South Coast Dredging Association

MAREA: High-level Plume Study

Technical Note DDR4323-03

HR Wallingford

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Document Information

Project	South Coast Dredging Association
Technical subject	MAREA: High-level Plume Study
Client	South Coast Dredging Association (via Emu Ltd)
Client Representative	Ian Taylor (Dr Steven Freeman)
Project No.	DDR4323
Technical Note No.	DDR4323-03
Project Manager	Alan Brampton
Project Director	Richard Whitehouse

Document History

Date	Release	Prepared	Approved	Authorised	Notes
29/04/09	1.0	JS	AHB	MPD	Draft version
16/11/09	2.0	JS	MPD	TJC	Revised version following comments
09/03/10	3.0	JS	KAF	RJSW	Revised version following further comments

Prepared J Spearman

Approved K Fitzmaurice

Authorised R Whitehouse

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1. Introduction

1.1 BACKGROUND

A Marine Aggregates Regional Environmental Assessment (MAREA) is being undertaken for the South Coast Dredging Association (SCDA) to inform both new marine aggregate dredging licence applications and licence renewal applications off the south coast of England. The study region, shown in Figure 1, includes the coastlines of Dorset and Hampshire between Durlston Head and Hurst Castle; of the Isle of Wight from the Needles to Ryde, and of Hampshire and West Sussex east of Gilkicker Point. However, the tidal harbours of Poole, Christchurch, Portsmouth, Langstone, Chichester, Pagham and Shoreham have been excluded as has the inner part of the Solent.

An important part of the MAREA is to assess the effects of marine aggregate dredging on the physical environment of the study region. At present, such dredging is carried out in numerous areas both to the west and the east of the Isle of Wight (Figure 1) by the companies comprising SCDA (CEMEX UK Marine Ltd, Hanson Aggregates Marine Ltd, Kendall Brothers (Portsmouth Ltd), Northwood Fareham Ltd, United Marine Dredging Ltd, Volker Dredging Ltd and Westminster Gravels Ltd).

As part of the input to this Regional Environmental Assessment, SCDA (through Emu Ltd.) commissioned HR Wallingford to provide a high-level assessment of the footprint of potential impacts resulting from the dispersion of dredging plumes. This report provides a summary of the studies undertaken to define the footprints arising from dredging at each of the (existing and proposed) Licence Areas which form part of the Assessment.

This study considered both the footprints of dispersion of fine sediment plumes and the footprints relating to the longer term dispersion of sand released into the water column during the dredging process. In both cases, the footprints derived during the study were based on reference field studies from the literature. The results of the reference studies have been re-interpreted for the physical conditions of the individual sites but where there was uncertainty in this procedure an emphasis was placed on a conservative and precautionary assessment of the footprint at each site.

Figure 1 shows the Licence Areas considered in this study.

1.2 OBJECTIVES

The objectives of this study were as follows:

- To identify the footprints relating to the dispersion of fine sediment plumes arising from proposed dredging at each of the identified (existing and proposed) Licence Areas; and
- To identify the footprints relating to the dispersion of sand arising from proposed dredging at each of the identified (existing and proposed) Licence Areas.

1.3 SCOPE OF THE STUDY

This report represents a *high-level* assessment, designed to identify areas where impacts arising from proposed aggregate dredging could *potentially* occur and rule out areas where impact is unlikely to occur. This sort of study allows a better understanding of how potential impacts from the proposed dredging may be manifested at this early strategic stage without recourse to more detailed site-specific modelling. Moreover, this high-level study facilitates the targeting of detailed modelling to areas of possible concern allowing reduced emphasis in less sensitive areas.

It is important to note that the footprints identified in this study *do not* necessarily correspond to areas of significant physical impact. They merely highlight areas where impact may or may not occur; the MAREA will assess the significance of potential impacts within the identified footprints.

1.4 PRECAUTIONARY NATURE OF THE STUDY

This study is conservative in nature being based on the dredger (currently used in the South Coast MAREA study area) which has the potential to give the greatest impact and assuming that dredging will occur throughout the whole of each of the existing and proposed dredging Licence Areas.

In addition, the footprints of potential impact as a result of sand and fine sediment dispersion are based on:

- Peak concentrations likely to be experienced (which are typically experienced at any location for a few hours a day at most and only then during dredging of the relevant part of the Licence Area);
- An over-estimation of the distance over which the plume disperses. Most of the literature details excursion of plumes relative to the moving dredger location at the time of measurement, rather than the excursion from the position of the dredger when the plume measured was initially released. This causes the distance of movement of the plume to be over-estimated (since the dredger moves away from the measurement location while the plume is travelling). The methodology of this study overlooked this aspect for the sake of simplicity and precaution. However, as a result of this the footprints of the fine sediment highlighted will be an over-estimate (spatially) of the actual footprints.

1.5 CONTENTS OF THE REPORT

The remainder of this report consists of a further eight chapters.

Chapter	Contents
2	Description of the release of sediment during dredging operations
3	Summary from the literature of the results of field measurements of plumes released during dredging operations
4	Description of the methodology used to derive the footprints of plume dispersion for each of the identified Licence Areas and presentation of the footprints
5	Description of the flow model used to undertake the high-level studies
6	Summary from the literature of the results of field measurements of dispersion of fine sand released during dredging operations
7	Description of the methodology used to derive the footprints of fine sand dispersion for each of the identified Licence Areas and presentation of the footprints

2. Release of sediment into the water column during dredging operations

The process of loading the dredger entails pumping a mixture of solids and water from the seabed into the hopper of the dredger (which is usually partially full of water at the start of loading). The solids content in the pumped mixture is relatively low (approximately 25% by volume) and so the vessel fills quickly with water while loading. In order to allow the vessel to load a full cargo of sand and gravel without becoming overloaded, the excess water in the hopper is returned overboard through overflow spillways. The returned water also contains a proportion of suspended solids (typically fine sands and silt). Once returned to the sea, this sediment will be dispersed horizontally and vertically in the form of a plume by tidal flows and wave action and be advected by the tidal currents. The processes of advection and dispersion will continue until the sediment concentrations are reduced to close to background levels. The increase in suspended sediment concentrations and the enhanced deposition (if any) resulting from these fine sediment plumes could potentially have an impact on local ecology.

In addition to returns to the water column by the overflow spillways, most aggregate dredgers have the ability to modify the composition of sediment retained within the hopper by screening (passing the water/solids mixture over a metal mesh). Screening is undertaken in order to increase the proportion of gravel (or sand) in the hopper and results in a further return to the water column of a mix of sediment size fractions (including a small proportion of silt and fine sand), together with a quantity of water. The sediment water mixture released in this manner contains coarser material and usually has a greater density and velocity on entering the water surface than the overflow mixture. The greater momentum and negative buoyancy of the screening discharge, and its coarser sediment, mean that the screening plume will descend more rapidly to the bed. In the case of screening for gravel (undersize screening), there is usually a significant proportion of fine sand (and a smaller proportion of silt) additionally released. The coarse material (mostly various fractions of sand) settling onto the bed from the screening plume can potentially be transported away from the dredging area by tidal currents and waves, albeit more slowly than the fine material released into the water column. The dispersion of this sand can locally alter the nature of the bed sediment, making it finer and potentially altering the benthic communities where these changes occur.

In some circumstances screening is undertaken to remove coarser material (often referred to as ‘scalping’ or ‘reverse screening’), such as pebbles or gravel, from the load. In this case, the rejected material will fall almost immediately to the bed and will not, in normal conditions, be transported out of the dredging area.

3. Summary of the literature relating to the measurement of fine sediment plumes resulting from aggregate dredging

3.1 INTRODUCTION

This chapter briefly describes the measurements of fine sediment plumes resulting from aggregate dredging which form the basis for the approach taken in this study to identify fine sediment plume footprints. Only aggregate dredging studies are considered because the *in situ* sediment particle size distribution is a key factor in the nature of the resulting plumes and aggregate dredging occurs in areas with very specific sediment types.

3.2 OWERS BANK

The Owers Bank study (HR Wallingford, 1996) consisted of a field measurement campaign with the aims of understanding and quantifying the increase in sediment concentrations due to resuspension by dredging operations; and tracking the spread and dispersion of the plumes of re-suspended material.

Measurements were made from a 15m survey vessel during a period of neap tides (chosen so that plume concentrations would be greater) in August 1995. Suspended solids concentrations were measured within the overflow plume from three trailer suction hopper dredgers which were operating on the existing licensed site on the Owers Bank. The vessels were: the City of Rochester (United Marine Dredging Ltd, 1300m^3 capacity) undertaking screening for gravel; the Arco Severn (ARC, now Hanson Aggregates Marine Ltd, 1300m^3 capacity) undertaking 'all-in' loading; and the Geopotes XIV (Ham Dredging, now Van Oord, under contract to South Coast Shipping, now CEMEX UK Marine Ltd, 7500m^3 capacity). Note that the Geopotes XIV has a centrally mounted spillway and does not have a facility to screen material but is considerably larger than the other two dredgers.

The technique employed for plume visualisation was to use a vessel mounted broad band ADCP (Acoustic Doppler Current Profiler) to track the plume. This device was shown to be successful in tracing the plume over large distances. Water samples from the plume were taken and analysed to give suspended sediment concentrations. The field measurements showed that the suspended sediment concentrations within the plume reduced to background conditions over the distances identified in Table 1.

Measurement of the suspended solids for the Arco Severn and the City of Rochester showed that the plume decayed to background levels within 300-500m of the dredger. The same measurements indicated that the concentration increases caused by the plume had reduced to below 50mg/l within 130m, and to below 20mg/l within 200m, of the City of Rochester.

The Geopotes XIV plume travelled further because of the higher concentration of sediment present in the overflow from this dredger. In particular, concentrations of silt close to the dredger were an order of magnitude higher for the Geopotes XIV than the two other dredgers.

Table 1 Results of Owers Bank measurements

Dredger	Arco Severn	City of Rochester	Geopotes XIV
Distance from dredger over which plume was observed to fall to background levels	Less than 500m	300m[1]	Greater than 1000m (exact value not recorded)

3.3 HASTINGS SHINGLE BANK

Aggregate dredging has been undertaken at the Hastings Shingle Bank Licence Area since 1988. Since this time a variety of studies have been undertaken which investigated different aspects of the potential effects of dredging.

On 7th October and 18th November 1999 Cefas undertook measurements of suspended sediment concentrations in plumes generated by aggregate dredging (Cefas, 2001). The measurements were undertaken by towing a Cefas ESM2 logger behind a research vessel between 5m and 10m below the sea surface and by making transects of the plume at various distances from the dredgers. The dredgers monitored were: the Arco Adur (Hanson Aggregates Marine Ltd., 2400m^3 capacity) on 7th October; and the Sand Falcon (CEMEX UK Marine Ltd, the capacity in 1999 was 4000m^3 although this has since been increased to 5000m^3) on 18th November. On both occasions the cargo was an 'all-in' load and no screening occurred.

The measurements of the plumes from the Arco Adur were interpreted in HR Wallingford (2009a). This report indicated that the plume from the Arco Adur was diluted to background levels over a distance of around 1.5km from the dredger and around 600m from the point of release (which is different from the position of the dredger because during the time that the plume moves from the release point to the measurement point, the dredger has moved a considerable distance). The same measurements indicated that the concentration increases caused by the plume had reduced to below 50mg/l within 200m of the Arco Adur (around 80m from the point of release), and to below 20mg/l at a distance of 300m of the dredger (around 100m from the point of release).

This report did not consider the plumes from the Sand Falcon because the dispersion of dredging plumes in this case was obscured by the more complicated nature of the movement of this dredger. However it is noted here that the results presented in the Cefas (2001) report suggest that the distance over which the Sand Falcon plumes were diluted to background conditions was greater.

3.4 EASTERN ENGLISH CHANNEL

In 2008 HR Wallingford led a field measurement campaign on behalf of the East Channel Association (an association of aggregate dredging companies) to measure suspended sediment concentrations of plumes generated by aggregate dredging in the Eastern English Channel. The results of this study were not available at the time of writing but reports from the survey team (*pers.comm*. Jim Rodger and Mark Lee, Dredging Research, HR Wallingford, 2009) indicate that the plumes were followed typically for a hour, but up to an hour and a half, using ADCP, until the plumes were no longer traceable against the background concentrations. The maximum distance over which a plume was tracked was just under 6km and the dredgers investigated were Class A vessels (of around 2400m^3 capacity).

[1] Dredging while at anchor

3.5 RACE BANK

Over the period 1994-1997 Race Bank was the focus for a series of studies focussed on the potential for dredging plumes generated by aggregate dredging in Area 107, to affect an over-wintering ground for berried hen crabs, some 6.5km away (Cefas, 1998). The area is located offshore of Skegness, with a tidal excursion of 9-11km.

In May-June of 1995 a series of ADCP transects across the wake of a dredger were undertaken at increasing range. It was found that the sediment plume became indistinguishable from background concentrations at distances of more than 2500m during spring tide conditions and 1200m during neap tides.

3.6 DISCUSSION

The measurements of plumes from dredgers are summarised in Table 2 and show that plumes may travel several kilometres from a dredger, the longest distance reported being around 6km. Chapter 4 explains that for these reference cases, the water depth, current speed and overflow discharge are the main factors in the variation in the distances over which plumes have been observed to disperse. Screening was not found to be an important factor in the dispersion of the plume. Although the higher concentrations of material in the screening plume might be considered to increase the distance over which the plume would be detected; the density effect (negative buoyancy) generated by the greater volume of material tends to pull the plume down and cause it to settle more rapidly. The nature of the *in situ* sediment can also be important but aggregate dredging tends to occur in sandy/gravelly conditions where silt contents are no more than a few percent so the *in situ* fine sediment content does not tend to vary very much from one site to another.

Table 2 Summary of measured plume data in the literature

Site	Water depth [m]	Current speed [m/s]	Dredger pumping rate [m^3/s]	Plume excursion [km]
Owers Bank City of Rochester (Screening for gravel)	18	0.25	1.25[2]	0.3
Owers Bank Arco Severn (All-in load)	18	0.6	1.25[2]	0.55
Hastings Shingle Bank (All-in load)	25-30	0.5	1.7[3]	1.5
Eastern English Channel (Screening for gravel)	40-50	1.1	2.0[4]	6
Area 107/Race Bank	15-20	Up to 1.0	2.0[5]	2.5

[2] Pumping rate based on estimate for information from Hitchcock (1997).
[3] Pumping rate based on figures presented in Resource Management Association (2002)
[4] Pumping rate estimated based on (as yet) unpublished analysis of monitoring in the Eastern English Channel (*pers.comm.* Dr Tom Benson, HR Wallingford, 2009).
[5] The report (Cefas, 1998) suggests, on the basis of the information given about other measurements, that the capacity of the dredger which was being monitored would be in the range 2300-3500m^3 and therefore a pumping rate of 2m^3/s has been estimated.

3.7 MEASURED BACKGROUND CONCENTRATIONS IN THE AREA OF PROPOSED DREDGING

Suspended sediment concentrations in calm conditions in the English Channel west of the Isle of Wight were reported in Velgrakis *et al* (1999). These measurements relate to particles less than 63µm in size and do not take coarser particles into consideration, but suggest typical (calm, near bed) summer concentrations of a few mg/l rising to around 40mg/l in winter.

In the vicinity of the disposal sites east of the Isle of Wight, Cefas holds limited monitoring data for winter suspended sediment concentrations just to the north of the Nab Tower disposal site, which lies within the area considered in this study. These indicate that concentrations range from 4 to 45 mg/l with a mean around 25 mg/l (Cefas, 2001); unfortunately no corresponding summer data exists and it is not clear where and at what depth these measurements were taken or how they were taken.

Water sampling taken at Hastings Bank, further east along the Channel, during extreme storms (wind force 6 to 7 after 24 hours of up to force 9) on March 13 and 14 1994 (Southcoast Shipping, 1994) indicated that extreme events result in background concentrations (at mid-depth as well as near the bed) of 220-320mg/l.

These measurements provide evidence of concentrations of up to 45mg/l of the finest sediment fractions under normal conditions for most of the area considered in the South Coast MAREA. Under storms these concentrations can rise significantly to levels of the order of 300mg/l.

4. *Development of a high-level approach to the dispersion of dredging plumes based on experience in the field*

4.1 INTRODUCTION

The data derived from field measurement studies and summarised in Table 2 were used together with established theory regarding 2-dimensional dispersion of turbulent flows to produce a methodology for assessing the footprint of dredging plumes.

The data above were essentially used to provide reference conditions. An existing flow model of the South Coast region was used to provide information on tidal currents and water depth. Comparison of the reference flows, water depths and pumping rate with spring tide current speeds and water depths at the sites considered in the MAREA allowed the likely maximum plume dispersion distances at each of these sites to be deduced.

4.2 IMPORTANT PROCESSES IN THE DISPERSION OF DREDGING PLUMES FROM AGGREGATE DREDGERS

The dispersion of plumes arising from aggregate dredging is the result of a number of different dispersion processes:

- The entry into the water column of the overflow (or screening) jet to form a dense plume of material;

- The 'dynamic plume' phase whereby the plume accelerates downward under its own weight and accelerates horizontally due to the ambient current flow, entraining ambient water as it moves;
- At some point the dynamic plume will either impinge onto the bed (if depths are sufficiently small and the density difference sufficiently large) where it forms a density current (which eventually mixes with the overlying waters), **or** the plume will become so dilute that it is no longer accelerated by its density (and form a passive plume directly);
- The final phase where the plume (now termed 'passive') is mixed by turbulent diffusion and shear dispersion resulting from the action of the tidal flow boundary layer;
- In addition less significant plumes can be formed near the bed from disturbance by the drag-head or at the surface as some of the main plume is trapped in the vessel wake or brought to the surface by air bubbles.

This high-level assessment is interested in the three most important variables which affect the dispersion of the plume: the ambient current speed, the water depth and the rate of input of solids into the water column via the overflow process.

The nature of the sediment, i.e. the proportion of fine material in the overflow, is also important in terms of the dispersion of the plume and is represented when detailed site-specific modelling is carried out. It is not possible to consider the detailed make-up of the sediment in this high-level study. It is conjectured that over the distances that plumes have been observed to disperse, the sand fractions (with the possible exception of *very* fine sand, i.e. diameter less than 120μm) would settle to the bed, and so in a sense, for this plume study, only the rate of release of the finest fractions is of interest. The proportion of silt in the *in situ* material dredged by aggregate dredgers is typically in the range 0-5% but the proportion of silt in the overflow tends to be significantly larger (up to ten times) as demonstrated by: measurements at several dredging areas undertaken by Hitchcock (1998); aggregate dredging companies at Hastings Bank (HR Wallingford, 1993, Resource Management Association, 2002); and HR Wallingford in the Eastern English Channel (*pers.comm.* Nigel Feates, Dredging Research, HR Wallingford, 2009).

4.3 DISPERSION THEORY

For the purpose of this assessment the plume dispersion process was characterised into:

- The near-field mixing during the descent of the dynamic plume; and
- The far-field mixing arising from the passive plume phase.

4.3.1 Near-field (dynamic) mixing

The near-field mixing is a complex process which includes both turbulent and forced entrainment processes (Lee and Cheung, 1990), the influence of the ambient current and the potential for interaction with the propeller wash and ship wake. These processes can be built into a numerical dispersion model (for example, Spearman 2003; 2005 and Appendix 1) but for this section it will suffice to consider the simpler analytical model of buoyant plumes in a cross-flow developed by Chu and Goldberg (1974). This model states that, ignoring the initial jet momentum, the growth of the radius of the plume is given by:

$$b = \left(\frac{15}{4}\right)^{\frac{1}{3}} \left(0.5 L_b x^2\right)^{\frac{1}{3}} \text{ where } L_b \text{ is given by } \frac{g \Delta \rho V D_0^2}{\rho u^3} \qquad (1)$$

where:
b is the plume radius;
x is the horizontal distance;
ρ is the density of the surrounding seawater;
$\Delta\rho$ is the density difference between the plume and the ambient water;
V is the velocity of the overflow discharge at its exit point;
D_0 is the diameter of the discharge orifice;
u is the ambient current speed; and,
g is the acceleration due to gravity.

Equation 1 shows that the radius of the plume arising from near-field mixing is reduced by a larger ambient current speed but increases with overflow discharge. There is no obvious dependence of the near-field mixing on depth except that the near-field mixing will be reduced upon impact with the bed and therefore shallower depths may reduce the extent of mixing.

4.3.2 Far-field (passive) mixing

The far-field mixing commences when the plume no longer has sufficient density and momentum to induce mixing through its own motion. The mixing now becomes a function of turbulent diffusion (caused by random fluctuations in current speed and direction) and shear dispersion (caused by parts of the plume encountering different current speeds). If the plume has spread through the water depth, the longitudinal and lateral dispersion of the plume is proportional to the shear velocity, and hence the current speed, and the water depth (Elder, 1959, Fischer *et al*, 1979). In this situation, therefore, the time taken to disperse to a given low value of concentration is inversely proportional to both current speed and water depth. However, this basic result does not accurately describe the behaviour of the plume for two reasons:

- Firstly, for a significant part of the duration of the plume dispersion, the plume has *not* expanded through the water depth. The longitudinal and lateral dispersion of the plume in this case varies with the water depth (Fischer *et al*, 1979) and as result the time taken for the plume to disperse to background conditions increases with water depth.
- Secondly, throughout the passive plume phase sediment settles out of the plume onto the bed. The amount of sediment that can settle out in a given time increases as water depth reduces and therefore the time taken for the plume to disperse will tend to increase with depth.

4.3.3 Discussion

The evidence from dispersion theory is that:

- The time taken for the plume to disperse increases with water depth;
- The initial mixing is reduced by the current speed which will also tend to increase the time taken to disperse; and

- The distance, *D*, over which the plume disperses is equal to *ut* (where *u* is the current speed and *t* is the time taken to disperse).

On this basis it is considered that the distance over which the plume disperses should increase with both current speed and depth. In addition the time taken to disperse (and the distance over which the dispersion occurs) is a linear function of the rate of input of sediment (Fischer *et al*, 1979). It is therefore postulated that the distance over which the dispersion of the plume occurs is, in general, proportional to the product of the current speed, the water depth and the sediment input, i.e.,

$$D \propto uh\dot{M} \qquad (2)$$

where:
D is the distance over which the plume disperses;
u is the current speed;
h is the water depth; and,
$\dot{M}$ is the rate of input of sediment into the water column.

The rate of input of sediment is in general not well known but is the product of the discharge from the dredger and the sediment concentration in the overflow. The concentration of the overflow is a function of the *in situ* sediment particle size distribution but because coarser fractions are more likely to settle in the hopper the overflow tends to contain an increased proportion of the finer fractions. Moreover, on release from the dredger the remaining coarse particles will fairly rapidly settle out of the plume so that in the far-field only the finest fractions of clay/silt (and potentially *very* fine sand) remain in the plume. Aggregate dredging is concentrated in areas where there is a low (0-5%) clay/silt content and so the sediment particle size distribution in the plume in the far-field is much more similar than the *in situ* sediment content in dredging areas would suggest. For the purposes of this high-level study we made the assumption that the far-field sediment contents in plumes are sufficiently similar to be able to compare the results of field measurements from different areas without making detailed analysis of the *in situ* seabed and plume sediment contents.

Since the rate of sediment input is proportional to the volumetric discharge of overflow from the dredger, which is principally a function of the pump equipment of the dredger. On this basis, it is expected that:

$$D \propto uhQ \qquad (3)$$

where:
Q is a typical pumping rate of the aggregate dredger.

It should be noted that the dredging pumps of most of the UK aggregate dredging fleet, regardless of the hopper capacity of the various dredgers, are broadly similar. However there are one or two dredgers which can pump at significantly higher rates from the typical average. Discussions with SCDA resulted in the identification of the Arco Dijk as the dredger which currently pumps at the highest rate, pumping at discharges around 70% higher than the typical dredger average (*pers.comm.,* Rob Langman, Hanson Aggregates Marine Ltd, 2009). The Arco Dijk forms the basis for the footprints of fine sediment plumes which are discussed and presented below.

4.3.4 Validation of the formula for dispersion distance

Equation 3 was validated using the sources described in Chapter 3 and summarised in Table 2. The results are shown in Figure 2. It is clear that the distance taken to disperse is well described by Equation 3.

There are limitations to the application of this equation. In particular, as the dredger size increases it is not true that the distance over which dispersion will occur can indefinitely increase. At some point other physical constraints, such as the period of time over which current flow will be in one direction and the magnitude of such current flow, will become important. However, as long as Equation 3 is not stretched beyond the range of data upon which it is based, it appears to form a useful and reliable basis for *high-level* evaluation of the extent of the dredging footprint.

4.4 DERIVATION OF THE FINE SEDIMENT PLUME FOOTPRINTS

4.4.1 Methodology

The distances over which plumes will disperse were scaled using Equation 4 and the results of the reference measurements presented in Table 2, i.e.,

$$D = D_{ref}\left(\frac{uhQ}{u_{ref}h_{ref}Q_{ref}}\right) \qquad (4)$$

where:

D	is the distance over which the plume disperses;
u	is the current speed;
h	is the water depth;
Q	is a typical pumping rate of the aggregate dredger; and
$_{ref}$	refers to the reference measurement for the Hastings Shingle Bank in Table 2.

The distance and the direction of dispersion were calculated for points along the boundary of each Licence Area, for times throughout a spring tide, using current patterns calculated every 20 minutes throughout a spring tide (see Section 4.4.2). Using the flow model information the path of each plume event was tracked and the point when the plume disperses into the background was derived. This produced a large scatter of points. The envelope of these points was taken as the footprint of plume dispersion from the Licence Area.

Footprints of peak concentration were also derived for peak (depth-averaged) concentrations of 20mg/l, 50mg/l and 100mg/l above background. The footprint of the 20mg/l contour was derived by using the measured relative rate of decay of the plume at Hastings Shingle Bank (Cefas, 2001, Figure 3) to describe the general decay of plumes in the Southern Coast Region.

The interpolation of the measurements, shown in Figure 3, indicates that plume concentrations reduce to 20mg/l above background at roughly 300m from the dredger, indicated by the dashed lines on the figure, and that background concentrations are attained (to within a few mg/l) at a distance of 1500m from the dredger. The figure suggests that the concentration falls to 20mg/l within approximately 20% of the distance at which the concentrations in the plume approach background concentrations, and this has been used as an approximation in this study.

This assumption is a reasonable approximation in the high-level context of this assessment. Faster (or slower) currents (than those measured at the Hastings site) would tend to increase (or decrease) both the overall distance before the plume approaches background conditions and the point at which concentrations of 20mg/l above background were attained in a broadly linear fashion. Dredgers with greater (or reduced) pumping rates would linearly increase (or reduce) the distance from the dredger to the 20mg/l contour but would also linearly increase (or reduce) the distance to the point where the plume approaches background conditions.

For the footprints of peak (depth-averaged) concentrations 50mg/l and 100mg/l above background a different approach was used as these concentrations are likely to be experienced within the near-field (i.e. within a few hundred metres and probably less) of the dredger where the plume exhibits dynamic plume behaviour (i.e. is subject to the effects of initial momentum from the dredger and negative buoyancy). The derivation of footprints was made on the basis of a combination of measured field data from Owers Bank (1996) and numerical models developed at HR Wallingford (Spearman *et al*, 2003; 2005) and using insights from this field/model data in a pragmatic but precautionary manner.

Figure 4 shows the results of measurements of measured suspended sediment concentrations with distance from the City of Rochester (hopper capacity: 1300m^3) dredging (while anchored) at Owers Bank in August, 1995. The measurements show that the high concentrations in the dynamic plume were not measured more than 100m or so from the dredger (and note that since the dredger was at anchor, this distance represents the distance from the release point also), concentrations reducing rapidly from hundreds of mg/l to 10-15mg/l over this distance.

In addition the dynamic plume model (Spearman *et al*, 2003; 2007) was utilised to reproduce the near-field mixing from a variety of scenarios that might be expected to occur. A brief description of this model is given in Appendix 1. The model was used to identify the concentration in the dynamic plume as the plume impinges onto the bed, albeit as a diffuse body of water that may extend several metres from the bed. Variation in dredging speed, current speed and pumping rate, and water depth were considered while typical overflow concentrations from aggregate dredging activity were taken from measurements at Hastings Shingle Bank (HR Wallingford, 1993, Resource Management Association, 2002). The dynamic plume model confirmed the rapid settling observed for the City of Rochester at Owers Bank but also suggested, for the variety of scenarios that might be expected to occur that concentrations would reduce below 100mg/l at distances of no more than 100m from the release point and would reduce below 50mg/l at distances of no more than 200m from the release point. These distances would be reduced in times of low current speed.

The footprints or envelopes of plume dispersion were calculated for the dredger with the highest pump rate currently being used in the SCDA region, the Arco Dijk (see Section 4.3.3 above).

4.4.2 Results

The following footprints were established:

- The footprint over which the fine sediment plume raises suspended sediment concentrations above background levels (see Figures 5a to d), which can be interpreted as 'no more than a few' mg/l above background levels.

- The footprint over which the fine sediment plume can raise suspended sediment concentrations by more than 20mg/l (depth-averaged) above background levels (see Figures 6a to d).
- The footprint over which the fine sediment plume can raise suspended sediment concentrations by more than 50mg/l (depth-averaged) above background levels (see Figures 6a to d).
- The footprint over which the fine sediment plume can raise suspended sediment concentrations by more than 100mg/l (depth-averaged) above background levels (see Figures 6a to d).

The footprints shown in Figures 5 and 6 have been supplied to EMU as GIS shape files on CD. However, 'peak concentration' figures can give the reader the impression that such footprints represent the plume itself and not the 'envelope' of the plume through throughout the dredging process. To set Figures 5 and 6 in context a snapshot impression of the plumes from dredging in three areas during ebb tide conditions is presented in Figure 7.

Figures 5a to d show the footprints over which the plume raises suspended sediment concentrations above background levels. It can be seen that the envelope(s) of areas that will experience some change in concentrations form three main areas, west and east of the Isle of Wight and further east off from the coast at Worthing. Figures 6a to d show that the footprints related to the peak concentrations of 20mg/l, 50mg/l and 100mg/l are relatively close to the dredging area boundaries. Figure 7 shows that the at any given time the plumes cover a small area and areas of the plume at any time with concentration increases of over 50mg/l covering a smaller area still.

4.5 CONCLUSIONS

The high-level plume study undertaken, reported here, shows that the predicted increases in suspended sediment concentration, that will be experienced outside each of the proposed Licence Areas, will be less than 20mg/l above background except when dredging occurs close to the boundary of a Licence Area. Even when this does occur, suspended sediment concentrations more than 50mg/l above background levels are only likely to be experienced within 200m of the Licence Area boundary and concentrations more than 20mg/l above background levels are only likely to be experienced within 1km of the licence area boundary.

These concentration increases will be experienced only while dredging occurs and only in the streamline of the dredger. As a result for the vast majority of the time over the licensing period at any given point in the study region there will be no increases in suspended sediment concentration above background levels.

Even when concentration increases, which can be characterised as a few tens of mg/l above background levels, occur, these concentrations are less than the increases which occur naturally as a result of variation in tidal conditions and waves (as detailed in Section 3.7).

Although it is beyond the scope of this report to comment on the significance or otherwise of these conclusions for biology, it is clear that in purely physical terms the plumes resulting from the proposed dredging will have a minimal effect on suspended sediment concentrations within the study region.

5. Description of flow model

The flow model used was the HR Wallingford TELEMAC-2D model of the English Channel (Figure 8) which includes the Southern North Sea as far north as Den Helder and Cromer and the English Channel as far west as Lizard Point and Île d'Ouessant. This model has been previously used for a variety of studies (HR Wallingford, 2000, 2002, 2009a, 2009b) and has been shown to successfully reproduce the general patterns of tidal range and current magnitude throughout the English Channel. The flow model has not been calibrated in detail in the area of interest using measured data as this was not requested by the client to be included in the scope of this high-level assessment.

The bathymetry for the regional model is presented in Figure 8 and was taken from Admiralty Charts using C-MAP data. The boundary conditions in the model at the south western (English Channel) boundary and the northern (North Sea) boundary were determined from a harmonic analysis using published information from the national BODC (British Oceanographic Data Centre) database.

Typical predicted spring tide current patterns from the flow model on ebb and flood tides are shown in Figures 9 and 10. Further information is given in HR Wallingford (2009b).

6. Summary of the literature relating to the dispersion of sand released onto the bed during aggregate dredging

6.1 INTRODUCTION

This chapter briefly describes field measurement studies relating to changes in seabed substrate, potentially resulting from the dispersion of fine sand released from aggregate dredging activity. Only aggregate dredging studies in the UK are considered.

6.2 AREAS 122/3 AND 351

Areas 122/3 and 351 are located east of Bembridge, Isle of Wight, and thus are located within the South Coast region. A number of field studies investigating the effects of dredging in these areas on the surrounding benthic community were undertaken in 1999 & 2000 (Boyd and Rees, 2000; Hitchcock and Bell, 2004; Newell *et al*, 2004). Peak current speeds in these areas are in excess of 1m/s and aligned in an approximately ENE–WSW direction (Brampton, 1993; Hitchcock and Bell, 2004).

Area 351 has been dredged exclusively by trailer suction hopper dredgers. In contrast, Area 122/3 has been dredged almost entirely by static suction hopper dredgers, although a limited amount of trailer dredging has also been carried out since 1998. Prior to 1991, very little was dredged from Area 122/3 but in later years annual extraction increased, peaking at around 140,500t in 1999 (*pers.comm.* A. Bellamy – cited in Boyd and Rees, 2002). Extraction rates are substantially higher from Area 351 than Area 122/3, with approximately 500,000t of sand and gravel being removed from the site in 1999 (Crown Estate records). Screening was not undertaken in either of these areas.

A survey of benthic macrofauna at a total of 131 sampling stations in the vicinity of the North Nab Production Licence Area 122/3 was carried out in March 1999. Additional samples were collected in September 1999 (Newell *et al*, 2004; Hitchcock and Bell, 2004). The sampling stations were chosen to quantify the benthos both within the dredging areas and in zones potentially affected by deposition, as well as in control zones well outside any area of potential impact of dredging activity. In addition, high resolution side-scan sonar and bathymetry was processed (Hitchcock and Bell, 2004). Following these activities, in June 2000 (Boyd and Rees) sampling of bed sediments was undertaken along transects extending up to 5km (Area 122/3) and up to 2km (Area 351) from the areas of most intensive dredging.

The conclusions arising from these studies were as follows:

- Sediment changes were found up to 1-2km from the point of dredging and consisted of a reduction in the degree of sorting of the sediment (a measure of how the different particle sizes of sediment are distributed) and changes in the percentage of silt/clay (which increased by up to 10% in weight from the typical local values of a fraction of a percent) (Boyd and Rees, 2002).
- In the vicinity of the dredging in Area 122/3, the zones of sandier gravels extended some 1500–2000m away from the dredge location and corresponded well with the predominant tidal flow axes through the active dredge zone. These may be a result of geological conditions, but were judged more likely to have occurred as a result of the dredging activities (Hitchcock and Bell, 2004).
- The community structure of benthic infauna in the vicinity of the dredging in Area 122/3 was apparently unaffected by dredging. However, outside the immediate boundaries of an intensively dredged zone, there was an enhancement of species diversity, population density, biomass and mean body size of the macrofauna in deposits surrounding the dredged zone (Newell at al, 2004). The authors suggested the possibility that this reflects organic enrichment from the dredge site.

6.3 AREA 222

The effects of dredging at Area 222 have been reported in detail by Boyd *et al* (2002; 2003 and 2005) and this section draws on these sources.

Area 222 is located approximately 20 miles east of Felixstowe off the southeast coast of England in water depths between 27m and 35m LAT. The tidal ellipse in the region is aligned in a NNE–SSW direction and Boyd *et al* (2003) report that the maximum spring tidal current velocities reach 1.5m/s with a NNE near-bed residual.

This site was first licensed for sand and gravel extraction on 16 December 1971. Historical records indicate that the annual rate of extraction peaked in 1974 at 872,662 tonnes. Extraction was maintained at a somewhat lower level, but still in excess of 100,000 tonnes per annum, until 1995. The site was last dredged in 1996, when approximately 12,000 tonnes was removed. At this site, screening of the cargoes was carried out routinely.

Samples for analysis of the macrobenthic fauna and sediment particle size were collected in June 2000. A side-scan sonar survey was conducted in June 2000 to provide an indication of the spatial distribution of sediments in the wider area encompassing the dredged site and to estimate the likely spatial extent of both direct and indirect effects of dredging.

Evidence from the side-scan sonar survey suggested that the seabed in this area had been dredged outside Area 222 (without a licence) some time prior to the introduction of an automatic system for monitoring the location of dredging activity in 1993. The area of disturbed seabed extended up to 1000m away from the northern limit of the extraction site. Sediment transport features associated with the zone of out of area dredging appeared to extend up to 2500m away from the northern boundaries of the former extraction site (Boyd *et al*, 2002; 2003).

On the basis of these studies it can be concluded that the identifiable zone, where the sediment substrate can be seen to be affected, can therefore be assumed to be in the range 1500-2500m from the point of dredging.

6.4 AREA 430

Area 430 is located in relatively deep water of 28-34m depth off the coastline of Suffolk. The eastern part of the Licence Area was (in 2004) exploited for gravel using screening. The total annual cargo loaded for the year May 2002 to April 2003, between two companies, was estimated to be around 490,000 tonnes based on a total of 1,160,000 tonnes pumped and 670,000 tonnes returned to the seabed following screening (Newell *et al*, 2004).

In the winter of 2003/2004 a combination of studies (Newell *et al*, 2004b; Andrews, 2004) investigated the effects of dredging at Area 430 on the sediment and benthos of the seabed. The investigations found that the sediment footprint was traceable for up to 4km northwards (in the direction of the net sediment transport) from the dredging area with a smaller detectable effect on benthos extending for 1750m. Any noticeable change to the sediment structure southward was contained within the Licensed Area.

6.5 AREA 106

This Licence Area is located in shallower water of 18-20m depth off the coastline of Lincolnshire. Peak currents are in the region of 0.6-0.7m/s (Compass Hydrographic Surveys, 2004) and seabed transport is reported to be weak. The average sand:gravel ratio of the resource is relatively high at 60:40, so a suitable gravel content in the cargo can be obtained by relatively light screening. The total cargo loaded in the period May 2002 to April 2003 was approximately double that at Area 430, amounting to as much as 1,160,000 tonnes. The estimated tonnage of material rejected was 460,000 and the total tonnage of material pumped in the year was therefore estimated as 1,620,000 tonnes. Compared with Area 430, the rate of dredging was higher but the proportion of material screened and returned to the bed was less (28.6% at Area 106 compared with 57.7% at Area 430).

In the winter of 2003/2004 a combination of studies (Newell *et al*, 2004b; Andrews, 2004) investigated the effects of dredging at Area 106 on the sediment and benthos of the seabed. The ‘footprint’ of impact on sediment composition was symmetrical and was found to extend for less than 450m to the north (Andrews, 2004). Newell *et al* (2004b) report that the footprint extended up to 250m north and south of the zone of ‘High Intensity’ plume deposition.

6.6 AREA 408

Area 408 is located approximately 100km east of the Humber Estuary. The Licence Area has been dredged by trailer suction hopper since 1996. The seabed sediments in the survey area comprise mixed sands and gravels. Coarse sandy gravels occur mainly within the boundary of the Licence Area with fine well-sorted sands extending to the south-east of the dredged sites.

The gravel content varies and so screening occurs to a varying extent across the site. In 2000 production was 290,000 tonnes (1999: 250,000 tonnes; 1998: 950,000 tonnes) and around 250,000 tonnes of this (85%) was estimated to be rejected through the screening process (1999: 205,000 tonnes; 1998: 510,000 tonnes) (Newell *et al*, 2002).

In July and August 2000 a survey of benthic biological resources was undertaken in the vicinity of the Licence Area. Further studies of the sediment transport and morphology of the sea bed (Coastline Surveys Europe Ltd., 2002) and of the sediment grab sample data (Evans, 2002) were undertaken subsequently and these showed that dredging and overboard screening may be associated with deposition of well-sorted fine sands and transport of these sands to the south-east of dredge sites within Area 408.

In summary Newell *et al* (2002) stated,

> *'The zone of impact on benthic biomass extends for up to 500m to the north-west of the actively dredged site, but for as much as 2000-4000m to the South East. This accords well with the net south-east dispersion of sediment from the dredge site established from tide and bedform evidence in the survey area'.*

7. Development of an approach based on experience in the field

7.1 INTRODUCTION

The data derived from the field measurement studies summarised in Chapter 6 were used to produce a high-level methodology for predicting the footprint of the dispersal of fine sand from dredging areas. However, these footprints are more difficult to characterise in the same manner as for fine-grained sediment (Figure 3) because there is more uncertainty in the prediction of the natural net sand transport in and around the dredging areas. Additionally, in some of the areas considered, wave action could, potentially, contribute significantly to the sediment transport. Therefore a simpler approach is used than that proposed for the fine sediment plumes, based on the evidence presented in Chapter 6.

The maximum distance over which the effects of dredging have been shown to cause changes in the character of sediments on the seabed surface is 4km (Area 408, Section 6.6). A conservative approach is therefore used which assumes that the footprint arising from sand dispersion will include the seabed up to 4km from the boundary of each Licence Area in the direction of the net sediment transport residual, as calculated on the basis of the local tidal current residual. In addition the maximum distance over which the effects of dredging have been shown, or identified as the most likely candidate, to produce bedforms is up to 2.5km (Area 2.2.2, Section 6.3). On this basis footprints of up to 2.5km from the boundary of each Licence Area in the direction of the net sediment transport residual were also derived.

7.2 METHODOLOGY

Using the flow model described in Chapter 5 the direction of net residual sediment transport for a mean spring tide was calculated for each point of the boundary of each Licence Area. The locations 4km from each boundary point in this direction were also calculated. The footprint of the sand dispersion was taken as the envelope of all these points together with the original boundary points. The footprints are shown in Figures 11a to d. Also shown in Figures 11a to d are envelopes corresponding to 2.5km from the boundary of the dredging areas. This 2.5km envelope corresponds to the footprint where bedforms could potentially be observed as a result of dredging, based on the published results of investigations for Area 222 (Boyd *et al*, 2002; 2003; 2005). The 4km envelope corresponds to a larger footprint where changes in particle size distribution of the sediments on the seabed surface might be observed.

Figures 11a to d show that the sand dispersion footprints from three main areas to the west and east of the Isle of Wight and further east off from Worthing. It is noted that the 4km and 2.5km envelopes are conservative in relation to the distances over which changes in bedforms or surface sediments have been observed for dredging areas within the study area, as they are based on the maximum extent of impact ever recorded in UK waters as a result of aggregate dredging. In Area 122/3 (see Section 6.2) the distances over which changes (which *potentially* could have arisen from dredging) have been observed to occur are 2km or less and are limited to changes in the nature of the substrate (rather than changes in bedforms).

The directions of sand transport from the dredging areas suggested in Figures 11a to d broadly agree with the characterisation of sand transport identified in the literature, for instance in Velegrakis *et al* (2000); SCOPAC (2004); and Stride (1982), which are summarised in Figure 12. The surficial sediments in the region of the proposed dredging areas of the South Coast Region are shown in Figure 13. The figure shows that the vast majority of the dredging areas in the region are located in gravel, sandy gravel or gravelly sand. For these areas, therefore, the deposition of fine sand may change the natural character of the seabed surface.

The exception to this general observation is Area 499 in the east of the study area which is located on a patch of sand. In this particular proposed dredging area, the effects of the dispersion of sand from the dredging process is likely to be reduced both in magnitude and in distance from the boundary of the dredging areas. This is because the locally active bedforms will tend to mask any bedforms that might have resulted from dredging and the presence of active fine sand will tend to mask any potential transport of fine sand from the dredging. In this dredging area it is reasonable to assume that there will be no discernible impact from sand dispersion.

In addition it should be pointed out that the Nab Tower disposal site, which is the main disposal site for the Solent, is located adjacent to the dredging areas immediately east of the Isle of Wight. The average placement over the period 1998-2007 is reported to be around 400,000 tonnes dry solids by the Defra disposal returns database, of which the vast majority was maintenance material. However, it is noted that large capital operations took place in 1996/1997 for Southampton Docks with around 5.5M tonnes dry solids being placed at Nab Tower in 1997. The contribution of this placed sediment to transport through the adjacent dredged areas is significant when compared to the release of sediment arising from dredging activity.

7.3 FATE OF RELEASED SANDY SEDIMENT

The sediment pathways are presented in Figure 12. There is a sand transport 'parting' located offshore of the Isle of Wight. For offshore areas in the east of the study area sand will be transported into the convergence zone around the sand banks offshore of Dungeness. For offshore areas in the west of the study area sand will be transported westward down the English Channel.

Inshore and east of the Isle of Wight sand can travel north-west into the Solent or eastward along the coast. Inshore and west of the Isle of Wight, sand is either drawn westward along the coast or into the offshore sediment transport pathways.

8. *Potential for cumulative effects*

8.1 INTERACTION BETWEEN FINE SEDIMENT PLUMES

Where any two or more of the proposed dredging areas lie close to one another there is the possibility (as shown in Figures 5a to d) that plumes from dredgers in two adjacent areas might interact. This event is not likely to occur very often simply because the chances of two dredgers, dredging in the relevant parts of adjacent areas so that plumes can interact with each other is likely to be relatively low. In theory the interaction could occur in two ways. One way is where plumes, generated in different areas, meet and coalesce to form one larger plume. The second way is for a dredger to be dredging within the plume generated by a dredger in a different area.

For plumes that meet and coalesce, the physical laws of dispersion theory mean concentrations within the plumes are not additive but instead create a larger plume with similar concentrations to those of the separate plumes. In this sense the peak concentrations resulting from dredging identified in Chapter 4 are not exceeded in areas where the plume footprints overlap. Instead the peak concentrations will be experienced slightly more frequently in these areas over the lifetime of the licensing period.

For plumes created by a dredger operating in the plume of another dredger the two plumes in this case *would* be additive. For plumes created by a dredger operating in the plume of (i.e. in the streamline of) another dredger the two plumes in this case *would* be additive. However, for this cumulative effect to be significant it would require two dredgers (in different Licence Areas) dredging in each others streamline within 200m or so of each other which is likely to occur rarely, if at all, during the License Period.

As a result of these considerations there is little potential for significant cumulative effects resulting from plume interaction between Licence Areas.

8.2 INTERACTION BETWEEN DISPERSION OF FINE SAND FROM DIFFERENT LICENCE AREAS

In order for cumulative effects to occur in the dispersion of fine sand it is necessary for the dispersion footprints to overlap in areas *outside* of a Licence Area. Figures 11a to d show that it is possible for some interaction of the dispersion of sand to occur:

- To the west of the Isle of Wight in the vicinity of Licence Areas 124/2, 137, 434, 437, 465/1, 465/2 and 500;

- To the east of the Isle of Wight, in the vicinity of Areas 122/2, 122/3, 340, 351, 372/1 and 451; and

- Offshore of Worthing, in the vicinity of Areas 122/1A, 123A, 124/1A, 122/1C, 123C, 124/1C, 122/1D, 123D, 124/1D, 122/1E, 123E, 124/1E, 396/1, 396/2, 435/1, 435/2, 453 and 488.

On the basis of this high-level study it is not possible to infer the degree of (physical) significance of this cumulative interaction, but it is noted that the footprints identified are a maximum and the extent of any cumulative effect in practice will be less than that shown in Figures 11a to d. The potential significance of cumulative impact in this area will be identified in the MAREA.

9. Conclusions

This report has examined the results of field investigations relating to the dispersion of fine sediment plumes and of sand dispersion caused by the release of material during aggregate dredging activities in UK waters. For both mechanisms a methodology has been developed which gives a high-level assessment of the potential extent of the dispersion footprint, and of the peak concentrations likely to arise from the proposed dredging. The results of the study are presented as a series of figures showing the geographical extent of the footprints.

The predicted footprints of dredging plumes are conservative in nature being based on the dredger that is currently used in the SCDA region which will give the greatest impact, and assuming that dredging will occur throughout the whole of each Licence Area. The established footprints of sand dispersion are based on the greatest extents of impact that have been observed (and reported on) from dredging in UK waters.

Conclusions regarding fine sediment plumes arising from dredging

The high-level plume study undertaken concludes that the predicted increases in suspended sediment concentration that will be experienced outside each of the proposed Licence Areas will be less than 20mg/l above background except when dredging occurs close to the boundary of a Licence Area. Even when this does occur suspended sediment concentrations more than 50mg/l above background are only likely to be experienced within 200m of the Licence Area boundary and concentrations more than 20mg/l above background are only likely to be experienced within 1.5km of the Licence Area boundary.

These concentration increases will be experienced only while dredging occurs and only in the streamline of the dredger. As a result, for the vast majority of the time over the licensing period at any given point in the study region, there will be no increases in suspended sediment concentration above background. Even when concentration increases, which can be characterised as a few tens of mg/l above background, occur, these concentrations are less than the increases which occur naturally as a result of variation in tidal conditions and waves. It is beyond the scope of this report to comment on the significance or otherwise of these conclusions for biology, it is clear that in purely physical terms the plumes resulting from the proposed dredging will have a minimal effect on suspended sediment concentrations within the study region.

Conclusions regarding dispersion of fine sand

The vast majority of the dredging areas in the region are located in sediments which have sandy gravel or gravelly sand. In those areas it is possible that bedforms may be created from the fine sand and changes in substrate may occur. Providing quantitative information about the resulting significance of bedforms and changes to substrate are not part of the scope of this study. Instead, and appropriate to this high-level study, the literature has been analysed to identify potential footprints of fine sand dispersion of up to 4km (changes in substrate) and 2.5km (bedforms) which may arise from dredging; these are upper limits of potential dispersion based on experience in UK waters. The exception to this is at Area 499 which is situated in a sand deposit. In this dredging area it is reasonable to assume that there will be no discernible impact from sand dispersion over the sand fields within and around this Licence Area.

Conclusions regarding cumulative effects

Consideration of interaction of the potential for fine sediment plumes between Licence Areas indicates that there will be no significant cumulative effects from this mechanism.

Consideration of the potential for interaction of fine sand dispersion between Licence Areas identified the possibility for some interaction of the dispersion of sand to occur:

- To the west of the Isle of Wight in the vicinity of Licence Areas 124/2, 137, 434, 437, 465/1, 465/2 and 500;
- To the east of the Isle of Wight, in the vicinity of Areas 122/2, 122/3, 340, 351, 372/1 and 451; and
- Offshore of Worthing, in the vicinity of Areas 122/1A, 123A, 124/1A, 122/1C, 123C, 124/1C, 122/1D, 123D, 124/1D, 122/1E, 123E, 124/1E, 396/1, 396/2, 435/1, 435/2, 453 and 488.

However, on the basis of this high-level study it is not possible to infer the degree of significance of this cumulative interaction. The potential significance of those cumulative effects will be assessed as part of the MAREA.

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Figures

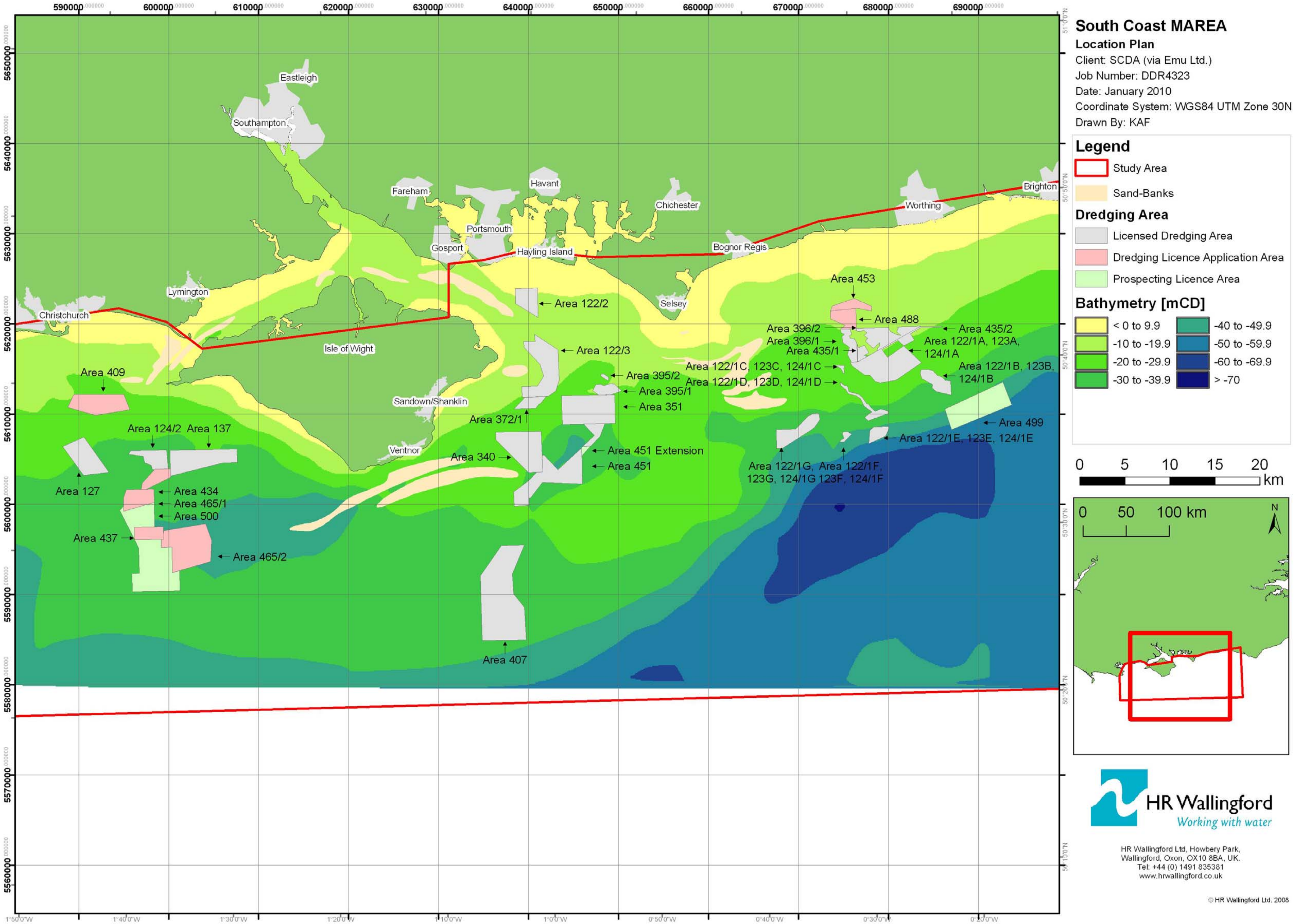

Figure 1 Location plan showing study area and licensed dredging areas

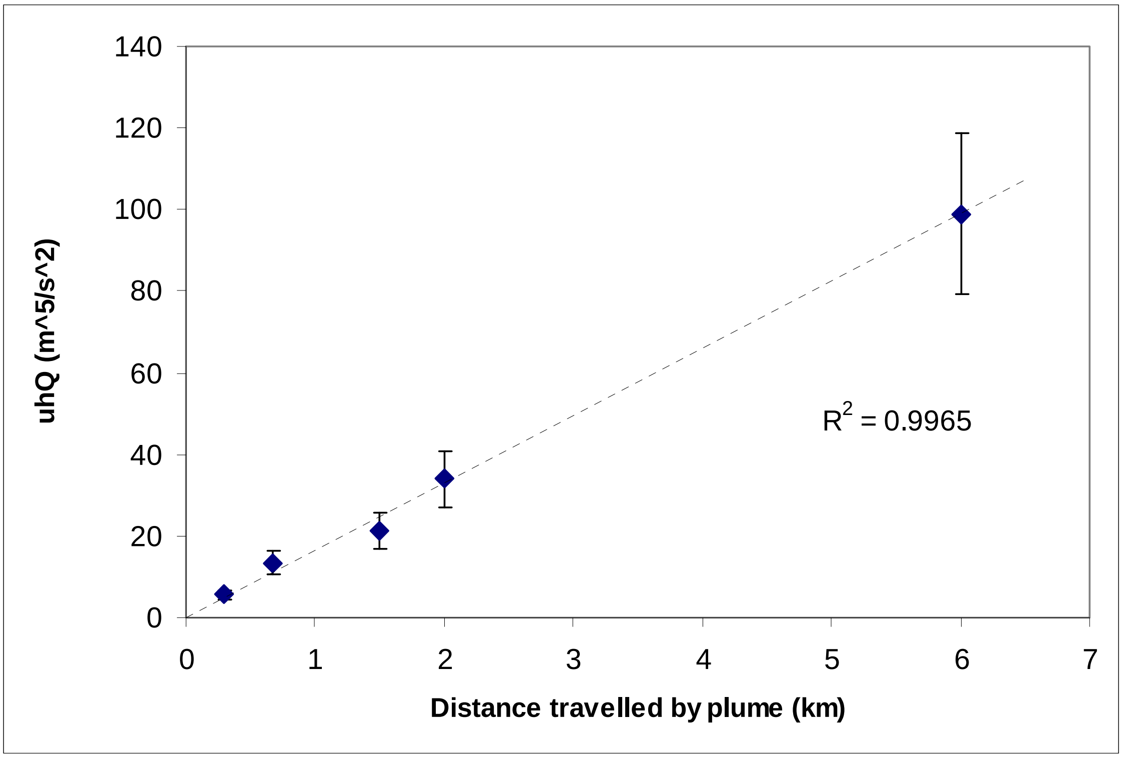

Figure 2 Validation of Equation 3 from field data

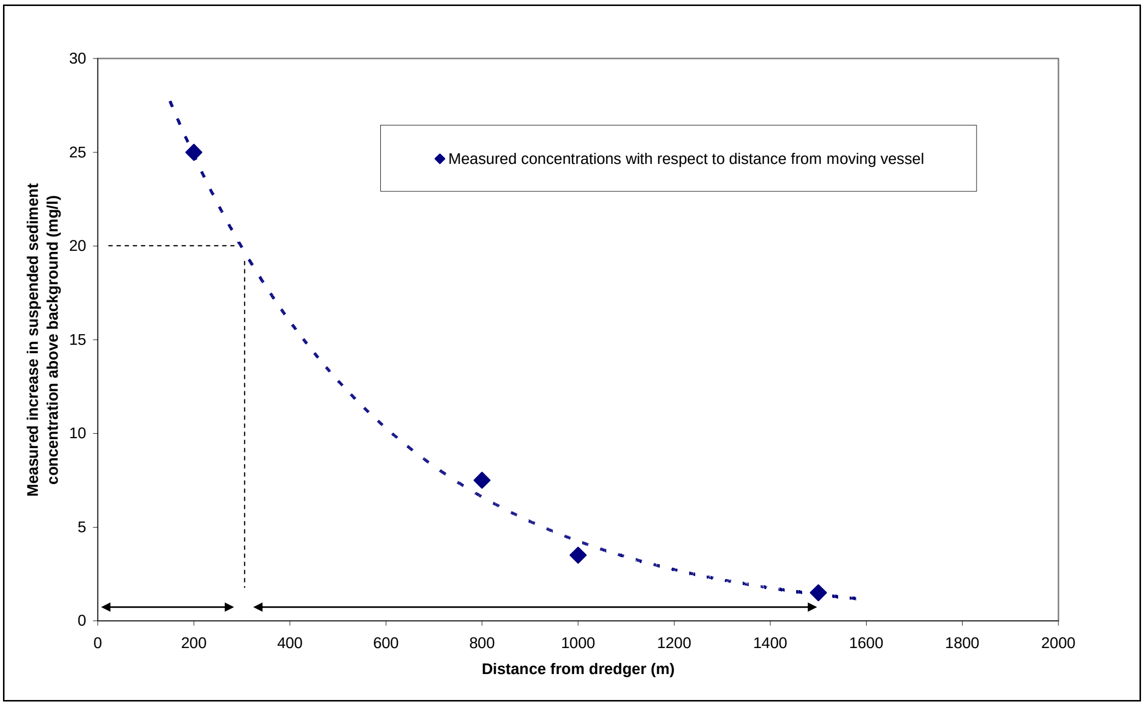

Figure 3 Summary of CEFAS measurements of dredging plumes from the Arco Adur at Hastings Shingle Bank 1999

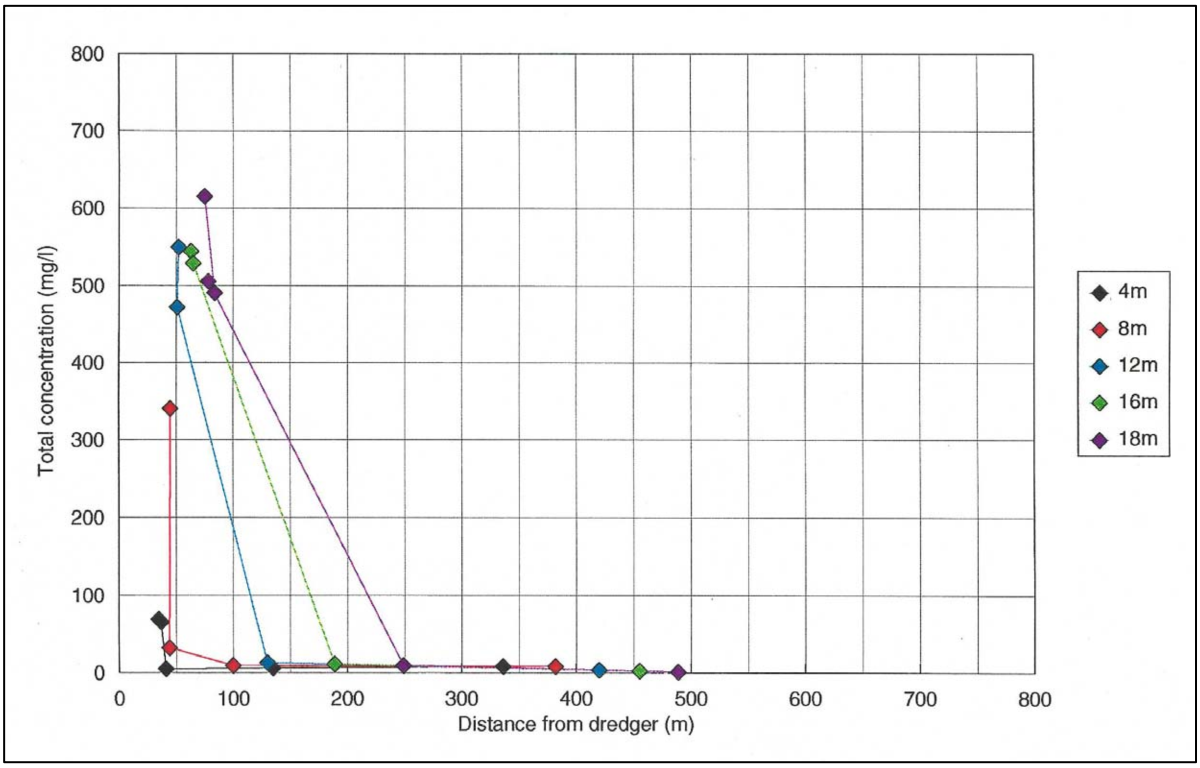

Figure 4 Variation of measured suspended sediment concentration with distance from dredger, City of Rochester 21 August 1995 (reproduced from the original, HR Wallingford, 1996)

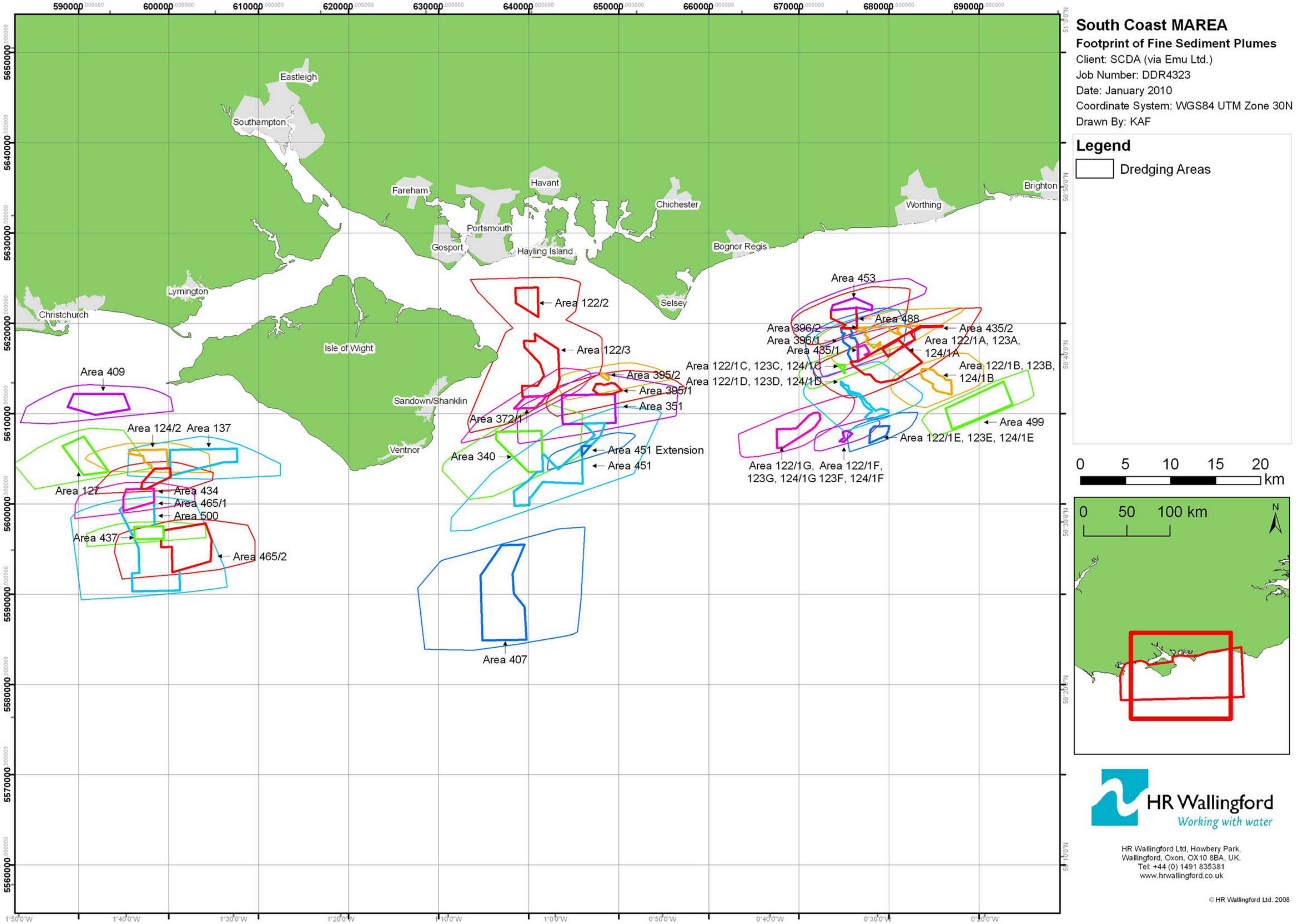

Figure 5a Predicted footprint of fine sediment plumes arising from proposed aggregate dredging.
Thick continuous line: Dredging area boundary; Thin continuous line: footprint of changes in concentration for Arco Dijk vessel

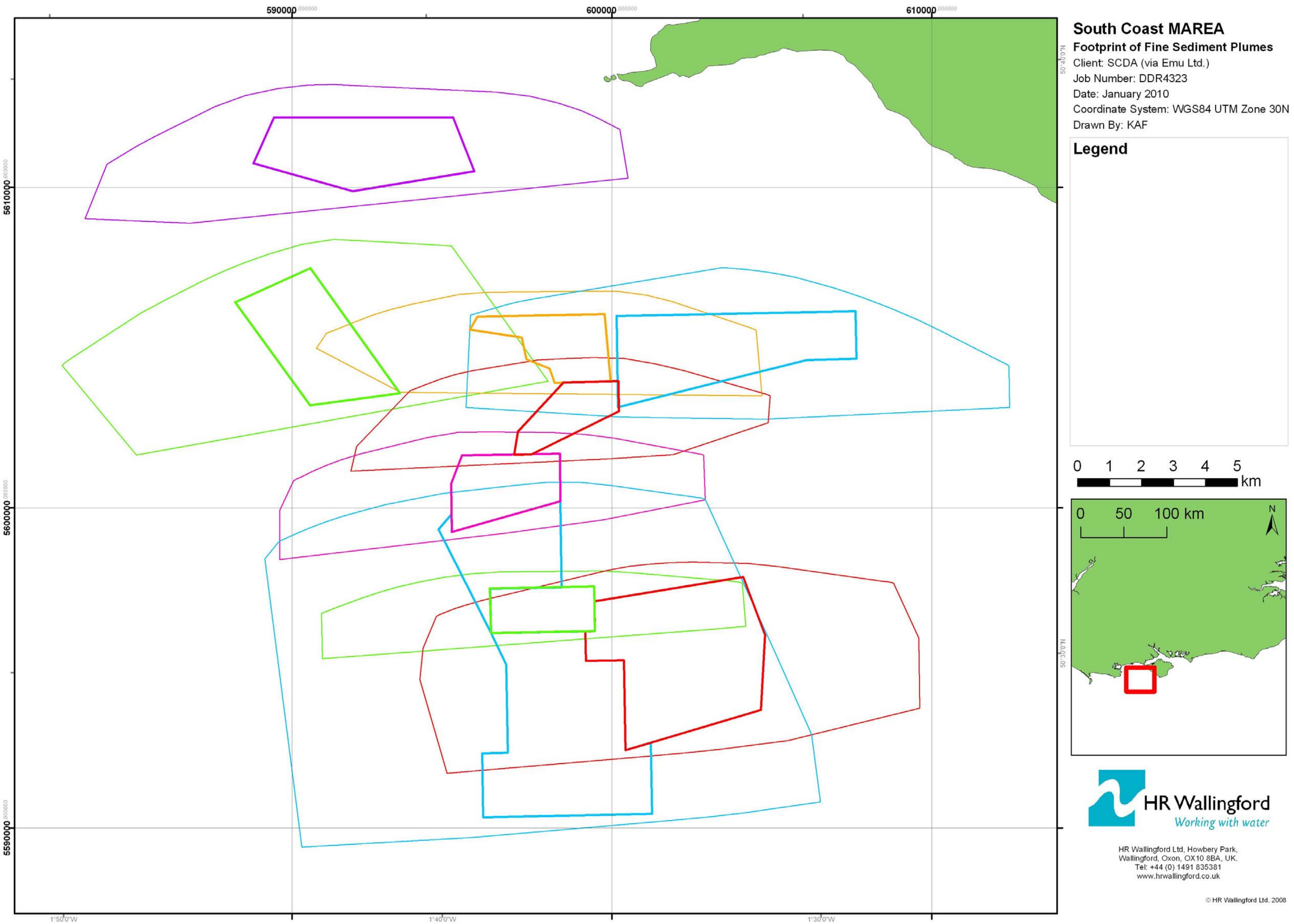

Figure 5b Predicted footprint of fine sediment plumes arising from proposed aggregate dredging (western area)

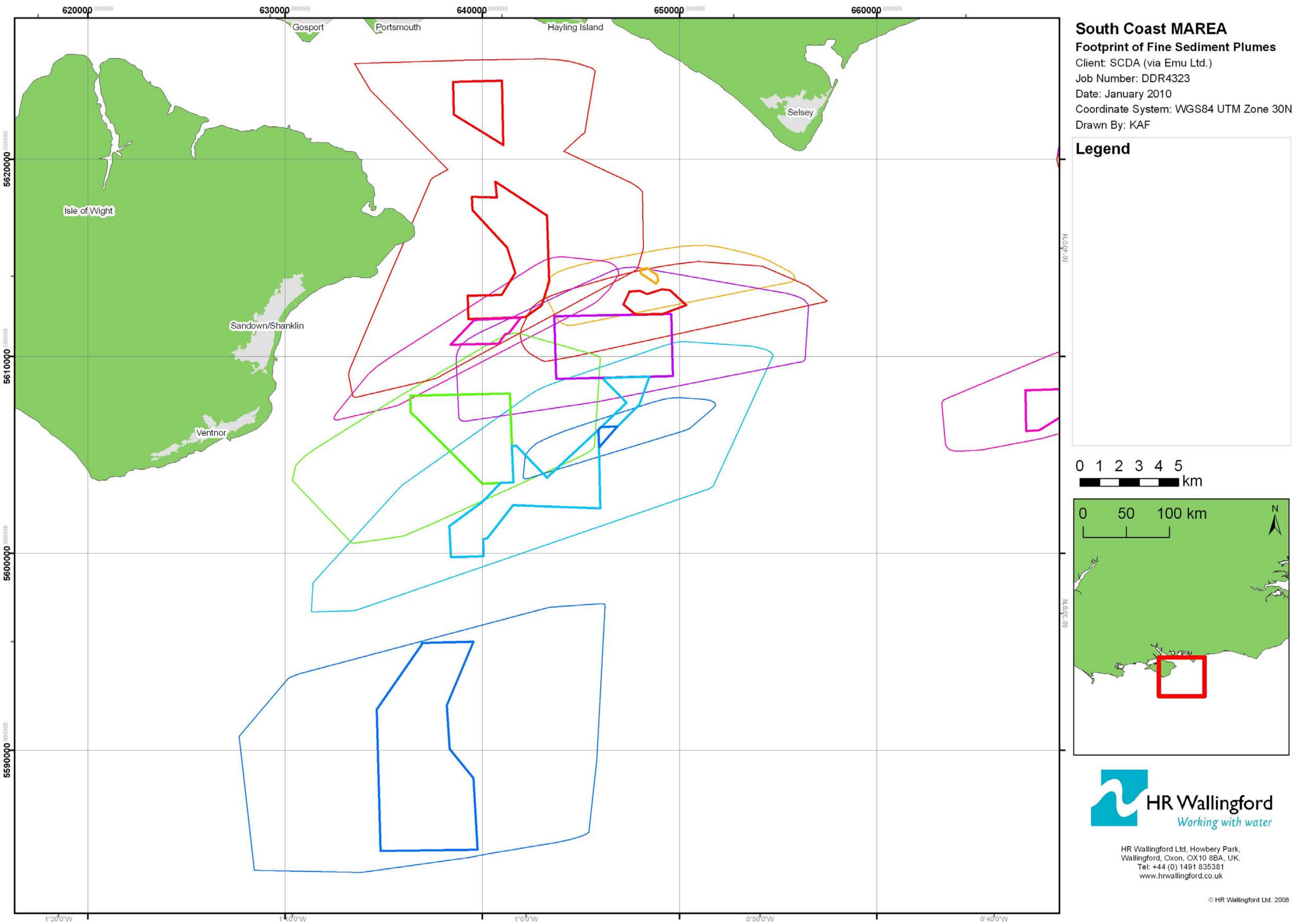

Figure 5c Predicted footprint of fine sediment plumes arising from proposed aggregate dredging (eastern area)

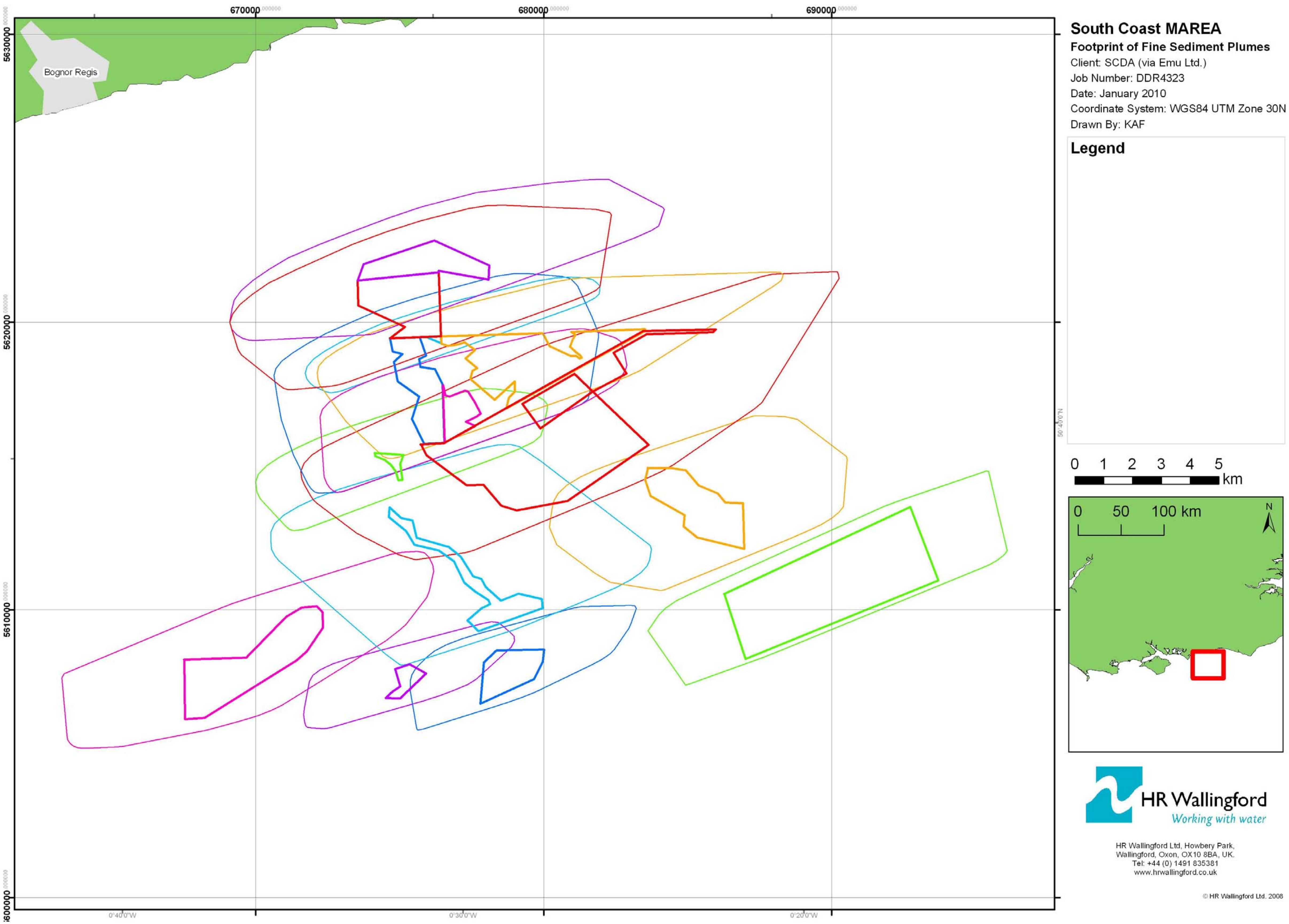

Figure 5d Predicted footprint of fine sediment plumes arising from proposed aggregate dredging (far eastern area)

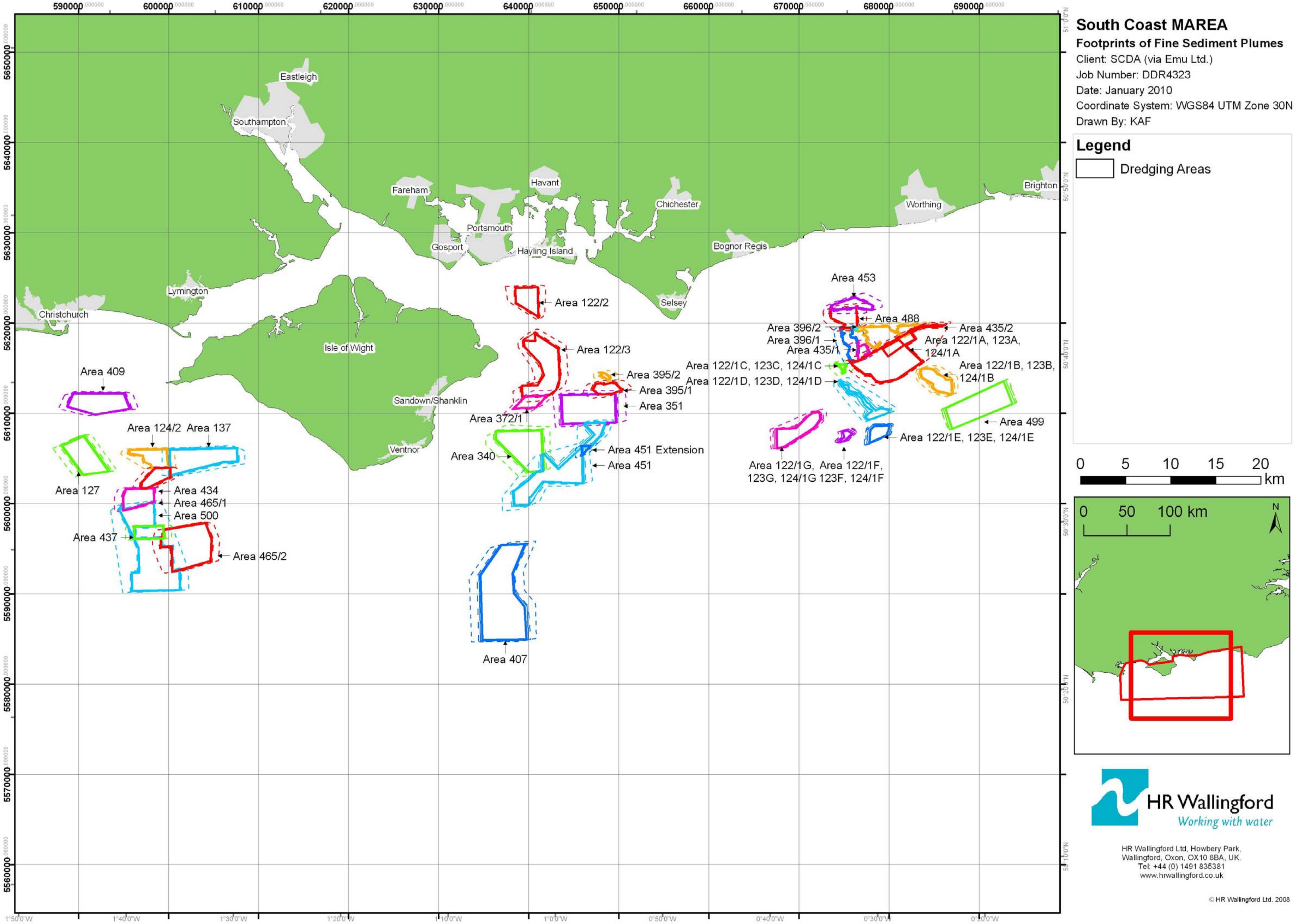

Figure 6a Predicted footprints of fine sediment plumes arising from proposed aggregate dredging for Arco Dijk vessel
(thick continuous line: Dredging Area boundary; thin continuous line: 100mg/l peak concentration contour; long dotted line: 50mg/l peak concentration contour; and short dotted line: 20mg/l peak concentration contour)

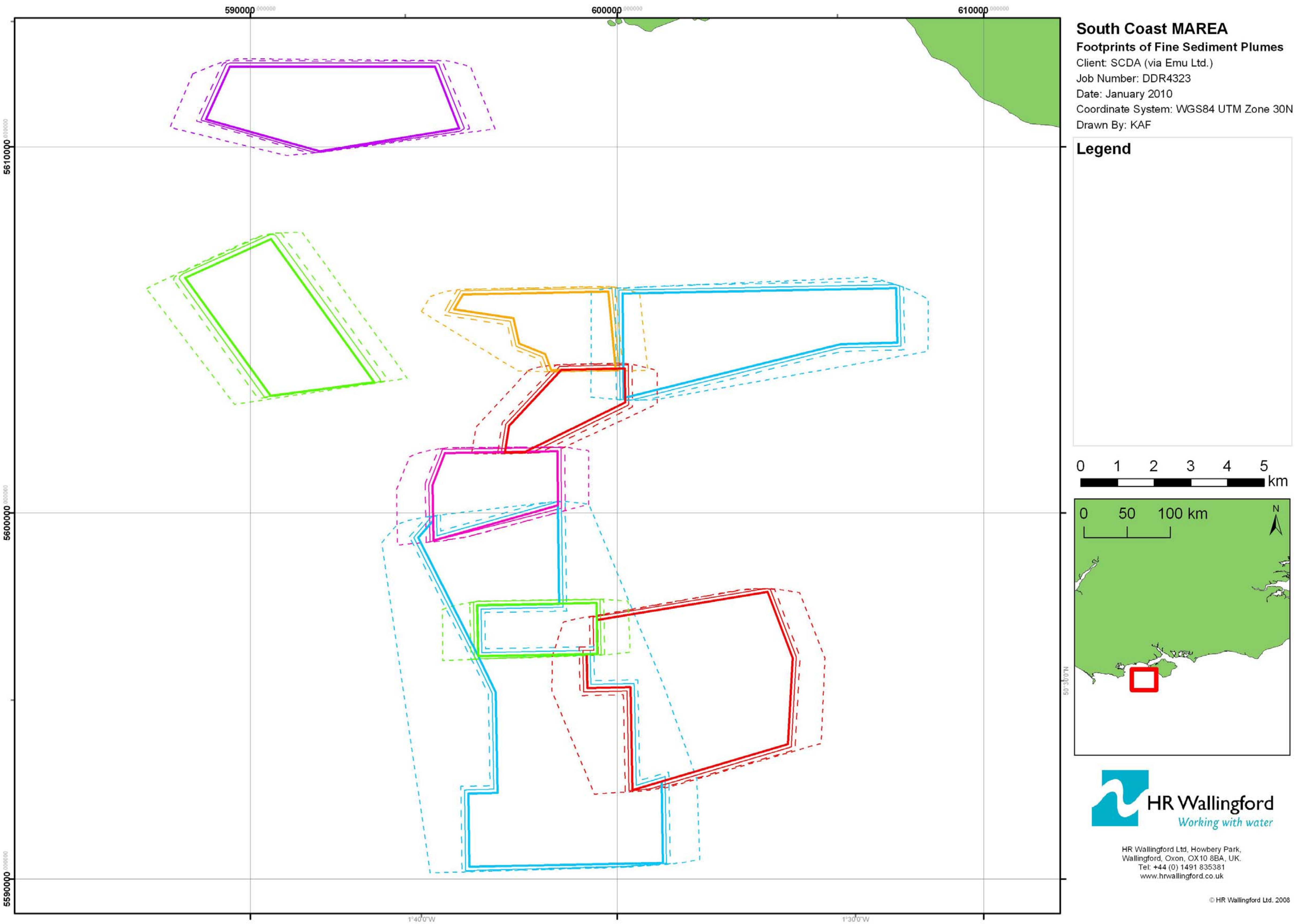

Figure 6b Predicted footprints of fine sediment plumes arising from proposed aggregate dredging for Arco Dijk vessel (western area)

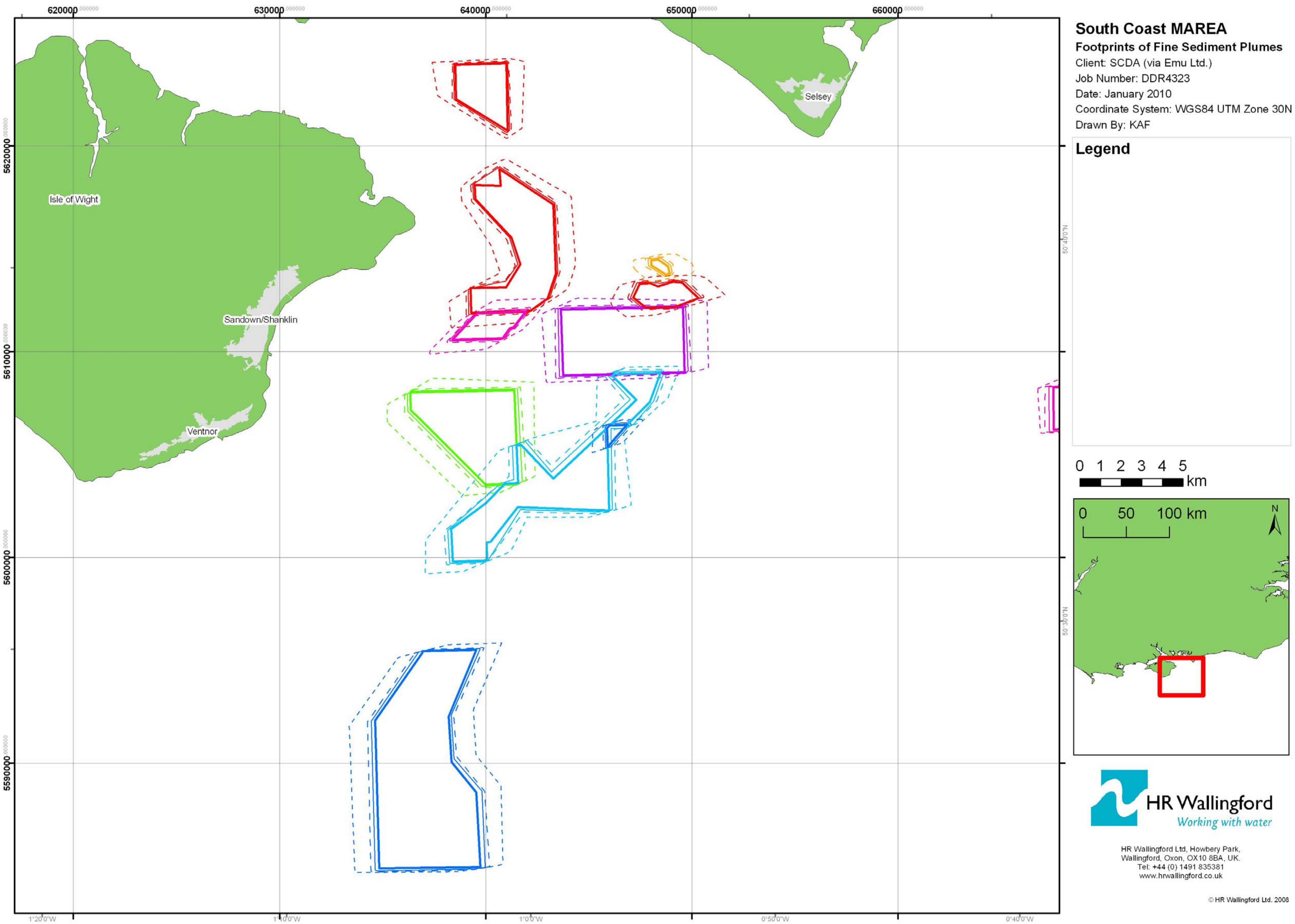

Figure 6c Predicted footprints of fine sediment plumes arising from proposed aggregate dredging for Arco Dijk vessel (eastern area)

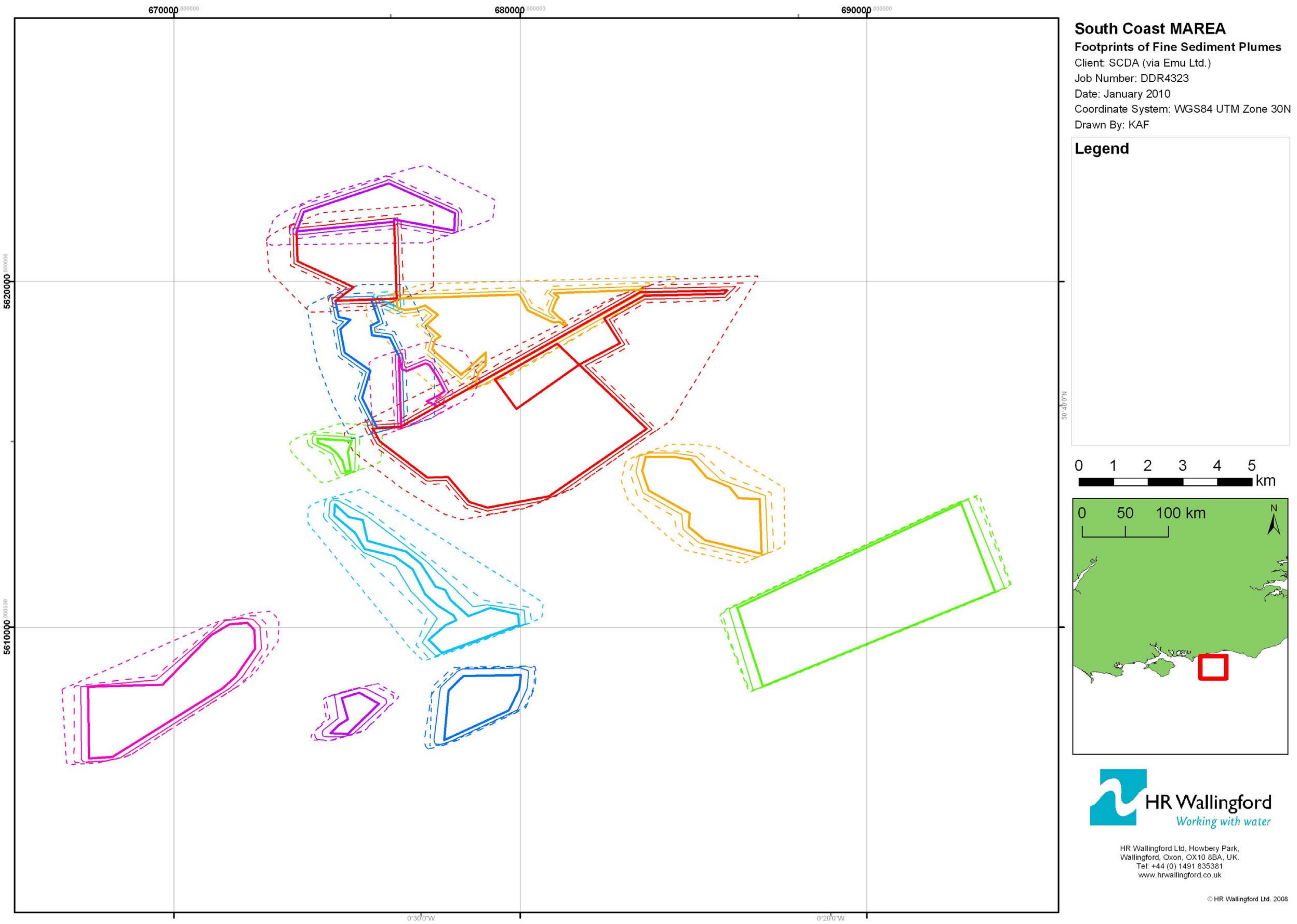

Figure 6d Predicted footprints of fine sediment plumes arising from proposed aggregate dredging for Arco Dijk vessel (far eastern area)

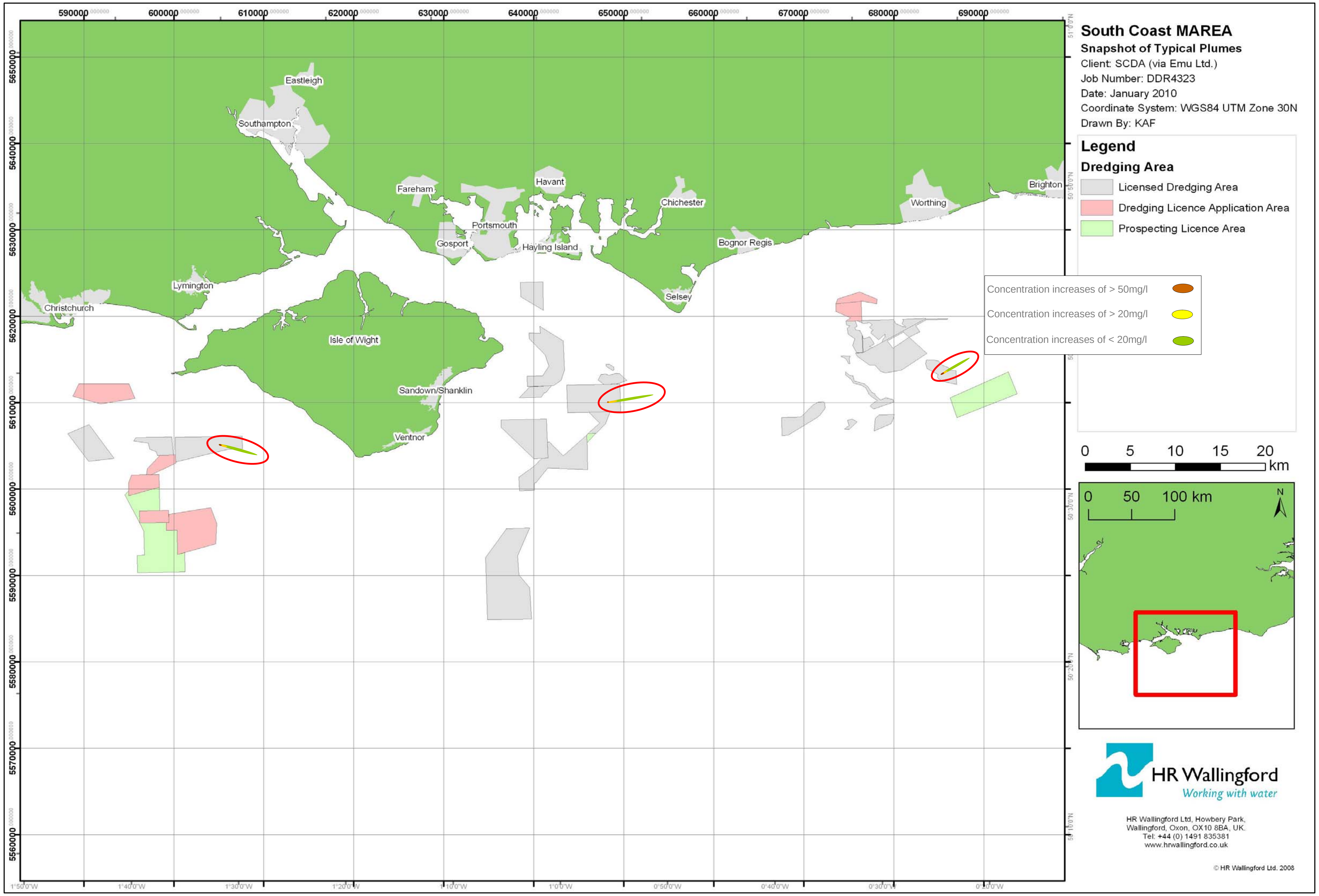

Figure 7 Snapshot of typical plumes resulting from dredging at three areas on the floodtide (position of plumes highlighted by red ellipses)

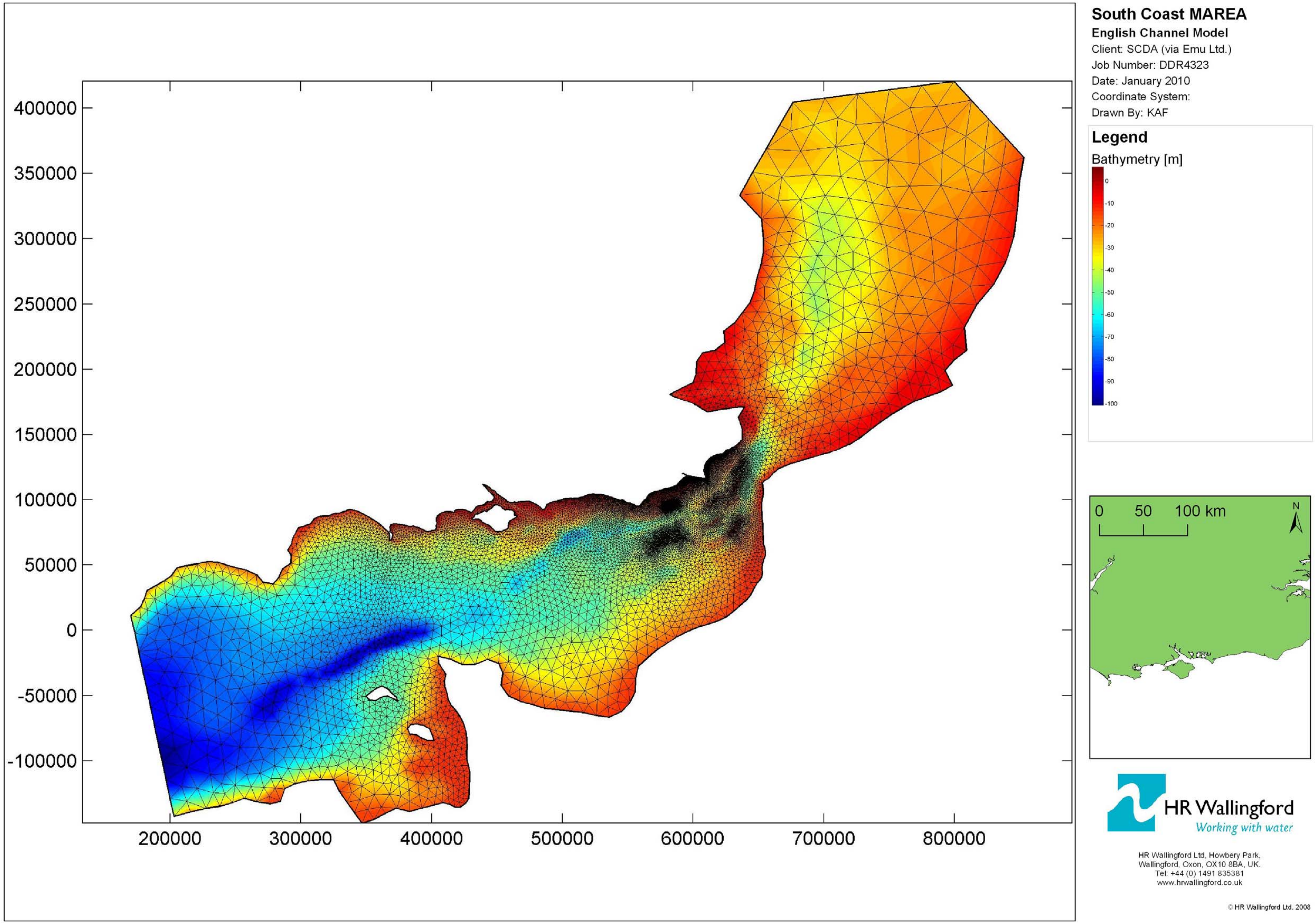

Figure 8 Bathymetry and coverage of English Channel model

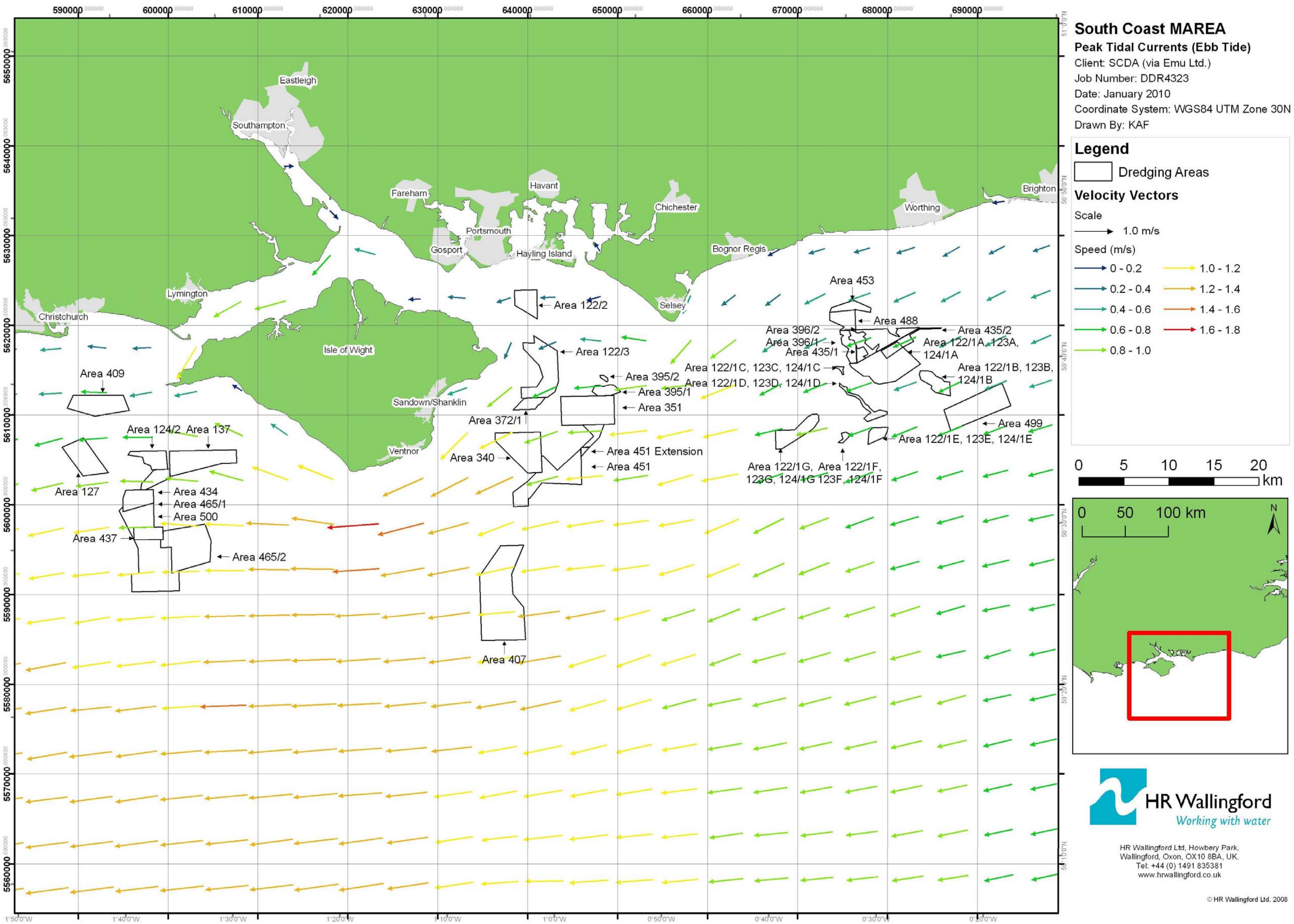

Figure 9 **Predicted spring tide current patterns at peak ebb**

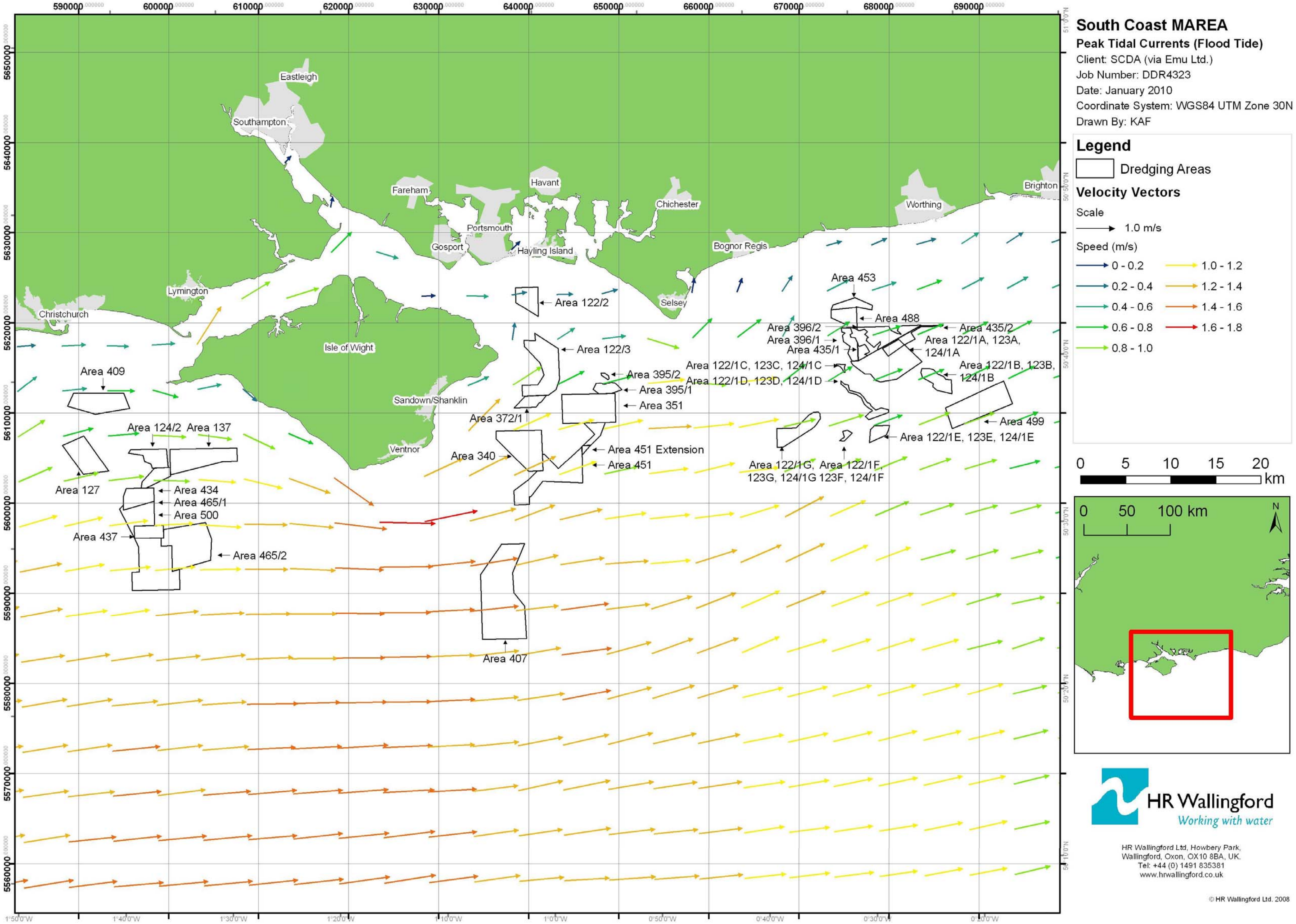

Figure 10 Predicted spring tide current patterns at peak flood

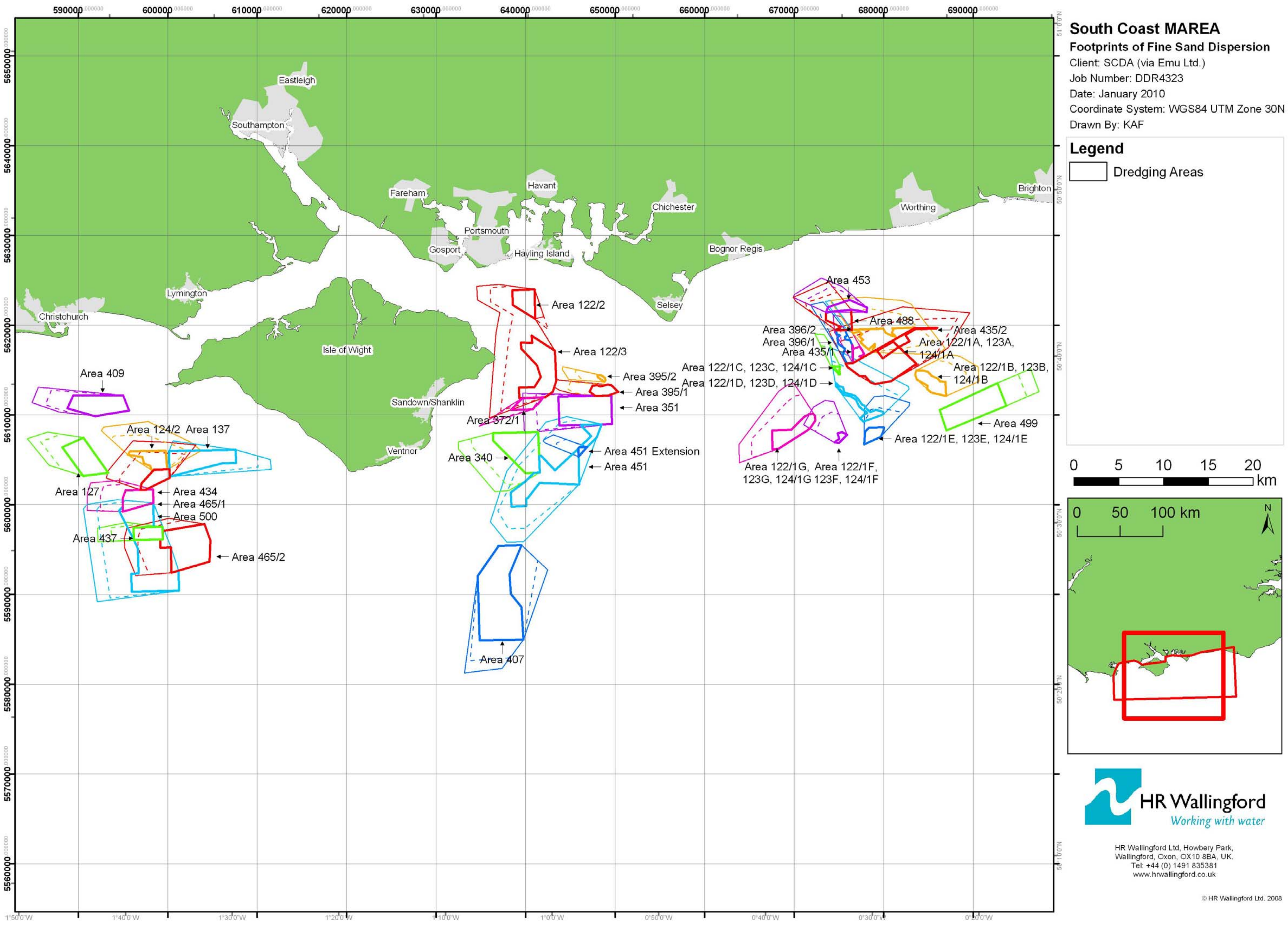

Figure 11a Predicted footprint of fine sand dispersion arising from proposed aggregate dredging
(thick continuous line: Dredging Area boundary; dotted line: footprint of bedforms; thin continuous line: footprint for changes in particle size distribution)

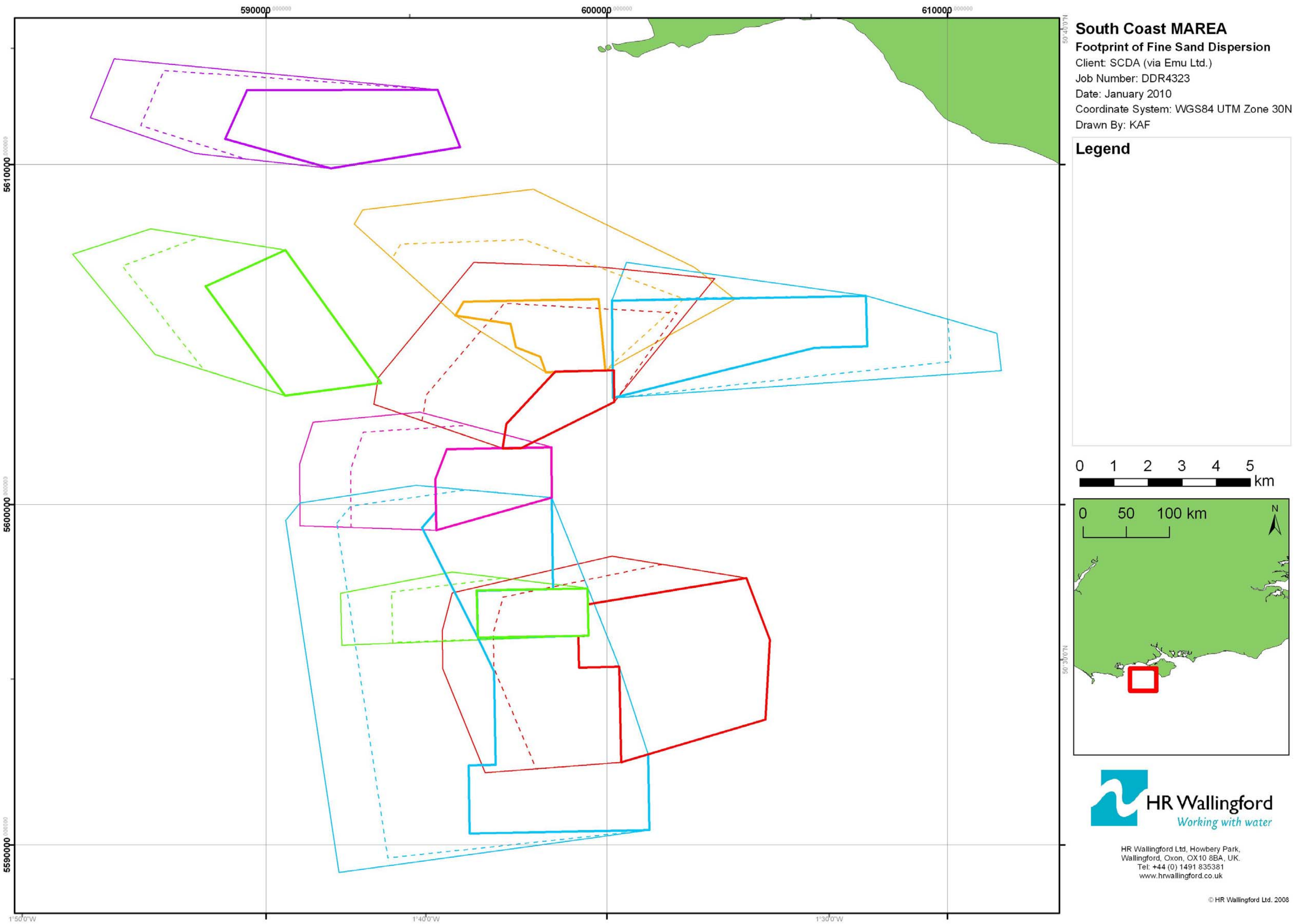

Figure 11b Predicted footprint of fine sand dispersion arising from proposed aggregate dredging (western area)

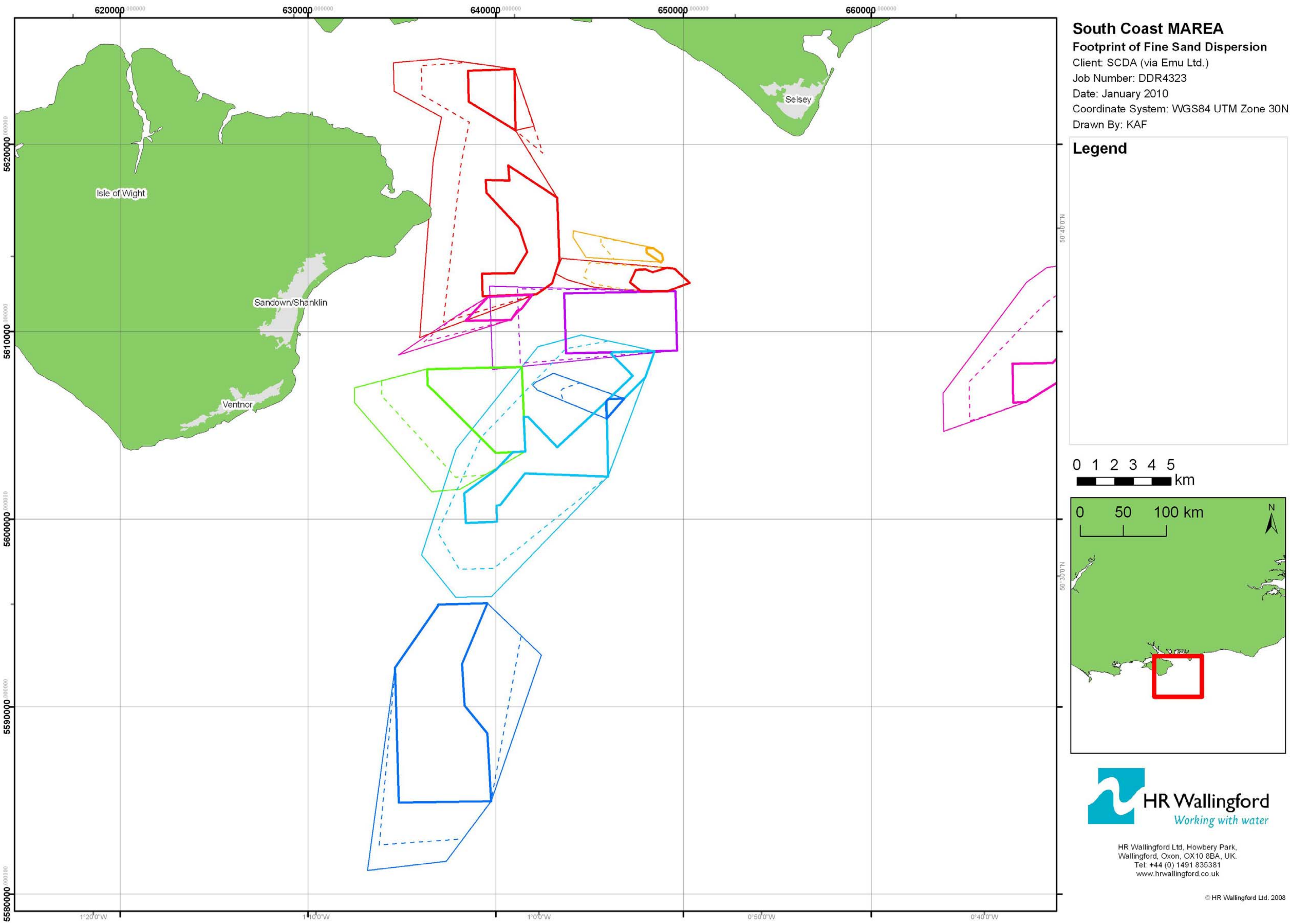

Figure 11c Predicted footprint of fine sand dispersion arising from proposed aggregate dredging (eastern area)

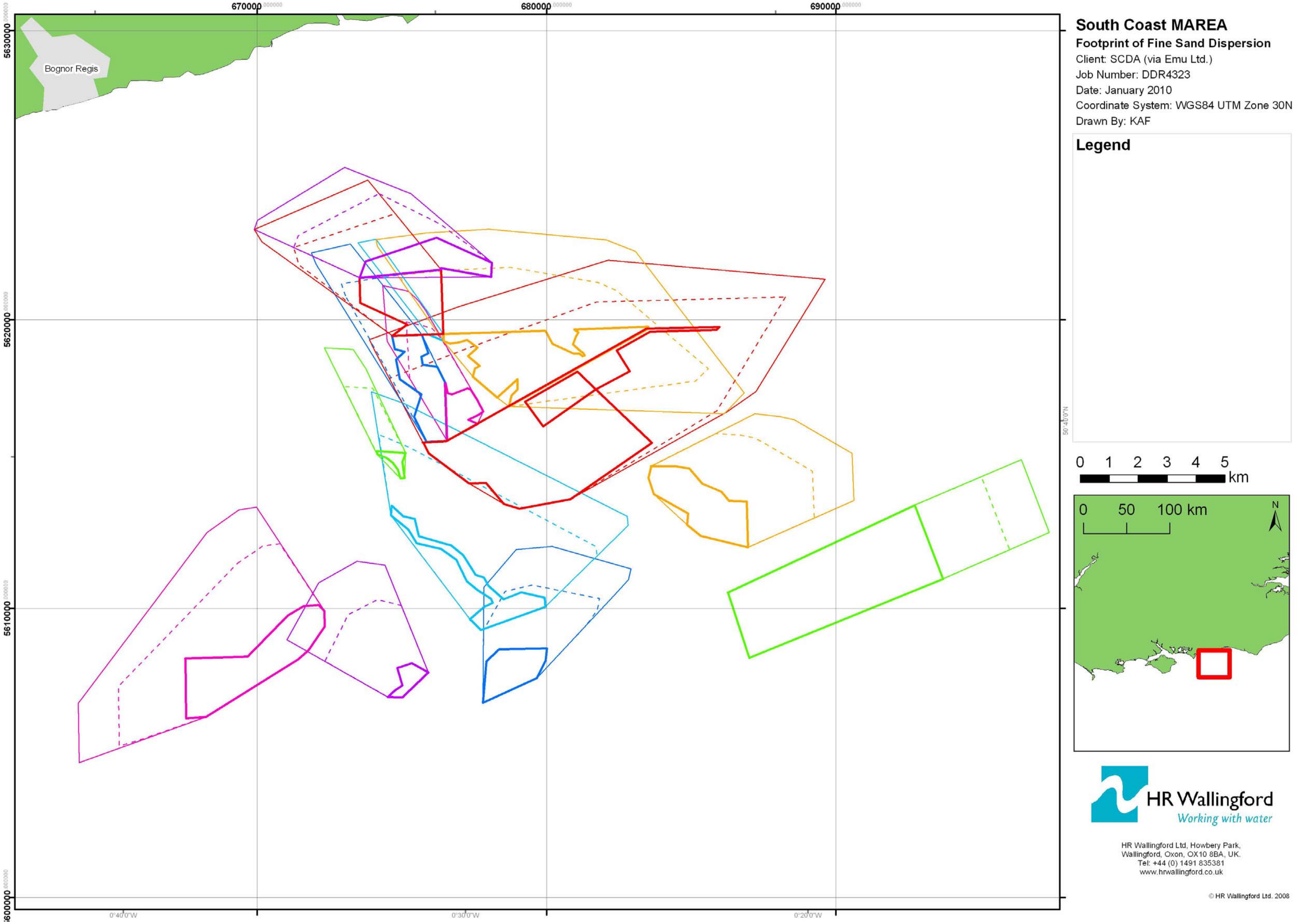

Figure 11d Predicted footprint of fine sand dispersion arising from proposed aggregate dredging (far eastern area)

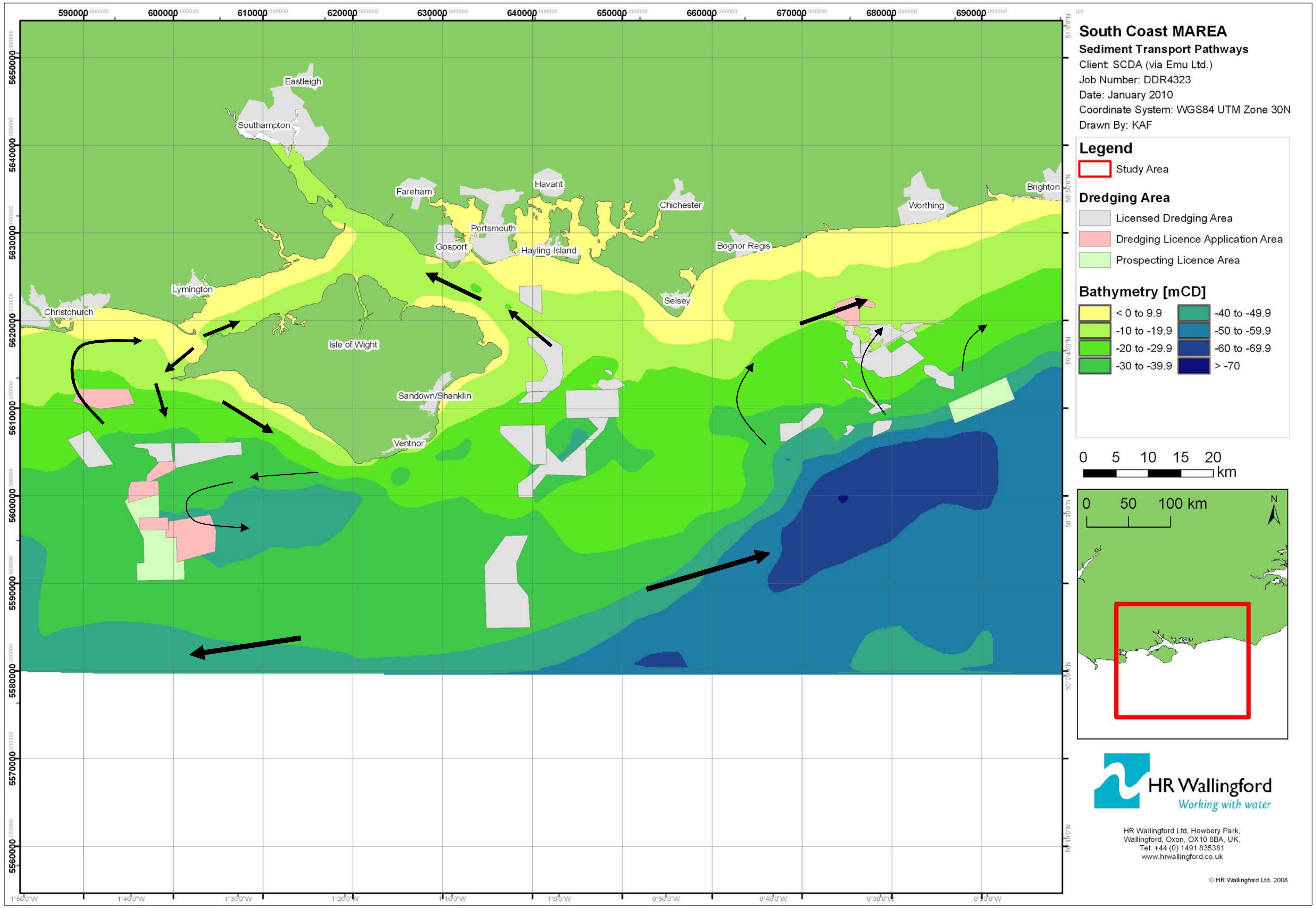

Figure 12 Summary of sediment transport pathways in the vicinity of the Isle of Wight
(thicker arrows indicate pathways which are more clearly defined)

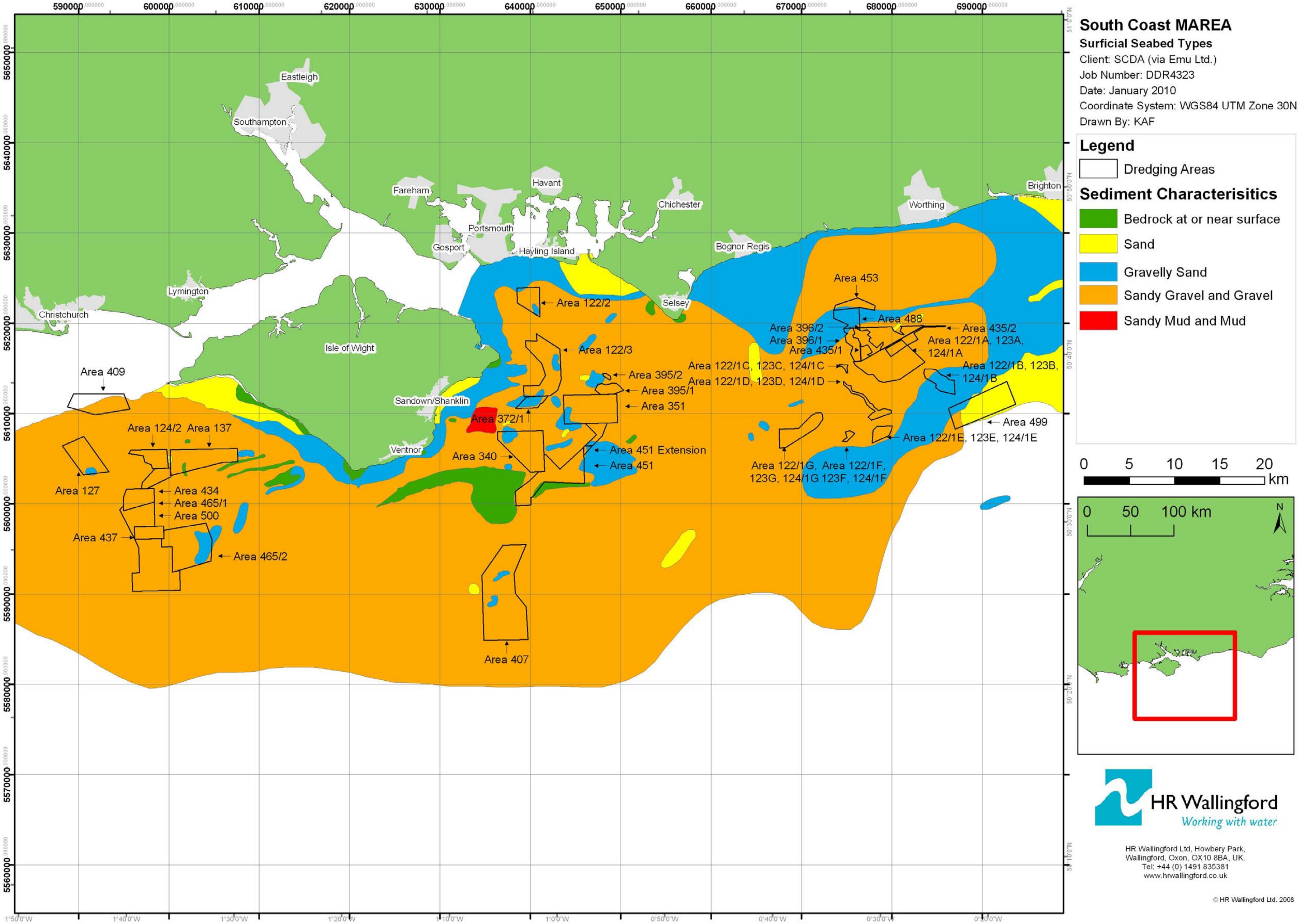

Figure 13 Surficial seabed types in the vicinity of the South Coast dredging region

Appendix 1 Description of the SEDTRAIL-RW(3D) dynamic plume module

INTRODUCTION

The dynamic plume module models the near-field mixing that occurs as the negatively buoyant jet of the overflow mixes with the surrounding waters.

INITIAL DESCENT

The descent of the dynamic plume is reproduced using a Lagrangian technique whereby a thin disc (which can be thought of as a section of a bent cone) of the released dynamic plume is tracked as it moves downward under the forces of momentum and negative buoyancy. The technique has been used for both dredger plume and outfall plume modelling (e.g. Koh and Chang, 1973, Brandsma and Divoky, 1976, and Lee and Cheung, 1990), though not for a moving source like the Trailer dredger which is the focus of this paper.

Entrainment of ambient water into the plume is modelled using the formulations of Lee and Cheung (1990) and accounts for both shear entrainment (i.e. as occurs in jets and dominates the initial stages of the dynamic descent) and forced entrainment (which dominates in the latter stages of descent and is due to the flow of ambient water into the plume). The increase in mass due to shear entrainment is given by:

$$\Delta M_s = 2\pi\rho_a b_k h_k E\Delta t\left|V_k - u'_{amb}\, cos\,\phi_k\, cos\,\theta_k\right| \qquad (1)$$

where:

$$E = \sqrt{2}\,\frac{\left(0.057 + \dfrac{0.554\sin\phi_k}{F^2}\right)}{\left(1 + 5\dfrac{u'_{amb}\cos\phi_k\cos\theta_k}{\left|V_k - u'_{amb}\cos\phi_k\cos\theta_k\right|}\right)} \quad \text{with} \quad F = \frac{\left|V_k - u'_{amb}\cos\phi_k\cos\theta_k\right|}{\left(g\dfrac{\Delta\rho}{\rho}b_k\right)^{1/2}} \qquad (2)$$

and where ΔM_s is the increase in plume mass due to shear entrainment, F is the local densimetric Froude number and is based on Schatzmann (1979, 1981), ϕ is the angle between the plume descent and the horizontal, θ_k is the angle between the jet descent and the x-axis, b_k is the radius of the dynamic plume element at time step k, h_k is the thickness of the dynamic plume element, ρ is the density of the plume, V_k is the speed of the dynamic plume element, ρ_a is the density of the ambient sea water, $\Delta\rho$ is the difference in density between the plume and the ambient water, Δt is the time step, and u'_{amb} is the current speed (in the coordinate system moving with the dredger) of the ambient fluid. The formula suits a wide range of flows and gives the correct buoyancy for a pure jet (no buoyancy just momentum) and a pure plume (no initial momentum, just a density difference) (Lee and Cheung, 1990).

Lee and Cheung (1990) also derived an equation for forced entrainment arising in a three dimensional trajectory. The resulting entrainment is as follows:

$$\Delta M_k = \rho_a u'_{amb}\, h_k b_k \left[2\sqrt{sin^2\,\phi_k + sin^2\,\theta_k - (sin\,\phi_k\, sin\,\theta_k\,)^2} + \pi \frac{\Delta b_k}{\Delta s_k} cos\,\phi_k\, cos\,\theta_k \right. \tag{3}$$

$$\left. + \frac{\pi}{2} b_k \frac{(\cos\phi_k \cos\theta_k - \cos\phi_{k-1}\cos\theta_{k-1})}{\Delta s_k} \right] \Delta t$$

where ΔM_k is the increase in plume mass due to forced entrainment, s_k is the distance travelled by dynamic plume in timestep k, and Δb_k is the change in plume radius, $b_k - b_{k-1}$.

There are three different contributions to forced entrainment which are all significant at different times suggesting that none of these terms can be neglected. The first term represents the forced entrainment due to the projected area of the crossflow while the second and third terms represent corrections due to the growth of the plume radius and the curvature of the trajectory (Frick 1984, Lee and Cheung, 1990). The descent phase is terminated either when the plume impinges on the bed or when the vertical (downward) speed becomes less than zero (as may happen in strongly stratified conditions) or when the dynamic plume becomes sufficiently diffuse that it becomes a passive plume.

Two experiments were chosen for the calibration of the dynamic descent – Chu and Goldberg (1974) and Chu (1975). In the case of these experiments, the plume was simulated by injecting dyed saline solution vertically downward/upward into a flume through a hypodermic needle/injection pipe. Conditions corresponded to Reynolds numbers of 2,500-11,000. Figure 1 shows a comparison of the model predictions of the path of the plume with the results of test 2001 from Chu and Goldberg (1974). In this particular test a dense fluid ($\Delta\rho$=115kg/m^3) was injected (at the surface) with an initial velocity of 0.3cm/s while the current of the ambient fluid in the channel was 0.04cm/s. For the sake of continuity with Chu and Goldberg's paper. The observations and model predictions of vertical height, Z, and horizontal distance X of the plume are scaled with respect to the buoyancy length scale, l_b , given by,

$$l_b = \frac{4F_0}{\pi \rho_a u_{amb}^3} \tag{4}$$

where F_0 is the buoyancy flux given by $F_0 = {}^1/_4\, \pi D^2 g(\rho - \rho_{amb}) u_{amb}$, D is the initial diameter of the release, and u_{amb} is the current speed of the ambient fluid in the channel.

Figure 2 compares the model predictions of the path of the plume with the results from Chu (1975). The test consisted of the injection upwards near the bed of a 3% saline solution through an injection pipe of 1.0cm diameter at 5cm above the channel bottom. In this example (Test 5004) the initial discharge velocity of the dense fluid was 8.36cm/s and the current speed of the ambient fluid in the channel was 0.5cm/s. The observations and model predictions of the vertical height, Z, and horizontal distance, X, are scaled by the diameter of the release (D = 1.0cm).

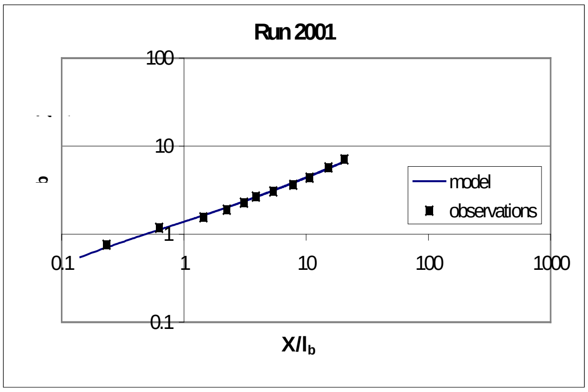	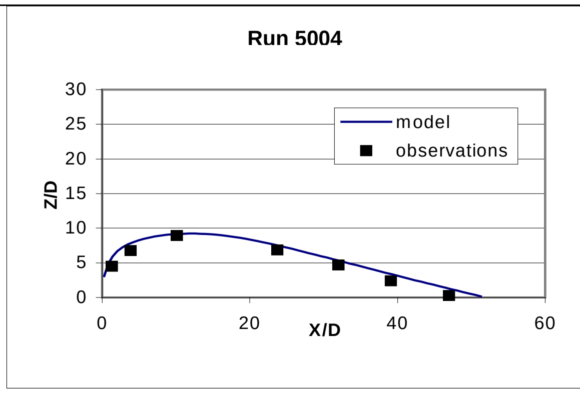
Figure 1. Comparison of dynamic plume plume model with the results of Chu and Goldberg (1974). Definitions given in text.	Figure 2. Comparison of dynamic model with the results of Chu (1975). Definitions given in text.

COLLAPSE ON BED

Collapse onto the bed is reproduced using an equation attributed to von Karman. For dense thin layers, on a horizontal bed, the horizontal speed of propagation of the front of the resulting density current along the bed, is related to the thickness of the density current and the gravitational acceleration modified for buoyancy (Hallworth et al, 1998).

Including friction, to first order in $\left(\frac{C_D x_f}{h_f}\right)$ (Spearman et al, 2003) , yields,

$$u_f \approx F\left(\frac{g' h_f}{1+\frac{4C_D x_f}{7h_f}}\right)^{1/2} \qquad (5)$$

where u_f is the horizontal speed of propagation of the front of the resulting density current along the bed, h_f is the thickness of the density current, $g' = g^{\Delta\rho}/_{\rho}$ is the gravitational acceleration modified for buoyancy, F is the Froude number of the flow, taking a value of approximately 1.19 (Huppert and Simpson, 1980), C_D is the drag coefficient and x_f is the half-length of the density current (from its centroid to the front of the current).

In the model the propagation of the current is achieved by repeated application of Equation 20, assuming a flat or near flat bed level in the vicinity of the density current, keeping track of the concentrations of each sediment fraction in the plume and allowing the sediment particles to settle out continuously. A 'box-model' approach has been used to describe the shape of the density current - ie the density current height is assumed constant over the length of the density current. Box model approaches have been shown to give a good approximation to the collapse of the density current (Hallworth et al, 1998). As the density current lengthens continuity of mass implies that the thickness of the density current reduces. All of the fractions are considered to be uniformly mixed, vertically and along the length of the current. Deposition onto the bed is calculated by keeping a running total of the deposition flux for each fraction from the density current. This sediment distributed over the bed following Bonnecaze et al (1996), who developed the following equation for the total density of sediment deposited on the bed,

$$m_{bed}(x) = \rho_{part} A^{1/2} \sum_i \varphi_{i0} \beta_i^{2/5} W(\beta_i^{2/5} x / A^{1/2}) \tag{6}$$

where x is the distance from the point of impact, A is the initial cross-sectional area of the plume (equal to $l_0 h_0$ where l_0 and h_0 are the initial length and depth of the density current), W is given by $W(x)=0.820/(1+0.683x^2+0.017x^8)$, ρ_{part} is the density of the particulate plume, φ_{i0} is the initial volume of the *ith* sediment fraction expressed as a proportion of A, β_i is given by $ws_i / \left(g_0'^{1/2} A^{1/4}\right)$ and ws_i is the settling velocity for particles of the *ith* sediment fraction.

The settling rate is calculated using Soulsby's (1997) formula for particles greater than 62 microns (fine sand and bigger) in size,

$$w_s = \frac{\upsilon}{d}\left[\left\{10.36^2 + 1.049 D_*^3\right\}^{1/2} - 10.36\right] \text{ where } D_* = \left[\frac{g(s-1)}{\upsilon^2}\right]^{1/3} d \tag{7}$$

where ν is the kinematic viscosity of water, s is the specific gravity of the sediment particle, and d the particle diameter. For particles less than 62 microns in size (silt sized and smaller) the common power law relationship depending on concentration is used (e.g. Whitehouse et al, 2000) which represents the process of flocculation by increasing settling velocity with concentration,

$$w_s = aC^b \tag{8}$$

where a and b are user defined constants. These will be selected on the basis of field data, or where this is not available, the literature.

The bed collapse phase ends when the turbulence within the density current has reduced sufficiently to allow mixing with ambient waters at which point the density current can be regarded as a passive plume. The density current will not mix with the overlying water unless the flux Richardson number, R_f , becomes less than a value between 0.1 and 0.2 (Monin and Yaglom, 1971, Turner, 1973). The formulation for the Richardson number used in the model is,

$$R_f \approx \frac{g' h_f}{u^2} \tag{9}$$

This formulation is used by other researchers (e.g. Parker et al, 1987, Odd and Cooper, 1989) and is more often referred to as a bulk Richardson number.

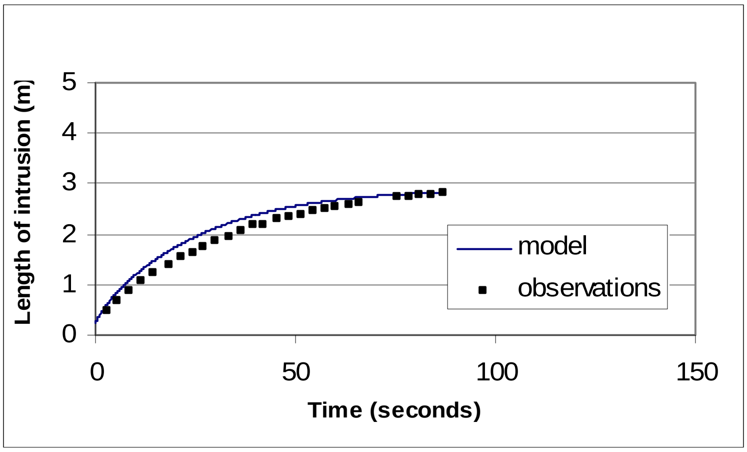

Figure 8. Comparison of bed collapse model prediction of progress of density current front over time with the results of Hallworth et al (1998) for particulate currents. Figure shows observed and predicted collapse of a particulate density current (ie suspended sediment) generated by releasing water containing silicon-carbide particles of size 37μm with an initial plume excess density above the ambient water of 100kg/m^3.

The experiments chosen for the validation of the collapse of two-dimensional dynamic plumes resulting from impact on the bed are those undertaken by Hallworth et al (1998). These include the intrusion of compositional currents (ie formed by dissolving salt into water), particle currents (ie those formed by suspended sediment) and both types of currents under the influence of ambient current flow. Figure 8 compares the model predictions of the collapse of the density current and observations by Hallworth et al (1998).

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