MARINE AGGREGATE MINING

BENTHIC & SURFACE PLUME STUDY

FINAL REPORT

To:

UNITED STATES DEPARTMENT OF THE INTERIOR
MINERALS MANAGEMENT SERVICE
&
PLUME RESEARCH GROUP
(ARC Marine Ltd)
(South Coast Shipping Company Ltd)
(United Marine Dredging Ltd)
(HR Wallingford Ltd)

MMS OCS STUDY NUMBER 99-0029

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ABSTRACT

A comprehensive and authoritative study of sediment plumes generated by marine aggregate mining operations in the UK has been completed. A thorough literature review has identified, with some notable exceptions, a paucity of conclusive information applicable to the marine aggregate mining industry in general, and in particular to the UK situation. Information is more widespread for other forms of dredging activities but is shown to be largely inappropriate for general application to most marine aggregate mining scenarios.

Extensive sampling campaigns have determined the sediment source terms of benthic and surface plumes. These support earlier (unpublished) results and are corroborated by other contemporary studies world-wide. Marine aggregate mining vessels currently working in the UK are shown to return, as overspill and unwanted screened material, between 0.2 and 5 times the cargo load. Further, the importance of detailed prospecting and reserve evaluation data is reinforced for predicting the likely magnitude and variation of such overboard returns.

Baseline measurements of the range of increased turbidity that may be generated have been obtained. A total of 162 Continuous Backscatter Profiling (CBP) transects across plumes have been recorded and post-processed using in-house programs. CBP transects show the bulk of the plume settling out of the water column (or, more strictly, settling to within 1.5m of the seabed) within 300m (sands) to 500m (silts) downstream. This corresponds to a time period of 10-15 minutes since release. Coarse sands (> 2mm) and gravels settle out virtually instantaneously. We propose that the far field visible ‘plume’ extending beyond the boundaries of measured suspended sediment load discernible above background conditions is an organic admixture of fats, lipids and carbohydrates agitated by the dredging process and with little sediment content.

We recommend as Best Practice that assessments of plumes from dredging operations are founded on pertinent, well designed sampling and testing programmes. We have shown there are significant productivity gains through the competent use of Continuous Backscatter Profiling (CBP) techniques with precise navigational control to effectively track and delimit the plume boundaries. This significantly improves confidence in the interpretation of results as representative of the maxima and minima conditions.

The development of a benthic plume by the hydrodynamic and physical interactions of the draghead on the seabed has been firmly established by the present work. We have shown however, using underwater imaging, suspensate sampling from around the draghead and CBP techniques, that the magnitude of the draghead plume is minor in comparison with the surface plume. Contribution of the overboard returns to the suspended load is 4-5 orders of magnitude greater than from the draghead. It is considered that the impact of the draghead plume may be deemed negligible in comparison to any surface plume effects.

Hopper overflow and the screening process is thus of dominant importance in the establishment of dispersive plumes from marine aggregate mining. Plume excursion is dependent on (among other factors) the total quantity of sediment rejected, the particle size of the sediments and tidal current velocity. Further, the rate and manner of overboard return is important in defining the initial stages of plume descent as a density current (Dynamic Phase) which subsequently controls the location and quantity of material available for conventional advection and dispersion (Passive Phase). Our work confirms that, as a general principle, the rate of deposition of material from the dispersing plume is much faster than would be assumed from conventional Gaussian diffusion models and that sedimentation is largely confined to distances of a few hundred metres from the point of discharge.

Importantly this suggests that the impact of dredging on benthic biological resources may be confined to the immediate vicinity of the dredged area. Little is known of the impact within Licence areas worked commercially, in the surrounding deposits, nor of the rate of recovery following cessation of dredging. Of particular interest is the possible impact of organic material released into the water column which may play an important role in the (well-documented) enhancement of secondary production in deposits surrounding dredged areas. This requires further investigation both as part of our understanding of plumes associated with marine aggregate mining and with establishing the impact on biological food webs leading to commercially exploitable fish stocks.

STATEMENT

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SECTION 1 - INTRODUCTION

1.1 The UK Marine Aggregate Dredging Industry

Marine aggregate mining in the United Kingdom for construction purposes has averaged 20-28 million tonnes per annum over the past 9 years (*see* Table 1.1) totalling 213.6 million tonnes. In 1995, some 26 million tonnes of sand and gravel was won from marine sources (permitted removal 45 million tonnes), with slightly over 18 million tonnes landed on the south and east coast, including Thames Estuary ports. Total tonnage increased slightly to 26.6 million tonnes in 1996. 12% (3.3 million tonnes) was landed at English Channel ports. Aggregate for fill and beach nourishment purposes varied between 0.8 million tonnes in 1993 to 5.2 million tonnes in 1995 and is likely to form a significant growth area into the next decade. 42 vessels are presently known to be engaged in UK marine aggregate mining. Marine dredged aggregate supplies 18% of England and Wales' total aggregate demand, rising on a regional basis to over 30% of total demand for the South East of England (BMAPA, 1995). The UK industry is second only to Japan, where 85% of all aggregate are supplied from marine sources (Tsurasaki *et al*, 1988, *in* Selby & Ooms, 1996).

UK Government forecasts state that a provision for the supply of 320 million tonnes of marine aggregate should be made over the period 1992-2006 (DoE Minerals Planning Guidance (MPG) Note 6, 1994). This requires maintaining output at over 20 million tonnes per annum. Clearly, a co-ordinated resource management approach including industry, government and the public is required. MPG (6) states; "*There will be a presumption against extraction unless the environmental and coastal impact issues are satisfactorily resolved*". MPG (6) is presently under review, and is expected to be reissued in 1999.

Year	East Coast	Thames Estuary	South Coast	Bristol Channel	Liverpool Bay	Rivers	Fill & Beach Nourishment	TOTAL	% landed abroad
1988	10.0	2.95	5.53	2.96	0.43	0.07	3.86	**25.8**	9.2
	(15.8)	*(6.35)*	*(8.96)*	*(5.00)*	*(2.1)*			***(42.07)***	
1989	10.9	3.6	5.70	2.91	0.47	0.12	4.34	**28.04**	9.0
	(16.8)	*(6.35)*	*(10.87)*	*(4.98)*	*(2.1)*			***(41.1)***	
1990	10.9	2.1	6.19	3.25	0.49	0.10	2.26	**25.29**	15.1
	(16.4)	*(6.35)*	*(13.81)*	*(5.03)*	*(2.1)*			***(46.05)***	
1991	9.22	1.51	5.28	2.07	0.31	0.04	1.93	**20.36**	22.6
	(16.4)	*(6.35)*	*(12.1)*	*(5.19)*	*(1.26)*			***(41.3)***	
1992	10.26	1.5	4.79	2.39	0.31	0.02	1.29	**20.56**	30.7
	(16.4)	*(6.35)*	*(13.55)*	*(5.19)*	*(1.38)*			***(42.87)***	
1993	9.81	1.22	4.36	2.17	0.38	0.01	0.8	**18.75**	33.2
	(16.3)	*(6.35)*	*(10.15)*	*(5.11)*	*(0.7)*			***(38.61)***	
1994	11.29	2.0	4.93	2.26	0.29	0.02	1.29	**22.08**	30.1
	(16.0)	*(6.35)*	*(9.74)*	*(4.81)*	*(0.81)*			***(37.74)***	
1995	12.3	1.66	4.43	2.29	0.28	0.01	5.17	**26.14**	26.1
	(16.0)	*(6.85)*	*(13.55)*	*(4.84)*	*(0.80)*			***(42.04)***	
1996	11.21	1.12	4.74	2.02	0.29	0.02	7.22	**26.62**	25.1
	(18.5)	*(6.65)*	*(13.25)*	*(4.62)*	*(0.68)*			***(43.7)***	
Mean	**10.65**	**1.96**	**5.11**	**2.48**	**0.36**	**0.05**	**3.13**	23.74	**22.3**
	(16.5)	***(6.44)***	***(11.78)***	***(4.97)***	***(1.33)***			*(41.72)*	

Table 1.1 *Summary statistics of the United Kingdom marine aggregate dredging industry. Figures show tonnage (million tonnes per annum) actually removed compared with maximum permitted removal (italics in brackets) on a regional basis. Tonnage landed abroad calculated as percentage of total dredged (modified from: The Crown Estate 1989-1997)*

Without doubt there is an increasing awareness of the full range and importance of the environmental issues of relevance to the marine aggregate mining industry. Latterly, however, there has been a growing collection of alleged and largely unsubstantiated concerns, in particular over the potential impact of the generated plume on seabed fisheries resources, but also of aggregate dredging operations in general.

By the very presence of a draghead acting upon the seabed during a dredging operation, changes in the physical environment will be observed within and, to a certain extent, beyond the dredged area. Generally, these are considered of a short term nature, such as the resuspension and subsequent settlement of sediments or medium term, such as the temporary removal of benthos and subsequent recolonisation. Any removed fractions may or may not be replaced by naturally occurring, omnipresent sea bed processes over the longer term. Semi-permanent changes such as removal of coarse sediments may also be considered, whereby the removed sediment fractions are unlikely to be replaced by similar material during present day (geological sense) naturally occurring seabed processes.

'Impacts' of dredging may further be considered in terms of spatial effects, where most of these will be localised in nature, for example, changes in bottom topography. The spatial impact of plumes, however, may extend beyond the boundary of the dredged area, and in combination with the easily identified visual surface expression, has thus attracted much recent attention for investigation and monitoring. Any impact determined to be due to the formation of a plume and its associated effects must however be put into perspective and considered in association with all other aspects of the dredging operation, a process undertaken during the preparation of the Environmental Assessment (EA).

The Environmental Assessment must determine the relative importance of plume and turbidity generation and will necessarily require assessment of each dredging scenario within its proposed environment, fully taking into account natural and artificial variables. Not only is an understanding of plume generation and dynamics therefore required but also knowledge of baseline conditions, natural environmental variability and responses to disturbances in the vicinity of the dredged areas.

The environmental significance of sediment plumes and other forms of disturbances which are inevitably generated by all forms of dredging operations has long been recognised (*see, for example*, Taylor & Saloman, 1968; Kaplan, 1974; Oulasvirta *et al*, 1978; Saloman *et al*, 1982, also Pagliai *et al* 1985; Borst *et al*, 1994; Morton, 1996). In conjunction with dredging of cohesive sediments (principally maintenance dredging but also capital dredging) and deep ocean minerals mining (*for example see* Lavelle *et al*, 1981), a number of studies have investigated the sources of plumes, their mechanisms of advection, dispersion and sedimentation, and their physical and biological effects (*see, for example*, Böhlen, 1978 & 1980; Kojima, 1986; Madany, 1987; Oulasvirta *et al*, 1988; Åker *et al*, 1990; Nielsen *et* al, 1991; Burnett & Whiteside, 1992; Drapeau *et al*, 1992; Vitanen, 1993; Thevenot & Johnson, 1994; Tubman *et al*, 1994; Pennekamp *et al*, 1996).

The information available specifically for marine aggregate mining is less widespread. The International Council for the Exploration of the Sea (ICES) maintains an annual review of the impacts of marine dredging for aggregate (*see, for example*, ICES, 1992a; 1992b; 1993; 1994; 1995; 1996). Reviews of aspects of sand and gravel extraction practices overseas and impacts thereof include van der Veer *et al* (1985), de Groot (1986), Hurme & Pullen (1988), Charlier & Charlier (1992) and Hammer *et al,* (1993). Recently the impacts of specific forms of marine mining including precious metals, marine aggregate and heavy mineral sands have been assessed in a detailed study for the United States, Department of the Interior, Minerals Management Service (MMS) (C-CORE, 1996).

The results of few environmental impact studies have filtered through into the scientific community, principally through the medium of ICES (*see, for example*, Sips & Waardenburg, 1989; van Moorsel & Waardenburg, 1990 & 1991; de Jong & van Moorsel, 1992; van Moorsel, 1993 & 1994). However, many environmental studies and impact assessments have been commissioned by industrial sponsors (including the marine aggregate industry) in recent years but these largely remain '*Commercial In Confidence'* or within the '*grey literature*' of non-refereed, technical reports with little circulation amongst the wider scientific community.

Our review of the literature indicates there is little information available relating to detailed investigations of plumes *per se* in UK waters; these have largely been undertaken abroad. Impacts and descriptions of the generated plume have been reported elsewhere (*see* Willoughby & Crabb, 1983; Poiner & Kennedy, 1984; Clarke *et al*, 1990; Foster *et al*, 1991). More recently , a number of authors have dealt with the dynamics of the plume generation and behaviour (Land *et al*, 1994; Bonetto, 1995; Jensen *et al*, 1995; Weiergang, 1995; Whiteside *et al*, 1995; Paris & Martinez, 1996).

Information specifically generated for aspects of the UK industry is more scarce. Reviews of the UK marine aggregate dredging industry have been prepared by Nunny & Chillingworth (1986); Drinnan & Bliss (1986); Pasho (1986) although the latter two were commissioned for overseas interests. Further information appears sporadically in the ICES literature. Gross impacts associated with marine aggregate extraction on local biological communities have been assessed by Shelton & Rolfe (1972); Millner *et al* (1977); Rees (1987); Lees *et al*, (1990); Kenny *et al*, (1991). Biological and geological conditions and responses to disturbance have been reported by Dickson *et al* (1979); Kenny & Rees (1994; 1996). Physical observations of the impacts of dredging were made by Dickson & Lee (1973) and Price *et al* (1978) with little further work appearing until Davies & Hitchcock (1992). Observations of the physical behaviour of plumes appears limited to that which has been reported largely since the inception of the this project (*see, for example*, Marsh, 1994; Hitchcock & Drucker, 1996; Dearnaley *et al*, 1996). It is known that other studies are in progress, particularly some recently funded by MAFF, from which results are expected shortly.

Mitigation tools such as silt screens, silt curtains and anti-turbidity overflow systems (Ofuji & Ishimatsu, 1976; Nakata *et al*, 1989; Horii, 1996) have been reported overseas, although many European technological improvements may exist as internal reports and under restrictions of patent.

1.2 Project Background & Purpose

Interest in the potential of marine aggregate mining from the United States Federal Outer Continental Shelf (OCS) as a source for beach recharge and barrier island protection material has grown rapidly in recent years as State resources of such material (predominantly within three miles of the coastline) have become depleted and/or polluted. The suitability of these deposits for construction purposes is also being examined. Additionally, increasing concern over potential deleterious coastal effects as a direct or indirect consequence of nearshore dredging activities has resulted in increased interest in the reality of offshore exploitation. Federal waters will largely be beyond the limit of regular seabed interaction by predominant wavebase conditions and only remotely connected to onshore/offshore processes.

The Office of International Activities and Marine Minerals (INTERMAR) of the Minerals Management Service (MMS), a Bureau within the United States Department of the Interior, has clear responsibilities for providing environmental analysis and assessment information facilitating the responsible management of these resources. This project was formulated to encompass several key elements of interest to INTERMAR and the MMS's Marine Minerals Programme. Principally, the requirements for information regarding the origin and dynamics of benthic and surface sediment plumes, previously identified in several INTERMAR and State/Federal Task Force documents, are addressed by this project.

In the United Kingdom, the Department of the Environment (DoE) adopted document *Guidance On Environmental Assessment for Marine Aggregate Dredging Proposals* as prepared by the ICES Marine Environmental Quality Committee Working Group (ICES, 1993) has become a *proforma* by which environmental assessments in the U.K. for marine aggregate extraction are prepared. This document has been incorporated within the U.K. Ministry of Agriculture, Fisheries and Food *(MAFF)* Directorate of Fisheries Research (DFR) Laboratory Leaflet No. 73 *Guidelines for assessing marine aggregate extraction* (Campbell, 1993). Summarising a central objective of this project, Items 1.2.1vi & vii (Campbell, 1993) require detailed consideration of:

- *vi transport and settlement of fine outwash sediment suspended by the dredging activity or from an outwash plume;*
- *vii effects of onboard screening/grading*

Complementing the DoE guidelines, the scoping document prepared by the International Council for the Exploration of the Sea *(ICES)* Marine Environmental Quality Committee (ICES, MEQC 1993) highlights the need for establishing data on;

- (2a) ... *stability, mobility and turbidity of bottom sediments and natural suspended loads*

- (3a) ... *information on predicted transport and settlement of fines suspended by the dredging activity, from an outwash plume or from onboard screening/grading*

This study is timely for contribution to the competent production of environmental statements and assessments as existing and developing legislation dictates at both national and international levels. The environmental information is relevant to dredging operations for sand and/or gravel on the U.S. continental shelf, either during the preparation of environmental impact statements, or during review of marine mineral development plans.

Further, the study results may be interpreted to indicate technological areas in which operational efficiency may be increased, mitigating some environmental consequences of the operations and assisting development of an environmentally responsible offshore industry.

1.3 Project Approach & Objectives

Recognising the technological, environmental and legislative management practices forged during the successful development of the United Kingdom marine aggregate industry, the MMS initiated interagency discussions with responsible parties in the U.K. Information gathered resulted in the MMS acting as prime funding agency for this project to provide important environmental data to advance their developing legislation and management structures.

Coastline Surveys Ltd has a respected and broadening track record in marine minerals' resource prospecting, environmental monitoring and dredging research and provided in-depth expertise to undertake this work.

The growing status of environmental investigations in the U.K. and the catalytic effect of funding provided by MMS, encouraged and supported Coastline Surveys Ltd (CSL) in securing active participation by the key major U.K. aggregate dredging companies (ARC Marine Ltd, South Coast Shipping Company Ltd and United Marine Dredging Ltd) and the coastal studies' research facility of HR Wallingford Ltd, Ports & Harbours Division. Specialist consultants Marine Ecological Surveys Ltd partnered CSL for preparation of the benthic ecology literature review.

Participation in this project has enabled all project partners to gather hitherto unavailable data on the content and behaviour of sediment plumes developed during normal marine aggregate mining activities both at the sea surface, in mid-water and near the seabed. The U.K. dredging industry has been able to provide valuable seatime aboard a variety of working dredgers on numerous occasions. Importantly a representative sample of the main stream industry working under normal commercial conditions has been investigated.

The objectives of this study may be summarised;

- *to acquire and define source term data on the content of benthic plumes*
- *to acquire and define source term data on overboard plumes*
- *to investigate likely sediment excursion and settling depths*
- *to appraise the changes in seabed character in mind of implications for continued dredging and environmental impact*
- *to appraise technological implications of the study findings*

Requirements by the U.K. industrial partners for several site specific environmental studies arose during the progress of the project. These were encompassed into the project on a collaborative basis, with industry providing additional finance largely to cover charter of coastal survey vessels and MMS extending further use of the U.S. Government survey equipment. The results of these studies are incorporated within this review.

Readers of this Report are reminded that the examination of plumes forms only part of the full Environmental Assessment procedure. Whilst we have treated the subject of plumes in some detail, plumes should rarely play the most significant role in the Environmental Assessment.

1.4 Project Methodology

This project has concentrated on obtaining detailed and comprehensive field measurements of plume dynamics and environmental parameters to understand the significance of the developed plumes. The definition of the fundamental source terms of plumes and observation of their subsequent behaviour in the field has allowed significant revisions to traditional modelling scenarios (*see, for example,* HR Wallingford, 1996).

It is important to clarify that this project is concerned with characterising the generation, behaviour and decay of sediment plumes generated by marine aggregate dredging in shallow (less than 40m) coastal waters within 100km of the coastline. We are not concerned with review of all physical disturbances caused by the operations *per se*, nor with the impacts of capital and maintenance dredging of cohesive deposits. Plume characteristics and impacts associated with the dredging of cohesive deposits will be similar in principle but wider ranging due to greater advection and dispersion, and the important role of contaminants bound to the clay fractions.

The zone of significant impact surrounding a dredging operation has been observed in the field to be far less than modelling exercises have historically suggested. The approach adopted within this project provides key baseline data for refining analytical and mathematical predictive studies. It has become apparent during the conduct of the project that the significant number of parameters involved in the development of plumes and the significance of any subsequent impact is not only very complex, but also largely site specific. Whilst modelling provides the useful "what if?" scenarios at the planning stage, it is not considered a replacement for undertaking field monitoring exercises. Executed competently, and combining physical and biological parameterisation, such field campaigns need not be more expensive than detailed modelling itself.

In order to refine prediction of the likely excursion of a plume, key factors that define the 'source terms' have been investigated. The rate *(kg/s)* and total quantity (t) of overboard discharge of sediment via overspill and screening is fundamentally important. These will vary according to the operating characteristics of the vessel, environmental parameters and the nature of the seabed material. Sediment characteristics of the material returned overboard, *e.g.* particle size distribution and total mass, are required. Parameters on the dynamics of the receiving water body including water depth, wave motions, current strength, duration and direction are required not only for detailed modelling of predicted plume behaviour but also for comparing results between different monitoring campaigns.

The project has committed to integrating modern and traditional monitoring techniques and equipment. Central to the project has been the application of the innovative and technologically advanced R.D. Instruments' BroadBand Acoustic Doppler Current Profiler (ADCP™). This has enabled accurate monitoring of the plumes formed during the dredging operation, and subsequent high confidence in the location of samples representing the suspended solids maxima and minima, through use of the 'acoustic backscatter' function. This approach enables levels of accuracy of data not economically possible to obtain using a spread of conventional instrumentation.

Combination of accurate field observations with the traditional modelling scenarios has resulted in modifications to the theory of behaviour of the developed plume directly (*see, for example,* HR Wallingford, 1996) and following similar results elsewhere (*see, for example*, Land *et al*, 1995; Weiergang 1995; Jensen, 1995; Whiteside *et al*, 1995; Pennekamp *et al*, 1996). These further concluded that the traditional predictive techniques have overestimated the diffusive ability of the dredge plume.

1.5 Report Structure

This Final Report principally contains the results of field investigations characterising the plume of sediments suspended by aggregate dredging activities. The report has been prepared following completion of all the major objectives set out during the original project proposal. It follows a no-cost extension to the project funding by MMS and the Research Group to allow a complete review of data collected early in 1997, delayed by poor weather conditions from late 1996. During 1998 further important information has been gathered investigating the magnitude of organic loading of the water column during dredging operations. Further spillway samples were also obtained which support the results reported herein.

This Final Report is now made available to the project sponsors taking into account the constructive and supportive responses received to the draft report.

Section 2 presents a comprehensive literature review to consider the source, transport and fate of the suspended material. Examples are drawn from the aggregate industry world-wide. A brief overview of the predictive modelling practices that are used in UK for many of the aggregate Licence applications is given.

Section 3 reviews the methods of monitoring plumes that have historically been developed for monitoring dredging of principally cohesive sediments and which are applicable to aggregate dredging activities. A full description of the techniques developed within this project for field evaluation of sediment plume behaviour is given. This includes principles and practical application of Doppler profiling techniques, herein termed *Continuous Backscatter Profiling* (CBP).

Section 4 reports the field phases of the project that have been completed during this project. Detailed explanation of the measurements of the source terms of sediment plumes are presented. The results for the monitoring of plumes generated by various dredging plant and loading differing cargoes under normal working conditions are reported. The transport rates and sedimentation zones are analysed. Investigation into the magnitude of the hitherto unstudied benthic plume arising from the action of the draghead on the seabed is described. Finally in Section 4.4 we present a hypothesis for the far field component of the surface plume.

Section 5 reviews results of selected pertinent parallel studies, many of which have only lately been concluded. These have been conducted overseas independently. The results from all studies generally conform within the range of expected variation.

Section 6 addresses the complex interactions between the benthic ecology and dredging activity and is reported following an extensive and thorough literature survey. Recommendations are made for supplementing the paucity of information that exists for assessing the benthic response of communities to disturbances, especially for UK waters.

Section 7 identifies outstanding scientific requirements which merit further study to complement this Report and others recently produced. These recommendations are not presented in any specific order of importance, but it is considered that most objectives can be realised within 12-18 months of this report date, answering many current questions.

Conclusions remarks and recommendations are presented in Section 8.

SECTION 2 - PLUMES: SOURCE, TRANSPORT & FATE

2.1 The Importance Of Plumes

Suspended sediment plumes created by dredging operations are of interest in physical, biological and general environmental terms. A plume may be considered to have both positive and negative effects. Any effect will vary in its importance according to its location. What is important in one location may not be so important in another. A plume may have effects whilst it is in suspension, and further, different effects during and following settlement. The detailed study of the impacts of plumes is therefore site-specific. Generic guidelines may be produced to standardise the requirements and specifications for site specific studies of plumes contributing to the competent conduct of an Environmental Assessment (EA). Examination of the impact of a sediment plume attributable to aggregate dredging forms *part* of the Environmental Statement (ES).

Mode	Effect	Perceived Impact
SUSPENSION	reduced light penetration	reduced algal growth reduced visibility reduced primary productivity
	increased suspended solids	visual impact decreased respiratory capacity decreased reproductive capacity decreased feeding capacity deterrence of spawning modification of migration routes
	increased nutrient flux	increased feeding opportunity increased reproduction rates
SETTLEMENT	increased sedimentation rates	smothering of slow moving bottom dwellers blocking of filter feeders smothering of seabed fauna smothering of hard bottom communities silting of crab and lobster holes
	changes in sediment type	alteration of seabed sediment particle size distribution alteration in character of sediment supply to beaches
	new sedimentation regimes	smothering of archaeological sites

Table 2.1 *Summary of the impact of plumes generated by aggregate dredging operations in particular, which generally concern only non-cohesive, granular sediments. Dredging of cohesive sediments have further implications, but detailed consideration is outwith the scope of this report.*

The field studies and comprehensive world-wide review of recently published literature strongly confirm the importance of recognising the specific interactions between the type of dredging activity, the geology and the environment. It is therefore necessary to consider the specific types of dredging technology that is applicable to the UK marine aggregate industry. The geological, biological and oceanographic environment in which the disturbance occurs will determine the impacts and the consequential relative significance of those impacts on the environment and other users of the environment.

2.2 Aggregate Dredging Methods

2.2.1 Trailing Suction Hopper Dredgers

Currently, aggregate dredging in the United Kingdom is predominantly undertaken by trailing suction hopper dredges (TSHD) (Plate 2.2.1a TSHD Sand Heron). These seagoing vessels contain all the necessary plant for highly automated and efficient operations including self discharge in port. Specifications for some of the U.K. marine aggregate mining fleet are reproduced in Table 2.2.1. For dredging in waters deeper than about 32m, the dredge pump may be mounted on the dredge pipe, rather than in the hull of the dredger.

Plate 2.2.1a *TSHD Sand Heron*

During loading, one or two suction pipes are trailed across the seabed at slow speed (<4m/s) whilst the sediment/water mixture is pumped aboard the vessel. The draghead at the end of the suction pipe in contact with the seabed may in its simplest form be of a plain pipe-end arrangement such as the 'Sharks Mouth' with a size little more than the diameter of the suction pipe. More commonly either a 'Fixed Visor' (varies from approximately 1.5m to 2.5m in width) or a 'California' type adjustable visor (1.75m to 2.75m width) (plate 2.2.1b) are used. Modern dredgers tend to favour the latter type.

Plate 2.2.1b *'California' Type draghead*

During loading, excess seawater is allowed to overflow from the hopper either by deck level spillways or a central chute. Overflow of lean mixture, predominantly containing some clays, silts and fine sands promotes retention of a full cargo of solids (Plate 2.2.1c).

There are some exceptions to permissible overflow, usually encountered when dealing with cohesive sediments, predominantly of silt/clay fractions, whilst undertaking capital or maintenance dredging of ports or harbours. In these cases there may be a risk of remobilising heavy metal contaminants bound to the sediment into the water column or creating very dense clouds of fine sediment. Such scenarios are unlikely during the mining of marine aggregate.

Economic *in situ* gravel/sand assays may contain 15-55% gravel, whereas most commercial cargo requirements will dictate 35-70% gravel content (A.R. Hermiston, *pers. comm.*) depending on customer requirements, local geology and ship performance. In order to improve the quality of the cargo, 'screening' techniques during loading are often used to reject the fractions of the pumped mixture not required. Such beneficiation improves the overall load/unload & process cycle timings considerably whilst not raising problems of generating large quantities of unwanted materials on land. Cargoes containing incorrect proportions of aggregate sizes will be difficult for the dredging company to sell. Some extraction licences in the U.K. do not permit screening during loading (*e.g.* Shingle Bank, Hastings).

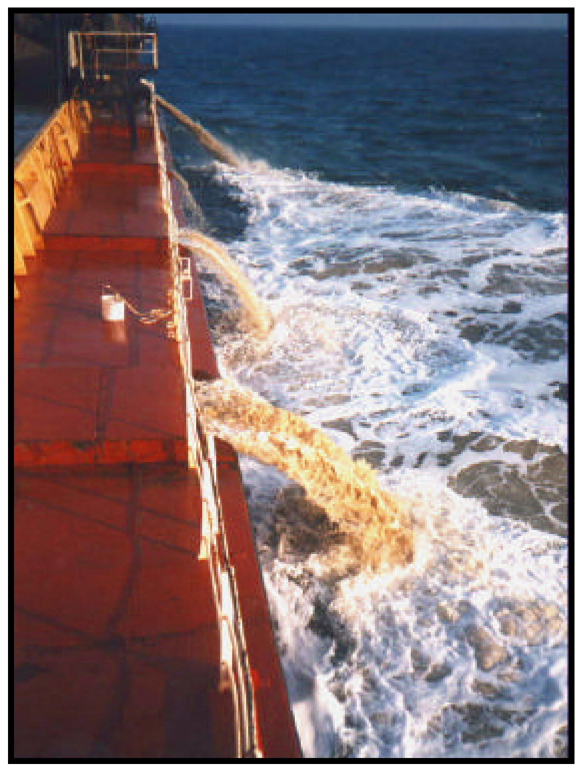


Plate 2.2.1c *Overflow from the ARCO Severn*

The vessel Master has the ability to raise and lower the draghead from the seabed to alter the density of the pumped mixture (to avoid 'choking' the dredge pump) and to wash-off any contamination of the cargo, for example by silts and clays *etc*. The draghead may also be lifted clear of the bottom to avoid any known obstacles or patches of poor materials, the locations of which will be recorded on the navigation plotting system. Special ‘dump valves’ may be fitted within the loading pipes which allow the pumped mixture to be instantaneously returned overboard, should contaminants, such as clays, be seen by the dredge Master before the material enters the hopper. On board instrumentation is becoming more widespread for semi-automation.

To facilitate fast turnaround in port, most vessels are equipped with self-discharge machinery, in the form of bucket wheels (*see* Plate 2.1.1a), scraper buckets, grabs or ‘back-actors’. Cargoes can be discharged direct to wharfage without shore based plant costs. The larger trailing suction hopper dredgers are expected to work on a year round basis, with only limited interruptions due to the severest weather conditions.

The idealised concept of ‘strip mining’ using trailing suction hopper dredgers (*for example*, promulgated in Nunny & Chillingworth, 1986), is seldom realised. In practice, the dredge vessel will operate within a prescribed dredge run (based on geological prospecting & monitoring) with the track of the vessel scribing an ‘hour glass’ appearance (Davies & Hitchcock, 1992).

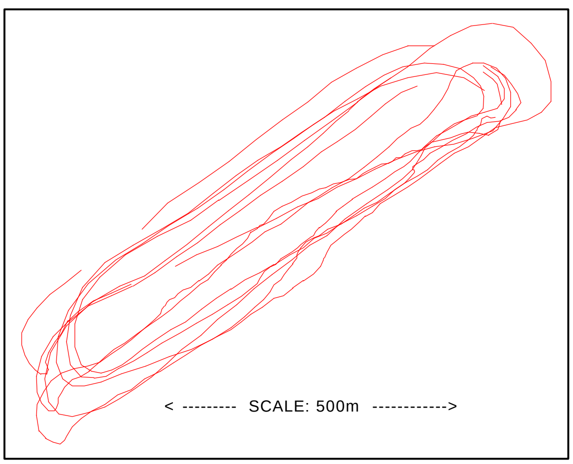


Figure 2.2.1 *Navigation plot from the ARCO Severn Electronic Monitoring System (EMS) working an English Channel Licence, 21st August 1995. The proportion of the seabed remaining undisturbed between successive passes is clear. At the ends of the dredge run, superimposition of some successive passes occur. The size of the dredge run is limited (approximately 1100m x 250m), taking advantage of a localised channel deposit amongst a surrounding seabed of poorer grade deposits. The dredge run is oriented parallel to the dominant ebb and flow tidal currents.*

Within a licence area, there will be numerous discrete ‘dredge-runs’ and these will not usually encompass the whole licence footprint due to geological and operational constraints, for example, pockets of silt or clay, contamination by wreck debris, turning circles, navigation, pipelines/cables, exclusion zones (Figure 2.2.1). There will be an amount of seabed not physically disturbed by the dredging process, although this may be impacted in other ways. This has important ecological implications (*see* Section 6.7). At the ends of the dredge-run, when the vessel is turning, and near the middle of the run, lowering of the seabed may be slightly more than in other parts of the run, as successive trails superimpose on one another. The development of a ‘trailer track’ (Nunny & Chillingworth, 1986) does not appear widespread (*pers. obs. and* Davies & Hitchcock, 1992).

2.2.2 Anchor Dredging

The trailing suction hopper dredgers technique has largely superceded the practice of ‘anchor dredging’, although it can be favoured in certain circumstances. During anchor dredging the vessel lies at anchor whilst loading. The dredge pipe is forward facing, and the draghead of simple form. During the loading process, the dredger swings in an arc at the end of the anchor line, and/or moves forward slowly by hauling in the anchor chain. Anchor dredge vessels are generally smaller (Plate 2.2.2 Sand Swan) and often older than the majority of trailing suction hopper dredgers. Presently, there are only two dedicated anchor dredgers (Sand Swan and Sand Swift; G Singleton, *pers.comm.*), although some smaller existing dredgers can operate under both modes and there are new vessels under construction capable of both anchor and trailer dredging.

Plate 2.2.2 *Anchor dredger Sand Swan*

The static nature of anchor dredging allows small, localised deposits to be worked where permitted. Sometimes this may be to some considerable depth below the surrounding seabed, although in the U.K. present licensing arrangements restrict removal to a maximum of 3m below surrounding seabed level. This is advantageous on small licences or where the resource is patchily distributed. On even or thin but extensive resources the trailing suction hopper dredgers is the preferred method.

	Dredge Pipe Diameter	Hopper Capacity	Power	Type
ARCO ‘A’ Class x 4	700mm	4500 t	3942hp	TSHD
ARCO ‘T’ Class x 2	700mm	3500 t	3400hp	TSHD
ARCO ‘S’ Class (Severn)	700mm	2200 t	2460hp	TSHD
ARCO ‘D’ Class x 2	450mm	1300 t	1550hp	TSHD
Camdijk		3110 m^3	5400hp	TSHD
Cambrae		3000 m^3	5840hp	TSHD
Cambeck		2740 m^3	4400hp	TSHD
Cambourne		2600 m^3	4400hp	TSHD
Peterston		483.7 m^3	810hp	SHD
Bowcross		765 m^3	1000hp	SHD
Welsh Piper		785 m^3	1329hp	SHD
Kaibeyar	400mm		595hp	SHD
KB II	450mm		660hp	TSHD
Sospan		700 m^3	1750hp	TSHD
Solent Lee		525 m^3	875hp	SHD
Sand ‘H’ Class	850mm	2500/2700 m^3	3823kW	TSHD
Sand ‘W’ Class		2227 m^3	1942/3529kW	TSHD
Sand ‘K’ Class		2070 m^3	3382kW	TSHD
Sand Swan		890 m^3	846kW	SHD
Sand ‘S’ Class		818 m^3	861kW	SHD
City of Westminster		2793 m^3	3790kW	TSHD
City of London		2652 m^3	3790kW	TSHD
City of Rochester		1271 m^3	2104kW	T/SHD
City of Portsmouth		770 m^3	932kW	TSHD
City of Southampton		751 m^3	783kW	TSHD
City of Bristol		751 m^3	783kW	TSHD
City of Swansea		570 m^3	634kW	TSHD
City of Chichester & Cardiff		1425 m^3	2720kW	TSHD
Britannia Beaver	700mm		3942hp	TSHD

TSHD = Trailing Suction Hopper Dredger SHD = Suction Hopper Dredger

Table 2.2.1 *United Kingdom Marine Aggregate Dredgers (modified from*: World Dredging, Mining & Construction, *March 1997)*

2.3 Key Terminology

Seston may be considered as the total particulate matter suspended in seawater and includes plankton, detritus, inorganic solids *etc*. This may also be referred to as Suspended Particulate Matter (SPM). The terms ‘turbidity’ and ‘suspended solids concentrations’ are different, although commonly interchanged:

Turbidity is a measure of the ability of a liquid to transmit light *i.e.* it’s ‘cloudiness’. It is often expressed in terms of the light extinction coefficient, ‘k’, and is an indicator of the total amount of matter in suspension, the *seston*. Turbidity cannot be consistently correlated with a mass of sediment in suspension due to changes in the optical characteristics of different sediments according to size, shape and refractive index.
Suspended solids concentration is the mass of solids in a given weight or volume of fluid, referred to as concentration by weight (C_w) or by volume (C_v). Increases in suspended solids and turbidity are not proportional, and will vary according to the sediment properties. Conversion of turbidity to suspended solids concentrations is possible only when turbidity sensors are calibrated with a turbidity standard and with suspended matter from the monitoring site.

Suspended Solids Concentration (SSC) may be considered that part of the seston which is of inorganic origin. Strictly, SSC and SPM are therefore not an interchangeable or comparable quantity. The difference between them will depend on the amount of pre-treatment in the laboratory that is undertaken to remove the organic material from SPM before weighing and recording the SSC. Most data do not make the distinction between the two figures, and commercial laboratories will not undertake the extensive pre-treatment required unless expressly required to do so.

2.4 Plume Sources

During dredging operations, 'plumes' of disturbed sediment will be created within the water body mass. The form and magnitude of these are governed by three principal components (Figure 2.4a).

- the dredging technique, including type of dredging plant in operation, method of overboard returns, operational conditions such as speed over the ground
- sensitivity to suspension and resuspension of the bed material i.e. the ease at which bed material will be disturbed and will remain in suspension, largely determined by the characteristics of the sediment (geotechnical, rheological and micro-biological)
- condition of the surface waters i.e. water depth, current velocity, turbulence, salinity *etc*.

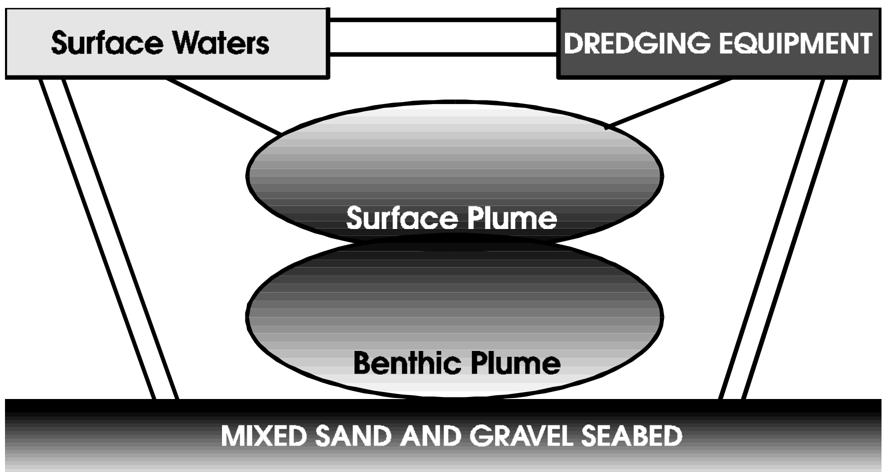


Figure 2.4a *Interaction between dredging plant, the seabed and the water column affecting turbidity (from Pennekamp* et al, *1996 modified)*

2.4.1 Benthic Plumes

Hydrodynamic and mechanical interaction of the draghead with the seabed will 'throw' finer grained sediment into suspension around the draghead from where it can be transported before settling out. Plumes thus created have been termed '*Benthic*' plumes.

If the draghead pushes material aside, rather than sucking sediments up, small levées are formed (Davies & Hitchcock, 1992). These will stand up above the surrounding levels of the seabed, and hence be more prone to erosion and entrainment into suspension (*see* Section 4, Figure 4.1.1). Although not strictly forming the benthic plume, the levée sediments are likely to be eroded soon after the draghead has passed, depending on local conditions, and so may add to the overall plume development. The volume of material within such levées may be significant, with up to 12% of the material displaced by the draghead (Davies & Hitchcock, 1992).

'*Secondary*' benthic plumes may be formed when fine material which has settled out immediately following cessation of the dredging operation, is eroded by peak tidal currents. In the pre-dredging condition, this material would already have been eroded and deposited in protected areas behind the lee of larger particles or micro-topographical structures, and so would otherwise not be available for creation of a secondary plume. It is conceivable that a cycle of erosion, deposition and re-erosion over the successive tidal cycles may continue to expand the areal impact of the dredging operation, beyond the immediate formation zone of the plumes by the dredge vessel (if the magnitudes of the tidal currents are asymmetric). At some point however, this must be considered as equating to a natural process.

2.4.2 Surface Plumes

'*Surface*' plumes are created by the overboard discharge of excess pumped waters containing sediment ('overspill') and by the process of onboard screening, '*beneficiation*', during the loading operation. During the latter, the gravel or sand content of the cargo is improved through rejection of the unwanted fractions overboard continuously during loading ('rejection').

Overspilling is necessary to allow the hopper to fill with solids to an economic level. The overspill will contain fine sediments that are maintained in suspension by the turbulence within the hopper. Commonly there are three to five deck level spillways on each side of the vessel for overspill. The material freefalls over the side of the vessel. As the draught of the vessel changes during the loading cycle, the distance of freefall will decrease, reducing entrainment of air, but also reducing the momentum of the discharge.

Some larger (*for example* TSHD Geopotes XIV) and newbuild (*for example* TSHD City of Cardiff) vessels are fitted with a central single spillway, which decreases the surface area of the discharge available to entrain air. Such discharges are usually subsurface, exiting the vessel through the keel and consequently releasing material some 5-10m below the sea surface (depending on vessel draught). Whilst clearly reducing some of the overspill characteristics previously mentioned, a paradox exists in that the plume so formed is immediately in front of the ship propellers, which will induce considerable turbulence and will often force the plume back to the surface. This will significantly interrupt the density current settling effect which otherwise plays an important role in reducing the overall impact of plume dynamics.

Several overseas vessels have been fitted with a secondary pipe similar to the main dredge pipe which returns the overspill or rejected material to immediately above the seabed. Whilst this is a relatively common option for trench mining vessels, this has not been undertaken within the U.K. aggregate dredging fleet. Although costly, investigation of this option may prove to limit the extent of plume development at the surface and be particularly useful for dredging in sensitive areas or areas with high fines contents. It is unlikely to be technically realistic as a retrofit option due to limitations on power availability. Recycling of the overspill/reject sediment-laden waters back into the draghead may both increase the solids/water content and recycle any material that had otherwise been lost, some of which may be desired cargo.

During the loading process sediments are therefore placed into suspension about the dredging operation by the action of the draghead on the seabed and the overboard return of surplus or rejected mixtures. Initially two distinct forms of plumes are recognised. After a short time interval, of the order of seconds to minutes in shallow coastal water depths of 15-35m, these will combine to form one continuous plume within the water column.

2.5 Plume Transport

The finer sediment fractions of the overspill and reject surface plumes will move away from the point of discharge by three separate mechanisms: advection by tidal currents; diffusion by turbulence; and settling. Coarser sediments will be transported a lesser distance away from the point of discharge. The location of settlement will be dependent on the settling velocity of the sediment, the carrying capacity of the water column and (dependent on wave-induced turbulence) the distance the tidal currents are consequently capable of advecting the sediments before deposition.

2.5.1 Advection Of Cohesive Sediments

Advection of a plume containing suspended sediments and any other particulate or suspensates will be dependent predominantly on the velocity of the tidal currents at the site concerned and the velocity and direction of the dredge vessel itself. The consummate velocity vector will determine the excursion of the plume before settlement permits the sediment to reach the seabed. Mathematical modelling applied to dredging scenarios in the UK commonly considers the tidal flows as constant depth-averaged or surface current vectors obtained by the British Hydrographic Office. Unless detailed and complex models are applied, any non-linearity in the tidal flows, reduction in velocity with depth or vertical velocity components are not included.

2.5.2 Diffusion Of Cohesive Sediments

Diffusion of the suspended sediments will occur due to natural turbulence within the water column Ignoring the turbulence induced by the action of the outwash from the dredger and by the vessel propellers themselves, the concentration distribution through space and time of a slug of cohesive sediment can be assumed to follow a Gaussian distribution (*see, for example*, HR Wallingford, 1993). It is assumed that the water velocity, water depth and diffusion coefficients remain constant throughout the plume. Tidal velocities are assumed to remain in line with the x-axis.

$$c(x,y,z) = c_b + \frac{m}{4\pi t h \sqrt{(D_x D_y)}} \exp\left[-\frac{1}{4t}\left[\frac{x^2}{D_x} + \frac{y^2}{D_y}\right] - \frac{w_s t}{h} \right]$$

where; c_b = background concentration
m = mass of material released at $t=0$
h = water depth
D_x, D_y = diffusion coefficients
w_s = settling velocity

The x & y axes are horizontal with the x-axis aligned with the current flow and the y-axis perpendicular to it. The origin x=y=0 is always taken to be the centre of the plume and is hence mobile due to advection. (HR Wallingford, 1993) The models commonly allow for a number of distinct release events which simulates the continued release of material from the dredger in different locations (when trailer dredging).

2.5.3 Settling Of Cohesive Sediments

Much of the plume modelling work which has been carried out in the UK over recent years (largely by HR Wallingford) incorporates the settling of cohesive sediment into the Gaussian diffusion calculations within the term;

$$\left[\frac{-w_s t}{h}\right]$$

It is generally assumed that constant settling rates of the order 0.1mm/s - 1.0mm/s are suitable for the cohesive material (*c.f.* Section 4.2.3).

Only recently (*see* Section 5.2) and following field observations (*see* Section 4.2) that the excursion of the plume did not in reality extend as far as the Gaussian models suggested (*see*, Land *et al*, 1995; Whiteside *et al*, 1995), have *in situ* attempts been made to quantify a realistic figure that is specific to the aggregate dredging scenario and which reflects the special hydrodynamic and physical conditions under which the sediments are released (*see* Section 4.4). These studies are ongoing, and indicate that the settling velocities of excess dredged sediments during aggregate extraction are not uniform between areas observed, with considerable variability within areas (M. P. Dearnaley, *pers. comm.*).

2.5.4 Transport Of Sand

A simplified but comprehensive set of empirical formulae have been established by van Rijn (1987) and modified following Grass (1981; *In:* HR Wallingford, 1993) to estimate the sediment transport rate Q_t.

$$Q_t = A.U.\left(\sqrt{U^2 + B.U^2_{rms}} - U_{crit}\right)^{n-1}$$

where; $n = 3.4$
U = depth averaged velocity (m/s)
U_{rms} = rms orbital velocity

and where A, B and U_{crit} are defined by;

$$A = \frac{\rho_s d_{50}\{0.005(d_{50}/h)^2 + 0.012 D_*^{-0.6}\}}{\{(g_s-1)gd_{50}\}^{1.2}}$$

$$B = 0.08/C_D$$

for $0.1m<=d_{50}<=0.5mm$;

$$U_{crit} = 0.19(d_{50})^{0.1}\log(4h/d_{90})$$

for $d_{50}>0.5mm$;

$$U_{crit} = 8.5(d_{50})^{0.6}\log(4h/d_{90})$$

$$D_* = d_{50}\{((g_s-1)g/\nu^2)^{1/3}$$

$$C_D = \left[\frac{0.4}{\ln(h/z_o)^{-1}}\right]^2$$

where; ρ_s = sediment density (kg/m^3)
d_{50} = median particle diameter (m)
d_{90} = 90 percentile particle diameter (m)
h = water depth (m)
g_s = particle specific gravity (~2.65)
g = gravitational acceleration (m/s^2)
C_D = drag coefficient of the seabed ($z_0 = 0$)
ν = kinematic viscosity of water at 10°C ($\nu = 1.4\text{x}10^{-6}$ m^2/s)

2.5.5 Settling Of Non-Cohesive Sediments

Particles greater than sand sizes (>2mm) are generally assumed in the context of aggregate dredging to fall to the seabed instantaneously and consequently are ignored.

In a clear, still fluid, the particle fall velocity (w_s) of a solitary fine particle of 100µm or less (Stoke's Range) can be described by:

$$w_s = 1/18.\ ((g_s - 1).g_w.D^2_s / \nu))$$

where: w_s = particle fall velocity
g_s = particle specific gravity (~2.65)
g_w = water specific gravity (~1.026)
g = gravitational acceleration (m/s^2)
D_s = particle size
ν = kinematic viscosity coefficient

For suspended sand particles in the range 200-1000µm, the following equation can be used (Zanke, 1977; *In:* van Rijn, 1987):

$$w_s = 10\,(\nu / D_s)\left\{\left[1 + \frac{0.01(g_s-1)gD_s^3}{\nu^2}\right]^{0.5} - 1\right\}$$

For particles larger than 1000µm, the following can be used (van Rijn, 1987):

$$w_s = 1.1\,((g_s-1).g_w.D_s)^{0.5}$$

These formulae are applicable for suspension concentrations of less than approximately 400ppm. For higher concentrations, the presence of the surrounding particles will reduce the particle fall velocity. For normal flow conditions with particles in the range 50-500µm, the reduced particle fall velocity can be described by the following (van Rijn, 1987):

$$w_{s,m} = (1-c)^m\, w_s$$

where m = 4.65 - 2.32 for large & small particles respectively (Maude & Whitmore, 1958)
= 4 for sand particles(van Rijn, 1987)
c = sediment concentration

However, it must be noted that counteracting, or replacing, the reduced particle fall velocity, $w_{s,m}$, will be the development of settlement enhancing 'Density Current' effects at high suspended sediment concentrations. Further consideration is outwith this report, but the role and the theory of 'Density Currents' within the dredged sediments plume is receiving detailed investigation elsewhere (*see, for example*, Whiteside *et al*, 1995; HR Wallingford, 1996). The traditional treatment of density currents applies more usually to fine-grained, cohesive sediments. However it is the specific discharge manner of the aggregate dredging operation which appears to create such a phenomenon best described also as a density current.

2.6 Plume Settlement

Plumes of suspended sediment created by dredging activities will augment existing concentrations of suspended sediment before decaying to background levels. The time required for the concentration levels to return to background will be a function of:

(i) the length of time for the water body at that point to be replaced by unimpacted waters with background levels of sediment. This will be directly dependent on water body current velocities (flushing time)

(ii) time taken for sediment to settle out of suspension. This is dependent on characteristics of the receiving medium such as water depth, salinity, density, viscosity, turbulence; of the sediment itself such as structure (i.e. as individual particles or as flocs), grain size, shape and density; and of other influences such as hindrance, buoyancy (entrapped air), gas content of sediments, initial sediment velocity (momentum) on entering the water body, *etc*.

The greater the density contrast between the discharge plume and surrounding waters and the less diffuse the discharge source, the more likely the plume is to behave as a density current and rapidly descend to the base of the water column. Impacts will tend to be more localised. During descent of the plume, friction at the edges of the plume may entrain sediment into the surrounding waters.

When dealing with density currents associated with dumping of dredging material (maintenance and capital dredging of principally cohesive fine sediments), observations of resuspension on impact with the seabed have commonly been made (*see* Lavell, 1981). However, it is likely that the magnitude of any density currents formed by aggregate mining overboard returns using present techniques will not cause significant resupension on impact with the seabed.

Table 2.6.1a presents a range of traditional theoretical and laboratory determined settling velocities for potential suspensates that may be encountered and which have been of direct relevance to plume studies. Material coarser than sand may be assumed to settle virtually immediately.

From observations within this project and by others (*for example*, HR Wallingford, 1996) the presence of flocs is now considered important. The settling velocity of flocs is not related directly to their size, and so does not follow Stokes Law.

Gibbs (1985) presents the following relationship to define the settling velocity of flocs:

$$U = 1.73\, D_f^{0.78}$$

where U is the settling velocity (cms^{-1}) and D_f is the floc diameter. Using this equation, the settling velocities for a range of flocs can be determined (Table 2.6.1b). The terminology microflocs (<100μm) and macroflocs (>100μm) is that proposed by Eisma (1986).

Particle Description		Size (μm)	Settling Velocity (cms^{-1})
Sand	Fine	200	2.1417
	Very fine	100	0.67
Silt	Coarse	50	0.1816
	Medium	20	0.0298
	Fine	10	0.00749
Clay	Very fine	5	0.00187
		1	0.0000748

Table 2.6.1a *Settling velocities of unhindered discrete particles (grain size descriptions based on Folk, 1980)*

Density gradients of the receiving waters may make an (unknown) contribution to the variation in settling velocities observed. It is known that the water temperature near the seabed may be *circa.* 1^{o} C less than the surface waters (A.R. Hermiston, *pers. comm.*). Rapid and intense mixing of these cooler bottom waters with the warmer surface waters may cause density driven micro-currents. Coupled with changes in pressure, it is postulated that some physico-chemical precipitation may occur under calm conditions which is a component of the surface froth and 'sheen', visible for some time at the surface. This may also be observed by the CBP techniques (*see* Sections 4.2.2, 4.2.3 and 4.4).

Floc Description	Size (μm)	Settling Velocity (cms-1)
Macroflocs	2000	0.493
	1000	0.28711
	500	0.1672
	200	0.08182
Microflocs	100	0.04765
	50	0.02775
	20	0.01358
	5	0.0046

Table 2.6.1b *Settling velocities of unhindered flocs (floc descriptions based on Eisma (1980)*

Particles in suspension will settle in different ways depending on the suspension concentration. Based on the concentration and the tendency of the particles to interact, there are four principal type of sedimentation (Paris & Martinez, 1996);

(i) discrete: in low SSC the particles settle individually without grouping, according to more classical sedimentation theories

(ii) flocculant: in dilute suspensions particles group together increasing their mass and settling at a faster rate, especially applicable for fine cohesive sediments

(iii) zone: in intermediate suspensions the particle forces are sufficient to hinder settling of neighbouring particles so that they tend to stay in relatively fixed positions and they tend to settle as a unit

(iv) compression: high concentrations which encourage the particles to form a structure

If discharge is slow, or at little differential to surrounding waters, entrainment is likely to occur more rapidly and the plume will quickly diffuse throughout the water column. The particles will then behave more characteristically according to the principles of *Stokes Law*. Such a plume will reside in the water column for longer, will be advected further by tidal currents and hence will impact wider area. However, deposition per m^2 will be correspondingly lower assuming a given quantity of material entering the water column. The opposing perspectives on the benefits or otherwise of slow settling rates are summarised in Table 2.6.1c.

Of importance in terms of evaluating the effect of suspended sediment plumes is the distance that sediment can travel before settling out of suspension (i.e. gross excursion and hence area of impact). The gross area of impact may then be subdivided into smaller zones of reducing impact away from the source, which will be dependent on the different settling rates for different particle sizes and hence accumulation rates at different points.

Fast Settling Rate	Slow Settling Rate
Impacts limited seabed area	Impacts far wider seabed area
Higher accumulation rate	Lower accumulation rate
Greater smothering	Lower smothering
Over-sanding of resource	Carries unwanted fines away from resource
Limits potential for cumulative effect	Cumulative effect potential with neighbouring licences
Unable to reach sensitive areas	May reach sensitive areas

Table 2.6.1c *Pros and cons of the development of plumes and transport away from the immediate dredge site. Dredging companies may prefer transport of fines away from the actively dredged area to avoid "oversanding" of the resource and re-screening on subsequent loading.*

It is known that inorganic sediment is present in the sea as flocculated aggregate with settling speeds many times greater than those of the constituent grains (McCave, 1975, *in* Moore, 1977). Particles of different sizes are known to respond differently to gravity and turbulent forces. In an initial, unflocculated suspension this will cause random variations in particle movement accompanied by abundant particle collisions. Because of their larger relative surface area and proportionally greater adhesive force, the smaller particles will tend to flocculate most rapidly. Larger grains are not sufficiently active to flocculate to other single grains but they do adhere to the soft and irregularly shaped flocs composed of smaller grains. As the particles become larger, the movements become more uniform and the suspension reaches a steady state where the movements of the largest grains equal that of the largest flocs and further flocculation ceases (Kranck, 1973 *in* Moore 1977).

Muschenheim (*cited in:* Messieh *et al,* 1991) noted that rapid flocculation of clay-sized particles and/or intense vertical mixing may accelerate the particle settling velocity, thus allowing sediment to reach the seabed at lesser distances from discharge platforms. Davies (1984) records similar observations occurring within 500m radius of a dredger, although he does not specify water depths and/or current velocities.

J. Rees (*pers. comm.*) has noted a far-field near-bed extension to the range of elevated suspended concentration levels reported herein. Few details appear to date within the press. It is considered that this 'benthic boundary layer plume' reported in the far-field may be the result of floc formation, maintained in suspension by turbulence within the boundary layer. The existence of such flocs will vary geographically in response to the geological nature of the substrate, in particular the mineralogy of the clay constituents. Further, flocculation at the same site will vary over time, in response to seawater temperature, salinity and overall viscosity. This is an important feature which may have further ramifications, but knowledge is at an early stage and research is ongoing.

SECTION 3 - INVESTIGATING PLUMES

The development of a simple and universally applicable model of turbidity induced by capital and maintenance dredging associated with largely cohesive sediments is considered practically impossible at present (Pennekamp *et al*, 1996). When considering the specific sphere of aggregate extraction, which occurs within a limited range of environmental boundaries (water depth, geology, distance to market *etc.)*, the prognosis is more optimistic. Nonetheless, the variability of the marine environment and dredging operations may restrict the development of generic guidelines to those of defining 'Best Practice' for study and monitoring thereof, with recourse to site specific investigations for individual Environmental Assessment and Licence application.

With increasing requirements for assessing the impact of the plume on the seabed, fish stocks and benthos *etc*., greater quantification of the levels of suspended solids within the plume has been required. In Section 2 we identified the sources for plume formation associated with commercial aggregate dredging in particular. The scale of the operations requires proper targeting of monitoring effort, competently planned to maximise resources and minimise excessive costs.

The primary source terms required for assessment of the plume impact have been outlined earlier. This Section outlines some of the methods that are available for measurement of both the source terms (for predictive capabilities) and monitoring methods (for refinement of the predictive models) available. Competent, well executed field measurements provide indisputable evidence of the impacts measured on the survey day and are invaluable. Rigorous field calibration of equipment, *in situ*, is indispensable.

3.1 Variability Of Natural Systems

Prior to attempting to measure suspended solids concentrations (SSC), or changes in SSC attributable to dredging, knowledge must be obtained of the background SSC likely to be encountered and the range of natural variability that may be expected during the monitoring period. Table 3.1 lists values obtained for total particulate matter (as seston).

Interpretation of the results of fieldwork and, especially, modelling, must be viewed in the context of the range of natural variation in suspended solids concentrations. Results from a limited number of measurements in the English Channel (HR Wallingford, 1993) suggest a storm range of 8ppm to 6ppm and calm condition results of 0.01ppm to 12ppm (surface to near bed respectively). Subsequent modelling indicated an increase above background levels of up to 5ppm for two tides and 1ppm for as many as 6 tidal cycles. These results appear significant, until compared with more extensive field sampling campaigns obtained over greater periods in similar areas of the English Channel (Table 3.1).

Reference	Locality	Comments	dry wt (mg/l)
Bassindale (1943)	Bristol Channel (UK)	At Weston-Super-Mare	30-900
Postma (1961b)	Wadden Sea	coastal	1000
Manheim *et al* (1972)	Gulf of Mexico, USA	surface (offshore)	0.125
Chave (1965a)	SW Florida, Caribbean	surface	5
Chester & Stoner (1972)	English Channel	surface	1.719
Chester & Stoner (1972)	Irish Sea	surface	1.680
Buss & Rudolfo (1972)	Cape Hatteras, USA	surface (offshore)	0.1
Buss & Rudolfo (1972)	Cape Hatteras, USA	midwater (offshore)	1-2
Buss & Rudolfo (1972)	Cape Hatteras, USA	bottom (offshore)	0.5-2
Gajewski & Uscinowicz (1993)	Baltic Sea	depth average	1.8
HR Wallingford (1997)	Owers Bank, UK	depth average	0-30
HR Wallingford (1997)	Rye Bay & Harwich	depth average, storms	220-410
Dyer & Moffat (1992)	southern North Sea	depth average - summer	5-30*
Dyer & Moffat (1992)	southern North Sea	depth average - winter	38-42*
Environment Agency (1992-4)	English Channel	surface	<2 - 76*
Environment Agency (1992-4)	English Channel	midwater	<3 - 97*
Environment Agency (1992-4)	English Channel	bottom	<2 - 76*

Table 3.1 *Selected values of seston (dry weight). Values marked * are given as Suspended Solids concentration (modified from Moore, 1977; Dyer & Moffat, 1992; HR Wallingford, 1993; Environment Agency, 1997)*

Recent long term results prepared by Stevenson (1992, *in* HR Wallingford, 1996) considers that SSC need to be established over a three month period (at a minimum) to determine the relationship between tidal range and SSC. Little quantified data exist on the requirements for relating SSC to seasonal variations, but data spanning at least 2 years would be required.

3.2 Measurements Of Turbidity

Measurement of turbidity is often perceived as a generally lower cost option than extensive sampling and testing of suspensates. Turbidity can be measured in a number of ways, the simplest of which is a white circular 'Secchi Disc', some 300mm in diameter, lowered into the water column until no longer visible from the surface. From this depth the Coefficient of Extinction is determined. Electronic turbidity measuring methods are grouped into optical transmissivity, optical backscatter and acoustic backscatter techniques.

With the development of optical transmissivity and optical backscatterance techniques, turbidity has been expressed in terms of Jackson Turbidity Units (JTU) or Nephelometry Turbidity Units (NTU), which are approximately equivalent. More recently the Formazin Turbidity Units (FTU) are quoted which are referenced to a Standard Solution suitable for field deployments. Pyle & Griffin (1974, *In:* Moore, 1977) suggest legal turbidity standards should ultimately be defined in terms of light requirements or silt tolerance of organisms needing protection and it may therefore be realistic to define permissible levels as percentages above background. However, detailed knowledge on the interaction of suspended solids and tolerance levels is site specific both in the mineralogy of the disturbed sediments and in the type of biological community disturbed.

3.2.1 Optical Transmissometer

The most common method, for which there are numerous products on the market with slight technical and performance differences, is that of the optical transmissometer. This records the extinction in light between the emitter and receiver that is dependent on the frequency of the light source, optical path length, water composition, size and refractive index of the particles and sediment concentration. A monochromatic light source of approximately 660nm wavelength is least affected by dissolved constituents of seawater. This is passed over a fixed optical pathlength, commonly 50 - 250 mm, for recording by a photodiode receptor.

Some instruments use a beam splitting arrangement to avoid potential problems in degradation of the light source. The relationship between beam attenuation and concentration is linear for a given particle composition and is generally determined empirically using filtered sample calibration at the site of interest. A range of Standard Formazin turbidity solutions may also be prepared for calibration with site samples. The maximum particle size measurable is approximately 50µm. The system is not suitable for sand suspension measurements, *i.e.* particles greater than 63µm diameter. Concentrations up to 5g/l are measurable using progressively shorter transmission pathlengths. Measurements will be affected by small air bubbles in the water column and possibly by other factors such as humic acid from peaty soil (HR Wallingford, 1996). For use in scenarios where sunlight may cause problems, transmissometers are also available which utilise an infra-red light source.

3.2.2 Optical Backscatter

This method utilises an 850-950nm infrared source and a silicon photodetector. Infrared radiation is scattered by the particles in front of the photodetector. The level of the photocurrent is linearly proportional to the mass concentration of the scattering particles. Optical backscatterance techniques have been developed which are suitable for muds (up to 5000mg/l), silts and sands (up to 100,000mg/l).

The sensitivity will vary according to the particle size, shape and refractive index and may vary by more than a factor of 200 for different sediments. This enforces the requirements for accurate calibration on site, and for re-calibration should the particle sizes or composition differ significantly. Any fines will grossly distort a calibration based on predominantly sandy sized sediments

3.2.3 Acoustic Backscatter

Acoustic Doppler current profiling techniques utilise the transmission of a beam of sound into the water column by 3 or 4 highly directional 2.5 degree beamwidth) transducers arranged in a 'Janus' configuration, inclined at 30 degrees to the vertical. The transducers are driven by a common power amplifier, but with four independent receiver channels. Data is acquired from the ADCP Deck Box using a PC running the mission planning, acquisition and post-processing software 'Transect' supplied by RD Instruments. Backscattered sound from plankton, small particles, air bubbles and small scale inhomogenities in the water ('scatterers') are received by the transducer.

The received signal differs by a Doppler frequency shift proportional to the relative velocity difference between transducer and scatterers. A rapid and continuous series of time based 'range-gated' transmissions enables a profile of the water column, divided into 'bins' which may be as small as 0.25m, to be computed knowing the precise geometry of the beams and a measured or assumed value for the speed of sound in water. Each cell or ‘bin’ of data is allocated velocity components in x, y and z directions. Bins are grouped into ‘ensembles’, which are recorded instantaneously (during the plume tracking exercise) or can be averaged over time or distance (as for current metering or wide scale oceanographic investigations). These data can then be manipulated either in real-time or post-processed to provide detailed representation of the water velocity movements through the water column.

The fundamental assumption is made in that the ‘scatterers’ will be moving at the same rate as the cell of water they are in. The transducer may be stationary, or velocity and heading can be input from external sources *e.g.* from a Global Positioning System (GPS) sensor and gyro compass.

Alternatively velocity can be determined using *bottom tracking* of the seabed by the 4th beam.

Collecting such density of data by impellor or electro-magnetic current meter (EMCM) methods would be prohibitively costly. The primary function of Doppler current profiling techniques is to record continuous current velocities through depth and, depending on the equipment, dynamically using a moving boat. A secondary function of some systems enables the operator to display the acoustic strength of the returned signals for each bin. This will be affected by the SPM. When used in Vessel Mounted (VM) (Figure 3.2.3a) mode this provides a graphic illustration of relative differences in acoustic backscatter, and hence represents relative variations in suspended solids concentration (Figure 3.2.3b).

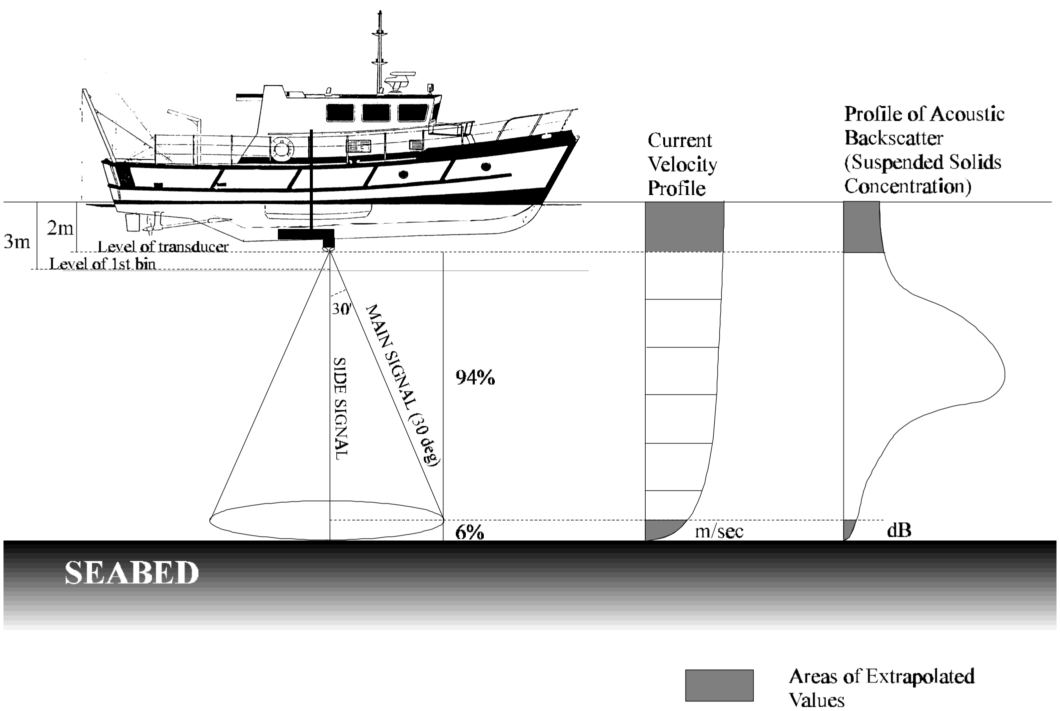


Figure 3.2.3a *Deployment arrangement for Vessel Mounted Acoustic Doppler Current Profiler (VMADCP) as developed during this study for Continuous Backscatter Profiling. Upper and lower part of current and suspended sediment profiles are calculated by extrapolation based on values within measurable range*

Since the early 1980s, Acoustic Doppler Current Profiler have become routine instruments for physical oceanographers and they are now fitted to many oceanographic research vessels. Doppler current profiling and acoustic backscatter measurements have been used since the late 1980s for observing distributions of suspended particulate matter, particularly zooplankton following the work of Flagg & Smith (1989). Recently, its’ use has been extended for observing sediments suspended by dredging and dredged material disposal operations, particularly cohesive sediments in the U.S.A., (*see, for example,* Thevenot & Kraus, 1993; Ogushwitz, 1994) and studying wastewater outfalls (Dammann *et al*, 1991). The usefulness of ADCP techniques as interdisciplinary instruments are now well established.

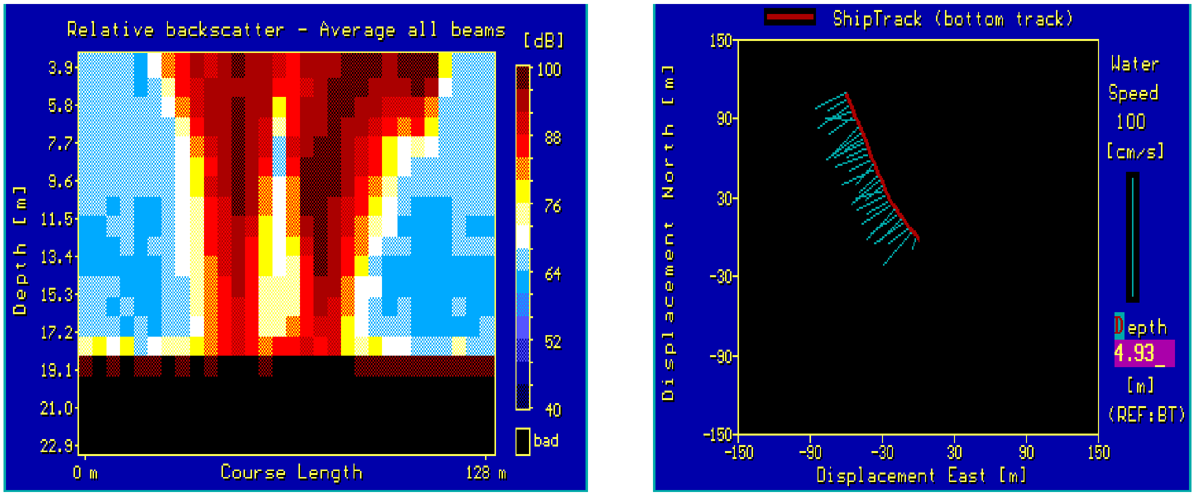


Figure 3.2.3b *Acoustic Doppler Current Profiler™ screen dump showing plume of suspended sediment either side of dredge vessel, immediately astern. Higher suspended solids concentrations are shown in darker colours, the seabed appears black. Clear waters appear in light blue. The darker returns on the starboard side of the ship (right hand side of the figure) reflect the combined overspill and reject plume, whereas the port side of the ship contains only material overspilled. The independent plumes formed either side of the vessel are separated at this distance astern, and are just joining together at depth. Right side shows current velocities proportional to 'stick' length, and direction, recorded simultaneously, whilst traversing along the transect at left.*

There are some significant limitations when using Doppler current profiling techniques for plume monitoring. The most critical is the presence of air bubbles in the water column. Air bubbles transmit the sound signal at a significantly different speed to that of the surrounding waters (due to compression) and will induce considerable noise into the displayed results. It is not possible to circumvent them. When monitoring the passage of a vessel, the wake will appear similar to that of a plume, requiring detailed field notes to explain the apparent 'plume'. Further fieldwork with gravimetric analysis of suspended matter from the monitoring location enables site specific correlation tables to be generated and thus provide conversion to SSC.

The transect shown in Figure 3.2.3b must be viewed bearing in mind the presence of air bubbles and their acoustic signature, caused not only by the motion of the vessel, and the action of the propellers, but also by the 'plunging effect' of the overboard discharge. As will be shown later, it is considered that the sediments within the plume may have air bubbles attached to the particles (which act as buoyancy) and will mask the true acoustic signature of the suspended sediments.

It is presently generally considered for bio-oceanographic monitoring that acoustic backscatter from ADCP cannot be practically calibrated at sea by users (*see* Roe & Griffiths, 1996). Calibration difficulties have meant that virtually all measurements presented have been based on relative backscatter measurements. These relative data are useful for providing semi-quantitative distribution patterns, but they are not comparable over different hydrographic regimes because of the variation in sound absorption with temperature and salinity. Furthermore they cannot be used to compare backscatter at different depths, and they will inevitably provide generalised backscatter/biomass relationships (Roe *et al*, 1996).

Working on oceanographic-scale plankton investigations, recent work by Roe *et al* (1996) improves these relative data by comparing the mean volume backscattering strength (MVBS) within each depth cell of the ADCP using the manufacturers calibration data together with the *in situ* temperature and salinity conditions and the internal electronics temperature and noise levels. This is then compared to concurrent temperature and salinity data from a towed undulating hydrographic sensor platform (SeaSoar) in order to accurately calculate the sound absorption coefficient α, a principle component in determining absolute values for measured backscatter.

The following section outlines techniques for determining suspended solids concentrations and also outlines recent investigations into the use of ADCP equipment for measuring the suspended solids concentrations of plumes generated by various types of dredging activities.

3.3 Measurements Of Suspended Solids Concentrations

3.3.1 Water Sampling

Water sampling devices are as diverse in appearance as they are in complexity. There are numerous Patent and Trademark models available on the market although many are variations on a theme. The simplest form of sampling will be a bucket on a line for use in the surface waters. For deeper waters, sampling bottles with spring loaded plugs or valves at each end are attached to a weighted line and lowered to the required depth. Operation cycle can be of the open-close or close-open-close type.

The bottle can be triggered by sliding a messenger weight down the suspension wire and thus tripping a release mechanism, for example ELE Water Trap, N.I.O, Niskin, van Doorn and Ruttner sampling bottles. The CB sampling device uses a small DC current to trap a sample. The Casella bottle is operated by a sharp pull on the lowering line.

The maximum size of samples generally available from water sampling bottles is about 10 litres although equipment of at least 30 litres capacity is available. A string of bottles may be arranged in a *cast* or bottles may be arranged in a 'rosette' formation.

In situations where suspended solids concentration is known to be low, larger samples are required and these will generally be obtained by pump sampling. In depths greater than approximately 35m the pumps will have to be submersible. Pump sampling however has time delays due to the time taken for a discrete sample from a certain location to pass from the suction point to the delivery and storage point.

If the pump capacity is too low, or the settling velocity of larger particles of sediment too high, such larger particles may tend to be left behind in the rising suction tube, therefore artificially reducing the mean particle size. The limitations of pump sampling and possible underestimation of particle sizes have been well documented (*see, for example,* Nelson & Benedict, 1951; Crickmore & Aked, 1975).

3.3.2 Gravimetric Analysis

Laboratory analysis of discrete samples by filtration remains a standard reference method for determining suspended sediment concentrations. Known volumes of seawater are passed through pre-weighed, washed membrane filters of known pore size *e.g.* Millipore 0.45µm +/- 0.02µm, under suction (1/3 ATM) and rinsed with distilled water. The filters are dried at 75^{o}C to constant weight.

The difference in weight of the membrane will be that attributable to the total suspended particulate matter. There are many newer laboratory methods available for determination of suspended solids concentrations involving, for example, centrifuges, radioactive absorption, laser diffraction *etc*. but all have inherent difficulties.

3.3.3 Particle Size Distribution

For examining the dispersion of a plume it is essential to know the range of material sizes that will be dispersed. Particle size analysis is a standard laboratory procedure and a variety of methods are available, depending on the size range of the sample to be tested. Laser diffraction techniques apply to the smaller fractions, less than 5µm. However this analysis is usually carried out on fully disaggregated sediments, which may obscure information pertaining to the *in situ* behaviour of the sediments.

3.3.4 Acoustic Backscatter

The ADCP Deck Box maintains a feedback voltage to the transducers at a constant signal voltage level. The feedback control voltage (Automatic Gain Control - AGC) required varies according to the intensity of the received echo at the transducer, *i.e.* is proportional to the level of acoustic backscatter. The AGC values are the average of the four individual beam values. The AGC value is converted to relative backscatter (dB) depending on several environmental factors including the electronics temperature, factory calibration of the transmitter and receiver and the beam pattern and sensitivity of the transducers. At a typical electronics temperature of 28^{o}C, the relative backscatter conversion equates to 0.42dB/AGC count.

Absolute backscatter has been calculated (*see, for example,* Roe *et al*, 1996) for each depth layer (removing the effects of spherical spreading of the beam, attenuation and changes in the isonified volume) according to the RD Instruments' Technical Note (1990) and following the concept of determining the mean volume backscattering strength (MVBS). Detailed consideration of such procedures is considered outwith the scope of this thesis.

A number of investigators have further attempted to correlate the backscatter sound strength (dB) of a returned signal with suspended solids concentration (mg/l) with varying degrees of success (Thevenot & Kraus, 1993; Tubman *et al*, 1994; Ogushwitz, 1994). Land *et al* (1994) report statistically acceptable correlation with optical silt meters and water samples for sediment in the range 5 - 75µm with a mean particle diameter 10µm and concentrations up to 1000mg/l.

Lohrmann & Huhta (*In:* Tubman *et al*, 1994) calibrated a 2.4MHz BroadBand ADCP in a purpose-built laboratory calibration tank using material obtained by grab from the seabed of the site to be studied. Although suspended solids concentrations determined by the ADCP were considered to agree 'reasonable well' with the water sample analyses, the maximum error was considered to be ± 60% at 50mg/l. This is largely explained by the theory of Rayleigh backscattering used by the ADCP, which itself can only be accurate to ± 50%. Thevenot & Kraus (1993) hypothesised that flocculation of the material could be a contributing factor to the differences between laboratory and field calibrations.

The techniques involve very careful and rigorous calibration by field sampling which must be repeated at frequent intervals, especially when particle characteristics such as mineralogy and refractive index are expected to change. Table 3.3.4 summarises the measurements that must be recorded during the survey in order to correlate backscatter strength with suspended solids concentrations.

Within this project, the use of Doppler current profiling techniques, in particular in Vessel Mounted configurations, has concentrated on accurately representing the gross morphology of the plume in real-time. This enhances the positioning of other sampling equipment such as water bottles or pump sampling apparatus within the plume for acquiring the suspended solids concentrations.

During post-processing the concentration of solids within a water sample can be confidently placed into perspective within the plume and so apply that concentration to immediate regions of equal acoustic strength to facilitate building graphic representations of the plume behaviour. Correlation of the acoustic strength of the return with suspended solids concentrations has not been attempted.

Speed of sound throughout water column	Corrects for	Beam spreading
Salinity gradient throughout water column	Corrects for	Water absorption
Temperature gradient throughout water column	Corrects for	Water absorption
Particle size expected throughout survey	Corrects for	Beam attenuation
Particle density and compressibility	Corrects for	Beam attenuation
Supply voltage to equipment	Corrects for	Power output variations
Temperature of the electronic circuits	Corrects for	Amplification circuitry

Table 3.3.4 *Table of minimum measurements that must be collected during Doppler current profiling surveys in order to correlate acoustic backscatter with suspended solids concentration (modified from Land* et al, *1994)*

The US Army Corps of Engineers (USACE) Dredging Research Program (DRP) undertaken between 1988 and 1995 at a cost of $35 million has investigated many facets of applied research and development to dredging operations. A significant study by this project was the development of the PLUme MEasurement System (PLUMES) (Kraus & Thevenot, 1992) which also utilised commercially available broad band acoustic Doppler current profiling equipment. The results have been successfully used to document the actual movement of the sediment plume for resource agencies, who were concerned that the plume did not impinge on nearby environmentally sensitive biological regions (Hales, 1995). At least $5 million were saved in not having to conduct extensive environmental studies related to designation of new disposal sites at these locations.

The results obtained both through this research and also reported recently world-wide demonstrate the enormous potential for ADCP operations providing real-time data acquisition and representation of hydrographic and oceanographic conditions. Conventional sampling programmes are enhanced through efficient targeting of resources and confidence in the resultant data. However, analysis of backscatter data for correlation with suspended solids concentrations must take account of the fact that ADCP observations may represent concurrent changes in particle concentration and particle morphology without discmination.

3.3.5 Aerial Photography

Observation of plumes developed by dredging activities is often easily observed by aerial photography. In good conditions this will clearly show the surface expression of a 'plume' (Plate 3.3.5). It has been known for commercial air traffic to report the presence of a major 'oil pollution incident' to the Coastguard, which on investigation has proved to be the surface plume from intensive dredging activities. The results from this study, however, clearly indicate that such comparison of a dredge plume with an 'oil-spill' is sensational and inappropriate.

Plate 3.3.5 *TSHD Sand Harrier*

Modern aerial photogrammetric techniques are such that, given suitable marker buoys located about a plume by differential GPS techniques, accurate measurements of the surface expression of the plume may be made.

3.3.6 Satellite Imagery

Whiteside *et al* (1995) report the use of satellite imagery to illustrate the contrasting natural turbidity regime which exists around Hong Kong. Images may be produced with sufficient resolution to identify the plumes from individual vessels. However, processing of data is presently perceived as costly, and is likely only to be of benefit to major dredging operations, such as in Hong Kong. Technological developments may however, within only a few years, allow such information to become realistically appropriate.

3.3.7 Seabed landers

A number of recent offshore investigations in the U.K. have developed the use of small seabed 'landers'. These frames are deployed on the seabed and host an array of instrumentation to monitor both background and enhanced water quality parameters. Equipment used includes optical and acoustic backscatter sensors for turbidity, electromagnetic current meters, pressure sensors and time-series water sampling devices for suspended solids measurements.

3.4 Monitoring Strategies

The development of plumes are a comparatively short-lived affair compared with many other oceanographic observations. The monitoring strategy must therefore be designed mindful of the fact that results will fluctuate both over very short distances (metres) and in time (seconds).

If historical background data on natural suspended solids concentrations and turbidity are not available at a sufficient resolution for the study area, it will be necessary to obtain such information. Background levels may be established over a period of several months for tidal component variations, or at least one year for seasonal variations. These requirements dictate remote monitoring equipment, and the development of the benthic landers provides a suitable long term frame upon which to mount such campaigns. Concurrent information on wave conditions, tidal velocities, wind velocities *etc*. will also be required.

It is necessary to consider the sampling frequency of long term deployed equipment. Solid state data loggers have increasingly large storage capacities and deployment periods, largely due to improvement in battery technology. A popular approach is to 'burst sample' for perhaps thirty seconds every fifteen minutes and record the average figures. This will account for the majority of oceanographic variations of short (wave motions) and medium (tidal components) term variations. There may be considerable differences for specific requirements, and these are treated comprehensively in the standard oceanographic texts (*see, for example*, Tolmazin, 1985)

HR Wallingford (1974) report variations in instantaneous output from silt transmissometers of up to 20% from the mean for a series of twenty, three second measurement bursts. Stevenson (1992) reports significantly greater variation for higher concentrations (up to 1000ppm) which exemplifies the smoothing effect that sampling by pumps may have on averaging instantaneous variations.

For the purposes of plume monitoring it is essential to know (a) where the plume is and (b) where the sampling equipment is in relation to the plume.

3.4.1 Continuous Backscatter Profiling (*CBP*)

Acoustic Doppler current profiling equipment provides the most suitable technique available today for real-time monitoring of the formation of a plume. Used in a complementary role to siltmeter and water sampling activities, modification of the sampling strategies can be made during the progression of the survey based on in the field observations.

'*Continuous backscatter profiling*' (CBP) may be considered analogous to continuous seismic profiling

(CSP). Detailed descriptions of the principles of using the acoustic backscatter function of the ADCP™ can be found in Land *et al* (1994) and Weiergang *et al* (1995).

Continuous observations of the strength of acoustic signals returned by particles in the water column are processed in real-time to create on screen displays with horizontal time and vertical water depth axes. The colouring of the individual bins of data are user configurable and relative to the strength of the returned echoes and hence the amount of 'scatterers' in the water column. This may include organic and inorganic particles, air bubbles *etc*.

The monitoring strategy may be designed in a number of ways using a suitable coastal survey vessel. Firstly a survey programme may observe successive transects across and along the plume axes recording the variation in acoustic signal strength with the ADCP™. The transects are arranged consecutively further downstream of the dredging operation, with one transect upstream before and after the campaign to establish background conditions.

If a midwater drogue with surface marker is deployed immediately downstream of the dredge operation, each transect across the plume may pass adjacent to the drogue. That is to say each transect will observe the same parcel of water at different times after release of material to the water column. The apparent time based settling rate of the material may then be observed.

Alternatively, the vessel may hold station adjacent to the drogue surface marker and continuous observation of the apparent settling characteristics of the plume observed.

The acoustic backscatter function of the ADCP™ can be used with considerable success to efficiently display a real-time graphical representation of the gross morphology of the plume. However, even with careful planning and control it is both difficult and essential to ensure that the water samples obtained can be correlated to a specific 'bin' of data recorded by the ADCP™.

Within this project the ADCP™ has been used principally to position the sampling equipment within the plume and have confidence that the sample analysis results are applicable to maxima, minima or otherwise. Other workers, (*see for example* Land *et al* 1994; Weiergang *et al*, 1995), have taken this concept further and attempted to correlate the acoustic strength with suspended solids concentration, a matter receiving considerable debate at present.

To produce competent analysis of the ADCP™ data, the position of the ADCP™ survey vessel and the dredge vessel are required to some degree of accuracy, best provided by Global Positioning System (GPS) techniques operating in Differential mode (dGPS). Ensuring that the two vessels are operating on the same datum, position accuracies better than 5m should be readily attainable.

SECTION 4 - RESULTS OF OUR INVESTIGATIONS

Coastline Surveys Ltd have undertaken numerous and varied investigations into aspects of the dispersion of plumes associated with marine aggregate mining. This baseline project was divided into three main areas of interest, each with separate phases of investigation;

Phase One: ***determination of surface overspill and screening/rejection source terms and contributions to plume generation***

Phase Two: ***evaluation of plume survey, monitoring and representation techniques***

Phase Three: ***determination of benthic plume source terms generated by action of the draghead on the seabed***

Field campaigns undertaken during the project timespan have characterised overflow and, to a limited extent reject sediment/water mixtures, to determine the source terms of the surface plume. This has been done from a number of different vessels in different operational licence areas with different geological conditions. Table 4.0.1 summarises the field campaigns that have been undertaken during this project.

An extensive monitoring survey using the acoustic backscatter function of an Acoustic Doppler Current Profiler (ADCP™) was undertaken in August 1995 and a smaller exercise was undertaken in January 1997.

Also in January 1997, concurrent with the ADCP™ profiling, underwater video cameras and pump sampling equipment was mounted on the dragarm and draghead of a TSHD during normal operations.

4.1 Phase One - Surface Plume Source Terms

The source term for modelling a surface plume is the quantity and quality of the suspended sediments. This may best be expressed by as a rate *i.e.* as unit weight of dry solids per unit time or per loading operation. Particle size distribution and shape (with very fine cohesive particles also density and mineralogy), are fundamental factors that will affect settlement rates and hence horizontal excursion. These must be investigated.

Prior to this study, few attempts appear to have been made to define these source terms using field data (notably some preliminary work undertaken by ARC Marine Ltd, SCS Ltd and UMD Ltd in 1992). Historically, analyses have largely been based on dredge manufacturer's equipment design and operator's performance data.

A fundamental objective of this study has been to collect reliable field measurements on source terms. The recent studies in Hong Kong have also considered the importance of field data and have collected detailed datasets (Land *et al*, 1994).

4.1.1 Overspill Volume

Other than manufacturers' specifications on the pumping capacities of the dredge pumps, only the newer design of dredgers have electronic forms of loading gauges. On the largest vessel sampled, these had not been calibrated since manufacture of the ship. On the smaller vessels, loading gauges are not generally available.

Consequently it was necessary to determine the rate at which the pump worked, by verifying manufacturers' specifications, in order to establish the quantities of material involved. It was then necessary to determine the proportion of the pumped material which was discharged overboard through rejection or through the spillways. Information generally available from manufacturers quotes pumping rates as water only, rather than water and sediment.

A number of options have been considered to determine the volume of material passing through the spillways, bearing in mind strict cost limitations.

Discussions with waste disposal and discharge consultants were initiated but abandoned largely due to the heavy financial implications of furthering their suggestions.

Date	Vessel	Loading Time	Screening Method	Licence Area	Samples Obtained
29.07.93	ARCO Adur	3 hours 10 mins.	14 mm screen (SAND)	202 Cross Sands	5 overspill
05.08.93	ARCO Adur	4 hours 20 mins.	10 mm screen (SCR BAD)	202 Cross Sands	8 overspill
06.08.93	ARCO Adur	3 hours 00 mins.	14 mm screen (SAND)	202 Cross Sands	7 overspill
08.08.93	ARCO Adur	4 hours 50 mins.	10 mm screen (SCR BAD)	212/5 Norfolk Bank	14 overspill
09.08.93	ARCO Adur	4 hours 40 mins.	10 mm screen (SCR BAD)	202/5 Cross Sands	12 overspill
11.08.93	ARCO Adur	5 hours 30 mins.	10 mm screen (SCR BAD)	242/8 Lowestoft Bank	15 overspill
12.08.93	ARCO Adur	4 hours 50 mins.	10 mm screen (SCR BAD)	212/5 Norfolk Bank	13 overspill
28.11.94	ARCO Severn	5 hours 10 mins.	10 mm screen (100mm SCALP)	124/1 Owers Bank	39 overspill
30.11.94	ARCO Severn	4 hours 10 mins.	10 mm screen (100mm SCALP)	124/1 Owers Bank	37 overspill
01.12.94	ARCO Severn	5 hours 40 mins.	10 mm screen (100mm SCALP)	124/1 Owers Bank	48 overspill
06.01.95	ARCO Severn	2 hours 10 mins.	no screens (ALL-IN)	124/1 Owers Bank	18 overspill
11.05.95	ARCO Severn	3 hours	no screens (ALL -IN)	124/1 Owers Bank	36 overspill
13.05.95	ARCO Severn	4 hours 10 mins.	10 mm screen (100mm SCALP)	124/1 Owers Bank	44 overspill
19.08.95	ARCO Severn	3 hours 30 mins.	no screens (ALL -IN)	124/8 Owers Bank	47 overspill
20.08.95	ARCO Severn	3 hours 40 mins.	10 mm screen (100mm SCALP)	124/8 Owers Bank	46 overspill
21.08.95	ARCO Severn	3 hours 30 mins.	10 mm screen (100mm SCALP)	124/8 Owers Bank	49 overspill
17.12.96	ARCO Severn	2 hours 30 mins.	no screens (ALL -IN)	124/1 Owers Bank	18 x draghead plume samples
14.01.97	ARCO Dee	3 hours	10mm screen (100mm SCALP)	124/1 Owers Bank	13 x draghead plume samples + video camera + ADCP
16.01.97	ARCO Dee	2 hours 45 minutes	10mm screen (100mm SCALP)	124/1 Owers Bank	video camera
17.01.97	ARCO Dee	2 hours 25 minutes	10mm screen (100mm SCALP)	366 Hastings Bank	video camera

Total samples collected: 469 (31 draghead plume, 408 overspill and 30 reject chute samples)

Total days at sea: 29

Table 4.0.1 *Summary of field work campaigns undertaken during this project*

Determination of the overspill volume has been assessed by a variety of techniques:

- seabed disturbances **-** analysis of seabed draghead disturbances by using detailed sidescan sonar mapping and processing to calculate sediment volume disturbed during each load (Davies & Hitchcock, 1992)

- time series analysis **-** comparison of manufacturers' specifications for pumping rates, loading times and range of variations

- analysis of the solids' concentration of the overspill and rejected suspensates by extensive sampling and laboratory testing

- *in situ* measurements using conventional vane and modern electromagnetic current meters combined with high quality video records and PC image processing to determine flow rates

- by combining field observations and design specifications of the loading performance of typical TSHD, the total dry solids returned through overspill can be estimated

Comprehensive analysis of the seabed disturbances caused by aggregate dredging activities had been undertaken immediately prior to this project and is reported in Marine Technology (MTD) Report No. GR/G 20059, Davies and Hitchcock, 1992. Observations during the MTD project suggested considerably more seabed material was disturbed than was loaded aboard the dredger.

Detailed measurements of high resolution sidescan sonar images of the draghead furrows were manipulated and processed using novel modelling techniques. Identification of different shape seabed furrows was largely attributable to particular types of draghead operated by different vessels. Plate 4.1.1a shows the condition of the seabed after passage of the draghead, and unaltered deposits alongside. The development of small sand ripples, orientated perpendicular to the direction of passage of the draghead is clear and has been observed from sidescan sonar imagery (Davies & Hitchcock, 1992).

Plate 4.1.1a *Underwater image taken 2 weeks after trial dredging off Norfolk showing effects of draghead on removal of coarse sediment and development of small sand ripples within the dredge furrow. Area of photograph about 0.7m2 (from Crown Estate, 1994)*

'W' and 'M' shape furrows, largely caused by 'A' class and 'T' class dredge vessels mainly using 'California' Type dragheads (but not always), suggested most disturbance at the seabed. Figure 4.1.1a illustrates the principle types of furrow that were identified and their main features. Table 4.1.1a summarises the proportions of draghead furrows measured from sidescan sonar imagery.

Plate 4.1.1b *TSHD ARCO Thames almost fully loaded, English Channel, August 1995*

	'T' Type furrow	'M' Type furrow	'W' Type furrow
Profile Depth (m)	0.547	0.522	0.342
Profile Width (m)	2.822	2.509	3.687
Levée Height (m)	n/a	0.224	0.220
Overall Width (m)	2.822	3.884	4.824
Net Cut Depth (m)	0.547	0.401	0.187
Outer Slope Angle (^{o})	n/a	10.98	18.07
Profile Cross Section (m^2)	0.665	0.514	0.391
Levée Cross Section (m^2)	n/a	0.113	0.083

Table 4.1.1a *Summary of principle draghead furrow dimensions obtained using sidescan sonar imagery and modelling techniques (after Davies & Hitchcock, 1992)*

Davies & Hitchcock (1992) provides a first approximation to the amount of material that is displaced, mostly removed from the seabed, partially retained as the cargo load and otherwise returned overboard. Using a series of averages, for recorded field data, a 'T' class dredge vessel (load of 3400 tonnes) (Plate 4.1.1b) was observed to displace 16,194 tonnes of material, creating levées totalling 1,919 tonnes, and consequently generating overboard returns of some 10,875 tonnes of sediment. The data suggest that 3-6 times the cargo load is disturbed on the seabed, with 0.5-2 times the cargo left on the seabed as levées or other internal microstructures. The overboard returns suggested by this data may therefore be of the order 2 - 4 times the cargo load.

Detailed time series analysis of the loading rates for differing types of cargo was then undertaken to determine a second approximation of the volume of material returned overboard (Table 4.1.1b).

	ARCO Severn			ARCO Adur		
Area	All-in	Stone	Sand	All-in	Stone	Sand
106	---	---	---	---	4:18 (11) *3:12-7:30*	4:01 (5) *2:48-6:42*
112	4:36 (1)	6:06 (2) *4:36-7:36*	9:12 (2) *7:06-11:18*	---	---	---
124/1	3:35 (30) *2:06-4:24*	4:03 (197) *2:18-6:42*	---	---	---	---
124/2	3:36 (1)	4:41 (8) *3:12-5:30*	---	---	---	---
127	3:26 (6) *2:42-4:15*	4:11 (43) *2:18-6:18*	---	---	5:00 (1)	---
202	---	---	---	1:39(2) *1:30-1:48*	6:22 (82) *4:00-9:36*	---
212	---	---	---	---	6:11 (109) *4:18-9:12*	2:13 (9) *1:48-3:00*
221	---	4:27 (2) *3:54-5:00*	4:02 (3) *3:36-4:18*	---	6:22 (30) *4:48-8:24*	---
242	3:17 (4) *2:42-4:45*	4:07 (49) *2:18-7:18*	---	---	6:43 (26) *4:24-9:00*	---
328	---	---	---	---	6:04 (63) *2:30-10:54*	---
361	---	---	---	---	6:58 (31) *4:42-10:36*	---
366	2:58 (36) *2:18-3:48*	---	---	3:06 (1)	---	---
888	2:46 (10) *2:15-3:15*	---	---	---	---	---
All areas	3:14 (88) *2:06-4:45*	4:07 (301) *2:18-7:36*	6:01 (5) *3:36-11:18*	2:08 (3) *1:30-3:06*	6:13 (353) *2:30-10:54*	2:52 (14) *1:48-6:42*

Table 4.1.1b *Analysis of loading times for 'A' Class and 'S' Class TSHD. Variations due to loading area geology and cargo type, plus other factors such as weather and cargo pump condition*

The third approximation for the quantity of material returned overboard involves analysis of the specific gravity of the overboard returns through the reject chute and the spillways. To determine the quantity of material pumped it is assumed that the density of material pumped will remain constant for different types of cargo *e.g.* all-in or screened. However it is likely in practice that this will vary within certain operational limits, according to the geology of different licences. By experience, dredge Masters will operate the vessel at the optimum pump mixture density. Alterations may be made by changing speed over the ground, angle of the draghead on the seabed, or with some dragheads, opening water inlet valves.

Vessel Type	Cargo Type	Loading Time	Pumping Rate	Volume Pumped
‘A’ Class	no screening (all in)	1 hour 55 minutes	$7750m^3/hr$	$14,854m^3$
‘A’ Class	screening for sand (stone out)	3 hours 5 minutes	$7750m^3/hr$	$23,895m^3$
‘A’ Class	screening for stone (sand out)	4 hours 50 minutes	$7750m^3/hr$	$37,460m^3$
‘S’ Class	no screening (all-in)	3 hours 20 minutes	$4500m^3/hr$	$15,000m^3$
‘S’ Class	screening for stone (sand out)	4 hours 23 minutes	$4500m^3/hr$	$19,725m^3$

Table 4.1.1c *Time series analysis of average loading performance for selected vessel types under normal conditions as observed during field work*

Analyses of some 408 samples have enabled average suspended solids concentrations and particle size distributions (not all of the dataset) to be determined. These have been further analysed using a simplified iterative loading model to determine the correct input quantities to return the observed outputs from the dredger.

The average density of the pumped mixture for an ‘A’ class type vessel has been determined as 1.2128 kg/m^3 and for ‘S’ class as 1.1974 kg/m^3 (B. Jackson *pers. comm.*). Using these values, and from Table 4.1.1c, an ‘A’ class vessel loading a stone cargo (sand out), pumping approximately $37,460m^3$ of mixture, will therefore pump 12,158 tonnes of dry solids mixed with some 33,356 tonnes of seawater. Retaining 4,185 tonnes of sediment as cargo, it therefore follows that some 7,973 tonnes of sediments will be returned overboard during the load.

From Table 4.1.1c a range of values for the volume of material pumped can be determined according to vessel type and load. Loading times for an ‘A’ class type vessel will vary between less than 2 hours for ‘all-in’, averaging 4 to 6 hours for screening. Exceptionally, cargoes may take 9 to 10 hours to load though this is commonly due to bad weather or worn dredge pump impellor. The smaller ‘S’ class vessels take a shorter length of time to load under normal conditions, loading less material at a slower rate.

Modern dredgers such as the City of Cardiff have pumps capable of loading mixture at $1.5m^3/s$. Vessels such as the City of London and City of Westminster (similar to ‘A’ class) will load mixture at approximately $2m^3/s$ (A. Bellamy, *pers. comm.*)

Ignoring the quantity of sediment disturbed at the seabed but not actually raised from the seabed, a ‘loading efficiency’ may be considered as the ratio of load retained to the quantity of sediment pumped and thus averages 37% for a screened stone cargo (1:3). Similarly, loading efficiencies may be 58% for screened sand cargo and as high as 93% for ‘all-in’ cargoes. Table 4.1.1d presents some comparisons for different vessels.

Cargo Type	‘A’ Class
no screening (all in)	93%
screening for sand (stone out)	58%
screening for stone (sand out)	34%

Table 4.1.1d *Loading efficiencies for ‘A’ Class vessels. Loading efficiency is defined as the ratio of load retained to the total quantity of sediment pumped*

Finally, a fourth set of data was collected to clarify the distribution of overboard returns between overspill and rejection by screening. Detailed measurements of the flow velocities encountered within the overspill weirs were made (Plate 4.1.1c). Using a combination of traditional vane (Valeport) current and modern electromagnetic (Marsh McBirney) current meters combined with high resolution computer processed video imagery, the rate of material passing over the spillways was determined. Measurements were made (some 15000 at 2 second intervals) for the duration of the load for different cargoes. The differences between overspill rates during loading all-in and screened cargoes can consequently be attributed to the proportion of pumped mixture passing overboard through the reject chute (Table 4.1.1e).

Date	Cargo Type	Ship	mean overspill velocity (m/s)	mean depth (m)	mean rate (m^3/s)
06.01.95	all-in	'S' Class	2.505	0.079	0.336
11.05.97	all-in	'S' Class	2.345	0.074	0.310
13.05.97	stone (sand out)	'S' Class	1.54	0.051	0.178

Table 4.1.1e *Summary of the flow observations made in the starboard side aft spillway (per overspill channel). The difference between screening and non-screening assists derivation of the ratio between overspill and rejection by screening*

Plate 4.1.1c *Electromagnetic current meter and measuring gauges set within the spillway of the ARCO Severn. Simultaneous video imaging and analysis has enabled calculation of volume, determination of overflow rate and therefore ratio of overspill to rejection components*

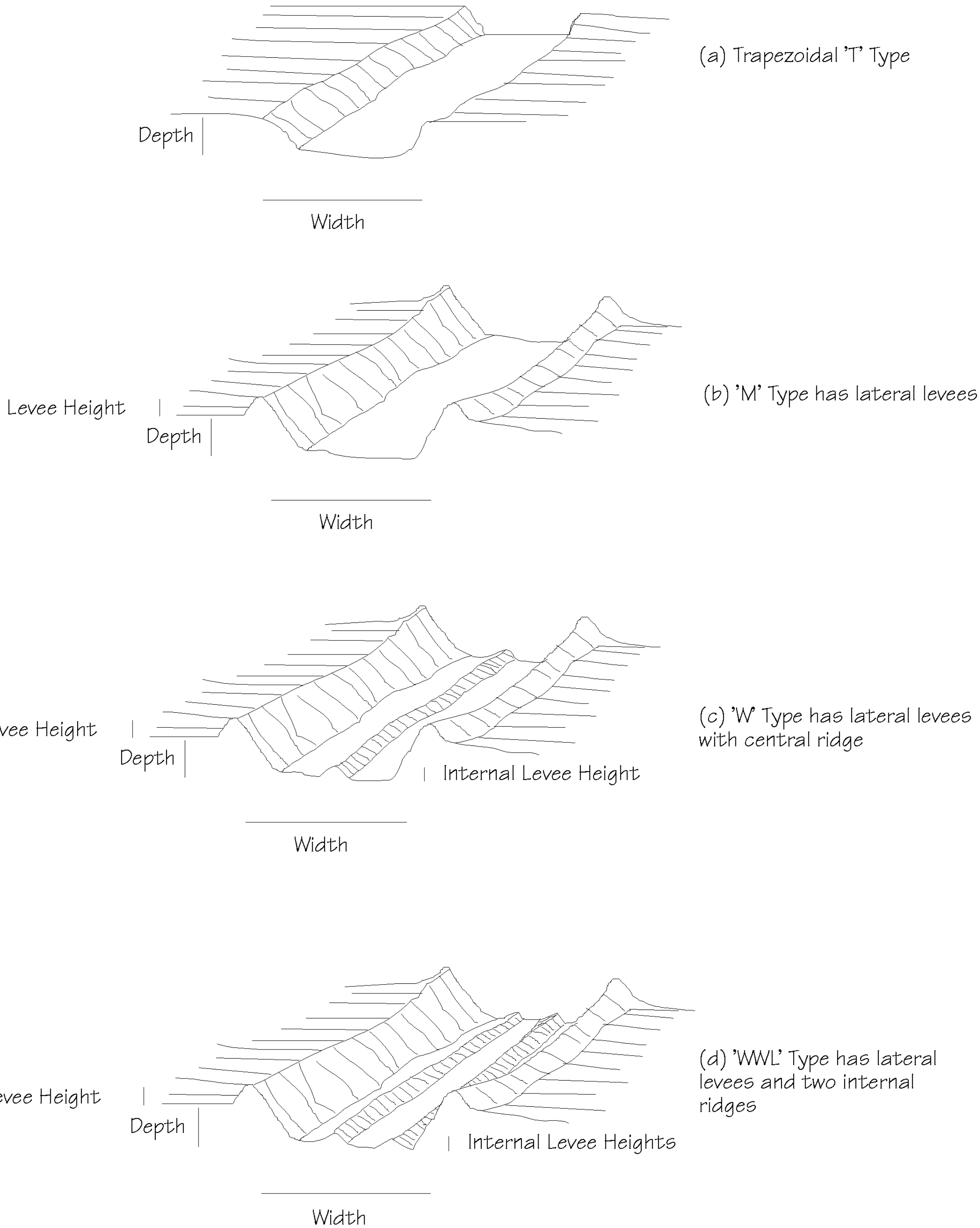


Figure 4.1.1 *Primary seabed furrow characteristics formed by dragheads commonly used for aggregate dredging in the United Kingdom*

4.1.2 Volume Returned Overboard Due To Screening

Screening of the pumped mixture is necessary to improve the stone content of most cargoes to that which is required by the market. A dredged cargo containing too much sediment of the wrong fraction, be it too little or too large, will be rejected by the Customer.

With some notable exceptions, screening during loading is permitted on all Licence areas in the UK. Screening may become necessary due to Licences working through various grades of deposit, licences with marginal quantities of the sediment fraction required, wear of the dredge pump or special Customer requirements.

Whilst meeting Customer requirements through using screening at sea, the Dredging Company may not favour extensive use of the practice largely due to (a) increased wear and tear on the dredging plant and (b) perceived impacts of a larger plume generated over a longer period.

A proportion of a given plume may be attributed to the process of screening. Not only is solids material returned overboard at a higher concentration, but this is done for a longer period.

Using a combination of time series analysis, measurements of the overspill volume and concentrations during a number of loads and from manufacturers specifications, estimates have been made of the contribution of screening to the overboard returns. Table 4.1.2a summarises these for the ‘A’ class type of vessel.

Overboard returns via	% solids pumped	% water pumped
reject chute	88%	35%
spillways	12%	65%

Table 4.1.2 *Proportions of material returned overboard by an ‘A’ Class vessel due to screening and overspill when loading a stone cargo (sand out) as a percentage of the total amount returned overboard during normal aggregate dredging based on field measurements and processing*

4.1.3 Granulometric Distributions Of The Overspill Sediments

Sampling campaigns have been conducted in a number of areas aboard different sizes of dredge vessels. Over four hundred samples have been obtained from the hopper overflow and thirty samples from the screening reject flows using equipment and techniques developed for the study. There has been no conscious control over the geographical location of the sampling campaigns, making best available use of vessels wherever they may become available. Some 30-40 samples are obtained from each loading effort, generally from alternate spillways on the starboard side. For operational safety, stations on the port side have not been sampled on these particular vessels since that is the side of the dredge pipe and there is a hazard of injury from the suspension wires.

Sampling was attempted using Van Doorn remotely tripped sample bottles but these were damaged during the deployment, largely due to the significant volumes of material concerned. Secondly, sampling tubes were designed and fitted to the spillways in order to direct overspill back towards the deck for placing in a container. Whilst these were successful during ‘all-in’ loading, when there is no screening, overflow during screened loading is reduced to such an extent that the sampling tubes were no longer suitable.

The simplest, and what has proven the most effective, is to collect overspill using a bucket suspended by a rope. Some degree of care is required to ensure the bucket is not ripped out of the surveyors’ hands, and also to ensure a representative sample is obtained. To avoid retaining an unrealistic proportion of coarse sediment due to splashing out of the finer sediment laden waters, it was found that a large 20 litre bucket best suited sample collection used in a number of small attempts, say 1-2 litres each time.

During the collection of samples it was noted that due to vessel trim and motion, regions of the spillway will be sediment rich and others lean. The sediment rich areas may again be subdivided into coarser and finer sediment zones. Using the number of small samples reduced potential inaccuracies here.

Plate 4.1.3 *Sampling from the overspill*

Table 4.1.3a below presents the source terms of overspill determined for approximately 360 samples obtained from two different dredge vessels working a total of five different Licence Areas. As would be expected, it is evident that the overspill solid/water ratio varies considerably according to the mode of dredging *i.e.* whether screening is taking place or not, for example, during loading of screened stone cargoes aboard an 'S' Class vessel solids content of the overspill may vary up to threefold. For the studies undertaken here, concentrations of overflow sediments vary between 5.5kg/l and 35.2 kg/l, with a mean of 19.95kg/l, depending on the dredger.

Vessel Type	Cargo Type	Licence Area	Solid/Water Ratio (kg/1000l)	S.G. Of Mixture (S_m)	Solids By Volume (C_v) (%)	Solids By Weight (C_w) (%)
'A' Class	sand	202/5 Cross Sands	35.2	1.046	2.809	7.115
'A' Class	stone	202/5 Cross Sands	22.2}	1.038}	2.332}	5.950}
		242/8 Lowestoft	18.3} 29.3	1.036} 1.043	2.189} 2.593	5.599} 6.588
		212/5 Norfolk	30.3}	1.043}	2.628}	6.676}
'S' Class	stone	124/1 Owers Bank	16.0}	1.035}	2.105}	5.391}
			14.3	1.034	2.043	5.237
		124/8 Owers Bank	5.5}	1.028}	1.718}	4.428}
'S' Class	all-in	124/1 Owers Bank	25.4}	1.040}	2.448}	6.236}
			18.6	1.036	2.202	5.630
		124/8 Owers Bank	6.7}	1.029}	1.765}	4.545}

(Specific Gravity (S_m) of sand/gravel = 2.65)
(Specific Gravity (S_w) of seawater = 1.025)

Table 4.1.3a *Source terms of overspill from aggregate dredgers during normal commercial operations*

Towards the end of loading, especially on the larger vessels, gravel sized material is often washed out of the hopper. Consideration of the results must bear this in mind, as it may suddenly alter the appearance of net losses in the final stages of loading.

A number of samples were duplicated at 10 litre and 20 litre sizes to assess any sensitivity of the results to sample volume and sampling techniques. None was found.

Granulometric analysis of the samples by accredited soils laboratories has provided information on the particle size distribution of the overboard returns. This is a key requirement in providing a basis for the determination of the impact of a plume. Evaluation of each fraction of sediment is necessary to assess transport rates and settlement patterns. Table 4.1.3b summarises the observed distribution of particle sizes of material sampled in the overspill.

Importantly, independent results of a similar order have been recorded recently elsewhere, which supports the methodology and interpretation used in the this project. Gajewski & Uscinowicz (1993) report overspill source term values of 1.5kg/l to 11.25kg/l with a mean of 7.87 kg/l, using a smaller dredger. Particle size distribution data was fine sand (0.25-0.125mm) mean 56.3%, very fine sand (0.125-0.063mm) mean 10.1% and less than 1% fines (<0.063mm) (*see* Land *et al*, 1994; Whiteside *et al*, 1995; HR Wallingford *et al*, 1996;

see also Willoughby & Foster, 1983; Pagliai *et al*, 1985; Bonetto, 1995*).*

Particle Size (mm)	Combined Cargoes ‘A’ Class	Combined Cargoes ‘S’ Class	Sand Cargo Only ‘A’ Class	Sand Cargo Only ‘S’ Class	Stone Cargoes ‘A’ Class	Stone Cargoes ‘S’ Class	All-In Cargo Only ‘A’ Class	All-In Cargo Only ‘S’ Class
<0.063	39.3%	22.2%	18.4%	n/a	42.7%	22.7%	n/a	22.0%
0.063-0.125	14.3%	15.3%	5.2%	n/a	15.8%	16.9%	n/a	12.7%
0.125-0.250	8.2%	34.6%	24.5%	n/a	5.4%	35.6%	n/a	32.8%
0.250-0.500	14.5%	24.5%	36.8%	n/a	10.8%	22.2%	n/a	28.3%
0.5-1.0	8.1%	2.4%	9.7%	n/a	7.8%	1.9%	n/a	3.2%
1.0-2.0	2.8%	0.5%	2.8%	n/a	2.8%	0.4%	n/a	0.5%
>2.0	12.8%	0.5%	2.6%	n/a	14.7%	0.3%	n/a	0.5%

Table 4.1.3b *Proportions of materials in overspill discharge measured from two different dredge vessels (all results, sand, stone & ‘all-in’ cargoes)*

4.1.4 Granulometric Distributions Of The Reject Chute Sediments

Collecting information on the reject chute has been limited due to the physical nature of the discharge. The volume and velocities encountered are considerable which requires any field equipment to be extremely rugged. A limited number of samples have, however, been obtained from an ‘A’ Class vessel which have then been analysed following similar procedures to the overspill samples (Plate 4.1.4). Full particle size analysis has been carried out by accredited laboratories.

Plate 4.1.4 *The practicalities of sampling the screened-off material from the reject chute*

Table 4.1.4 summarises the distribution of the particle sizes amongst the rejected materials for the ‘A’ Class vessel type only.

It must be remembered that these are provisional datasets only based on a limited number of samples. There is considerable difference between the distributions for the two types of cargo, as would be expected. However, it is somewhat surprising how much of the required cargo is actually lost through the reject chute. When loading a stone cargo, for example, 18.5% of the rejected material, amounting to some 1298 tonnes (31% of the cargo load), is of a size greater than 2mm, much of which may be desired cargo.

It is proposed that further investigation of the rejected material is carried out. This may assist in improvements to loading efficiency.

Particle Size	Sand Cargo Only		Stone Cargoes	
(mm)	'A' Class	'S' Class	'A' Class	'S' Class
<0.063	0.1%	n/a	1.0%	n/a
0.063-0.125	0.2%	n/a	0.9%	n/a
0.125-0.250	2.1%	n/a	8.9%	n/a
0.250-0.500	10.1%	n/a	31.4%	n/a
0.5-1.0	9.9%	n/a	27.3%	n/a
1.0-2.0	4.1%	n/a	12.0%	n/a
>2.0	73.5%	n/a	18.5%	n/a

Table 4.1.4 *Proportions of materials in reject discharge measured from the 'A' Class dredge vessels (screening for sand and stone cargoes)*

4.1.5 Dredging Scenario: Screening For Stone Cargo Using Large Trailing Suction Hopper Dredger Of 'A' Class Type

Continuing the previous example in Section 4.1.1 for the loading of an 'A' class dredger, using Tables 4.1.1b through to Table 4.1.4 (8 Tables) we can calculate the following:

(1) 12,158 tonnes of dry solids are loaded with 4,185 tonnes of dry solids retained as cargo. 7,973 tonnes dry solids pass overboard split as 957 tonnes due to overspill and 7016 tonnes due to rejection by screening.

For this particular type of screened stone cargo, the data having been obtained from a Southern North Sea location, the ratio of retained to rejected material is approximately 1:2. This would indicate an *in situ* particle size distribution of 34% stone to 66% sand (including fines) sized material on the seabed. We must assume there is no bias of sediment sizes pumped caused by preferential extraction and/or seabed screening occurring within the suction and pumping processes.

The *in situ* distribution calculated correlates well with the prospecting data obtained through grab sampling and vibrocoring at the site which indicate an average of 30% gravel, 69% sand and 1% silt (A.R. Hermiston, *pers. comm.*)

(*2) coarse material (> 2mm): some 140 tonnes (14.7% of 957 tonnes) material greater than 2.0mm will be lost overboard through the spillways, mostly towards the end of loading as the cargo approaches the top of the hopper. 1,298 tonnes of sediment greater than 2mm will pass over the reject chute. This equates to a overboard returns rate of material entering the water column of 8.0kg/s and 74.6kg/s respectively*.

Assuming an average ground speed of 1 knot this equates to a flux of material entering the water column at 4.1kg/s/m and 38.4kg/s/m respectively. Much of the material is likely to be in the size range 2.0mm - 10.0mm due to the reject screen size used. Material of this size and coarser sizes can be expected to fall almost instantaneously to the seabed with very little horizontal displacement.

Video records of draghead activity during normal loading operations (A.R. Hermiston, *pers. comm. and* Davies & Hitchcock, 1992) clearly indicate such material reaching the seabed directly under the vessel.

Measurements (scaled from photographs) of the average size of the individual plumes entering the sea surface (which vary according to vessel draft) give an estimate of the entry surface area into the water column as 5.88m^2 for the overspill plumes and 1.5m^2 for the reject chute.

The flux of coarse material entering the water column can therefore be estimated as 0.18kg/m^2 of sea surface for overspill and 6.6kg/m^2 for the reject chute at a speed of 2 knots (0.36/kg/m^2 and 13.2kg/m^2 respectively for 1 knot).

(3) sand fractions (0.063mm to 2.0mm) will amount to 407 tonnes (23.4kg/s) and 5,647 tonnes (325kg/s) from the overspill and rejection processes respectively. At a ground speed of 2

knots this would equate to 1.0kg/m^2 for overspill and 55.8kg/m^2 for rejection of sand.

(4) silt and clay fractions (<0.063mm): up to 408 tonnes of fines may be lost through overspill and 70 tonnes via the rejection process (23.5kg/s and 4.0kg/s respectively). Again, at a speed over the ground of 2 knots, this equates to a flux entering the top of the water column at a rate of 1.0kg/m^2 due to overspill and 0.69kg/m^2 due to screening.

Sediments of this size may be expected to disperse more slowly than the coarser fractions, typically with a settling velocity in the range 0.1-1.0mm/s. In its simplest form, the settling velocity can be determined by Stoke's Law assuming that the flows within the water column do not have any vertical components. Residence time in suspension and current flow and direction will therefore determine the excursion pattern before settlement. Resuspension of the recently-settled material before consolidation must further be considered.

The relationship with settling velocities and the importance of correct determination of settling velocities as applicable to the actual sediments disturbed by the dredging operation, rather than settling rates of idealised, single particles is crucial to correct study of plumes and is discussed further elsewhere in this report.

4.1.6 Variance Of Data

Throughout the investigation, it has become clear that there is significant variation in operating performances between ships, between licences, between cargoes for different Customers and even between different crews of the same vessel. The production of definitive tables stating the various throughputs of the system is unlikely to be realised. We have, in this report, attempted to produce mid-range figures for much of the data.

It is accepted that there will be significant differences between these data and any further data that may be obtained, concerned with specific ships and specific case studies. Nevertheless, the field data are considered to be accurate to some 10-15% on the day of measurement, and the consequent manipulation of data is expected to realise answers that conform to this accuracy.

It is expected that in reality, some parameters for various different types of ships and Licence conditions may vary by 50% or more. The critical importance of obtaining valid field data to investigate dredging equipment or conditions not encountered during this study cannot be overstated.

The following Table, 4.1.6, demonstrates the variability that may be encountered between different cargoes on the same licence area, albeit with some slight local geological differences (hence the use of different 'runs' or 'zones').

Particle Size	All-In Cargoes Only, S Class		Stone Cargo Only	
	Area 124/1/1	Area 124/1/8	Area 124/1/1	Area 124/1/8
<0.063mm	5.5%	48.1%	6.2%	68.3%
0.063-0.125mm	14.1%	10.6%	18.9%	11.1%
0.125-0.250mm	41.5%	19.0%	44.1%	11.6%
0.250-0.500mm	33.8%	19.7%	27.2%	7.7%
0.5-1.0mm	4.1%	1.8%	2.3%	0.7%
1.0-2.0mm	0.6%	0.5%	0.4%	0.5%
>2.0mm	0.4%	0.3%	0.9%	0.1%

Table 4.1.6 *Proportions of materials in overspill discharge measured from one dredge vessel in two different portions of the same Licence Area ('all-in' and stone cargoes only)*

It is implied by the data above that the silt content of Area 124/1/8 is some ten fold greater than that of Area 124/1/1. In truth, analysis of the detailed prospecting and reserve evaluation data reveals

that the exploitable geology of Area 1241/1/1 is in fact a broad paleo-terrace reserve consisting largely of sand and gravel. Area 124/1/8 however is a localised river channel deposit consisting of sands and gravels but over, and surrounded by, clays and silty clays respectively.
It therefore seems likely that when loading on Area 124/1/8, any slight positional deviation away from the localised gravel/sand deposit will result in dredging appreciable amounts of silt/clay deposits which are then immediately washed back overboard (by raising the draghead and pumping water only across the top of the cargo). Similar positional deviations within Area 124/1/1 would not result in similar contamination of the cargo by such silty/clay sediments.

The accuracy of both the known dredger position and real-time reference to geological information is therefore important. It follows that geological survey information must be at a higher density in areas of patchy resource, than in broader sheet-formation reserves.

4.1.7 Summary Of Source Term Observations

The data on plume source terms which have been collected during this project conform well with other sources of information. We have substantiated earlier projections of overboard losses of sediments based on analysis of seabed disturbances (Davies & Hitchcock, 1992). The quantities of material displaced on the seabed and subsequently returned overboard *via* the reject chute and spillways conform with very little discrepancy. Estimations (by multiple techniques) of the volume of material returned overboard and the proportional split of such volumes have been made and these agree (within the range of error) for each determinable factor. Field investigations of the content of the overspill and reject mixtures have conformed with expectations, predicted from seabed sediment reconnaissance and cargo analysis. 409 samples have been obtained from the overspill. Information with regard to the content of the rejected mixture is not statistically robust (only 30 samples) and further field information is required. This needs to be obtained from different types of cargo (sand and stone) and from different classes of dredger. Data from an 'all-in' cargo are useful for comparison.

In order to evaluate the impact of marine aggregate dredging, three distinct scenarios exist; loading all-in; screening for sand; and screening for stone. Further combinations of scenarios may be considered related to the type of dredging; anchored or trailing; size of dredger; type of screening (central 'boiling box' and ramp or screening towers); type of overspill (central column or conventional spillways); and geology. It is therefore important to consider each application of a dredging 'activity' in relation to its specific format.

In broad terms, we can summarise the source term information and the primary dredging scenarios as presented in Table 4.1.7 below.

Cargo Type	'A' Class	'S' Class	'T' Class*
no screening (all in)	0.2 - 1	0.5 - 1.5	0.5 - 1
screening for sand (stone out)	2 - 3	2 - 4	2 - 3
screening for stone (sand out)	3 - 5	3 - 4	3 - 4

* estimated from Davies & Hitchcock (1992)

Table 4.1.7 *Proposed dimensionless values for the quantity of material returned overboard (rejected and overspill) as a multiple of the cargo load during normal aggregate dredging based on extensive field measurements and processing. A further 12% will be disturbed at the seabed and left as microstructures associated with the passage of the draghead. The lower disturbance values may be expected at the start of a dredging licence life period - with time and the resource becomes thinner and the potential for 'oversanding' occurs, which may increase the loading times.*

It follows that using Table 4.1.7 and a known ship cargo capacity *e.g.* a 'T' Class (3400 tonnes), we can estimate that for a screened sand cargo scenario some 6800 tonnes of sediment may be returned overboard. A further 1224 tonnes will be pushed aside on the seabed and left as microstructures associated with the passage of the draghead (*for example*, levées, internal ridges *etc.*) That is to say the gross sediment displacement by the draghead will be 11424 tonnes. Using the same ship to load an all-in cargo, the gross disturbance will be 5712 tonnes (3400 tonnes cargo; 1700 tonnes overboard; and 612 tonnes displaced but not removed from the seabed). It must be remembered that these will vary, perhaps up to a factor of 2, according to a combination of dredge vessel, dredge vessel pump wear, weather conditions and Master experience.

When loading a stone cargo (sand out), the proportional split of the overboard returns between the reject chute and overspill is approximately 7:1 (solids) and 1:2 (water) respectively. Further, the Tables indicate the percentages of overspill as sediment size fractions. This fundamental information allows not only refining of the source term inputs to numerical models, but also an assessment of the efficacy of loading and screening processes. Table 4.1.3b indicates that, for example, when loading sand cargoes on an ‘A’ Class dredger, 61.3% of the overspill (*approx*. 5130 tonnes) is of size 0.125-0.5mm).

Importantly for numerical modelling, the density of the overspill jet may often, but not always, be greater for larger vessels than smaller vessels. From Table 4.1.3a the overspill mixture during loading stone cargoes on an ‘S’ Class has an average Specific Gravity of 1.034, whereas for screened stone cargoes on an ‘A’ Class, the overflow Specific Gravity is 1.043. The greater the density contrast between the overspill jet and the water column (Specific Gravity of seawater 1.026 @ 15^{o}C), the more intense the development of the a ‘Density Current’ will be and hence accelerate the settling of the overspill sediment to the seabed, allowing less advection away from the dredge site. Straightforward Gaussian diffusion modelling techniques will not take into account this contrast, and hence tend to further overestimate the extent of plume excursion.

The verification of numerical models using competent field data is essential for realistic appraisal of the impacts of dredging operations. Without such data, responsible numerical modelling must be based on the ‘Precautionary Approach’, a worthy principle which may unfortunately lead to unnecessary sterilisation of workable reserves, and unwarranted concern on the extent of potential impact on the surrounding environmental resources.

4.2 Phase Two - Monitoring Plume Generation & Decay

A core objective of this project has been to monitor the growth, movement and decay of sediment plumes developed during marine aggregate dredging operations. Emphasis has been placed on the competent collection of representative field information that will assist to develop and augment realistic modelling techniques using validated data.

Pursuant to these objectives, several programmes of fieldwork have been undertaken. Monitoring of the dredge plumes using chartered survey vessels has been successfully undertaken. Interim results have been published in Conference Proceedings (Hitchcock & Drucker, 1996) and incorporated in Technical Reports (HR Wallingford, 1996).

Herewith are presented the full set of results derived from the field monitoring data obtained to date. Selected ADCP™ transects and profile suites are presented.

4.2.1 Monitoring Methodology

Acoustic Doppler current profiling techniques have existed for military purposes since the late 1970s but have really only become commercially viable within the last 10 years. The techniques have received extensive research and commercial application within the US and Far East, but have only relatively recently become a realistic survey tool available within the UK.

Four highly directional transducers, arranged at 90^o in the horizontal and inclined outward at 30^o in the vertical (so called 'Janus' configuration), emit acoustic pulses into the water column which are reflected from suspended particulate matter. The measured Doppler shift of the returned echo is used to calculate particle (scatterer) velocity in the direction of each of three beams and, by inference, determine the current velocity components in those directions. The fourth acoustic beam can be used to *'bottom track'* and so calculate the velocity over the ground of the unit, and also for data integrity. Alternatively, unit movement can be input from an external source such as a high precision dGPS system. Both methods were used here. Measurements from the three beams are then combined with the known orientation (by fluxgate compass or gyro input) and horizontal velocity of the profiler, to derive current speed and direction relative to earth co-ordinates. Considerable attention must be paid to calibrating the compass to compensate for local magnetic variation aboard the survey vessel, to avoid inducing potentially large errors in the calculations. Air bubbles will interrupt the two way travel time of the pulse and are known to corrupt the received data.

The received signals are then broken down by 'time gating' into discrete 'bins' of data, each as small as 0.25m vertically with the 1200kHz BroadBand system as used. Each 'ensemble' then recorded consists of up to 30 vertical bins of data, or less in shallower water. Data are not available for the top 3m or bottom 6% of the water column for the configuration used (*c.f.* the RDI 600kHz NarrowBand Doppler profiler which loses data for the bottom 15% of the water depth). The received signals are internally compensated for gross attenuation of the signal which is dependent on water depth (beam spreading), acoustic absorption (temperature and salinity) and reflector attenuation (particle size, shape, density and compressibility).

It was found that a scale of 40-100dB best represented the variation in acoustic backscatter attributable to the dredging operations monitored during August 1995, whilst a scale range of 60-120dB was more suitable for the January 1997 monitoring campaign. The absorption coefficient α was determined as 0.418 (based on frequency of 1200kHz, water temperature of 16^oC, pH of 8.0, pressure of 1.0 atmosphere and salinity of 35ppt which is assumed linear near 35ppt and includes magnesium sulphate, boric acid and viscous terms). An echo intensity scale value of 0.43dB per AGC count was used and the speed of sound was computed for each ensemble.

In order to deploy the RDI 1200kHz BroadBand ADCP from the 15m survey vessel chartered on all occasions for the fieldwork campaigns, an over-the-side bracket was designed and built in-house which rigidly held the ADCP transducer unit in such a manner as to be (i) away from significant localised sources of magnetic influence; (ii) vertically positioned under the lifting derrick to be used for the deployment of the sampling equipment; and (iii) aligned exactly fore and aft. The latter point is less important for backscatter observations, but is extremely important for obtaining true-vector current measurements. To overcome potential problems of magnetic interference with the transducer head built-in fluxgate compass, a KVH 316AH external fluxgate compass was interfaced to the Deck Box by RS232C serial communications port A. Repeated and reversing transects in known directions (line of sight with Ministry of Defence Naval compass calibration marks on land) were made. An installed deviation of 2^o on the first and third installations, and better than 1^o on the second installation were observed, and this is further accounted for within the data acquisition software.

At the scale of the investigation, it was considered important to plot the results accurately. All the surveys utilised the commercial survey navigation software "HYDRO" produced by Trimble Navigation International Ltd. The surveys were planned using the Ordnance Survey OSGB36 grid using local transformations calculated for the Licence Area where the work was carried out. A survey quality differential GPS provided a position solution to both PCs with accuracy better than ±5m r.m.s. A dedicated PC was utilised to provide steering plan information for the survey vessel helmsman with a second dedicated PC acquiring and storing the ADCP data, with backup data recorded on tape drive. All equipment is owned and was provided by Coastline Surveys Ltd.

Sufficient personnel are required to operate the survey and ADCP computers whilst simultaneously liasing with the dredge vessels involved, deploying and recovering drogues, and undertaking water temperature, salinity, and sampling casts. Accurate notes of all operations and movements of the survey vessel and the dredgers have proven to be indispensable in accounting for many variations, initially similar in appearance.

The ADCP processor was configured such that each ensemble comprised the average value of four consecutive pings for each of the four transducers. Bin size was 1.0m vertical permitting a theoretical range of 30m water depth at a frequency of 1200kHz. To complete one cycle, and record one ensemble of data, takes approximately 4.5 seconds. The resultant bin size is therefore 1m vertical by 12m horizontal at a survey speed of 5 knots (2.5m/s). At a survey speed of 1 knot the bin size will be 1m vertical by x 2.5m horizontal. Ensembles are recorded continuously throughout the survey period, resulting in a hypothetically available dataset of some 312,000 individual current observations over a 13-hour period, obtained by over one million transducer operations.

For current measurements the data are averaged in the field over a (user-definable) 60 second period for real-time display of velocity magnitudes and directions, and for presentation over 250m horizontal distance. Post processing of the data is possible using different time periods or equipment parameters. For Acoustic Backscatter measurements, instantaneous values of the average of the four beams was used for rapid real-time update.

The intensity of the reflected acoustic pulse can be used as a means of representing the relative concentration of suspended particles. Present research is investigating possible calibration of the system for direct measurement of concentrations, but this is at an early stage and is susceptible to the variability of many instrument parameters including transducer power output (*e.g.* manufacture variation, input voltages) and thermal noise and temperature of the circuitry, in addition to environmental parameters.

Plate 4.2.1 *Coastal survey vessel Wessex Explorer used for the plume monitoring surveys.*

Transects across or along the plume axis using the acoustic backscatter function of the ADCP^{TM} were obtained to generate of suspended solids concentration (SSC) information about the dredging activity in a number of ways:

- successive transects perpendicular to the track of the dredger were made to identify the growth and decay of the plume between each pass of the dredger. This would also identify whether there is any cumulative effect leading to an overall gradual build up of SSC levels

- transects were plotted diagonally downstream across the wake of the dredger, expanding the distance away from the centreline of the plume, so that lateral dispersion and longitudinal excursion and time-based decay (settlement) could be determined

Additionally, detailed current measurements were made by continuously executing transect lines along a predetermined track for a thirteen hour period. One complete circuit was timed to take one hour. Each point on the circuit was therefore observed every hour. Review of the current vector plots indicates in a clear manner the time and variation of changes in direction and velocity of the currents, both areally and vertically (*see* Coastline Surveys Ltd, 1995; for complete dataset).

The 15m survey vessel “Wessex Explorer” (Plate 4.2.1) was equipped with water bottle and pump sampling equipment, optical transmissometers (three of varying range), temperature/salinity probes (two), and an RD Instruments’ 1200kHz BroadBand Vessel Mounted Acoustic Doppler Current Profiler (ADCP^{TM}) owned by MMS.

On the successful basis of the results obtained and reported herein, use of a Vessel Mounted ADCP^{TM} is considered to be fundamental to accurate monitoring of the plume generation and decay. Confidence can be applied to the results when considering whether observed SSC obtained by water sampling represent the maximum and minimum conditions existing.

Detailed time records and subsequent analysis of the relative dGPS positions of the survey vessel and dredge vessels at all times enabled correlation of the distance and time function of the plume behaviour.

4.2.2 Owers Bank, August 1995

During August 1995, an extensive field monitoring programme was undertaken at a currently licensed aggregate extraction site off the South Coast of the UK to study the generation and decay of benthic and surface plumes arising from a variety of different dredge vessels employing different dredging techniques. The analysis of results is now largely completed and the principal observations are expressed herein.

The objectives of the monitoring exercise were:

- *to measure background suspended solids concentrations (SSC) prior to commencement of dredging (no dredging took place inside the area within the previous 24 hours). One small dredger worked an area to the south of the monitoring area approximately 12 hours before fieldwork commenced but this was considered not to impinge on the study*

- *to use the ADCP^{TM} in Vessel Mounted configuration to locate the limits of the plumes developed, and identify turbidity maxima and minima as identified by the relative values of the acoustic backscatter*

- *to identify the shape and form of the underwater plumes*

- *to quantify the increase in suspended solids concentrations as a consequence of the dredging operation*

- *to map the dispersion and spread of the plumes away from the dredger including delimiting the point of return to background SSC*

- *to determine the dilution of the plume as a function of time*

The data are presented here representing groups of normal commercial dredging scenarios that were encountered during the survey. Excellent weather conditions and detailed logistical planning enabled different modes of dredging (anchored and trailing), different capacity dredgers (from 2000 tonnes to 5000 tonnes) and different overboard returns methods (over the side discharge and central, underwater discharge) to be investigated.

The plumes arising from three dredge vessels were monitored during normal loading operations. The calm weather conditions enabled safe close-quarters manoeuvring by the survey vessel adjacent to the working dredgers. A combination of ‘all-in’ and screened (stone only) cargoes were loaded by trailer suction and anchor suction techniques over a three day period.

The study was conducted over neap tides to ensure greater accuracy of deployment of the water sampling equipment vertically under the survey vessel. Lower current velocities also enabled closer working by the survey vessel alongside the dredge vessel. Importantly, the plume was expected not to disperse as quickly, therefore enabling more measurements to be made within areas of greater concentrations, for particle size analysis.

4.2.2.1 Tidal Regime

In order to put into context the extent of any plumes identified and monitored, it is essential to have detailed knowledge of the tidal current regime existing at a study site. Information on both tidal conditions during any survey work and peak tidal conditions that may exist are required. Data obtained when considering the extent of plume excursion must be related to the state of tide at the time of monitoring.

During the August 1995 plume tracking, tidal velocity data was also acquired by the ADCP^{TM} used. Immediately following the plume monitoring exercise, a detailed tidal current monitoring exercise was undertaken also using the

ADCP™ to establish peak spring tidal conditions at the site. A software program (VMAP) was developed in-house to interrogate the RDI Transect™ post processing output files, calculate the significant descriptive statistics, and output the results in graphical and current vector map forms.

Peak current velocities encountered at the site were 0.97m/s (west bound ebb tide) direction 258°T and 1.07m/s (east bound flood tide) direction 070°T. Mean tidal velocities were 0.56m/s and 0.72m/s respectively (excluding the slack phases). This compares to measurements obtained during the plume tracking exercise when peak current velocities encountered reached 0.6m/s. Other than for a limited time period around slack water, the current patterns were largely linear. Water depths across the site are approximately 22m.

Separate studies conducted nearby during October 1995 compared Doppler current profiling data acquired here with that of an InterOcean S4 self recording current meter. This proved highly successful with correlation coefficients r = 0.983 (velocity) and r = 0.967 (direction).

Not apparent through the use of a single point current meter, such as the S4, the ADCP™ data showed that there was some reduction in current velocity with depth. Average velocities at 15m depth are within 8% of average surface velocities.

4.2.2.2 General Appearance Of Plume

The surface expression of a freshly generated plume in calm waters is characterised by 'swirls' of dirty froth formed by the turbulence of the overboard returns entering the water surface (Plate 4.2.2.2).

Plate 4.2.2.2 *Surface expression of plume as frothy foam with sheen visible in calm conditions*

The screened reject mixture creates the most amount of froth since this is the greatest volume and velocity. During sea conditions other than flat calm, this is quickly dispersed. The 'froth' may contain some naturally occurring precipitate released from the sediment and/or induced through the turbulent mixing of seawater. It is proposed that a significant component of the surface expression of the plume has biological origins. This is expanded further in Section 4.4 and the attached paper Annex 1.

From the deck of the survey vessel, the visible top several metres of the water column contains upwelling clouds of sediment-laden turbulent water. These may be several metres in diameter. Small shell fragments may be temporarily suspended but these rapidly disperse and settle. There are sometimes significant volumes of entrained air bubbles.

During calm conditions there is occasionally an apparent 'sheen' to the water surface, but not observed in every licence area. It is postulated that such a 'sheen' may be due to the disturbance of small quantities of organic matter naturally present in the seabed sediments.

4.2.2.3 Plume Sampling Results

A total of 162 background and through plume transects were made using the ADCP™ equipment to generate real-time continuous backscatter profiles. Sets of data which clearly discriminate the plume and which have reliable sampling data have been interpreted and are presented here.

Water samples of 0.5 litre, 2.0 litre and 10 litre volume were obtained using an array of remotely operated sample tubes, deployed with pressure transducer (depth indicator) and two suspended solids meters. 145 water samples were taken at varying depths within the plume corresponding to turbidity maxima and minima identified in real-time by the ADCP™. Whilst holding station adjacent to a midwater drogue with surface marker buoy, 20 vertical profiles were also recorded by ADCP™ with simultaneous water sampling and optical measurement of the suspended sediment concentrations.

The majority of water samples were analysed for total solids content. A number were selected for determination of the silt/sands ratio *i.e.* the split between particle sizes greater than and less than 0.063mm. Further, a small number of these samples were analysed by laser diffraction techniques for sandy sediment particle size distribution. The generally low SSC prevented full particle size characterisation of more samples. In expectation of such difficulties, some larger samples were collected: however these still did not contain enough sediment for full analysis.

Correlation of the sediment particle size and concentration records with the records from the infra-red transmissometer mounted adjacent to the sampling array indicated a persistent discrepancy. The ranges of turbidity variations recorded by optical techniques were much less than those determined during the laboratory analysis of the field plume samples. This is considered due to the high sand content, rather than silt, in suspension. Such a restriction is largely dependent on the technique, although different manufacturers of equipment claim suitability over different size ranges (*see, for example, equipment products such as D & A Electronics OBS, WS Ocean TRB-1, Alec Electronics etc.)*.

When considering the concentrations of suspended sediments in the water column plume, it is important to consider whether or not the vessel is steaming with or against the tide. If the latter, the dilution effect will be greater, and hence the apparent concentration lower, than if the vessel is steaming with the tide.

4.2.2.4 Background Conditions

Background suspended solids concentrations were determined prior to the start of survey operations on each day of the monitoring exercise. Observed levels were in the range 3-23mg/l average 14mg/l. Interestingly the sand content (>0.063mm) of these samples varied from 14% to 75%.

4.2.2.5 Plume Generated By The ARCO Severn, 19th August 1995

The ARCO Severn loaded an all-in cargo over a period of 3 hours and 15 minutes from Licence Area 124/1 Zones 1 and 8. The cargo is recorded as 50% stone content (>5mm). Background measurements of SSC varied from 3-10mg/l averaging 7mg/l.

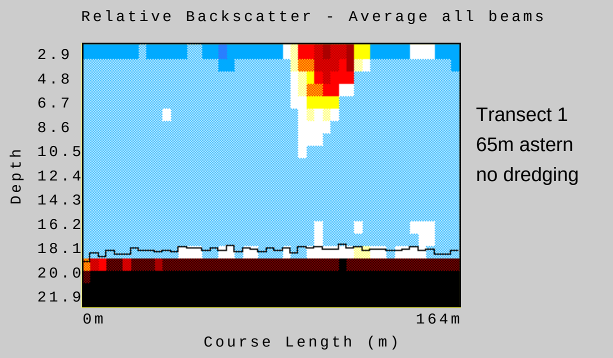
Using the equipment aboard the survey vessel, a number of transects and vertical rapid drop profiles were carried out. 7 vertical sampling profiles were obtained collecting 25 water samples. Table 4.2.2.5 below records the concentrations determined from the subsequent laboratory analysis.

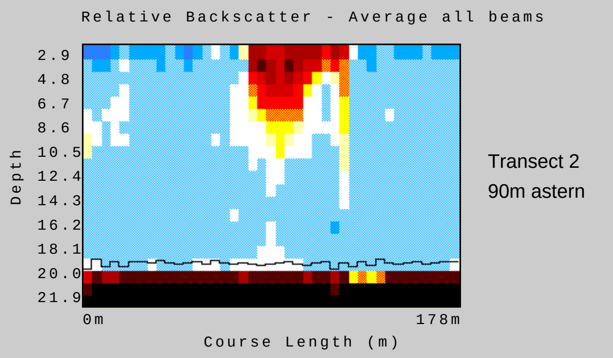
The composite Figure 4.2.2.5a shows the CBP records along with the track of the vessel used during the survey. The relative positions of the survey vessel and dredger are clear. The first transect provides an indication of the care needed when interpreting the CBP data: the record was obtained before dredging or overflow commenced and is solely a result of aeration in the water caused by motion of the vessel (at slow speed) and effects of the propeller. The second transect shows the very similar appearance, soon after dredging has commenced, and is a result of limited overflow of almost clear waters. The series of transects further demonstrates the value in using CBP to assist in delimiting the plume boundaries, and ensuring confident placing and interpretation of water samples.

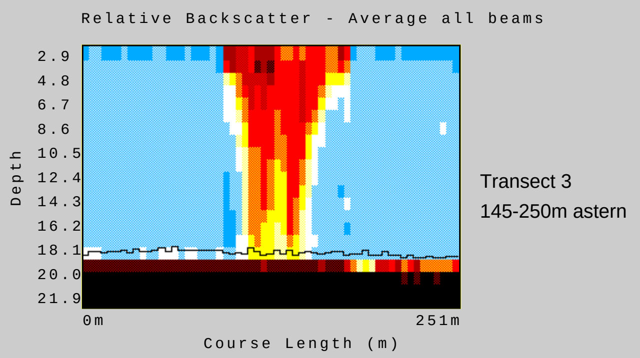
From Table 4.2.2.5 and Figure 4.2.2.5b it is clear that the Total Suspended Solids Concentration rapidly decreases with distance away from the dredger. Within 300-550m, concentrations are at or near to background conditions. The water sample sediments are predominantly sandy with less than 1-2% silt content. Concentrations of silty sediments (<0.063mm) are less than 25mg/l, and reduce to background limits over similar distances (Hitchcock and Drucker, 1996).

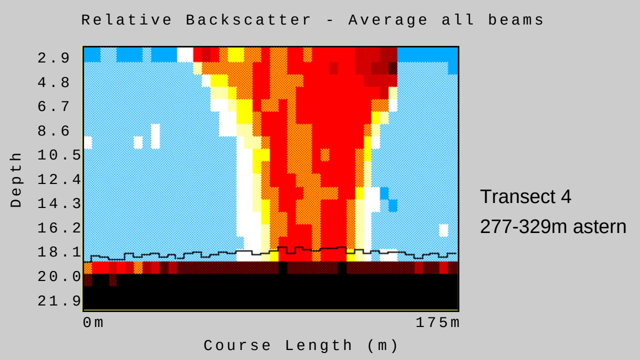
Samples with the highest concentrations of solids were obtained within 200m of the dredger near the end of the loading period when overflow would be nearing maximum solids content (as the level of material in the hopper is near the hopper rim). Total SSC ranged from 1170-1346mg/l, the highest being obtained within several metres of the seabed at 175-200m from the dredger. Total SSC levels at 500-600m from the dredger approximate to but still exceed background levels. This is probably a result of the multiple dredge runs combined with low tidal current flow (thus limiting dispersion) causing a short term intensifying effect.

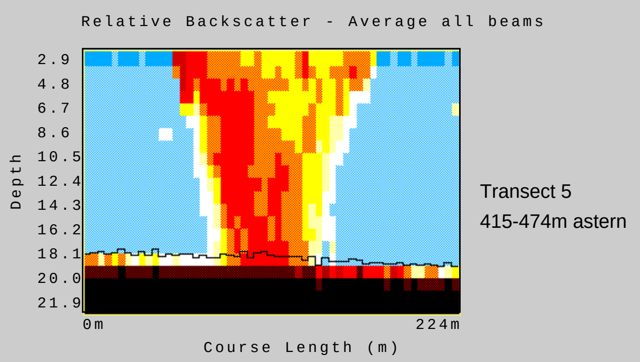
Water samples taken 15 minutes after the dredging operation ceased showed that Total SSC had returned to background conditions observed at the start of the day.

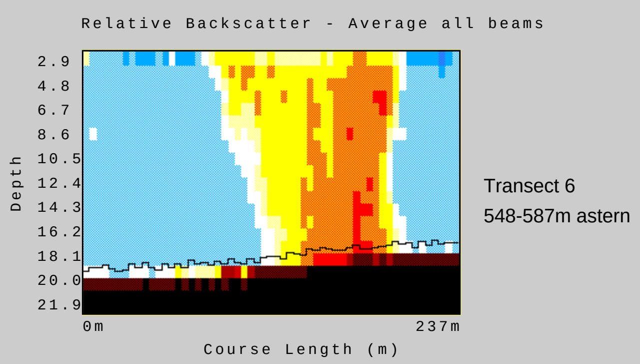


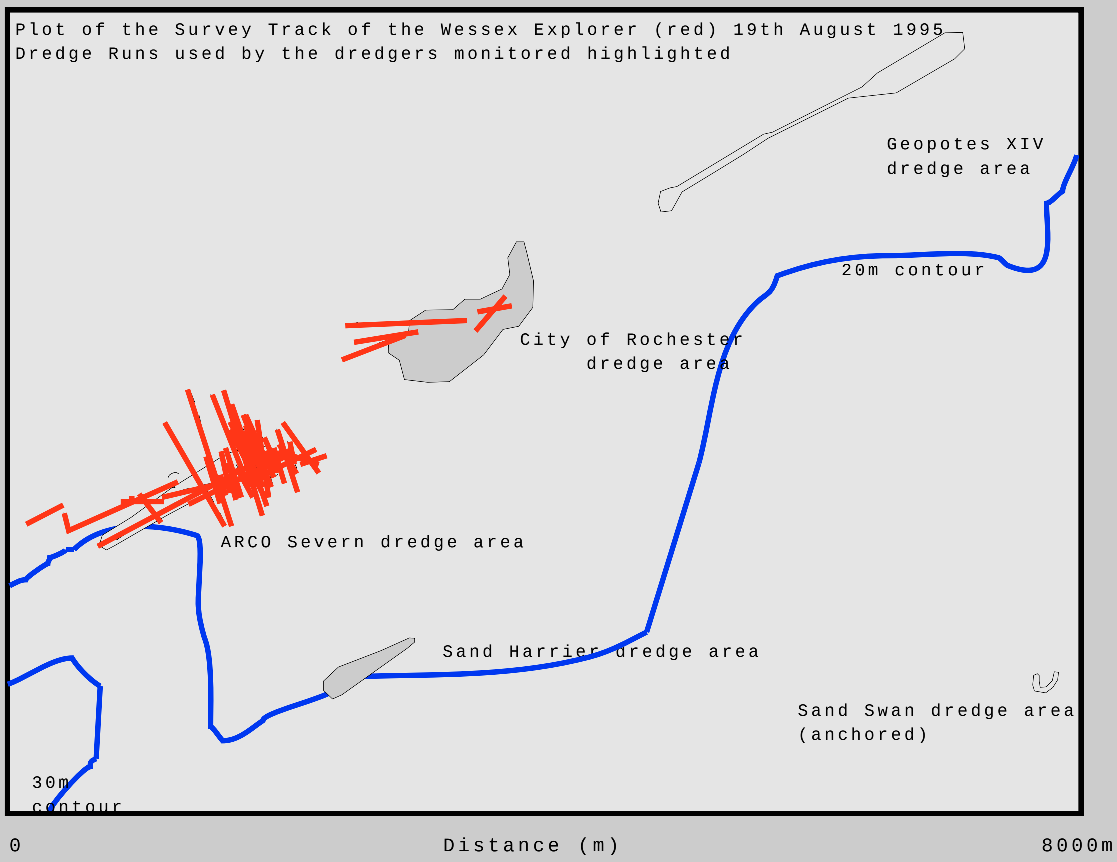


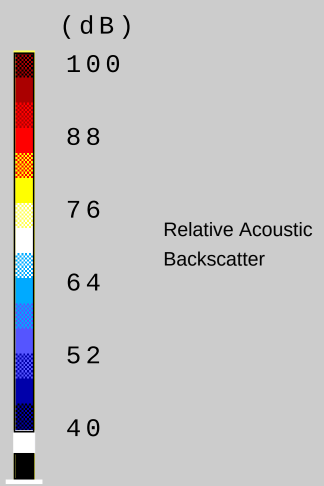












Composite Plot of Plume Monitoring Campaign carried out on the 19th August 1995, English Channel. The Acoustic Backscatter Transects were obtained using an RDI 1200kHz BroadBand Acoustic Doppler Current Profiler.

The series of transects depicted on the left were obtained whilst monitoring the plume from the TSHD ARCO Severn.

Transect 1 was taken before dredging commenced, in a position close astern of the ARCO Severn (less than 65m) to determine the appearance of the wake of the dredger, as observed by the ADCP. This clearly shows the appearance of aeration in the water caused by the passage of the vessel, and the effect of the single propellor. It is indistinguishable from a dredge plume and reinforces the need for competent field operations with rigorous survey practices.

Transect 2 was obtained immediately astern of the dredger, less than 20m, just as overflow commenced. It is clear that the overspill has not yet reached the seabed. It is known from overspill samples taken that there is very little solids content to the overspill at this stage. The 'finger' of material reaching down the right hand side of the dredger is due to the ship being trimmed slightly to starboard, thus overspilling more material that side, rather than the port side. The small target area at the seabed is most probably the benthic plume formed by the draghead. The total suspended solids concentration of a surface sample near the centreline of the plume is 96mg/l.

Transect 3 at 145-250m astern shows the overspill from both sides of the vessel reaching the seabed. Turbulent diffusion of the plume has not reached the point where distinction between the port and starboard sources is impossible.

Transect 4 at 277-329m astern records the two separte plumes from the 3rd transect joining together to form a single plume. The plume is stll relatively narrow, with little lateral diffusion or dispersion. Total suspended solids

Figure 4.2.2.5a

Time (BST)	Transect Number	Depth (m)	Distance Astern (m)	Total Concentration (mg/l)	silts (<0.063mm) (mg/l)
17:06	-	0	491	46	n/d
15:33	19AU12	0	300	42	n/d
15:46	19AU15	0	102	96	n/d
15:50	19AU19	0	245	99	n/d
16:40:20	19AU29	4	597	30	n/d
16:40:55	19AU29	8	585	26	n/d
16:41:22	19AU29	12	573	18	n/d
16:41:51	19AU29	16	561	18	n/d
16:42:37	19AU29	18	534	18	n/d
16:42:24	19AU29	18	549	22	n/d
17:10:30	19AU34	4	675	10	n/d
17:11:03	19AU34	8	691	13	n/d
17:11:30	19AU34	12	707	13	n/d
17:12:21	19AU34	18	724	25	n/d
17:12:30	19AU34	18	740	38	n/d
17:56:58	19AU41	4	201	47	n/d
17:57:29	19AU41	8	227	304	0
17:57:51	19AU41	12	248	582	0
17:58:16	19AU41	18	259	613	6
18:38:17	19AU45	4	94	723	7
18:38:52	19AU45	8	111	103	n/d
18:39:18	19AU45	12	138	1170	0
18:39:45	19AU45	16	156	1171	0
18:40:12	19AU45	18	178	1346	13
18:40:28	19AU45	18	194	1225	25

Table 4.2.2.5 *Summary of suspended solids concentrations sampled from the plume developed by the ARCO Severn, 19th August 1995.*

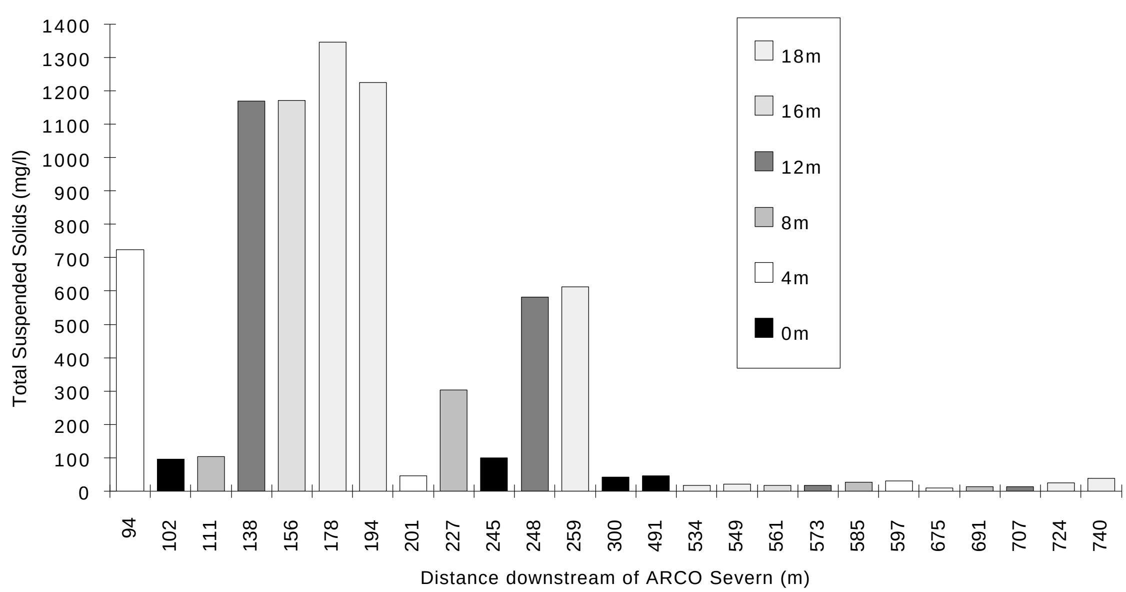


Figure 4.2.2.5b *Total suspended solids concentrations of samples taken from the plume decreasing with distance away from the ARCO Severn, Owers Bank, 19th August 1995.*

4.2.2.6 Plume Generated By The ARCO Severn, 20th August 1995

Background measurements were obtained before dredging commenced within the study area. These were higher than the previous day, averaging 19mg/l. It was noted that a small dredge vessel had been operating on the extremity of the study area overnight, completing the loading immediately prior to the background sampling.

The ARCO Severn loaded a screened stone cargo in the same area as on the previous day (Area 124/1 Zones 1 and 8) taking 3 hours 40 minutes.

Table 4.2.2.6 summarises the plume samples taken. The data suggest that within 800m from the dredge vessel, the majority of the plume had settled to within a few metres of the seabed. This is probably maintained in suspension by turbulent conditions existing within the benthic boundary layer.

Composite Figure 4.2.2.6 presents the CBP records for a series of transects through the ARCO Severn plume taken on the 20th August 1995. The development of the plume and it’s subsequent decay is quite clear. The apparent alteration in asymmetry is due to the survey vessel proceeding port to starboard through the plume and then the reverse on successive transects.

Time (BST)	Transect Number	Depth (m)	Distance Astern (m)	Total Concentration (mg/l)	silts (<0.063mm) (mg/l)
11:22:00	20AU13	18	810	25	n/d
11:23:03	20AU13	18	817	61	n/d
11:24	-	0	800	2	n/d
11:25	-	0	820	7	n/d
11:51	-	0	851	5	n/d
16:15	20AU42	18	-	3	n/d
16:27	20AU42	12	-	3	n/d
16:33	20AU42	14	-	4	n/d

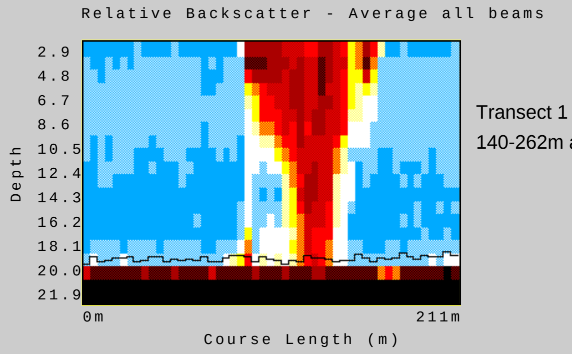
Table 4.2.2.6 *Summary of suspended solids concentrations sampled from the plume developed by the ARCO Severn, 20th August 1995*

Recent investigations undertaken off the East Coast of the United Kingdom support the view that the majority of the plume settles very quickly. In addition the observations suggest that there exists a ‘benthic boundary layer plume’ with suspended sediments at concentrations of the order of 100mg/l (although sample results are not yet available) up to 1m from the seabed which has been located up to 8km from the dredge site (J. Rees, *pers. comm.*). Further results are expected shortly.

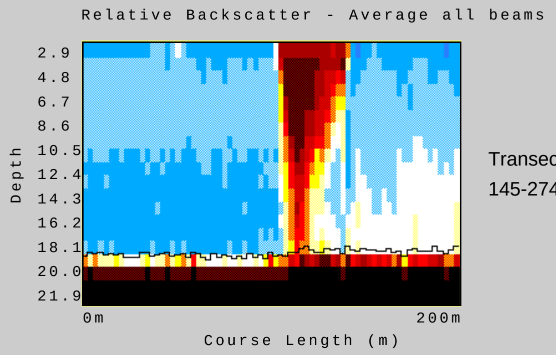
Vessel mounted ADCP™ data, obtained during this project does not indicate such a phenomenon. However, the nature of the algorithms used are such that data so close to the seabed is within a ‘corruption zone’ and is therefore unreliable within this benthic boundary layer. It would be necessary to deploy the ADCP™ in a seabed mounted frame, upward looking, to attempt to track the movement of the plume, although there is a similar, smaller corruption zone at the beginning of the ADCP™ record as well.

We are aware of only one particular form acoustic backscatter sensor designed for such an application. The Aquatec Electronics Ltd. “Acoustic Back Scatter System (ABS)” is a three-frequency sensor in the range 1 MHz to 6 MHz, typically set at 1 MHz, 3 MHz and 6 MHz. The system is designed to measure the sound reflected by sediments at 1cm intervals from the sensor, to a range of 128cm or 256cm. The Acoustic BackScatter System may be used to obtain profiles of suspended sediment concentration and sediment size in the near bed zone and to monitor ripple formation. The Acoustic Back Scatter System has greater sensitivity to coarser, sandy suspensions than optical backscatter systems, which are more sensitive to fine, silty material. Neither instrument establishes the sediment concentration directly, since the relative backscatter is also a function of the grain size and shape. Calibrations may be carried out in laboratory conditions using samples of actual seabed material from the deployment site. Water samples were not collected within 2m of the seabed, to avoid potential damage to the equipment spread.

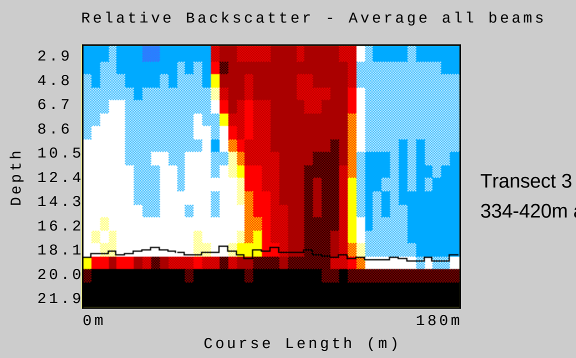
Samples taken at 1350m from the dredger, located using a mid water drogue as well as visual and ADCP™ techniques, indicate return to background concentrations throughout the water column. Further samples taken 1 hour after completion of dredging operations (16:15-16:33), confirmed that indicate that SSC have returned to background levels within such a time period.



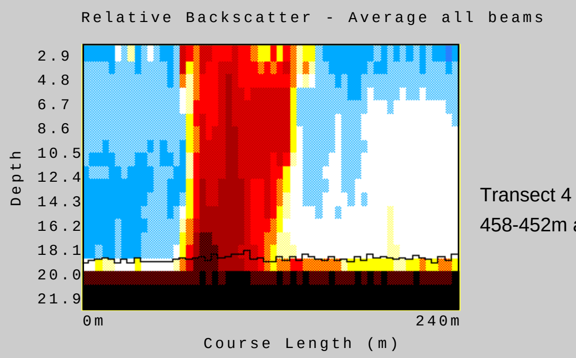
Transect 1
140-262m astern



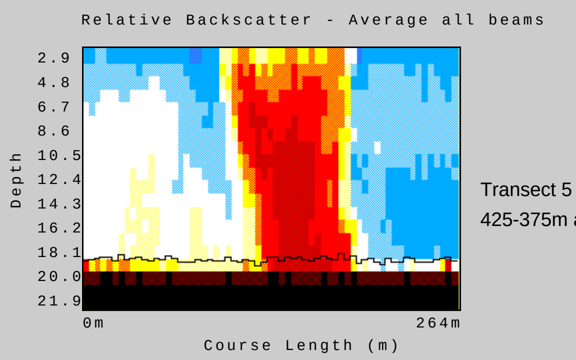
Transect 2
145-274m astern



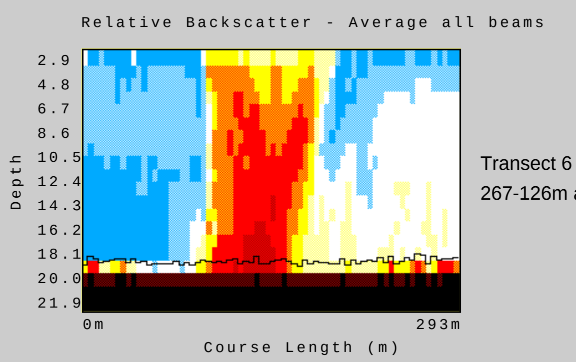
Transect 3
334-420m astern



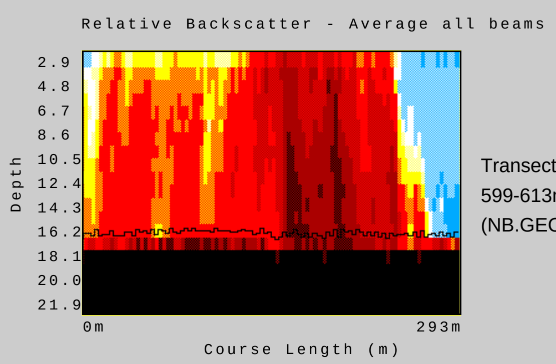
Transect 4
458-452m astern



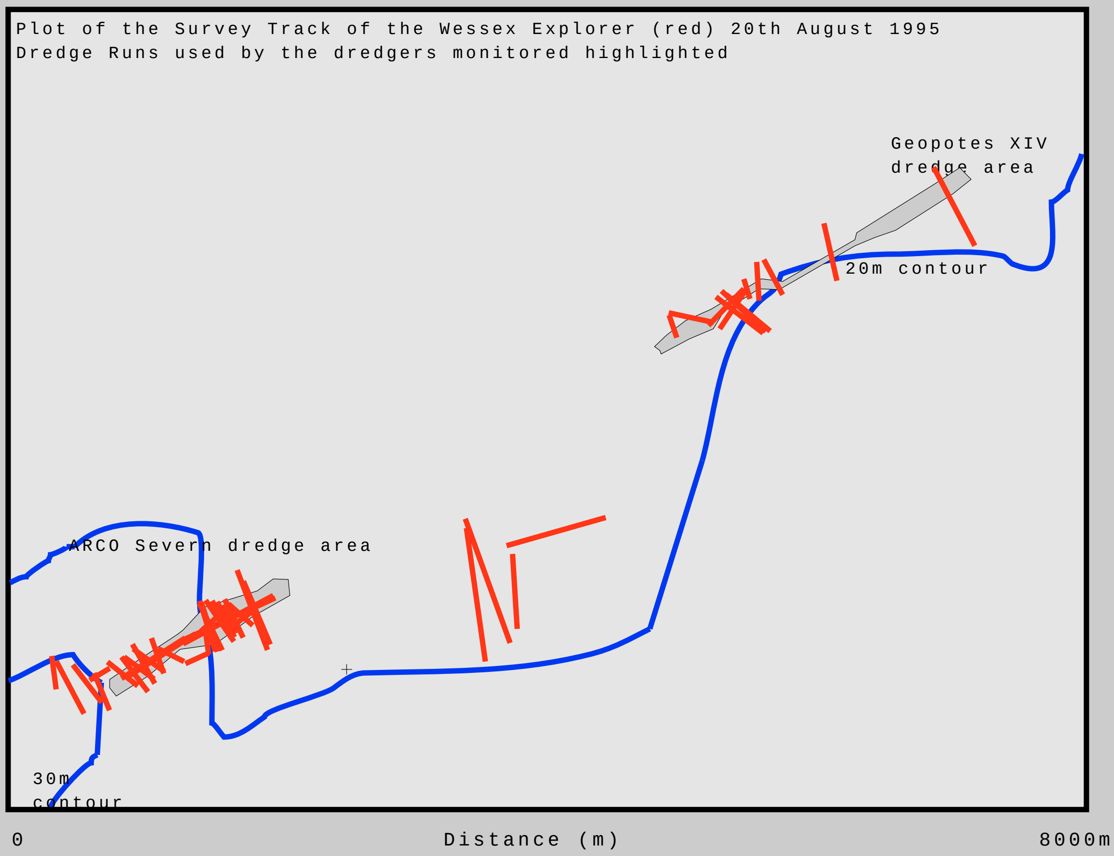
Transect 5
425-375m astern

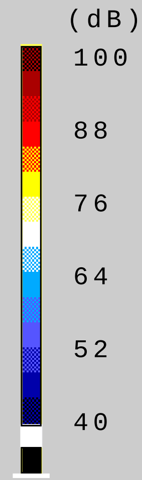


Transect 6
267-126m astern



Transect 7
599-613m astern
(NB.GEOPOTES XIV)





Relative Acoustic
Backscatter

Composite Plot of Plume Monitoring Campaign carried out on the 20th August 1995, English Channel. The Acoustic Backscatter Transects were obtained using an RDI 1200kHz BroadBand Acoustic Doppler Current Profiler.

The series of transects depicted on the left were obtained whilst monitoring the plume from the TSHD ARCO Severn.

Transect 1, obtained minutes after dredging commenced, shows the development of several components of the plume. At a distance of just 140-262m astern, the asymmetry of the region of high acoustic returns shows, (left to right), little overspill on the port side of the dredger and much more overspill on the starboard side. This latter component is due to a combination of the vessel listing slightly to starboard and the rejected material also being discharged on the starboard side. The rejected component is that which is most likely to have already reached the seabed at the point of this transect. On the port side, at the seabed, the development of the plume attr ibutable to the draghead motions on the seabed can be seen quite clearly. This is some 3m high by less than 2m wide at this point.

Transect 2 was recorded at a similar distance to Transect 1, 145-274m astern of the dredger, but in the reverse direction ie the starboard side of the ship is on the left side of the record. Again this shows much material reaching the seabed very quickly under the reject chute, with little overspill from the port side. The draghead plume is indistinguishable from th e background clutter.

Transect 3 (334-420m astern), Transect 4 (458-452m astern), Transect 5 (425-375m astern) and Transect 6 (267-126m astern) represent the decay of the plume after dredging has finished (the dredger is drifting). This explains the apparent inconsistency that the plume appears to be dispersing, whilst the transect are successively closer to the dredge position. Without inputs from the dredger at the sea surface, the plume becomes less intense at the surface first, (Transect 5), more so by Transect 6. That is to say, this series of transects represents the decay of the plume with time at an approximate position, rather than representation of the time and distance decay of the other series of transects presented.

4.2.2.7 Draghead Plume Generated By The ARCO Severn, 20th August 1995

Given that the integrity of ADCP™ data is compromised within the bottom 6% of the water column, it is to be expected that acoustic backscatter observations would be limited. However, we have obtained several transects of good quality which contain good indications of the likely dimensions of the draghead plume.

The resolution of the ADCP™ using a 'bin' size of 1m was adequate to successfully record the benthic plume emanating from the motion of the draghead on the seafloor, approximately 30m astern and downtide of the draghead.

Figure 4.2.2.7 shows a CBP record of the relative acoustic backscatter for this transect. The formation of small plume attributable to the draghead is clearly visible near the seabed, slightly left of centre of the main plume. This is on the port side of the dredge vessel, and corresponds with the beam of the dredger extremely well. A small reject plume can be identified near the sea surface on the starboard side of the vessel, separate from the overspill contributions.

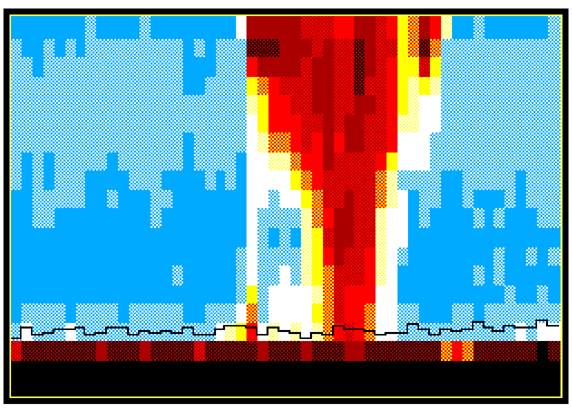


Figure 4.2.2.7 *Continuous Backscatter Profile 30m astern of the ARCO Severn, obtained on 20th August 1995. Figure clearly shows development of a small plume emanating from the draghead*

Within the limits of resolution of the ADCP™, it is estimated that the dimensions of the benthic plume at this point are less than 3m high and less than 2m wide. Similar observations were not made on any other pass close astern of any other dredgers during this campaign.

4.2.2.8 Plume Generated By The Geopotes XIV, 20th August 1995

Opportune measurements of the Geopotes XIV TSHD were made during the 20th August 1995. This is a much larger vessel than the other vessels monitored, with a hopper capacity of 7,472m^3 and maximum dredging depths of 36-42m.

Plate 4.2.2.8 *TSHD Geopotes XIV*

The vessel loads using one or two dragheads with overspill and screened-off material discharged through a central spillway, exiting under the vessel keel. The loading rate of the Geopotes XIV is considerably greater than many other UK vessels. The plume generated by the Geopotes XIV visually appeared to have the highest SSC of the plumes observed and this was borne out by the ADCP™ data and water samples collected.

A maximum total suspended solids concentration of 2473mg/l was sampled at 80m astern of the dredger, 12m below the surface. Further samples above and below during the same vertical profile are above 1000mg/l. The silt content of sediments from these water samples was also greatest, ranging from 4% near the surface to 66% near the seabed.

Two factors must be considered with the Geopotes XIV data. In addition to the considerably higher loading rate, prospecting and reserve evaluation data suggests that the geology of the seabed where the Geopotes XIV loaded contains a higher silt content than other areas under consideration here.

Detailed analysis of the EMS output data supplied to the Crown Estate shows that the Geopotes XIV regularly lifted the draghead clear of the seabed with several interruptions to the loading process. Discussion at the time with the Master of the vessel explained this was due to the patchiness of clean (silt-free) material.

The placement in the water column of the samples which had high silt content is important. When sampled, near the seabed, silt contents of up to 58% were observed. Current velocities recorded at the time indicate an east bound flood flow of 0.30m/s.

Considering the vertical and horizontal displacement of the particles from the dredger to the point of sampling (18m and 100m respectively), the enhanced settling velocity required to reach such a position can be derived by simple trigonometry and must be of the order of 5.5cm/s. Clearly, this is far in excess of the normal settling velocity for particles of this size and further determinations are needed. It is considered unlikely that this suspension was part of the benthic plume formed by the draghead interaction with the seabed.

There is growing evidence within this study, and supported by others (*see, for example,* HR Wallingford, 1996; Whiteside *et al*, 1995), that the silt/clay fractions may have either agglomerated, attached to larger particles, or, most likely, be transported to the seabed by the formation of a density current.

The initial entry velocity of the mixtures into the water column will be important. The Geopotes XIV, by virtue of the single, central discharge point, will be more likely to demonstrate any development of a density current. Table 4.2.2.8 summarises the water sample data obtained from the Geopotes XIV plume.

Time (BST)	Transect Number	Depth (m)	Distance Astern (m)	Total Concentration (mg/l)	silts (<0.063mm) (mg/l)
14:00	-	0	136	107	n/d
14:02	-	0	115	172	n/d
14:10:41	20AU33	4	46	998	90
14:11:00	20AU33	8	77	1474	59
14:11:21	20AU33	12	80	2473	145
14:11:40	20AU33	16	84	2326	209
14:11:50	20AU33	16	98	220	128
14:14:01	20AU33	18	98	1583	16
14:14:10	20AU33	4	143	44	29
14:28:20	20AU35	4	202	135	23
14:28:48	20AU35	8	180	186	32
14:29:06	20AU35	12	150	11	4
14:29:23	20AU35	16	130	112	9
14:29:37	20AU35	18	100	74	5
14:30:34	20AU35	4	70	137	23
14:30:50	20AU35	4	42	29	n/d

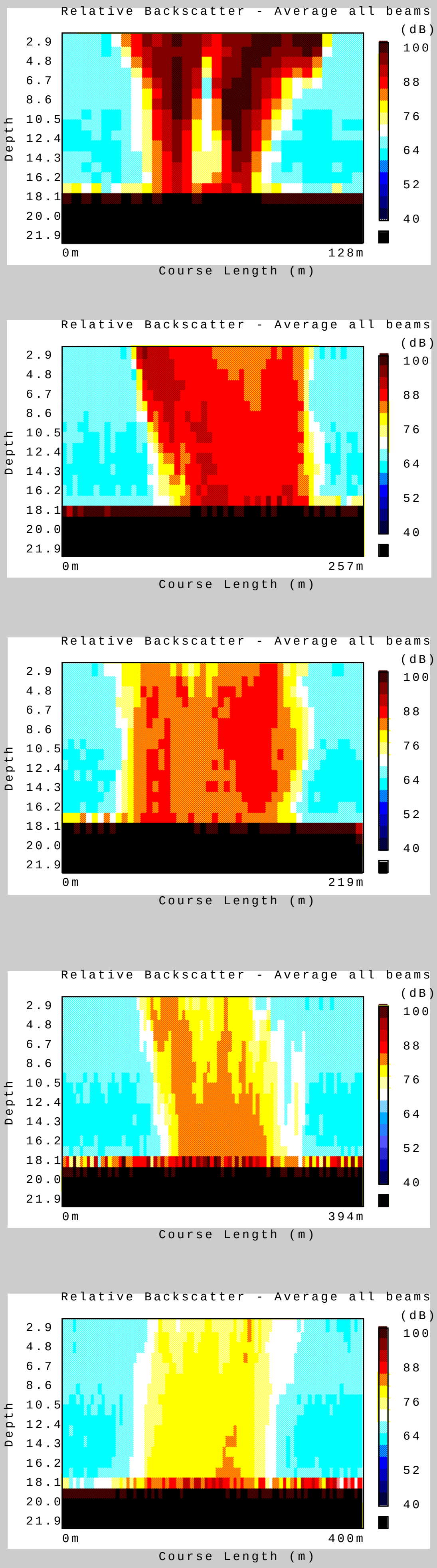
Table 4.2.2.8 *Summary of suspended solids concentrations sampled from the plume developed by the Geopotes XIV, 20th August 1995. The percentage silt content is generally within the range of values expected from the prospecting data*

4.2.2.9 Plume Generated By The City Of Rochester, 21st August 1995

The development of the plume attributable to the actions of the TSHD City of Rochester whilst dredging at anchor (Plate 4.2.2.9a) has been addressed in some detail (Hitchcock & Dearnaley, 1995; Hitchcock & Drucker, 1996; HR Wallingford, 1996). However, further interpretation of the data has been undertaken, using the in-house developed software *BMAP*.

Figure 4.2.2.9 presents a *BMAP* bitmap image processed from some 16 Continuous Backscatter Profiles across the plume downstream of the anchored dredger position. Each of the three images represents the development of the plume, in terms of Acoustic Backscatter level (dB) at different levels within the water column (5m, 10m and 15m below water surface). It is clear that there is a rapid initial settlement of material (indicated by the small dark region, less than 300-500m long). Sample data indicate return to background conditions by this distance (see Table 4.2.2.9). There then follows a period where the visual boundaries of the surface expression of the plume steadily become indistinct. The ‘plume’ is only traceable using the ADCP™. Samples do not indicate suspended solids above background conditions. At 4000m downstream (corresponding to approximately 2.7 hours, the ‘plume’ is indistinguishable. Figure 4.2.2.9 also presents a selected series of the ADCP™ transects used to process the bitmap image downstream of the City of Rochester. Again, clearly demonstrated is rapid initial settling of the plume sediments, “Dynamic Phase”, followed by a slower dispersion (horizontal and vertical) period, “Passive Phase”.

The track of the survey vessel, at various distances away from the dredger, is also shown.



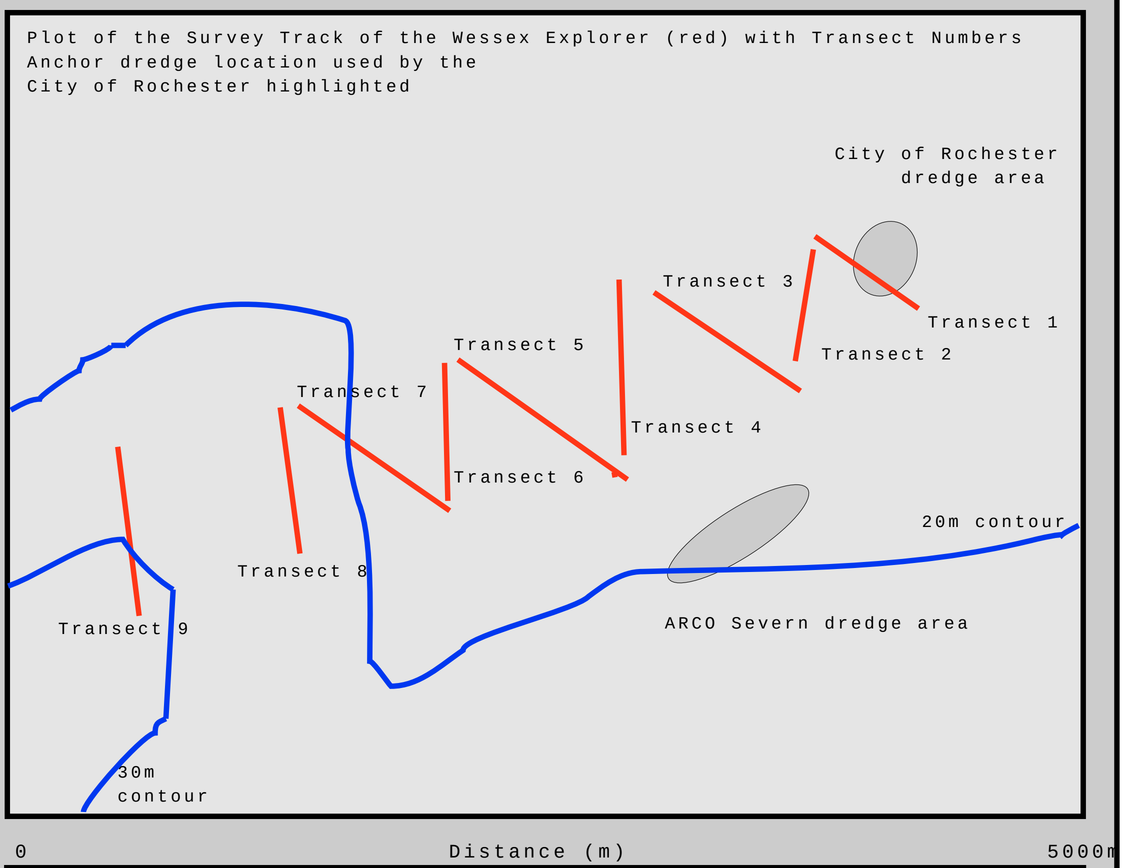
Transect 1
80m astern

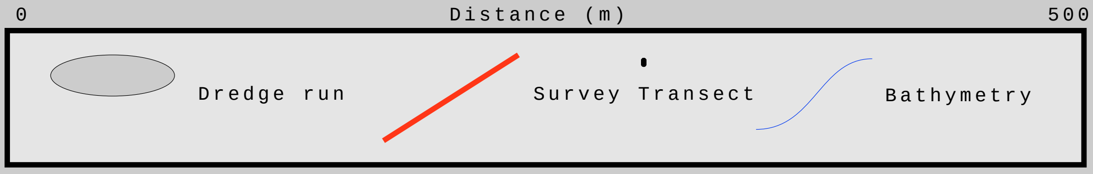
Transect 2
205m astern

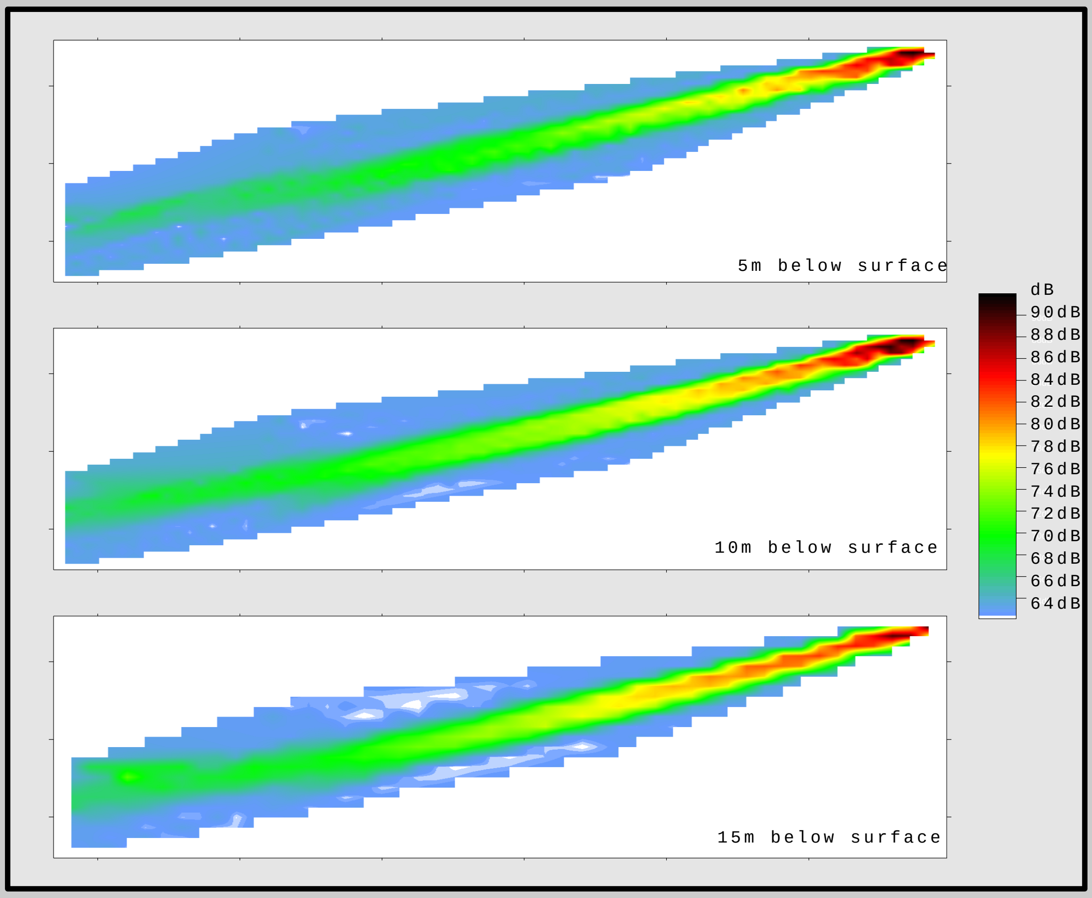
Transect 3
365m astern

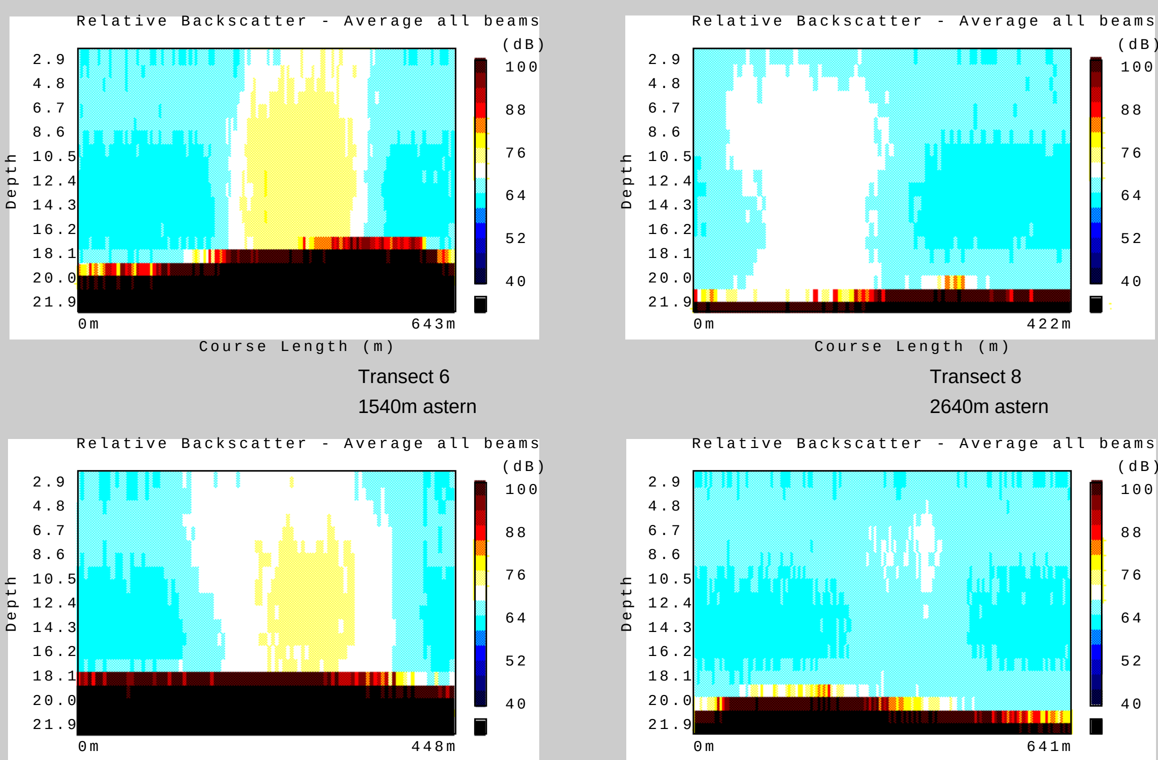
Transect 4
590m astern

Transect 5
880m astern









Transect 6
1540m astern

Transect 8
2640m astern

Transect 7
1835m astern

Transect 9
3335m astern

Composite Plot of Plume Monitoring Campaign carried out on the 21st August 1995, English Channel. The Acoustic Backscatter Transects were obtained using an RDI 1200kHz BroadBand Acoustic Doppler Current Profiler.

This series of 9 Transects was recorded across the plume emanating from the anchored TSHD City of Rochester. Simultaneous current measurements analysed at the start end of the transect indicate a mean surface flow of 53cm/s reducing to 35cm/s and mean bottom flow of 35cm/s reducing to 23cm/s in direction 250 degrees.

Sampling data indicate that at less than 100m from the dredger,total suspended solids concentrations ranged 480-611mg/l in the lower water column and 80-340mg/l in the upper water column.

Most of the sand had settled out reaching background levels within 250m. In 20m of water with 40cm/s current this implies a minimum settling velocity of 32mm/s.

Similarly the silt content of the samples reached background levels within 480m. This implies a minimum settling veloci ty of 17mm/s

Although the sample data indicated background levels for total solids

Figure 4.2.2.9

The location of the plume, including the effects of aeration, are clearly discernible from the background, unaltered backscatter levels. It can be seen that the bulk of the plume has reached the bottom almost instantaneously, and there is little significant material still in suspension beyond 300m at the surface and 500m at 15m below the surface. This is verified by the results of the water sampling which indicated SSC returning to background levels of 5-10mg/l after similar distances. A distance of 300-500m in this instance equates to a dispersal time of 10-15 minutes since release.

Time (BST)	Transect Number	Depth (m)	Time since Discharge (@0.4m/s) (secs)	Total Concentration (mg/l)	silts (<0.063mm) * (mg/l)
11:08:07	21AU19	4	103	5	n/d
11:09:48	21AU19	8	238	9	n/d
11:11:46	21AU19	12	361	13	n/d
11:13:18	21AU19	16	482	11	n/d
11:14:50	21AU19	18	624	9	n/d
12:01:52	21AU20	4	88	69	4
12:02:20	21AU20	8	112	32	4
12:02:54	21AU20	12	131	472	3
12:03:33	21AU20	16	167	528	5
12:04:03	21AU20	18	200	505	7
12:04:03	21AU20	18	215	3	2
12:06:16	21AU20	4	338	6	1
12:24:09	21AU21	4	93	65	1
12:24:50	21AU21	8	114	340	29
12:25:20	21AU21	12	133	549	3
12:25:50	21AU21	16	163	544	6
12:26:20	21AU21	18	193	615	4
12:26:35	21AU21	18	215	490	5
12:35:35	21AU21	4	840	8	n/d
12:37:08	21AU21	8	955	8	n/d
12:38:40	21AU21	12	1050	3	n/d
12:40:10	21AU21	16	1138	2	n/d
12:41:35	21AU21	18	1223	1	n/d
13:35:25	21AU21	4	4353	2	n/d
13:37:00	21AU32	8	4548	2	n/d
13:38:30	21AU32	12	4638	2	n/d
13:40:10	21AU32	16	4738	1	n/d
13:41:40	21AU32	18	4828	2	n/d
13:43:30	21AU32	14	4938	2	n/d
15:11:45	21AU35	4	10223	0	n/d
15:13:30	21AU35	8	10328	1	n/d
15:15:06	21AU35	12	10424	1	n/d
15:16:36	21AU35	16	10484	1	n/d
15:18:36	21AU35	18	10604	2	n/d

* n/d = not determined

Table 4.2.2.9 *Summary of suspended solids concentrations sampled from the plume developed by the City of Rochester, 21st August 1995*

Plate 4.2.2.9a *TSHD City of Rochester nearly completing loading a screened cargo at anchor, English Channel, August 1995. Monitoring of the plume from this vessel indicated that suspended solids concentrations were largely returned to background levels within 300-500m downstream. Gross plume was tracked for a further 3000m.*

It is an inherent and unavoidable feature of the ADCP™ that the acoustic backscatter information from the bottom 6% of the range is corrupted by interference from acoustic side lobe returns. This effectively negates inspection of the bottom 1.1m of the water column, in 18m water depth. The contemporary concept of a benthic boundary layer plume excursion, that may well be restricted to less than 1m from the seabed, can therefore neither be refuted nor substantiated from this data and monitoring technique.

The width of the plume downstream of the dredge operation is generally less than 100m each side, reaching a maximum of 140m some 1500m downstream of the dredge vessel, beyond the limit of measurable suspended solids above background limit. At the 500m downstream position, plume width is 80m each side. Gajewski & Uscinowicz (1993) report maximum plume width of 50m each side of dredge track. This width will largely be determined by the axis of the tidal currents, turbulence and water depth.

At a distance of 400m to 600m away from the City of Rochester, the surface expression of the plume becomes less readily discernible by eye (from 3m above). Surface water transmissometer readings reduce to background levels some time before this.

Plate 4.2.2.9b shows the surface plume developed by a slightly larger dredger (TSHD Sand Harrier). Although obtained on different days using different dredgers, the scale of the plumes are largely in keeping with the proportional scale of the dredgers (the Sand Harrier is larger than the City of Rochester - 2500m^3 versus 1271m^3 respectively). Further, the Sand Harrier is dredging whilst underway (therefore dispersing the overboard returns into a greater volume of water). It may be perceived that the resultant Sand Harrier plume would be at least twice that of the City of Rochester. Scale measurements (from an incomplete photographic record) indicate that the Sand Harrier plume is somewhat less than this. At 100m astern, the plume is just 70m wide, increasing to 135m at 500m astern, where it becomes more dispersed. The turbulent nature of the overboard returns, maintaining small clouds of upwelling very fine sediments, are also clear from Plate 4.2.2.9b.

Plate 4.2.2.9b *Multiple sediment plumes formed by successive passes of the TSHD Sand Harrier. The plume is less than 70m wide, 100m astern of the dredger. Sampling data from this study would indicate that suspended solids concentrations at the far right hand side of the picture would be approaching background conditions*

4.2.2.10 Multiple Plumes Generated By The ARCO Severn, 19th August 1995 & Geopotes XIV, 20th August 1995

During the ADCP™ monitoring, the ARCO Severn (2200t) worked a course with some subsequent lines parallel and adjacent to the previous runs, rather than exactly duplicating. This gave rise to the clearly discernible "multiple plumes", shown on Figure 4.2.2.10. This figure clearly shows the older plumes containing less suspended sediment (and other backscatterers) downstream of the present position of the dredger.

The scale of Figure 4.2.2.10 is similar to the scale of Plate 4.2.2.9a (2500m^3 TSHD Sand Harrier) obtained during a previous dredge monitoring exercise in the English Channel.

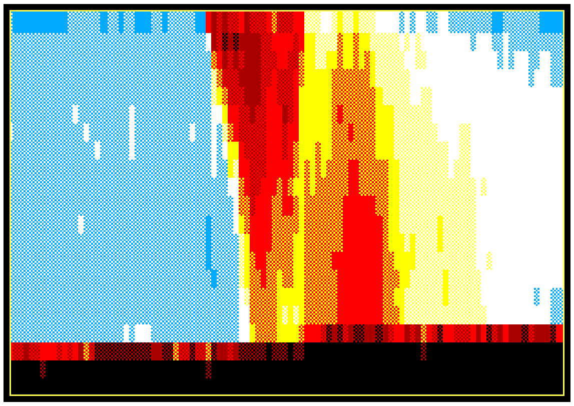


Figure 4.2.2.10 *Multiple plumes observed by Continuous Backscatter Profiling (CBP) formed by the ARCO Severn, 19th August 1995*

4.2.2.11 Plume Generated By The Geopotes XIV, 21st August 1995

A brief set of transects was obtained during the latter part of the loading period of the Geopotes XIV on the 21st August 1995. Figure 4.2.2.11 is a composite of the data obtained. An interesting observation is the first transect, obtained 88-130m astern of the dredger. This clearly shows a very 'tight' plume formed, with very little entrainment of sediments at the edges of the plume during the early stages of release. This reveals two things; (a) the intensifying effect of a central spillway, and (b) gives very strong support to the concept that the plume sediments settle very quickly as a density current immediately after release (the *Dynamic Phase*, Whiteside *et al*, 1995). That is to say, due to the concentrating of all overboard returns within a single central spillway, the development of a density current is virtually indisputable from the data. Interestingly, the draghead plume is not discernible at this range, although it is not known what type of draghead is fitted to the Geopotes XIV (commercially sensitive).

The next two transects again support the view that the plume settles very rapidly over the first 10-15 minutes, slowing down as it does so, such that the 4th transect reflects what is becoming known as the *Passive Phase* (Whiteside *et al*, 1995).

Horizontal dispersion is more apparent with the edges of the plume less discernible both visually at the sea surface and as identified by the ADCP^{TM}.

It must be remembered that all the while the sediments are settling to the seabed, displayed by the ADCP^{TM} as apparently less relative acoustic backscatter, concurrently entrained air bubbles are rising to the surface and thereby also reducing the relative acoustic backscatter. The ADCP^{TM} may therefore be considered to give a *Worst Case* representation of sediments within the water column, since some of the acoustic scatterers will not be sediments.

4.2.2.12 Overspill Samples Obtained From The ARCO Severn During The Monitoring

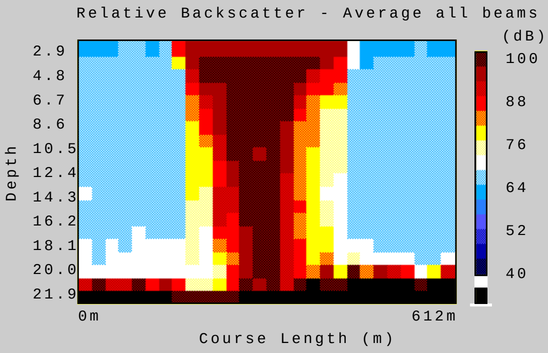
Overspill samples were obtained from the spillways of the ARCO Severn during the monitoring campaign. These samples have been analysed for full particle size characteristics. Table 4.2.2.12 summarises the results. The data have been divided into each cargo loaded, to identify different characteristics of each load.

The spillway samples range in suspended solids concentration from 2267-14210mg/l, averaging 6178mg/l. The total solids concentration of overspill during loading all-in is greater than during screening, although the silt content (fines <63µm) is slightly less. The fraction <63µm constitutes the majority fraction of the overspill. No particles greater than 2mm were obtained from the overspill, unlike previous sampling campaigns.

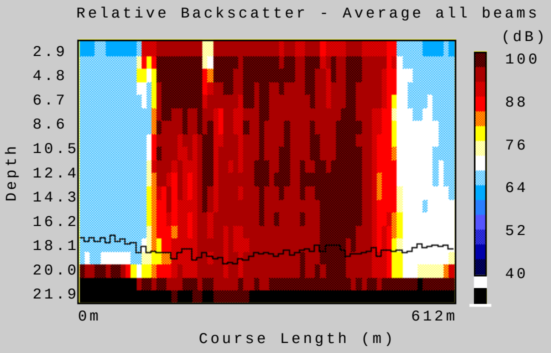
The results from these two loads are commensurate with the results obtained from other monitoring campaigns aboard the ARCO Severn (*see results of Phase One)*. Surprisingly, the data indicate only a very weak relationship between time elapsed since loading commenced and both the quantity and grade of sediments passing overboard via overspill. None of the samples from the ARCO Severn contained material greater than 2mm diameter.

	Ratio (mg/l)	% <63µm	% >63µm	% >125µm	% >250µm	% >500µm	% >1000µm
all-in	6737.69	48.10	10.60	18.95	19.69	1.83	0.51
stone	5655.06	67.84	11.31	11.78	7.82	0.69	0.55

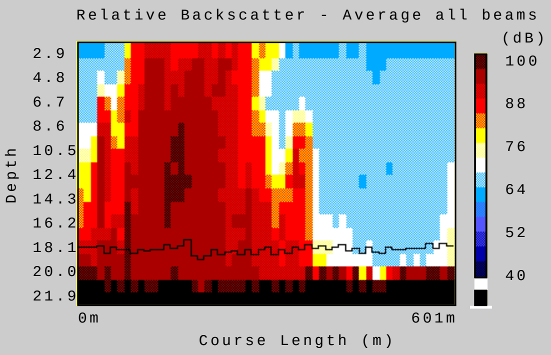
Table 4.2.2.12 *Summary of overspill sample sediment characteristics obtained from the ARCO Severn spillways during loading of an all-in cargo (19.08.95) and screened cargo (20.08.97).*



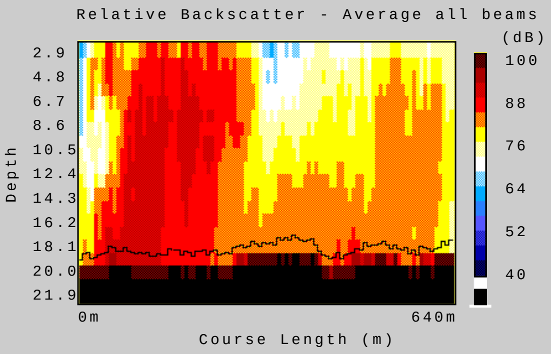
Transect 1
88-130m astern



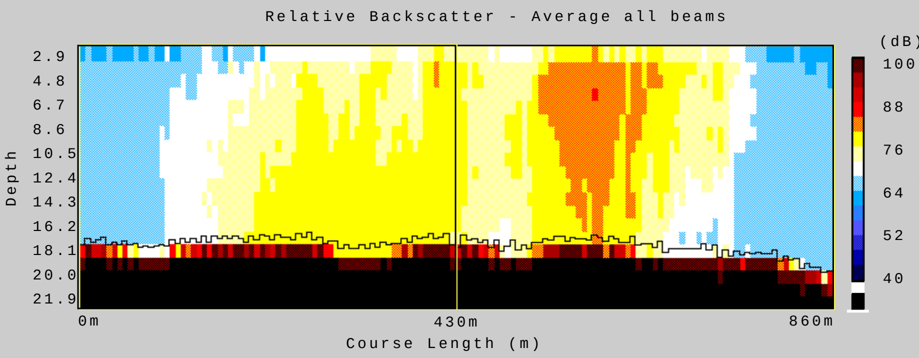
Transect 2
206-583m astern



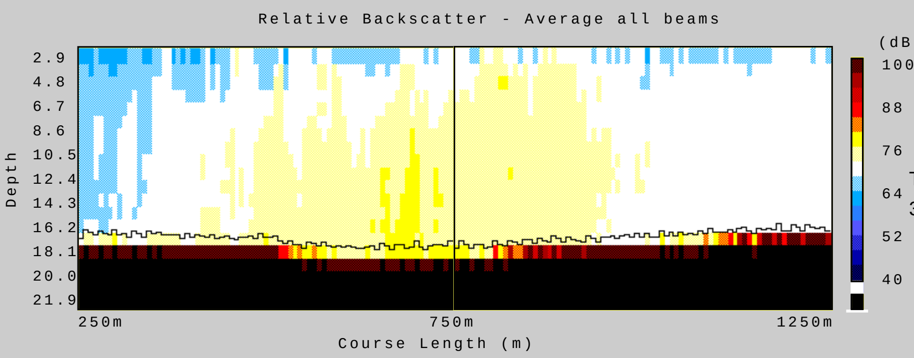
Transect 3
663-918m astern



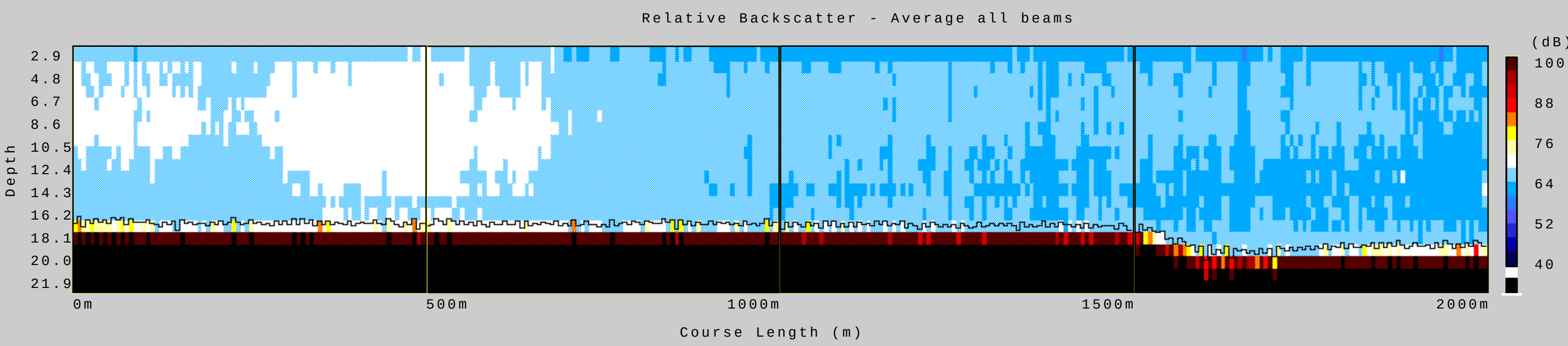
Transect 4
972-2103m astern



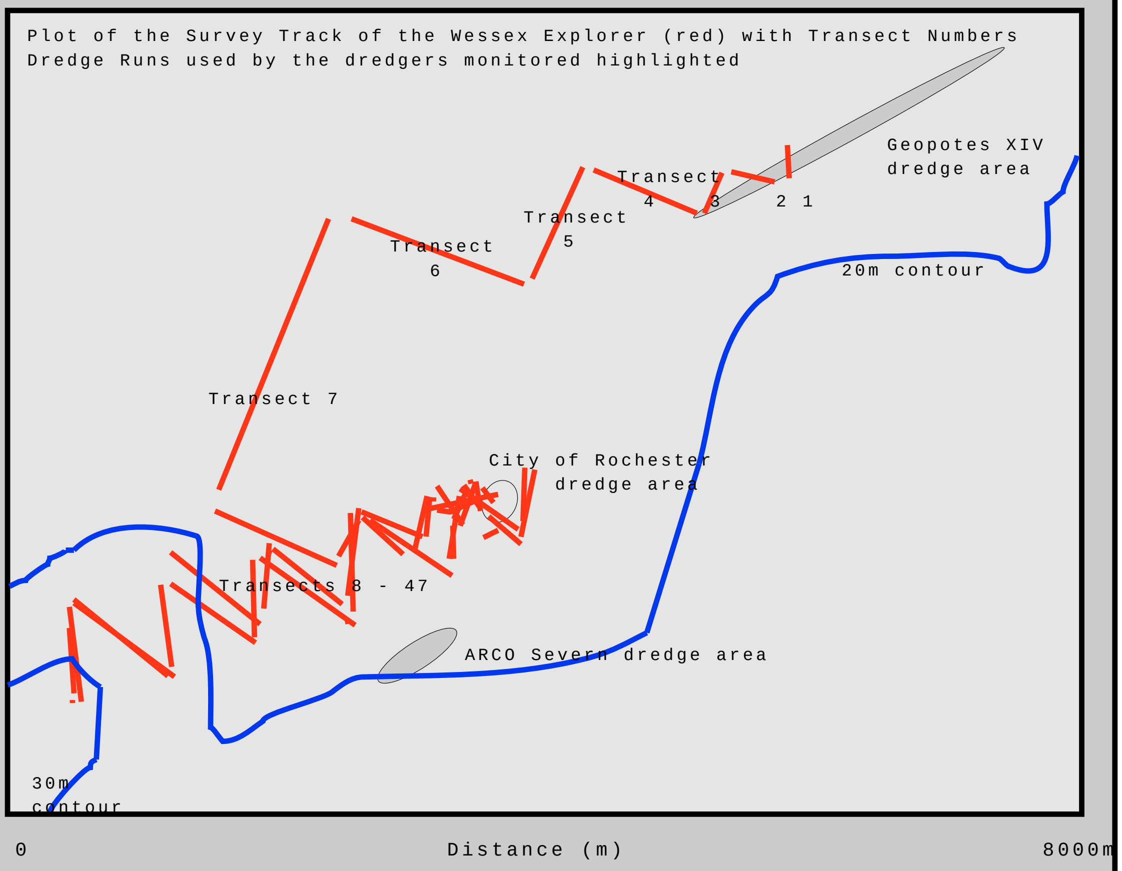
Transect 5
2205-3026m astern

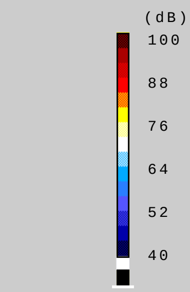


Transect 6
3176-4500m astern



Transect 7
4670-6633m astern





Relative Acoustic
Backscatter

Composite Plot of Plume Monitoring Campaign carried out on the 21st August 1995, English Channel. The Acoustic Backscatter Transects were obtained using an RDI 1200kHz BroadBand Acoustic Doppler Current Profiler.

The series of transects away from the Geopotes XIV show the rapidly settling and dispersing plume.

Transect 1, taken very close astern of the dredger (88-130m) shows a very tight plume, with little dispersal. Clearly visible is the intense central portion to the plume attributable to the central spillway, exiting under the hull. The development of a density current is strongly confirmed by this transect. There is very little entrainment of sediment at the outside edges of the plume. The top of the plume is pushed back to the surface by the propellors. The ADCP will be affected to an unknown degree by entrained air bubbles, especially at this range from the dredger. No samples were taken, but by comparison with other data obtained, the total suspended solids concentration will be of the order 1000-2000mg/l.

Transects 2 and 3 (at 206-583m and 663-918m astern respectively) show the plume settling rapidly, with some entrainment of sediment at the sides of the plume into the surrounding waters. Transect 3 shows clear waters over the top of the plume waters, suggesting some temporary stratification.

Transect 4 at 972-2103m astern depicts the most recent plume with a secondary, probably 20-30 minutes older, plume alongside.

Transect 5 (2205-3026m astern) shows a much greater horizontal dispersion of the very fine scatterers that the ADCP observes. Sampling does not indicate a suspended solids concentration above

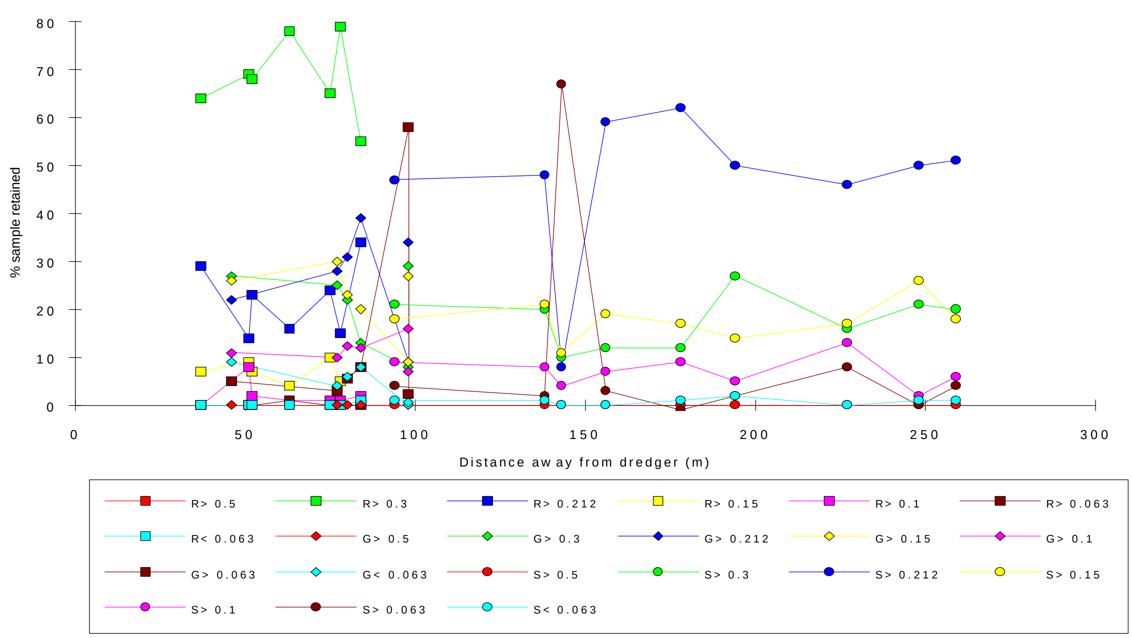
Figure 4.2.2.11

4.2.2.13 *Particle Size Distribution Of Plume Samples Obtained During The Owers Bank August 1995 Monitoring Campaign*

140 suspensate samples were obtained throughout the water column downstream of the dredger positions to characterise the plume. Geolocation of the samples in time and space has enabled calculation of minimum settling velocities based on the observed settling patterns (*see* Section 4.2.2.8). Where concentrations allow, samples have been further analysed to provide the silt/sand ratio and in some cases, full particle size analysis (Table 4.2.2.13 and Figure 4.2.2.13). The silt contents are largely within the ranges expected from the prospecting data.

Dredger	Load	Distance away	% of sample passing sieve size (mm)					
		From dredger	0.5	0.3	0.212	0.150	0.1	0.063
Geopotes		46	100	73.33	52.38	26.67	15.24	8.89
Geopotes		77	100	75.44	47.02	16.67	7.37	4.21
Geopotes		80	100	78.36	53.33	24.31	12.41	6.26
Geopotes		84	100	76.80	52.71	27.58	16.49	8.76
Geopotes		98	100	91.61	83.01	73.98	58.49	0.00
Geopotes		98	100	70.47	36.81	10.24	2.56	0.59
Rochester	Stone	37	100	35.71	7.14	0.00	0.00	0.00
Rochester	Stone	51	100	30.68	17.05	7.95	2.27	0.00
Rochester	Stone	52	100	31.60	9.43	2.36	0.47	0.00
Rochester	Stone	63	100	21.69	5.82	1.59	1.06	0.00
Rochester	Stone	75	100	35.02	11.55	0.72	0.00	0.00
Rochester	Stone	78	100	21.03	6.15	4.10	0.51	0.00
Rochester	Stone	84	100	45.03	11.11	3.51	1.17	0.58
Severn	All-in	94	100	78.75	32.50	13.75	5.42	0.83
Severn	All-in	138	100	80.09	31.94	10.88	3.24	0.23
Severn	All-in	143	100	90.20	82.35	70.59	66.67	0.00
Severn	All-in	156	100	77.26	29.14	10.60	2.65	0.00
Severn	All-in	178	100	77.23	26.62	8.76	3.15	1.23
Severn	All-in	194	100	72.60	23.42	8.67	4.45	1.64
Severn	All-in	227	100	84.42	38.31	20.78	7.79	0.00
Severn	All-in	248	100	79.37	29.15	2.69	1.35	0.45
Severn	All-in	259	100	80.39	29.80	10.59	5.10	0.78

Table 4.2.2.13 *Particle size distribution of overspill suspensates, ARCO Severn, August 1995.*



Sieve sizes in mm Prefix R = City of Rochester G = Geopotes XIV S = ARCO Severn

Figure 4.2.2.13 *Size spectra (mm) of sediments obtained from samples within the plume downstream of three dredgers. Percentage of samples retained on sieves of sizes as indicated*

4.2.3 Discussion Of The August 1995 Owers Bank Observations

The monitoring of surface sediment plumes generated by marine aggregate dredging operations operating under normal commercial conditions and constraints has been successfully accomplished using a combination of new and traditional sampling and survey techniques. Rigorous fieldwork and post-processing procedures have been developed to ensure the maximum benefit is gained from such measurements. Considerable care and effort has been placed in developing the procedures. The monitoring team has comprised professional personnel with scientific and commercial awareness of the nature of the phenomenon to be monitored and the equipment and techniques available to do the work. The integral support of the Industry has enabled realistic appraisal of the factors governing the operations. Modification of the procedures to allow for field variations was possible.

A total of 162 Transects across the plume have been recorded using the ADCP^{TM}. Continuous Backscatter Profiling (CBP) has been shown to be fundamental to executing confident sampling programmes, with full knowledge of the suspended solids concentration minima and maxima within the plumes developed. We have developed a number of in-house programs to process and interrogate the outputs from the RDI Transect software. Equipment interfaces have been developed to facilitate the surveys. The ADCP^{TM} transects show the bulk of the plume settling out of the water column (or, more strictly, settling to within 1.5m of the seabed) within 300 (sands) to 500m (silts) downstream. Coarse sands (> 2mm settle out virtually instantaneously). This corresponds to a time period of 10-15 minutes since release. The plume was visually discernible over a greater distance.

It was possible to track the apparent plume advecting downstream away from the City of Rochester using the ADCP^{TM} over a distance of some 3.5km, even though for some 3km of that distance the concentrations in the plume were not significantly different to background levels (obtained from sampling and transmissometer readings). Similar results were observed, though not in as much detail, for the Geopotes XIV and the ARCO Severn. This effect is attributed to an unknown combination of the presence of minute air bubbles (nearer the dredger than in the far field), bio-chemical precipitates and/or organic material entrained and vigorously disaggregated before return to the water column during the dredging operation.

It is possible from the biological data reviewed (*see* Section 6) and from field observations of trawling activity behind dredgers, that the negative impact is largely limited to an aesthetic impact, with little impact imposed on the surrounding biological communities. Enhancement of feeding opportunities and protection from predation may be a positive effect of the extended plume component. Further investigation is required and is discussed in Section 4.4.

The contemporary concepts of the development of Dynamic and Passive Phases during the plume generation and decay are strongly supported. The evidence for the development of density currents during the Dynamic Phase and their importance is compelling. Settling velocities for silt have been calculated to be of the order 17-55mm/s (compared with more standard 0.1-1.0mm/s). Interestingly, more reasonable and comparable figures for sands are derived (circa 30-60mm/s). It is postulated that the figures for silts are, in effect, a preliminary determination of the settling velocity of the density current formed during the initial Dynamic Phase. It is reasonable to expect that, given more data obtained closer to the dredge vessels (less than 500m range), higher settling velocities may be encountered under certain conditions. Further, it is suggested that significant particle agglomeration occurs with the sediments settling as particle assemblages having settling velocities substantially higher than the individual member particles. Whilst more determinations of these settling rates are required, importantly this shows the possible hazards inherent in the application of a single particle settling velocity within models of suspended sediment plumes arising from dredging operations.

The vertical velocity component recorded by the ADCP^{TM} is presently being investigated by the author as a further source of information on the magnitude of the downward plume velocity in the initial stages when entry velocity into the water column from the vessel will be significant. Figure 7.3 records the upward (positive) and downward (negative) velocity components 80m astern of the dredger. The central region of the figure clearly shows a downward water body velocity of some 15-20cm/s with corresponding upwelling at both margins of similar magnitude. Further investigation is required to determine the utility of such data.

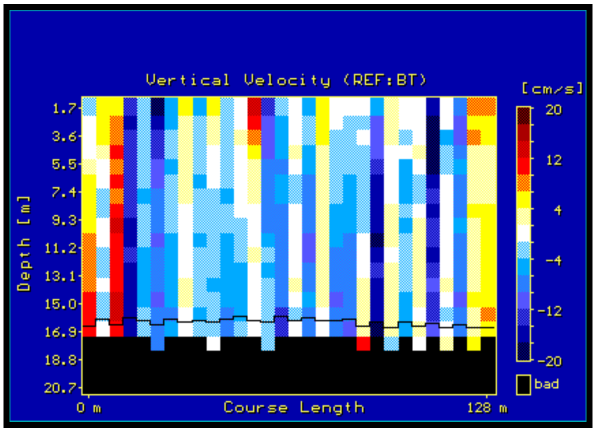


Figure 7.3 *Vertical velocity component 80m astern of the ARCO Severn, 21 August 1995. Positive figures are upward velocity; negative figures are downward velocity. Other than at both margins of the transect, there is a general downward velocity of some 10-15cm/s within the plume. 'Upward' water movement may be due to rising air bubbles. The comparative relative backscatter for this transect is shown as Transect One of Figure 7.2.9.*

Detailed analysis of the mineralogy of the sediments at the dredged sites has not been determined. It is known that the presence of the clay mineral montmorillonite enhances the flocculation of the fine particles. To what extent this may explain the difference between the plume excursion in different (in the geological sense) licence areas is not clear.

The benthic plume was clearly identified on only one of 162 CBP Transects recorded astern of the three dredgers monitored. Samples were not obtained from within the benthic plume. It is evident that the benthic plume is quite small in comparison to the surface plume and is rapidly engulfed by the rapidly descending density current.

The following section investigates the development of the benthic plume at and just above the seabed through novel use of underwater cameras and imaging combined with water sampling and concurrent ADCP profiling from an attendant survey vessel in a separate field campaign.

4.3 Phase Three - Benthic Plume Source Terms

Data collected within this project (principally the August 1995 Owers Bank investigations) support the view that the benthic plume attributable to the hydrodynamic and mechanical interactions of the draghead with the seabed might be of much less quantitative significance than that generated at the surface through overspill and screening. The evidence collected by CBP methods has recorded only rare insights into the size of the benthic plume. No other observations appear to be available within the reviewed literature. Nonetheless, this has made study of the benthic plume no less important, if only to authoritatively clarify the actual characteristics.

A monitoring campaign was undertaken in order to sample the plume formed by the draghead. Analysis of simultaneous underwater video images has provided an estimate of the gross size, shape and morphology of the draghead plume in real time. Opportunity was also provided by the industrial partners to collect further CBP information on both the draghead benthic plume and the surface plume formed by a different class of dredge vessel. This section herein presents the results of the work carried out.

Weather conditions for the study were not ideal, following an unsettled period. Previous arrangements for undertaking the work in more favourable weather were thwarted by vessel breakdown, commercial requirements for the vessels elsewhere and adverse weather. It must be noted that the dataset collected during this campaign is not to the high quality of that obtained during earlier work within this project, principally as a result of the prevailing weather conditions experienced during the survey. However, this does not significantly detract from the conclusions reached.

4.3.1 Benthic Plume Sediments

To acquire source term data on the content of the benthic plume, it has been necessary to develop an economical yet efficient method of obtaining water samples from approximately 30m water depth. Various pumps and pumping arrangements were tested on three field trips, obtaining a limited number of samples. Considerable care was exercised to ensure that the capacity of the pump was such that any inertia of the sediments within the sample tube was overcome and that the samples were therefore representative, that is to say no separation of the fractions was introduced by the sampling system. The samples obtained were subsequently tested for total suspended solids concentration, and where possible, determination of the ratios of sediments less than and greater than 63µm (*i.e.* silts and sands, respectively).

Fieldwork was undertaken over a three day period in January 1997 from the 1300 tonne capacity TSHD ARCO Dee (Plate 4.3.1a), loading all-in and screened cargoes under normal operating conditions from Licences in the English Channel.

Plate 4.3.1a *TSHD ARCO Dee used for the benthic plume monitoring work*

The three sampling locations (designated A, B and C) were positioned; (A) approximately 1.2m above the base and in line with the rear end of the draghead; (B) 1.2m above the base and 0.5m inboard of the hinge point of the draghead / dredge pipe; and (C) 0.5m above and 0.8m in front of the draghead (see Plate 4.3.1b). Also visible on Plate 4.3.1b are the two SIT cameras used to observe the formation of the plume, enable measurements of scale and ensure the sampling points represented the fully formed plume.

Plate 4.3.1b *'California' Type draghead fitted to the ARCO Dee with two underwater cameras and three water sample positions*

Table 4.3.1a presents a summary of the samples obtained from the benthic plume using sampling tubes and pumps actually mounted to the draghead obtained. The nearbed background suspended solids (within 1.5m of the seabed) prior to the start of the survey were 18mg/l - 33mg/l (samples 1A and 1B). This relatively high background figure reflects the disturbed nature of the environment following the recent passage of two short gales. It can be seen from Table 4.3.1 that the average total solids concentration within the plume varies from 24mg/l close astern of the draghead to 31-37 mg/l closer to the side and slightly in front of the draghead. This is approximately twice that of the background conditions.

Evidence from the video imaging confirms that (a) background turbidity was higher than on previous video imaging campaigns; (b) development of the plume is highly variable over very short timescales; and (c) the developed plume is largely a result of pushing material in front of the draghead, rather than the subsequent scraping of the draghead over the seabed.

The draghead was trailed across the seabed without dredging to assess the effect of the near field suction. Samples 8 (A, B, & C), 9(A, B, & C) and 12(A, B & C) (all excluded from the calculation of the mean suspended solids value) were taken when the dredge pump was switched off and the draghead was on the seabed. These account for the highest suspended solids recorded during the campaign and are roughly twice that observed during normal dredging procedure. It is evident that the suction of the pump plays an important role in reducing the size of the benthic plume. Adjusting the speed of the vessel across the seabed to minimise the build-up of sediment in front of the draghead is therefore important for both efficient operation and reduction of the plume formed. This corroborates the conclusions reached in Davies & Hitchcock (1992) that the 'bulldozer effect' of the draghead motion plays a significant role in the efficiency of the dredging process (at the draghead end).

The silt content of the samples obtained when the dredge pump was not running are some 3-4 times greater than the *in-situ* concentration available from the prospecting data. This suggests preferential disturbance of the fine sediments further into the water column (such that they were sampled) with the larger sandy sized sediment not being thrown as far vertically. From the video images obtained about the draghead, it is evident that small fragments of broken shells are thrown further in the water column, as might be expected.

Sample Number	Total Solids (mg/l)	Silt (mg/l)	Sample Number	Total Solids (mg/l)	Silt (mg/l)	Sample Number	Total Solids (mg/l)	Silt (mg/l)
1A	33	n/d	1B	18	n/d	3C	44	n/d
2A	30	n/d	2B	19	n/d	4C	41	n/d
2A	20	n/d	3B	61	n/d	5C	27	n/d
3A	20	n/d	4B	56	n/d	7C	37	n/d
3A	21	n/d	5B	37	n/d	9C	22	n/d
4A	17	n/d	5B	17	n/d	10C	24	n/d
4A	23	n/d	6B	20	n/d	11C	22	n/d
5A	16	n/d	7B	21	n/d	12C	121	37
5A	20	n/d	8B	111	40	13C	28	n/d
6A	16	n/d	8B	32	n/d			
7A	19	n/d	9B	27	n/d			
7A	22	n/d	9B	120	56			
8A	20	n/d	10B	43	n/d			
9A	73	n/d	10B	64	n/d			
10A	24	n/d	11B	65	n/d			
11A	21	n/d	12B	105	67			
12A	20	n/d	13B	20	n/d			
13A	21	n/d						
mean	**24**	n/d	**mean**	**37**	**54**	**mean**	**31**	**37**

Table 4.3.1 *Summary of samples obtained during the benthic plume monitoring campaign, January 1997. Sampling equipment was mounted at three points on the (small) 'California' Type draghead of the TSHD ARCO Dee.*

Detailed analysis of the video images recorded during the campaign has enabled a preliminary calculation of the dimensions of the plume. This is established by comparison of known reference points on the draghead and their visibility or not during the recording. Only the video images obtained on the 15th January 1997 have proven suitable for interpretation, as has also been the case for the sample data due to poor weather conditions.

The draghead of the ARCO Dee is some 1.2m wide and may be expected to dig into the seabed some 0.35m (Davies & Hitchcock, 1992). Some penetration of the draghead below the surface veneer of sediments is necessary to avoid processing of recently deposited fine sands and silts.

The results from this analysis can reasonably be applied to slightly larger vessels and ‘California’ Type dragheads. It is known that the range of penetration of these types of draghead into the seabed is relatively small (compared with, for example, fixed visor types). The frontal area of contact of the draghead with the seabed is similar to that of a large beamtrawl. These have been studied to some extent and no significant impact determined (*see, for example,* Sydow *et al,* 1990).

We consider that the information obtained and processed herein provides a realistic assessment of the order of magnitude of the benthic plume source terms. Further field information would statistically refine the data.

From the video images, it appears important that the draghead maintains contact with the seabed to avoid the partial loss of suction as the draghead lifts off, and still exerts a disturbing effect on the seabed. This will be related to the seabed topography and geology, the weather conditions and the efficient operation of the swell compensator, and operator experience. The design of a ‘California’ Type draghead (two independent ‘feet’) is important in providing the improved continued contact with the seabed.

The ARCO Dee plume is estimated to vary between $0.67m^2$ and $6.78m^2$. The higher figures are considered to be present some 10% of the loading period and predominantly appears to be formed when the draghead loses contact with the seabed (due to seabed morphology and/or sea surface motion), reducing the near field suction effects. The smaller plume size is recorded when the draghead moves slowly across the seabed and occurs some 15% of the observed period.

Preliminary observations suggest from these data that the benthic plume averages approximately $2.7m^2$ ($\pm$ $2.1m^2$) at the point of formation, about the draghead. From the data recorded in Table 4.3.1, we can calculate the following;

<u>FOR WORST CASE</u>

From field information:

speed over ground	= 2 knots
current speed against vessel	= 2.5 knots
speed of water past draghead	= 4.5 knots
velocity of water past draghead	= 8.334m/s

From video image processing:

$6.78m^2$ large plume observed for 10% of load
$0.67m^2$ smallest plume observed for 15% of load
$2.70m^2$ (mode) plume observed for 75% of load

Rate of material placed in suspension necessary to produce plume of average concentration 31mg/l is thus;

$8.334m/s \times 6.78m^2 = 56.50m^3/s$
$56.5m^3/s$ @ 31mg/l = 1.82kg/s
$8.334m/s \times 0.67m^2 = 5.58m^3/s$
$5.58m^3/s$ @ 31mg/l = 0.18kg/s
$8.334m/s \times 2.70m^2 = 22.5m^3/s$
$22.5m^3/s$ @ 31mg/l = 0.73kg/s

Hence for one, five hour load (18000 seconds), a vessel similar to the ARCO Dee would place into suspension about the draghead the following;

18000s x 10% x 1.82kg/s	= 3276kg
18000s x 15% x 0.18kg/s	= 486kg
18000s x 75% x 0.73kg/s	= <u>9855kg</u>
TOTAL	= 13617kg

of which up to 5992kg (44%) may be of silty sized material(<63µm).

From the video imaging and sampling of the benthic plume we can conclude that the quantity of sediment displaced into the water column by the draghead is very small, in essence accounting for less than one hundredth of the quantity of sediment otherwise returned overboard via overspill and rejection through screening. It is not surprising therefore that observations of the benthic plume using CBP techniques is rarely possible.

4.3.2 Plume Developed By The ARCO Dee Observed Using Continuous Backscatter Profiling (CBP)

During the same benthic plume monitoring campaign outlined in Section 4.3.1, opportunity arose to perform further CBP of the plume developed during aggregate dredging. Based on the results of the August 1995 monitoring campaign, it was hoped that good records would be obtained indicating the plume formed by the draghead, observed from positions close astern.

Weather conditions were not ideal for the conduct of CBP monitoring. It is clear from the data obtained before dredging commenced, that background suspended solids concentrations were higher than previously experienced at the site.

A vertical profile of samples obtained prior to dredging ranged from 8mg/l (surface), 11mg/l (midwater) to 14mg/l (4m above bottom). Once dredging commenced, further samples obtained from within the dredge plume near the surface ranged from 23mg/l to 53mg/l, all obtained within 200m of the stern of the vessel. A surface sample obtained within 20m astern of a spillway contained 159mg/l sediment, of which 10% comprised silty sized sediment (<63µm). Further midwater and near bed samples were not obtained due to equipment failure.

Figure 4.3.2a shows the ‘plume’ recorded using the ADCP[TM], before dredging has commenced. The backscatter is clearly due to aeration caused by the twin screws of the ARCO Dee.

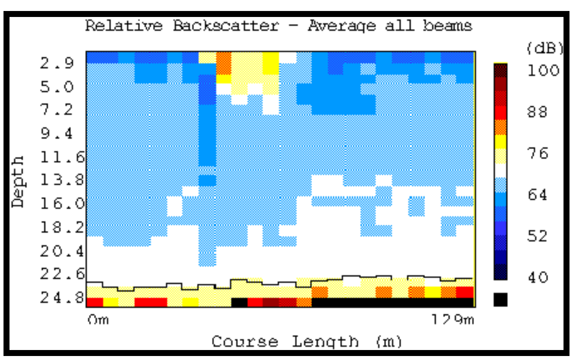


Figure 4.3.2a *CBP transect showing aeration caused by the twin screws of the ARCO Dee, before any dredging operations had commenced.*

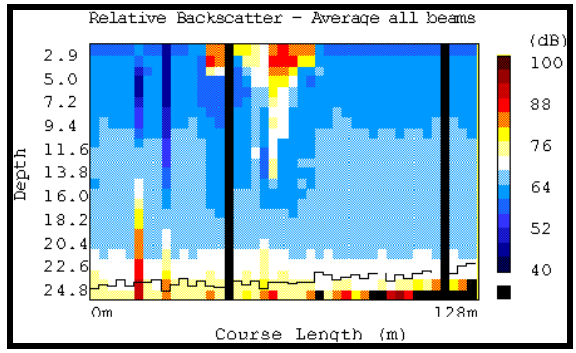


Figure 4.3.2b *CBP transect showing what is interpreted to be the plume formed by the draghead near the seabed. This plume appears not directly under the main vessel disturbance due to the angle of the survey path relative to the ship and draghead.*

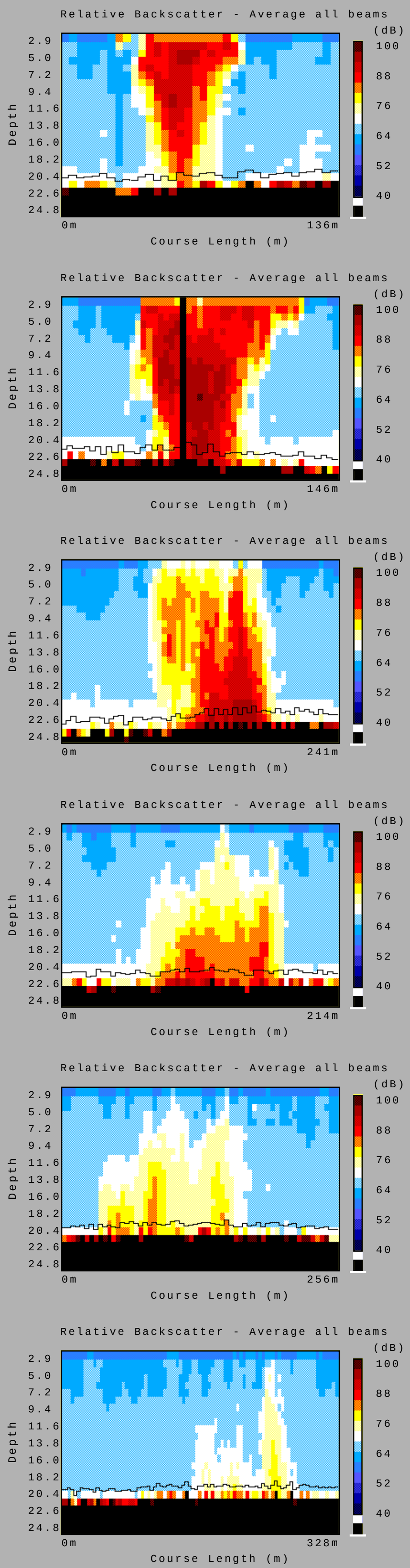
Figure 4.3.2b records the only profile obtained (out of 56) on which the plume from the draghead is discernible, some 20m astern, before dredging commenced (*i.e.* the dredge pump was switched off). We know from the underwater video (Section 4.3.1) that the size of the draghead plume is exaggerated to some extent when in this situation, which is very unlikely during normal dredging operations. Also visible on Figure 4.3.2b is the plume caused by the very early stages of overflow, before any sediment reaches the seabed. Visual records from the survey boat indicate that this surface ‘plume’ may largely be aeration, with very little sediment observed.

Composite Figure 4.3.2c presents CBP data obtained from a series of transects across the plume of the ARCO Dee. It can be seen that the plume is quite small compared to the data obtained from the August 1995 campaign and is probably related to the ship size.

Plate 4.3.2 *View astern of the ARCO Dee showing the smaller plume formed by this size of vessel.*

The CBP data of Transects 1 and 2 clearly show the development of the 'Density Current' effect, accelerating the movement of material towards the seabed. Very little entrainment of sediment at the edges of the plume by turbulence is apparent in Transect 1. The quickly descending density current reaches the seabed virtually immediately underneath the dredger (within a ships' length). The sediments will move to the seabed with a velocity considerably greater than the free fall, single particle velocities associated with their particle diameters, as determined widely by laboratory and field observations.

Transect 2 shows the bulk of the plume content reaching the seabed at a distance of only 180m astern (highest recorded backscatter levels). The plume becomes asymmetric near the surface, largely due to wind driven currents in the surface waters, in addition to the further input on the port side of rejected material.



Transect 1
35m astern

Transect 2
180m astern

Transect 3
345m astern

Transect 4
560m astern

Transect 5
915m astern

Transect 6
1620m astern

Composite Plot of Plume Monitoring Campaign carried out on the 15th January 1997, English Channel. The Acoustic Backscatter Transects were obtained using an RDI 1200kHz BroadBand Acoustic Doppler Current Profiler.

The series of transects depicted on the left were obtained whilst monitoring the TSHD ARCO Dee. The solid black bands are formed when backscatter levels suddenly reach high levels (for example due to aeration). The data is blanked completely rather than artificially 'clipped' to a potentially misleading level.

Transect 1, obtained minutes after dredging with full overspill commenced, shows the development of a narrow plume at the base, with width at the surface little more than the breadth of the dredger. The quickly descending plume which has just reached the seabed typifies the development of a 'Density Current' effect, rapidly transporting sediments to the seabed, faster than their freefall, individual particle behaviour would exhibit. Very little entrainment of sediments at the edges of the plume is evident.

Transect 2 represents what is probably the most intensive region of the plume, with backscatter levels high throughout depth. The plume shows lateral dispersion though entrainment at the edges of the plumes, with surface currents (including wind effect) distorting the asymmetry of the plume.

Transects 3-6 clearly show the rapid settlement of the plume towards the seabed. No with-depth SSC data are available. It is considered that background levels of suspended solids would be attained closer to the dredger than Transect 4.

The continuation of the 'plume' beyond this point is considered to be due to backscatter caused in part by aeration and physico-chemical factors, but largely due to organic components disturbed and fragmented by the dredging process. The disintegration of benthic macro- and meiofauna tissues will release significant quantities of lipids, cabohydrates and proteins which will generally remain in suspension longer than

Figure 4.3.2c

It is considered that the major constituent of the 'plume' recognisable in Transects 4-6 is actually of organic origin and this is explored in more detail in Section 4.4.

The wind and wave conditions during the time of the survey are important. Strong winds will induce drift in the surface layers thereby altering the advection rate for tidal currents alone. Wind will also generate surface waves which will tend to enhance diffusion by turbulence. The net effect of winds and/or waves will be to increase the rate of dispersion. Combined with the higher background levels of suspended sediments that may be present in coastal waters due to mobilisation of surface sediments, the detection time of plume sediments in unsettled conditions may be expected to be some time less than in calm conditions.

4.3.3 Discussion Of Benthic Plume Observations

In conclusion, we may therefore consider that the motion of the draghead upon the seabed causes only a small plume, commonly <3.0m^2 which is barely detectable from the surface using high resolution continuous backscatter profiling (CBP). The total velocity difference between the draghead and the water column will vastly change the advection, dispersion and suspended solids concentrations.

Suspended solids concentrations within the draghead plume have been measured to be of the order 30-40mg/l. The silt content may be enhanced, up to 44%, although the statistical reliability of this figure is low. Importantly, the likely significance and subsequent impact of such a plume is considered small, and in truth minor in comparison with the inputs of sediment (<1.0% by weight) to the surface waters through overspill and screening. In the coastal regions of the southern North Sea where the majority of marine aggregate extraction takes place, concentrations of 30-40mg/l may be largely indistinguishable from natural background conditions.

The type of draghead monitored is considered important, not only the size, but more importantly the design. Maintaining full contact with the seabed reduces the plume size. The test condition of disturbance without suction causes a significantly larger disturbance, not expected during normal working activities.

Importantly, observations from the deck of the survey vessel, and from the dredger (*for example, see* Plate 4.3.2), correlated with the water samples obtained, indicate that elevations of suspended solids 10-35mg/l above background levels of 10-20mg/l are clearly distinguishable by eye. That is to say, concentrations of suspended solids do not have to be significantly above background to be visible and consequently perceived as detrimental. The following section explores the hypothesis that the far field (away from the dredger) backscatter recorded is largely organic in origins, rather than sedimentological.

4.4 Consideration Of The CBP Component Apparent Beyond The Limits Of Suspended Solids Above Background Conditions

Throughout the development of the Continuous Backscatter Profiling technique for observing the location of the plume, it has become apparent that there is a non-sediment component which is both visible at the surface and recorded by the ADCP™. This has been tracked for up to 3.5-4.0 km from the dredger using the CBP and is alleged to be visible from aircraft over greater distances. Composite Figure 4.2.2.9 clearly displays this, both with the CBP transects and the three depth image plots.

Early progress and technical reports prepared during the course of this project considered that such additional scatterers observable by the ADCP™ (Hitchcock & Dearnaley, 1995) could be of biological or chemical origins. The possibilities of continued aeration at these distances is considered unlikely.

Herein, we present the hypothesis that much of the scatterers and visual particles are derived from the disintegration of benthic invertebrate organic tissue matter during the dredging process.

Table 4.4 (below) presents data for the biomass of benthic macrofauna recorded from coastal sediments in UK waters in areas of potential aggregate extraction. Up to 70 samples of 25-30kg sediment each were obtained from 50 stations using a $0.2m^2$ Hamon Grab. The data are expressed as the mean values of ash free dry weight (AFDW) in grammes and has been calculated from blotted wet weight using conversion factors from Eleftheriou & Basford (1989).

The AFDW represents the materials from the tissues: the conversion factors take into account the non-tissue components such as the shells of molluscs *etc.* and principally comprise proteins, carbohydrates and lipids. It is considered likely that these form the bulk of the scatterers observed by CBP.

By way of an example, we may estimate the following order of magnitude for the quantity of organic material returned overboard during a dredging operation.

Assuming a Hamon Grab sample of 30kg is representative for the sample results presented in Table 4.4, we can derive an *in situ* AFDW as follows;

from Table 4.4:
in situ AFDW is 3.9g +/- 1.6g per $0.2m^2$
= 3.9g per 30kg AFDW
= 19.5g per m^2
= 130ppm AFDW

From Section 4, we know that during screening a 4500 tonne dredger may typically return overboard some 8000 tonnes of sediment via the reject chute and spillways.

from Section 4.1 (sediments);
losses from screening & overspill = 8000 tonnes
therefore organic matter released during loading of screened 4500 tonne cargo is;
(3.9g x 30kg/1000kg) x 8000t AFDW
= 1036.5kg
= 1.04 tonnes AFDW organic matter derived from benthic invertebrates

Expressing this as a concentration (from the known volume of water rejected);

from Section 4.1 (water);
losses from screening & overspill = 35000 tonnes
therefore 35000t water contains 1.036t AFDW
therefore 1kg water (=1 litre) contains
(1.036/35000) AFDW / litre
= 0.0296g/litre
= approximately 30mg/l

That is to say, the concentration of AFDW in the outflow from the dredger may be approximately 30mg/l, and during the loading of a screened cargo some 1.04 tonnes of broken up biomass may be discharged. This organic matter then disperses with time (at a slower rate than the sediments), and hence is visible by the ADCP™.

This figure assumes that all the invertebrates disturbed are fragmented. Lees *et al*, (1992) reported the condition of invertebrates captured using a 5mm mesh within the spillways, and concluded that a proportion of individuals appeared unharmed. It is expected that sampling with finer mesh may reveal a higher mass of constituent body parts, if not whole individuals. However, within the range of values for AFDW in the sediment samples, the value of 30mg/l is acceptable.

Comparison with data for detritus-rich environments suggests that such enrichment is significant. For example, Seiderer & Newell (1985) analysed kelp bed seawater and recorded 300-400µg.C.litre^{-1} and 46-71µg.N.litre^{-1}. Mann (1982) has established the conversion rate 10g.C.per m^2 corresponds to approximately 26g AFDW per m^2. Therefore, the detritus load of kelp bed seawater may be determined as 0.780-1.040mg/l AFDW.

Site	Mean AFDW per 0.2m^2	+/- 1 SD
Lowestoft, Norfolk	4.4	
Isle of Wight	5.59	8.97
Folkestone, Kent	4.95	23.55
Orford Ness, Suffolk	3.18	3.49
Lowestoft, Norfolk	1.49	3.49
MEAN for all sites	3.9	1.6

Table 4.4 *Biomass of benthic macrofauna recorded for coastal sediments within potential aggregate extraction sites within the UK. Data are expressed as ash-free dry weight (AFDW) in grammes per 0.2m^2 Hamon Grab sample (modified from Kenny & Rees, 1996; Newell & Seiderer, 1997a,b,c)*

Consequently, it can be seen that the enhancement of the detritus load of the overspill/reject mixtures is of the order 30 times greater than that of a rich kelp bed community. The Mean Annual Biomass for phytoplankton in the English Channel is 4g/m^2 dry weight (Harvey, 1950 *In:* Tait, 1980).

The release of significant quantities of such material into the water column is likely to significantly enhance secondary production surrounding dredged areas, a phenomenon which has been reported elsewhere (*see, for example,* Poiner & Kennedy, 1984).

Further, the specific gravity of seawater is usually within the range 1.024 - 1.028. Organic material varies from less than 1.000 to approximately 1.200. The overall density of much of the zooplankton is usually within the range 1.040 with fish tissues about 1.070. The specific gravity of many fats and oils within pelagic organisms is about 0.91 (Tait, 1980). Conversely, the specific gravity of sediment particles, many of which are quartz silica or calcium carbonate is in the range 2.300 to 2.700. The greater the (positive) density difference between the seawater and the settling particles, the faster the particles will settle.

In summary, the admixture of fats, lipids and carbohydrates may well account for the visible non-sediment component of plumes associated with marine aggregate dredging which has been observed repeatedly during this project (*see* Sections 4.3.2 & 4.3.3). The interaction of the of fats, lipids and carbohydrates with sediments is not known at this stage. Further, the consequential effect on sediment buoyancy is unclear, and hindrance of the settling of very fine (<20µm) sediments may give rise to the extended visual surface colour to the plume observed many times.

It is therefore considered of prime importance to obtain data on the AFDW and biochemical composition of the plume waters. This is quite simply performed, and would enable confirmation, or rejection, of this important conjecture. Authoritative explanation of the (aesthetically) major component of the surface plume is sorely needed.

The follow up investigation to this section is included at the end of the main report, as Annex 1.

SECTION 5 - RESULTS OF OTHER INVESTIGATIONS

5.1 Impact Within The Dredged Area

The increased exploitation of marine deposits and the physical impact of dredging works has been widely reviewed (*see* Shelton & Rolfe, 1972; Dickson & Lee 1973; Cruikshank & Hess, 1975; Eden, 1975; Millner *et al*, 1977; de Groot, 1979b; van der Veer *et al*, 1985; Glasby, 1986; Gajewski & Uscinowicz, 1993; ICES, 1993; Land *et al*, 1994; Whiteside *et al*, 1995; Hitchcock & Dearnaley, 1995; Hitchcock & Drucker, 1996; Hitchcock, 1997).

Dickson & Lee (1973) studied the recovery of test pits dug by anchor dredge in gravel deposits of the Shingle Bank, Hastings, off the south east coast of England. They found that the pits were very slow to fill and were still visible after two years. In another study, van der Veer *et al* (1985) described the recovery of pits in sandy substrates in the Dutch Wadden Sea. They showed that in this instance pits in channels with a high current velocity filled within one year, but those in the lower current velocities which occur in tidal watersheds took 5-10 years to fill whilst those in tidal flat areas were still visible after 15 years. In contrast, dredge furrows in the Bristol Channel have been observed to disappear within 2-3 tidal cycles or less, due to high sediment mobility.

Because the deposits required for marine aggregate are coarse, and sediment disturbance by wave action in any case limited mainly to depths of less than 30 metres even during storm conditions, it follows that not only is the fauna likely to be removed in patches from the dredged areas, but pits and furrows are likely to be persistent features of the sea bed topography for several years except in areas where the sands are mobile.

Such sediment movement as does occur is mainly through slumping of the sides of the pits and subsequent infilling by fine particulates transported by tidal currents into the pits which reduce current velocity and act as sediment traps. This can lead to heavily anoxic sediments and to colonisation by a community which differs considerably from that in the original deposits (Shelton & Rolfe, 1972; Dickson & Lee, 1973; Kaplan *et al*, 1975; Bonsdorff, 1983; Hily, 1983; van der Veer *et al*, 1985; Hall, 1994).

Side-scan sonar records in coastal waters of the southern North Sea show that the sea bed is crossed by a series of dredge tracks which are 2-3 metres wide and up to 50 cm deep (van Moorsel & Waardenberg, 1990a & b; Kenny & Rees, 1994) although deeper troughs of up to 2 metres were recorded from areas where the dredge head had crossed the area several times.

Davies & Hitchcock (1992) studied high resolution sidescan sonar profiles of a large number of dredge cuts produced by different dredge vessels operating on different U.K. Licence Areas. They found that the average cut depth ranged from 0.34m-0.55m and cut width from 2.5m-3.7m depending on the type of draghead and substrate. Somewhat deeper troughs of up to 70 cm were reported for the Baltic (Gajewski & Uscinowicz, 1993).

In this case removal of the surface 0.5 metres of deposit would be sufficient to eliminate the benthos from the deposits in strips, the total removal depending on the intensity of dredging at a particular worked site.

Despite the shallower depth of removal, the evidence suggests that infilling of the troughs from trailer suction dredging takes at least 12 months in the Baltic and is achieved partly by slumping from the sides and partly by transport of fine material by bottom currents into the sediment traps formed by the dredged furrows (Kaplan *et al*, 1975; Hily, 1983; van der Veer *et al*, 1985; Gajewski & Uscinowicz, 1993). Progressive removal of the original sandy gravel and its replacement by fine sand has also been reported for the sediments off Dieppe by Desprez (1992). In the case of experimental furrows dredged by trailer suction in gravel deposits of the southern North Sea off the Suffolk coast of England, even shallow depressions of only 20-30 cm depth were still visible on side-scan sonar records made up to four years later (Millner *et al*, 1977).

Rather unexpectedly, Kenny & Rees (1994, 1996) found an increase in the particle size of deposits in the dredged areas, possibly reflecting the exposure of coarse deposits at depth below the surface gravel layers. In this study which was carried out in the southern North Sea, the dredged furrows were visible with side scan sonar even after 2 years. Similar results have been reported for dredging tracks off the French coast at Dieppe (Desprez, 1992), although winter storms obliterated tracks within a few months on the Klaverbank in the Dutch sector of the North Sea (Sips and Waardenberg, 1989; Van Moorsel & Waardenberg, 1990, 1991). In general, dredge tracks will persist for varying times depending on the rate of local sediment fluxes. Recent measurements suggest this may be as short as only a few days in high energy environs such as the Bristol Channel and Norfolk Banks, but periods as long as several years for more stable deposits along the south coast of the U.K. (A. R Hermiston, 1998, *pers.comm.)*

Both anchor dredging and trailer suction dredging thus both have an important potential impact on the biology of the dredged areas, since no benthos is likely to occur below the dredged depth. This can be expected to lead to a patchy distribution of organisms, reflecting the differences between the dredged furrows and the intervening undredged surfaces. Such recolonisation as occurs within the dredged areas is likely to be by migration of adults through transport on tidal currents (Rees *et al* 1976; Hall, 1994); by transport in sediments slumping from the sides of the pits and furrows (McCall, 1976; Guillou & Hily, 1983); by the return of some undamaged components through outwash from the chutes and spillways (*see* Lees *et al*, 1992; MAFF, 1993); and by colonisation and subsequent growth of larvae from neighbouring populations. In this case, a clear succession of colonising species is to be anticipated, leading to the establishment of definite clusters, or patches in benthic community composition depending on the type of deposits which have infilled the dredged areas and the time since the recolonisation sequence started.

Author	Date	Distance	Water Depth	Current Velocity	Particle Sizes
Åker, Häkkinen & Winterhalter	1990[*]	200-300m			
Davies	1984[*]	< 500m	N/A	N/A	silts, clays
HR Wallingford	1994[#]	< 11000m	25m	1.75m/s	very fine sands
		< 5000m			fine sands
		< 1000m			medium sand
		< 50m			coarse sand
HR Wallingford	1993[#]	< 6500m	25m	0.9m/s	very fine sands
Pennekamp *et al*	1996	<1.5hrs	N/A	low	clays/silts
Gajewski & Uscinowicz	1993	<300m	8-25m	low	sands
Kioerboe & Moehlenberg	1981	<1000m	N/A	N/A	background
Poopetch	1982	<800m	N/A	N/A	background

Table 5.1 *Summary table of results of similar dredging plume study investigations. Note however that these are largely concerned with the behaviour of fine silts and clays, rather than sediments associated with aggregate mining.*

5.2 Impact Adjacent To The Dredged Area

Although a good deal of concern has been expressed about the possible impact of marine aggregate extraction on coastal resources (*see* ICES, 1992a, b), the possible scale of impact outside the immediate dredged area from the settlement on the seabed of fine material temporarily suspended by marine aggregate dredging is poorly understood.

It has often been assumed for the purposes of simulation models for British coastal waters that the dispersion of material rejected *via* the reject chute and spillways during the dredging process is controlled by Gaussian diffusion principles and that suspended material could be carried by tidal currents for as much as 20-km on each side of a point source of discharge.

Indeed, in water depths up to 25m and peak spring tide velocities of 1.75m/s, very fine sand may travel up to 11km from the dredging site, fine sand up to 5km, medium sand up to 1km and coarse sand less than 50m (HR Wallingford, 1994). In current regimes with a lower peak velocity of some 0.9m/s, similar sized material may only travel up to 6.5km from the point of release (HR Wallingford, 1993). Worst case estimates have suggested that sediment plumes may persist for up to 4-5 tidal cycles (HR Wallingford, 1994).

Interestingly, detailed and extensive monitoring campaigns associated with the construction of the Størebælt Link have detected suspended sediment related to a specific dredging operation up to 35km from the source. However simulations have shown that 6km from the operations, the monthly average surplus SSC caused by some of the most intensive dredging operations were at the same level as the background concentration (2 mg/l).

More recently, Acoustic Doppler Current Profiling (ADCP) techniques have been used to determine plume dispersion in relation to spoils dispersal from both commercial aggregate dredgers (Hitchcock & Drucker, 1996) and in relation to capital dredging works and sand mining (Land *et al*, 1994; Whiteside *et al* 1995). Remote airborne and satellite imagery has also proved to be a useful tool in defining the contours of sediment dispersal (Whiteside *et al* 1995).

As referred elsewhere within this Report, recent studies made on the dispersion of sediment plumes generated from dredging operations suggest, however, that the area of impact of outwash from dredging activities is smaller than results of modelling based on Gaussian diffusion principles imply, especially where the proportion of silt and clay in the deposits is low.

A comprehensive study has been undertaken in the Baltic Sea (Gajewski & Uscinowicz, 1993). Observing plume formation from trial trailer dredging operations, they found that the majority of sediment from the plume fell into traps placed near the seabed within 50m of the dredge track. At distances greater than 50-metres the amount of material settling on the seafloor decreased rapidly (Figure 5.2a). Current movements were low. Settling rates at 50m were less than 1200g/m^2. Settlement within the dredge furrow was estimated at 5-10mm, which has been correlated with a settlement rate of ca. 7500-15000g/m^2.

Importantly, Gajewski and Uscinowicz conclude that the disturbance of the light extinction field, i.e. the SPM field caused by dredging is only significant adjacent to the operation (up to 50m). Further, any geomorphologic impact caused by the sediment plume is localised and short lived.

Åker, Häkkinen & Winterhalter (1990) report that turbid waters could not be detected further than 'a few hundred meters' downcurrent from the dredger. Normal water quality variations caused by current activity and storm suspension were found to be greater than that caused by sand extraction. They also consider that the operation had no clearly detectable effect on fishing in the general area.

Van der Veer (1979, *In:* van der Veer *et al*, 1985) measured overflow concentrations of suspended sediment from a small dredger to be 6300 mg/l, within range of the results obtained here. Background concentrations were found to average 60 mg/l.

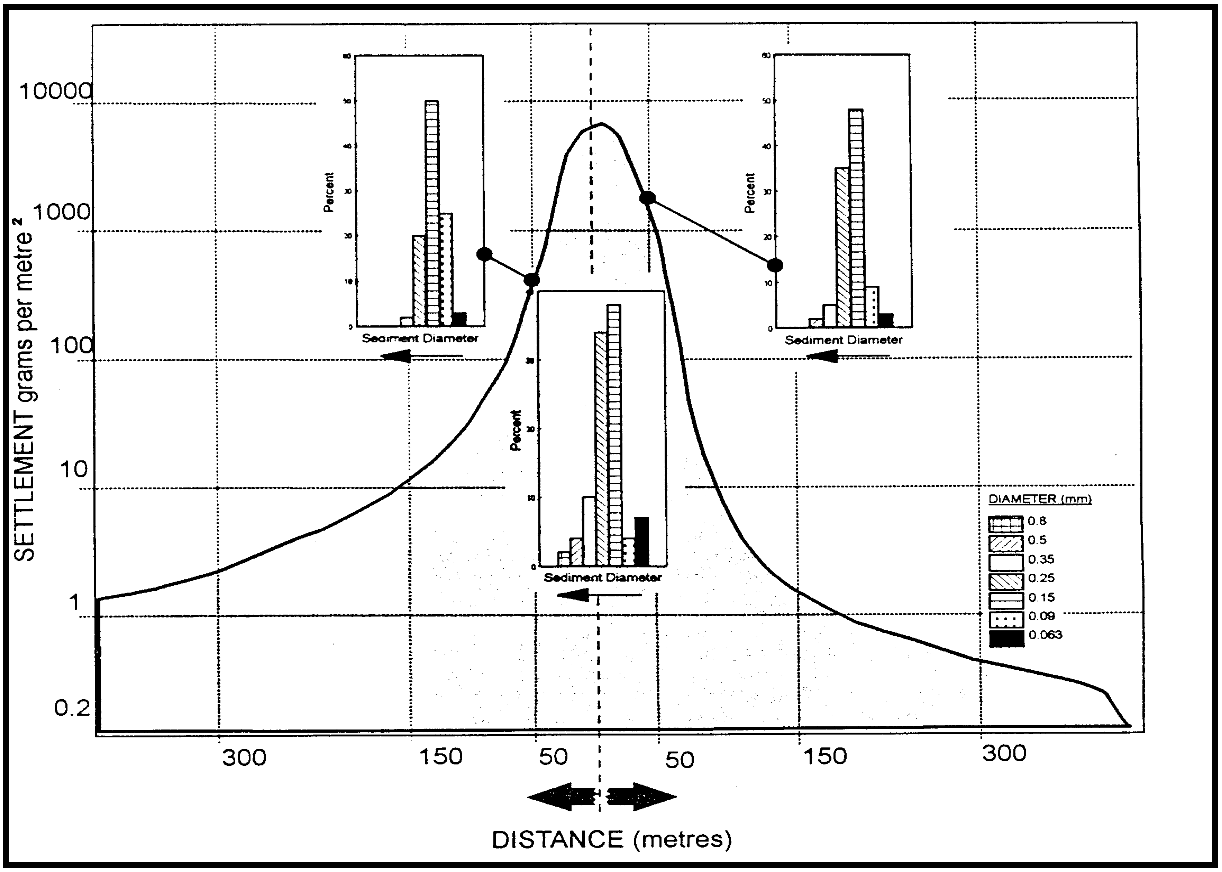


Figure 5.2a *Diagram showing the settlement of overflow sediments during dredging operations from trailer dredging in the Baltic. Particle size profiles for the sediments deposited in the track of the dredger and 50-metres on each side of the dredger are also shown. Note that the main deposition of sediment was confined to distances within 150m on each side of the dredger track (after Gajewski & Uscinowicz, 1993)*

The recent study by Whiteside *et al* (1995; *see also* Johanson & Boehmer, 1975; Gayman, 1978) has shown that the behaviour of plumes discharged during sand dredging can best be regarded as comprising an initial "Dynamic Phase" during which the sediment-water mixture descends rapidly to the seabed as a density current jet at a rate which depends on the overflow density, the diameter of the discharge pipe, the water depth, the velocity of discharge and the speed of the dredger.

During its passage through the water column and following impact with the seabed the sediment is dispersed into the water and forms a well-defined plume astern of the dredger. This second longer phase has been referred to as the "Passive Phase" of dispersion by Whiteside *et al* (1995) and starts approximately 10 minutes after outflow. During this phase the material behaves in a relatively simple settling mode according to Stokes Law, the plume then decaying to background levels after a period of 2-3 hours.

Their study showed that approximately 100 metres (corresponding to approximately 3 minutes from the overflow) astern of a dredger working in Hong Kong waters the plume surface sediment concentrations were from 75-150 mg/litre. Levels were halved in 10 minutes and reduced to 20-30 mg/litre after 30 minutes. This approached the recorded background suspended solids concentration of 10-15 mg/litre and indicated that only a relatively small proportion of the fines category (<63-mm) remained in the water column at the start of the passive phase of dispersion ten minutes after discharge. Even then, their data suggest that the settlement rate of the plume continued to be more rapid than simple particle settlement would suggest.

A plume dispersion model developed by Whiteside *et al* (1995) for the surface layer (the upper 8-metres of the water column) for up to 40-minutes after discharge is shown in Figure 5.2b and compares well with plume decay measurements in the vicinity of the dredger. The contours for sediment deposition evidently remain as a narrow band extending for approximately 100-metres on each side of the track of the dredging vessel, much as recorded by Gajewski & Uscinowicz (1993) for Baltic waters.

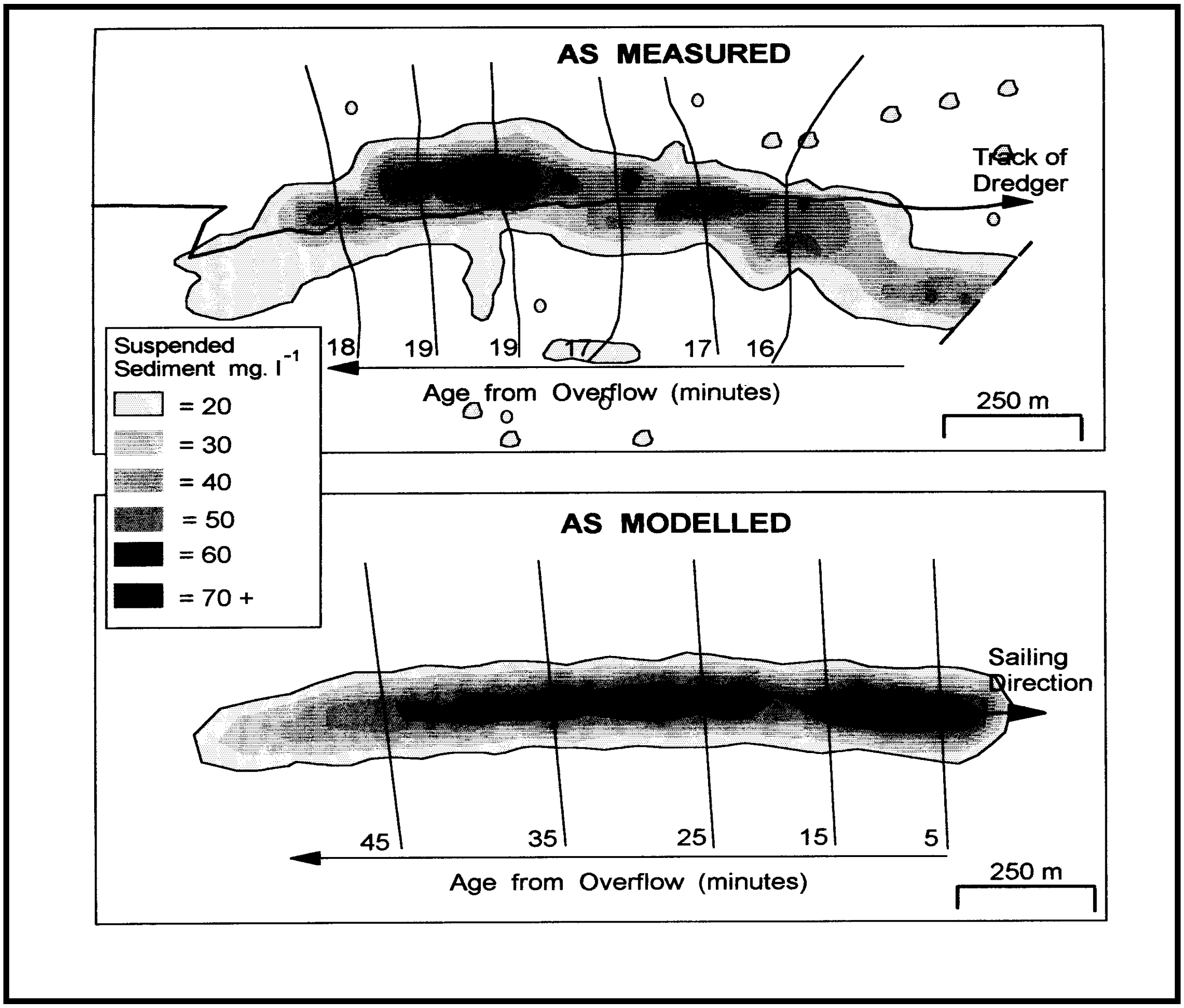


Figure 5.2b *Contours of suspended sediment concentrations astern of a trailer dredger operating in Hong Kong waters. Upper diagram shows contours as measured in the upper 8 metres of water across the plume at various time intervals up to 18 minutes after discharge. Lower diagram shows the output of a simulation model developed for sediment dispersion based on rapid sedimentation during an initial "Dynamic Phase" followed by a second longer "Passive Phase", which starts approximately 10 minutes after outflow (after Whiteside* et al, *1995)*

The turbidity plume caused by a combination of the draghead motions on the seabed and propeller screw disturbances were observed by Poopetch (1982). Fifteen minutes after dredging commenced, observations were also made of the plume developed due to hopper overspill. All plumes were observed to fully admix within 200m downstream of the vessel. Initial sediment concentrations in the surface seawaters adjacent to the overspill reached 3500mg/l, rapidly decreasing to 500mg/l within 50m downstream. Background levels of suspended solids concentrations were resumed at 150m laterally and within 800m longitudinally downstream.

Investigations in Hong Kong were undertaken at an early stage when marine dredging for aggregate was considered (Holmes, 1988). The concern for plume impingement on sensitive spawning grounds necessitated monitoring of water quality during dredging operations. The investigations concluded that within the water column the practical effects of enhanced suspended solids concentrations is difficult, if not impossible to assess. The effects were observed to be short lived and of limited areal extent and therefore concluded that suspended sediment impacts within the water column were negligible, away from spawning and mariculture zones. Interestingly, and probably related to the sampling methodology and dredging technique, SSC in the hopper surface waters was only 10000-30000 mg/l, reducing rapidly to 5000 mg/l adjacent to the dredger in the sea. A rapid dilution is therefore observed. Holmes (1988) observed that (1) the sand fraction settled quickly within a few hundred metres of the dredger (at a rate of 46mm/s for 320µm particles) and (2) the pelitic fines content will settle much slower at 0.1-1 mm/s and will therefore disperse over a wider area, observed up to 4km (Figure 5.2c).

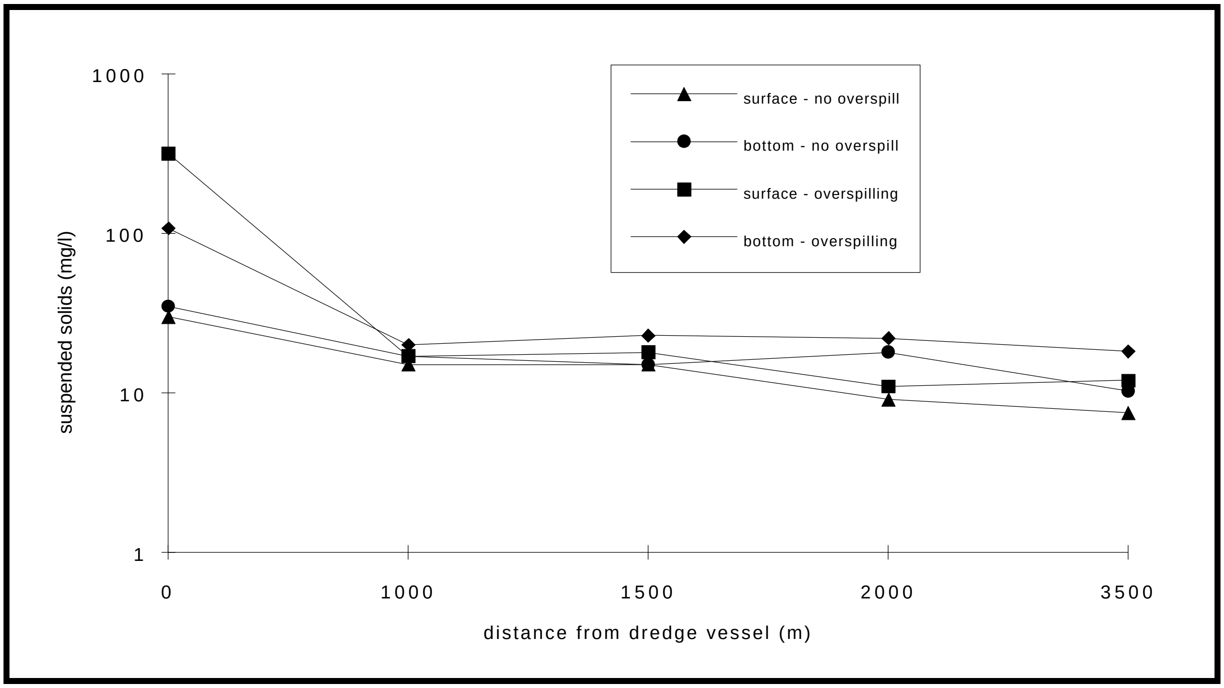


Figure 5.2c *Reduction in suspended solids concentration away from dredge vessel. Background concentrations away from site were 16mg/l (modified from Holmes, 1988)*

Kiørboe & Møhlenberg (1981) monitored the operation of a sand suction dredge in the Øresund, Denmark and concluded that any SSC likely to be detrimental were not present more than 150m downstream of the dredge. Levels adjacent to the dredge were up to 5000mg/l, rapidly decreasing to 100mg/l at 150m. Background levels were regained at 1000m downstream.

ICES (1986) report the detailed investigations that have been carried out in the Baie de Seine, France. During the course of the study, aspects of the overflowing sediments and there behaviour were observed. During the initial stages of the dredge loading operation, when the hopper is quite empty, particles in suspension in the overspill were all less than 315µm with some 15-20% less than 40µm. Later during the load, particle size increases to over 600µm. The fines content (<63µm) remained of the same order.

Using radioactive labelling of sediments, investigators also observed that the dispersion of the dredged material is limited in extent (ICES, 1977). An area of only 50 - 70 km^2 surrounding the dredge vessel exhibited increased turbidity. Particles less than 40µm were found to settle within 1500m of the dredge site.

Hayes *et al* (1984) reports on plume sampling whilst dredging silty clays in Grays Harbour, Washington, using a trailing suction hopper dredger. Observations indicated that the plume was largely dissipated (indistinct from background levels) and/or settled out within 300m of the dredger. It must be noted that the seabed disturbed and hence plume formed consisted only of fine grained silts and clays, and would therefore be expected to persist longer than those produced during aggregate dredging.

Willoughby & Crabb (1983) observed by aerial photography that the lateral dispersion of the plume rarely exceeded 200m with the plume-laden waters and clear water boundary clearly defined. Background SSC were observed as 3mg/l. Peak concentrations observed were at 0.5 hour old waters, having SSC of 20-25mg/l above background. After 2 hours, the SSC regained background concentrations of less than 3mg/l. The visible plume persisted for 8 hours overall.

Willoughby & Foster (1983) developed dispersion models to map the deposition rates of sediment following a two year period of intensive dredging on the Middle Banks, Queensland, Australia. A

200m wide corridor was predicted oriented downstream of the dredging area at 500m intervals. Table 5.2 below summarises the data predicted by their model.

Concentrations of suspended sand-sized material were reported to decay to background levels over a distance of only 200-500 metres from the point of release into the water column from a commercial aggregate dredger. Willoughby & Foster (1983) estimated that the sediment deposition 500-metres outside the boundary of the dredged area was 29.6kg.m^{-2} (23mm.m^{-2}). At 1-km deposition was 21.2kg.m^{-2} (16mm.m^{-2}), at 1.5-km it was 1 kg.m^{-2} (12mm.m^{-2}), at 2 km it was 10.7kg.m^{-2} (8mm.m^{-2}) and finally at 2.5-km from the boundaries of the dredged area the estimated deposition was less than 7.6kg.m^{-2} (6mm.m^{-2}).

Distance downstream from boundary of dredge area (m)	**Total Deposition after two years**	
	kg/m^2	mm/m^2
500	29.6	23
1000	21.1	16
1500	15.0	12
2000	10.7	8
2500	7.6	6

Table 5.2 *Estimated total deposition to south of Middle Banks, Australia, following two years of dredging activities removing 14 million cubic metres of sand from 5km^2 of seabed (from Willoughby & Foster, 1983)*

There is a good deal of evidence from other surveys that disturbance of sediments by dredging may release sufficient organic materials to enhance the species diversity and population density of organisms outside the immediate zone of deposition of particulate matter. Disturbance of the sediments may thus enhance benthic production outside the immediate zone of deposition provided that contaminants from polluted sediments are not associated with the disposal of spoils.

These studies confirm that the initial sedimentation of material discharged during outwash from dredgers does not, as had been widely assumed, disperse according to the Gaussian diffusion principles used in most simulation models, but behaves more like a density current (Land *et al*, 1994; Whiteside *et al* 1995; Hitchcock & Dearnaley 1995; *for review, also see* Pennekamp *et al* 1996) where particles are held together by cohesion during the initial phase of the sedimentation process. The principal area likely to be affected by sediment deposition is much less than the "worst case" scenarios predicted from conventional Gaussian diffusion simulation models, and is mainly confined to a zone of a few hundred metres from the discharge chutes. These recent results confirm earlier studies (*see*, *for example*, Poiner & Kennedy 1984; Willoughby & Foster 1983).

The results reviewed above thus suggest that the impact of dredging activities mainly relate to the physical removal of substrate and associated organisms from the seabed along the path of the drag head and to the impact of subsequent deposition of sediment from outwash during the dredging process. The evidence from direct studies on the sedimentation of particulate matter suggests that the impact of sedimentation on biological resources on the sea bed is likely to be confined to distances within a few hundred metres of the dredger where the deposits are sands and gravels.

It should be remembered, however, that discharge of dredge spoils from maintenance and capital dredging works in estuaries may result in much larger dispersion plumes which reflect the dominantly fine particles and strong sub-parallel current flows which occur in estuaries, and that the same processes which result in the release of dissolved organic matter can also result in the release of bound surface contaminants from the sediments into the water column.

5.3 Ongoing Research

Undoubtedly, further research into and monitoring of the generation and behaviour of plumes issuing from dredging operations is required. In the UK it is known that CEFAS (formerly MAFF) are undertaking further studies into the development of the benthic boundary layer excursion. Results are expected to be published shortly.

Additionally, DETR (formerly DoE) are funding research into improving the existing theory and methods for describing the magnitude and dispersion characteristics of the plume of fine material which is released during aggregate dredging (M Dearnaley *pers. comm.*). An important objective of this study is the establishment of appropriate settling velocities for the sediment fractions of the plume, which we have shown (by field monitoring) to be different to traditional, single particle behaviour. Using a purpose built settling column (Plate 5.3), observations of the settling velocity are determined through analysis of that fraction of the sample which has reached the base of the settling column after a known time. Results are due shortly.

Plate 5.3 *Measuring settling velocity aboard the ARCO Severn*

Section 7 outlines proposals for further research which requires addressing in the short to medium term (next 1-4 years). Of immediate importance, and which this project will continue to address through continuation of studies until May 1998, is firstly the acquisition of source term data for the reject chute, and secondly investigation of the biological content (5µm < Ø < 5mm) of the overspill and plume waters (Section 4.4).

SECTION 6 - IMPACTS ON BENTHOS

6.1 Introduction

The importance of benthic communities in marine food webs leading to commercially exploitable yields of fish have been widely recognised. Early models for the North Sea (*see* Steele, 1974) suggested that of net primary production by the phytoplankton, approximately 80% was consumed by pelagic herbivores such as copepods and euphausiids, and 20% fell to the sea bed as a detrital input to the benthic community. At each step of the food web, relatively large amounts of 80-90% of the material entering the consumers is re-mineralised and returned to the water column to support further primary production by the phytoplankton, leaving a small proportion incorporated into consumer biomass.

Because of the complexity of marine food webs, and the major dissipation of energy at each step of the food chain, the empirical model proposed by Steele (1965; 1974) for the North Sea and shown in Figure 6.1 indicates that out of 100 g Carbon. $m^{-2}.y^{-1}$ produced at the sea surface as net primary production by the phytoplankton, only 0.3 g Carbon. $m^{-2}.y^{-1}$ appears as yield to man through the pelagic food web, and approximately 0.13 g Carbon. $m^{-2}.y^{-1}$ from demersal fish.

Despite the huge dissipation of materials which occurs at each step in the food web, however, sufficient Carbon evidently flows through the detrital food web, even in plankton-based ecosystems such as the North Sea, for as much as 30% of total fish production to be dependent on conversion through the community which lives on the sea bed.

More recent analyses of the trophic structure and fluxes of Carbon in shelf waters of the North Sea by Joiris *et al* (1982) suggest that as much as 50% of the annual phytoplankton production sinks to the sea bed as detritus and is supplemented by faecal pellets of the zooplankton (*see also* Smetacek, 1984). The benthos is thus heavily implicated in Carbon flow in coastal systems, and becomes of increasing importance in shallow waters where production by benthic algae (macrophytes) and seagrasses largely replaces that derived from the phytoplankton (*see* Taylor & Saloman, 1968; Thayer *et al*, 1975; Mann, 1982; Moloney *et al*, 1986; Newell *et al*, 1988).

Benthic communities thus play a central role in the transfer of materials from primary production by the phytoplankton, benthic macrophytes and coastal wetlands through the detrital pool into higher levels in the food web, including commercially exploitable fish. Most estimates suggest that even in phyto-plankton-based systems such as the North Sea, the yield to man through the benthos to demersal fish stocks is likely to approach 30-40% of that derived through the pelagic system. Partly for this reason, the populations of benthic communities which live on and in sea bed deposits have been widely studied in integrated investigations on the effects of disturbance from a variety of natural and other sources.

Early studies include extensive physiological-toxicological work on the potential impact of suspended sediments on commercially significant organisms (Loosanoff, 1962; Sherk, 1971; Sherk *et al*. 1972, 1974; Jokiel, 1989; *for review, see* Moore, 1977). Such studies have been extended to include the potential impact of dredging works on the ecology of biological communities in coastal embayments and estuarine ecosystems (Morton, 1977; Conner & Simon, 1979; Johnston, 1981; Giesen *et al*, 1990; Onuf, 1994).

Comprehensive studies of the impact of dredging for marine aggregate and sand on marine communities in European waters have been carried out by Millner *et al* (1977), Pagliai *et al* (1985), Sips & Waardenburg (1989), van Moorsel & Waardenburg (1990, 1991), and Kenny & Rees (1994, 1996). Reviews of the impact of sand and gravel extraction include those of the International Council for the Exploration of the Sea (ICES, 1975, 1977, 1992a, b; 1993), Gayman (1978), de Groot (1986), Nunny & Chillingworth (1986), Hurme & Pullen (1988) and Charlier & Charlier (1992). A recent review for the Minerals Management Service, U.S. Department of the Interior containing a number of specific case histories on the impact of marine mining has been given in a C-CORE publication (1996: *see also* Ellis, 1987).

Despite the work which has been carried out over the past 30-years, the non-biologist could be forgiven for being bewildered by the diversity of the results and the difficulties of making more than the most general predictions on the effects of dredging activities including marine aggregate extraction on biological resources. Essentially most studies show that dredging itself is usually accompanied by a significant fall in species numbers, population density and biomass of benthic organisms. The rate of recovery is, however, highly variable depending (among other factors) on the type of community which inhabits the deposits in

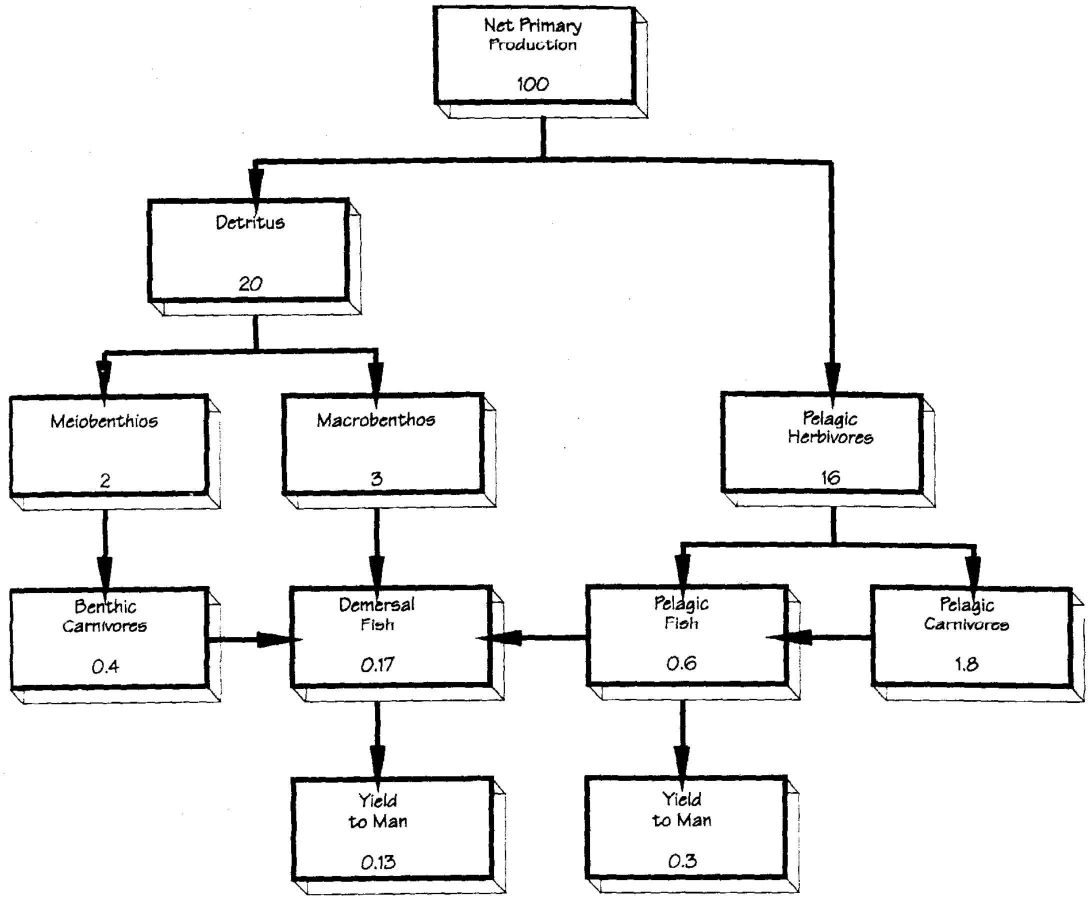


Figure 6.1 *Simplified empirical Carbon flow diagram for the phytoplankton-based ecosystem of the shelf waters of the North Sea. Note that of the 100 grams Carbon per metre^2 per year ($100gC.m^{-2}\ yr^{-1}$) of sea surface produced by the phytoplankton, the yield to man through pelagic food webs and pelagic fish is estimated to be $0.3gC.m^{-2}yr^{-1}$, whilst that through benthic food webs is $0.13gC.m^{-2}yr^{-1}$, or about 30% of the total exploitable fish yield to man (based on Steele, 1965)*

In general, rapid rates of initial recolonisation have been reported for some coastal deposits where the organisms are mainly mobile "opportunistic" species which have a rapid rate of reproduction and growth. Such organisms may also be able to recolonise the deposits by migration of the adults (*see* McCall, 1976; Conner & Simon, 1979; Salomon, *et al*, 1982; Guillou & Hily, 1983; van der Veer *et al*, 1985; Pagliai *et al*, 1985; Clarke & Miller-Way, 1992; Rees & Dare, 1993; van Moorsel, 1994).

In contrast, long-lived and slow-growing species, especially those in high latitudes may take several years before larval recruitment and subsequent growth of the juveniles allows restoration of the original community composition and biomass.

The process of "recovery" following environmental disturbance is generally defined as the establishment of a successional community of species which progresses towards a community which is similar in species composition, population density and biomass to that previously present, or at non-impacted reference sites (C-CORE, 1996; *see also* Ellis & Hoover, 1990). Typically values range from up to one year in fine-grained deposits such as muds and clays (Ellis *et al*, 1995), although even in the fine deposits which characterise coastal ecosystems such as the Dutch Wadden Sea, van der Veer *et al* (1985) report that recolonisation takes 1-3 years in areas of strong currents but up to 5-10 years in areas of low current velocity.

Longer recovery times are reported for sands and gravels where an initial recovery phase in the first 12-months is followed by a period of several years before pre-extraction population structure is attained (van Moorsel, 1994; Kenny & Rees, 1996).

Even longer times may be required for biologically-controlled communities which characterise coarse deposits (*see* Garnett & Ellis, 1995), although the evidence is conflicting for coral reef communities. Some studies report long-term damage to coral resources from sedimentation associated with dredging (Dodge & Vaisnys, 1977; Bak, 1978; Dodge & Brass, 1984; Madany *et al*, 1987; Hodgson, 1994; *for review, see* Maragos, 1991).

Other studies suggest that corals themselves may be tolerant of short-term increases in siltation associated with dredging (Marszalek, 1981; Brown *et al*, 1990) but that modification of community structure of other components of reef communities such as fish species are detectable after multivariate analysis of species composition (Dawson-Shepherd *et al*, 1992).

Recovery times following disturbance from a variety of sources, including dredging works may be extended in colder waters at high latitudes where communities typically comprise large slow-growing species which may take many years for recolonisation and growth.

In a Swedish fjord system, for example, a recovery which was indistinguishable from natural variations was established only after 8-years following closure of a pulp mill (Rosenberg, 1976), whilst de Groot (1979; *see also* Wright, 1977; Aschan, 1981) reports that recovery of communities within the Arctic Circle may take more than 12 years compared with estimates of approximately 3 years for deposits off the coast of the Netherlands. Similar extended time-scales for recolonisation by the benthic community have been reported for Antarctic waters by Oliver & Slatterly (1981).

The concept of ‘recovery’ of biological resources is itself not an easy one to define for complex communities whose composition can vary over time, even in areas which remain undisturbed. Whether a community is identical in species composition and population structure following cessation of dredging thus to some extent begs the question of whether the biodiversity would have remained stable over that period of time in the absence of the disturbance by dredging.

That is, the *actual* climax community which is attained may not be an appropriate measure of ‘recovery’ after a long period. Probably a more practical approach to the question of ‘recovery’ will be recognition of the establishment of a community which is capable of maintaining itself and in which, say, 80% of the species diversity and biomass has been restored.

This implies a substantial restoration of the carrying capacity of the benthic food webs leading to fish, even though the precise species composition may not be identical to that recorded in the pre-dredged system.

This issue of whether biological resources have been restored, and how this should be assessed, is of considerable importance in areas such as Canadian coastal waters where recovery of seabed resources forms part of a Statutory obligation following cessation of mining (*see also* C-CORE, 1996).

Despite the complexity of the results for specific dredged areas, some firm general principles governing community structure following environmental disturbance have emerged in recent years and these appear to be generally applicable to a wide variety of communities both on the land and on the sea bed. The application of such concepts to coastal communities allows some credible predictions on the scale of impact of environmental disturbance such as that imposed by dredging and dredged spoils disposal, and importantly gives some insight into how long it might take for recovery in dredged areas and the surrounding deposits once dredging has ceased.

The following sections provide a framework within which the biological impact and subsequent recovery of benthic resources can be understood, with examples drawn mainly from the impact of dredging activities in nearshore waters and estuarine systems.

6.2 General Features Of Community Structure

Most general models of community structure are based on the concept that biological communities do not form a series of distinct groups or assemblages along an environmental gradient, but show a corresponding gradient in community composition.

Species which colonise habitats with unpredictable short-term variations in environmental conditions at one end of an environmental gradient of stability are subject to frequent catastrophic mortality. Such conditions occur in many shallow-water, intertidal and estuarine habitats and are characterised by populations which tend to have a high genetic variability which allows at least some components of the population to survive environmental extremes (*see* Grassle & Grassle, 1974; Guillou & Hily, 1983).

Such organisms are thus selected for maximum rate of population increase, with high fecundity, dense settlement, rapid growth and rather a short life-cycle. They are well-suited to rapid invasion and colonisation of environments where space has been left by a previous catastrophic mortality, whether this has been induced by natural factors or disturbance by man. Such components have been designated "***r***-strategists" in a pioneer work by MacArthur & Wilson (1967; *see also* Pianka, 1970), although we prefer to use the term “Opportunists” for all such colonising species. “Opportunists” rely on a large investment in reproductive effort, rather than mobility, for success in colonising habitats made available by the catastrophic destruction of the previous community (*see* Gadgil & Solbrig, 1972; McCall, 1976).

Many communities living in unstable environments may comprise small, highly mobile species which are able to take advantage of recently created empty habitats quickly and to colonise them with large populations. These mobile colonisers are often associated with frequently-disturbed habitats (*see* Osman, 1977). We distinguish these as “Mobile Opportunist" species (*see also* MacArthur, 1960; Grassle & Grassle, 1974). All such "Mobile Opportunists" are *r*-strategists with life cycle traits of small size, high fecundity, rapid growth and high mortality.

Under the stable conditions which occur at the other end of the environmental continuum, the community is controlled mainly by biological interactions, rather than by extremes of environmental variability. Here the organisms have an "Equilibrium Strategy" in which they are selected for maximum competitive ability in an environment which is already colonised by many species and in which space for settlement and subsequent growth is limiting. Such organisms are designated "***K***-strategists" or “Equilibrium species” and devote a larger proportion of resources to non-reproductive processes such as growth, predator avoidance and investment in larger adults (MacArthur & Wilson, 1967; Gadgil & Bossert, 1970; McCall, 1976). Between these two extremes are communities whose species may be intermediate between those which occur at the two extremes of the environmental gradient and have different relative proportions of “Opportunistic” ***r***-strategists and “Equilibrium” ***K***-strategists.

Between these two extremes are communities whose species may be intermediate between those which occur at the extremes of the environmental gradient and have different relative proportions of ***r***-strategists and ***K***-strategists. The characteristics of ***r***-selected and ***K***-selected "Equilibrium Species" are summarised in Table 6.2 (based on McCall, 1976; Rees & Dare, 1993), although it should be emphasised that the distinction is to some extent an arbitrary one, and is blurred in habitats which are subject to only mild environmental disturbance.

Changes in the structure and physical size of the infauna along a gradient of environmental conditions have been described in relation to organic pollution by Pearson & Rosenberg (1978) and in relation to physical disturbance by Rhoads *et al* (1978), Oliver *et al* (1980) and by Gray & Pearson (1982). These are illustrated in a schematic diagram in Figure 6.2a. Essentially such studies show that community composition of benthic infauna (those that live within the deposits) along an environmental gradient is the result of a complex interaction between physico-chemical factors which operate at one end of the gradient and biologically-controlled interactions under the more uniform environmental conditions which occur in deeper waters (*see* Sanders, 1969; Boesch & Rosenberg, 1981).

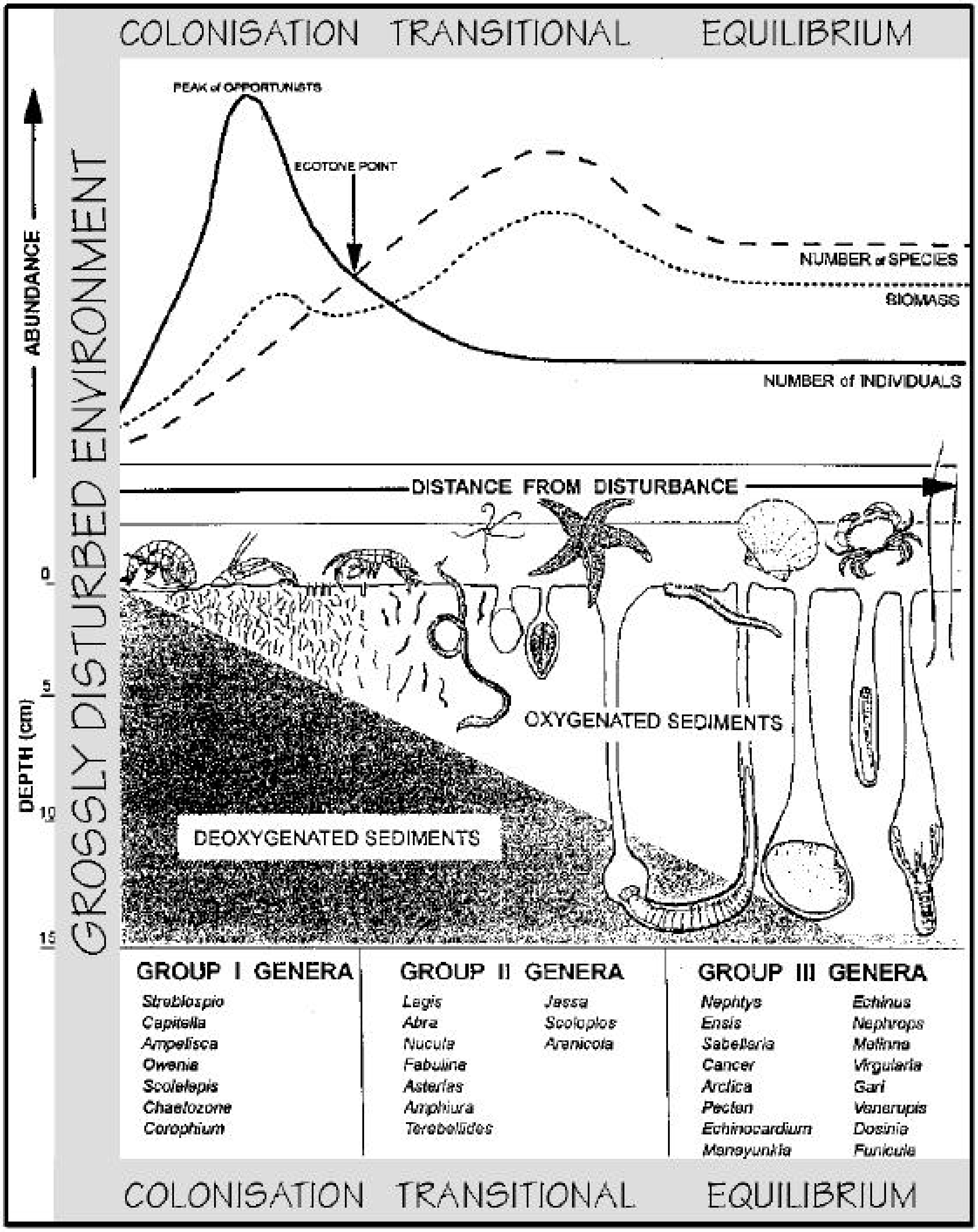


Figure 6.2a *Pictorial diagram showing the ecological succession which characterises benthic communities through a gradient of environmental disturbance. Note that in highly disrupted environments (on the left side of the diagram) few organisms may be capable of survival. In polluted or semi-liquid muds the sediments are colonised by few (resistant) species but which can attain very high population densities. As the stability of the environment increases, these* "Opportunistic" ***r****- selected species are replaced by increased species variety, including slower-growing* ***K****-selected, slow growing species. Finally in environments of high stability the community is dominated by*

"Equilibrium" *species with complex biological interactions between members of the community (based on Pearson & Rosenberg, 1978; Rhoads* et al, *1978).*

The large species which comprise the burrowing infauna of stable habitats and those with low organic content maintain oxygen levels in the deposits down to considerable depths (*see* Flint & Kalke, 1986) and often have complex interactions with neighbouring species including smaller species whose survival depends on their association with large burrowing components (Figure 6.2a).

The importance of bioturbation in both enhancing species diversity and in exclusion of potentially competitive species has been widely documented (Gray, 1974; Rhoads, 1974; Lee & Swartz, 1980; Carney, 1981, Rhoads & Boyer, 1982, Thayer, 1983). Comprehensive reviews by Pearson & Rosenberg (1978) and Hall (1994) summarise the impact of disturbance by a wide variety of factors including storms, dredging, fishing and biological activities on benthic community structure. Biological interactions may also control community composition on the surface of the deposits. The presence of surface-dwelling bivalves, for example, may allow colonisation by barnacles, ascidians and other epifaunal species that would not otherwise occur in the surface of the sediments.

In other stable habitats, the activities of suspension-feeding mussels produces consolidated silt deposits which then allow deposit-feeders such as the polychaete *Amphitrite*, the burrows of which in turn provide specialised shelter for the commensal scale worm, *Gattyana* (Newell, 1979).

Several studies have shown that the activities of the infauna may also inhibit, rather than facilitate the occurrence of potential competitors for space. In an important study by Rhoads & Young (1970), it was shown that the benthic environment may be significantly modified by the burrowing and feeding activities of deposit-feeding organisms.
This "bioturbation" results in the production of an uncompacted surface layer of faecal material which may result in the transfer of fine material to the sediment-water interface by turbulent mixing (Wildish & Kristmanson, 1979; Snelgrove & Butman, 1994) and may lead to the exclusion of potential competitors by deposit feeders (Woodin, 1991; Woodin & Marinelli, 1991).

This inhibition of one type of population by the activities of another has been termed "amensalism" by Odum & Odum (1959) and has since been described in many habitats (Aller & Dodge, 1974; Nichols, 1974; Driscoll, 1975; Eagle, 1975; Johnson, 1977; Myers, 1977a, b; Brenchley, 1981; De Witt & Levinton, 1985; Brey, 1991; Flach, 1992).

Loss of these "key species" in ***K***-dominated equilibrium communities following disturbance by dredging or other activities can lead to a collapse of the entire biologically-accommodated community even though individual species may be apparently tolerant of environmental disturbance. The colonial polychaete *Sabellaria spinulosa*, for example, provides a complex habitat which is associated with a wide variety of species which would not otherwise occur (*see* Holt *et al*, 1995). This polychaete undergoes a natural cycle of accretion and decay along with the associated community with a periodicity of from 5-10 years (Wilson, 1971; Gruet, 1986). Disturbance of communities which are dominated by ***K***-strategists may therefore take many years for recovery of their full community composition even though recolonisation by individual components may occur comparatively rapidly.

As the amount of organic matter in the sediments increases along a gradient towards the fine silts and muds which characterise estuarine habitats, the larger species and deep-burrowing forms are replaced by large numbers of relatively inactive small suspension-feeding and surface deposit-feeders including polychaete worms, bivalves and holothurians. This reduction in the species diversity and extent of sediment bioturbation results in an increased sediment stability and a restriction of the oxygenated layer to the surface of the sediments.

Species in the intermediate parts of the environmental gradient shown in Figure 6.2a are thus relatively smaller than their counterparts in deeper waters and comprise a "transitional community" which is confined to a restricted habitat in the surface oxygenated layer of sediment and comprises components which have many intermediate characteristics between typical ***r***- and ***K***-selected species. Because the ***K***-selected components in the community live for longer, the individuals must be able to tolerate short-term changes in environmental conditions including siltation. They therefore have generally wider limits of physiological tolerance than ***r***-selected species which respond to environmental change by selection of genetically adapted components of the population during each of the many reproductive cycles per year. The transitional community comprises more species than the equilibrium community shown in Figure 6.2a because of invasion by opportunistic species, but the species variety and mean size rapidly decline as the organisms are increasingly crowded into the upper oxygenated layer at the sediment-water interface. The region between this "transition community" and those dominated by large populations of a restricted variety of small opportunists has been referred to as the "Ecotone Point" by Pearson & Rosenberg (1978) and is shown in Figure 6.2a.

EARLY COLONISING SPECIES **r -** selected	**EQUILIBRIUM SPECIES** **K -** selected
1. Mainly opportunistic species - (a) early reproduction - (b) many reproductions per year - (c) rapid growth - (d) early colonisers - (e) often catastrophic mortality	1. Equilibrium species - (a) delayed reproduction - (b) few reproductions per year - (c) slow growth - (d) late colonisers - (e) low death rate
2. Small body size	2. Large mobile animals
3. Generally surface deposit feeders	3. Deposit and suspension feeders
4. Short life span: generally < 1 year	4. Long life span; several to many years
5. Population size variable, usually well below carrying capacity of environment and recolonised frequently	5. fairly constant in time; saturated community in equilibrium with carrying capacity of environment. No recolonisation necessary.
6. Brood protection with investment of energy into larval food provision (*lecithotrophic)*	6. No brood protection; larvae widely distributed in the plankton
EXAMPLES	
Streblospio benedicti *Capitella capitata* *Owenia fusiformis* *Ampelisca abdita* *Scolelepis fuliginosus* *Chaetozone setosa* *Jassa marmorata*	*Nephtys incisa* *Ensis directus* *Sabellaria spinulosa* *Arctica (Cyprina) islandica* *Echinocardium cordatum* *Nephrops norvegicus* *Melinna cristata* *Nucula* sp. *Amphiura filiformis* *Terebellides* sp. *Virgularia mirabilis* *Gari fervensis* *Tellina crassa* *Venerupis rhomboides* *Dosinia exoleta* *Scoloplos armiger* *Abra alba*

Table 6.2 *Summary of the significant population characteristics of* ***r****- and* ***K****- selected species with examples of organisms commonly encountered within aggregate dredging areas of the United Kingdom waters (based on Pianka 1970; McCall 1976; Rees & Dare 1993; Holt* et al *1995).*

Finally at the extreme end of the physical gradient shown in Figure 6.2a, there is a further restriction of habitat space to the upper oxygenated layer of sediment. This results in a progressive elimination of species and to communities dominated by ***r***-strategists which are selected for small size, high fecundity and an ability to recolonise rapidly following catastrophic mortality (*see* Pearson & Rosenberg, 1978; Gray & Pearson, 1982). Very high population densities of these ***r***-selected opportunists can occur (the "Peak of Opportunists" in Figure 6.2a) before these decline as organic pollution or high environmental disturbance eliminates even these rapid colonisers.

A useful tool which can be used to determine the extent of impact of environmental impact from a variety of sources is a plot of the proportional contribution of each species in the community to the overall population density of the assemblage as a whole. These curves have been designated "***K***-dominance curves" by Lambshead *et al* (1983) and have been widely used in environmental impact studies in recent years (Warwick, 1986; Clarke & Warwick, 1994).

Obviously the equilibrium communities characteristic of undisturbed (or unpolluted) environments have a high species diversity and each component species

makes a relatively small contribution to the overall population density. Conversely, as a point source of disturbance is approached the (sensitive) species are replaced by large numbers of those (resistant) members of the community which are capable of survival. This can lead to as much as 80-90% of the population being dominated by only one or two "Opportunists" or ***r***-selected species at the "Peak of Opportunists" shown in Figure 6.2a.
A typical set of results taken from a recent survey of coastal communities in the eastern English Channel is shown in Figure 6.2b (Newell & Seiderer, 1997c). From this it can be seen that as much as 78% of the community in unstable unconsolidated mobile deposits at Site 1 was represented by just one species, the "Opportunist" amphipod crustacean *Ampelisca brevicornis,* and that additional species each made only a relatively small additional contribution to the population.

Further along the gradient of sediment stability in mixed sands and shells at Site 2, the dominance by one species (*Sabellaria* sp.) alone was approximately 45%. Finally in the stable environmental conditions of coarse gravels and boulders at sites 3 & 4 there was a very large species variety of over 300 species and a relatively uniform species distribution with dominance values of only 12-15%.

Estimation of ***K***-dominance curves adjacent to dredging works and other point sources of environmental disturbance is thus potentially useful because it can be used as a relatively simple index to define the area of immediate impact. It can also be used to determine whether this is enlarging or decreasing with time, without the necessity of the complex analysis of community structure which is required for interpretation of the wider impact on community structure in the "Transition Zone".

These distinctions between the lifestyles and adaptive strategies of ***r***- and ***K***-selected species are of fundamental importance because they go some way towards accounting for the differences in the rate of recovery which has been recorded for biological resources following disturbance by episodic events such as dredging. Clearly, the species composition and rate of recovery of biological communities following cessation of dredging will depend to a large extent on whether the original communities were dominated by ***r***-strategists or ***K***-strategists and on the time which is required to develop the complex associations which characterise interactions between the ***K***-dominated "Equilibrium" community. Knowledge of the key faunal components and their lifestyle thus allows some predictions on the impact of dredging and spoils disposal on biological resources and on the subsequent rate of recovery of marine community composition following cessation of dredging.

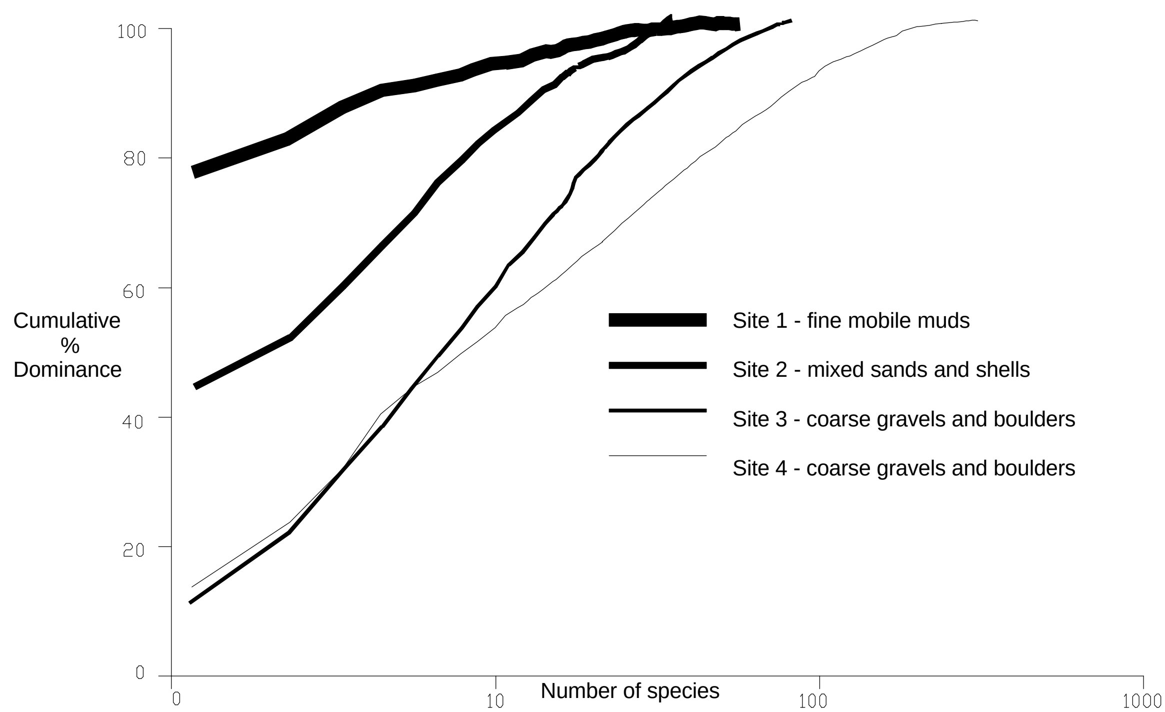


Figure 6.2b *A set of typical **K**- dominance curves showing the proportional contribution of individual species to the overall community in fine mobile muds, in mixed sands with shells and in stable habitats comprising coarse gravels and boulders, located off the Kent coast (UK) at West Varne in 1996. The fine mobile muds are dominated by the* "Opportunist" *amphipod crustacean,* Ampelisca brevicornis, *whilst the more stable deposits have a higher total species complement each of which makes a relatively small contribution to the overall population density (based on Newell & Seiderer, 1997c).*

6.3 Ecological Succession & The Recolonisation Process

These general features of the structure of benthic communities apply not only to successional stages along a gradient of environmental variability, but also to the successive sequence of populations which recolonise deposits after the cessation of environmental disturbance.

McCall (1976) and Rees & Dare (1993) have recognised the occurrence of three main types of benthic components of marine communities based on the distinction between ***r***-strategists and ***K***-strategists. Group I species comprise those which colonise first after a community has been removed by disturbance. They comprise large populations of small sedentary tube-dwelling deposit-feeders which have rapid development, many generations per year, high settlement and death rates. Examples include the polychaete worms *Streblospio*, *Capitella capitata*, and *Owenia fusiformis* as well as the amphipod *Ampelisca*. That is, the Group I community comprises mainly ***r***-strategists.

Group II species comprise mainly bivalve molluscs such as *Tellina*, *Nucula* and *Abra*, the tube worm *Lagis (= Pectinaria*) and the common starfish (*Asterias rubens*). There is no absolute distinction between this community and the primary colonisers, but the components attain a lower peak abundance than the smaller ***r***-strategists and have a slower recruitment and growth rates.

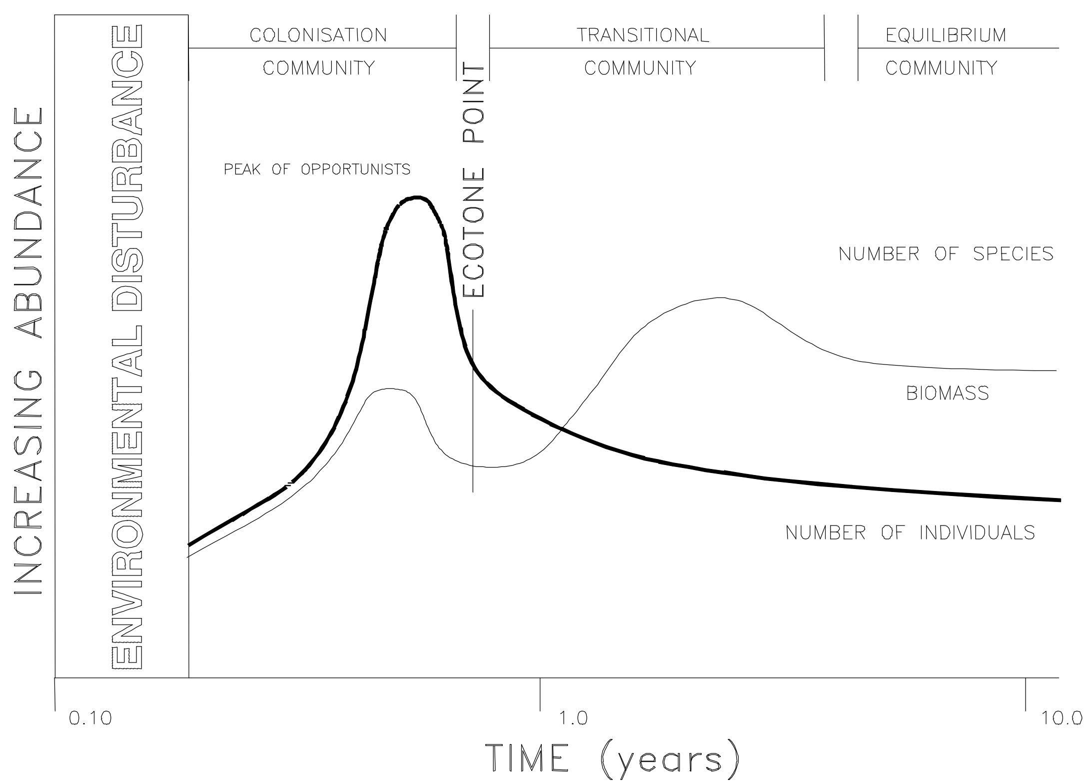


Figure 6.3 *Schematic time series diagram showing a colonisation succession in a marine sediment following cessation of environmental disturbance. Initial colonisation is by* "Opportunistic" *species which reach a peak population density generally within 6 months of a new habitat becoming available for colonisation after the catastrophic mortality of the previous community. As the deposits are invaded by additional (larger) species, the population density of initial colonisers declines. This* "Ecotone Point" *marks the beginning of a* "Transitional

Community" *with high species diversity of a wide range of mixed* ***r-*** *and* ***K-*** *selected species. This period may last for 1-5 years depending on a number of environmental factors, including latitude. Provided environmental conditions remain stable, some members of this transition community are eliminated by competition and the community as a whole then forms a final* "Equilibrium Community" *comprising larger, long-lived and slow growing species with complex biological interactions with one another (based on Pearson & Rosenberg, 1978)*

Finally Group III species comprise larger slow-growing ***K***-strategists such as the polychaete *Nephtys*, the reef-forming "Ross" worm (*Sabellaria*), razor shell (*Ensis*), sea urchins such as *Echinocardium* and *Echinus*, scallops (*Pecten*), the ocean quahog (*Arctica islandica*), the edible crab (*Cancer pagurus*) and larger burrowing crustaceans such as *Nephrops* and *Callianassa*.

The changes in species variety, abundance of individuals and biomass during the recolonisation process is shown in Figure 6.3. Inspection of Figure 6.2a shows that initially the sediments are almost devoid of benthic macrofauna.

The initial colonising species are few, but the number of individuals (population density) increase rapidly with time to a peak of (Group I) opportunist species. As time passes, the short-lived opportunistic species (***r***-strategists) decrease in numbers and biomass as more species invade the area. This transition point where the community is poor in species, population density and biomass is the same "Ecotone point" shown on the spatial gradient in Figure 6.3.

Prior to this, the community is characterised by large populations of a few small opportunistic species; after this time the species variety increases, as does the biomass, but the population density declines. This Group II community is a transitional one where the maximum number of species has invaded the newly-available space, and is followed by a phase where some species are eliminated by competition and the community returns to the (somewhat lower) species composition and biomass characteristic of the undisturbed Group III community.

The sequence shown in Figure 6.3 indicates that colonisation is likely to follow a definite time course of progressive invasion by large numbers of opportunistic species in the first instance, followed by a wider species diversity during the "transitional phase" and finally by a consolidation phase when competition between the ***K***-strategists for the limited space available results in the elimination of some of the transitional colonisers (*see also* Warwick *et al*, 1987).

The biological diversity in any particular community will then reflect the frequency of disturbance and represent a balance between invasion and subsequent growth of colonisers, and losses by extinction and displacement (*see* Huston, 1994). In areas where environmental disturbance is unevenly distributed, this may lead to a mosaic of communities, each at different stages of the successional sequence shown in Figure 6.3 (*see* Johnson, 1970; Grassle & Sanders, 1973; Whittaker & Levin, 1977; Connell, 1978), and may partly account for the patchiness of marine communities in dredged areas.

The time taken for recovery of the full species composition and for subsequent exclusion of some of the transition community following the growth of larger ***K***-strategist "Equilibrium Species" in a particular area will depend largely on the components which occur under natural conditions.

In shallow water and estuarine conditions, where the community is in any case dominated by opportunistic species, recovery to the original species composition may be very rapid and coincide with the 'Peak of Opportunists' in Figure 6.3. In the stable environmental conditions of deeper waters, the replacement of the initial colonisers in the transitional community following complex biological interactions between the ***K***-strategists may take several years.

6.4 The Impact Of Dredging On Biological Resources

6.4.1 Sensitivity To Disturbance

The impact of disturbance by the drag head during marine aggregate dredging has been reviewed in Section 6.2. The effects of sediment deposition and spoils disposal outside the immediate boundaries of dredged areas in coastal waters has also been widely studied and includes extensive physiological-ecological work on a wide variety of animals including plankton, benthic invertebrates and fish species (*for reviews, see* Sherk, 1971; Moore, 1977).

Early studies by Loosanoff (1962) showed that different species of commercially significant filter-feeding molluscs were differently affected by suspended sediment. Subsequent studies by Sherk (1971) and Sherk *et al* (1974) included both plankton and fish species. They showed that as in the case of bivalves, fish species have varying tolerances of suspended solids, filter-feeding species being more sensitive than deposit-feeders and larval forms being more sensitive than adults (*see also* Matsumoto, 1984).

Many of the macrofauna which live in areas of sediment disturbance are well-adapted to burrow back to the surface following burial (*see* Schafer, 1972). Studies by Maurer *et al* (1979) showed that some benthic animals could migrate vertically through more than 30-cm of deposited sediment, and this ability may be widespread even in relatively deep waters. Kukert (1991) showed, for example, that approximately 50% of the macrofauna on the bathyal sea floor of the Santa Catalina Basin were able to burrow back to the surface through 4-10 cm of rapidly deposited sediment. There is little information on the depths of deposition of material derived from the screening process and hopper overflow from aggregates dredging, other than that predicted by modelling techniques (*see, for example,* HR Wallingford, 1993). Such field information that is available suggests that deposition depths are very small beyond 150 metres from the track of a dredger (*see* Gajewski & Uscinowicz, 1993). Further work is required.

A good deal of the apparent "recolonisation" of deposits following dredging or spoils disposal may therefore reside in the capacity of adults to migrate up through relatively thin layers of deposited sediments, or to migrate in during periods of storm-induced disturbance (*see* Hall, 1994).

There is good evidence that the activities of filter-feeding bivalves, in particular, can play an important part in controlling the natural phytoplankton and seston loads in the water column (Cloern, 1982), to an extent that food may become a limiting resource in the benthic boundary layer at the sediment-water interface (Wildish & Kristmanson, 1984; Fréchette *et al* 1989, 1993; *see also* Dame, 1993; Snelgrove & Butman, 1994) as well as on coral reef flats and in cryptic reef habitats (Glynn, 1973; Buss & Jackson, 1981). Because the suspension-feeding component is evidently highly effective in removing particulate matter from seawater, the release of large quantities of suspended matter can lead to a loss of suspension-feeding components through clogging of the gills. This has led to a corresponding increase in the community of deposit-feeders in some areas such as St Austell Bay off the south-west coast of England (Howell & Shelton, 1970).

In general, however, most recent studies of filter-feeders which live in coastal waters show that bivalves, in particular, are highly adaptable in their response to increased turbidity such as can be induced by periodic storms, dredging or spoils disposal and can maintain their feeding activity over a wide range of phytoplankton concentrations and inorganic particulate loads (Shumway *et al* 1985, 1990; Newell *et al* 1989; Newell & Shumway 1993; Iglesias *et al* 1996; Navarro *et al* 1996; Urrutia *et al* 1996).

Although these studies on the physiology of individual species can give some insight into the differing susceptibilities of the macrofauna to increased turbidity, or to burial from dredger outwash, in general it is difficult to make predictions of the impact of dredging on whole communities from the results of studies on individual species.

Partly for this reason, and because the interactions between the components of natural populations are complicated in space and time, most recent studies on the impact of spoils disposal and dredging works have been carried out on whole communities, rather than individual species. Such studies have concentrated on three main features of benthic communities, namely the number of individuals (population density), number of species (the diversity) and the biomass (to give an index of the growth following recolonisation).

Sampling is conventionally carried out by means of a grab which allows collection of a sediment sample from a known area of seabed deposits which are then eluted through a 1-mm mesh sieve to extract the macrofauna. Sediment samples from fine deposits such as occur in coastal embayments, lagoons and estuaries are relatively easy to obtain by means of equipment such as the Van Veen and Smith-McIntyre grabs, the Ponar Grab (Ellis & Jones, 1980) or the more recent Day grab whose jaws are held closed by the tension of the wire from which the grab is suspended rather than by a spring-loaded mechanism (*see* Holme & McIntyre, 1984).

Sampling of coarser gravel deposits is, however, complicated by the fact that the larger stones become trapped between the jaws of conventional grabs, leading to extensive losses through "washout" from the grab. Partly because of this problem, most work on coarser deposits has been carried out with semi-quantitative dredges such as the Anchor dredge (Forster, 1953; Holme 1966; Kenny *et al* 1991) or the Ralier du Baty dredge used by Davoult *et al* (1988).

More recently, however, Sips & Waardenburg (1989) and Kenny & Rees (1994) have used a Hamon grab for quantitative studies on the fauna of gravels and sands. The Hamon Grab (Plate 6.4.1) takes a scoop out of the seabed deposits, rather than relying on the closure of opposing jaws (*see* Holme & McIntyre, 1984).

Plate 6.4.1 *Recovery of Hamon Grab during quantitative investigation of benthic fauna (Coastline Surveys Ltd)*

This greatly reduces the problem of fauna losses through "washout" during the sampling process and the Hamon grab is now widely used in the quantitative evaluation of the benthos in coarse sands and gravels. We have developed a modified Hamon Grab (Plate 6.4.1) with varying bucket geometry of square and cylindrical form for improved sampling efficiency. These buckets are formed of stainless steel to reduce contamination when conducting pollutant investigations.

Studies such as Kenny & Rees (1994) and Newell & Seiderer (1996c) emphasise that the macrofauna may vary considerably even over relatively short distances, and that a proper understanding of the distribution of benthic communities is necessary if damage to potentially important communities is to be avoided during dredging operations. Figure 6.4.1 shows, for example, the distribution of two important members of the benthic community in mixed gravel, sand and muddy deposits off the coast of East Anglia in August 1996 (Newell & Seiderer, 1997b).

Further inspection of Figure 6.4.1 shows that the main population of the reef-building tubeworm, *Sabellaria spinulosa* ("called "Ross" by fishermen) occurs in the north-western part of the survey area, and corresponds with a localised patch of coarse stones and cobbles which give sufficient stability to support a rich reef community. This species may be predated upon by the pink shrimp (*Pandalus*) (*see* Warren, 1973) and is potentially important as a feeding ground for a variety of demersal fish species.

In contrast, the populations of the comb-worm (*Lagis = Pectinaria koreni*) occur in mobile muddy sands in the south-west of the survey area. This species is an important prey item for sole (*Solea solea*), dab (*Limanda limanda*) and plaice (*Pleuronectes platessa*) (*see* Lockwood, 1980; Basimi & Grove, 1985; Carter *et al* 1991; Horwood, 1993; *also* Peer, 1970) and therefore represents a food resource within the survey area which requires conservation.

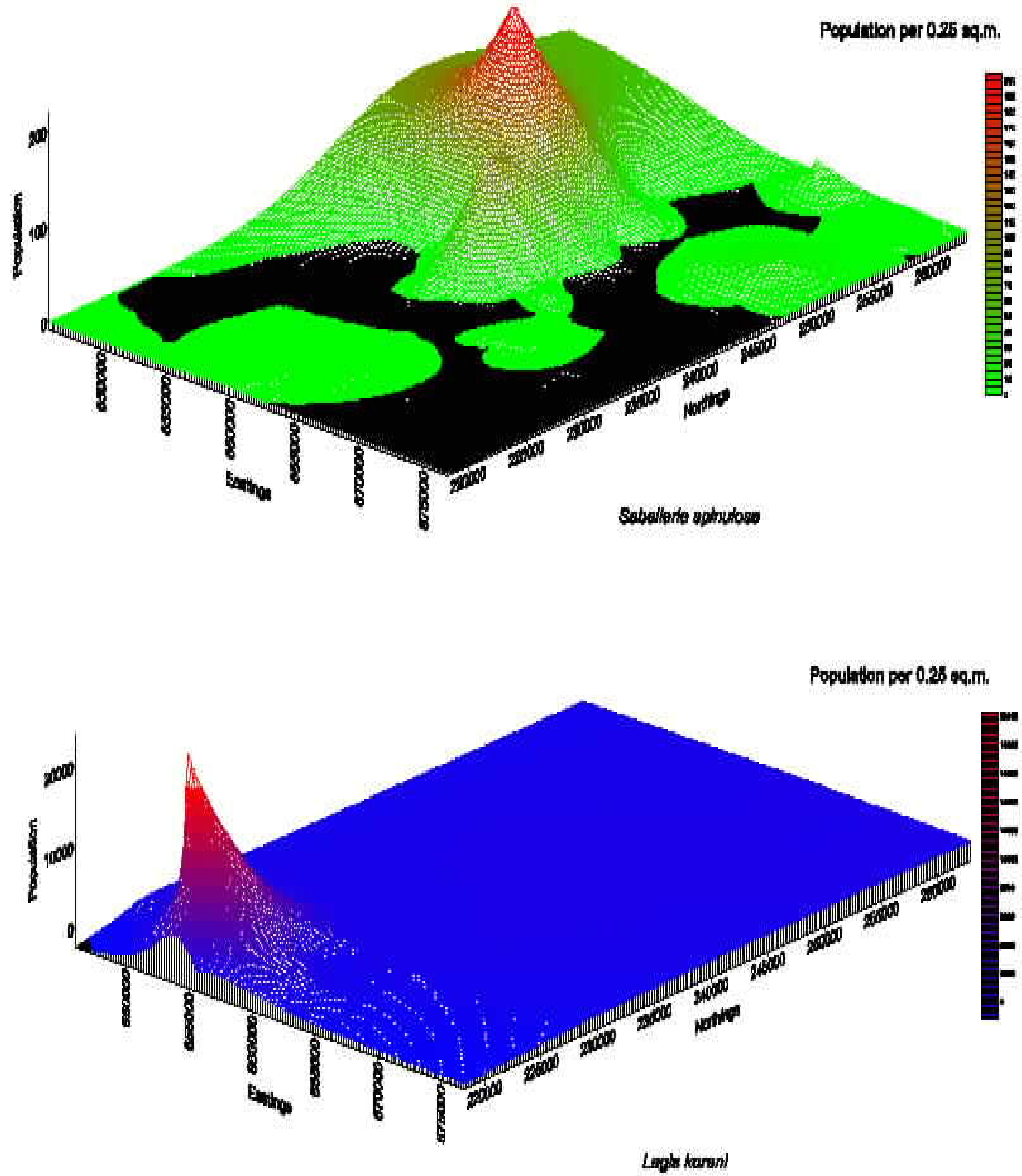


Figure 6.4.1 *Schematic diagram of a survey area off Suffolk (southern North Sea) showing distribution of the comb worm* (Lagis koreni) *in fine deposits of the survey area, and that of the colonial "Ross" worm* (Sabellaria spinulosa) *in areas where coarse boulders provide a stable environment for the development of reef-forming species. Population density in numbers of individuals per 0.25m^2 sample obtained using a Hamon Grab (Newell & Seiderer, 1997b)*

6.4.2 Impacts To Diversity & Abundance

The impact of dredging on benthic communities varies widely, depending among other factors on the intensity of dredging in a particular area, the degree of sediment disturbance and recolonisation by passive transport of adult organisms (*see* Hall, 1994) and the intrinsic rates of reproduction, recolonisation and growth of the communities which normally inhabit the particular deposits.

Some examples of the impact of dredging on the species variety, population density (number of individuals) and biomass of benthic organisms from a variety of habitats ranging from muds in coastal embayments and lagoons, to oyster shell deposits and to sand and gravel deposits in the Southern North Sea are summarised in Table 6.4.2. This shows that both maintenance and marine aggregate dredging can be expected to result in a 30-70% reduction of species diversity, a 40-95% reduction in the number of individuals, and a similar reduction in the biomass of benthic communities in the dredged area.

LOCALITY	**HABITAT TYPE**	**% REDUCTION AFTER DREDGING**			**SOURCE**
		Species	**Individuals**	**Biomass**	
Chesapeake Bay	Coastal Embayment Muds-sands	70	71	65	Pfitzenmeyer, 1970
Goose Creek, Long Island, New York	Shallow Lagoon Mud	26	79	63-79	Kaplan *et al*, 1975
Tampa Bay, Florida	Oyster shell	40	65	90	Conner & Simon, 1979
Moreton Bay, Queensland, Australia	Sand	51	46	-	Poiner & Kennedy, 1984
Dieppe, France	Sands-gravels	50-70	70-80	80-90	Desprez, 1992
Klaverbank, Dutch Sector, North Sea	Sands-gravels	30	72	80	van Moorsel, 1994
Lowestoft, Norfolk, UK	Gravels	62	94	90	Kenny & Rees, 1994
Hong Kong	Sands	60	60	-	Morton, 1996
Lowestoft, Norfolk, UK	Sands-gravels	34	77	92	Newell & Seiderer, 1997a

Table 6.4.2 *Table showing the impact of dredging on benthic community composition from various habitats.*

Despite the major impact of dredging on benthic community composition within dredged areas, there is little evidence that deposition of sediments from outwash through the spillways during the dredging process has a significant impact on the benthos outside the immediate dredged area. Poiner & Kennedy (1984) showed that the population density and species composition of benthic invertebrates adjacent to dredging works on sandbanks in Moreton Bay, Queensland, Australia increased rapidly outside the boundaries of the dredged area, as might be anticipated from the relatively small amounts of sediment which are deposited beyond a few hundred metres of the dredger trail. The population density and species diversity recorded from a transect across a dredged area in Moreton Bay in July 1982 by Poiner & Kennedy (1984) is shown in Figure 6.4.2a. Stephenson *et al* (1978) and Jones & Candy (1981) both document the enhanced diversity and abundance of benthic faunas near to dredged channels. Poiner & Kennedy (1984) showed that there was an enhancement of benthic biota close to dredged areas at Moreton Bay, Queensland and that the level of enhancement decreased with increasing distance from the dredged area up to a distance of approximately 2 km. They ascribe this to the release of organic nutrients from the sediment plume, a process which is well-known from other studies (Ingle, 1952; Biggs, 1968; Sherk, 1972; Oviatt *et al* 1982; Walker & O'Donnell, 1981). The occurrence of a similar phenomenon applicable to marine aggregate dredging operations, was identified in Hitchcock & Dearnaley, 1995, and is outlined in Section 4.4.

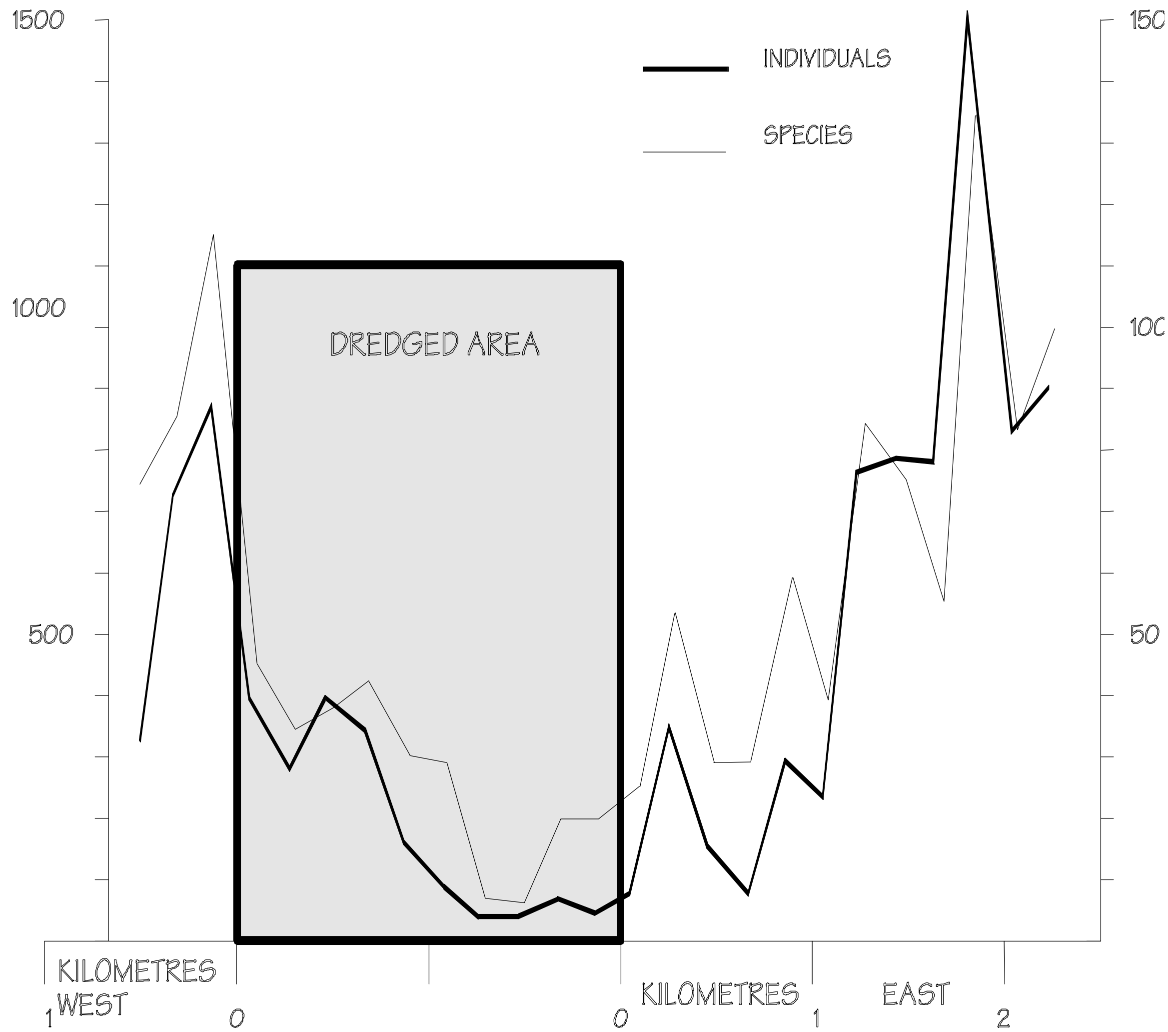


Figure 6.4.2a *Diagram showing the number of individuals and species of benthos recorded in July 1982 on a transect crossing a dredged area on a sub-littoral sandbank in Moreton Bay, Australia. Note that species variety and population density increased rapidly outside the immediate boundaries of the dredged area (based on Poiner & Kennedy, 1982)*

Other than this study, there is surprisingly little detailed information on the precise boundaries of biological impact surrounding areas which have been dredged for sands and gravels. The circumstantial evidence from the boundaries of sediment deposition suggest, however, that biological impact is likely to be confined to the immediate vicinity of the dredged area.

One of the problems with assessing the impact of dredging works and the recovery of benthic communities over time is that biological communities are often subject to major changes in population density and community composition, even in areas which are apparently unaffected by dredging. The concept of whether a community has '*recovered*' cannot therefore be taken to imply that marine community composition is necessarily stable over long time periods and that communities in dredged areas should therefore be expected to return to their pre-dredged species composition. By way of an example specific to potential aggregate extraction, variations in the population density and species composition of the large bivalve population recorded between 1988 & 1991 in the sand and gravel deposits of the Klaver Bank in the Dutch sector of the North Sea by van

Moorsel (1994) are shown in Figure 6.4.2b. This shows the major change in population of the bivalve, *Dosinia exoleta* between the Summer of 1988 and the Spring of 1989 and the loss of the large bivalve, *Arctica islandica* from the deposits even before aggregate extraction had taken place.

A short period of aggregate extraction was carried out in the study area on the Klaverbank in the Summer of 1989. Thereafter clear differences emerged between the large populations of bivalves in "control" areas outside the dredged zone and those within the dredged area despite the natural variations in species composition and population density which evidently occurred in the deposits of the survey area. These differences persisted until the end of the survey period in Autumn of 1991, suggesting that this slow-growing component of the benthos remains impacted for at least two years after cessation of dredging.

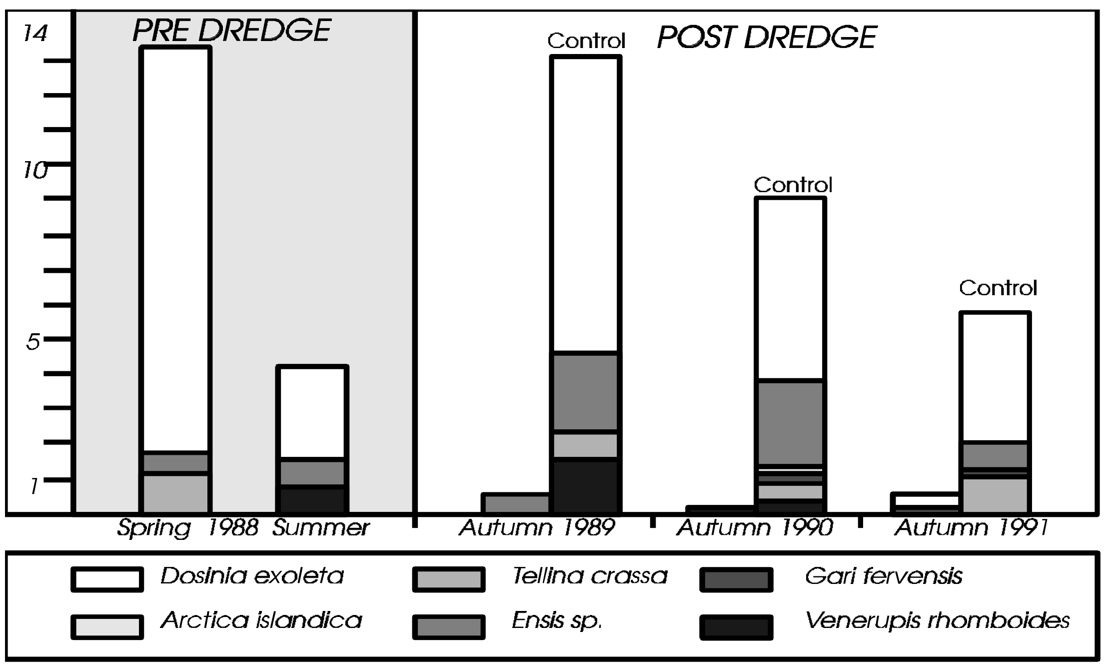


Figure 6.4.2b *Diagram summarising the changes in population density and species composition of large bivalves on the Klaverbank in the Southern North Sea between 1988 and 1991. Pre-dredging values in 1988 show major seasonal changes in density and species composition. After dredging in the summer of 1989, large differences in population density and species composition emerged between dredges and control areas, and these differences persisted for at least two years (after van Moorsel, 1994)*

6.5 The Process Of Recolonisation & Recovery

These complex changes in community structure following dredging, and which occur during the recovery process are difficult to assess by mere inspection of the data for species composition, population density and biomass. Most recent studies on community structure in relation to environmental gradients, whether these are natural or induced by man, therefore use relatively sophisticated analytical techniques which incorporate the type of species as well as their individual population densities and biomass to assess changes in community structure.

The use of these techniques is beyond the remit of this review, but useful accounts for the biologist are given in Kruskal (1977), Hill (1979), Field *et al* (1982), Heip *et al* (1988), Magurran (1991), Warwick & Clarke (1991), Clarke & Green (1993), Clarke & Warwick (1994, and references cited therein).

Probably the most widely-used methods are detrended correspondence analysis (DECORANA), an ordination technique which arranges stations along axes according to their similarity in species composition (Hill, 1979). This is often used in association with two-way indicator species analysis (TWINSPAN) to identify species which characterise particular parts of an environmental gradient such as might be imposed, for example, by dredging or spoils overspill, or communities in relation to wider spatial gradients (*see* Eleftheriou & Basford, 1989).

A second approach is the use of non-parametric multivariate analyses of community structure as outlined by Field & McFarlane (1968), Field *et al* (1982) and Clarke & Warwick (1994). This procedure has recently become available in a convenient software package PRIMER (Plymouth Routines in Multivariate Ecological Research) and is now widely used in the analysis of benthic community structure in European coastal waters.

Despite problems in the interpretation of long-term studies on the abundance and composition of marine communities, studies which are carried out over even relatively short time periods can give important information on the recovery process following cessation of dredging.

The most comprehensive analysis to date of the impact of aggregate dredging on community composition and on the process of recolonisation and recovery in mixed gravel deposits is that of Kenny & Rees (1994, 1996). They carried out an intensive dredging programme by suction trailer dredger in an experimental area off Lowestoft, Norfolk in the Southern North Sea and subsequently monitored the recovery over a period of eight months in the first instance, although this was increased to two years in an extended study of the recolonisation process (Kenny & Rees, 1996).

Dredging occurred in April 1992 over a period of 4 days, during which the TSHD "*Sand Harrier*" removed a total of 52,000 tonnes of mixed aggregate from an area measuring 500-metres by 270-metres, an estimated 70% of the surface deposits down to an average depth of 0.3-metres having been removed from the experimental area. The species variety, population density and biomass in the experimentally-dredged site was then compared with that in a reference site nearby over the eight month period between March and December 1992.

The results from their study are summarised in Figure 6.5a. This shows that the number of species in the dredged site declined from 38 to only 13 species following dredging, whereas the number of species remained at about 35 during the 8-month period at the reference site. The number of species in the dredged area subsequently increased somewhat in the following 7-months, suggesting that some recolonisation occurs even over this relatively short time interval.

The average population density for all taxa of 2769 individuals recorded by Kenny & Rees (1994) prior to dredging was reduced after dredging to only 129 individuals per m², compared with a relatively uniform invertebrate population density of 3,300 individuals per m² in the reference site. Again, the population density showed a significant increase in the 7-months after dredging had ceased.

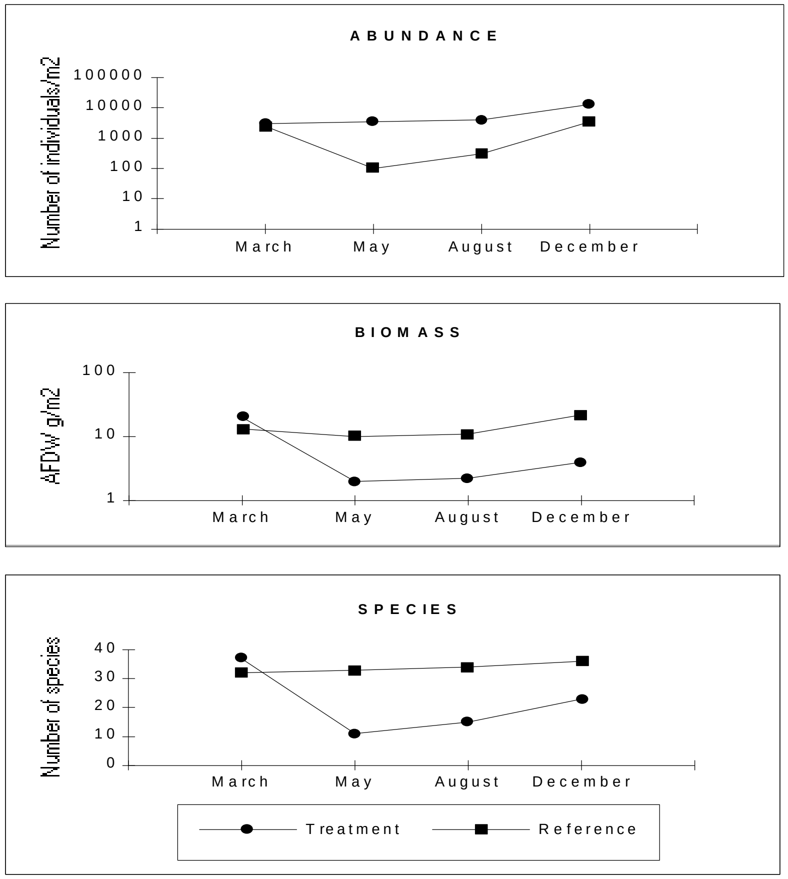


Figure 6.5a *Graphs showing the mean values for the abundance of individuals (No. per m^2) from five Hamon Grab samples each of 0.25m^2 taken in a dredged site and at a reference site. Dredging occurred in April, and samples were taken in the pre-dredged deposits in March 1992 and through to December 1992. Values for biomass are expressed as grams ash-free dry weight per m^2 from the five Hamon Grab samples. The average number of species in each of the five Hamon Grab samples is also shown. Note that there was a significant increase in species variety and abundance during the 7-month post-dredging period, but that the biomass increased only slowly. This indicates that recruitment was mainly of small individuals by larval settlement. Despite this recolonisation, it is clear that population density, biomass and species variety had not recovered at the end of the 7-month post-dredging period (after Kenny and Rees, 1994)*

Inspection of Figure 6.5a shows that the high biomass of 23 grams (Ash-free dry weight) per m² was reduced to only 1 gram (AFDW) per m² after dredging. This reflects the removal of relatively large macrofaunal species such as the mussel, *Modiolus modiolus* from the dredged sediments and was followed by a slower rate of increase in the post-dredging period than that recorded for population density (number of individuals). This implies that recolonisation was initially by small individuals which then grew relatively slowly during the 7-months after dredging had ceased.

Figure 6.5b shows the output of a non-metric Multidimensional Scaling (MDS) ordination (*see* Kruskal, 1977; Kruskal & Wish, 1978; Field *et al* 1982) of the data for the macrofauna sampled in gravel deposits before dredging of the experimental site off Norfolk, and in the seven months after dredging (*after* Kenny & Rees, 1994). Their multivariate analysis of community structure prior to dredging and during in the months following dredging shows a number of important features of the recolonisation process which highlight the general principles of succession outlined in Figure 6.2.

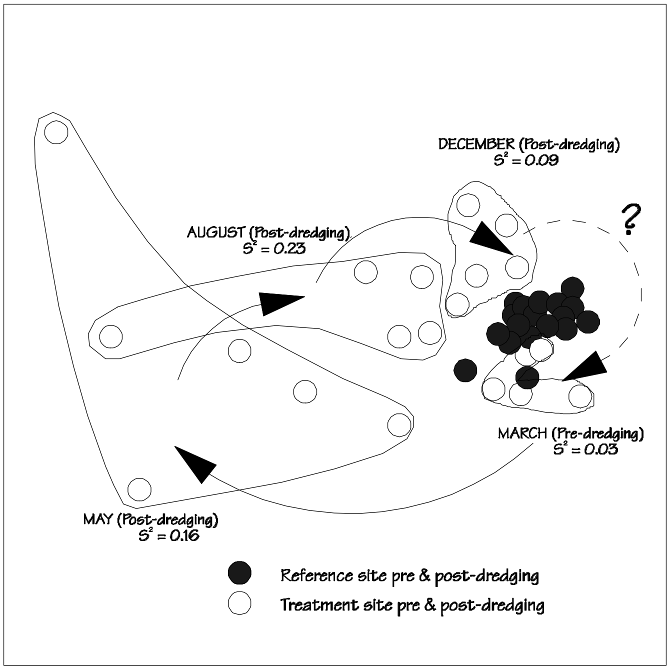


Figure 6.5b *Two dimensional multi-dimensional scaling (MDS) ordination for the benthic communities in a survey area off Norfolk, UK, in March 1992 prior to dredging, and in May, August and December 1992 following trial dredging. Note that dredging of the experimental area resulted in an initial impact on community structure which differed from that in control areas and to that in the deposits prior to dredging. In the following months community structure became more similar to that in the undredged deposits, but was still distinct at the end of the 7 month post-dredging monitoring period (after Kenny & Rees, 1994)*

The first point which is clear from their results is that the community within the dredged site prior to dredging in March 1992 formed a small "cluster" on the MDS ordination. This indicates that the communities sampled within the experimental site were similar to one another, and were also evidently very similar to those in the reference site since they are close together on the MDS ordination. The distances between samples (circles) or sample groups (lines) indicate their biological dissimilarity.

The experimental area was again sampled in May 1992, one month after completion of dredging. At this stage it can be seen from Figure 6.5b that dredging had resulted in two important changes in community structure. First, the communities in all the samples from the dredged site were well-separated in the MDS plot from those in March and from those in the reference site. This implies a major change in community composition following dredging. Second, the communities at each of the sampling sites within the dredged area were different from one another. This is indicated by the fact that they have an increased derived variance (S^2) and no longer form a tight "cluster" on the MDS ordination shown in Figure 6.5b (*see also* Warwick & Clarke, 1993). This increased variance would be expected when some samples were taken from the dredged furrows themselves whilst others were from areas between furrows.

One of the interesting features of this study is that it shows that much of the initial process of colonisation of the gravel deposits off the Norfolk coast was accomplished within the following 7-month period. Inspection of Figure 6.5b shows that the community in the dredged area became more similar to those in the surrounding deposits of the reference area, and to those in the pre-dredged site and also had a closer internal similarity to one another (S^2 reduced to 0.09) in the months following cessation of dredging. This shows that many of the commoner species present in the dredged area in March 1992 prior to dredging had recolonised by December 1992. The clear difference from both the reference site and the community prior to dredging suggests, however, that many of the rarer components of the community had not yet colonised the dredged area in the following 7-months.

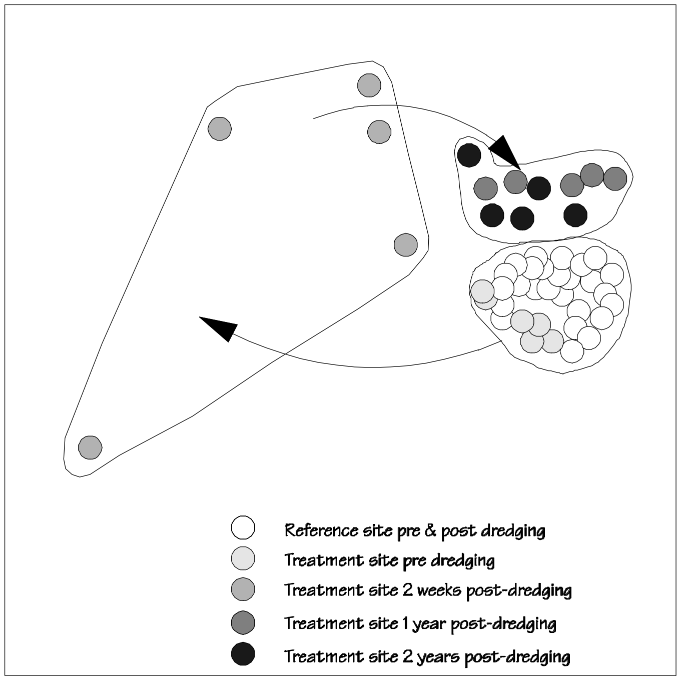


Figure 6.5c *Two dimensional multidimensional scaling (MDS) ordination for the benthic communities in a survey area off Norfolk, UK, in March 1992, and for the following two years post-dredging. Note that despite the increasing similarity of the community in the dredged area to those in the surrounding sediments over the two year post-dredging period, recovery had not been fully accomplished even after two years (after Kenny & Rees, 1996)*

The study was then extended to include data for a two-year period following dredging. These results are reported by Kenny & Rees (1996). They showed that although recruitment of new species, especially ***r***-selected species such as the barnacle *Balanus crenatus* and the ascidian, *Dendrodoa grossularia* had occurred by December 1992, even at the end of a two-year period both the average species abundance and biomass for the dredged area were lower than those in the reference site.

It is also clear from the work of Kenny and Rees that the community composition in their study dredged area was not restored even two years after dredging. Inspection of Figure 6.5c shows the tightly clustered samples from the reference site and from the pre-dredged experimental site in March 1992. The marked shift in community composition and the increased variation between samples taken in May 1992 two weeks after dredging is shown, as well as data collected in May 1993, one year post-dredging and in May 1994, two years after dredging.

It is apparent from Figure 6.5c that despite the significant recolonisation which had evidently occurred within 7-months of dredging, the community in the dredged area remained distinct from that in the reference area and from that in the deposits prior to dredging, even after two years. Whether this reflects residual differences in the nature of the deposits following dredging, or the long time period required for establishment of the rarer components of the original community is not yet known.

The results which have been reviewed above thus show that the process of recolonisation involves two distinct phases; first recolonisation of species composition and population density by settlement of small individuals as larvae and juveniles; second a period of growth during which the biomass approaches that in the undisturbed deposits.

Inspection of Figure 6.5c shows, however, that in the gravel deposits of the Southern North Sea this process had only entered its initial phase of partial restoration of community structure in the 7-month period which followed cessation of dredging, and that full recovery may take several years, much as would be anticipated for typical equilibrium communities on the sea bed (*see* Figure 6.3).

6.6 The Rate Of Recovery Of Biological Resources

The rates of recovery of biological resources following capital and maintenance dredging, disposal of dredged spoils and marine aggregate dredging have been widely studied in other habitats and conform with the general principles of ecological succession shown in Figures 6.2 and 6.3.

That is, communities which inhabit fine semi-liquid and disturbed muds comprise "opportunistic" ***r***-selected species which have a high rate of recolonisation and which can reach high population densities within weeks or months of a catastrophic mortality. Conversely, communities which inhabit less disturbed deposits of deeper waters or coarse substrata have complex associations and are characterised by large slow-growing species which are selected for maximum competitive advantage in a habitat where space is already crowded. These large, slow-growing ***K***-selected species recolonise only slowly following disturbance and may take several (or many) years for recovery of full species composition and biomass.

Table 6.6a shows the rates of recovery of the benthic fauna following dredging in various habitats. We have included semi-liquid muds from freshwater tidal areas and have arranged the data along a gradient of increasing environmental stability and predictability through estuarine and coastal muds to sands and gravels and coral reef assemblages. Inspection of the data summarised in Table 6.6a shows that recovery of the benthic fauna in highly disturbed semi-liquid muds can occur within weeks. This is associated with an ability for species such as *Limnodrilus* sp., *Ilyodrilus*, *Coelotanypus* sp. and *Procladius* to migrate through the surrounding deposits and to recolonise disturbed muds as adults. A similar recolonisation of disturbed deposits in dredged channels may also account for the relatively fast recolonisation of some muds and sands in nearshore waters, especially those where tidal currents may transport juveniles into the dredged area (*see* Hall, 1994).

Inspection of the recolonisation rates reported in the literature and summarised in Table 6.6a suggest that a period of 2-4 years is a realistic estimate of the time required for recovery in gravels and sands, but that this time may be increased to more than 5-years in coarser deposits, including coral reef areas.

Interestingly, the data for areas in Tampa Bay, Florida, which had been dredged for oyster shell suggest that a period of as much as 10-years may be required for recovery following complete defaunation whereas a recovery time of only 6-12 months is required for recovery following partial dredging and incomplete defaunation (*see* Benefield, 1976; Conner & Simon, 1979).

This suggests that areas of undisturbed deposits between dredged furrows may provide an important source of colonising species which enable a faster recovery than might occur solely by larval settlement and growth (*see also* van Moorsel, 1993; 1994).

There are unfortunately insufficient data available to suggest guidelines on what proportion of the original community should be left intact to optimise recovery of equilibrium communities on the seabed. However, by the very nature of the sometimes patchy distribution of aggregate resources, dredging constraints such as water depth and contaminants such as clay pockets, it is becoming common practice for certain areas of seabed to be ‘zoned off’ and protected from dredging either throughout the life of the Licence, or on a rotational basis as extraction proceeds across a Licence Area. Such ‘zoning’ may have multiple mitigation benefits in not only providing potential recolonisation stocks but also providing recognised areas for other sea bed users. In the case of gold and diamond placer mining, the orebody is often quite patchy and in this case the least impact and fastest recovery has been achieved by intensive mining in patches, after which the extraction vessel moves well away to another high-grade patch leaving the mined area to recover undisturbed (D.V. Ellis, 1998, *pers.comm.)*

Other more complex environmental factors also evidently affect the rate of recovery of dredged areas. Studies in the Dutch Wadden Sea by van der Veer *et al* (1985) show that the recovery of species composition and biomass of benthic organisms was related to the speed of infilling of dredged pits. These data are summarised in Table 6.6b which shows that even 16-years after cessation of dredging, no recovery of the benthos had occurred on a tidal flat at Terschelling Sand. On a tidal watershed at Oosterbierum a partial recovery of 85% of the species and 39% of the biomass had occurred after 4 years.

This is typical of recolonisation by small individuals which were in the process of growth towards the original biomass levels of the undisturbed deposits, a process which would clearly take several further years.

Locality	Habitat Type	Recovery Time	Source
James River, Virginia, USA	Freshwater semi-liquid muds	+/- 3 weeks	Diaz, 1994
Coos Bay, Oregon, USA	Disturbed muds	4 weeks	McCauley *et al*, 1977
Gulf of Cagliari, Sardinia	Channel muds	6 months	Pagliai *et al*, 1985
Mobile Bay, Alabama, USA	Channel muds	6 months	Clarke *et al*, 1990
Chesapeake Bay, USA	Muds and sands	18 months	Pfitzenmeyer, 1970
Goose Creak, Long Island, New York	Lagoon muds	> 11 months	Kaplan *et al*, 1975
Klaverbank, (Dutch Sector) North Sea	Sands and gravels	1-2 years (excl. bivalves)	van Moorsel, 1994
Dieppe, France	Sands and gravels	> 2 years	Desprez, 1992
Lowestoft, Norfolk, UK	Gravels	> 2 years	Kenny and Rees, 1994, 1996
Dutch Sector, North Sea coastal waters	Sands	3 years	de Groot, 1979, 1986
Tampa Bay, Florida	Oyster shell (complete defaunation)	> 4 years	US Army Corps of Engineers, 1974
Tampa Bay, Florida	Oyster shell (incomplete defaunation)	6 - 12 months	Conner and Simon, 1979
Boca Ciega Bay, Florida	Shells and sands	10 years	Taylor and Salomon, 1968
Beaufort Sea	Sands and gravels	12 years	Wright, 1977
Florida coastal waters	Coral reefs	> 7 years	Courtenay *et al*, 1972
Hawaii coastal waters	Coral reefs	> 5 years	Maragos, 1979

Table 6.6a *Summary of rates of recovery of the benthic fauna following dredging in various habitats. Note that highly disturbed sediments in tidal freshwaters and estuaries which are dominated mainly by opportunistic (**r**-strategist) species have a rapid rate of recovery. Recovery times increase in stable habitats of gravels and coral reefs which are dominated by long-lived components with complex biological interactions controlling community structure. Longevity and slow growth is also associated with slow recolonisation rates in sub-arctic seas. Examples have been arranged along a gradient from disturbed muds of freshwater-tidal estuarine conditions to stable reef assemblages.*

In the tidal channels, both the rate of infill and recolonisation was related to the speed of currents. Here a partial recovery of 57% of the species and 67% of the biomass was recorded after 3-years in a tidal channel at Paesensrede, with greater recovery and in shorter time periods being recorded in areas of faster current. Even then, it will be noted that the species composition had not recovered and that the biomass evidently became dominated by fewer species of relatively large size compared with those in the surrounding deposits.

The likely recolonisation rates for the benthic community of estuarine muds, sands, gravels and reef areas have been superimposed onto a generalised colonisation succession in Figure 6.6, and allows some predictions to be made on the rates of recovery of deposits following dredging. The fine muds which characterise coastal embayments, estuaries and lagoons are likely to be colonised by large populations of a relatively restricted variety of "Opportunistic" ***r***-selected species which are capable of rapid colonisation within months of space being made available for colonisation and growth.

Area	Habitat	Time Interval Since Dredging	% Recovery	
			Species	Biomass
Terschelling sand	Tidal flat	16 years	0	0
Oosterbierum	Tidal watershed	4 years	85	39
Paesensrede	Tidal channel	3 years	57	67
Holwerderbalg	Tidal channel	2 years	64	100
Kikkertgat	Tidal channel	1 year	88	116

Table 6.6b *Table showing the percentage recovery recorded in a variety of habitats in the estuarine Dutch Wadden Sea following dredging up to 15-years previously* (*based on van der Veer* et al*, 1985)*

Because such deposits are subject to regular disturbance under natural conditions prior to dredging, the ecological succession recovers to the colonisation phase shown in Figure 6.6a, but does not proceed to the development of ***K***-selected slow-growing species within the community. Recovery of the "normal" community in disturbed deposits such as muds can therefore be achieved within months of cessation of dredging, or disposal of spoils.

The natural communities of gravel and sand deposits, however, contain varying proportions of slow-growing, ***K***-selected equilibrium species, depending amongst other factors on the degree of disturbance by waves and the speed of tidal currents. In this case, the "tail" of the sigmoid recovery curve becomes more pronounced because the rarer components of the equilibrium community may take several years to recolonise the deposits, even after the main components of the community have become established. Where the deposits are sandy, periodic mortality of the long-lived components may result in major seasonal changes in community composition such as occurs in the North Sea on the Klaver bank (van Moorsel, 1994), and as has been reported for the sediments of Liverpool Bay by Eagle (1975).

Under these conditions, the community will be held in a transitional state by natural environmental disturbance, and is likely to recover within a period of 2-3 years after cessation of dredging.
There is good evidence that disturbance of the deposits by man may result in a shift from the "Equilibrium Community" characteristic of undisturbed deposits towards the "Transitional Community" which characterises deposits in areas of natural environmental disturbance.

Studies by de Groot (1984) suggest, for example, that the increasingly heavy bottom gear used by trawlers has been associated with a shift in community composition of the benthos of the North Sea, and this also applies to the benthos of the Wadden Sea.

As might be anticipated from the successional sequence shown in Figure 6.6, long-lived components such as molluscs and larger crustaceans in nearshore waters such as the Wadden Sea have decreased in numbers and diversity over the years and have been replaced by larger populations of rapidly growing polychaete species (Riesen & Reise, 1982; Reise, 1982; Reise & Schubert, 1987).

Finally, the community recovery curve for reef communities indicates that a period of 8-10 years may be required for the long process of establishment and growth of the long-lived and slow-growing ***K***-selected species and for the development of the biological interactions which are familiar to those who have observed the immense diversity and complexity of life on undisturbed reef structures.

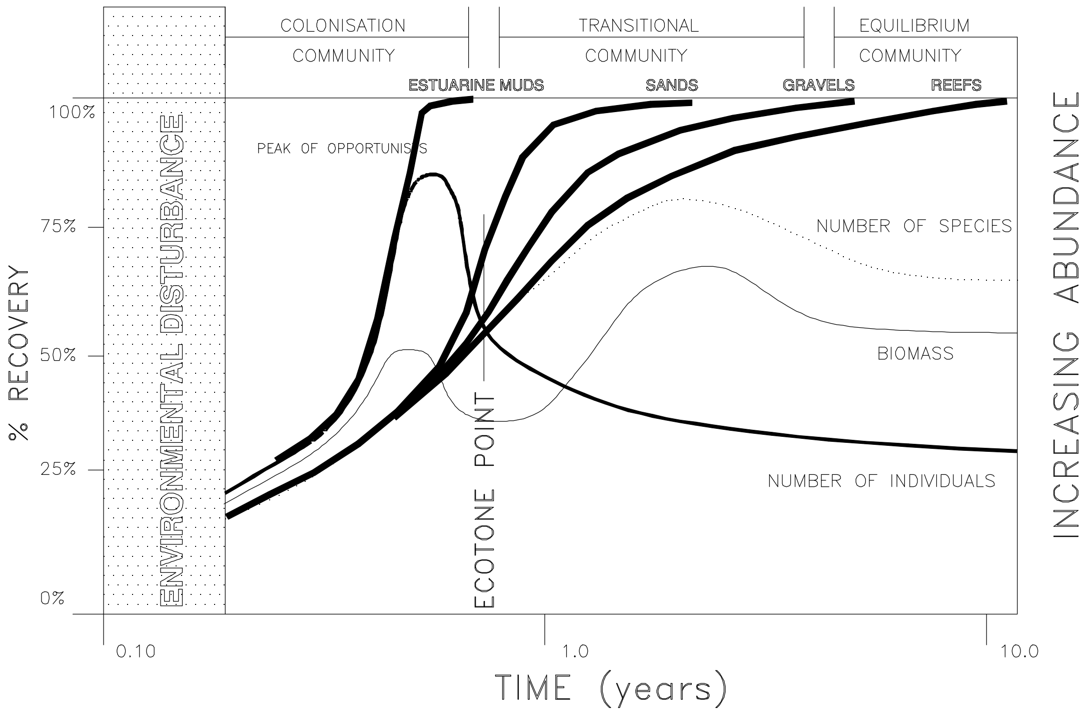


Figure 6.6 *Schematic diagram showing the likely recolonisation rates for the benthic community of estuarine muds, sands, and reef areas. The curves for recovery have been superimposed onto a generalised colonisation succession and allows some predictions to be made on the rates of recovery of deposits following dredging. Note that the fine muds which characterise coastal embayments, estuaries and lagoons are likely to be recolonised by a relatively restricted variety of* "Opportunistic" ***r****- selected species within months of space being made available for recolonisation and growth. Because such deposits are subject to regular disturbance, the succession recovers to the colonisation phase, but does not proceed to the development of long-lived slow growing* ***K****- selected species. The natural communities of sands and gravels, however, contain varying proportions of slow growing* ***K****- selected equilibrium species depending on the degree of disturbance by waves and currents. These communities are held in a transitional state by natural environmental disturbance and are likely to recover within a period of 2-3 years after cessation of dredging. Finally, the recovery curve for reef communities indicates that a period of 8-10 years may be required for the long process of establishment and growth of the long lived and slow growing* ***K****- selected species characteristic of* "Equilibrium" *communities.*

6.7 Community Composition and Seabed Stability

The influence of sediment composition in controlling the composition of communities of animals which live on the sea bed has been widely recognised since the pioneer studies of Petersen (1913), Thorson (1957) and Sanders (1958). Most recent evidence suggests, however, that the precise relationship between biological community composition and specific properties of the sediments is poorly understood. In some estuaries and shallow water coastal embayments, fine grained and silty deposits clearly support an entirely distinct community compared with those from mobile sands or on stable substrata such as rocks and boulders.

On the other hand it is a matter of common observation that although very fine mobile muds may be dominated by "Opportunistic" species such as the amphipod *Ampelisca brevicornis* or the polychaete *Lagis koreni*, the same silts can become consolidated into clays and then support long-lived and sedentary "Equilibrium" species such as the boring piddock bivalves *Pholas dactylus* and *Barnea parva* as well as an epifauna of hydroids, ascidians and other species more characteristic of reefs. Clearly, the stability of the sediment, rather than particle size itself, is of importance in controlling community structure. In other instances it is clear that the deposits on the seabed undergo a complex process of consolidation or "armouring" which allows the establishment of communities which are more typical of rocks and reefs and which reflects the complex relationships between the physical deposits and biological activities of the animals themselves.

The relationship between community composition and sediment type in deeper waters of the continental shelf is less well documented than that for estuaries and lagoons. Some early studies suggest that macrobenthic communities can be distinguished on a basis of sediment granulometry (Glémarec, 1973; Buchanan *et al*, 1978; Flint, 1981) but other studies have shown little correlation (Buchanan, 1963; Day *et al*, 1971). Efforts to identify what physical properties are of greatest importance in controlling the structure of marine communities are often frustrated by the fact that most of the sediment variables obtained from conventional sorting methods are interdependent since they are expressed as a percentage of the total sample (see Weston, 1988). A high percentage of silt, for example, is inversely related to the percentage of the other sediment components. Again, many of the physical properties of sediments are linked with other features such as depth of disturbance by wave action, strength and duration of currents, and may themselves be linked with complex biological interactions including the surface area available for microbial food components, and the presence of species which can exclude potential competitors. Partly for this reason, most recent studies have concluded that the complexity of soft-bottom communities defies any simple paradigm relating to a single factor, and that there should be a shift towards understanding relationships between the distribution of organisms in terms of a dynamic relationship between the sediments and their hydrodynamic environment.

According to this view, complex shear forces at the sediment-water interface are considered to play a dominant role in controlling food availability, settlement of larvae, microbial food availability, pore water flow and other environmental features which affect the benthic organisms which inhabit marine deposits. It is therefore considered unlikely that any one factor alone, or even a combination of single granulometric properties, can account for the distribution in most sedimentary habitats (for review, see Snelgrove & Butman, 1994).

Despite this emerging view that sediment granulometry itself is unlikely to control the composition and distribution of biological communities on the sea bed, concern has been expressed that dredging for marine aggregates can result in significant changes in sediment composition. Studies off Dieppe, France have shown, for example, a large increase in the proportion of fine sand in deposits which have been intensively worked for marine aggregates (see Desprez, 1992; ICES, 1992, 1993). Again, the infill of pits and grooves from dredging for marine aggregates is commonly dominated by the fine deposits which are capable of mobilisation by shear stress induced by waves and tidal currents (Dickson & Lee, 1972; Shelton & Rolfe, 1972; Millner *et al* 1977).

If sediment composition were of importance in controlling biological community composition, such changes following dredging could potentially prevent subsequent recolonisation by communities which were similar to those which occurred in the deposits prior to dredging (see Windom, 1976) and could by implication affect the nature and abundance of food organisms for commercial fish stocks.

We have analysed the relationship between biological community composition and the sediment granulometry in undredged coastal deposits in the English Channel and southern North Sea and find that both biological communities and the sediments fall into relatively distinct Groups or communities when analysed by multivariate techniques (Newell & Seiderer, 1997d). However there is little evidence of any correspondence between the distribution of different sediment types and biological communities in the survey areas. Analysis of the Spearman rank correlation between the similarity of biological communities and any one, or a combination of particle size indices show that granulometric properties of the sediments are likely to account for a maximum of only 30% of the variability of the biological component, leaving approximately 70% determined by other environmental factors.

The conclusion to be drawn from these results is that they support recent views that biological community composition is not controlled by any one, or a combination of simple granulometric properties of the sediments such as particle size distribution. It is considered more likely that biological community composition is controlled by an array of environmental variables, many of them reflecting an interaction between particle mobility at the sediment-water interface and complex associations of chemical and biological factors operating over long time periods.

Such interactions are not easily measured or analyzed, but the results clearly suggest that restoration of sediment composition after completion of dredging for marine aggregates is not, within broad limits, a prerequisite for the establishment of marine communities which are comparable with those which occurred in the deposits prior to dredging.

What is possibly of more importance in controlling the time course of recovery of an equilibrium community characteristic of undisturbed deposits is the process of compaction and stabilisation. This will reflect changes in sediment composition, but is also in equilibrium with seabed disturbance from tidal currents and wave action, both of which show spatial variations and interactions with water depth. The processes associated with compaction and stability of seabed deposits may therefore largely control the establishment of long-lived components of "Equilibrium" communities and account for the dominance of "Opportunistic" species in the initial stages of colonisation of recently sedimented material in unconsolidated deposits after the cessation of dredging.

6.8 Conclusions

At the beginning of this section, we assessed the importance of the benthic community to fisheries production and outlined our intention of providing an ecological framework within which the impact of dredging can be understood. We have shown that systems models for shelf waters such as the North Sea suggest that the flow of materials from primary production by the phytoplankton passes partly through planktonic grazers, but that 20-50% sinks to the seabed either from dead and decaying phytoplankton cells, or as faecal material derived from the feeding activities of the grazing zooplankton (Steele, 1974, Joiris *et al* 1982; Newell *et al* 1988). Such material then passes into the benthic food web, whose production in turn forms an important food resource for demersal fish.

It has been estimated from empirical models developed for the North Sea that as much as 30% of total fisheries yield to man is derived from benthic resources (*see* Figure 6.1). Production by the benthos is therefore important, not only as a resource in itself, but as a key food resource for demersal fish stocks. It becomes an increasingly important component of the marine food web in nearshore waters where primary production by larger macrophytes and seagrasses living on the seabed largely replaces that from the phytoplankton in the water column (for review, *see* Mann, 1982).

From this it is clear that reclamation of large areas of coastal wetlands, coastal embayments or estuaries can have a potentially important effect on the supply of materials and energy to marine food webs, and that even in plankton-based deeper water ecosystems such as the North Sea, fish yields based on benthic production are sufficiently large to warrant proper conservation of benthic resources. Our review has therefore concentrated on the nature of benthic communities, their susceptibility to disturbance by dredging and land reclamation works, and on the evidence which is available for the recovery times required for the re-establishment of community structure following dredging or spoils disposal.

Our review of the literature shows that the communities of nearshore habitats are characterised by large populations of a relatively restricted variety of species which are well-adapted to exploit space which has become newly available by episodic catastrophic mortality. Such species are generally small, often mobile ("Opportunistic") and are selected for maximum rate of population increase, with high fecundity, dense settlement, rapid growth and rather a short life-cycle. Such species have been designated "***r***-strategists" (*see* MacArthur & Wilson, 1967, Pianka, 1970) and their population characteristics allow a rapid recovery of the initial community structure in deposits which are naturally subjected to high levels of environmental disturbance. It is therefore not surprising to find that there are frequent reports in the literature of community recovery times which range from a few weeks to several months for disturbed deposits such as semi-liquid muds in tidal freshwaters, estuaries, lagoons and dredged channels (*see* Table 6.6a & Figure 6.6).

In deeper waters, or where the substratum is sufficiently stable to allow the long-term survival of benthic organisms, the habitat tends to be crowded. Under these conditions, organisms have an "Equilibrium Strategy" and are selected for maximum competitive ability in an environment in which space for colonisation and subsequent growth is limiting. Such species have been designated "***K***-strategists" and devote a larger proportion of their resources to non-reproductive processes such as growth, predator avoidance, and investment in larger adults (MacArthur & Wilson, 1967; Gadgil & Bossert, 1970). Because the ***K***-selected species live longer, they tend to have wider limits of physiological tolerance which allows them to survive those variations in environmental conditions which occur in their habitat.

Many have active site selection phases which include chemical recognition of the presence of adults of the same species, a strategy which ensures that environmental conditions have been within the limits of tolerance for long enough to allow survival of other members of the same species (*for review, see* Newell, 1979).

Such ***K***-selected species develop complex biological associations with other long-lived components of the community, and may alter the environment in such a way as to both allow the presence of many other species which would not otherwise occur, and also inhibit other potential competitors for space.

Biological interactions between the components of "Equilibrium Communities" which are characteristic of stable substrata thus lead to the development of complex communities which may take many years, or decades to re-establish following destruction. It is therefore not surprising to find that as one moves along a gradient of increasing sediment stability from muds through sands to gravels and reefs, there is a corresponding increase in the times which are reported for recovery of community structure (Table 6.6a).

Knowledge of the components which comprise the benthic community on the sea bed, whether these are ***r***-selected or ***K***-selected, thus gives important information not only on key resources which may require protection, but on the likely rate of recovery following dredging. Inspection of the schematic colonisation succession shown in Figure 6.6 suggests that a recovery time of 6-8 months is characteristic for many estuarine muds whilst sands and gravels may take from 2-3 years depending on the proportion of sand and the local disturbance by waves and currents. As the deposits become coarser, estimates of 5-10 years are probably realistic for the development of the complex biological associations between the slow-growing components of equilibrium communities characteristic of reef structures.

Our information presented herein suggests that processes associated with compaction and stabilisation of seabed deposits may largely control the time-course of recovery of these long lived components of 'Equilibrium' communities and account for the dominance of 'Opportunistic' species in the initial stages of colonisation of recently sedimented and unconsolidated material following cessation of dredging. Further work to identify the rhealogical and structural properties of the deposited sediments is required to further consolidate these observations.

SECTION 7 - RECOMMENDATIONS FOR FURTHER STUDIES

The United Kingdom marine aggregate industry faces increasing difficulties in obtaining Licences for dredging in coastal waters. To a large extent these concerns are centred on two main issues:

- *what is the rate of recovery of physical and biological resources in dredged areas and in the surrounding deposits after cessation of dredging? Some reports indicate a relatively rapid recovery in mobile deposits (see*, for example*, van Moorsel 1994) whereas others show that recovery in coastal waters is incomplete even after as much as 12 years (Wright, 1977).*

- *what is the extent of the "footprint" of impact on physical and biological resources outside the boundary of the dredged area? Most predictive models based on settlement velocities estimated from Stokes' Law and Gaussian diffusion principles suggest that fine particles may remain in suspension for up to 6 tidal cycles and could therefore result in a deposition 'footprint' extending for up to 20km in each direction of the ebb and flood tides. This has led to speculation that fisheries resources, breeding grounds and the food webs upon which fish depend could be impacted some considerable distance from worked licences.*

We have shown, within this report, that there is considerable variation between the predicted model plume and that identified through field monitoring. Our observations have been observed independently elsewhere in recent projects world-wide. There is however, only a limited amount of information for U.K. waters. Site specific investigations will be important. Assessment should be made of the relative difference between impact of the largest and smaller dredgers operating in the U.K. Further, appraisal of the ecological and physical significance of the proposed and actual rates of extraction should be addressed.

It is clear that the marine aggregate industry and the Regulatory and Monitoring Authorities together need to specifically address the questions of the rate of recovery of physical and biological resources within the dredged areas following cessation of dredging, and to establish beyond reasonable doubt that the impact is confined to the immediate zone of active sedimentation close to the dredged site. As a precursor to this, 'recovery' must be defined in such a way that 'recovery' is a realistic and viable goal.

The literature review herein has indicated that the rate of recovery of areas which have not been completely defaunated is about 10x faster than in areas which have been completely defaunated. From the review of dredging operations and procedures, in particular the patchiness of the workable resource, zoning, and dredge lanes, it seems likely therefore that the rate of recovery of a commercially dredged site may be significantly faster than that reported for intensively dredged trial sites, which so far provide the only quantitative information on recovery rates for UK waters.

There is, therefore, a clear requirement for an authoritative assessment of the extent of impact and rate of recovery of resources within and adjacent to commercially dredged areas. The assessment would be required to meet the rigorous inspection and concerns of the Regulatory Authority, Fisheries Associations and Conservation Bodies who require treatment of Licence applications using the "Precautionary Approach", which to date has assumed that impact zones could be large and that full recovery of physical and biological resources is likely to be slow. Concurrently, the proposals must remain economically reasonable and technologically attainable for the dredging industry.

The techniques for establishing both the zone of impact and the recovery of resources are well established. It is feasible for the results of the necessary studies to be assembled within the next 12-18 months, which would provide key information for licence applications currently in preparation.

In Section 4.4 of this report, we have proposed approximate values which we have estimated for potential organic enrichment to the surface waters within the plume caused by the dredging operation. In Annex 1 following, the results of the work proposed and the actual measured values for organic enrichment are presented, which are in good agreement with those postulated in Section 4.4.

In Section 7.3, a number of small scale investigations are proposed that may be conducted quickly and with moderate resources to assess certain issues raised within this report. The assessment of the organic enrichment of the plume is considered a priority and should be addressed in the short term to account for the plume appearance, behaviour and impact. The techniques are readily available and can be undertaken with limited resources. It is suggested that data on the organic content is obtained during the next set of field data collection in order to confirm, or discount, this hypothesis.

All of the proposals herein are considered to be realistic goals for industry appraisal within the next two to three years, with some results potentially available within 8-10 months. The information will allow scientific fact to replace poorly informed speculation and unwarranted allegations of permanent damage to the seabed and benthic environment. Knowledge of such information will enable competent and authoritative monitoring programmes to be emplaced and workable mitigation measures to be developed. Unnecessary sterilisation of useable resources may justly be avoided.

7.1 Rate Of Recovery Within Dredged Area & Surrounding Deposits

As mentioned previously within this report, there have been few detailed studies on the impact of dredging on biological communities on the seabed in the United Kingdom, or on their subsequent rate of recovery following cessation of dredging. The most frequently cited work is for an intensively dredged experimental site off the UK Norfolk Coast (Kenny & Rees, 1994; 1996), from which it was concluded that recovery was substantial but remained incomplete even 2 years after cessation of dredging in the experimental area.

As noted previously, it must be remembered the experimentally dredged area mentioned above differs significantly from most commercially dredged areas. Our comprehensive review indicates that there is no information, similar to the studies by Kenny *et al*, available to confirm the extent to which commercially dredged areas conform to the results of experimentally dredged areas.

Evidence of the potential for significant variation of recovery rates due largely to the intensity of dredging operations is suggested, for example, by the results of investigations of shell dredging activities off Tampa Bay, Florida, which reported up to 10 years required for recovery of benthic communities following complete defaunation, whereas recovery from incomplete defaunation was completed within 6-12 months (*see* Benefield, 1976; Conner & Simon, 1979).

Studies such as these provide clear evidence that areas of physically undisturbed deposits between the furrows may provide an important stock of colonising species that are available for rapid lateral migration over the limited distances to the freshly disturbed seabed within the furrows (*see also* Section 6).

It follows that where complete defaunation does occur, migration distances for colonisers are much greater, posing predator threats etc., and consequently resulting in the longer recovery times (*see also* van Moorsel, 1993, 1994).

7.1.1 Field Study Proposal One

A study of the physical impact of dredging within a commercially dredged area and its surrounding deposits should be combined with a qualitative study of the biological resources to establish the following;

(i) the impact within a commercially dredged area compared with surrounding undisturbed sites

(ii) the progression of recovery of physical and biological resources within the areas where dredging has been completed

It is anticipated that a commercially dredged licence area will show a more rapid recovery than experimentally dredged areas, and that seabed topography is likely to be restored rapidly in the relatively shallow coastal deposits of the UK aggregate industry (*c.f.* evidence from many overseas investigations largely conducted in deeper, less disturbed waters) (Newell *et al*, 1998).

It is suggested that a region of past intensive and extensive dredging activity containing a number of Licences, exploited over a considerable number of years would provide a suitable assessment for this proposal. The history of phased dredging, conceded areas and zoning undertaken on the 'Norfolk Banks' provides a range of examples of presently, recently and long-since worked areas, with 'refuge' zones between them.

Considerable information is available within the "Norfolk Banks" area in the form of geological prospecting reports and Environmental Statements containing some benthic investigations data. The results of Kenny & Rees (1996) would be geographically similar for comparison of commercially dredged and experimentally dredged results.

7.2 The Extent Of Dredging Activity "Footprint"

The concern that the modelled and observed behaviour of a dredging plume is significantly different requires further investigation. It is known (see, *for example*, Gajewski and Uscinowicz, 1993; Whiteside *et al* 1995; Hitchcock & Dearnaley, 1995; Land *et al*, 1996; reviewed in Newell *et al*, 1998) that the settling velocities of the plume observed in the field do not conform to established settling velocities of similar sized (discrete) particles determined through laboratory tests. This is considered due to a combination of factors including initial entry velocity of the mixture into the water column, cohesion of the fine particles to the coarser particles (which are separated during laboratory particle size analysis) and the formation of density currents (*see* Chapters 2 & 4).

The potential for a major zone of impact stretching as much as 20km along the tidal current flow in each direction is therefore remote. Importantly, very recent research (J. Rees *pers. comm.* 1997) has observed passage of a 'plume' within the benthic boundary layer (approximately less than 1m from the seabed) at distances of up to 8km from the dredging activity. Suspended solids concentrations are not known, but are likely to be of the order 80-100mg/l. It is possible therefore that where seabed roughness and induced turbulence exists, the excursion of a small, fine component of the plume may be extended.

There has not, however, been any investigation of the actual field impact of dredging on biological and physical resources within and immediately adjacent to commercial dredging activity.

Determination of the actual settlement pattern of the plume has had limited address (*see* Gajewski & Uscinowicz, 1993). Deployment of settlement traps / devices to determine real deposition rates away from the dredge zone will support and refine all previous plume investigations and modelling, and relate directly with benthos studies.

Analysis of tracer sediments is unfortunately limited to defining the settlement pattern of the tracers (which are, by definition, required to and are marketed to mimic the behaviour of the discrete particles within the sediment), rather than the behaviour of the dredged sediments interacting not only with each other but also with the biological and chemical conditions prevalent.

Further the vigorous agitation of the dredging process is as yet an unknown process.

The determination of "*Contours of Impact*", a procedure well documented for point sources of environmental disturbance and stress, could be determined authoritatively for dredging activities. A detailed study of the changes in sediment granulometry and seabed topography across the dredged area and corresponding relationships with biological resources has been submitted for funding, under an extension of the present contract with the MMS. This is anticipated to commence in October 1998 through to September 2000 with early results available during late 1999.

7.2.1 Field Study Proposal Two

During extensive resource prospecting and reserve evaluation surveys carried out during 1997, we have obtained non-quantitative evidence that the zone of impact on biological resources is indeed small and confined to the immediate vicinity of the dredged area (Newell & Hitchcock, *memo to* ARC Marine, August 1997).

We therefore recommend that an integrated physical and biological monitoring survey is carried out on an existing, licensed aggregate extraction area to authoritatively establish the zone of impact surrounding the dredged area. It is considered important to gather information on the actual sedimentation pattern of the dredged sediment overboard returns, unaltered by treatment or tagging. We therefore strongly suggest development of a robust and simple technique for deployment of purpose built sediment traps suitable for midwater and seabed deployment. The recently raised issue (J Rees *pers. comm.*) of a "benthic boundary layer" plume extension (*circa* less than 1m high) needs to be addressed and could be considered concurrently. The utility of sediment trap data is reinforced, for example, by Drapeau *et al* (1992) and Gajewski & Uscinowicz (1993).

This would provide indisputable field evidence that the zone of impact, which to date potentially extends as far as the plume has been modelled using the "Precautionary Principle", is actually much more confined, and falls well within the zone of plume excursion as identified through recent field monitoring. Such an exercise may also temper some of the (growing) perceived 'cumulative effects' of neighbouring Licences.

It is anticipated that the biological response zone to the plume will actually not extend as far as the limits of the observed plume, considering the capacity of the benthos to cope with natural variations in suspended solids concentrations, sediment stability and sediment accretion rates.

By this means, correlating an observed plume impact zone with an observed biological impact zone will provide, for the first time, unequivocal evidence of the relationships between benthos and plumes and an assessment of the levels of enhanced suspended solids concentrations which can be ascribed to particular benthic responses, whether negative or positive.

7.3 Aesthetic Plume Impacts, Far Field Effects And Perception

The aesthetic impact of the far field plume raises the potential criticism that since the surface expression is extensive, therefore the plume must be detrimental to the environment. A significant cause of concern, and which subsequently arouses a perception of negative impacts of plumes, may be resolved by investigation of the content of the visual far field plume; be it biological, physico-chemical or geological. The sediment plume is a very visual phenomenon; explanation of the visual component will probably satisfy more objections than many other perceived and identified physical impacts.

7.3.1 Field Study Proposal Three

It is proposed that further monitoring of the water column plume is undertaken using a combination of water sampling (with testing for geological, biological and physico-chemical components), VMADCP™, Optical Backscatter and Transmissometer Sensors, and Aerial Photogrammetry.

As outlined in Section 4.4, it is proposed that, to a large extent, the far field plume visible by the unaided eye and recorded by Continuous Backscatter Profiling has significant biological origins. It is proposed that during the next phase of fieldwork undertaken either from a dredger or from a separate survey vessel, water and plankton samples are obtained to assess the quantity of biomass in suspension within the overflow and reject sources. It is considered that this need not in the first instance be a high cost exercise: a limited sampling campaign will ascertain the presence, or otherwise, of elevated organic levels.

Further, it is considered necessary for the biological parameters distinguishing positive, negative and no effects to be determined. Some data may already exist, and it is only necessary therefore to competently apply such data to the UK marine aggregate mining plume.

Preliminary discussions with Aerial Photogrammetry companies have concluded that given known ground markers (navigational buoys, marker buoys *etc*.) and their known locations, scaled and quite accurate dimensions of the visual plume extent can be made. These can be correlated with concurrent observations by ADCP™ and sample test results to explain the character of the far field plume.

SECTION 8 - CONCLUSIONS & RECOMMENDATIONS

The impact of human activities on environmental resources is inevitable but it is important to distinguish between well documented and perceived impacts. Competent determination of the impact of an activity not only requires information on the nature of the disturbance (comprehensively investigated and presented herein), but also on the background conditions pre-disturbance (of which there is scattered existing data that requires consolidating) and the subsequent response of the environment to that disturbance (of which there is little information spread world-wide and even less for UK waters, reviewed in Section 6). That is to say, anthropogenic disturbances must be put into the context of natural disturbances before assessment of significance.

Our reviews suggest that comprehensive collation of background and baseline environmental conditions is required. Furthermore, field data on the response of the environment to disturbances, in particular the biological response, is urgently required. Net sediment accretion due to re-sedimentation in itself may not be the most important issue: the ability of the benthic habitants to move away, burrow upward, outgrow or otherwise survive such increases in bed level *ie* the response of the environment to disturbance, is more important.

The information summarised in this report provides baseline measurements of the range of increased turbidity that may be generated by a aggregate dredging operation, its sources, likely extent and potential mitigation. The baseline review of likely biological impacts based on current information may subsequently be used by during the preparation of an EA for consideration in the context of the local situation. This project has not, however, attempted to determine the impact of elevated turbidity *per se*. This question is best answered on a site-specific basis in the Environmental Assessment of a specific dredging proposal. Rather this project highlights the significant differences between historical predictions and the actual behaviour of plumes generated by marine aggregate mining through comprehensive monitoring in the field. The results of this study have been shown to correlate well with similar studies recently published world-wide.

It is intended that the data reported herein be incorporated into the development of predictive modelling studies essential for management purposes. Further, the importance of plume behaviour is significant if it can be shown, or there may be reasonable grounds for concern, that the activities are having or there is the potential to have, an deleterious effect on the environment. An understanding of the physical and biological resources of the seabed is therefore a key requirement for formulating the Impact Hypothesis of the Environmental Assessment.

The throughput of sediments within the dredging system has been studied on a ‘Process’ basis. Each stage of the dredging process, (at the drag head, screening, and overspill) has been appraised. Losses from the system back to the water column have been identified. The plume processes of advection, dispersion and settlement have been investigated.

It is evident from the review of the literature that the study of commercial aggregate dredging operations and associated environmental disturbances is much more limited than similar information for other forms of dredging *but* is at the same time also developing quickly in response to greater application of responsibilities and generally heightened environmental awareness. It is further evident that a vast majority of the information available resides in unpublished, commercial reports which are largely un-proferred for peer review and subsequent discussion and dissemination amongst the wider scientific community. There is therefore, a clear need for development of authoritative, peer reviewed assessments of the impacts of the aggregate dredging operations.

We have collected and present herein a substantial dataset of field observations on the source terms for sediment plumes generated by commercial marine aggregate mining operations in the UK. The information provides fundamental support to quantifying the impact of dredging operations on the environment.

We have outlined the principal components of the marine aggregate dredging process which influence the development of sediment plumes. Methods of field investigation and monitoring are reviewed. This report recommends that further information is acquired on the source terms of sediments attributable to the reject chute for screened sand and gravel cargoes, and from vessels with different loading processes. Notwithstanding this, further information on all aspects of source terms will enhance the present database.

Combination of accurate field observations with the traditional modelling scenarios has resulted in modifications to the theory of behaviour of the developed plume directly (*see, for example,* HR Wallingford, 1995; Weiergang, 1995; Jensen, 1995; Whiteside *et al*, 1995; Pennekamp *et al*, 1996). These also concluded that traditional predictive techniques might overestimate the diffusive abilities of the dredge plume.

We recommend as Best Practice that monitoring of plumes issuing from dredging operations comprises a well designed and pertinent sampling and testing programme. We have shown there are significant productivity gains through the competent use of Continuous Backscatter Profiling techniques using acoustic Doppler profiling equipment with precise navigational control to effectively track and delimit the plume boundaries. This will significantly improve confidence in the interpretation of results as representative of the maxima and minima conditions.

We have accounted for the quantities of material disturbed at the seabed and their subsequent processing through the dredging system, quantifying the various outputs from the dredging operation, which act as inputs to the marine environment. The importance of detailed prospecting and reserve evaluation survey data in managing the cargo quality available from adjacent dredge runs, separated by only 500m, is emphasised by this work.

Amongst the many factors affecting the total quantity of sediment returned overboard during loading of a single cargo, the primary factors are the type of dredger, type of cargo and seabed geology. Aggregate dredge vessels may return sediments overboard amounting to between 0.2 and 5 times the cargo load. The size distribution of the overboard returns will be skewed, according to the cargo being loaded. Some 30% of the sediments lost overboard may actually be of cargo ‘grade’ (depending on the Customer requirements).

Development of techniques to monitor the sediment plume using acoustic Doppler current profiling equipment, herein termed *Continuous Backscatter Profiling* (CBP), has given considerable insight into the restricted magnitude of plume excursion when compared to predictive numerical models. Confidence in locating the sampling programme within the plume is promoted.

In general, the sand component of a plume (both from the reject and overspill sources) is not sampled beyond a distance greater than 300m (horizontal tidal current velocity vector = 0.35m/s) from aggregate dredgers normally operated in UK waters. This implies a net forced settling rate of 21mm/s, which agrees well with estimates of free particle settling velocity calculated from laboratory exercises. Further, the silt content of samples (<63µm) becomes indistinct from background conditions beyond approximately 500m from the dredger. This implies a forced settling rate of 12.6mm/s. Typical modelling values are of the order 0.1-1.0mm/s for silt sized particles. The importance of floc (dis)aggregation is not known. Interestingly, elevated suspended silt concentrations at distances of up to 1000m were observed for larger dredgers, such as the Geopotes XIV, which are not commonly used in UK waters.

Enhancement of sediment fall velocity is attributed to the development of intense localised density currents. These are introduced by the increased suspended solids concentrations and enhanced by the entry velocity of the sediments into the water. This concept is supported by independent overseas observations. The development of a density current for the larger sediments may be important in dragging the finer material to the seabed with it. The further process of aggregation of the fine sediments to the coarser, more quickly settling sediments is unknown. Research efforts are some way to establishing *in situ* values for the fall velocity of overspill sediments as a Density Current.

The comprehensive literature review on benthic ecological characteristics of aggregate resources provides a detailed insight into the complex two-way interactions between the benthos and seabed sediments. The population characteristics of nearshore ‘Opportunistic’ communities are such that they allow a rapid recovery of the initial community structure in deposits which are naturally subjected to high levels of catastrophic environmental disturbance. In more stable seabed conditions ‘Equilibrium Strategists’ develop a greater tolerance to environmental variations often facilitating the existence of sub-communities which would not otherwise survive in those conditions, but are characterised by a slow growth rate and long recovery time following disturbance.

Knowledge of the components which comprise the seabed community is therefore important not only to assess potential protection of communities, but also to assess likely community recovery times. By definition the sands and gravels targeted for aggregate extraction may be of community composition such that initial recovery times of 2-3 years are reasonable in circumstances of complete defaunation, with estimates of 5-10 years realistic for full recovery of the complex biological associations between the slow growing components of Equilibrium Communities characteristic of reef structures. It is likely that the recovery for partially defaunated seabeds (likely to be formed by commercial dredging operations) may be faster than that reported for completely defaunated communities. The sensitivity of the benthos to seabed stability is recently reviewed in Newell *et al*, (1998).

Our review of the impact of aggregate dredging on benthic biological resources shows large site-specific differences both in the effects of dredging itself and in the rate of recovery. Further, it must be assumed that such impacts are dependent on both the physical nature of the environment and on the biological communities resident in a particular area. Kenny & Rees (1996) note that in the highly disturbed natural environment of the Norfolk Banks in the Southern North Sea dredging may be of little long term biological significance due to the potential speed of physical and biological recovery following dredging (*c.f.* Wright, 1977). It would not be possible to apply the same results to other dissimilar areas without site specific studies. Nevertheless, the perception of recent studies is encouraging for the commercial aggregate industry and it may be possible to develop some generic guidelines.

Similarly, we have shown that it is largely inappropriate to apply the observations and results of investigations into other forms of dredging to the particular circumstances of marine aggregate mining. Specifically, marine aggregate mining targets only a limited range of geological sediments, within limited oceanographic parameters utilising a limited range of dredging plant. The marine aggregate industry is Customer driven and as such, Customer demand will keep such parameters within very little tolerance. Other forms of dredging, *i.e.* capital, maintenance and environmental clear-up, concern themselves with far wider ranging objectives, and the effects of these will require specific investigation.

The development of a benthic plume by the hydrodynamic and physical interactions of the draghead on the seabed has been firmly established by the present work. We have shown using underwater imaging, suspensate sampling from around the plume and CBP techniques that the magnitude of the draghead plume is minor in comparison with the surface plume. Contribution of the overboard discharge to the suspended load is 4-5 orders of magnitude greater than from the draghead. It is further considered that the impact of the draghead plume may be deemed negligible in relation to any surface plume effects.

Discharge of material from hopper overflow and the screening process is thus of dominant importance in the establishment of dispersion plumes from marine aggregate mining activities. The extent of the plume is dependent on (among other factors) the total quantity of sediment rejected, the particle size of the sediments and the velocity of the tidal current flow. Further, the rate and manner of discharge is important in defining the initial stages of plume descent as a density current (Dynamic Phase) and controls the quantity of material subsequently available for more conventional advection and dispersion away from the point of discharge (Passive Phase). Our work confirms that, as a general principle, the rate of deposition of material from the dispersing plume is much faster than would be assumed from conventional Gaussian diffusion models and that sedimentation is largely confined to distances of a few hundred metres from the point of discharge.

Importantly this suggests that the impact of dredging on benthic biological resources may be confined to the immediate vicinity of the dredged area, although little is known of the impact within areas worked commercially, in the surrounding deposits nor of the rate of recovery following cessation of dredging. Of particular interest is the possible impact of organic material released into the water column by the dredging processes which we surmise may account for much of the relatively large visible 'plume' which extends beyond the boundaries of measured suspended sediment load discernible above background conditions. The release of such material may play an important role in the well-documented enhancement of secondary production in deposits surrounding dredged areas and requires further investigation both as part of our understanding of plumes associated with marine aggregate dredging and with establishing the impact of these activities on biological food webs leading to commercially exploitable fish stocks.

This study thus provides, for the first time, detailed information on the plume characteristics from a variety of commercially operating marine aggregate mining vessels, and further investigates the physical disturbances generated at the seabed. Details of such source terms provides key data for modification of existing and development of new descriptive and predictive models of plume dispersion, and conforms well with contemporary studies of plume generation from other sources.

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with specialist contributions by:

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L. J. Seiderer

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ANNEX 1

RESEARCH PUBLICATIONS PRODUCED DURING THIS STUDY

1) **Drucker, B.R. & Hitchcock, D.R.** (1996) Environmental Management of sand and gravel and aggregate resources on the Outer Continental Shelf: The United States versus The United Kingdom experience and ongoing co-operation between the two countries. *Oceanology International 96. The Global Ocean-Towards Operational Oceanography. Conference Proceedings Vol 1 Spearhead Exhibitions Ltd. Surrey KT3 3LZ.* **ISBN 0 900254 12 2.** pp. 153 - 164

2) **Hitchcock, D.R.** (1994) Investigation of surface plumes associated with marine aggregate production in the United Kingdom - Preliminary results Report to ARC Marine Ltd, United Marine Dredging Ltd & South Coast Shipping Co. Ltd. **Ref No. 94-555-33** Coastline Surveys Ltd. 15pp

3) **Hitchcock, D.R.** (1997) Aspects of sediment disturbance associated with marine aggregate mining. Unpublished PhD Thesis, University of Wales, 213pp

4) **Hitchcock, D.R. & Dearnaley, M.P.** (1995). Investigation of benthic & surface plumes associated with marine aggregate production in the United Kingdom: Overview of Year One *Proceedings of XVth Information Transfer Meeting, Gulf Coast Region INTERMAR*, New Orleans, USA. 10pp

5) **Hitchcock, D.R. & Drucker, B.R.** (1996) Investigation of benthic and surface plumes associated with marine aggregates mining in the United Kingdom. In: *The Global Ocean-Towards Operational Oceanography. Proceedings of the Oceanology International Conference, 1996. Spearhead Exhibitions Ltd. Surrey KT3 3LZ.* **ISBN 0 900254 12 2. Vol. 2.** pp. 221 – 234

6) **Hitchcock, D.R., Newell, R.C. & Seiderer, L.J.** (1998) Overspill Outwash Study Area 430 (Southwold). Confidential report to United Marine Dredging Ltd & South Coast Shipping Co. Ltd. **Ref No. 98-674-103** Coastline Surveys Ltd. 31pp

7) **Newell, R.C., Hitchcock, D.R. & Seiderer, L.J.** (1998) Organic enrichment associated with outwash from marine aggregate dredging: a probable explanation for surface sheens and enhanced benthic production in the vicinity of dredging operations. *Marine Pollution Bulletin,* in press

8) **Newell, R.C., Seiderer, L.J. & Hitchcock, D.R.** (1998) The impact of dredging works in coastal waters: a review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea bed. *Oceanography and Marine Biology Annual Review*, ***36***, pp. 127-178

Hitchcock, D.R. & Hermiston, A.R. (1997) Presentation of study results to MAFF, Dredging Industry and Regional Sea Fisheries Groups, Chichester

PAPER (7) INCLUDED IN THIS REPORT (FOLLOWS)

Organic Enrichment Associated with Outwash from Marine Aggregates Dredging: A Probable explanation for Surface Sheens and Enhanced Benthic Production in the Vicinity of Dredging Operations.

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ABSTRACT.

Despite concern over the impact of marine aggregates dredging on benthic community composition within dredged areas, the scale of impact outside the boundaries of the dredged area from the settlement on the sea bed of fine material temporarily suspended by the dredging and screening process is poorly understood. Most recent studies of dispersion of sediment plumes generated by marine aggregates dredging, including those reported here, suggest that the area of impact of outwash from dredging activities is smaller than estimates based on Gaussian diffusion models, especially when the proportion of silt and clay in the deposits is low.

This paper presents evidence which suggests that the "far field" visibility of the dispersing plume is associated with organic enrichment derived from fragmented marine benthos discharged with the outwash water. These are the first direct measurements of the organic composition of the outwash from a marine aggregates dredger, and are based on a cargo loaded from a hitherto largely unexploited site to the east of Southwold, Suffolk. The values therefore probably represent maximal concentrations for coastal deposits and reach concentrations of as much as 1.454 grams AFDW per litre of which 0.007 grams per litre (0.48%) comprises lipids.

Such material appears to be of sufficient concentration to match the known removal of benthos from the dredged sediments, and is clearly sufficient to account for the presence of a detectable "plume" beyond the point at which inorganic solids have fallen to background levels. The fact that significant quantities of lipids are associated with this material may reduce the rate of sedimentation of fragmented material and account for the commonly-observed surface "sheen" at the extremity of the dispersing plume. Even allowing for the dispersion which must occur downstream from the dredger, it seems likely that the organic matter derived from fragmented invertebrates in the dredger outwash may account for the enhanced species diversity and population density of benthic invertebrates recorded by others beyond the boundaries of dredged areas.

INTRODUCTION

The increased exploitation of marine deposits for aggregates, and the physical and biological impacts of dredging works has been widely reviewed (Dickson & Lee, 1972; Shelton & Rolfe, 1972; Cruikshank & Hess, 1975; de Groot, 1986; Nunny & Chillingworth, 1986; ICES, 1993; Newell *et al*, 1998). Essentially, the physical impact of dredging works is dependent partly on the method of dredging, and partly on the amount and grade of deposits rejected by screening, and overspill from the hopper. A typical modern sea-going aggregates dredger operating in U.K. waters is self-contained and uses a centrifugal pump delivering approximately 7750 $m^3.h^{-1}$ to lift the aggregates from the sea bed into a hopper of approximately 5,000 tonnes capacity, a process which takes 2-8 h depending on the amount of screening which is required to attain a cargo load of suitable quality.

Estimates by Hitchcock & Drucker (1996) suggest that for a suction trailer dredger of 4,500 tonnes hopper capacity operating on the Owers Bank, off the south coast of U.K., approximately 750 tonnes of solids are discharged through overspill and as much as 7,223 tonnes through the screening reject chutes. Water discharge is 21,387 tonnes from overspill and 13,499 tonnes through screening. The screened material is thus discharged in relatively high concentration through a reject chute whilst a larger volume containing a relatively low concentration of suspended solids overflows from the hopper.

The impact of such dredging on benthic communities varies widely depending, among other factors, on the intensity of dredging and the type of community which occurs in a particular area. Most estimates indicate that both maintenance dredging and marine aggregates dredging operations can be expected to result in a 30-70% reduction of species diversity, a 40-90% reduction in the number of individuals, and a similar reduction in the biomass of benthic communities in the dredged area.

Despite concern over the impact of marine aggregates dredging on benthic community composition within dredged areas (see ICES, 1992a;b), the probable scale of impact outside the boundaries of the dredged area from the settlement on the sea bed of fine material temporarily suspended by the dredging and screening processes is poorly understood. In its simplest form, the settlement velocity and residence time of particles discharged during screening and from hopper overflow can be estimated from Stoke's law. If the residence time of particles in the water column is known, the duration and speed of local currents and turbulence will then determine the excursion pattern before settlement. Estimates of dispersion of material based on these Gaussian diffusion principles suggest that coarse material settles rapidly below the point of discharge from the dredger, a feature which has been verified in studies at sea (Gajewski & Uscinowicz, 1993). Very fine sand particles have been estimated to travel up to 11-km from a dredge site at Owers Bank off the south coast of U.K whilst similar estimates based on Gaussian diffusion models for fine silt particles (<0.063 mm) suggest that this material could remain in suspension for up to 4-5 tidal cycles and be carried for as much as 20-km from the point source of discharge (H R Wallingford, 1993; cited in Hitchcock & Drucker, 1996).

Most recent studies on the dispersion of sediment plumes generated by marine aggregates dredging suggest, however, that the area of impact of outwash from dredging activities is smaller than estimates based on Gaussian diffusion models, especially when the proportion of silt and clay in the deposits is low. This appears to be due to complex cohesive properties of the discharged sediment particles that settle on the sea bed as a density current and reflects flocculation and initial entry velocity of the overspill/reject mixtures into the water column. The discharged material thus does not conform to settlement rates based on specific gravity and size of the component particles themselves (Land *et al*, 1994; Whiteside *et al*, 1995; Hitchcock & Dearnaley, 1995; Hitchcock & Drucker, 1996). Such studies show that settlement of the inorganic particulate load discharged from marine aggregates dredging is mainly confined to a distance of a few hundred metres from the point source of discharge.

The surface plume is, however, visible as a "slick" for a considerable distance beyond that at which suspended inorganic solids have fallen to background levels. This has been ascribed to the possibility of air bubbles and entrainment of organic matter into the water column from the dredging process (Hitchcock & Drucker, 1996).

It is the purpose of this paper to present evidence which shows that this "far field" visibility of the dispersing plume is associated with organic enrichment probably derived from fragmented marine benthos discharged with outwash water. Such material appears to be of sufficient concentration to match the known removal of benthos from the dredged deposits, and may account for the enhanced benthic species diversity and population density reported for deposits surrounding dredged areas (see Poiner & Kennedy, 1984).

MATERIAL & METHODS.

1. Continuous Backscatter Profiling (CBP).

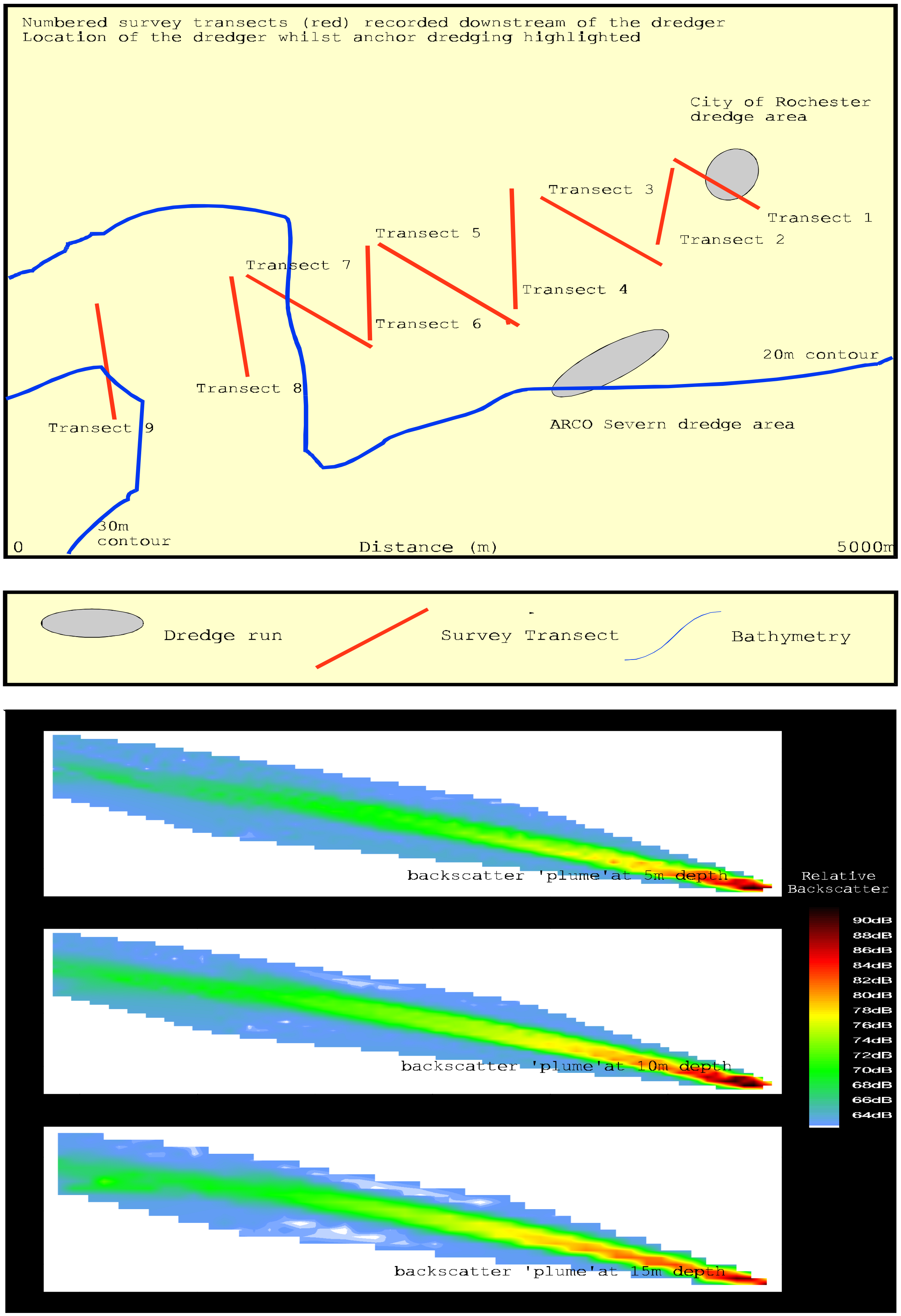
Acoustic Doppler current profiling techniques utilise the transmission of a beam of sound into the water column by 3 or 4 highly directional (2.5° beam width) transducers arranged in a "Janus" configuration, inclined at 30° to the vertical. Backscattered sound from plankton, small particles, air bubbles and small-scale heterogeneities in the water ("scatterers") are recorded by the transducer. The primary function of Doppler current profiling techniques is to record continuous current velocities through depth and, depending on the equipment, dynamically using a moving boat. This technique is widely used and is gaining increasing acceptance worldwide. A secondary function of some systems enables the operator to display the acoustic strength of the returned signals as affected by the suspended particulate matter, and hence record variations in scatterers, generally interpreted as suspended solids concentrations (see Land *et al*., 1994; Whiteside *et al*, 1995; Weiergang *et al*, 1995).

Acoustic backscatter transects reported in our study were obtained using an RDInstruments 1200 kHz Broadband Acoustic Doppler Current Profiler (ADCP) which was operated from a survey vessel downstream of a marine aggregates dredger during normal loading operations on the Owers Bank, off the south coast of U.K. during 1995. Additional samples of the composition of the outwash to verify the predictions made from the Owers Bank data were obtained from a dredger operating off Southwold, Suffolk in April 1998. Doppler current profiling techniques and acoustic backscatter measurements have been used extensively for observation of the distribution of suspended particulate matter, particularly zooplankton following the work of Flagg & Smith (1989). Similar techniques have recently been used for observations on suspended solids associated with dredging and dredged material disposal operations, particularly cohesive sediments (Thevenot & Kraus, 1993).

A number of investigators have attempted to correlate backscatter sound strength (dB) of the returned signal with suspended solids concentration (mg/l) with varying degrees of success (Thevenot & Johnson, 1994; Tubman *et al*, 1994). Land *et al* (1994) reported statistically acceptable correlation with optical silt meters and water samples for sediments in the range of 5-75 mm with a mean particle diameter of 10 mm and concentrations up to 1000 mg/l. Lohrmann & Huhta (In: Tubman *et al*, 1994) calibrated a 2.4 MHZ Broadband ADCP in a purpose-built laboratory calibration tank using material obtained by grab from the sea bed of the site to be studied. Although suspended solids concentrations determined by the ADCP were considered to agree "reasonably well" with the water sample analysis, the maximum error was considered to be $^{+}_{-}$ 60% at 50 mg per litre. Thevenot & Johnson (1994) suggest that flocculation of the material could be a contributing factor to the differences between field and laboratory calibrations. Detailed discussion of the principles of using the acoustic backscatter function of the ADCP™ can be found in Land *et al* (1994) and Weiergang *et al* (1995).

In the study reported here, the acoustic backscatter function of the ADCP™ has been used to display a real-time semi-quantitative graphical representation of the gross morphology of the plume in relation to distance and water depth across a number of plumes generated by dredgers operating on the Owers Bank, off the south coast of U.K (see also Hitchcock & Dearnaley, 1995; Hitchcock & Drucker, 1996; Hitchcock, 1997). Continuous observations of the strength of acoustic signal returned by particles in the water column were processed in real-time on screen displays with horizontal time and vertical water depth axes. The colouring of the individual boxes of data (shown in Figure 1) are user-configurable and relative to the acoustic strength of the returned echoes, and hence to the amount of "scatterers" in the water column. Importantly, this may include organic and inorganic particulates, air bubbles etc, so that complementary samples of suspended solids are required to interpret the plume morphology.

Figure 1: Relative positions of the survey vessel tracks and position of the anchored dredger during monitoring



Broadband 1200 kHz ADCP techniques do not return valid data within the lowest 6% of the water column. Within the context of this paper, our observations do not include this boundary region of the water column. A different approach is required in order to assess the behaviour of suspended and settling material within such a layer at the sediment-water interface.

2. Positions of the Survey Data.

To produce competent analysis of the ADCP™ data, the position of the ADCP™ survey vessel and the dredger vessel was fixed by Global Positioning System (GPS) techniques operating in Differential mode (dGPS). A position accuracy of better than 5 metres was attained for both survey vessel and operating dredger.

3. Suspended Solids.

Water samples were taken from the hopper spillways by three successive dips of a 20 litre bucket lowered directly into the flow, taking care not to obtain more than 3 litres of sample, and transferred to a single 10 litre container. A series of samples were taken at known times during the entire loading process and gave an even spread of data throughout the load. Separate samples of up to 2 litres of overspill water were taken for organic analysis. Due to difficulties of sampling in the high velocity flow from the screening reject chutes, direct measurements on material discharged by this route are the subject of a further field experiment to be conducted in the near future.

Two samples of approximately 2 litres of sea water were taken at depths of 4 m, 8 m, 12 m, 16 m and 18 m depth at varying distances up to 3.5 km downstream of an operating dredger and the size distribution of suspended solids determined by standard gravimetric techniques (see also Hitchcock & Dearnaley, 1994; Hitchcock & Drucker, 1996; Hitchcock, 1997). These data were then compared with background samples taken each day before dredging commenced, and with samples taken upstream of the dredger. Background suspended solids concentrations were between 5-10 mg per litre.

4. <u>Ash-Free Dry Weight</u>.

Water samples of approximately 2 litres were collected from the hopper spillways and immediately deep-frozen in plastic containers. These were then transported frozen to the laboratory for analysis. The water samples were filtered through pre-weighed GF/F filters to remove the sedimentary particles > 0.7 mm in diameter. The sediments were dried in an oven at 40^{o} C until a constant weight was achieved. The filters were then heated in a muffle furnace to 500^{o} C for 24 h. The ash-free dried weight was calculated from the difference between the sediment weights.

5. <u>Lipid Analysis</u>.

Water samples collected and deep-frozen as described above were filtered through a glass fibre filter to remove the suspended solids in the sample. The volume extracted was recorded before beginning the filtration process. The water sample was then double extracted into dichloromethane, concentrated on a rotary evaporator, and blown down to dryness under a stream of nitrogen. The sediments were also extracted using dichloromethane and these extracts were combined with the lipids from the water.

6. <u>Data Processing</u>.

The RD Instruments' data acquisition software "Transect" is used to generate many of the graphics of relative backscatter and current velocity. However, in order to assess depth-related variations of relative acoustic backscatter, current velocity and current direction, two in-house software routines have been developed in order to further analyse the ASCII output from the Transect software. These are Velocity MAP (VMAP) and Backscatter MAP (BMAP). The latter program is concerned with analysis of depth relative variation of the relative backscatter recorded by the ADCP™. Processing of the Transect files involves generating an ASCII file which contains, in tabular format, all the easting, northing, depth and relative backscatter values, as well as all other system and observed variables. These are then modelled using a simple contouring package to produce pixilated images of the contoured relative backscatter levels at required depths for comparison (see Hitchcock, 1997).

RESULTS

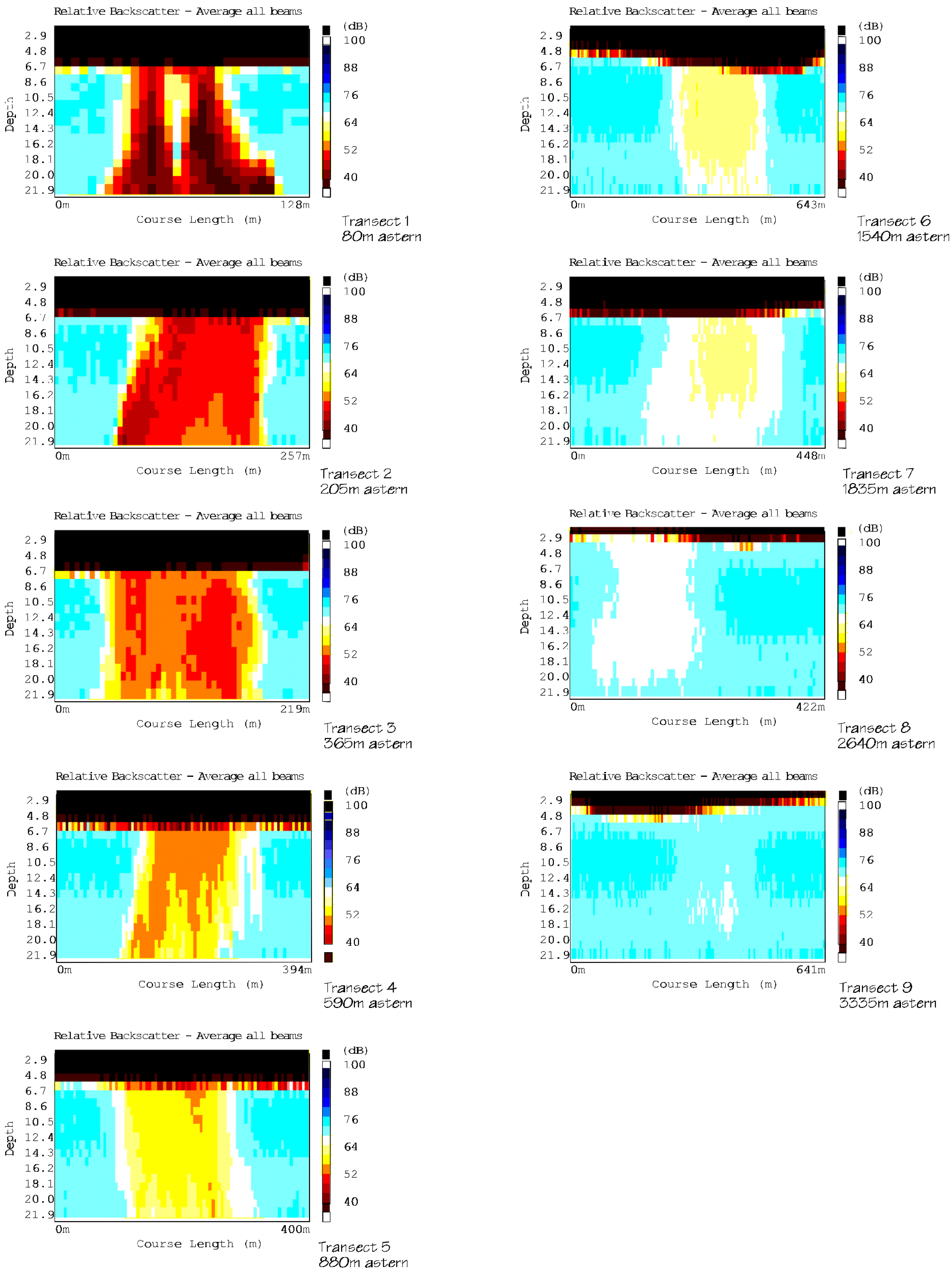
1. DEFINITION OF PLUME MORPHOLOGY.

The results of a plume monitoring programme carried out behind a trailing suction hopper dredger TSHD dredger *City of Rochester* operating whilst anchored on 21st August 1995 are summarized in Figures 1-3. The Acoustic Backscatter Transects were obtained using an RDI 1200kHz Broadband Acoustic Doppler Current Profiler (ADCP). A series of 9 transects was recorded across the plume. Simultaneous current measurements analysed at the start and end of the transect indicate a mean surface flow of 53 cm/sec reducing to 36 cm/sec and a mean bottom flow of 35 cm/sec reducing to 23 cm/sec in a direction of 250 degrees. Water sampling data indicate that at less than 100 m from the dredger, total suspended solids concentrations were 480-611 mg/l in the lower water column and 80-340 mg/l in the upper water column.

Figure 1 shows the distribution of the transects and the horizontal distribution of contours of relative backscatter in relation to the dredger, at depths of 5m, 10m and 15m below the surface. The corresponding vertical depth profiles at varying distances up to 3,350 metres astern of the dredger are shown in Figure 2.

The variation of suspended sediment concentration measured independently by water sampling at various depths and with distance behind the dredger is shown in Figure 3. From this it is clear that at 250 m astern of the dredger the majority of suspended solids are not detectable within the water column above the 6% water depth ADCP data corruption zone above the sea bed. Inspection of Figure 3 also shows that even the finest silt-sized particles largely disappear from the water column within a distance of 480 metres downstream of the dredger.

Figure 2: ADCP cross sections of the relative acoustic backscatter decreasing in intensity with range away from the dredger and becoming more disperse. Identifiable suspended solids concentrations reduce to background at 300m to 500m from the dredger. Sampling has shown that the ADCP is probably discriminating elevated levels of organics beyond this region and as far downstream as 3000m-3500m.



Returning to Figures 1 & 2, it is clear that the acoustic backscatter results still indicate a significant plume of dispersing material beyond the 480 metres where the inorganic particulate load was considered to have reached background levels. This "plume" was detectable visually and by ADCP techniques for a distance of 3335 metres astern of the dredger. This was considered to be due to either aeration (considered unlikely at such distances), physico-chemical precipitates or entrainment of organic matter from the sediments when first reported by Hitchcock & Dearnaley (1994) and Hitchcock & Drucker (1996). The following section presents some estimates of the quantities of organic matter which could be attributable to benthic invertebrates fragmented by dredging within the dredged area.

2. ESTIMATES OF ORGANIC ENRICHMENT BASED ON BENTHIC BIOMASS.

There are relatively few studies where the biomass of benthic invertebrates has been quantified in sufficient detail to allow some estimates of the contribution which they might make to organic enrichment in the dredger outwash. Lees *et al* (1992) have reported that some components of the fauna in the outwash of the suction trailer dredger *Arco Tyne* appeared undamaged, but that worms and many crustaceans appeared susceptible to physical damage as a direct consequence of the dredging operation even if they were subsequently returned to the sea in the outwash. For the purposes of estimating the potential contribution represented by fragmentation of the benthos, it is probably realistic to use figures which are available for biomass reduction in dredged areas. These suggest a figure of some 70-90% reduction of biomass within the boundaries of dredged areas (for review see Newell *et al*, 1998).

Table 1 shows figures for the biomass of benthic macrofauna recorded from coastal sediments in U.K waters prior to dredging. Data are expressed as the maximum values recorded, the minimum values and the mean ash-free dry weight (AFDW) in grams for up to 70 samples taken at 50 stations using a 0.2 m^2 Hamon grab. Data for the biomass have been calculated from the blotted wet weight using conversion factors in Eleftheriou & Basford (1989). Values for a site off Lowestoft, Norfolk have been recalculated from Kenny & Rees (1996), all other values are recorded in reports by Newell & Seiderer (1997a-d).

Table 1. Table showing the biomass of benthic macrofauna recorded from coastal sediments in UK waters prior to dredging. Data are expressed as the maximum values recorded, the minimum values and mean Ash-free Dry Weight (AFDW) in grams for up to 70 samples taken at 50 stations using a $0.2m^2$ Hamon Grab which took an average sample of 17.7 kg sediment. Data for the biomass have been calculated from blotted wet weight using conversion factors from Eleftheriou & Basford (1989). The mean value for all stations has been calculated from the total data where N=242.

SITE	**AFDW of Benthos (g per $0.2m^2$)**					**SOURCE**
	Max	**Min**	**Mean**	**S.D.**	**N**	
Lowestoft, Norfolk	-	-	4.4	-	-	Recalculated from Kenny & Rees (1996)
St.Catherine's, Isle of Wight	48.45	0.03	5.59	8.97	52	Newell & Seiderer (1997a)
Folkestone, Kent	23.5	0.01	4.95	23.55	70	Newell & Seiderer (1997b)
Orford Ness, Suffolk	67.14	0.001	3.18	9.70	60	Newell & Seiderer (1997c)
Lowestoft, Norfolk	21.13	0.01	1.49	3.49	60	Newell & Seiderer (1997d)
MEAN	40.055	0.0127	3.767			
S.D.	21.881	0.0122	14.28			
N	4	4	242			

Inspection of Table 1 shows that the maximum biomass can be as high as 67.14 grams AFDW and as low as 0.001 grams AFDW per 0.2 m^2 Hamon grab sample, reflecting the high variability of benthic community composition in coastal sand and gravels deposits. The average maximum values for all survey areas was 40.06 grams AFDW. The average of the minimum values was 0.0127 grams AFDW and the mean for all 242 samples at all sites was 3.767 grams AFDW per 0.2 m^2 Hamon grab sample.

These data allow some estimates to be made of the likely contribution which fragmented benthos could make to the organic content of outwash from a typical working dredger, assuming complete removal of the benthos along the path of the draghead from the dredger. Field records show that the mean volume of sediment from which the macrofauna was extracted was as follows: St Catherine's, Isle of Wight (not measured), Folkestone, Kent 11.790 litres (SD 5.30; N=133); Orford Ness, Suffolk 13.86 litres (SD 4.31; N=59); Lowestoft, Norfolk 15.13 litres (SD 5.28; N=57). The mean volume sampled per station for all survey areas was 13.6 litres. The specific gravity of the sediments is approximately 1.30, so the average weight of sediment from which the macrofauna was extracted was 17.67 kg. Multiplication by the total amount of sediment processed by a dredger during normal loading operations allows calculation of the biomass of organic matter associated with the dredged material.

Table 2 shows the mass of organic matter (AFDW) estimated to be discharged from a typical marine aggregates dredger of 4,500 tonnes hopper capacity based on the biomass of benthic invertebrates shown in Table 1, the tonnes of sediment processed during a normal loading operation and the volume of water discharged through spillways and screening. Calculations are based on an estimated 12,158 tonnes of solids processed and a total water discharge of 34,866 tonnes (Hitchcock & Drucker, 1996).

Table 2. Table showing the mass of organic matter (AFDW) estimated to be discharged from a typical marine aggregate dredger of 4,500 tonnes hopper capacity. Estimates based on the biomass of benthic invertebrates shown in table 1, the tonnes of sediment processed during a normal loading operation (12,158 tonnes) and the volume of water discharged through hopper spillways and screening chute (34,866 tonnes). The mean value for all stations has been calculated from the total data where N=242.

SITE	**AFDW of Organic Matter estimated to be derived from Benthos**					
	Tonnes per Cargo			**mg AFDW per litre**		
	Max	**Min**	**Mean**	**Max**	**Min**	**Mean**
Lowestoft, Norfolk	-	-	3.0267	-	-	86.809
St.Catherine's, Isle of Wight	32.3284	0.0206	3.8453	995.90	0.5908	110.288
Folkestone, Kent	16.1655	0.0069	3.4051	463.6	0.1973	97.662
Orford Ness, Suffolk	46.1851	0.0007	2.1875	1324.6	0.0197	62.740
Lowestoft, Norfolk	14.5352	0.0069	1.0250	416.9	0.1973	29.398
MEAN	27.55	0.0088	2.592	790.25	0.2513	74.34
S.D.	15.05	0.0084	9.823	431.69	0.2413	281.74
N	4	4	242	4	4	242

Inspection of Table 2 shows that relatively large quantities of organic matter could be derived from fragmentation of the benthos. During a normal loading of 4,500 tonnes of cargo, a maximum of some 46.2 tonnes AFDW of organic matter could be discharged in the 34,866 tonnes of outwash from the dredger. A minimum of 0.0007 tonnes AFDW and an average for all areas of 2.590 tonnes AFDW organic matter discharged per cargo is indicated in Table 2. Since the volume of outwash is known, the concentration of organic matter can be calculated from the biomass data. This indicates that a maximum of 1,324.6 mg AFDW per litre could be derived from the benthic biomass recorded off Orford Ness, Suffolk, and a mean for all areas of 74.34 mg AFDW per litre in the outwash at the point of discharge.

Many of the fragmented marine invertebrates are likely to be rich in lipids, and may thus account not only for the "far field" scatter recorded by ADCP techniques but also the characteristic surface "slick" which can be seen well downstream of the point at which suspended inorganic particle load is indistinguishable from background levels. The following section presents the results of analysis of the outwash from an operational dredger to determine the concentration of organic and suspended solids load which occurs in the outwash of a dredger during normal loading operations.

3. ORGANIC ENRICHMENT OF SPILLWAY DISCHARGES.

Table 3 shows the volume of water, dry weight of particulate matter (grams) and ash-free dry weight (AFDW, grams) of control seawater samples and a series of 20 spillway samples taken during normal loading operations by a modern suction trailer dredger of some 5,000 tonnes hopper capacity. Data are for a cargo loaded off Southwold, Suffolk in April 1998. Values for the background inorganic and organic matter recorded from the control seawater samples have been subtracted in the final column to give concentration of sediment (grams per litre) and organic matter (AFDW mg per litre) in water discharged from the dredger during the course of the loading operation. Samples 1-15 (inclusive) are for an unscreened "all-in" cargo. Samples 16-20 are for outwash from a cargo from which the fine sand component had been removed by screening and discharged through a separate reject chute.

Table 3. Table showing the volume of water, dry weight of particulate matter (g) and Ash-free Dry Weight (AFDW - g) of control seawater and a series of 20 samples of hopper overspill taken during normal loading operations by a modern suction trailer dredger of approx. 5,000 tonnes hopper capacity. Data are for a cargo loaded off Southwold, Suffolk in April 1998. Values for the background inorganic and organic matter recorded from the control sample have been subtracted in the final columns to give sediment concentration (g.l-¹) and organic matter (AFDW mg.l-¹) in the water discharged from the dredger during the course of the loading operation. Samples 53-97 (incl.) are for an unscreened "all-in" cargo. Samples 105-135 are for outwash from a cargo from which the fine sand component had been removed by screening and discharged through a separate reject chute.

Sample #	**Reference #**	**Volume of water (ml)**	**Dry weight (g)**	**Weight after combustion (g)**	**Difference (g)**	**Overspill composition**	
						Sediment (g.l-¹)	**Organic matter (mg.l-¹)**
Control		620	0.4782	0.3196	0.1586	-	-
1	53	790	4.2665	3.9873	0.2792	4.5322	97
2	56	770	6.1127	5.6126	0.5001	6.7736	393
3	59	830	8.1938	7.5065	0.6873	8.5284	572
4	62	800	8.7111	6.2725	2.4386	7.3251	2792
5	65	730	11.599	8.0563	3.5433	10.5205	4854
6	68	640	6.6583	6.2726	0.3857	9.2854	347
7	71	850	10.221	9.4816	0.7397	10.6393	614
8	74	610	10.978	10.1562	0.8218	16.1340	1091
9	79	810	5.9273	5.4039	0.5234	6.156	390
10	82	770	8.3737	7.7814	0.5923	9.5902	513
11	85	900	5.1144	4.9859	0.1285	5.0245	-
12	88	830	16.315	15.5592	0.7561	18.2305	655
13	91	770	12.969	12.1248	0.8444	15.2310	841
14	94	810	11.751	10.6112	1.1398	12.5847	1151
15	97	710	11.251	10.2055	1.0461	13.8584	1217
16	105	840	6.3182	5.6749	0.6433	6.2403	510
17	115	720	18.570	14.2991	4.2711	19.3445	5676
18	120	1070	17.193	15.5822	1.6115	14.0473	1250
19	130	1000	7.7477	7.2049	0.5428	6.6894	287
20	135	580	32.913	30.2219	2.6914	51.5912	4384
MEAN		791.5	11.059	9.8500	1.2093	12.6163	1454.4
SD		116.9	6.5312	5.9167	1.1364	10.1736	1683.9

Inspection of Table 3 shows that the outwash recorded from the dredger working in hitherto unexploited deposits off Southwold, Suffolk comprised approximately 12.6 grams per litre of suspended solids and as much as 1454.4 mg AFDW per litre of organic matter. This is close to the highest value of 1324.6 mg AFDW calculated to be available from the macrofauna reported by Newell & Seiderer (1997c) for the Shipwash Gabbard area off Orford Ness, Suffolk (see Table 2) and may reflect locally rich benthic resources in the dredged deposits off Southwold.

It is clearly of interest to determine whether the lipid content of the organic matter recorded in the outwash is sufficiently high to account for the characteristic surface "sheen" observed in the far field of dispersing outwash plumes downstream from dredging operations. Table 4 summarises the lipid content of a sample of sea water and a series of 20 samples of hopper outwash taken during the loading operation off Southwold, Suffolk in April 1998. Values for the background lipid recorded from the control sea water sample have been subtracted in the final column to give the lipid (mg per litre) in the water discharged from the dredger during the course of the loading operation. Inspection of Table 4 shows that the lipid content of the outwash samples was highly variable, probably reflecting the type of fragmented invertebrate material discharged at the time the samples were taken. Values as high as 50 mg per litre were recorded, the average for the series of 20 samples being 6.94 mg per litre. Based on this average value, the lipids represent 0.48% of the 1454.4 mg per litre organic matter discharged.

Table 4. Table summarising the lipid content of a sample of seawater and a series of 20 samples of hopper outwash taken during normal loading operations by a modern suction trailer dredger of approx. 5,000 tonnes hopper capacity. Data are for a cargo loaded off Southwold, Suffolk, in April 1998. Values for the background lipid recorded from the control seawater sample have been subtracted in the final column to give the lipid concentration ($mg.l^{-1}$) in the water discharged from the dredger during the course of the loading operation.

Sample #	**Reference #**	**Lipid Concentration ($mg.l^{-1}$)**	
		In Sample	**In Overspill**
Control 1		0.12	-
1	53	0.70	0.58
2	56	0.31	0.19
3	59	50.66	50.54
4	62	0.16	0.04
5	65	0.57	0.45
6	68	26.32	26.20
7	71	0.43	0.31
8	74	0.24	0.12
9	82	0.30	0.18
10	85	0.39	0.27
11	88	0.36	0.24
12	91	45.01	44.89
13	94	4.15	4.03
14	97	0.59	0.47
15	105	3.30	3.18
16	110	5.82	5.70
17	115	0.53	0.41
18	120	0.59	0.47
19	130	0.36	0.24
20	135	0.43	0.31
Table 4 (continued)			
MEAN	-	-	6.941
SD	-	-	15.135

It is now possible to summarise the mass discharges and concentrations of materials from a suction trailer dredger of 5,000 tonnes hopper capacity loading a cargo off Southwold, Suffolk in April 1998. The volume of water discharged is based on the difference between the pumping rate of 7750 m^3 and 5.5 hr loading time recorded during the survey, and an average value of 14,073 tonnes recorded for solids pumped during loading. The results are summarised in Table 5.

Table 5. Table summarising the mass discharges and concentration of materials from a suction trailer dredger of 5,000 tonnes hopper capacity loading a cargo off Southwold, Suffolk, in April 1998. Volume of water discharged is based on the difference between a pumping rate of 7,750 $m^3.h^{-1}$ and 5.5 hr loading time recorded during the survey, and an average value of 14,073 tonnes for solids pumped during loading. Values for sediment in the screening reject chute have been estimated from the cargo loaded and pumped solids.

	Total tonnes discharged per cargo	**Concentration measured in outwash ($g.l^{-1}$)**
Water	28,552	-
Sediment in hopper outwash	360	12.608
Sediment rejected by screening	8,713	-
Organic matter (AFDW)	41.5	1.454
Lipids	0.20	0.007

This shows that a total of 28,552 tonnes of water were discharged by the dredger during the loading period of 5.5 hours off Southwold, Suffolk in April 1998. For a cargo of 5,630 tonnes, it was estimated that 8,713 tonnes of material were rejected via the screening chute and 360 tonnes through outwash from the hopper spillways. Organic matter measured in the outwash and assumed to apply to the entire water discharge from both screening chute and hopper outwash was as much as 41.5 tonnes comprising 0.20 tonnes of lipids. The corresponding concentrations recorded in the outwash of the dredger were 12.6 grams per litre of sediment, 1.45 grams AFDW of organic matter and 0.007 grams per litre of lipids. The values for sediment in the outwash are rather lower than the 750 tonnes cited by Hitchcock & Drucker (1996) and may reflect the fact that (a) their original study was for worked deposits on the Owers Bank whereas the outwash data recorded here was for a hitherto unexploited area with a lower proportion of fine material, and (b) the technique of loading differed considerably between the two dredgers (central loading chute in 1996 as opposed to two variable loading towers in 1998).

CONCLUSIONS.

The values cited here are the first direct measurements of the concentration of organic matter in the outwash from a marine aggregates dredger, and are based on a cargo loaded from a hitherto largely unexploited site to the east of Southwold, Suffolk. The values therefore probably represent maximal concentrations for coastal deposits and are likely to be less than this in heavily-exploited areas where the biomass of benthic invertebrates has been reduced within the dredged area.

Clearly, the discharge of as much as 1.45 grams AFDW of organic matter per litre of outwash from the dredger during loading operations in areas where the benthic fauna is rich is sufficient to account for the presence of a detectable "plume" beyond the point at which inorganic suspended solids have fallen to background levels. The fact that significant quantities of lipids are associated with this material may reduce the rate of sedimentation of fragmented material and account for the commonly observed surface "sheen" at the extremity of the dispersing plume.

It is of interest to compare the organic input from dredged material described above with that from a typical detrital-based ecosystem. Kelp bed seawater in the Southern Benguela upwelling ecosystem near Cape Town, South Africa, contains 300-400 mm carbon per litre and 46-71 mg nitrogen per litre (Seiderer & Newell, 1985). Mann (1982) gives the following ratio for AFDW to carbon: 1 gram Carbon = 2.6 grams AFDW organic matter. The detrital load in the seawater of kelp beds is therefore 0.780-1.04 mg per litre. By comparison, the organic loads discharged from the dredging operation recorded above are 1.45 grams per litre. That is, about 1000 times the organic content of some of the richest detrital ecosystems in the world. Even allowing for the dispersion which must occur downstream from the dredger, it seems likely that the organic matter derived from fragmented invertebrates in the dredger outwash is sufficient to account for the enhanced species diversity and biomass of benthic invertebrates beyond the boundaries of dredged areas reported by others (see Poiner & Kennedy, 1984).

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MAFF GUIDELINES

INFORMATION REQUIRED BY UNITED KINGDOM MINISTRY OF AGRICULTURE, FISHERIES AND FOOD, DIRECTORATE OF FISHERIES RESEARCH FOR THE PURPOSES OF EVALUATING THE IMPACT OF SEABED AGGREGATE EXTRACTION ON THE MARINE ENVIRONMENT

(*from* Campbell, 1993)

BACKGROUND

1. The EC Directive on ‘The assessment of the effects of certain public and private projects on the Environment’ (85/337/EEC) was adopted on the 27 June 1985 and came into effect in July 1988. The effect of the Directive is to require an Environmental Assessment (EA) to be carried out, before development consent is granted, for certain types of major project which are judged likely to have significant environmental effects. Exploitation of mineral resources is identified in the Directive as an activity which might, under certain circumstances, require a supporting EA.

2. An explanatory booklet, ‘Environmental Assessment: a guide to the procedures’, has been prepared by the Department of the Environment in conjunction with the Welsh Office (Department of the Environment/Welsh Office, 1989). The booklet describes the legislation and the criteria which trigger the requirement to provide an EA. It also provides guidance for the content of an EA.

3. The guidelines which follow set out MAFF’s requirements relevant to those elements of the environmental assessment of a proposed extraction area for which the Ministry is responsible.

INTRODUCTION

4. The [primary] effects of marine aggregate extraction on the marine environment will be physical, due to possible changes in sediment topography and type through removal of material and resettlement of fine particles. There will also be secondary biological effects as a consequence of seabed alteration and disturbance resulting in modification of benthic infaunal and epifaunal assemblages with consequent effects upon food supply for higher organisms including commercial fish and shellfish species.

5. The International Council for the Exploration of the Sea (ICES) Working Group on the Effects of Marine Aggregate Extraction upon Fisheries has conducted a comprehensive literature review on the impacts on fisheries and the marine environment in general of sand and gravel extraction (ICES, 1992). However, the significance to the wider marine environment of such dredging-induced changes will clearly depend upon the size and location of the licensed areas.

6. The considerations relevant to the deposit of dredged material at sea, including disposal site assessment, contain many common features with those of aggregate extraction. In the UK, dredged material disposal is regulated by a licensing system which reflects undertakings within the International Waste Disposal Conventions (the Oslo and London Conventions). The technical groups within these Conventions have developed specific guidance for dredged material disposal. This guidance forms the basis of the subsequent technical considerations for marine aggregate extraction.

NATURE OF THE DEPOSIT

7. The resource should be identified by its geographical location (latitude and longitude) and described in terms of:

- i the bathymetry of the area;
- ii the distance from the nearest coastline;
- iii the geological history, including the source and type of material, mean thickness of deposit, evenness of the deposit over the proposed extraction area, the nature of the underlying deposits and sediment particle size as well as the geological stability of the deposit;
- iv the natural mobility of the bottom sediments;
- v the presence of current or proposed extraction activities nearby.

8. The total quantity of material in the resource should be estimated along with proposed extraction rates and the expected lifetime of the deposit.

PHYSICAL IMPACT

9. To assess the physical impact of aggregate extraction activities, information should be provided on;

- i local hydrography including tidal and residual water movements;
- ii wind and wave patterns and characteristics, average number of storm days per year;
- iii bedload sediment transport including occurrence of sand waves;
- iv natural suspended sediment loads;
- v storm or wave-induced bottom activity;
- vi transport and settlement of fine sediment suspended by the dredging activity;
- vii dispersion of an outwash plume resulting from hopper overflow or onboard processing and its impact on normal and maximum suspended sediment load;
- viii implications for prevailing wave/current regime and local water circulation resulting from removal or creation of (at least temporarily) topographical features on the seabed;
- ix implications for the modification of longer term processes and bed-load movement;
- x nature and type of nearby coastline and implications for coastal erosion

BIOLOGICAL IMPACT

10 The principal biological impact of marine aggregate extraction is the disturbance and removal of benthic infauna and epifauna and alteration of the substrate upon which colonisation depends. Where the remnant substrate is identical to the undisturbed surface sediments (and this is normally required by licence condition), disturbance may be temporary and the extraction area will be recolonised. To assess the biological impact of aggregate extraction, the following information will probably be required:

- i an assessment of the benthic community structure(s) (species type and abundance) within the proposed extraction area which may include temporal (e.g. quarterly) as well as spatial variations;
- ii information on the fishery and shellfishery resources, including spawning areas, with particular regard to benthic spawning fish (e.g. herring and sand eels), nursery areas, over-wintering grounds for ovigerous crustaceans and known routes of migration;
- iii the predator/prey relationships between the benthos and demersal fish species (e.g. by stomach content investigations);
- iv the method of dredging, including the effect of different suction equipment upon the seabed and benthic fauna;
- v the estimated recolonisation time for the denuded sediments;
- vi a list of areas of special scientific or biological interest, such as adjacent Sites of Special Scientific Interest (SSSI), Marine Nature Reserves (MNR) and Marine Consultation Areas (MCA), Marine Special Protection Areas (SPA), sites designated under the 'Ramsar' convention, the World Heritage Convention or the UNEP 'Man and the Biosphere' Programme;
- vii areas of natural beauty or significant cultural or historical importance in or adjacent to the proposed extraction area.

INTERFERENCE WITH OTHER LEGITIMATE USES OF THE SEA

11 The assessment should consider the following in relation to the proposed programme for exploitation of the resource;

- i the number of vessels to be used and the duration of dredging campaigns (for example, daily, weekly, occasionally);
- ii seasonal commercial fishing patterns, including type of gear used, distribution, value and number of fishermen involved;
- iii shipping lanes;
- iv military exclusion zones;
- v engineering uses of the seabed (e.g. adjacent extraction activities, undersea cables and pipelines);

- vi adjacent areas of the sea designated as sites for the disposal of dredged material and sewage sludge;

- vii location of wrecks (with an indication of their historic status) and war graves;

- vii recreational uses of the area (e.g.. sport angling, diving).

EVALUATION OF IMPACT

12 In evaluating the overall impact, it will be necessary to identify and quantify the marine and coastal environmental consequences of the proposed activity and the basis of a monitoring plan as well as setting out why the proposal is not thought likely to effect other interests of acknowledged importance to the area.

13 These consequences can be summarised as an Impact Hypothesis, which will draw on the results of earlier studies of environmental characteristics and their variability. The Impact Hypothesis will also indicate where measures need to be taken to mitigate the effects of the proposed dredging or associated operations.

14 It will then be necessary to consider the steps that might be taken to mitigate the effects of extraction activities. This may include:

- i the selection of dredging equipment and timing of the dredging operations to limit impact on benthic communities and spawning cycles;

- ii modification of dredging depth limit changes to hydrodynamics and sediment transport;

- iii zoning the area to be licensed or scheduling extraction campaigns to protect sensitive fisheries or to respect access to traditional commercial fisheries.

15 It may also be necessary to demonstrate the need to exploit the resource in question, through careful, comparative consideration of local, regional and national need for the material in relation to the identified impacts of the proposal and the relative environmental costs of provision from other sources, both marine and on land.

MONITORING

16 **Definition:** In the context of assessing and controlling the environmental effects of marine aggregate extraction, monitoring is the repeated measurement of an effect whether direct or indirect on the marine environment.

17 Monitoring of the marine environment is generally undertaken for the following reasons;

i to establish whether licence conditions are being observed;

ii to establish whether licensing conditions are preventing extraction activities having adverse effects on the marine environment;

iii to provide the necessary evidence to demonstrate that the control measure applied are sufficient to ensure that any lasting environmental damage does not result from exploitation of marine resources;

iv to improve the basis on which licence applications are assessed by improving knowledge of field effects which are not readily estimated by laboratory or literature assessment.

18. Monitoring operations are expensive for they require considerable resources both at sea and in subsequent sample and data processing. In order to approach a monitoring programme in a resource-effective manner, it is essential that the programme should have clearly defined objectives, that measurements made can meet those objectives, and that the results be reviewed at regular intervals in relation to those objectives. The monitoring scheme should then be continued, reviewed or even terminated.

19. **Impact Hypothesis**: The Impact Hypothesis prepared from the environmental assessment summarises the effects of the proposal on the marine environment. It is an important element in the establishment of a monitoring programme. Before any monitoring programme is drawn up and any measurements are made, the following questions should be addressed;

- i what measurements are necessary to meet specified objectives?
- ii what is the purpose of monitoring a particular variable or biological effect?
- iii in what environmental compartment or at what locations can the measurements be made cost effectively?
- iv how many measurements are necessary to meet specified objectives
- v for how long should the measurements continue to be made to meet the objective?
- vi what should be the temporal and spatial scale of measurements be made to test the hypothesis?

20. The extraction of marine aggregate has a primary impact at the seabed. Thus, although a consideration of water column effects cannot be discounted in the early stages of planning the monitoring, it is often possible to restrict subsequent monitoring to the seabed.

21. Where it is considered that the effects will be largely physical, monitoring may be based on remote methods such as sidescan sonar to identify changes in the character of the seabed. These measurements may require a certain amount of sediment sampling to establish ground truth.

22. Biological sampling to assess changes in the benthic community structure may also be appropriate provided there is a scientific basis for the interpretation of the resulting data.

23. In order to assess the impact, it will be necessary to take account of any natural biological variability. This is best achieved by comparing the physical or biological status of the affected areas with reference sites located away from the extraction site. Such reference sites can be identified during the preparation of the Impact Hypothesis.

24. The spatial extent of sampling will need to take into account the area designated for extraction, any possibility of operating outside the licensed area and the mobility of fine material raised into suspension by the dredging activity.

25. Since the effects of marine aggregate extraction will have some similarities in different sites, it will be appropriate to conduct biological monitoring programmes at a few carefully chosen sites. It is also appropriate to consider 'far afield' effects of extraction such as the relationship between spawning grounds and areas of recruitment. Measurements relating to the timing of extraction should be conducted at each site.

26. Concise statement of monitoring activities should be prepared. Reports should detail the measurements made, results obtained, their interpretation and how these data relate to the monitoring objectives. The frequency of monitoring will depend on the aims and will be related to the scale of extraction activities and the anticipated period of consequential environmental changes which may extend beyond the cessation of extraction activities.

PREPARATION OF ENVIRONMENTAL STATEMENT

27. The environmental statement should describe the information used as the basis of the environmental assessment and should set out the results of the assessment in the form of an Impact Hypothesis. It will detail all the significant effects of the proposal that have been identified and briefly explain why the proposal is unlikely to affect other interests or areas of acknowledged importance in the vicinity of the proposal.

28. The environmental statement should set out any measures or changes to the proposal designed to ameliorate the effects of the proposal that were identified in the Impact Hypothesis. Where it is not possible to ameliorate the effects of the proposal the statement should provide details of the reasons why the benefits of the proposal outweigh its environmental effects.

29. The environmental statement should describe the monitoring needed to ensure that the Impact Hypothesis is valid and any ameliorative measures are effective.

EXAMPLE OF A SCOPING DOCUMENT FOR ENVIRONMENTAL ASSESSMENT FOR A MARINE DREDGING PROPOSAL (*from* ICES, 1993)

SCOPE

The form and content of the Environmental Statement are anticipated to be as follows;

1 Project Details

⇒ location and size of licence area;
⇒ volume of material to be extracted;
⇒ type of material to be extracted;
⇒ proposed method of dredging;
⇒ vessel numbers and movements;
⇒ dredging programme, including phasing, period of working and frequency;
⇒ discharge of fines - quantity and composition;
⇒ onshore proposals - landings and onward transportation;
⇒ project related employment.

2 The Site and its Environment

a) Physical Aspects

⇒ bathymetry of licence areas and surroundings;
⇒ geological history - type of material, mean thickness and evenness across the area, nature of underlying deposits;
⇒ local hydrography - currents, tides and residual water movements, wave patterns, meteorological influences such as storm frequency;
⇒ stability, mobility and turbidity of bottom sediments and natural suspended sediment loads;
⇒ water quality and existing pollution levels.

b) Biological Aspects

⇒ the benthic community structure - species type and abundance, temporal and spatial variations;
⇒ the fishery and shellfishery resource - including sole areas, nursery areas, over-wintering grounds for ovigerous crustaceans and known routes of migration;
⇒ predator/prey relationships between the benthos and demersal fish species;
⇒ context of the biotic resource in relationship to the surrounding area - i.e. its *relative* importance.

c) Human Environment

⇒ economic importance of the fishery and shellfishery resource - catch and landing statistics, value and employment levels;
⇒ other dredging activity in adjacent areas - existing and/or proposed;
⇒ waste disposal, including sewage sludge;
⇒ offshore oil and gas industry - adjacent exploration and/or production activity, pipelines;

⇒ other seabed features - cables, wrecks, war graves;
⇒ shipping lanes/navigation requirements;
⇒ MoD exclusion areas and uses;
⇒ leisure activities in the area.

d) The Policy Framework

⇒ statutory designations;
⇒ relevant EC directives, conventions and agreements;
⇒ UK Government Policy, Mineral Planning Guidance Notes and aggregates policy.

3 Assessment of Effects

An analysis of the likely significant effects, including a description of the forecasting methods used.

a) Physical Effects

⇒ effects of dredging directly on the seabed - including condition of the substrate after dredging;
⇒ effects of removal of material on the natural sediment movement regime and topographical features on the seabed, including potential effects on coastal erosion and deposition processes;
⇒ implications of changes in topographical features on prevailing wave/current regime and local water circulation;
⇒ information on predicted transport and settlement of fines suspended by the dredging activity, from an outwash plume or from on-board screening/grading.

b) Biological Effects

⇒ effects of dredging activity on the benthic infauna and epifauna including any transboundary effects;
⇒ estimated recolonisation time for the denuded sediments;
⇒ effects of the settlements of fines on the benthic community over the predicted affected area;
⇒ further analysis of the effects on the fishery and shellfishery resources, including spawning areas, with particular regard to sole fisheries, crustaceans, and the predator/prey relationship between the benthos and demersal fish species.

c) Effects on Human Environment

⇒ analysis of the consequences of any predicted changes in fishing patterns, including landings, value and employment;
⇒ effects on, or conflicts with, other existing or proposed sea uses - adjacent dredging areas, oil and gas industries, dumping, navigation, MoD activities, cables and pipelines, wrecks etc.;
⇒ employment in dredging activities.

d) Other Indirect and Secondary Effects

⇒ indirect employment implications at receiving ports;
⇒ onward transportation from receiving ports.

4 Mitigation of Effects

The steps proposed to mitigate the effects of extraction activities. These may include:

⇒ measures to limit impact on benthic communities and spawning cycles through the selection of dredging equipment and timing of dredging operations;
⇒ measures to protect fisheries interests through zoning the licence area and/or scheduling extraction to avoid the most sensitive seasons;
⇒ modification of dredging depths to limit changes to hydrodynamics and sediment transport.

5 Accident, Risks and Hazards

⇒ measures to safeguard against identified risks - primarily shipping risks

6 Monitoring

⇒ setting of objectives for a monitoring programme;
⇒ proposals for monitoring arrangements before, during and after dredging operations, in order to meet the specified objectives.

7 Non-technical Summary

⇒ a non-technical summary of the information provided in the ES