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Large scale use of muddy dredged materials for sustainable flood defences and habitat management - AE0260

Summary Report

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Summary

Large scale use of muddy dredged materials for sustainable flood defences and habitat management - AE0260

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Dredged material may be used directly in the creation or remediation of muddy habitats such as salt marshes and mud flats. This type of beneficial use, promoted by Defra under FEPA II, would actually meet three aims: to use dredged material beneficially; to maintain or increase biodiversity; and to support coastal defences in a more integrated and sustainable manner. Less than 1% of the 30-40 million tonnes of dredged material produced in the UK is used beneficially to enhance or create new mud flat or salt marsh systems as use has been limited to small scale trials and schemes. Concerns about the behaviour of muddy dredged material placed on inter-tidal areas (in the context of habitat creation schemes or otherwise), could limit the application of such techniques. By improving scientific knowledge and understanding of the impact, if any, of such schemes and the manner in which they evolve it may be possible to gain sufficient confidence in the technique, ultimately, one may hope, allowing bigger scale, more widespread use.

Defra recognised the importance of previous approaches to the use of cohesive sediments for flood defence and habitat purposes. In January 2003 HR Wallingford and CEFAS were commissioned by Defra to carry out research to improve the knowledge and understanding of the key processes governing the success or failure of beneficial use schemes which utilise the placement of muddy dredged material. Defra wanted research and development work to build on previous small-scale beneficial use studies undertaken by HR Wallingford (Defra Project AE0904, 1997-2001) and CEFAS (AE0231, 2000-2004). The main emphasis of this study was to undertake physical and biological monitoring of a large beneficial use scheme constructed within the timescale of the project funding and then to go on and use this data to investigate the recovery of this site.

The scheme monitored as part of this study was in the Orwell Estuary and part of the amelioration measures for the development of the Trinity III(2) Container Terminal at Felixstowe. The study aimed to look at the issue of larger scale application of muddy dredged material and to more comprehensively monitor the changes in physics and biology after placement. The scheme monitored is the UK's largest direct placement of muddy material onto an existing intertidal area utilising in excess of 200,000m^3 of muddy material.

The results have led to an increased understanding of ecological recolonisation providing a sound basis for discussion of the timescale of biological recovery of direct intertidal placement. As a result the study provides a basis for improved confidence in the sustainable use of muddy dredged material at larger scales in flood defence and habitat management.

The key findings from the study are:

- The colonisation of the created mudflat is occurring within 12 to 24 months and abundance of mud species is high;

- Practical experience of mud placements shows that they can deliver some habitat functioning within 6 months;
- A clear scientific underpinning of relationships for the ecology and the environmental conditions for this site has been identified;
- A unique data set has been generated:
  - from which to make predictions on ecological development at similar locations; and
  - which is valuable to other researchers and practitioners.
- Practical experience has been gained of the different bunding methods and their role in recolonisation; and
- The knowledge gained provides an evidence base for further beneficial use through direct placement of muddy material has been extended

The work undertaken in this project is aimed at helping the UK meet its obligation to the EU of developing ecosystem-based approach by 2010 and meeting OSPAR requirements e.g. for the Quality Status Report.

The findings of this five year research project were disseminated and discussed at a workshop held in December 2006 at the Institution of Civil Engineers and at the Annual Flood and Coastal Management Conference in York (Dearnaley *et al*, 2007).

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1. Introduction

1.1 BACKGROUND

Dredged material may be used directly in the creation or remediation of muddy habitats such as salt marshes and mud flats. This type of beneficial use, promoted by Defra under FEPA II, would actually meet three aims: to use dredged material beneficially; to maintain or increase biodiversity; and to support coastal defences in a more integrated and sustainable manner. Less than 1% of the 30-40 million tonnes of dredged material produced in the UK is used beneficially to enhance or create new mud flat or salt marsh systems (Bolam et al., 2003) as use is limited to small scale trials. Concerns about the behaviour of muddy dredged material placed on inter-tidal areas (in the context of habitat creation schemes or otherwise), could limit the application of such techniques. It appears that to a degree such concerns are fuelled by a lack of detailed studies. There is therefore interest in carrying out such studies, thereby reducing the level of uncertainty associated with the technique. By improving our scientific knowledge and understanding of the impact, if any, of such schemes it may be possible to gain sufficient confidence in the technique, ultimately, one may hope, allowing bigger scale, more widespread use.

In January 2003 HR Wallingford and CEFAS were commissioned by Defra to carry out research to improve the knowledge and understanding of the key processes governing the success or failure of beneficial use schemes which utilise the placement of muddy dredged material. The main emphasis of the study was to undertake physical (reported in HR Wallingford 2005; HR Wallingford 2006a; HR Wallingford 2006b) and biological monitoring (reported in CEFAS 2007a) of a large beneficial use scheme constructed within the timescale of the project funding and then to go on and use this data to investigate the recovery of this site (reported in CEFAS 2007b). The findings of this five year research project were disseminated and discussed at a workshop held in December 2006 at the Institution of Civil Engineers. Participants were from the Central Dredging association (CEDA) Liaison Group for the promotion of the Use of Dredged Material. The results were also presented at the Annual Flood and Coastal Management Conference in York (Dearnaley *et al*, 2007).

The scheme selected for monitoring within this project was part of the habitat enhancement scheme associated with the Trinity III (Phase 2) Container Terminal extension at Felixstowe at the mouth of the Orwell Estuary in East Anglia.

The Shotley side (Suffolk side) of the scheme was selected as the focus for the studies (Figure 1.1). This involved the direct placement of material on the foreshore of the estuary which was confined behind different sorts of bunds constructed from imported or in-situ materials. The dredged material recharge was carried out at Shotley in distinct areas that were concurrently recharged in September 2003 with uncontaminated, fine-grained material from maintenance dredging of the berths and approaches to the Port of Felixstowe.

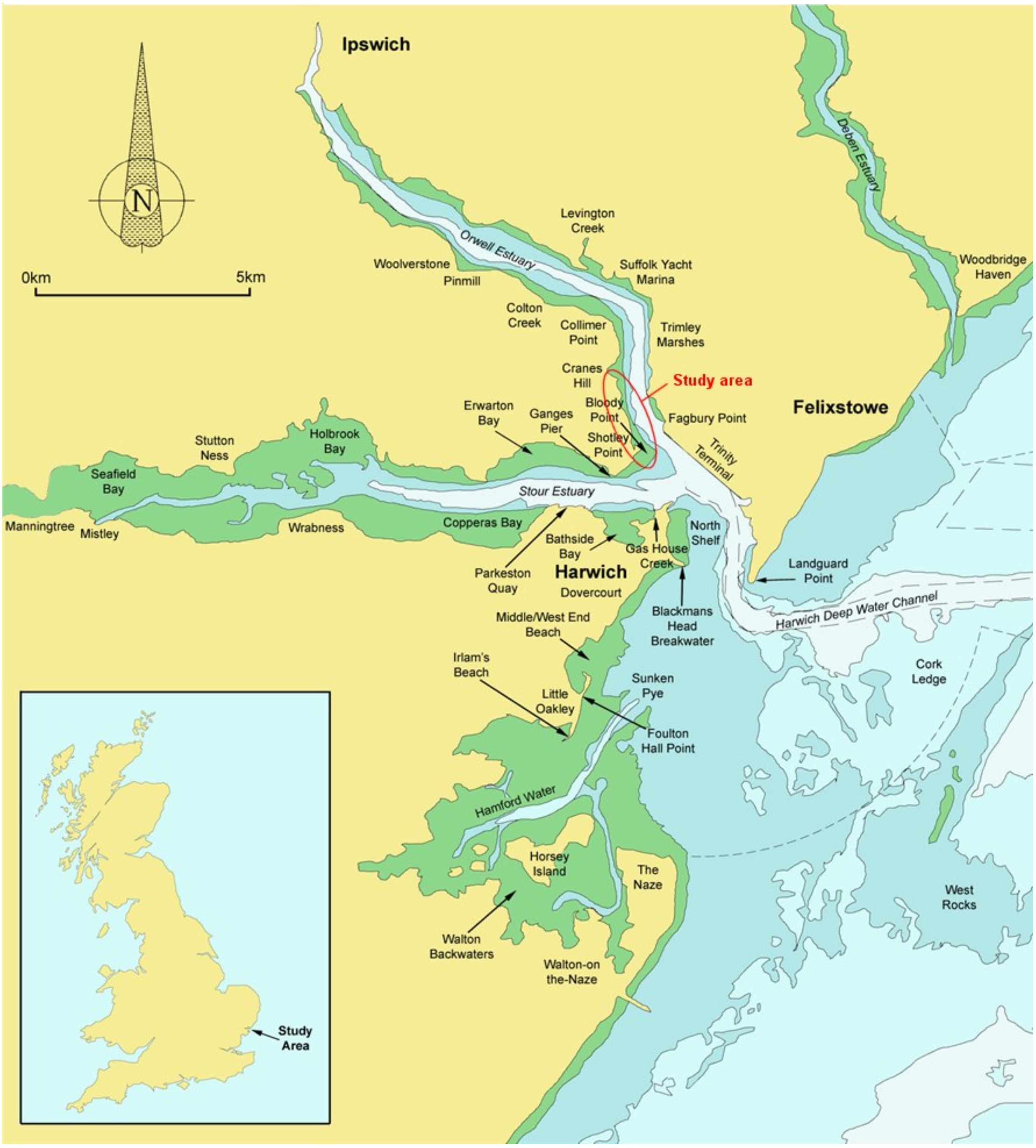


Figure 1.1 Location of the study area

Each of the four placement areas monitored by CEFAS and HR Wallingford had a retaining bund or bunds, constructed to hold the recharged material. The bunds consisted of either in-situ bed material, existing gravel material or clay material arising from the capital dredging associated with the port expansion.

Each area of placement varied in elevation and wave exposure, and therefore the site provided a unique opportunity to investigate how biological recolonisation was affected by these attributes at realistic spatial scales.

The scheme itself was completed in September 2004, and a *Compensation*, *Mitigation* and *Monitoring* Agreement (CMMA) for the extension was put in place. FEPA consents were issued for the habitat enhancement schemes and the disposal of capital silts at sea, which included monitoring conditions. Other information and data gathered at the site on behalf of Harwich Haven Authority, acting for the Port of Felixstowe, outlines the results from monitoring undertaken relating to on-going mitigation and monitoring commitments for the whole scheme (Harwich Haven Authority *et al* 2005; Harwich Haven Authority *et al* 2006). Some of the information reported in these two documents relates to the Shotley habitat enhancement scheme, and although less detailed than this study, it is of interest, as discussed later in this report.

Under FEPA, Part II, a licence is required to deposit any article or substance, below the Mean High Water Spring tide (MHWS) mark, either in the sea or under the seabed, within United Kingdom Waters or United Kingdom Controlled Waters. Section 8 (2) states that the licensing authority has a statutory duty to consider what practical alternative disposal options are available before granting a disposal licence. The policy of the Authority is to encourage licensees to make maximum use of dredged material, for example, in the recharge of beaches, enhancement of mudflats and salt marsh, or the creation of habitat. A separate licence category is provided for licences in respect of operations involving the beneficial use of material, more than 50% of which has been derived from dredging activity and which would otherwise have been disposed of at sea. Promoting beneficial use schemes fulfils UK commitments under OSPAR and the London Convention, of which the UK is a signatory. Many different uses of dredged material exist, the feasibility of which depends in part on the properties of the material being used in the scheme. Muddy dredged material applications are more limited than for sandy material. In England and Wales the main benefit attributed to the use of muddy material is recycling or retaining of fine sediment within the same sediment system. This can be achieved through the selection of local disposal sites and the use of agitation dredging techniques. In England and Wales by far the majority of “beneficial use” can be attributed to this approach. However, a very small proportion of the total volume of muddy material dredged is placed directly in some manner to achieve a benefit and this example of habitat enhancement is a small, but important, subset of the available opportunities for using muddy material beneficially. Other opportunities exist to help address the sediment balance within an estuarine system including sediment replacement programmes mentioned earlier, for example, subtidal placements or water column recharge. Also, muddy dredged material has been used at managed realignment schemes to raise levels inside the sites prior to inundation to enhance the habitat function. In the future many more managed realignment sites will be required to meet UK Biodiversity Action Plan targets. Technical uncertainty introduces an element of risk into any salt marsh creation project. Risks may also arise in that there is the possibility that the desired habitat type does not develop over a reasonable period. Despite this risk, Managed realignment is now a much more accepted technique than a few years ago.

There is also a wider context. Intertidal habitats (i.e. saltmarsh, soft muddy and granular habitats) help to maintain the geomorphological form and functioning of estuaries. They are capable of sustaining the populations of internationally and nationally important overwintering birds. Muddy habitats are important for fisheries, especially in the context of nursery grounds and the provision of habitat for shell fisheries. The potential benefits of mudflats and salt marshes, as part of long term sustainable coastal flood defence measures (through attenuation of wave energy) has long been recognised. Biodiversity issues are a key concern now and in the future. If sites are designated Natura 2000/European sites (which many of our estuaries are) then the need to mitigate or compensate for actions arising from development projects/proposed works as part of the Conservation (Natural Habitats &c.) Regulations 1994 is of importance.

In addition, if successful in creating habitats, schemes could help meet the UK Biodiversity Action Plan. Biodiversity policy is needed to halt the decline in designated habitats (salt marshes and mudflats included). The placement of muddy dredged material may also have a future role to play in Defra's high level target of no net loss of saltmarsh for capital schemes.

For all these reasons understanding of the success of beneficial use schemes using larger amounts of muddy material requires comprehensive monitoring programmes over meaningful timescales.

Finally, the Water Framework Directive is putting increased demands on the way waterways are managed. Habitat enhancement schemes may help fulfil future requirements of the Water Framework Directive to restore transitional and coastal waters to good ecological status. Saltmarshes and mudflats may help with pollution control and water quality (nutrient cycling and sediment retention- wetland habitat can act as a nutrient and pollutant sink), as well as with waste decomposition and disposal (micro-organism processes and scavenging).

The research presented in this report fits the Defra Environmental Strategy Research Programme, in that it seeks to improve the evidence base to support policies on the environment and sustainable development. Specific objectives include improving the quality of data collected for the support of relevant policies and strategies.

The scientific data set collected in this report is unique and comprehensive both at the UK national level, and also by reference to literature from other countries. A considerable amount of information has been collected and collated and is further reported in five technical reports (HR Wallingford 2005; HR Wallingford 2006a; HR Wallingford 2006b; CEFAS 2007a; and, CEFAS 2007b).

1.2 OBJECTIVES

The objectives of the Defra study were:

1. To undertake detailed measurement of physical processes occurring at a site where a large scale placement of muddy dredged material is to be undertaken. The monitoring to include conditions prior to placement, in the initial period following placement and following evolution of the site.
2. To undertake ecological monitoring at a site where a large scale placement of muddy dredged material is to be undertaken. The monitoring to include conditions prior to placement and then extending over a logarithmic temporal sampling period.
3. To assess the factors influencing ecological recovery at the site and to develop an ecological model of the evolution of the large scale placement of muddy dredged material, utilising as necessary the results of process measurements and modelling.
4. To disseminate guidance regarding the predictive techniques available for design and impact assessment of large scale beneficial use schemes involving direct placement of dredged material onto intertidal areas

To accomplish the monitoring programme for Objective 1 a series of field surveys was carried out by the Field Services Unit of HR Wallingford prior to, during and after placement of the dredged material. The work began in May 2003 with the initial series of measurements finishing in September 2004. This is reported in HR Wallingford, March 2005 (EX5108). Further bathymetric and sampling surveys were undertaken in

April 2005 and September 2005 and these are reported in HR Wallingford, March 2006a (EX5180). The biological monitoring results for Objective 2 are presented in CEFAS February 2007a. HR Wallingford, March 2006b (EX5181) describes the work undertaken by HR Wallingford to assist CEFAS in addressing Objective 3 whilst CEFAS February 2007b describes the ecological modelling results for the project.

1.3 REPORT STRUCTURE

This report summarises the project undertaken by HR Wallingford and CEFAS on behalf of Defra. Chapter 2 outlines the use of muddy dredged material in UK and summarises previous related projects. Chapter 3 describes the scheme monitored within this project. Chapter 4 gives details of the physical and ecological monitoring undertaken and key results gained. Chapter 5 summarises the findings and main lessons learnt from the Ecological Modelling. Chapter 6 gives a summary of the results of the project and a discussion of the role for direct placement of dredged material in the UK. Appendices provide additional information on the project relevance to Defra policy and UK legislation and list the various outputs of the project.

2. *Use of muddy dredged material in UK*

2.1 BACKGROUND

Total maintenance dredging in the UK is typically 30 to 40 million wet tonnes per year. Most material has a high fines content.

Over the last decade most muddy dredged material is placed offshore at (historic) licensed disposal sites with approximately 50% placed at disposal sites within estuary systems. Some 5-10% is recycled through trickle charge schemes with only 0-0.5% used in other beneficial use schemes.

A number of beneficial use options exist, these are well described in a previous study report (HR Wallingford, 2001) and in summary include:

- Direct Placement which can involve intertidal nourishment and intertidal and subtidal trickle charge
- Confined Placement. Often confined by gravel bunds
- Placement behind seawalls prior to managed realignment to raise levels.
- Trickle Charge, which can be intertidal, subtidal and water column
- Agitation Dredging involving the release material to the system at the point of dredging.

2.2 PREVIOUS RELATED PROJECTS

This project builds on knowledge gained during previous research projects undertaken by HR Wallingford and separately by CEFAS.

2.2.1 The beneficial use of muddy dredged material (AE0904, 1997-2001)

This project undertaken by HR Wallingford was reported in 2001 (HR Wallingford, 2001). The project focused on the practical lessons learnt and considered: dredging plant and options for beneficial use, issues associated with scheme assessment, monitoring of schemes, guidance on factors influencing the success of a scheme and lessons learnt from "small" schemes. It raised issues associated with the larger scale use of muddy material and provided recommendations regarding communication amongst practitioners and regulators, monitoring and highlighted the need to address the larger scale use of material.

The schemes monitored or reviewed as part of AE0904 included:

- North Shotley, Orwell
- The Horse, Stour
- Horsey Island, Walton Backwaters
- Salt marsh remediation, Blackwater
- Sediment recycling, Amble Marina, Northumberland
- Essex Marinas, Crouch, Blackwater, Walton Backwaters
- Suffolk Yacht Harbour, Orwell
- Parkstone Yacht Club, Poole Harbour
- Sediment replacement schemes, Harwich Harbour and Stour Estuary.

2.2.2 Ecological monitoring of beneficial use options (AE0231, 2000-2004)

This project was undertaken by CEFAS and reported in 2004. Based on ecological processes and environmental effects this project considered: the characteristics of UK-licensed dredgings, the ecological consequences of inter-tidal placement of fine-grained dredged material (beneficial use) for habitat creation/flood defence, the environmental effects of ongoing and new beneficial use and sea disposal schemes and provided a decision-making framework for dealing with licence applications, incorporating new criteria for determination of environmental consequences.

Ecological time-series sampling was conducted at the following four beneficial use schemes for macrofauna, meiofauna and sediment properties:

- Westwick Marina, Crouch Estuary
- Titchmarsh Marina, Walton Backwaters
- North Shotley, Orwell Estuary
- Horsey Island, Walton Backwaters.

The project recommended that longer-term datasets are needed on the development and biological recovery of beneficial use schemes and an assessment of larger-scale beneficial use schemes was required.

3. Large scale use of muddy dredged materials for sustainable flood defences and habitat management - AE0260

3.1 SCHEME SELECTION

This study has been undertaken by HR Wallingford and CEFAS. The detailed objectives are outlined in Section 1.2. The overriding aims were:

- To improve knowledge and understanding of the key processes governing the success or failure of beneficial use schemes utilising muddy material.

- To focus on recording physical and ecological change and then considering methodologies for predicting ecological change based on physical process.

It is worth noting here that the project was set up to monitor a suitable scheme using a large volume of muddy material. The project was not going to undertake the scheme itself and therefore relied upon being able to monitor a scheme implemented by a third party. The project had to select a scheme to monitor from those available within the timescale of the project.

The research required a scheme with over 100,000 cubic metres of muddy dredged material for placement and when the project was conceived in 2002 the possibilities included Dibden Bay amelioration scheme; Environment Agency proposals on Horsey Island; and Trinity III(2) amelioration scheme.

The Dibden Bay scheme did not occur but in 2003 it was confirmed that the Trinity III(2) scheme would proceed and at that time the Environment Agency proposals for Horsey Island were uncertain. The Trinity III(2) scheme was therefore selected.

3.2 DESCRIPTION OF SCHEME - CONSTRUCTION

The Trinity III(2) scheme was designed to have flood defence and habitat value. The area of mudflat fronted and protected a seawall that the Environment Agency were committed to defend. It was accepted by English Nature and other regulators as a medium term measure (reversible) within an eroding estuary system.

The scheme was designed for the direct placement of muddy materials onto a "poor quality" intertidal. The muddy dredged material placements were from 0.1 to 1m deep and confined by different types of bunds - clay, gravel and "in-situ material" bunds in different areas.

The four separate recharge areas monitored by both CEFAS and HR Wallingford are shown in Figures 3.1 and 3.2. These four sites represented a good cross section of varying physical conditions so resources focused on these sites and two smaller recharge areas within the overall scheme were not subject to ecological monitoring. These two smaller sites are therefore not referenced further in this report. Figure 3.2 also shows the spatial differences in selected (mean ± SE, n = 5) environmental variables for each of the four sites averaged over the 24-month study period. The environmental variables presented are related to the elevation (bed level), density (surface density), and exposure (wave height) of recharged material.

Figure 3.1 Location of the four intertidal recharge sites in the Orwell Estuary. This view of the recharge sites faces to the South.

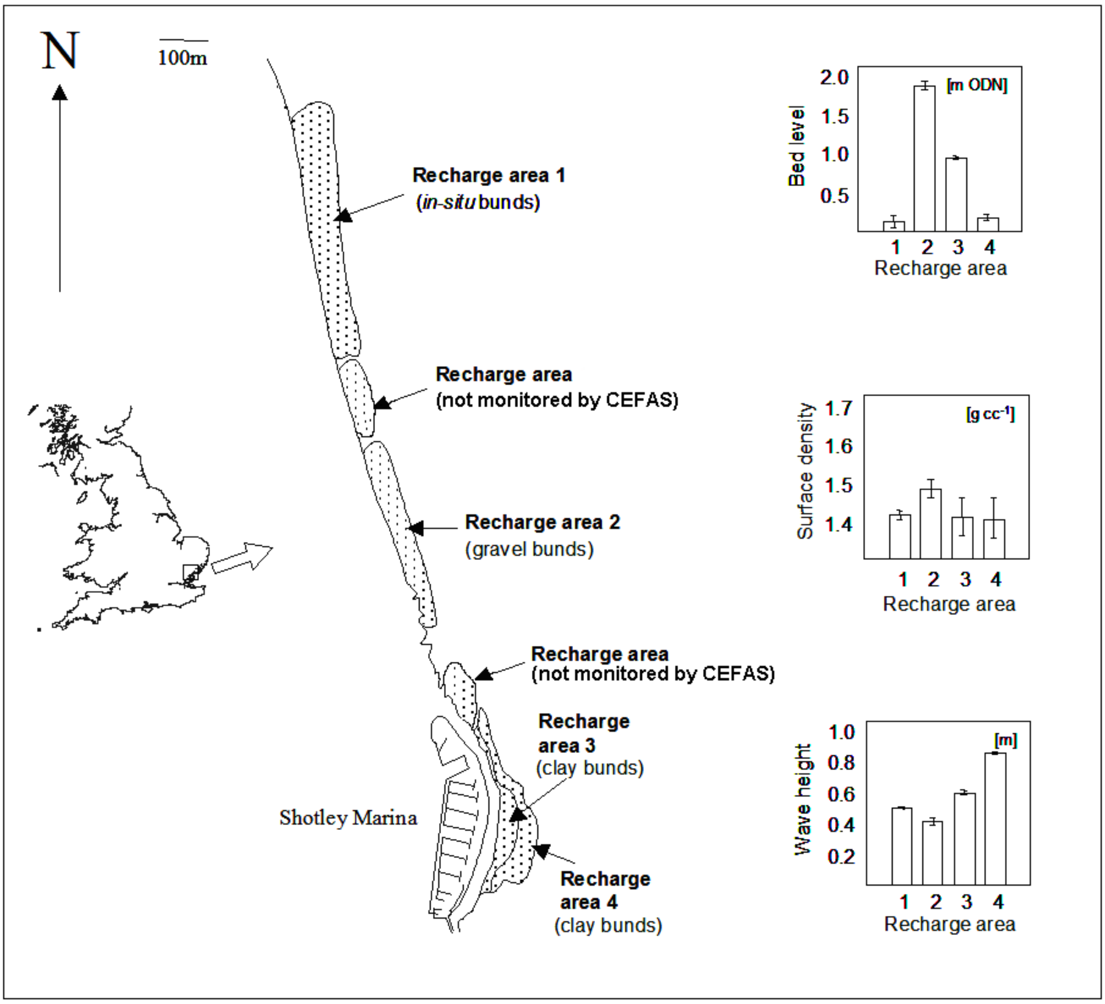


Figure 3.2 Location of the intertidal recharge sites. All sites were monitored by HR Wallingford for physical parameters. Four recharge sites were also monitored by CEFAS for biological parameters. The spatial differences in selected environmental variables are shown for the four selected sites.

The dates for placement of silts into each area are as follows:

Area 1	11 Sept 2003	to	12 Sept 2003
Area 2	1 Sept 2003	to	1 Sept 2003
Area 3	3 Sept 2003	to	7 Sept 2003
Area 4	3 Sept 2003	to	7 Sept 2003

The construction process is briefly described in this report with further details outlined in HR Wallingford (2005). Essentially each area of placement had a retaining bund or bunds constructed to hold the pumped muddy material (illustrated conceptually in Figure 3.3).

For Areas 3 and 4 clays arising from the capital dredge were pumped onto the foreshore (see Figure 3.4). Following clay placement the clays were worked into bunds to retain the material (Figure 3.5) and then the bunds were infilled with muddy material. This is illustrated for Area 2 in Figure 3.6.

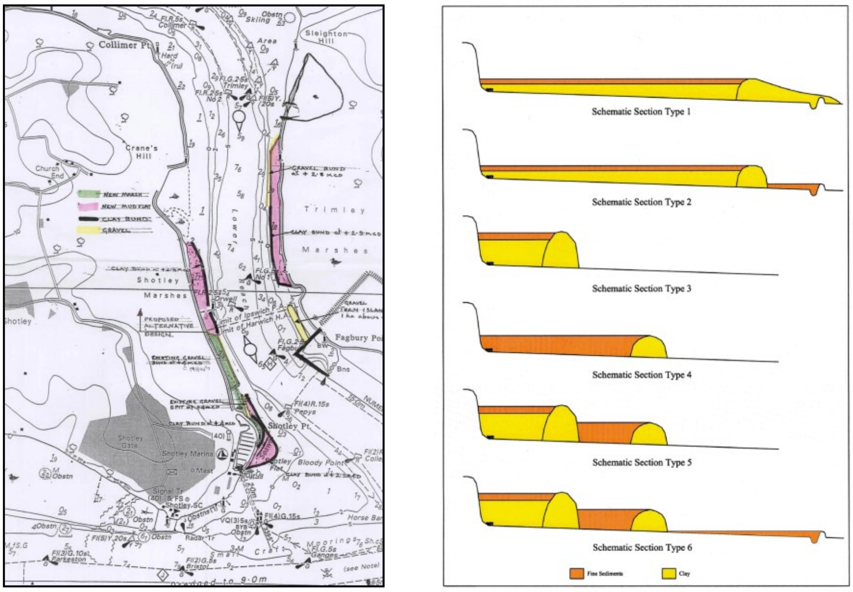


Figure 3.3 Scheme layout

The bunds were either existing gravelly material (Area 2), clay material arising from the Trinity III(2) capital dredge (Areas 3 and 4) or constructed from in-situ bed material (Area 1). All muddy infill was of material from maintenance dredging at HHA.

Figure 3.4 Areas 3 and 4 - Pumping clays ashore

Figure 3.5 Areas 3 and 4 creation of the clay bunds

Figure 3.6 Area 2 - Pumping muddy material behind gravel bund

The material for the Area 3 and Area 4 bunds was a mixture of London clay with flint, Upper & Lower Greensand clays, Keuper Marl & Sandstone and alluvial gravels. The clay bunds were formed into a crescent shape (Figure 3.7). There were two levels in the main recharge area adjacent to Shotley Marina, an upper terrace (Area 3) with a level of approximately +3.5m CD and a lower terrace (Area 4) at +2.5m CD, (Figure 3.7). The initial pumping of the clays onto the foreshore for the bunds took place in early Spring 2003, but it wasn't until August 2003 when a amphibious excavator, on hire from Holland, was delivered to the site that the final construction and shaping of the retaining bunds was completed (Figure 3.7).

Figure 3.7 Area 3 and 4- showing upper and lower terrace

The Dutch-designed "Sneider" amphibious excavator was assembled with two large buoyancy floats with a track system to replace the normal metal tracks. This arrangement allowed the unit to work on the soft inter-tidal areas.

The first trial pumping of silt from the Felixstowe berths was carried out in Area 2 on 1st September 2003 (Figure 3.6). This area was initially bunded in 1999 but due to settlement and continued roll back of the gravel bund it was possible to contain more material within this area finally enabling salt marsh levels to be attained within the site. This operation took some 9-10 loads of material, each being approximately 1200 m^3. A support barge was beached and anchored with two "spud" legs at high water in the centre of the area (Figure 3.8). The trailing suction hopper dredger ‘SOSPAN DAU’ moved offshore and coupled up to a long buoyant delivery pipe protruding from the bow of the barge (Figure 3.8). This allowed the dredger to discharge its load at low water. The pumped mud suspension then had a short settling period before the tide inundated the area.

Figure 3.8 Area 2 - Sospan Dau and beached support barge

Next the barge was moved to the northern-most (upstream) limit of Area 4 on the HW of 2nd/3rd September 2003. A buoyant floating delivery pipeline was anchored ashore alongside the western edge of the reclamation area. This pipeline had several outlet positions so that the exact discharge location for the pumped mud could be easily changed without the need to move the pipe. This fixed pipe was then coupled to the barge to allow the filling of the new lagoon areas from a single barge site.

The southern limit of the upper terrace (Area 3) was filled first followed by the northern end of the same terrace. The lower terrace (Area 4) was simultaneously filled as the upper terrace overtopped. These areas were completed by Sunday 7th September 2003.

A new method of constructing an intertidal retaining structure for Area 1 had been devised by Hans Visser (Boskalis) and John Brien (Harwich Haven Authority), whereby the amphibious excavator scraped its bucket in arcs creating mud banks some 0.3 m high with a "ditch" inshore. Four parallel bunds were formed in this way and filled from a single location via the feed pipeline positioned at the toe of the seawall, upstream of the sewer outfall pipeline and extending upstream to the start of the saltings. The pipeline was broken back as the terrace areas filled. The depth of silt/mud in these terraces varied from 0.8 m in the deeper ditches, created by the excavator, to 0.05 - 0.2 m across the existing mudflats. Figure 3.1 gives an aerial view clearly displaying the parallel bund terraces.

4. Monitoring of scheme

4.1 OVERVIEW

The entire scheme involves habitat enhancement at Trimley and Shotley, which has been monitored by Harwich Haven Authority (HHA) on behalf of the Port of Felixstowe as part of consent with annual reporting to Regulators under the monitoring agreement associated with Trinity III(2) extension. Details of the beneficial use schemes that have been implemented by the HHA were provided in the 2001 Annual Report (PDE and HR Wallingford, 2001) and recorded in the Compliance Report (Royal

Haskoning and HR Wallingford, 2003b). Most recent monitoring results are given in Harwich Haven Authority 2005; 2006).

This research project (AE0260) involved undertaking detailed monitoring of the Shotley “half” of the scheme. HR Wallingford focused on the monitoring of the physical processes while CEFAS monitored the ecological development. The requirement for physical data soon after placement was recognised from the onset of the project so more frequent monitoring was undertaken in the earlier stages of the research so that key data could collected.

Overall, the monitoring undertaken focused on relating biology and physical processes with the key question in mind “Are we able to predict the ecological development of the placement?” CEFAS undertook ecological modelling of the faunal data using abiotic variables provided by HR Wallingford. Further input on the physical parameters at the CEFAS measurement locations was provided using HR calibrated models of the area. The following abiotic parameters were determined: Bed elevation; inundation; water depth; current speed (modelled); bed shear stress (modelled); particle size distribution; bed density and wave characteristics (modelled).

4.2 PHYSICAL MONITORING (OBJECTIVE 1)

4.2.1 Introduction

Objective 1: To undertake detailed measurement of physical processes occurring at a site where a large scale placement of muddy dredged material is to be undertaken. The monitoring to include conditions prior to placement, in the initial period following placement and following evolution of the site.

This objective was met by HR Wallingford who, to accomplish the monitoring programme, carried out a series of field surveys between May 2003 and September 2005, these being prior to, during and after placement of the dredged material (HR Wallingford 2005; HR Wallingford 2006a and HR Wallingford 2006b). The detailed physical study of the initial placement was undertaken to provide a better understanding of what happens to cohesive sediments shortly after placement, which is not reported for previous small scale studies.

The programme included the following main elements:

1. Bathymetric surveys
2. Topographic cross-section surveys
3. Wave and current measurements
4. Measurement of bed density profiles
5. Bed sampling
6. Water level measurements
7. Local meteorological measurements.

The results of the physical monitoring were used to validate flow and wave models of the study area.

4.2.2 Bathymetric surveys

Forty lines of soundings were run at 50 metre centres normal to the alignment of the main channel nominally starting at the toe of the seawall or edge of the saltings and run offshore as far as the deep water channel. To increase the density of measurements over the southern end of the placement area an additional 15 lines were sounded at 50m centres to cover the southern extreme of the survey area and in the vicinity of Areas 3 and 4 an additional seven lines were sounded at 25m centres.

The bathymetry measurements were carried out during periods of calm river conditions over the high water periods on spring tides, when the ‘wetted’ area (to the level of Mean High Water Spring tides) was maximised.

Between August 2003 and September 2005, the bathymetry was surveyed on the seven occasions as listed below:
Survey 1 - 31st August to 11th September 2003
Survey 2 - 27th.to 30th September 2003
Survey 3 - 7th to 11th November 2003
Survey 4 - 6th to 9th March 2004
Survey 5 - 2nd to 4th September 2004
Survey 6 - 6th to 25th April 2005
Survey 7 - 16th to 21st September 2005

Comparison of the seven surveys showed that between the toe of the bunds and the deep water channel there were only minor changes in the measured bathymetry between August 2003 and September 2005 (Figure 4.1). In some cases, the bathymetry measurements extended inshore over the outer bund of the recharge area (Figure 4.2). These measurements generally showed an inshore movement and lowering of the bund and a lowering of the level of the pumped material. Changes to the bund and the filled material are discussed further in the “Topography” section below.

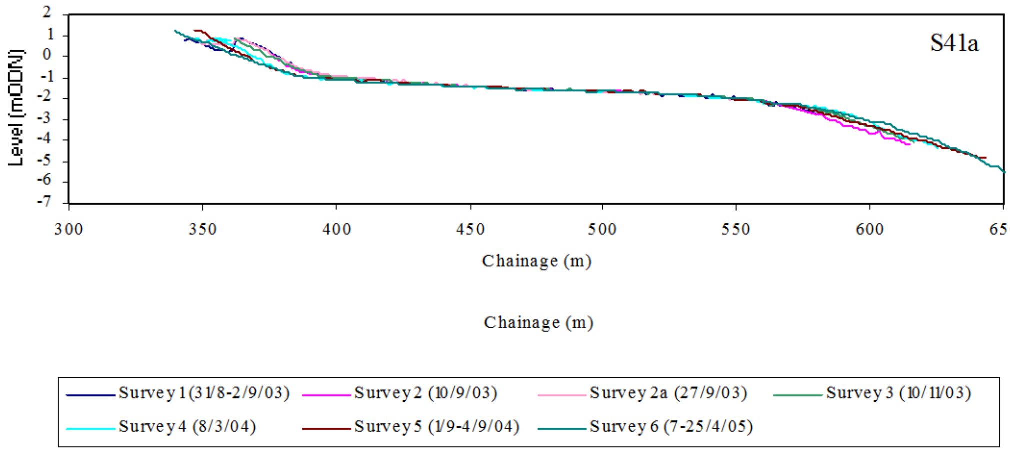


Figure 4.1 Areas 3 and 4 - Example of small changes to recharge area bathymetry

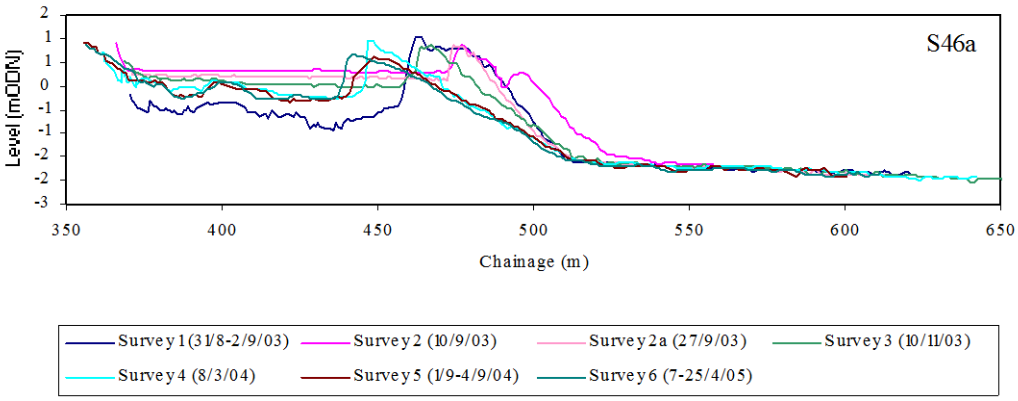


Figure 4.2 Areas 3 and 4 - Example of large changes to recharge area bathymetry

4.2.3 Topographic cross-section surveys

In order to accurately identify and quantify any changes in shape of the Shotley recharge over time, sixteen cross-section lines were surveyed in detail by topographic methods.

Surveying was achieved using a combination of spirit levelling and total station observations.

Each of the sixteen sections was surveyed between the MHWS and MLW marks (the latter depending on the state of tide at the time of the survey) (HR Wallingford 2005; 2006a).

Between August 2003 and September 2005, the cross-sections were surveyed on the nine occasions as listed below. (Note that not all sections were surveyed on each occasion).

Survey 1 - 3rd to 4th September 2003
Survey 2 - 9th to 11th September 2003
Survey 3 - 15th to 19th September 2003
Survey 4 - 28th September to 1st October 2003
Survey 5 - 8th to 13th November 2003
Survey 6 - 6th to 10th March 2004
Survey 7 - 2nd to 4th September 2004
Survey 8 - 26th to 28th April 2005
Survey 9 - 18th to 20th September 2005

Comparison of the nine topographic surveys undertaken between September 2003 and September 2005 showed that significant changes to the bed elevation had occurred between the toe of the bund and the seawall. The degree of change in elevation varied widely from one recharge area to another. At the up river recharge site (Area 1) the changes in bed elevation were relatively small (Figure 4.3), whereas at the down river site (Areas 3 and 4) the changes were considerable (Figure 4.4). The general trend in changes to the bathymetry was for the pumped material to lower in elevation, primarily because of consolidation, and for the bund to recede towards the seawall due to wave action.

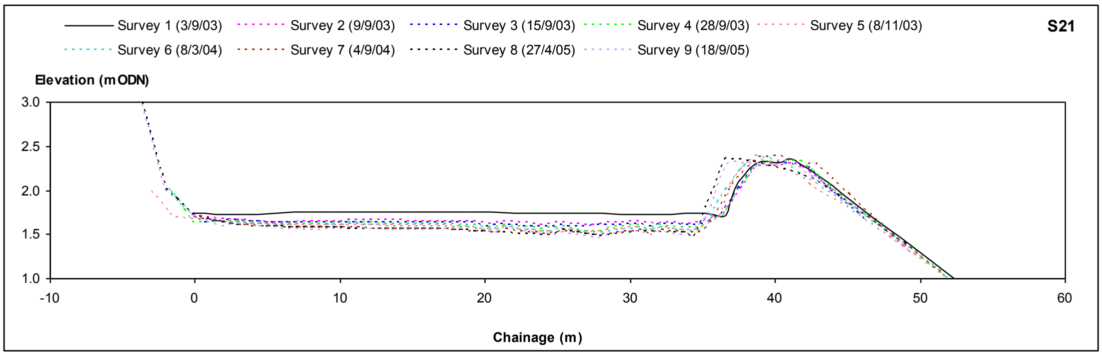


Figure 4.3 Area 1 - Example of small changes to the cross-section

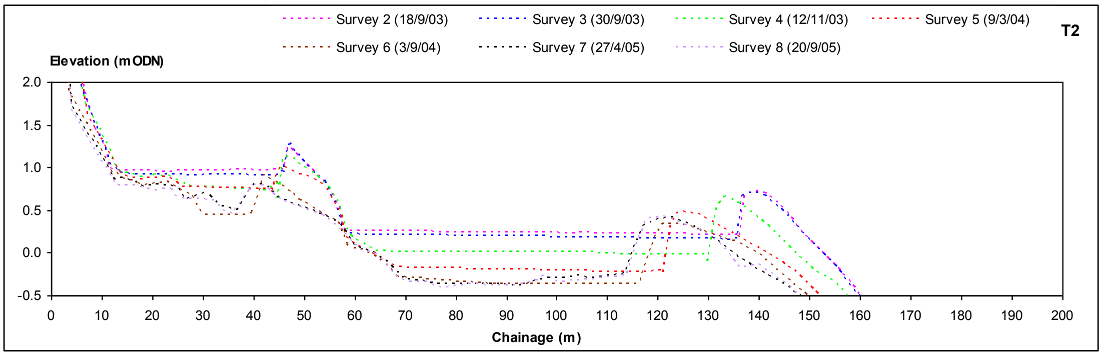


Figure 4.4 Areas 3 and 4 - Example of large changes to area cross-section

4.2.4 Wave and current measurements

Near-shore waves and currents were measured between May and July 2003 using a Macrowave logger and a Nortek AWAC and between September and November 2004 using a Nortek AWAC only. Further details are given in a technical report from this study (HR Wallingford, March 2005). A different deployment site was selected for each of the two measurement campaigns as shown in Figure 4.5.

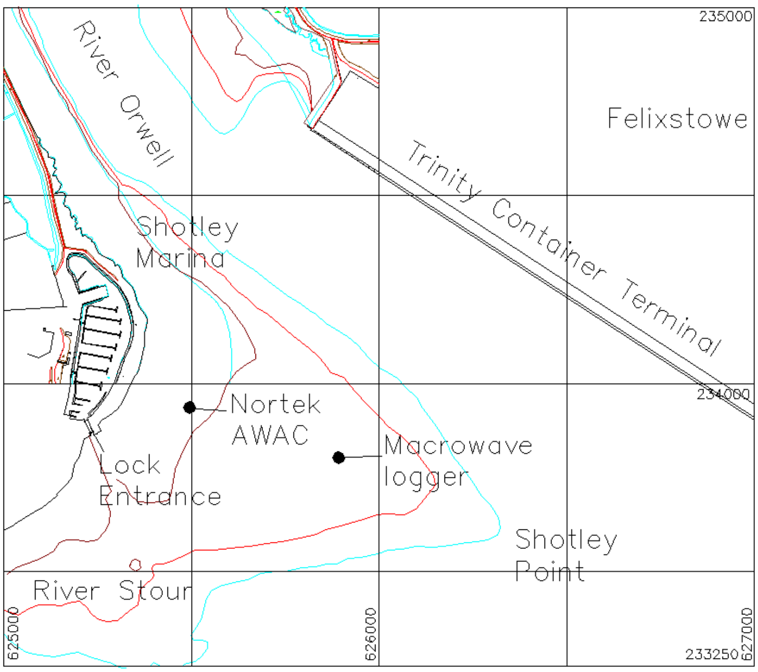


Figure 4.5 Location of wave and current measurement instruments

The Nortek AWAC (Acoustic Waves And Currents) is designed to measure both the through-depth current profile and the wave spectrum using acoustic Doppler technology combined with pressure measurements. Current data is presented as a time series of speed and direction 2.0m above the bed (September to November) in Figure 4.6. The measured wave data is presented as a time series of height and period for the same instrument deployment in Figure 4.7.

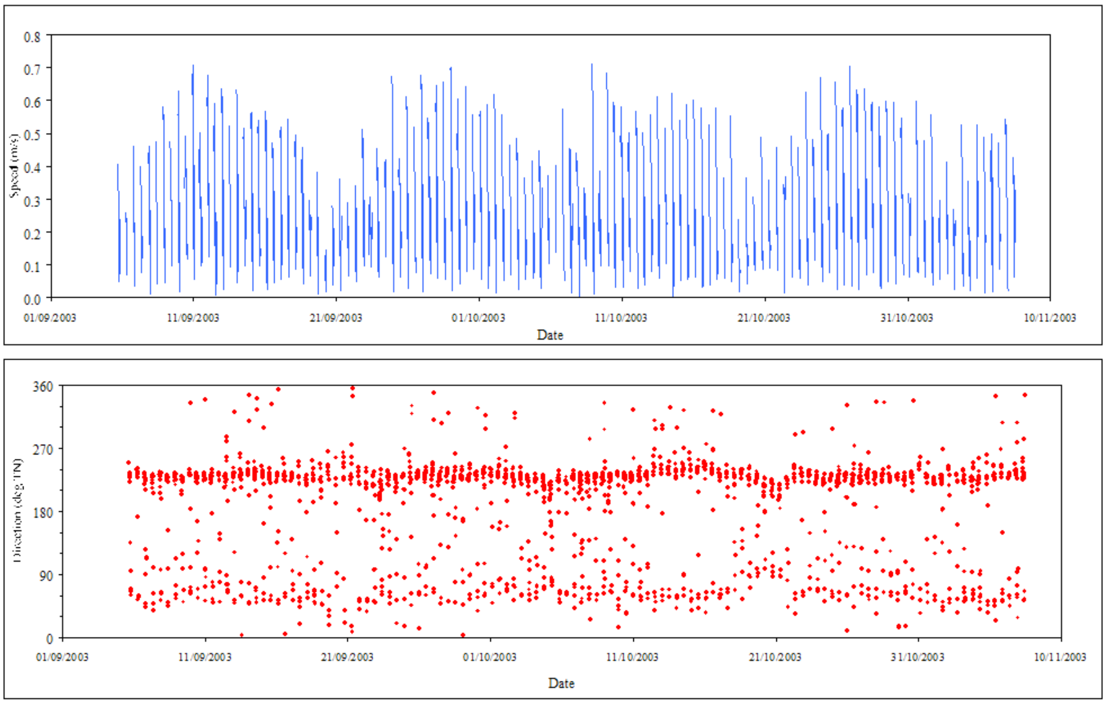


Figure 4.6 Nortek AWAC current speed and direction at 2.0m above the bed

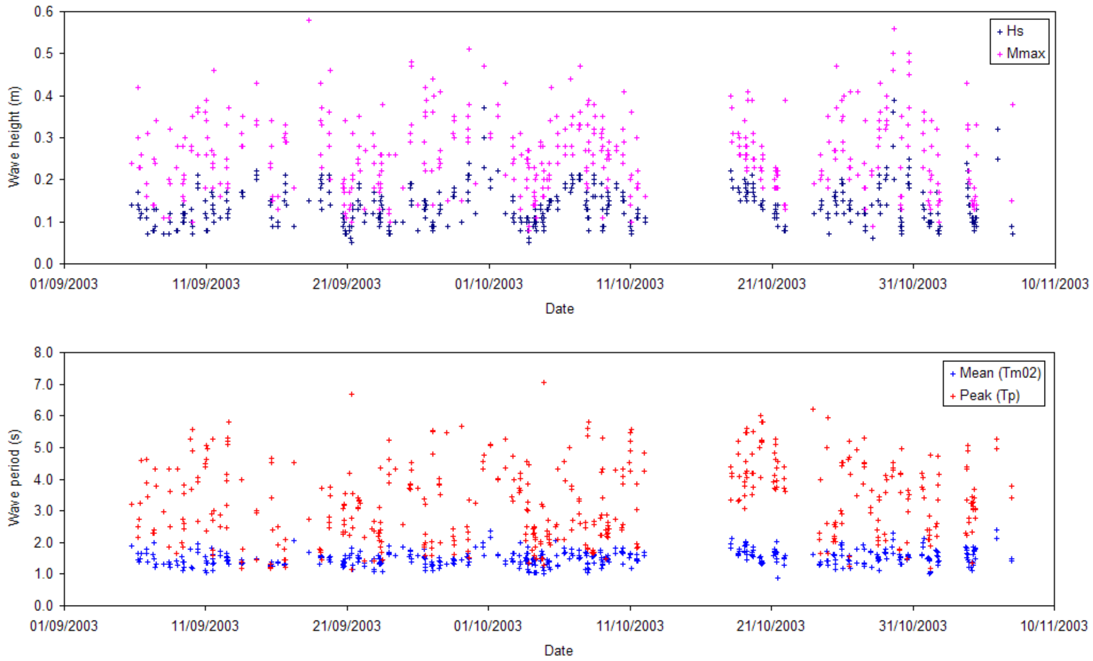


Figure 4.7 Nortek AWAC wave height and period

4.2.5 Measurement of bed density profiles

In order to identify the spatial extent and density of the pumped dredged material and to monitor the change in characteristics with time within the lagoon areas vertical profiles of density versus depth were made at 27 specific sites throughout the survey area.

The density probe was mounted on the end of a graduated 3m long aluminium pole, which enabled it to be manually pressed into the surface sediments. Measurements of bed density were made between the surface and the termination point at 5cm increments. Each vertical profile extended to full penetration with reasonable pressure applied to the supporting pole. In general, the termination point coincided with the interface between the bottom of the mud layers and the original intertidal bed level which was typically composed of more consolidated clays and gravels.

The density profiles showed a gradual increase in density in Area 2 where the pumped deposits dry for long periods of the tide (Figure 4.8). Profiles for Areas 1, 3 and 4 show that the density of the material in the majority of the areas has changed little since the original deposition (Figure 4.9).

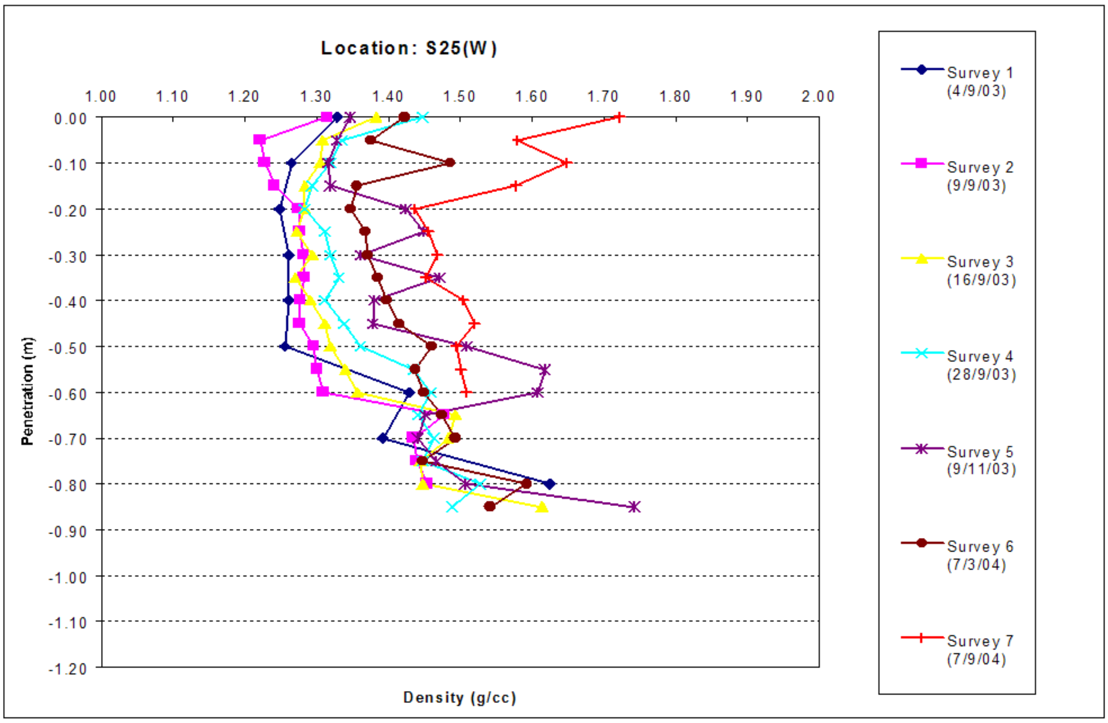


Figure 4.8 Bed density measurements in Area 2

Large variations in the bed density were often measured in the top 5-10 centimetres as can be seen in Figure 4.8. These increases were predominantly due to the inshore migration and overtopping of sands and gravels over the fringes of the mud deposits.

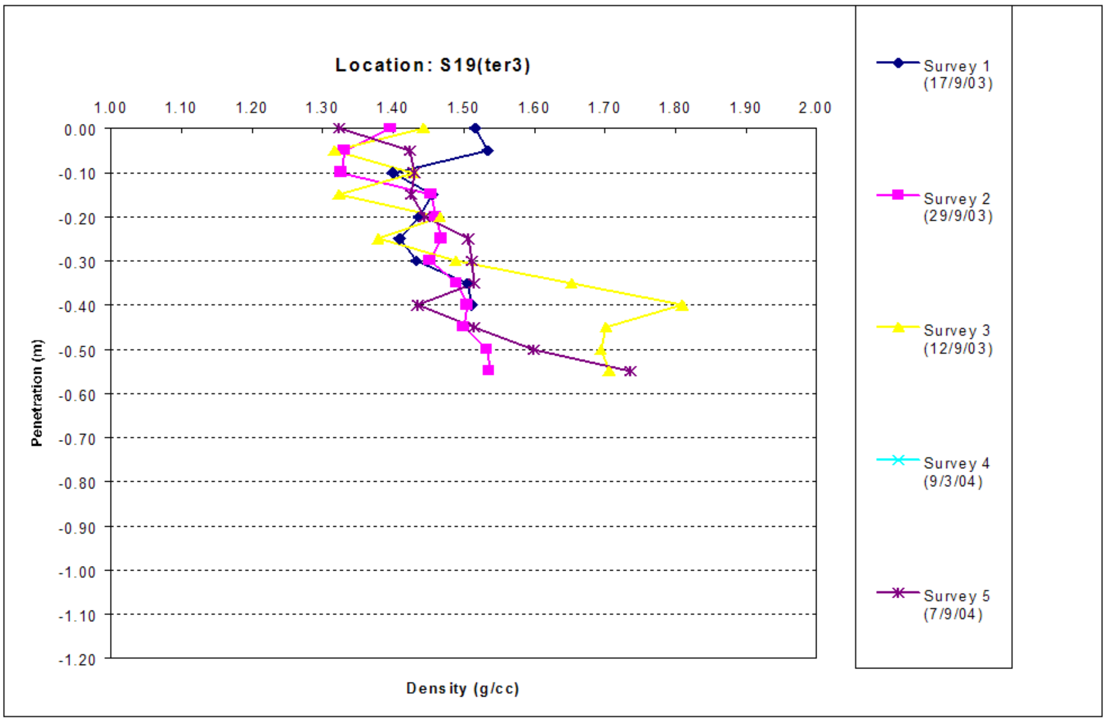


Figure 4.9 Bed density measurements in Area 1

4.2.6 Bed sampling

In order to monitor any changes in the physical properties of the deposited dredged material, a surface sediment sample was taken at each density profile location. Between 20 and 25 bed samples were collected from specific locations within the study area during six occasions between September 2003 and September 2005.

The samples of bed material were mostly collected from the undisturbed surface 5cm of the mud and stored for transportation to the HR Wallingford Sedimentation Laboratory.

Particle size distribution (PSD)
A number of representative samples from each survey were selected for analysis of full Particle Size Distribution (PSD). The material comprised predominantly fine silts or mud with fine sand.

The basis of the analytical method was to first wash the sample / sediment through a 63µm aperture sieve. The sand fraction retained on the 63µm sieve was then passed through a stack of sieves of pre-determined sizes to produce a particle size distribution for the material greater than 63µm. The fine fraction that passed through the 63µm sieve was analysed using a FRISCH Laser Particle Sizer. The two data sets were then combined to produce a particle size distribution curve for the whole sample.

The results of the variation in PSD measured at a control location to the north of, and outside of, recharge Area 1 during the course of the two-year sampling programme are shown in Figure 4.10.

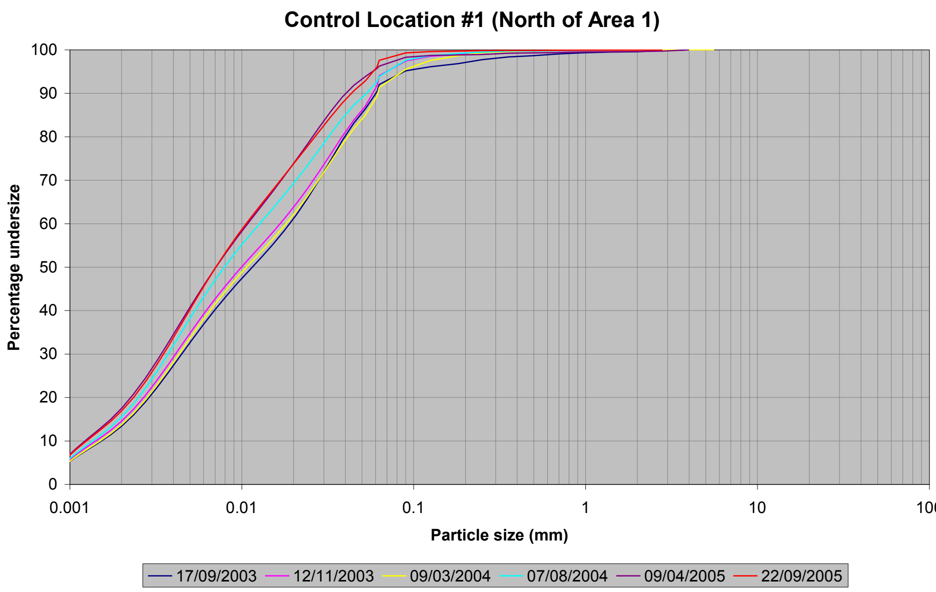


Figure 4.10 Particle size distribution (PSD) of surface bed samples

Figure 4.10 shows the variability in the PSD of the surface sediments that exists naturally at this location. During the course of the sampling programme, the median particle size (d_{50}) is shown to gradually become finer, changing from about 12 µm in September 2003 to about 7 µm in September 2005.

The results of the measurement of the PSD of selected bed samples taken from within recharge Areas 1, 2 and 3 and 4 are shown in Figure 4.11.

Figure 4.11 shows that trends in variation with time of the PSD can be identified from one recharge area to another. The results from the three sampling locations in Area 1 (of which location number 4 is shown in Figure 4.11) were very comparable during the two-year period of sampling, and similar to those measured at the control point outside of the recharge area. During the course of the sampling programme, the d_{50} varied between 6 and 8 µm, though no clear trend was apparent.

The results from the five sampling locations in Area 2 (of which location S27(E) is shown in Figure 4.11) show that there was a tendency for the surface material to coarsen during the two-year sampling period with the d_{50} varying between about 6 and 10 µm.

The PSD measured at the four sites in Areas 3 and 4 (of which location T1 2/3 on the lower terrace is shown in Figure 4.11) show a much larger variation with time than that measured at the up-estuary recharge Areas 1 and 2. The PSD analysis shows that between September 2003 and April 2005 the d_{50} increased from about 5 µm to 600 µm. An increase in particle size of this magnitude must have been associated with an accumulation of coarse sand and shingle at the sampling location. Sampling locations further up the Area 4 terrace showed a smaller variation in particle size. Between April and September 2005 the d_{50} became finer, reducing from 600 µm to about 80 µm (similar to that measured during 2004). This reduction to "normal" levels can be associated with a migration of the coarse material away from the measurement position.

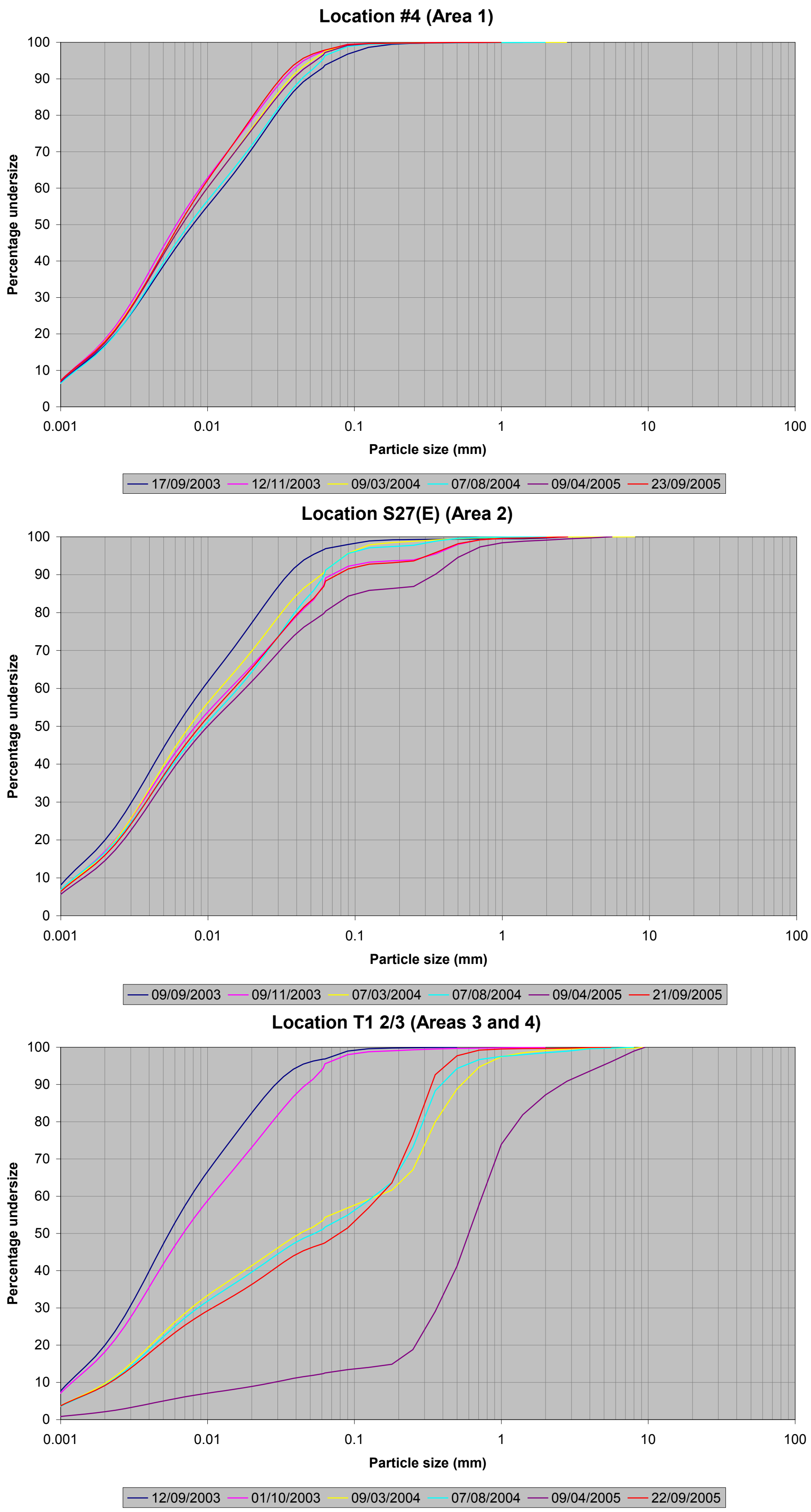


Figure 4.11 Particle size distribution (PSD) of surface bed samples

Loss on ignition (LOI)

Additional analysis was carried out to measure the percent loss-on-ignition (% organic matter) to quantify the mass of combustible material present in each sample. The results of the loss on ignition (LOI) analysis for each of the bed sample locations for recharge Areas 1, 2, 3 and 4 are shown in Figure 4.12. Included in the Area 1 plot are measurements made on samples collected from the control point, which was located to the north of, and outside of, recharge Area 1.

Figure 4.12 shows that trends in the LOI (% organic matter) can be identified from one recharge area to another. The LOI results from the three sampling locations in Area 1 followed each other very closely during the two-year period of sampling, varying between about 8% and 10%. This area was first sampled about two weeks after the recharge was completed, after which the LOI increased to a level above that measured at the control position. After about 11 months, the LOI was not significantly different to that measured at the control position and the general trend was for the LOI to reduce by a small amount with time.

The results from the five sampling locations in Area 2 show a similar trend over the measurements period to that observed in Area 1. Surface bed samples were first taken from this area two days after the recharge was completed. In this case, the LOI at all sites reduces before the increase measured during the third sampling campaign. After this time, the LOI is more variable than that measured in Area 1 though the general trend is for the LOI to reduce. During the sampling period the LOI varied between about 8% and 12%.

The LOI measured at the four sites in Areas 3 and 4 show a much larger variability than that measured at the up-estuary recharge Areas 1 and 2. This area was first sampled between one and five days after the recharge was completed, after which time there was a large divergence in the measured LOI. The largest variation in LOI was measured at the southernmost, low-level sampling location, where the LOI varied between about 10% and 2%. The LOI at those sampling locations further inshore varied to a lesser degree.

Although there was no clear seasonality to the measured LOI in any of the recharge areas, there was a strong correlation with particle size distribution (PSD). Samples taken from within Areas 1 and 2 showed only small variations in both LOI and PSD whereas Areas 3 and 4 showed large variations in both parameters.

In Areas 3 and 4 a reduction in LOI was clearly associated with a coarsening of the PSD. Similarly, an increase in LOI was accompanied by the surface material becoming finer. Areas 3 and 4 were more subject to variation in particle size, particularly at the southernmost, low-level, sampling sites due to exposure to wave activity.

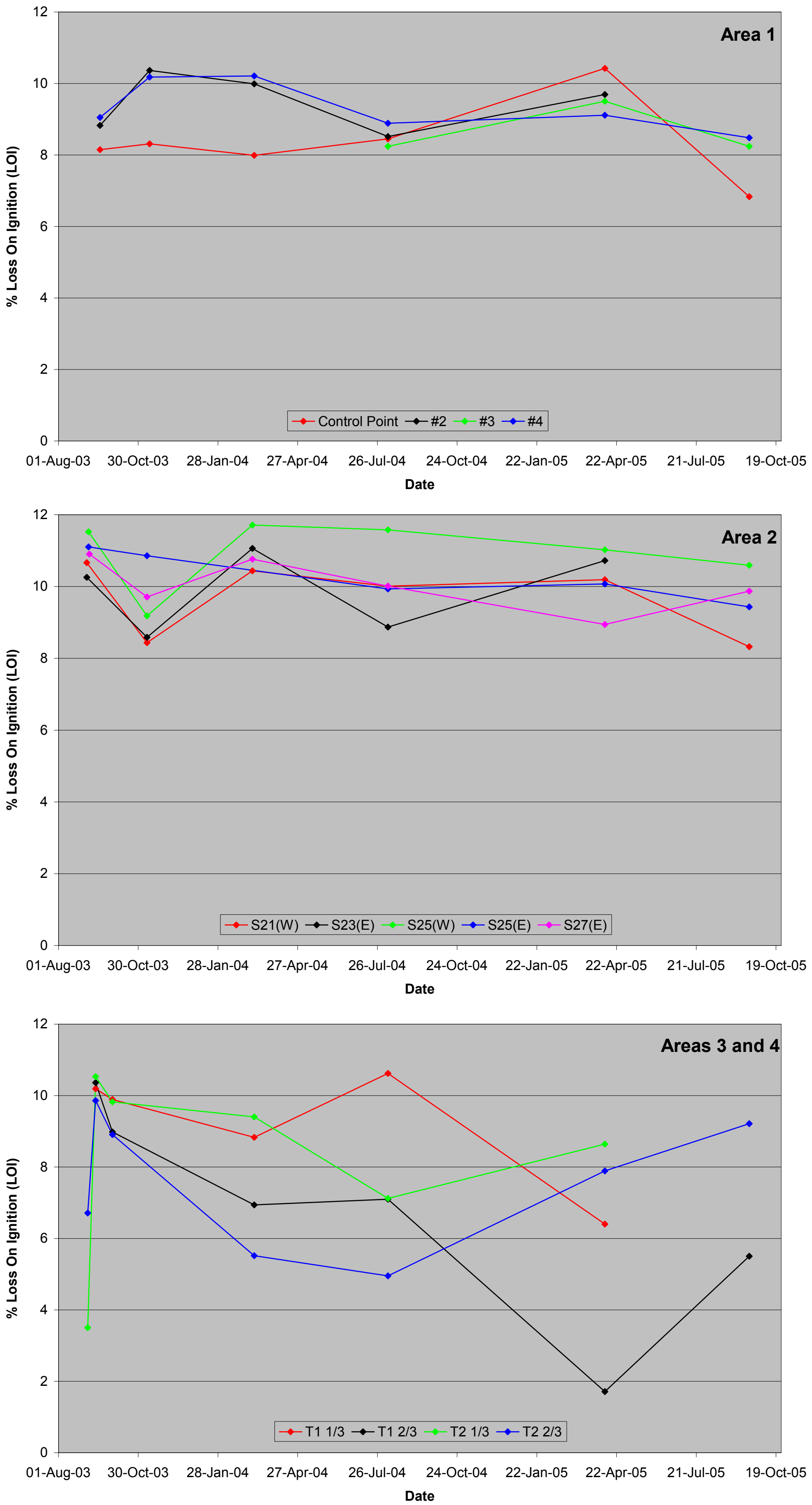


Figure 4.12 Percent loss on ignition (LOI) of surface bed samples

4.2.7 Water level measurements and tidal inundation

HR Wallingford measured water levels at Shotley Marina Lock entrance between 2 September 2003 and 31 May 2004. The measurements were taken at 10 or 15-minute intervals (HR Wallingford, March 2005, Chapter 4). From June 2004 onwards HR Wallingford acquired and used data from the Harwich Harbour tide gauge. Comparisons between the two gauges showed the data to be more-or-less identical.

The water level data was processed to provide the number of hours that the water level exceeded a particular value at each of the 140 CEFAS sampling locations during the course of each month. The actual bed level used for each CEFAS location was extracted from the HR Surveys (see "Bathymetric surveys" above) at the time of, or as near to the time of, the CEFAS survey.

The average period of time that each of the CEFAS survey positions was inundated during a mean spring tide was also calculated by computer model.

4.2.8 Local meteorological measurements

HR Wallingford installed a fully autonomous modular weather station, attached to a 4m alloy pole, on the quayside at Shotley Lock Entrance. Meteorological data was collected during the period 19 September 2003 and 6 February 2004.

The weather station recorded the following parameters to a data logger: Wind speed and direction (maximum, minimum and the average), air temperature, solar radiation and barometric pressure.

4.3 ECOLOGICAL MONITORING (OBJECTIVE 2)

4.3.1 Introduction

Objective 2: To undertake ecological monitoring at a site where a large scale placement of muddy dredged material is to be undertaken. The monitoring to include conditions prior to placement and then extending over a logarithmic temporal sampling period.

This objective was met by CEFAS who sampled the bed sediments on seven occasions between September 2003 and September 2005. The Shotley recharge was carried out in phases in distinct areas, as mentioned previously in Chapter 3 and shown in Figures 3.1 and 3.2. CEFAS sampled the bed sediments in each of the four areas. CEFAS took replicate samples at up to 20 locations on each of the seven occasions. Five samples were in Area 1, five in Area 2 and ten in Areas 3 and 4 (five in each of the upper tier (Area 3) and the lower tier (Area 4)). The actual locations of each sample within each of the Areas varied between surveys. This was statistical reasons when dealing with the ecological data.

Ecological monitoring, over a 24-month period, examined the development of macro- and meiofaunal (limited to first 12 months) communities and environmental parameters at four of these relatively large (up to approximately 0.05 km^2), intertidal recharge areas in an attempt to address the following questions:

1. How do attributes of macro- and meiofauna assemblages develop in time and space on newly recharged sediments?

2. What are the relationships between macro- and meiofaunal assemblages and environmental variables?

There are numerous mud flat species. Both meio- and macrofaunal communities were monitored by CEFAS. Macrofauna are animals large enough to be seen with the naked eye (larger than 500 µm) and are a direct food source for many waterfowl. Meiofauna are that part of the microfauna (the smallest animals in a community, not visible to the naked eye) which inhabit algae, rock fissures, and superficial layers of the muddy sea bottom e.g. nematodes. Meiofauna are ubiquitous, abundant and diverse and hold a key position in benthic food webs and in the functioning of newly created ecosystems. The species monitored in this project are therefore important in a management context.

The four species shown in Figure 4.13 were monitored in detail in this study and all have different behaviour and feeding mechanisms in sediments and have different functions and different predators. These four species are common to mud flats around the UK:

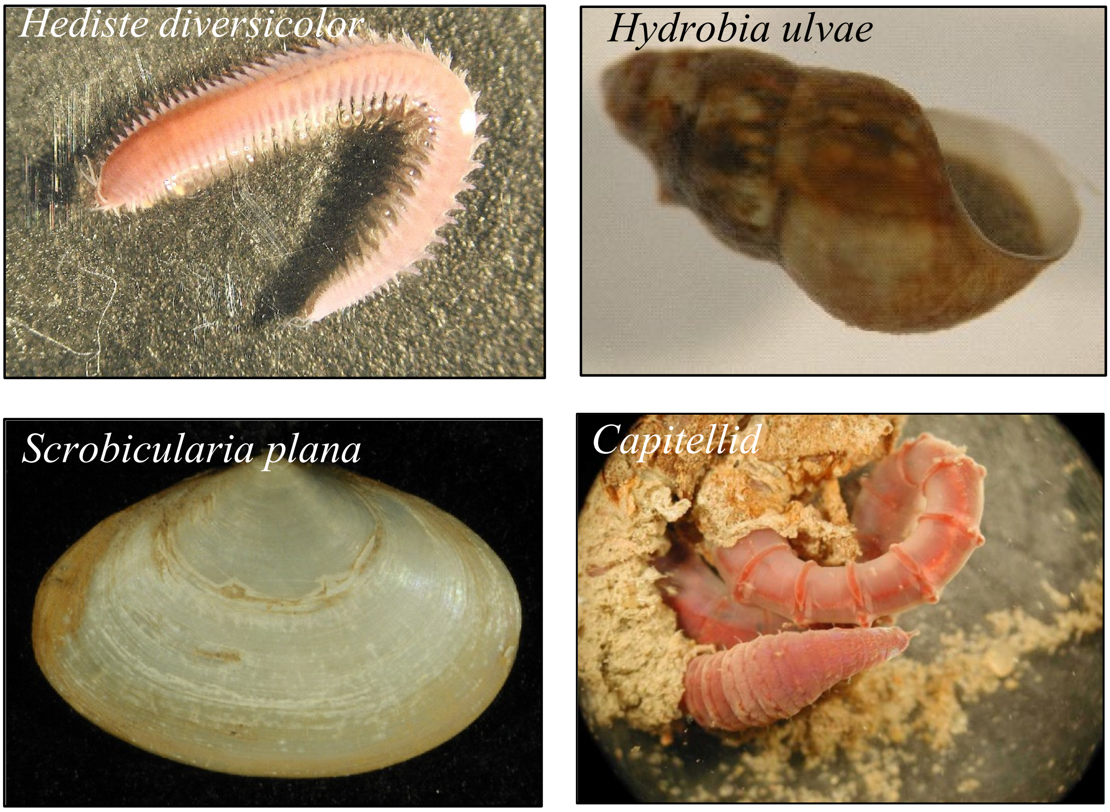


Figure 4.13 Monitored mudflat species (examples given above are macro-invertebrates)

1. *Hediste* is a burrowing worm that extends feeding tubes of up to 15cm and eats organic matter on the sea bed.

2. *Hydrobia* is a Snail (gastropod mollusc) which by contrast tends to live on sediment surface and moves around grazing on algae. Algae have a stabilising function on the mudflat surface. This is an example of where the biology alters the physical conditions.

3. *Scrobicularia* is a Bivalve mollusc that sits a few centimetres below the surface and effectively "hovers" the sediment surface for food with a siphon.

4. *Capitellia* is a subsurface deposit feeder.

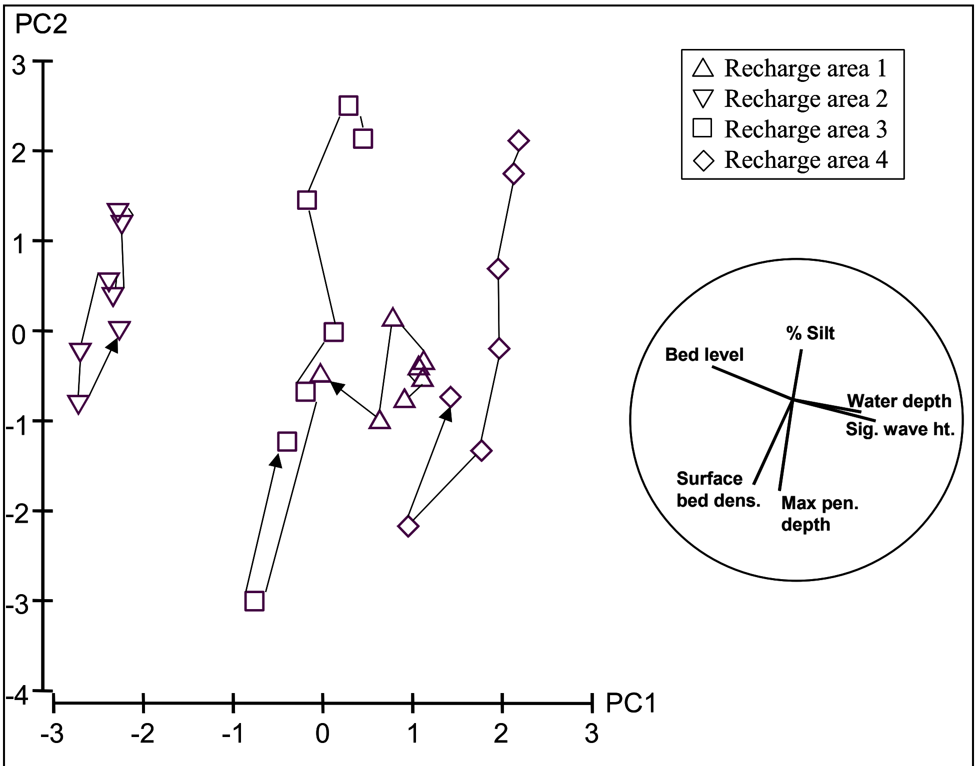
4.3.2 Summary of results

Both meio- and macrofaunal communities displayed significant temporal and spatial variability in recolonisation over the first 12 and 24 months post-recharge, respectively, at the four recharge areas studied.

The recharge areas represented distinctive environments, differing from each other by virtue of predominantly bed elevation and wave action. These factors were important in affecting the structure of benthic colonist communities. In general, recharge Area 1, a low level site with relatively little wave action, displayed a rapid initial recolonisation, and high numbers of both macrofauna and meiofaunal nematodes were present throughout the study. Recharge Area 2, with significantly higher bed level, regularly contained relatively low numbers of individuals and species, and had a distinctly different community structure. Recharge Areas 3 and 4, both much more wave-exposed but distinguished by differences in bed level, displayed very similar recolonisation: although initially slow, increased numbers of benthic invertebrates were present 12 months post-recharge and thereafter. The latter two areas exhibited much larger temporal variability in both environmental conditions (mainly sediment properties) and in biological characteristics.

Although it is not possible to elucidate the effects of any single environmental factor on colonist communities in the present study, the results have made a significant contribution towards understanding the importance of a number of site-specific factors (e.g. bed elevation, wave exposure) in affecting invertebrate recolonisation of fine grained beneficial use schemes. The fact that biota has established at the sites and fairly soon after placement would support the use of these types of placements in the future. However, site and scheme specific factors such as bed elevation and wave exposure affect invertebrate colonisation decisions would need to be made on a case by case basis.

It seems likely in the UK the main large scale use of muddy dredged material is most likely to come from raising land within managed realignment schemes where typically areas that would be flooded and become inter-tidal are presently too low in the tidal frame for mud flat and salt marsh species to colonise and remain sustainable under a scenario of rising sea level. The ecological data gathered in this study could not be directly extrapolated to such sites as other factors may play a role but it is probable that the relatively rapid recolonisation in some of the recharge sites recorded above can occur if physical conditions are set up to allow it. The other large scale use of muddy dredged material is likely to continue to be trickle charge/sediment recycling schemes where the desire to keep mud in the local system is recognised as a means to combat wider scale erosion or a sediment deficit across a system. The data collected in this study is not of direct relevance to such schemes.

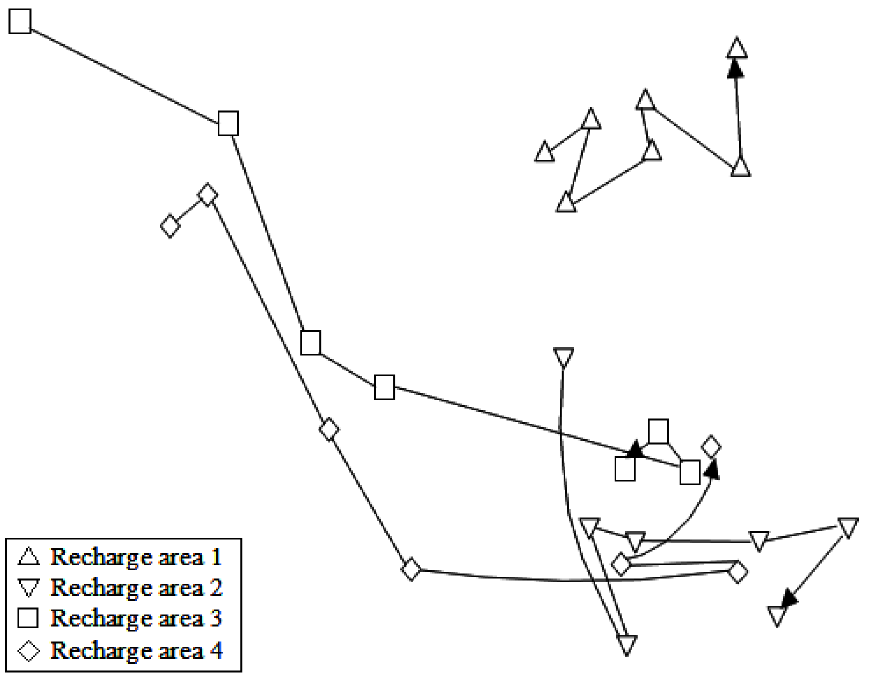


Principal components analysis (PCA) ordination based on mean normalised environmental data, showing temporal changes at the recharge sites over the 24-month study period.

Figure 4.14 Evolution of environmental conditions

The general spatial environmental characteristics, including temporal changes, of the four recharge areas can be revealed by the Principal Components Analysis (PCA) ordination plot (Figure 4.14). Each point on the graph, and how close the points are, reflect their physical characteristics and how similar the environmental conditions are. Recharge Area 2 is separate from other sites because of its high bed level separated and subsequent lower water depth and significant wave-height. There is very little temporal change along this plane for any recharge area, indicating that bed level, water depth and wave-height remain relatively constant over the 24-month study period. Area 4 is a low-level, relatively wave-exposed site, with Areas 1 and 3 lying between these.

For sediment properties, Areas 3 and 4 have a large temporal variability due to changes. Generally, the silt content decreased, while bed density and maximum penetration are in contrast increasing. Areas 2 and 1 show a smaller variability.



Community structure (numbers and species type) showing temporal variation over 24 month period of the study

Figure 4.15 Evolution of ecology. Non-parametric multi-dimensional scaling (MDS) ordination (based on Bray-Curtis similarity matrix on double-root transformed abundance data, replicates averaged for each station), showing temporal changes over the 24-month study period. Arrows follow the temporal sequence of 1 week to 1, 3, 6, 12, 18 and 24 months post-recharge.

Figure 4.15 displays some of the ecology information and uses abundance data. Area 2 shows a distinct community structure throughout the study. Areas 3 and 4 display large temporal variability but interestingly mimic one another through time. With time Areas 3 and 4 are moving towards Area 1 and displaying similar species and numbers to Area 1 (which was rich initially). That is to say for Areas 3 and 4 recolonisation was slow.

The dataset generated in this project progresses the scientific understanding compared to other data sets as it has gone one step further by looking at algorithm relationships between ecology and physics giving better predictive capacity.

Figure 4.16 uses the number of *hydrobia* to simply illustrate that the study has been able to define relationships between various biological attributes and the physics.

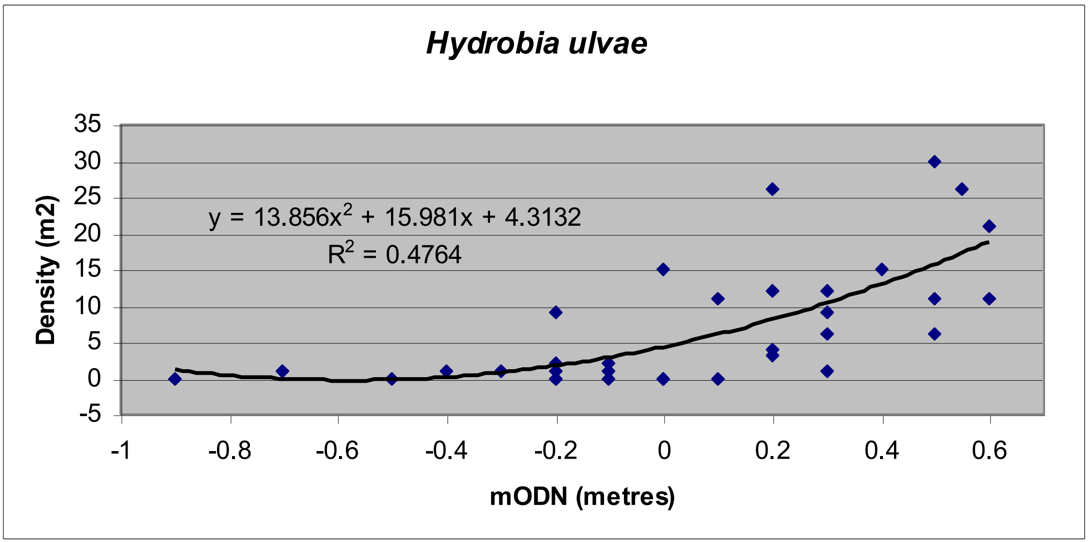


Figure 4.16 ***Hydrobia ulvae*** **vs. mODN for Area 1 data from all surveys and samples**

Results from the correlation analyses revealed statistically significant relationships between faunal and environmental variables. For example, bed elevation had a notable effect on nematode density and the number of species. Numbers of individuals and species generally increased with decreasing bed level.

While decreased bed level and increased water depth resulted in significantly increased abundances, number of species and diversity, there was no significant relationship between these community attributes and significant wave height (wave exposure). There were also significant relationships between non-sediment related properties and community attributes: abundance, number of species and diversity increased and evenness decreased with increased maximum penetration depth, and increased surface bed density led to significantly increased number of species and diversity

The abundance of most species grew significantly at all sites as the total inundation period since the completion of the mud infill increased.

In addition, the temporal changes in biological and environmental parameters observed in the present study indicate that sediment-related properties are also important in shaping macrofaunal community development (CEFAS 2007a). Sediment silt content was reported to affect macrofaunal recolonisation at three other beneficial use schemes in south-east England (Bolam and Whomersley, 2005).

The relationships giving the best fits in this study are for numbers of taxa not for individual species, which is useful as these are more generic for use at other similar locations (there is much debate on the value of species specific data versus summary biotic data in ecological science). The relationships observed in this study are obviously testable by others or testable using other datasets.

The report by CEFAS (2007a) discusses the different routes by which recolonisation may occur (planktonic larvae, burial survival, bunds etc) and highlights that; the bunds may be important. However, without quantitative data on the abundances of macrofauna and meiofaunal nematodes on the *in situ* bunds it is not possible to unequivocally conclude as to the importance of these bunds for the initial recolonisation processes at Area 1. The inherent seasonality of planktonic larvae may have been responsible for the delayed infaunal density increases in Areas 3 and 4. Overall, results may indicate that the recharge areas, despite the similarities in initial dredged material properties and timing of recharge, may have had different macrofaunal recolonisation mechanisms. The delay in Areas 3 and 4 is of scientific interest and to date no site specific or generic data is available, however, the important point is that by the end of the monitoring period these mud flats were still successful in ecological terms and will be playing a role in the functioning of the system.

4.3.3 Measuring ecological success of the scheme

An assessment as to how well these schemes recolonised relative to any reference situation is not possible as, when assessing the success of beneficial use schemes, reference stations suffer from several inadequacies (Bolam and Whomersley, 2003; 2005; Schratzberger et al., 2006). In summary, references provide a limited capacity upon which to base recovery because, firstly, spatial heterogeneity within mudflat habitats often leads to significantly different communities at small scales, and secondly, as the recharge changes the tidal elevation of the bed surface the recharged areas are likely to have different biological communities by virtue of different environmental regimes. Attempts to make recommendations as to the relative success of the four recharge areas in terms of providing functioning macrofaunal communities by comparing them with the communities observed at similar schemes in the south-east UK coast (sampled under Defra-funded project AE0231, Cefas) has been made in this study and details are given in Appendix 1 of the CEFAS report 2007a.

This initial assessment of the ‘health’ of the macrofaunal communities of Shotley 2003 recharge Areas 1-4, however, must be taken with caution for several reasons. Firstly, as two of the schemes are in different estuarine systems, it is expected that they will display different biological characteristics. Secondly, the health of the communities during 2002 (18 months post-recharge for each scheme) are presented: any temporal variability between then and 2005 (18 month post-recharge for recharge Areas 1-4) cannot be accounted for.

This initial assessment has indicated that the communities of recharge Areas 1-4 are relatively ‘rich’ in terms of univariate indices, although reduced densities of recharge Area 2 is expected given its relatively high bed level. While the use of comparable schemes (both recharge area and reference communities) do not offer an ideal situation upon which to assess recovery of the Shotley recharge areas (for reasons given above) the fact that the same general conclusion is reached relative to all 3 would strengthen the conclusion regarding the success of the Shotley schemes.

Further understanding of the long term ecological functioning of different systems is needed but could not be addressed within the budget of this project. The use of muddy dredged material will continue to have some uncertainty but increased confidence that species will recolonise and some form of ecologically functioning system can be created is given by the findings of this study for this location.

5. Ecological Modelling (Objective 3)

5.1 INTRODUCTION

Objective 3: To assess the factors influencing ecological recovery at the site and to develop an ecological model of the evolution of the large scale placement of *muddy dredged material, utilising as necessary the results of process measurements and modelling."*

This objective was met by CEFAS and HR Wallingford. CEFAS undertook an "ecological modelling" study using the data collected in carrying out Objectives 1 and 2. Ecological modelling is defined in this project as investigating and explaining the relationships between environmental data (both modelled and observed physical parameters) and biological (macrobenthic invertebrate) data obtained from intertidal mud flats on the Orwell Estuary following dredge material recharge (CEFAS, 2007b). The hydrodynamic data collected by HR Wallingford was adapted and analysed to give information on bed levels, water depths, tidal inundation, current velocities, bed shear stresses, bed material characteristics (size and density) and wave characteristics. To provide the required details for some of these parameters modelling work was undertaken to reproduce wave and flow conditions across the whole recharge site. (HR Wallingford, March 2006b – where the data is provided in seven tables – one for each of the surveys undertaken by CEFAS).

5.2 SUMMARY OF ECOLOGICAL MODELLING

5.2.1 Aims and approach

The ultimate aim would be to develop an ecological model of the processes involved. In this project "ecological modelling" is defined as investigating and explaining the relationships between environmental data (both modelled and observed physical parameters) and biological (macrobenthic invertebrate) data obtained from intertidal mud flats on the Orwell Estuary following dredge material recharge. The approach taken, was to first use the ordination technique of Principal Component Analysis (PCA) on centred and standardised environmental data (effectively this is the same as transforming and normalising the data) having first selected those variables with the least co-variation. Full details and results are given in the project report- CEFAS 2007b. The selected list of environmental parameters is shown in Table 1 below. The environmental data is described in HR Wallingford (2005, 2006a, 2006b).

Table 1 Description of environmental data and codes used in the analysis and ordination outputs

Description & units	Parameter code
Survey level (metres, ordnance datum Newlyn)	mODN
Time submerged on a mean spring tide (hours)	MST
Maximum current speed (m/s)	Csp
Average current direction during inundation (degrees true)	Cdir
Average soft mud bed shear stress (N/m^2)	Bst
Sediment grain size d50	D50
Sediment percentage silt content	%Silt
Sediment surface density (g/cm^3)	Sd
Sediment surface to 0.1m density (g/cm^3)	sd0.1
Sediment max depth density(g/cm^3)	Dmax
Significant wave height (m)	Hs
Wave period (s)	Tp
Wave direction (degrees true)	Wdir
Average orbital bed shear stress (N/m^2)	Urms

In the first instance, the use of ordination diagrams was used to optimally display how the biological community varies with the environment between sites (for any given survey) and also between surveys (for any given Area). Relationships identified were then subject to more rigorous statistical testing.

The principal numerical method employed to undertake this investigation was canonical ordination (see CEFAS, 2007b) which was undertaken using the CANOCO v4.5 software (CANOnical Community Ordination).

Canonical ordination is a technique for relating the species composition of communities to their environment. It is a combination of ordination and multiple regression. Ordination techniques such as principal components analysis and correspondence analysis are commonly used to reduce the variation in community composition so as to observe significant gradients in the data. Subsequently the ordination diagram is interpreted with the help of external data, for example by calculating correlation coefficients between environmental variables and ordination axis, or subject to more rigorous statistical testing. The theory and justification of this approach is given in Guisan et al. (2002) and is also in part justified by the analysis presented in CEFAS (2007b) describing the results for Objective 2. This clearly shows significant biotic variation between surveys (seasonal and annual variation in the biology) compared to the abiotic variation between Areas over time. Such seasonal variation in the biota, if not accounted for, has a tendency to reduce the correlation between the biological and environmental parameters. Therefore, it was important to consider the surveys separately when investigating the biotic and environmental relationships.

5.2.2 Environmental Results

Variation in the environment between the four Areas (for a given survey)

Based upon the Principal Component Analysis (PCA) for each survey it was apparent that there was significant variation between the physical attributes of each of the four Areas and that this had generally remained consistent over time in relation to the principal components of mODN, Hs, Urms, Dmax, Cdir.

Immediately following the placement of dredged material the physical characteristics of Areas 3 and 4 were similar in terms of Dmax, Urms and Hs. After 12 and 24 months some consistent differentiation between Areas 3 and 4 was observed such that Area 3 had increased elevation (mODN) and was subject to greater Urms compared to Area 4 which is lower in the tidal frame. Area 1 had demonstrated the greatest abiotic variation between surveys, for example after 1 week there was little consistent dominance of any one (or few) environmental parameters, but after 12 months samples were best explained by the dominance of Cdir and Dmax. However, 24 months later percentage silt appeared to be relatively important at Area 1, possibly because of less wave exposure experienced by this Area.

The characteristics of all four Areas can best be summarised by considering the physical properties associated with quadrants of the ordinations as shown in Figure 5.1, namely;

Area1 low elevation and low bed stress (because of reduced tides and wave effects)
Area 2 high elevation and low bed stress
Area 3 high elevation and high bed stress (because of wave action)
Area 4 low elevation and high wave height

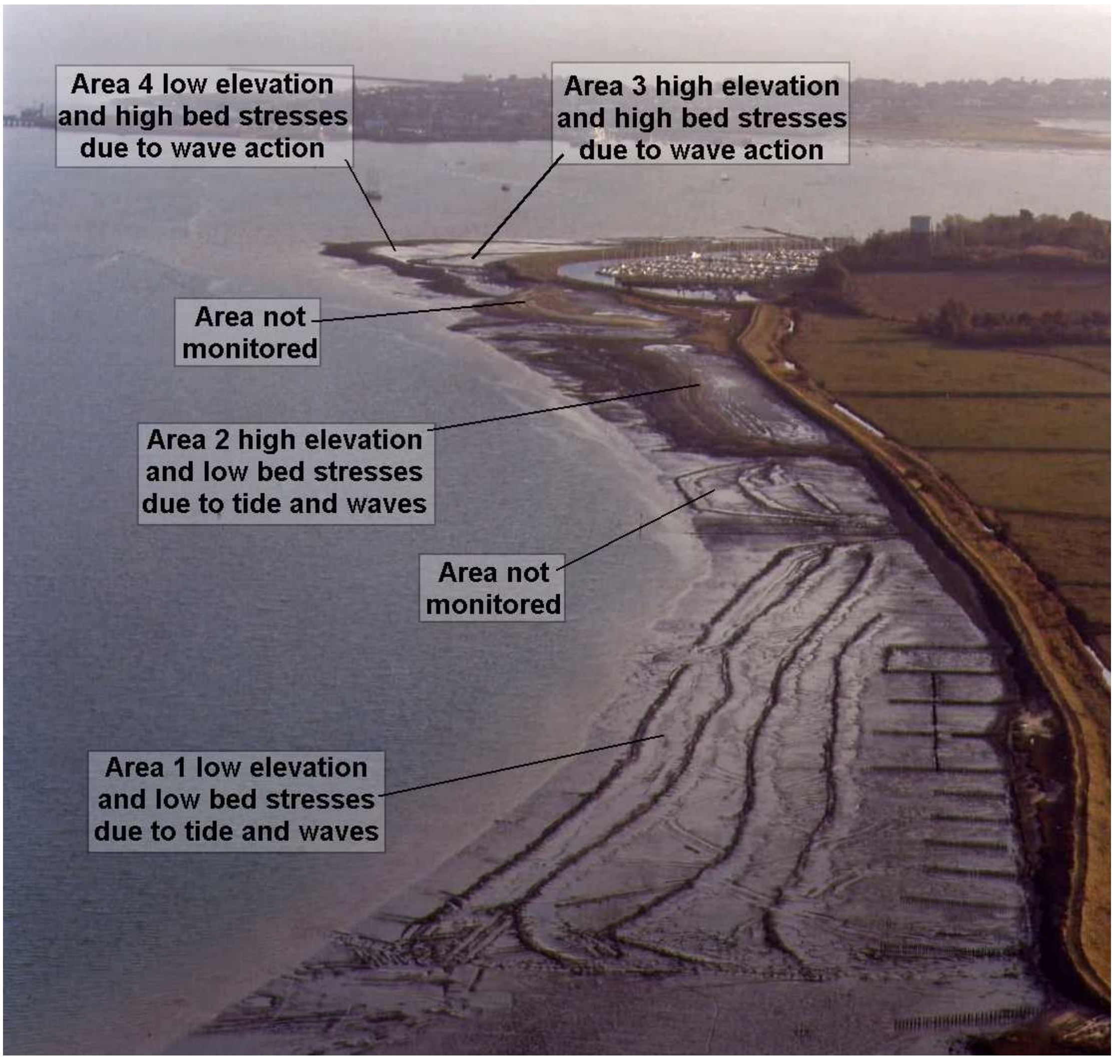


Figure 5.1 Location of the four intertidal recharge sites and physical properties associated with quadrants of the ordinations

Variation in the environment with time (for a given Area)

The analysis suggested that there was considerable spatial variation between samples in terms of their environmental characteristics such that samples taken from the same location on repeated surveys tended to show greater similarity to each other than to samples taken at the same time from different locations. This was particularly the case for Areas 1 and 2 where there was little evidence of survey sample clusters over time in the ordinations. However, Areas 3 and 4 (which are arguably more exposed in terms of significant wave heights) did exhibit survey clusters of samples, albeit there is still evidence of sample grouping by specific location within each Area. Nevertheless, Areas 3 and 4 did appear to be changing physically over time in a way not seen at Areas 1 and 2. For example, Area 3 had increased in sediment surface density (sd) and had also witnessed a reduction in the sediment percentage silt content (% silt), whilst Area 4 appeared to have experienced a reduction in elevation (mODN) over the same time period.

On this basis, it might be expected that temporal changes in the biota will be most significantly correlated to environmental changes at Areas 3 and 4, whereas most of the temporal biological variation at Areas 1 and 2 may be attributed to other factors not measured including biological processes.

5.2.3 Ecological Results

5.2.3.1 General

The results clearly show significant biotic variation between surveys (seasonal and annual variation in the biology) compared to the abiotic variation between sites over time. Such seasonal variation in the biota, if not accounted for, has a tendency to reduce the correlation between the biological and environmental parameters. Therefore it was important to consider the surveys separately when investigating the biotic and environmental relationships.

5.2.3.2 Environmental data: The physical variation between sites

Based upon the PCA for each survey it is apparent that there is significant variation between the physical attributes of each of the sites and that this has generally remained consistent over time in relation to the principal components of survey level (mODN), significant wave height (Hs), Average orbital shear stress (Urms), sediment maximum depth density (Dmax), average current direction during inundation (Cdir).

In summary, four distinct areas emerged and their key physical properties can be described as follows: Area 1, low elevation and low bed stress (as a result of reduced tides and wave effects); Area 2, high elevation and low bed stress; Area 4, low elevation and high wave height and; Area 3, high elevation and high bed stress as a result of wave action (Figure 5.1).

5.2.3.3 Environmental data: Investigate responses over time

The analysis presented in CEFAS 2007b suggests there is considerable spatial variation between samples in terms of their environmental characteristics such that samples taken from the same location on repeated surveys tend to show greater similarity to each other than samples taken at the same time from different locations. This is particularly the case for Area 1 and Area 2. In other words the differences between areas are significant and continue over time.

The results also show that it might be expected that temporal changes in the biota will be most significantly correlated to environmental changes at Areas 3 and 4 which appear to be changing physically over time in ways not seen at sites 1 and 2. For example, Area 3 has increased in sd and has also witnessed a reduction in the % silt, whilst Area 4 appears to have experienced a reduction in elevation (mODN) over the same time period. In contrast, most of the temporal biological variation at Areas 1 and 2 may be attributed to other factors not measured.

5.2.3.4 Biotic and environmental relationships: Relationships between sites

The community structure at the four sites reflects the differences in the environmental characteristics which predominate at each of the sites with the exception of Area 1 which after 12 months exhibits a community structure which favours the relative dominance of silt. The relative difference in silt between the sites is small and other factors tend to dominate the conditions at the other sites so it may be argued that it is the absence of high Hs and Urms and mODN which is of greater significance for Area 1 and not the dominance of silt. Nevertheless, the relationship between percentage silt and the biological characteristics of Area 1 and the other sites is significant and can be used as a predictor for total number of individuals (Figure 5.2).

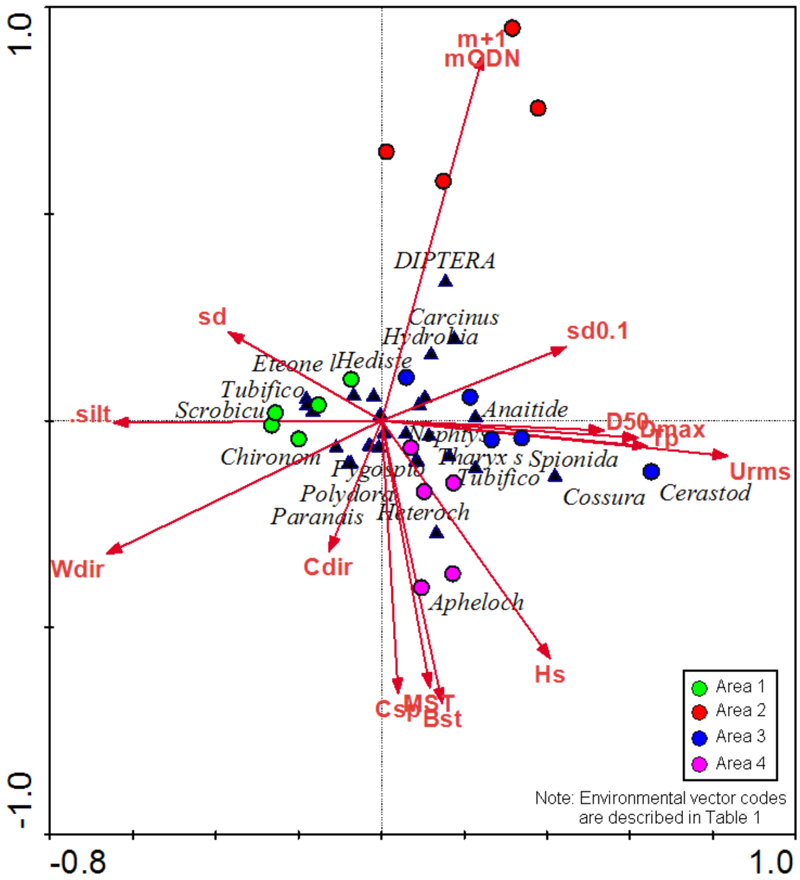


Figure 5.2 **DCCA tri-plot on double root transformed species abundance data with sample and species ordination superimposed along with the environmental vectors 24 months after recharge**

By contrast, tidal elevation of the mudflat measured as mODN has a clear and highly significant influence on the community structure, most notably on the total number of species and this response was evident for both the 12 and 24 month surveys such that there is a high negative correlation between mODN and number of species (Figure 5.3) The conditions at sites 3 and 4 are predominantly associated with increased wave exposure and whilst the exposure appears to regulate total number of individuals and can be used as a predictor (Figure 5.4) it is not significantly correlated to a reduction in the number of species.

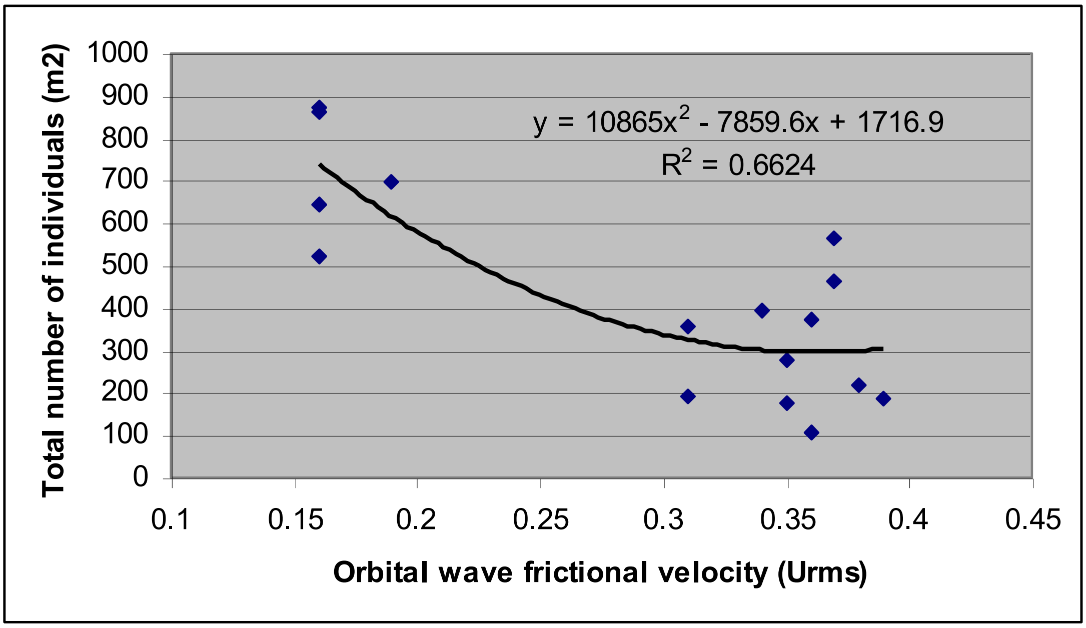


Figure 5.3 **Relationship between Total number of individuals and wave orbital frictional velocity 12 months after recharge**

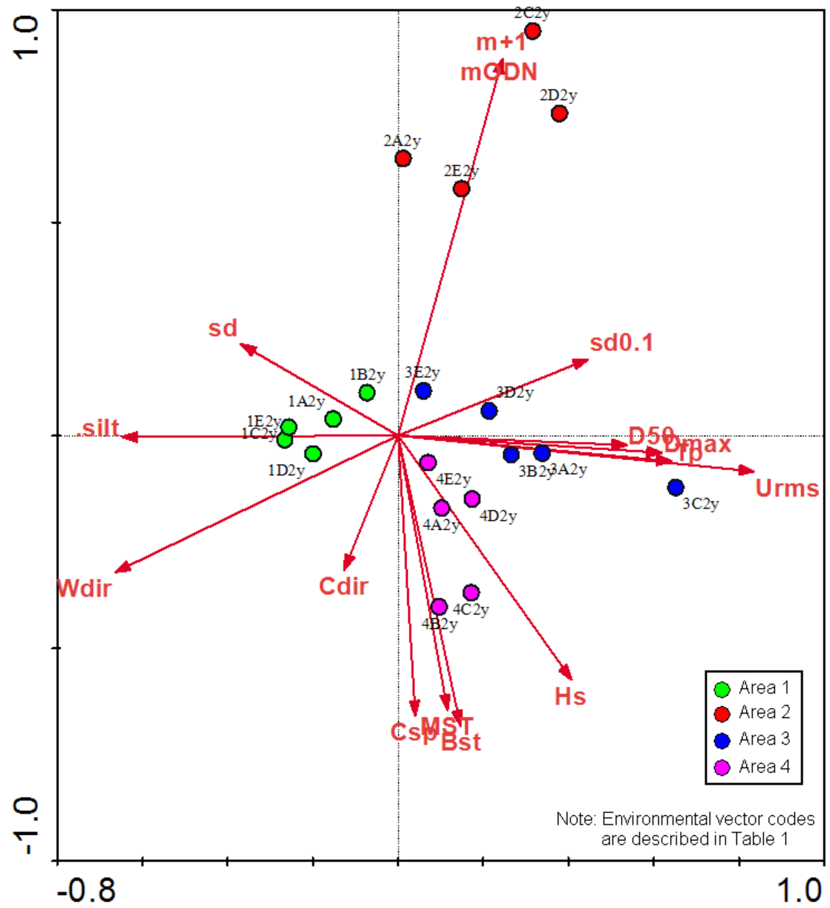


Figure 5.4 **DCCA performed on double root transformed species abundance data showing biotic sample similarities superimposed on environmental vectors 24 months post recharge**

5.2.3.5 Biotic and environmental relationships: Relationships over time

It is clear from the results presented in CEFAS 2007b that *Hydrobia ulvae*, and *Hediste sp.* favour conditions with increased mODN compared to other taxa. By contrast *Tubificoides benedii*, *Scrobicularia sp*. and the total number of individuals favour conditions with higher percentage silt content. *Pygospio elegans*, *Paranais litoralis* and Nudibranchia favour conditions with relatively high significant wave height conditions (Hs). Whilst it is expected that specific species will vary significantly in terms of their community dominance from one year to the next it should nevertheless be possible to predict trends in community structure at a more fundamental level. For example, changes in total number of species and individuals in response to the dominant environmental factors are more likely to be defined in a reliable way particularly when only two years of Area-specific data are available. Functional response curves have been established based upon the identified principal environmental components (mODN, %silt, average orbital bed shear stress (Urms) and sediment surface density (sd).

Species specific responses are nevertheless valid for the time at which they are observed and given sufficient data relating to spatial and temporal changes in conditions it should be possible to build up confidence to allow a realistic set of species specific predictions to be made, particularly if this is supported by further environmental modelling of hydrodynamic process which are likely to influence the recruitment pathways and other important factors.

6. Wider Discussion and Study Conclusions

6.1 DISCUSSION

Routine maintenance dredging and capital dredging typically generate 30-40 million tonnes of material annually. The majority of this material may be characterised as muddy is not contaminated and could be defined as a resource. Whilst it may be argued that much of this material is placed back into the estuary or coastal system from which it is removed, only a very small fraction of the material can be claimed to be used in a direct beneficial manner.

Dredged material may be used directly in the creation or remediation of muddy habitats such as salt marshes and mud flats. This type of beneficial use, promoted by Defra under FEPA II, would actually meet three aims; to use dredged material beneficially, to maintain or increase biodiversity and to support coastal defences in a more integrated and sustainable manner.

Until 2003 direct beneficial use placements of muddy material in the UK utilised of the order of 10,000m^3 of material. Concern was expressed over any scheme which proposed to dramatically extend the volumes of material used from these levels due to the risk of material having unforeseen negative consequences elsewhere on the coast, in an estuary or along a river but also due to the uncertainty of how the biology would behave on a larger scale for example, whether biota will re-colonise an inter-tidal site. This study aimed to look at the issue of larger scale application to improve scientific understanding of the issues involved.

The measures of success and goals warrant a mention as how to measure success may need to be clarified and agreed upon at the planning stage and an appropriate monitoring plan set up. For example, environmental goals in a beneficial use scheme may be defined as achieving objectives based on agreed-upon replacement values of the lost or degraded mud flat resource. Using improved scientific knowledge of how the created mud flats evolve and understanding the quality of the mud flat created is clearly important. Monitoring would be an integral part of any scheme.

6.2 CONCLUSIONS OF THE STUDY

This study aimed to look at the issue of larger scale application of muddy dredged material and to more comprehensively monitor the changes in physics and biology after placement. The scheme monitored is the UK's largest direct placement of muddy material onto an existing intertidal area. The results have led to an increased understanding of recolonisation providing a sound basis for discussion of the timescale of recovery of direct intertidal placement. As a result the study provides a basis for improved confidence in the sustainable use of muddy dredged material at larger scales in flood defence and habitat management.

The key findings from the study are:

- The colonisation of the created mudflat is occurring within 12 to 24 months and abundance of mud species is high;
- Practical experience of mud placements shows that they can deliver some habitat functioning within 6 months;
- A clear scientific underpinning of relationships for the ecology and the environmental conditions for this site has been identified;
- A unique data set has been generated:
  - from which to make predictions on ecological development at similar locations; and
  - which is valuable to other researchers and practitioners.
- Practical experience has been gained of the different bunding methods and their role in recolonisation; and
- The knowledge gained provides an evidence base for further beneficial use through direct placement of muddy material has been extended.

6.3 QUALITY OF THE HABITAT CREATED

1. Fisheries: The Stour and Orwell have a diverse fish and shrimp fauna and offer important nursery grounds for commercially important fish. These estuaries also include valuable shellfish species e.g. cockles and oysters. Fish data collected by HHA shows trends but at this stage it is mostly not possible to identify reasons for changes observed as they can be a result of natural fluctuations. It is certainly not possible to link existing fish data with results from this study.
2. Bird populations: From the data on birds gathered for the scheme outside this project several key points emerge. The five yearly data review being undertaken by Harwich Haven Authority on behalf of Felixstowe port includes two sets of data for general bird distribution and abundance: low water over wintering bird counts and the analysis of high water count data available through Wetland Bird Survey (WeBS[1]) data for the system (5 year trends in comparison with regional/

[1] WeBS is jointly run by the British Trust for Ornithology, The Wildfowl and Wetlands Trust, Royal Society for the Protection of Birds and the Joint Nature Conservation Committee. The Wetland Bird Survey (WeBS) is the scheme which monitors non-breeding waterbirds in the UK. The principal aims of WeBS are to identify population sizes, determine trends in numbers and distribution and to identify important sites for waterbirds.

national trends). These provide a good basis for summarising bird usage of the area.

Waterfowl usage of the area dropped slightly following the construction of the bunds, mainly due to a decrease in Dark bellied Brent geese and Widgeon. Disturbance from the scheme and the resulting consistency of the recharged sediment probably accounted for this. The most recent surveys have seen an increase and subsequent decrease in total numbers, but no one increasing or decreasing trend is clear.

In addition, fluctuations in bird counts across the Stour and Orwell have been recorded. It is important to consider the information in conjunction with other available data:

a. Any data needs to be compared/ analysed against a wider knowledge of bird distribution and abundance. Species are declining on a national and regional level and therefore any measured declines are unlikely to be due to local conditions alone, if at all;
b. Similarly, for some of the species the declines recorded represent returns to "normal" population levels after periods of increases whilst for other species the declines are of no particular concern as they are prone to fluctuations (Harwich Haven Authority *et al*., 2005);
c. The bird count data may not give a true behavioural pattern. Anecdotal information suggests that the site (both the managed realignment and the mud flat placements) is being used regularly by several waterfowl species, and that no obvious change in usage has occurred as a result of recharge (Harwich Haven Authority *et al*.,2006).

3. Vegetation: Saltmarsh colonisation was reported in 2005 to have been limited to the middle recharge site with desiccated bands of pioneering *Salicornia* forming. *Spartina* is also present (Harwich Haven Authority *et al*., 2005). Since then, saltmarsh development across the middle bund has increased significantly and swards of *Salicornia* occurring in dense aggregations are now reported (Harwich Haven Authority *et al*., 2006).

6.4 UK PERSPECTIVE: WHERE ARE WE NOW?

In the five years since the conception of this project little has changed in terms of UK use of muddy material. The requirements for sustainable use of muddy material have not changed but practical delivery of such use is developing only slowly. Direct placement of material is still undertaken at very small scales (typically a few 10's of thousand m^3/year), placement of material into realignment sites has been undertaken at larger scale (Wallasea Island utilising about $0.5Mm^3$ of muddy material) but use of material within realignment sites depends upon site specific issues and practical availability and delivery of material.

Trickle charge/sediment recycling remains the most widely used beneficial use of muddy dredged material with all signs that this will continue and develop particularly for some of the smaller volume dredging activities. Logically sediment recycling replicates the natural process when undertaken on a "little and often basis". However, owing to its wider scale of influence compared to placement schemes the measurement of the effect and success of sediment recycling is much harder to achieve. Typically sediment recycling proceeds on the basis of historical precedence and on having no reported adverse impact on a range of site specific concerns.

Under FEPA II[2], Defra needs to continue to consider the practical alternatives of disposing of dredged material. Confidence in the various alternative options for use of dredged material needs to be increased. The use of muddy dredged material is feasible and can be environmentally acceptable (HR Wallingford, 2001). Moreover, further benefits can ensue from using muddy dredged material, such as for coastal protection and habitat conservation.

Scientific findings from this study will continue to assist the UK to support international and regional conventions that involve dredged material disposal, sustainable development and biodiversity issues (e.g. London, OSPAR, Ramsar and the Biodiversity Conventions). They also provide a valuable scientific dataset and evidence base to aid Defra's role as a competent authority under the Habitats Directive.

Port and coastal developments often lead to the requirement for mitigation or compensation under the habitats directive. It is common understanding that compensation measures should eventually result in habitat areas which are in quality and quantity similar to the threatened ones, and located in close vicinity to the original site. Creating a functioning habitat comparable to other mud flat systems in the area is not easy to achieve. Typically monitoring would be needed along with a good understanding of the system. The muddy habitats created may be of ecological and commercial value. Specifically and often reflected in regulations and legislation, birds and fisheries are of importance and muddy habitats have an important role here.

Perhaps more importantly in terms of habitat creation is the desire to achieve the targets of the UK Biodiversity Action Plan. The present targets include for the creation of 600ha per year of mudflat and 140 ha per year of saltmarsh. The principal instrument for creating this habitat is managed realignment. Another use for direct placement of muddy material is in raising land levels within a realignment site to improve the functioning of the site as an intertidal habitat. The largest direct beneficial use of muddy material in the UK has been at Wallasea Island in the Crouch Estuary where about 0.5Mm^3 of muddy material was placed in bunded areas at the rear of the realignment site prior to breaching.

[2] Food and Environment Protection Act, 1985 Part II

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HR Wallingford, March 2006b. Report EX5181. Preparation of data to be used for assessing the factors influencing ecological recovery at Shotley.

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Appendices

Appendix 1. Project relevance to Defra Policy and UK legislation

Legislative drivers

- Food and Environment Protection Act (Part II) (FEPA)
- Conservation (Natural Habitats &c.) Regulations 1994
    - Maintenance dredging protocols

Policy areas

- *Beneficial use* of dredged material has to be looked at as part of the FEPA licensing process (part II). Promoting beneficial use schemes fulfils UK commitments under OSPAR and the London Convention of which UK are signatories. Other requirements under OSPAR e.g. for the Quality Status report.
- *Sustainable coastal defences:* Socio-economic advantages of mudflats and salt marshes as part of a long term sustainable coastal flood defence policy. Relevant to Defra/EA joint research programme on flood and coastal erosion risk management.
- *Biodiversity:* Designated Natura 2000/European sites need to mitigate or compensate for actions arising from development projects:
    - If successful in creating habitats, schemes could help meet the UK Biodiversity Action Plan. Supports UK commitments as a signatory to RAMSAR Convention, Biodiversity Convention. Managed realignment[3] sites could play a large role in meeting these needs. For a number of potential locations dredged material is likely to be needed to raise levels as typically fields adjacent to, and protected by, coastal sea walls are lower lying than the intertidal ranges required for wanted mud flat and salt marsh habitats.
    - International Biodiversity- a key challenge for the next decade will be the delivery of the WSSD (World Summit on Sustainable Development) commitment to significantly reduce the rate of biodiversity loss by 2010.
- *Ecosystem Approach*
  UK commitment to the EU of developing the ecosystem-based approach by 2010
- *Water Framework Directive:* may help to fulfil future requirements to restore transitional and coastal waters to good ecological status.
- *Waste minimisation*
- *The Defra Environmental Strategy Research Programme-* seeks to improve the evidence base to support policies on the environment and sustainable development.
- *Flood management/ marine waterways*- Defra and the Environment Agency have a joint research and development programme on flood and coastal erosion risk management.. The programme seeks to improve flood and coastal erosion risk management through improved understanding of the underlying processes.

[3] The policy of Managed Realignment involves the placement of a new Managed Realignment flood defence landward of the existing flood defences or realignment to higher ground. This policy would be achieved through the partial or complete removal of the existing flood defences or through regulated tidal exchange. This policy would be gradually implemented and regularly monitored in order to study any potential effects on the overall estuary shape.

Appendix 2. List of reports and publications from this project

Reports:

- Reports on physical monitoring

1. HR Wallingford, March 2005. EX5108. Field Measurements – May 2003 to September 2004 and,

2. HR Wallingford, March 2006a. EX5180. Field Measurements – April and September 2005

These reports describe the data set on hydrodynamic and physical characteristics collected by HR Wallingford from May 2003 to September 2005.

3. HR Wallingford, March 2006b. EX5181. Preparation of data to be used for assessing the factors influencing ecological recovery at Shotley.
This report describes the work undertaken by HR Wallingford to assist CEFAS in addressing Objective 3. To that end the hydrodynamic data collected by HR Wallingford has been adapted and analysed to give information on bed levels, water depths, tidal inundation, current velocities, bed shear stresses, bed material characteristics (size and density) and wave characteristics. To provide the required details for some of these parameters modelling work was undertaken to reproduce wave and flow conditions across the whole recharge site.

- Reports on ecological monitoring

[4.CEFAS Progress Report, December 2004. Progress towards large scale use of muddy dredged material for sustainable flood defence and habitat management (AE0260)

5.CEFAS Progress Report, August 2005. Progress towards large scale use of muddy dredged material for sustainable flood defence and habitat management (AE0260)

These reports outline the temporal sampling of the biological attributes at the Shotley placement sites for 6 months and 12 months after placement, respectively.]

6. CEFAS. February 2007a. Stefan Bolam and Michaela Schratzberger. Large scale use of muddy dredged materials for sustainable flood defences and habitat management: Biological Field Measurements: September 2003 to September 2005.

7. CEFAS. February 2007b. Andrew Kenny. Large scale use of muddy dredged materials for sustainable flood defences and habitat management: Ecological Modelling.

Papers:

Schratzberger M, Bolam SG, Whomersley P & Warr K (2006). Differential response of nematode colonist communities to the intertidal placement of dredged material. Journal of Experimental Marine Biology and Ecology 334: 244-255

Bolam, S.G., Schratzberger, M., Whomersley, P., Dearnaley, M. submitted. Macrofaunal recolonisation of dredged material on intertidal areas: factors responsible for spatial and temporal patterns. Estuarine, Coastal and Shelf Science

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Presentations:
Mike Dearnaley and Paul Whomersley CEDA Meeting, June 2005

Mike Dearnaley. DECODE (Determination of the Environmental Consequences of Dredged material Emplacement. December 2003

Mike Dearnaley. DECODE December 2005. Queen Mary College, University of London

Stefan Bolam, Michaela Schratzberger, Andrew Kenny. DECODE December 2005. Queen Mary College, University of London.

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Mike Dearnaley and Stefan Bolam (2006). CEDA Liaison Group for the Promotion of the Use of Dredged Material. Institution of Civil Engineers. December 2006.

Workshop
The findings of this five year research project were disseminated and discussed at a workshop held in December 2006 at the Institution of Civil Engineers. Participants were from the Central Dredging association (CEDA) Liason Group for the promotion of the Use of Dredged Material. A key area of discussion was the issue of smothering and its implications for conservation, and therefore for licencing. Evidence was presented which demonstrates that under certain conditions smothering is not a concern. This is because the data shows, the biota can quickly recolonise, allowing the system to return to a functioning mud flat of value to fisheries and bird populations.