Thames Estuary Dredging Association

MAREA: Wave Study

Technical Note DDR4318-04

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Document Information

Project	Thames Estuary Dredging Association
Technical subject	MAREA: Wave Study
Client	Thames Estuary Dredging Association (via ERM Ltd.)
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Project No.	DDR4318
Technical Note No.	DDR4318-04
Project Manager	A H Brampton
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Document History

Date	**Release**	**Prepared**	**Approved**	**Authorised**	**Notes**
29/06/09	1.0	TJE	NPB	AHB	First draft for client review
9/07/09	2.0	TJE	NPB	AHB	Revised draft after client review
28/10/09	3.0	TJE	NPB	AHB	Second draft for client review
	4.0	NPB	AHB	RJSW	
09/04/10	5.0	NPB	AHB	RJSW	Final version

Prepared ....

Approved ....

Authorised R Whitehouse ....

Contents

Contents continued

Contents continued

1. Introduction

A Marine Aggregates Regional Environmental Assessment (MAREA) is being undertaken for the Thames Estuary Dredging Association (TEDA) to inform both new marine aggregate dredging licence applications and licence renewal applications offshore from the Thames Estuary. The study region covers the outer Thames Estuary and extends seaward beyond 2° East. The study region includes the open coastlines of Kent between North Foreland and Whitstable, of Essex east of Clacton-on-Sea and of Suffolk as far north as Dunwich (see Inset in Figure 1).

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 outer parts of the Thames Estuary (Figure 1) by the companies comprising TEDA (Britannia Aggregates, CEMEX UK Marine Ltd, Hanson Aggregates Marine Ltd, United Marine Dredging Ltd and Volker Dredging 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.

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.

TEDA 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 ERM Ltd.

1.1 STUDY OBJECTIVES AND SCOPE

This study investigates changes in wave conditions which have been caused by past aggregate dredging, or that may in future arise following proposed future deepening of the seabed by aggregate dredging. The study considers the cumulative effects on waves of extraction from all currently licensed and proposed new licence areas in the TEDA study region. In the past, concerns have been expressed that such dredging might change wave conditions as far inshore as the coastlines of Kent, Essex and Suffolk.

Many previous Coastal Impact Studies have been carried out in connection with applications for aggregate dredging in this region and have shown that such changes are unlikely. However, this present study provides an opportunity to re-examine the possibility that past dredging might have changed waves along the coastline of the study region using a new modelling technique. The wave modelling carried out then goes on to consider possible future changes in waves if plans for further dredging are accepted.

Unlike previous Coastal Impact Studies, however, this present study also includes an investigation of changes in wave conditions throughout the study region, i.e. within the extraction areas themselves and at all locations between those areas and the coastline. This allows a more thorough assessment of the implications of wave changes to coastal processes and offshore hydrodynamics.

It should be remembered, however, that this modelling of wave propagation has been carried out, on a broad scale, for the whole study region shown in Figure 1. Importantly, this report predicts where there will be **no** changes in wave conditions within the study region as a result of past and planned future aggregate dredging. These results, in particular, show no alteration in waves along the coastlines of Kent, Essex or Suffolk as a result of either past or proposed future dredging.

However, this report also indicates where such potentially significant changes may occur. Such changes in wave heights are generally restricted to within or 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 wave conditions, 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 waves 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 wave conditions approaching and travelling through the study region. It also explains the choices of the models used, and how the various representations of the seabed bathymetries were achieved. Finally, it describes the model runs that were carried out.
3	This Chapter presents the results from the modelling and interprets these in the context of the likely changes in both wave conditions during very severe storms and of the seabed morphology surrounding the dredging areas.
4	Still within the context of possible changes in wave condition, Chapter 4 discusses the potential interactions between offshore aggregate dredging and other uses of or developments within the study region.
5	This final Chapter presents the main conclusions, specifically indicating where results from the present study can be used to inform specific licence applications within the study region, or if a further detailed assessment may be required at that time.

2. *Wave modelling procedure*

Predicting possible changes in wave propagation is often a major component of the studies of the effects on the physical environment of any proposed aggregate dredging. This assessment is usually submitted at the time of the formal application for any extraction licence.

The present regional study provides an opportunity to review the effects on waves of all past dredging, and of proposed future dredging, within the Thames Estuary region on a cumulative basis taking into account relinquished, existing and proposed areas. This review contributes to the MAREA by identifying potentially important changes in wave conditions before any formal application is made either to extend existing extraction licences, or for licences for new areas.

Carrying out such a regional assessment of waves first requires the choice of a suitable computational model to predict the way that waves propagate across the whole study region. The model also must be capable of accurately representing the changes in seabed levels caused by dredging and therefore requires information on the seabed levels in the various extraction areas before and after dredging. Finally, running such a model requires the choice and specification of appropriate tidal levels and of the offshore wave conditions approaching the dredging areas from a variety of directions.

These three main aspects of the wave modelling carried out in this study are discussed in Sections 2.2 to 2.4. However, before that it is helpful to provide a brief description of how aggregate dredging can affect wave conditions within and beyond the boundaries of the dredging areas.

2.1 PHYSICAL PROCESSES

The lowering of the sea floor by marine aggregate dredging alters the way that waves travel over that part of the seabed. When extraction takes place in deep water areas, changes in wave conditions are likely to be small except in the immediate vicinity of the dredging area. These localised changes may only be a concern where there are features of interest close to the extraction area, whether natural such as sandbanks or man-made such as cables and pipelines.

However, where dredging takes place in shallow water, which in this study can be considered as less than 20m at lowest tidal level, there is a possibility that changes in wave conditions could occur as far away from the extraction area as the coastline.

The wave propagation mechanisms that may be altered by dredging the seabed can be divided into two main classes, as briefly explained below.

2.1.1 Energy-conserving processes

As waves travel towards a shoreline and enter shallower water, they are affected by a number of processes that alter, predominantly, their height and direction. These changes occur because the varying water depths lead to changes in the speed of propagation of both the wave crests and the wave energy.

When waves travel inshore with their crests parallel to the seabed contours, the changes in water depth give rise to “shoaling”, in which the changes in speed of the propagation of wave energy lead to changes in wave height. In very shallow water, close inshore, where the waves decelerate quickly, shoaling leads to a rapid increase in wave height that eventually causes the waves to break.

Where waves approach the seabed contours obliquely, the variation in the speed of propagation along the wave crests also causes the waves to change direction, a process known as refraction. Over complex seabed contours, refraction will lead to the focussing of waves in some areas, but a reduction in wave heights elsewhere. This effect is very similar to that of light being focussed or scattered by convex or concave glass lenses.

One unusual but important consequence of wave refraction over a dredged area can be to induce a partial reflection of waves at the seaward edge of the deepened area. Where the change in depth between the general seabed level and the bottom of the dredged area is sufficiently large, then some of the wave energy can be reflected, even if the side slopes of the dredged area are very shallow. Partial reflection of waves from aggregate dredging areas tends to occur only when both the wave period is long, for example in extreme storm conditions, and when the waves approach the seaward boundary of the dredged area obliquely. As will be seen later, however, there is some evidence that such a process can occur in the outer Thames Estuary MAREA study region during very severe storm conditions, when wave periods are unusually long.

Overall, however, neither shoaling nor refraction/reflection alter the total wave energy flux; but simply redistribute it over the sea surface.

Where there is a strong spatial variation in wave heights, a further energy-preserving process can become important, namely wave diffraction. Diffraction can most easily be described as transferring wave energy laterally, i.e. along the direction of the wave crests, from areas of higher to lower wave heights, and results in a "smoothing over" of changes in the wave height (and direction) caused by seabed features. Although more commonly associated with wave propagation into the lee of a harbour breakwater, diffraction also occurs landward of large seabed features, for example after the partial breaking of waves over a sandbank.

2.1.2 Energy-dissipating processes

In addition to the energy-preserving processes described above, there are a number of mechanisms that do alter the total flux of wave energy as it propagates towards a coastline from the open sea. Some processes, such as friction at the seabed or partial breaking over the crest of a sandbank, will convert wave energy into turbulence; others such as the continuing input of energy by the wind, will increase wave energy as it travels on towards the shoreline.

In shallow water areas (i.e. less than 20m deep), the lowering of the seabed by aggregate dredging can reduce the energy dissipation that occurs as waves pass the area. An example of this is where proposed dredging would remove or lower a mound or bank of sediment. If this natural feature causes wave breaking, because of the shallow water depths over its crest, then lowering it will increase wave heights landward of the dredging area; this effect could then hypothetically extend as far as the coastline. As a result, wave conditions will be different on the landward side of the dredged area to those either side of it, although wave diffraction will then act to reduce this variation as the waves travel onward towards the coast.

In addition, since most aggregate dredging areas lie a considerable distance offshore, winds will continue to alter waves as they travel over and past such deepened areas of the seabed. In particular, wind action reduces any spatial variability in wave conditions (i.e. their height, period and direction) as they travel away from the dredged area.

2.2 CHOICE OF A SUITABLE COMPUTATIONAL MODEL

In some parts of the UK, there has been concern that aggregate dredging could cause changes to waves at the coastline, and thus cause lowering of beaches and erosion of the shoreline. In response to this concern, previous assessments of the effects on waves of aggregate dredging have concentrated on predicting potential changes in wave conditions close inshore and, if necessary, suggesting changes to dredging plans to ensure that any changes would be insignificantly small.

The choice of an appropriate computer model to predict change in coastal wave conditions brought about by aggregate dredging has reflected this primary concern. Previous Coastal Impact Studies carried out by HR Wallingford in connection with the numerous aggregate dredging areas in the outer Thames Estuary have used a model known as TELURAY. This and similar models based on the same theory and equations, have provided a consistent approach for all offshore aggregate dredging applications over some 20 years.

This model works by using the concept of wave “rays”, i.e. lines that are everywhere at right-angles to the wave crests, and it produces results at single “target points” that are typically chosen in water depths of about 5m and close to the coastline. This model is known to be conservative, in the sense that it ignores some of the processes that in reality reduce the changes in wave conditions caused by dredging, particularly wave diffraction. Each run of the TELURAY model only produces information on predicted changes in wave conditions at a single location. It is, however, able to consider a wide range of incident wave conditions, i.e. different wave heights, directions and periods approaching one or more dredging areas from offshore.

There are a number of reasons why this model has not been used in the present study. First it was decided that there was a need to produce information on changes in wave conditions caused by aggregate dredging not only close inshore, but also in and around the extraction areas themselves, and at locations between these and the shorelines of the Suffolk, Essex and north Kent. This would allow the prediction of changes in wave conditions not only close inshore but in offshore areas of importance. These might be, for example, the locations of wind farms, over wreck sites, pipelines, or navigation channels and over seabed areas of conservation interest, for example because of their distinctive morphology, habitats, plants or animals.

Second, the TELURAY model is proprietary software that is not generally available, e.g. to other organisations that might like to audit the predictions of change in wave conditions made in this Regional Environmental Assessment. It was considered important in this study that any wave propagation model used could be obtained by other interested parties, and sufficient information about the modelling provided that an independent check on the results obtained could be carried out.

Finally, it was felt by the study team and the TEDA members that the conservatism that had resulted from the use of the TELURAY model in previous studies was probably excessive to the extent that the predicted changes in wave conditions due to aggregate dredging could be misleading. This type of model is also now considered to be out of date by many consultants.

It was therefore decided to choose a different computational model that did not have the disadvantages of TELURAY. As a first step, it was first felt to be important that any computational model used should be publicly available and well validated, ideally in areas in or close to this study region or for similar situations elsewhere.

For this study, a suitable model also needed to allow the input offshore wave conditions to be defined by a directional spectrum, i.e. with a realistic spread of energy over both direction and period, and to provide predictions of the waves at every point within the model domain as they travel from offshore to the coast. For the specific purpose of assessing proposed aggregate dredging, see Section 2.1, the model should also be able to predict changes in waves as they travel over dredging areas by considering:

- Wave shoaling;
- Wave refraction;
- Wave diffraction;
- Dissipation of wave energy at the seabed by friction;
- Dissipation of wave energy by wave breaking; and
- Further modification and generation of waves by winds beyond the dredging areas.

All of these processes, with the exception of the last, may change as a result of seabed lowering by offshore aggregate dredging. Any model that can include all of these processes and deliver results at closely-spaced intervals over the whole study region (i.e. providing results in and around the dredging areas, and between them and the coastline) will necessarily require a significant amount of computing effort. Finally, the model chosen will need to be able to examine the effects of aggregate dredging on a reasonably wide range of incident wave conditions at acceptable cost. For this study, it was decided not to consider just the largest waves likely to occur in the study region, but a range of wave approach directions i.e. from 30° N, 60° N, 90° N, 120° N and 150° N, thus covering all of the sectors from which large waves are likely to arrive.

Bearing all of the above in mind, we agreed with the TEDA members to use a wave propagation model known as SWAN (Simulating Waves Nearshore). This state-of-the-art model, developed and made available by the Technical University of Delft (TU Delft) in The Netherlands, is a 3rd generation spectral wave transformation suitable model for coastal wave studies. This model has also been used by others wishing to investigate wave propagation approaching the UK coastline (see for example HR Wallingford, 2004 and Stansby et al. 2006) and more specifically for investigating the effects of aggregate dredging on wave conditions (Walkden and Stansby, 2006). Further details of the SWAN model are given in Appendix 1.

SWAN includes the effects of refraction and shoaling, seabed friction, diffraction, wave breaking and wave-wave interactions. The model is ideally suited to the transformation of wave energy spectra over relatively large coastal areas. This is particularly true where the features of the seabed, such as offshore banks, result in depth-induced wave breaking and wave–wave interactions. The model also includes wave generation by wind within the model area. SWAN therefore is especially useful in regions such as the southern North Sea where wave conditions are dominated by those waves generated locally by winds.

Despite the fact that SWAN is a well-developed and widely-used model, it still cannot be expected to be absolutely precise. As with all computational models that involve many millions of calculations, there will be numerical inaccuracies that accumulate and eventually become noticeable. In addition, SWAN solves a number of partial differential equations numerically using an iterative technique to converge to a value that lies within a range of acceptable accuracy. Changes in the model, such as introducing lowered areas of seabed to represent dredging, may result in slightly different values being computed within this range.

Bearing this in mind, predicted wave heights, for example, cannot be expected to be accurate to better than perhaps 2 to 3%, i.e. 10 to 30 centimetres assuming an offshore significant wave height in the range of 5 to 10m. This sort of inaccuracy is smaller than changes in such large wave heights that could be discriminated, for example by a wave-rider buoy, and would not be considered significant in the context, for example, of the design of a coastal defence or the calculations of beach response to severe storm events. As an example, a recent study of the effects of a nearshore wind-farm on wave conditions along the coastline at Great Yarmouth stated that changes in wave heights of less than 2% due to the installation of the wind farm can be regarded as insignificant (CEFAS, 2006).

When looking for any effects of aggregate dredging at long distances from the extraction areas themselves, however, this numerical inaccuracy can mask any genuine but small changes in wave conditions and/ or produce similarly small changes that are purely an artifice of inaccurate numerical computations. It is therefore essential that the SWAN model results, as with those from many similar models, are interpreted with care and using an appreciation of the physical processes involved, rather than taken entirely at face value.

2.3 SPECIFYING THE SEABED LEVELS IN THE STUDY REGION

Aggregate, i.e. sand and gravel has been extracted from the seabed offshore in the outer parts of the Thames Estuary for many years, and the present licensed dredging areas are shown in Figure 1. When the MAREA is complete, the TEDA companies will apply individually to renew their licences, many 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.

To assess the impact of aggregate dredging, both in the past and in the future, three representations of the bathymetry within the study region were produced.

- A “baseline” bathymetry, in which the seabed levels in each existing or previous 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 previous dredging area have been established using the latest survey of those areas; and

- A “post-dredging” bathymetry in which future seabed levels in each existing and proposed new dredging area have been defined. These have been predicted by combining the present-day bed levels and the present plans of the TEDA members for extraction within these in the medium term future.

It is important to note here that each bathymetric data set cannot be ascribed to any particular year. The digital data from the Hydrographic Office 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) while the information provided by the TEDA members is based on surveys of individual dredging areas that will generally not have been carried out in the same year as for any other area. Similarly, the date at which dredging was started in the existing areas varies.

In addition, even if it was possible to obtain a complete and detailed survey of the seabed over the whole study region at some date before dredging started, and another very recent similar survey of “present day” bed levels, many of the changes in depths would **not** be a result of aggregate dredging. Computer model predictions of changes in wave conditions caused by the changes in seabed levels between those surveys would not be able to 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 the sediments arising from such dredging in designated disposal areas on the seabed.

The primary purpose of this report is to investigate how past and proposed future aggregate dredging, on its own, has or might alter wave conditions in the study region. In order to concentrate on just this cause of change, the three 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. This latter bathymetry was produced using older surveys, or information on past dredging including the amounts of sand and gravel extracted, or a combination of the two.

For future dredging, whether from existing or possible new areas, the TEDA members have sought to represent possible depth changes that might be brought about by the year 2030 (approximately). 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 proposed depth changes would remove virtually all of this material. The predicted increases in depth in the post-dredging bathymetry may be caused by dredging that is already occurring in existing licensed areas, and/ or by anticipated future dredging in those same areas and/ or in possible new areas.

Within any individual area, the future depth changes proposed by the TEDA members are considered to be 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.

However, the actual amounts dredged in each individual area by about 2030 will, in reality, depend firstly on the scale of the applications made for licence extensions (for existing areas) or for new areas, secondly on the conditions that may be placed on any 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.

These various factors mean that while the predicted future bed levels in any particular individual extraction area might be close to the actual changes by about 2030, it is almost certain that the total amounts of aggregate that will be removed from the TEDA region by this date will be substantially less than implied by the sum of all the bed level changes represented in this study. In this study, therefore, predicted future changes in wave conditions in and around any single dredging area may be realistic, but this would mean that changes around another area or areas might be over-estimated.

For the remainder of the study region, i.e. outside the past, present and possible future aggregate dredging areas, the bed levels were assumed to be the same for all three bathymetries and were taken from the most recent digital bathymetric data set available from the UK Hydrographic Office (via Seazone Solutions Ltd). We have therefore deliberately avoided including any changes to the seabed outside the limits of licensed or proposed new dredging areas. Any changes in wave conditions that are predicted can then be directly attributed to aggregate extraction.

The three bathymetric data sets were then compared with one another 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 2 shows the changes in depths in the TEDA region already caused by aggregate dredging (i.e. the present-day minus the pre-dredging bathymetry). 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 seabed levels, 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.

Figure 3 shows the changes in depth that would occur as a result of the current plans for further dredging in this region (i.e. the post-dredging minus the present-day bathymetry). Notice that the boundaries of the dredging areas are coloured differently to show whether they have been relinquished, are currently licensed, are proposed new areas for which an extraction licence has been applied for or, finally, are possible future extraction areas which are currently being prospected.

The future depth changes shown in Figure 3 are intended to provide a conservative estimate of the lowering of the seabed that might take place in the future, i.e. that the depth changes represented would produce a much larger volume of sand and gravel than would in reality be dredged from the **overall** study region.

The only exception to this general description of future dredging plans is for the proposed new Area 504, in the south-eastern corner of the study region. The extent and depth of the sand and gravel deposits in this area are still being investigated, so the assumed future depth changes are hypothetical; detailed and probably more restricted plans for dredging are still being developed. For this regional study, the assumed lowering of the seabed in this area is based on an estimate of the amounts to be 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 depth or extent of extraction than used in this study, the wave modelling results presented in this report will still be valid.

Note that in Figure 2 and 3, the boundaries of the dredging areas are coloured differently to show whether they have been relinquished, are currently licensed, are proposed new areas for which an extraction licence has been applied for or, finally, are possible future extraction areas which are currently being prospected.

2.3.1 Summary of SWAN model grid

Each of the three bathymetries used in the SWAN modelling was represented by a single rectangular grid, comprising over 125,000 nodes separated by 250m from their nearest neighbour to the north and east. The details of this grid are given below:

Table 1 SWAN model grid

Grid origin (UTM zone 31N)		Grid spacing (m)		Number of cells	
x	y	x	y	x	y
365000	5690000	250	250	296	432

2.4 CHOICE OF INPUT CONDITIONS

The final step in the establishment of the wave model process was to choose the incident wave (and associated wind) conditions and tidal levels that would be input to the SWAN model. These choices are explained below.

2.4.1 Selection of incident wave conditions

Wave conditions in the southern North Sea can be severe when winds are strong and blow consistently from a fixed direction for a sufficient period of time. However, in general the wave climate is in general much less severe that that experienced off the western seaboard of the UK. Because the predominant wind directions are from the west or south-west, there can be long periods when the coastlines of Kent, Essex and Suffolk receive very little wave energy from the North Sea.

To assess the potential effects of aggregate dredging on wave conditions, it has been necessary to choose suitable combinations of wave height, period and direction for input to the SWAN model. It has been standard practice in such assessments, for many years, to concentrate on those severe wave conditions that not only pose the greatest dangers to coastal defences, shipping and the natural environment but also tend to have the longest wave periods. The longer the period of a wave train, the greater the effect of changes in bed levels will be on those waves through refraction, diffraction and energy dissipating mechanisms such as friction at the seabed (see Section 2.1).

These largest waves are also of greatest concern to those building structures in or at the edge of the sea, for example wind turbines, breakwaters or seawalls. For the design of coastal defences for intensely developed urban areas, for example, it is necessary to consider wave conditions so severe that they can only be expected to occur once, on average, every 200 years, i.e. to have only a 0.5% chance of occurrence in any single year. If such waves do not pose a serious threat to a coastal defence, then it can be safely assumed that a more frequently occurring wave event, of smaller height and period, will pose less of a threat.

Exactly this approach has been adopted in the present study, in order to examine the effects on waves of marine aggregate dredging in the Thames Estuary region. If very severe wave conditions at the outer edge of the study region are chosen in the same way as they would be for the design of a coastal defence, then it can be assumed that the changes on these caused by the dredging will be as large and probably larger than for more frequently occurring waves. This “worst case” approach has therefore been adopted in the present study.

Having made this decision, considerable further work is needed to define these very severe incident wave conditions. As pointed out previously in Section 2.2, it is important to ensure that each wave condition considered is realistically represented, i.e. by a directional spectrum that specifies the spread of the wave energy over both direction and frequency. In addition, it is important that the effects of dredging are predicted for a range of different incident wave (and associated wind) directions. Within this study region, the continuing action of the winds on waves as they travel from offshore, over the dredging areas and on towards the coastline needs to be included in the modelling process.

For this, it is first necessary to obtain a realistic offshore wave “climate”, i.e. information on the probability of occurrence of wave conditions arriving from different directions at the seaward edge of the study region. This information on more frequently occurring wave conditions can then be extrapolated to estimate much rarer events.

Since there is insufficient long-term measured wave data to provide reliable information on offshore wave conditions at the seaward edge of the study region, an alternative method has to be used. This problem has been solved previously by using the outputs from a numerical wave forecasting model, such as one of those routinely run by the UK Meteorological Office. This approach has been used recently for several studies of flood and coastal defences along the coastlines of the Thames Estuary that have been commissioned by the Environment Agency and local coastal authorities.

Further, results from previous studies involving the prediction of nearshore wave conditions in the UK, e.g. for Defra/Environment Agency by HR Wallingford (2004) and by academic research workers (Stansby et al, 2006) have shown that the SWAN model in combination with boundary data from the Met Office European Wave Model gives good agreement against measured data. These previous studies have therefore shown that the approach chosen for this study should provide reliable predictions of wave conditions within this study region. Hence, for this study, information on predicted wind and wave conditions near the outer edge of the study region was obtained from the UK Met Office European wave model for the period April 1990 to March 2006.

Because of the considerable north/south extent of the study region, individual storm wave conditions along its eastern edge will vary, and as will the wave climate along that boundary. As a result, predictions of wave conditions were obtained for five points selected from the UK Met Office European wave model, summarised in Table 2. As an example of the results from this model, Figure 4 presents a “wave rose” which summarises the wave climate at one of the five locations, and shows the probability of occurrence of various wave heights arriving from different directions.

Table 2 Offshore wave climate locations (from UK Met Office European wave model)

Point	Degrees North	Degrees East
1	52.50ºN	1.93ºE
2	52.00ºN	1.93ºE
3	51.75ºN	1.93ºE
4	51.50ºN	1.93ºE
5	51.25 ºN	1.93ºE

The information on wave conditions at these five locations was reviewed, and it was concluded that:

- For waves approaching from the north-east, the wave climates from Points 1 and 2 would be used to estimate the most severe wave conditions;
- For waves approaching from the east, the wave climates from Point 3 would be used to estimate the most severe wave conditions; and
- For waves approaching from the south-east, the wave climates from Point 5 would be used to estimate the most severe wave conditions.

Note here that this approach simplifies the expected variation in individual wave conditions along the seaward boundary of the study region, by assuming wave heights and energy are equal to the greatest value predicted along that eastern edge of the model grid. This is a conservative approach, i.e. it will tend to over-estimate wave heights and periods entering some parts of the study region.

To provide specific wave conditions for input to the SWAN model, it was then necessary to analyse the information about the general wave climate at each of the five offshore points and predict the height and period of very severe waves approaching from each of the five different directions that were chosen for this modelling (see Section 2.2).

For each directional sector, the wave height distributions were extrapolated using a three-parameter Weibull probability distribution (Appendix 3) to estimate the wave height and wind strength for an event with a 1 in 200 year return period. Once the two principal parameters, i.e. the significant wave height and the associated wind speed, had been predicted for the 200-year return period event, it was then necessary to select an appropriate mean wave period for each extreme wave condition. This was achieved by examining the correlation between wave heights and periods in the relevant offshore wave climate, and then using this correlation to ascribe a wave period that would be expected for the derived wave height for a 1 in 200 year return period event. In doing this, care was taken to err on the side of caution in choosing the wave period, i.e. biasing the choice to select a longer wave period than would have been chosen if the average value for any given wave height had been used. Using this predicted mean wave period, a frequency spectrum was derived for each storm condition and the peak wave period evaluated.

The following table summarises the results of this process. For each direction the significant wave height (approximately equal to the mean of the highest third of the individual wave heights in a wave record) is predicted along with the associated peak wave period (i.e. the period at which the greatest amount of wave energy within the frequency spectrum occurs). These offshore wave conditions are exactly the same as we would have produced for a study to predict extreme offshore wave conditions as part of a design study for a coastal defence or a harbour breakwater within the study region.

Table 3 Extreme incident wave conditions

Return period (years)	Direction (ºN)	Wind speed (ms^{-1})	Significant wave height (m)	Peak wave period (s)
200	30	24.98	5.86	11.1
200	60	20.80	5.49	10.8
200	90	22.52	5.43	10.7
200	120	21.21	3.76	8.9
200	150	23.24	4.22	9.4

The greatest wave heights approach from 30 ºN. Extreme wave conditions approaching from other directions than those listed in Table 3, for example from 0 ºN (±15 º), have smaller wave heights and periods. In addition, much of the wave energy associated with waves approaching from other directions would be smaller and generally travelling parallel to or away from the coasts within the TEDA region. Any changes in such waves brought about by aggregate dredging would thus be smaller, and of much less concern from the viewpoint, for example, of coastal defence.

2.4.2 Tidal levels

To assess the impact of the dredging at different tidal levels, two still water levels were considered. These corresponded to a high tidal level (equal to Mean High Water Springs, MHWS) i.e. +4.5m above Chart Datum (CD) and to a low tidal level (equal to Mean Low Water Springs, MLWS) (+0.5m CD) at Clacton. Note that in such a large study region, tidal ranges vary quite considerably so that these chosen high and low water levels, which are applied uniformly over the model grid, will be slightly different to the values of MHWS and MLWS at locations other than at Clacton. Unless aggregate the predicted changes in wave conditions If aggregate dredging was predicted not to alter wave conditions at some point of interest for either of these two chosen tidal levels, there is no good reason to consider other and potentially more complicated representations of the variations in tidal heights in the study region.

The results from the wave modelling carried out for the higher tidal level are of primary interest to those concerned about the possible effects of offshore aggregate dredging on coastal defences or the erosion of beaches and cliffs. However, the increase in water depths caused by dredging is proportionately greater at low tide. Results from the model runs for a sea level of MLWS can therefore be expected to be greater, providing a "worst case" prediction of the extent and size of changes to wave conditions caused by such dredging.

2.4.3 Sensitivity tests

The five severe wave conditions and the two tidal levels discussed above were input in turn to the SWAN model, which was then run for all three representations of the seabed discussed in Section 2.3, i.e. the pre-dredging, present day and post dredging bathymetries. This resulted in a total of 30 model runs. For each incident wave condition and tidal level the results for the three different bathymetries are then compared to show the effects of past and proposed future aggregate dredging in the Thames Estuary. The results of the modelling of these wave conditions are described in Section 3 of this report.

It was decided in specifying the modelling of wave propagation, however, that there would be merit in examining the sensitivity of the results obtained from these 30 SWAN model runs to modest variations in the input wave conditions. This sensitivity testing was planned to allow, for example, the investigation of the possible effects of climate change on the conclusions drawn about the effects of aggregate dredging. The specification of the extra SWAN model runs, however, was delayed until the results from the primary 30 sets of results had been examined, on the basis that effort in such sensitivity testing would be concentrated on the combinations of wave directions and tidal level of greatest concern.

After these results had been produced and digested, it was found that the greatest changes in wave conditions occurred when they approached from 30°N, as would have been expected given that these waves have the longest wave period. Subsequent SWAN model runs to test the sensitivity of the results to variations in wave conditions were therefore carried out only for waves approaching from 30°N. Two further wave conditions were examined as follows:

- A wave condition that occurs more frequently than the 200 year return period wave condition, i.e. for a wave height that is exceeded about 5% of the time that waves approach from this direction. Such a wave height is likely to be experienced from some direction for about 40 to 50 three hour periods in an average year in the study region; and

- An even more extreme wave condition than the 200 year return period wave from 30°N, to represent a possible increase in storm occurrence as a result of global warming. This possible “future extreme” condition had a significant wave height 10% greater and a wave period 5% greater than the present-day 200-year return period wave condition introduced in section 2.4.1 above.

The former of these extra wave conditions was chosen to indicate the possible effects of changes in wave height on the morphology of the study region in and surrounding the dredging areas. If for at least 95% of the time that waves approach from this direction the changes are insignificant at any location, for example on the coastline, and given that any changes are likely to be even less for any other wave direction, then it seems reasonable to deduce that the overall sediment transport regime and hence the processes of morphological change will not be affected at that point.

In the context of the design of coastal defences, the current advice from Defra/Environment Agency is that a “future extreme” condition as defined in the second bullet point above has to be considered. This is to check that decisions made about the choice of any defence scheme are not sensitive to the possible effects of climate change as a result of global warming, in particular to a possible increase in the frequency and intensity of severe storms. It is therefore sensible to carry out the same wave modelling in the context of assessing the possible effects of marine aggregate dredging on wave conditions. Note that using this future extreme wave condition does not mean that such an increase in storminess is necessarily expected; it may be that severe storms become rarer and less intense in future years. Instead, considering this wave condition helps in the decision-making process given the uncertainty about some of the effects of global warming.

3. *Discussion of Results*

3.1 RESULTS PRESENTATION

As discussed in Section 2.4.1, the effects of aggregate dredging on wave conditions in the study region have been assessed by studying the propagation of the same very severe wave conditions that would be used in the design of coastal defences, i.e. with an expected annual probability of occurrence of just 0.5% or, alternatively, an expected average return period of 200 years. If there are no significant changes in wave conditions for such rare events, then it can be concluded that any changes for more frequently occurring events would be smaller still. To carry out this investigation, these extreme offshore wave conditions were input into the SWAN model together with one of the assumed tidal levels (MHWS or MLWS) and one of the bathymetries (pre-dredging, present-day or post-dredging), resulting in a total of 30 runs (five wave directions, two tidal levels and three bathymetries).

Not all of the results from these 30 model runs are presented in this report. However, to illustrate the results obtained on the wave heights throughout the modelled domain, Figures 5 and 6 present significant wave height plots as predicted by the SWAN model for the present-day bathymetry. These figures correspond to the 60ºN incident condition for the MHWS and MLWS tidal levels respectively.

Similar results have been obtained for all five of the incident wave directions considered (i.e. 30ºN, 60ºN, 90ºN, 120ºN and 150ºN) for all three bathymetries and for both tidal levels. Figures 5 and 6 show results from just two of the many SWAN model runs undertaken. In these example figures, the general reduction in wave heights as they enter shallow water over the whole of the study region is clear. This is largely the result of refraction which causes the waves to turn and head more directly towards the coastlines of Kent to the south, and of Essex and Suffolk to the east. As this occurs, the incident wave energy is spread across the width of the estuary, resulting in wave heights reducing. In the shallowest water, close to the coast, the effects of friction and wave breaking also reduce wave heights.

As well as this general reduction, there are local changes in wave heights that are of note. As waves travel over the various large sandbanks in the estuary, the SWAN model predicts a marked reduction in wave heights in their lee as a result of frictional effects and breaking, over the banks. For this incident wave direction, i.e. 60ºN, the areas of reduced wave heights lie to the west and landwards of the banks. This effect is more obvious in Figure 6, because at low tide the water depth over the crest of these banks is smaller, and the wave energy losses correspondingly greater. As waves that have crossed over these banks travel onwards to the coast, however, their heights gradually increase again, partly due to diffraction of energy into the lee of the banks and partly as a result of re-growth of waves as a result of the winds that continue to act on them.

Only where the banks are close to the shoreline, e.g. the Whiting Bank to the south of Orford Ness, do they provide any significant degree of shelter to the coastline itself. Those further offshore, such as the Inner Gabbard and The Galloper, have only very localised effects on wave conditions.

Before going on to discuss the predicted changes in wave conditions caused by aggregate dredging, it is important to make some preliminary comments on the interpretation of the changes that are presented. As with all computational models, it is possible to print out, or compare results to a very high level of precision. For example, the predicted significant wave height at any location in Figure 5 could be quoted to better than a micron (10^{-6} of a metre).

However such numerical precision does not reflect the accuracy of the model's predictions. The SWAN model will certainly predict any significant changes in wave conditions caused by aggregate dredging. However where changes are very small, these may be impossible to differentiate from the inaccuracies in the computational calculations, for example those resulting from numerical rounding errors. These affect the capacity of SWAN to predict wave heights to better than perhaps ±2-3%, or less than ±5cm where this is larger. So where the SWAN model predicts changes in wave conditions that are only of this size, or smaller, then it has to be remembered that these results could be no more than an idiosyncrasy in the calculations rather than a genuine change.

In view of this, the comparison of the model results presented in this study have been presented bearing in mind this likely limit of modelling accuracy, and changes smaller than 1% are not shown on the figures showing these comparisons. Note however that any changes of less than 2% are unlikely to be safely separable from the numerical uncertainties associated with the SWAN model itself, and are therefore should not be regarded as significantly different from zero, i.e. no change in wave heights.

Similar presentations of the spatial variations in wave height can be produced for all of the SWAN model runs, for example for the same incident wave conditions and tidal levels as shown in Figure 5 and 6 but for the Pre-dredging or the Post-dredging bathymetries. However, it is difficult to appreciate the rather localised and modest changes brought about by past or planned aggregate dredging by comparing figures of this type.

Therefore the main presentation and discussion of the effects of aggregate dredging in this report is by means of figures showing the **percentage changes** in significant wave height that have been calculated using the SWAN model. These figures have been produced by comparing the predicted wave heights for each bathymetry and at each grid point within the SWAN model, and calculating the differences in the wave heights. This type of figure is particularly useful in providing a rapid visual assessment of the scale and extent of changes in wave heights in and around the numerous dredging areas in the TEDA region.

3.2 DISCUSSION OF EFFECTS OF PAST AGGREGATE DREDGING ON 200 YEAR RETURN PERIOD WAVE CONDITIONS

The first set of model results discussed show predictions of how past dredging in the TEDA region would have altered the most extreme wave conditions considered in this study.

Figures 7 to 11 show the difference plots for SWAN model runs at MLWS for the present-day and pre-dredged bathymetries for each of the five incident wave conditions considered. These results are therefore from model runs in which the seabed levels are only different within existing or licensed dredging areas and show how much these extreme wave conditions might have changed within the TEDA region as a result of past aggregate dredging.

A comparison of these figures shows that the largest percentage changes in wave heights are generally predicted for waves approaching from 30°N and 60°N, and this is as expected since it is from these sectors that the waves approaching the Thames Estuary are both largest and have the longest period (see Table 3). Even for these exceptionally severe events, i.e. with a return period of 200 years, arriving at a very low tidal level, the effects of aggregate dredging in most of the existing licensed areas is limited to small areas within or just outside the boundaries of those areas. Note that these figures do not attempt to show percentage changes in wave height less than ± 1% since it is most unlikely that the SWAN model is capable of predicting such small changes accurately.

In this report, we do not place a difference emphasis on a wave height increase or on a decrease, since either might lead to unwanted changes in some aspects of the physical environment. For example, a decrease in wave heights at one point along a coastline might cause and increase changes in beach width, for example near the entrance to a port, which could be just as unwelcome as an reduction in beach widths caused by an increase in wave heights elsewhere along the same coastline.

Where there are changes caused by the lowering of the seabed by aggregate extraction, these are often partly caused by partial wave reflection from the seaward edge of the dredged area, a process described in Section 2.4.1 above. Such reflection typically results in increased wave heights to the seaward side of the dredged area and a reduction in wave heights on its landward side.

However, it is more often the case, particularly in the dredging areas in shallowest water i.e. close to the coast, that the increase in water depths caused by dredging reduces the dissipation of wave energy by friction and/or wave breaking as the waves travel over the extraction areas. Where the changes in wave heights extend beyond the limits of the dredging area boundaries, the percentage changes tend to be largest in shallower water areas, i.e. over some of the major sandbanks, where the wave heights have been reduced by friction and breaking.

Changes in wave conditions predicted by the SWAN modelling for the higher (i.e. MHWS) tidal level are, as would be expected, generally much less extensive and smaller in magnitude, and show that past aggregate dredging will not have affected coastal defences anywhere along the coastline of the study region. These results are presented in Figures 12 to 16. However, because the changes in wave heights caused by past aggregate dredging at this higher tidal level are noticeably smaller and more restricted in extent than those at MLWS, these figures are not discussed further here.

Overall, these percentage change figures (Figures 7 to 16) show that the changes in wave heights that could be attributed to aggregate dredging are generally very small, and hardly extend outside the limits of the extraction areas themselves.

However, the past dredging in two areas, namely Area 257 and the Long Sand Head area (licences 108/3, 109/1 and 113/1) is predicted to have caused small changes in waves over some distance outside their boundaries. For the exceptionally severe waves used in this modelling, at a high tidal level (MHWS), such changes in wave height are predicted to be less than 2% even in the dredging area itself. However, if such severe waves were to occur at the same time as a very low tidal level (MLWS), then changes in wave height of up to 3% may extend outside the dredged area to a maximum distance of about 7 km. It is doubtful, however, that such changes would ever be observable, however, given the likely natural changes in the sandbanks and channels in this area. Note here that in previous Coastal Impact Studies in which the effects of aggregate dredging on waves have been studied, the methods used would not have identified such localised changes in waves in or close to any extraction area.

Finally, it worth emphasising the important finding that, even for the exceptionally rare combinations of extreme waves and low tidal levels studied, this modelling has shown that past extraction in any or all of the aggregate dredging areas will not have caused any significant changes in wave heights close to any the coast in the TEDA region.

3.3 DISCUSSION OF EFFECTS OF PLANNED FUTURE AGGREGATE DREDGING ON 200 YEAR RETURN PERIOD WAVE CONDITIONS

Exactly the same wave modelling and presentation methods have been used to examine how these same extreme wave conditions might change in the future as a result of plans for future dredging in the existing and possible new extraction areas in the study region. Further runs of the SWAN model were carried out for the post-dredging bathymetry, in which seabed depths were altered to reflect the present views of the TEDA members on possible future extraction.

As pointed out in Section 2.3, the total amount of dredging within the whole of the TEDA region shown in Figure 3 is substantially greater than could realistically be expected to have taken place by about year 2030. The only exception to this is in the proposed new Area 504, in the south-eastern corner of the study region. The extent and depth of the sand and gravel deposits in this area are still being investigated, so the assumed future depth changes are hypothetical; detailed and probably much more restricted plans for dredging are still being developed. In a regional context, therefore, the SWAN modelling has predicted rather larger and more widespread changes in wave heights than are expected to actually occur in the future.

However, within any **individual** dredging area, except perhaps Area 504, the assumed future changes in bathymetry could be achieved by about 2030, depending on market conditions and the success within a competitive market of the company holding the licence for that area. Consequently, the predicted changes in wave conditions in and around each of these areas could be realistic.

The modelling therefore allows TEDA members to anticipate where the predicted changes in wave conditions might be regarded as unacceptable. In this case, it is likely that they would modify their dredging plans for specific areas before submitting a formal application for a new or renewed extraction licence.

Note that despite this conservatism, the SWAN modelling predicts no significant changes in wave conditions in many parts of the TEDA region as a result of planned future dredging. It can be safely deduced that if, as expected, the amounts dredged turn out to be less than assumed, then the actual changes in wave conditions in these areas will be the same or smaller than predicted in this study.

Close to some of the dredging areas, however, the SWAN modelling predicts there may be noticeable changes in wave conditions, at least during the exceptionally severe wave conditions considered. Where results from this modelling do show such changes, then these tend to be related to planned extraction from one or two nearby areas, and therefore may well occur if extraction in those particular areas does occur to the extent planned.

Figures 17 to 26 present the percentage changes in significant wave height at MLWS and MHWS between the (future) post-dredging and pre-dredging scenarios, and show how much the extremely severe wave conditions studied might be altered as a result of all past dredging and presently-proposed future aggregate dredging in the Thames Estuary region.

From these figures it can be seen that the presently anticipated future aggregate dredging in the Thames Estuary over the next 15 years, even considered together with past dredging, is predicted to have a negligible impact on wave conditions at or just offshore of the coastlines in the study region. Nowhere are wave heights close inshore predicted to change by as much as even 1% (or 1cm).

However, adjacent to some of the dredging areas where further extraction is planned, changes in wave heights of more than 3% have been predicted to occur well beyond the boundaries of some of the dredging areas, in particular, in the vicinity of Area 257 and the Long Sand Head area (licences 108/3, 109/1 and 113/1). The proposed future extraction plans for these areas could lower the seabed by more than 4m in places by about 2030.

For extreme waves approaching from 30°N, 60°N and 90°N the SWAN model predicts that this would result in wave heights to the south of these areas being increased and those just to the west of them being slightly decreased, particularly at low tide (see Figures 17, 18 and 19). This pattern of change is partly a result of reflection of the incoming wave energy where it encounters the deepened area of seabed. More commonly, the increase in water depths within the dredging areas slightly reduces the frictional dissipation at the seabed of these extremely large waves, leading to larger wave heights within and to landward, i.e. “down wave” of the dredging areas. However, this effect is rapidly reduced as the waves travel on towards the coast by the processes of wave diffraction and the further interaction between the waves and the winds particularly where the wave heights have been changed by the lowering of the seabed.

At this low tide level (MLWS), these results show that the extremely severe waves considered may be changed by over 10% for up to 7 km beyond the boundary of the extraction area for some of the incident wave directions combinations considered, and changes of 2% might be expected at twice this distance away from the southern edge of the Long Sand Head area (licences 108/3, 109/1 and 113/1).

Even if such a severe combination of exceptionally large waves and low tidal level were to occur, however, it is unlikely that such changes in wave heights would be detectable except very close to the dredging areas themselves. The expected duration of such extreme conditions would also be very short, and thus the effects of the predicted changes in wave conditions on the morphology of the seabed locally would also be very modest, localised and short-lived. Any potential effects of the predicted wave height changes on the nearby sandbanks, and on the channels between them, would therefore be small in comparison to the natural changes in these that occur almost continually.

In the context of possible effects of future aggregate dredging on coastal defences, it is the combination of such severe waves and a **high** tidal level that is a greater concern. For this situation, wave height changes of greater than 2% only extend up to 10 km away from the dredging area boundaries, and modelling shows no changes in wave height anywhere close to any coastline in the TEDA region.

Changes of a few percent in wave heights within or close to the boundaries of an offshore aggregate dredging area are only likely to be a concern if there are particular features of interest that themselves are within or close to that area. For the very severe wave conditions that were used to produce Figures 17 to 19, such changes might well be of potential concern to any fixed structures such as wind turbines founded on the seabed close to these two areas.

It is therefore suggested that where there are existing or planned developments very close to the boundaries of an aggregate dredging area, then a more detailed study of the potential interactions between those developments and the proposed future dredging would need to be carried out at the time of the extraction licence application for that area. Such a study would be able to represent the seabed bathymetry in greater detail than possible in this regional study, and to consider in a more focussed manner the potential changes that might be a concern.

In general, however, the extreme wave conditions used in this modelling are so rare that the changes caused to them by dredging would not have a significant effect on long-term sediment transport rates or changes in the morphology of the seabed outside the dredging areas themselves. This latter issue, i.e. of possible changes in seabed morphology, is returned to in the following section when discussing the predictions of changes in more frequently occurring wave conditions as one of the sensitivity tests carried out on the SWAN modelling results.

3.4 DISCUSSION OF RESULTS FROM SENSITIVITY MODELLING

The SWAN model runs carried out for extreme wave conditions, i.e. with an expected return period of 200 years, provide the main outputs from this study. However, it was decided to carry out some further sensitivity testing to assess whether the conclusions drawn from these would be altered by consideration of different wave conditions.

3.4.1 Climate change sensitivity tests

The results presented and discussed in Sections 3.2 and 3.3 above were obtained by running the SWAN model for wave conditions expected, at the present time, to have a mean return period of 200 years, or equivalently having a probability of occurrence of 0.5% in any year. In the future, however, one consequence of global warming **may** be to increase the intensity and frequency of severe storms. Government guidance is that the design of coastal defences should consider the possibility of such an increase in storminess and carry out sensitivity tests to check that any decisions made are sustainable in the light of such an outcome. This guidance goes on to recommend that the wave heights and periods used in coastal defence designs are increased by 10% and 5% respectively and used to examine the consequences of possibly increased storminess.

In recognition of this, it was therefore decided to examine whether the assessment of the effects on waves of aggregate dredging in the TEDA region would be affected by considering more extreme wave conditions than the 200 year return period waves used to produce Figures 7 to 26. For this sensitivity test, bearing in mind those previous results, it was decided to model the effects of dredging on the increased extreme wave conditions approaching from 30°N since this was expected to show the greatest changes in wave conditions. The results from this modelling are presented in Figures 27 and 28, which show the percentage wave height changes that have been predicted to be caused first by all the past dredging (Figure 27) and then by both this past dredging and all currently planned future dredging in the TEDA region together (Figure 28).

Because the main purpose of this sensitivity test was to check whether there would be any change in wave conditions along the coastlines of the region, and more particularly at any coastal defences, the results were produced solely for the higher tidal level, i.e. MHWS.

Comparing these figures does show that the planned future dredging, as represented in the post-dredging bathymetry, is likely to cause more widespread changes in wave conditions than for all previous dredging. However it should be remembered that at a regional level, the amounts of future dredging represented in the SWAN modelling are expected to be greater than the amounts that actually will be extracted over the next 15 years or so.

Despite this somewhat precautionary approach, however, Figure 28 shows no changes in wave conditions that extend very far towards to the coastline of Kent, Essex or Suffolk.

It should also be noted that no account has been taken in this modelling of the expected increase in mean sea level in the TEDA region as a result of global warming. This would slightly decrease any effects of aggregate dredging since the proportional increases in depths caused by that extraction would be smaller in such circumstances, and hence the effects of that dredging on wave conditions somewhat less.

3.4.2 Morphological change tests

In addition to testing the possible consequences of increased storminess, it was also decided to examine the effects of dredging on more frequently occurring wave conditions. As a general rule, long-term changes in the morphology of coastlines, or of the seabed, are likely to be mainly caused by moderate but frequently occurring events rather than by rare and short-lived severe storms. Examining the effects of aggregate extraction on a more frequently occurring wave condition therefore provides some indication of whether there might be changes in the morphology of the seabed in and around the dredging areas.

For this purpose, therefore, we again considered waves approaching from 30°N, since the largest and longest period waves arrive from this sector and these suffer the largest changes in the wave conditions over the dredging areas. Considering just waves conditions arriving from this sector, we then selected a wave height that was only equalled or exceeded 5% of that time in an average year. This wave height would occur even less frequently from other directions. Having chosen this wave height, we then estimated both its associated wave period, erring on the side of caution and choosing a rather longer wave period than would normally be expected, and the wind speed that would be expected during such wave conditions. This wave condition has a significant height of 2.3m and an associated peak wave period of 6.6 seconds. As a guide to the expected probability of such waves occurring, wave heights travelling into the Estuary will be smaller than this about 80 to 85% of the time.

This combination of direction, height, period and wind speed was then used as the input wave condition for six further SWAN model runs, i.e. for all three bathymetric scenarios and both tidal levels. The same type of plots as presented in Figures 27 and 28, showing the percentage changes in wave heights were then prepared for these model results. Figures 29 and 30 respectively show the predicted changes in heights for this more-frequently occurring wave condition, taking into account all past and proposed future dredging.

Even at MLWS, the predicted changes in wave height shown in Figure 29 are small and localised. At the higher tidal level, any changes (Figure 30) scarcely extend beyond the boundaries of the dredging areas themselves. The predicted changes in wave heights caused by past dredging alone were so small for this incident condition that they are not visible in such percentage change plots, so these are not presented.

Given the fact that this “5% exceedence from 30°N” wave condition is still both severe and uncommon, it can reasonably be deduced that for the vast majority of wave conditions, the changes in wave heights caused by past and planned future dredging in the TEDA region will be extremely modest and restricted to small areas in or just outside the dredging areas themselves. However, some care might be needed in examining the effects on waves of future dredging applications in Area 257 and the Long Sand Head area (licences 108/3, 109/1 and 113/1), if there are features of particular interest very close to the boundaries of proposed extraction areas, say within 1000m.

This study has considered all the likely future application areas within the TEDA region and calculated their combined effects on waves. If there are no concerns about the predicted changes in wave heights in or around any particular dredging area, then there will be no need to repeat the SWAN modelling during the studies for the specific licence application for that area, unless the future plans for extraction from it were to be increased.

Finally, it should be remembered that, in an overall context, the proposed future dredging plans for the TEDA region considered in this modelling are deliberately conservative. Where the changes in wave conditions shown in Figures 29 and 30 are insignificantly small, this over-estimation of the total amount of aggregate likely to be extracted means that the modelling has erred on the side of caution; it can be expected that the actual changes in these areas will be even smaller than predicted.

4. Aggregate dredging and in-combination effects

Aggregate dredging is only one of many human activities that affect the physical environment of the Thames Estuary. 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, has often led to substantial 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. 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 waves 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 future wave conditions in those areas and can thus contribute to the design and the assessment of the effects of those future developments.

This regional study of wave propagation has not tried to quantify any potential effects of aggregate dredging that might affect the marine physical environment “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, not least since it is not easy, and sometimes not possible, to obtain details of any other planned developments or operations within the overall study region.

This study has shown, however, that for most of the current and proposed extraction areas, any changes in even the most extreme wave conditions are small, and scarcely extend outside the boundaries of those areas. In these cases, such changes are most unlikely to affect other human activities or uses of the sea, or to result in an in-combination effect with them, unless these are located very close to or within the designated dredging areas.

In contrast to this general conclusion, the planned future dredging in two areas, namely Area 257 and the Long Sand Head area (licences 108/3, 109/1 and 113/1), are predicted to cause potentially more significant changes in wave heights for a considerable distance outside their boundaries. Even in these areas, for the great majority of the time, it is very doubtful that any changes in waves that may be caused by aggregate dredging would ever be detectable, especially given the likely natural changes in the sandbanks and channels in this part of the estuary. However, if the exceptionally severe waves used in this modelling occurred at the same time as a very low tidal level (MLWS), then changes in wave height of at least 10% may extend to a distance of about 7 km outside these areas.

Overall, it is reasonable to conclude from this study that, in the Thames Estuary, any in-combination effects on waves involving aggregate dredging are most 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. However, for projects situated close to aggregate dredging areas, especially their southern boundaries, additive, synergistic or antagonistic in-combination interactions affecting the environment may be possible.

Some of the specific activities and developments with a potential to cause, with aggregate dredging, an in-combination effect on waves within the study region are discussed 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 may therefore need to be considered in more detail in the Environmental Impact Assessment (EIA) carried out for a specific extraction licence application.

5. Conclusions

This study has considered all the present and future aggregate dredging in relinquished, existing and proposed areas in the Thames Estuary region and calculated their cumulative effects on waves travelling towards the coast. In this modelling, we have adopted a very precautionary approach, and studied changes in extremely severe wave conditions that are unlikely to recur, on average, less often than once every 200 years. The greatest changes in wave conditions over dredged areas occur when tidal levels are low, because the increase in water depth in those areas is proportionally greater at this state of the tide. Combining these extreme wave conditions with a low tidal level therefore produces input conditions that represent very unlikely “worst case” situations, ensuring a precautionary approach to assessing the effects of aggregate dredging in this study region.

5.1 EFFECTS ON WAVES OF PAST DREDGING

For almost all the aggregate dredging areas in the Thames Estuary, the total extraction to date has been shown to have had a negligible impact on wave conditions except within or very close to the boundaries of those areas. The greatest changes to waves are predicted in and around the Long Sand Head dredging area (licences 108/3, 109/1 and 113/1). Here our modelling indicates that changes in wave heights, for the most pessimistic wave and water level combination tested, might have increased by up to 3% over a rather narrow area stretching to the south of this dredging area. Such changes would be very difficult, if not impossible to measure, and are likely to be small compared to those caused by the natural movements of the sandbanks and intervening channels in this part of the outer estuary. There is no evidence at all to suggest that past dredging in this region could have caused changes in waves either close inshore or along any of the coastlines of North Kent, Essex and Suffolk.

At higher tidal levels and assuming the same extreme wave conditions, the modelling shows that the changes brought about by past dredging are smaller and even more restricted in spatial extent. It would be this combination of waves and tidal level that is of more concern from the viewpoint of the design or performance of coastal defences.

It can be safely deduced that changes in less severe but more frequently occurring wave conditions will be even less noticeable and restricted in area than has been predicted by considering the very severe wave conditions described above.

Overall, therefore, this wave modelling exercise shows that it would not be possible to detect and changes in the wave climate in any part of the Thames Estuary as a result of past aggregate dredging except perhaps within, or closer than a few hundred metres beyond the boundaries of most of the licensed dredging areas themselves. The only exception to this is the Long Sand Head area when, at a low tidal level, the most extreme waves are predicted to be altered by up to 3% further away than this.

5.2 PREDICTED EFFECTS ON WAVES OF FUTURE DREDGING

Our modelling then went on to consider the possible effects of future aggregate dredging on waves in the Thames Estuary region using the same combinations of severe waves and tidal levels. Rather than predicting the effects of just the extraction that is planned for the next 15 to 20 years, however, we again adopted a more precautionary approach. This involved assessing the effects on waves of all past and future dredging together.

The current plans for future extraction in some of the areas would result in considerably deeper excavations, and larger volumes being removed than in the past. As a result, rather more noticeable changes in waves were predicted, especially for the “worst-case” situation considered, i.e. of very severe waves arriving at low tide. As when considering the effects of past dredging alone, changes in waves caused by past and future extraction in most of the dredging areas were small and very restricted in extent outside the boundaries of those areas. In general, the greatest changes are predicted likely to occur to the south of the individual areas. However, even here, changes in wave height will not exceed 2% to 3%, and these are too small to be detected by measurements with any confidence.

In contrast to this general conclusion, however, the current plans for future dredging in two areas, namely Area 257 and the Long Sand Head area (licences 108/3, 109/1 and 113/1), are predicted to cause potentially more significant changes in wave heights for a considerable distance outside their boundaries. Even in these areas, for the great majority of the time, it is very doubtful that any changes in waves caused by aggregate dredging would ever be detectable, especially given the likely natural changes in the sandbanks and channels in this part of the estuary.

However, if the exceptionally severe waves used in this modelling occurred at the same time as a very low tidal level (MLWS), then changes in wave height of at least 10% may extend to a distance of about 7 km outside these areas. If existing or planned developments/ operations, or features of particular interest, lie close to the southern boundaries of these two areas, then the local changes to the physical environment caused by aggregate dredging may be of significance. Possible examples of activities that might be affected by change in the most extreme wave conditions are the deepening of a navigation channel or the installation of wind turbines.

However, if should be remembered that the chance of occurrence and duration of such an exceptional combination of a low tidal level and a 200-year return period wave condition are exceptionally small. As a result, the predicted changes in waves caused by aggregate dredging during those exceptionally severe conditions would not be of any concern in the context, for example, of affecting the seabed morphology near the dredging areas.

The results of modelling the effects of past and future dredging on the same extreme wave conditions arriving at high tide showed a similar pattern of changes, but with the magnitude and spatial extent of those changes considerably reduced.

To examine whether aggregate dredging, through altering wave conditions, might have some effect on the natural physical environment of the seabed, it was felt appropriate to examine how more frequently occurring and less severe wave conditions would be changed. While the wave conditions chosen for this purpose would still be regarded as severe, they were scarcely altered by the combination of past and planned future dredging. At the low tide level that was considered, changes in these wave heights were scarcely noticeable save near the south edges of the same two dredging areas, and even here the changes would be difficult to measure. At high tide, the changes in these wave conditions would be unnoticeable anywhere in the Thames Estuary region.

5.3 EFFECTS OF CLIMATE CHANGE

The potential consequences of global warming are of considerable concern in the context of coastal flooding and erosion, and new coastal defences are now routinely designed bearing these consequences in mind. The most widely agreed effect of global warming on the marine physical environment is a worldwide increase in mean sea level, due to thermal expansion of seawater and the addition of extra melt-water as a result of higher temperatures.

In the specific context of marine aggregate dredging, however, an increase in mean sea level would tend to reduce any changes in waves caused by the lowering of the seabed. Had we chosen to run the same wave conditions at a future low tide level perhaps 500 to 1000 mm higher than it is today, the predicted changes in those waves would be smaller than at present.

A further change that may occur as a result of global warming is that meteorological conditions over north-western Europe may also alter, for example altering wind directions and strengths and the path taken by deep depressions as they pass over or close to the British Isles.

Despite continuous and intensive research, involving many global and regional models of the atmosphere, no clear consensus has been reached about how weather patterns will change in general or, more particularly, how wind strengths, directions and durations during storm events might alter.

To reflect this uncertainty, Defra/ Environment Agency require that sensitivity tests on coastal defence designs are carried out to ascertain whether they could cope with, or perhaps be adjusted in future to cope with possible future increases in wave heights and periods. Possible increases in the most severe wave heights and period are of particular concern in this context.

In the present study, it was decided that the same approach should be taken to the assessment of the effects on waves of aggregate dredging. Those SWAN model runs that showed the greatest changes in wave conditions as a result of past and future aggregate dredging were therefore repeated with the offshore wave heights increased by 10% and their wave periods increased by 5%. To continue the precautionary approach adopted in this study, however, we did not increase the low tide level as this would tend to decrease the predicted effects of dredging on wave conditions.

As would be expected, this very conservative testing resulted in predictions of larger changes in wave heights over somewhat larger areas than any of the previous SWAN model runs. Even so, however, the same general conclusions about the modest extent of any noticeable changes in waves caused by aggregate dredging were confirmed. Other activities or developments close to the southern boundaries of Area 257 and the Long Sand Head area (licences 108/3, 109/1 and 113/1) might be affected by changes in wave conditions in the most extreme storms, and may cause some “in combination” effects on the physical environment.

However, even taking this exceptionally precautionary approach, there is no evidence that the combination of past and future dredging in the Thames Estuary will affect wave conditions except in a few areas within or close to the individual extraction areas. There is no evidence at all that suggests that such dredging in the Thames Estuary could affect wave conditions along or just offshore of any coastline.

6. References

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Figures

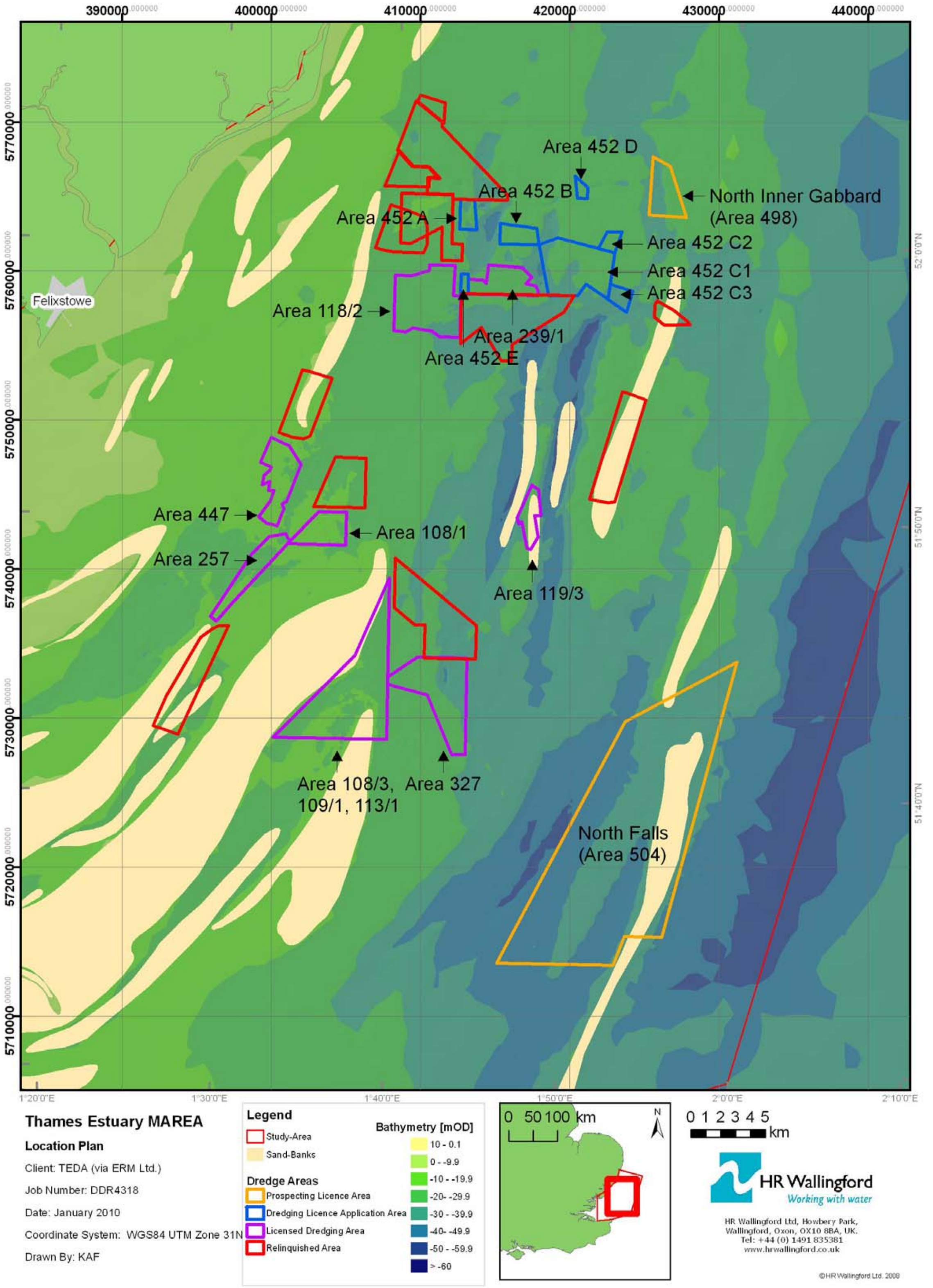


Figure 1 Present day bathymetry

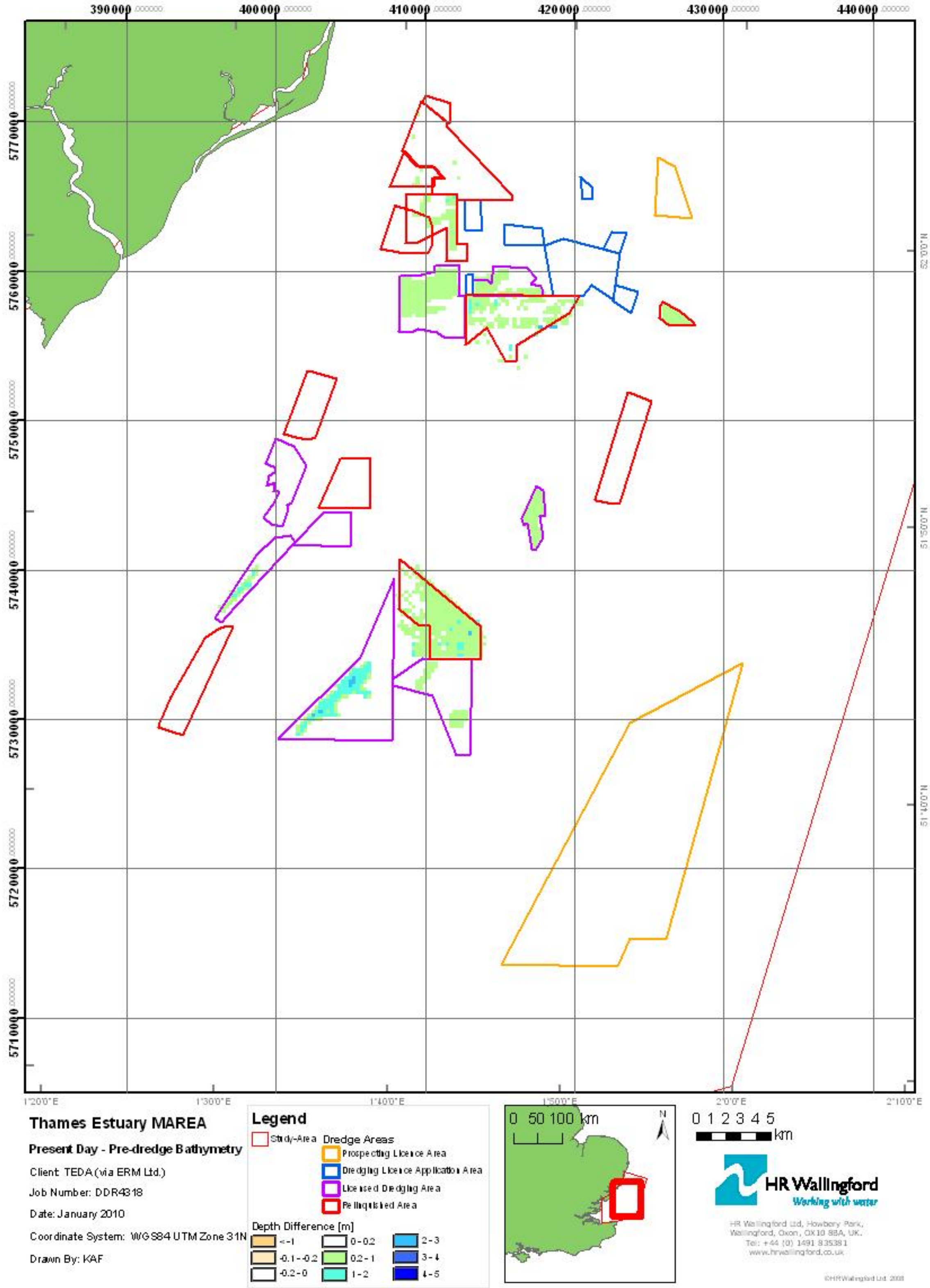


Figure 2 Past seabed lowering: Present day - pre-dredged bathymetry

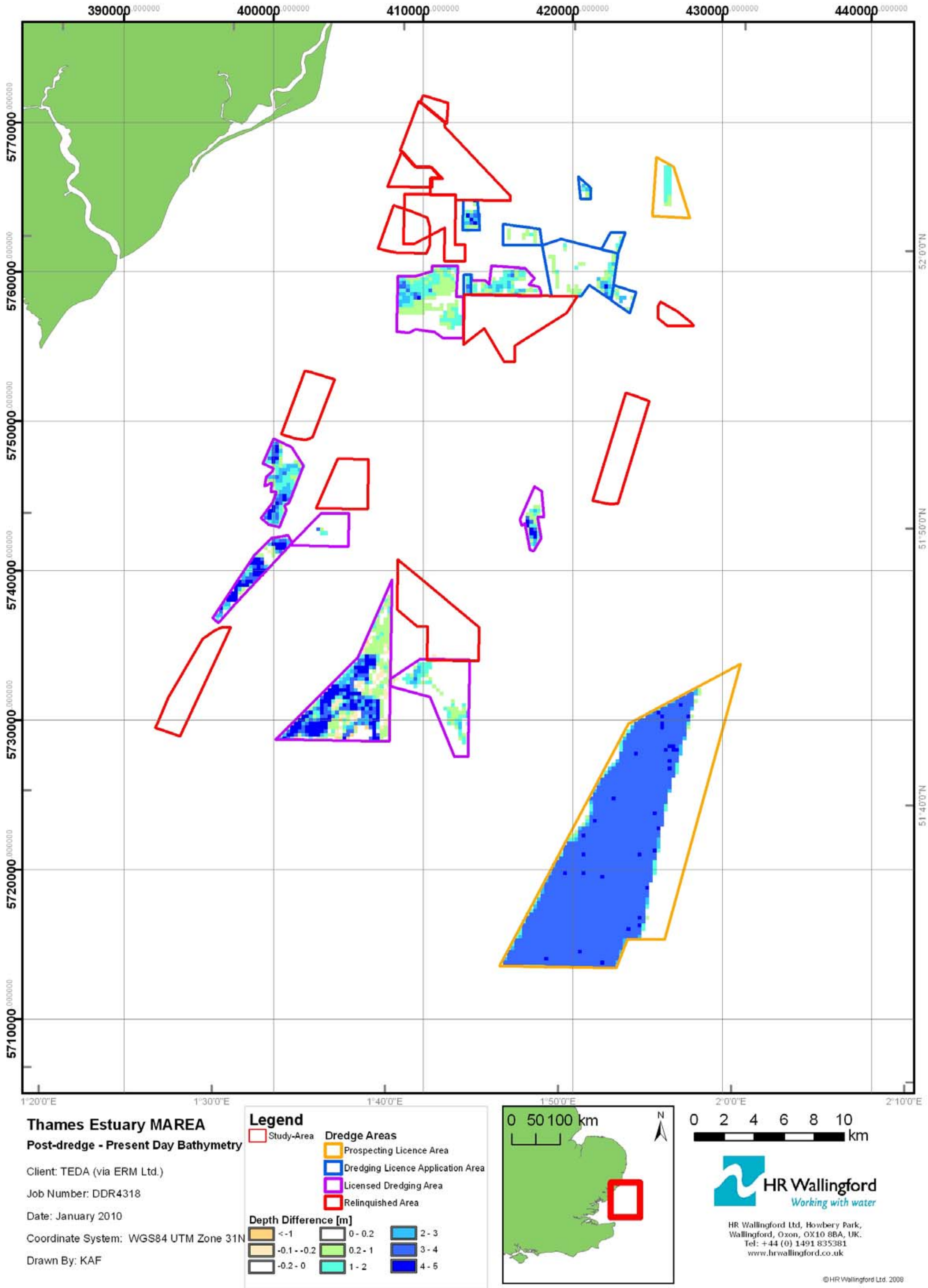
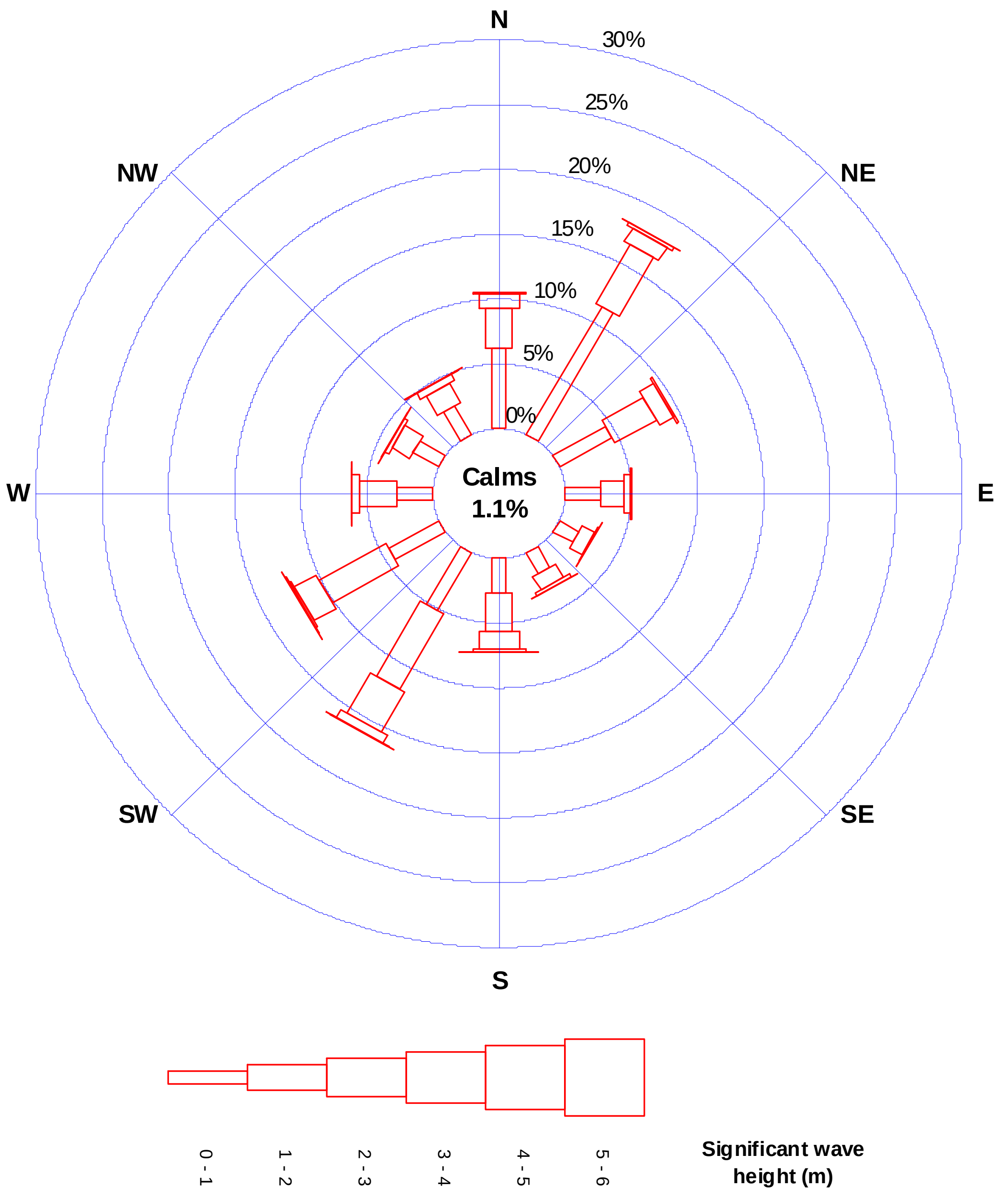


Figure 3 Anticipated future seabed lowering: Post-dredged - present day bathymetry

UKMO wave model data at 51.75N 1.93E



Notes: Percentage calm or variable data is indicated in centre of rose

Wave Rose

Figure 4 Wave rose for offshore climate at Point 3

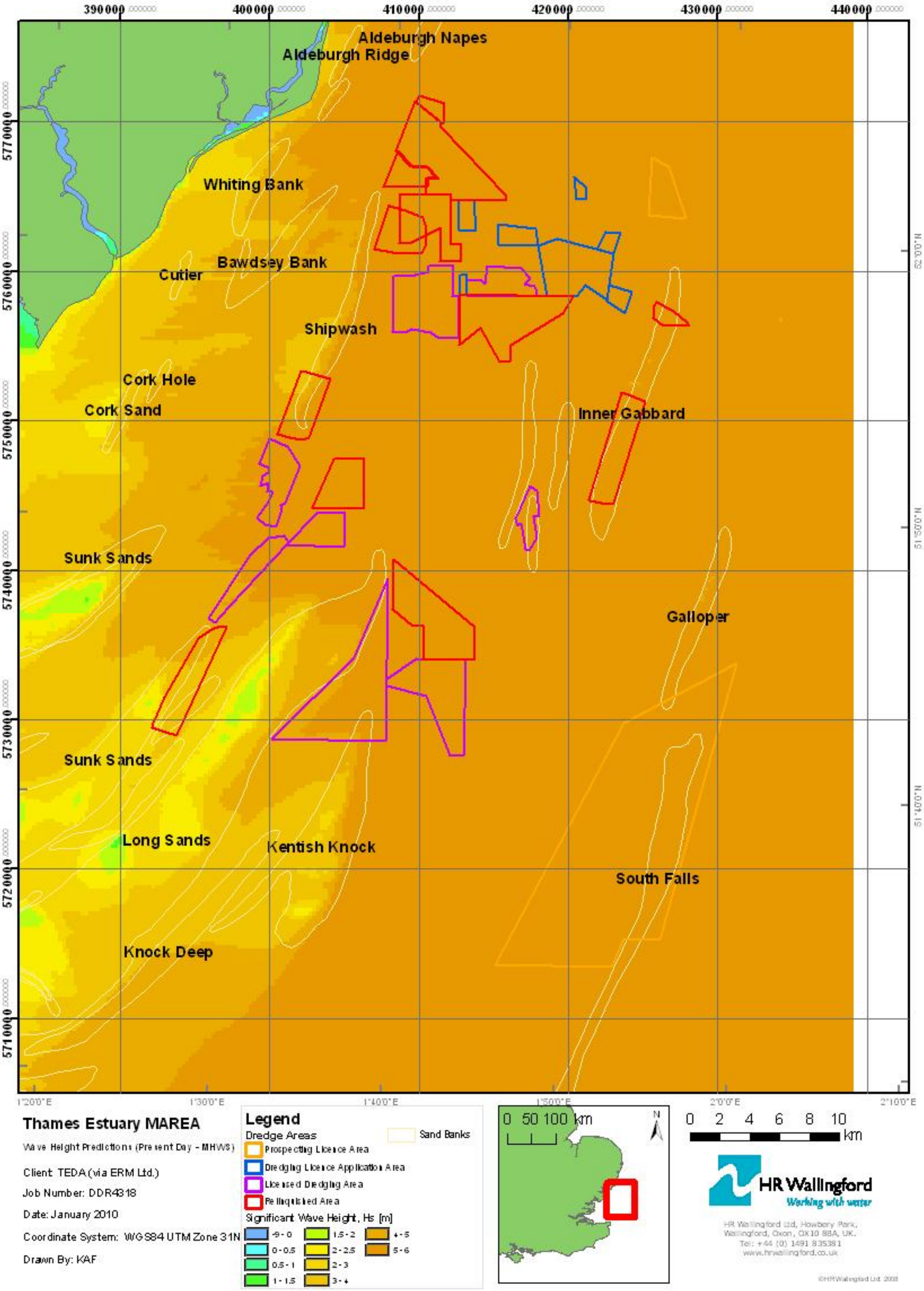


Figure 5 **Wave height predictions for a 200 year return period wave condition from 60°N at MHWS (present day bathymetry)**

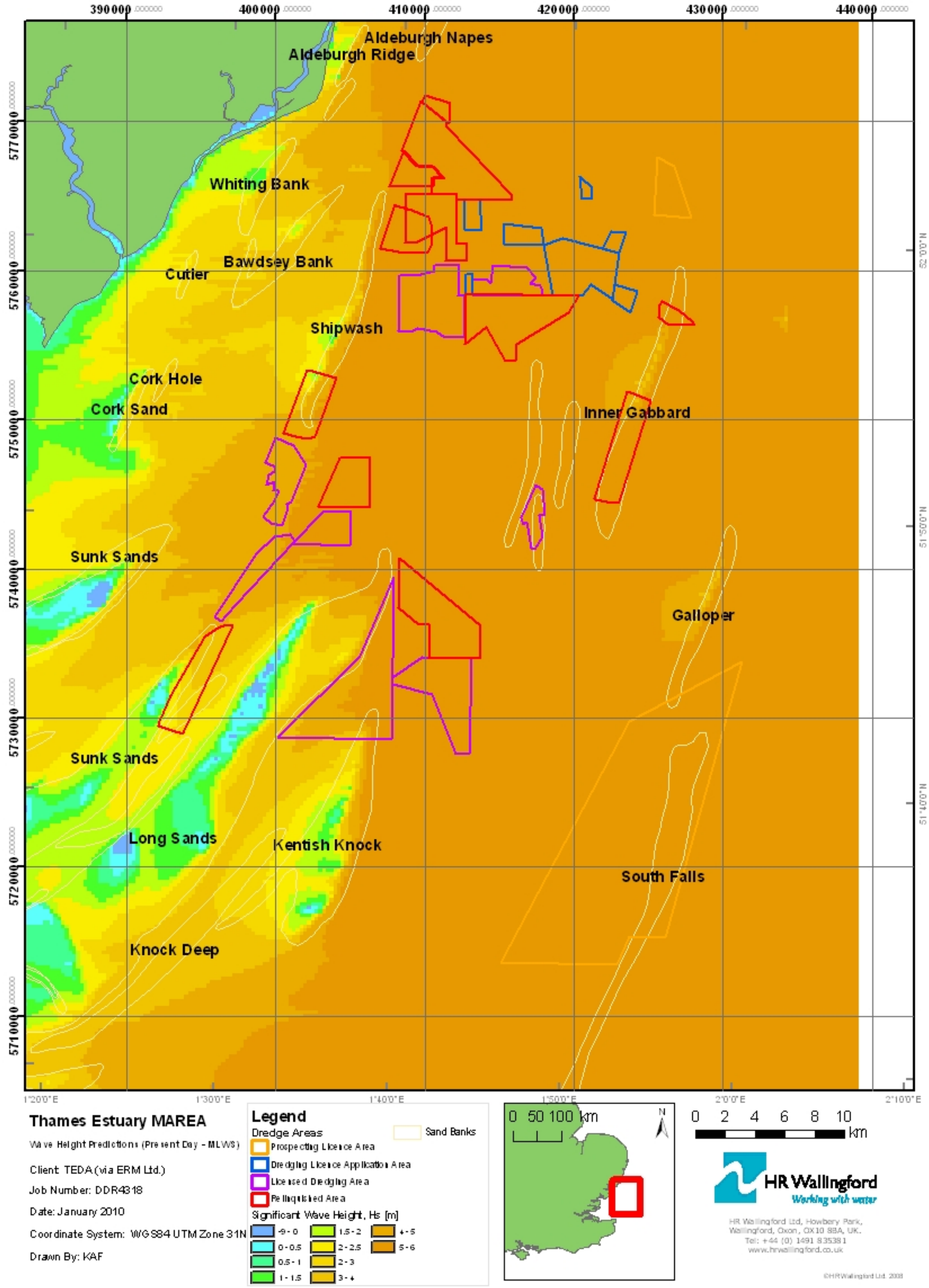


Figure 6 **Wave height predictions for a 200 year return period wave condition from 60°N at MLWS (present day bathymetry)**

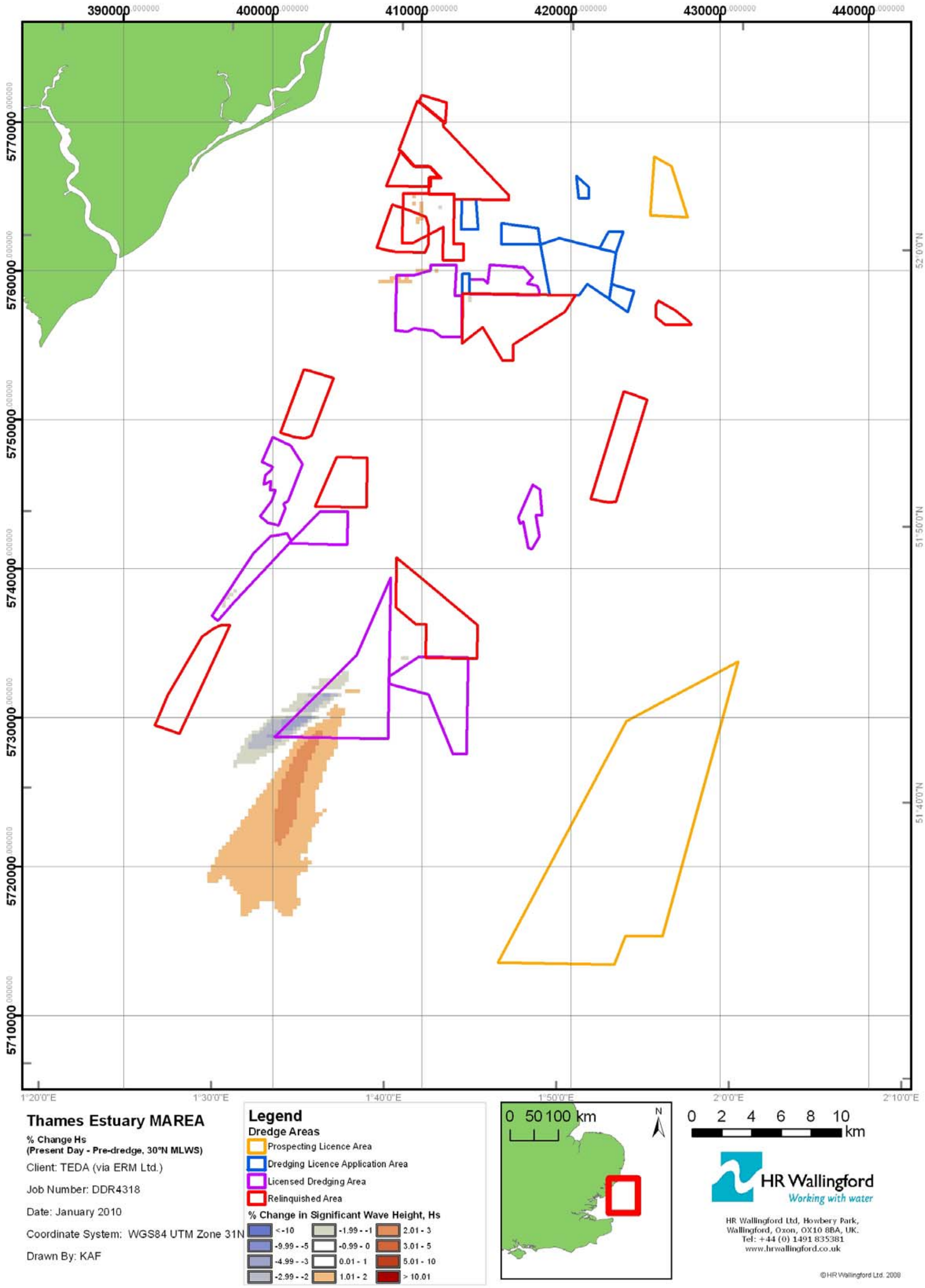


Figure 7 Changes (%) in wave height due to past dredging for 200 year return wave condition from 30ºN at MLWS

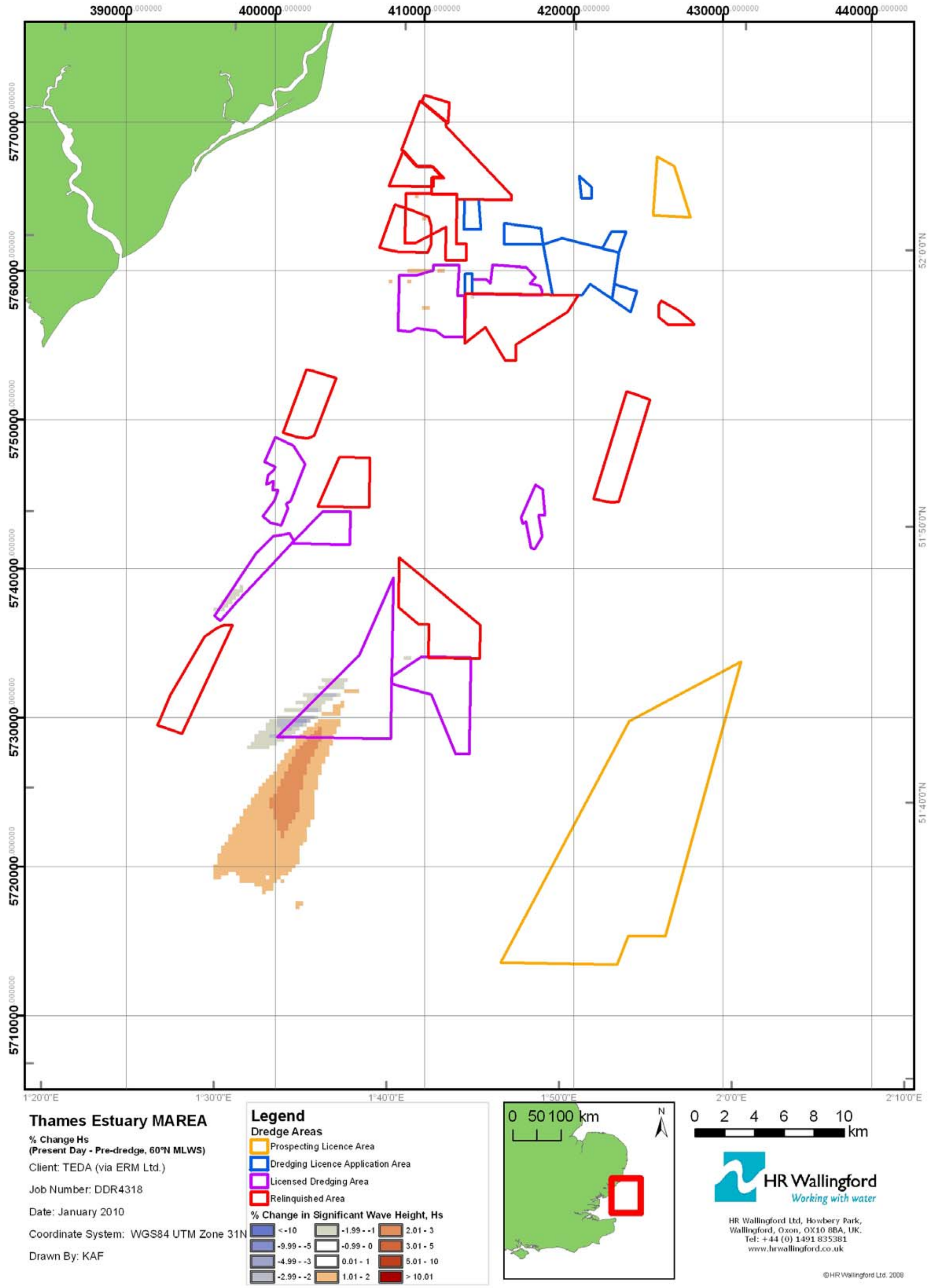


Figure 8 **Changes (%) in wave height due to past dredging for 200 year return wave condition from 60ºN at MLWS**

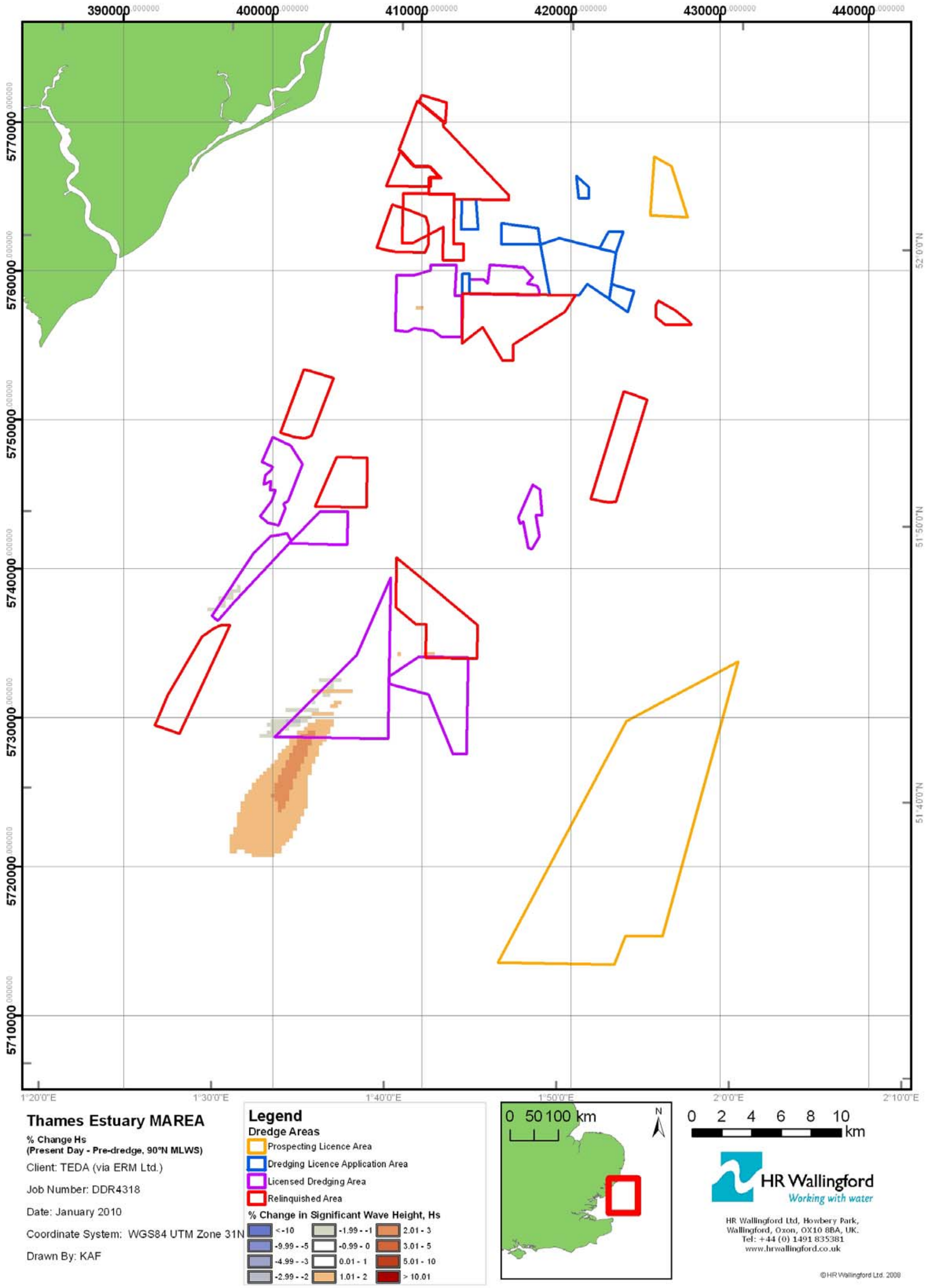


Figure 9 **Changes (%) in wave height due to past dredging for 200 year return wave condition from 90ºN at MLWS**

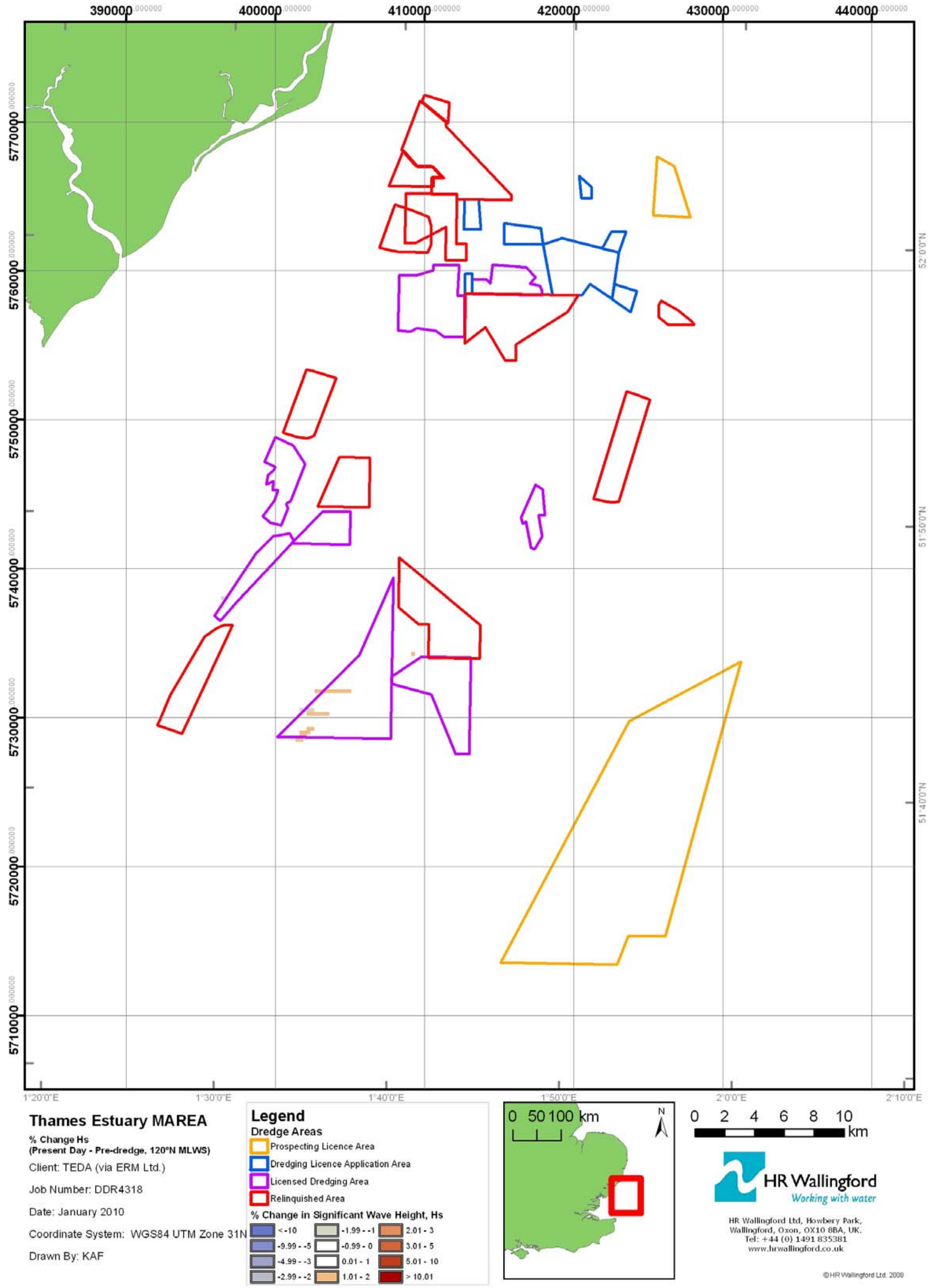


Figure 10 Changes (%) in wave height due to past dredging for 200 year return wave condition from 120ºN at MLWS

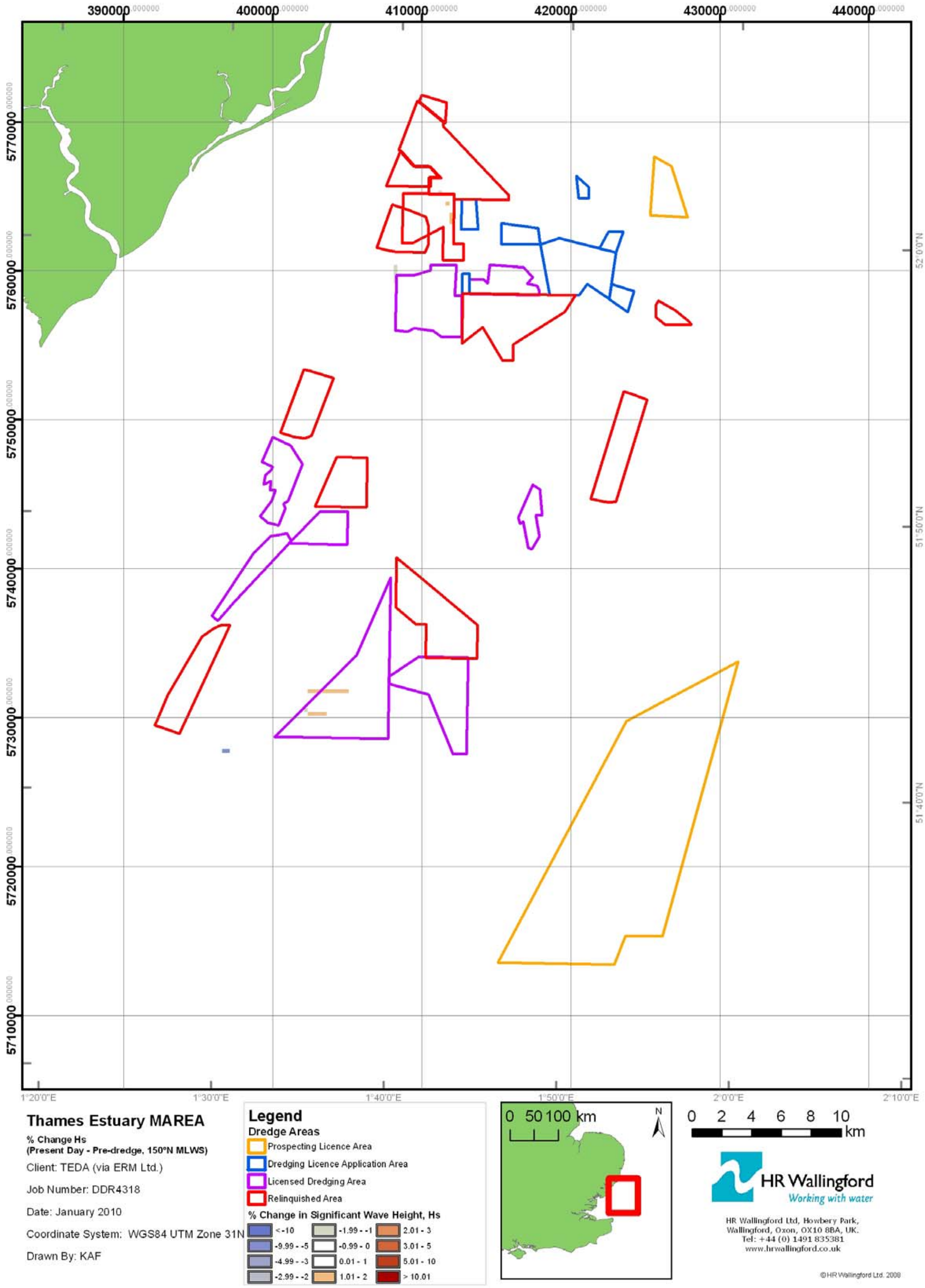


Figure 11 Changes (%) in wave height due to past dredging for 200 year return wave condition from 150ºN at MLWS

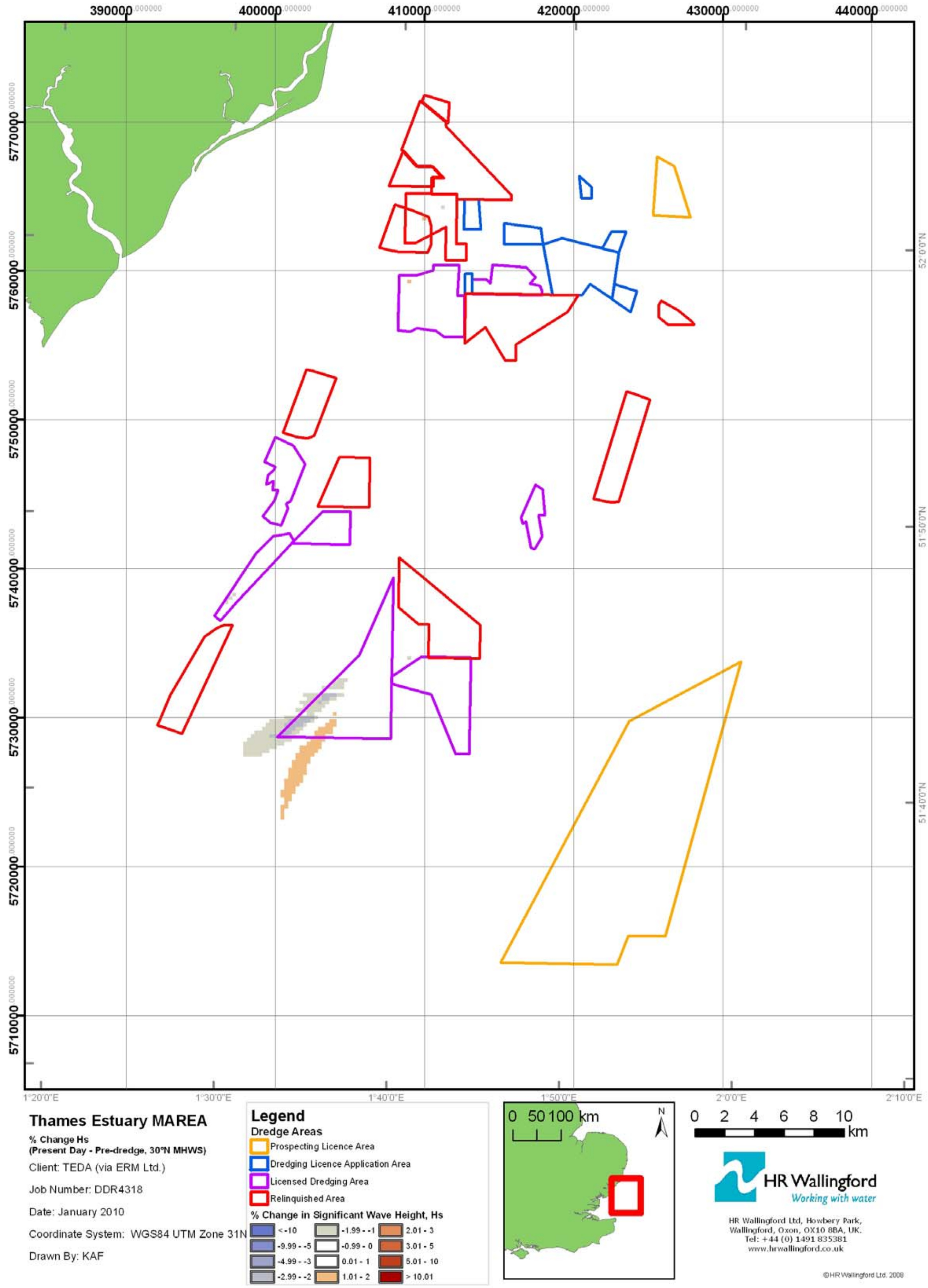


Figure 12 Changes (%) in wave height due to past dredging for 200 year return wave condition from 30ºN at MHWS

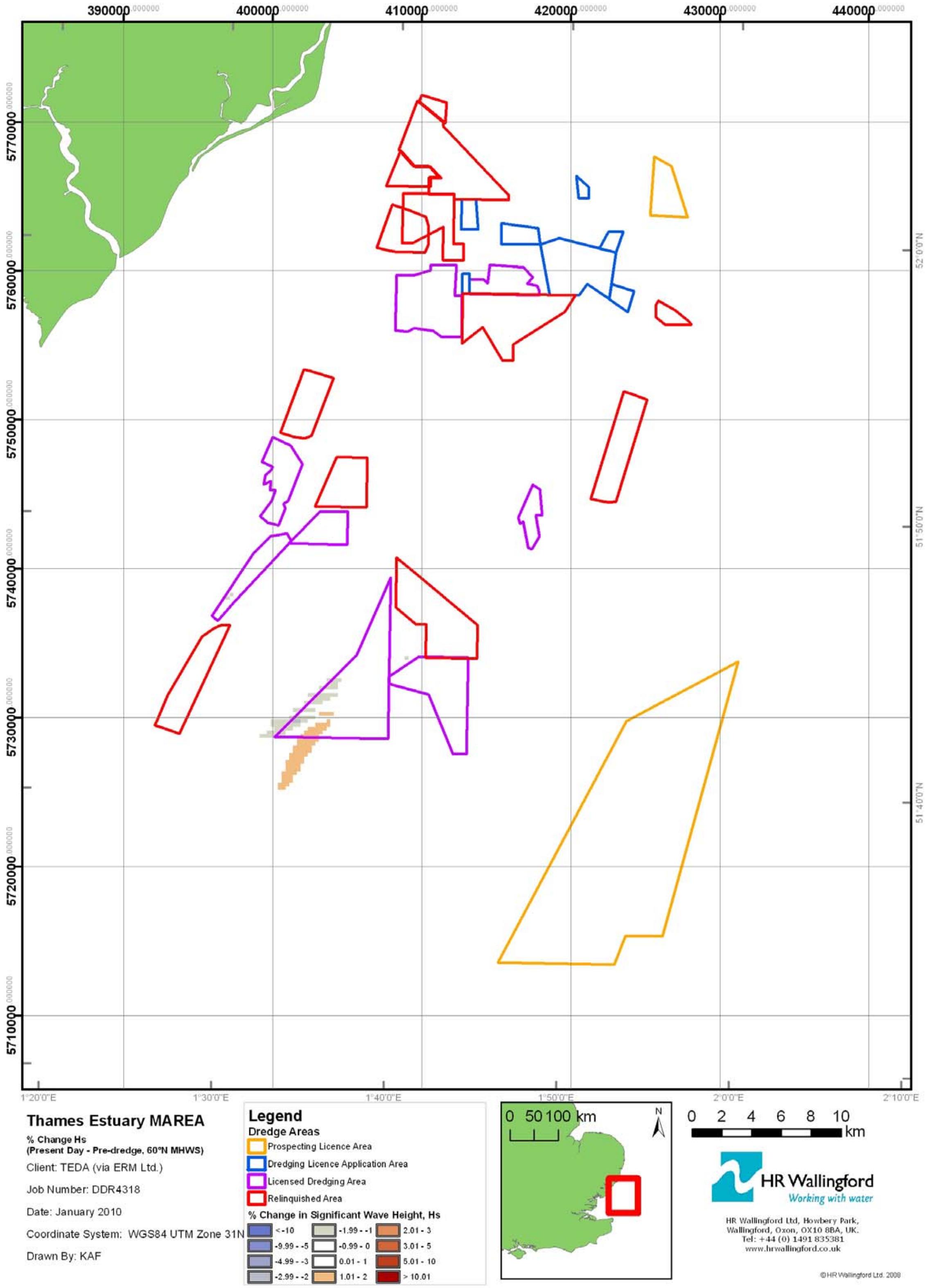


Figure 13 Changes (%) in wave height due to past dredging for 200 year return wave condition from 60ºN at MHWS

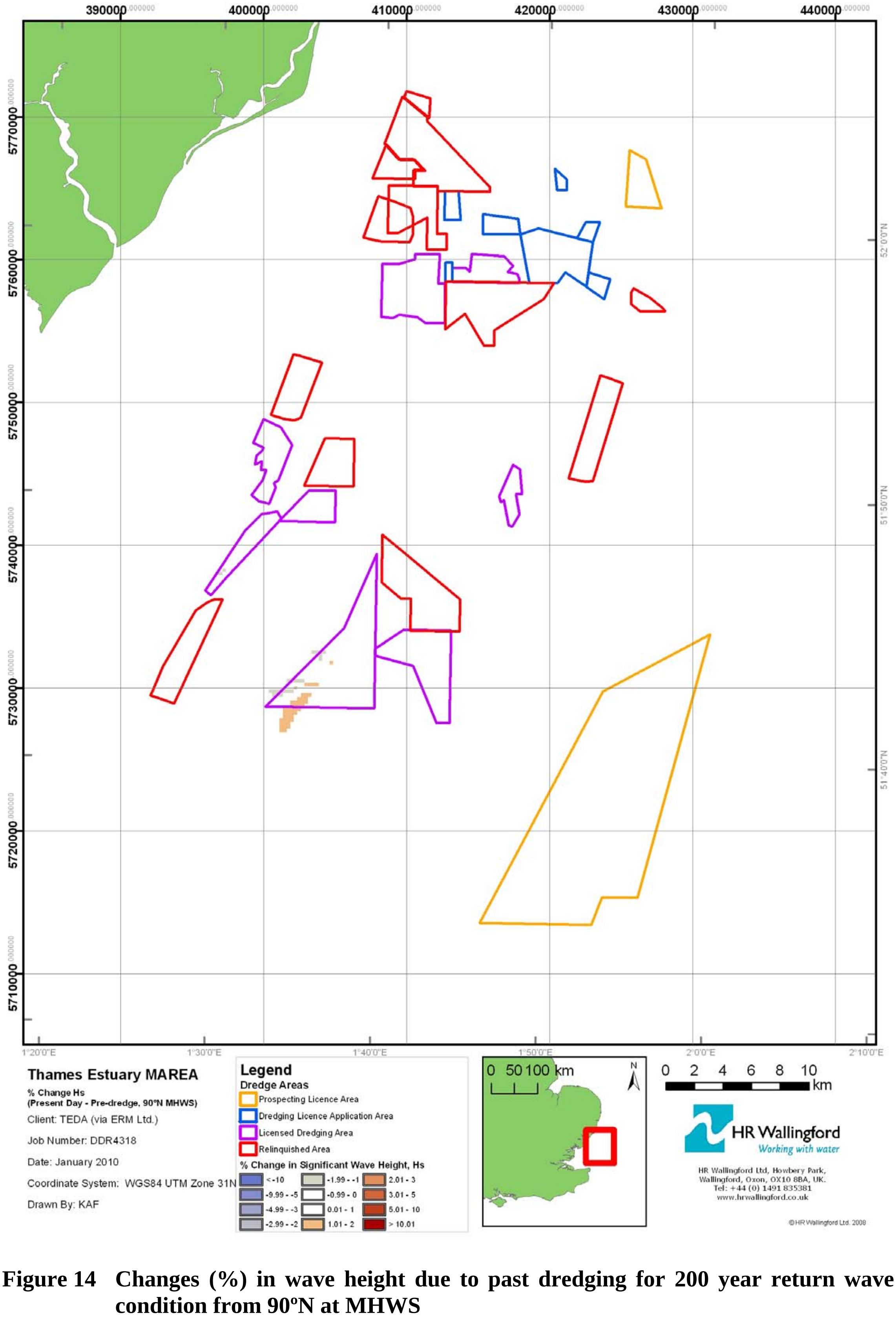


Figure 14 Changes (%) in wave height due to past dredging for 200 year return wave condition from 90ºN at MHWS

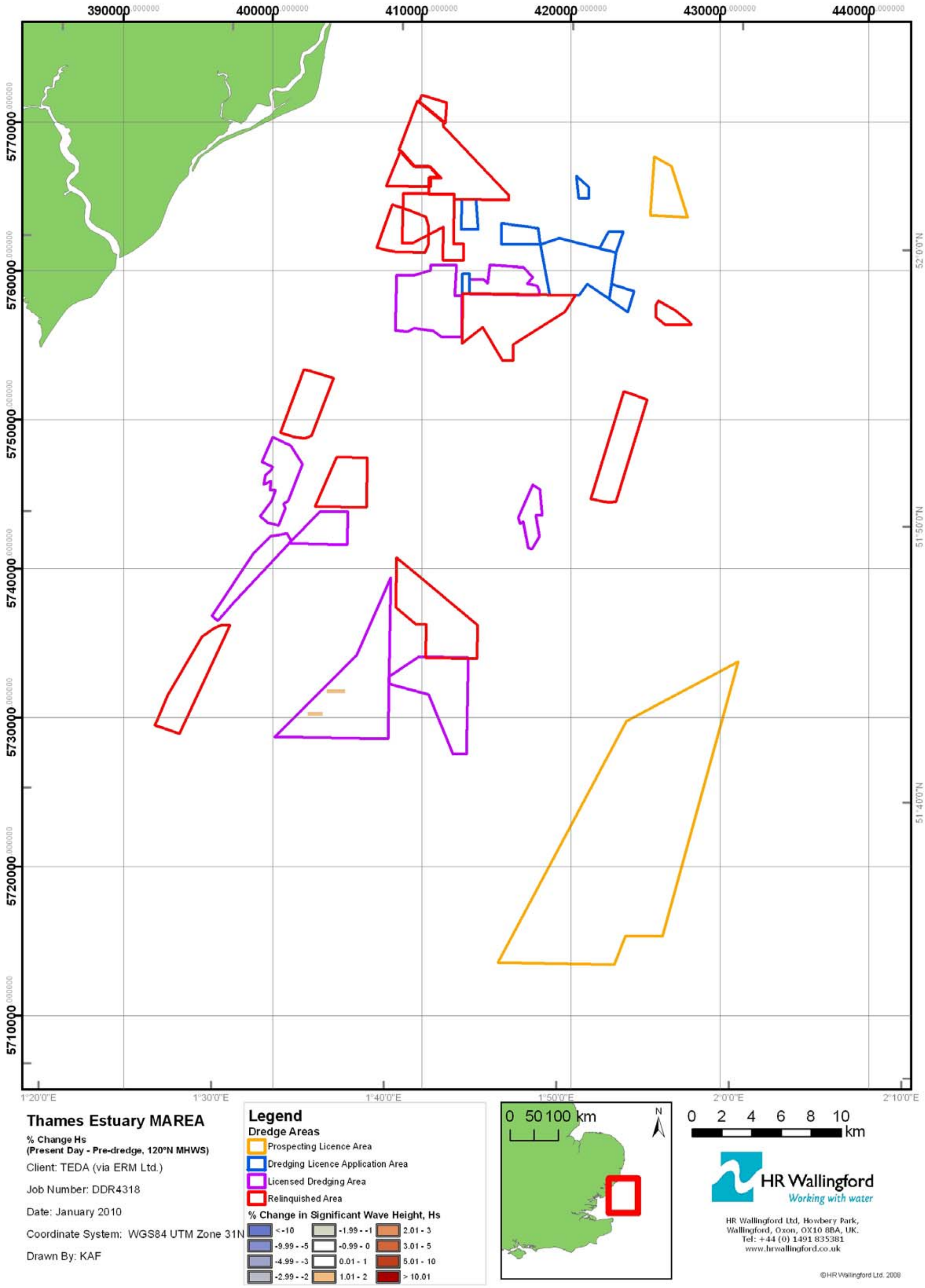


Figure 15 Changes (%) in wave height due to past dredging for 200 year return wave condition from 120ºN at MHWS

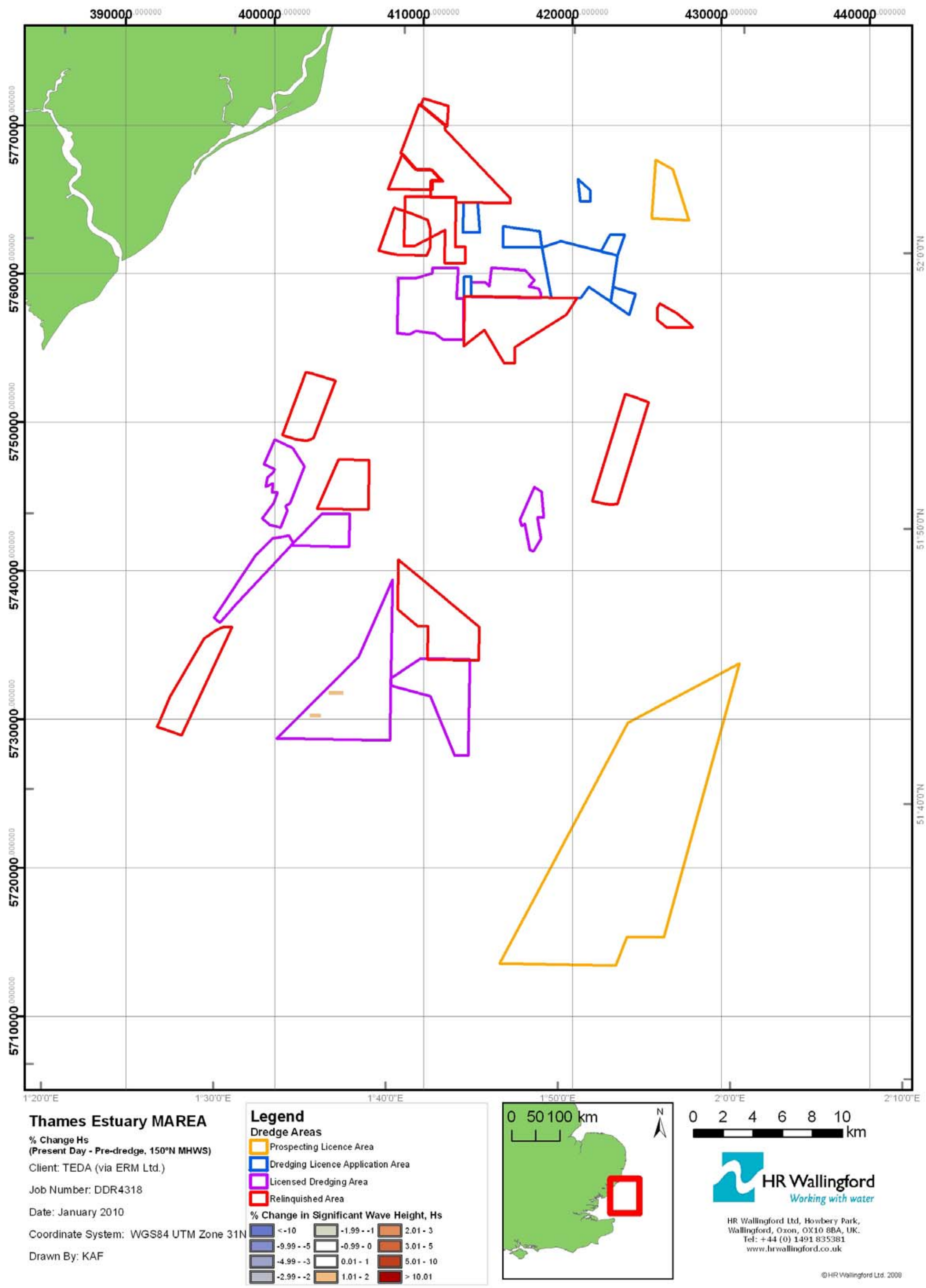


Figure 16 Changes (%) in wave height due to past dredging for 200 year return wave condition from 150ºN at MHWS

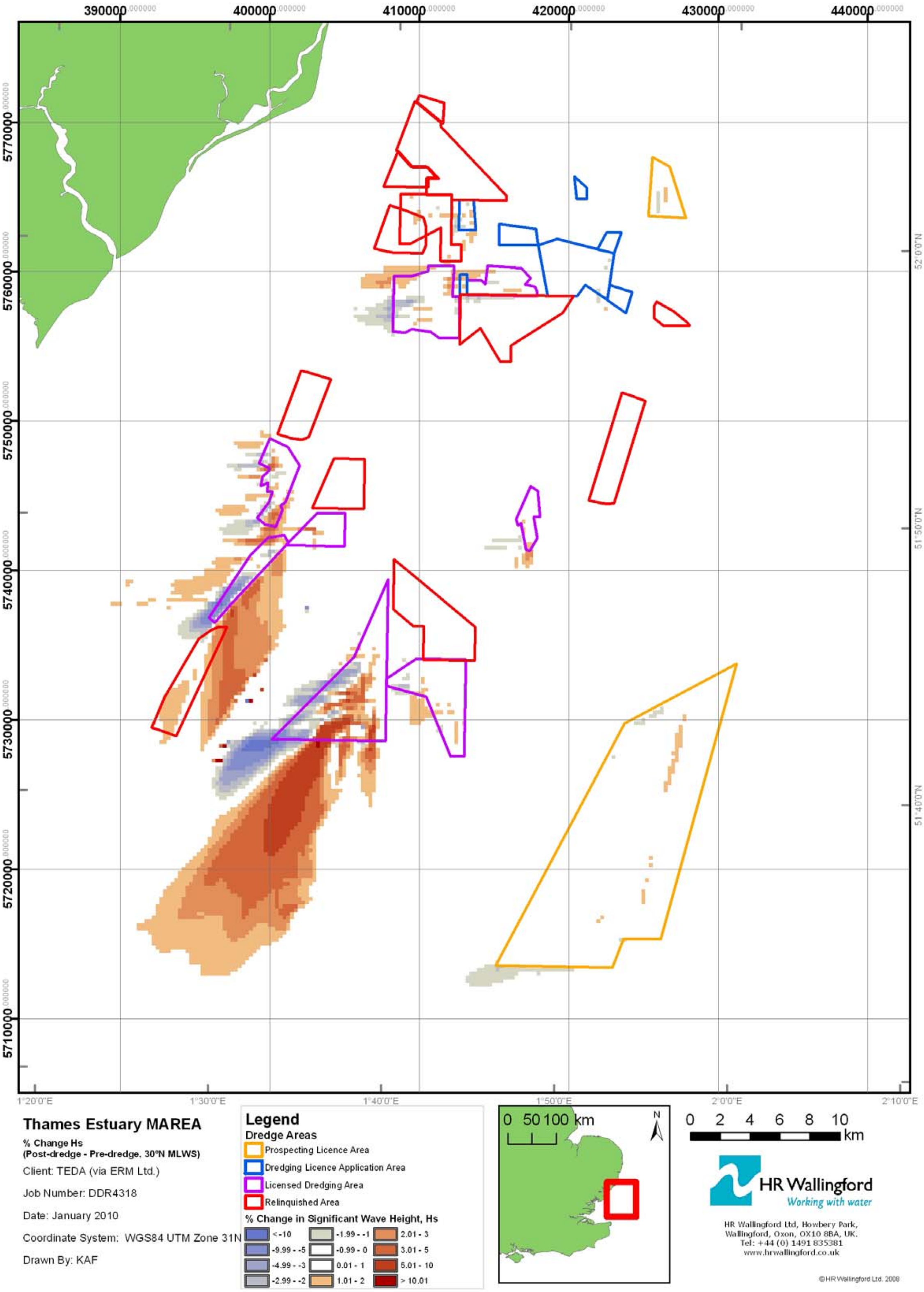


Figure 17 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 30ºN at MLWS

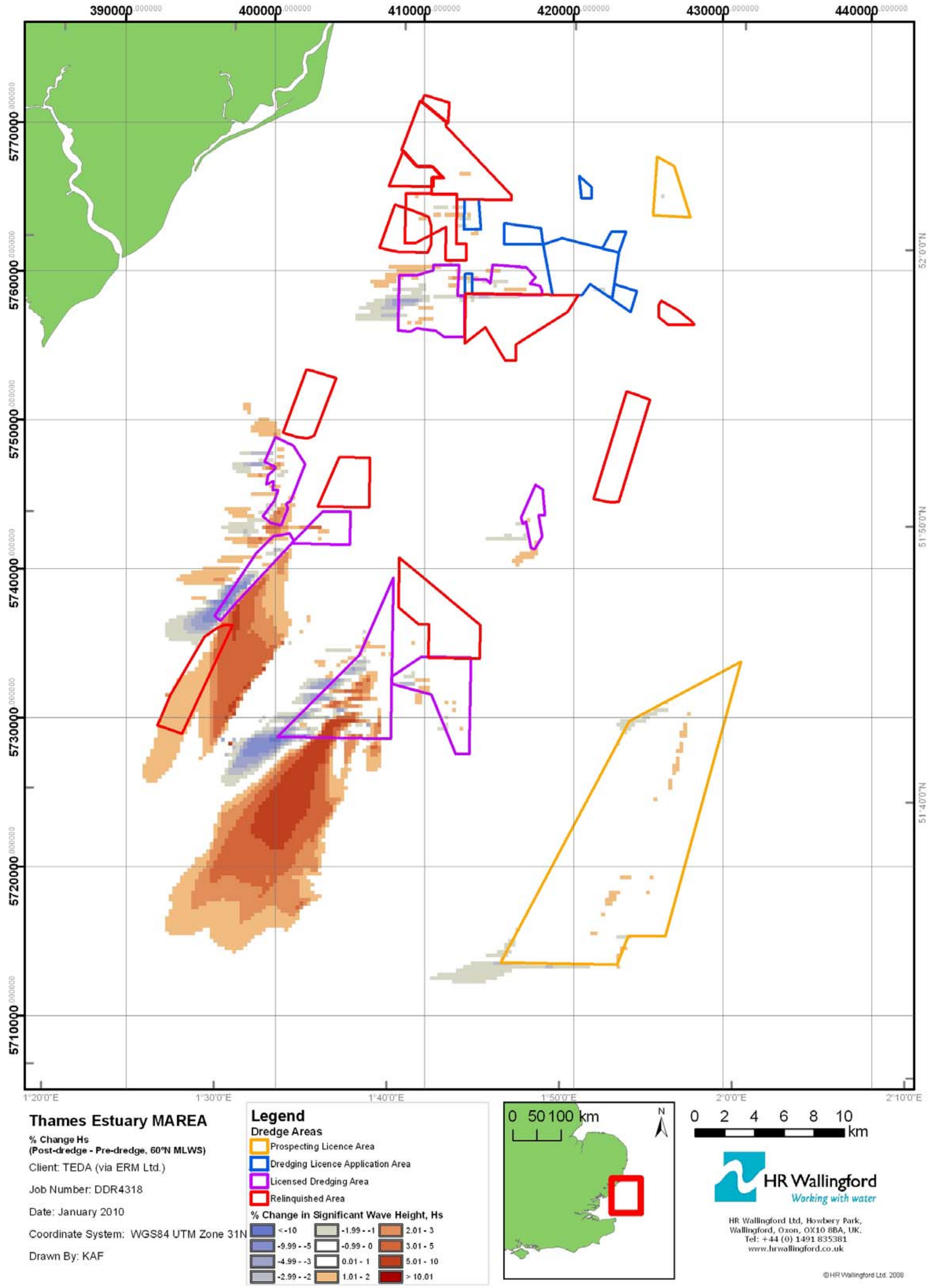


Figure 18 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 60ºN at MLWS

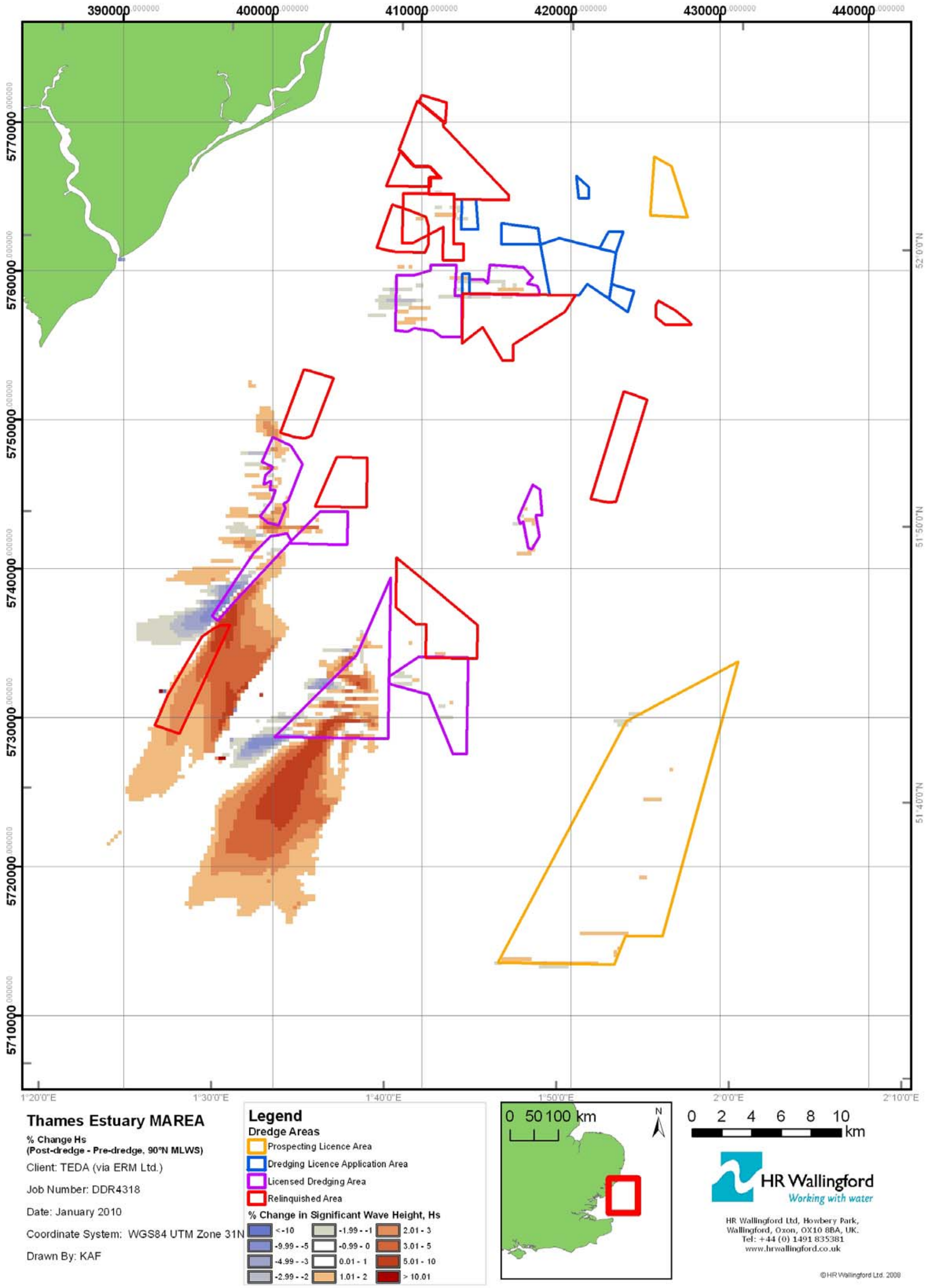


Figure 19 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 90ºN at MLWS

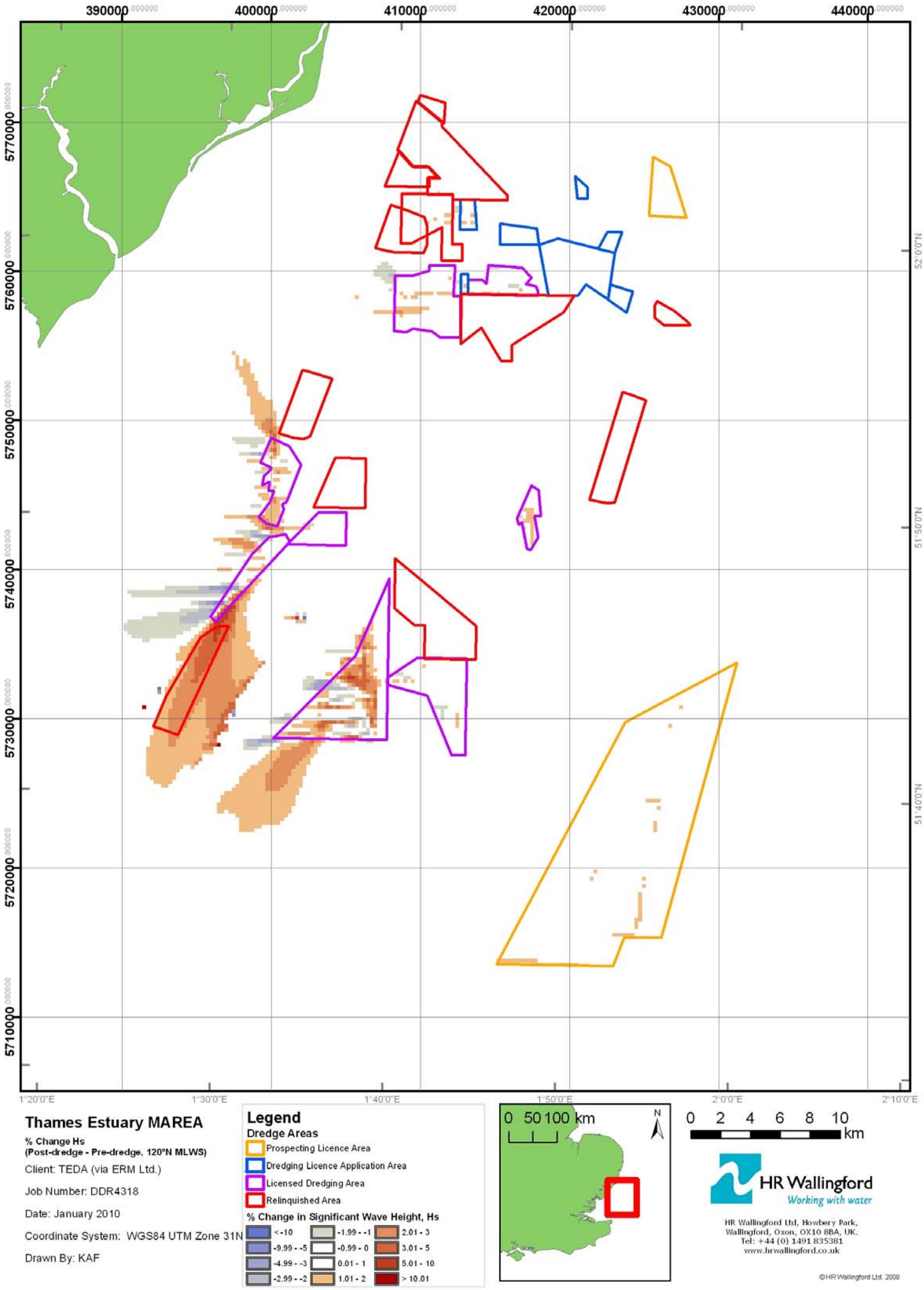


Figure 20 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 120ºN at MLWS

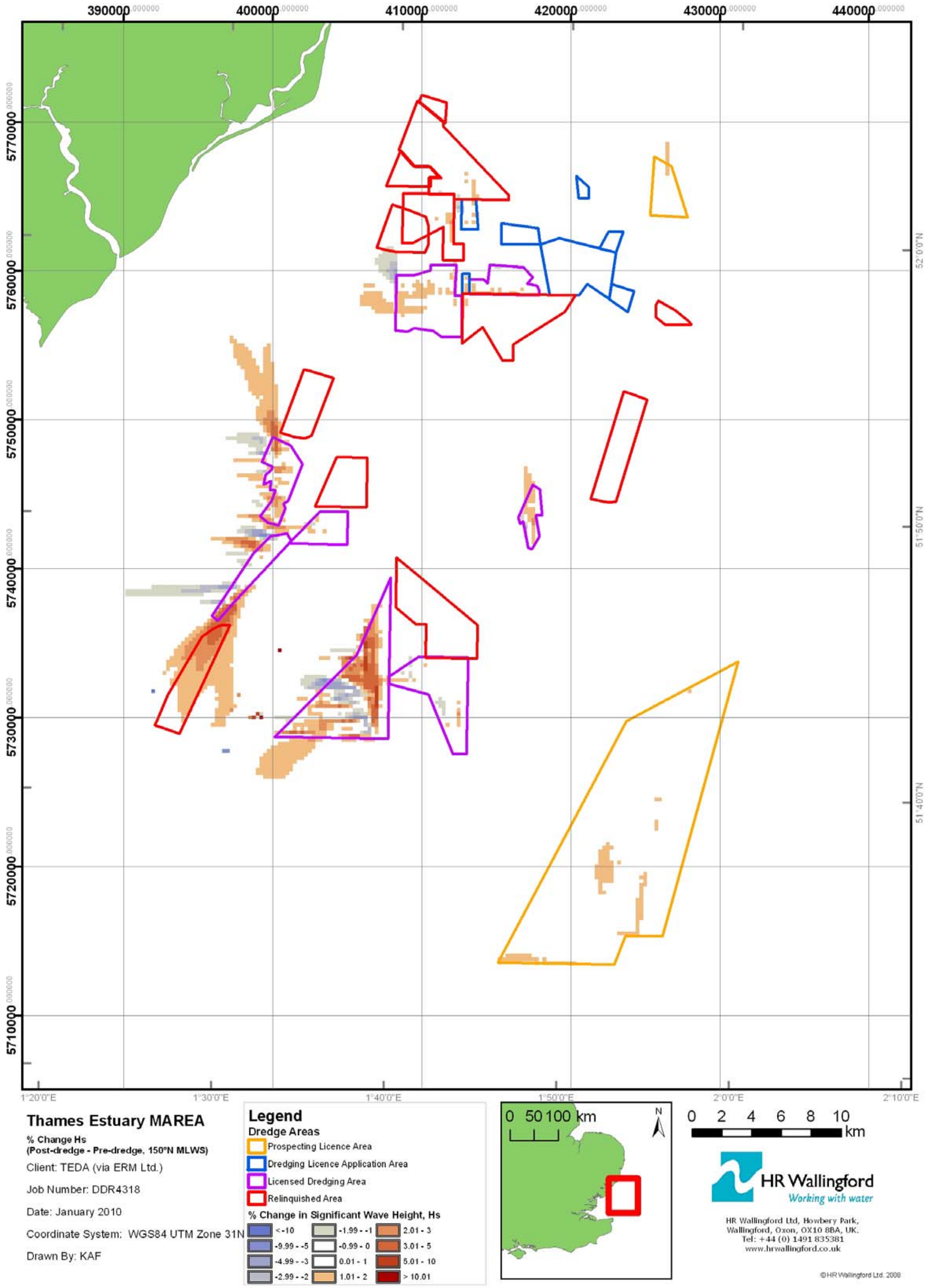


Figure 21 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 150ºN at MLWS

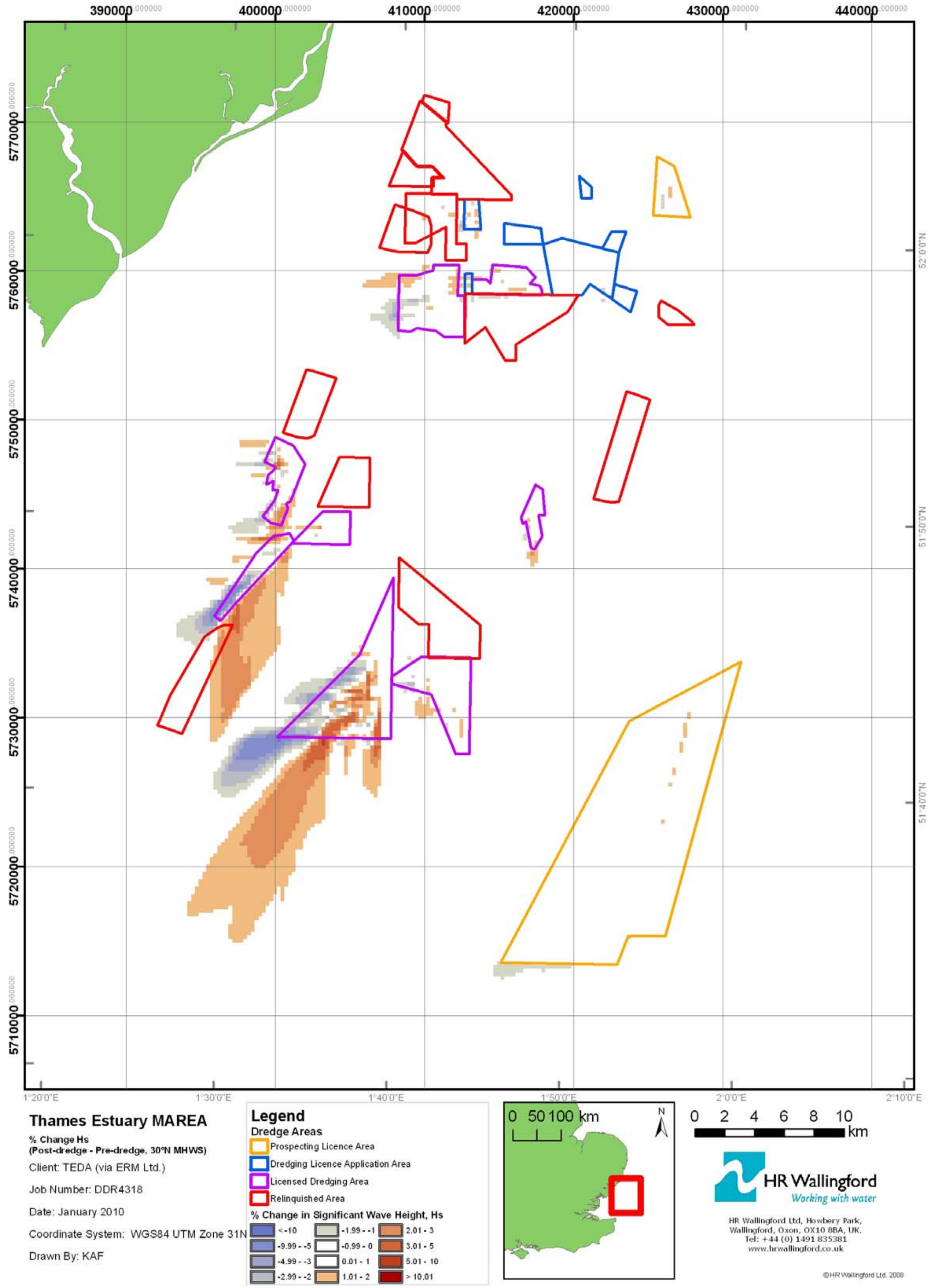


Figure 22 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 30ºN at MHWS

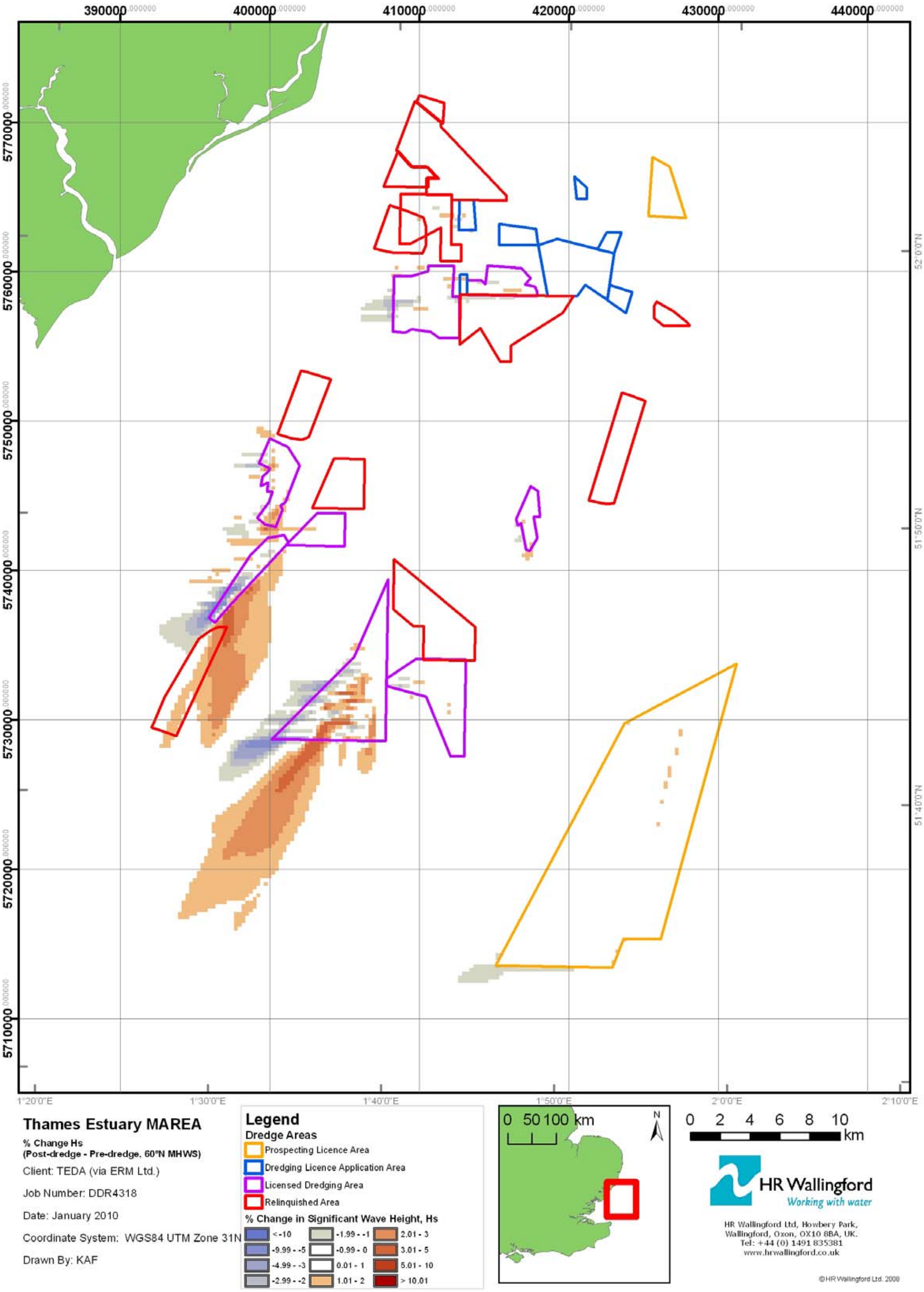


Figure 23 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 60ºN at MHWS

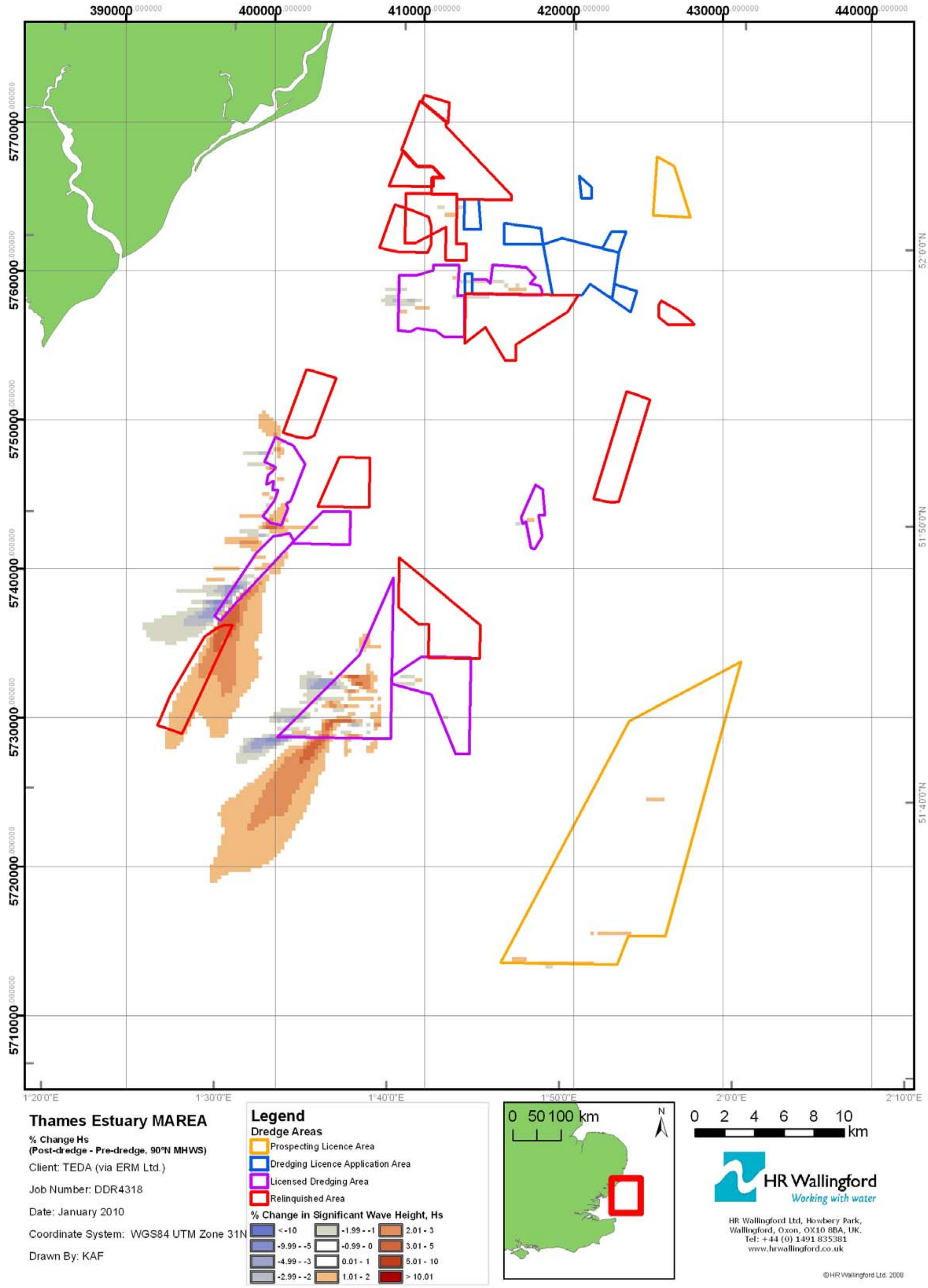


Figure 24 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 90ºN at MHWS

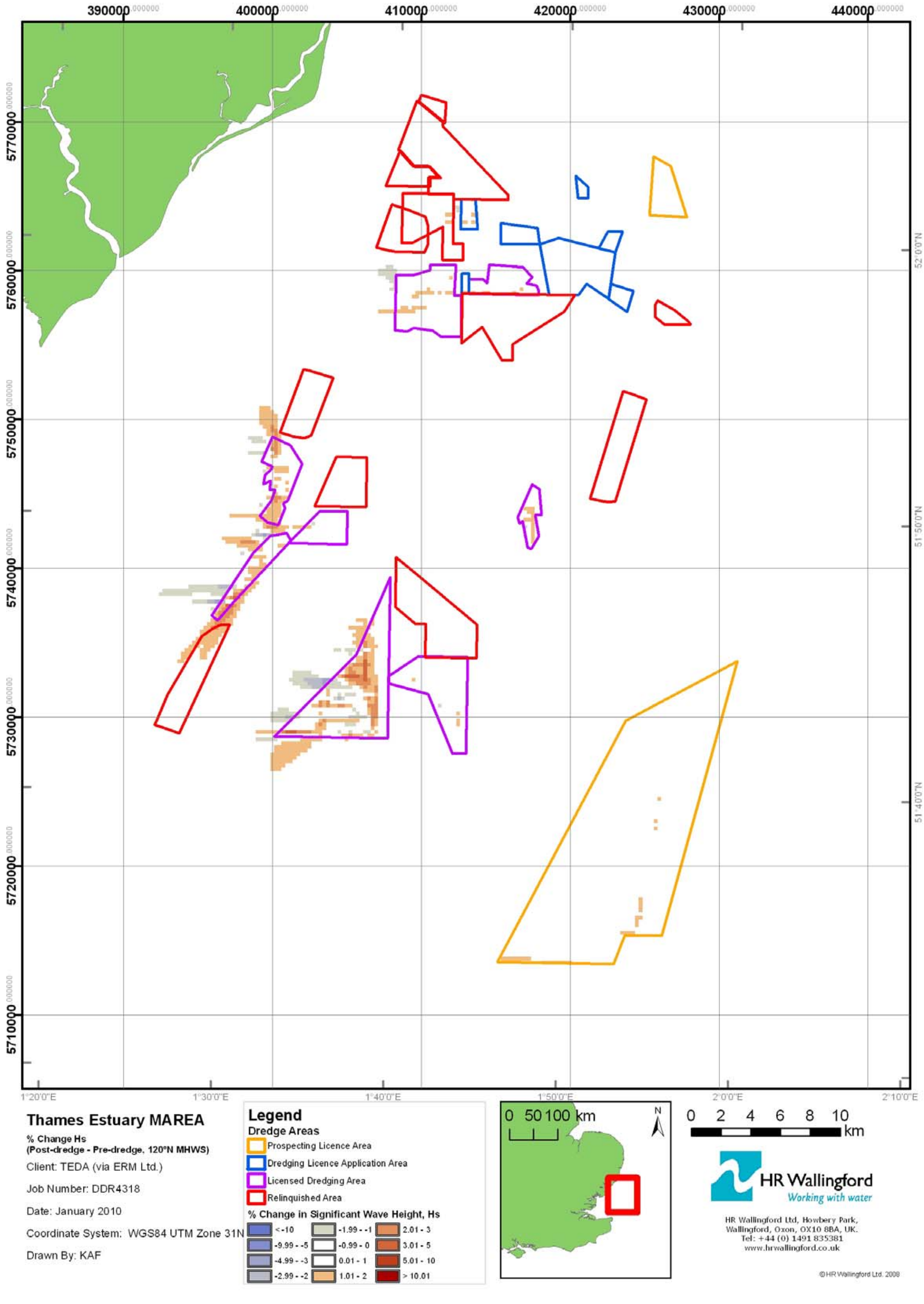


Figure 25 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 120ºN at MHWS

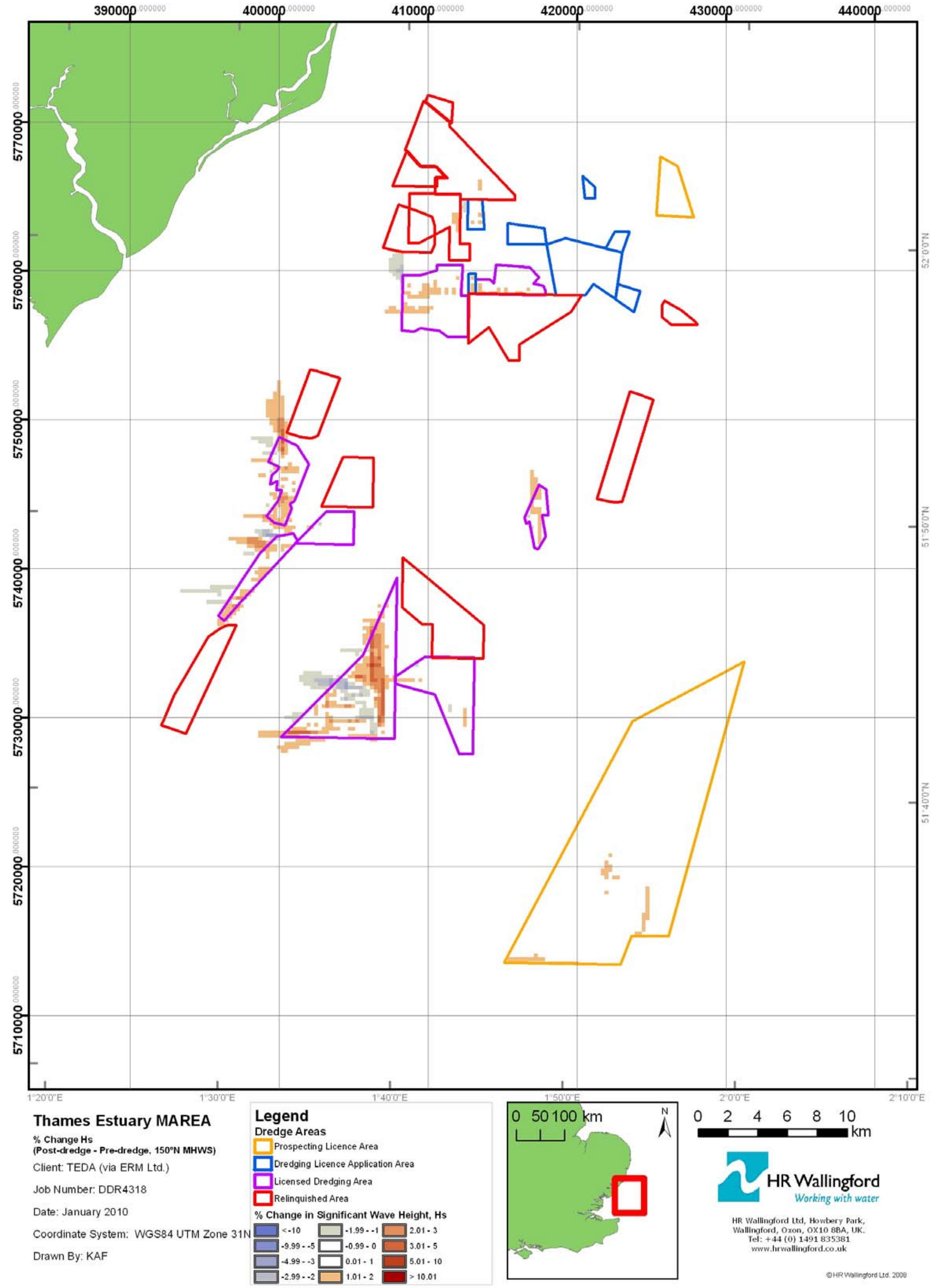


Figure 26 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 150ºN at MHWS

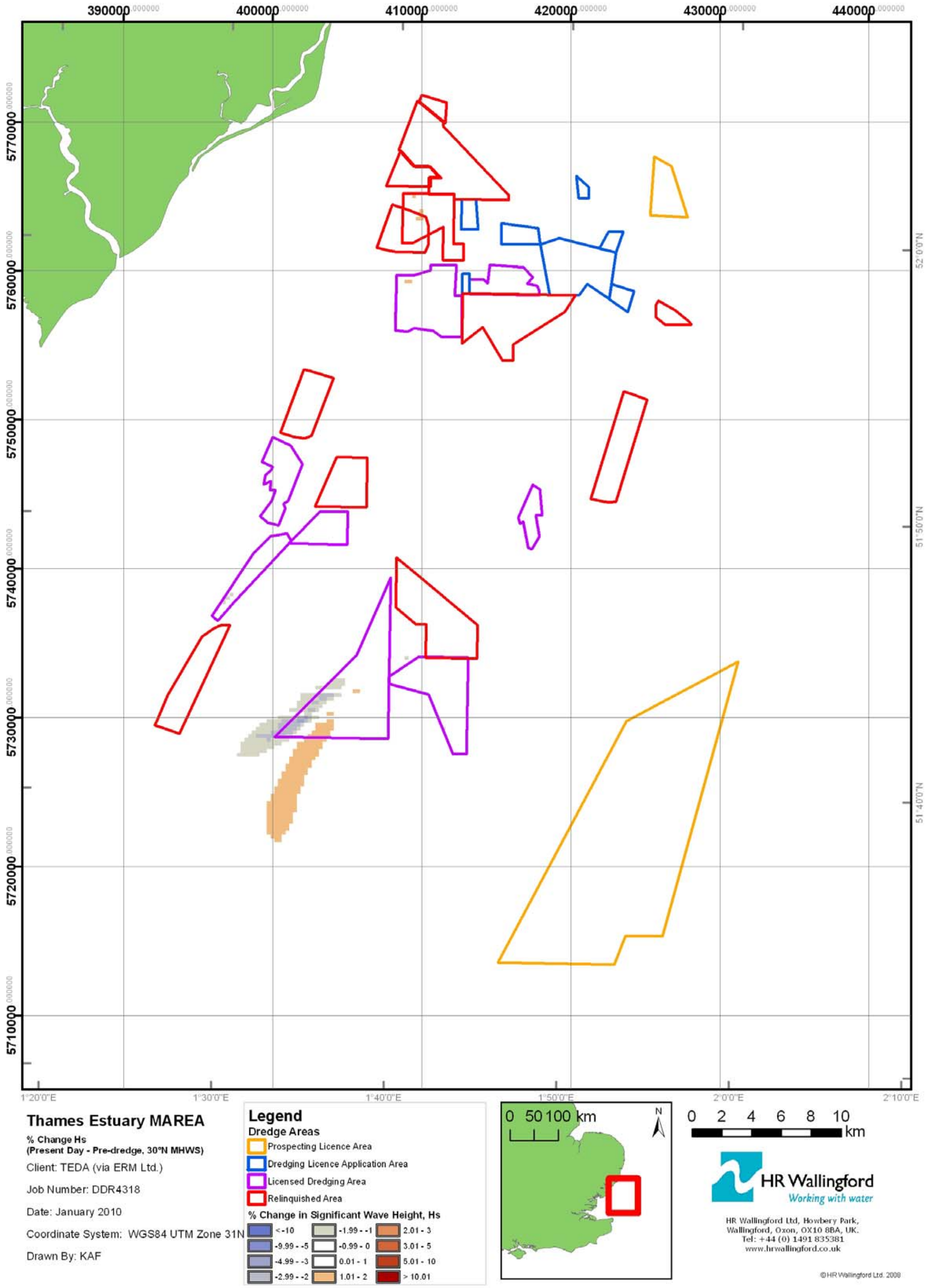


Figure 27 Changes (%) in wave height due to past dredging for 200 year return wave condition from 30ºN at MHWS and global warming (10% greater wave height and 5% greater wave period offshore)

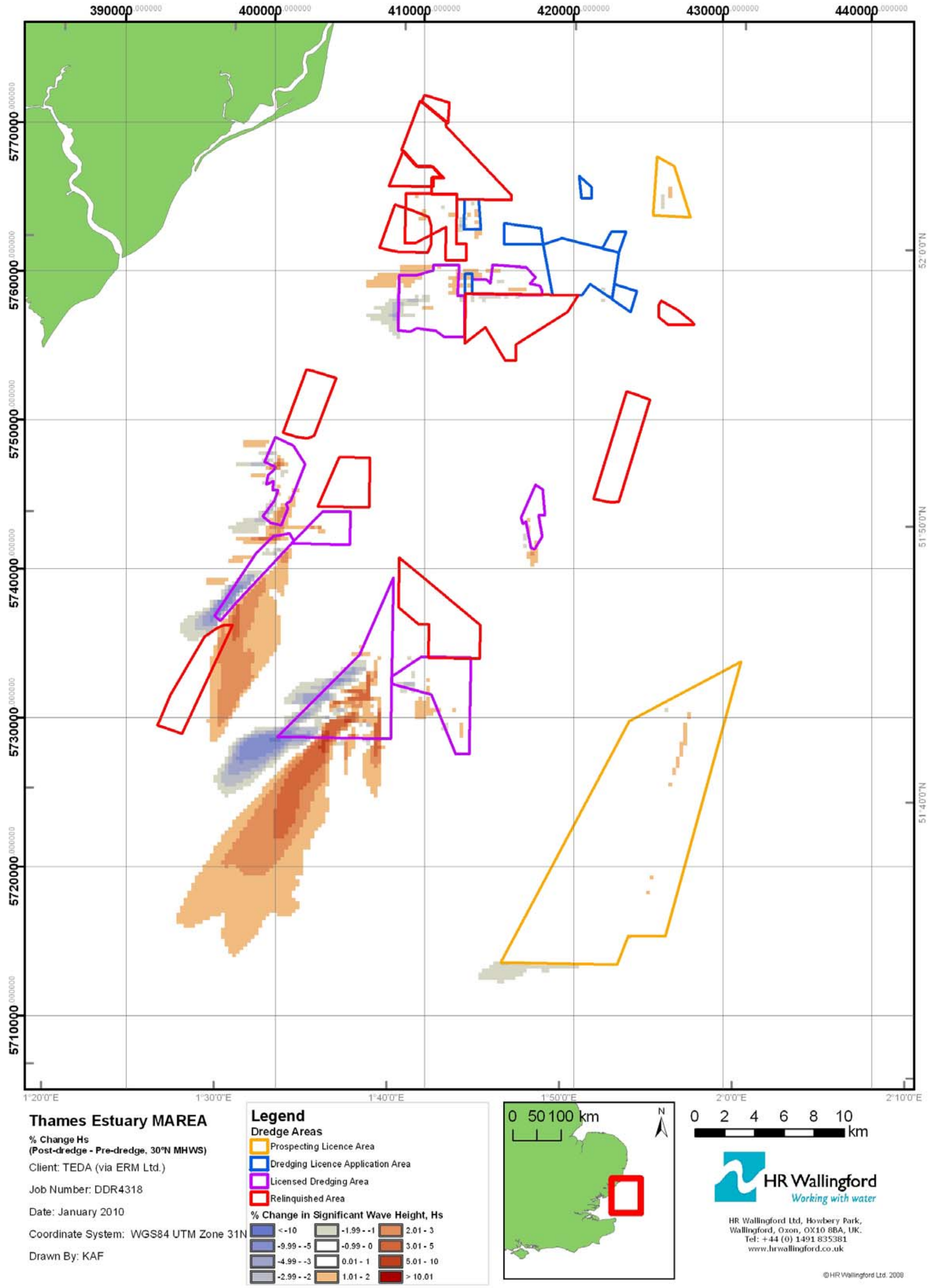


Figure 28 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 30ºN at MHWS and global warming (10% greater wave height and 5% greater wave period offshore)

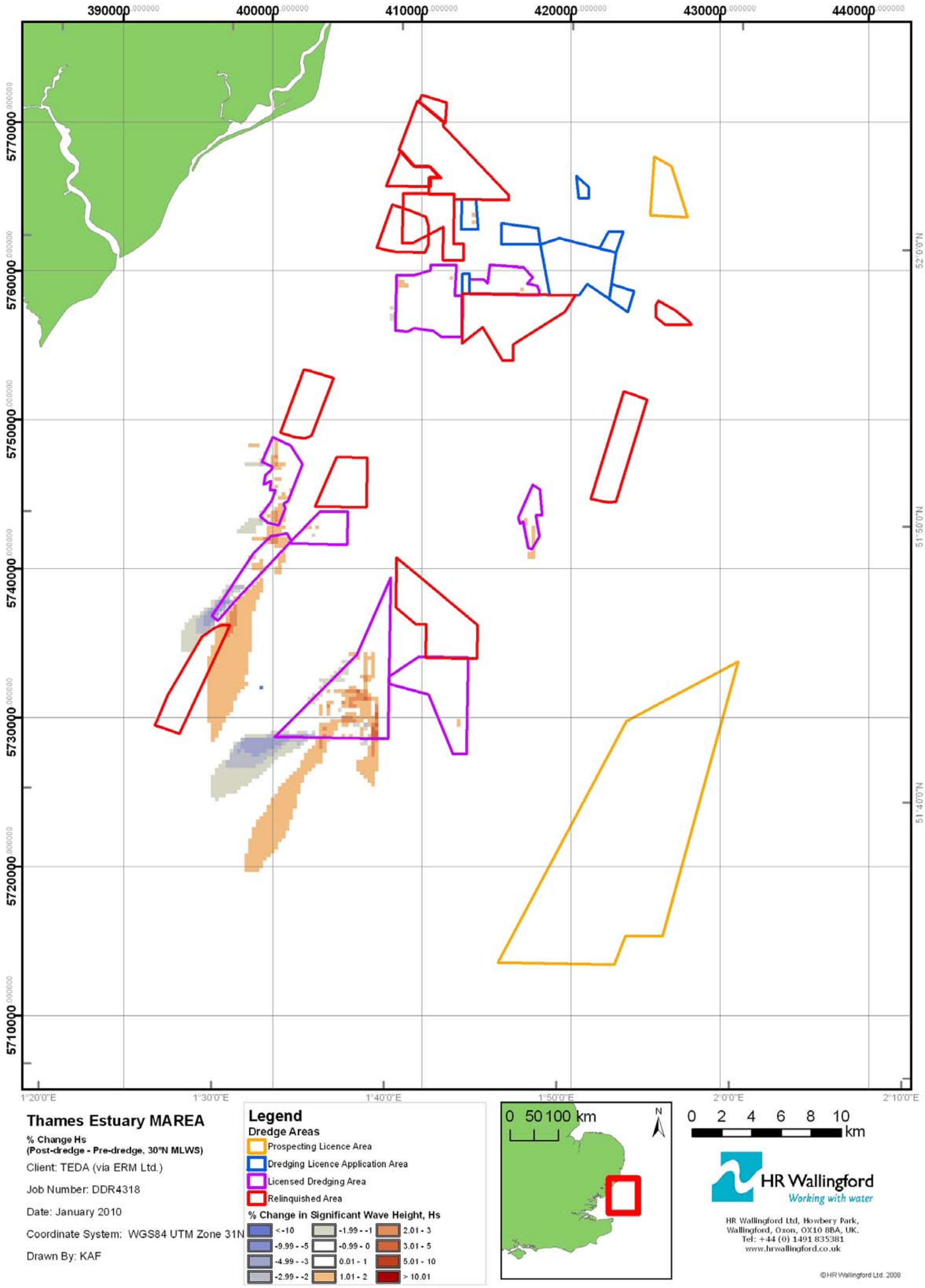


Figure 29 Changes (%) in wave height due to past and future dredging for 5% exceedence wave condition from 30ºN at MLWS

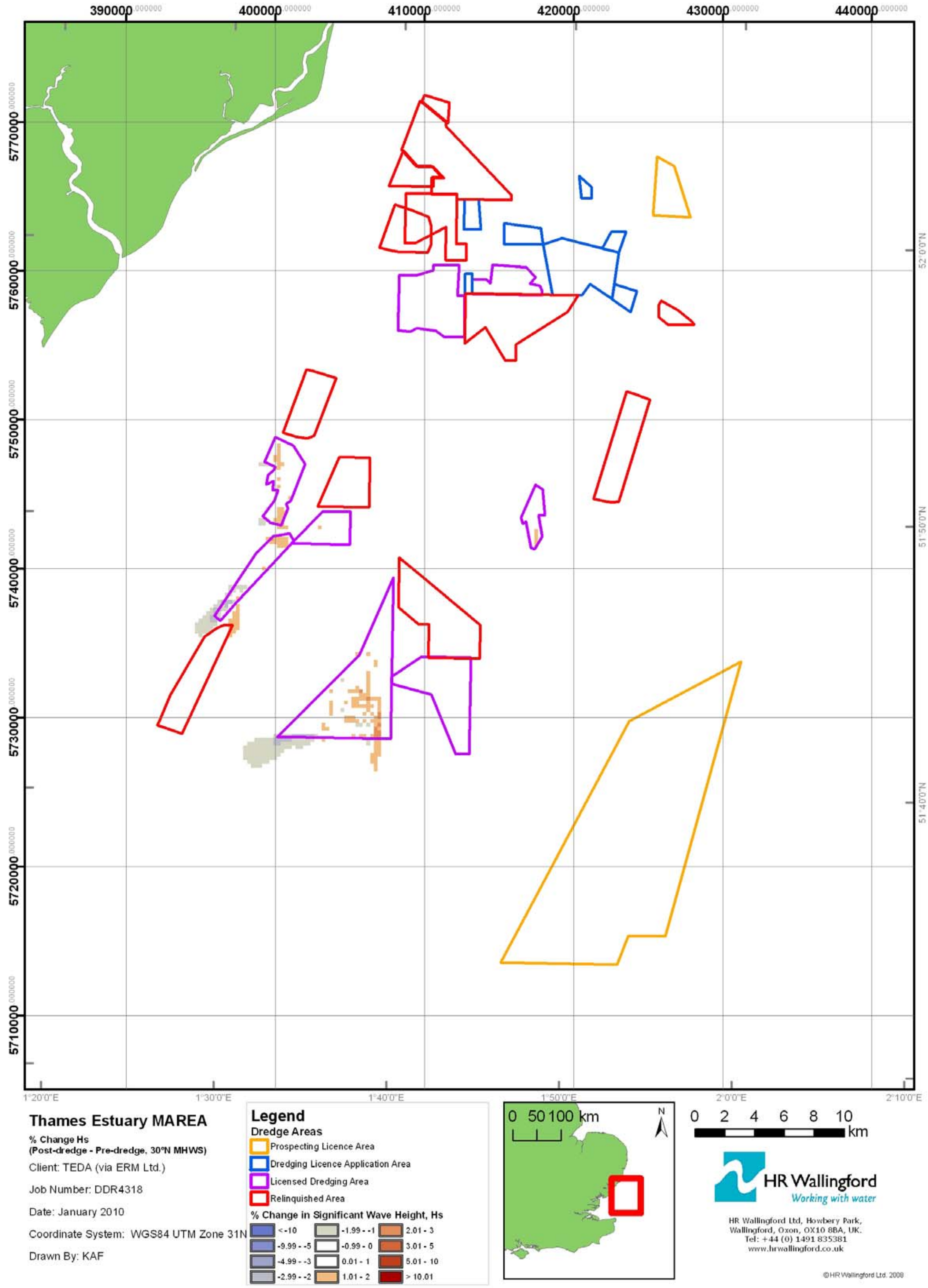


Figure 30 Changes (%) in wave height due to past and future dredging for 5% exceedence wave condition from 30ºN at MHWS

Appendices

Appendix 1 The SWAN wave transformation model

Introduction

SWAN is a computational spectral wave transformation model. It can be used to obtain realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, seabed, and current conditions. The model has been developed by the Technical University of Delft (TU Delft).

SWAN is based on a fully spectral representation of the wave action balance equation (or energy balance in the absence of currents) with all physical processes modelled explicitly. No a priori limitations are imposed on the spectral evolution. This makes SWAN (Simulating WAves Nearshore) a third-generation wave model.

The model has been used successfully at numerous sites around the UK and in other parts of the world. It is designed to represent the following wave propagation processes:

- refraction due to spatial variations in seabed and current,
- shoaling due to spatial variations in seabed and current,
- blocking and reflections by opposing currents,
- transmission through, blockage by or reflection from obstacles (such as coastlines or breakwaters).

The following wave generation and dissipation processes are also represented in SWAN:

- generation by wind,
- dissipation by whitecapping,
- dissipation by depth-induced wave breaking,
- dissipation by seabed friction,
- diffraction
- wave-wave interactions (quadruplets and triads),
- obstacles.

The SWAN wave model has been conceived to be a computationally feasible third-generation spectral wave model for waves in shallow water (including the surf zone) with ambient currents.

The SWAN wave model

The SWAN model represents the waves in terms of the two-dimensional wave action density spectrum $N(\sigma,\vartheta)$, even when nonlinear phenomena dominate (e.g., in the surf zone). The independent variables are the relative frequency σ (as observed in a frame of reference moving with the action propagation velocity) and the wave direction ϑ (the direction normal to the wave crest of each spectral component). The action density is equal to the energy density divided by the relative frequency: $N(\sigma,\vartheta) = E(\sigma,\vartheta)/\sigma$.

In SWAN the two-dimensional wave action density spectrum may vary in time and space. Its evolution is described by the spectral action balance equation, which for Cartesian coordinates is (e.g. Hasselmann et al., 1973):

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}C_x N + \frac{\partial}{\partial y}C_y N + \frac{\partial}{\partial \sigma}C_\sigma N + \frac{\partial}{\partial \vartheta}C_\vartheta N = \frac{S(\sigma,\vartheta)}{\sigma} \tag{1}$$

The first term in the left-hand side represents the local rate of change of action density in time. The second and third term represent propagation of action in geographical $x-$ and $y-$space (with propagation velocities C_x and C_y respectively). The fourth term represents shifting of the relative frequency due to variations in depths and currents in time (with propagation velocity C_σ in $\sigma-$ space). The fifth term represents propagation of action in $\vartheta-$ space (depth-induced and current-induced refraction) with propagation velocity C_ϑ. The expressions for these propagation speeds are taken from linear wave theory. The term $S(\sigma,\vartheta)$ at the right hand side of the action balance equation is the source term representing the effects of generation, dissipation and non-linear wave-wave interactions.

The formulations for the generation, the dissipation and the quadruplet wave-wave interactions are taken from the WAM model (WAM Cycle3, WAMDI group, 1988, and optionally WAM Cycle4, Komen et al., 1994). These are supplemented with a spectral version of the dissipation model for depth-induced breaking of Battjes and Janssen (1978) and a more recently formulated discrete interaction approximation for the triad wave-wave interactions (Eldeberky and Battjes, 1995).

Transfer of wind energy to the waves

The transfer of wind energy to the waves is described in SWAN with a resonance mechanism (Phillips, 1957) and a feed-back mechanism (Miles, 1957). The corresponding source term for these mechanisms is commonly described as the sum of linear and exponential growth:

$$S_{in}(\sigma,\vartheta) = A + B \times E(\sigma,\vartheta) \tag{2}$$

in which A and B depend on wave frequency and direction, and wind speed and direction. The effects of currents are accounted for in SWAN by using the apparent local wind speed and direction. The expression for the term A is due to Cavaleri and Malanotte-Rizzoli (1981, revised by Tolman, 1992). Two optional expressions for the coefficient B are used in the model. The first is due to Snyder et al. (1981), re-scaled in terms of friction velocity by Komen et al. (1984). The second expression is due to Janssen (1991) and accounts explicitly for the interaction between the wind and the waves by considering atmospheric boundary layer effects and the roughness length of the sea surface.

Whitecapping

Whitecapping is primarily controlled by the steepness of the waves. In presently operating third-generation wave models (including SWAN) the whitecapping formulations are based on a pulse-based model (Hasselmann, 1974), as adapted by the WAMDI group (1988):

$$S_{ds,w}(\sigma,\vartheta) = -\Gamma \tilde{\sigma} \frac{k}{\tilde{k}} E(\sigma,\vartheta) \tag{3}$$

where Γ is a steepness dependent coefficient, k is wave number and $\tilde{\sigma}$ and $\tilde{k}$ denote a mean frequency and a mean wave number, respectively (cf. the WAMDI group, 1988). The value of Γ depends on the wind input formulation that is used. Since two expressions are used for the wind input in SWAN, two values for Γ are used. The first is due to Komen et al. (1984), and is used in SWAN when the wind input coefficient of

Komen et al. (1984) is used. The second expression is an adaptation of this expression based on Janssen (1991). It is used when the wind input term of Janssen (1991) is used.

Depth-induced dissipation
Depth induced-dissipation may be caused by seabed friction, by seabed motion, by percolation or by back-scattering on seabed irregularities. For continental shelf seas with sandy seabeds, the dominant mechanism appears to be seabed friction, which can generally be represented as:

$$S_{ds,b}(\sigma,\vartheta) = -c_{bed}\,\frac{\sigma^2}{g^2\sinh^2(kd)}\,E(\sigma,\vartheta) \tag{4}$$

in which c_{bed} is a seabed friction coefficient. Many models have been proposed. Hasselmann et al. (JONSWAP, 1973) suggested use of an empirically obtained constant. This seems to perform well in many different conditions as long as a suitable value is chosen (typically different for swell and wind sea; Bouws and Komen, 1983). A nonlinear formulation based on drag has been proposed by Hasselmann and Collins (1968), which was later simplified by Collins (1972), and is also implemented in SWAN. More complicated, eddy viscosity models have been developed by Madsen et al. (1988). The effect of a mean current on the wave energy dissipation due to seabed friction is not taken into account in SWAN.

Depth-induced wave breaking
Although the process of depth-induced wave breaking is still poorly understood and little is known about its spectral modelling, the total dissipation (i.e. integrated over the spectrum) can be well modelled with the dissipation of a bore applied to the breaking waves in a random field. And laboratory observations show that the shape of initially uni-modal spectra propagating across simple (barred) beach profiles is fairly insensitive to depth-induced breaking. This has led Eldeberky and Battjes (1995) to formulate a spectral version of the bore model of Battjes and Janssen (1978) which conserves the spectral shape. Their expression has been expanded in the SWAN model to include direction:

$$S_{ds,br}(\sigma,\vartheta) = \frac{D_{tot}}{E_{tot}}E(\sigma,\vartheta) \tag{5}$$

in which E_{tot} is the total wave energy and D_{tot} (which is negative) is the rate of dissipation of the total energy due to wave breaking according to Battjes and Janssen (1978). The value of D_{tot} depends critically on the breaking parameter $\gamma = H_{\max}/d$ (in which $H_{\max}$ is the maximum possible individual wave height in the local water depth d). In SWAN γ has a constant value (default is 0.73 corresponding to the mean value of the data set of Battjes and Stive, 1985).

Wave transmission
SWAN can estimate wave transmission through a structure such as a breakwater. Since obstacles usually have a plan area that is too small to be resolved by the bathymetric grid, in SWAN, an obstacle is modelled as a line. The transmission coefficient is defined as the ratio of the (significant) wave height at the down-wave side of the breakwater over the (significant) wave height at the up-wave side. If the crest of the breakwater is such that waves can pass over, the transmission coefficient is taken from Goda et al. (1967) and is expressed as a function of wave height and freeboard (difference in crest level and water level).

Note that a change in wave frequency is to be expected as well as a change in wave height, since often the process above the breakwater is highly non-linear. But given the little information available, SWAN assumes that the frequencies remain unchanged over an obstacle (only the energy scale of the spectrum is affected and not the spectral shape).

Nonlinear wave-wave interactions
In deep water, quadruplet wave-wave interactions dominate the evolution of the spectrum. They transfer wave energy from the spectral peak to lower frequencies (thus moving the peak frequency to lower values) and to higher frequencies (where the energy is dissipated by whitecapping). In very shallow water, triad wave-wave interactions transfer energy from lower frequencies to higher frequencies often resulting in higher harmonics (Beji and Battjes, 1993; low-frequency energy generation by triad wave-wave interactions is not considered here).

A full computation of the **quadruplet wave-wave interactions** is extremely time consuming and not convenient in any operational wave model. A number of techniques, based on parametric methods or other types of approximations have been proposed to improve computational speed. In SWAN the computations are carried out with the Discrete Interaction Approximation (DIA) of Hasselmann et al. (1985). Eldeberky and Battjes (1995) introduced a discrete triad approximation (DTA) for co-linear waves, obtained by considering only the dominant self-self **triad interactions**. Their model has been verified with flume observations of long-crested, random waves breaking over a submerged bar (Beji and Battjes, 1993) and over a barred beach (Arcilla et al., 1994). A slightly different version, the Lumped Triad Approximation (LTA) was later derived by Eldeberky (1996) and is used in SWAN.

Cycle III of SWAN is stationary and optionally non-stationary, formulated in Cartesian (recommended only for small scales) or spherical (small scales and large scales) coordinates. The stationary mode should be used only for waves with a relatively short residence time in the computational area under consideration (i.e. small travel time of the waves through the region compared to the time scale of the geophysical conditions: wave boundary conditions, wind, tides and storm surge). A quasi-stationary approach can be taken with stationary SWAN computations in a time-varying sequence of stationary conditions.

The current version of SWAN can be used on any scale relevant for wind generated surface gravity waves, as the model now uses more accurate numerical propagation schemes and can compute on spherical co-ordinates (longitude, latitude), allowing calculations in laboratory situations, coastal regions, shelf seas and oceans. However, SWAN is specifically developed for coastal applications, which would usually not require such flexibility in scale. And it must be emphasized that on oceanic scales SWAN is certainly less efficient on oceanic scales than WAVEWATCH III and probably also less efficient than WAM.

Fully implicit numerical schemes are used in the SWAN model for propagation in both geographic and spectral spaces (an iterative, forward-marching, four-sweep technique due to Ris et al., 1994). This scheme is unconditionally stable in contrast with the explicit schemes of conventional spectral wave models.

Typical results

(i) Colour contour plots of significant wave height, H_s, and vector plots of mean wave direction over the model area.

(ii) Tables of H_s, T_z, T_p and mean direction at a selection of inshore locations. For example the model can be used to investigate which offshore wave conditions lead to the worst inshore wave heights at a particular site.

(iii) SWAN also calculates fields of wave-induced forces per unit surface area, wave orbital velocities, and a variety of other parameters. Such results can be used directly as input into a sediment transport model.

(iv) 2D (frequency and direction) spectrum at a selection of inshore location. Information of this type would normally be required as input to a numerical harbour model or a mathematical model of beach processes. In addition this information would also be needed at the wave paddle positions in a physical model in order to generate the correct random wave sequence for design studies.

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Appendix 2 Bathymetry data sources

Company	AREA	PRE-DREDGE	PRESENT	POST-DREDGE
UMD	**Area 108/1**	108_1 pre&present day bathy 1998.txt	108_1 pre&present day bathy 1998.txt	See email outlining dredging area coordinates and lowered depth
UMD	**Area 109/1**	109 predredge bathy OSGB36.txt	Area 109 present day bathy OSGB36.txt	109 post dredging bathy OSGB36 Version 2.txt
CMX	**Area 118/2**	SeaZone and 1m shallower in dredged area (see GIS files *118_2 UTM ED50 z31dredge boundary*)	SeaZone	SeaZone minus resource thickness (*118_2 UTM ED50 z31 res.xls*)
HAML	**Area 119/3**	SeaZone + tonnages off take	SeaZone	1997 Isopach NN contour_polyline.shp
CMX	**Area 239/1**	SeaZone and 1m shallower in blue areas in see GIS files *239 OSGB dredge boundary*	SeaZone	SeaZone minus resource thickness (*239 OSGB res.xls*)
UMD	**Area 257**	257 predredge bathy OSGB36.txt	257 present day bathy OSGB36.txt	257 post dredging bathy OSGB36.txt
CMX	**Area 327**	SeaZone and 1m shallower in dredged area (see GIS files *327 OSGB dredge boundary*)	SeaZone	SeaZone minus resource thickness (*327 OSGB res.xls*)
CMX	**Area 447**	See pre-dredge bathy file: *447 UTM WGS z3 pre.xyz*	*447 UTM WGS z3 pre.xyz*	Pre-dredge bathy minus file *447 OSGB res.xls*
CMX	**Area 452 A**	SeaZone	SeaZone	SeaZone minus resource thickness (*452 LLOSGB res.xls*)
CMX	**Area 452 B**	SeaZone	SeaZone	SeaZone minus resource thickness (*452 LLOSGB res.xls*)
CMX	**Area 452 C1**	SeaZone	SeaZone	SeaZone minus resource thickness (*452 LLOSGB res.xls*)
CMX	**Area 452 C2**	SeaZone	SeaZone	SeaZone minus resource thickness (*452 LLOSGB res.xls*)
CMX	**Area 452 C3**	SeaZone	SeaZone	SeaZone minus resource thickness (*452 LLOSGB res.xls*)
CMX	**Area 452 D**	SeaZone	SeaZone	SeaZone minus resource thickness (*452 LLOSGB res.xls*)
CMX	**Area 452 E**	SeaZone	SeaZone	SeaZone minus resource thickness (*452 LLOSGB res.xls*)
	Area 498 or North Inner Gabbard	SeaZone	SeaZone	See word document provided with coordinates of dredging area and lowered amounts
UMD	**Area 287**	287 pre-dredge bathy UTM31N.txt	287 present day & post dredging bathy UTM31N.txt	287 present day & post dredging bathy UTM31N.txt

Company	AREA	PRE-DREDGE	PRESENT	POST-DREDGE
CMX	**Area 116/1**	SeaZone and 1m shallower in dredged area (see GIS files *116 OSGB dredge boundary*)	SeaZone	SeaZone
CMX	**Area 364**	364_1 OSGB pre.DAT 364_2 OSGB pre.DAT 364_3 OSGB pre.DAT	364_1 OSGB post.csv 364_2 OSGB pre.DAT 364_3 OSGB post.csv	364_1 OSGB post.csv 364_2 OSGB pre.DAT 364_3 OSGB post.csv
CMX	**Area 113/2**	SeaZone and 1m shallower in dredged area (see GIS files *113_2 OSGB dredge boundary*)	SeaZone	SeaZone
HAML	**Area 111/1**	SeaZone + tonnage off take	1111-xyz.csv –OSGB (1998)	1111-xyz.csv -OSGB
HAML	**Area 112/2**	SeaZone + tonnage off take	1122-xyz.csv -OSGB	1122-xyz.csv -OSGB
HAML	**Area 112/3**	SeaZone + tonnage off take	1123-xyz.csv -OSGB	1123-xyz.csv -OSGB
HAML	**Area 119/1**	SeaZone + tonnage off take	1191-xyz.csv –OSGB (1998)	1191-xyz.csv -OSGB
HAML	**Area 119/2**	SeaZone + tonnage off take	1192-xyz.csv –OSGB (1998)	1192-xyz.csv -OSGB
HAML	**Area 504 (or North Falls)**	2008 bathymetry 150m_contour_polyline.shp	2008 bathymetry 150m_contour_polyline.shp (2008)	Postdredge bathymetry full 150m_contour_polyline.shp

Appendix 3 Prediction of extreme wave conditions (Weibull)

There are several different methods of estimating extreme events from limited data. They are based upon the idea of fitting a standard probability distribution to the range of data which is available. The extreme wave heights are then obtained by substituting the corresponding extreme probability levels into the fitted equation.

For this approach to work properly, the data should be a representative sample, for example one year of continuous record, and not be unfairly weighted in favour of one particular time of the year. In addition, the probability theory demands that the recorded events be independent. A suitable method is to use a large number of regularly measured H_s values and to assume that the lack of independence between neighbouring values will be overcome by virtue of the volume of data involved (Ref 1).

The three-parameter Weibull distribution (Equation 1) has previously been found to be the most reliable and consistent method of fitting distributions of wave data. The parameters of the distribution are calculated after plotting the various exceedence levels on Weibull scaled graph paper (Equation 2), and drawing the best fit straight line through the points. As a check, this procedure is reproduced by a computer program and the results compared.

<u>Extreme Value Distribution</u>

$$P(H_s) = 1 - \exp[-\{(H_s - a)/b\}^c] \qquad (1)$$

where H_s = significant wave height
P = probability less than H_s
a, b, c are parameters to be found

<u>Weibull Scales</u>

$$\log\{-\log(1-P(H_s))\} = c\,\{\log(H_s-a) - \log b\} \qquad (2)$$

$y = \log\{-\log(1-P(H_s))\}$ x and y are plotted
$x = \log(H_s-a)$ on linear scales

Waves of a given return period (N years) are determined graphically from the appropriate probability. In order to calculate the correct probability, it is necessary to set the duration or persistence of the return period event. For example, if three hours were chosen (as in this study), there would be a total of 2922 hour periods per year, and the probability of the 10 year return period event would be:-

$$P(\text{10 year event}) = 1 - 1/(10 \times 2922)$$

$$= 0.999966$$

Note that the expected highest individual wave (H_{max}) in a sequence is related to H_s by the approximate formula:-

$$\frac{H_{max}}{H_s} = (1/2\ln N)^{1/2}$$

where N = the number of waves in the sequence

Also note the following modification to cope with conditional probabilities, for example extremes from a particular direction sector or those occurring during a particular season of the year. The qualifying data, for example that lying in a particular direction sector, is treated as a full 100% sample for the purposes of calculating the general distribution of H_s. However, the number of "events" per year (2922 above) is reduced to the number occurring within the sector (or season) or interest.

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