# Anglian Offshore Dredging Association

## Marine Aggregate Regional Environmental Assessment: Tidal Flow and Sediment Transport Study

## Technical Note DDR4472-05

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# 1. Introduction

A Marine Aggregates Regional Environmental Assessment (MAREA) is being undertaken for the Anglian Offshore Dredging Association (AODA) to inform both new marine aggregate dredging licence applications and licence renewal applications offshore from the coastline of Suffolk and Norfolk. The study region (Figure 1) covers the area offshore of the coastline between Cromer and Orford Ness to a distance of around 10km offshore of the Great Yarmouth block of dredging areas.

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 within the study region (Figure 1 and Table 1) by the companies comprising AODA (British Dredging Ltd, CEMEX UK Marine Ltd, Hanson Aggregates Marine Ltd, Sea Aggregates Ltd, Tarmac Marine Dredging Ltd (formerly United Marine Dredging Ltd) and Volker Dredging Ltd).

**Table 1 Dredging Areas**

| Licence Area | Status | Company |
|---|---|---|
| Area 202 | Licence | Hanson Aggregates Marine Ltd |
| Area 212 | Licence | Hanson Aggregates Marine Ltd |
| Area 228 | Licence | Volker Dredging Ltd |
| Area 240 | Licence | Hanson Aggregates Marine Ltd |
| Area 242 | Licence | Hanson Aggregates Marine Ltd |
| Area 251 | Licence | British Dredging Ltd |
| Area 254 | Licence | Tarmac Marine Dredging Ltd |
| Area 296 | Licence | Tarmac Marine Dredging Ltd |
| Area 319 | Licence | British Dredging Ltd |
| Area 328 A | Licence | Hanson Aggregates Marine Ltd |
| Area 328 B | Licence | Hanson Aggregates Marine Ltd |
| Area 328 C | Licence | Hanson Aggregates Marine Ltd |
| Area 360 | Licence | CEMEX UK Marine Ltd |
| Area 361 A | Licence | Hanson Aggregates Marine Ltd |
| Area 361 B | Licence | Hanson Aggregates Marine Ltd |
| Area 361 C | Licence | Hanson Aggregates Marine Ltd |
| Area 401/2 A | Licence | Hanson Aggregates Marine Ltd |
| Area 401/2 B | Licence | Hanson Aggregates Marine Ltd |
| Area 430 | Licence | CEMEX UK Marine Ltd<br>Tarmac Marine Dredging Ltd |
| Area 454 | Application | CEMEX UK Marine Ltd |
| Area 494 | Application | Tarmac Marine Dredging Ltd |
| Area 494 | Prospecting | Tarmac Marine Dredging Ltd |
| Area 495A | Application | Hanson Aggregates Marine Ltd |
| Area 495B | Application | Hanson Aggregates Marine Ltd |
| Area 496 | Application | Sea Aggregates Ltd |

The past, current and planned future aggregate dredging areas within the study region are also shown in Figure 1. These dredging areas have been a major source of sand and gravel for the construction industry in south-eastern England, as well as for beach recharge along the East Anglian coastline.

In this figure, the boundaries of the dredging areas are coloured differently to show whether they have been already been relinquished, are currently licensed, are proposed new areas for which an extraction licence has already been applied or, finally, are possible future extraction areas which are currently being prospected.

AODA appointed HR Wallingford Ltd to carry out an assessment of the effects of past and proposed future aggregate dredging on the physical environment within this study region as a part of this MAREA, which was being compiled by Emu Ltd.

## 1.1 STUDY OBJECTIVES AND SCOPE

This report considers the effects of changes in seabed bathymetry arising from aggregate dredging, on tidal currents and on the transport of sediment over the seabed that is caused by these currents. Previous studies of planned offshore aggregate dredging around the UK coastline have shown that any predicted changes caused to tidal currents are generally small and restricted to the areas within and surrounding each individual extraction area. Measurable changes in currents have not previously been predicted to occur anywhere further away from any dredging area than the maximum dimension of the area itself.

Since aggregate dredging areas lie well offshore from the coastline, it has generally not been necessary to carry out specific modelling of any changes in tidal currents in Coastal Impact Studies. In some cases, however, aggregate dredging has been proposed in areas close to pipelines or other features of interest on the seabed. The same methods that were used in these situations to examine the effects of dredging within a single area on tidal flows have been applied in this regional study. However, in this report we have examined the cumulative effects of both past and proposed future dredging in all the licensed and proposed extraction areas in the study region.

Substantial changes in tidal flows may affect the rates and directions of the sediment transport that those currents cause. In previous studies, the effects of aggregate dredging on sediment transport have been found to be localised and only noticeable within or very close to the particular dredging area. Certainly, any effects of aggregate dredging on sediment transport rates have not previously been predicted to affect UK coastlines. However, because there are numerous aggregate dredging areas in close proximity within the study region, and there may be plans for other development projects near to these areas, the predicted changes in tidally-induced sediment transport have been investigated in this report.

It should be remembered, however, that this modelling of tidal flows and sediment transport has been carried out, on a broad scale, for the whole study region shown in Figure 1. Importantly, this report also predicts where there will **not** be changes in these quantities as a result of past and planned future aggregate dredging.

However, this report also indicates where such potentially significant changes may occur. These generally are restricted to within, or to quite small areas close to, the boundaries of the individual extraction areas. If there are specific sensitivities in these areas, for example natural or man-made features that might be affected by changes in flows or sediment transport, these will need to be studied further when an application is made for an extraction licence for the specific dredging area (or areas) closest to the features of interest. These more specific studies will allow the existing seabed and the proposed dredging plans to be represented in greater detail, and hence provide a better assessment of whether the changes in flows or sediment transport rates could have a significant environmental impact.

### 1.2 CONTENTS OF THE REPORT

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

| Chapter | Contents |
|---|---|
| 2 | This chapter describes the numerical modelling procedures used to predict tidal flows, and the sediment transport that they cause. It explains the choices of the models that were used, the representations of the seabed bathymetries and the model runs carried out. |
| 3 | This chapter presents the results from the modelling. It interprets these in the context of the likely changes in the seabed surrounding the dredging areas. |
| 4 | Still within the context of possible changes in tidal flows and the associated sediment transport, chapter 4 discusses the potential interactions between offshore aggregate dredging and other uses of, or developments within, the study region. |
| 5 | Finally, chapter 5 presents and interprets the main conclusions from the modelling. In particular, this chapter indicates whether results from this regional study are sufficient to inform specific licence applications within the study region, or if a further and more detailed assessment of the predicted changes may be required at that time. |

# 2. *Modelling procedure*

### 2.1 INTRODUCTION

The tidal flow and sediment transport modelling carried out and described in this report has been based upon a previous and very detailed project known as Phase 2 of the Southern North Sea Sediment Transport Study (SNSSTS2) (HR Wallingford *et al.*, 2002). That project was carried out for a consortium of local coastal authorities, the Environment Agency, English Nature (now Natural England) and the British Marine Aggregate Producers Association (BMAPA).

Sediment movements in the southern North Sea influence the eastern English coastline through supplying or removing beach material, so it is important to understand these processes to improve our understanding of coastal evolution and hence be better able to predict and manage such changes. More relevant to this study, understanding sediment movements is important in assessing the possible effects of proposed offshore aggregate dredging on the coastline or on other offshore developments or operations.

Accordingly, SNSSTS2 was designed to provide a detailed appreciation and broad understanding of sediment transport along the eastern coastline of England between Flamborough Head in Yorkshire and North Foreland in Kent, on the south side of the Thames Estuary. This study was undertaken between 2000 and 2002 by a research consortium comprising HR Wallingford, Cefas (Lowestoft Laboratory), the University of East Anglia, Posford Haskoning and an independent consultant, Dr Brian D'Olier.

The outcomes of SNSSTS2 are presented in HR Wallingford *et al*. (2002). This report is supported by 15 Appendices containing detailed information on various facets of the study (see *http://www.sns2.org/theproject.html*).

Much of the background information presented in SNSSTS2, i.e. on the bathymetry and sediment distribution in the Southern North Sea, on the propagation of tides and surges and on the sediment movements over the seabed is very relevant to the present MAREA. Since the SNSSTS2 project outputs are freely available (see *http://www.sns2.org/project-outputs.html*) there is no advantage in reproducing the baseline assessment of tidal flows and sediment transport presented in the SNSSTS2 report.

What SNSSTS2 did not do, however, was to specifically predict the effects of past aggregate dredging, or the possible effects of proposed future aggregate dredging, on tidal flows and on sediment transport within the southern North Sea. This report describes how the modelling carried out in SNSSTS2 has been extended to examine these potential effects of such dredging within the MAREA study region.

## 2.2 MODELLING APPROACH

### *2.2.1 SNSSTS2 regional model*

In SNSSTS2, a range of methods and approaches were used to provide information on sediment transport over the seabed in the study region, including data collected as part of a consultation exercise, interpretation of new field data and seabed maps and the application of numerical modelling methods.

The SNSSTS2 numerical model studies were aimed at providing complementary information to observations and measurements of sediment transport. These models had the advantage of allowing the various hydrodynamic and sediment transport processes to be represented as required, and the sensitivity of the sediment transport patterns to these processes to be determined. Both area and profile models were used in SNSSTS2. The area models simulated sediment transport processes in two horizontal dimensions, for a range of typical conditions, whereas the profile models were used to analyse sediment transport along and close to the coast, incorporating the effects of a wide range of wave conditions as well as tidal effects. In the present study, it is the movement of sediment over the seabed in and around the dredging areas that needs to be considered. Since these areas are in deep water, where waves alter the rates of sediment transport rather than its direction, we have adapted the area models of tidal flows and sediment transport used in SNSSTS2 to predict the effects of aggregate dredging within the MAREA study region.

The regional modelling carried out in SNSSTS2 was based on HR Wallingford’s existing Southern North Sea area model which extends from north of Flamborough Head in the North Sea to Plymouth (in Devon), and stretches across the English Channel and North Sea to the European mainland. This is a 2D depth-averaged flow model with the capability to simulate tidal and wind driven flows, wave action and sediment transport. Choosing to set the boundaries this far away from the study region enabled good resolution of the tidal propagation through the Straits of Dover into the lower part of the Southern North Sea and towards the coastline of East Anglia from the deeper water areas on the northern part of the North Sea as well..

The computational technique used to simulate tidal flows in SNSSTS2 is a finite element model developed by LNH-EDF of France and known as TELEMAC. This software has been used and developed at HR Wallingford for many years and for many comparable applications. TELEMAC has the significant benefit of allowing fine model resolution in specified areas, which can simulate flows over a very large area but allows a more detailed representation of the flow field in a sub-area of particular complexity or interest. More details of this model are provided in Appendix 2 to this report and at the website (www.telemacsystem.com).

In this study, as in SNSSTS2, the overall tidal flow model was run by supplying a time history of water levels along the two open boundaries – north and east in the North Sea and in the south-west approaches of the English Channel. These water levels were determined from a harmonic analysis using published information from the national British Oceanographical Data Centre (BODC) database. Calibration and validation of this model has been carried out in previous studies by comparing predicted water levels and currents with observations made by the UK Admiralty at a large number of locations along the coastline, and offshore of them, within the study region. A fuller description of the comparisons between predicted and measured tidal propagation can be found in Appendix 12 of HR Wallingford *et al.* (2002), and we have not repeated this in the present report.

### 2.2.2 Model refinements for the present study

The very large spatial extent of this model means that it is not possible to represent the seabed morphology at high resolution everywhere. However as in the present study, when attention needs to be focussed on a particular area, in the southern North Sea, , it is possible to adjust the model grid spacing in that area to provide more detailed and accurate predictions of tidal flows and sediment transport patterns.

The model grid used in the present study was established with much smaller (triangular) finite elements near the existing and proposed dredging areas than further offshore. This refined model mesh allowed the seabed in and around the dredging areas to be well reproduced, and allowed us to adjust the bathymetry to represent the effects of past and proposed future dredging within these areas (see Section 2.3). This also means that the extent and magnitude of the likely changes in tidal flows and sediment transport in and around each of the dredging areas can be predicted in detail, while still allowing a regional overview of the combined effect of all such dredging in the MAREA study region.

It should be noted, however, that there was no scope in the present study to validate predicted tidal currents in and around the dredging areas following the refinements to the existing model, for example by using measurements. This may be advisable if there is a concern that the changes in flows identified in this regional and broad-scale modelling study could have an adverse effect on the environment or other features of interest close to a dredging area that would require a more detailed consideration at a later date.

### 2.2.3 Sediment transport

Any changes in tidal currents, predicted by the TELEMAC flow model as a result of past or planned future aggregate dredging, will alter the sediment transport that the tides cause. The extent and magnitude of changes to such transport, however, will also depend on the type of sediment on the seabed (i.e. the size and weight of the particles), on the morphology of the seabed (i.e. its slope and roughness) and on the particular tidal conditions. In any given water depth fine-grained sand, for example, is much more likely to be disturbed and transported by tidal currents than coarser sand or gravel.

Sediment transport is also much weaker when tidal ranges are smaller, i.e. during neap tides rather than spring tides. The effects of winds and variations in atmospheric pressure in the North Sea also affect tidal levels and currents, particularly when storm surges occur. It was not practicable to consider a wide range of different tidal conditions and their effects on sediment transport in this broad-scale regional study.

Also it was not necessary to model the many factors affecting sediment since the emphasis was on determining the likely extent and magnitude of any changes caused by aggregate dredging. The approach chosen in this study, therefore, seeks to identify where there may be noticeable and frequent changes in sediment transport as a result of aggregate extraction. In this way, attention can be drawn to those areas where such dredging may have a potentially significant effect on the environment and, conversely, identify other areas where no changes are predicted to occur.

The sediments on the surface of the seabed in the study area vary considerably from area to area, and it is impractical for an REA to examine the transport of all of these many different types of sediment. In order to interpret possible changes to sediment transport, in the context of the potential effects on either the natural environment or on man-made feature or activities, it was decided to err on the side of caution in the choice of the tidal conditions and sediment grain sizes studied. If in some areas, for example close to a coastline, the changes in predicted sediment transport under these assumptions were zero, or too small to be a concern, then it can be concluded that this would also be the case when tidal ranges were smaller or if the sediment particles in those areas were larger and hence less affected by changes in tidal current speeds. For this reason, we have chosen to consider the transport of medium sized sand with a median grain diameter of 0.4mm, based on analysis of BGS data. Sensitivity modelling using a median grain diameter of 0.3mm and 0.5mm was also undertaken. Over most areas of the study region where aggregate dredging takes place, the seabed sediments tend to have a proportion of gravel and will be much less mobile than this medium sized sand. The effects of dredging on the rates of transport of that coarser sediment will be, in reality, smaller than predicted by our numerical modelling.

Sediment transport over the seabed in the AODA region was simulated using the HR Wallingford SANDFLOW model. This is a non-equilibrium finite element sediment transport model that simulates the total load (suspended and bedload), with input flows from TELEMAC. Further details on this model can be found in Appendix 3.

This model has the capacity to represent the additional effects of wave action on sand transport; however, we have not attempted to do this in the present study. While waves can affect the rates of sediment transport, the predictions of the spatial extent and pattern of changes in transport caused by aggregate dredging will not be very different if calculated with or without the effects of wave stirring. SANDFLOW has the capability of masking discrete areas of the seabed with deposits of a chosen grain size, and other areas devoid of sediment. However, in this study, all the model simulations were performed assuming an abundant supply of material over the whole study region. This approach is preferred because it results in model predictions that are not dependent on this initial starting condition. However, this does require care to be taken when interpreting the model results.

The SANDFLOW model can output the sediment flux at any instant within the period simulated. However, for the present study it was considered more useful to provide information on the net sediment transport over a tidal cycle to focus on the longer-term transport rates and pathways. It is this net transport, also known as the residual sediment flux, which has been analysed in detail in this report. This approach is appropriate when considering the possibility of aggregate dredging leading to deposition on or erosion of sediments from the seabed surrounding the extraction areas. In general, the possibility of changes in the seabed morphology, for example scour or siltation, is usually more of a concern than changes in sediment transport rates themselves; increases in net transport suggest possible erosion (scour) of the seabed while reductions may lead to deposition (siltation) of sediment.

## 2.3 SPECIFYING THE SEABED LEVELS IN THE STUDY REGION

### *2.3.1 Introduction*

Aggregate, i.e. sand and gravel, has been extracted from the seabed offshore from the East Anglian coast for many years, and the presently licensed dredging areas are shown in Figure 1. When the MAREA is complete, the AODA companies will apply individually to renew their extraction licences, several of which expire in the next few years. In addition, some companies are considering making applications for extraction licences for new areas within the study region.

The purpose of this report is to analyse how past and proposed future aggregate dredging in the study region, on its own, has altered or might in future alter tidal flows and the associated transport of sediment over the seabed. In order to concentrate on just this cause of change, representations of seabed levels in the region were produced which differed from each other only in those areas where aggregate dredging has taken place or is proposed in the future.

To assess the impact of aggregate dredging on tidal flows, three representations of the bathymetry within the study region were provided to HR Wallingford by Emu Ltd. The three representations of the bathymetry used are:

- A "baseline" bathymetry, in which the seabed levels in each existing or relinquished dredging area represent the situation before any dredging was started. We refer to this as the "pre-dredged" bathymetry.
- A "present day" bathymetry in which seabed levels in each existing or relinquished dredging area have been established using the latest survey of those areas (Figure 1). The differences in bed levels between this and the "pre-dredged" bathymetry will very largely be the result of past dredging in existing or relinquished licence areas.
- A "post-dredging" bathymetry in which seabed levels in each existing and proposed new licence area at the end of a future period of dredging have been defined (see section 2.3.3). These have been predicted by combining the present-day bed levels and the present plans of AODA members for extraction in the medium term future.

For the assessment of changes in tidal flows and sediment transport presented in this report, we have examined the effects of all past and proposed future dredging together. As a result, only the first and third of these bathymetries were used in the modelling of tidal flows and associated sediment transport. Despite this, it is helpful to describe how all three of the bathymetric representations were produced, and this the subject of the following two sub-sections.

### *2.3.2 Representing the past and present-day bathymetries*

Starting first with the representation of the past and present-day bathymetries, it is important to note that the sole purpose of this report is to investigate how past and proposed future aggregate dredging might alter tidal flow conditions, and the associated sediment transport, in the study region. In order to concentrate on just this cause of change, therefore, these two bathymetric representations were produced so that they differed from each other only in those areas where aggregate dredging has taken place or is currently proposed. "Present day" bed levels in existing dredging areas were obtained from the aggregate dredging companies, who also provided information on bed levels in those areas before dredging started. The "pre-dredging" bed levels were produced using older surveys, or information on patterns and amounts of past dredging or a combination of the two.

The differences between these bathymetric grids are not sufficient to be clearly visible in the same type of presentation as shown in Figure 1. Because of this, therefore, Figure 2 has been produced to show the changes in depths in the various dredging areas. The differences in bed levels in these two bathymetries are very largely the result of past dredging, but in some cases, small depth changes are found in parts of the licensed areas where no dredging has taken place. This is either a result of natural sediment transport processes altering the seabed, for example the movement of sand waves or sandbanks or because of slight differences in the interpolation of often coarsely-spaced depth soundings in the older survey data that has been used.

It is important to note that neither of these bathymetric data sets can be ascribed to any particular year. The most up-to-date digital data obtained from the Hydrographic Office, for example, is a collage of information from many different surveys carried out over the last 10 to 15 years (and possibly even longer ago in some areas). Similarly, the information provided by the AODA members is from surveys that were carried out in different years in different dredging areas, reflecting the fact that dredging was started in the various areas at different times.

In addition, even if it were possible to obtain a complete and detailed survey of the seabed over the whole region at some date before dredging started, and another very recent similar survey of present day bed levels, many of the changes in depths between these dates would be caused by natural processes rather than by aggregate dredging. The numerical predictions of changes in tidal currents between these two dates would not then discriminate between the effects of aggregate dredging and those caused by natural changes, such as the movement of sandbanks, or by other human activity, for example dredging navigation channels and depositing sediments arising from such dredging onto designated areas on the seabed.

Therefore in the remainder of the study region, i.e. outside the past and present future aggregate dredging areas, the bed levels in the study area were assumed to be the same for both the past and present bathymetries and were taken from the most recent digital bathymetric data set available from the UK Hydrographic Office (via Seazone Solutions Ltd).

### 2.3.3 Representing future dredging

For future dredging, whether from existing or possible new areas, the AODA members have defined water depth increases that might be brought about from proposed dredging to the year 2030 (approximately) within each dredging area. In general, these changes have been based on their accurate information on the depths and spatial extent of the sand and gravel deposits. In some areas, the depth changes proposed would remove almost all of this sediment. Figure 3 shows changes in depth that would be caused by these plans for further dredging in this sub-region (i.e. the post-dredging minus the present-day bathymetry). Within any individual area, the future depth changes shown in Figure 3 are considered realistic in terms of the known resources of sand and gravel, and are achievable within the expected lifetime of any new extraction licences. This applies for both proposed new extraction areas and for existing areas from which further dredging is planned.

Achieving all the depth changes shown in Figure 3 by about 2030 would result in a much larger volume of aggregate being extracted than is expected to be achieved in reality, based on past rates of dredging in this region. In this particular study, therefore, the predicted changes in tidal flows or sediment transport rates in and around any individual dredging area could occur. However, this would mean that changes around another area, or areas, are likely to be over estimated.

For this regional study, the assumed lowering of the seabed in this area is based on an estimate of the amounts removed and likely maximum depth of dredging in this area. More detailed extraction plans for this area will be developed before a formal extraction licence application is submitted. If these more detailed plans propose no greater depths or extent of extraction than assumed in this study, the tidal flow and sediment transport modelling results presented in this report will still be valid.

Looking forwards, the actual amounts dredged in each individual area by about 2030 will, in reality, depend firstly on the scale of applications made for licence extensions (for existing areas) or for new areas, secondly on the conditions that may be placed on permissions to dredge in these areas and thirdly on the proportion of the permitted extraction that actually takes place during the lifetime of any licence (typically up to 15 years). Some of these licences may be granted within a few years from now while other licence applications may take much longer to prepare and then be determined.

For the remainder of this “post-dredging” bathymetry, i.e. outside the past, present and possible future aggregate dredging areas, the bed levels in the study region were assumed to be the same as for the past and present-day bathymetries i.e. the most recent digital bathymetric data set available from the UK Hydrographic Office.

Finally, the three bathymetric data sets were then compared and checked to ensure that in each area the changes in bed levels between pre-dredging and present day, and between present-day and post-dredging were a good representation of the past and the presently-planned future dredging respectively. Figure 4 shows the difference between post-dredging and pre-dredging levels.

## 2.4 CHOICE OF INPUT CONDITIONS

The final step in the establishment of the modelling process was to choose the conditions to be input to the flow and sediment transport model. These choices are explained in Sections 2.4.1 to 2.4.4.

### 2.4.1 Selection of tidal range

As mentioned in Section 2.2, the main objective of this sediment transport modelling is to identify whether aggregate dredging is likely to alter sediment transport patterns on a regular basis, and to provide guidance on which areas of the seabed might experience deposition of sediment, or where erosion and scouring might take place.

For this purpose, we have therefore chosen to consider a single tidal range equivalent to that of a mean Spring tide. This same tidal range was used for much of the flow and sediment transport modelling undertaken for SNSSTS2 (see Appendix 12 of HR Wallingford *et al*., 2002).

### 2.4.2 Selection of seabed roughness length values

Because of the wide range of sediment types on the seabed in the study region, the hydraulic roughness of the bed, which influences both tidal propagation and current speeds, varies considerably. This issue was investigated in detail in the SNSSTS2 during the calibration of the TELEMAC model; various sensitivity tests were carried out to derive a suitable representation of the bed roughness. Further information on this can be found in Section 2.2 of HR Wallingford *et al.* (2002). At the conclusion of those tests, it was decided to use a bed roughness length that varied spatially across the model domain (see Figure 8 of HR Wallingford *et al.* 2002). Although this did not greatly alter the results obtained using a uniform value (equivalent to a Nikuradse grain roughness, $k_s$, of 0.1m), in the present report we have chosen to be consistent with the modelling carried out in SNSSTS2.

### 2.4.3 Selection of sediment grain size

In the sediment transport modelling carried out in SNSSTS2, a number of different sediment sizes were considered, namely 0.1mm (fine sand), 0.4mm (medium sand) and 2mm (coarse sand / fine gravel). The majority of the sediment transport modelling undertaken in that study, however, assumed the seabed had a uniform covering of fine sand (median grain size of 0.1mm) over the whole of the Southern North Sea. Not surprisingly, predicted sediment transport rates in areas where the seabed sediments were coarser than this were over-estimated.

In the present study, interest needs to be focussed more precisely on the seabed in and close to the various offshore aggregate dredging areas which lie on a part of the seabed which is typically sandy gravel. In this part of the study region, there is likely to be little fine sand available for transport by the tides, and the SNSSTS2 for the coarser sediments (0.4mm and 2mm) are likely to provide more realistic sediment transport rates.

In this regional study we have therefore chosen to predict the transport of medium sized sand, i.e. with a median grain size of 0.4mm and also to undertake a series of sensitivity runs using a median grain size of 0.3mm and 0.5mm. Changes in the transport of sand of this size are potentially relevant to possible effects of dredging in those extraction areas close to mobile sandbanks such as Cross Sand (for example, Area 202).

### 2.4.4 Choice of seabed bathymetries for use in the modelling

In modelling that was carried out in an earlier stage of the present MAREA studies (HR Wallingford, 2010a), it was decided to present results on the effects on **waves** of past dredging and then of past and all future dredging. This showed that the predicted changes caused by future dredging were greater than those caused by the aggregate dredging already carried out, but still within acceptable limits. The subsequent interpretation of those modelling results and the recommendations made in respect of further studies with respect to flow and sediment transport were very largely based on the results obtained from modelling the combined effects of past and planned future dredging.

In view of this, in the modelling of the effects of aggregate dredging on **tidal flows,** and associated sediment transport, it was decided only to compare results obtained using the pre-dredging (i.e. baseline) and the post-dredging bathymetries. The changes predicted by this approach will be larger and more widespread than if only past dredging was represented. More importantly, however, future studies and any decisions made about future licence applications will be based on the results obtained by considering the combined past and future dredging in the study region. By taking this approach and bearing in mind the over-estimation of the total future dredging in this region, this report errs on the side of caution.

In summary, therefore, the tidal flow and sediment transport models were run for first the pre-dredging bathymetry and then for the post-dredging bathymetry. The changes in the results were then compared to assess the potential cumulative effects of all past and proposed aggregate extraction.

# 3. *Discussion of results*

## 3.1 RESULTS PRESENTATION

The purpose of the study is to show how aggregate dredging might have altered, or may in future alter, tidal current speeds and net sediment transport rates over the whole study region. The main results from the computational modelling are presented here to provide an overview of the spatial extent and magnitude of predicted changes, both within and outside the numerous dredging areas.

There is no simple way of assessing whether or not such changes may be significant in the sense of having the potential to provide some environmental benefit or cause harm. This judgement can only be made with detailed knowledge of the environmental sensitivities of the areas within which changes are predicted to occur.

For example, the Marine Life Information Network (MarLIN) points out that “The sensitivity of a species (or community) is an estimate of its intolerance to damage from an external factor and is determined by its biological and physical characteristics. Sensitivity must be estimated (assessed) in response to a change in a specific environmental factor and to the magnitude, duration, or frequency of that change.” In this specific biological context, MarLIN presents the following characterisation of Tidal Strength (see http://www.marlin.ac.uk/glossaries/waterflowrate.php).

| | |
|---|---|
| Very strong | >3 m/s |
| Strong | 1.5-3 m/s |
| Moderately strong | 0.5-1.5 m/s |
| Weak | <0.5 m/s |
| Very weak | Negligible |

MarLIN point out that many species and biotopes occur under a range of water flow conditions. A prolonged change in current speeds of two categories is more likely to affect a range of species than if current speeds only move to an adjacent category. See 'Changes in Water Flow' http://www.marlin.ac.uk/sensitivitybenchmarks.php.

In interpreting the results presented in this report, therefore, there could well be a potential change in marine plant and animal communities if tidal speeds were to change by two categories or more, e.g. from just under 1.5m/s to over 3m/s or from just over 1.5m/s to less than 0.5m/s. This would correspond to current speed changing by more than 50%. If the predicted changes were only a few percent, however, the MarLIN guidance suggests that the effects on marine life would not be particularly concerning. The broad pattern of predicted tidal current fields is shown in Figures 5 and 6 for flood and ebb tides and the maximum speeds on a spring tide in Figure 7 for pre-dredge conditions. The broad similarity between this pattern of flow speeds and the post-dredge pattern in Figure 8 is evident.

However, there may be other features of interest, for example wrecks or pipelines, close to aggregate dredging areas which might be more sensitive to changes in current speeds or in net sediment transport rates. In presenting such changes, it should be remembered that any numerical modelling of tidal flows, and especially of sediment transport, inevitably has a degree of uncertainty. This means that it is not possible to be confident about any very small changes that are predicted to occur as a result of aggregate dredging. A judgement therefore has to be made about the potential significance of predicted small changes in current speeds.

In this report, we have not shown changes where the modelling indicates that aggregate dredging would only alter peak current speeds by 5% or less. This type of change is comparable to the naturally occurring variations in peak tidal current speeds that might be expected to occur on two days when the same tidal range is predicted to occur. Even if changes greater than this are shown within an area of particular interest, the predictions made in this regional study should be treated as cautionary rather than precise. Any potentially significant changes may need to be assessed in more detail during the Environmental Impact Assessment studies for the specific dredging area, or areas, closest to the particular features of interest.

However, any changes in current speeds that are predicted at this regional scale to be too small to be reliably regarded as different from zero should not require further investigation during the licence-specific EIA stage.

As previously pointed out, in other parts of this MAREA and in similar studies elsewhere, it was found that changes in physical processes due to past dredging were predicted to be small when compared to those likely to be caused by planned future dredging. So to err on the side of caution in this particular modelling exercise, we have studied the effects of both past and future dredging together. The changes predicted by this approach will be greater than if we had only considered either the past dredging or the planned future dredging on their own.

Even with the restricted number of model runs carried out, i.e. for just two bathymetries, a single mean spring tide and a single sediment size, the volume of computational model results that could be presented is very substantial. However, to interpret the results in the specific context of assessing the greatest changes that aggregate dredging might cause, it is possible to use a much smaller number of those results. For example, at about the time of high and low tide, tidal currents and sediment transport rates are much smaller than they are roughly three hours before or after those times. It is likely for any practical purpose, for example when considering possible scour around seabed structures or changes in marine plants and animals, that changes in the fastest current speeds that will be of most concern.

Following the consideration of changes in the speeds of tidal currents, attention is then turned to considering possible changes in the movement of sediment over the seabed. Such changes will be of interest if there are concerns about the potential for long-term changes in the seabed morphology outside the dredging areas. In this context, any changes in the net sediment transport rate over the tidal cycle are of much greater interest than the transport rate at any particular stage during that cycle. We consider this particular aspect of changes caused by dredging in Section 3.3.

## 3.2 EFFECTS OF CHANGES IN BATHYMETRY DUE TO AGGREGATE DREDGING ON TIDAL FLOWS

The TELEMAC flow model runs carried out in this study allow an instantaneous snap-shot of the depth-averaged current speeds and directions at any location in the study region, and indeed over a much larger part of the North Sea, at any stage of the tidal cycle. As examples, Figures 5 and 6 show the predicted flows at the peak of the flood tide and ebb tide respectively for the pre-dredging bathymetry.

Supplementary model plots are presented in Appendix 1. Figures A1.1 and A1.2 (plotted on a regular grid for ease of viewing) show that in the vicinity of the dredging areas, the peak currents flow roughly to the south on the flood tide, and roughly north during the ebb tide. The spatial variations in the current speeds in the area north and west of the dredging areas reflect the presence of the large sandbanks, with the faster flows in the channels between these. Over much of the area of greatest interest, the flows at the peak of the ebb tide tend to be marginally greater than during the flood tide. The fastest predicted current speeds are up to 1.4m/s and this is classified by MarLIN as a “Moderately strong” Tidal Strength. Close to the coastline the peak predicted current speeds are around 0.2m/s (classified as “Weak”).

The pattern of maximum current speed at any time during a spring tide is plotted in Figures 7 and 8 for the pre-dredging and post-dredging bathymetries respectively. Identifying the changes between these visually is very difficult. Therefore, to draw particular attention to the changes that past and proposed future dredging would cause a different presentation of the model results has been used.

Figure 9 summarises the differences in maximum current speeds as predicted for the post-dredging and pre-dredging bathymetries. The changes due to past dredging alone would be much smaller than those presented in this figure. This comparison of the pre-dredging and post-dredging situations show that tidal currents are most strongly increased at the immediate northern and southern ends of the dredging areas. At these locations, maximum current speeds have increased by up to 0.1m/s within a few hundred metres of the dredging areas and up to 0.3m/s at some isolated points. Tidal currents are most strongly increased at the northern and southern ends of the dredging areas because the increased water depth attracts a greater tidal discharge through those areas. As this increased discharge enters and leaves the dredged areas, it causes faster current speeds over the un-dredged areas of the seabed and between dredged areas, such as on the boundary between Areas 228 and 251 (see Figure 1 for areas). Conversely, flows alongside the dredging areas (i.e. to the east and west) tend to reduce. A maximum reduction in current speeds of 0.2m/s occurs immediately alongside the dredging areas.

However, away from the dredging areas themselves, any changes in the maximum current speed are typically less than 0.05m/s, and this is considered to be too small a change to be safely discriminated by the model being used. Much larger changes in current speeds than this will occur frequently and widely over the nearshore sandbank system as these banks shift their position and change shape naturally.

Within the dredging areas themselves increases or decreases occur depending on the bathymetry variations in each area, reflecting for example different depths of dredging within each area. The majority of the changes to current speeds within the dredging areas show a reduction of around 0.1m/s. There are however, locations where the current speed has increased by up to 0.3m/s or decreased by up to 0.2m/s.

It should be borne in mind that changes in tidal currents in and around the other dredging areas in this study region have been predicted assuming that all the proposed future dredging in each area was carried out. This is a very conservative assumption. If the actual amounts of extraction within these areas are smaller, then the predicted extent and magnitude of changes in the tidal flows in and close to these areas will be reduced.

An alternative way of presenting the predicted changes in tidal currents is to show the percentage changes. Therefore the actual maximum current speed changes shown in Figure 9 have therefore been converted to show percentage changes and are presented in Figure 10.

The results shown in Figure 10 demonstrate the predicted changes in peak current speed are less than 20%, with the greatest changes generally restricted to the dredging areas themselves and the approaches to them. The exception to this is in the area to the west of Areas 251 and 319, where reductions in currents of around 5% are predicted. These modest reductions in the maximum tidal current speed are largely restricted to areas where the bed levels are more than 10m below mean sea level, but are also predicted to occur over a small area in shallower water on South Cross Sand. To place these localised changes into context, however, it can be seen in Figure 9 that the actual changes in the maximum current speeds are only about 5cm/s; for the remainder of the tidal cycle, or during tides of smaller range, the changes in current speeds on and around the edges of South Cross Sand would be smaller still.

The significance of such small changes in current speeds here or elsewhere depends on the sensitivity of the seabed, or what is on or above the seabed in such areas, to any alterations in the tidal currents. For example, when considering possible effects on marine plants or animals, such a small decrease in current speeds would not affect the Tidal Strength classification suggested by MarLIN (see section 3.1 above). On this basis, it seems most unlikely that changes in peak current speed of less than 5% would have any damaging effect on marine life.

To address the concern that small changes in tidal currents might significantly alter the naturally dynamic morphology of the numerous sandbanks that lie between the dredging areas and the coastline, it is preferable to assess changes in the sediment transport rates (see section 3.3 below).

Finally, if there are specific features of interest such as pipelines, cables or wrecks, situated close to one of the dredging areas and which may be sensitive to changes in current speeds, then the results of this broad-scale regional modelling exercise will need to be refined as a part of the EIA carried out to support the extraction licence application for that particular area.

In summary, it seems unlikely that the small changes in tidal currents predicted in this modelling exercise will result in any noticeable changes to the environment except, perhaps, where there are either existing features of interest or existing/ planned developments in areas where the predicted changes in peak tidal current speed exceed 5%. Where this is the case, changes in tidal currents, and the effects of these changes, might need to be studied in greater detail at the time of applying for an extraction licence.

Where no changes in current speed are shown in Figures 9 and 10, then this indicates that the model is predicting the same situation before and after dredging, to within the expected range of accuracy of the computations made. In the areas shown in white, it can be assumed that **no significant** changes in tidal currents will be experienced as a result of all past and proposed future dredging.

## 3.3 EFFECTS OF AGGREGATE DREDGING ON SEDIMENT TRANSPORT

Much of the modelling of tidal flows and the associated sediment transport in the present study builds upon the work carried out in Phase 2 of the Southern North Sea Sediment Transport Study (see HR Wallingford *et al*., 2002). However, as pointed out previously, this study only considered one representation of the seabed contours, and did not try to investigate how marine aggregate dredging has affected, or might in future affect tidal flows or the associated sediment transport processes. The present study has extended the modelling in SNSSTS2 to provide a regional overview of the effects of such dredging on sediment transport caused by tidal flows.

In those areas where peak tidal currents are predicted to be altered by aggregate dredging, as illustrated in Figures 9 and 10, this will change the sediment transport rates at those times. The net sediment transport rate over a tidal cycle, however, does not depend solely on the current speeds at the peak of the ebb or the flood tide; rather it is the sum of all the instantaneous sediment transport rates at every stage of that cycle. Changes in this net sediment transport over the tidal cycle provides a better basis on which to assess whether the morphology of the seabed at any location might be altered as a result of the cumulative effects of past and proposed future aggregate dredging.

It was therefore decided to build upon the modelling of tidal currents previously described and predict the net sediment transport rates over a spring tide cycle for both the pre-dredging and post-dredging bathymetries. The results of this sediment transport modelling need to be interpreted with some care. In this regional study, the main interest is not in detailed estimates of how much the sediment transport rates might change as a result of dredging. Any numerical modelling of sediment transport rates over the large AODA area would, in any event, be subject to considerable error because of the considerable variations in tidal ranges and sediment grain sizes, which cannot be adequately investigated within the constraints of this regional study.

What is more important, and practical, is to identify those areas of the study region where significant changes in net sediment transport patterns and rate changes **might** occur. This in turn helps to identify those areas where changes in the seabed morphology might occur as a result of aggregate dredging. By considering medium-sized sand and a larger tidal range than average, the modelling carried out will tend to over-estimate the areas within which the natural sediment transport regime might be affected by past and proposed future aggregate dredging. As for other aspects of this study, it was considered that the effects of past dredging on sediment transport were likely to be smaller and less of a concern than proposed future dredging, and that considering both would produce the largest changes, thus erring on the side of caution (Section 2.3.3).

Our modelling has predicted the net transport, over a spring tide, of an assumed uniform sediment covering the whole AODA region, first for the pre-dredging bathymetry and then again for the post-dredging bathymetry. The choice of the size of this sand sediment, i.e. 0.4mm, has been discussed in Section 2.4.3 and is generally smaller than normally found on the seabed surface in the dredging areas, where the median grain sizes range between 0.15mm and 2mm. We have also undertaken sensitivity runs using a median grain size of 0.3mm and 0.5mm and plots showing these results are presented in Appendix 1.

The net sediment transport magnitudes are plotted in Figures 11 and 12 and overall look quite similar. These results show a very wide range of net sediment transport rates, ranging from virtually zero to several thousand cubic metres per metre width of transport path each spring tide. Because of this, it is impractical to present changes in sediment transport rates meaningfully using the same methods as used to produce Figure 10, where a simple percentage increase or decrease is shown.

Because of this, it was decided to present results to show where the natural, i.e. pre-dredging, net transport rates are predicted change as a result of past and proposed future dredging by more than 500 kg/metre per tide (for grain size of 0.4mm, 0.3mm and 0.5mm respectively). This choice is based on taking a limit of 5% of the highest rate predicted in the outline of the dredging area, namely around 10,000 kg/m/tide, and reflects our view that in this area a difference of 500 kg/metre per tide is the smallest change in sediment transport rates that it is safe to identify using our modelling method.

Figure 13, based on the modelling carried out for a median grain size of 0.4mm, shows changes to the net sediment transport rates as a result of all past and proposed future dredging. Where these are large enough to be discriminated by the model, they occur within the dredging areas themselves or in adjacent areas to the north and west of them. Changes within the dredging areas themselves are varied, since the increase in tidal flow caused by the bed lowering may mean that the tidal discharge in that area increases as well as the water depth. As a result, it is not easy to tell in advance whether current speeds and sediment transport rates will increase or decrease. However, based on experiences to date, such changes to the hydraulic regime of these areas are usually of little concern in comparison to the changes to the environment within those areas caused by the physical impacts of the dredging process itself.

Outside the dredging areas, particular attention needs to be paid to the predicted changes in net transport rates on or close to the sandbanks that lie between the dredging areas and the coastline of the study region. These banks are constantly shifting, as a result of natural changes in the tidal current and sediment transport regimes, and as they alter, so their effects on waves reaching the coastline change. These banks act as an effective natural breakwater, especially when tidal levels are low, reducing wave heights reaching the beaches between Winterton and Lowestoft. As the positions of the banks and the channels between them change, the exposure to wave action at any location along this shoreline is affected, in turn causing changes in the width of the beaches. Such changes have always occurred and will continue to occur in the future whether or not aggregate dredging takes place to seawards of these sandbanks. It is important, however, that such dredging does not add to these changes since this might have, or be felt to have and adverse effect on wave conditions along this part of the coast.

Figure 13 shows four areas where sediment transport rates are predicted to alter close to the nearshore sandbanks. Sediment transport rates are predicted to increase to the north of Areas 202 and 254 extending close to the eastern edges of Middle Cross Sand and North Cross Sand (see Figure 1 for locations), although for the most part these changes are in areas where the seabed level is more than 20m below Mean Tide Level.

There is a predicted decrease in sediment transport rates in the deep water channel between Area 319 and South Cross Sand, although this decrease hardly extends into the 10m contour surrounding this sandbank. Finally, there is a predicted increase in transport rates to the west of North Scroby Sand, again largely restricted to the deep channel between that sandbank and Middle Cross Sand.

While there is some evidence that dredging may cause changes in sediment transport rates in the rather deep channels between the outer sandbanks to landwards of them, there is very little change predicted over the sandbanks themselves, i.e. within the 10m contours surrounding them. This is despite the fact that in places, for example just to the west of Area 319, the sandbanks lie close to the boundaries of the dredging areas.

These predicted changes need to be interpreted with care given the broad-scale nature of the sediment transport modelling presented here, and the conservative approach adopted in terms of over-estimating the total amounts of extraction that is likely to take place in this region. It should also be remembered that this modelling has made simplified assumptions regarding the uniform size and spatial distribution of sediments on the seabed. Figures 11, 12 and 13 do not take into account whether there is sand-sized sediment available to be transported at a given locality. In many parts of the dredging areas the seabed is gravelly sand which commonly is naturally immobile, and elsewhere the seabed sediments are coarser and less likely to be transported that these model results suggest.

In view of this, it is recommended that the results summarised in Figure 13 are interpreted in two ways. Firstly, where there are no predicted changes in net sediment transport rates in or close to a particular location or area of seabed, then this regional study can be regarded as a good indication that no significant changes to the seabed morphology or the sediment transport regime are likely to occur as a result of the cumulative effects of past and proposed future aggregate dredging. This does not, of course, rule out continuing natural changes especially in and around the inshore sandbanks of Scroby and Holm Sands.

Second, where this regional modelling shows where there may be changes in sediment transport rates in the vicinity of specific dredging areas, and if these changes may affect existing or planned developments or sensitive features of interest on the seabed, then these may need to be investigated in greater detail as the applications for future dredging from those areas are prepared. At that stage, a more detailed assessment of the existence and type of seabed sediments can be used, along with more detailed bathymetry than that used in this regional study, to assess any possible significance of changes to the natural sediment transport regime

In such cases, the more detailed modelling of tidal currents and sediment transport processes may provide reassurance about the magnitude and environmental significance of such changes. Alternatively this more detailed assessment may suggest modifications to restrictions on the extraction plans, or require specific monitoring in and around that area to avoid adverse effects.

Finally, it should be remarked that the modelling described above considers the long-term effects on sediment transport caused by the changes in seabed levels, i.e. after all the presently proposed aggregate dredging in this region has been completed. As dredging proceeds, it will cause extra disturbance and the movements of sediments over the seabed within and around the extraction areas. The generation and dispersion of the fine sediment plume caused by the dredging operations themselves is considered in a companion report (HR Wallingford, 2010b).

# 4. Aggregate dredging and in-combination effects

Aggregate dredging is only one of many human activities that affect the physical environment of the study region. Other activities include:

- Some types of commercial fishing that cause disturbance of the seabed and its sediments;
- Dredging carried out for navigational purposes and the associated disposal of the dredged material, which not only alters the water depths but also potentially alters waves, tidal currents and the movement of sediments over the seabed;
- The construction of breakwaters, seawalls and groynes along the coastline of the region, which has often led to very significant changes in waves, currents and sediment transport rates locally, leading to changes in the nearshore seabed; and
- The seabed in the study region is crossed by cables, and outfalls etc, and these both affect and are affected by waves, tides and sediment transport processes.

In the future, there may be other developments in the study region, for example the installation of wind turbines as has already taken place in Scroby Sands to the west of the dredging areas. For some of these existing and potential future activities and developments, comprehensive studies are routinely undertaken to assess the impacts they may have on the environment, including the physical environment, as part of the process by which necessary consents are obtained. For others, such environmental studies are not required or are more limited in scope. In general, however, all such assessments concentrate on an individual project and its environmental effects rather than considering the possible “in combination” effects of a specific project with others nearby, even if these are of a similar nature.

Over the past 20 years, the marine aggregates industry has included the cumulative effects of all currently licensed and proposed new dredging areas when assessing the effects on the coastline of planned future extraction. This present study is an extension of this well established practice. It provides an indication of how aggregate dredging in multiple areas, often very close to one another, could affect tidal currents, and hence in the associated sediment transport of medium-grained sand, anywhere within this study region. Where future developments or uses of the sea close to any of the dredging areas are planned, this study helps quantify both the present-day and the future tidal flows and sediment transport rates in those areas and can thus contribute to the design and the assessment of the effects of those future developments.

This regional study of tidal flows has not tried to quantify any potential effects of aggregate dredging that might affect the environment of the study region “in combination” with effects from other human activities, for example due to the deepening of a navigation channel or the construction of coastal defence schemes. This would be a very complicated task, since it is not often possible to obtain details of all the planned developments or operations within the overall study region.

Overall, it is reasonable to conclude from this study that any in-combination effects on tidal currents and sediment transport involving aggregate dredging are unlikely unless other projects are located close to boundaries of those dredging areas. Consequently it is not considered possible that there would be any such in-combination effects with projects along the shorelines in the study region, for example the construction or maintenance of coastal defences.

Some of the specific activities and developments within the study region with a potential to combine with aggregate dredging to produce an effect on the environment are considered within the in-combination impacts section of the overall Marine Aggregate Regional Environmental Assessment (MAREA) to which this study contributes.

However, any judgement about the magnitude of such interactions would require specific information and more detailed modelling than has been possible in this regional study. Potentially significant interactions that are identified will therefore need to be considered in more detail in the Environmental Impact Assessment (EIA) carried out for the extraction licence application for a specific dredging area.

# 5. Conclusions

This modelling study has assessed the changes in tidal currents, and in associated sediment transport rates, that would result from both past and proposed future aggregate extraction in the AODA study region. The main aim of this modelling has been to identify the likely spatial extent of potentially noticeable changes in currents and in the associated sediment transport rates.

The modelling has erred on the side of caution, by considering a spring tide, when currents are stronger than normal, and by assuming the surface sediment is medium-sized sand, when in reality much of the seabed is covered by coarser sand and gravel. Because of this, the spatial extent and magnitude of the predicted changes in both current speeds and net sediment transport rates are greater than will occur in reality. In addition, the total amount of dredging represented within this study region is a maximum scenario considered to be larger than is likely to take place before about 2030.

Even by adopting this precautionary approach the majority of the predicted changes in maximum current speeds are less than 5%. Areas greater than this tend to occur within the dredging areas themselves or close to the boundaries of the dredging areas. The exception to this is in the area over the seabed to the west of Areas 251 and 319, where reductions of 5% extend to the outer toe of the sandbank complex. There is also predicted to be a small area of reduced current speed on South Cross Sand. The corresponding predicted changes in transport of sediment this sandbank are not noticeable.

The main changes in sediment transport rates are confined to the dredging areas themselves although there is some increase in transport to the north of Area 202 and 254, just to the east of Cross Sand aand in the deep channel between North Scroby and Middle Cross Sands. Reduction in transport is predicted to occur in the deep water channel lying between South Cross Sand and Areas 251 and 319. While these changes do not seem likely, for example, to have a major impact on marine plants or animals within these limited areas, the present study report cannot assign significance to possible changes to other features of interest. This will depend upon the locations and sensitivities of such features, and would be better considered using more detailed modelling of the tidal flows and sediment transport as part of the application for extraction licences for these particular areas..

In summary, therefore, this regional scale modelling exercise is sufficient to assess the potential effects on tidal currents or sediment transport of both past and proposed future extraction from most of the dredging areas in the study region. When licence applications are submitted for an individual area, any further more detailed assessments of such effects would only be warranted for those areas where this present regional study has indicated changes extending outside the boundaries of that area that might affect other activities or features of interest on the seabed that may be sensitive to such changes, and where there are existing or proposed features of interest in the area where such changes have been predicted. Examples of such features include pipelines, offshore wind turbines and historic wrecks, and possibly natural features of the seabed, for example assemblages of marine plants and animals.

Where such further studies are considered appropriate, the present study will provide a good starting point from which more detailed refinements of the model can be made and localised assessments of changes in tidal currents and sediment transport can be carried out.

# 6. References

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HR Wallingford (2010a). Anglian Offshore Dredging Association Marine Aggregate Regional Environmental Assessment: Wave Study, HR Wallingford Technical Note DDR4472-04, November 2010.

HR Wallingford (2010b). Anglian Offshore Dredging Association: Marine Aggregate Regional Environmental Assessment: Plume Study, HR Wallingford Technical Note DDR4472-03, November 2010.

# *Figures*

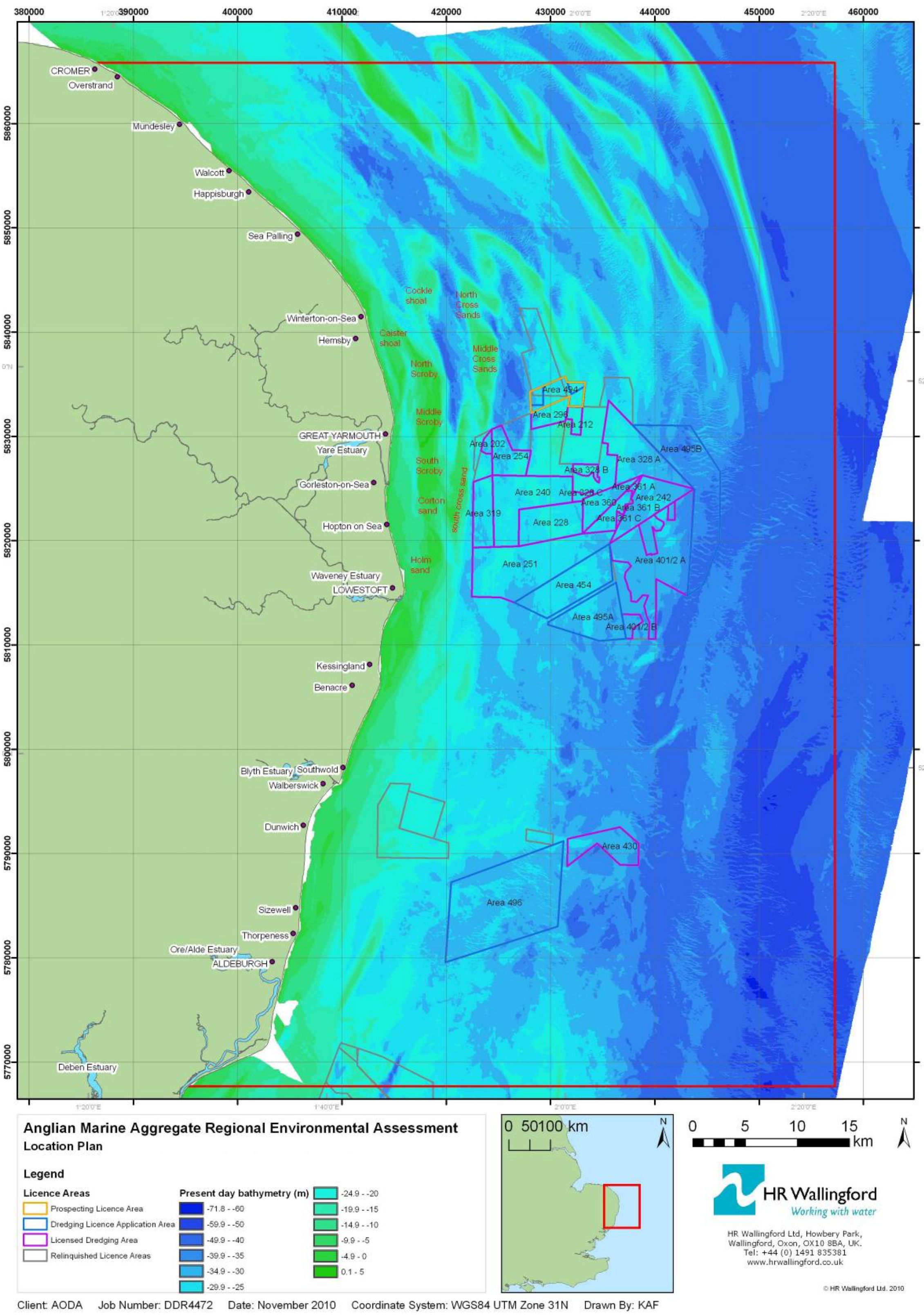


**Figure 1 Study region boundary and aggregate dredging areas**

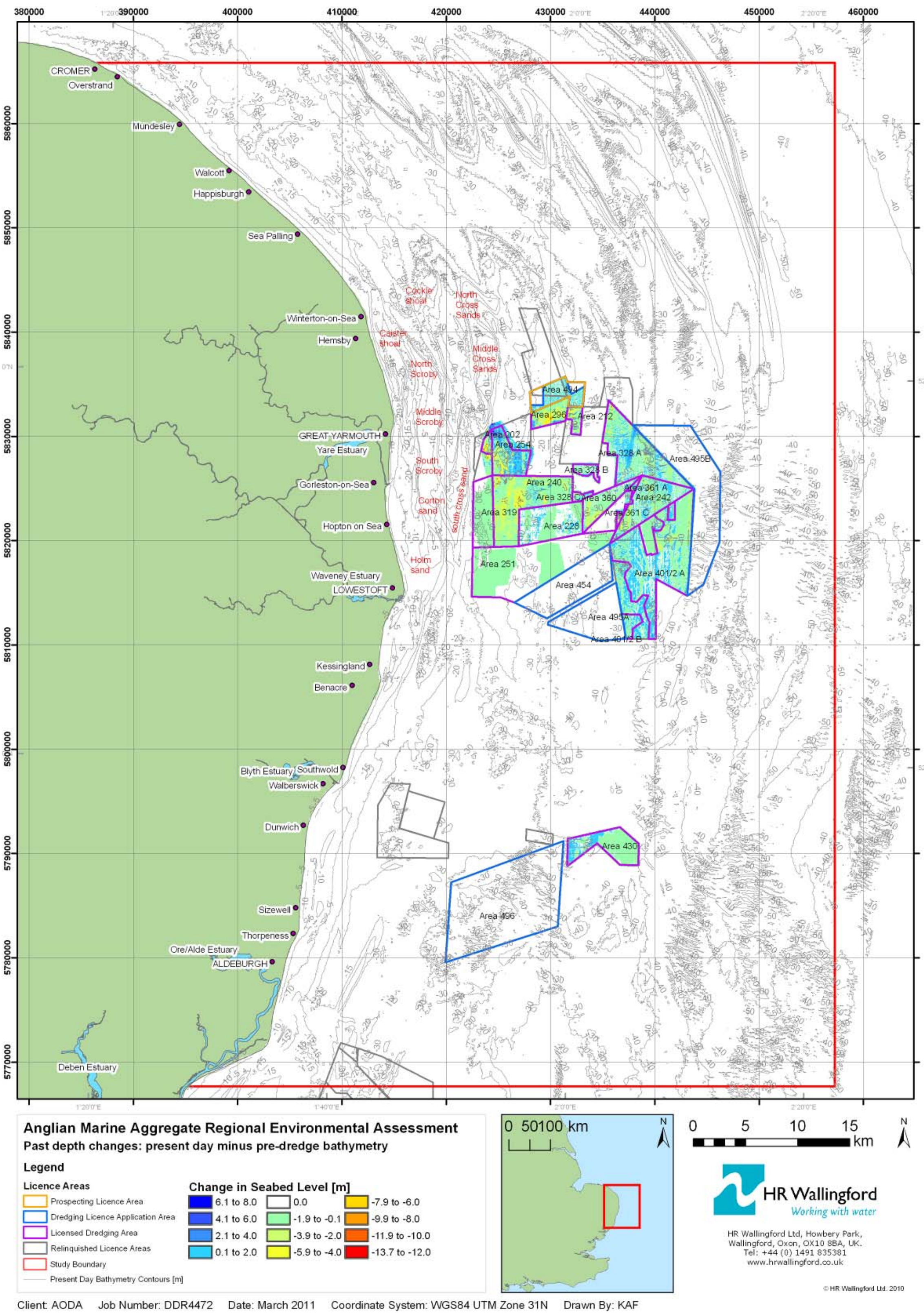


**Figure 2 Past seabed lowering: Present day - pre-dredge bathymetry**

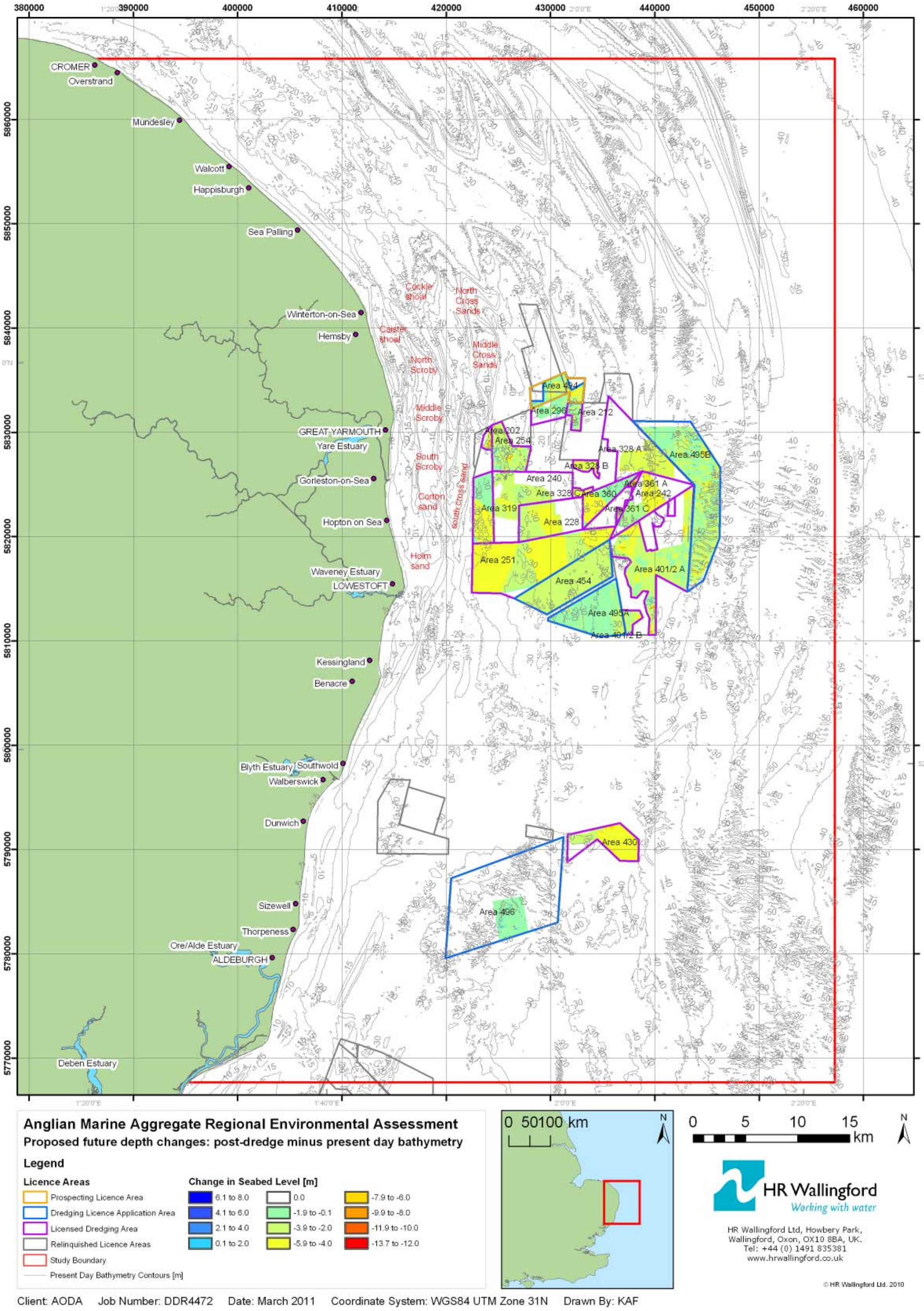


**Figure 3 Anticipated future seabed lowering: Post-dredge - present day bathymetry**

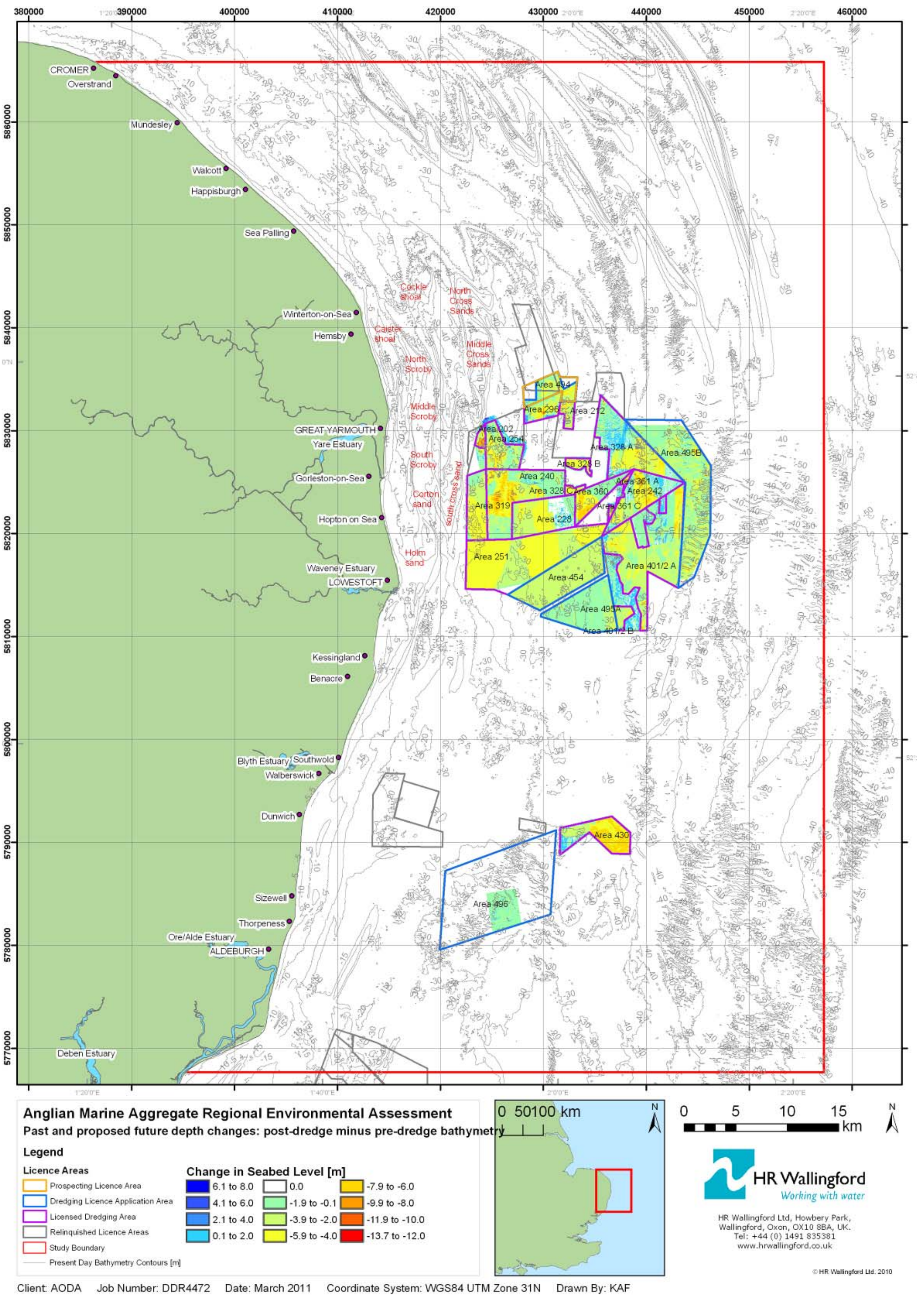


**Figure 4 Past and anticipated future seabed lowering: Post-dredge – pre-dredge bathymetry**

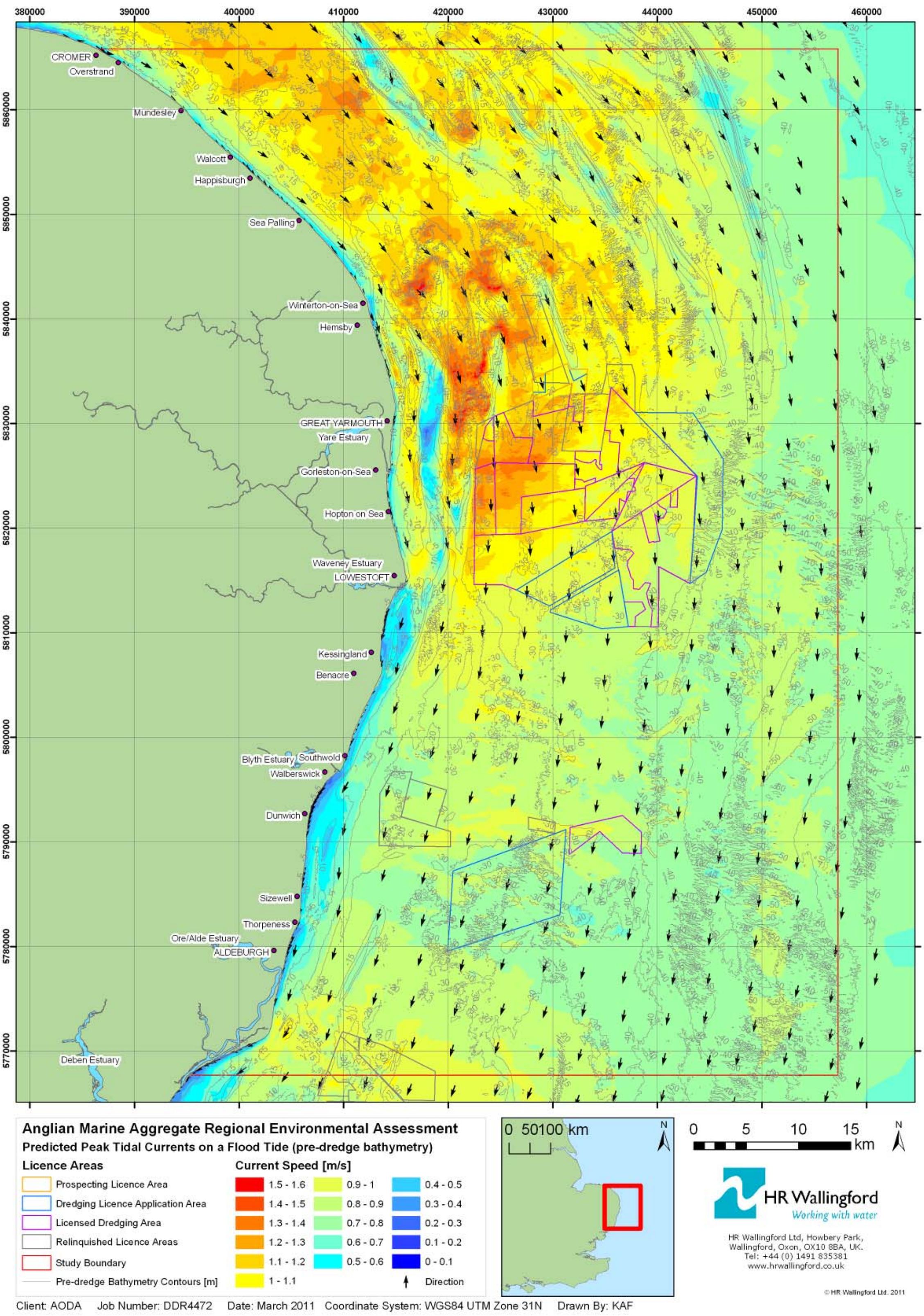


**Figure 5** Predicted peak tidal currents – flood tide (pre-dredge bathymetry)

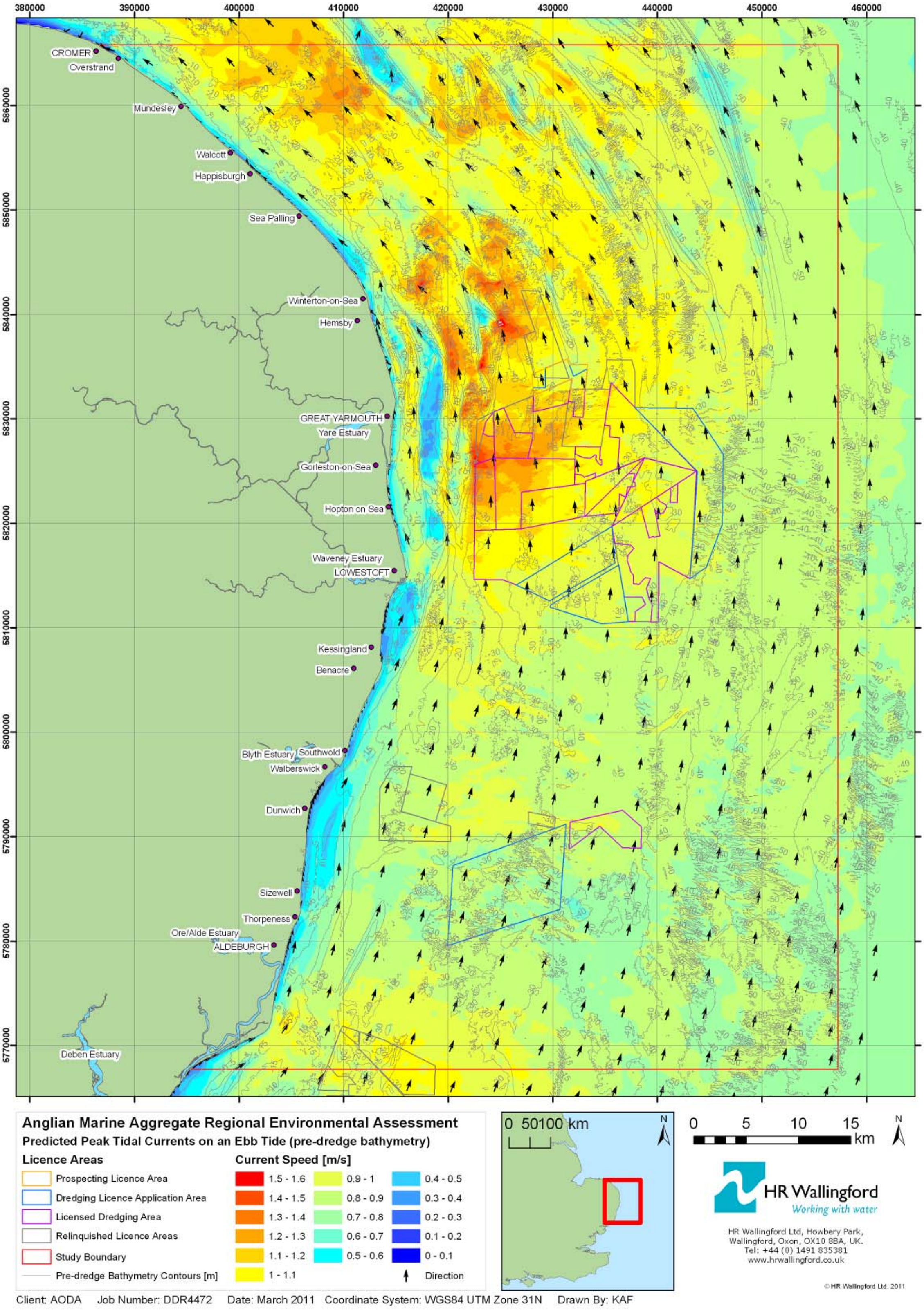


**Figure 6 Predicted peak tidal currents – ebb tide (pre-dredge bathymetry)**

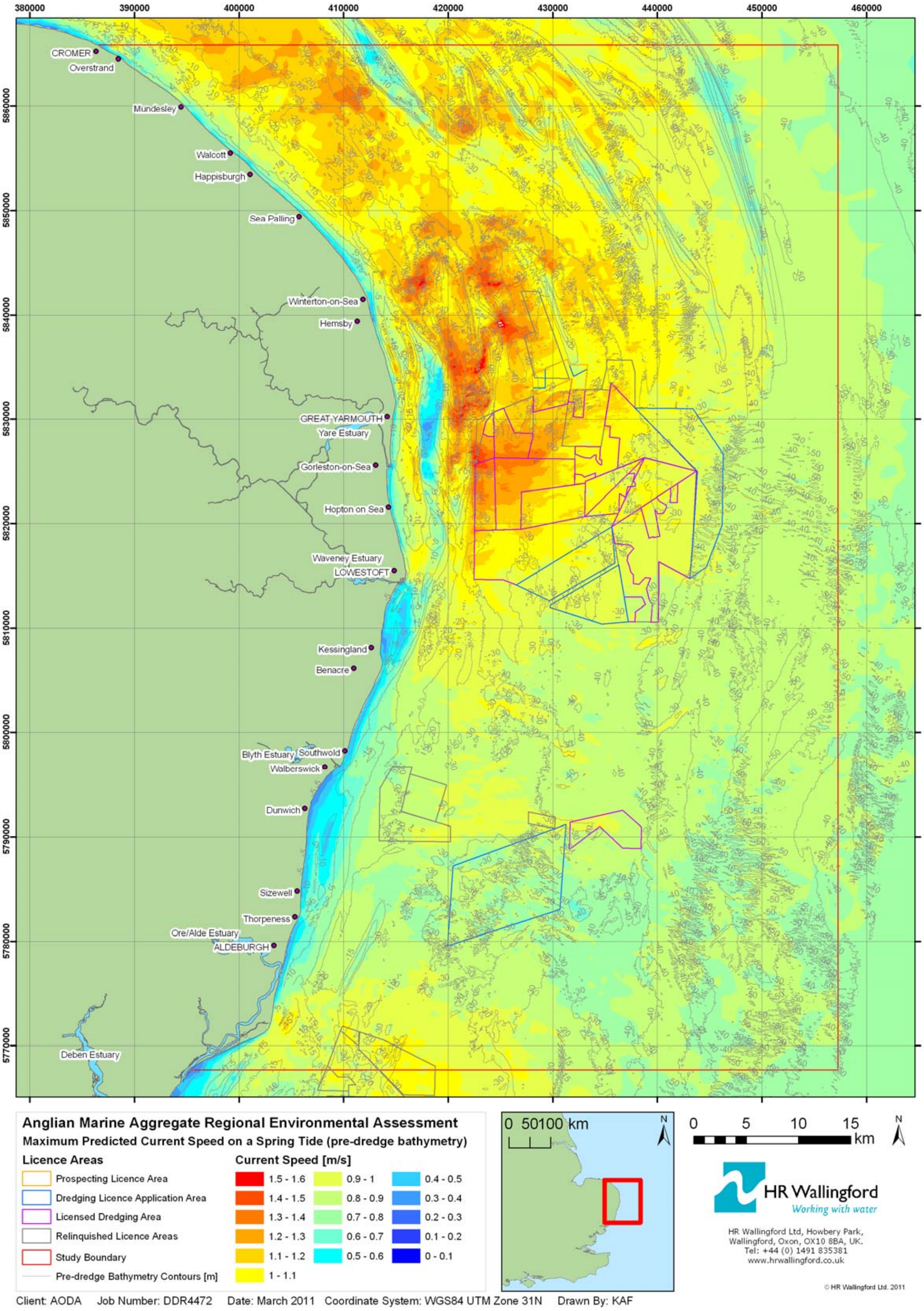


**Figure 7 Maximum predicted current speed on a spring tide (pre-dredge bathymetry)**

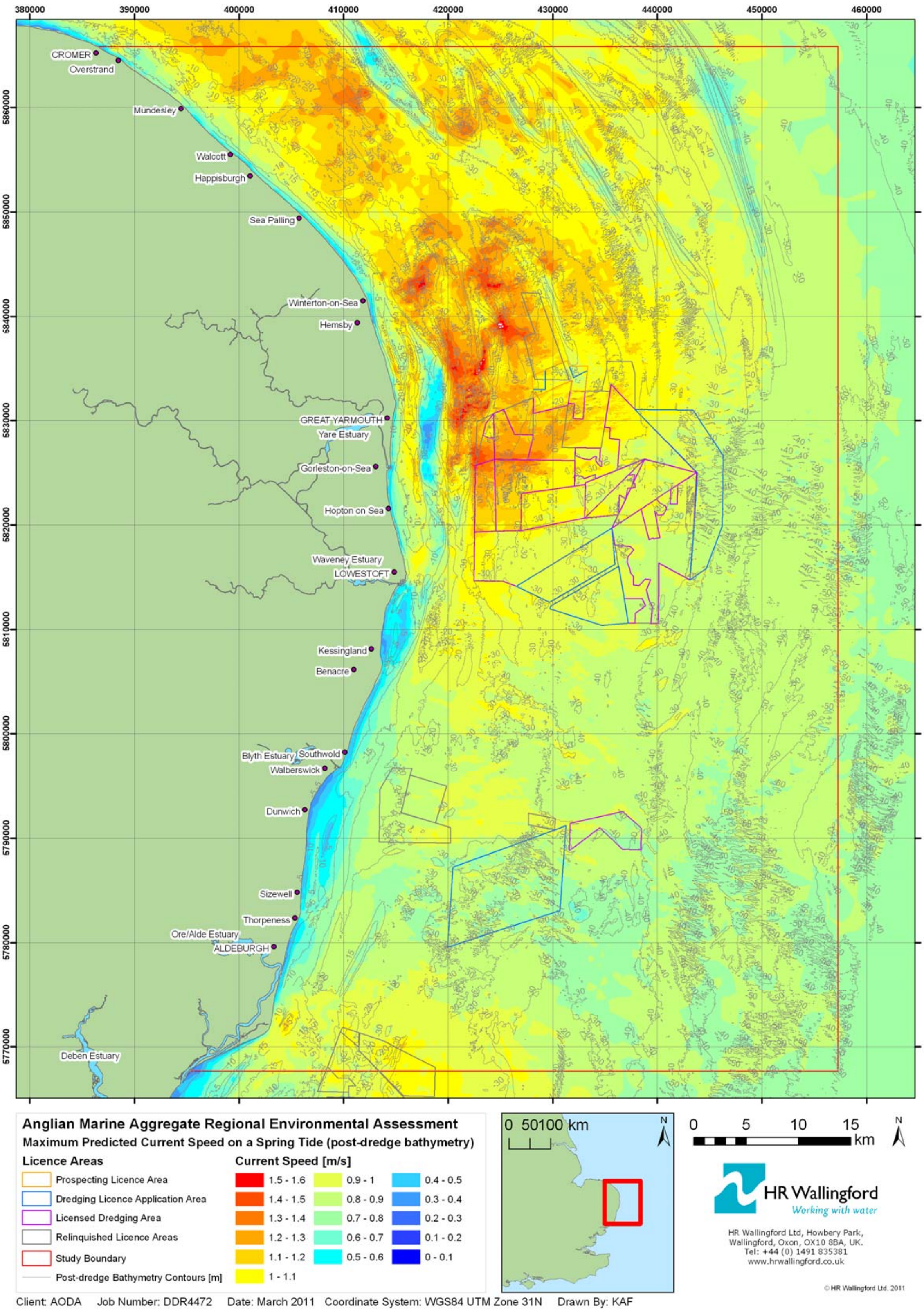


**Figure 8** Maximum predicted current speed on a spring tide (post-dredge bathymetry)

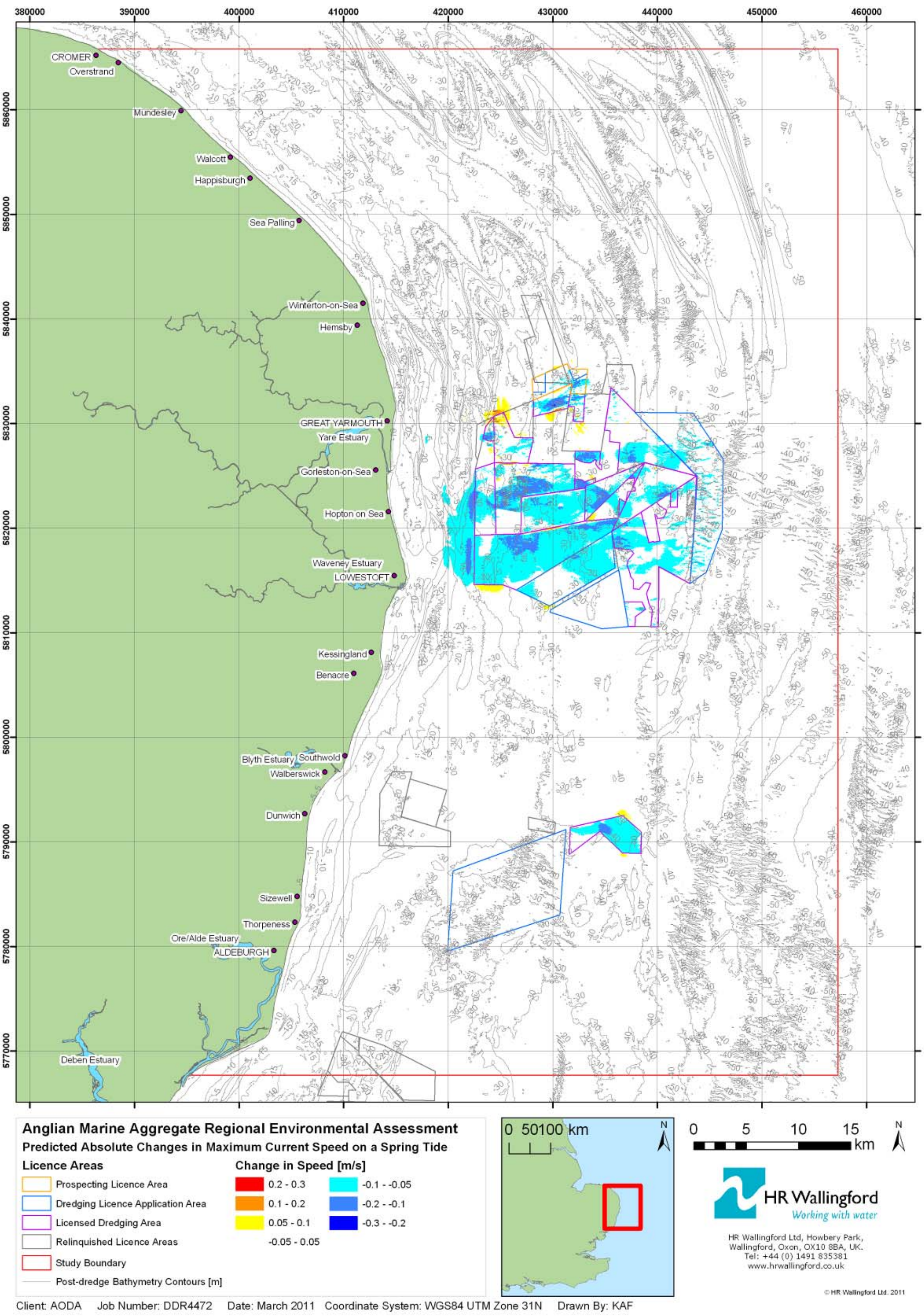


**Figure 9** **Predicted absolute change in maximum current speed on a spring tide (post-dredge minus pre-dredge bathymetry)**

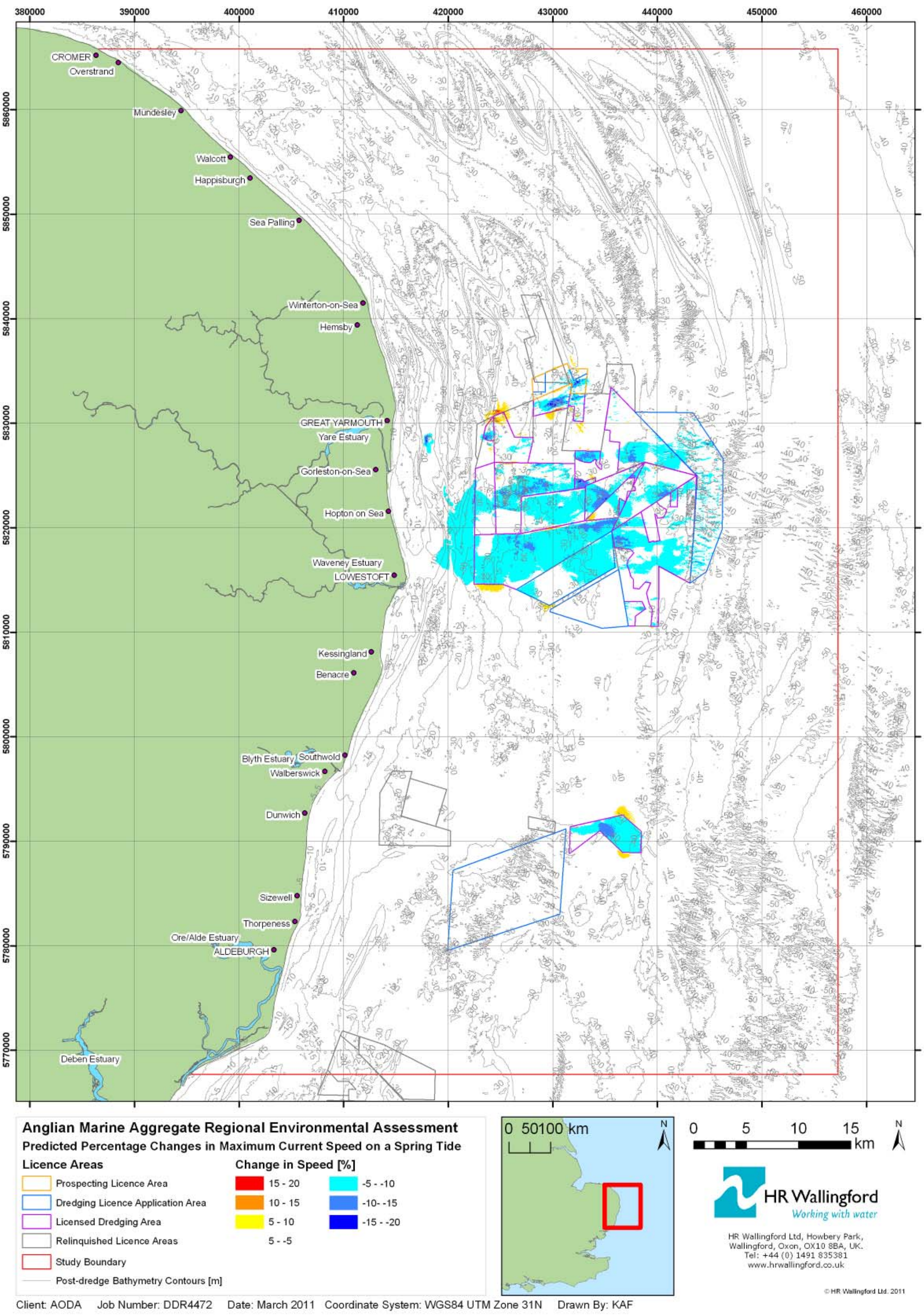


**Figure 10 Predicted percentage change in maximum current speed on a spring tide (post-dredge minus pre-dredge bathymetry)**

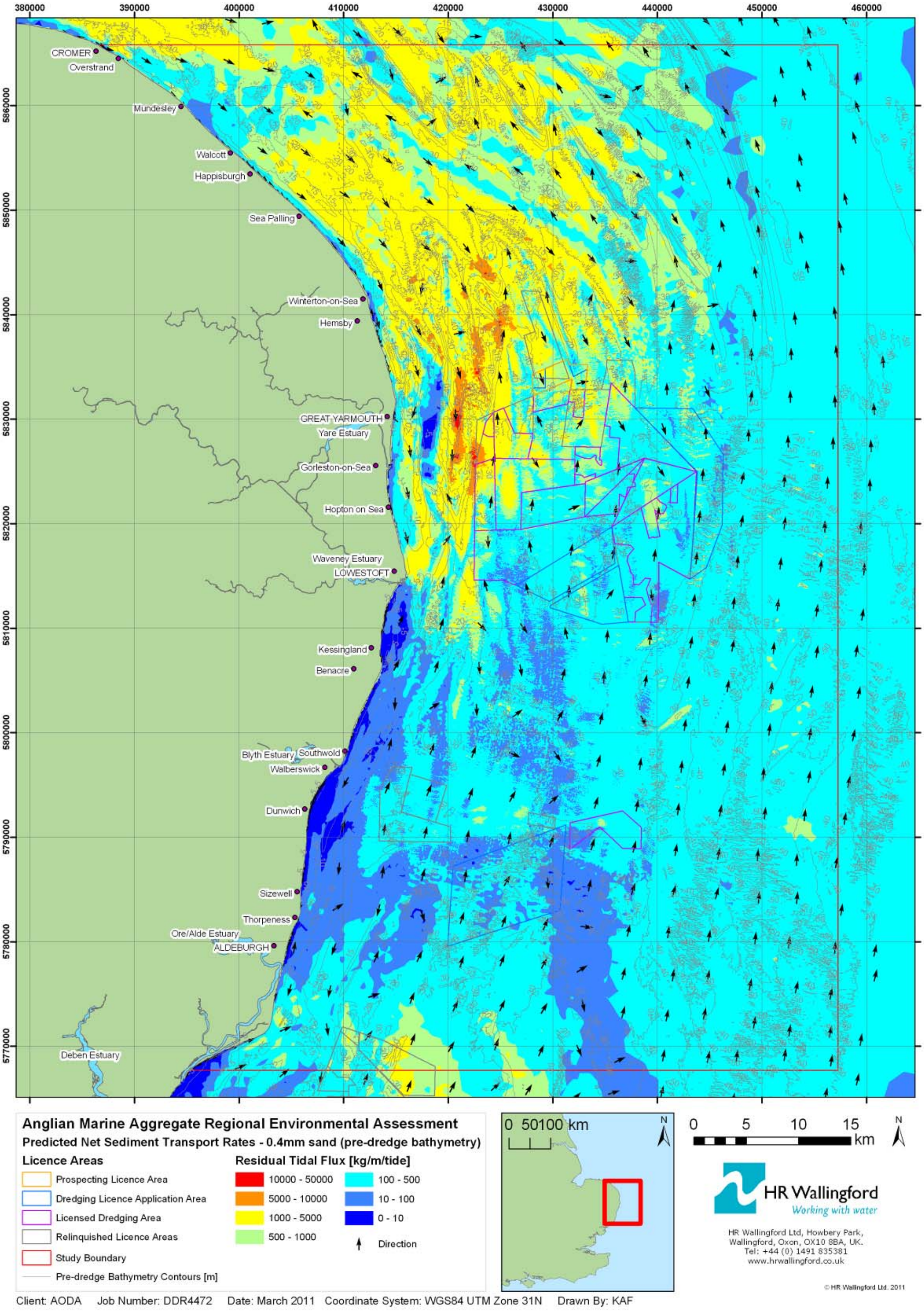


**Figure 11** **Predicted net sediment transport rates – pre-dredge bathymetry (0.4mm sand)**

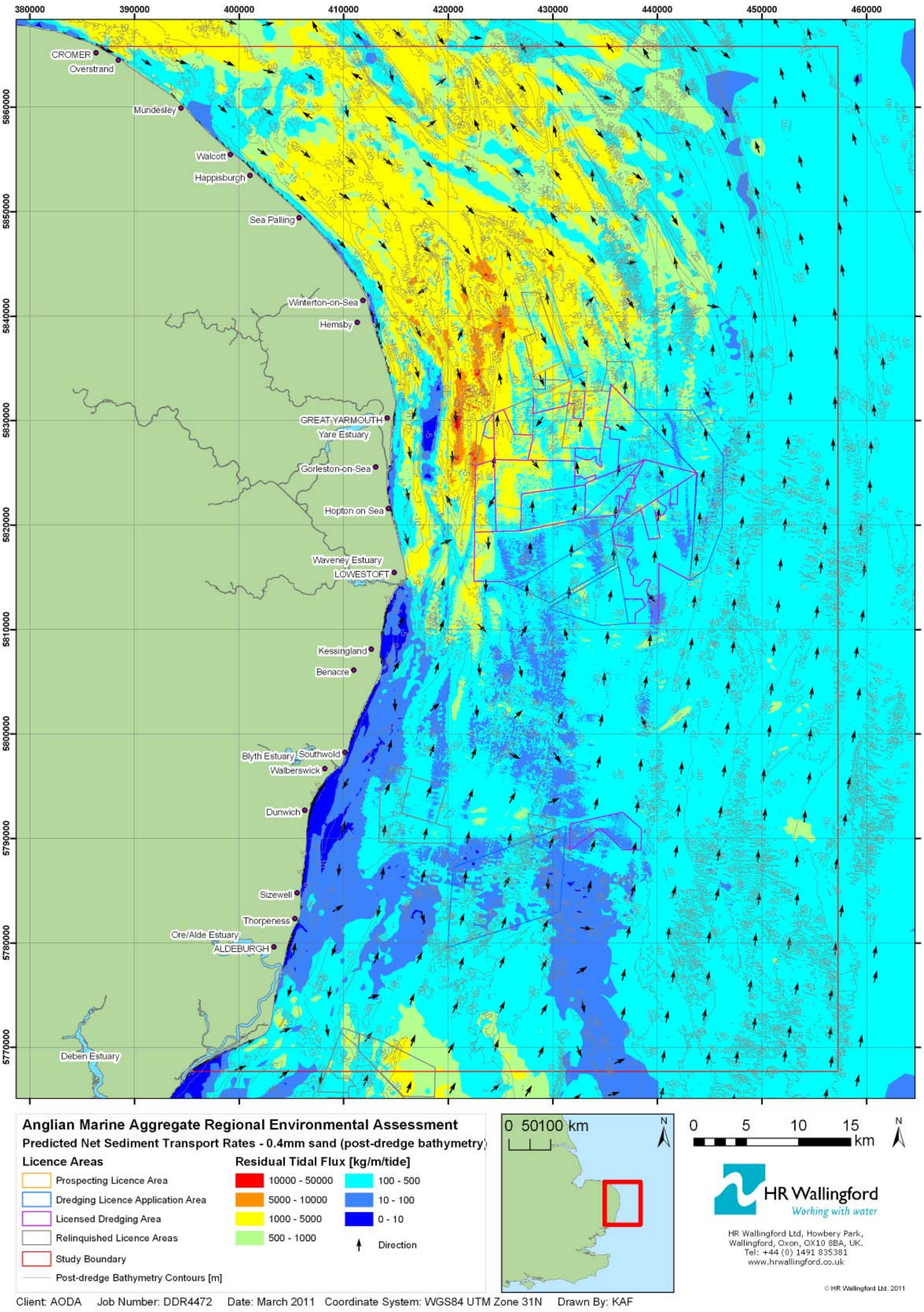


**Figure 12** **Predicted net sediment transport rates – post dredge bathymetry (0.4mm sand)**

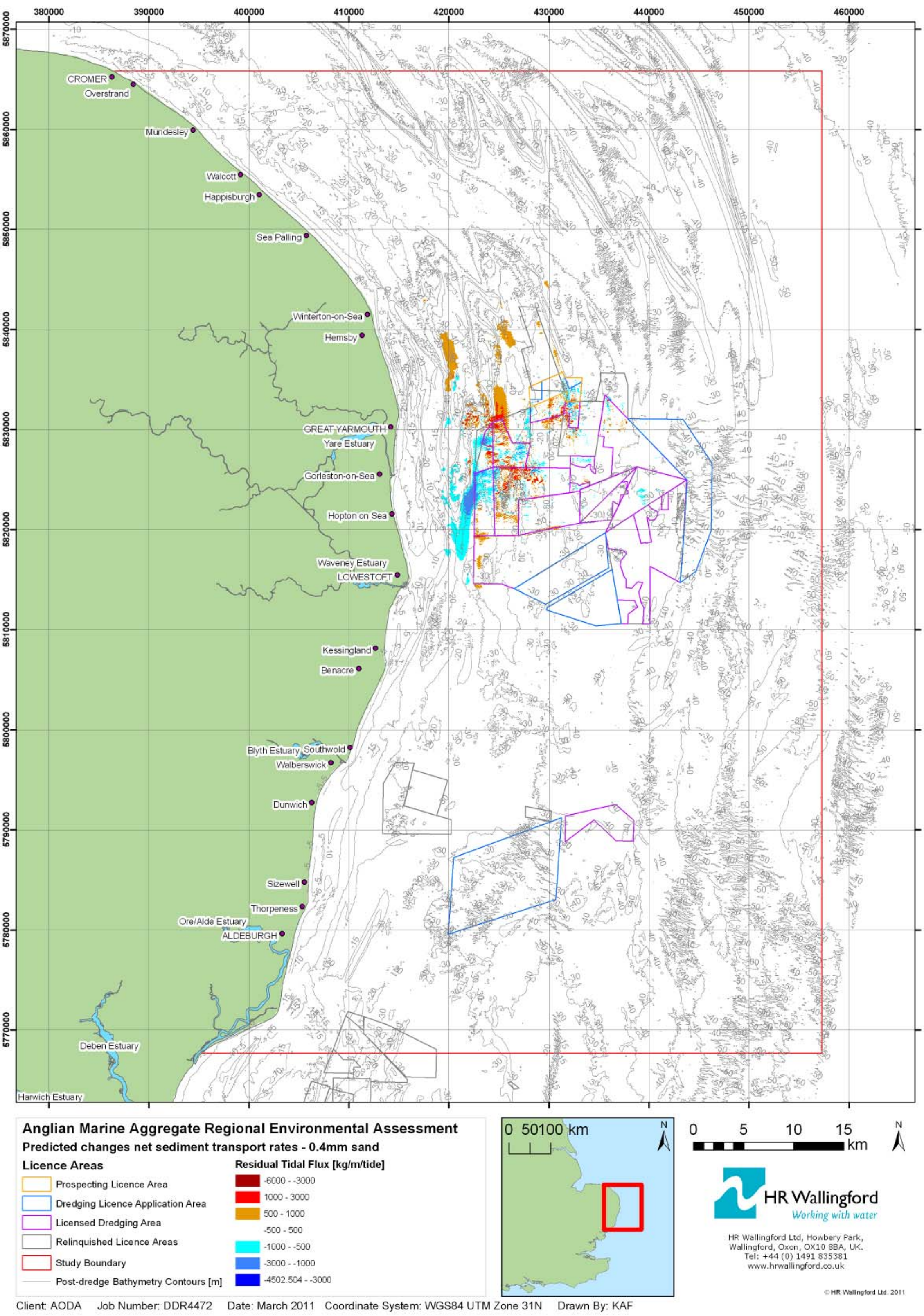


**Figure 13** Predicted changes in net sediment transport rates (0.4mm sand)

# *Appendices*

# Appendix 1 Supplementary model results

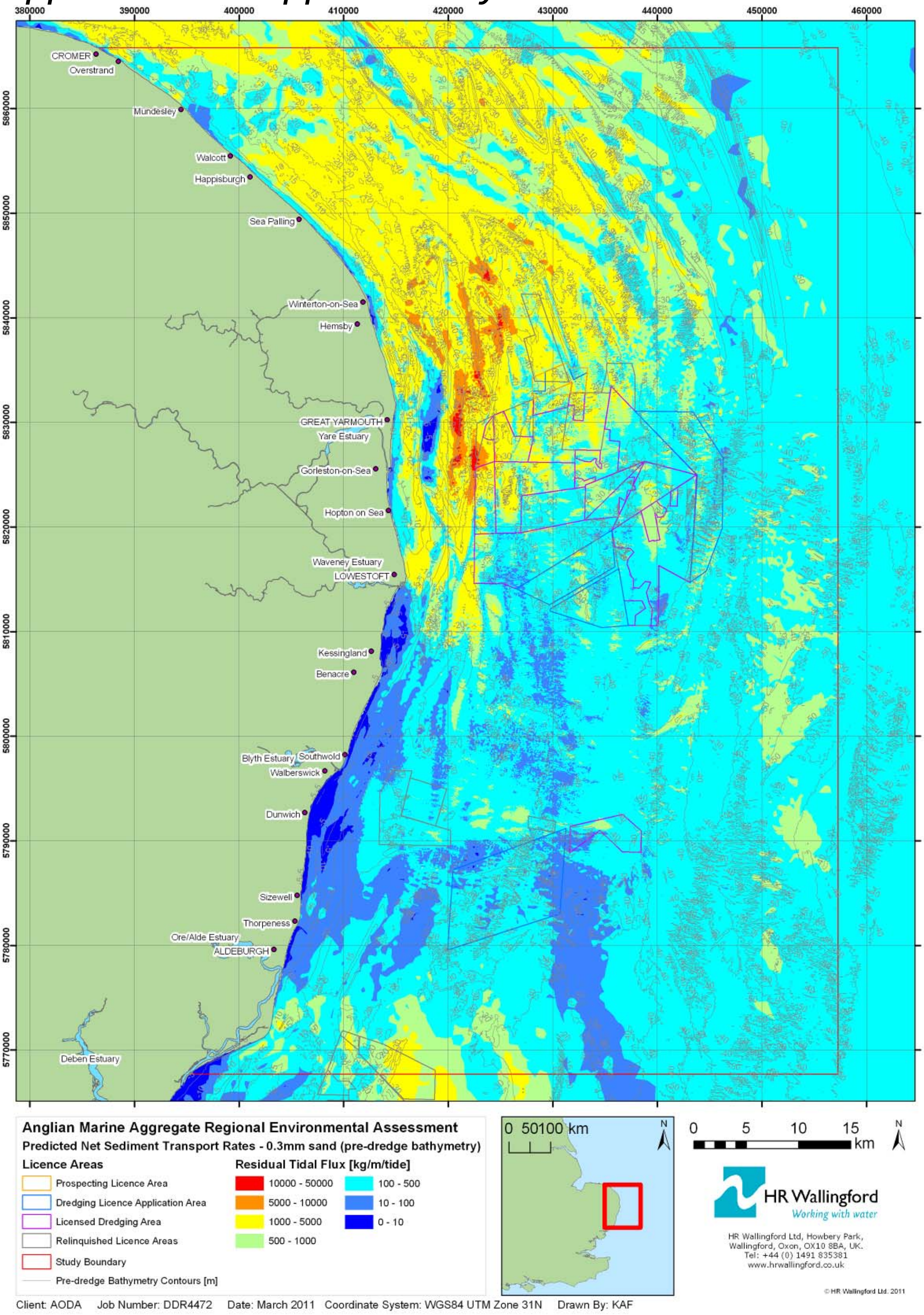


**Figure A1.1 Predicted net sediment transport rates – pre-dredge bathymetry (0.3mm sand)**

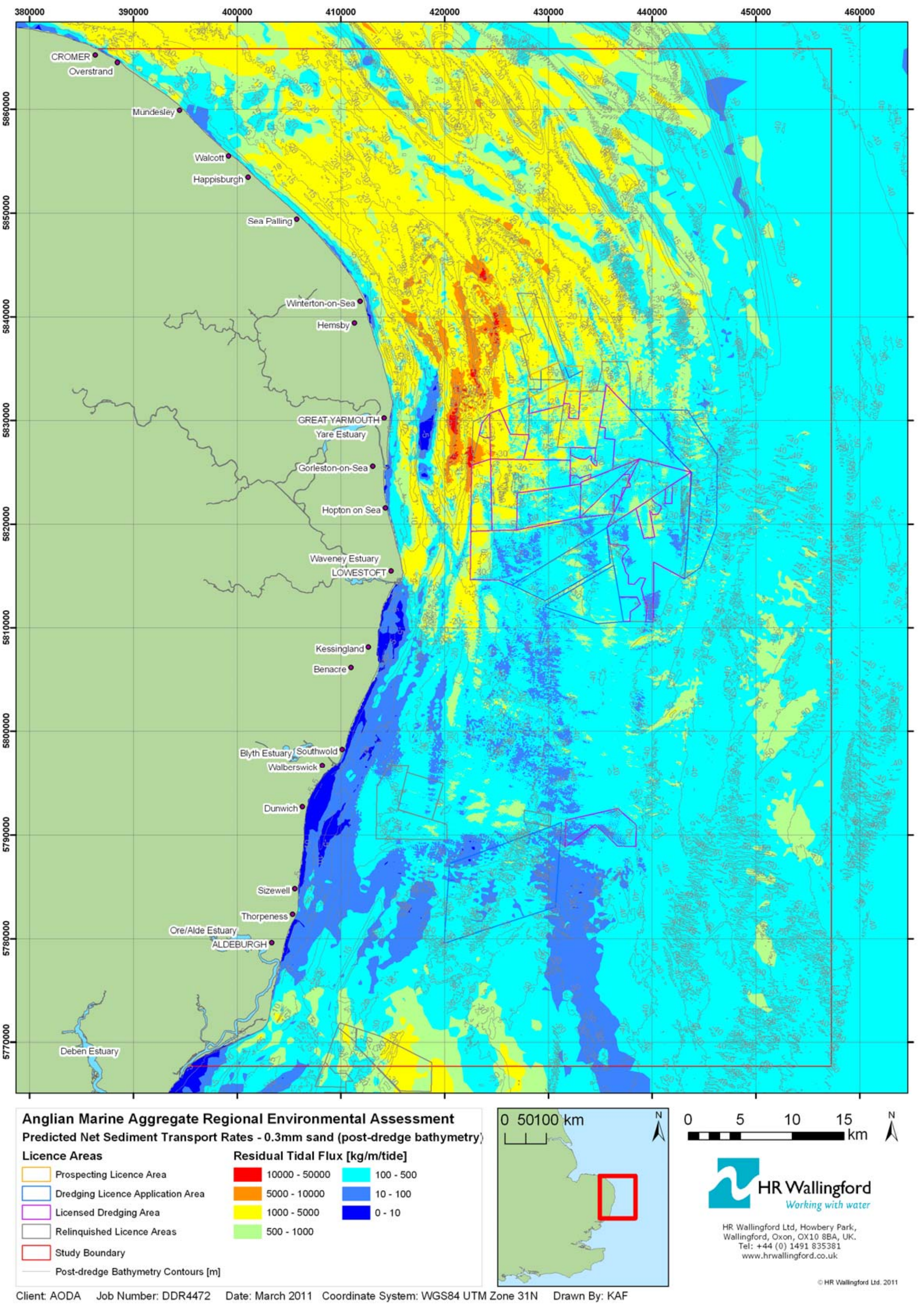


**Figure A1.2 Predicted net sediment transport rates – post dredge bathymetry (0.3mm sand)**

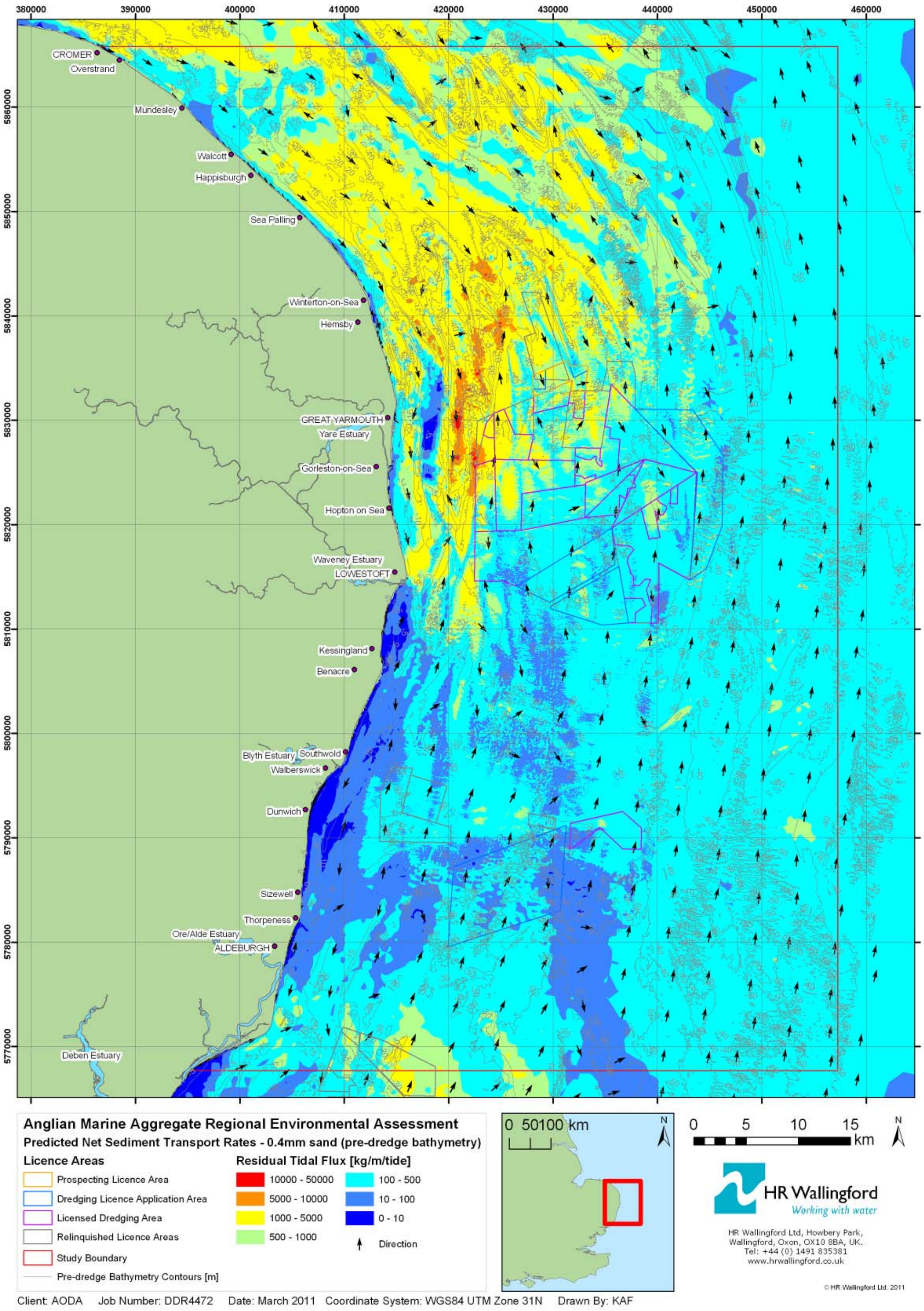


**Figure A1.3** Predicted net sediment transport rates – pre-dredge bathymetry (0.4mm sand)

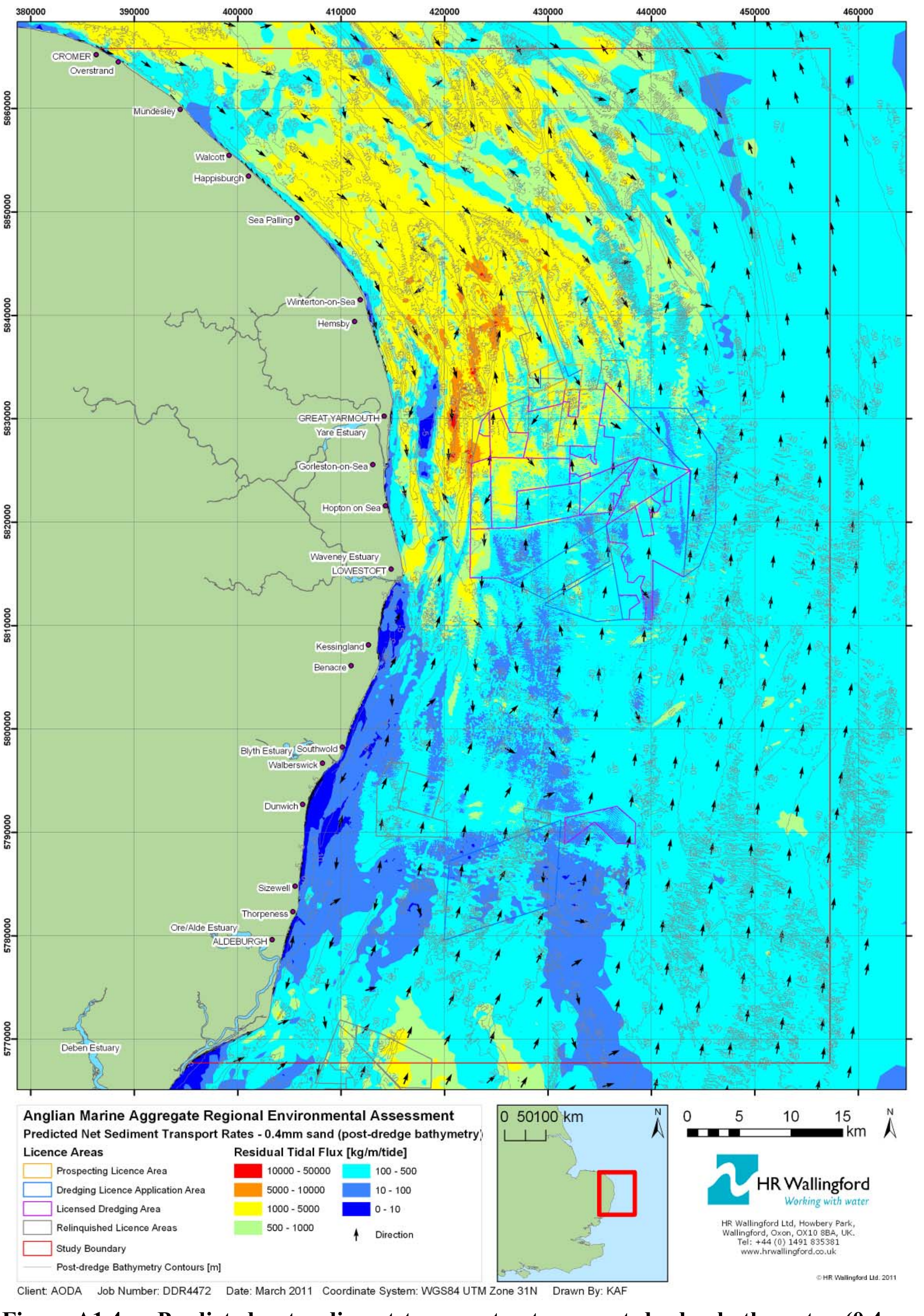


**Figure A1.4 Predicted net sediment transport rates – post dredge bathymetry (0.4mm sand)**

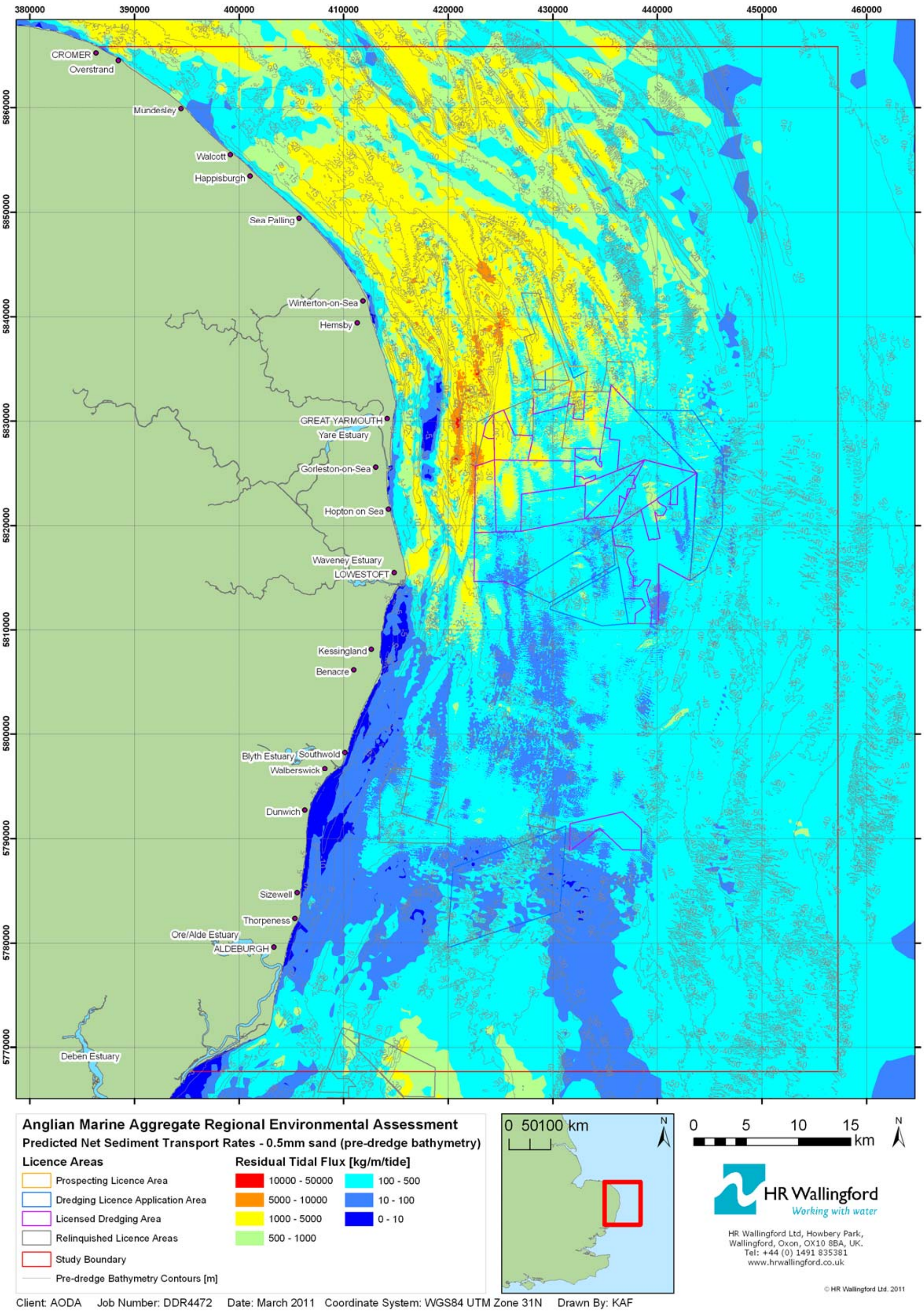


**Figure A1.5 Predicted net sediment transport rates – pre-dredge bathymetry (0.5mm sand)**

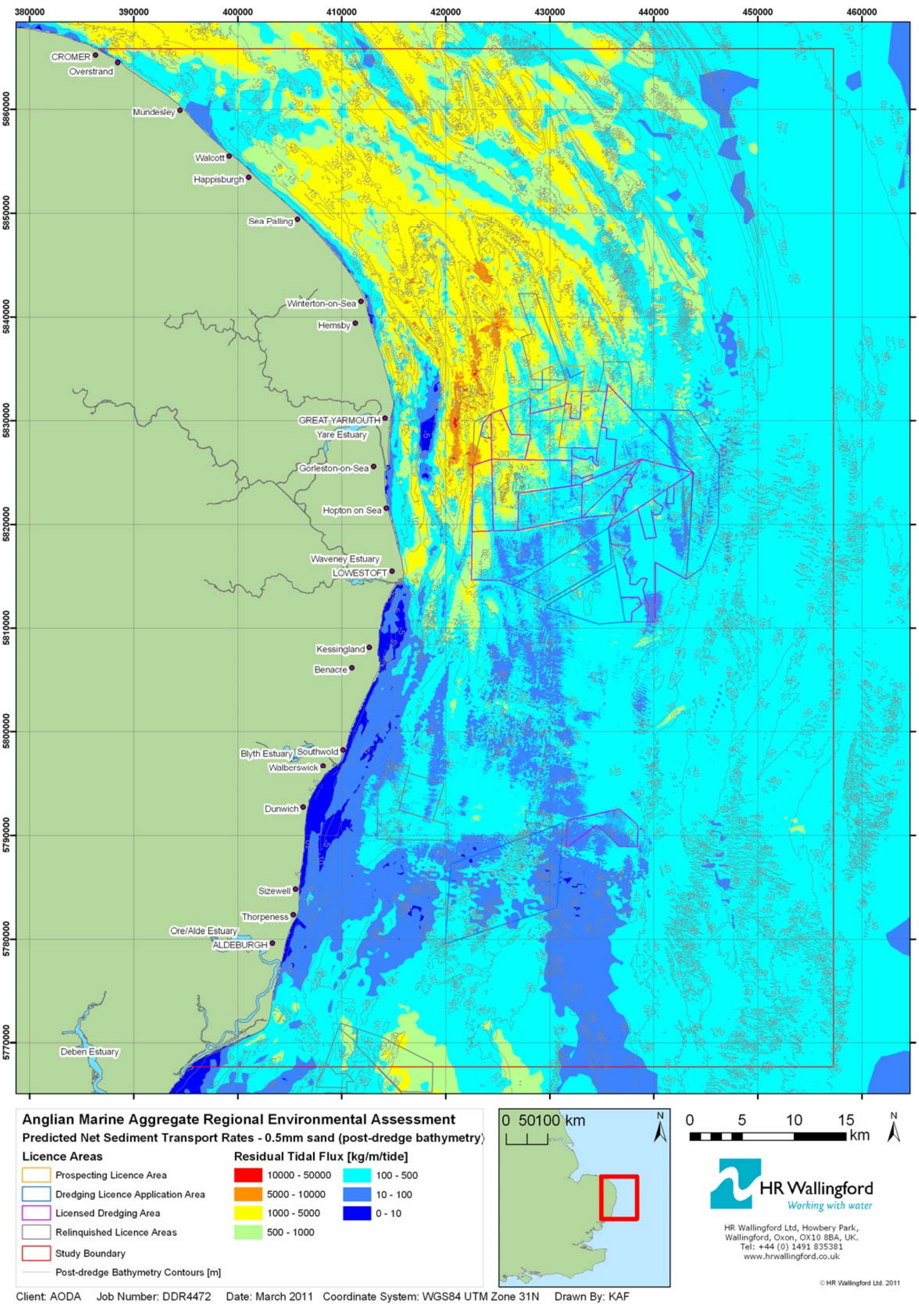


**Figure A1.6 Predicted net sediment transport rates – post dredge bathymetry (0.5mm sand)**

# Appendix 2 The TELEMAC tidal flow model

## Description of model and main areas of application

TELEMAC-2D is a sophisticated flow model, which was originated by LNH in Paris, for free surface flows. It solves the 2D depth-integrated shallow water equations that are used to model flows in rivers, estuaries and seas. It uses finite element techniques so that very flexible, unstructured triangular grids can be used. It has been developed under a quality assurance system including the application of a standard set of validation tests.

The model can simulate depth integrated tidal flows in estuaries and seas including the presence of drying banks. It can also simulate flows in rivers including turbulence structures resulting from flow obstructions and transcritical flows.

The advantage of using finite elements lies primarily in the possibility of using a very flexible grid. This is superior to using an orthogonal curvilinear grid as the user has far more complete control over grid refinement with a finite element system.

The applications of TELEMAC have included studies of tidal flows, storm surges, floods in rivers, dam break simulations, cooling water dispersion and infill of navigation channels.

## Theoretical background and solution methods

TELEMAC solves the shallow water equations on an unstructured finite element grid (usually with triangular elements). The various variables (bed elevation, water depth, free surface level, and the **u** and **v** velocity components) are defined at the nodes (vertices of triangles) and linear variation of the water and bed elevation and of the velocity within the triangles is assumed.

When the model is used a time-step is chosen and the computation is advanced for the required number of time-steps. There is no particular limit on the time-step for a stable computation but it is best to ensure that the Courant number based on propagation speed is less than about 10. It is found that if the solution is nearly steady then few computational iterations are required at each step to achieve the required level of accuracy, which in TELEMAC is computed according to the actual divergence from the accurate solution. The computation at each time-step is split into two stages, an advective step and a propagation-diffusion step.

## The advective step

The advective step is computed using characteristics or stream-wise upwind Petrov-Galerkin. The characteristic step makes it possible for the code to handle such problems as flow over a bump giving rise to locally supercritical flow and eddies shedding behind flow obstructions.

## The propagation/diffusion step

The finite element method used is based on a Galerkin variational formulation. The resulting equations for the nodal values at each time-step are solved using an iterative method based on pre-conditioned conjugate gradient (PCG) methods so that large problems are solved efficiently. Several PCG solvers are coded and a selection is available to the user. The complete matrix is not assembled. Instead an element by element method is used so that most of the operations are carried out on the element matrices; this is computationally more efficient, both in speed of execution and in memory requirements. Rather than using Gauss quadrature exact analytical formulae are used for the computation of matrices. Symbolic software was used to draw up the formulae used. The software makes it possible to carry out a second iteration of the solution at each time-step in order to represent the non-linear terms in a time centred way, otherwise these terms are treated explicitly.

### Boundary conditions

Boundary conditions are applied at solid boundaries where a "zero normal flow" and either a slip or non-slip boundary condition are applied. At open boundaries a selection of possibilities can be invoked depending on whether the flow is subcritical or supercritical or whether a wave absorbing boundary using a Riemann invariant is needed. A water discharge along a boundary segment can also be applied and the software distributes the flow along the segment chosen. This facility is valuable when running models of river reaches and the discharge in a cross section may be known rather than the velocity at each point in the cross-section.

### Grid selection

The model can be run with a Cartesian grid for modelling rivers, estuaries and small areas of sea, with the possibility to apply a uniform Coriolis parameter, or on a spherical grid for larger areas of sea in which case the Coriolis parameter is computed from the latitude at each node. The effect of a wind blowing on the water surface and causing a set-up or wind induced current or of an atmospheric pressure variation causing an inverted barometer effect can be included, as can a k-epsilon model of turbulence if required.

### Friction

The bed friction can be specified via a Chezy, Strickler or linear coefficient, or a Nikuradse roughness length. A variable friction coefficient over the model area is a possibility. Sidewall friction can also be included if wanted. Viscosity can be imposed as a given eddy viscosity value or a k-epsilon model can be used if needed.

### Tracer calculation

TELEMAC-2D includes also the capability to simulate the transport of a tracer substance. The tracer is again computed using an advective step followed by a propagation/diffusion step. Tracer boundary conditions can be applied at model inflow boundaries. The tracer calculation has been used in order to simulate cooling water dispersion and mud transport. Sources of water and/or of tracer can be specified in terms of the discharge required and the x and y co-ordinates of the location.

### INPUTS

TELEMAC requires as input a finite element grid of triangles covering the area to be modelled. Bathymetric data from which the bed elevation at each node can be computed is also required covering the area. A file of keyword values is used to steer the computation (supplies bed roughness, time-step, duration of run etc).

### Methods of inputting the data

The finite element grid may be provided by a standard FE grid generator such as I-DEAS or SIMAIL. The software STBTEL (part of the TELEMAC suite) is used to read the output file from the grid generation software. The bathymetry is input using a digitising tablet and the SINUSX software is used to capture the bathymetry data. The data is stored in a form to be read into the TELEMAC system and depths interpolated to the model nodes.

### Methods of checking and amending input data

SINUSX is a powerful interactive graphical software that can be used to check and amend the input data. Bathymetric curves can be duplicated, deleted, smoothed, moved etc.

### Time to set up/calibrate/run/amend model

This depends on the form in which the data is supplied. Typically 1-2 days to digitise the chart data and 1-2 days to create the finite element grid. Boundary conditions may take a day to prepare. A run may take 1 to 5 hours to run a tide (for a 2000 cell model). The duration of the calibration process is hard to generalise as it depends entirely on particular circumstances.

## OUTPUTS

### Output parameters

The user can select from a range of output parameters including u and v velocity, u and v discharge, water level, bed level, water depth, tracer concentration and Froude number.

### Output files

The TELEMAC output is contained in a single binary file which can be input to the graphics post-processor RUBENS. A listing file contains reflection of the input keywords and information on time-step reached, number of iterations to convergence etc. This file can be used to monitor the progress of a run.

### Output plots

Results from the TELEMAC system are processed using the interactive graphics system RUBENS. This is a powerful and friendly environment in which figures can be produced interactively. By pointing and clicking time history plots, cross sections, vector plots and contour plots of any parameter at any position can be produced. Parameters other than those input can be calculated in RUBENS and plotted.

## GENERAL

### Interaction and compatibility of the model with other models

The main modules apart from TELEMAC-2D itself (the 2D flow model code) are SINUSX and RUBENS (described above).

The TELEMAC suite includes a bed load transport model (TSEF) and a suspended load model (SUBIEF). Also a wave model ARTEMIS that solves the mild slope equation.

The TELEMAC modelling suite also includes a quasi-3D random walk model for pollution transport modelling and a detailed water quality model with many water quality parameters including dissolved oxygen balance and particulates.

### Quality Assurance

The software has been developed under the quality assurance procedures required by the French Electricity Industry. This has included the production of an extensive dossier of validation tests.

### Validation

Validation tests on TELEMAC include:

- Simulation of eddies produced behind bridge piers. This test case includes the ability of the model to produce an unsteady solution from steady boundary conditions (von Karman vortex street).
- Drying on a beach.
- Simulation of the tides on the continental shelf including the Bay of Biscay. This model has been closely compared with the observed tides at coastal sites.
- Flow over a step in the bed with critical flow and a hydraulic jump. This solution is compared with the analytically known solution to this problem.

# Appendix 3 The SANDFLOW sediment transport model

## Description of model and main areas of application

SANDFLOW-2D is the sand transport modelling module of the TIDEWAY-2D system. SANDFLOW-2D uses the flows calculated by TIDEFLOW-2D to study the transport, deposition and erosion of non-cohesive (sandy) sediment and thereby identify areas of potential siltation and erosion. SANDFLOW-2D has also been adapted to use the flows produced by the TELEMAC flow model for sand transport calculation.

## Theoretical background and solution methods

The sediments under consideration here are very fine and fine sands ($d_{50}$~ 0.06 to 0.25 mm) which mainly move in suspension. The model can also be used to identify trends in the case of medium sand ($d_{50}$~ 0.25 to 0.5 mm). If the sediment contains a high proportion of clay or silt particle sizes less than 0.06 mm, it would be more appropriate to use the MUDFLOW-2D (TIDEWAY) or SUBIEF (TELEMAC-2D) models.

The main factors controlling sand transport are:

- \- advection by currents
- \- settlement under gravity
- \- turbulent diffusion in all directions (but only the vertical component is of significance under most circumstances)
- \- exchange of sediment between the flow and the bed

The study of sand transport generally is very difficult but more so in the case of estuaries or coastal areas. This is because the water movements are continually changing, with the rise and fall of the tide, and there is usually a wide range of sediments on the bed and areas without mobile sediment, leading to unsaturated loads in the water.

## Method

Although sand transport in estuaries is really an unsteady, 3D problem, it has been shown by HR Wallingford that it can be dealt with using a 2D, depth-averaged model provided special provision is made to account for the vertical profile effects of the sediment concentration. Under these circumstances the depth-averaged, suspended solids concentration c(x, y, t) satisfies the conservation of mass equation.

$$\frac{\partial}{\partial t}(dc) + \alpha\left[\frac{\partial}{\partial x}(duc) + \frac{\partial}{\partial y}(dvc)\right] = \frac{\partial}{\partial s}\left(dD_s\frac{\partial c}{\partial s}\right) + \frac{\partial}{\partial n}\left(dD_n\frac{\partial c}{\partial n}\right) + S \qquad (1)$$

where

| | | |
|---|---|---|
| (u,v) | = | depth-averaged components of velocity (m/s) |
| $D_s$ | = | longitudinal (shear flow) dispersion coefficient ($m^2/s$) |
| $D_n$ | = | lateral (turbulent) diffusivity ($m^2/s$) |
| (x,y) | = | Cartesian co-ordinates in horizontal plane (m) |
| (s,n) | = | natural co-ordinates (parallel with and normal to mean flow) (m) |
| t | = | time (sec) |
| d | = | water depth (m) |
| S | = | erosion from or deposition on the bed ($kg/m^2/s$) |

$\alpha$ = advection factor to recover the true sediment flux from the product of depth-averaged quantities

## Advection factor ($\alpha$)

This is introduced to compensate for the omission of the vertical profile in the sediment flux terms.

$\alpha = T/qcd$ (2)

where

T = $\int_o^d q'c'dz$ is the sand transport (kg/m width/s)
q = the depth-averaged water speed $(u^2 + v^2)^{1/2}$

and q',c' are the full three-dimensional velocity and concentration variables.

Since the highest concentrations occur near the bed it follows that $\alpha \leq 1$. Typical values of $\alpha$ can be obtained by evaluating equation (2) for sand transport profile observations or from the integration of theoretical solutions for suspended solids profiles. However, in practice, it is usually acceptable to take $\alpha = 1$ on the grounds that the external and internal sources of mobile sediment are not well enough known to justify a more precise formulation.

## Bed exchange relations

The simplest formulation of the bed exchange relation is

$$S = \beta_s \, \omega_s \, (c_s - c) \qquad (3)$$

where

$c_s$ is the depth-averaged concentration when the flow is saturated with sediment ($kg/m^3$)
$\omega_s$ is the representative settling velocity (m/s)
$\beta_s$ is a profile factor to compensate for integrating out the vertical profile of suspended sediment ie to correct for higher sediment concentrations near the bed.

Deposition or erosion takes place depending on whether the instantaneous sediment load (c) exceeds or is less than the saturated value ($c_s$). Pick up of sediment from the bed is prevented if there is no sediment available on the bed. A shortage of material on the bed is reflected in a low concentration of suspended solids being advected away by the flow.

Typical values of $\beta_s$ could be obtained from actual observations of sediment profiles or from theoretical considerations. However, HR Wallingford has derived an analytical expression for this so that bed exchanges are performed automatically. This involves simplifying the vertical diffusivity relation and a profile mixing factor is introduced to enable the user to increase or decrease the effective mixing during calibration of the model.

## Sediment transport relation

The evaluation of bed exchanges requires a depth-averaged sediment concentration ($c_s$). Sandflow-2D obtains this from a sediment transport relation specified by the user. Three sand transport relations are supplied in the package (Ackers-White, van Rijn and a simple power law) and since the source code is provided other relationships can be added by the user if preferred.

The choice of sand transport relation needs care. It should be borne in mind that most relationships found in the literature are based on river or channel data where sediments are more narrowly graded than in estuaries. Also there is normally a small proportion of cohesive material in estuary sediments and this can alter the transport properties. If possible, sand fluxes should be measured at the study site, and if such data is available it may be best to use it to obtain the best-fit power law relation for the site.

### Diffusion

The dispersion ($D_s$) and diffusion ($D_n$) coefficients are not well defined. When viewed in close enough detail the whole motion appears advective; but when viewed on a coarser grid the smallest motions appear diffusive. Thus selection of the appropriate diffusion or dispersion coefficients depends on the grid size of the model - one model will treat as advection what a coarser grid model will treat as diffusion or dispersion.

Fortunately, the solutions to the equation are not normally sensitive to $D_s$ and $D_n$. As a first approximation, $D_n$ = Bdu, where d and u are representative depths and velocities. It has been found that B is usually in the range 0.01 (for fairly uniform depths and smooth beds) to 0.1 (for irregular geometry and/or rougher beds).

$D_s$ is automatically calculated by the program for each model cell depending on the local depth and velocity to give more diffusion in the direction of flow. The overall scale of $D_s$ can be changed using the relative dispersion parameter (in keyword DIFFUSION). This normally has the value unity but it can be adjusted upwards or downwards during calibration to get agreement between the model results and any dispersion observations that may be available.

### Numerical model

A simple, explicit, upstream finite difference technique is used to solve the advection - diffusion equation. Flux corrections are not considered to be necessary because the background concentrations of suspended sand are normally fairly uniform throughout the model in contrast to POLLFLOW-2D applications that have one or two point sources and correspondingly steeper concentration gradients.

The use of an explicit method introduces a stability constraint on the computing time step ($\Delta t$).

$\Delta t < \Delta s/(\text{maximum flow velocity})$

where $\Delta s$ is the grid size (TIDEWAY) or separation between nodes (TELEMAC-2D) in metres.

Generally, this does not pose any problems in practice because the allowable $\Delta t$ is usually much larger than the TIDEFLOW-2D time step and there is only a single equation to solve in the process model compared to three in TIDEFLOW-2D. Under these circumstances an explicit method is preferred because it enables the user to understand the code more easily and to modify the treatment of the physics of the processes being simulated. Note that where TELEMAC-2D is being used the values of $\Delta s$ will vary and so the minimum value of $\Delta s$ is the most important in terms of stability.

The treatment of the dispersion ($D_s$) and diffusion ($D_n$) terms introduces another stability constraint.

$\Delta t < \Delta s^2/4\ D_{max}$

where $D_{max}$ is the maximum of $D_s$ and $D_n$.

This constraint is normally weaker than the advective stability limit but the user should be aware that a high value of diffusivity can lead to an instability. In the event of problems the possible violation of both limits should be checked.

## Application of the model

The application of the model and interpretation of the results requires a good understanding of sand physics. Firstly it is important to choose representative values for the main parameters. Ideally these should be based on laboratory tests of actual sediment samples from the site. It is also important for the modeller to be aware of the limitations of this type of model when applied to real sites.

In addition it should be appreciated that sand transport is not an exact science. Accordingly, whatever model is used, and whatever parameter values are chosen it is essential that results are interpreted correctly. Provided this is done the model will be a valuable engineering tool.

## Calibration/validation

Calibration of sediment models is difficult because bed changes are usually too slow or too variable to measure anything significant for comparison. Sometimes historical charts or dredging records may be available but even then it is unlikely that the sources of suspended sediment can be quantified for the relevant period. Sometimes it is possible to get scaling factors for model results in cases where information is available and use these to estimate siltation in the new situation, but in many cases one is forced to use the best available values for the parameters and to demonstrate that the siltation and erosion patterns produced by the model agree with the observed state of the estuary or coastal region being studied.

Some evidence to support the physical realism of the model is given by the following results of simulation of sand transport in a flume and of observations from the Thames estuary.

The computer model results were compared with the results of a laboratory experiment performed in a flume with a length of 30m, a width of 0.5m and a depth of 0.7m. The discharge was measured by a circular weir. The mean flow depth was 0.25m and the mean flow velocity was 0.67 m/s. The bed material had a $d_{50}$ = 230μm and a $d_{90}$ = 320 μm. The median diameter of the particles in suspension was estimated to be about 200 μm, resulting in a representative fall velocity of 0.022 m/s (water temperatures 9°C). The stream bed was covered with bed forms having a length of about 0.1m and a height of about 0.015m. Small Pitot tubes were used to determine the vertical distribution of flow velocity. Water samples were collected simultaneously by means of a siphon method at four locations to determine the spatial distribution of the sand concentrations. At each location (profile) five samples were collected at a height of about 0.015, 0.025, 0.05 and 0.22m above the average bed level and these were integrated to give the suspended load transport. The HR SANDFLOW-2D model was run for the same conditions assuming the overall shear velocity was 0.0477 m/s and the results in Figure 1 shows that the model could be calibrated if suitable data is available.

The model was compared with some flume data to test its response to a change in the sediment load. It was shown that the model simulation could be calibrated by adjusting the settling velocity and vertical diffusivity parameters. This procedure is justified for practical applications because in nature these parameters are not well defined. For example, there is no unique settling velocity because the suspended load would contain a range of sediment sizes and the true nature of the vertical diffusivity is not yet fully understood.

The basic physics of the model was then checked against real field data from Foulness in the Thames Estuary. There was a wide range of sediment sizes in the data but the model was only used to simulate individual fractions. The saturation concentrations in the model were calculated using a cubic velocity relation derived from the observed sand fluxes.

Results from the model simulation of the 75 to 100 µm sand fraction are shown in Figures 2 and 3 plotted at half hourly intervals with a sequence number showing the progression through the tide. The model has a similar hysteresis effect to the observations on both stages of the tide. The systematic underestimation of concentrations during the ebb is probably due to a different availability of sediment sizes not allowed for in the simplified model. Nevertheless the demonstration confirms the general validity of the model in a natural situation.

An example of the agreement achieved during validation, between the SANDFLOW-2D model results and observed sediment distribution is shown in Figure 4. Note in particular the agreement between the areas of potential erosion predicted by the model and areas of rock bed, and also the areas of potential deposition and areas of sand bed observed.

## INPUTS

### Input data required

SANDFLOW-2D requires as input the elevation and flow results from a TIDEFLOW-2D run or a TELEMAC-2D run, together with information describing the initial distribution of sand on the bed. A boundary data file is also required to specify sediment concentrations at the model edges with respect to time. Other parameters required include the typical size of sand and its basic properties such as settling velocity and threshold stress for initiation of motion.

### Methods of inputting the data

Data is input to SANDFLOW-2D using ASCII data and steering files and unformatted direct access results files from TIDEFLOW-2D or the TELEMAC-2D equivalent. The steering files are set up using the context sensitive editor included in the user interface.

### User interface

A keyword driven interface controls all aspects of using SANDFLOW-2D from setting-up a model through to analysis of the results. The interface includes file management functions, graphical presentation of results and utilities for results analysis and file format conversion.

## OUTPUTS

### Output parameters

SANDFLOW-2D calculates concentrations of suspended sediment and distributions of erosion and deposition are stored at user selected intervals during the run. SANDFLOW-2D calculates suspended sediment concentration, erosion and deposition throughout the model area for each time step through the tide.

### Output files

Each run of the SANDFLOW-2D model generates three output files. Two of these files contain the suspended concentrations and bed deposits. The third output file; the List File contains run information.

## Output plots

The results from the SANDFLOW-2D may be represented using report quality-graphics utilities included in the TIDEWAY-2D system or, where TELEMAC-2D has been deployed, the RUBENS visualisation system. Contour plots of suspended concentrations and/or bed deposits at user selected times and concentration-time and deposit-time plots at selected locations can be produced.

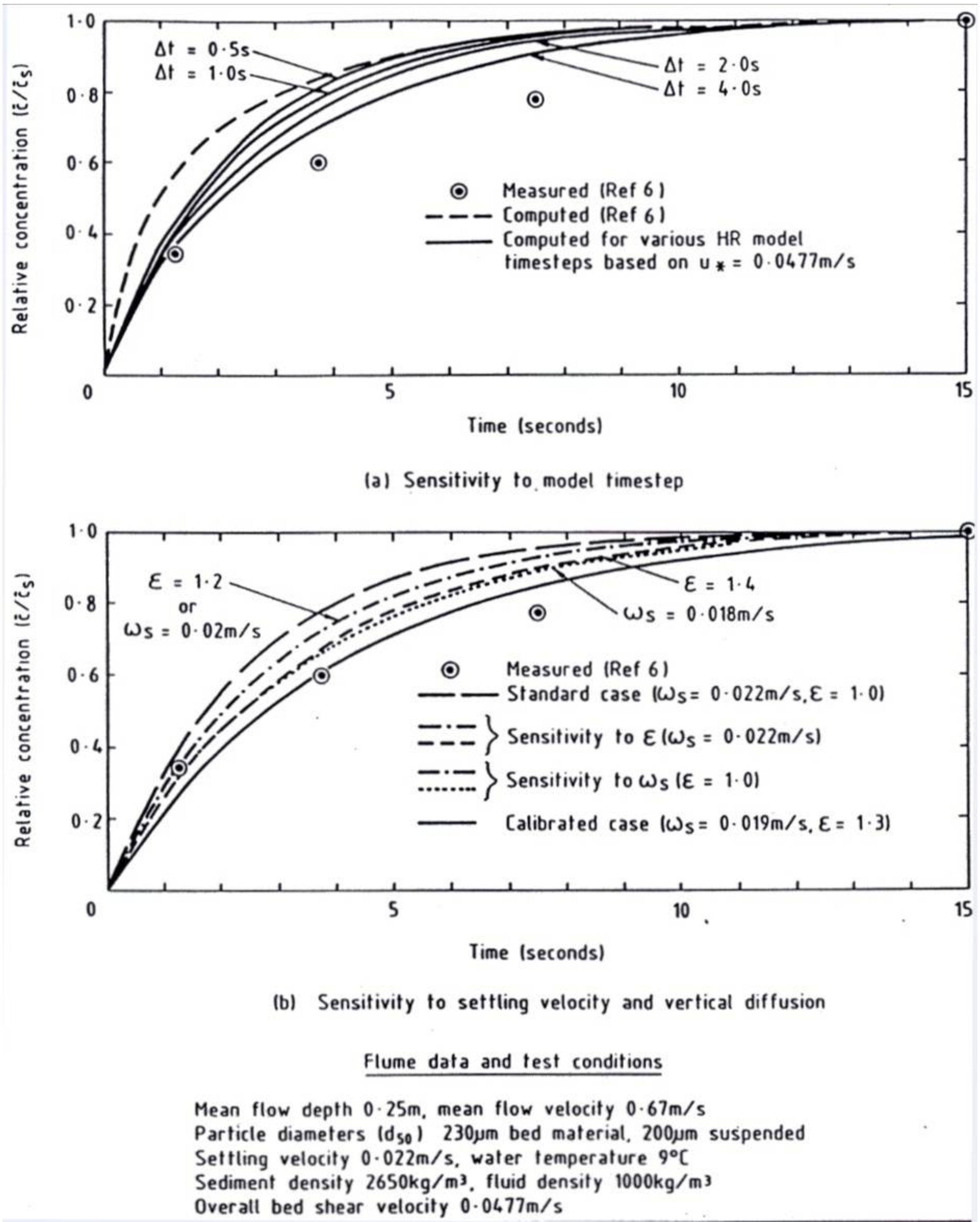


***Figure 1 Computed and measured evolutions of sediment load***

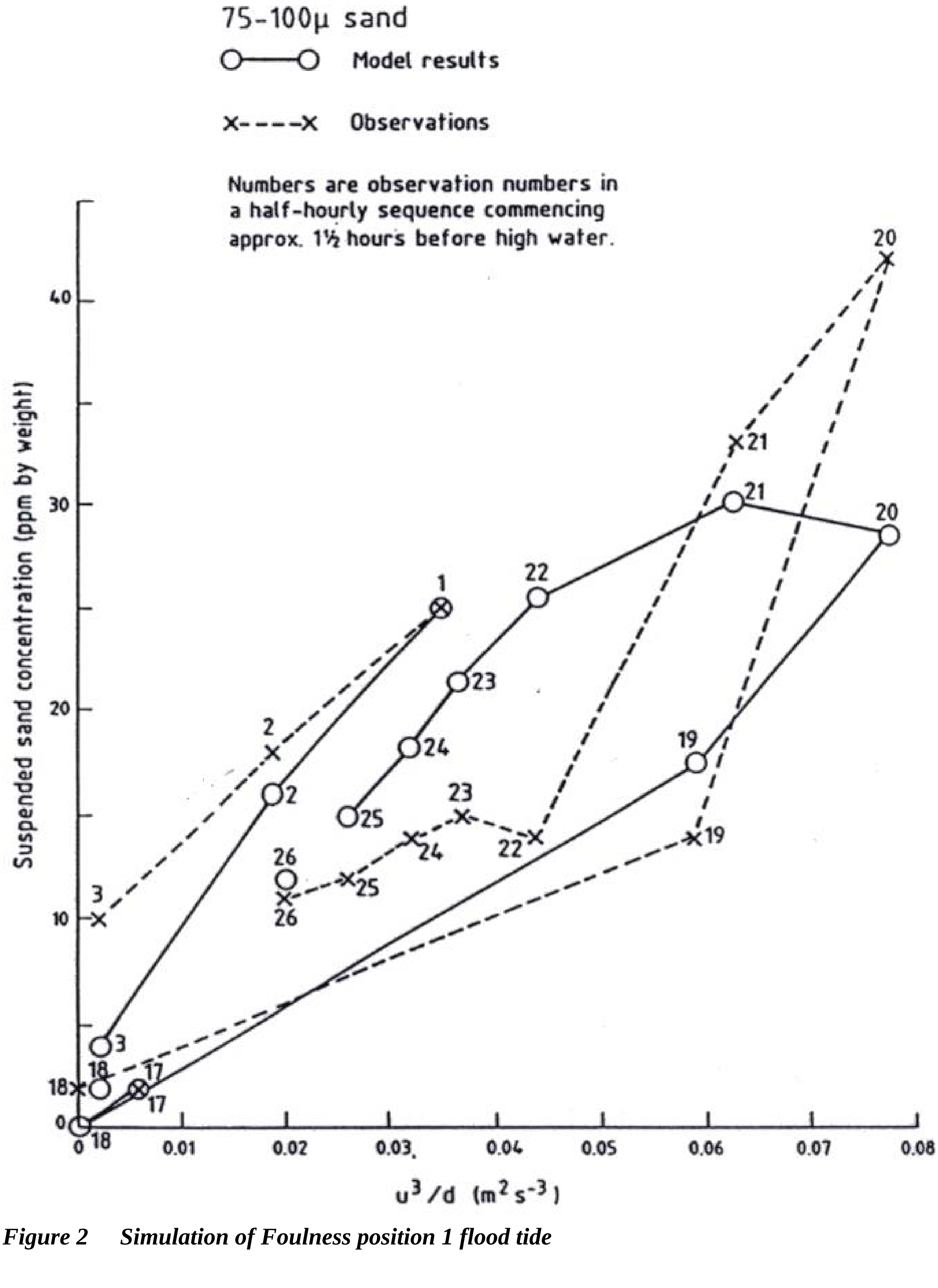


*Figure 2 Simulation of Foulness position 1 flood tide*

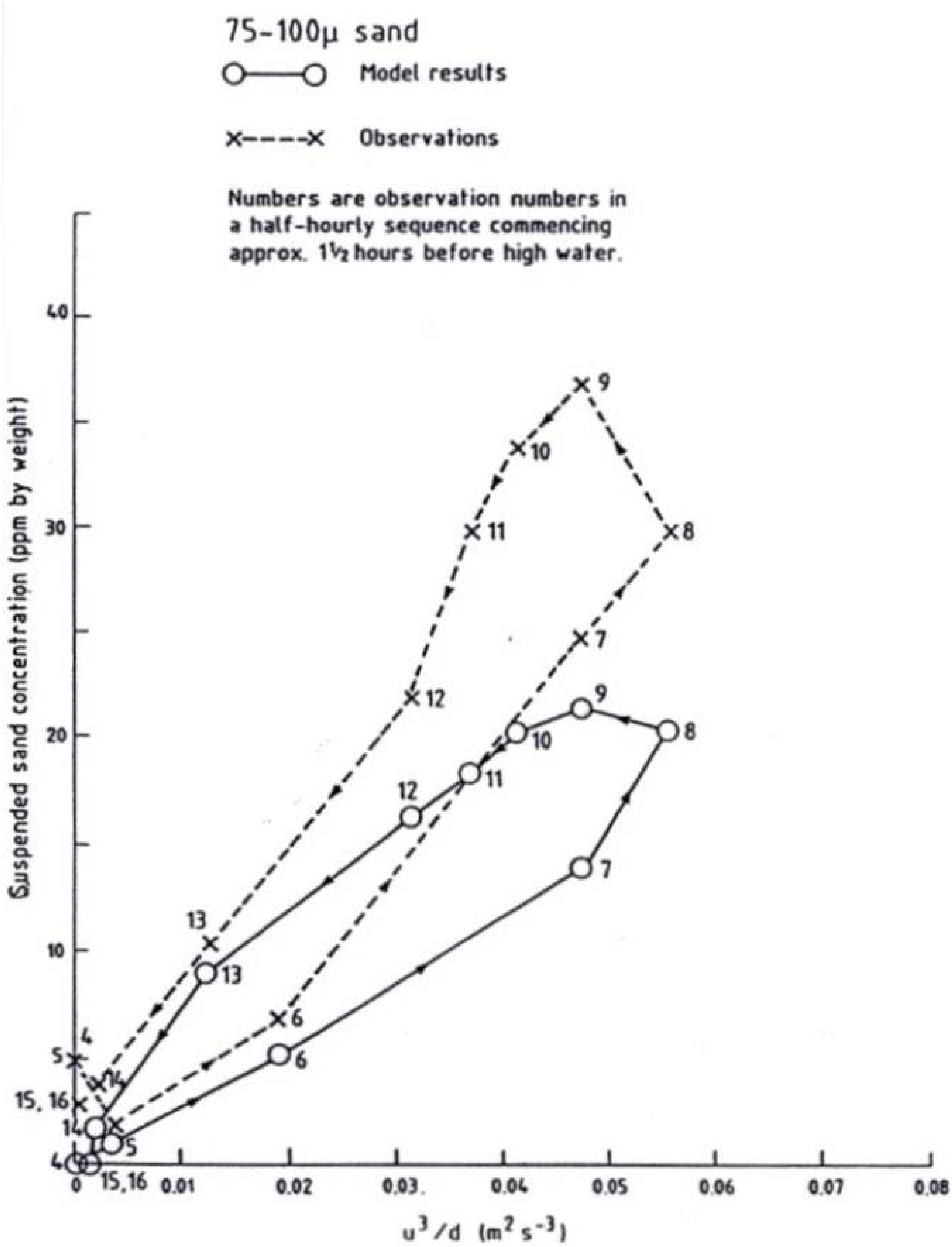


*Figure 3 Simulation of Foulness position 1 ebb tide*

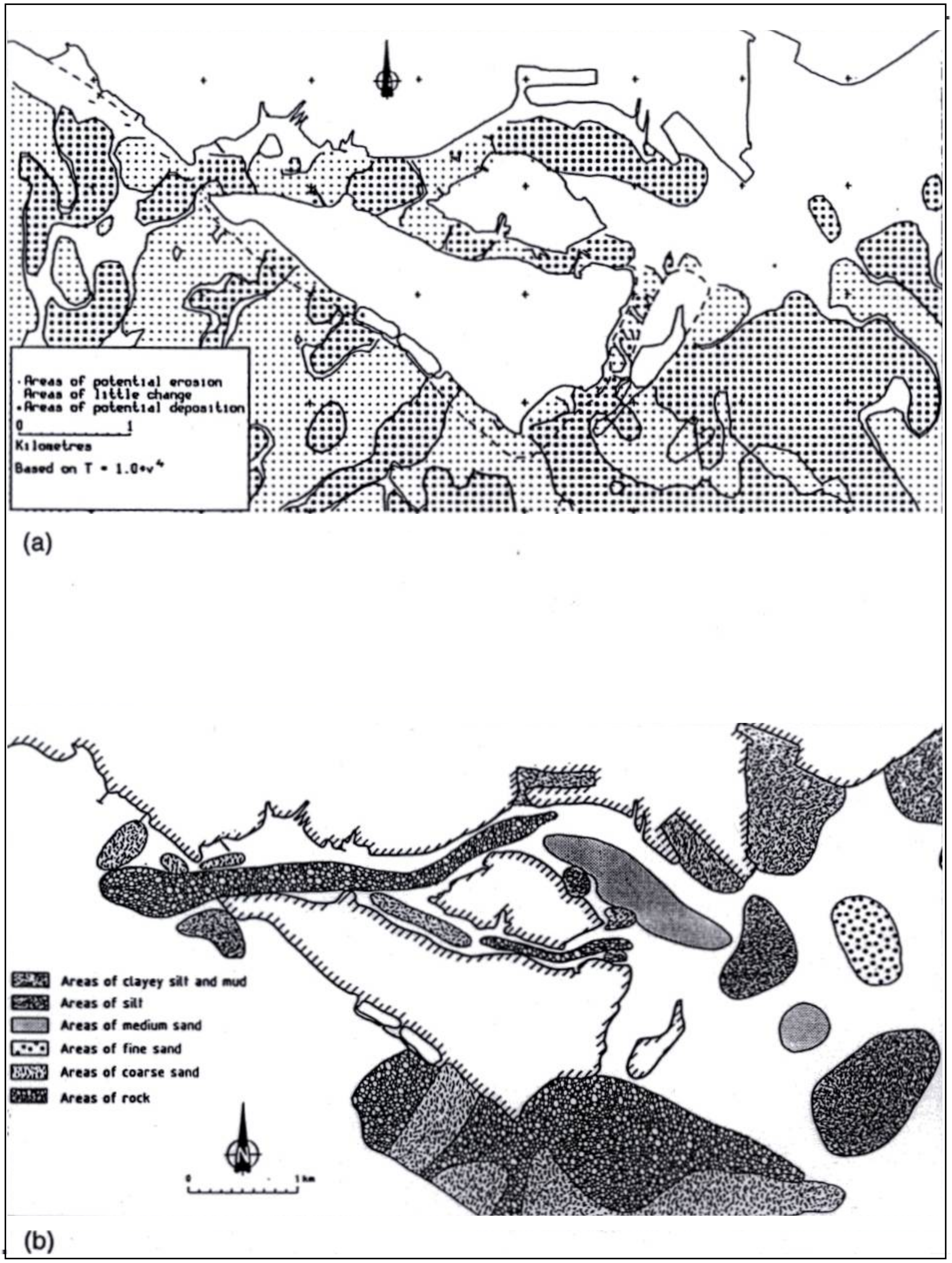


*Figure 4* ***Comparison of sand erosion/deposition areas in model (a) with observed sediment distribution (b)***