INTRODUCTION

1.1 Background to the Study.

The Office of International Activities and Marine Minerals Division (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 all mineral resources within federal waters of the Outer Continental Shelf (OCS). This zone extends seaward from 3 miles offshore of the State Coastline Boundary to 200 miles offshore. Recent years have seen an increasing interest in the sand and gravel resources of this zone largely associated with increasing awareness of oceanographic, geomorphologic and environmental problems associated with aggregate extraction within nearshore State waters.

MMS has the authority under Public Law 102-426 (43 U.S.C. 1337(k)(2)) (31.10.1994) to negotiate, on a noncompetitive basis, the rights to OCS sand, gravel, and shell resources for shore protection, beach and wetlands restoration projects. Resources may also be used in construction projects funded in whole or part by or authorized by the Federal government. In 1999, this law was amended to prohibit charging State and local governments a fee for using OCS sand resources, although competitive leasing and fees remain for other uses, including commercial recovery of offshore sand and gravel for use as construction aggregate.

Recognising the technological, environmental and legislative management practices forged during the successful development of the United Kingdom marine aggregate industry, and continuing the valuable exchange of technical and environmental information between the U.S. and U.K., the MMS initiated a second project with Coastline Surveys Limited assisted by Marine Ecological Surveys Limited. This project would build not only on the conclusions of the first generic project carried out in the UK by the same contractors (Hitchcock *et al*, 1998), but also integrate subsequent research in the U.K. closely with other MMS coordinated projects in the U.S.

The project encompasses several key elements of interest to INTERMAR and the Marine Minerals Programme of MMS. Principally, the requirements for integrated information regarding the impact of benthic and surface sediment plumes, on physical and biological resources of the seabed, previously identified as a key requirement in several INTERMAR and State/Federal Task Force documents, are addressed by this project.

MMS maintains a full listing at www.mms.gov/intermar/environmentalstudiespage.htm of studies completed under the OCS Marine Studies Program:

Completed Studies

Marine Mining Literature Search Study (Generic)
Marine Mining Mitigation and Technology Study (Generic)
Marine Mining Placer Mining Test (Generic)
West Florida Shelf Benthic Repopulation Study (Generic)
Wave Climate Modeling and Evaluation Relative to Sand Mining on Ship Shoal, Offshore LA, for Coastal and Barrier Islands Restoration (Site-Specific)
Synthesis of Hard Mineral Resources on the Florida Panhandle Shelf (Site-Specific)
Environmental Surveys of OCS Sand Resources off Virginia (Site-Specific)
Investigation of Benthic and Surface Plumes Associated With Marine Aggregate Dredging Activities (Generic)
Environmental Surveys of OCS Sand Resources Offshore Alabama (Site-Specific)
Development of Criteria to Evaluate Wave Refraction Models (Generic)
Surveys of Sand Resource Areas Offshore Maryland/Delaware and the Environmental Implications of Sand Removal for Beach Restoration Projects (Site-specific)
Environmental Surveys of OCS Sand Resources Offshore New Jersey (Site-specific)
Wave Climate and Bottom Boundary Layer Dynamics with Implications for Offshore Sand Mining and Barrier Island Replenishment, South-Central Louisiana (Site-specific)
Study of the Cumulative Effects of Marine Aggregate Dredging (Generic)
Design of a Monitoring Protocol/Plan for Environmentally Sound Management and Development of Federal Offshore Sand Borrow Areas Along the United States East and Gulf of Mexico Coasts (Generic)
A Numerical Modeling Examination of the Cumulative Physical Effects of Offshore Sand Dredging for Beach Nourishment (Generic)

Ongoing Studies

Collection of Environmental Data Within Sand Resource Areas Offshore North Carolina and the Environmental Implications of Sand Removal for Coastal and Beach Restoration (Site-specific; Draft report will be delivered late November 2002)
Integrated Study of the Biological and Physical Effects of Marine Aggregate Dredging (Generic; Final report will be delivered January 2003)
Environmental Surveys of Potential Borrow Areas on the East Florida Shelf and the Environmental Implications of Sand Removal for Coastal and Beach Restoration (Site-specific; Draft report expected lend of calendar year Summer 2002; Final Report February 2003)
Environmental Surveys of Potential Borrow Areas Offshore Northern New Jersey and Southern New York and the Environmental Implications of Sand Removal for Coastal and Beach Restoration (Site-specific; Draft report due mid-February 2003; Final report due mid-April 2003)
Model Development or Modification for Analysis of Benthic and Surface Plume Generation and Extent During Offshore Dredging Operations (Generic; Final products due February 2003)
Winter Water Bird Survey of Offshore Shoals From Northern New Jersey to the Virginia/North Carolina Border (Interagency Agreement with Fish and Wildlife Service) (Final report due September 2003)
Field Testing of a Physical/ Biological Monitoring Methodology for Offshore Dredging and Mining Operations (Generic/Site-specific – being conducted at Sandbridge Shoal, offshore Virginia via Cooperative Agreement with VIMS) (Phase 1: $58,000; Phase 2: $564,469)(Final report due May 2004)
Environmental Investigation of the Use of Shoals Offshore Delaware and Maryland by Mobile Benthos and Finfish Species (Site-specific/Generic; Final Report due January 2005)
Worldwide Analysis of Shipwreck Damage Caused by Offshore Dredging: Recommendations for Pre-operational surveys/mitigation During Dredging to Avoid Adverse Impacts (Generic) (Final report due November 2003)
Wave-Bottom Interaction and Bottom Boundary Layer Dynamics in Evaluating Sand Mining at Sabine Bank for Coastal Restoration, Southwest Louisiana (GOM LSU CMI) (Final report due May 2005)

Studies to be Procured FY 2003

Investigation of Finfish Assemblages and Benthic Habitats Within Potential Borrow Areas in Federal Waters Offshore Southeastern Texas and Southwestern Louisiana
Review of Existing and Emerging Environmentally-Friendly Offshore Dredging Technologies (Budgeted Amount
Analysis of Potential Biological and Physical Dredging Impacts on Offshore Ridge and Shoal Features/Engineering Alternatives and Options to Avoid Adverse Environmental Impacts
Focused Analysis/Review of Benthic Assemblages on Ridge and Shoal Features of the U.S. East and Gulf of Mexico Coasts

Table 1.1: Completed and planned studies commissioned by the Environmental Studies Program, INTERMAR.

1.2 Purpose of the Study

Confirming the importance of generic research programs, USACE Technical Note DOER-E2 (December 1998) assessed the implications of environmental windows on operations and maintenance (OM) dredging in marine and freshwater environments, including removal of sands and gravels. Importantly, DOER-E2 identifies that 68% of USACE Districts cite turbidity, suspended sediments and/or sedimentation issues as a reason for enforcing environmental windows for operations. The authors observe that many restrictions are emplaced on the basis of ‘limited, subjective or non-existent’ data, possibly exceeding precautionary principles, and leading to controversial costs implications.

For the past decade or so, a good deal of concern has been expressed about the potential impact of marine aggregates extraction on coastal resources (International Council for the Exploration of the Sea, ICES, 1992a,b; 1993, 2001, 2002). This includes impacts on the physical composition and stability of coastline features, on fish and fisheries (*see,* for example, Wilber and Clarke, 2001), wildlife resources and on the marine food webs upon which they depend. Much of this concern in British waters centers on the possible impact of dispersed material rejected *via* the reject chute and spillways during the dredging process and which has been variously estimated to travel up to 15-km on each side from the point source of discharge by the ebb and flood tidal streams.

Studies from the early to mid 1990s off the Dutch coast (van Moorsel and Waardenburg, 1990, 1991; van Moorsel, 1993, 1994) and off the Norfolk coast (Kenny and Rees 1994, 1996) have concentrated mainly on the impact of dredging operations on the variety and abundance of bottom-dwelling (benthic) species within dredged areas, and on the subsequent recovery of diversity and biomass following cessation of dredging. The possible scale of impact of sediment deposition outside the immediate dredged area is, however, largely unknown. It remains a key factor in assessing the likely impact of marine aggregate mining on other uses of the marine environment including recreation, commercial fisheries and aquaculture, and conservation of biological and other resources including historic wreck sites.

Partly to address the question of the scale of physical impact outside the immediate dredged area, Acoustic Doppler Current Profiling (ADCP) techniques have recently been used in studies of plume dispersion from both commercial aggregate dredgers (Hitchcock and Drucker, 1996) and in relation to spoils disposal from capital dredging works (Whiteside, Ooms and Postma, 1995). These studies essentially confirm that the initial sedimentation of material discharged during spoils disposal or from 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 where particles are held together by cohesion during the initial phase of the sedimentation process.

In an earlier study carried out by Hitchcock *et al.* (1998) and funded primarily by the Minerals Management Service, U.S Department of the Interior, Washington (Contract No 14-35-001-30763), evidence was presented which showed that the fate of material rejected by screening during marine aggregate dredging can be defined by Acoustic Backscatter Profiling (ABP) techniques combined with conventional water sampling methods (Thevenot and Johnson, 1994; Weiergang, 1995; Hitchcock and Dearnaley, 1995; Hitchcock and Drucker, 1996; Hitchcock *et al.,* 1998).

The results of that study, obtained mainly from the Owers Bank on the south coast of U.K. and the work of others (*see* Land *et al.,* 1994; Whiteside *et al.,* 1995) suggested that the settlement of material from the water column is controlled by the velocity of entry and the complex cohesion properties of the reject material *en masse*, rather than by the density and dispersion rates of individual particles in the discharge.

As a result, the zone of initial deposition of reject material from commercial aggregate dredgers is much less than that predicted from some simple dispersion models based on Gaussian diffusion principles. Direct measurement of the rate of settlement of inorganic components of the screened material show that deposition is mainly confined to distances of up to 1 km from the point of discharge, a result which is confirmed by direct measurements of deposition rates on the sea bed (*see* also Gajewski and Uscinowicz, 1993).

Hitchcock *et al.* (1998) summarised the impact of marine aggregate dredging on benthic biological resources, and rates of recovery reported following the cessation of dredging in varying types of deposits, based on reports in the literature worldwide. These studies showed a 60-80% reduction in population density, species diversity and biomass within dredged areas. Recolonisation and recovery of biomass was reported to vary from a few months to up to 15 years. Review of the literature suggested that the rate of recovery was fastest in unconsolidated deposits such as muds and sands; these are colonised by 'opportunistic' species that are well adapted to rapid recolonisation and growth following episodic mortality.

In contrast, more consolidated and coarser deposits are colonised by a wide variety of slow growing 'equilibrium' species that may take several years for recolonisation following disturbance. In general, a period of 2-3 years has been commonly recorded for restoration of species composition and benthic biomass in sands and gravels that are exploited by the marine aggregates industry in the U.K. (Hitchcock *et al.*, 1998; Newell *et al.*, 1998).

Despite the information that is available on the impact of dredging on biological communities on the sea bed, there have been surprisingly few comprehensive studies on the impact of dredging and the nature of the recolonisation and recovery processes within commercially-exploited areas. The studies by Kenny and Rees (1994, 1996) and by Kenny *et al.* (1998) on an experimentally-dredged site off the coast of Norfolk, U.K., suggest that initial colonisation may occur within months of the cessation of dredging, but that the process of stabilisation of community structure and restoration of biomass may take several years.

Recent studies by van Dalfsen and Essink (1997), Essink (1997), van Dalfsen *et al.* (1999), Désprez (2000) and Sardá *et al.* (2000) support the view that the process of recolonisation and recovery in commercially-exploited sand borrow sites is a complex one involving initial colonisation by fast-growing 'opportunistic' species that are replaced and supplemented by a wider species diversity of slow-growing 'equilibrium' species after cessation of dredging. Such work has been confined to the dredge sites themselves. No data have hitherto been available on the impact of discharge of material by screening and outwash from the dredger beyond the immediate boundaries of the dredged site.

The quantities of material rejected by screening are significant, and have a potential for impact on biological communities outside the boundaries of the dredged area. Estimates by Hitchcock and Drucker (1996) showed that for a 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 were discharged through overspill and as much as 7,223 tonnes from the screening reject chute, per cargo.

In a more recent study of a newly exploited deposit off Southwold, Suffolk, U.K. in April 1998, it was shown that for a cargo of 5,630 tonnes, 8,713 tonnes of material were rejected through the screening chute and 360 tonnes through outwash from hopper discharge (Newell *et al.*, 1999). That is, estimates to date suggest that 1.6-1.7 times the cargo load is discharged into the surrounding water column during normal loading of a screened cargo of gravel in U.K coastal waters. This figure may be higher for particular cargoes, reaching 3-4 times the cargo load (Hitchcock and Drucker, 1996).

This material comprises not only a large inorganic particulate load, but also contains significant quantities of organic matter. Values recorded in dredger outwash for newly exploited deposits off Southwold, Suffolk, were as high as 1.454 g per litre ash-free dry weight (AFDW) of which 0.007 g per litre (0.48%) comprised lipids (Newell *et al.*, 1999). This organic matter appears to be derived from fragmented benthic invertebrates 'processed' during dredging. Such material has a much lower specific gravity than the inorganic components of the dredger outwash and may be associated with 'far field' acoustic backscatter which is detectable at distances of as much as 3,335 m downstream of a dredger during normal loading of a screened cargo off the Owers Bank, U.K. (Hitchcock and Drucker, 1996; Hitchcock *et al.*, 1998).

Newell *et al.* (1999) suggested that the organic enrichment from fragmented invertebrates in the dredger outwash may account for the enhanced benthic species diversity and population density of benthic invertebrates commonly recorded beyond the boundaries of dredged areas (*see* Poiner and Kennedy, 1984). There have, however, been no direct studies of organic content of the outwash of dredgers in heavily exploited areas, nor of the impact of either this material or the particulate components on biological communities outside the boundaries of dredged areas.

1.3 Study Objectives.

Overspill and, more importantly, screened and rejected material will disperse downstream and cause an impact. It is important that this is quantified. There have been many predictions of dispersion by modeling techniques and many of these have subsequently been modified, sometime substantially, in the light of our fieldwork programmes. Assessment of the actual impact on the seabed (physical and biological) will enable correlation with the predicted dispersion of material, actual dispersion of material (footprint) and impact of settled material (footprint of significant impact, rather than any impact no matter how small).

The evidence from the ADCP studies referred to above firmly suggests that the biological impact of sediment deposition surrounding a dredged area is likely to be much smaller than has been predicted from conventional sediment deposition simulation models in the past, and there is a good deal of scattered information in the literature supporting this view. The principal theme of this project is therefore to carry out an *integrated* Physical and Biological Resource Impact study on a *worked* site with a view to establishing the nature and extent of impact contours on the seabed surrounding the dredged site. The scope and methodology for the project follows from the research requirements identified from a comprehensive review of the impact of marine aggregates dredging on the physical and biological resources of the seabed (Newell, Seiderer and Hitchcock, 1998).

With the above in mind and taking note of ongoing developments in this and other projects, the study necessarily adapted to best resolve the following key questions in relation to marine aggregate mining in a commercially-worked Licence Area:-

- Does the use of ADCP techniques supported by traditional water sample characterisation still provide a best value approach to defining the gross morphology of the dispersing plume and any sub-divisions attributable to different sources and processes?

- Is there a detectable impact on the sedimentary provinces that may be caused by marine aggregate mining?

- Can high-resolution sidescan sonar mosaic imagery provide broad scale mapping at sufficient resolution to identify any impacts due to mining operations either due to changing sedimentary or biological community?

- Is there a detectable impact of marine aggregate mining on key features of benthic biological community structure including species diversity (*S*), population density (*N*), biomass (*B*) or body size (*B/N*)?

- Is there a detectable impact on community structure as assessed by non-parametric multivariate techniques?

- How far beyond the immediate limits of the dredged area do such impacts extend?

- Can any impact on community structure beyond the boundaries of the dredged area be related to 'far-field' deposition of material in the outwash?

- Are there differences in impact of anchor dredging where material is essentially exploited at one site, and trailer-dredging over a wider area?

- What is the nature and rate of the recolonisation and recovery processes in a commercially dredged area?

- Can any recommendations be made on the scale, frequency and number of samples required for cost-effective monitoring of the impact of sand and gravel mining on sea bed resources?

1.4 Project Structure

The project team structure is shown below (Figure 1.4). The integration of physical and biological components within the same project is fundamental to providing coherent results and recommendations that are applicable and acceptable to the industry and regulatory authorities.

Within the organisations we hold all personnel, equipment and experiences necessary to complete the works. This has been used to maximum benefit for the project with some of the adverse weather problems encountered during fieldwork at the site being overcome by team members, resources and facilities being able to be diverted from other neighbouring projects to collect data at reduced re-mobilisation costs. Experience shows clearly that dredge plume monitoring must be conducted during calm, clear conditions in order to precisely co-locate the ADCP, water samples, and other monitoring devices with reduced geographical error.

The research platform for all survey work was the multi-purpose research and survey vessel M.V. FlatHolm. This 300-dwt vessel provided a stable research base for the work with accommodation and endurance enabling intensive field campaigns to maximise the short weather windows that were available. Dedicated survey accommodation enabled the complete spread of equipment to be mobilised at once, with enough room for sample storage (nearly 3000kg of sediment samples were obtained).

Faunal identification for biological community analysis is also carried out within the team structure at the premises of Marine Ecological Surveys Ltd (MESL). MESL staff hold British Natural History Museum Id.Q. qualifications in marine macrofaunal identification. The responsiveness of the laboratory has further enabled samples obtained at opportune times to be analysed quickly.

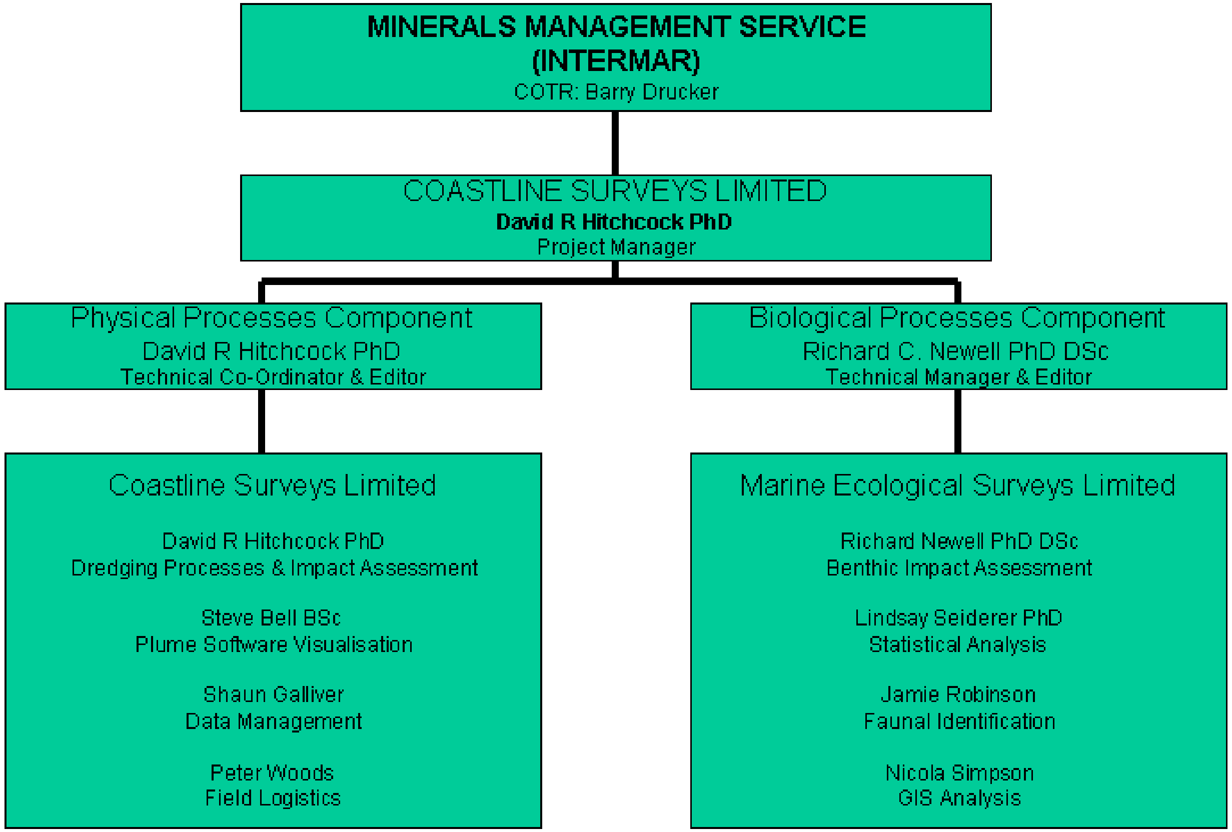


Figure 1.4 Management diagram showing key personnel, affiliations and primary responsibilities.

Plate 1.4. 24m Research and survey vessel M.V. Flat Holm used for the surveys at Licence Area 122/3

1.5 Study Site North Nab 122/3

Choice of a suitable study site presented some difficulties because the effects of the dredging process itself, important for the U.S. industry case, needed to be distinguished from secondary impacts of discharge of overboard screened material. A complicating factor is that in many dredged sites, trailer dredging occurs over a relatively wide area so that impacts may be dissipated in space and time.

A small heavily-exploited aggregate area to the east of the Isle of Wight, off the south coast of U.K. known as the North Nab Production Licence Area 122/3 was selected as study site for a number of clear cut reasons. This site is licensed to and managed by United Marine Dredging Ltd (UMD). Firstly, although the amount of aggregates removed from the area is quite low, up to 150,000 tonnes per annum, material is extracted from very localised 'sweet spots', each of the order of a few hundred metres square. This makes the operation one of the most intensively dredged sites per unit area. Secondly, the area was licensed in 1989 and has a comprehensive historical record of dredging activities, locations and volumes. Any impacts that may be created by the operations could reasonably be expected to be established by the time of the investigation. Finally, although material is not screened (common in many U.K. operations, especially in the North Sea), 'all-in' loading without screening is a feature of 75% of South Coast licences (A. Bellamy, *pers. comm.*). It is also the predominant technique of loading cargoes in the U.S., although recent signs are that screening of cargoes (rejection of unwanted particle size fractions at sea, or *beneficiation*) may become prevalent in the U.S. as well.

The North Nab study area is therefore representative of the majority of the Licence Areas on the south coast of the United Kingdom, in contrast with those of the southern North Sea which are generally heavily-screened, usually to remove unwanted sand-sized fractions. Smaller dredgers, *circa* 2300 tonnes capacity, mainly operate on the North Nab licence Plate 1.5a).

The location of the study site and boundaries of the Licence Area are shown in Figures 1.5a and 1.5b, together with the strength and direction of the tidal streams and broad boundaries of the area surveyed. Figure 1.5c records the sampling stations. Within the boundaries of Licence Area 122/3, also shown are the sub-areas that have been exploited for gravel by different techniques (trailer suction dredging or anchor suction dredging), and the time since dredging started.

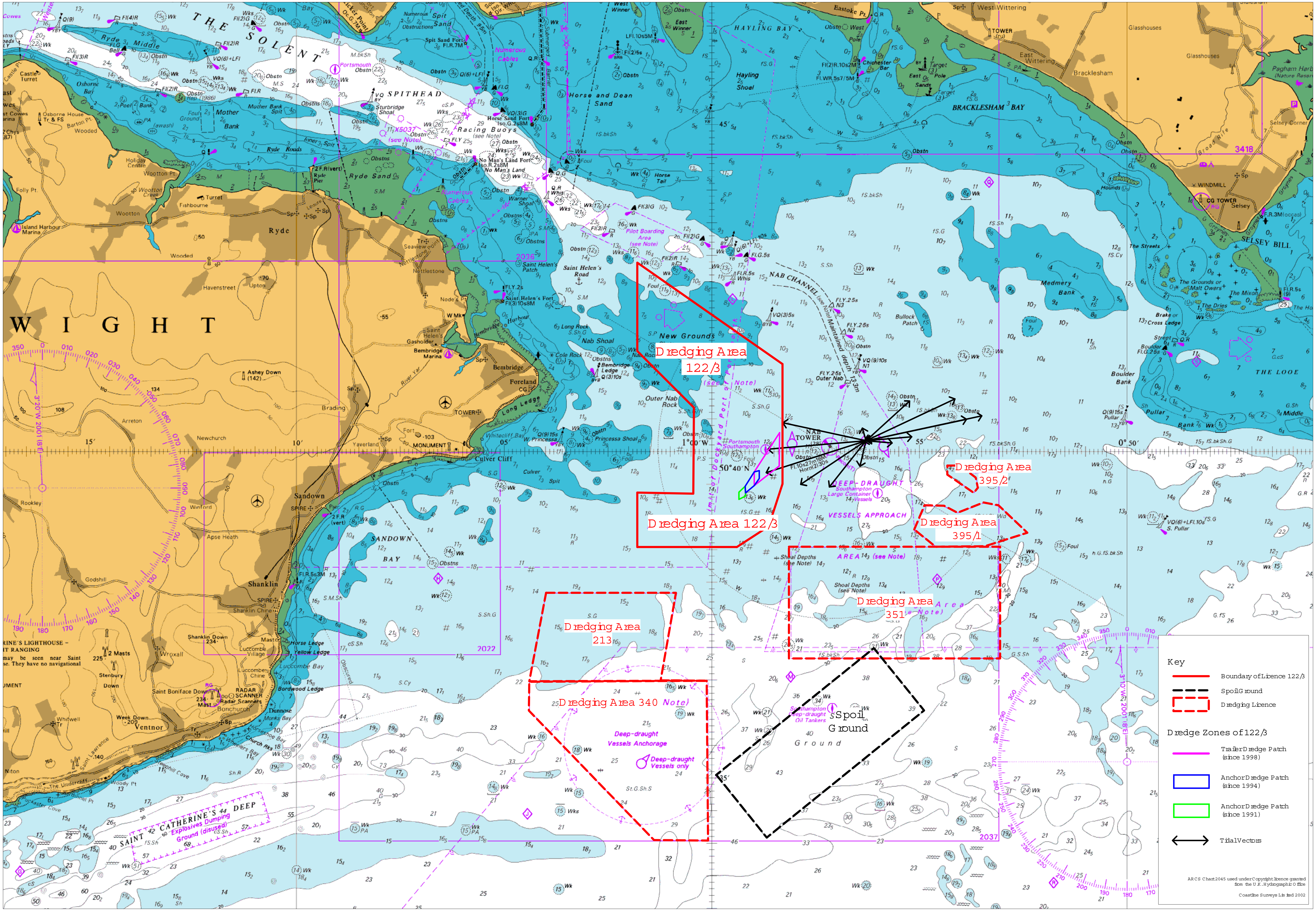


Figure 1.5a: Map of the Survey Area & Licence 122/3 in relationship to the Isle of Wight, bathymetry and adjacent dredging licences

Plate 1.5a. *City of Chichester* 2300 tonne capacity dredger operated by UMA working on the North Nab licence.

The variety of loading techniques at North Nab is important for several reasons. Firstly, the presence of the two techniques in two distinct zones can be used to make a first comparison to assess the individual impact of the two principal methods of aggregate exploitation on benthic biological communities, although it should be pointed out that less material is removed by trailer dredging than from the anchor-dredged site. Differences between the two dredging sites may therefore reflect dredging intensity, rather than the type of dredging method used.

Secondly, the results also allow some comparisons of the nature of the recolonisation processes and rates of recovery in relation to anchor-dredging and trailer-dredging, as well as an assessment of the impact of the relatively small quantities of material discharged in the outwash for unscreened ('all-in') cargo loads.

Third, on a practical point, measurements of plume generation and decay originating from an anchored vessel are more straightforward to interpret on the basis of time-distance plots, due to the single source location. A trailing vessel will have a moving discharge zone that will compound the interpretation of the stage of plume development at any given point and hence time. Similarly, the variable distance from the moving discharge point will compound impacts observed at any point on the seabed. This is important for determining not only the source terms for development of predictive models and assessments of impact for new extraction licences, but very important for field validation of the outputs from models.

It is important to emphasise, however, that what is not included in this study is an assessment of the impact of the large quantities of material discharged through reject chutes as part of the screening process, common in other licence areas (Plate 1.5b), as mentioned earlier. Similarly it is not known to what extent this quantity of material would affect physical impacts on sediment distribution, transport and sedimentation, bedforms etc, nor the biological impacts and rates of recolonisation reported in this project for North Nab Licence Area 122/3.

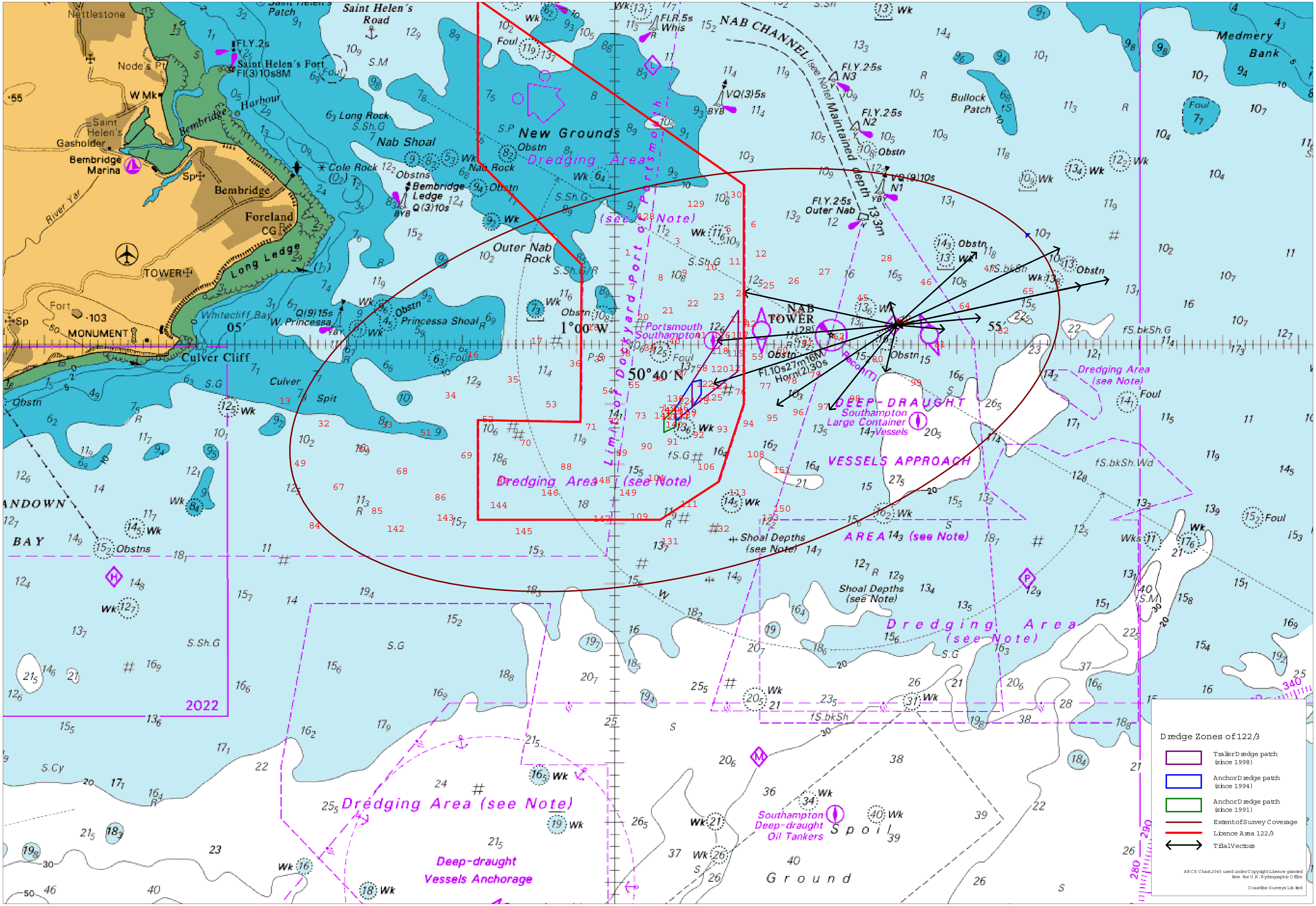


Figure 1.5b: map of the Survey Area in detail showing grab sample positions and extent of survey coverage

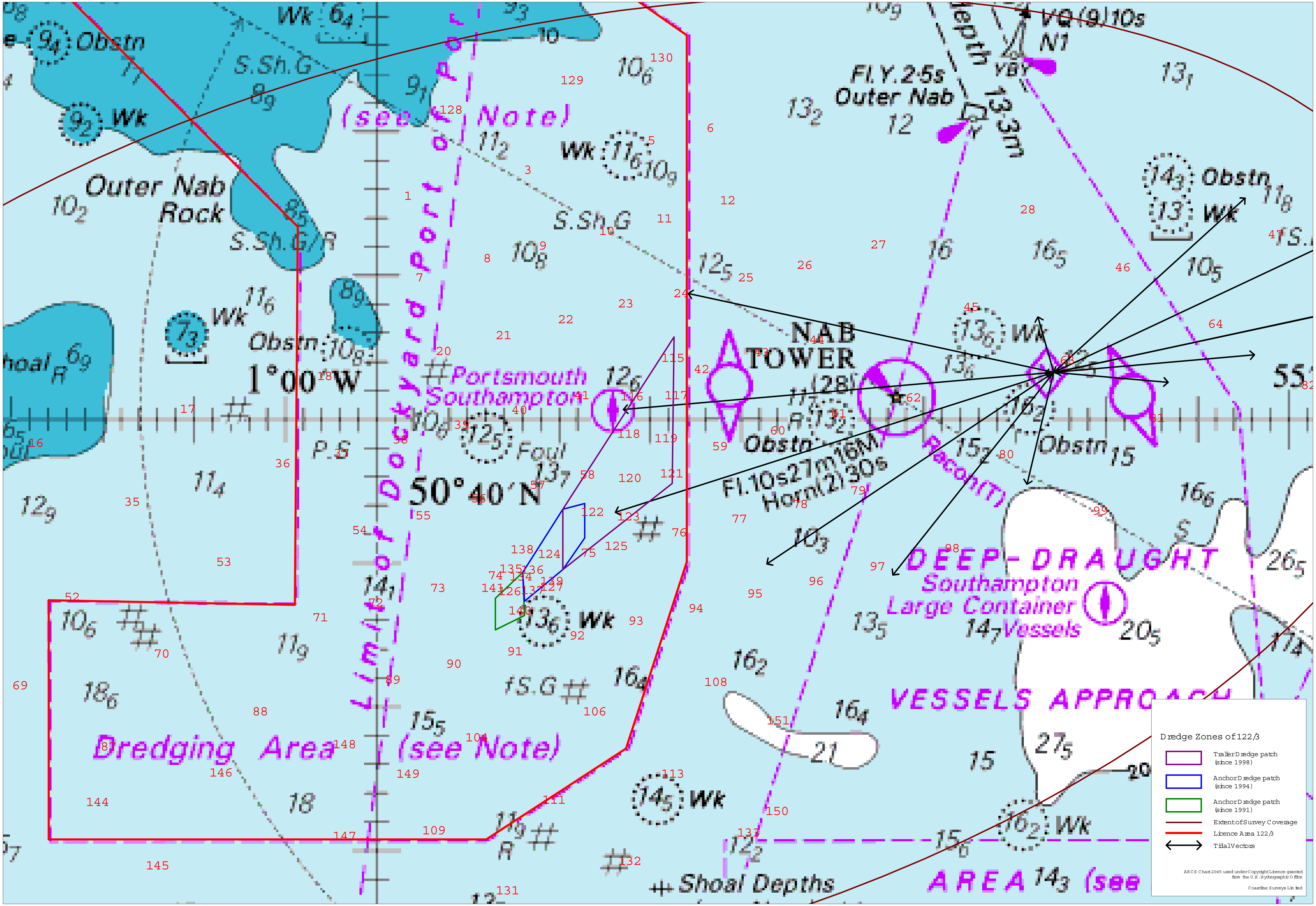


Figure 15c: Detail locations of the sampling strategy used to assess impacts within the intensively dredged areas

Quite simply, analysis of the impact of dredging of fully-screened cargoes requires a comparative study at another site using similar techniques to those used in this project which have been proven in their principle and execution and which can be further refined in light of the observations made. The nature and rate of the recolonisation processes also require a specifically designed and systematic study that is co-ordinated with differing dredge techniques in a worked Licence Area. Some of the biological components of such a study have recently been completed for a screened, trailer dredged area in the central North Sea off the Humber estuary at Production Licence Area 408 (Newell *et al* 2002). Rather unfortunately this work was undertaken during routine monitoring operations and the physical aspects of the site were not addressed in a combined study.

Plate 1.5b. Intense dredging with screening on a southern North Sea aggregates licence.

2.0 STUDY SITE ENVIRONMENT

2.1 Geological Setting

The Eastern Solent comprises solid chalk overlain by Tertiary clays and sands with a veneer of recent sediments. The Eastern Solent represents a drowned valley and flood plains of the proto Solent that flowed southward into the origins of the present English Channel during the late Devensian when sea levels were roughly 120m below present level.

Rising sea levels of the Holocene Transgression from 15,000 years BP to 5000 years BP caused the river valley to flood and deposit fluvial gravels and sands throughout the flood plains. These nearshore sand deposits form the resources for the local beaches, whilst the gravel deposits form the basis of the regional dredging industry activities.

2.2 Seabed Morphology

The study site is in a relatively flat region of the seabed in the 15-18m water depth (*refer* Figure 1.5a) gently inclining to the south and southwest. The southern boundary of the study site reaches 20m water depth LAT with the shallowest waters to the north in 12-14m. There are no significant bedforms recorded or major topographic features. Tidal currents flow generally along the contours.

2.3 Seabed Surficial Sediments

Surficial sediments of the area comprise Holocene sands and gravels deposited during the transgressions of the period, together with reworked Recent sediments. The licence area in particular is characterised by a high proportion of gravels, with some gravelly sands and very little silt content, typically less than 2%. A more detailed assessment of the sediment characteristics is discussed in the results section.

2.4 Hydrodynamic Conditions

East Solent tidal currents have been investigated and reported extensively in connection with the aggregate dredging applications and with development of shoreline management plans (SMP) by the local district authorities.

The tidal dispersion curve for tidal diamond **N** (UKHO Chart No. BA 2045 latitude 50° 40.1' N; 000° 56.4' W) indicates that tidal streams close to the eastern boundaries of the dredging area comprise a main tidal stream of up to 1.8 knots at 078° on the flood and 1.6 knots at 252 ° on the ebb. The sum of movement during one tidal phase (excursion) is a maximum of 6-7 nautical miles during the Spring tides. The direction of flow is fairly uniform with the ebb tide flowing generally to the west-southwest and the flood to the east-northeast. Figure 2.4 demonstrates the flow pattern and tidal residual. The mean spring tide range is 3.7m and neap range only 1.7m.

HW	Direction	Spring (m/s)	Neap (m/s)
-6	085	1.30	0.56
-5	078	2.96	1.48
-4	078	3.33	1.67
-3	065	2.78	1.48
-2	048	1.67	0.74
-1	345	0.37	0.19
0	282	2.41	1.30
1	265	2.78	1.30
2	252	2.96	1.48
3	236	2.22	1.11
4	218	1.67	0.74
5	193	0.74	0.37
6	095	0.74	0.37

Table 2.4 Tidal components at Nab Tower for Spring and Neap tides at hourly tidal states.

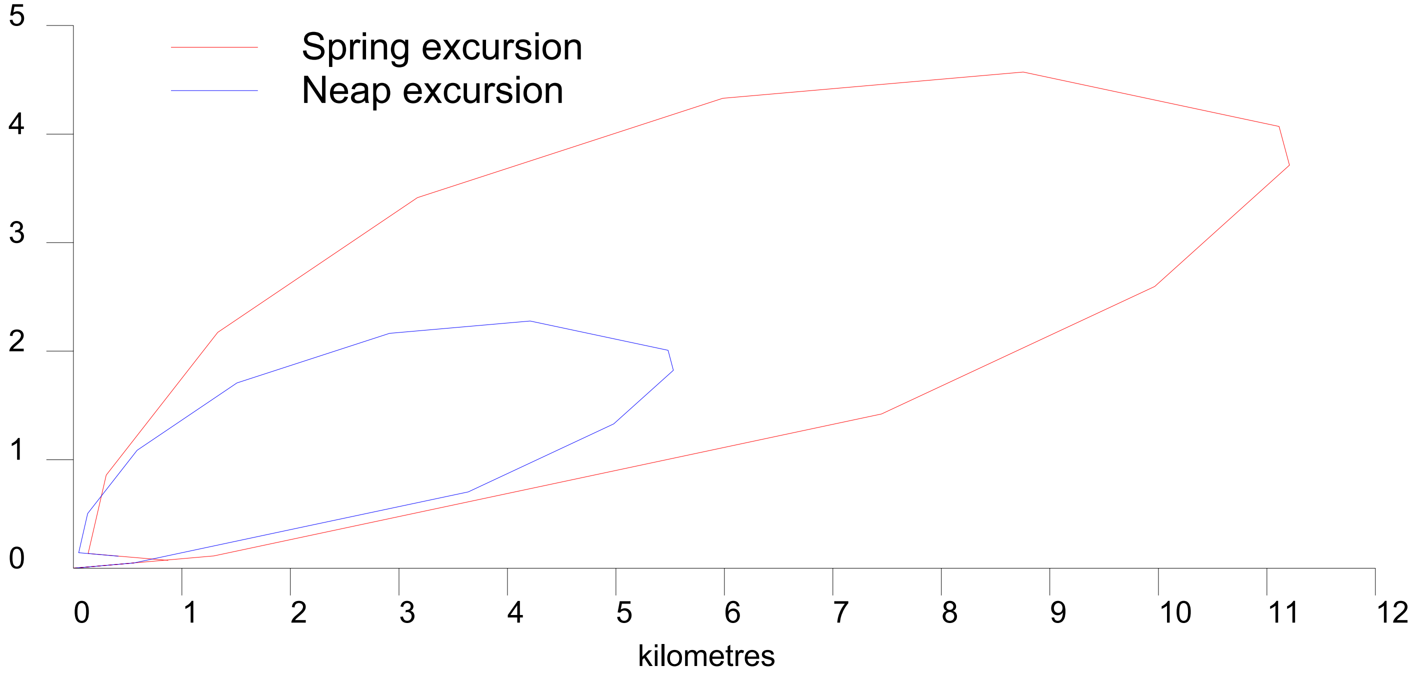


Figure 2.4. Tidal excursion for Nab Tower Tidal Diamond 'E'. Low water at 0,0. Note the residual water displacement of the spring tide to the east (almost 900m) and for the neap tide (less than 500m). Also, a particular time based package of water (at t=0, low water) will return to within 200m of its starting position after t=11 hours, and, on a spring tide, will replicate its position after 12 ¾ hours.

It is important to consider the tidal excursion carefully. From Table 2.4 and Figure 2.4 for the Nab site, it is clear that sediments emanating from an anchor dredge operation lasting some 3 hours may impact a body of water varying between 1.5km length (neap tide, 2.5 hours before low water to 0.5 hours after low water) to 9km length (spring tide, 0.5 hours after low water to 3.5 hours after low water). On a spring tide the impact will therefore have greater areal extent, but on a neap tide the intensity of the impact may be greater due to less dilution of the returned sediments. Neap tides result in a residual movement to the east of some 400m, but spring tides result in a residual movement of nearly 900m to the east per tidal cycle.

Extreme offshore waves come from the south-to-south west sector, which has the longest fetch, into the open channel and thence Atlantic Ocean. The highest waves from this direction range in magnitude between 3.7m for a return period of 0.1 years to 5.7m for a return of 100 years (HR Wallingford, 1997).

3.0 MATERIALS AND METHODS - SITE CHARACTERISATION

Six field campaigns were undertaken during the course of the project. During March and June 1999 141 seabed samples were obtained over the entire area, including some repeat stations. In September 1999, a further 10 samples were obtained close into the dredge site, as it became apparent that the effects of the dredging activity were much more limited in proximity to the dredging activity and, more than likely, located primarily within a few hundred metres of the active zone. In August 2000, a further 10 samples were obtained from within the active zone again, during an opportune effort to make a preliminary assessment of the expected rate of recovery.

March 13th – 14th 1999	First field campaign, 95 sites grabbed.
June 8th 1999	Further 46 grab sites sampled
June 9th – 10th 1999	Whole area sidescan sonar and mosaic at 250m range and bathymetry at 400m linespacing
September 7th 1999	Additional 10 grabs taken close to dredge area for biological nearfield information
January 17th 2000	Dredge area surveyed by sidescan sonar and mosaic at 75m range and bathymetry at 100m linespacing
February 1st 2000	Overspill and organic measurements from 2300 tonne capacity dredger *City of Chichester* working North Nab Are 122/3
August 15th 2000	Dredge area surveyed by sidescan sonar at 50m range and bathymetry at 50m linespacing over central area.
August 16th 2000	Underwater video work, plus 10 grabs taken in preparation of dredger arrival (poor conditions)
June 2001	ADCP of *City of Chichester*, Multibeam bathymetry / sidescan sonar Underwater video

Table 3. Summary of successful fieldwork operations. Unsuccessful mobilisation and abandonment due to weather or other factors excluded.

The primary navigation system used for these surveys was a Trimble 4000SSi 18-channel GPS unit. This survey grade receiver is of the dual-frequency type with 18 parallel channels accessing the L1/L2 carrier phase, L1/L2 P code and L1 C/A code. Differential corrections were provided by an SBA-1 IALA Beacon receiver in RTCM 1.04v2 format or a FUGRO SeaSTAR/OmniSTAR combined GPS and SPOT beam differential receiver. Stated accuracies are better than 5m and 1m respectively. Secondary receivers were in place, and comprised a Trimble 7400 RSi GPS unit with differential corrections.

Output from the shipborne receiver, after receiving real-time corrections, is via RS232 protocol communications to the Coastline Surveys Ltd PC-based Integrated Navigational Positioning System (INPS). Differential position data was output from the primary receiver through RS232C communications configured as NMEA0183 Lat/Long output for input to the PC computer and logged using the navigation survey program, Trimble HydroPRO v1.3 and v1.5. The GPS antennae were mounted vertically above the echosounder transducer to obviate the need to apply offsets. Offset errors for other sensors were reduced by accurately detailing the offsets and applying heading in real-time, generated by a digital fluxgate compass and a TSS Meridian gyrocompass.

The control and planning of the survey was based on the Airy Spheroid with grid co-ordinates expressed in metres and decimetres on the Ordnance Survey of Great Britain 1936 (OSGB) National Grid. The dGPS unit was configured to output serial information in the International Standard WGS84 co-ordinate system to the INPS, which then converts the co-ordinates to the OSGB datum using the national parameters for translation, modified for local variance, based on information available from the Ordnance Survey of Great Britain.

The INPS computer recorded the location of the survey vessel. The co-ordinates are graphically presented on a helmsman’s monitor along with the survey line plan to enable steering of the vessel along the predetermined track. A vessel cross track error image enables the helmsman to remain on line, generally within 10m.

Navigational data, time and water depths were recorded ("fixed") at a nominal track time interval of 3 or 6 seconds, corresponds to a horizontal fix interval of approximately 5-10m depending on speed, determined by the survey operations underway. At each "fix" a "fix pulse" is generated by the INPS and is transmitted to the echosounder and thermal printers. Every fix generates a pulse, which prints simultaneous annotation on the echosounder, sonar and geophysical records. The INPS records the instantaneous, minima, maxima and average readings of depths generated by the echosounder digitiser. The records presented here are based on instantaneous calculations.

For quality assurance, prior to and after the survey, the dGPS position solution was checked against known positions to establish any gross errors. The calibration data indicated no need for an offset to be applied to the survey data recorded. During the survey, the solutions of all positioning systems were constantly monitored against each other to indicate any instability in one or other of the systems.

During the resolving of the positional information, a 'quality factor' is generated for each observation. This number, GDOP (Geometric Dilution Of Precision) is based on the number of satellites available, their geometry in space and their heights above the horizon. A GDOP figure greater than 8 indicates an unsatisfactory solution to the position information and is tagged to enable simple recognition. There were no difficulties with satellite signal and differential correction reception.

3.1 Bathymetry

An Odom 'Hydrotrac' survey grade digital thermal echosounder with 200T5HAD 8^{o} 208kHz transducer was used to digitally obtain the bathymetric data. The echosounder transducer is permanently mounted in the hull of the survey vessel well forward and on the centreline. This is 2.5m below the water line during normal survey speeds with normal trim attitude, and immediately below the GPS antenna horizontal reference position. A Seatex MRU-5 multi-axis motion sensor removed vessel motions from the survey record. Standard calibration checks were carried out at the beginning, during and end of each survey period.

Accuracies of bathymetric systems in shallow water are primarily a function of echosounder installation, performance and digitising, tidal recording and translation, co-tidal correction factors (if applied) and meteorological and atmospheric conditions. Additional errors in successive surveys can be caused by, amongst others, lateral differences in vessel track (horizontal accuracy) not precisely repeating previous sounding points. In zones of active sediment movement, changes in seabed topography (especially migratory sand waves) can appear as net changes in seabed levels, whereas the data actually represents a mere shift in sediments. In areas of steep relief, small horizontal position differences can cause seemingly larger vertical inaccuracies.

It is essential to use a motion sensor for any type of bathymetric surveys where the data may be used for subsequent volumetric analysis, or data accuracy will degrade beyond the level of assessment and 'noise' in the dataset will exceed the volumes of change.

Tidal data was recorded at 15-minute intervals on an automatic tidegauge reduced to Chart Datum. Using co-range and co-tidal corrections, the readings are translated to the survey area. During the processing algorithms, tidal heights are subtracted from the heave-corrected and spike-smoothed raw water depths.

It has been assumed, in the absence of other information, that the tidal readings obtained are sufficiently representative across the whole of the site not to require a network of tidegauges across the site or adjustment of the tidal heights at the extremity of the survey area for hydraulic gradient and tidal delay.

Tidal reduction techniques follow the approved UK Hydrographic Office and British Admiralty methods for tidal records and reduction of data to datum. Sources referred to include Admiralty Tide Tables N.P. 201-00 (Hydrographer of the Navy, 1999), Admiralty Tidal Handbook No.2 "Datums for Hydrographic Surveys", N.P. 122(2) (Hydrographer of the Navy, 1975) and "Hydrographic Surveying", EM 1110-2-1003 (USACE, 1994). Using the Simple Harmonic Method A (ATT, NP201-00), Admiralty Tide Predictions for tidal heights during the survey have been compared to the observed data. There is generally good agreement between the sets of data, and this confirms the accuracy of the tidal monitoring and reduction procedure adopted.

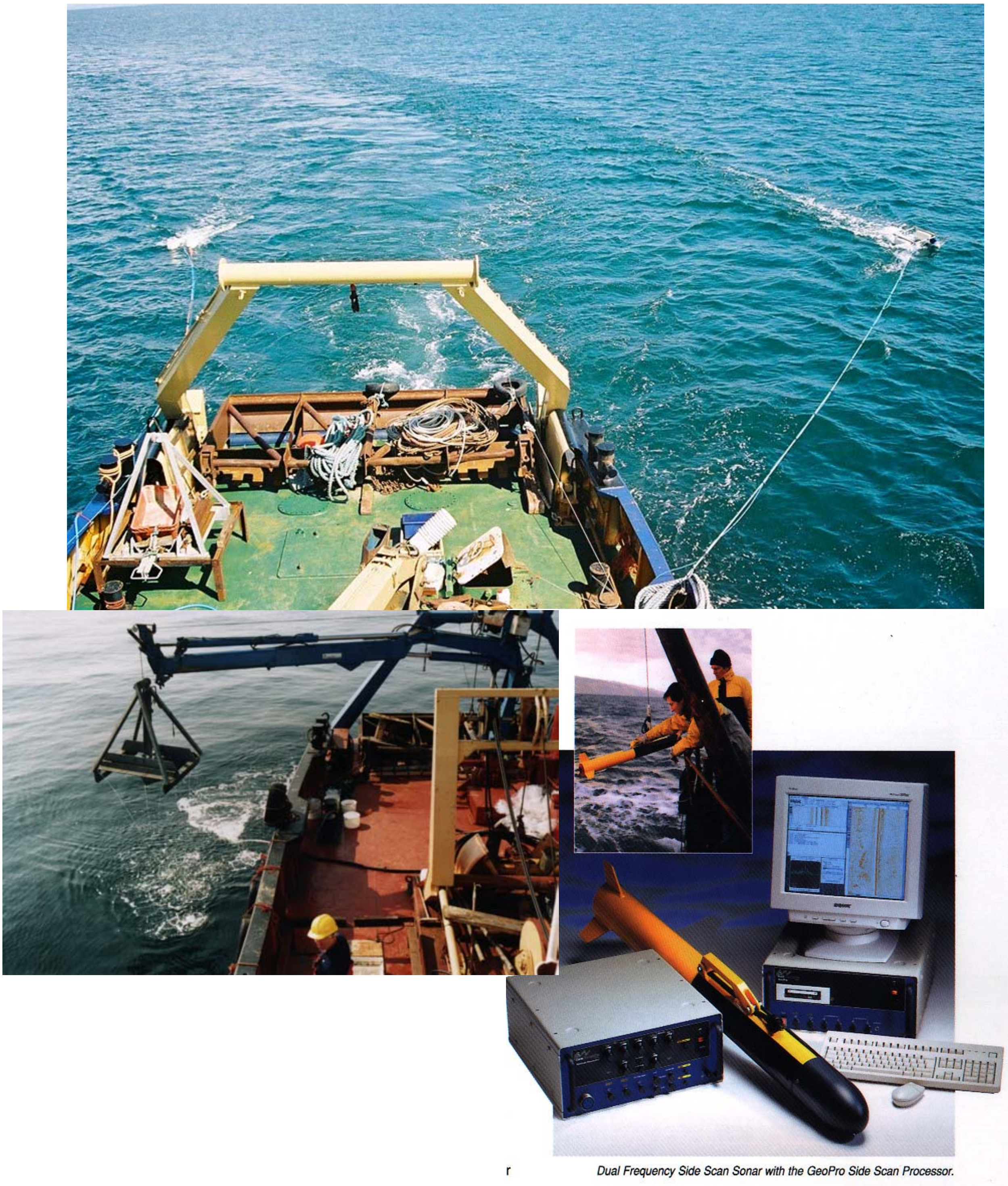


Plate 3.1. Fieldwork aboard the MV Flat Holm – showing sidescan sonar and Hamon Grab.

3.2 Sidescan sonar digital mosaicing

A GeoAcoustics 159D Dual Frequency 125kHz/410kHz side-scan sonar towfish was deployed from the centre of the stern of the vessel on an 8mm co-axial armoured tow such that the towfish 'flies' at the optimum height equivalent to 10% of the sonar range. The towfish was interfaced to a GeoAcoustics SS941 Transceiver Unit to control gain and record quality, and to a GeoPRO digital sonar mosaicing system. High quality greyscale images were also printed using an Ultra 200 3 channel Thermal Recorder. The recorder was interfaced to the INPS for fiducial event marking and the layback of the towfish from the tow point entered into the INPS and mosaicing system for good positional accuracy.

The survey progressed at a speed of approximately 1.0-1.5m/s (2-3 knots). Faster speeds will degrade record quality and object resolution and identification.

The recorder sweep speed was set such that the records were presented at a slant range of 100m per side. A swath of seabed some 200m wide was isonified with each pass with these settings in suitable water depths. The side-scan sonar transceiver was set to operate at 125kHz frequency for the duration of the survey with the higher frequencies available for target search and identification, if needed.

The side-scan sonar image, which may be considered as an 'oblique facsimile' of the seabed, was inspected and features identified during the survey in real-time. During post-processing, seabed surface topography and sedimentary characteristics are transferred to a seabed features plan. Correcting for the antenna offset and layback of the towfish from the GPS antenna, and the vessel heading, the position of individual features and targets can be plotted.

The characteristics of seabed features and seabed materials can be assessed on the basis of their appearance on the side-scan sonar records. In broad terms, the criteria for discriminating between rock, gravel, sand, silts/clays and manmade features are as shown in Table 3.2

Against a background of a sandy seabed, debris can be located and identified reliably, since there will be a reasonable contrast between the moderate reflectivity of sand and high reflectivity of objects. This contrast is reduced in areas of higher background seabed reflectivity, such as gravelly or rocky terrain. This is more so for the latter seabed, since shadows cast by rocks may obscure the location of any debris. When passing close to navigation buoys, the system is of sufficient resolution to be able to discern anchor chains and scour patterns caused by the moorings.

Rock:	high acoustic reflectivity, textural variation
Gravel:	high acoustic reflectivity, little textural variation
Sand:	moderate acoustic reflectivity, textural variation showing megaripples and/or sand waves
Silts/Clays:	low acoustic reflectivity, no textural features
Manmade:	high acoustic reflectivity, limited areal extent, regular shape, non-conformity with other features

Table 3.2. Summary of principle sidescan sonar textural interpretations. Secondary information such as attitude, sonar-grazing angle, order of shadows and returns etc are equally important in quantifying the above.

The characteristics of the seabed materials can be assessed on the basis of their appearance on the side-scan records and 'ground-truthed' using grab sample and/ or diver data.

The GeoAcoustics SS941 transceiver system is particularly useful for geological surveys in that the gain of the system is not continually adjusted as the strength of the received signal varies with geology, as is common with some other systems. In this way, the Automatic or Adaptive Gain Controls does not obliterate changes in the acoustic reflectivity of the changing substrate and different geological provinces can be readily identified.

During normal conditions of towage in shallow water, i.e. along straight lines, the possible error in position for the sonar towfish is estimated to be +/- 0.5m. When steering a course with deviations from the straight line and when steering across the current direction, positional errors of the fish can be slightly greater, although the restricted length of the tow will limit this.

When positioning targets from the side-scan records, the single major factor in determining the location of a target is the variation of the towfish heading relative to the course over the ground of the survey vessel, due to degrees of motion- freedom of the towfish. Rigidly mounting the sonar fish to the vessel, or reducing the length of the layback, reduces this effect, since the heading of the vessel is constantly recorded by the INPS. Where features are identified on more than one survey line the position of the feature is more reliably determined. Positional errors due to towfish heading will be larger at greater ranges from the towfish. By simple trigonometry, a five-degree heading error at 50m range will produce a positional error of +/-2.2m whilst at 200m range it would be +/- 8.6m.

Some 350 kilometres of high resolution sidescan sonar and bathymetry has been processed. These have allowed us to create high quality fully orthorectified digital mosaics of the seabed, over which discriminators of the footprints of impact of the dredging operation can be laid for further analysis.

3.3 Positions of Biological Sampling Stations

The positions of the sampling stations were chosen to assess biological resources both within the dredging areas and in zones potentially affected by deposition, as well as in control zones well outside any area of potential impact of dredging activity. The dredge history of sites within the survey area was obtained from records held by United Marine Aggregates who operate North Nab Production Licence Area 122/3.

The survey zone was determined by pre-analysis of the dredge history of the site and assessment of tidal movements within the region. Tidal streams reach up to 1.0ms^{-1} on the flood (078^{o}) but only 0.8ms^{-1} on the ebb (252^{o}). Maximum tidal excursion is slightly less than 12km to the east and west. All information available from other survey areas suggests than any impact of deposition of material rejected during the dredging process is confined well within one tidal dispersion and is likely to be confined to a distance of less than 3 km (*see* Poiner and Kennedy, 1984; Whiteside *et al*., 1995; Hitchcock and Drucker, 1996; reviewed in Newell *et al*., 1998).

Based on the information obtained in previous studies on an area some 20km to the east, we therefore designed the survey and sampling regime to extend up to 6km in each direction, with the axis of the investigation aligned with the tidal excursion. Further, and also based on previous research, the width of the survey area was delimited to 1000m.

These sampling stations cover a potential zone of impact associated with deposition of material from dredging activities in the extraction area. They allow comparison with "control" sites outside any likely impact of dredging activity as well as with areas directly impacted by extraction of marine aggregates from within the boundaries of the dredging area. The positions of the sampling stations are shown in Appendix Table 1 and Figure 1.5b.

Additional samples were taken on 7th September 1999 to define the impact of dredging within the boundaries of the intensively dredged part of the Licence Area, and to give some information on the relation between past dredging within the site and recovery of biological resources. The positions of stations, which were used to assess the impact of dredging within the intensively dredged part of Licence Area 122/3, are shown in the enlargement of the survey site map in Figure 1.5c.

Samples of deposits were also taken for subsequent particle size analysis. Notes on the position of each sample, the volume of sample taken with the 0.2m^2 Hamon grab, and the percentage stones, gravel and sand in the deposits are included in Appendix Table 1.

3.4 Collection and Extraction Procedures

A standard 0.2m^2 Hamon Grab was deployed from the 23.3m survey vessel MV Flat Holm operated by Coastline Surveys Ltd to collect the samples. Use of this grab has the advantage that loss of material by "washout" from the jaws experienced with conventional grabs is reduced (*see* Holme and McIntyre, 1984; Sips and Waardenburg, 1989; Kenny and Rees, 1994; van Moorsel, 1994). The samples also allow strict comparison with the results of surveys elsewhere using a similar grab. Some stages in the deployment of the Hamon grab and the subsequent separation and preservation of the fauna are shown in Plate 3a.

The samples were released from the grab onto a 1mm mesh-sorting tray, the contents of which were transferred to 10 litre buckets and preserved in formalin for subsequent separation and identification. Separation of the biological material was carried out in the laboratory by elution with a large volume of tap water through a 1mm mesh sieve, and by careful manual separation of the residual fauna from the remaining sediment (Plate 3b). The biological material was then preserved in methanol for subsequent identification and enumeration. A reference collection of key taxa was retained for future reference. Some examples of the macrofauna from the North Nab survey site are shown in Plate 3c.

Plate 3.4a. Some stages in the deployment of the Hamon Grab and the subsequent separation and preservation of the fauna on board the survey vessel MV Flat Holm. The dredger *City of Cardiff* and the Isle of Wight are shown in the background.

Plate 3.4b. Separation of biological material from the sediments was carried out by elution over a 1mm mesh sieve. This was followed by careful sorting of the residual macrofauna, which were identified under a stereomicroscope.

Plate 3.4c. Some examples of the macrofauna from the North Nab Research Area. Taxa included *Sabellaria*, sponges, serpulids (*Pomatoceros*) upper photographs; bryozoa (*Flustra*), numerous amphipods (*Ampelisca*) middle photograph; hydroids (*Tubularia*) and the American slipper limpet (*Crepidula*) lower photographs.

3.5 Analysis of Outwash Samples

Aliquots of well-shaken samples of outwash water were filtered through a pre-weighed Watman GF/C filter, washed with distilled water, dried at 105°C and re-weighed to determine total suspended solids. Each filter was then carefully folded, placed in a crucible, weighed and ashed at 650°C in a muffle furnace. After cooling, the filter + crucible were re-weighed to determine the weight of volatile solids. The ashed solids were then calculated from the difference between the total suspended solids and volatile solids. All results were expressed as mg per litre.

3.6 Biomass Determination

The blotted wet weight of the main faunal groups was measured. These data were then used to estimate total biomass as ash-free dry weight in grams using conventional conversion factors for each of the faunal groups. These were *Polychaeta* = wet weight x 0.155, *Crustacea* = wet weight x 0.225, *Mollusca* = wet weight x 0.085, *Echinodermata* x 0.08; Miscellaneous Groups including *Porifera* and *Bryozoa* = wet weight x 0.155 (Eleftheriou and Basford, 1989).

3.7 Particle Size Analysis

One factor that has been thought to affect benthic community composition in seabed deposits is sediment type (*see* Pearson and Rosenberg, 1978; Weston, 1988; Clarke and Miller-Way, 1992), although much recent evidence suggests that sediment granulometry itself may be less important than the consolidation of the deposits (*see* Seiderer and Newell, 1999, Newell *et al*., 2001).

In total, some 177 grab samples were obtained over 4 phases of the work using the Standard 0.2m^2 Hamon-type grab, deployed from the MV Flat Holm. Sub-samples of up to 5 litres of sediment were taken for particle size analysis. This material was sealed in strong plastic bags with a label on both the inside and on the outside of the bag. Most of these samples were analysed for benthic community (*see* Hitchcock *et al*. 2002b).

Grain size analysis of the fractions 0.075mm – 125mm by sieving (according to BS1377 and BS812: Part 102) determined the principal components of the seabed sediments and the results were expressed using conventional Wentworth Classification to give percentage composition of each particle size.

Similarity analysis of the sediment size distributions was performed using non-parametric multivariate analysis methods similar to those outlined in Section 3.10 for biological community composition. The data input to the multivariate analysis of sediment composition is summarised in Appendix Table 2.

3.8 Thematic Maps GIS

All of the GIS maps used in this report were generated using MapInfo Professional Version 6.0 and/or AutoCAD 2000. These are both comprehensive desktop-mapping tools that enable multiple layers of data to be viewed geospatially.

Thematic mapping is a powerful method for analysing and visualising univariate data. The data are given graphic form by scaling or shading so that they are visible on a map and therefore readily comparable with other data already located on the map. Patterns and trends that are difficult to detect in tabular form can be easily visualised. In addition to this, thematic scaling or shading does not entail interpolation between the stations at which samples were taken and thus problems associated with interpolation of results between spatially distinct stations are avoided.

3.9 Dominance & Diversity

One measure of the uniformity of species composition in natural communities is to plot so-called “k-dominance” curves which show the percentage of a population which is represented by each of the species within the community (*see* Lambshead *et al*., 1983; Clarke, 1990; Warwick, 1993).

Communities with a wide range of species generally have a k-dominance curve which shows no evidence of a major dominance by one or a few species. In contrast, where there is an environmental stress imposed on a community, sensitive species are replaced by large numbers of those (resistant) species that are capable of survival. This leads to a reduction in species variety and a numerical dominance by one or a few resistant species. In these cases the community may show as much as 80-90% dominance by one or two (resistant) species.

3.10 Analysis of Invertebrate Community Structure

The statistical methods which we have used to analyse the structure of the invertebrate communities of the coastal sediments to the east of the Isle of Wight follow the methods of Field *et al*. (1982; *see* also Walker *et al*., 1979; Warwick and Clarke, 1991; Clarke and Green 1988; Clarke, 1993; Clarke and Warwick, 1994a; Kenny and Rees, 1994; Somerfield *et al*., 1994). We have used these methods in our previous surveys of benthic communities in proposed marine aggregates licence areas off St Catherine's, Isle of Wight, in the West Varne Area 432 off Folkestone, in the vicinity of Area 454 off Lowestoft, Norfolk, in the vicinity of Area 452 off Southwold, Suffolk (Marine Ecological Surveys, 1996a,b; 1997a,b), and in the central mid English Channel (Marine Ecological Surveys, 1999a,b).

The procedure comprises five stages:-

(a) Transformation of the data.
(b) Construction of a Similarity Matrix.
(c) Classification to form a dendrogram from the similarity matrix
(d) *Ordination to check and confirm the relationships indicated by the Group*
(e) *Average Sorting dendrogram in stage (c).*

(a). Stage 1. Transformation of the Raw Data.

One of the problems commonly encountered in an analysis of community structure is that some species are dominant.

There are several ways in which the statistical weighting of such dominant species can be reduced in the analysis. We have used the `Root-Root` transformation of Stephenson and Burgess (1980) in our studies of benthic communities in the deposits to the east of the Isle of Wight.

$$Y_{ij} = \sqrt{\sqrt{X_{ij}}} = X_{ij}^{0.25} \quad \text{...(1)}$$

Where X_{ij} is the raw data score of the *i*-th species in the *j*-th sample, and Y_{ij} is the corresponding transformed score. It has the important practical advantage that the absolute values for the counts of dominant species is less important than in an index based on untransformed data.

(b). Stage 2. Similarity Matrix.

Comparison of each sample with every other sample using a measure of similarity leads to the formation of a triangular similarity matrix. A wide range of similarity indices has been reviewed by Washington (1984). Good accounts can also be found in Heip *et al*. (1988) and Magurran (1991). Field *et al*. (1982) used the well-known measure of Bray and Curtis (1957) and this is the index that we have used in our analyses. It is algebraically equivalent to the Czanowski coefficient used by Field and McFarlane (1968) and by Day *et al*. (1971). The Bray-Curtis measure is not affected by joint absences, but gives more weight to abundant species than to rare ones when comparing samples.

A measure of the dissimilarity between samples is often used for the construction of a similarity matrix *viz*:-

$$\delta_{jk} = \frac{\sum_{i=1}^{N} (Y_{ij} - Y_{jk})}{\sum_{i=1}^{N} (Y_{ij} + Y_{jk})} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where δ_{jk} is the dissimilarity between the *j*-th and *k*-th samples summed over all *N*-species, Y_{ij} is the score for the *i*-th species in the *j*-th sample, and Y_{ik} is the score for the *i*-th species in the *k*-th sample. δ_{jk} ranges from zero (identical scores for all species) to 1.0 (no species in common). In practice, it is convenient to use the Similarity (S_{jk}) in its percentage form:-

$$S_{jk} = 100(1 - \delta_{jk}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

The application of a measure of similarity results in a triangular matrix whose entries compare each of the *N*-samples with every other sample. This matrix can be arranged as a trellis diagram (*see* Sanders, 1958), but is more conveniently summarised in diagrammatic form as a dendrogram or ordination. The latter method is being increasingly used in the analysis of multispecies community structure, and has been used in our surveys of spatial variations in the benthic communities in coastal waters.

(c). Stage 3. Classification.

Methods available to produce a dendrogram from the similarity matrix have been described by Clifford and Stephenson (1975). The most successful and widely used procedure is `Group Average Sorting` which joins groups of samples together at the average level of similarity between all members of one group and all members of another.

Although this method of classification is simple, and is becoming widely used in ecological studies, Field *et al*. (1982) caution that there are several disadvantages in the use of dendrograms as a sole method of classification of the samples. They recommend that an additional method of presentation is used to investigate the relationships between the samples.

If the results of the two methods agree, then assumptions inherent in the dendrogram method evidently do not lead to artificial similarities and relationships between samples. They recommend `Multidimensional Scaling` (MDS) as a method of ordination. We have used both methods in our analyses of benthic communities in coastal deposits, and have found that in general there is good agreement between the two.

(d). Stage 4. Ordination.

Multidimensional Scaling (*see* Kruskal and Wish, 1978) produces an ordination of the *N*-stations in a specified number of dimensions. Field *et al*. (1982) used non-metric MDS, for which there are two widely available computer programs, namely M-D-SCAL and KYST (*see* Kruskal, 1977) and more recently PRIMER (Clarke and Warwick, 1994b). Field *et al*. (1982) used the version M-D-SCAL 5 MS in their analysis of spatial variations in the meiofauna of the Exe estuary, U.K. We have used the PRIMER version in a series of studies of invertebrate community structure in relation to potential perturbation from dredging activities (Marine Ecological Surveys, 1996a,b; 1997a,b, 1999a,b). The groups that were identified as different communities have been colour coded and the corresponding colours superimposed onto a map of the survey area.

4.0 MONITORING OF AGGREGATE MINING OPERATIONS

4.1 Background

Comprehension of plume morphology formed by dredging activity at each site is fundamental in assessing any impacts of dredging beyond the limits of physical disturbance by the dredge head. It is primarily by this mechanism that any impacts will be extended beyond the active dredge zone. Over the past decade, we have developed novel techniques for tracking development and decay of marine mining plumes using a combination of the latest ADCP systems and traditional water sampling techniques. New advances in software analysis and presentation enable hitherto unknown representation of plume structure.

The form and magnitude of the plume is governed by three principal components;

(1) the dredging technique, including type of dredging plant in operation, method of overboard returns, and operational conditions such as speed over the ground;

(2) sensitivity to suspension and resuspension of the bed material i.e. the ease with which the bed material will be disturbed and will remain in suspension, largely determined by the characteristics of the sediment (geotechnical, rheological and micro-biological); and

(3) condition of the overlying waters i.e. water depth, current velocity and shear, turbulence, temperature, wave climate, salinity etc.

A full description of ADCP systems procedures is outwith the scope of this report, but *see* Thevenot and Johnson (1994), Land *et al*. (1994) and Hitchcock *et al*. (1998). A brief overview is included in section 4.2. The utility of ADCP techniques as interdisciplinary instruments are now well established and accepted.

4.2 Theory of Approach

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 beam width transducers arranged in a 'Janus' configuration, inclined at 30 degrees to the vertical. The transducers for the RDI 1200kHz BroadBand system used in this project 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 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 gyrocompass. 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 suspended particulate matter (SPM). When used in Vessel Mounted (VM) (Figure 4.2a) mode this provides a graphic illustration of relative differences in acoustic backscatter, and hence represents relative variations in suspended solids concentration (Figure 4.2b).

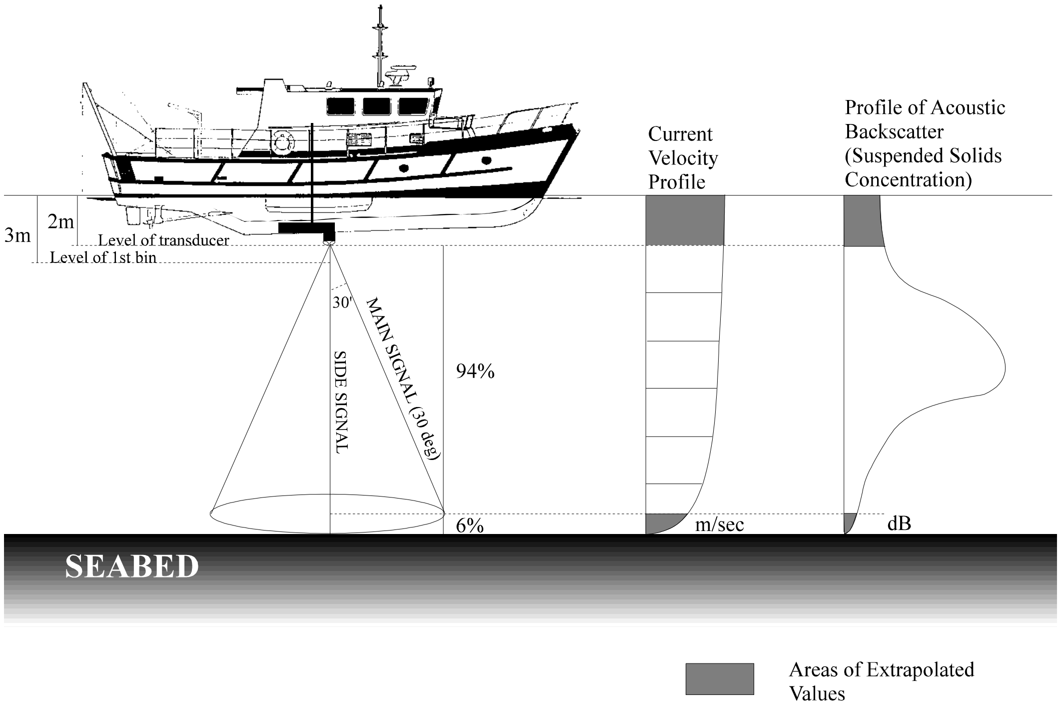
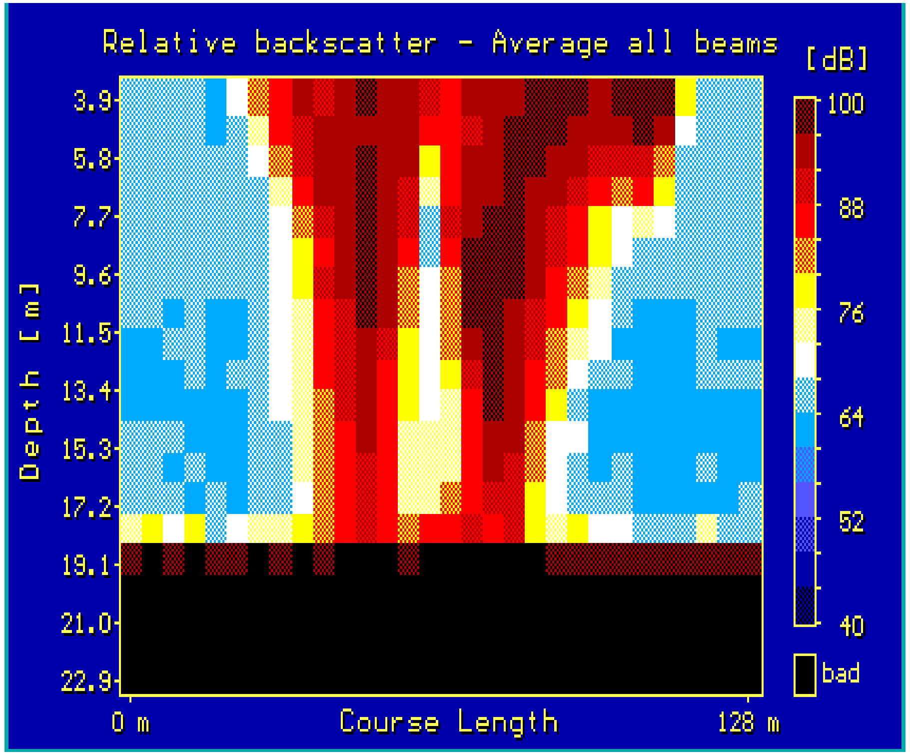


Figure 4.2a. Deployment arrangement for Vessel Mounted Acoustic Doppler Current Profiler (VMADCP) as developed during this study for Continuous Backscatter Profiling. Upper and lower part of current and suspended sediment profiles are calculated by extrapolation based on values within measurable range

Since the early 1980s, Acoustic Doppler Current Profilers 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 and 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 and Kraus, 1993; Ogushwitz, 1994) and studying wastewater outfalls (Dammann *et al*, 1991).



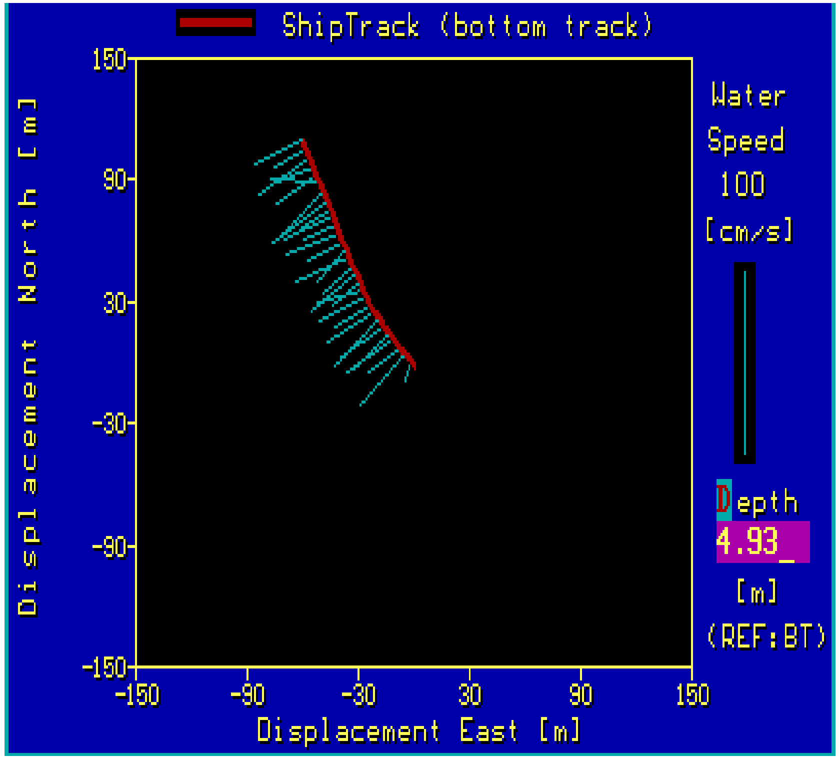


Figure 4.2b LEFT SIDE: the Acoustic Doppler Current Profiler™ screen dump showing plume of suspended sediment either side of dredge vessel, immediately astern. Higher suspended solids concentrations are shown in darker colours, the seabed appears black. Clear waters appear in light blue. The darker returns 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 4.2b 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' (initial entry velocity due to gravity and pumping) of the overboard discharge.

It is presently generally considered for bio-oceanographic monitoring that acoustic backscatter from ADCP cannot be practically calibrated at sea by users (*see* Roe and 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 a, 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.

4.3 ADCP Monitoring

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).

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 and 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 - 75mm with a mean particle diameter 10mm and concentrations up to 1000mg/l.

Lohrmann and 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 'reasonably 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 and 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 that must be repeated at frequent intervals, especially when particle characteristics such as mineralogy and refractive index are expected to change. 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 (Plate 4.3a) within the plume for acquiring the suspended solids concentrations.

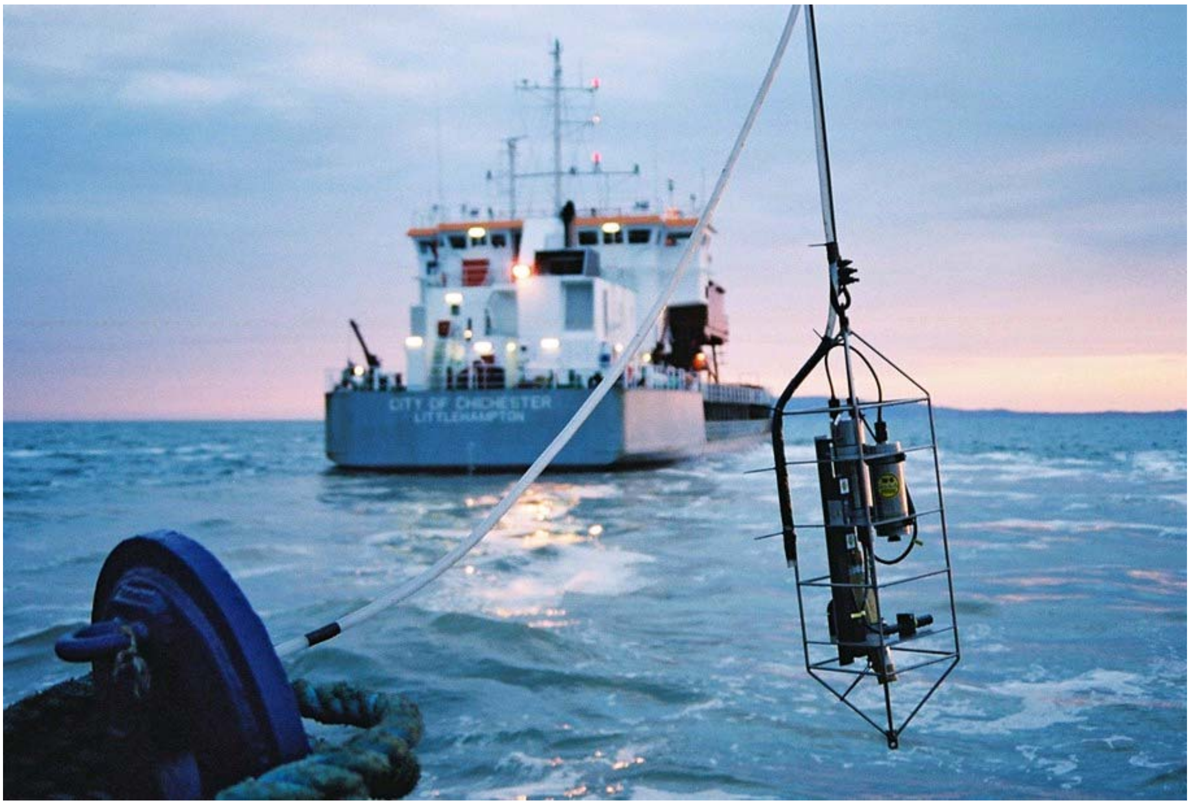


Plate 4.3a. Deployment of water sampling equipment in the plume generated by the *City of Chichester*

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.

The U.S. 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 and Thevenot, 1992) which also utilised commercially available broadband 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 worldwide 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 discrimination.

The sediment plume generated by a small suction dredger, the City of Chichester, was monitored by ADCP techniques during the loading of an 'all-in' cargo. An RDI 1200kHz BroadBand unit was deployed over the bow of the survey vessel (Plate 4.3) and the equipment and software configured for moving vessel mode. ADCP transects across the plume were conducted at differing ranges from the anchored dredge vessel, to determine the plume shape and morphology. Two distinct monitoring strategies were followed. In the first, the survey vessel conducted transverse profiles perpendicular to the plume axis at set distances downstream of the dredge vessel, and produced a series of profiles indicative of the status of the plume and its dispersing morphology. Water samples taken at varying points along each transect and at different depths give sediment mass per litre of seawater (suspended sediment concentration). Each of these profiles represents a time-dependent status of the plume, and the rate of dispersion and settlement of the sediments can be determined.

Plate 4.3b. ADCP unit deployed from bow of the survey vessel MV Flat Holm

Secondly, the survey vessel deployed a mid-water drogue with a surface buoy in the plume just downstream of the dredge vessel. The survey vessel then conducted vertical and transverse profiling away from the dredger, always passing through the same parcel of water as indicated by the drogue surface buoy. This technique gives a time-based status of the plume but also removes some of the variability of the loading process and the 'pulsing' of overboard spilling of sediments from the dredge vessel. Specifically, within this study, we have not attempted to calibrate the ADCP backscatter signals with particular suspended sediment concentrations.

4.4 Data Processing

The RD Instruments' data acquisition software 'Transect' is used to generate many of the graphics of relative backscatter and current velocity that are shown within this report. However, in order to assess the with-depth variations of relative acoustic backscatter, current velocity and current direction, two programs have been written to further analyse the ASCII output from the Transect software.

Velocity MAP (VMAP) enables the user to select the specific bin depths of interest (or all depths) and extracts relevant data from the Transect ASCII file on an iterative basis. Each bin is ascribed with respective values for x (easting), y (northing) and z (depth) components, with the corresponding value for current direction and magnitude. Sub-routines convert this data into AutoCAD Drawing Interchange Format (.DXF) for plotting as fully annotated drawings. Data for each depth is assigned an individual layer name. Within AutoCAD, the user can select the depths required for presentation, and produce a straightforward plot of the tidal conditions throughout each circuit. VMAP allows the user to change the averaging period over which measurements may be plotted, either by time or distance basis.

BMAP (Backscatter MAP) is a program similar to VMAP in that is was written to post-process the output ASCII files from the Transect software. However, BMAP concerns itself with investigating the with-depth variation of the relative backscatter recorded by the ADCP™. Processing of the Transect files involves generating an ASCII file that contains, in tabular format, all the easting, northing, depth and relative backscatter values, as well as all other system and observed variables. These are presently modelled using a simple contouring package to produce pixelated images of the contoured, relative backscatter levels at the required depths for comparison. Figure 5.4c shows the example of the plume as monitored at three depths as an output from BMAP. From this figure it is clear what the extent of the high backscatter levels are, and the rapidity with which they decrease to levels slightly elevated above background.

The representation of the plume has been undergoing continual refinement, and in late 2001 we upgraded to *Slicer v.3* which provides us with much enhanced capabilities for visual three-dimensional representation (easting, northing and depth) of the plume with a fourth component (relative backscatter) indicated by colour. Figures 5.4a and 5.4b were produced using this technique and some routines developed in-house for manipulating the data from BMAP format to *Slicer.*