing material at a licensed offshore site to the use of small cutter suction dredgers continually discharging into the surface waters resulted in a major reduction in dredging costs (Foy, 1985 referenced in Finney, 1987).

4.8.2 Water injection dredging

Water injection dredging is a particular form of agitation dredging (see Section 2.6.2). Whilst it is acknowledged that many site specific studies have been undertaken to examine the impact and efficiency of the water injection dredging technique most of these studies remain commercially confidential (for example HR Wallingford, 1990).

Fairgrieve (1996) recently presented the water injection dredging technique to the UK Association of Harbour Masters. In his paper he described the monitoring that has been undertaken at a number of sites around the world using various forms of tracers injected into the muddy material as it is fluidised. The monitoring has largely been focused on identifying what happens and where the fluidised mud goes rather than monitoring increases in suspended sediment in the water column.

4.8.3 Ploughing

A bottom leveller dredge produces very high concentrations in a sharply defined layer near the bed and has a far lesser influence in the remainder of the water column. Some quantification of resuspension around plough dredgers has been undertaken. However, resuspension is largely associated with the material type and mode of operation.

4.8.4 Harrowing
Harrowing is typically undertaken over sand bars. As such very little muddy material is likely to be resuspended during operations.

No reported measurements of resuspension by harrowing were available.

4.9 Hard rock dredging
In the Florida Keys, the nature and shallow depth of the bedrock dictates that dredging be accomplished by a technique that is usually associated with hard-rock mining and is therefore referred to here as hard-rock dredging. It is a relatively slow process, typically requiring several weeks or months to complete canals that in areas of loose sediment could be dredged hydraulically in days. The process involves:

- drilling shot holes with a portable rotary rig;
- fracturing the rock with explosives;
- removing the rubble with a dragline or clam-shell scoop;
- trucking the rubble to a fill site.

Griffin (1976) describes the dredging of an entrance channel to Hawk channel in Upper Key Largo, Florida. Mean low water depths are typically 0.6 to 1.8m and the tidal fluctuations do not exceed 0.6m. Suspended sediment measurements were taken during the dredging operation and some of the results are shown in Table 8.

The measured values show that the use of a silt screen (so-called "diaper") had a considerable influence on the suspended sediment concentrations. The measurements taken on 18 May 1973 show surface concentrations of 66ppm inside the silt screen compared to 18ppm just outside. However, a leak in the silt screen allowed high concentrations to escape at one corner. This illustrates the possible gap between theoretical turbidity reduction methods and the practicalities of their implementation. Furthermore, Griffin suggests that the suspended sediment contained within the silt screen is too fine to settle permanently to the bed and will be eroded once the silt screen is removed, thus having a delayed contribution towards the long term resuspension associated with the dredging.

4.10 Resuspension by hopper or barge
Hopper overflow during dredging causes greater turbidity (see Tables 1 and 5), but can considerably reduce the dredging costs by enabling a higher density of spoil to be transported in the hopper to the disposal ground. A large number of studies have therefore been carried out in order to gain a better understanding of the environmental and economic consequences.

Eight barge overflow tests were carried out in Mobile Bay, Alabama and have been described in Clarke and Imsand (1990). The overflowing was carried out above the edge of a channel. The following table shows the maximum suspended concentrations (in mg/l) measured at various distances from the hopper, at the surface, near the bottom in the channel and within the shallower waters (less than 6m deep) outside the channel.

distance from barge	50m	125m	300m	2,500m
surface	50	60	49	38
near bottom	6,292	5,980	1,622	143
shallow waters	189	212	161	46

It was found that the majority of the overflow slurries descended rapidly to the bottom and were not carried far downstream in the upper or middle portion of the water column. In fact, the material appeared to accumulate in the deep portion of the navigation channel.

Several sets of measurements have been carried out by HAM dredging (Volbeda, 1983). Measurements carried out in Pepel Channel in Sierra Leone during overflow with a cross-channel current showed that the majority of the overflow material returned straight to the bottom, while the agitation effect by the cross-currents was 10 to 15% of the total overflow. Further studies in Fos (France), Bombay (India) and Penang (Malaysia) all displayed a negligible agitation effect.

4.11 Placement and discharge

Extensive measurements of resuspension associated with bottom placement of dredged material at offshore sites have been made. However, very few measurements associated with different aspects of placement and discharge have been reported.

4.11.1 Discharge into the water column

Discharges into the water column have been examined on a number of occasions particularly relating to the overflow from aggregate dredgers. Some recent measurements and estimates of release rates are described in further detail in Sections 5.7 and 5.8.

4.11.2 Temporary storage of material

No direct measurements of resuspension from temporary storage areas have been reported. However from recent trenching works on the South Coast it is understood that with construction during the summer months very little loss occurred.

4.11.3 Reclamation and nourishment

Often monitoring is undertaken during large scale reclamation and nourishment operations. However, this monitoring is usually commercially confident and remains unpublished. For example monitoring associated with the placement of material excavated from the Channel tunnel was undertaken by HR Wallingford (1989). Similarly monitoring associated with the construction of the Oresund link is forming a major element of ongoing studies.

4.11.4 Pipeline transport

No published data on resuspension associated with pipeline transport has been published. However, as stated in Section 2.8.4, any such losses are likely to be insignificant unless contaminated.

4.11.5 *Offshore placement at licensed disposal sites*

Sustar et al (1976) and Malherbe (1989) describe the disposal process through the bottom of a barge or hopper in the following terms:

- The convective descent phase. During this very rapid phase, the solid material settles in the form of a density current rather than as individual particles, so settling velocities calculated for individual particles do not apply.

- The second phase consists in a dynamic vertical collapse characterised by horizontal spreading upon contact with the bottom. Collapse is driven primarily by a pressure force and resisted by inertial and frictional forces. The material flattens out into a horizontal circular shape with a small vertical dimension. The circular shape can be stretched under the influence of currents and seabed slope.

A method which has been used to determine the behaviour of placed material is that of labelling the material in the hopper with radio-active tracers. Malherbe (1989) describes separate labelling of the sand and of the finer sediments carried in the hopper during experiments at the S1 disposal ground in the southern bight of the North Sea. These experiments demonstrated the two stage behaviour of placed material described above. The majority (95-99%) of the labelled sediments were initially caught in a vertical density current, until they were close to the bed, when the vertical density current changed into a horizontal one, influenced in direction by the tidal currents and the seabed slope. Within one day, about 70 to 80% of the material had disappeared and all the fine-grained material had been dispersed.

In a study at Long Island Sound (Gordon, 1974), it was found that close to 99% of the total material released from the barges was confined to a well-defined 3.5 to 4.5m thick layer close to the bed.

Radioactive tracer studies of spoil disposal have also been carried out in Thailand by HR Wallingford (1982). It was found that the placed material tended to spread into a long, narrow deposit along the axis of the direction of the tidal currents. There was no evidence of any short term mobility of the spoil after the initial deposition.

In the Carquinez site described by Sustar and Wakeman (1977), for water depths of 14m, concentrations of the order of thousands of mg/l were recorded in a well-defined layer about 2m thick close to the bottom.

Bokuniewicz et al (1978), summarising several field studies concluded that during the disposal of dredged material, significant concentrations of solids are found only in a well-defined bottom layer, and impacts in the upper water column are minimal (less than 1% of the material remains in the upper water column in most cases). The descending jet of material was described as acquiring the lateral speed of the currents in the receiving water, hence displacing the point of impact, but without dispersing or disrupting the jet.

Sustar et al (1976) describes the plume of resuspended material created in the upper water column during disposal as being caused by shear stresses generated by the interface between the descending material and the ambient water, by overflow just prior to release and by any disturbance due to propeller wash. These stresses result in turbulent eddies which are said to entrain between 1 and 5% of the total mass out of the main descending cloud and into suspension in the upper water column.

A number of studies aimed at estimating the proportion of placed material lost to the upper water column are quoted in USACE, 1986) and have been summarised in Table 9.

In the Long Island Sound study (Gordon, 1974), it was estimated that only about 1% of the total material released from the barges remained in suspension in the upper water column and was dispersed over a significant distance.

The USACE carried out several studies at separate sites in San Francisco Bay (Suatar and Wakeman, 1975). In the Carquinez site study, 1 to 5% of the total material was estimated to remain in the upper portion of the water column. However, this report suggests that the source of much of the surface plume was spillage/overflow from the hoppers as the vessel turned on its disposal runs and from vessel disturbance of the released jet.

Bokuniewicz et al (1978), in their summary of a number of field studies suggested that suspended sediment increases in the upper water column are generally caused by less than 1% of the placed material.

Norton et al (1984) concentrate on examining the dispersal of pollutants, but it does show measured suspended sediment concentrations taken over a large area containing a disposal site in Liverpool Bay. These show no marked spatial variations in suspended sediment concentration that could be correlated with disposal activities.

In the tests at the S1 dumping site in the North Sea described by Malherbe (1989), it was estimated that the natural calm weather background levels of suspended sediment could be doubled by the disposal activities and that the plume of resuspended material could be detected over approximately half a tidal cycle.

Land (1989) showed that the bottom-surge created by placement of dredged marine mud from a trailer dredger had a density in the region of 1,150kg/m^3 and came to a halt on a level seabed at distances of between 120m and 175m from the impact point. It was suggested that the density was largely the result of erosion and entrainment of the soft sea bed material in the impact zone. The density of the plume of descending material was estimated to be only marginally higher than that of seawater. The proportion of material released from the trailer that was considered to be resuspended into the water column was estimated to be less than 5%.

5 *Recent field studies*

5.1 Introduction

The purpose of this chapter is to describe in detail some of the more recent monitoring programmes that have been undertaken in recent years. In particular further details of the studies described in Sections 5.3 and 5.6 are provided in the accompanying volume of Appendices to this report.

All the studies described in this Chapter have made use of acoustic backscatter techniques. Aspects of some of the studies remain commercially confidential.

5.2 Plume Measurement System of the USACE Dredging Research Programme

In 1988, the US Army Corps of Engineers (USACE) established the Dredging Research Program (DRP) as a seven year interlaboratory research effort to develop technologies to reduce the cost of dredging. Two major field experiments have been undertaken by the USACE using RDI Acoustic Doppler Current Profilers (ADCP) to determine suspended solids concentrations. These experiments represent the first use of the instrument in this manner and have been carried out as part of the PLUmes MEasurement System (PLUMES) under development by the DRP Technical Area One.

The first study (USACE, 1991), the Mobile, Alabama, field data collection project, had the following objectives:

a) to collect comprehensive data on sediment dynamics for verifying and improving numerical simulation models of the short term fate (minutes to hours after release) of dredged material placed in open water;

b) to investigate and refine sediment plume monitoring procedures;

c) to evaluate acoustic instrumentation for measuring sediment plume dynamics, and

d) to collect field data on coastal bottom boundary layer processes.

USACE (1991) presents the data for meeting the first three objectives and provides a good data base for comparison with numerical simulations. It also contains information for conducting similar field exercises. Simultaneous measurement of backscatter intensity from the suspended sediments by two independent and different acoustic systems, made together with water sampling, allowed intercomparison of the acoustic instruments and provides a first step towards field calibration of the ADCP technique. The recorded plume dynamics include the initial descent, bottom surge, generation of internal waves and evolution of the plume under different conditions.

The second study (USACE, 1992) was undertaken to monitor the movement of dredged material placed with a single-point pipeline discharge. The placement was in an area adjacent to a major oyster seeding ground in the Chesapeake Bay Estuary, an area of environmental concern. The programme of monitoring built on the work undertaken in the study described above. The objectives of the study were to:

a) to collect sediment concentration and current data to determine the potential for dredged material to reach the oyster seeding ground, and

b) to continue development of the PLUMES monitoring procedures for dredged plumes.

The field measurements included two days of background monitoring prior to dredging operations, and three days of monitoring during dredging operations.

The background data showed that during the peak ebb and flood phases bottom sediment was resuspended into the water column. During the dredging acoustic monitoring did not detect dredged material migrating onto the oyster grounds, and water samples showed no alteration of suspended sediment concentration in these areas.

5.3 Channel deepening to Londonderry, Lough Foyle

In 1992 HR Wallingford were commissioned by Londonderry Port Harbour Commissioners through the Anthony D Bates Partnership to undertake long term monitoring of suspended solid concentrations at three locations in the vicinity of dredging works associated with deepening of the navigation channel to Londonderry. An upstream site on a disused jetty was selected together with a seaward site on one of the light towers adjacent to the navigation channel. A further site was selected alongside a cooling water inlet for the nearby power station.

Two Phox transmissometers were installed at each of the three sites and a local fisherman was employed to clean and check the installations periodically and report back to HR on their operation every three days. Service visits by HR personnel were made every three weeks when routine calibration and downloading of the loggers was undertaken.

The monitoring was continued throughout the period of dredging and for a further period of one month after completion of the dredging. The long term monitoring was able to demonstrate that there were no significant increases in suspended solids concentrations in the vicinity of the cooling water intake (HR Wallingford, 1993).

A strong correlation between tidal range and suspended sediment concentration was observed. Analysis of the data collected was unable to isolate any correlation in suspended solid concentration with freshwater flow, wind/wave action or dredging activity.

Suspended sediment concentrations at the three sites varied between 50mg/l and 700mg/l on spring tides and 10mg/l to 50mg/l on neap tides. The mean tidal concentration varied between 20mg/l and 350mg/l on the flood tide and 20mg/l and 150mg/l on the ebb tide over the measurement period.

A further issue associated with the work was the question as to whether material resuspended during the deepening of the approach channel was confined to the channel or whether it spilled out of the channel into the shallow waters either side of the channel. Analysis of the data at the seaward station adjacent to the channel was unable to identify any increases in suspended sediment concentration coincident with passage of the trailer dredger. However, the instrument was deployed so as to sample at ten minute intervals, so identification of very short term increases of suspended sediment concentration might not have been possible.

To further investigate the resuspension from the dredged approach channel HR were commissioned to use a combined suite of instruments to visualise and quantify the increases in suspended sediment concentration associated with the different dredging plant being used at the site. The work was undertaken in conjunction with Wimpey Environmental who supplied and operated the RDI ADCP and Westminster Dredging Ltd who were the

Dredging Contractors. During the field measurements staff from Hydronamic, the research division of Boskalis were on site in Ireland.

The work is described in detail in HR Wallingford (1993). The Appendix from that report which describes the plume monitoring is reproduced here as Appendix 1. A summary of the results of the monitoring has been presented in Teal et al (1993) and has also been further discussed by Bates (1996).

An RDI 1200kHz Narrow Band ADCP was installed to the port side of Westminster Dredging's vessel "Plover" and used to follow the evolution and fate of sediment plumes resuspended by various forms of dredging activity being undertaken. Transmissometers, remotely triggered water samples and pumped water samples were used to quantify the suspended sediment concentrations within the plume. The ADCP instrument was used to identify the location of the plume. No attempt was made to calibrate the backscatter signal from the ADCP in terms of suspended sediment concentrations. This strategy was adopted for a number of technical reasons. The main reason being that, whilst a number of successful attempts have been made to quantify suspended sediment concentrations from backscatter signal strength with RDI instruments, none at the time of the Londonderry measurements had demonstrated a calibration in such a dynamic situation in the immediate vicinity of dredging activities.

The dredging plant that was successfully monitored were:

- the trailer dredger Cornelia
- the trailer dredger WD Medway
- the grab dredger WD Dredgewell
- the plough dredger Norma

Maximum concentrations of 3,200mg/l were observed close to the bed behind the Cornelia. Near surface measurements at this stage indicated concentrations of about 500mg/l. Whilst the Cornelia was dredging in the navigation channel it was possible to detect a plume, apparently emanating from the bed in the area where the draghead was. The plume was about 20m wide and gave a stronger backscatter near the bed. The plume was found to encroach onto the side slope but not to spill up the slope out of the navigation channel into the shallower water adjacent to the channel. After 20 minutes it was no longer possible to detect the passage of the dredger or the plume generated by the dredger with the ADCP or the other water sampling equipment.

Experiments were carried out whilst monitoring the WD Medway to investigate the effects of the passage of the vessel when it was not dredging. It was found that a strong plume was observed in the backscatter record that was confined to about the top 3m of the water column. This was attributed to aeration. Similar results for the WD Medway were determined as for the Cornelia, namely that the plumes generated by the dredging decayed to close to background over a period of about 20 minutes.

Monitoring was carried out in the vicinity of the WD Dredgewell (Plate 2). Measurements about 10m from the point of dredging demonstrated peak concentrations of 3,500mg/l close to the bed and 250mg/l at the surface, which was close to background). At a distance of 150m downstream from the dredger it was no longer possible to identify the plume generated by the dredging. It was noted that a complete cycle of operation for the grab took about one minute to complete and it was possible to clearly identify this periodicity at a short distance from the dredger in the record of backscatter and suspended solids concentrations measured with the transmissometer.

A number of ADCP profiles were carried out around the plough Norma (Plate 11). It was very difficult to interpret the backscatter from these profiles. This was considered to be due to the turbulence and aeration associated with the plough operation. Water sampling was unable to detect any significant resuspension in the vicinity of the ploughing. For some of the time Norma was working in sandy areas of the channel which, if resuspended, would be less remain in the water column for significantly less time than silt.

5.4 Agitation dredging at Sheerness

Further opportune measurements were made by Wimpey Environmental and HR Wallingford in July 1993 in conjunction with the Port of Sheerness about the Agem One whilst carrying out capital dredging at Sheerness (Teal et al, 1993). The operation of the Agem One is fairly simple, material is sucked up from the bed, passed through a series of disaggregators on deck, aerated and then discharged into the surface waters (Plate 8). The aim is that the aerated mixture will remain as a near surface plume and be advected away by the tidal currents at the site.

An RDI 600kHz Broadband Acoustic Doppler Current Profiler (BBADCP) was mounted on the side of the survey vessel MV "Medway Surveyor". The ADCP was configured to collect measurements from 1.8m below surface to 1m above seabed at 0.5m intervals. Signals were transmitted at 9 hundredths of a second intervals and averaged over 4 seconds.

Measurements were collected during the ebb tides of 13 and 14 July 1993 since dredging operations were limited to the ebb tides only. In addition to the measurements, transmissometer readings and surface water samples were collected during the ebb tide of 14 July 1993. Transmissometer measurements were collected using a Partech IR40C transmissometer. Water samples were collected using a Cassela Water Sampler.

ADCP measurements would normally be made whilst the vessel steamed across the dredged plume at intervals along its length, such that the limits of the plume both laterally and longitudinally were defined. However, in this case, the dredger was positioned alongside the berth, such that it was not possible to conduct transects across the plume. Therefore, transects were collected longitudinally along the plume and in zig-zags to define its spatial distribution.

ADCP measurements, transmissometer readings and water samples were collected whilst the vessel held station within the plume. Instantaneous transmissometer readings were collected at 0.5m intervals through the depth of the plume. The transmissometer was positioned to coincide as closely as possible with one of the beams of the ADCP. Transmissometer readings were recorded to the nearest 5 seconds. Profiles were collected immediately downstream of the dredger, 150m downstream of the dredger and 300m downstream of the dredger in order to obtain comparison data over a range of conditions.

Due to the proximity of the plume to the jetties from where material was being dredged lateral transects were limited so longitudinal transects were run to establish the extent of the plume.

The BBADCP provided good resolution of the plume however, it was not possible to differentiate between backscatter from air bubbles and the material resuspended. It appeared possible to identify the rising air bubbles with distance from the dredger. Initially the solids/water/air mixture descends as a density plume. The solids are then mixed into the water column and advected. Air bubbles however, begin to rise.

5.5 Construction of pipeline trench, South Coast of England

Further work was undertaken in conjunction with Boskalis Westminster during the summer of 1994 whilst a pipeline trench was being constructed on the south coast of England. The operation involved dredging through clay and chalk using the cutter suction dredger Orion. Material was pumped from the Orion to the spray pontoon S'Gravenhage at a rate of about 400kg/s. From there it was diffused to the bed to form a temporary storage mound on the sea bed some 200m to the east. After construction of the trench and laying of the outfall the dredging plant changed positions so that the temporarily stored material was replaced over the outfall pipe in the trench. It is understood that it was not necessary to obtain any additional backfill material for the operation. Most of the temporarily placed material was thus able to be reused.

The monitoring that was undertaken involved the use of a similar suite of instruments as for the Londonderry monitoring. Staff from Hydronamic once again participated in the monitoring. Measurements were made around both the cutter suction dredger and the spray pontoon whilst dredging through chalk.

Although the plumes of resuspended material released during the dredging were highly visible because of the chalk content, apart from very close to the operation, the concentrations of resuspended material were observed to be generally less than 30mg/l compared to a background concentration of 10mg/l. These figures indicated a flux of material from the cutting operation of less than 0.5% of the production rate. Resuspension from the spray pontoon during the period of measurement was considered to be about ten times greater than that from the cutter. The detailed results of these measurements remain confidential to Boskalis Westminster and are reported in HR Wallingford (1994).

This brief description of the study has been provided in this report to demonstrate the application of the combined water sampling and acoustic technique to other dredging plant.

5.6 Maintenance dredging on the River Tees

The opportunity arose in the summer of 1994 for HR to undertake a series of controlled experiments during maintenance dredging of the River Tees. The Tees and Hartlepool Port Authority made available their dredger the 'Hoertenesse' and a survey vessel. Monitoring using ADCP and standard water sampling methods was undertaken whilst the dredger was working in both sandy and muddy reaches of the estuary.

Following the field measurements detailed analysis of the ADCP measurements was undertaken (HR Wallingford, 1995a) to estimate sediment fluxes through the monitored section of the estuary. Following this analysis a Gaussian diffusion model which had been used for dispersion assessment studies was applied to determine whether the model could represent the observed fluxes (Gravelli, 1995). A summary of Gravelli's report has been included as Appendix 2. The study clearly showed the ability of the simple Gaussian diffusion model to represent the observed fluxes of material when a variable input source from the moving dredger was used. A source of between 20 to 30kg/s of mud was applied when the dredger was trailing and overflowing in the muddy reaches of the estuary.

5.7 Measurements of resuspension rates during UK aggregate dredging operations

HR Wallingford have undertaken numerous assessments of the dispersion of fine material resuspended during marine aggregate production. The source terms for the dispersion studies come from an analysis of bed material type and discussions with the dredger operator as to the likely operating scenario. In recent years a number of dredging contractors have undertaken measurements of overflow during the dredging operations. As part of this study HR Wallingford supported Coastline Surveys in undertaking further spillway measurements.

A further extension to this co-operation between HR Wallingford, Coastline Surveys and the Dredging Contractors was a dedicated field survey in the English Channel using ADCP and water sampling techniques to examine suspended solids concentrations in the plumes of material resuspended during dredging as a means of verifying and refining the predictive techniques adopted in earlier and future assessments. The results of this study are described in HR Wallingford (1996b).

Some of the results of the studies described above have been presented in Hitchcock and Dearnaley (1995). The results presented in the remainder of this section have been taken from that paper.

Spillway measurements made by the dredging contractors during the loading of an all-in cargo showed that some 11kg total dry solids per m^3 of overspill would pass over the spillways, with about 50% being of silt/clay particle size (<0.063mm). During the loading a total mass equivalent to 6% of the cargo was released back into the water column. The loading period was about 2.5 hours.

Preliminary results based on the analysis of measurements of a number of screened cargoes demonstrated the impact of screening. These showed that some 35kg total dry solids per m^3 of overspill was released to the water column, with about 40% being of silt/clay particle size. However, it was estimated that the screening process released about 500kg total dry solids per m^3 via the reject shute. Of this approximately 1% was of silt/clay particle size. During the loading and screening a total mass equivalent to about twice that of the total cargo was estimated to be released back into the water column. The loading period was about 5 hours.

Measurements using ADCP and water sampling techniques demonstrated that whilst it was possible to track a plume for up to 3.5km from the dredging area 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 and supported the theory that density and momentum differences between the overflow and water column during the first few minutes of resuspension may be the most important factor controlling short term resuspension of the dredged material.

It should be noted that the ADCP monitoring was carried out at a licence area which contains between two and three times the silt content of other licensed areas.

A number of recommendations have been made associated with this study and these will be investigated through forthcoming studies funded by the Dredging Contractors and the Department of the Environment.

5.8 Dredging activities in Hong Kong

Hong Kong is engaged in a major programme of construction which includes reclamation. This has resulted in a need for large quantities of marine sand for fill. In fact it is estimated that about 210 million tonnes has been utilised in this way since 1990 (Whiteside et al, 1995). There has been an increasing requirement in Hong Kong to undertake Environmental Impact Assessments associated with marine mining and, 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. HR has multilayer flow models of Hong Kong waters and employs these as the advective force for examining the fate of plumes of fine material resuspended by dredging.

Specific field measurements have been carried out to examine the resuspension during dredging. These have recently been reported by Whiteside et al (1995). In this paper the 90 minute loading of the 8,225 m^3 trailer dredger HAM 310 has been presented. 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). With these figures it can be seen that approximately 80% of the material dredged was retained and that the average rate of overflow 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.

Recently, through field measurements using ADCP techniques (Land et al, 1994), it has become apparent that the processes occurring during the first few minutes of the plume generation 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. (Whiteside et al (1995). HR Wallingford (1995b) have investigated the processes that may be occurring during this initial phase of the development of a plume. The unpublished HR work has been summarised by Whiteside et al (1995) and they have 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 much of the resuspended fine material may settle to the bed with settling velocities in excess of that of a natural muddy suspension.

5.9 Monitoring associated with the Oresund Link

The Oresund Link connecting Copenhagen with Malmo crosses the environmentally sensitive Oresund. The construction of the link involves some major dredging and land reclamation (a total of 7 million cubic metres is estimated (Jensen et al 1995)). The background suspended solids concentration in Oresund is low, generally 1 to 3 mg/l, partly because there is limited supply of fine grained material to the area and partly due to the practice of intensive sewage treatment of Sweden and Norway (Jensen et al, 1995). A restriction has been placed on all dredging operations in the Oresund project. There is an overall limit of 5% spill with conventional dredging equipment set 200m beyond the limits of the dredging area. Additionally daily and weekly restrictions have been placed on maximum spillage rates along the alignment of the link. A spill monitoring programme based on numerical modelling of the sediment spill has been proposed. The programme has been implemented by the Danish Hydraulic Institute (DHI).

The implementation of the monitoring programme has required the use of ADCP determined suspended sediment concentrations along a number of profiles to determine sediment fluxes. This data will be fully checked against laboratory analysis and optical monitoring. Weiergang (1995) describes in some detail the analysis method that has been adopted for determining suspended sediment concentrations and fluxes from the acoustic backscatter signals. The paper considers in detail the non-linear effects between the scattering cross section of the suspended sediment particles and the backscatter strength. The analysis undertaken enables the possible uncertainties in the estimates of concentrations due to these effects to be evaluated. The paper concludes that the uncertainties are insignificant and that it seems that the process of estimating concentrations from backscatter strength using the Broad Band 1200 kHz ADCP is fairly precise for the type of suspended sediment in question. In the paper of Jensen et al (1995), which describes the use of the measured flux data within the overall numerical modelling of the sediment spill, an estimated uncertainty of 25% in the measured sediment flux is quoted. In Weiergang's paper uncertainty of 3 to 16% is quoted for the range of concentrations between 3 and 500mg/l.

6 The long term impact of dredging activities on suspended sediment concentrations

6.1 Introduction

As discussed in the Chapter 1 dredging activities can generate both immediate and long term increases in suspended solids concentrations. This study has addressed the methods by which various researchers have attempted to quantify the immediate and short term increases in suspended solids concentrations associated with a variety of different dredging activities. In this chapter consideration is given to some of the longer term consequences of dredging activity on suspended solids concentrations.

When considering these longer term effects, it is even more important than with the immediate resuspension mechanisms that the increases in suspended sediment concentration are considered in the context of the variability of the suspended sediment concentrations. This variability is associated with natural phenomena and other human activities.

In this chapter the longer term effects are discussed under the sub headings of:

i) Impacts associated with capital dredging;
ii) Impacts common to all dredging;
iii) Agitation dredging, and
iv) Long term impacts associated with offshore placement.

It should be noted that there is some commonality between items i), ii) and iii) under this breakdown.

6.2 Impacts associated with capital dredging

6.2.1 Changes to hydrodynamics

The dredging may influence the hydrodynamics in an area to such an extent that areas of the adjacent sea bed which were previously stable begin to erode releasing material into the water column during periods of high waves and currents. For example deepening a navigation channel may lead to increased wave activity adjacent to the channel resulting in increased erosion of the sea bed. Conversely a deepened navigation channel may tend to train tidal and fluvial flows leading to a reduction in currents elsewhere and a tendency for deposition creating new areas of soft deposits which may be eroded during storm conditions. Deepening of a harbour area may actually result in the creation of a sediment trap leading to a reduction in the amount of suspended sediment in the vicinity of the harbour.

6.2.2 Slumping

The capital dredging may initially create areas of the sea bed which are not initially stable under the prevailing hydrodynamic regime. Under some conditions slumping of the sea bed into the dredged area may occur. Such slumping is common with the construction or deepening of navigation channels, where often it is not possible to establish stable channel side slopes during the initial capital dredge which will become stable in the long term. Other slumping that is common is from areas below open piled berths into the adjacent dredged berth.

6.2.3 Increased requirement for maintenance

In cases where the capital dredging is being undertaken for purposes of improved navigation and development of port facilities the dredging is, more often than not, likely to lead to an increasing requirement for maintenance dredging. Which in turn will lead to an increase in the long term release of bed material into the water column.

6.2.4 Increases in resuspension and erosion by shipping

It has been noted in various preceding sections that vessel movements can resuspend bed material. Improvements in navigation channels and larger berth areas result from economic activity. This economic activity will be in the form of either more vessels transitting a channel or larger vessels or both. Whilst the dredging activity is not responsible for this increased vessel activity the effect of the increased traffic may lead to greater resuspension of bed material and erosion of bank material. Both effects can lead to increased levels of suspended sediment concentrations.

6.3 Impacts common to all types of dredging

6.3.1 Changes to the surface of the bed

All forms of dredging result in a disturbance of the sea bed. This disturbance will in most cases be in the form of an increased roughness of the sea bed by development of certain small scale bed features. These include the furrows left by the passage of a drag head or the debris thrown aside by the rotation of a cutter head. Whilst dredging plant and instrumentation is continually being developed to improve the efficiency of the removal of material from the sea bed these local effects will still occur. In many cases smoothing of the bed is subsequently undertaken using a plough.

However, it should be noted that the net effect of some capital dredging projects, such as channel deepening can remove irregularities in the sea bed effectively reducing friction.

6.3.2 Fluidisation of the sea bed

When dredging intensively in silt over a prolonged period one of the often reported effects is fluidisation of the bed. This produces a blanketing effect smothering near bed features. After the dredging has been completed the fluidised layer may persist for some time. Resuspension of material from this layer by natural processes may be achieved at greater levels than from the sea bed prior to dredging.

It should be noted that very little is known about the properties of such fluidised layers.

6.4 Agitation dredging

Agitation dredging in the UK is generally only employed for the purposes of maintenance. However, the case described in Section 5.4 is one where the agitation method was used for capital dredging. The methods include sidecasting from trailer suction dredgers, ploughing and harrowing from small tug like vessels, water injection techniques and surface dispersion by suction dredgers.

Agitation dredging techniques employ some mechanical agitation of the bed material leading to the generation of bed material in a form whereby natural forces will transport the material away from the dredging site. The physics of the processes involved are often poorly understood and little monitoring has been openly reported. However, it can be observed that since all material removed from the site of interest is transported and dispersed in a low density form there is a strong likelihood of subsequent resuspension of some of this material in the period following completion of the dredging operation. In some cases, the agitation dredging undertaken is almost continual, such as the maintenance dredging at the Port of Bristol (Plate 7), and isolating immediate impacts from longer term phenomena is not possible.

Agitation dredging usually only involves the removal of small quantities from a relatively small area. In the past the operation has not required the identification of the fate of the dredged material. However, at the time of writing water injection dredging and ploughing are the only forms of agitation dredging that do not require a MAFF licence.

Questions to be raised on agitation dredging in the light of resuspension and long term impact include:

- where will the material settle down?
- will it be harmful there?
- can this process be controlled?

6.5 Long term impacts associated with placement

6.5.1 Offshore disposal

The processes of removal, transport and placement of material originating from the bed inevitably lead to a change in the physical properties of the material by the time it has been placed at its selected location - be that an offshore disposal site or an intertidal salt marsh regeneration scheme. Consequently, if the hydrodynamic regimes were similar at the two locations, there is an increased potential for the material to be resuspended from the placement site, compared to the situation if material had been transported in an undisturbed state between the two locations.

In some cases disposal sites are referred to as non-dispersive and material that is placed there will be retained. However, in the UK there are very few such sites. More often a site will be non-dispersive for a particular type of material that is placed there, such a gravels or boulder clay. However, the majority of UK disposal sites are dispersive for the maintenance material that is placed there. It can be argued that long term resuspension of material from placement sites is not a result of the dredging but a result of the choice of the location. However, some dredging techniques will lead to a greater change in the physical properties of the dredged material than others. For example grab dredged material will tend to retain more structure and strength than trailer dredged material when placed at the same offshore site.

If a site is known to be dispersive it can be inferred that material placed there must, in the long term, be resuspended and transported away from the site. In the case of disposal of silt this must imply an increase in suspended sediment concentrations at the site. In the case of the offshore disposal of sands, which is less common, increases in suspended or bed load concentrations will depend upon whether the water column approaching the disposal site is carrying a saturated sediment load or not. However, in most cases it can be argued that concentrations in the vicinity of an offshore disposal site must be increased above background levels by the disposal at the site. Little is known about the variability of suspended sediment concentrations in offshore locations, especially during storm conditions when most of the resuspension must take place. Quantification of this increase, involving the deployment of MAFF DFR Minipods (see Section 3.7.4) is the subject of an ongoing MAFF DFR funded research project at HR. During the course of the study bed frames with instruments to measure the variability of suspended sediment concentrations and hydrodynamic conditions have been deployed during the winter months at a number of UK offshore disposal sites.

As a final remark on the importance of the resuspension of material from offshore disposal sites, it should be noted that many of these sites in UK waters have been in use for more than a century. The continued disposal of dredged material at these sites forms an important part of the sediment regime in the area. Changes to the coastline in the area of these sites may be associated with increased mobile suspended sediment accumulating on the shoreline, such behaviour has been postulated for the Wirral in the UK.

6.5.2 Monitoring placement at offshore sites

The primary dumping efficiency is measured by comparing the differential volumes of material on the dumping ground to the dumped volumes of dredged material. Malherbe (1989) calculates the primary dumping efficiency for the S1 dumping ground in the southern bight of the North Sea for each year between 1962 and 1989. This was found to vary between 20 and 40%. Vibrocoring of the sea bed in the dumping ground revealed a sediment consisting of almost pure sand. It was concluded in this report that during the dumping process practically all the fine sediment (finer than 0.063mm) was washed out and constituted the major part of the dumping losses. The dumping ground was therefore covered with sandy sediments, while outside the dumping area, the soil was enriched with muddy sediments.

The work done by Tavolaro (1982) in the New York Bight consisted of monitoring an exceptionally large number of dumping operations resulting in the disposal of over 600,000m^3 of dredged spoil. By carrying out a volumetric comparison of pre disposal and post disposal site bathymetry, he concluded that 96.3% of the material settled within the proximity of the disposal site.

Experiments have been carried out during dredging of the approach channel to Buenos Aires in the Rio de la Plata in order to determine the most effective method of disposing of the dredged spoil without it returning to the channel (Waters and Thorn, 1975). Four tests were carried out in order to compare the effectiveness of hopper overflowing, dumping through hopper doors outside the channel, and sidecasting at various distances from the channel. Of these, the bottom dumping was found to be the most efficient, and measurements showed that 93% of the spoil came to rest on the bed within the area of the disposal site.

The Farallon site described by Sustar and Wakeman (1977) showed that even in 67m of water, most of the material could be subsequently identified on the bottom and the spread was limited to an area 150m × 300m.

In the Long Island Sound study (Gordon, 1974), The author concluded that 80% of the material was deposited within 30m of the impact point and 90% within 120m.

The low proportion of material remaining on the bed quoted by Malherbe (1989), 20-40%, shows a marked contrast with the values of around 90% or even higher quoted for the New York Bight, for the Rio de la Plata, for the Farallon site and for the Long Island Sound study. The higher values do however appear to fit in better with the values of 1 to 5% quoted in the previous section for the proportion of material lost to the upper water column.

6.5.3 Backfilling borrow pits

The extensive programme of construction in Hong Kong has lead to the development of many marine borrow pits. Sand is won from the pits by first removing layers of muddy material and placing this either in already worked out pits or offshore disposal sites. After the sand has been removed by normal means (see Section 5.8) the pit is ready for backfilling. Some of the pits in Hong Kong have been backfilled with contaminated material which has then been capped. Other pits have been backfilled with clean material generated from the development of other borrow areas. HR Wallingford have undertaken numerous studies associated with the potential for resuspension of material from the backfilled pits and also with the impact of dispersion of fine sediments arising from the extraction and backfilling processes. A general summary of the studies involved in assessing the backfill level within the pits is provided in Premchitt et al (1993).

In the case of contaminated dredged material, it is particularly important to minimise any spreading of the material during dumping. In the River Scheldt, such a problem was overcome by realising a pit for receiving the spoil and then by filling the pit with contaminated sludge by means of an underwater diffusor (van Wijck et al, 1991 and van Hoof et al, 1991). A monitoring programme revealed that the increase in turbidity during dumping was limited to the direct surroundings, below the diffusor and that any spreading of silt outside the area could not be detected.

A further method for reducing resuspension during dumping which has been suggested, is to perform the discharging operation within the enclosure of a large silt screen. No records have been found, however, of the implementation of this method.

6.5.4 Beneficial use of dredged material

The beneficial use of dredged material is presently an area of much interest. MAFF now require as part of the disposal licence application procedure demonstration that possible beneficial uses for the dredged material have been examined.

Burt et al (1996) have just completed a major review of the options for the beneficial use of dredged material and monitoring of such schemes.

Resuspension from material used in a beneficial manner needs to be considered as part of the environmental impact assessment of such schemes. Some schemes are proposed to act as sources of resuspension. Possibly feeding salt marshes and inter-tidal areas at the same time as reducing wave energy in these locations. Little is known of the behaviour of dredged material used under such circumstances and rapid resuspension should be expected for this type of application.

7 Uncertainties and assumptions to be made in modelling the resuspension of material associated with dredging activity

7.1 Introduction

Numerous techniques for modelling the resuspension, transport and subsequent settlement of dredged material are available. It is not the purpose in this chapter to review the various numerical models that are available. The reader is referred to recent guidelines produced by HR Wallingford for that purpose (Cooper, 1996).

The purpose of this chapter is to demonstrate where some of the uncertainties lie in parameterising either the properties of the dredged material or the processes whereby the material is introduced into the water column. Given the level of uncertainty in sediment transport predictions and the additional uncertainties associated with the dredging process it is usually most appropriate to undertake studies where a series of sensitivity tests can be achieved.

The main assumptions/parameterisation that usually needs to be made concern the following:

i) the release rate of the material from the dredging activity;

ii) the initial mixing of the released material;

iii) the settling velocity of the resuspended material;

iv) the erosion properties of placed material;

v) the consolidation properties of placed material;

vi) the fluidisation of the material;

vii) the hydrodynamic conditions at the site of interest;

The following sections only refer to muddy material. In cases where the dredged material is pure sand the reader is referred to such documents as the Manual of Marine Sands (Soulsby, 1994).

7.2 Release rate of material from the dredging activity

Determination of the release rate of material from a particular dredging activity is generally difficult and subject to inaccuracies. For example, establishing the proportion of discharge through the reject chute compared to that over the deck level spillways is both a practical and theoretical problem. However, where such measurements have been made they have lead to the deduction that the quantity of material released by the dredger into the water column may not be the most appropriate source term for subsequent dispersion studies owing to the importance of rapid removal of released material from the water column by density flows to the bed (Whiteside et al, 1995 and HR Wallingford, 1996b).

Establishing the release rate from the dredging operation may not be a necessary element of studies associated with the short term impact of plumes of material resuspended by the dredging. However, in order to fully understand the processes associated with the dredging operation it is necessary to consider all stages of the resuspension process. If it is required to consider the longer term impacts of the operation, quantification of the absolute amounts of bed material disturbed by the dredging may be important. If material that subsequently returns to the seabed in the form of a density flow is more likely to be resuspended by natural processes than the undisturbed bed then again quantification of the relevant processes is important.

7.3 Initial mixing of released material

In previous sections mention has been made of the processes whereby density differences between the released water/solids mixture from the dredger and the momentum of the released material generate a density flow of released material towards the bed. Such flows have been shown to reduce the initial impact of resuspension assuming that when the flow impacts on the bed material is not resuspended immediately into the water column.

Studies by HR Wallingford (1995b) demonstrated the sensitivity of the release to density difference, initial momentum, angle of input, tidal current strength and water depth. The studies showed that in all cases the density flow effect dominated the initial stages of the resuspension process. The effect should account for the observed vertical distribution of resuspended sediment. Furthermore it is evident that, using the assumption of uniform discharge, a single discharge beneath the hull compared to discharge through a number of deck level spillways was advantageous in terms of enabling the released material to rapidly impact on the sea bed.

The greater the production rate the higher the momentum of the released material. For example, material periodically released into the water column by a grab dredger may be released at a sufficiently low rate that most of the material is resuspended into the water column to be subsequently advected away from the dredging site.

If material does impact on the sea bed how does it subsequently behave? The process is fundamentally no different to the impact of material on the sea bed during placement at a disposal site. With muddy material the generation and subsequent movement of layers of fluid mud is likely to be important. Is this process related to the observation that when intensive dredging in muddy areas occurs the presence of fluid mud is often reported?

In the absence of full understanding of the initial processes associated with plume formation, it is usually inappropriate to concentrate on sophisticated representation of the subsequent advection of the plume of fine material when in fact it is not known what quantity of material is present in the plume.

In the absence of full knowledge of all the processes occurring, a practical approach can be to make an assumption concerning the proportion of fine material available within the water column to be advected by tidal currents. The assumption must be that this proportion of the material resuspended is no longer subject to vertical movement because of density and initial momentum. In this case a new source term is derived. This could be described as the source of resuspended material available for short term dispersion. When measurements of suspended sediment concentration are made in the general vicinity of a dredging operation, say 100 to 200m, the concentrations measured might be considered to be representative of this source term.

7.4 Settling velocity of resuspended material

Naturally occurring suspensions of cohesive material (concentrations in the range 0 to 2,000mg/l) have been observed to have settling rates in the range 0.1 to 2mm/s. Some of the larger aggregates of particles (flocs) in suspension may have significantly higher settling rates whilst the majority of particles (but only a small proportion of the mass) may in fact have settling rates which are orders of magnitude less than 0.1mm/s.

Muddy material that is resuspended by dredging may have different properties to a naturally occurring suspension. There is a possibility of a proportion of the suspension being coarse grains with a high settling rate. The particles may be in large aggregates or the muddy material may adhere to coarser material (particularly in the case of marine mining of coarse sediments). It is also possible that the settling properties of the resuspended fine material change with time.

Direct measurement of the settling velocity of fine material resuspended by dredging activities will be undertaken in the course of future DoE funded research.

7.5 Erosion properties of placed material

Dredged material that ends up on the sea bed, either by placement or as a result of losses during the removal process may be resuspended by the hydrodynamic regime at the site. This may happen almost instantaneously, for example in the case of generation of fluid mud in an area subject to high tidal currents. Alternatively resuspension may not occur until storm conditions occur at the site. In some locations a permanent deposit may be formed.

In cases where this process of resuspension may be important, assumptions have to be made concerning the properties of the material on the bed. Measurement of insitu, sub-tidal erosion properties of any material is a developing field. At present evidence from laboratory experiments on what are often non-representative material types has to be employed. Again this is a major area of uncertainty which should not be overlooked when considering the range of sensitivity tests that should accompany any numerical predictions of the resuspension of dredged material from the sea bed.

The MAFF funded project that HR Wallingford have just commenced (see also Section 6.5.1) is aimed at quantifying the erosion properties of some types of dredged material so that they can be better represented in numerical models.

7.6 Consolidation of placed material

A further process that may be of importance in some situations is the rate of consolidation of dredged material on the sea bed. If material consolidates rapidly then resuspension may be reduced. Alternatively if the material does not consolidate it could be considered as representing a potential source of resuspension over a long time period. Based on historical evidence it is considered that at most of the UK offshore disposal sites consolidation is unlikely to be a major issue. However, when considering some of the possible beneficial uses of dredged material consolidation rates may become critical. A question arises as to whether the method of dredging impacts on the manner in which the material may subsequently behave.

Few observations of consolidation rates in the field are available. However, the backfilling of the borrow pits in Hong Kong has demonstrated clearly the fact that increasing depth of placed material reduces the consolidation rate.

7.7 Fluidisation of bed material

Fluidisation of the bed has been mentioned within this report under a number of different areas. Where fluid mud exists it can represent the most significant transport mechanism, hence the effectiveness of water injection dredging in removing muddy material from areas of the sea bed. The processes whereby fluid mud is generated are poorly understood and there are almost no field measurements available to provide further insight. The generation of fluid mud by the action of the draghead and arm during maintenance dredging of silt may also be important.

In general terms it is probably more important to understand the significance of fluid mud formation associated with impact of plumes of dense material on the bed than it is to examine the water injection dredging system in detail. This is because the majority of dredging of silt in the UK is by trailer dredger.

At present any assumptions made for the purposes of numerical modelling of fluid mud generation and movement associated with dredging operations can only be based on scanty information. Again appropriate sensitivity tests should accompany predictive model results.

7.8 Hydrodynamic conditions at the site of interest

Compared to numerical modelling of sediment transport the prediction of hydrodynamic conditions at a particular site can be undertaken with a significant degree of confidence. However, it is possible to waste resources by inappropriately representing the hydrodynamic regime prior to undertaking sediment transport predictions, if the major uncertainties lie in a number of fundamental assumptions concerning the physical processes and properties of the material involved.

This is why the process adopted by HR for most assessments of the dispersion of fine material resuspended by dredging uses a simplistic Gaussian diffusion model and a schematised representation of the tidal currents.

If initial modelling demonstrates a significant impact it is possible to adopt more sophisticated approaches as required. However, it should be noted that fundamentally all the modelling studies presently require good field data associated with some of the processes described in this chapter before they can be applied with confidence. The methodology evolving in Hong Kong (Whiteside et al, 1995) provides a good example of how the requirement for demonstrating the impact of dredging operations has rapidly improved the understanding of some aspects of the resuspension of bed material associated with dredging operations.

8 Guidelines on resuspension of material by dredging activities

8.1 General comment

The guidelines presented in this chapter should not be viewed as hard and fast rules. The resuspension of material during dredging activity is dependent upon numerous factors and consultation with the Dredger Operator should be undertaken wherever possible. Practical experience associated with the impacts of the proposed dredging operation, combined with and supported by some of the information provided in this report and others, should be considered as the appropriate starting point from which to consider the potential impacts of a particular dredging activity.

8.2 Resuspension processes

8.2.1 Timescales

Within this report there has been considerable discussion of the physical processes which occur after a water and solids mixture has been released by dredging activity into the water column. Three timescales have been considered. These are: immediate; short term and long term. Long term impacts are discussed in Section 8.3. The immediate timescale is one of minutes and relates to the initial mixing of the released material into the water column. The short term timescale might be considered as one of hours. That is processes which occur during the entire dredging operation and continue afterwards until all the material resuspended by the dredging operation has found an initial resting place on the sea bed. Longer term processes are those that are responsible for resuspended dredged material from its initial resting place on the sea bed. Obviously there are cases of overlap between the timescales described above.

8.2.2 Immediate processes

The processes which occur in the immediate timescale are the following:

i) the rapid settling of the released material towards the bed in the form of a density current.

ii) the potential effects of the impact of the density flow on the bed which may be resuspension of released material or bed material, or generation of a low density fluidised layer on the bed.

Guidance

There is some evidence available concerning these processes. In general with a high volume, high production such as overflowing of large trailer hopper dredgers or agitation dredging with suction dredgers these processes may be the most critical in identifying the potential source of material that is available to be transported and advected in the short term. The significance of these processes in the longer term has not been considered.

Measurement of the release rate of material from direct measurements on board the dredger such as spillway measurements or deductions based on productivity will provide the rate of input of sediment for the processes which occur in the immediate timescale. These release rates should not necessarily be used as input to process which occur in the short term.

Release rates from dredging activity are dependent entirely upon the production rate. It has been estimated that release rates from large trailer dredgers screening for gravel may be as much as 4,000kg dry solids per m^3 dredged and retained in the hopper. The majority of the material released into the water column in this case will be sands. The release rate of fines into the water column is likely to be at least an order of magnitude lower.

8.2.3 Short term processes

Short term processes include:

i) advection of resuspended material in the water column, and

ii) settling of resuspended material through the water column

Guidance

The most important factor associated with short term processes is determination of the amount of material in the water column that is influenced by short term processes. As discussed above this is not necessarily the release rate of material from the dredger. At present it is not possible to accurately predict the proportion of material released from a dredging operation that is then available for transport by short term processes. The most appropriate method appears to be direct measurement in the field behind representative operations. By measuring the fluxes of material in suspension down tide of a dredging operation the short term source term can be quantified. The "S-factors" presented in Table 1 could be used as a basis for such source terms in the absence of field measurements.

The settling of sandy material is well documented. However, the settling of fine material (<0.063mm) is less well understood. The assumption that fine material resuspended by dredging activity will settle at rates similar to fine material that is naturally in suspension (ie. in the range 0.1 to 2.0mm/s) may be inappropriate. Fine material released from a dredger may be in the form of denser aggregates than occur naturally or may be attached to coarser particles. Direct measurement in the field using a visualisation technique is probably the most appropriate method for determining the importance of this effect. Another approach that could be applied is to determine the size distribution of released material before and after disaggregation. Both these techniques will be applied during a forthcoming DoE funded research project at HR.

8.2.4 Longer term processes

Longer term processes include:

i) resuspension of dredged material that has settled to the bed,

ii) consolidation of dredged material on the bed, and

iii) movement of fluidised layers on the bed.

Guidance

Determination of the source terms for longer term processes is more difficult than for the short term processes. For the case of trailer dredging both the release rate of the material from the dredger and the impact of the draghead on the sea bed are required. A proportion of material released into the water column will impact immediately on the bed and this is potentially a source for the longer term processes. However, an additional source is the material that settles to the bed after short term transport is complete. In most cases this additional source term can be ignored since it is likely to represent only a few percent of the released material. Little is known about the potential magnitude of the long term source associated with the disturbance of the sea bed generated by the general disturbance of the bed by the dredging plant.

Almost nothing is known of the properties of materials on the bed that are generated by dredging activity. For material that settles out of suspension then it may be appropriate to consider that this material behaves much as natural fresh deposits. An appropriate critical erosion threshold can be defined. However, for the majority of the material to be considered, such as fluidised layers generated by the overflow the properties of the material are unknown. For material placed at an offshore disposal site estimates of the erosion resistance of the material can be made based upon the material's density. However, no field measurements have yet been made of the erosion resistance of material that has been disturbed by dredging. This is the subject of an ongoing MAFF project at HR.

The consolidation of a deposit of material arising from dredging activity is poorly understood. The best assumption that can presently be made is that the material will behave in a similar manner to natural muds tested in the laboratory.

The movement of fluidised layers of mud on the seabed can be represented in numerical models but without good insitu field data it is not possible to identify the importance of different parameters such as viscosity, density, thresholds for movement or entrainment.

8.3 Guidance on monitoring

As can be seen from Section 8.2, there is a requirement for significant monitoring of different dredging techniques. Most of the focus has been on identifying and subsequently predicting the short term resuspension. However, the question remains as to whether the short term impacts are the most important.

As described above both release rates from the dredger (the source term for all the processes described above) and measurement of the short term source term, at some distance, equivalent to perhaps five minutes tidal advection, downstream of the dredging activity have been undertaken. Such measurements should continue. Ideally these measurements should be made simultaneously so that the immediate processes can be quantified. The measurements now tend to be made using ADCP techniques combined with other water sampling methods. Such measurements have been well documented elsewhere and there are a number of standardised procedures.

Little monitoring has been undertaken of the movement of fluidised material on the seabed and this is an area requiring further work.

Long term monitoring of the resuspension of material from offshore disposal sites has been instigated under the MAFF research project being undertaken at HR. Such long term monitoring could also be undertaken in the vicinity of other dredging activities.

As has been demonstrated by recent studies (Sections 5.8 and 5.9) monitoring associated with a dredging operation can often be optimised by the appropriate application of numerical modelling techniques. Such numerical modelling can aid identification of the spatial and temporal extent of any monitoring.

Most importantly monitoring to establish natural background concentrations and the variability of this background associated with natural and anthropogenic activities is vital in order to place the impact of resuspension caused by dredging in the proper context.

8.4 Guidance on predictive modelling

A discussion of some of the assumptions and uncertainties associated with numerical prediction of the resuspension of material by dredging has been provided in Chapter 7. The most important point to note is that given the uncertainties it is very important to undertake adequate sensitivity analysis when applying predictive modelling techniques to this field.

9 Conclusions

In general it can be stated that resuspension during dredging operations will be dependent on soil characteristics, hydrodynamic conditions and dredging method applied. Hardly any technique is available to predict beforehand resuspension or turbidity levels, and measurement of actual resuspension during dredging is difficult and rather inaccurate, although qualitative techniques are rapidly developing.

The real environmental impact of resuspension of material by dredging operations cannot with any accuracy be defined, and should always be balanced against impact of other natural and anthropogenic processes. All impacts should be balanced against the impact of the removal of the material from the dredging area.

10 Acknowledgements

This study was undertaken by members of the Ports and Estuaries Group at HR Wallingford.

HR would like to thank the following for their support for this project:

Tees and Hartlepool Port Authority
Boskalis Westminster Dredging
ARC Marine Ltd
Londonderry Port and Harbour Commissioners
Coastline Surveys Ltd
Anthony D Bates Partnership
Richard Meerkerk (Hydronamic bv)
Gerard van Raalte (Hydronamic bv)
Douglas Stewart (formerly of Wimpey Environmental)

11 References

Andrassy, C. and J.B. Herbich, (1988) Generation of resuspended sediment at the cutterhead, Dock and Harbour Authority, vol.67, no.797, pp.207-216.

Barnard, W.D. (1978) Prediction and control of dredged material dispersion around dredging and open water pipeline disposal operations. Technical Report DS-78-13 US Army Engineer Waterways Experiment Station, CE Vicksburg, Mississippi, 112pp.

Bates, A. (1996) Reopening the navigation channel to the Port of Londonderry. In Proceedings of the Institute of Civil Engineers, Water Maritime and Energy, vol.113, Issue 1.

Blokland, T. and G.H. van Raalte, (1988) Determination of dredging induced turbidity, CEDA Dredging Day, Hamburg, 1988.

Blokland, T. (1986) The turbidity caused by various dredging techniques: an analysis of measurements in Rotterdam and Delfzijl (in Dutch). MKO 110.18-R8647, Gemeentewerken Rotterdam Ingenieursbureau Havenwerken, The Netherlands.

Blokland, T. et al (1986) Environment conscious dredging and disposal, turbidity measurements Delfzijl (in Dutch). Co.110.18-R8631, Minimalisering Kosten Onderhoudsbaggerwerk - Dredging Research Association.

BMAPA (1994) Aggregate from the sea - why dredge? Public information booklet, London, UK.

Bokuniewicz, H.J. et al, (1978) Field study of the mechanics of the placement of dredged material at open water sites. Technical report D-78-7, prepared by Yale University for the USACE, WES, Vicksburg, Mississippi, 1978.

Brahme, S.B. and J.B. Herbich, (1986) Hydraulic model studies for suction cutterheads, ASCE Journal of Waterway, Port, Coastal and Ocean Engineering, vol.112, no.5, September 1986.

Buchberger, C. (1993) Removal technologies for contaminated sediment. In Proceedings of CEDA dredging days, Amsterdam.

Burt, T.N. et al, (1996) Beneficial uses of dredged material. HR Wallingford Report SR 462.

Clarke, D. and D. Imsand, (1990) An environmental assessment of overflow dredging in Mobile Bay, Alabama, USACE Information Exchange Bulletin, vol. D-90-1.

Cooper, A.J., (1996) Guidelines for the use of computational models in coastal and estuarial studies. Benchmark tests for flow models. HR Wallingford, Report SR 456.

Crickmore, M.J. and R.F. Aked, (1975) Pumped samplers for measuring sand transport in tidal waters. Conference on Instrumentation in Oceanography, Bangor, Wales, pp.311-326.

Dearnaley, M.P. (1991) Flocculation and settling of cohesive sediments. HR Wallingford, Report SR 272.

van Doorn, T. (1988) Dredging polluted soil with a trailing suction hopper dredger, Proceedings of CEDA Dredging Day, Environmentally acceptable methods of dredging and handling harbour and channel sediments, Hamburg, 28 September 1988.

Dredging and Port Construction (1995) The International directory of dredgers, vol. XXII, no.8, pp.11-42.

Dredging Research (1995) SEDIVIEW. Technical information on the SEDIVIEW technique for determining suspended sediment concentrations from ADCP backscatter data. Information prepared by Dredging Research Ltd.

Fairgrieve, J. (1996) Developments in Maintenance Dredging. Presented at UK Harbour Masters Association meeting February 1996.

Finney, N.H. (1987) Maintenance dredging and spoil disposal at UK ports. In Maintenance dredging. In Proceedings of a conference organized by the Institution of Civil Engineers and held in Bristol on 20-21 May, 1987.

Foy, G. (1985) The use of cutter suction dredgers by the Port of Bristol Authority. Paper prepared for the British Ports Association in March 1985.

Gemeentewerken Rotterdam (1988) Turbidity measurements during dredging with a bucket dredger in the North Sea Canal (in Dutch). Co.110.18-R8809, CSB Bagt 416, Gemeentewerken Rotterdam Ingenieursbureau Havenwerken, The Netherlands, April 1988.

Gordon, R.B. (1974) Dispersion of dredge spoil dumped in near-shore waters, Estuarine and Coastal Marine Science, vol.2, pp.349-358, 1974.

Gravelli D. (1995) Application of a model for the dispersion of material resuspended by dredging activity in the River Tees. Final training report for Techware period April to July 1995.

Griffin, G.M. (1976) Dredge-fill in the coral reef tract of the northern Florida Keys, Proceedings of the specialist conference on Dredging and its environmental effects, Mobile, Alabama, January 1976.

Hayes, D., McLellan, T. and C. Truitt, (1986) Demonstrations of innovative and conventional dredging equipment at Calumet Harbour, Illinois, USACE, WES, Vicksburg, Mississippi.

Herbet, C., Betbeder Mahber, J.L. and J. de Wiled, (1995) Sydney Airports parallel runway. The beneficial use of sand dredged in Botany bay. In: Proceedings of the 14th World Dredging Congress, Amsterdam, November 1995.

Herbich, J.B. (1992) Environmental effects of dredging activities. In Handbook of dredging engineering, (ed) Herbich J.B., McGraw Hill.

Herbich, J.B. and J. de Vries, (1986) An evaluation of the effects of operational parameters on sediment resuspension during cutterhead dredging using a laboratory model dredge system. Report no.CDS 286, Centre for dredging studies, Texas A&M University.

Hitchcock, D.R. and M.P. Dearnaley, (1995) Investigation of benthic and surface plumes associated with marine aggregate production of the United Kingdom. Presented at US Minerals Management Service transfer meeting, December 1995.

van Hoof, J., Claeys, C. and L. Ponnet, (1991) Underwater disposal of dredged material in Doeldok: final evaluation of the pilot project, Characterisation and Treatment of Sludge Congress (CATS).

HR Wallingford (1974) Thames flood prevention investigation. Continuous silt monitoring. Report EX 671.

HR Wallingford (1982) Thailand coastal ports project. Navigation channel improvements at the Port of Ban Don: Radioactive tracer experiments to examine the disposal of dredged spoil. Report EX 1055.

HR Wallingford (1989) Marine works at Shakespeare Cliff - The monitoring of suspended solids concentrations in the adjacent coastal waters during 1988. Report EX 1743 (Confidential)

HR Wallingford (1990) Water injection dredging of mud - Field monitoring in Harwich Harbour, Phase 1. Report EX 2159 (Confidential).

HR Wallingford (1992a) Estuarine muds manual. Report SR 309.

HR Wallingford (1992b) Tees barrage study, Upriver siltation. Report EX 2432 (Confidential).

HR Wallingford (1993) Londonderry Channel deepening, Monitoring of suspended sediments - Lough Foyle. Report EX 2813 (Confidential).

HR Wallingford (1994) Shoreham Outfall, Turbidity monitoring during dredging. Report EX 3044 (Confidential).

HR Wallingford (1995a) Estimation of sediment fluxes from ADCP backscatter data. Unpublished paper PHR 118.

HR Wallingford (1995b) Initial dispersion phase of plumes of sediment arising from sand dredging overflow. Unpublished paper PHR 119.

HR Wallingford (1996a) Tilbury Docks, Monitoring of suspended sediment concentrations in the impounding waters. Report EX 3340 (Confidential).

HR Wallingford (1996b) Dispersion studies at Owers Bank. Report EX 3335 (Confidential).

Huston, W. and W.C. Huston, (1976) Techniques for reducing turbidity with present dredging procedures and operations. Contract report D-76-4, USACE, WES, Vicksburg, Mississippi, May 1976.

Jensen, A., Valeur, J., Thorkilsen, M. and J. Weiergang, (1995) The use of numerical modelling in monitoring of dredging spoils. In Proceedings of the 14th World Dredging Congress, Amsterdam, November 1995.

Kirby, R. and J.M. Land, (1991) The impact of dredging - A comparison of natural and man-made disturbances to cohesive sediment regimes. In Proceedings of CEDA dredging days, Amsterdam, November 1991.

Land J.M. (1989) The backfilling of offshore borrow pits. Lecture to the Hong Kong Institution of Engineers Geotechnical Division.

Land, J.M., Kirby, R. and J.B. Massey, (1994) Recent innovations in the combined use of acoustic doppler current profilers and profiling silt meters for suspended solids monitoring. In Proceedings of 4th Nearshore and Estuarine Cohesive Sediment Transport conference, Wallingford.

Lunz, J.D., Clarke, D.G. and T.J. Fredette, (1984) Seasonal restrictions on bucket dredging operations. In Proceedings of the Conference Dredging 84, Florida, November 1984.

MAFF (1995) Data from the public register of dredging licence returns for the period 1985 to 1992.

Malherbe, B. (1989) Case study of dumping in open areas. In Proceedings of the International Seminar on the Environmental Aspects of Dredging Activities, Nantes.

McLellan, T.N., Havis, R.N., Hayes, D.F. and G.L. Raymond, (1986) Methods for reducing sediment resuspension from dredging operations, USACE, WES, Vicksburg, Mississippi, 1986.

Nelson, M.E. and P.C Benedict, (1951) Measurement and analysis of suspended sediment loads in streams. Transactions of the American Society of Civil Engineers, vol.116, pp.891-918.

Nakai, O. (1978) Turbidity generated by dredging projects, Management of bottom sediments containing toxic substances. In Proceedings of the 3rd US-Japan experts meeting, EPA-60073-78-084, pp.31-37, 1978.

Norton, M.G., Jones, P.J.W., Franklin, A. and S.M. Rowlatt, (1984) Water quality studies around the sewage sludge dumpsite in Liverpool Bay. Estuarine, coastal and shelf science, vol.19, no.1, pp.53-67, July 1984.

Pennekamp, J.G.S., and M.P. Quaak, (1990) Impact on the environment of turbidity caused by dredging, Terra et Aqua, no.42, April 1990.

Pennekamp, J.G.S, Blokland T. and E.A. Vermeer, (1991) Turbidity caused by dredging compared to turbidity caused by normal navigational traffic. In Proceedings of CEDA dredging days, Amsterdam, November 1991.

Pequegnat, W.E., Smith, D.D., Darnell, R.M., Presley, B.J. and R.O. Reid, (1978) An assessment of the potential impact of dredged material in the open ocean. Technical report D-78-2, USACE, WES, Vicksburg, Mississippi.

Premchitt, J., Rodger, J.G., Evans, N.C., Ip, K.L. and Dearnaley, M.P. (1993) Geotechnical aspects of contaminated mud dredging and disposal in Hong Kong. In Proceedings of Seminar on Geotechnics and the Environment 93, Hong Kong.

Rees, J. (1995) Sediment fluxes perpendicular and parallel to the Holderness Coast using advanced near bed measuring systems - Tetrapod and Minipods, In Proceedings of 30th MAFF Conference of River and Coastal Engineers, Keele University, July 1995.

Reinking, M.W. (1993) The development of special remedial dredging technique: The environmentally friendly auger dredger. In Proceedings of CEDA dredging days, Amsterdam.

Richardson T.W. (1984) Fundamentals of agitation dredging. In Proceedings of the Conference Dredging 84, Florida, November 1984.

Sandaert, P., Claessens, J., Marain J. and J. Smits, (1993) The scoop dredger, a new concept for silt removal. In Proceedings of CEDA dredging days, Amsterdam.

Soulsby, R.L. (1994) Manual of marine sands, HR Wallingford, Report SR 351.

Stevenson, J.R. (1992) Accuracy of Marine Siltation Predictions - Developments in the Analysis of Silt Monitoring Data. HR Report SR 293.

Sustar, J. and T. Wakeman, (1977) Dredge material study, San Francisco Bay and Estuary - main report, US Army Engineer District, San Francisco, California, 1977.

Sustar, J.F., Wakeman, T.H. and R.M. Ecker, (1976) Sediment-water interaction during dredging operations. In Proceedings of the specialist conference on Dredging and its environmental effects, Mobile, Alabama, January 1976.

Tavolaro, J.F. (1982) Sediment budget study for clamshell dredging and disposal activities, US Army Engineer District, New York, 1982.

Teal, C.J., Stewart, D.L., Dearnaley, M.P. and T.N. Burt, (1993) Environmental monitoring of dredging activities. In Proceedings of CEDA dredging days, Amsterdam.

Thorne, P.D., Vincent, C.E., Hardcastle, P.J., Rehmen, S. and N. Pearson, (1991) Measuring suspended sediment concentration using acoustic backscatter devices. Marine Geology, vol.98, pp.7-16.

Thorne, P.D., Hardcastle, P.J. and R.L. Soulsby, (1993) Analysis of acoustic measurements of suspended sediment. Journal of Geophysical Research, vol.98, no. C1, pp.899-910.

Truitt, C.L. (1986) The Duwamish Waterway capping demonstration project: engineering analysis and results of physical monitoring. Technical report D-86-2, USACE, WES, Vicksburg, Mississippi, 1986.

USACES (1986) Fate of dredged material during open water disposal, Environmental Effects of Dredging Technical Note EEDP-01-2, USACE, WES, Vicksburg, Mississippi, September 1986.

USACE (1988a) Sediment resuspension by selected dredges, Environmental Effects of Dredging Technical Note EEDP-09-2, USACE, WES, Vicksburg, Mississippi, March 1988.

USACE (1988b) A preliminary evaluation of contaminant release at the point of dredging, Environmental Effects of Dredging Technical Note EEDP-09-3, USACE, WES, Vicksburg, Mississippi, April 1988.

USACE (1991) Mobile, Alabama, Field data collection project, 18 August to 2 September, Technical Report DRP-91-3. USACE, WES, Vicksburg, Mississippi, September 1991.

USACE (1992) Tylers Beach, Virginia, Dredged material plume monitoring project, 27 September to 4 October. Technical Report DRP-92-7. USACE, WES, Vicksburg, Mississippi, December 1992.

Volbeda, J.H. (1983) Overflow effects when trailing very soft silts and clays. In Proceedings of the 10th World Dredging Congress, Singapore, pp.547-556, 1983.

Waters, C.B. and M.F.C. Thorn, (1975) A quantitative experimental comparison of spoil disposal methods. In Proceedings 1st Int. Symp. on Dredging Technology, BHRA, 1975.

Weiergang, J. (1995) Estimation of suspended sediment concentrations based on single frequency acoustic doppler profiling. In Proceedings of the 14th World Dredging Congress, Amsterdam, November 1995.

van Wijck, J., van Hoof, J. and J. Smits, (1991) Underwater disposal of dredged material: a viable solution for the maintenance dredging works in the river Scheldt, PIANC no.73, 1991.

Tables

Table 1 Indicative values for the mass of sediment resuspended per m^3 of dredged material (Kirby and Land, 1991)

DREDGER TYPE	S FACTOR (kg/m^3)
Trailer (limited overflow)	typically 15
Trailer (no overflow)	typically 7
Trailer (no overflow or ALMOB)	typically 3 - 4
Grab (open, no silt screen)	12 - 25*
Grab (closed, with silt screen)	11 - 20*
Grab (closed, with silt screen)	2 - 5*
Bucket	15 - 30*
Cutter	approximately 6
Cutter (reduced swing and rotation speeds)	approximately 3
Dustpan	approximately 4
Backhoe (no silt screen)	12 - 25*
Backhoe (with silt screen)	5 - 10*
Auger	5
Auger (reduced rate of advance)	3
Pneuma	effectively nil+

* depending on the size of grab or bucket - the smaller it is the greater the resuspension.

\+ no resuspension but also no effective production.

Table 2 Measurements of turbidity around a grab dredge

Location	Merwedehaven, Rotterdam	Hollandsche IJssel	Hollandsche IJssel	Hollandsche IJssel	Zierikzee	Black Rock Harbour	Duwamish Waterway	Calumet River
Date	12/08/86	19/05/88	19/05/88	19/05/88	1990	N/A	N/A	N/A
Soil composition	54% <16µm 8% >63µm	40% <16µm 23% >63µm	40% <16µm 23% >63µm	40% <16µm 23% >63µm	N/A	Sandy organic clay, 90% fines	Sandy clayey silt	N/A
In situ density (kg/m^3)	1145 top 0.6m 1300 below	1360 top 0.25m 1560 next m	1360 top 0.6m 1560 next m	1360 top 0.6m 1560 next m	N/A	N/A	N/A	N/A
Dredging technique	open $1.1m^3$ grab, no silt screen	watertight $3m^3$ grab with silt screen	open $2.5m^3$ grab with silt screen	watertight $3m^3$ grab, no silt screen	self propelled hopper grab, watertight grab	open clamshell ($10yd^3$)	open clamshell	open clamshell
Production (m^3/h)	90	102	84	166	N/A	N/A	N/A	N/A
Current velocity	0.05m/s	0.1m/s	0.2m/s	0.04m/s	negligible	0.05-0.25m/s	0.1-0.3m/s	N/A
Water depth	11m	5m	5m	5m	2.5m	N/A	N/A	N/A
Background concentration	20ppm	35ppm	35ppm	35ppm	50ppm	surface: 45ppm bottom: 69ppm	surf: 11ppm bed: 26ppm	10 - 12ppm
Turbidity increase	35ppm	20ppm	35ppm	100ppm	90-105ppm	× 15.9	× 6.1	surf: 40ppm bed: 140ppm
Duration of turbidity increase	1hr	1hr	1hr	1hr	N/A	N/A	N/A	N/A
resuspension of sediment	$3kg/m^3$	$5kg/m^3$	$10kg/m^3$	$20kg/m^3$	$11kg/m^3$	N/A	N/A	N/A

Table 3 Typical sediment disturbances around a clamshell dredge at Almeda Naval Air Station

depth of meas.	Background (ppm)	Centreline (ppm)		50m off centreline (ppm)		100m off centreline (ppm)	
		max	avg	max	avg	max	avg
1m	24	170	70	40	29	-	-
5m	34	172	88	214	68	33	29
10m	37	118	33	-	-	-	-

%trans: Percent light penetration through 10cm light path
length: distance in m with reduced light penetration
level: lowest percent light transmission reading not necessarily sustained over the length

Table 4 Measurements of turbidity around a bucket ladder dredger

Location	Noordzeekanaal, Amsterdam
Date	25/11/87
Soil composition	65% <16μm 16% >63μm
In situ density (kg/m^3)	1100 top 0.25m 1300 next metre
Dredging technique	0.7m^3 buckets
Production (m^3/h)	714
Current velocity	0.06m/s
Water depth	14m
Background concentration	15ppm
Turbidity increase	110ppm
Duration of turbidity increase	1hr
resuspension of sediment	20kg/m^3

Table 5 Measurements of turbidity around a trailing suction hopper dredge

Location	3e Petroleumhaven, Rotterdam	3e Petroleumhaven, Rotterdam	Buitenhaven, Delfzijl	Buitenhaven, Delfzijl	Gray's Harbour, Washington	Gray's Harbour, Washington
Date	29/05/85	29/05/85	15/04/86	16/04/86	N/A	N/A
Soil composition	58% <16µm 5% >63µm	58% <16µm 5% >63µm	74% <16µm 10% >63µm	74% <16µm 10% >63µm	N/A	N/A
In situ density (kg/m^3)	1170 top 0.6m 1300 below	1170 top 0.25m 1300 below	1100 top 0.3m 1300 next 1.5m	1100 top 0.3m 1300 next 1.5m	N/A	N/A
Dredging technique	no overflow	overflow	little overflow	little overflow	dragarm with overflow	dragarm without overflow
Trail length	200m	200m	100m	100m	N/A	N/A
Hopper volume	6100m^3	6100m^3	803m^3	803m^3	N/A	N/A
Production (m^3/h)	5400	4125	1750	1750	N/A	N/A
Current velocity	none	none	none	0.2m/s	N/A	N/A
Water depth	13m	13m	9m	9m	N/A	N/A
Background concentration	40ppm	75ppm	60ppm	70ppm	28 - 60ppm	12 - 54ppm
Turbidity increase	150ppm	400ppm	10ppm	20ppm	surface: 100ppm bottom: 700ppm	surface: negligible bottom: 40-50ppm
Duration of turbidity increase	1hr	1hr	0.5hr	1hr	N/A	N/A
resuspension of sediment	4kg/m^3	13kg/m^3	1kg/m^3	5kg/m^3	N/A	N/A

Table 6 Typical sediment disturbances around a trailing hopper dredge

project	depth (m)	background (ppm)	Centreline		50 m off centreline		100m off centreline	
			max (ppm)	avg (ppm)	max (ppm)	avg (ppm)	max (ppm)	avg (ppm)
Mare Island Strait	1	33	210	210	60	43	12	12
	5	83	110	64	46	46	49	49
	10	123	1,110	743	2,600	337	260	233
Richmond Harbour	1	31	82	65	51	45	23	23
	5	33	39	33	55	55	20	20
	10	39	200	145	-	-	32	32
Alameda Naval Air Station	1	35	188	131	-	-	-	-
	5	28	47	42	-	-	-	-
	10	38	58	58	-	-	-	-

Table 7 Measurements of turbidity around a cutterhead dredge

Location	Calumet Harbour	James River
Date	N/A	N/A
Soil composition	Soft organic clay/silt, 80% fines	Silty clay
In situ density (kg/m^3)	N/A	N/A
Dredging technique	cutterhead (12-in)	cutterhead
Trail length	N/A	N/A
Hopper volume	N/A	N/A
Production (m^3/h)	N/A	N/A
Current velocity	0.00-0.05m/s	0.15-0.7m/s
Water depth	N/A	N/A
Background concentration	surface: 2ppm bottom: 5ppm	surface: 42ppm bottom: 86ppm
Turbidity increase	× 2.0	× 3.8
Duration of turbidity increase	N/A	N/A
resuspension of sediment	N/A	N/A

Table 8 Maximum plume concentrations measured during 'hard-rock' dredging within 1ft of water surface

Date	Background concentration (ppm)	plume concentration (ppm)	location of sample	measurement method
16/11/72	1 - 2.5	>40	200ft downcurrent from dredge (no diaper)	T-100
11/12/72	2	>40	200ft downcurrent from dredge (no diaper)	T-100
	1.4	48	138ft downcurrent from dredge (no diaper)	Scat.
26/12/72	0.5 - 1	>40	132ft downcurrent from dredge (no diaper)	T-100
18/05/73	1 - 2.5	66	2ft inside diaper	T-10
		18	2ft outside diaper	T-10
		38	5ft outside diaper at leaky corner	T-10
30/05/73	3	212	over edge of diaper at leak	T-100
01/06/73	2	37	30ft outside leaky diaper	T-10
		34	300ft downcurrent from leaky diaper edge	T-10
07/08/73	2.5 - 5	22	186ft downcurrent, outside diaper	T-10
		28	294ft from dredge in small turbid area nearshore	T-10
09/08/73	1 - 2.5	120	over edge of diaper at leak	T-10

Measurement methods:

T-100 1m optical transmissometer in situ
T-10 0.1m optical transmissometer in situ
Scat. Laboratory measurement of light scattering

Table 9 Fate of dredged material during open water disposal

Source	site	depth (m)	bottom currents (m/s)	sediment	dredge type	disposal type	disposal volume (m^3)	monitoring technique	% of sediment remaining in upper water column
Gordon (1974)	Long Island Sound	18 - 20	0.05 - 0.3	silt-clay	clamshell	scow	920-2300	T	1
Sustar and Wakeman (1977)	Carquinez	14	0.1 - 0.25	silt-clay	trailing suction hopper	hopper	1000	T+G	1 - 5
Bokuniewicz et al (1978)	Ashtabula (Lake Erie)	15 - 18	0 - 0.2	sandy silt	trailing suction hopper	hopper	690	T+G	1
	New York Bight	26	0.05 - 0.25	marine silt	trailing suction hopper	hopper	6100	T+G	1
	Saybrook (Long Island Sound)	52	0.2 - 0.7	marine silt	clamshell	scow	1100	T+G	1
	Elliott Bay	67	0 - 0.2	sandy silt	clamshell	scow	380-540	T+G	1
	Rochester (Lake Ontario)	17 - 46	0 - 0.2	riverine silt	trailing suction hopper	hopper	690	T+G	1
Tavolaro (1982)	New York Bight	16 - 24	N/R	silt and clay	clamshell	scow	1400-3000	M	3.7
Truitt (1986)	Duwamish Waterway	20 - 21	0.06	silt-clay	clamshell	scow	840	G+M	2 - 4

Monitoring techniques:

T Transmissometer
G Gravimetric
M Mass balance

Plates

Plate 1 **Visual impact of dredging operations (see Sections 5.5 and 5.7 for details)**

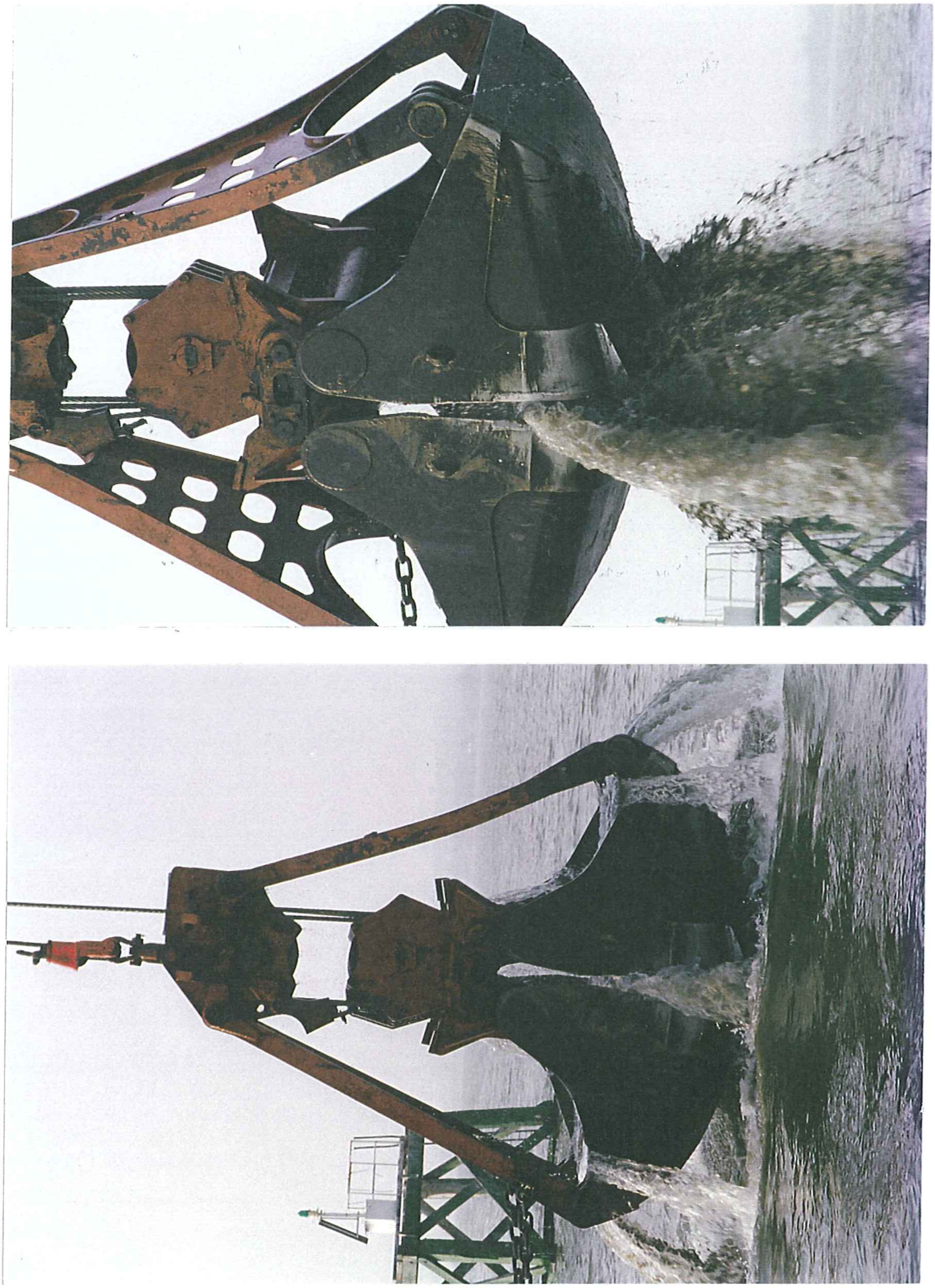


Plate 2 Grab dredger operating in Lough Foyle, Northern Ireland

Plate 3 Bucket / trailing suction and grab dredgers operating in The Yemen

Plate 4 **Trailing suction hopper dredger 'Geopotes 14' operating in the English Channel**

Plate 5 Trailing suction dredger 'Arco Severn' operating in the English Channel

Plate 6 Cutter suction dredger 'Orion' operating in the English Channel

Plate 7   Agitation dredging in the Bristol Channel

Plate 8 Suction / agitation dredger 'Agem One' operating at Sheerness

Plate 9 Auger dredger operating in Poole Harbour

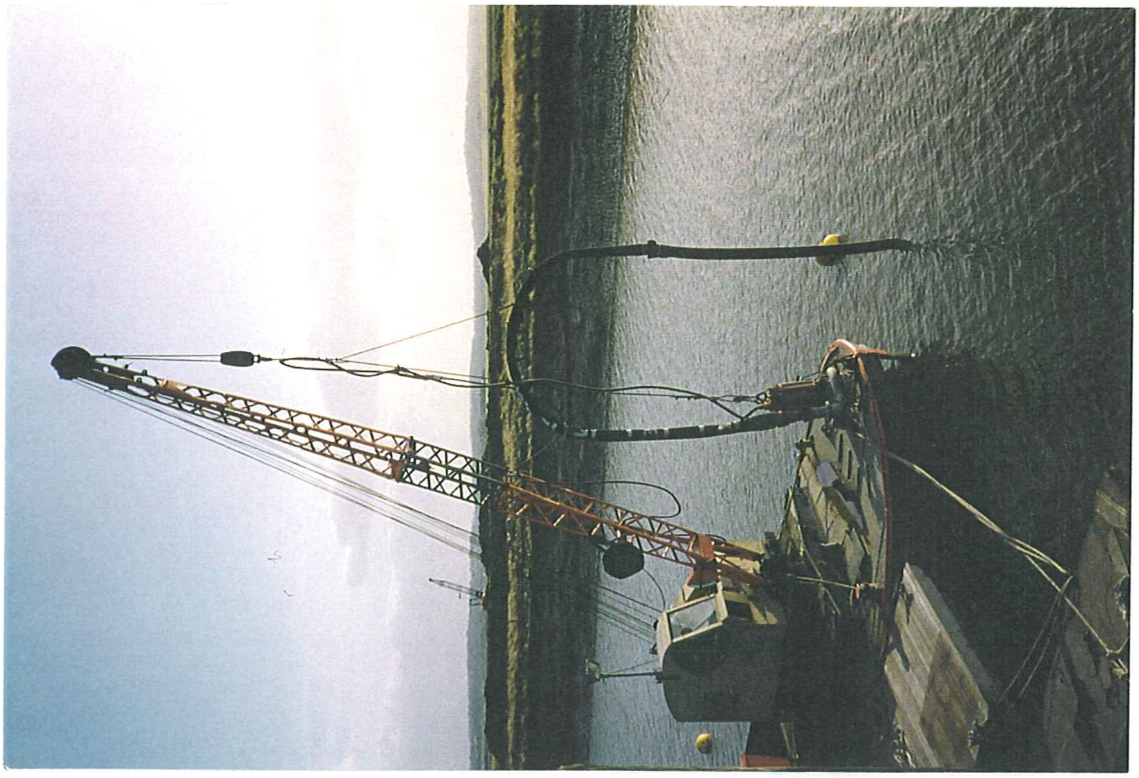
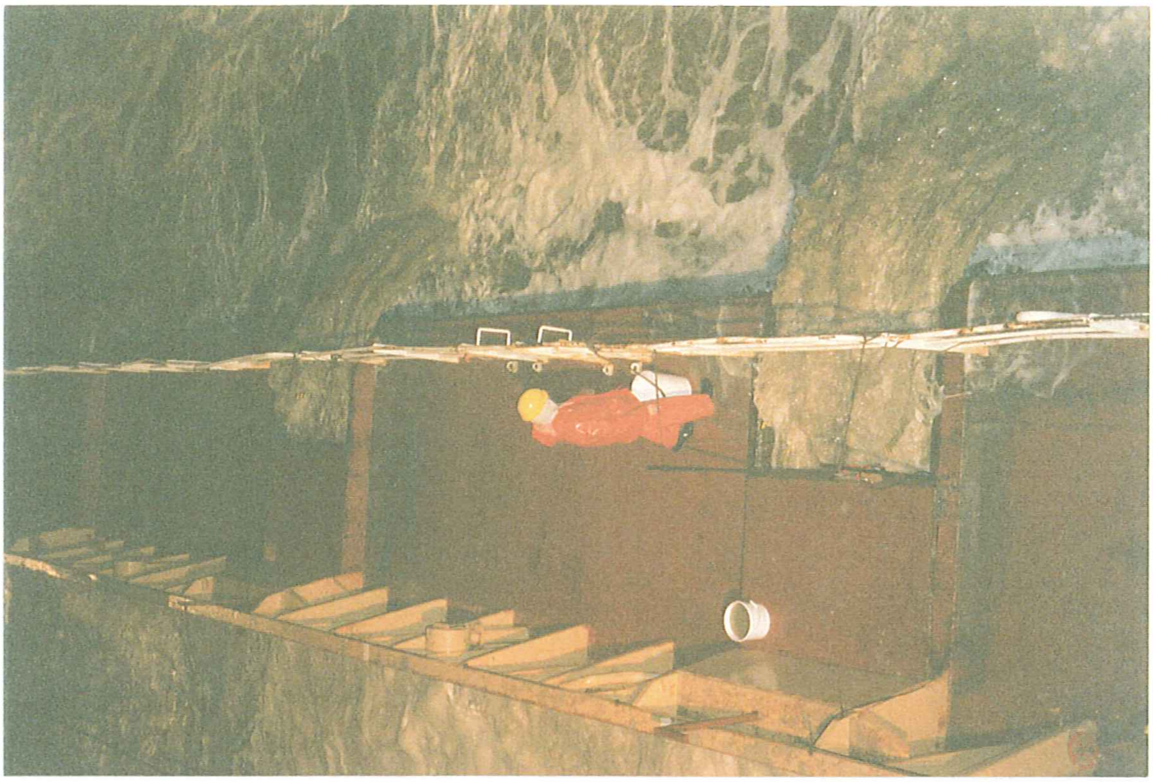


Plate 10 Other small suction dredgers

Plate 11 Plough 'Norma' operating in Lough Foyle, Northern Ireland



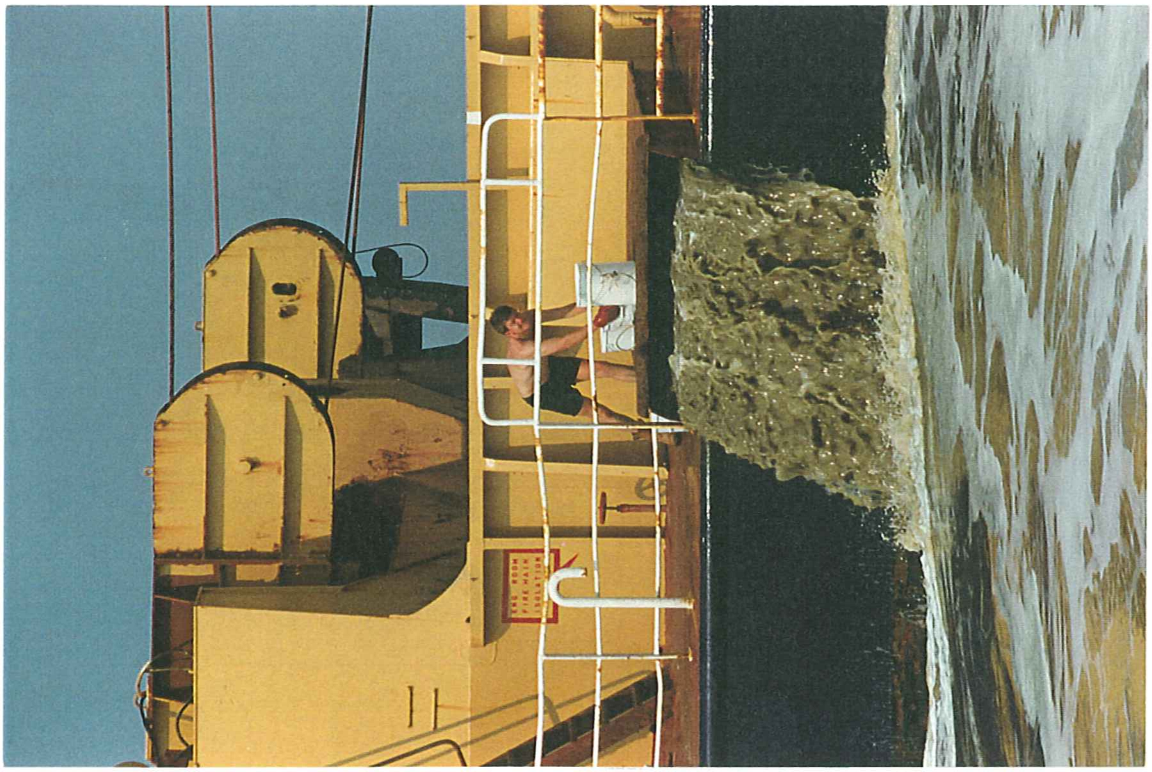


Plate 12 Overflow from the aggregate dredger 'Arco Severn' operating in the English Channel

Resuspension of bed material by dredging

An intercomparison of different dredging techniques

Volume 2: Appendices

M P Dearnaley
N G Feates
T N Burt
M N H Waller

Report SR 461
February 1996

HR Wallingford

Address and Registered Office: **HR Wallingford Ltd.** Howbery Park, Wallingford, Oxon OX10 8BA
Tel: + 44 (0)1491 835381 Fax: + 44 (0)1491 832233

Contents

Page

Title page
Contract
Summary
Contents

Volume 1

1 **Introduction** 1
- 1.1 Background 1
- 1.2 Objectives 2
- 1.3 Structure of report 3

2 **The resuspension of bed material by different dredging activities** 3
- 2.1 Introduction 3
- 2.2 Grab Dredgers 3
- 2.3 Bucket Ladder Dredgers 4
- 2.4 Trailing Suction Hopper Dredgers 5
- 2.5 Cutter Suction dredgers 7
- 2.6 Special purpose dredgers - 'environmental dredging' 8
  - *2.6.1 Auger dredgers* 8
  - *2.6.2 Dustpan dredger* 8
  - *2.6.3 Scoop/Sweep dredger* 8
  - *2.6.4 Disc Bottom Cutterhead Dredgers* 8
  - *2.6.5 Horizontal profiling grabs* 9
  - *2.6.6 Pneuma Pump* 9
- 2.7 Special purpose dredgers - 'low cost maintenance dredgers' 9
  - *2.7.1 Agitation dredging* 9
  - *2.7.2 Water injection dredging* 10
  - *2.7.3 Ploughing* 10
  - *2.7.4 Harrowing* 10
- 2.8 Hard rock dredging 10
- 2.9 Resuspension generated by the hopper or barge 10
- 2.10 Placement and discharge 11
  - *2.10.1 Discharge into the water column* 11
  - *2.10.2 Temporary storage of material* 11
  - *2.10.3 Reclamation and nourishment* 12
  - *2.10.4 Pipeline transport* 12
  - *2.10.5 Offshore placement at disposal sites* 12

3 **Techniques available for measuring the resuspension of suspended solids by dredging activity** 12
- 3.1 Introduction 12
- 3.2 Turbidity and suspended solids concentration 13
- 3.3 Natural variability of suspended solids concentrations 13

Contents continued

3.4 Determination of suspended solids concentration 13
3.4.1 Gravimetric analysis 13
3.4.2 Particle size determination 14
3.4.3 Water sampling 14
3.5 Turbidity measurements 14
3.6 Acoustic techniques 15
3.7 Other remote techniques 16
3.7.1 Side scan sonar records 16
3.7.2 Aerial photographs 16
3.7.3 Satellite images 16
3.7.4 Specialist bed frames 16
3.8 Monitoring strategies 16

4 Review of published information 18
4.1 Introduction 18
4.2 Guidelines 18
4.2.1 Resuspension and productivity 18
4.2.2 Other factors affecting resuspension 18
4.3 Grab dredges 19
4.4 Bucket ladder dredge 20
4.5 Trailing suction hopper dredges 20
4.6 Cutter suction dredge 21
4.7 Special purpose dredgers - 'environmental dredgers' 22
4.7.1 Auger dredgers 22
4.7.2 Dustpan dredger 22
4.7.3 Scoop dredger 22
4.7.4 Disc bottom cutterhead dredger 23
4.7.5 Horizontal profiling grabs 23
4.7.6 Pneuma Pump 23
4.8 Special purpose dredgers - 'low cost maintenance dredgers' 23
4.8.1 Agitation dredgers 23
4.8.2 Water injection dredging 23
4.8.3 Ploughing 23
4.8.4 Harrowing 24
4.9 Hard rock dredging 24
4.10 Resuspension by hopper or barge 24
4.11 Placement and discharge 25
4.11.1 Discharge into the water column 25
4.11.2 Temporary storage of material 25
4.11.3 Reclamation and nourishment 25
4.11.4 Pipeline transport 25
4.11.5 Offshore placement at licensed disposal sites 26

5 Recent field studies 27
5.1 Introduction 27
5.2 Plume Measurement System of the USACE Dredging Research Programme 28
5.3 Channel deepening to Londonderry, Lough Foyle 29
5.4 Agitation dredging at Sheerness 31

Contents continued

5.5 Construction of pipeline trench, South Coast of England 32
5.6 Maintenance dredging on the River Tees 32
5.7 Measurements of resuspension rates during UK aggregate dredging operations 33
5.8 Dredging activities in Hong Kong 34
5.9 Monitoring associated with the Oresund Link 35

6 The long term impact of dredging activities on suspended sediment concentrations 35
6.1 Introduction 35
6.2 Impacts associated with capital dredging 36
6.2.1 Changes to hydrodynamics 36
6.2.2 Slumping 36
6.2.3 Increased requirement for maintenance 36
6.2.4 Increases in resuspension and erosion by shipping 36
6.3 Impacts common to all types of dredging 37
6.3.1 Changes to the surface of the bed 37
6.3.2 Fluidisation of the sea bed 37
6.4 Agitation dredging 37
6.5 Long term impacts associated with placement 38
6.5.1 Offshore disposal 38
6.5.2 Monitoring placement at offshore sites 39
6.5.3 Backfilling borrow pits 39
6.5.4 Beneficial use of dredged material 40

7 Uncertainties and assumptions to be made in modelling the resuspension of material associated with dredging activity 40
7.1 Introduction 40
7.2 Release rate of material from the dredging activity 41
7.3 Initial mixing of released material 42
7.4 Settling velocity of resuspended material 42
7.5 Erosion properties of placed material 43
7.6 Consolidation of placed material 43
7.7 Fluidisation of bed material 44
7.8 Hydrodynamic conditions at the site of interest 44

8 Guidelines on resuspension of material by dredging activities 44
8.1 General comment 44
8.2 Resuspension processes 45
8.2.1 Timescales 45
8.2.2 Immediate processes 45
8.2.3 Short term processes 46
8.2.4 Longer term processes 46
8.3 Guidance on monitoring 47
8.4 Guidance on predictive modelling 48

Contents continued

9	**Conclusions**	48
10	**Acknowledgements**	48
11	**References**	49

Tables

Table 1	Indicative values for the mass of sediment resuspended per m^3 dredged (from Kirby and Land, 1991)
Table 2	Measurements of resuspension around a grab dredge
Table 3	Typical sediment disturbances around a clamshell dredge at Almeda Naval Air Station
Table 4	Measurements of resuspension around a bucket ladder dredger
Table 5	Measurements of resuspension around a trailing suction hopper dredge
Table 6	Typical sediment disturbances around a trailing hopper dredge
Table 7	Measurements of resuspension around a cutterhead dredge
Table 8	Maximum plume concentrations measured during 'hard-rock' dredging within 1ft of water surface
Table 9	Fate of dredged material during open water disposal

Plates

Plate 1	Visual impact of dredging operations
Plate 2	Grab dredger operating in Lough Foyle, Northern Ireland
Plate 3	Bucket/trailing suction and grab dredgers operating in The Yemen
Plate 4	Trailing suction hopper dredger 'Geopotes 14' operating in the English Channel
Plate 5	Trailing suction dredger 'Arco Severn' operating in the English Channel
Plate 6	Cutter suction dredger 'Orion' operating in the English Channel
Plate 7	Agitation dredging in the Bristol Channel
Plate 8	Suction/agitation dredger 'Agem One' operating at Sheerness
Plate 9	Auger dredger operating in Poole Harbour
Plate 10	Other small suction dredgers
Plate 11	Plough 'Norma' operating in Lough Foyle, Northern Ireland
Plate 12	Overflow from the aggregate dredger 'Arco Severn' operating in the English Channel

Volume 2

Appendices

Appendix 1	Channel deepening to Londonderry, Lough Foyle
Appendix 2	Maintenance dredging on the River Tees

Appendix 1

Channel deepening to Londonderry, Lough Foyle

Appendix 1 Channel deepening to Londonderry, Lough Foyle

BACKGROUND

Towards the end of January 1993 HR were approached by the Londonderry Port & Harbour Commissioners (LPHC) via the Anthony D. Bates Partnership as to the possibilities of undertaking an exercise to determine the pattern of sediment dispersion created by dredging on the Londonderry Channel deepening project. The method of measurement suggested was to use the Acoustic Doppler Current Profiler (ADCP) deployed in such a manner so as to display and record the pattern and distribution of varying concentrations of suspended sediments. This is a relatively new technique that has been used previously in Hong Kong by Dredging Research Ltd and in the United States on the Dredging Research Program. Accordingly HR subcontracted Wimpey Environmental Limited (WE) to provide equipment and expertise to deploy the ADCP.

In view of the importance of the research subject to the dredging industry the Contractor, Westminster Dredging Ltd, also contributed to the fieldwork. This additional involvement meant that an enormous amount of co-operation was available on site.

The field exercise was set up for the period of large spring tides between 8 and 12 February 1993.

AIMS

The primary interest of LPHC concerned the operation of the trailer dredgers Cornelia (6,000m^3) and WD Medway II (3,500m^3) in the approach channel and turning circle area. The concern was to identify whether material being resuspended by the drag head was being dispersed beyond the limits of the navigation channel. Additionally the fate of material entering the water column during periods of overflow was of interest. Soil conditions in the approach channel, which is approximately 15km long, range from slightly silty sands, to mixtures of cohesive organic silty clays.

If time permitted the WD Dredgewell (5m^3 grab) and the plough Norma were also to be examined.

THEORY

In normal operational mode the ADCP works on the principle that there is a measurable frequency shift between acoustic signals transmitted from the instrument head and return signals which have been reflected from the seabed and from particles in the water column. These frequency shifts are used to calculate the current velocities and the vessels track over the ground. A recent innovation has been to use the measured strength of the returning acoustic signals as an indication of the suspended sediment concentrations.

As part of any exercise using the ADCP to assess suspended sediment concentrations it is essential to collect calibration data for the suspended sediment. This data can either be in the form of bottle sample analysis or can be measured in situ using optical monitors similar to those deployed at the long term monitoring sites.

TECHNIQUES EMPLOYED

The broad aim of the work was to investigate the operation of the trailing suction dredgers WD Medway II and Cornelia. Secondary to this was to study the operation of the grab dredger WD Dredgewell and the plough Norma.

Various techniques of field measurement had been discussed between HR and WE prior to the field exercise, but it was considered that the most important element of the field exercise would be to introduce and maintain sufficient flexibility in the techniques and programme so that the optimum amount of data could be collected in the shortest time without interfering with the operational procedures. Broadly four techniques were identified:

1. By making a series of transects across the channel at one location during the operation cycle of one of the trailing suction dredgers it was proposed to establish;

    i) the background levels of suspended sediment,
    ii) the nature and magnitude of the plume of material released into the water column by the operation and
    iii) the impact of the dredging operation and whether material is dispersed out of the confines of the channel.

2. By making a transect away from the dredger following the plume of suspended sediment to confirm the concentrations of material within the plume.

For the grab and Plough, which can be considered as generating point sources of material two additional techniques could be employed:

3. Circling of the dredger to determine natural background levels of suspended sediment and the location and orientation of any plume of dredged material.

4. A series of transects across any plume that was found at fixed distances from the dredger.

Standard sampling techniques were used to determine the levels of suspended sediment on the transects. This information has two purposes, firstly to try to calibrate the backscatter information provided by the ADCP and secondly to act as a quantifiable measurement of suspended sediment concentrations within a plume of resuspended material.

An optical suspended solids monitor and salinometer were mounted on a line suspended via a davit and winch over the side of the vessel. Also attached to the line was a hose through which the river water could be pumped aboard the vessel into sample bottles for subsequent analysis. The line was kept taught by a 75lb streamlined lead weight secured to the end of the rope.

It should be noted that whilst the ADCP could be used to generate good results at speeds approaching 5 knots the deployment of an optical monitor and water sampling gear on this occasion could not safely be carried out when underway at speeds greater than about 2 knots and even then the equipment had to be kept within a couple of meters of the surface. Thus in order to obtain calibration samples throughout the water column the vessel had to be stationary, although drifting with the flow was unavoidable. During these stationary periods the ADCP remained logging and hence calibration exercises were carried out during these periods.

In general a transect might be made and then some point within the transect returned to for a through depth profile of water samples and optical measurements to be made. This does introduce a delay into the technique but, in the absence of other calibration techniques this was unavoidable. As a technique for establishing the concentrations within the plume itself this was very useful.

PROGRAMME

8 February
Arrival on site, installation of ADCP and water sampling equipment on board the vessel WD Plover (Plate 1), some preliminary tests of the system in the approach channel looking at the backscatter associated with the normal passage of trailers and hoppers. This backscatter was largely associated with propeller wash inducing bubbles into the water column.

9 February
Headed up channel to Redcastle Light to await inward trip of Cornelia, then followed Cornelia inward taking a number of transects in front and astern of vessel. The same method was employed on the outward trip until Cornelia had a full load. At this stage went to investigate the Dredgewell in the turning circle prior to the arrival of the Medway II. Made a sequence of transects in the turning circle as the Medway II filled over a 30 minute period.

10 February
In turning circle with Dredgewell. Then headed out to the channel to examine the plough Norma prior to the arrival of the Medway II. Followed Medway II in first without overflow and then whilst overflowing. Sampled within the overflow. The Dredgewell moved out into the approach channel to Drumskellan (km 6) to work in heavy clay.

11 February
Made transects downstream of Lisahally works at Culmore Point and at Coolkeeragh Power Station intake to compare with the silt monitors recording in the area. Then went out into the main channel to Norma at km 5.5 and made some circuits around her and transects downstream. Carried out a series of transects downstream of Dredgewell (km 6) and then went back upriver to Londonderry to examine the natural suspended sediment concentrations within the turbidity maximum. The Medway II was undergoing a crew change at this stage and the Cornelia had left the site. Returned to the turning circle at 18:00 and began making a series of transects to establish the background suspended sediment concentrations prior to the arrival of the Medway II in the turning circle at 18:40. A series of transects were made running across the turning circle and within the main river channel during the loading of the Medway II. Overflowing commenced approximately 30 minutes after dredging started and continued for about 15 minutes. After the Medway II had left the turning circle a number of cross sections were repeated to determine the fate of material re-suspended within the turning circle.

12 February

Medway II was at the disposal site in the morning and the Dredgewell and Norma had both been thoroughly examined on the previous days. Accordingly the opportunity was taken to examine the natural suspended sediment concentrations and flows upstream, within and downstream of the turning circle. Demobilisation from the Plover at Londonderry took place in the afternoon.

Although the study was being funded by two separate organisations and the results were of research interest, this did not conflict with working to the main objectives of the LPHC. The trailer dredgers worked for between 1-2 hours whilst filling and then left the area for the disposal site. The round trip to the disposal site taking about 4 hours. This meant that in these periods the Dredgewell and Norma could be examined. On 11 February with the Medway II being the only trailer on site the monitoring was extended after dusk so as to optimise the data collection. In the morning of 12 February, it was not considered appropriate to re-examine the Dredgewell and Norma, rather a series of runs were made to investigate the flows in the area of the turning circle. This released the tug Plover for other duties early in the afternoon and gave adequate time for demobilisation and travelling to catch the overnight ferry from Belfast.

RESULTS

Calibrations

Plates 2 and 3

Several calibration trials were carried out during the ADCP survey. Most of the calibration trials consisted of stopping the vessel and making through depth measurements of suspended solids by either recording the output from the optical suspended solids monitor, or by taking pumped samples for subsequent analysis in the HR Sedimentation Laboratory (or, as in many cases, by both methods simultaneously). It should be noted that although the vessel is stopped some drifting is unavoidable.

Whilst the through depth measurements were being made (taking up to about 8 minutes) the signal from the ADCP run was recorded and the data file saved and stored for subsequent analysis. Plates 2 and 3 show screen dumps of each of the ADCP calibration runs. The overlay shows the suspended solids concentration at the approximate sampling point thorough the depth and with respect to time. The fine black line close to the bed in each of the colour plates is the 15% line (15% of the total depth) below which the backscatter information from the ADCP may not be as clear as that received from elsewhere through the depth.

It can be seen from Plates 2 and 3 that in most cases a sufficiently large increase in measured concentration is associated with a change in backscattered signal from the ADCP ie. a different colour band. The colour scale is shown on the right hand side of the plate and relates each colour band to a return signal strength. The greater the strength of the return signal the higher the suspended solids concentration is. Generally low concentrations exist close to the water surface (depicted as light/dark blue, closer to the bed higher concentrations are normally found (depicted as light/dark red). Intermediate colours (white and yellow) represent intermediate concentrations.

In some cases the plume generated by the passing of a dredger can be seen. In Plate 3 at HW-0.18 to HW-0.02 hours a plume can be seen passing beneath the vessel with a relatively small core of high concentration (depicted in yellow). Associated with this yellow 'plug' the through depth profiling also detected a small region of relatively high concentrations (360mg/l compared with the surrounding 45mg/l).

In other cases very little difference in through depth concentration was detected. Plate 2 at HW+0.52 to HW+0.57 hours shows only small changes in the returned ADCP signal (depicted light blue, yellow and white). The measured concentrations shown on the overlay confirm that the through depth variations were fairly constant (and low) at about 65mg/l.

The maximum concentration measured by pump sampling (3,200mg/l) was obtained close to the bed at HW+3.28 hours (Plate 3). The ADCP record confirms the proximity to the bed (depicted as black). The red layer above this, however, is also shown to be of a high concentration (2,770mg/l). Above the 15% line the concentrations are shown to be fairly steady. It is interesting to note here that the pumped sample taken from within the white band immediately above the 15% line shows the concentration to be 470mg/l ie. lower than that in the water column above it (540mg/l). The colour banding endorses this observation showing a deep band of yellow above that of the white.

Plate 4

Two further calibration trials were carried out over a plume generated by WD Medway II dredging in the navigation channel approximately 1km downstream of Ture Point.

The ADCP transect made at HW+4.27 to HW+4.32 hours appears to show two independent areas of low suspended solids concentration at about 5m below the surface (depicted in blue). These areas are in fact one and the same as the vessel was being held relatively stationary apart from a small amount of unavoidable drift, which in this case took the vessel from one side of the plume, over the plume, and back again. The concentrations measured by pumped sampling are shown in the overlay. In this case there is little agreement between the measured concentrations and the image generated by the ADCP. The concentrations do however support the detection by the ADCP of a low concentration pocket close to the bed.

The second calibration trial carried out at this location consisted of making a continuous through depth profile of concentration using pumped sampling and the optical monitor at a fixed position over a relatively long period. The ADCP record is shown in Plate 4 at HW+4.34 to HW+4.41 hours. The measured suspended solids concentrations are shown on the associated overlay. In this case there is some evidence of a relationship between concentration and colour though nothing which holds throughout the exercise.

From the calibration trials it is often possible to quantify each of the ADCP run colours into approximate bands of suspended solids concentration. However the determined colour scale only occasionally holds true for the entire ADCP run during which the calibration was undertaken. From one run to another a given colour can represent a wide range of concentrations depending on the conditions at that point. This occurs because the ADCP does not record the absolute intensity of backscatter but rather a relative backscatter. The threshold of this relative backscatter can alter between successive 'pings'. Despite this the benefits of having an instantaneous quantative 'impression' of the generated plume are enormous.

Cornelia

Plates 5a and 5b

The 6,400m^3 trailing suction hopper dredger Comelia was studied whilst she was dredging sand in the navigation channel, inward bound at Redcastle Light. A series of transects were made across the navigation channel astern of the vessel in order to observe the dispersion and decay of the generated plume. The ADCP images from each of the transects are presented in Plates 5a and 5b.

The first transect of the series was made across the channel as Cornelia approached (HW+1.23 to HW+1.27 hours, Plate 5a). This provided a base background condition which shows that the suspended solids concentrations in the channel, prior to the passage of the dredger, are well distributed as would be expected. Once the dredger has passed (HW+1.37 to HW+1.39 hours, Plate 5a) a 20m wide plume, generated by the trailing arm, can clearly be seen throughout the water depth, with the highest concentrations observed close to the bed.

At the time of the next cross-channel transect (HW+1.40 to HW+1.42 hours) the mid-channel plume can be seen to have reduced in concentration, particularly closer to the surface. The plume encroached onto the side slope.

By HW+1.43 to HW+1.45 hours the plumes are decaying with higher backscatter (red) only present close to the bed. There is now a fairly wide band of relatively clear water between the plumes on the sideslope and mid channel. Subsequent transects (Plate 5b) show that the plumes continue to disperse and reduce in concentration, tending towards the original (pre-dredge) base line condition. Passage of the Cornelia is not detectable at the site after about 20 minutes.

WD Medway II

Plate 6

It has been established that air bubbles affect the return signal from the ADCP in a similar way to changes in the concentration of suspended solids. In order to ascertain the extent of the effect of air entrained into the water column due to propeller action a trial was carried out on the 3,500m^3 trailing suction hopper dredger WD Medway II. A transect was first made in front of Medway II thus providing a base background condition. A second transect was then made 200m astern of the vessel. The recorded transects are reproduced in Plate 6 which shows that the passing (non-dredging) vessel generates a 'bubble plume' some 65m wide. Close to the bed the return signal from the ADCP remains largely unaffected, whereas at 3m below the surface large variations were detected due to the rising bubbles.

This exercise demonstrates the effect which bubbles in the water can have on the data received from the ADCP. This shows the importance of firstly being aware of when there are likely to be bubbles present in the water column, and secondly, being able to distinguish between real changes in suspended solids concentration and those apparent changes due to entrained air.

Plate 7

Plate 7 shows a series of transects made at Longfield Light in the navigation channel of WD Medway II dredging in mud. The first transect (HW+3.12 to HW+3.13 hours) was made in front of the vessel thus providing a typical background return signal. A second transect was made 250m astern of the vessel once it had passed (HW+3.18 to HW+3.19 hours). This shows very clearly a dense 25m wide plume of material throughout the depth of the water column (depicted in red). Near to the surface and close to the bed the concentrations are less than in the centre of the plume, which is about 4.5m below the surface. Through the centre of the plume the signal from the ADCP is lost due to turbulence caused by the passage of the vessel.

A third transect was made well astern of Medway II at HW+3.29 to HW+3.30 hours. This shows that concentrations in the surface 4m have returned to background level. Concentrations in the remainder of the water column have also reduced though not as much.

Plate 8

Plate 8 shows a series of transects made astern of WD Medway II dredging in mud at Longfield Light in the navigation channel. At HW+4.02 to HW+4.04 hours (100m astern of the dredger) a 30m wide plume is clearly visible in the centre of the channel. There is also some evidence of increased concentrations on the channel side slope. As in Plate 7 the centre section of the plume is lost, probably due to turbulence caused by the passage of the vessel.

The succeeding transect (HW+4.04 to HW+4.05 hours) shows that the effect of the passage of the dredger has largely diminished. Concentrations are mainly affected between 2 and 4 metres below the surface. Subsequent transects show the plume diminishing further as concentrations return towards a typical background level.

WD Dredgewell

Plate 9

Dissipation of the plume generated by the operation of the grab dredger WD Dredgewell was studied whilst she worked in heavy clay on the channel side slope adjacent to Longfield Light.

Plate 9 shows a series of transects made downstream of the Dredgewell which was continually operating. The first transect was made immediately astern of the dredger at HW+2.50 to HW+2.51 hours. This shows the 30m wide plume at the top of the side slope. It is interesting to note that in this case the generated plume is wider close to the surface than at the bed. It was observed during the field exercise that as the grab was lifted clear of the water a surface plume was generated by the draining of silt laden water from the bucket back into the water. Large clods of clay also fell back into the water which would have inevitably have contributed to the density of the surface plume.

The next transect was made 50m downstream of the Dredgewell at HW+2.54 hours. The plume is still present though it is now of a lower suspended solids concentration indicating that either the majority of the material has settled onto the bed or the plume has dispersed within the channel (or both). The width of the plume remains at about 30m.

A transect made 100m downstream of the Dredgewell at HW+2.57 to HW+2.58 hours shows that the plume has almost completely dispersed with channel concentrations having returned to a typical background level. Similarly the last transect made at HW+3.01 to HW+3.02 hours (150m downstream of the Dredgewell) shows no evidence of the plume still being present.

The maximum concentration recorded in the plume alongside the Dredgewell was about 3,500mg/l close to the bed (surface -4m), reducing to 250mg/l at 1m below the surface.

In general measured concentrations were not as high as this but it was observed that the highest concentration was consistently measured close to the bed.

Norma

A number of ADCP transects were carried out adjacent to the plough Norma. The return signals from these transects were very often difficult to interpret or indeed the signal was lost altogether in some cases. This was undoubtedly due to the enormous amount of turbulence generated by the ploughing process. However, standard measurements of suspended solids concentrations in the vicinity of the plough were unable to detect significant increases above background levels. It should be noted that in many cases Norma was working in sand which firstly settles back to the bed more quickly than silt and secondly is not detected by the optical suspended solids monitor.

Turning circle area

Plate 10

A transect made across the turning circle showed two separate plumes approximately 100m apart. At the time when the transect was made. The Medway II had just left the turning circle after having finished dredging. The reason for the two plumes was that Medway II was dredging in circuits over the turning area, dredging first in one direction then turning and dredging back in the opposite direction. It is interesting to note that between the two plumes the near bed suspended solids concentrations are higher that to either side of the dredged area.

It was discovered that an eddy existed within the turning circle. There may therefore have been a tendency for material to accumulate in the turning circle during dredging rather than to be immediately dispersed upstream or downstream.

CONCLUSIONS

- From the calibration tests it is often possible to quantify each of the ADCP run colours into approximate bands of suspended solids concentrations determined from coincident water sampling.

- The determined colour scale only occasionally holds true for the entire ADCP run during which the calibration was undertaken.

- From one ADCP run to another a given colour can represent a wide range of concentrations depending on the conditions at that point.

- Because of the narrow band ADCP beam configuration backscatter information close to the bed (less than 15% of the total depth) may not be as clear as that received from elsewhere in the water column and must therefore be treated as being less reliable.

- The passage of a non-dredging vessel generates a 'bubble plume' which is detected by the ADCP, and visually presented in the same way as a turbidity plume.

  It is therefore very important to firstly be aware of when there are likely to be bubbles present in the water column, and secondly, being able to distinguish between real changes in suspended solids concentration and those apparent changes due to entrained air.

- ADCP runs carried out astern of the trailing suction dredgers showed that the generated plume could be very clearly located though not necessarily quantified in terms of suspended solids concentrations.

- It was observed that the generated plume remained within the confines of the navigation channel and could be detected up to about 300m astern of the vessel (Medway II dredging in mud).

- ADCP transects made 100m downstream of the grab dredger WD Dredgewell working in heavy clay indicated that the generated plume had almost completely dispersed.

- Return signals from ADCP transects made adjacent to the plough Norma were very often difficult to interpret due to the amount of turbulence generated by the ploughing process. Standard measurements of suspended solids concentrations in the vicinity of the plough did not detect any significant increases above background level.

- The trials carried out in Lough Foyle illustrated that the ADCP was an excellent tool for indicating the location and relative density of plumes generated by the dredging processes in operation.

- Further development of both the associated software and water sampling technique is required in order to improve the quantification of the observations in terms of in-situ suspended solids concentrations.

ACKNOWLEDGEMENTS

The assistance of various staff of Westminster Dredging Limited throughout this study is gratefully acknowledged. In particular thanks go to Tony McDonald the boatman of the tug Plover throughout the week. His willingness to participate in the manoeuvres required for the monitoring exercise was most welcome.

This study was carried out by Dr M P Dearnaley and Mr N G Feates from HR Wallingford and Dr D L Stewart of Wimpey Environmental Limited. Mr T N Burt (HR Wallingford) and Mr G van Raalte (Hydronamic bv) participated in the survey on the 9-11 February.

Plate 1 ADCP installed on WD Plover in Culmore Bay

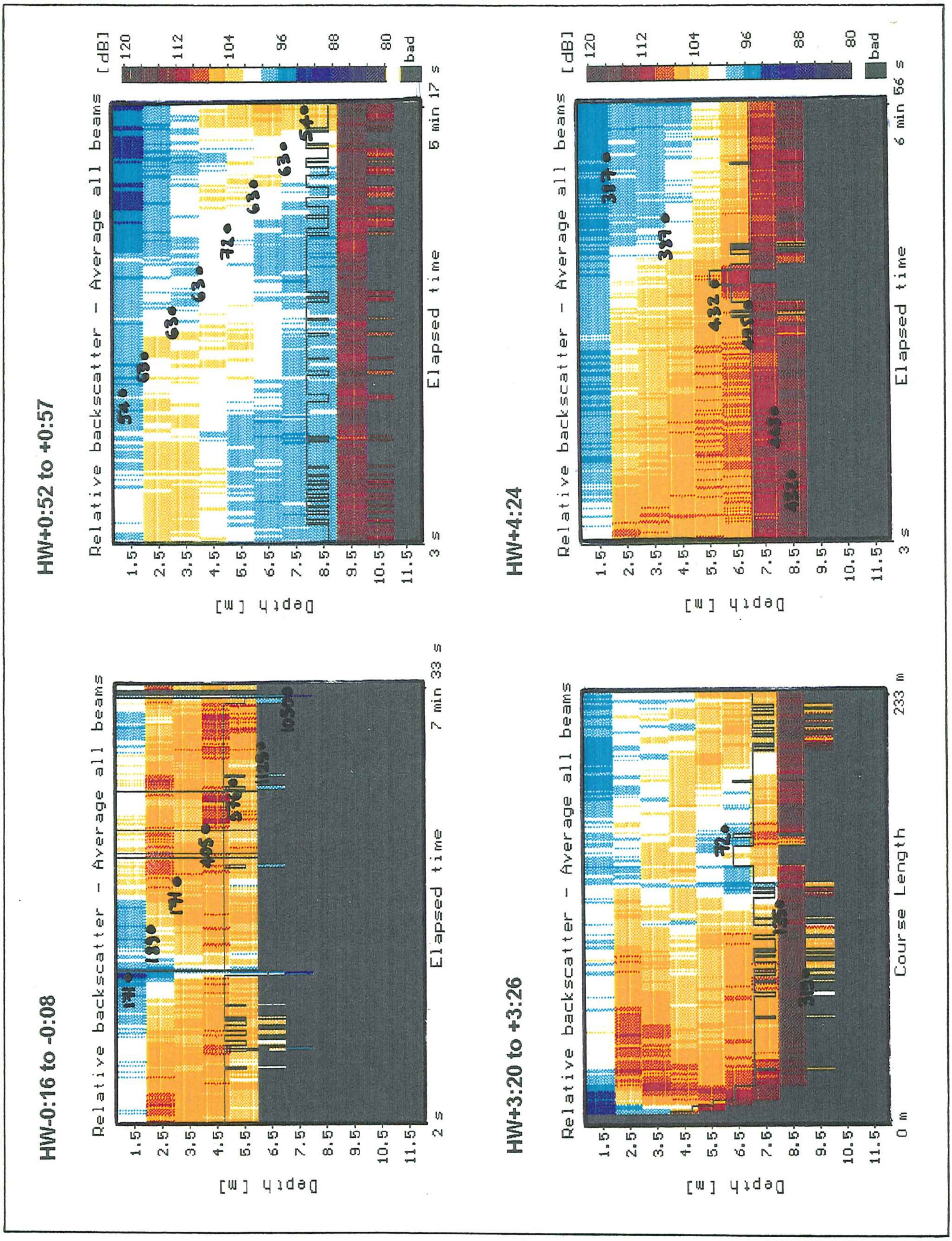


Plate 2 ADCP calibration trials

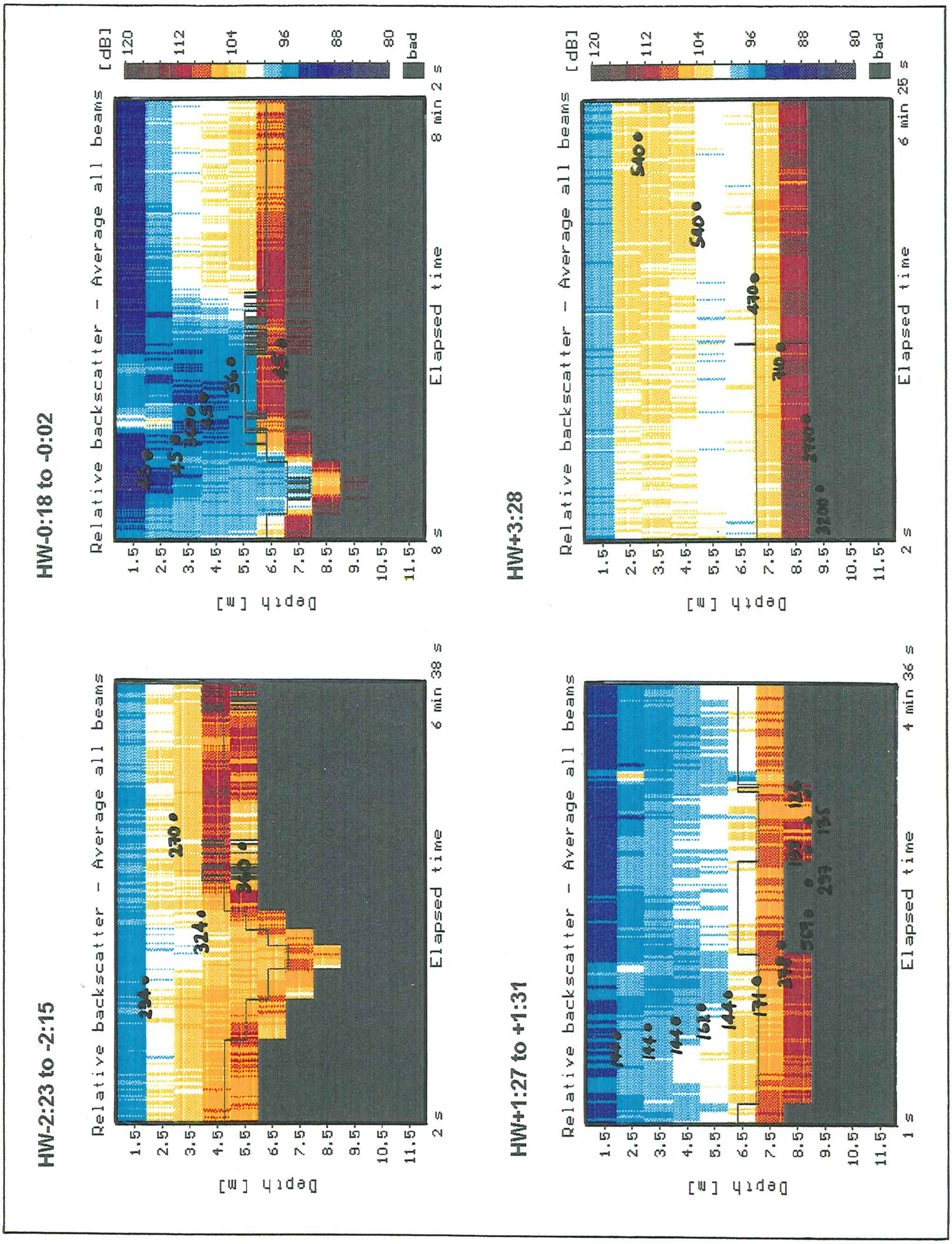
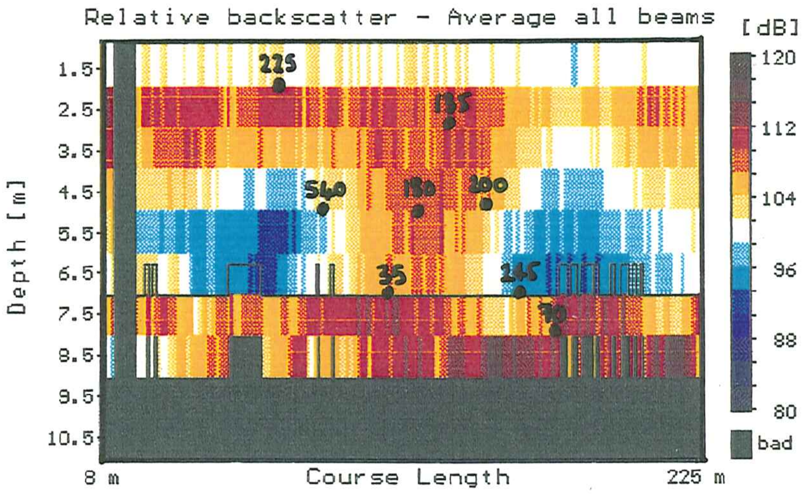


Plate 3 ADCP calibration trials

HW+4:27 to +4:32



HW+4:34 to +4:41

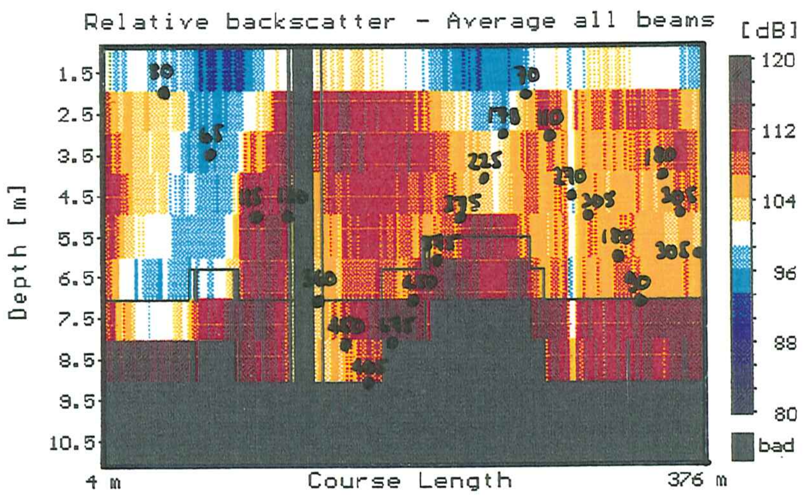


Plate 4 ADCP calibration trials

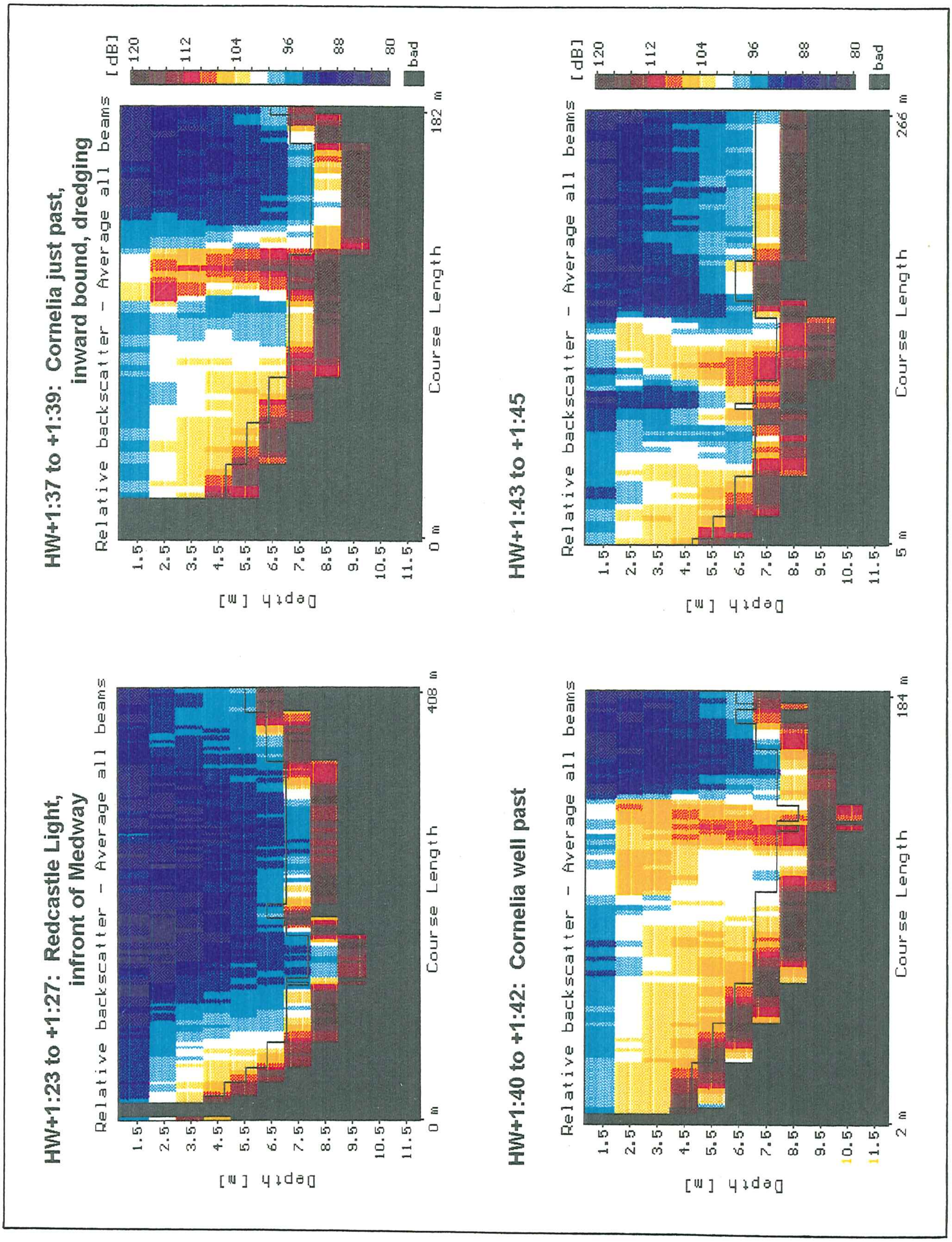


Plate 5a Dissipation of plume generated by Cornelia dredging in sand - Redcastle Light area

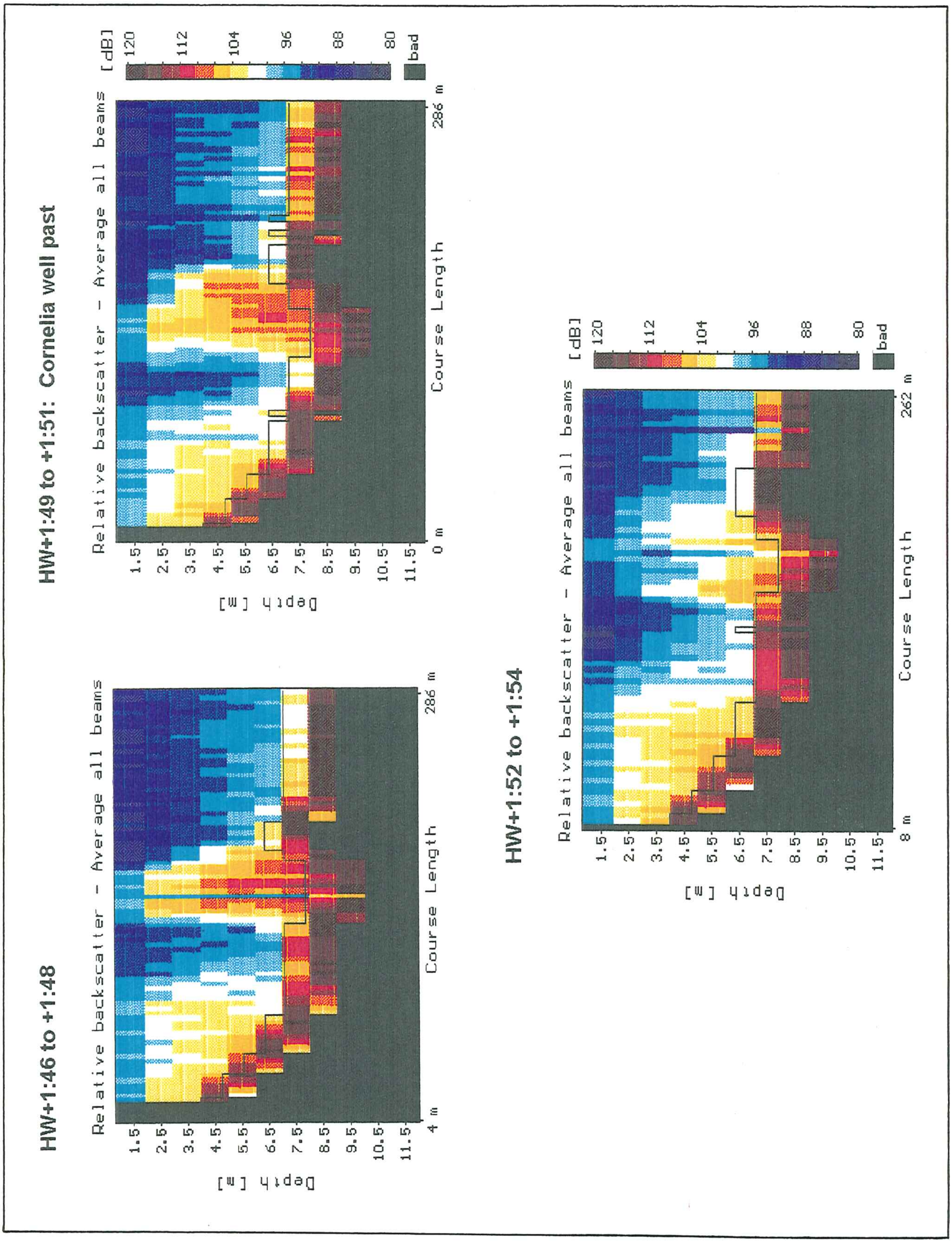
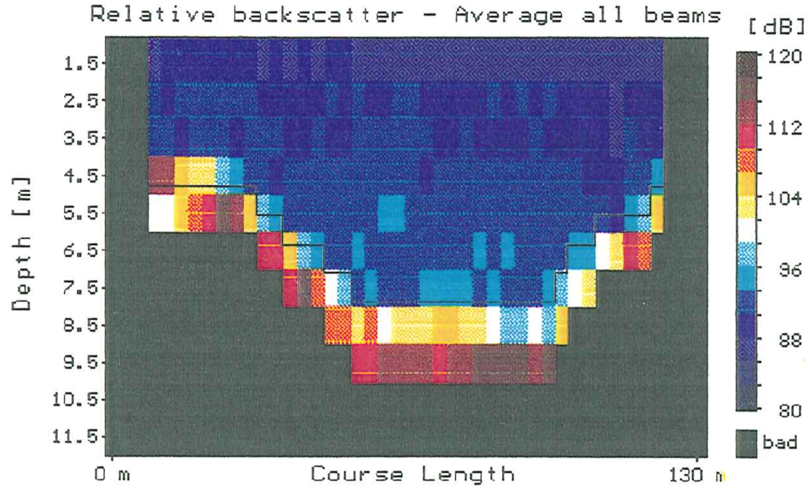


Plate 5b Dissipation of plume generated by Cornelia dredging in sand - Redcastle Light area

HW+2:54 to +2:55: Upstream and infront of Medway,
dredging but no overflow



HW+3:01 to +3:02: 200m astern of Medway

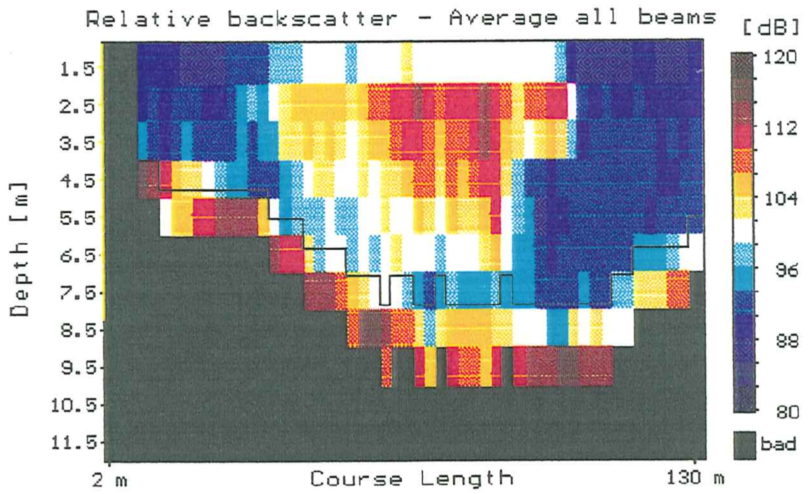


Plate 6 Backscatter from ADCP due to the passage of Medway II - Longfield Light area

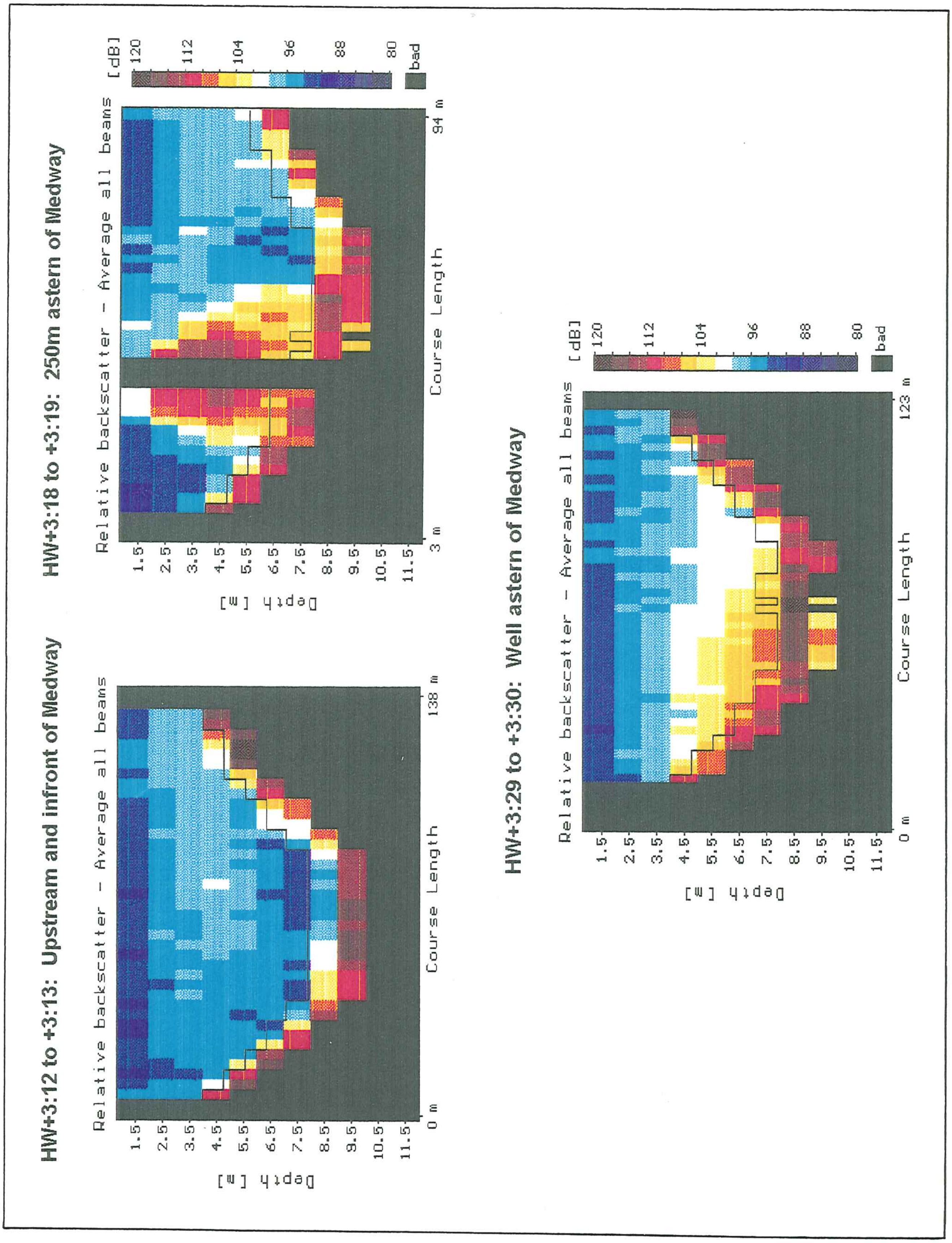


Plate 7 Dissipation of plume generated by Medway II dredging in mud - Longfield Light area

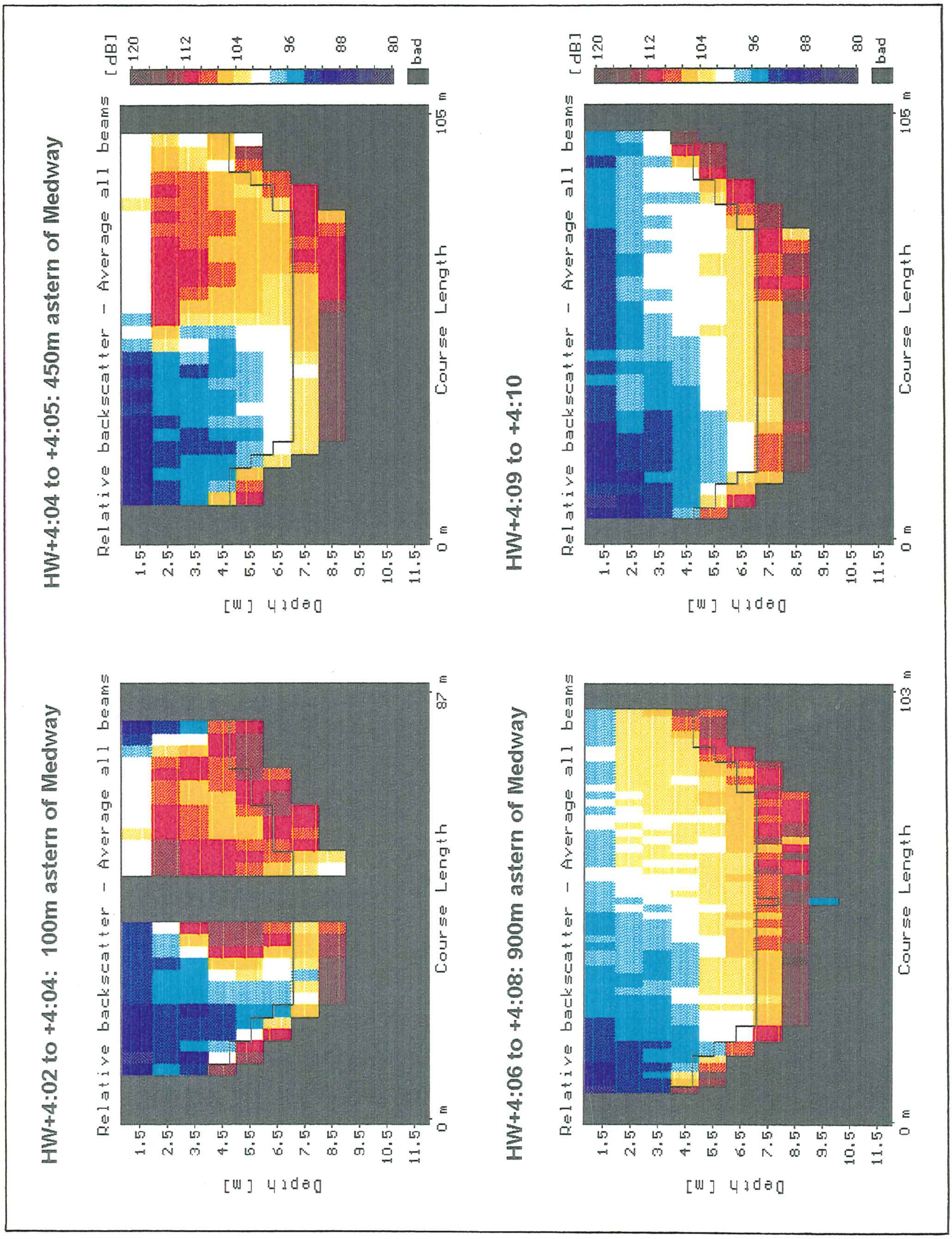


Plate 8 Dissipation of plume generated by Medway II dredging in mud - Longfield Light area

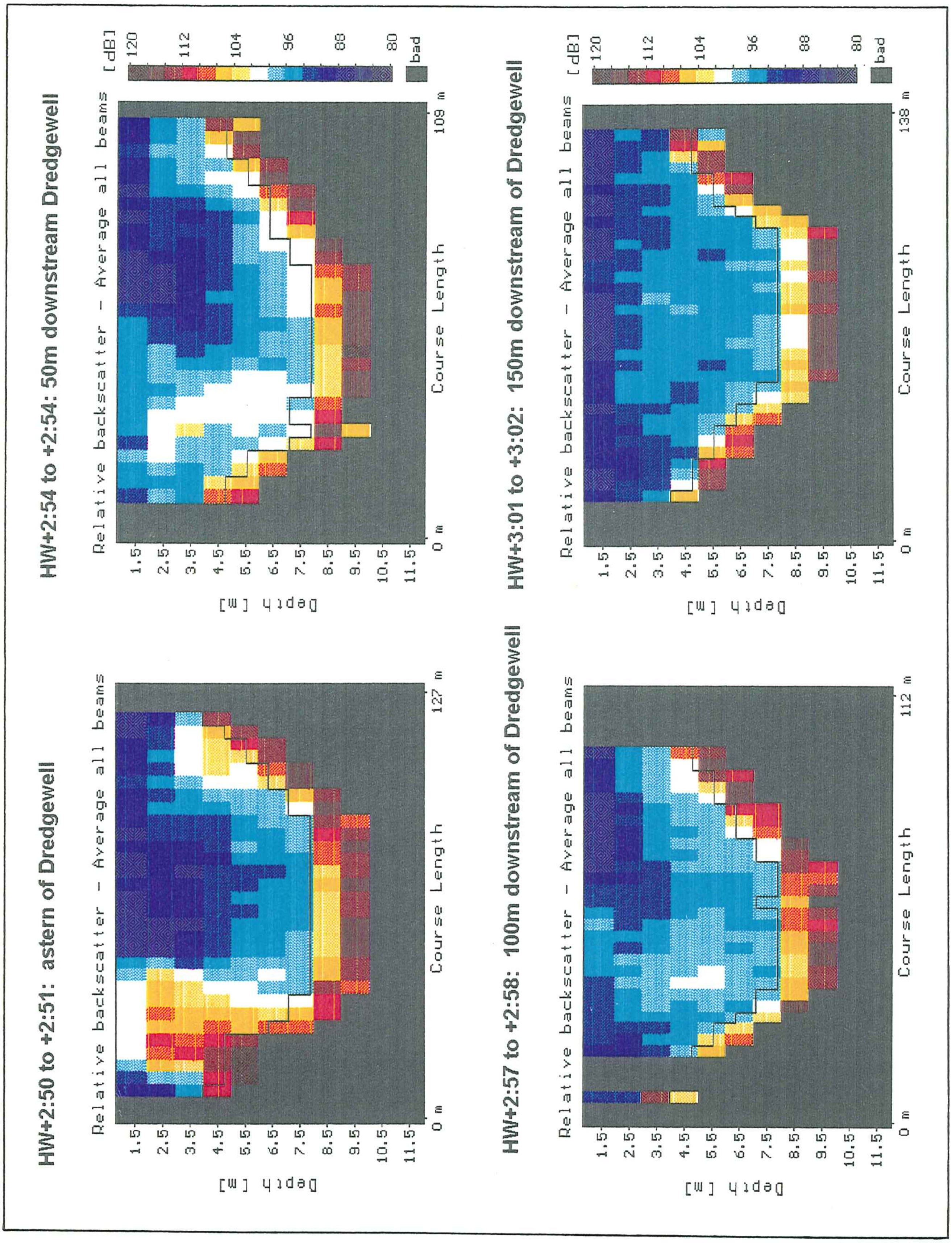


Plate 9 **Dissipation of plume created by Dredgewell dredging in mud - Longfield Light area**

HW+6:45 to -5:43: Turning circle, Medway just left

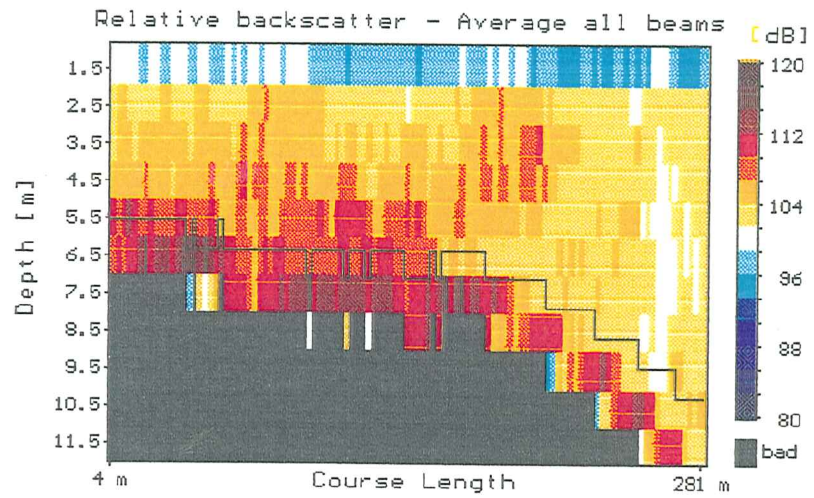


Plate 10 Plumes generated by Medway II having just finished dredging in the turning circle

Appendix 2

Maintenance dredging on the River Tees

Appendix 2 Maintenance dredging in the River Tees

Introduction

Background

Dredged material dispersion is of considerable interest in a number of activities including the dredging and open water disposal operations in harbours and estuaries and the turbidity associated with marine mining of sand, gravel or other constituents of the sea floor. Historically maintenance dredging has been carried out using local experience to determine when and where to dump the dredger spoil. In addition, and perhaps more importantly, dredging exercises in channels which pass through industrial areas involve moving sediments which may have significant accumulations of pollutants. These either become concentrated on the spoil grounds, or thrown into suspension in the mud clouds caused by dredging works. It is clearly of interest then, from an environmental point of view as well as from an engineering standpoint to gain greater insight into the dispersal of material arising from dredging operations.

Mathematical models are recognised as useful tools in many research programmes, and in the context of dispersal of dredged spoil, polluted or otherwise, they attempt to answer the two questions regarding where the material goes to and what happens to it on the way. The answer to the first question is also governed by the hydrodynamic processes taking place in the area of dispersal. The answer to the latter question is also governed by the physical processes of sediments falling to the bed.

The main object of this report is to compare ADCP measurements of dredged soil dispersal with the results of a simple diffusion model. This is also a validation exercise for the model.

Outline of the study

The River Tees is located in the North East of England on the North Sea Coast. The estuary is of the partially mixed type. Tidal currents are significant, and so the whole water mass moves up and down the estuary with the flood and ebb tides. Consequently, in addition to the current shear at the salt water/freshwater interface, friction at the estuary bed generates turbulence which causes even more effective mixing of the water column than that caused by waves at the fresh water/salt water interface. The currents caused by the mixing of freshwater and salt water in partially mixed estuaries are referred to as residual currents and they are, typically, less than 10% of the magnitude of the tidal currents superimposed on them. However, they are important when we consider how sediment is transported. Hence the estuarine sediments in the River Tees are likely to be a mix of fluvial and marine origins.

The objective of the study is to improve the understanding of the dredging processes and may therefore lead to improvements in dredging efficiency. While the measurements will give an indication of the impact of the practise of overspill and may enable further optimization of the dredging cycle, both in sand and silt dredging, the application of the model will provide an economic means of predicting the dispersion of dredged material in tidal waters.

Report structure

The first element of the study described in this report is the collection of further field data from the River Tees estuary. In Chapter 2 there is a brief description of the VMADCP measurements and of some results from these measurements. The model used for the simulations is discussed in Chapter 3 as are the tests of the dispersion patterns during the dredging. Finally, the conclusions drawn from this work are described in Chapter 4.

Backscatter measurements with the VMADCP

Methodology

One element of the study described in this report is the collection of further field data from the River Tees estuary. The purpose of the measurements was to determine the suspended sediment concentrations within sediment plumes generated by a trailer suction dredger operating in both sand and silt reaches of the river. As well as providing information about the concentrations within the sediment plume, the measurements also enabled the dimensions of the plume to be observed and recorded as it evolved and decayed.

The measurements were carried out with an RD Instruments (RDI) Vessel Mounted Acoustic Doppler Current Profiler (VMADCP) deployed in such a manner as to display and record the pattern and distribution of varying concentrations of suspended material. This is a relatively new technique which has only been used by HR for some recent studies. The field exercise was undertaken during the high spring tides of 9-10 August 1994.

The VMADCP measures Doppler frequency shift between acoustic pulses transmitted by the instrument and the return signals reflected from scattering particles such as phytoplankton, bubbles and suspended sediment in the water column. Four acoustics beams are each projected at 30° to the vertical and at equal 90° spacings in the horizontal plane. The vertical resolution of the instrument is 1.0m. The frequency shift is then used to infer the local water velocity relative to the instrument and the vessel track over the ground. A recent innovation has been to measure the strength of the returning acoustic signals as an indication of the suspended sediment concentrations in the water column. This enables the location and approximate dimension of a plume of material to be determined.

Data processing occurs in two stages. The first takes place within the VMADCP and determines how many acoustic pulses are used to compute the velocity or relative backscatter readings relayed from the VMADCP to the onboard computer. The second stage of processing occurs in the onboard computer and mainly affects the displaying of the data.

Because of the beam configuration and operation mode data from close to the bed (up to 6% of the water depth) is not processed reliably due to possible reflections directly from the sea bed. Similarly, because the VMADCP is mounted below the surface of the water, a short 'blank' period is required before backscattered signals are measured. The VMADCP, therefore, does not process data measured in the top 1.5m of the water column. Where necessary an estimate of the flow field in these parts of the water column can be made by extrapolating from intermediate depths.

Sediment fluxes

As part of this study, a computer programme was developed which enabled the sediment flux through each transect to be calculated.

Previous studies resulted in the view that the most accurate method for calculating sediment flux involved the conversion of the VMADCP backscatter data into suspended solids concentrations followed by the integration of the estimated concentrations and the associated VMADCP current measurements to provide fluxes of sediment in suspension.

In order to carry out this method of determining fluxes, a relationship between relative backscatter intensity and suspended solids concentrations was first derived based on the range of relative backscatter returned by the VMADCP during each particular transect.

Calculation of fluxes

For each transect the sediment flux is calculated independently for each bin through the water column. The computer program first checks that the returned level of backscatter intensity from at least 3 or the 4 beams is within a predetermined error band, typically 10dB. If this test is not satisfied then the data from that bin is not processed. If the test is satisfied the beam intensities within the error band are averaged for further processing. In addition to averaging, the minimum and maximum intensities are extracted. Based on the relationship determined, as described in the previous section, the minimum, mean and maximum backscatter intensities are converted into suspended solids concentrations.

Associated with each ensemble within a transect is a course length which corresponds to the distance that the survey vessel has moved between ensembles. The sediment fluxes in each bin within an ensemble in the east and north direction are therefore calculated based on:

$$\text{Flux} = \text{Concentration} \times \text{Course Length} \times \text{Current Speed} \times \text{Bin Depth}$$

$$[kg/m^2/s] = [kg/m^3] \times [m] \times [m/s] \times [m]$$

The total flux along a transect line is the sum of all the fluxes calculated within each bin of each ensemble.

Results

During the two days of VMADCP measurements 6 loading cycles of the trailing suction dredger 'Heortnesse' were observed, 3 whilst dredging in sand reaches of the river and 3 whilst dredging in silt reaches. For each loading cycle the data obtained from each of the transects was processed as described in the previous sections.

Figure 1 shows examples of 3 transects made whilst dredging silt. The figure shows the visual representation of the plume in terms of relative backscatter intensity. Higher suspended solids concentrations are represented by higher levels of relative backscatter intensity. Also shown is the course taken by the survey vessel, current speed and direction.

Figure 2 illustrates the computed variation in the mean sediment flux with time in the East and North directions for a 3 hour period whilst dredging silt. For clarification each passage of the dredger is also marked. The figure clearly shows a sudden increase in sediment flux soon after the passage of the dredger. This increase is generally larger during the weiring phases of the dredging operation. As the generated plume disperses and settles back onto the bed of the river so the computed flux steadily reduces back to the pre-dredging background level.

The mathematical model

General description of the physical processes

The dispersion and deposition of suspended solids depends mainly on magnitude and direction of the tidal currents, on the settling velocity of the sediment and on the natural turbulence within the flow.

Current velocity

The movement of particles originating from a surface source is distinct from the motion of particles originating from the bed. In the latter case motion is caused by water flowing over the bed and sediment may be carried at a reduced velocity as in the case of a contact load, or intermittently as the case of a saltation load. From a surface source however, the horizontal velocity of a particle is determined by the bulk movement of the water into which it falls. This motion is known as advection.

Settling velocity

The trajectory of the particles comprises the horizontal component of velocity imparted by advection and a vertical component of velocity is dependent on the characteristics of the flow, such as turbulence, and on the properties of the sediment itself. The latter can be further divided into properties of the particle such as size, shape and density, and those of the sediment as a whole such as its tendency to flocculate. The settling velocity reflects these properties.

Diffusion

In a current an initially dense cloud of suspended material is advected away from the source at the same rate as the current. Longitudinal diffusion, caused by the differences in current velocity between the surface and the bed, is orders of magnitude smaller than the effects of advection. Lateral diffusion determines the rate of spread of the cloud, and occurs by reason of the natural turbulence generated within the moving current. Within an estuary, where the scale of turbulent eddies is restricted laterally, the cloud moving with the current may form a long thin ribbon, spreading sideways only very slowly. In open water, however, turbulence occurs over a much wider range of scales and the rate of mixing length will be dependent on the relative sizes of the cloud and the turbulent eddies.

The differential equation

The model described attempts to simulate the dispersion of spoil over a wide area. It does not make provision for the mechanism that give rise to very local dispersal. The model is based upon the equation for the conservation of matter simplified to represent the mean concentration of suspended solids over the depth and deposition on the bed as a function of distance from the source and time.

The basic differential equation is

$$\frac{\partial}{\partial t}(dc)+\frac{\partial}{\partial x}(duc)+\frac{\partial}{\partial y}(dvc)-\frac{\partial}{\partial x}(dD_x\frac{\partial c}{\partial x})-\frac{\partial}{\partial y}(dD_y\frac{\partial c}{\partial y})+W_s(c-c_e)=0$$

where:

c = depth averaged concentration (kg/m^3)
d = water depth (m)
x,y = coordinate directions parallel and normal to the flow (m)
u,v = flow velocity in the x and y directions respectively (m/s)
D_x,D_y = diffusion coefficient in the x and y directions respectively (m^2/s)
W_s = particle fall velocity (m/s)
c_e = depth averaged background (kg/m^3) ($c > c_e$)
t = time (s)

The model is a steady state analytical model in which a release of material is considered to be either steady and continuous or instantaneous. Depth is uniform throughout and the longitudinal and lateral diffusion coefficients are set to constant values. The zone of interest is subdivided into a number of relatively small cells of dimensions Δx and Δy and the model determines either the concentration or the deposition at each node of the grid.

The initial dispersion of silt and clay sized particles released into the water column has been modelled for this study using a Gaussian diffusion model. The model assumes a constant bed level and a uniform velocity distribution. Both of these assumption are only approximations and in reality the variability of these terms creates additional turbulence and hence additional dispersion. It is also assumed that the flow is unidirectional. Since diffusion is greatest in the same direction of the flow, this assumption means that the direction of greatest diffusion is always the same. A further assumption is that the settling velocity of suspended material is constant and the same for all the particles; in this way it is not related to the concentration of fines in the plume.

Diffusion is the spread of material away from the main cloud. This occurs under the influence of natural turbulence within the moving currents. Longitudinally, in the direction of flow, there is, however, an additional, more important mechanism. This is caused by the differences in water velocities between the bed and the surface. Longitudinally, diffusion is therefore considerably higher than laterally.

Taking account of these assumptions the basic equation reduces to:

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

This partial differential equation is the continuity equation for the spread of material from a source. The terms represent the rate of change of concentration with time, the rate of decrease of concentration per unit volume by advection, longitudinal diffusion, lateral diffusion, and loss of material from suspension due to deposition, respectively.

The method of Carslaw and Jaeger (Ref 1) can be used to solve this equation for the instantaneous release of a slug of material into the water column. This gives a gaussian concentration profile with the centre moving downstream at velocity u, and with a decay term to represent material falling out of suspension to the bed.

The model is developed by repeatedly applying a number of such solutions over short time periods and adding them together to represent a continuous release of material.

Once the material has settled out of the water column, the possible re-erosion of this material is not considered in this model. In practice, however it is estimated that more often than not the majority of cohesive material that settles out during slack water periods is re-eroded during the subsequent peak flow period. In this respect therefore, the model underestimates the suspended concentrations.

The velocity is also assumed to be horizontal, so the effect of any vertical or density current is not represented, along with the associated additional turbulence.

Application of the model

A number of model runs were made changing values of the diffusion coefficients D_x and D_y, of the number of time steps at which material is released from the dredger and of the rate of release of the material.

Tests with field data

The model was set up to represent the 3 hour period of dredging shown in Figure 2. The depth averaged values of the velocity were extracted from the ADCP data and interpolated in order to obtain them for each temporal step, in this case every 300 seconds.

In order to represent the movement of the dredger as realistically as possible it was decided to change the speed of the dredger according to the direction of the current. When the dredger was moving in the same direction as the current, the velocity of the dredger in the water was 0.5m/s, and when the dredger was moving against the current, its velocity was 1m/s relative to the water.

Results and comparisons with field data

The results of the final run are visible in Figure 3. It is possible to compare the response of the model for the sediment flux with the results of the observed data for the mean sediment flux (Figure 2). It is clearly visible that the response of the model is acceptable both in qualitative and quantitative terms: we have obtained the highest values of sediment flux (between 20 and 30Kg/s) at time steps close to the passage of the dredger and this echoes the results of the observed data.

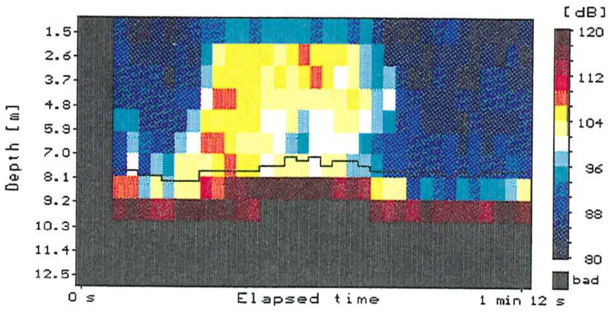
Conclusions

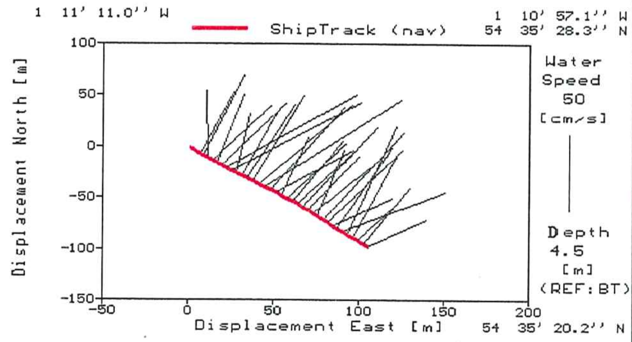
A computational model was applied to simulate the dispersion of dredger material in the estuary of the River Tees, which is located in the North East of England on the North Sea coast.

The model was based on an analytical solution of a simplified differential equation which described the spread of material from a source. It was assumed that the current velocity, depth of flow and turbulent diffusion remained constant for the length of a plume, the flow was parallel to the x-direction and the material was fully mixed throughout the depth.

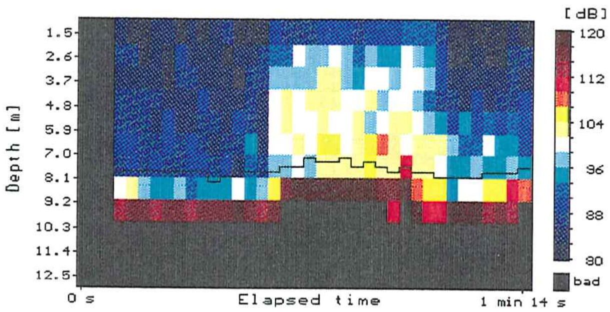
The application of the model has provided an economical means of predicting the dispersion of dredged material in tidal waters. The runs were made based as closely as possible on the field data obtained during the programme of measurements carried out on the River Tees estuary in August 1994. From this study a sudden increase in the values of sediment flux is emphasized after each passage of the dredger. This increase seems to be larger during the weiring phases of the dredging operations.

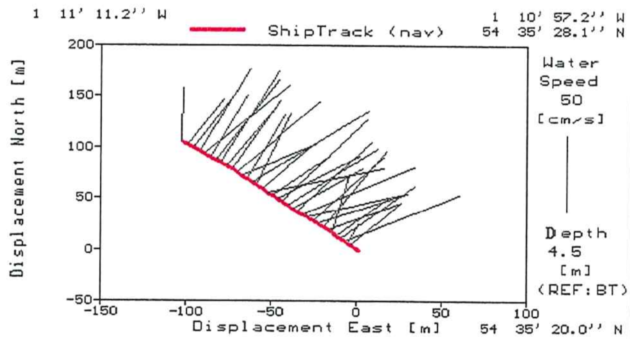
Transect T10A022
SE transect 09:26:24 - 09:27:30



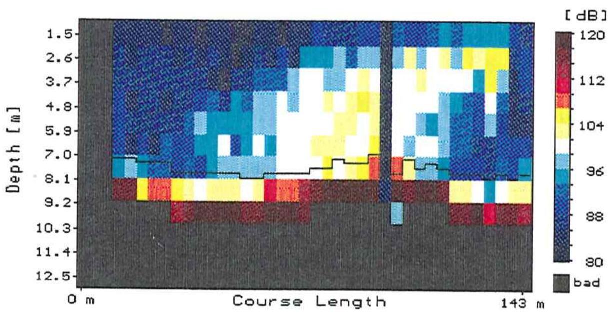


Transect T10A023
NW transect 09:32:41 - 09:33:55





Transect T10A024
Transect 09:39:05 Wilton just passed on north side. Dredger passes 09:40:57 (bow), 09:41:34 (stern)



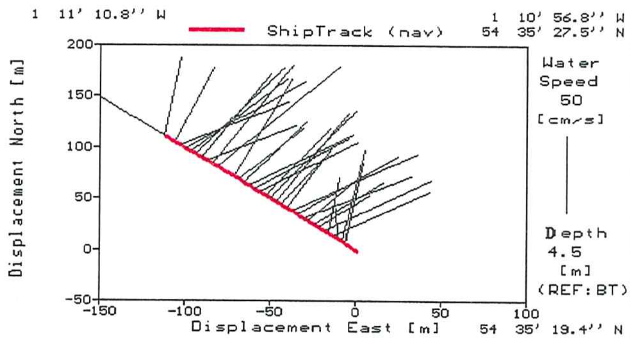


Figure 1 Examples of transects through the plume showing relative backscatter and current speed and direction

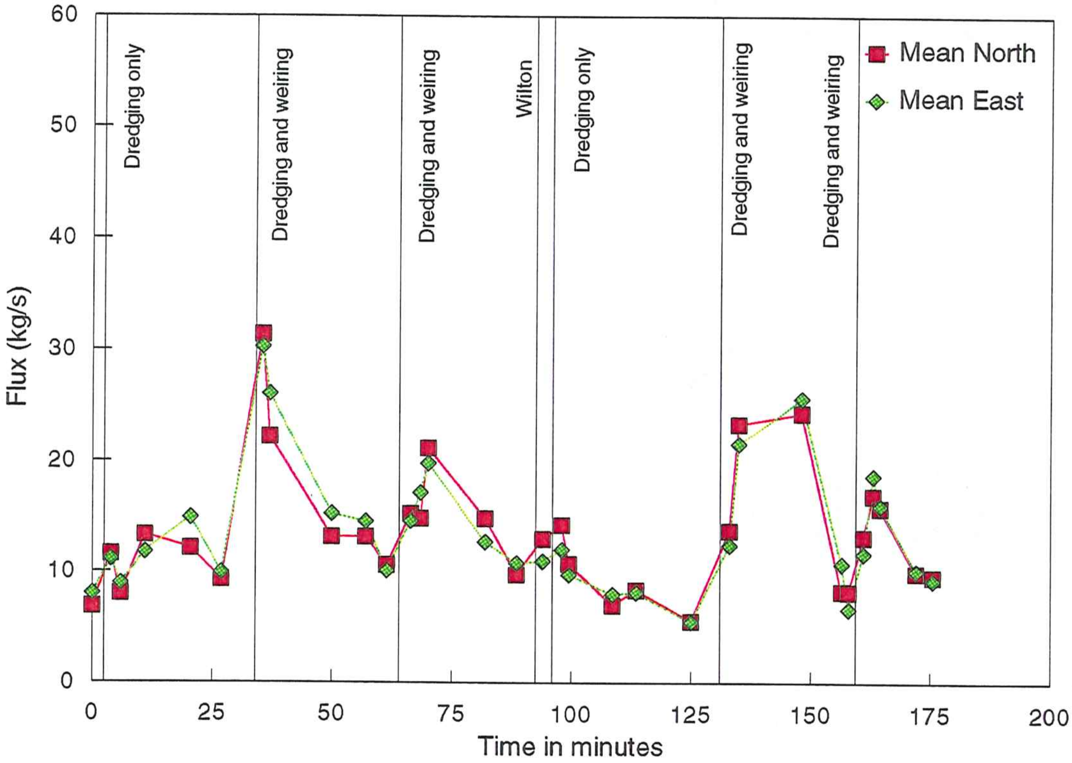


Figure 2 Measured sediment flux based on ADCP and water sample data

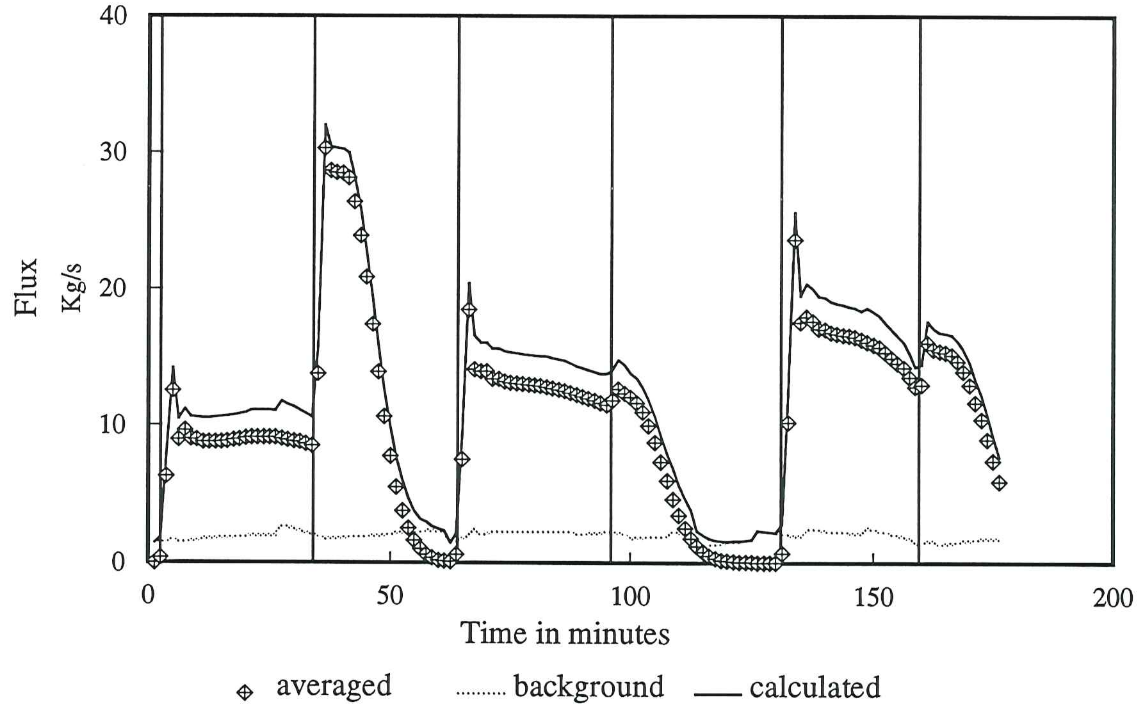


Figure 3 Calculated sediment flux using the computational model