6.4 **Dredge Plumes – Conclusions**

Dredge plumes are an additional source of relatively fine sediment in mixed sand-gravel regions which would be otherwise unavailable beneath an armouring layer of immobile gravel. This makes more sediment potentially available for transport in the vicinity of dredging license areas with implications for the development of sediment scour and accumulation around nearby archaeological sites.

Depending upon the intensity and method, the action of marine aggregate dredging may introduce high concentration sediment slurry into the water column, forming a plume. When trailer suction hopper dredging (the most common method for dredging in UK waters), the greatest quantities of sediment are sourced from the dredging vessel as screened or overflow material; a significant amount of resuspension also occurs near to the seabed due to mechanical agitation by the dredge head itself.

Dredge plumes are described as having a number of characteristic ‘life cycle stages’, namely: an initial dynamic phase where the plume settles nearly vertically under gravity as a concentrated and distinct density plume at a rate determined by the actual concentration and composition of the plume; a second active phase where high concentration plume material flows along the seabed; a transitional dilution phase affecting parts of the plume at all locations; a latter passive phase where the majority of the plume has become dispersed and diluted to the point that it is only advected with the ambient flow.

With the exception of only very fine particles (typically a small proportion of the total sediment load of a plume), it is the fate of most plume material to be redeposited onto the seabed. Coarser material settles more quickly and closer to the source of input; finer material may be transported further in the passive phase of the plume therefore being deposited in a corridor aligned with the tidal axis. From numerical modelling studies, the long term cumulative thickness of deposition will be greater closer to the source of such plumes.

Dredge plumes have been observed using proxy measurements from acoustic backscatter data (higher suspended sediment concentration increases acoustic reflectivity). Such studies have typically been conducted using a vessel mounted profiling device which is used to transect a plume as it develops. This method has provided information about the spatial development and dispersion of plumes but introduces temporal distortion. To address this, new techniques were developed to interrogate the backscatter data from the many profiling instruments at the *Unknown Wreck* study site.

The data were analysed to yield the ambient fluctuating signal of backscatter over two spring-neap cycles (not considered in transecting studies due to the duration of observation required). Several signal processing techniques were developed to identify deviation from the smooth ambient signal and thence dredge plumes. This enabled further study of the character of dredge plumes as they advected over the site and a semi-quantitative measure of the relative increase in suspended sediment
concentration. A review of the extant literature concerning conversion of backscatter to actual suspended sediment concentration demonstrated that techniques developed thus far are not accurate within the range of naturally observed variation. Techniques are also developed using specific instrument makes and models introducing significant uncertainty in the conversion of raw backscatter data into meaningful backscatter quantity for other instruments. Comparison of data from the variety of instruments used in the present study indicated significant variation in the derived quantities of backscatter (before conversion into SPM or other quantities) associated with instrument make, model, operating frequency and even between individual transducers.
Chapter 7. The Third Field Study Site: The Eastern English Channel

This Chapter contains the results of the separate case study set up as a variation order to the original proposal, including Objectives 18.1-18.4. The third field study site was the UC-65, located in the central part of the Eastern English Channel. This site was brought to the attention of the project by Hanson Aggregates Marine Limited as an opportunity to extend the core objectives of the original proposal whilst benefiting also from the huge quantity of environmental data being collected in the area as part of a regional environmental assessment program. The site was also unique as it was the only site in UK waters where aggregate dredging was due to commence for the first time within the time scale of this project. The site therefore provided an opportunity for specific baseline survey and for subsequent changes to be monitored. This was undertaken using a Remotely Operated Vehicle (ROV) which collected detailed video footage of the wreck; this was subsequently analysed to yield the location and height of sediment accumulations or scour and the distribution of sediment types (sandy, gravelly, etc). The results were interpreted in the context of the results of the more detailed studies undertaken of the first two field study sites (Chapters 4 and 5) and in the laboratory (Chapter 3).

An introductory literature review of the geology, tidal, wave and sedimentary characteristics of the English Channel with emphasis on the Eastern English Channel is contained in Section 7.1. The results of repeated high resolution surveys demonstrating seasonal and inter-annual variation in the site and the potential effect of dredge plumes following the recent initiation of marine aggregate dredging are shown in Section 7.2.
7.1 The Geology, Sediments and Oceanography of the English Channel

7.1.1 Introduction

The following section of the report provides a review of the extant literature describing hydrodynamics and sediment distribution within the EEC and, more specifically, in the ECR. A Regional Environmental Assessment of the ECR is currently being prepared by The Resource Management Association (RMA) which will combine the results of new detailed surveys and extant data of the geology and oceanography of the region; however, this is currently unavailable. Potential impacts on the environment resulting from aggregate dredging in the EEC may only be determined once all natural characteristics of the environment are understood.

Fine sediments introduced into the water column by on site screening processes during dredging activity leads to the formation of sediment plumes that are subsequently advected and dispersed. The physical processes involved and the potential impact of dredge plumes on the surrounding environment has been the subject of many studies. Section 6.1 of the report provides a description of the dynamics of dredge plumes in tidal environments. The following review provides an
overview of the hydrodynamics characteristic to the English Channel and ECR, and describes the distribution of material throughout the regions in terms of composition and quantity. Material transports, both along the bed and in suspension are also identified in terms of their direction and flux.

### 7.1.2 Tidal regimes

Water movement in the English Channel is dominantly tidal (Harris et al., 1995) in water depths exceeding 30m (Newell et al., 1998); the primary contribution being the lunar M2 tidal constituent (Anthony, 2002) typically producing a semi-diurnal tidal pattern. Some of the world’s largest tidal ranges (maximum ranges of 15m) are observed in the central southern part of the Channel, near to the Channel Islands and the Baie du Mont-Saint-Michel (east of the Cotentin peninsula); a typical range, however, is of the order 6-10m (Larsonneur et al., 1982). The strength of the tide in the English Channel may be calculated at any point from the position of the amphidromal points. The location of amphidromal points around the UK and the distribution of co-amplitude and co-phase lines are shown in Figure 199. As shown in Figure 200, a direct result of this spatial distribution is that tidal velocities vary significantly between the western approaches and the EEC regions; peak tidal velocities also vary across the width of the Channel (north/south) but more so in the western approaches. Maximum velocities of 2ms⁻¹ are observed off the northern point of the Cotentin Peninsula and decrease with distance to the east and west; velocities are also significantly decreased within semi-enclosed coastal bays. Similar descriptions of tidal streams in the EEC were also outlined in other important studies by Posford Haskoning, (2002) and Pingree, (1980).
Although the English Channel is a physically complex environment, it is possible to accurately, numerically predict the spatial variation in hydrodynamics over long time scales using the known tidal constituents and physical interactions. Such models have been used in several environmental and sediment transport studies described in later sections (e.g. Grochowski et al., 1993a; Mauvais, 1991; Pingree, 1980). Using a combination of field observations and these mathematical models, Pingree, (1980) was able to determine that tidal oscillations in the western Channel manifest as a progressive wave whilst in the eastern Channel they manifest instead as a standing oscillation. As a result, high water in the west corresponds approximately to peak tidal flows, whereas in the east, high water corresponds to slack water conditions. In the EEC (with boundaries at the Dover Straits to the east and at the Isle of Wight - Cotentin Peninsula axis to the west), the tide is flood-dominated with minimum velocities occurring at the eastern boundary; velocities increase with distance west towards the Cotentin Peninsula (Grochowski et al., 1993b).

In addition to the tidal velocity distributions describing short term fluxes, (e.g. Grochowski et al., 1993a), more complex simulations have been undertaken to describe the long-term tidal circulation in the Eastern English Channel (Mauvais, 1991). Along with a general long term flow towards the Dover Straits (also identified by Pingree, 1980), more complex circulation patterns were highlighted (Figure 201), particularly in the Central English Channel associated with large scale flow interaction with the Cotentin Peninsula and the Isle of Wight. The results of tracer studies and observations of sediment distribution correlate closely with the suggested flow patterns. Contrary to the circulation residuals of Mauvais, (1991), tidal patterns through the Dover Straits are suggested by Grochowski et al., (1993a) to be ebb dominant in the deeper central part of the Straits but flood-dominant on the south eastern side. This interpretation was supported by the observation of sediment transports material into the North Sea in the central part of the Straits but not at the margins. Eddies are also formed in this region as a result of the shear boundary (Grochowski et al., 1993b).
The residual flow of water has implications for sediment transport processes through the Dover Straits which forms the eastern boundary of the EEC region. To investigate residual transport and dispersion process in this region in more detail, Sentchkev and Korentenko (2005) modelled the transport of neutrally buoyant particles in a Lagrangian numerical model (residual flows as shown in Figure 202).

In the model, four hundred particles were released in bulk into an 8km wide patch at each of three different locations in the EEC, specifically: an offshore region at the eastern end of the Channel, a near-shore region near France, and in the centre of the Dover Straits. The model was allowed to run over 30 tidal cycles, i.e. over a spring-neap cycle. The results demonstrated that the three chosen regions produce three very different results. Particles released centrally were transported slowly north-east whilst...
becoming gradually dispersed. Particles placed near to the French coast were transported rapidly north-east following the coastline with less dispersion across the tidal axis. Particles released in the central Dover Straits show little along-stream net transport but slight transport north west towards the English Coast. Residuals during spring tides were significantly greater than during neap tides. The implications of this study in relation to sediment transport are discussed further in later Sections.

7.1.3 Wave climate

The largest wave heights observed in the ECR propagate from directions of ~240° (storm driven waves and swell from the Atlantic) and 40-50° (storm and wind driven waves from the North Sea and Dover Straits). Waves from 240° are more frequent than those arriving from any other angle and have on average higher wave heights and longer wave periods (Posford Haskoning, 2002). Typical wave heights in eastern and central locations in the English Channel were described by Grochowski and Collins (1994) as 0.6m and 0.75m in water depths of 29m and 66m (indicated as (1) & (2) in Figure 203), respectively. In a study by Crickmore et al., (1972) wave periods approximately 10km offshore of Worthing (indicated as (3) in Figure 203) are typically in the range 6-10s.

Wave climate has also been investigated in terms of the typical orbital velocities induced at the bed. Crickmore, et al., (1972) undertook such a study to determine the maximum orbital velocities between the 10-25m depth contours; wave periods of 6-10s and wave heights of 3.05m and 6.10m were observed during the study. The results for these wave parameter ranges are shown in Figure 203. If the results of Crickmore (1967) are extrapolated to a depth of 30m, the predicted orbital velocities at this depth are approximately within the range ~0.25ms⁻¹-0.9ms⁻¹. In a separate study by Draper (1967), orbital velocities of 0.9 ms⁻¹ and 0.25ms⁻¹ were observed at 30m water depth for <1% and ~30% of the year respectively.

Figure 203. Maximum orbital velocity variation with depth for deep water wave heights of 3.05m and 6.10m, and for wave periods of 6s, 8s and 10s. From Crickmore (1972).
7.1.4 Sediment distribution

7.1.4.1 The English Channel

Seabed surface sediments in the English Channel below the 30m depth contour are primarily controlled by the large scale patterns of tidal forcing described in Section 1.1. The distribution of sediment facies corresponds generally to the magnitude of tidal velocity (shown in Figure 200b); generally coarser sediments are observed in regions of stronger flow and vice versa (Figure 204 and Figure 205). The Isle of Wight-Cotentin Peninsula axis experiences the strongest tides and consequently contains the coarsest material (Grochowski et al., 1993a). Mean grain size decreases to the east towards the Dover Straits with a relatively uniform distribution across the Channel (Figure 205), with the exception of more significant fining observed in the low-velocity embayments on the French coast and in the narrower sections close to the Dover Straits. Mean grain size also decreases to the west of the axis; however, a greater degree of cross channel variability is observed, associated with spatial variation in tidal velocity.

Figure 204. Surficial sediment composition of the English Channel (A). Classifications are based on the folk scale (B), as displayed (Hamblin et al., 1992).
Hamblin et al. (1992) also presents maps of the thickness of sedimentary deposits (Figure 206), the mean grain size of the sand fraction (Figure 207) and sorting of the sand fraction (Figure 208) in the northern half the English Channel. These demonstrate generally good agreement with the distribution of sediments outlined in a similar report by Anthony (2002). There is a decrease in mean grain size of the sand fraction from west to east and an increase in sediment deposit thickness towards the east and close to the French coast north of the Somme. The thickness of sediment layers reported by Hamblin et al. (1992) do not exceed 0.5m throughout the majority of the eastern Channel; however, in regions west of Beachy Head to the Dover Straits, sediment thicknesses increase up to and beyond 5m (some regions exceeding 30m thickness). Though less detailed, sediment thicknesses identified by Anthony, (2002), also highlight this trend of increased sediment deposit thickness at and around the French coastline between Somme and Boulogne. The mean grain size of the sand fraction increases from west of Beachy Head to the Dover Straits. There is a general transition from medium sands (diameter 0.5-0.25mm) to coarse sands (1-2mm). Sediments are reported as moderately sorted over much of the Channel area. Sediment is better sorted near to Beachy Head and strong spatial variation (both better and poorer sorting) is observed adjacent to the Dover Straits.
Figure 206. Thickness of seabed sediments in the English Channel (Hamblin et al., 1992).

Figure 207. Mean grain size of the sand fraction in the seabed sediments (Hamblin et al., 1992).

Figure 208. Sorting of the sand fraction in the sediments of the seabed in the English Channel (Hamblin et al., 1992).
7.1.4.2 The Eastern English Channel region

The ECR is underlain mostly with stable Tertiary, Palaeogene bedrock (Smith et al., 1975) comprising clays, sandy clays and silts, which tend not to penetrate the surface. Partly or wholly infilled palaeo-channels of mid-quaternary age are found in the region (Posford Haskoning, 2002). Overlying this, the surficial sedimentary layer is more complicated, varying in quantity and composition in an east-west direction due to spatial variation in tidal forcing outlined in Figure 200b. Figure 209 shows a sediment type distribution map of the Eastern Channel region, based on the top 40cm of numerous vibrocore samples collected in the region.

Surface sediments in the ECR mainly comprise a mixture of sand and 30% to 60% flint gravels. The sheet varies typically between 5m and 10m thickness. Sediments towards the east of the ECR have a progressively higher carbonate shell content and decreasing median grain size (from 5-10mm in the west to <1mm in the east). A schematic west-east cross section through the ECR (Figure 210) indicates an increase in abundance and depth of sand overlying the gravel resource towards the east. Sand waves of up to 11m height are able to form in the far east of the region.

Figure 209. Sediment distribution in the ECR. Values represent the average of the top 40cm of numerous vibrocores collected in the region. Composition is based on the Folk classification, as shown (adapted from Posford Haskoning, 2002).

Figure 210. Schematic cross section from west to east (left to right respectively) of sediments in the Eastern Channel Region (Posford Haskoning, 2002).
7.1.5 Sediment transport

7.1.5.1 Bedload transport

Sediment transport as bedload in the English Channel follows patterns formed by the actual and residual effects of tidal and wave forcing; patterns of sediment movement therefore vary between offshore and coastal regions. Patterns have been investigated and summarised in previous numerical or interpretive studies, e.g. those by Anthony et al. (2002), Pingree (1980), Grochowski et al. (1993a) or Harris et al. (1995). The studies agree that away from the coast in water depths greater than 30m tidal forcing is dominant, but in shallower water wave action and river outflow are of increasing importance.

In one such study, Grochowski et al., (1993a) calculated, using a numerical model, transport vectors of sand and mean sediment grain size fractions over the entire English Channel at a resolution of 2 square nautical miles. Figure 211 a) and b) show the calculated transport rates for the local mean grain size and the median sand fraction diameter, respectively. Transport rates are shown to be greatest in the central part of the Channel along the Isle of Wight-Cotentin Peninsula axis, with more subtle spatial variability in other areas. Sediment divergence and convergence zones are visible as regions of very low local transport potential with sediment transport indicated away from or towards the area, respectively.

A broad scale interpretation of the more detailed transport rate data is shown in Figure 212. In the tidally dominated regions of the English Channel, sediment transport is orientated parallel or subparallel to the long axis of the area (equivalent to the dominant tidal axis). Along this axis, net transport is to the east in the EEC and to the west in the Western Approaches; the Isle of Wight-Cotentin Peninsula axis therefore forms a bedload parting zone. Sediment convergence zones (see Figure 212a...
and Figure 211) are also identified to the south-west of the Dover Straits and in the far Western Approaches.

Net sediment transport from the EEC through the Dover Straits is predicted by Grochowski et al. (1993a) to occur close to the French coast only (see Figure 212a). This transport path is thought to explain the presence of large sand ridges described by Hamblin et al. (1992) and Anthony (2002), to the north of the Somme estuary. This transport path is bordered to the north by an ebb-tide dominant region bringing sediment from the Southern North Sea. The transport rate of sediment in this direction becomes limited south of the Dover Straits. Numerical predictions of residual water movement (an indicator of net sediment transport direction) by Sentchkev and Korentenko (2005) were described in Section 1.1; the results of the Dover Straits tracer experiment are shown in Figure 212b. The implied transport direction of sediment from the North Sea once in the central part of Dover Straits was north-west, towards the English coast.

![Figure 212. (a) Sediment transport pathways in the English Channel and Celtic Sea. (Grochowski et al., 1993a) (b) The location of 400 neutrally buoyant particles 30 tidal after being released into the central area of the Dover Straits in a modelled simulation of the Eastern English Channel (Sentchkev and Korentenko, 2005).](image)

In a slightly different approach, the spatial distribution of shear stress due to tidal flows at the seabed was estimated for all areas of the English Channel, using a numerical model, by Harris et al. (1995). Flows were simulated using the main (M2 and M4) tidal components; results showing the maximum bottom stress in all UK waters are displayed in Figure 213.

Wave driven sand transport has been highlighted in numerous studies to be of significant importance but only in shallow coastal regions of the shelf sea. In water depths of greater than 10m, due to attenuation of orbital velocity with depth, erosion and transport resulting from wind and wave action is generally small compared to tidally induced material flow (Mauvais, 1991). Bed sediments under propagating waves may be transported by the stronger orbital velocities and weaker residual currents induced by the wave motion in shallow water (Crickmore et al. 1972). Larger wave heights and periods induce greater orbital motion at the bed. Dispersal of any affected particulate matter in the direction normal to the wave front can also lead to landward transport.
Based on the sediment distribution of the Channel, extracted from published charts, the percentage of yearly time by which the median grain size and median sand size fractions are disturbed by wave action was numerically estimated from the depth-dependent near-bed currents by Grochowski and Collins, (1994). Results for median grain size material and the mean sand fraction grain size are shown in Figure 214. Wave conditions were based on long term measurements of wave height and inshore regions of less than 10m water depth have been excluded. Results suggest that in the EEC, in depths greater than 20m, median sediments are generally in motion for less than 1% of the year. This increases up to 5% for sand in some locations although the majority of the region experiences less. The Hastings Shingle Bank experiences sediment motion due to wave action alone for less than 1% of the year for both median sized sediments and the sand fraction generally. Another study by Channon and Hamilton (1976) suggests that sediments of median diameter $1.4\phi$ (~0.34mm) are moved by wave action for at least 3% of the year in depths of up to 100m in the Western Channel, greater than that predicted by Grochowski and Collins, (1994). The sediment grain size distribution, however, is identified to fall mostly between $0.97\phi$ and $1.83\phi$, the percentage motions for which are unknown. Storm periods were included in the calculations. The amount of time that critical orbital velocities were exceeded at various depths was drawn from Draper, (1967).

![Figure 213. Numerically estimated maximum bottom stress as induced by M2 and M4 currents. Bottom stresses are calculated in Dynes.cm$^{-2}$ where 1 Dyne = $1\times10^{-5}$ Newtons. Positions of the amphidromal points are marked ◦. From Harris (1995).](image-url)
7.1.5.2 Suspended sediment transport

Suspended sediment concentration varies spatially over the extent of the English Channel and temporally on a range of timescales. Annually averaged suspended matter concentrations are estimated at 3mgL\(^{-1}\) and 5mgL\(^{-1}\) for surface and bottom waters respectively over the entire eastern Channel (Eisma and Kalf, 1987). Measured by Concentrations of fine material (<63\(\mu\)m) were measured by Van Alphen (1990) to be generally higher closer to shore and during autumn and winter months. Results from nearshore surface waters in the Dover Straits have an average value of 6mgL\(^{-1}\) during summer (range 1.8mgL\(^{-1}\)) or 15.4mgL\(^{-1}\) during winter (range 22.8mgL\(^{-1}\)). Concentrations in offshore surface waters in the same region are typically lower with an average value of 2.2mgL\(^{-1}\) during summer (range 1.1mgL\(^{-1}\)) or 5.5mgL\(^{-1}\) during winter (range 8.3mgL\(^{-1}\)).

The time varying concentration of suspended particulates entering the eastern Channel across the Wight-Cotentin transect (between the Isle of Wight and the Cotentin Peninsula) was observed by means of water sampling by Velegrakis et al. (1999). Figure 215 shows the results obtained for bottom and surface waters. Suspended sediment concentrations are generally greater near to the English coast and in the northern half of the Channel. Concentrations were greater during the winter and early spring in 1994; concentrations were on average greater in September 1993 compared to the same period in 1994, demonstrating inter-annual variation also. Concentrations in the upper and lower water consistently differ by approximately...
4mgL$^{-1}$. Lateral and vertical variations in concentration agree with the earlier observations of Velegrakis et al. (1997). A suspended concentrations map of the EEC in early September, created from the indicated discrete sampling locations, is also shown in Figure 215. It also shows that suspended sediment concentrations become elevated close to coastal regions. High concentrations of suspended sediment are not necessarily associated with regions of high tidal velocities (e.g. near to the Cotentin Peninsula), likely due to a lack of suitable sediment to resuspend in these areas.

Figure 215. SPM concentrations (in mgL$^{-1}$) along the Wight-Cotentin transect in the (a) surface waters and (b) bottom waters. Distance and time denote the y and x axes respectively. (c) Surface water suspended sediment concentrations (in mgL$^{-1}$) in the eastern English Channel in early September, 1994. Sampling stations are indicated by a white circle. From Velegrakis et al. (1999).
Table 15. Summary of extant literature investigating annual suspended sediment fluxes through the Straits of Dover. From Velegrakis et al. (1999).

<table>
<thead>
<tr>
<th>Reference</th>
<th>SPM flux ($\times 10^6$ tonnes annum$^{-1}$)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Van Veen (1938)</td>
<td>4</td>
<td>Based upon limited observations of suspended sediment concentrations (SSC), but adequate current data for low-wind speeds</td>
</tr>
<tr>
<td>Eisma and Kalf (1979)</td>
<td>11.5-15</td>
<td>Using the net water flux data of Prandle (1978) and a SSC of 1.9 mg/l for offshore waters, together with a flux of 3.5x10-6 t.a-1 along the coast</td>
</tr>
<tr>
<td>Eisma and Irion (1988)</td>
<td>22-30</td>
<td>Using a mean SSC of 3 mg/l</td>
</tr>
<tr>
<td>Postma (1990)</td>
<td>2.5</td>
<td>Using the Van Veen (1938) current data, Wyrtki's (1952a,b) water flux data and different (mean) SSC data for offshore and near-shore areas</td>
</tr>
<tr>
<td>Postma (1990)</td>
<td>10</td>
<td>Using a mean SSC of 1.9 mg/l</td>
</tr>
<tr>
<td>Van Alphen (1990)</td>
<td>17</td>
<td>Using the water flux data of Van Veen (1938)</td>
</tr>
<tr>
<td>Grochowski et al. (1993a)</td>
<td>19.2</td>
<td>On the basis of SSCs measured during the FLUXMANCHE I Project, combined with the output from a 2-D hydrodynamic model (Salomon et al. 1993)</td>
</tr>
<tr>
<td>Jones et al. (1994)</td>
<td>9.4</td>
<td>Using current and SSC data from moored instrumentation (current meter, ADCP and transmissometer)</td>
</tr>
<tr>
<td>Pohlmann and Puls (1994)</td>
<td>13.6</td>
<td>Using CNEXO measurements cited in Van Alphen (1990) and assumptions on the SPM size (Eisma and Kalf, 1979)</td>
</tr>
<tr>
<td>McManus and Prandle (1997)</td>
<td>44.6</td>
<td>Using the net long-term water flux derived by Prandle et al. (1993) coupled with SSC observations</td>
</tr>
<tr>
<td>Lafite et al. (1999)</td>
<td>21.6 ± 2.2</td>
<td>On the basis of SSCs measured during FLUXMANCHE I combined with ‘average’ water flux, estimated by a 2-D hydrodynamic model (Salomon et al. 1993)</td>
</tr>
<tr>
<td></td>
<td>28.4 ± 2.8</td>
<td>Maximum fluxes, estimated on the basis of the FLUXMANCHE I SSC measurements and water fluxes due to tidal currents combined with south-westerly winds, estimated by a 2-D hydrodynamic model (Salomon et al. 1993)</td>
</tr>
<tr>
<td></td>
<td>18.2 ± 1.8</td>
<td>Minimum fluxes, estimated on the basis of the FLUXMANCHE I SSC measurements and water fluxes due to tidal currents combined with north-easterly winds, estimated by a 2-D hydrodynamic model (Salomon et al. 1993)</td>
</tr>
</tbody>
</table>

Estimated annual fluxes in and out of the EEC suggest that much of the material entering the region exits into the North Sea, however, maximum and minimum estimated fluxes form very large ranges. Estimates of the predicted annual transport rate in to the EEC through the Isle of Wight-Cotentin Peninsula cross-section range between 2-71Mt.a$^{-1}$ (million tonnes per annum); a mean estimate of 20Mt.a$^{-1}$ is suggested to be reasonable (Velegrakis et al. 1999).
Estimates of the annual transport rates of suspended sediment leaving the EEC region, into the southern North Sea previously made using experimental data and extant literature were summarised by Velegrakis et al. (1999); these are summarised in Table 15. The predicted values are in the range 2.5-44.6Mt.a\(^{-1}\). Large errors in estimated input and output are largely due to uncertainties in both water flux and sediment concentration. The similarity of the estimated input and output values mean that the EEC region is considered to be a bypass for fine grained suspended sediments passing through to the North Sea, rather than providing a significant source or sink (Velegrakis et al. 1999). Eddies induced by the lateral shear boundary in the Dover Straits act to locally deposit suspended material in this particular area (Grochowski et al. 1993b).
7.2 The Impact of Dredge Plumes and Upstream Dredging Activity: Case Study of the UC-65.

The video collected as part of these studies has been used in presentations by BMAPA and its members on several occasions.

7.2.1 Introduction

There are four perceived threats of aggregate dredging on artefact based sites:

1. Direct interaction with the dredge head
2. Changes in seabed site dynamics in response to upstream modification of the flow regime due to bed elevation changes through dredging.
3. Changes in site dynamics of inter-tidal and sub-tidal archaeology of localities adjacent to the dredging area (including the coastal zone).
4. Impacts of the dredge plume on wreck site formation.

This report describes a study addressing potential threat (4), that of the dredge plume on wreck site formation. A literature review describing dredge plumes and their potential effects may be found in Section 6.1.

The shipwreck of the First World War U-boat UC-65 is located within a new marine aggregate dredging license area in the central part of the Eastern English Channel (EEC). At the start of the study, no dredging had been carried out in the area and the wreck site could be considered to be anthropogenically unaffected, i.e. in (quasi-) equilibrium with the natural hydro- and sediment-dynamic environment. By conducting repeated, detailed surveys of the wreck, both before and after the start of dredging, it would be possible to observe the actual effect of dredging (and dredge plumes) on the wreck site.

7.2.2 The Story of the UC-65

(Courtesy of Periscope Publishing Ltd.)

UC-65 is one of the most remarkable of the World War One U-boats lost in the Channel. She stands out for a number of reasons. She was the fourth most successful UC-boat ever built, she was commanded by two of the most capable U-boat commanders of the war; she sunk a British cruiser and became the rare victim of an enemy submarine.
Chapter 7 – The Third Field Study Site: The Eastern English Channel

Section 7.2 – The Impact of Dredge Plumes and Upstream Dredging Activity: Case Study of the UC-65

Figure 216. The UC-65. Courtesy of Periscope Publishing Ltd.

Figure 217. The UC-97, a sister ship of the UC-65.

Figure 218. UC 44 Class U-boat: 1) Aft torpedo tubes 2) Electric motor 3) Main engine 4) Control room 5) Mine tubes 6) Forward torpedo tubes 7) Crew quarters (http://www.worldwar1.com)

Class: UCII (UC-65 series) Built at: Blohm & Voss - Hamburg
Length: 50.35m Displacement: 508t
Date sunk: 3rd November 1917 How sunk: HM Submarine C15
Historic Position: 50 28;00 17E Known Position: 50 30.25N; 0 28.37E
Crew losses: 22 (from 27) Commander: Klt. Claus Lafrenz

UC-65 was built in Hamburg and commissioned on 10th November 1916. She operated with the Flanders flotilla and as such came to be commanded in the first instance by the remarkable Otto Steinbrink. He was one of the finest submarine commanders of all time, whose prowess to this day inspires awe in all who learn of his exploits. Apart from single-handedly destroying around 210,000 tons of allied shipping, Steinbrink is remembered for another remarkable exploit. On a patrol in the North Sea aboard UB18, Steinbrink took on four British submarines, sunk one (E22) and stopped to pick up the survivors before evading the other three to escape. No wonder the Admiralty dreaded him!

Near to the wreck of UC-65 lies one of its more notable victims. Under the command of Steinbrink, the UC-boat despatched the cruiser HMS Ariadne off Beachy Head. In total UC-65 was responsible for the destruction of 103 ships! This remarkable number added up 112,859 tons of allied shipping.
Lafrenz was on the return leg his second patrol in UC-65 when on 3rd November off Beachy Head he was on the bridge with four others. In waters ahead lay the British submarine C15, under the command of Lt. E.H. Dolphin. Both submarines saw each other at the same time. While Dolphin flooded his torpedo tubes, Lafrenz opted to continue on course for home. He could see C15s periscope and remarked to those on the bridge that if a torpedo was fired at him, he would use the manoeuvrability of UC-65 to evade it. Shortly thereafter, a torpedo was spotted streaking toward UC-65. Lafrenz put the helm over and evaded it. Seconds later UC-65 exploded and sunk. Dolphin had fired two torpedoes, close spread. In so doing, Lafrenz paid for his overconfidence, because he could not have evaded both. The five men in the bridge were blown into the air. Coming down in the sea, they were the only survivors from UC-65. In being sunk in this manner, the minelayer became one of only two U-boats in the Channel sunk by HM Submarines. The other was UB72. For once, Lala had met his match.

As with all other survivors of U-boats, the five men were interrogated at the Admiralty. Much useful information was usually gathered from these sessions, even if the German sailors thought they were being evasive. Lafrenz's interrogation report makes interesting reading, for he was particularly helpful. From him, the allies learned how the U-boats were evading the Dover barrage - priceless information indeed.

The German high command had no idea what had happened to UC-65 for several months. This was at the time when many of the stars of the Flanders Flotilla were being killed. Indeed when Werner Fürbringer was sunk in UB110 in July 1918, he was amazed to be told by his interrogators that 'Lala' was alive. He was even more surprised by the extensive knowledge the Admiralty seemed to posses of all operational aspects of the Flanders Flotilla, which he assumed had come from Belgian spies.

Today the wreck of UC-65 lies at the position given above. It is a great dive, being a comparatively rare UC-Class. It is easy to see the damage done to her, because the wreck lies in two halves around 20 metres apart. The empty mine chutes can be seen in the bow section along with most of the features of this class. The stern section is also interesting, especially so, because the break is exactly at the point of the engine room entrance, allowing for a rare inspection of a pair of 1916-era MAN
diesel engines. The short-barrelled 88mm deck-gun is also an interesting item to examine.

7.2.3 Location of the study site

The UC-65 study site is located approximately 20nm SSW of Hastings in the middle of the central separation zone of the Eastern English Channel (Figure 220) in a water depth of approximately 41m. The position of the site as reported in the UKHO wrecks database is [0° 26.6898'E, 50° 30.2677’N] (WGS84 datum). The site experiences a typical tidal range of approximately 6-8m. The maximum surface tidal flow (spring tides) in the area is approximately 1.8kts during ebb tides and 2.3kts during flood tides. These values are less during neap tides. The orientation of the tidal axis obtained from seabed sonar images and in agreement with tidal flow data recorded on a single day during spring tides was approximately 080° (flood) and 260° (ebb).

Figure 220. The location of the UC-65 [0° 26.6898’E, 50° 30.2677’N] (WGS84 datum) in relation to the Eastern English Channel coastline, separation zone and the Dover Straits.

7.2.4 Present day layout of the UC-65 wreck site and description of the surrounding seabed

A swath bathymetry survey of the UC-65 and surrounding seabed was undertaken by the University of Southampton as part of this ALSF project 3365 in early November 2006. The resulting image, cropped to the extent of the site is shown in Figure 221. A side scan sonar image of the wreck is also shown which illustrates the same general layout of the site; however, the image is not of sufficiently high quality to yield significant information about sediment distributions and the date of data collection was not supplied.
The wreck of the UC-65 exists as a larger northern section (38m long) and a shorter southern section (13m long) separated by approximately 15m and both proud of the ambient seabed. The northern section is orientated 140°/320° and the southern section is orientated 160°/340° from north. Based on depth recordings taken by the ROV during the first survey, the diameter of the almost cylindrical sections are estimated to vary between 3.7 m ± 0.3 m and 3.2 m ± 0.5 m as the wreck tapers off towards the stern (the southern section).

Regions of accumulation are evident in the swath data, on both east and west faces of the northern section of the wreck and on the east face of the southern section. Regions of scoured bed are evident at the ends of both the north and south sections, especially in between the sections. Shallow scour pits (approximately 30-50cm deep) are visible in the swath emanating to the east side but are not evident towards the west. The more northern of the scour pits extends the greatest distance (approximately 300m), but has a smaller depth relative to the ambient bed close to the wreck. Scour emanating from the southern end of the northern section is of greater depth but extends less distance downstream. The southern section follows a similar pattern to that of the north section but with an even smaller extent. Scour pit pairs from the north and south sections are separated for a short distance close to the wreck by slightly elevated accumulation ribbons. Interpreting this observation on the basis of the results presented in Sections 3.4, 4.4 and 5.2 and other previous research (e.g. Saunders, 2004; or Caston, 1979), the dominant tidal axis is orientated approximately 80°/260° and net sediment transport occurs from WSW to ENE along this axis.
Figure 221. The UC-65 and surrounding seabed: (a) multibeam swath bathymetry data collected by the University of Southampton as part of the present study ALSF project 3365 on 09/11/06; (b) side scan sonar image courtesy of CEFAS. White regions to the east of the wreck in the sonar image are an acoustic shadow artefact.
7.2.5 Survey methodology

A remotely operated vehicle (ROV) was employed to conduct visual surveys of the wreck. ROVs remain tethered to the vessel and control station, receiving a continuous power supply and returning continuous digital data feeds. ROVs are controlled in real time by an operator or pilot, who is in turn guided by the scientific team. The particular ROV used was a Seaeye Falcon (shown in Figure 222). The ROV was of a suitable size for the task requirements (dimensions L=1.0m W=0.5m H=0.6m) and was provided and operated by Subsea Vision Ltd. The ROV was highly manoeuvrable in all axes and could continue to operate effectively for long periods, up to 300m from the vessel, even during reasonable tidal flow. It collected video continuously during the deployment using one of two onboard digital cameras (one low light monochrome and one colour camera) and additional light sources when required.

Figure 222. (Left) The Seaeye Falcon ROV (L=1.0m W=0.5m H=0.6m). Picture courtesy of Subsea Vision Ltd. (Right) An example still image of wreckage and sediment collected during the study.

Additional footage was also obtained from a previous scuba dive of the wreck by Periscope Publishing Ltd in September 1999. This provided approximately 25 minutes of digital colour footage collected by divers in good visibility. The original purpose of the dive was to record the appearance of the wreck itself so only part of the footage was used directly by the present study.

To observe any temporal variation in sediment composition, three separate ROV surveys (named ROV surveys 1, 2 and 3 herein) were completed with approximately a six months interval period. All of the ROV surveys were undertaken around slack water during neap tides; footage obtained from Periscope Publishing was collected in a period coming off springs going into neaps. The actual dates of the four surveys were:

Periscope publishing scuba dive footage:
2nd September, 1999.

University of Southampton ROV surveys:
9th November, 2005.
Because the Periscope Publishing survey and ROV surveys 1 and 2 were completed prior to the start of dredging, any differences observed are attributable to natural (e.g. seasonal) variations in sediment mobility or tidal strength. Differences observed in survey 3 however (after the start of dredging) might also be due to natural variability but potentially also to the nearby aggregate dredging.

### 7.2.6 Dredging activity near the site

The UC-65 study site is located within a recently acquired marine aggregate dredging license area 473 in the EEC region. The location of the UC-65 site within this license and relative to other adjacent license areas, the bathymetry and surrounding coastline is shown in Figure 223. Its proximity to dredging activity makes the site potentially susceptible to interaction with sediment dredge plumes.

Sediment plumes arise from dredging activity during on site screening processes which separate and return unwanted (typically fine) sediments into surface waters; a review of dredge plumes and the processes affecting them can be found in Section 6.1. Dredge plumes are clouds of increased suspended sediment concentration which may be either transported actively or advected passively, potentially interacting with nearby wreck sites. Plumes gradually deposit most of their sediment load with time but some very fine sediment may remain in suspension for very long time periods. Dredge plumes introduce mobile sediment to the bed which may result in increased sediment thickness (considered negatively in terms of benthic ecology) and burial of wreck sites (considered to be generally positive for archaeology). A number of more subtle potential threats are however posed by dredge plumes to wreck sites, for example:
An increase in advected sediment in suspension might increase abrasion of soft exposed material.

The advection of elevated turbidity over a site might modify (probably only slightly and temporarily) the rate or character of electrolytic interaction between the water and corrodbile materials.

A long term increase in ambient turbidity might encourage alternative organisms (e.g. filter feeders) to colonise the wreck, leading to different or possibly increased damage through biological action.

Additional sediment cover may further mask previously undiscovered sites.

Dredging activity took place in an upstream location (during flood tidal periods, potentially transporting dredge plumes over the site) on twelve occasions during the period between ROV surveys 2 and 3. Details of the timing of these activities have been provided by the license holders Hanson Aggregates Marine Ltd and CEMEX UK. These are listed in Table 16. The locations of the dredging lanes were also provided by Hanson Aggregates Marine Ltd, the corner coordinates of which are listed in Table 17. The location of the UC-65 study site relative to the active dredging lanes and the tidal axis are shown in Figure 224. The Figure shows that dredging activities occurred upstream of the site, therefore that any dredge plumes initiated during flood tides could potentially be advected towards the UC-65. The exact timing, quantity and location of material introduced into the water column forming a dredge plume and the exact oceanographic conditions at the time of release were not however available; this unfortunately prevents more accurate prediction of the likelihood of dredge plume interaction with the site. Another method of testing for the presence of dredge plumes locally would be to measure acoustic backscatter in the water column using a seabed mounted device as described in Section 6.2.

<table>
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</table>

Table 16. Reported instances of dredging activity occurring between ROV surveys 2 and 3 in lane 16 of license area 473 east.
### Table 17

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
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</table>

Table 17. Corner locations of dredging lanes 16a, 16b and 16c in area 473E. All coordinates listed are in WGS84 format (provided courtesy of Hanson Aggregates Marine Ltd).

### 7.2.7 Results

The following Section presents examples of the observational data extracted from the various surveys. Differences in sediment character or the relative location and volume of sediment accumulation or scour features observed between the surveys are described.

Figure 225 shows a schematic diagram of the wreck, produced to scale according to the side scan sonar image of the site (see insert). Indicated in the Figure are a number of easily identifiable physical features on the wreck, chosen as physical markers against which to compare bed levels or exact positions of accumulation/scour features.
The observed sediment distribution was documented using a series of still images taken from the video at chosen locations relative to the UC-65, shown in Figure 226. The images are presented in the following Sections in a table structure. Rows in the table represent the different locations whilst columns represent the four surveys in chronological order. Each video still is accompanied by a schematic diagram of the appropriate section of the wreck the location and viewing angle are indicated by a red dot and arrow. A more detailed description is provided for the first image and relative changes are then noted through the remaining time sequence.
Figure 226. Key to the location of video still images used for comparative study of the sediments surrounding the UC-65 wreck site. Locations 18-23 (ambient seabed) are not exact, however, in each case the relative direction is correct and the ROV is considered to be distant enough to consider the seabed at that location unaffected by the wreck.
When comparing images, the reader should note the following:

1. In cases where an item of reference is used as a visual aid but is difficult to distinguish, a black dotted line is superimposed as an additional aid. This was particularly needed for images collected during ROV survey 2, which suffered from particularly poor visibility.

2. When comparing images collected by the two available cameras, erroneous or exaggerated differences in seabed composition may be perceived; images produced on the colour camera tend to appear coarser due to effects linked to shadowing (from the added light source) and increased resolution. Potential misinterpretation is avoided in the present study as the analysis is being undertaken by experienced users of the data, using the original video footage (which is more informative than the still images in isolation). In the cases where direct comparison between images from the different cameras is necessary, descriptions are also provided of any differences that are actually evident. An example is provided in Figure 227 to describe this effect; both images are of the same area of seabed, taken on the same survey.

3. Each image contains visual metadata regarding the operation of the ROV. Values located top-right of the image are the date and the time (top and bottom respectively); values located top-centre of the image are the depth and the camera angle relative to the vertical (-90deg at nadir increasing to 0deg at horizontal); values located top-left are the ROV heading relative to north and the number of twists put into the umbilical since the start of the survey.

![Images of seabed with metadata](images)

Figure 227. An area of Seabed taken during the ROV Survey 2 (a) taken with a low light monochrome camera with no additional light source and (b) a colour camera with additional light provided from the ROV.

### 7.2.7.1 Around the main sections

Tables of images follow, comparing key locations around the main (northern) section of the wreck, at each of the four survey intervals.
1. Sandy seabed looking south from the perforated plate. Remains unchanged.

2. Sandy material at the base of an accumulation towards the south (note that the image is to the north of the grapnel). Steeper slope at the grapnel. Composition remains unchanged.

Remains unchanged.

Remains unchanged.

Remains unchanged.

Remains unchanged.

Remains unchanged.

Little overall change.

Little overall change.
3. Sand accumulation apex to the north of the ballast tank. Apex reaches up to the horizontal rib. Apex is aligned with the vertical rib (located ~1.65m from the top).

Increased accumulation of sand. Apex lies a little to the north of the vertical rib (located ~0.67m from the top).

Erosion of the accumulated region. Apex located higher than seen in the Periscope Publishing survey (located ~0.8m from the top).

Increased accumulation. Similar levels to ROV survey 1 (apex located ~0.8m from the top).

4. Metal coil situated below the ballast tank. Sandy material bordering a scoured area immediately below the ballast tank.

Matching composition and quantity.

Unchanged.
5. Sandy material, increasing in coarseness with a progression south from the apex. Similar composition (appears coarser under added light and high resolution colour camera). Similar composition. Note that the ROV is elevated from the bed.

7. Accumulation up to the conning tower. Apex situated on conning tower. Distance of apex from the top of the wreck is ~40-50cm.

Small increase in accumulation (<10cm). Apex now located to the south of the conning tower.

Remains unchanged.

Slight erosion. Matching apex location.

8. Accumulation at the southern end of the mine tubes (labelled M1 to M6 from south to north). Sand reaches shortly below the lip of mine tube1.

Increased accumulation above the lip of mine tube1. Height differences are of the order of 20cm.

Further accumulated. Additional height is of the order of 10cm.

Erosion of sand (lowest observed levels). Height decrease of the order of 50-60cm.
9. Northern end of the mine tubes (labelled M1-M6 from south to north). Debris hinders the view.

Appears to be less accumulated (though the perspective hinders the observation).

More accumulation than ROV survey 1. Less accumulation relative to Periscope Publishing dive.

Levels of sand are eroded. Lowest observed levels of sand.

10. Coarse material at the northern end of the wreck. Located at the north side of the debris field.

A little coarser.

Similarly coarse. Sandy material visible on the eastern side of the debris (top-right of image).
11. Very coarse material at the north end of the southern section. Wreck-end can be seen to the top-right of the image. Similarly coarse.

12. Sandy material building up on the western face of the southern section. Accumulation increases further south. Scoured (and coarser) around the wreck face. Similar. Composition change evident on the northern side of the image (left side). Similar. Scoured, coarser, region towards the face of the wreck (top left of image).
13. Sandy material around an item of debris on the western face.

Unchanged.

Remains unchanged.

14. Coarse material at the southern end.

Appears marginally coarser with a greater extent of scour.

Unchanged.

A little less coarse at the immediate end of the wreck. Scour pit remains generally very coarse.
15. South of the eastern side of the southern section. Sandy seabed at a cylindrical item of debris.

16. Sandy seabed at the northern end of the eastern face.

15. Similarly sandy seabed around the cylindrical item. (situated at the top of the image).

16. Similar grain size. Composition change evident, with coarse material at the north of the image (right side of the picture). Increasingly accumulated to the south.

15. Unchanged (cylindrical item situated at the top-right of the image).

16. Increased sand build-up (increasing to the south). Composition remains unchanged.

15. Grain size and accumulation remain largely unchanged.

16. Similar grain size and accumulation. Scoured region visible at the north end of the wreck face.
### 7.2.7.2 Between the northern and southern sections

The following table of images compares key locations around the smaller (southern) section of the wreck, at each of the four survey intervals.

<table>
<thead>
<tr>
<th>Gravelly armoured layer</th>
<th>Similar in composition</th>
<th>Remains unchanged</th>
<th>Remains unchanged</th>
</tr>
</thead>
<tbody>
<tr>
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<td>ROV Survey 1, 09/11/05</td>
<td>ROV Survey 2, 06/06/06</td>
<td>ROV Survey 3, 31/01/07</td>
</tr>
</tbody>
</table>
7.2.7.3 **Background Sediments**

Little temporal change is evident in the make-up of the background sediments over the four periods of observation. For this reason the images are provided alone without description.

*Periscope Publishing, 01/06/99  ROV Survey 1, 09/11/05  ROV Survey 2, 06/06/06  ROV Survey 3, 31/01/07*

18.

19.
Periscope Publishing, 01/06/99  ROV Survey 1, 09/11/05

ROV Survey 2, 06/06/06  ROV Survey 3, 31/01/07

20.

21.
Periscope Publishing, 01/06/99

ROV Survey 1, 09/11/05

ROV Survey 2, 06/06/06

ROV Survey 3, 31/01/07

22.

23.
Figure 228. Sediment composition of the surrounding seabed of the UC-65 at the time of the Periscope Publishing Ltd. dive. Regions of accumulation and scour, as well as relative (according to ambient) distributions in sediment size, are identified. Regions that were not observed during the survey are identified by a hatched box – colour classification in these regions is the expected distribution based on observations from alternative surveys.
Figure 229. Sediment composition of the surrounding seabed of the UC-65 at the time of the ROV survey 1. Regions of accumulation and scour, as well as relative (to ambient) distributions in sediment size, are identified. Regions that were not observed during the survey are identified by a hatched box – the colour classification in the unseen regions is based on observations from the other surveys.
Figure 230. Sediment composition of the surrounding seabed of the UC-65 at the time of the ROV survey 2. Regions of accumulation and scour, as well as relative (according to ambient) distributions in sediment size, are identified.
Figure 231. Sediment composition of the surrounding seabed of the UC-65 at the time of the ROV survey 3. Regions of accumulation and scour, as well as relative (to ambient) distributions in sediment size, are identified.
7.2.7.4 Spatial variability in sediment composition

On the basis of the video and still image data, maps summarising the distribution of sedimentary features observed during each survey were created and were shown in Figure 228 to Figure 231. Some locations were not observed during every survey and are therefore absent from the following analysis. During the three ROV surveys, occasional difficulties such as increased tidal velocity, poor light and bad weather hindered the coverage that would otherwise have been obtained. The footage provided by Periscope Publishing Ltd was not gathered with the same purpose as the present study and is therefore missing many areas of interest. ‘Missing’ regions are identified on the sediment distribution maps of Figure 228 through to Figure 231 by a hatched box (when appropriate).

Around the UC-65, regions of accumulated sand were observed on the east side of both the northern and southern sections (the downdrift side relative to ambient sediment transport). The accumulation against the east side of the northern section extends almost to the top of the wreck on that side, along the whole length of the section. A smaller accumulation with a well defined apex and stable location (but with significantly varying height and volume) was consistently visible on the western side of the northern section but was absent from the smaller southern section. Accumulations

Tidally aligned scour regions armoured with coarser gravely material, extend away from the end points of both sections of the wreck. The transition between scour pit and ambient bed occurs over very short distances (order of 2-3 meters) across the tidal axis. Local scour (a long shallow trough-like depression in the accumulated sand) of variable coarseness was evident along the base of the western face of both sections. Relative bed roughness visually estimated from the video increases steadily away from the wreck until background ambient conditions are reached. The distance over which this occurs depends upon the location and direction of travel: shortest across the tidal axis from the ends of the wreck site; greatest towards the ENE first traversing the larger sandy accumulations.

7.2.7.5 Temporal variability in sediment composition

When compared directly, the sediment composition maps in Figure 228 to Figure 231 exhibited the same general spatial patterns between the surveys with only slight differences in the levels of accumulation, scour and relative bed roughness.

Areas exhibiting significant change during the full observation period correspond to location numbers 3, 7, 8, 9, 10, and 14 in the results; these are identified again in Figure 232 (marked 1-6) and a summary of the observed changes is given, below. An additional location (marked 7) situated a short distance from the eastern side of the southern section does not have any associated video stills, but is included on the combined sediment distribution maps in Figure 228 to Figure 231.
- 1. Western accumulation. Minor variation in height and position. The initial dive footage shows a significantly lower apex, which is higher but then remain similar in the three ROV surveys with only small fluctuations.

- 2. Conning tower accumulation. Varies only slightly in height and position.

- 3. Southern mine tubes accumulation. Variation in height. Accumulation increases over first three observations. Final survey shows decreased levels.

- 4. Northern mine tubes accumulation. Variations in height and slope. Progressively decreased levels from survey to survey.

- 5. Northern end scour. Small changes in composition. ROV survey 2 shows marginally coarser material within the scour pit. ROV survey 1 and 3 show little difference.

- 6. Southern end scour. Small changes in composition and extent of scouring. Increased coarseness and scour during ROV surveys 1 and 2. Reduced levels for ROV survey 3.

- 7. Eastern side of southern section. Coarse material seen during ROV survey 1. Area is sandy during all other surveys (and progressively decreasing in sandiness away from the wreck).

7.2.7.5.1 Summary of temporal variations by survey interval

- **02/09/99 to 09/11/05.** The accumulations of sand on both the eastern and western sides of the UC-65 were of greater volume and came higher up the wreck in November 2005 than observed previously in September 1999. A relatively small decrease in the height of sediment accumulation adjacent to the northern mine tubes was observed and the southern scour of the northern section increased in visual roughness. The seabed sediments away from the wreck remained visually unchanged. The limited duration and different cinematographic style of the 1999 footage means that some regions of the wreck site are not directly comparable and other potential differences remain unknown.

- **09/11/05 to 06/06/06.** Gross variations between the first and second ROV surveys were minimal. There is an increase in the volume and height of sandy accumulations adjacent to eastern face of both northern and southern sections. There was a slight decrease in the height of the sandy accumulation on the western side of the northern section.

- **06/06/06 to 31/01/07.** Gross variations between the second and third ROV surveys were again minimal. The sandy accumulation on the western side of the northern section remains of similar volume and height. However, the sand accumulation on the eastern side of the northern section, decreases to its lowest observed level both
adjacent to the mine tubes and to the conning tower. Accumulations on the eastern side of the southern section remain apparently unchanged.

7.2.7.5.2 **Wave action**

Wave action is not considered to be important in the transport of sediment in deep water such as that at the site of the UC-65 (in the order of 40m). However, in case the general wave climate is affecting the system through indirect means, the wave climate measured at a location onshore of the site (the ‘Rustington’ Directional Wave Rider buoy) is shown in Figure 233. The figure demonstrates that wave action was relatively similar during the summer/autumn/winter period preceding the first survey, compared to the months in between the first and third ROV surveys. Larger waves (>1.5m wave height) were experienced in autumn/winter 2003 but no data was available for other years back to the periscope publishing survey in 1999. It is possible that the wave climate was generally more energetic during those times.

![Wave Climate Graph](www.channelcoast.org)

Figure 233. The wave climate measured at a location onshore of the UC-65 site (the ‘Rustington’ Directional Wave Rider buoy). Data courtesy of Channel Coastal Observatory. www.channelcoast.org.
7.2.8 Discussion and conclusions

Four video surveys were obtained from the First World War U-boat UC-65 wreck site. The site is located within a newly acquired marine aggregate dredging license area in the central Eastern English Channel. The first three surveys were conducted prior to the start of dredging activity in the area and represent time intervals of 74 months and 7 months; the final survey was collected after the start of dredging, a further 7 month interval. Results therefore provide very detailed spatial information at a reasonable temporal resolution about naturally occurring site variability on 5 year and seasonal time scales; also, the potential impact of upstream dredging activity through dredge plumes. The results presented in this report are a summary of a more detailed interpretation made by experienced observers also using the original video evidence.

Seasonal variations at the site (between winter 2005 and winter 2006) were observed by the three ROV surveys to be relatively small in relation to the typical height and volume of sediment accumulation. The observed seasonal variations were also small in comparison to the larger sediment volume changes observed over larger time scales, between autumn 1999 and winter 2005.

Upstream dredging activity and the associated creating of dredge plumes potentially increase the input rate of mobile material through settling of the advected plume or by changing the composition and thickness of the mobile bed upstream. The separation distance between the UC-65 site and the small number (12) of known dredging events is approximately between 2 and 5km. The literature describing dredge plume transport suggests that much of the material released during dredging would be unlikely to reach the UC-65. It may also be the case that mobile sediment introduced to the bed further upstream has not yet been transported as far as the UC-65 site.

The final (post dredging) ROV survey reveals no significant change in the quantities of sand accumulation around the site, implying no significant increase (or decrease) in the input rate of mobile sediment. Fluctuations in the height and implied volume of sediment accumulations on the updrift and downdrift sides of the wreck do not demonstrate any direct linkage, i.e. significant fluctuations in the volume/height of the accumulation on the western side of the north section are not necessarily mirrored by a similar polarity of change on the eastern side.

The conclusion is that whilst dredging activity and dredge plumes might provide some contribution to the UC-65 site dynamics at this early stage in the license area lifetime, the observed effects so far are insignificant compared to the observe natural variability, particularly on annual but also on seasonal time-scales. If repeated surveys are conducted in the not too distant future, any longer term impacts of upstream dredging may become more evident.
7.3 References - Chapter 7


7.4 The Third Field Study Site: The Eastern English Channel - Conclusions

A review of existing literature concerning oceanographic processes in the English Channel was undertaken. This was used to put into context, the more specific data collected at the third field study site in the central portion of the Eastern English Channel. The main findings of the study were as follows:

- Away from the shore, the English Channel is a tidally dominated environment.
- The amplitude and phase of the tidal signal varies spatially across the English Channel. The Eastern part is characterised as a standing wave (slack tide at high water) whilst the Western part is better represented as a progressive wave (slack water at mid tidal range).
- The largest tidal flow velocities are found along an axis between the Isle of Wight in Britain and the Cotentin Peninsula in France, decreasing gradually with distance along the axis of the Channel but increasing again in the East through the constriction of the Dover Straits.
- The resulting large scale patterns of residual sediment transport direction cause finer sediment (sands) to be removed in a net sense from areas of high energy and deposited in lower energy areas. Maps of seabed sediment distribution and directions of sediment transport pathways are available, based upon observations of seabed type and the interpretation of any bedforms found. Numerical modelling studies have produced more detailed results that are in broad agreement with the observed patterns.
- The direction of net sediment transport in water deeper than 14-16m is typically orientated to the tidal axis which in turn is typically parallel to the adjacent shorelines.
- Patterns of tidal flow and sediment transport in shallow, enclosed or constricted areas are more complex and in the case of shallow water (<14-16m) are more likely to be influenced significantly by wave action.

A unique opportunity was presented to the project, to study an established wreck site both before and after the commencement of dredging operations in a new license area. The shipwreck was a World War One German U-Boat, designation UC-65, located in approximately 40m of water, within a new license area, in the central part of the Eastern English Channel. The project collected underwater video footage of the site on three occasions, two of which were prior to the start of test dredging. Additional historical footage of the wreck (from 1999) was also obtained and used in the comparison.
The footage was interpreted for the location and relative height of sediment accumulation or scour features, measured at or against distinctive structures on the wreck. The relative seabed type (some degree of sandy, gravelly or mixed) was also assessed and maps of the site layout and distribution of sediment and bed features are presented in the main report.

All of the recorded seabed features demonstrated temporal variation under natural conditions (the first three data sets). Variation was most evident in the height (equivalent to the volume) of sandy accumulations. Further variation was observed in the final data set (collected following the start of dredging activity) but within the range of observed natural variability. The cause or causes of natural variability was not indicated by the data available, but on the basis of the literature review variability might be controlled by tidal cyclicity at spring-neap, solstice-equinox or annual (sub Metonic) time scales.

The present study has provided a detailed report of the baseline condition of the wreck and its natural variability. It is recommended that further monitoring work be undertaken after more extensive dredging around and near to the wreck. This will give a better indication of the long term effects of dredging.
Chapter 8. Recommendations for Exclusion Zones

This Chapter provides new guidelines for the design of exclusion zones to protect sites within, adjacent to or potentially at distal localities from aggregate dredging sites, deemed to be of significant potential or actual archaeological importance (satisfying Objective 19). The recommendations are compared to existing best practice in the UK and to similar recommendations made by an American study. Satisfying Objectives 20 and 21 and thus completing Phase 4, the recommendations presented here follow consultation with industry partners (Hanson Aggregates Marine Limited) and heritage partners (English Heritage and Wessex Archaeology). The project is continuing to disseminate this document to interested parties and is in discussion with English Heritage about the formal publication of the guidelines contained herein.

The recommendations and guidelines developed herein utilise extensively the broad range of laboratory data collected as part of this project relating to wreck-tidal flow-seabed interaction, these in turn were qualified and augmented by the field observations and supported by the literature reviews and conceptual studies.
8.1 **Guidelines for the Construction of Exclusion Zones around Submerged Archaeological Sites.**

8.1.1 **Introduction**

Once identified, sites considered by the relevant Heritage Organizations to be of significant actual or potential archaeological importance need to be protected from any further unnecessary damage or dispersion. It has not been in the remit of this project to define which archaeological sites merit an exclusion zone being applied merely how you would construct one where necessary. This is in order to maximize the quantity and quality of information that can be obtained from such sites by present and future generations. It has been identified in the literature reviews of the present study that degradation of underwater heritage material may be caused directly through numerous, naturally occurring physical, biological and chemical processes. These vary in rate and severity depending upon the particular environment of the site but are, in all cases, generally reduced by increasing the depth of burial. Vulnerable material that is buried in sediment (particularly in anoxic sediment) is better protected from the majority of agents of degradation. Potential or actual threats to archaeological sites by anthropological activity therefore include indirect actions which might change the thickness and/or nature of the sediment cover, in addition to activities that interfere directly with a site.

There are four perceived threats posed by aggregate dredging activities on nearby artefact based sites. In approximate order of increasing length scale (distance between dredging and the site) these are:

1. Direct interaction with the dredge head.
2. Changes in seabed site dynamics in response to upstream modification of the flow regime and sediment input rate caused by dredging.
3. Impacts of the dredge plume on wreck site formation.
4. Changes in site dynamics of inter-tidal and sub-tidal archaeology of localities adjacent to the dredging area (including the coastal zone).

The risk posed by the more direct threats (1-3) is increased when dredging operations occur ‘too close’ to the site. To increase separation between the two locations and therefore reduce risk, an exclusion zone is drawn, within which dredging operations are prevented. In practice, the need to protect heritage and the extent of an exclusion zone must also be balanced to some extent by the loss of available aggregate resource, imposed by the zone. Exclusion zones reducing threat (1) are of particular importance to the dredging industry as debris can also cause damage to dredging plant, contaminate the sediment load or compromise the integrity and safety of any ground tackle used for anchoring.
The relative risk and potential for mitigation through exclusion zones are considered in the following Sections for all of the perceived threats. The threat posed by direct interaction with the dredge head (threat 1) has been considered in more detail in Section 2.1. The threat posed by upstream modification of the hydro- or sediment-dynamic regime (threat 2) is examined in more detail in the Sections below. Certain aspects of dredge plume character and propagation (threat 3) are described in more detail in Section 6.1. The potential for damaging onshore-offshore linkage (threat 4) has also been considered in more detail in Section 2.2.

8.1.2 Previous approaches to the problem

Two existing examples of guidance documents for the design of exclusion zones were found and are described in more detail below. The approach of Wessex Archaeology (2003) is more qualitative and relies upon the opinion of an experienced appraiser. The approach of Michel (2004) is more quantitative but requires detailed information regarding each site and is relatively conservative. Both methods are subjective in terms of identifying the extent of the cultural resource and both methods permit flexibility in the final shape or size of the zone if special circumstances are identified by the appraiser.

8.1.2.1 Current best practice in the UK: The approach of Wessex Archaeology (2003)

The current best practice for the design of exclusion zones in the UK is outlined in the guidance note by Wessex Archaeology (2003). Wessex Archaeology currently provides identification, analysis and interpretation of archaeological sites in practically all dredging licenses in the UK. In the guidance note, they describe that dredging exclusion zones can be implemented to protect either discrete sites or more extensive areas. As exclusion zones preclude extraction of the resource within their area, specific evaluation may be warranted to confirm the presence, location and extent of archaeological and/or palaeo-environmental material. They also broadly suggest that each zone should be designed on the basis of the available geology, hydrology and sediment transport data to ensure the continued stability of the site throughout the license period. However, they do not provide published details of the methods by which this should be achieved.

In the regions studied as part of the present project (i.e. offshore gravel extraction sites in the UK), exclusion zones are described by a circular area, typically of radius 50-200m, centred upon and encompassing the site of interest, (Hanson Aggregates Marine, pers. comm.). These exclusion zone ranges are shown in Figure 234 in relation to the *Unknown Wreck* field study site.
The actual radius of individual exclusion zones is presently decided by experienced archaeologists, such as those at Wessex Archaeology, on a case by case basis. The zone is intended to: encompass the observed distribution of artefacts visible in geophysical data; provide additional distance to take account of uncertainty; to provide a safety buffer; and, to provide a rounded, practical figure. The dredging firms may also draw their own exclusion zones or extend those suggested by others if any other isolated debris (not necessarily of any archaeological importance) is identified that may cause damage to the dredge head or plant in the event of accidental contact.

8.1.2.2 The approach of Michel (2004)

An alternative, more quantitative method for the construction of exclusion zones was suggested by Michel (2004) in a consultation paper for the United States Department of the Interior. Its basis is formed by the principle that exclusion zone design should prevent any disturbance of the seabed within the area recognized as containing artefacts. Additional buffer distances relating to uncertainty and to the physical impact of dredging are considered separately and then summed to yield a total exclusion zone dimension.

As shown in Figure 235, the extent of the buffer zone outside the area known to contain artefacts should account for:

1. uncertainty in the actual extent of the resource location.
2. uncertainty in the actual location of the dredge head.
3. the gradient of the sediment slope that will develop between the conservation site and the final depth of the borrow area.
Michel suggests that there is an argument that all of the additional buffers should be applied; however, this might lead to an overly conservative estimate. Additional conservatism is introduced during the calculation of slope extent and migration as the transfer of material into the dredged zone during slope collapse (hence moving the origin of the slope) is not considered. To moderate the model, two sub-models are suggested, firstly by combining [(1) + (2)] and secondly by combining [(1) + (3)]. The user calculates the result of each pair and is advised to choose the greatest (most conservative) value. The example scenario given by Michel (2004) is shown in Figure 236.

When building this model, the user must acquire certain knowledge about each site being considered. This information includes the extent of the cultural resource, the stable slope angle of the sediment base and estimates of uncertainty or accuracy for all values, including navigational accuracy of the dredge head and vessel. Most values must be estimated using the best information available. The model is most sensitive to the chosen slope angle; in the absence of other information, Michel recommended a slope angle of 1:100 (0.57\(^\circ\)). This value was chosen as it is generally representative of slopes observed on naturally occurring open, flat seabed away from the coast.
Designers of exclusion zones are also advised of the potential threat caused by the development of “pedestals”, elevated islands of mobile sediment left within the exclusion zone which contain the buried resource at a height greater than the surrounding dredged surface. The threat is that pedestals may be eroded over longer time scales, eventually exposing the site. To avoid this, dredging activities (delineated by the exclusion zone) should not fully encompass the site but rather leave one side un-dredged, preferably the side from which mobile sediment is approaching, such that subsequent migration of the dredge slope is directed away from the site.

Examples of exclusion zones constructed using the recommendations of Michel (2004) are shown in Figure 237 for the Unknown Wreck study site on the Hastings Shingle Bank. An example resource uncertainty buffer of 50m and a dredge buffer of 50m (estimated using the recommendations of Michel, 2004 for the dredging vessels typically used) were applied. A slope angle of 1:50 was specified for illustration purposes. Including the resource itself, this produces a circular exclusion zone of approximately 385m radius. The maximum depth of extraction was assumed to be 5m (a value suggested as realistic by Hanson Aggregates Marine, pers. comm.), therefore, the maximum licensed depth of 10m would require an exclusion zone of nearly double the diameter. The recommended slope angle of 1:100 produces an exclusion zone of nearly double the (1:50) diameter. The suggested design to avoid pedestal development is also shown.
Figure 237. Exclusion zones designed using the recommendations of Michel (2004): (a) standard design, total radius approximately 385m for 5m extraction depth; (b) pedestal avoidance design. See text for more details. Swath image courtesy of Wessex Archaeology.

8.1.3 Addressing the threats posed by aggregate dredging through exclusion zones.

Each of the potential threats to wreck sites identified earlier in this Section are considered in more detail below. Variables important in the method of Michel (2004), such as the dredging buffer and slope angle, are also reviewed.

8.1.3.1 Threat 1 - Direct interaction with the dredge head.

In this case, significant threat is only posed by the occurrence of direct contact between the dredge head and the site, or any dispersed artefacts; hence, the basic definition of an exclusion zone addresses directly the first perceived threat. To be effective in separating any heritage material and the dredge head itself, the exclusion zone must simply encompass the extent of the resource with further allowance for uncertainty in the true extent of the resource, similar to the first sub-model of Michel (2004). The example shown in Figure 238 uses a circular outline of the resource/obstacle and a nominal 50m uncertainty buffer. If it is thought that smaller mobile pieces of wreckage may have been dispersed locally from a site of finite but not significant value, then the uncertainty buffer should take the form of the inner-dynamic buffer, described in Section 8.1.3.2 and Figure 239.

It is the statutory responsibility of the company, and by proxy the vessel Captain, to ensure that the boundaries of the dredging area and any exclusion zones are observed under the terms of the license agreement. The company must therefore provide suitable onboard technology to determine the relative location of the dredge head and any license boundaries, including exclusion zones. It is then the responsibility of the Captain to use that information, together with his experience and judgment, to avoid dredging within any exclusion zones. Therefore, no explicit allowances are made here for potential inaccuracy or error in the dredging process.
8.1.3.2 Threat 2 - Changes in seabed site dynamics in response to upstream modification of the flow regime and sediment input rate caused by dredging.

Seabed site dynamics may potentially be altered by upstream marine aggregate dredging. By lowering and roughening the surrounding seabed whilst also modifying the relative proportions of sand and gravel at the seabed surface, dredging can potentially either increase or decrease sediment mobility and may affect both local and regional sediment budgets. These changes may interact with nearby wreck sites over short (semi diurnal to spring neap) and longer (seasonal to decadal) time scales, potentially resulting in changes to the local equilibrium bathymetry. The following discussion considers the potential effects of dredging on: the tidal flow; the surrounding bathymetry; sediment availability and their combined effect on sediment mobility.

The potential effects have been found by the present study to be most important when they affect regions of sediment accumulation, rather than scour, as they are relatively more transient and sensitive to changes in sediment input/output through the site. It is reported in the literature (e.g. Sumer and Fredsoe, 2002; Whitehouse, 1998) that most regions of scour around two-dimensional objects (e.g. bridge supports and pipelines) are developed quickly, reaching an equilibrium depth and position within time scales in the order of hours or tidal cycles. Saunders (2006) also suggests that scour around three-dimensional objects (e.g. shipwrecks) can occur quickly (tens of days to a few years) relative to the age of the object. Scour may change in position or equilibrium depth as the wreck shape also changes due to damage or deterioration over longer time periods.

Values are suggested below for the width of modular buffer regions, similar to the approach of Michel et al. (2004); these are typically calculated from other parameters relating to the wreck. ‘Conservative’ values have been suggested wherever appropriate. In the case of the relatively smaller distances (e.g. associated with the...
inner dynamic buffer), the absolute values are considered to be accurate but the chosen conservative approach is to double the figure. In the case of larger distances (e.g. associated with the slope buffer), the chosen conservative approach is to use the greater suitable value within the range identified (of slope gradients, in this example). Since the completion of this project we have done additional work to support the use of a double/treble factor to produce the inner buffer and these will be presented as part of the Guidance notes to be produced in January 2008.

8.1.3.2.1 The spatial extent of the wreck site as a dynamic sedimentological system

By identifying and protecting areas actively involved in the sediment budget of sediment accumulations around the wreck, accumulations can be maintained and the sedimentary system stabilized.

In a natural environment unaffected by dredging, the patterns of scour and accumulation around a wreck can vary depending upon: (1) the level of the mean ambient bed level relative to the top of the wreck; and (2) the rate of mobile sediment input.

If the mean ambient bed level is, or increases to, a level above the height of the wreck, then over time the wreck will become entirely buried by sediment and will be unaffected by changes in seabed mobility (so long as the mean bed level is not affected). If the mean bed level decreases so that the wreck is partially exposed then the patterns of sediment erosion and accretion described in Section 3.4 will develop to a depth/height and volume controlled by the rate of sediment input. An optimum rate of sediment input will create accumulation features of full equilibrium extent and height. An above optimal rate of input will not increase the volume of the accumulation further; a below optimal rate will result in an accumulation of lesser equilibrium height and volume. The maximum height of accumulation adjacent to the wreck is a function of the stable slope angle for the accumulated sediment and the degree of turbulence shed by the wreck. The extent and location of scour features remain similar irrespective of sediment input rates, however, as discussed in Section 3.2 the maximum scour depth may vary. In particular, scour depth is greatest at ambient flow conditions corresponding to the threshold for motion for the sediment substrate. Coarser sediments and more poorly sorted sediments may act to reduce or limit the maximum scour depth. Large mobile bedforms may also cause the scour pit depth and form to vary over time.

If the mean bed level decreases to a level below the original level of the wreck, the response depends upon the sediment substrate. In sandy sediments, the wreck could be undercut and the wreck site base will be lowered; patterns of scour will persist and the volume and height of accumulation will be dependent upon the rate of sediment input. In gravelly sediments, the gravel presents a strongly erosion resistant surface and is the base layer to which local accumulations may erode; scour occurs where sand is winnowed from between the gravel and scour depths are somewhat reduced by the armouring effect of the gravel.

Three characteristic sub-regions of a wreck site are considered below, namely: downdrift; updrift; and laterally offset locations. Their extent and sensitivity to dredging are considered separately. In all cases, negative impacts relate to the removal of sediment or reducing the availability of mobile sediment. However, if dredging
works increase the amount of mobile sediment in the environment, there may also be beneficial ‘impacts’ to sites previously receiving less than optimal sediment supply, e.g. the volume of sediment accumulation may be increased and (less likely) the depth of scour regions might be decreased slightly.

**Downdrift locations**

This section considers the down drift side of the wreck, relative to the ambient sediment transport direction in the case of asymmetric transport, or on both sides in the case of more symmetrical ambient transport. The likely location of accumulation regions around a wreck was described in Section 3.4; this region can potentially extend up to 5-8 times the height of the wreck, depending upon the angle of attack and the width to height ratio of the wreck. For example, the *Unknown Wreck* study site on the Hastings Shingle Bank produces a full step height of 4-4.5m; the estimated extent of the downstream accumulation region is 32-36m, compared to an actual value of 35m.

If dredging causes disturbance of the seabed inside the described area, regions of sediment accumulation may become reduced. Sediment continues to accumulate in the area, however, this may occur at the expense of maintaining the existing volume or height of accumulation to the detriment of the wreck. If regions of local scour within a similar distance of the wreck become disturbed then the transport patterns supplying sediment to regions of accumulation may be interrupted. A conservative buffer distance to apply to this side of the wreck would therefore be in the region of 10-16H.

This same distance can be considered also to represent the distance within which there is an increased likelihood of finding artefacts broken from the wreck and subsequently transported. Mobile loose material would be transported following the same transport patterns as sediment in the near wake region. Artefacts with low transport potential (large mass and angular) might not be transported at all from the wreck whilst artefacts with very high transport potential (low mass and easily rolled) might continue to be transported by the ambient flow to large distances from the wreck site, becoming disperse and effectively lost from the wreck site. However, artefacts of intermediate mobility might be transportable in the more erosive environment of the scour pit but may then become immobile and deposited in regions of accumulation or at the inner wake/ambient flow boundary.

The results of the present study suggest that dredging at distances further than the extent of the local scour pit (i.e. beyond 5-8H, possibly in a distal scour pit or on unaffected bed), will not affect significantly the scour or accumulation around the wreck itself as the transport pathways effectively separate the two regions. Wrecks associated with symmetrical scour features may experience some linkage between more distal scour areas and those adjacent to the wreck and therefore a more conservative buffer distance is appropriate.

**Updrift regions**

This section considers the up drift side of the wreck relative to the ambient sediment transport direction in the case of asymmetric transport. An accumulation of sediment may develop naturally on this side as a result of the obstruction posed by the wreck to ambient net sediment transport. If this accumulation is disturbed directly by
dredging or starved of sediment supply by dredging further upstream, it may decrease in volume and height, exposing parts of the wreck. A secondary consequence may be that sediment transfer to the down drift side is reduced, also reducing the volume and height of regions of accumulation there. The extent of upstream accumulations can vary depending upon their volume but can be estimated: (a) directly from swath bathymetry data; or (b) by assuming that the accumulation extends to the top of the wreck (located distance $H_u$ above the ambient bed) and is composed mostly of sand with an estimated stable slope angle of $2^\circ$, i.e. extent = $H_u$/tan($2^\circ$). For example, the Unknown Wreck study site on the Hastings Shingle Bank sits 2m proud of the ambient bed level, therefore, extent = $2$/tan($2^\circ$) = 57m; for comparison, from swath data the accumulation extends approximately 50m. In environments with only limited mobile sediment (e.g. the Ariel or UC-65 study sites in the present study), accumulations will typically be more localised and will not extend to the top of the wreck at all, hence estimates using the slope method will be relatively conservative.

**Laterally offset regions**

This section considers the seabed to the sides of the wreck, perpendicular to the tidal axis. Laboratory measurements of flow patterns (Section 3.3) indicate that the wreck may interact with the seabed up to 1-2H from the lateral margins of the wreck, perpendicular to the flow axis. Because sediment transport in deep water is constrained to directions close to the tidal axis, seabed in more distant areas across the tide are effectively isolated from the wreck site. A conservative buffer distance to apply to this side of the wreck would therefore be in the region of 4H. In constructing exclusion zones, the identified inner region should remain undisturbed, making allowance for the development of stable slopes from the maximum dredge depth to the height of the existing mean bed level.

**The inner dynamic buffer**

All of the above considerations and recommendations are summarised in the example shown in Figure 239. In combination, the individually recommended distances produce an outline which can be completed as either a smooth ellipse or straight sided polygon. This outline represents the predicted outer limit of physical interaction between the site and the surrounding bathymetry. Disturbing significantly the sediments inside this boundary is predicted to alter the volume and height of regions of sediment accumulation, exposing the wreck.
8.1.3.2.2 Effect on flow character

Seabed lowering occurs in a gross sense across the license area as a direct consequence of aggregate extraction. The resulting increase in mean water depth over the region is in the order of 5-10 meters which may correspond to a significant proportion of the total depth. In the planning stages for license application, it is necessary to demonstrate through numerical modelling that such bed lowering does not affect tidal currents or wave action by more than 5% of normal values (see the guidelines provided in CIRIA, 1998 and an example for the Hastings Shingle Bank license in EMU, 2005). Small changes such as these will be less than the variability observed during regularly occurring spring-neap or longer-term tidal cycles and are therefore unlikely to impact significantly upon an affected wreck site. For example, tidal velocity ranges at the Hastings Shingle Bank and Owers Bank study sites vary naturally between 0.3 and 0.9ms⁻¹ (±50% from the mean value).

Bed lowering also occurs on the scale of individual dredging lanes and the many overlapping dredge furrows, resulting in a complex, roughened seabed. The furrows cause an increase in bed roughness that leads to an increase in ambient turbulence near to the bed. In the UK, dredging lanes and therefore the seabed furrows are typically aligned approximately to the tidal axis, except at turning points at the end of individual dredging lanes (Hanson Aggregates Marine Ltd, pers. comm.). Numerical studies by CEFAS (2006) indicate that locally elevated turbulence may be present in the order of several meters above the bed even when the angle of attack is small (10°) between the flow and the furrow; turbulence is increased most of all at the crests of the furrows. Dredge lanes are designed to be tidally aligned but individual dredge tracks are inevitably subparallel to this and also experience relative changes in angle of attack due to the progression of the tides (a 20° range at the two field study sites). An example of this is shown in Figure 240.

Figure 239. The inner dynamic region of the Unknown Wreck study site. See text for more details. Swath image courtesy of Wessex Archaeology.
Because the flow patterning controlling morphology around shipwrecks is Reynolds number independent (Sections 3.1, 3.3 and 3.4), an increase in the mean flow velocity or level of ambient turbulence will not change the shape, extent or character of the flow field produced around the wreck, therefore it will also not affect significantly the location or extent of the predicted regions of erosion or accumulation.

8.1.3.2.3 Effect on sediment character and mobility

The character of the seabed sediment is also potentially affected by on site screening of chosen sediment fractions which are returned to the seabed surface via dredge plumes. Typically it is finer sands that are screened, thus increasing the proportion of relatively mobile sediment at the seabed surface. However, such sediment may also become trapped or relatively less mobile in the furrows left by the dredging. Hence, the net result on sediment transport across and beyond the license area is a complex one; we suggest that this must therefore be estimated on a case by case basis by appropriately experienced persons.

If reduced sediment mobility and input to a particular site is predicted, then it is likely that the volume and height of sediment accumulation will decrease, exposing the wreck further. Unchanging or increased sediment mobility is not considered to be a threat; indeed the latter may be considered a positive outcome, potentially increasing sediment accumulation around the site.

8.1.3.2.4 Stable slope angles

In the model of Michel (2004), slope angle is possibly the most difficult parameter to estimate, yet as shown in Figure 236 it has the most significant effect on the final value. Naturally occurring slope angles are correctly identified as a complex function
of the regional bathymetry, geology and the sediment-dynamic environment. In the absence of other information, a slope of 1/100 ($0.6^\circ$) is recommended by Michel (2004). This value seems to be based upon the typical gradient of open sandy seabed in deep water (>20m), however, no additional information is provided.

The suggested gradient for mean bed level is indeed typical of open areas of naturally developed sandy seabed. Such a shallow gradient is formed as there are normally very few hard upstanding obstacles on the seabed and few naturally occurring mechanisms to set up steeper slopes. However, the presence of a shipwreck as a discrete obstacle and the action of marine aggregate dredging produces a situation which may (naturally) support steeper slope angles locally.

The suggested slope value should be modified substantially by the presence of gravel which increases the stability of the seabed, supporting greater slope angles. In comparison to slopes observed at the Hastings Shingle Bank, the suggested value is representative of typical gradients in open sandy seabed areas, but is small in relation to naturally present flow transverse slopes in regions of sandy gravel ($3-4^\circ$) or large sandwave stoss-side slope angles (1-2$^\circ$).

Slopes created artificially by marine aggregate dredging activities are created under more energetic circumstances and are therefore (initially) much steeper. Trailer suction hopper dredging produces long furrows in the seabed approximately 30cm deep with steep sides and small ‘levees’ (e.g. Boyd et al., 2004) whilst static dredging produces large pits up to 20m deep and 75m wide (e.g. SANDPIT, 2005). In both cases, slopes are initially created at the angle of repose for the sediment (28-35$^\circ$ depending upon the particular mixture of sand and gravel). As the gravel fraction of the sediment is immobile in deeper water in all but the strongest storm events, these slope angles can be maintained for many years and long term residual slope angles are relatively large (e.g. Newell et al. 1998; Andrews Survey, 2004; or Boyd, 2004 and the references therein). It is reported that in such regions, furrows and pits are gradually smoothened over long time periods by infilling with finer mobile sediment and small scale slumping of gravel, but not by slope migration. N.B. since the completion of this work we have undertaken further studies into the calculation of natural slope angles within dredge license areas based on swath data acquired as part of a standard EIA. The results from this minor study will be included in the Guidance notes document to be prepared between September 2007 and January 2008.

Slope angles produced by dredging activity that might remain stable may therefore be greater than that suggested by Michel et al. (2004). Extreme naturally occurring slope gradients on the Hastings Shingle Bank are $5^\circ$ in sandy gravels, and $2^\circ$ in dominantly sandy sediments. These are considered to be reasonable (and conservative) estimates of stable slope angles produced by marine aggregate dredging activity at a variety of length scales (dredge furrow, dredge lane and license area scales). The implied extent of such slopes is shown in Figure 241 for the case of the Unknown Wreck, assuming a maximum dredging depth of 5m.
The maximum depth of aggregate extraction from the original seabed level (which is needed as well as the slope angle in the calculation of a slope buffer) varies depending upon the deposit. Gravel deposits such as the Hastings Shingle Bank are typically thick and focused into smaller regions, hence this license permits extraction of up to 10m sediment thickness although it is not expected that the full depth will be utilised in the lifetime of the license (Hanson Aggregates Marine, pers. comm.). Sand deposits such as those found on the east coast of UK are thinner and more disperse, hence these licenses permit a smaller extraction depth (e.g. 2m, Hanson Aggregates Marine, pers. comm.). Older sediment deposits may become dewatered and compacted, increasing their stability beyond simple calculated values for loose elasic material of similar grain size distribution. Stable slope angles other than the suggested values may be inferred from naturally present bathymetry, observed either prior to the start of dredging or in areas of demonstrably similar geology that has experienced dredging a significant time in the past. As described earlier we have since developed a method to extract the best slope estimates for an area based on acquired swath bathymetry.

A sufficiently steep gravel stabilised slope angle leading up to a wreck might conceivably reduce the mobility of sediment transported from a lower bed level (e.g. the maximum extraction depth) to the unaffected (therefore relatively higher) seabed remaining around the wreck. The threat posed by reducing sediment supply in this manner is however difficult to quantify and would need to be estimated on a case-by-case basis through numerical modelling or desktop analysis.
Section 8.1 – Guidelines for the Construction of Exclusion Zones around Submerged Archaeological Sites

8.1.3.2.5 Natural changes in bed level

License areas in regions of highly mobile sand may experience (naturally occurring) regional scale bed erosion or accretion in the order of meters. The concept of a stable bed slope is difficult to resolve in this case and local exclusion zones in such areas can only directly address threats posed by direct interaction with the dredge head. Such large scale sediment mobility implies that dredging will not significantly (artificially) affect the input rate of sediment to the wreck site during active phases of bed lowering or accretion. Instead, the license application should demonstrate if possible that dredging activity will not cause: (a) bed lowering in excess of that occurring naturally; and (b) a long-term reduction in the mean bed level.

8.1.3.3 Threat 3 - Impacts of the dredge plume on wreck site formation.

Dredge plumes and their effect on the seabed are reviewed in Section 6.1. Although described as a threat, the act of additional sediment accumulation or burial of a wreck is generally considered to enhance rather than reduce the potential for preservation of material and site stability. However, a number of potential threats are posed, for example:

1. An increase in advected sediment in suspension might increase abrasion of soft exposed material.
2. The advection of elevated turbidity over a site might modify (probably only slightly and temporarily) the rate or character of electrolytic interaction between the water and corroducible materials.
3. A long term increase in ambient turbidity might encourage alternative organisms (e.g. filter feeders) to colonise the wreck, leading to different or possibly increased damage through biological action.

Examples of situations where these potential threats have been realized were not found in the literature. This may be because the potential threats are in fact not realized or because the effects are not significant or measurable in an actual or relative sense and therefore do not warrant detailed investigation. Accepting the possibility of effect, positive or negative, dredge plumes may impact relatively extensive areas, usually elongate and elliptical in shape, orientated to the dominant tidal axis. The concentration of suspended material or the thickness of material deposited at the bed by the plume is a function of distance from the source and any deposited material may be subsequently transported by natural processes. The nature and risk of effect posed by dredge plumes is therefore highly variable and prediction of net impact over long time periods is correspondingly difficult. The large area of the effect makes local exclusion zones an unsuitable method for mitigation of this particular threat.

8.1.3.4 Threat 4 - Changes in site dynamics of inter-tidal and sub-tidal archaeology of localities adjacent to the dredging area (including the coastal zone).

It was demonstrated in Section 2.2 that offshore aggregate extraction activities in water depths greater than 15m have very little potential to interact directly with the adjacent coastline. The propagation of any effects from dredging activity is mostly constrained to directions close to the tidal axis (typically parallel to the coastline).
Therefore, local exclusion zones around sites that are in locations significantly across the tidal axis from the license area are of limited or no practical use.

Dredging activity closer to the shoreline or in water shallower than 15m has greater potential to modify tidal and wave action and sediment transport in locations across the tidal axis or in the littoral zone (SANDPIT, 2005). This may result in beach drawdown which in turn may expose any buried archaeology present in adjacent inter- or sub-tidal locations. Such draw down affects most strongly the beach located directly onshore from the dredging. Any effect will likely then be propagated along shore in a direction and at a rate determined by the asymmetry, direction and rate of alongshore sediment transport. Using this basic model (Figure 242), sites located updrift of the dredge pit should be at less risk than those located directly onshore from or down drift of the extraction point. It should be noted that directions of net sediment transport do not represent the only direction of significant sediment transport over seasonal or annual timescales. The extent and shape of exclusion zones to protect such sites would be relatively large and complicated and would need to be calculated on a case by case basis using techniques and information described in SANDPIT (2005) and the references described therein.

![Figure 242. Schematic diagram of the potential impact of shallow water (static pit) dredging (in <15m depth) on the nearby coast and the relative risk posed to nearby inter- or subtidal archaeological sites.](image)

8.1.4 Conclusions

A local exclusion zone should encompass and protect all dynamic or sensitive regions of an archaeological site; it should also take into account any uncertainty involved. The total area therefore consists of two concentric ellipses - (1) the identifiable resource and (2) an inner buffer which encompasses the area of seabed which must remain unaffected for site stability. As described in Section 8.1.3.1, it is the statutory responsibility of the company and vessel Captain to observe exclusion
zones and so explicit allowance for potential inaccuracies in the location of the vessel or dredge head are not included here. The method described below is designed to maintain any existing major accumulations of sediment around a large wreck structure and encompasses the regions identified as most likely to contain artefacts detached from the wreck and transported short distances.

1. The resource and its extent are identified by competent persons from adequate and suitable data.

2. The tidal axis is obtained, e.g. from the orientation of scour features, by observing tidal flows locally, from national hydrographic records, or from regional scale models developed specifically for the purpose (this latter issues is currently being worked on by the University of Southampton as part of ALSF round 3).

3. In the case of a wreck with strongly asymmetrical scour, the dynamic regions that need to remain undisturbed can conservatively be considered to extend (relative to the tidal axis) from the edges of the main upstanding obstruction of the wreck:

   **Downstream:** up to 16 times the maximum step height posed by the wreck.

   **Laterally:** up to 4 times the maximum step height posed by the wreck.

   **Upstream:** \(\frac{\text{the mean height of the main wreckage above the ambient bed}}{\tan(2^\circ)}\).

4. If the scour patterns are strongly asymmetric then the scour tail indicates the direction of sediment transport from the wreck. If the wreck is located near to the updrift margin of the dredge area then the upstream side of the exclusion zone should ideally be extended to the edge of the license (e.g. Figure 237a); the lateral and downstream values should still be used for the other three sides of the zone.

5. If the scour patterns exhibit strong symmetry then the larger of the upstream/downstream values should be used instead for both ends.

6. If the tidal axis remains unavailable then the larger of the upstream/downstream values should be used as a radial distance from an appropriate central point of the site to create a circular exclusion zone.

7. A suitable polygon or ellipse is drawn to encompass the identified dynamic inner region. This should also encompass fully the resource and its extent as identified in (1).

8. The dynamic inner region also provides the best estimate of artefact transport and deposition (resource uncertainty). If, on the basis of other evidence, the assessing archaeologist is not satisfied that the area encompasses all of the locally dispersed artefacts, then the area may be extended to do so. This extension should only be applied after all of the recommended buffers have been calculated and plotted as protection may already be given by other buffers.

9. The slope buffer is calculated as \(\frac{\text{the maximum depth of dredging below the original level}}{\tan(\phi)}\), where \(\phi\) is the stable slope angle determined for the site either as that of existing slopes upstream of the wreck or using suggested
values of $\phi=5^\circ$ for gravelly sediments or $\phi=2^\circ$ for very sandy sediments. The licensee may also provide evidence in the form of locally observed slope angles to support the use of other values.

10. The wreck dimensions, inner dynamic buffer and slope buffer are added to produce the total exclusion zone (Figure 243a).

In the absence of the more detailed information required above, the diameter of an appropriate circular exclusion zone may be drawn using the simplified table in Figure 244.

A similar method should be followed when designing exclusion zones for items or sites of no intrinsic value where it is important to avoid direct contact but sediment removal is not considered an issue. In this case, the resource should be identified with an uncertainty buffer (Figure 243b). No allowance need be given for the orientation of the tidal axis.

Local exclusion zones are not considered a suitable method for mitigation of potential threat posed to archaeological sites located significant distances (approximately >500m, outside the maximum exclusion zone radius predicted by the present study for large extraction depths in sandy sediments) from the site of marine aggregate dredging. Potential threats posed directly by the advection and settling of dredge plumes are not considered to be significant and can be offset to some degree by the additional protection provided by sediment deposited by the plume.

Potential threats to sites located in intertidal or subtidal regions adjacent to the dredging area include modification of the sediment budget, tidal currents and waves. However, numerous studies have excluded the possibility of offshore dredging (water depth >15m, typical of that in the UK) affecting the sediment budget further onshore. The potential threat to the coast posed by offshore sites modifying tidal currents and waves is significant but the probability is limited through the environmental assessment process which limits the maximum extraction depth if a threat is detected.

Figure 243. Schematic diagram of the recommended exclusion zone for: (a) buried or upstanding wreckage with archaeological significance requiring long term protection; (b) avoiding buried or upstanding objects of no particular value.
Figure 244. A conservative lookup table for the recommended diameter of a circular exclusion zone (centred upon the wreck site) in the absence of the required information for a more detailed analysis. Based on a wreck site height of 5m above the bed; inner dynamic radius = \( \frac{15H}{g} \) ; inner dynamic diameter = \( 2 \times 15 \times 5m \); slope buffers for both gravelly and sandy sediments are shown.

Of concern to the industry is the exclusion or ‘sterilisation’ of significant volumes of aggregate from within the license area which has a direct impact on the total value of the available resource. Example calculations of the area (related to the volume) of resource sterilised by the exclusion zones recommended by the present study and by the current best practice method of Wessex Archaeology are compared in Figure 245. The Figure shows that the area sterilised by the two methods is similar in when the total depth of extraction is not large compared to typical values (2-3m in sands and 5-6m in gravels).
Decisions regarding when to apply a full exclusion zone and when to apply a smaller avoidance buffer should be made on the basis of the relative (archaeological) value of the obstacle/resource. This topic has not been addressed in the present study and is recommended as a subject for further research.

The exclusion zone design presented here is intended for offshore dredging activity (in water depths >15m below the lowest astronomical tide) which includes all of the currently held aggregate mining licenses. Aggregate dredging for other reasons (beach navigational channel maintenance, beach recharge works) in shallower water has greater potential to interact with the coastline and separate studies are necessary to predict the impact of any such works. The location of archaeological sites within the projected area of effect should then be taken into account with a precautionary approach, locating dredging downdrift of any identified archaeological sites relative to the direction of alongshore sediment transport.
8.2 References - Chapter 8


8.3 **Recommendations for Exclusion Zones - Conclusions**

The Conclusions of this Chapter may be found in Section 8.1.4.
Chapter 9. Summary of Output and Dissemination

As required by Phase 5 of the proposal, the project has continuously sought to discuss and disseminate the results and output. This was successfully achieved through a diverse range of forums, including, this final report (and its intermediate stages), internal and external reports, preparation of peer reviewed journal articles, attendance and presentation at national and international conferences, meetings with interested parties and development of a project website. A full list of output is given in Section 9.1.

In addition to the introduction and conclusion sections at the beginning and end of each Chapter, a brief overview of potential uses for the results of this large and diverse study is given in Section 9.2.
9.1  **Dissemination and Co-operative Work Undertaken as Part of the Project.**

9.1.1  **Lectures/talks:**

9.1.1.1  **MALSF conferences:**
EH, London (org. EH). (JKD)
SOAS, London (org. DEFRA). (JKD)  06/07/06
NOCS, Southampton (org. CMS). (JKD)  8/09/06
Fishmongers Hall, London (org. CEFAS). (JKD)  3/07/07

9.1.1.2  **Other:**
Poets corner lecture series, NOCS. ‘Measuring Flow Modification Around Large 3D Objects in the Coastal Marine Environment.’ (DOL)  11/05
Proudman Oceanographic Laboratories, Liverpool (JKD) 11/05
Hanson Aggregates Marine, Ltd. (DOL+JKD) approx 05/06
  CCPEM lecture series, University of Southampton (DOL) – ‘Flow around wall mounted 3D obstacles.’ 6/06
UK Young Coastal Scientists' and Engineers' Conference 06, University of Southampton – ‘Modelling Exclusion Zones for Marine Aggregate Dredging.’ (DOL) 20/04/06
Hanson Aggregates Marine, Ltd. (JKD)  28/7/06 (short meeting @NOCS)
CEFAS – Internal lecture series (JKD) 9/06
Geology, Geochemistry and Geophysics seminar series – ‘Evaluating regional to small scale sediment transport observed in geophysical data.’ (DOL) 24/10/06
3rd International Conference on Scour and Erosion – ‘Flow patterning around submerged three-dimensional obstacles.’ Amsterdam, The Netherlands (DOL)  3-4/11/06
2nd meeting of EU funded project MACHU, Lisbon, Portugal (DOL) 13-14/2/07
Resource Management Association (RMA) CEMEX, Southampton (DOL+JKD) 6/9/07
9.1.2 Reports/publications:

9.1.2.1 Peer reviewed journal:


9.1.2.2 To industry/internal/other:


9.1.3 Data exchange

9.1.3.1 Industry:
Provision of tidal flow data to HR Wallingford at the request of Hanson Aggregates Marine Ltd for purposes of numerical model calibration and validation.

Provision of ROV footage to Hanson Aggregates Marine Ltd.

9.1.3.2 Academic/other:
Provision of Hastings Shingle Bank tidal data summary to fishermen and fishing groups at Hastings and Eastbourne.

Provision of tidal flow data sets to the Channel Coastal Observatory (Hastings Shingle Bank and Owers Bank sites).
9.1.4 Consultation with… / Outreach to…

9.1.4.1 Industry:
Extensive and ongoing consultation with Hanson Aggregates Marine Ltd, the wider Resource Management Association (RMA) and the East Channel Association (ECA) regarding choice of study site, data availability, previous reports, information regarding the UK dredging industry.

Consultation with Hanson Aggregates Marine Limited regarding the new guidelines for the design of exclusion zones.

9.1.4.2 Academic/other:
The project sought to inform all key stakeholders prior to monitoring works were conducted at the three field sites. Besides the dredging industry, this involved informing or consulting varied groups including: the public; local fishermen and fishing organisations; HM Coastguard agencies; the Environment Agency; English Heritage; English Nature; the Crown Estate.

Dissemination/discussion of results to interested parties including CEFAS, JNCC, and Wessex Archaeology.
9.2 **Using Output from the Modelling Exclusion Zones for Marine Aggregate Dredging Project.**

This study has undertaken fundamental theoretical, laboratory and field based work to enhance our understanding of the interaction between shipwrecks and the hydro- and sediment-dynamic environments within which they are located. In combination, the studies have enabled new recommendations to be made on how to assess and manage the direct and indirect impacts of aggregate dredging on marine archaeological sites. In particular, the results of Chapters 3, 4 and 5 allow heritage managers and the aggregate dredging industry to:

- Identify the direction and character of ambient (local/regional scale) net sediment transport.
- Identify the direction of sediment (and therefore artefact) transport in the vicinity of a wreck.
- Identify the upstream/downstream influence of an archaeological site (shipwreck) on the local hydro- and sediment-dynamic regimes.
- Identify areas around the wreck likely to experience localised net erosion or accretion relative to the surrounding bed level.

This information can be used in a tertiary sense by heritage managers to provide:

- Information crucial to site specific management plans including targeted structural stabilization works, protective burial or pre-emptive armouring, etc.
- Advice when planning site excavations.
- An interpretation of the local (and regional) scale patterns of sediment transport, important to all seabed users and stakeholders.

As a primary objective of the project, the above information was combined in Chapter 8 as a series of recommendations, showing heritage managers how to provide robust guidance for the establishment of Exclusion Zones to dredging around archaeological sites. The outcome of these studies are also valuable to the dredging industry as they provide a more transparent rationale for the need for and design of exclusion zones, whilst ensuring that the area of resource excluded from the license is minimised.

The approaches described here can also be applied to the interpretation of sub-bottom geophysical data using the principles of uniformitarianism. Buried discontinuities and variable density sediment horizons could potentially be used to reconstruct previous patterns of scour and accumulation in previous times when the wreck was exposed or indeed in an earlier state of degradation. Reconstructed patterns
could be used to infer the shape, size and height of the wreck at the point of burial, also the sedimentary and tidal environment to which the wreck was previously exposed. Anomalous density lenses or horizons away from the main wreck site might be identified (or excluded) as being likely deposition regions for artefacts, on the basis of their location relative to the wreck and the predicted patterns of sediment transport.

The results of Chapters 2, 6 and 7 also provide information and guidance for managers to assess and remEDIATE other threats potentially posed by marine aggregate dredging. These include: direct interaction with the dredge head; the creation of dredge plumes; and onshore or linkage to other distal regions of seabed.

During this study, particular emphasis was placed on wrecks that provide a reasonably coherent obstruction above the seabed and that are located in environments which are:

1. Tidally dominated.
2. Experiencing ‘clear water’ and low level ‘live bed’ scouring conditions.
3. Not experiencing significant variation in the surrounding mean seabed level (i.e. the migration of large sandbanks).

These conditions are thought to be generally applicable to most gravel rich and mixed sand-gravel dredging license areas on the south coast of the UK, i.e. such areas are in relatively deep water (i.e. >15m below LAT) and have a typically thin veneer of mobile sediment. Wrecks located in other marine environments may exhibit dynamic features that deviate somewhat from the reported patterns. Early experiments suggest that sand dominated seaboDS exhibit similar patterning in terms of scour and accumulation to those studied here but that the height (or depth) and implied volume of these features may be different from the study sites described herein.

Further research is required to better understand the effect of: strong wave action; consistent clear water scour or very low input rates of mobile sediment; strong live bed scour (e.g. strong tidal flows over sandy seaboDS); and large changes in local seabed level (e.g. through inundation or exposure of the site by massive and sudden mobilisation of sediment).