South Coast Dredging Association

MAREA: Wave Study

Technical Note DDR4323-04

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1. Introduction

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

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

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 MAREA study region.

Many previous Coastal Impact Studies have been carried out in connection with applications for aggregate dredging in this region, and these studies have shown that changes to wave conditions at the coastline are small or non-existent. 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 then goes on to address 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 **not** be changes in wave conditions as a result of past and planned future aggregate dredging.

However, this report also indicates where such potentially significant changes may occur. These generally are restricted to within, or to quite small areas close to, the boundaries of the individual extraction areas. If there are specific sensitivities in these areas, for example natural or man-made features that might be affected by changes in 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 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 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 conditions is often a major component of studies into the environmental effects of proposed marine aggregate dredging. Such assessments are usually submitted at the time of the formal application for each extraction licence.

The present regional study provides an opportunity to review the effects on waves of all past aggregate dredging, and proposed future aggregate dredging, within the study region on a cumulative basis taking into account all 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 specific study region 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 ways in which waves can be altered by dredging the seabed can be divided into two main classes, as 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 South Coast 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 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, convert wave energy into turbulence; others such as the continuing input of energy by the wind, will increase the energy of waves as they travel on towards the shoreline.

In shallow water areas (i.e. less than 20m deep), the lowering of the seabed by aggregate extraction can reduce the energy dissipation that occurs as waves pass over that 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. As a result, wave conditions will be different on the landward side of the dredged area to those either side of that area, 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 South Coast 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 type of model uses 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 South Coast. 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, wrecks, pipelines, or navigation channels and 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 SCDA members that the conservatism that had resulted from the use of the TELURAY model in previous studies was probably excessive to the extent that predicted changes in wave conditions due to aggregate dredging could be misleadingly large. 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 aggregate dredging lowering the seabed. 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 240° N, 210° N, 180° N, 150° N and 120° 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 SCDA 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 model suitable for coastal wave studies. This model has also been used in many other studies investigating 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 domain. SWAN therefore is especially useful in regions such as the South Coast where conditions are dominated by 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 a significant wave height in the range of 5 to 10m. This sort of uncertainty is smaller than in the accuracy to which such large wave heights could be measured, 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 has 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 in the study region for many years, and the present licensed dredging areas are shown in Figure 1. When the MAREA is complete, the SCDA 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. One of the possible new licence applications could be for Area 477 which partly lies in the very south-eastern corner of the study region. This area is in deep water, and any effect on waves of dredging in it is likely to be small, and not extend as far inshore as any of the existing dredging areas east of the Isle of Wight. This study has therefore not considered the effects of proposed dredging in Area 477, and it has not been shown in Figure 1 as a result.

To assess the cumulative impact of aggregate dredging, both past and 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 and relinquished 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 SCDA members for extraction in the medium term future.

It is important to note here that each of the above representations of seabed levels in the study region cannot be ascribed to any particular year. In this large study region, the digital data on seabed levels available 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). Information provided by the South Coast Dredging Association (SCDA) 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 SCDA members have defined water depth increases that might be brought about from proposed dredging to 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 each area. In some areas, the proposed depth changes would remove all virtually of this sediment.

Within any individual area, the future depth changes proposed by the SCDA 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 applications made for licence extensions (for existing areas) or for new areas, secondly on the conditions that may be placed on permissions to dredge in these areas and thirdly on the proportion of the permitted extraction that actually takes place during the lifetime of any licence (typically up to 15 years). Some of these licences may be granted within a few years from now while other licence applications may take much longer to prepare and then be determined.

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 SCDA 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 west of the Isle of Wight already caused by aggregate dredging (i.e. the present-day minus the pre-dredging bathymetry), while Figure 3 shows the depth changes caused by the current plans for further dredging in this sub-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. Figures 4 and 5 present similar information on both the past and possible future depth changes in dredging areas to the east of the Isle of Wight.

To predict the changes in wave conditions caused by past and planned future dredging, it was decided not to set up a SWAN model for the whole study region but to establish two models for two sub-regions. The western SWAN model covers an area roughly corresponding to the areas shown in Figures 2 and 3, and the eastern model covers an area similar to that shown in Figures 4 and 5. This was possible because it was found that no wave conditions travelling over the dredging areas west of the Isle of Wight had been significantly affected before reaching them as they propagated over dredging areas to the east of the Isle of Wight, and vice-versa.

Because of the shape and location of the dredging areas, particularly in the eastern sub-region where they cluster along an ancient infilled river valley, now submerged, it was necessary to establish a very finely spaced grid for these models. The details of these two models are presented below.

Table 1 SWAN models - details of the depth grid

Model Grid	Origin (UTM 30N m)		Resolution (m)	Number of nodes	
	X	y		x	y
Western	571500	5578000	125	576	356
Eastern	614500	5578000	125	776	466

The western model therefore covers an area of about 72km (E-W) by 44.5km (N-S) and the seabed levels within it specified at over 200,000 nodes. The eastern model is larger, extending almost 97km E-W and 58km N-S, and having over 350,000 depth values.

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 study region are predominantly generated within the English Channel and Western Approaches, but are augmented by swell waves arriving from the North Atlantic that approach from the south-west. Because the fetch lengths to the south-west and west are the longest, and the winds in the study region are predominantly from the south-west and west as well, the largest and longest period waves approach from this sector. However, large waves can also approach from the east, south-east and south, and waves from these directions may be more influential in some areas, for example along the south-eastern coast of the Isle of Wight and the western side of Poole Bay. It is therefore important in this study to investigate the effects of aggregate dredging on waves approaching from a broad range of directions.

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.

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 study 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 larger than for more frequently occurring waves. This "worst case", i.e. precautionary approach has therefore been adopted.

Having made this decision, considerable further work is needed to define these very severe incident wave conditions. As pointed out previously, 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, and that a range of different wind (and hence incident wave) directions are considered.

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 one or more numerical wave forecasting models.

When predicting coastal wave climates in areas where waves can be generated and travel over hundreds of kilometres before reaching the coast, it is standard practice to use one of the global or large regional wave models such as those run by the Met Office. For this study region, this method is suitable for the prediction of waves that approach the study region from the south-west sector having perhaps travelled from the Atlantic Ocean and up the Western Approaches to the English Channel. This approach has been used recently for several studies of flood and coastal defences along the South Coast 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.

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

Location	Degrees North	Degrees East
W	50°30′N	2°4′W
M	50°30′N	1°16′W
E	50°30′N	0°28′W

Because of the considerable east/west extent of the study region, the wave climate experienced along its southern edge will vary. As a result, predictions of offshore wave conditions were obtained for three points selected from grid locations used by the Met Office European Wave Model. These points are equally spaced and close to the southern edge of the study region, and referred to as Points W (western), M (mid-boundary) and E (eastern). Their locations are defined in Table 2.

For waves approaching from the longer fetch lengths to the south-west, wave conditions predicted by the Met Office European Wave Model were used directly to estimate those components of the overall wave climate and to estimate the extreme wave conditions arriving from those directions.

For waves approaching from the south-eastern sector, however, it was found that the results from the Met Office European Wave Model were less reliable. Its rather coarse resolution, e.g. 25km, means that it cannot accurately reproduce the shape of the coastlines of the English Channel, and hence could not accurately reproduce the fetch lengths across the Channel. For winds and hence waves approaching from this direction, therefore, it is better to combine wind data from the Met Office European Wave Model and a site-specific wave prediction model known as HINDWAVE. This model, developed by HR Wallingford, has been in regular use for many years and has been validated against wave measurements at many coastal locations around the UK, including several sites in the study region.

Within the area of interest, HINDWAVE, sometimes in conjunction with a wave transformation model, has been validated against measured wave data off Littlehampton, in NW Poole Bay, off Seaford, off Southbourne and on Swanage Pier. Of these, only the Seaford comparison is available in the open literature (Hawkes, 1987), but extracts from consultancy reports can be made available on request to illustrate the other comparisons.

HINDWAVE has been used in many other site-specific consultancy studies in the area, without additional validation against field data. These include studies for Arun District Council, Bournemouth Borough Council, Chesil Beach, Chichester Harbour, Christchurch Bay, Hayling Island, Hurst Spit, Langstone Harbour, Medmerry, Pagham Harbour, St Catherines, Sandown, Shoreham and Worthing.

HINDWAVE has also been used in several regional studies including the prediction of waves in Poole Bay for Poole Borough Council, and for coastal strategy studies for the coastline between Pagham and Southampton Water. It has also been used for numerous Coastal Impact Studies for over the past 15 years and, and in previous research into the movements of sediment over the seabed both to the east and west of the Isle of Wight (see for example HR Wallingford 1993, 1995a and 1995b).

As an example of the results from this wave climate evaluation process, Figure 6 presents a "wave rose" which summarises the wave climate predicted by the Met Office model at the central offshore location M. This shows the probability of occurrence of various wave heights arriving from different directions. A full listing of the wave climates predicted for each of Points W, M and E is provided in Appendix 2 to this report. Wave climates predicted by the Met Office's model are presented for all three of these locations, but wave climates were only predicted using the HINDWAVE model at Points M and E.

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 location 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. The directional sectors for which this analysis was carried out are shown in **bold** in the predicted wave climates presented in Appendix 2.

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.

Tables 3 and 4 summarise 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 presents the input boundary conditions (waves and winds) for the western SWAN model that is used to predict the effects of aggregate dredging in all areas west of the Isle of Wight, while Table 4 presents similar information for the eastern SWAN model, which extends from St Catherine's Point to as far east as Brighton (see Section 2.3).

Table 3 Extreme incident wave conditions – western SWAN model

Return period (years)	Direction (ºN)	Wind speed (ms^{-1})	Significant wave height (m)	Peak wave period (s)
200	120	20.7	4.3	7.0
200	150	25.7	3.9	6.6
200	180	25.7	7.0	8.8
200	210	28.5	7.8	9.1
200	240	31.8	8.1	9.4

Table 4 Extreme incident wave conditions – eastern SWAN model

Return period (years)	Direction (ºN)	Wind speed (ms^{-1})	Significant wave height (m)	Peak wave period (s)
200	120	20.1	3.3	6.4
200	150	25.0	3.5	6.5
200	180	25.6	4.0	6.6
200	210	28.4	7.2	8.7
200	240	30.6	7.5	9.0

The greatest wave heights, for both the western and eastern model grids, approach from 240ºN. Extreme wave conditions approaching from other directions than those listed in Tables 3 and 4, for example from 270 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 travelling parallel to or away from the coast within the SCDA 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) and to a low tidal level (equal to Mean Low Water Springs, MLWS).

In this large study region, tidal ranges vary substantially, from Swanage which has the smallest tidal range along the coastline of England to Brighton where the ranges are much greater. As a consequence, the high and low water levels in the wave modelling were chosen to be different in the western and eastern SWAN models. For the model covering the area west of the Isle of Wight, the tidal levels chosen were 2.0m and 0.5m above Chart Datum (CD) corresponding to the MHWS and MLWS levels at Bournemouth. For the eastern SWAN model the tidal levels chosen were 5.7m and 0.5m CD, corresponding to the MHWS and MLWS levels at Bognor Regis.

These water levels were applied uniformly over the respective model grid, and will be slightly different to the actual values of MHWS and MLWS at locations other than at Bournemouth or Bognor Regis. 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 “worse 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 listed in Tables 3 and 4 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 South Coast region. 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 also 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 240°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 240°N. Two further extreme 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 240°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 two SWAN models together with one of the assumed tidal levels (MHWS or MLWS) and for 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 wave heights throughout the model domain, Figures 7a and 7b present predictions of how the height of the 200 year return period wave condition arriving at MHWS from 240ºN will alter as it travels towards the coast. These two figures cover the western and eastern SWAN models respectively, and show results for the present day bathymetry. Figures 8a and 8b show results for the same incident wave condition and bathymetry but at MLWS.

Similar results have been obtained for all five of the incident wave directions considered (i.e. 120ºN, 150ºN, 180 ºN, 210 ºN and 240 ºN) for all three bathymetries and for both tidal levels. Figures 7a, 7b, 8a and 8b 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, particularly in Figures 7a and 7b. This is largely the result of refraction which causes the waves to turn and head more directly towards the coastlines of Poole Bay and the Isle of Wight. 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. The model shows the shelter provided by Durlston Head to Swanage Bay, and by The Needles to the eastern part of Christchurch Bay. In some areas, the effects of large sandbanks on waves passing over them can also be seen, particularly in Figure 8b in which the lower tidal level increases the effects of friction and wave breaking over these features. These changes are particularly noticeable to the north of Culver Spit, inshore of Medmery Bank and, most obviously, over the shallow seabed offshore from Selsey Bill called The Looe. Here a number of banks, extending for over 10km along the southern edge of The Looe, reduce wave heights very dramatically, and help protect the coastline from these exceptionally large waves almost as far east as Bognor Regis. This effect is less obvious when tidal levels are high (see Figure 7b).

Similar presentations of the spatial variations in wave height could be produced for all of the SWAN model runs, for example for the same incident wave conditions and tidal levels as shown in Figures 7 and 8 but for the Pre-dredging or the Post-dredging bathymetries. However, it is difficult to see the rather localised and modest changes brought about by aggregate dredging by comparing figures of this type.

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 SCDA region. Another advantage of this sort of presentation is that the difference plots from the eastern and western SWAN models can be combined to provide a single figure for the whole SCDA study region.

Before going on to present and discuss the predicted changes in wave conditions caused by aggregate dredging in this way, 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 Figures 7 or 8 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 2% are not shown on the figures showing these comparisons. However, bearing in mind the cautionary comments about the accuracy of predicting wave heights, there is also a need, in some areas, to supplement the percentage change figures with more detailed presentations of the computed wave height changes.

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 SCDA region would have altered the most extreme wave conditions considered in this study.

Figures 9 to 13 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 licensed or relinquished dredging areas. The figures indicate how much these extreme wave conditions might have changed within the study region as a result of past aggregate dredging.

A comparison of these figures shows that the largest percentage changes in wave heights are predicted for waves approaching from 240°N and 210°N, and this is as expected since it is from this sector that the waves approaching the study region are both largest and have the longest period (see Tables 3 and 4). 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 are generally limited to small areas within or just outside the boundaries of those areas. Note that, as mentioned earlier, these figures do not attempt to show percentage changes in wave height less than ± 2% 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 greater than ± 2%, these may be 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 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. This is particularly marked in and around dredging Area 122/2, which lies 4km due south of the entrance to Langstone Harbour. Here, the seabed has been lowered by aggregate dredging, albeit very locally, by up to 15m (see Figure 4). Water depths, at lowest tidal level, have changed from less than 20m to more than 30m in parts of the south-eastern corner of this area. This very large increase in the initial water depths will have caused significant changes in waves passing over this area, not only by refraction but also by reducing the frictional dissipation of wave energy at the seabed. Such dissipation has little effect on waves in water depths greater than about 30m in this study region, but becomes more important closer to the coast.

Even for this area, however, changes in wave height greater than about 3% do not extend very close inshore, except when waves approach from 120°N and 150°N (see Figures 9 and 10). It should also be borne in mind that the actual changes in wave heights in and around this area are very modest, even in such an extreme situation. Figure 14 compares the percentage wave height changes in and around Area 122/2, as shown in Figure 9, with the **absolute** changes in wave height (in metres) predicted using the SWAN model.

Before any aggregate dredging, the significant wave height in and around Area 122/2, for this combination of extreme wave condition and low tidal level would have been about 2m. The predicted change of about 3% shown in Figure 9 therefore corresponds to a predicted increase of about 6cm in the significant wave height due to past aggregate dredging. Certainly such a change would not be measurable, and it is unlikely that the SWAN model results can be relied upon to accurately predict such a small absolute change in wave height.

Therefore, even considering the extremely rare and severe wave events used to produce Figures 9 to 13 and assuming that they coincided with low water on a spring tide, it is considered there could have been no significant effect on wave conditions along the coast of the study region as a result of past aggregate dredging. During such a very exceptional event, however, there would have been more noticeable changes in wave heights within or very close to the boundaries of Area 122/2 as a consequence of past dredging there.

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. These results are presented in Figures 15 to 19. The predicted changes in wave heights along the coastline of the study region during such severe events are clearly of relevance to the design and performance of coastal defences, and in that context any changes in wave conditions caused by aggregate dredging would be of particular interest to coastal local authorities. However, these figures show that changes in wave heights are predicted to extend outside the boundaries of only one of the dredging areas, Area 122/2. Even in this case, changes of greater than 3% hardly extend landwards of that area. There is therefore no evidence of any changes in wave conditions along the coastlines of the study region in these important, if very extreme, combinations of a high tidal level and 200 year return period wave conditions, and very little of changes outside the dredging areas themselves.

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

Exactly the same techniques 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 proposals of the SCDA members for possible future extraction.

As pointed out in Section 2.3, in total the amount of dredging within the whole of the SCDA region shown in Figures 3 and 5 is much greater than could realistically be expected to have taken place by about year 2030.

However in any individual area, the changes in bathymetry that were made (see Figures 3 and 5) 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 changes in wave conditions in and around any individual area that have been predicted in this study may be realistic, although they might be over-estimated for other licence areas. The modelling therefore allows SCDA 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.

Indeed, during the course of this regional wave modelling study, the future plans for dredging in three of the areas just to the east of the Isle of Wight, and west of Selsey Bill, were altered to avoid causing potentially unacceptable changes in wave heights along the coastline of the eastern arm of the Solent. The results discussed below are those obtained following the revisions of the future dredging plans in those three specific licence areas. The results from the SWAN modelling of the effects of both past and planned future dredging are presented in Figures 20 to 30.

However, despite considering very severe wave conditions at a low tidal level and the over-estimation of the total amounts of sand and gravel that might be removed, in most areas the SWAN modelling generally predicts no significant changes in wave conditions as a result of this planned future dredging. In these areas, 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 will be the same or smaller than predicted in this study.

Figures 20 to 24 show predictions of percentage wave height changes for the same extreme (i.e. 200 year return period) wave conditions and the same low tidal level, i.e. MLWS, as used to produce Figures 9 to 13. The changes shown in these figures have been calculated by differencing those wave heights predicted for the future post-dredged bathymetry from the situation before dredging in any of the aggregate extraction areas in the study region. Hence Figure 20 shows not only the effects of past dredging on extreme waves approaching from 120°N (as shown in Figure 9) but the additional affects of planned future dredging as well.

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 input of energy by winds in areas where the wave heights are smaller.

In these model runs, some effects of wave reflection (see Section 2.1.1) from the dredging areas can also be detected, especially around the dredging areas just to the east of the Isle of Wight. The differences in the spatial extent and magnitude of increases in wave heights on the "up-wave" sides of the dredging areas, and the corresponding decreases on the opposite sides of the dredging areas can be seen, for example, by comparing Figures 20 and 26 with Figures 24 and 30. In the former two figures, wave heights are predicted to increase lie to the east (and landward) close to dredging areas, while the zones where wave heights are predicted to decrease lies to the west. This is consistent with some of the incident wave energy approaching from the south and east being reflected from the eastern edges of the dredging areas.

The situation is reversed in Figures 24 and 30 where any increase wave height tends to be to the west (and landwards) of the dredging area, reflecting the approach of waves from the south and west. As some of the incident wave energy is reflected, the areas of a predicted decrease in wave heights tend to be to the east and landwards of the dredging areas. As would be expected, the effects of this partial reflection are greater and hence easier to see for the longest period waves, i.e. those approaching from 240°N. Figure 24 (for MLWS) and Figure 30 (for MHWS) show the results for these waves approaching from the south-west and show stronger evidence of wave reflections than when waves approach from the south-east (e.g. Figures 20 and 26).

Unlike the results for past dredging, where any significant changes to wave conditions are only localised, Figures 20 to 30 also indicate more noticeable cumulative effects on waves as they cross several dredging areas on their way towards the coast. In the clusters of dredging areas closest to the east coast of the Isle of Wight and those offshore between Bognor Regis and Worthing, changes in wave conditions that start in one area extend landwards into other extraction areas where dredging changes them further.

However despite the over-estimation of the overall amounts of future dredging that might be applied for in the SCDA region, the predicted changes in wave heights close inshore are generally still very small.

Some of the results presented in Figures 20 to 24, and similar figures produced assuming a high tidal level (see Figures 26 to 30), show predictions of small changes in extreme wave conditions close to the eastern and north-eastern coastlines of the Isle of Wight and from Portsmouth to Hayling Island on the mainland. For the most part, however, the magnitude of these changes is still less than 3%, i.e. below the likely limit of accuracy of the SWAN modelling results. Where there are changes greater than this, they are either close to the edges of the dredging areas or, less frequently, at isolated locations outside the general pattern of changes that the model predicts. Where changes are predicted at isolated spots well away from the dredging areas, for example off the entrance to Chichester Harbour, they are a consequence of inaccuracies in the SWAN model calculations, for example due to rounding and truncation errors, rather than being genuine change in wave conditions.

To put some of the largest predicted changes into context, some of the percentage changes in wave heights presented in Figure 24 are compared with the absolute changes in wave height in Figure 25. Both panes in this Figure show results obtained for the 200 year wave condition approaching from 240°N at MLWS, and cover in more detail a small part of the overall study region, i.e. part of the East Solent to the west of Selsey Bill. Even for this very severe combination of extreme wave conditions and low tidal level, changes in wave height of 10cm or more are restricted to the dredging areas themselves or to a restricted zone not extending very far landwards from their boundaries. These changes might be of concern if, for example, there were existing features of interest or planned developments within these zones. In this situation, it might be necessary to investigate changes in wave conditions in greater detail before applying for an extraction licence for the particular area implicated (Area 122/2). Taking a wider perspective, however, there is no prospect of the changes predicted in Figures 20 to 24 resulting in measurable changes in wave conditions along any coastline or having any effect on coastal defences or beaches.

For all the other areas considered in this regional assessment, the wave modelling indicates that even considering all the future plans for aggregate dredging together with that already undertaken, there are unlikely to be any significant effects on wave conditions close to any of the coastlines between Durlston Head and Brighton.

Any predicted changes in wave heights of greater than 2% hardly extend beyond the boundaries of the individual dredging areas to the west of the Isle of Wight. The predicted changes in and around the dredging areas on the Owers banks south of Worthing extend a little further towards the coast but reduce to insignificant levels a considerable distance offshore from it.

As would be expected, the predictions of changes in wave conditions at the time of high tide, shown in Figures 26 to 30 generally show the effects of aggregate dredging (both past and present) are smaller and cover a lesser area than the corresponding predictions at MLWS (presented in Figures 20 to 24).

However, this general pattern is not observed when comparing the results presented in Figures 24 and 30. These two figures both show results for an extreme wave condition (200 year return period) approaching from 240°N, and consider the effects on those waves of all past and planned future dredging. In the area just to the east of the Isle of Wight, Figure 30 shows the percentage changes in wave height are fractionally larger and extend somewhat further outside the dredging areas at MHWS than at MLWS (see Figure 24). Even so, there are no changes greater than 3% anywhere close inshore or along the coastlines of the eastern Solent. The same general remarks as made above about the potential significance of changes in wave height under the exceptional conditions considered still apply.

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 SCDA region would be affected by considering more extreme wave conditions than the 200 year return period waves used to produce Figures 9 to 30. 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 240°N since this was expected to show the greatest changes in wave conditions. The results from this modelling are presented in Figures 31 and 32, which show the percentage wave height changes that have been predicted to be caused first by all the past dredging (Figure 31) and then by both this past dredging together with all currently planned future dredging in the SCDA region (Figure 32).

Figure 31 presents the percentage changes in height that would be caused by past aggregate dredging in the SCDA region under this "future extreme" wave condition. To adopt a cautious approach, we have run this simulation at the low tidal level. The results obtained do not significantly differ from those produced for the present-day 200 year return period waves from the same direction (see Figure 13).

Figures 24 and 32, respectively, show the results at MLWS for the present-day and future 200 year return period waves approaching from 240°N. Comparing these, Figure 32 shows that there would be an increase in the extent of wave height increases near some of the dredging areas under the "future extreme" condition. However, in and around most areas, the changes even for this future "worst case" comparison are very modest. On the basis of this sensitivity testing, as recommended by the UK Government for the design of coastal defences, there is no reason to expect global warming to alter the effects of aggregate dredging on wave conditions along the coastlines of the SCDA region.

It should be noted that no account has been taken in this modelling of the expected increase in mean sea level in the SCDA 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 if sea levels were higher. The effects of dredging on the extreme future wave conditions will therefore be somewhat less than shown by the model results shown in Figures 31 and 32.

It should also be remembered that a conservative representation of the overall future extraction plans has been adopted, in which the total amounts of aggregate extraction from the study region has been over-estimated. If any predicted changes in wave conditions in and around a particular dredging area (or areas) are of concern, then the SCDA members have the option of adjusting their dredging plans for that area (or areas) before submitting a formal application for an extraction licence, whether for a new area or to allow further dredging within an existing licensed area.

In summary, therefore, even by considering a very severe combination of a low tidal level and wave conditions expected to recur, on average, once in 200 years, there is no reason to believe that a hypothetical increase in storm wave conditions following global warming would alter the conclusions drawn about the effects of dredging on wave conditions in the study region.

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, 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 240°N, since the largest and longest period waves arrive from this sector and these experience the largest changes in the wave conditions over the dredging areas. Considering just wave conditions arriving from this sector, we then selected a wave height that was only equalled or exceeded 5% of the time. 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 combination of direction, height, period and wind speed was then used as the input wave condition for three further SWAN model runs, i.e. for all three bathymetric scenarios at the lower tidal level. Table 5 shows the corresponding wave parameters used for modelling this 5% exceedence condition within the western and eastern SWAN model grids.

Table 5 5% exceedence wave conditions used in SWAN model

	Direction (ºN)	Wind speed (ms^{-1})	Significant wave height (m)	Peak wave period (s)
Western SWAN model grid	240	15.1	3.1	6.3
Eastern SWAN model grid	240	15.5	3.2	6.4

Figure 33 shows the predictions of the percentage changes in wave height under this condition as a result of past dredging in the region. The changes in wave heights predicted are very modest save in the vicinity of Area 122/2 where changes of greater than 2% extend a considerable distance inshore.
Figure 34 shows the predicted changes in heights at MLWS for this same more-frequently occurring wave condition, taking into account all past and proposed future dredging, and comparing this with Figure 33 demonstrates the potential effects of future dredging to be much more substantial than for that already undertaken. However, while modest percentage changes in this wave condition look to be very widespread and of potential concern, the actual changes in wave height are not very large. Figure 35 presents an enlargement of Figure 34 in and around Area 122/2 alongside an alternative presentation of the actual values of the predicted wave height differences. This shows that percentage wave height increases along the coastline between Portsmouth and Hayling Island might exceed 2% under this wave condition but the changes in height are less than 2cm. It should be remembered that the results shown in Figures 33 to 35 have been produced assuming a low tidal level, to err on the side of over-estimating the changes caused by dredging. From the viewpoint of coastal defences, it would be the changes in wave conditions at high tide levels that would be of concern, and at this state of the tide the changes would be smaller than shown in these figures.

It is concluded from these results that the small change to more frequently occurring wave conditions caused by future aggregate dredging are only likely to have a potential effect on hydrodynamics or seabed morphology within or very close to the dredging areas themselves. This in turn is unlikely to result in a significant change in the existing environment unless there are features of interest or planned developments very close to the boundaries of the dredging areas. In this case, such changes would need to be investigated in more detail at the time of submitting an application for an extraction licence for the specific dredging area giving rise to the changes in wave conditions.

4. Aggregate dredging and In-combination effects

Aggregate dredging is only one of many human activities that affect the physical environment of the shorelines and offshore waters of the central South Coast region of England. 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 very significant changes in waves, currents and sediment transport rates locally, leading to changes in the nearshore seabed; and
- The seabed in the study region is crossed by cables, and outfalls etc, and these both affect and are affected by waves, tides and sediment transport processes.

In the future, there may be other developments in the study region, for example the installation of wind turbines. For some of these existing and potential further 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. For some of the licensed dredging areas closest to the east coast of the Isle of Wight, however, the changes in wave heights during exceptionally severe storm conditions do extend a noticeable distance outside these areas, particularly at times when tidal levels are low.

Overall, it is reasonable to conclude from this study that 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 application areas offshore of the South Coast between Durlston Head and Brighton and calculated their cumulative effects on waves travelling towards the coast. In carrying out 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 South Coast region, 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 Area 122/2, which lies 4km due south of the entrance to Langstone Harbour. For this area, our modelling indicates that changes in wave heights, for the most pessimistic wave and water level combination tested, might be between 2% and 3% even as far away as the coastline between Southsea and Hayling Island. However, the actual changes in significant wave heights close inshore would be smaller than 5cm and very difficult, if not impossible to measure.

At higher tidal levels, under the same extreme wave conditions, the modelling shows that the changes brought about by past dredging are generally smaller and even more restricted in spatial extent. It would be this combination of waves and tidal level that is of greater concern from the viewpoint of the design or performance of coastal defences. Again, however, the predicted changes in wave conditions in and around Area 122/2 are noticeably greater than for the other dredging areas. Changes close to the coastline between Southsea and Hayling Island are very small.

It can be safely deduced that changes in less severe but more frequently occurring wave conditions will have been 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 any changes in the wave climate in any part of the study region as a result of past aggregate dredging except perhaps within, or closer than a few hundred metres beyond the boundaries of the licensed dredging areas themselves.

5.2 PREDICTED EFFECTS ON WAVES OF FUTURE DREDGING

Our modelling then went on to consider the possible future effects of aggregate dredging on waves travelling across the study 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 cumulative effects on waves of all past and future dredging.

In some of the areas, current plans for future extraction could 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 most pessimistic situation considered, i.e. of very severe waves arriving at low tide. However, as found when considering the effects of past dredging alone, changes in waves caused by past and future extraction in some of the dredging areas, for example to the west of the Isle of Wight, were small and very restricted in extent outside the boundaries of those areas.

The predicted changes caused by planned future dredging to the east of the Isle of Wight, where the natural water depths are shallower, were found to be larger, particularly in the cluster of extraction areas closest to the east coast of the Isle of Wight and south of the coastline between Southsea and Selsey Bill. Indeed, during the course of this regional wave modelling study, the future plans for dredging in three of these areas were revised, to avoid causing potentially unacceptable changes in wave heights along the coastline of the eastern arm of the Solent. The conclusions presented here are based on the results obtained following the reductions in the future dredging plans in those three specific licence areas.

Even with these changes, the SWAN modelling predicted that rather larger and more widespread changes in wave heights may occur in future than have been caused by past aggregate dredging. However, despite considering very severe wave conditions at a low tidal level and the over-estimation of the total amounts of sand and gravel that might be removed, in most areas in the study region, there will be no detectable change in wave conditions as a result of this planned future dredging. In these areas, it can be safely deduced that if, as expected, the amounts dredged turn out to be less than assumed, then the actual changes in waves will be the same or smaller than predicted in this study.

Future extraction, especially to the east of the Isle of Wight, can be expected to result in a greater amount of wave reflection at the edges of the licence areas than has been caused by past dredging. Also, there will be cumulative effects on waves as they cross several dredging areas on their way towards the coast. In the clusters of dredging areas closest to east coast of the Isle of Wight and those offshore between Bognor Regis and Worthing, changes in wave conditions that start in one dredging area extend landwards into other extraction areas where dredging changes them further.

However despite these greater changes, which in part are exaggerated because of the over-estimation of the total amounts of future dredging that might be applied for in the SCDA region, the predicted changes in wave heights close inshore are generally still very small. The greatest changes are predicted to occur at low tide close to the eastern and north-eastern coastlines of the Isle of Wight and from Portsmouth to Hayling Island on the mainland. Even taking the worst-case scenario considered, however, the changes in wave height are still less than 3%, i.e. smaller than the likely limit of accuracy of the SWAN modelling itself. As discussed in section 5.1, the greatest changes to waves after proposed future dredging has been carried out are predicted in and around the Area 122/2, which lies 4km due south of the entrance to Langstone Harbour. However, the actual changes in significant wave heights close inshore would be smaller than 5cm even in the severe wave conditions tested and very difficult, if not impossible to measure.

Closer to the boundaries of the dredging areas in shallowest water, the changes in wave height in extreme wave conditions are larger, especially to the north and east of those areas. If there are planned developments or features of particular interest close to the boundaries of such areas, these changes in wave conditions may be of importance. This study has identified where such changes may occur, and this will be helpful when considering whether more detailed studies need to be carried out as part of the site-specific Environmental Impact Assessment for individual licence applications.

To put these results into context, it must be noted 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. When more frequently occurring and less severe wave conditions were modelled they were scarcely altered by the combination of past and planned future dredging, even at Mean Low Water Springs.

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, as a result of the 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 in line with expected sea level rise. This assumption would have decreased the predicted effects of dredging on future 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 reached.

In summary, even by taking this exceptionally precautionary approach, there is no evidence that the combination of past and future dredging in the South Coast region 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 could significantly affect wave conditions along or just offshore of the coastline between Durlston Head and Brighton, or further afield.

6. References

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Figures

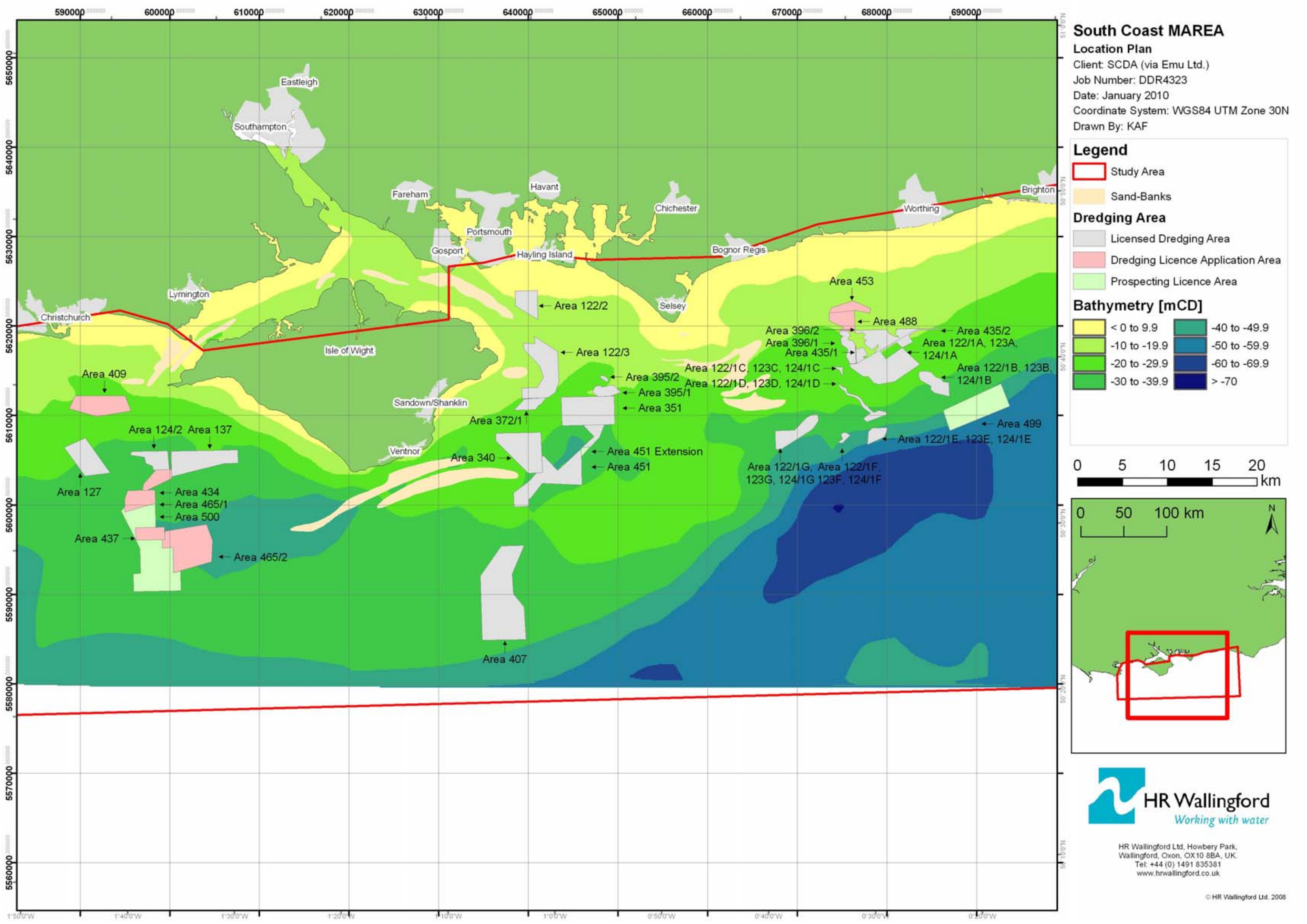

Figure 1 Location plan showing study region and aggregate dredging areas

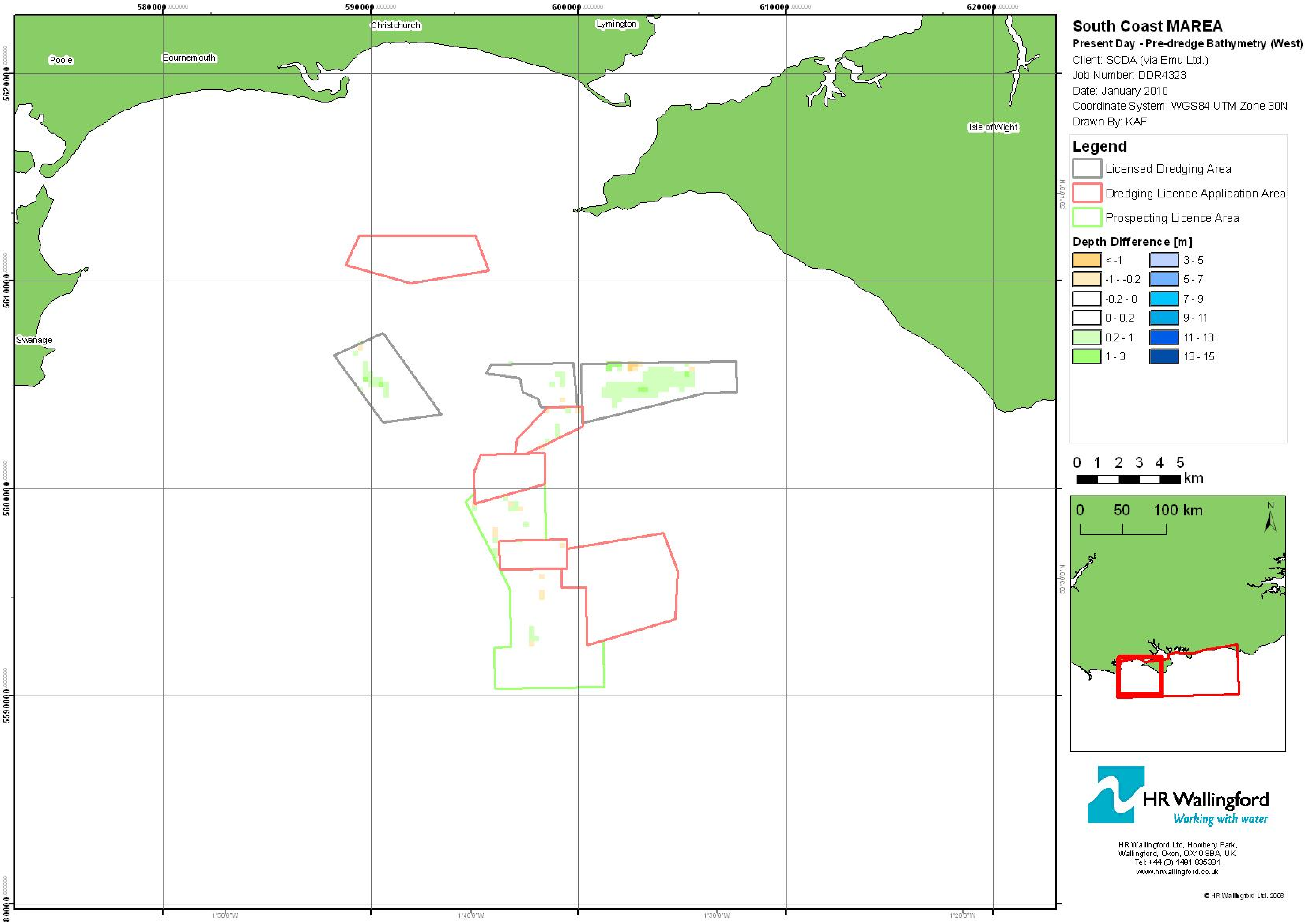

Figure 2 Past depth changes in existing licensed dredging areas west of the Isle of Wight

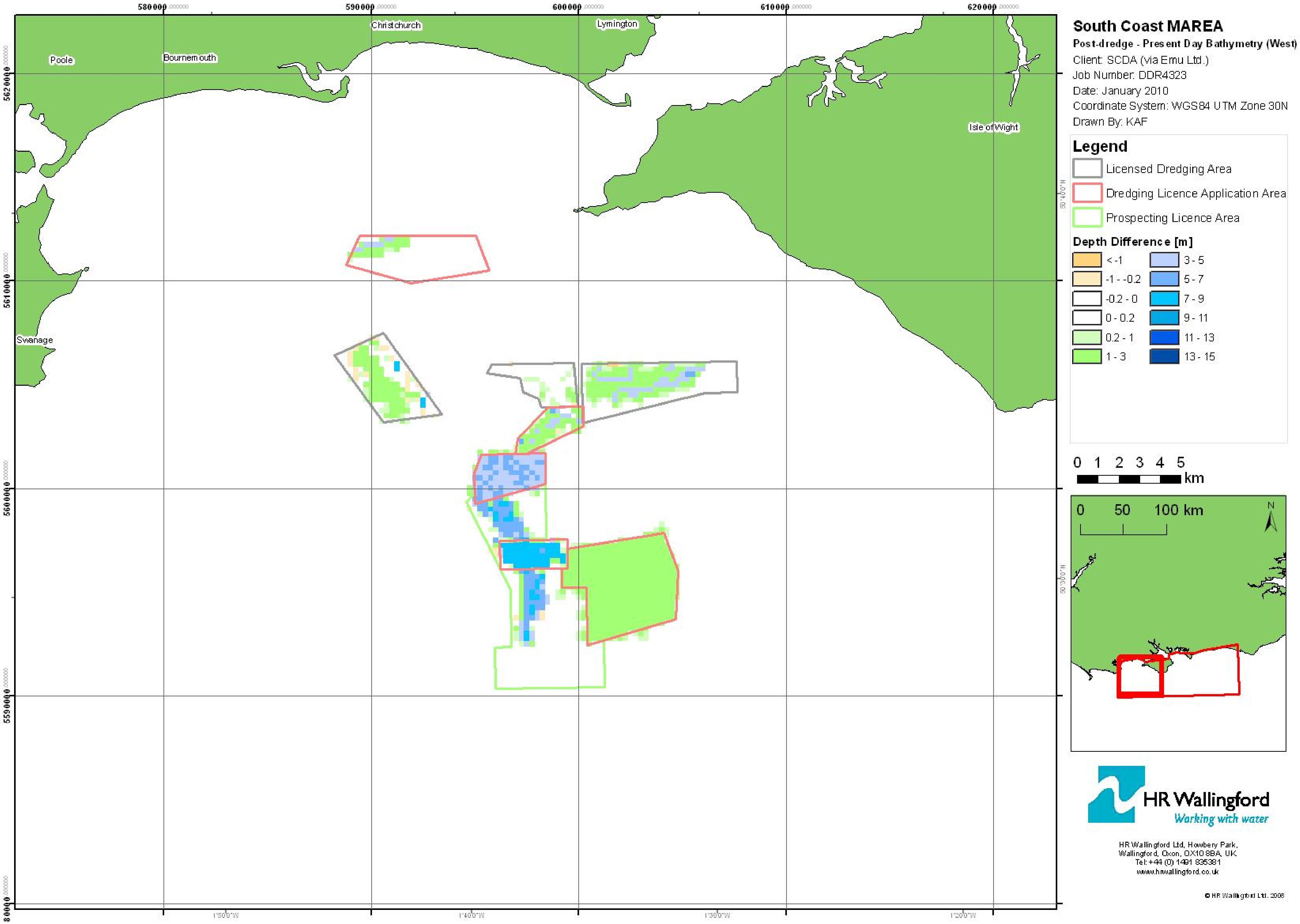

Figure 3 Plans for future depth changes in aggregate dredging areas west of the Isle of Wight

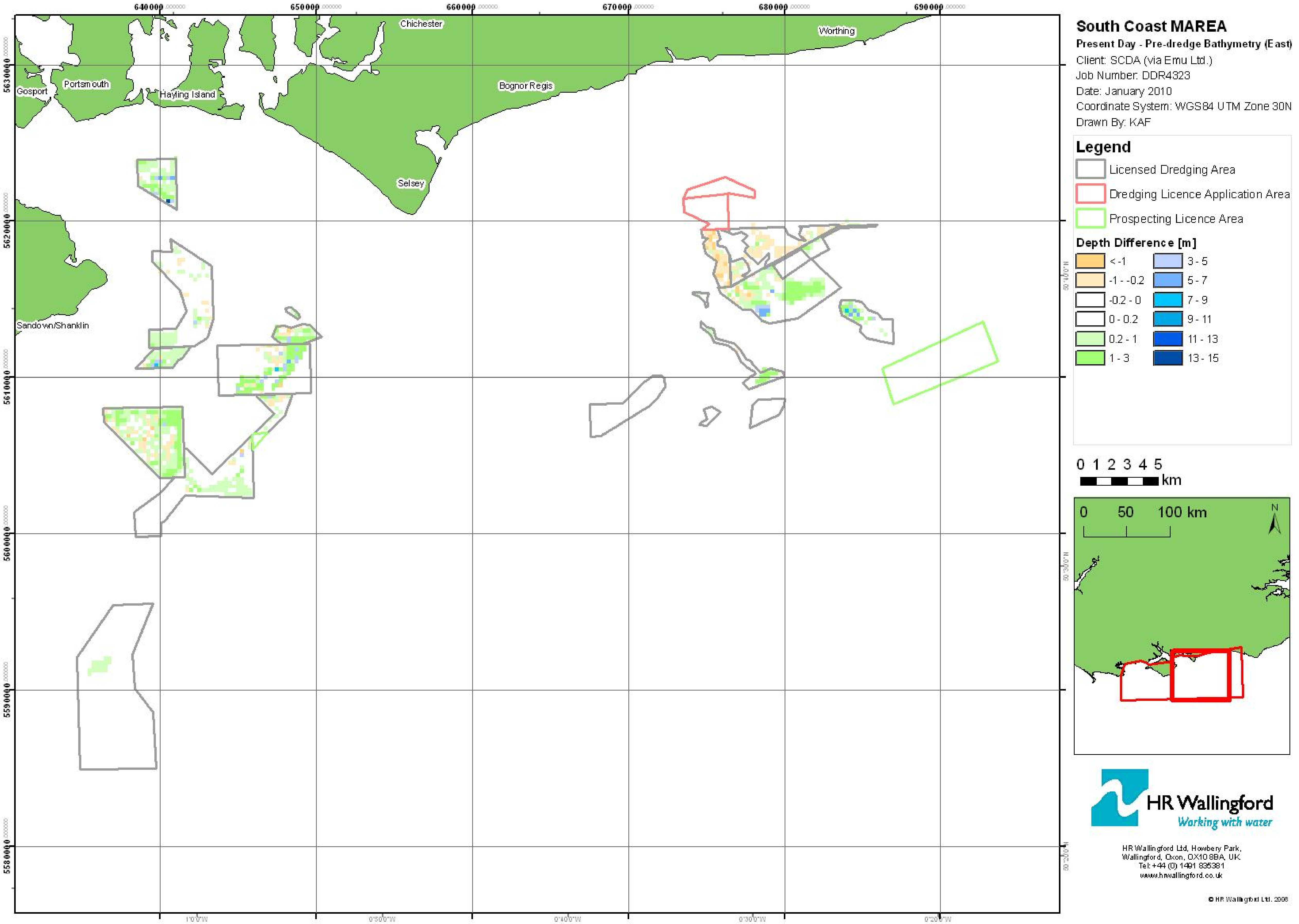

Figure 4 Past depth changes in existing licensed dredging areas east of the Isle of Wight

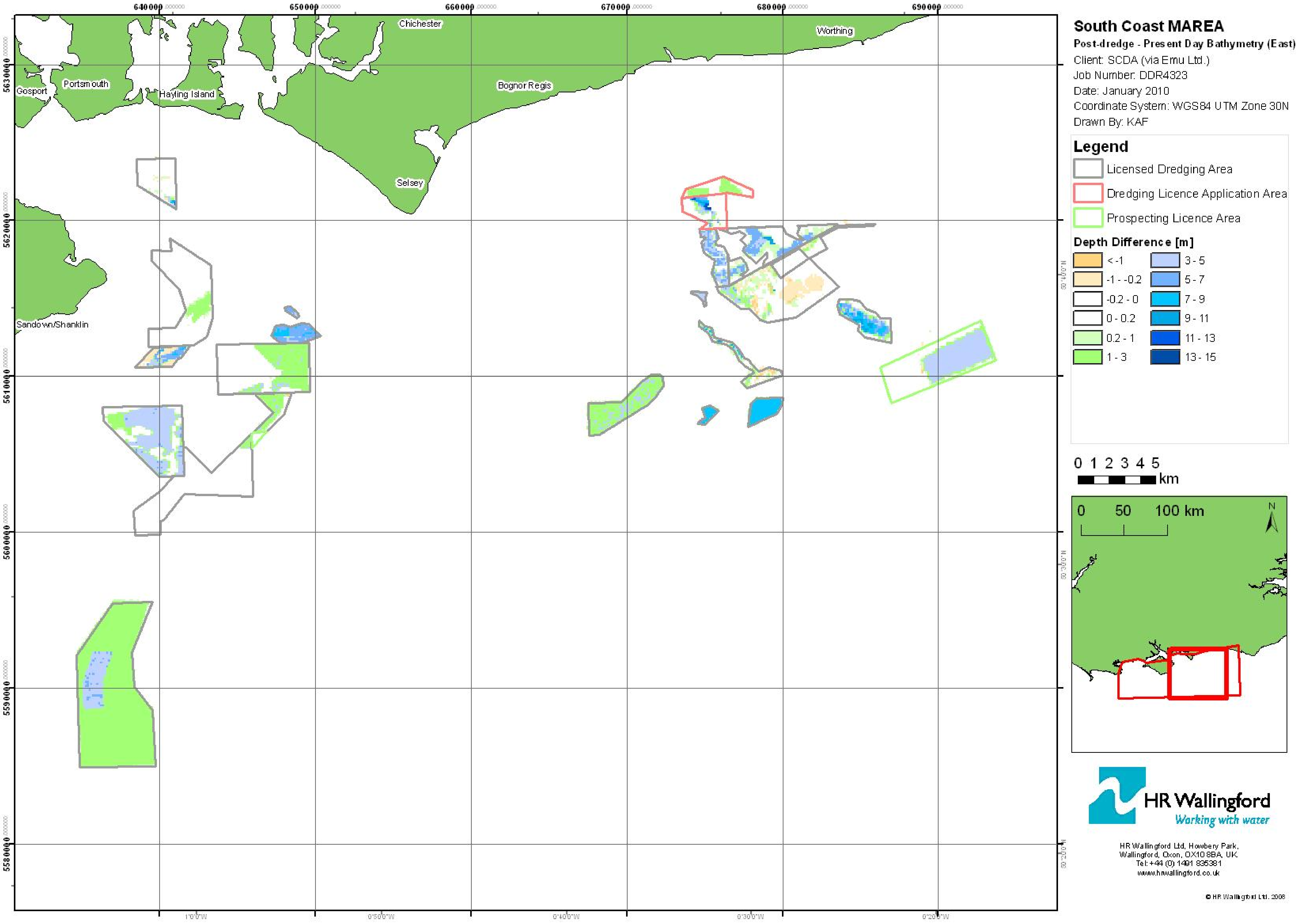

Figure 5 Plans for future depth changes in aggregate dredging areas east of the Isle of Wight

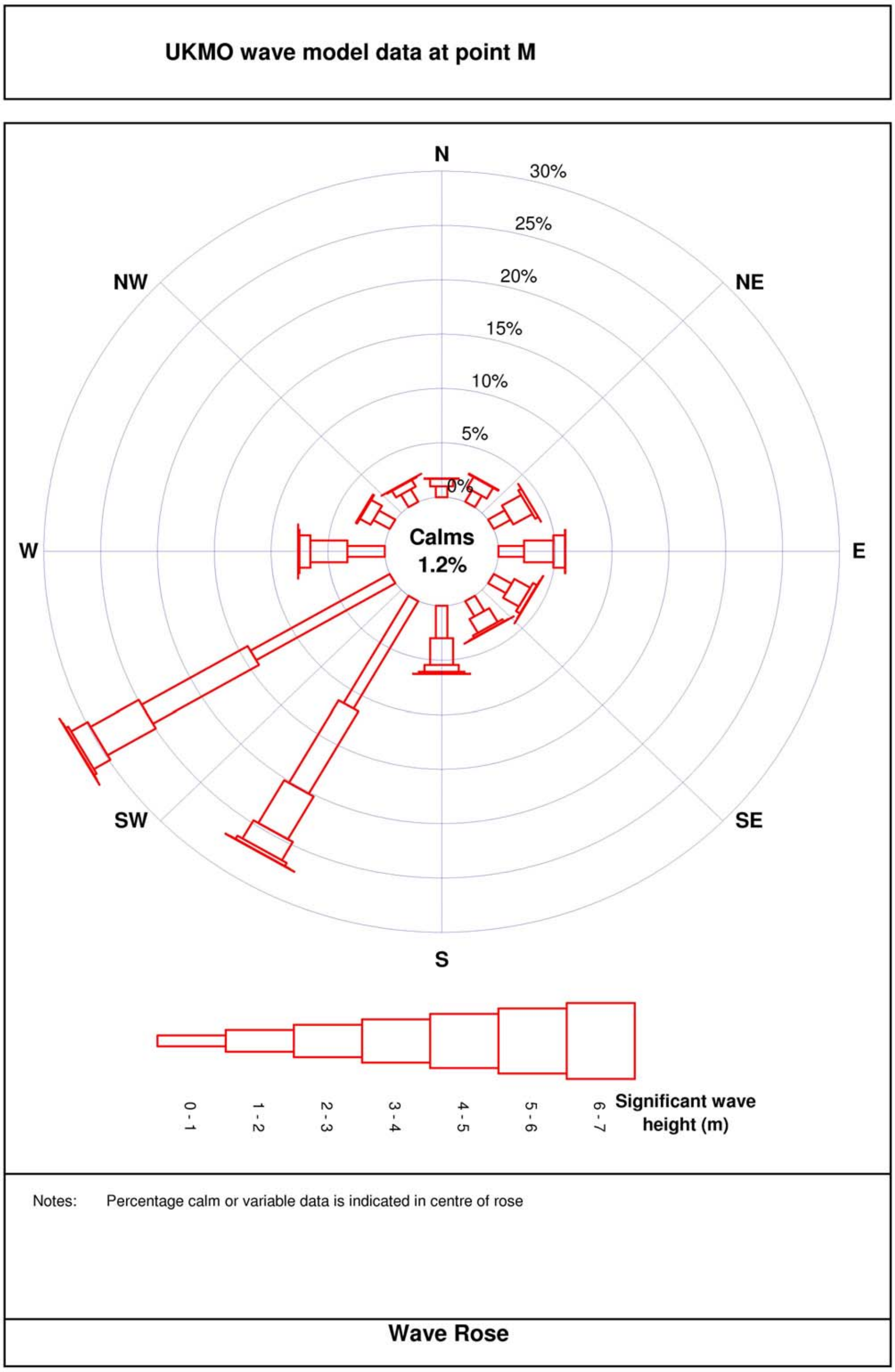

Figure 6 Wave rose showing wave climate at Point M at seaward edge of the study region

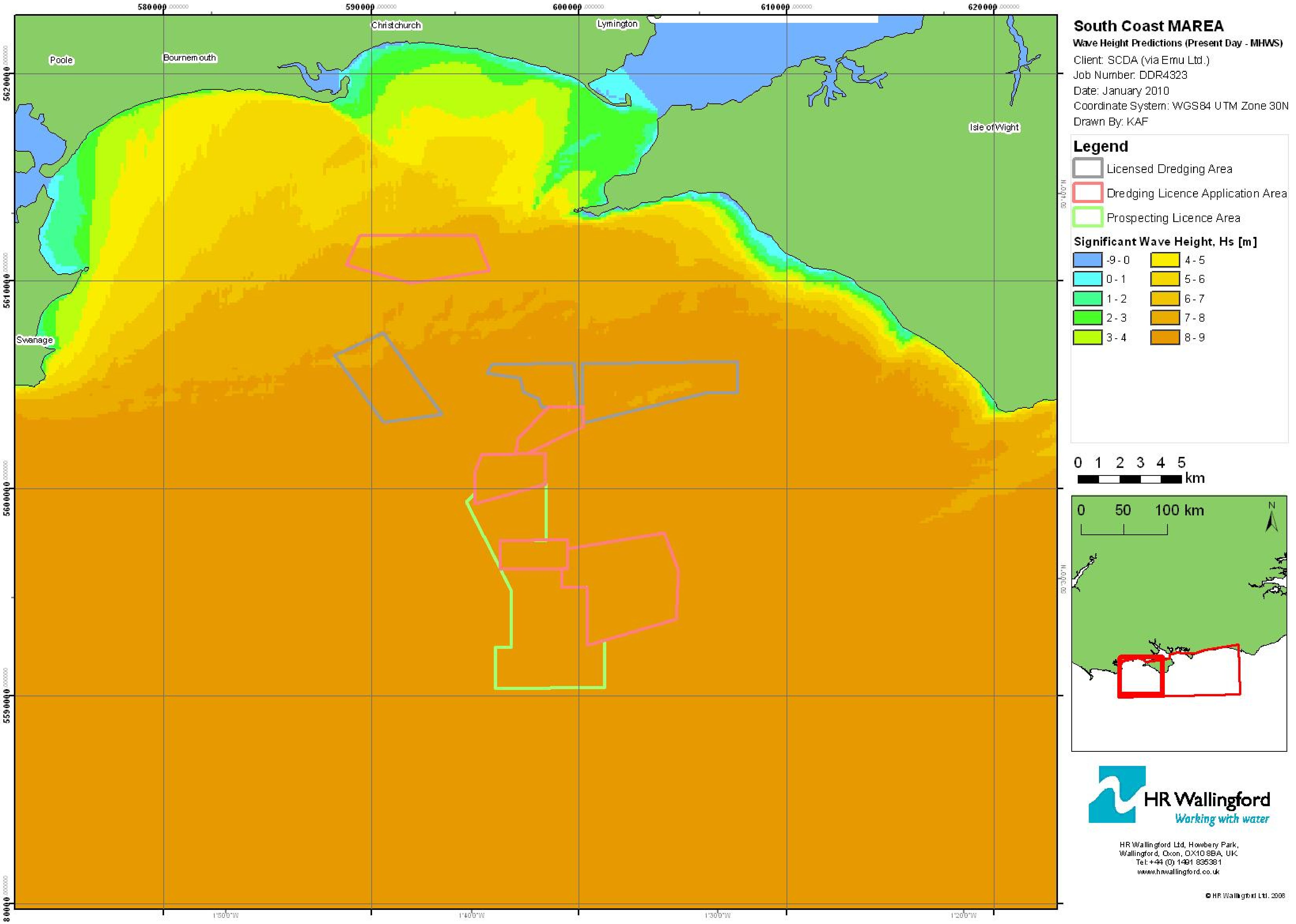

Figure 7a Wave height predictions for a 200 year return period wave condition from 240°N at MHWS (present day bathymetry) for areas west of the Isle of Wight

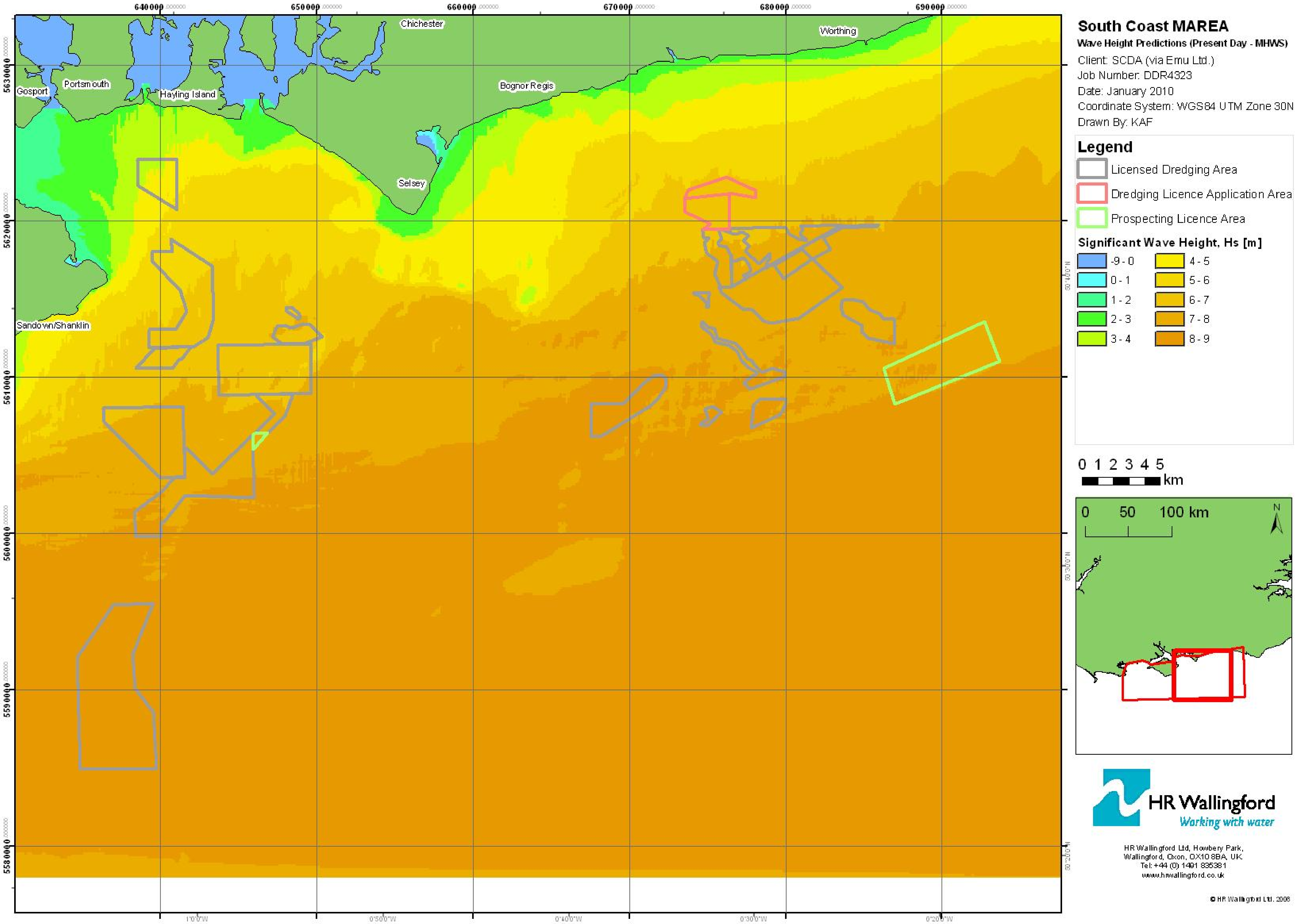

Figure 7b Wave height predictions for a 200 year return period wave condition from 240°N at MHWS (present day bathymetry) for areas east of the Isle of Wight

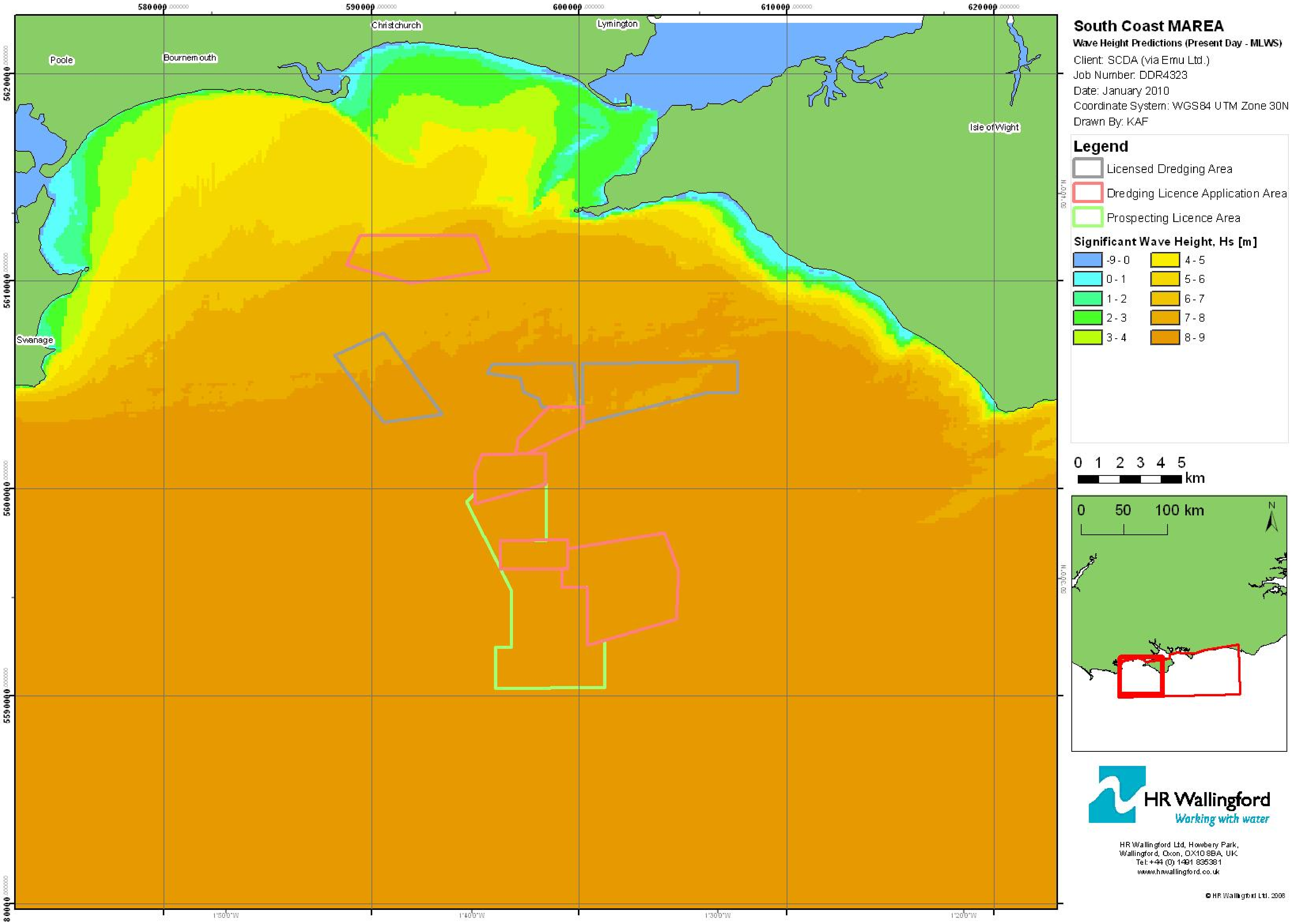

Figure 8a Wave height predictions for a 200 year return period wave condition from 240°N at MLWS (present day bathymetry) for areas west of the Isle of Wight

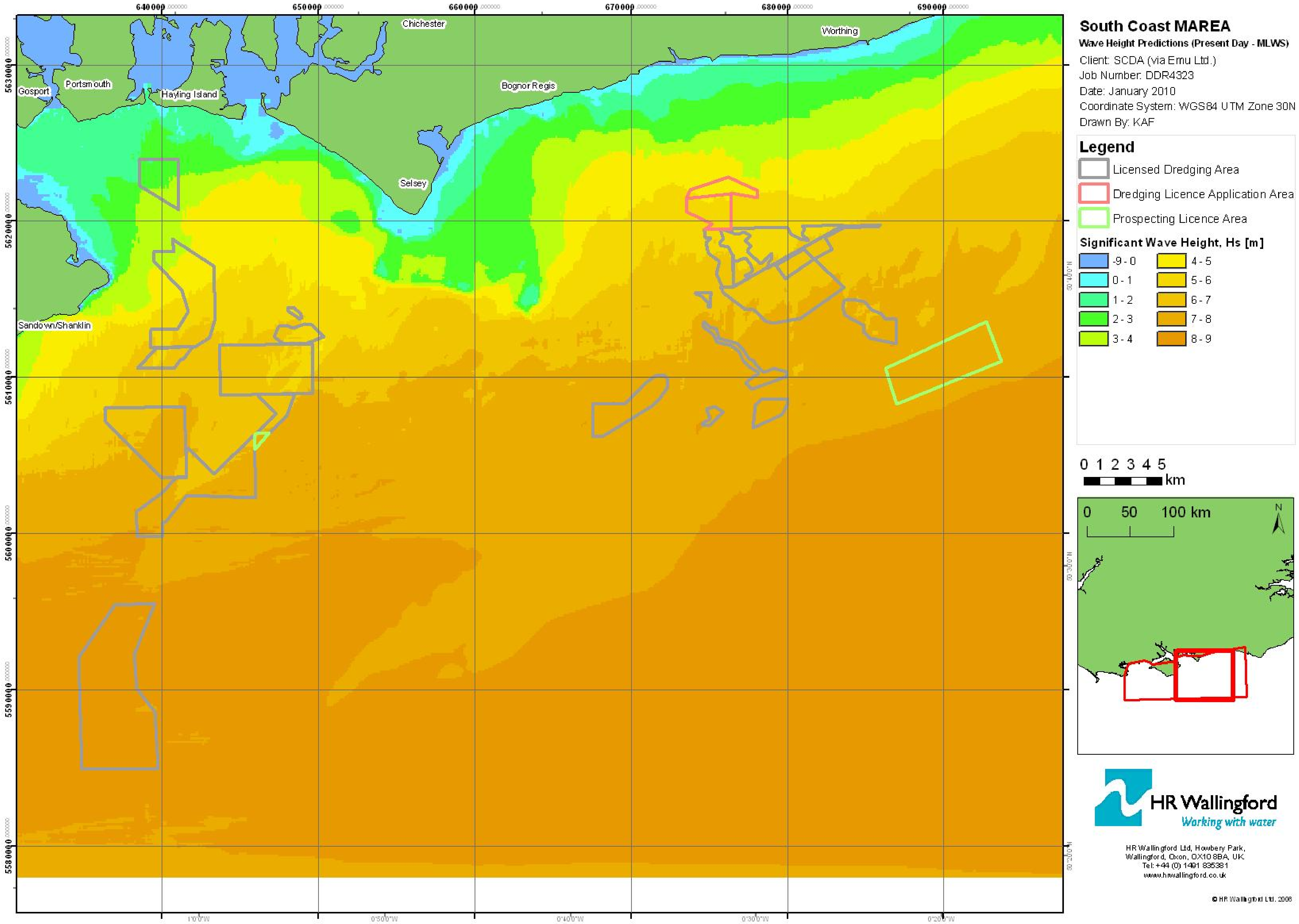

Figure 8b Wave height predictions for a 200 year return period wave condition from 240°N at MLWS (present day bathymetry) for areas east of the Isle of Wight

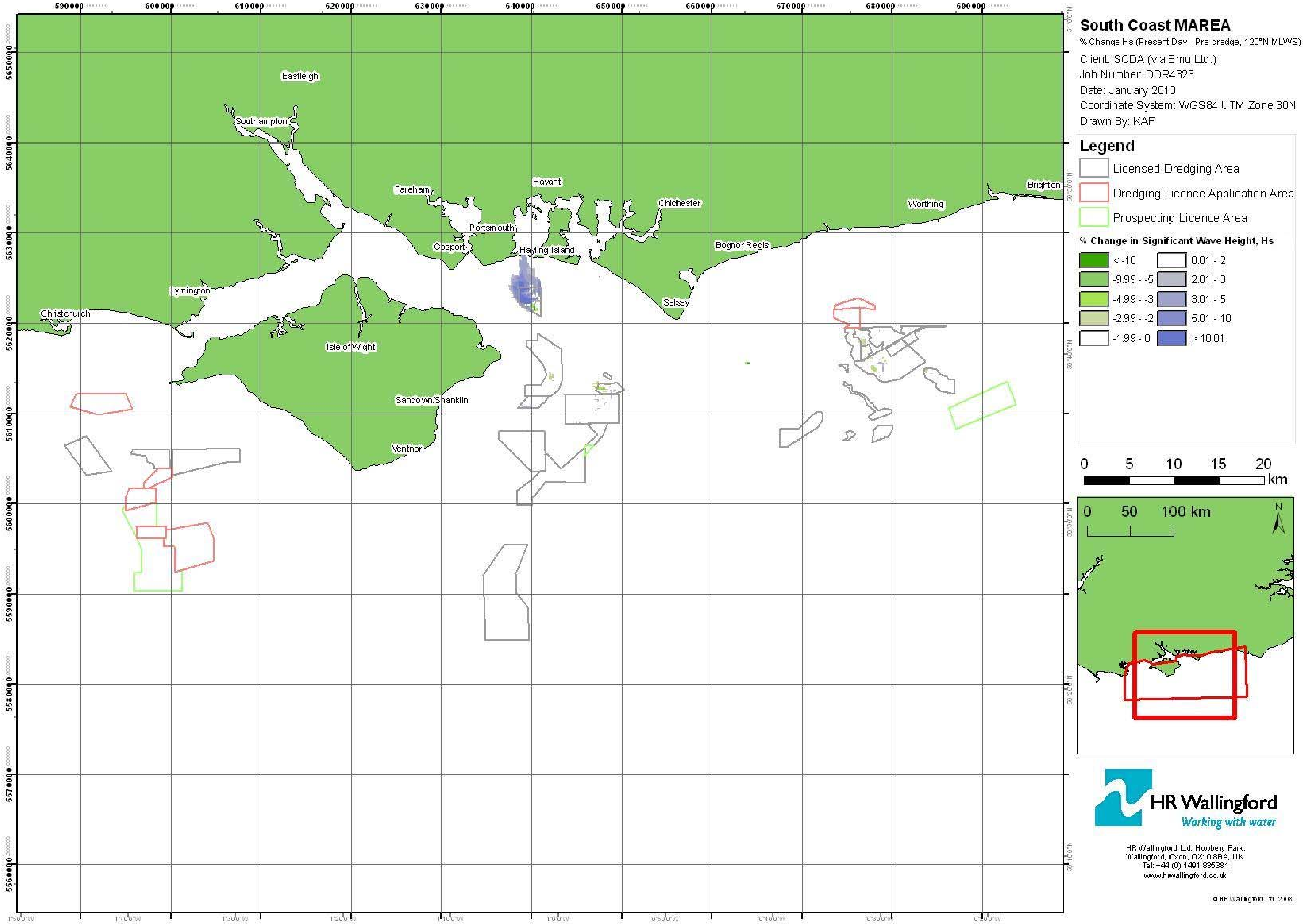

Figure 9 Changes (%) in wave height due to past dredging for 200 year return wave condition from 120ºN at MLWS

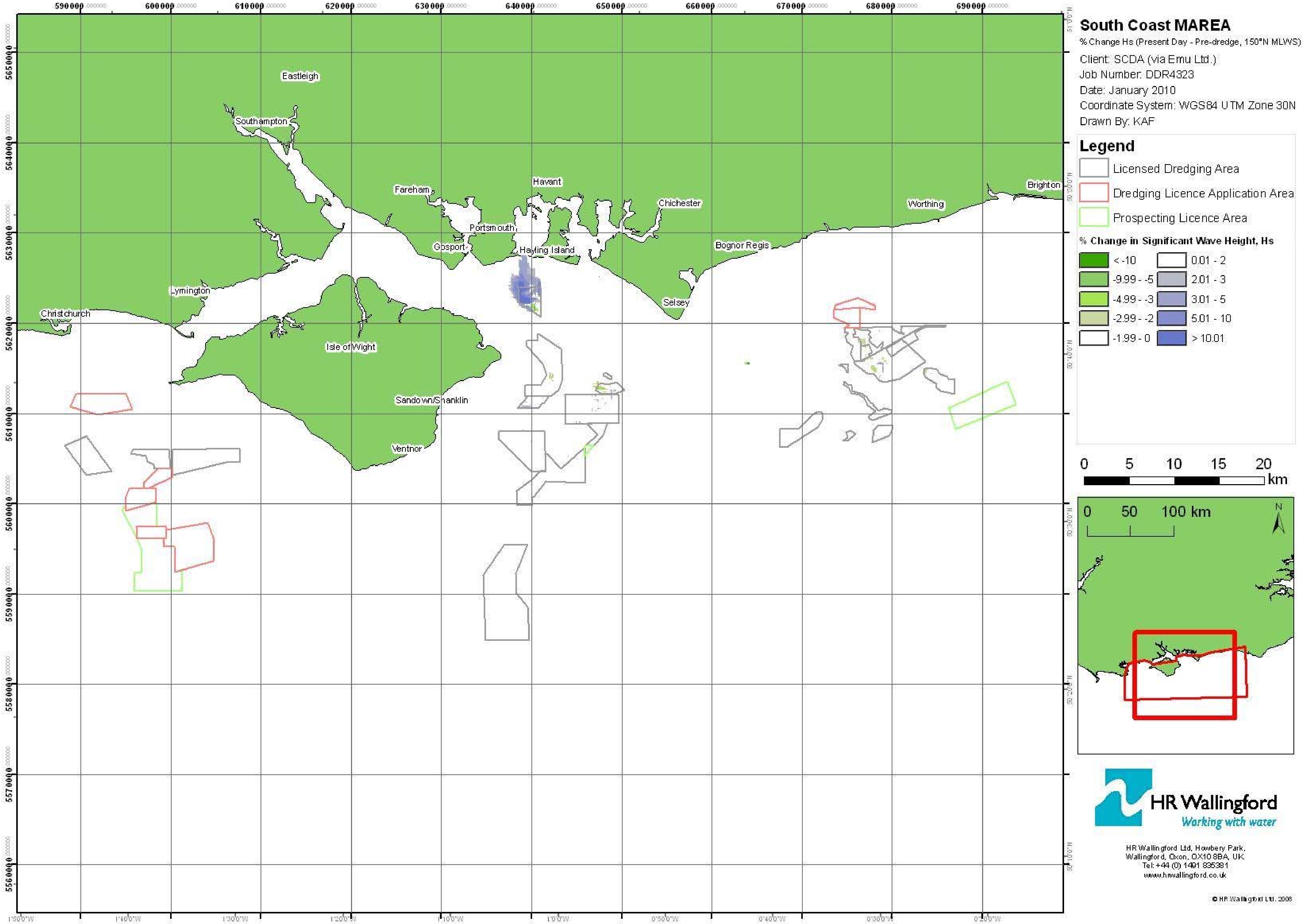

Figure 10 Changes (%) in wave height due to past dredging for 200 year return wave condition from 150ºN at MLWS

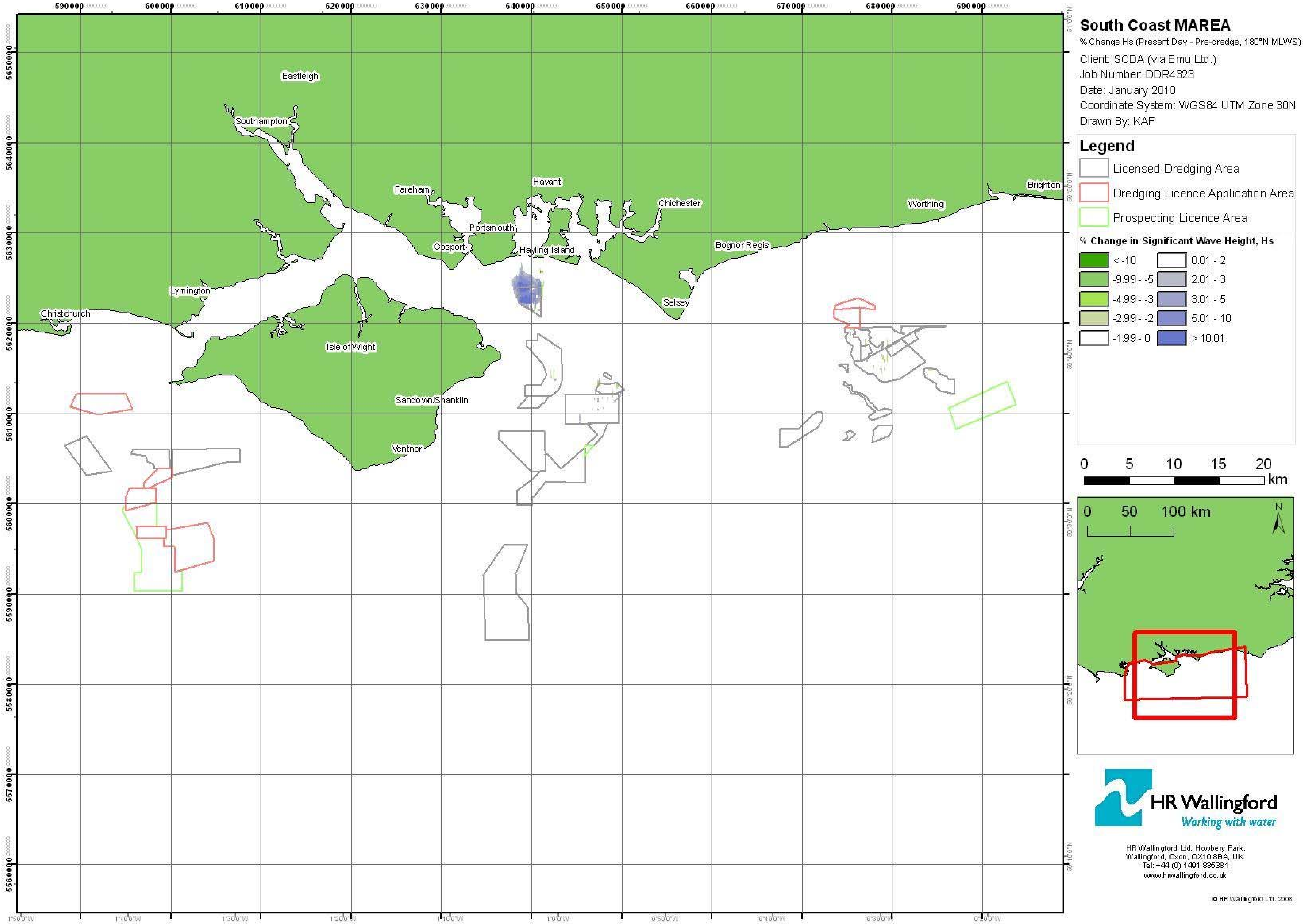

Figure 11 Changes (%) in wave height due to past dredging for 200 year return wave condition from 180ºN at MLWS

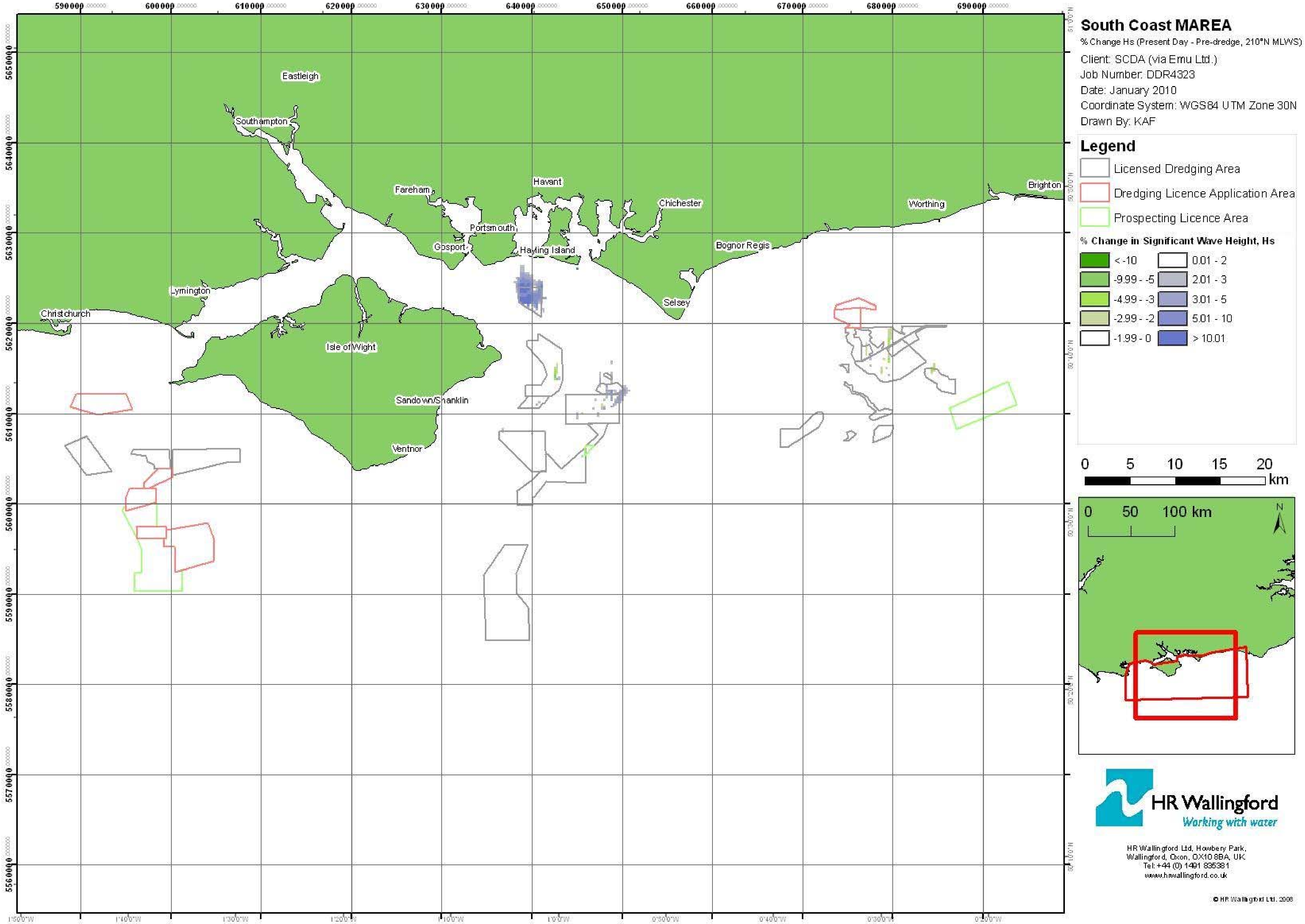

Figure 12 Changes (%) in wave height due to past dredging for 200 year return wave condition from 210ºN at MLWS

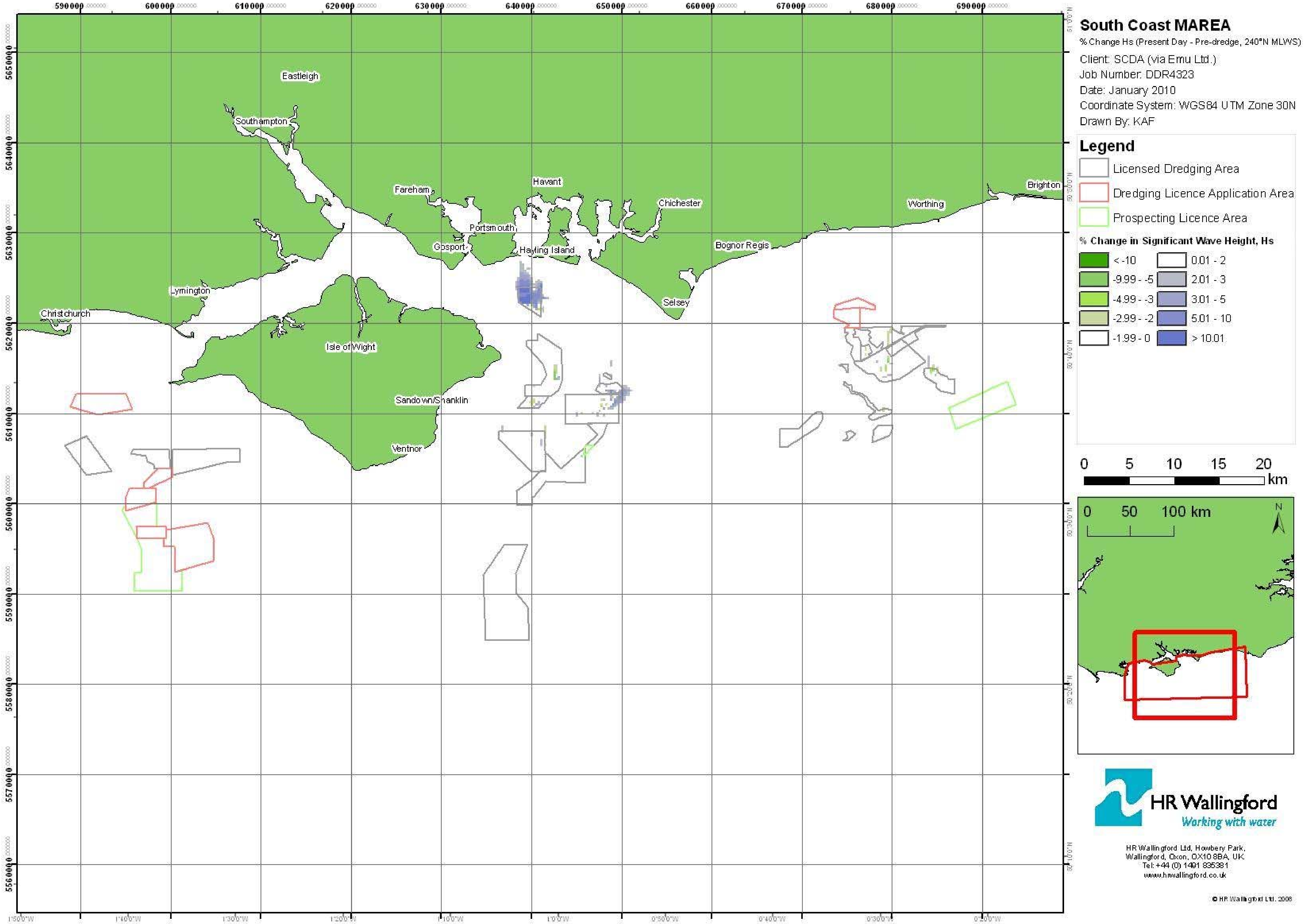

Figure 13 Changes (%) in wave height due to past dredging for 200 year return wave condition from 240ºN at MLWS

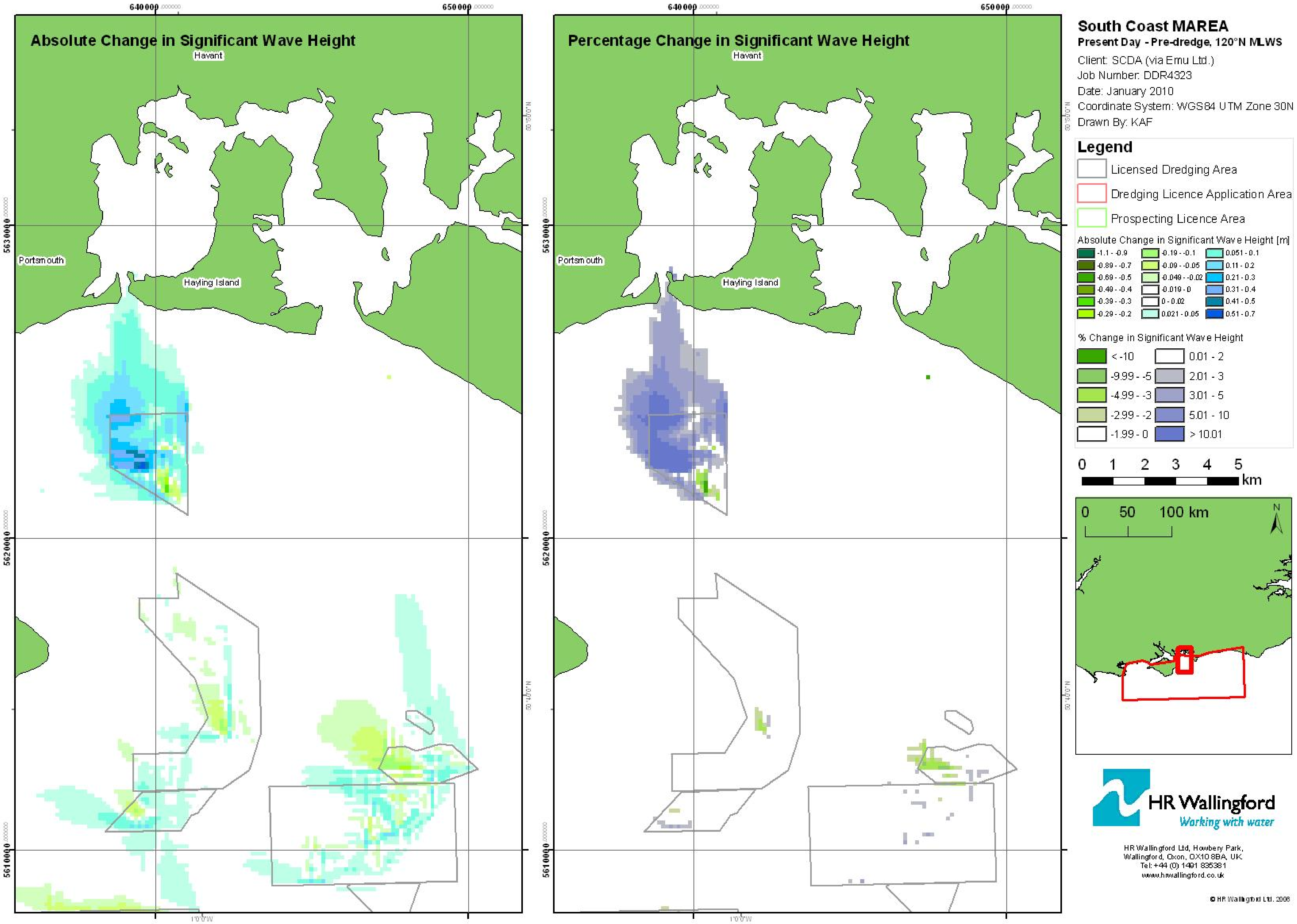

Figure 14 Past dredging: Comparison of percentage and absolute differences in wave height around Area 122/2 for 200 year condition from 120ºN at MLWS

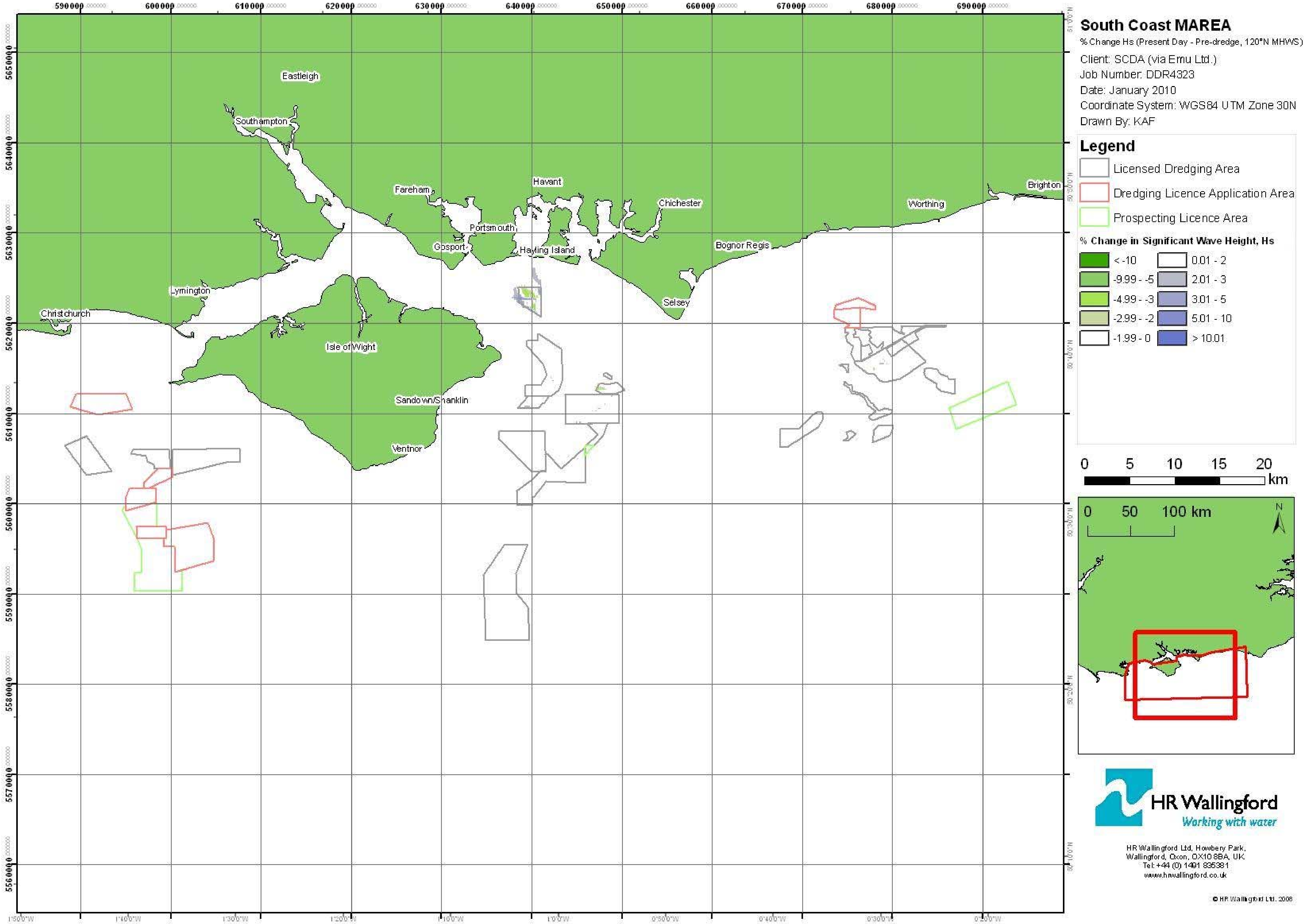

Figure 15 Changes (%) in wave height due to past dredging for 200 year return wave condition from 120ºN at MHWS

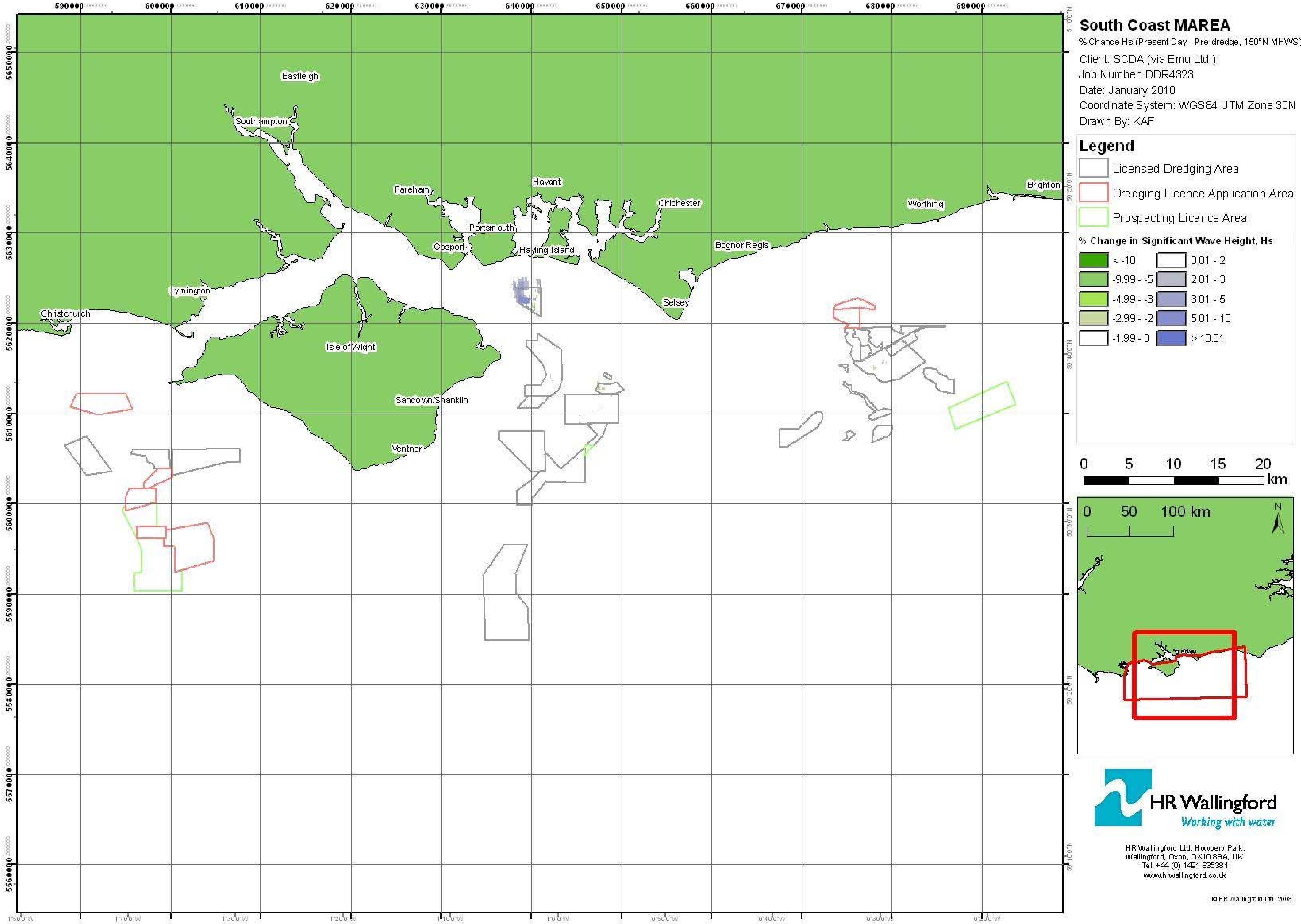

Figure 16 Changes (%) in wave height due to past dredging for 200 year return wave condition from 150ºN at MHWS

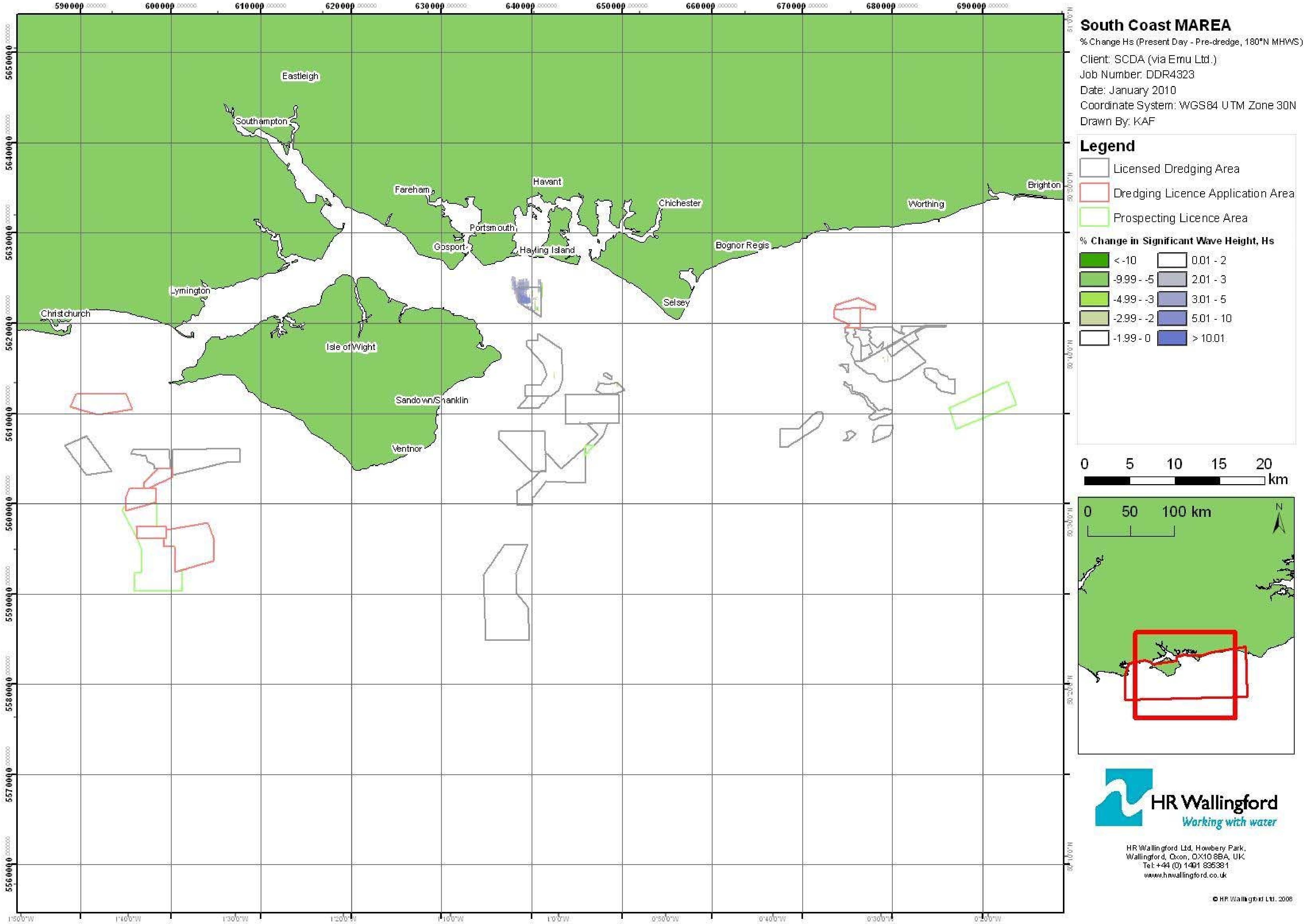

Figure 17 Changes (%) in wave height due to past dredging for 200 year return wave condition from 180ºN at MHWS

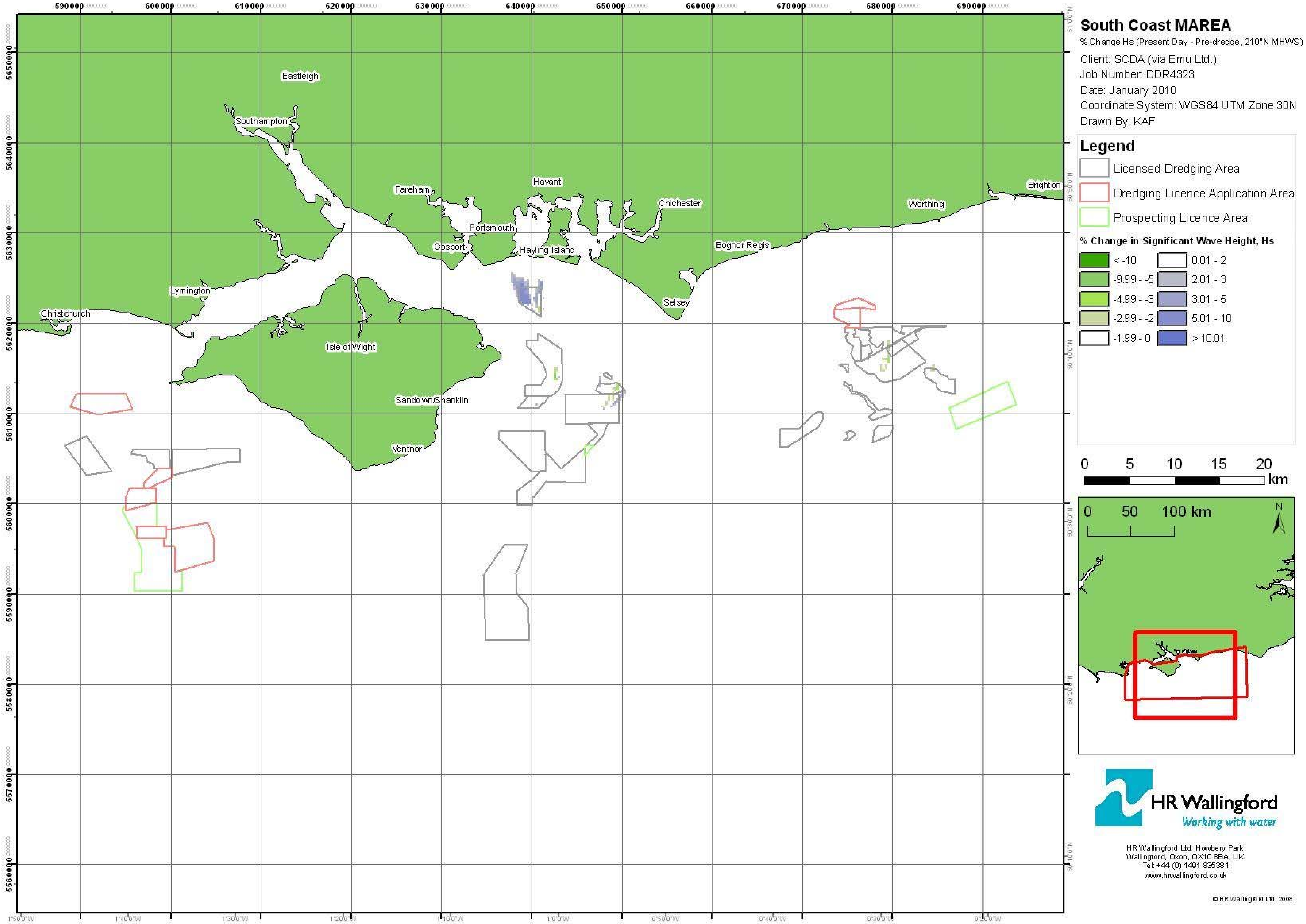

Figure 18 Changes (%) in wave height due to past dredging for 200 year return wave condition from 210ºN at MHWS

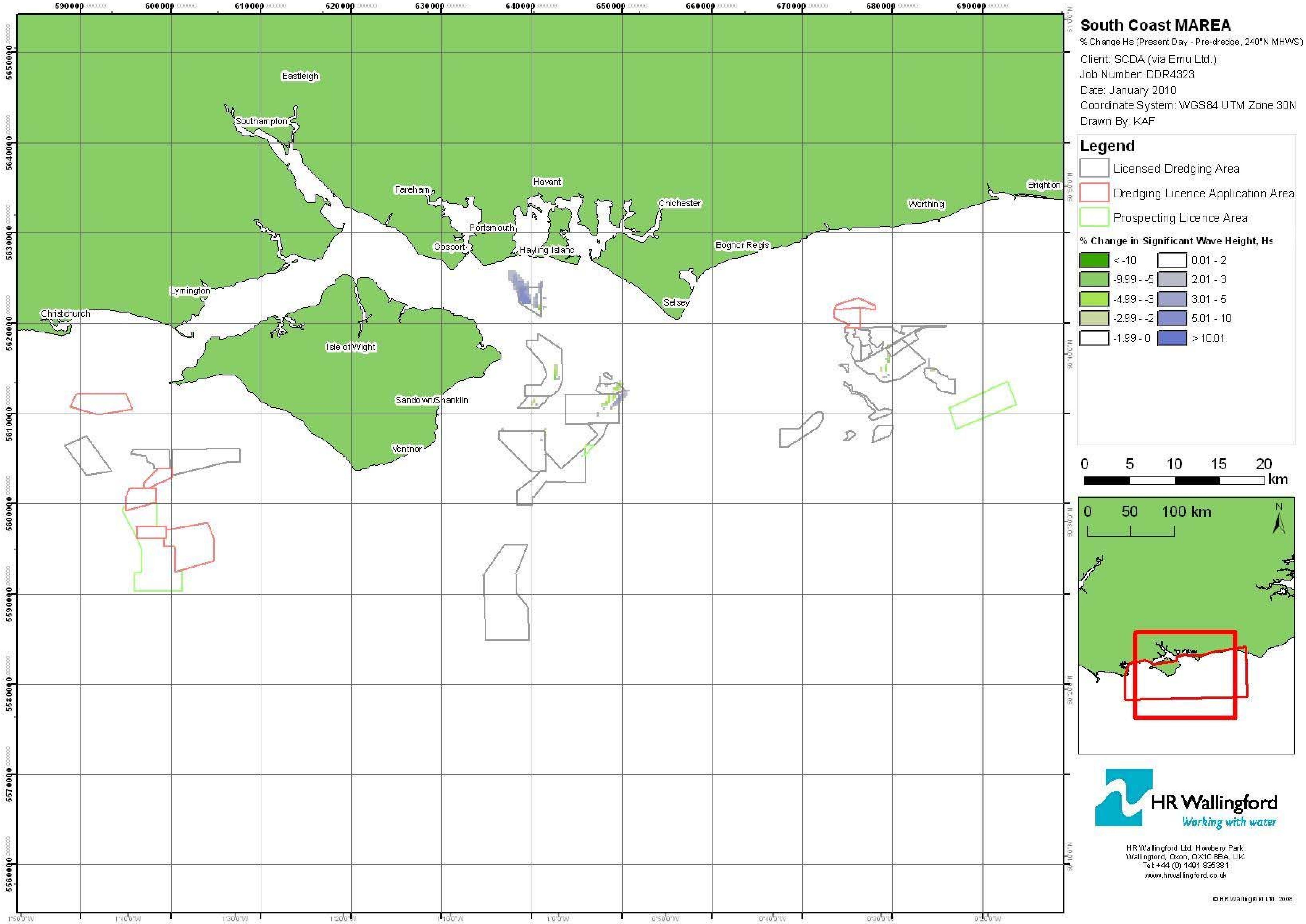

Figure 19 Changes (%) in wave height due to past dredging for 200 year return wave condition from 240ºN at MHWS

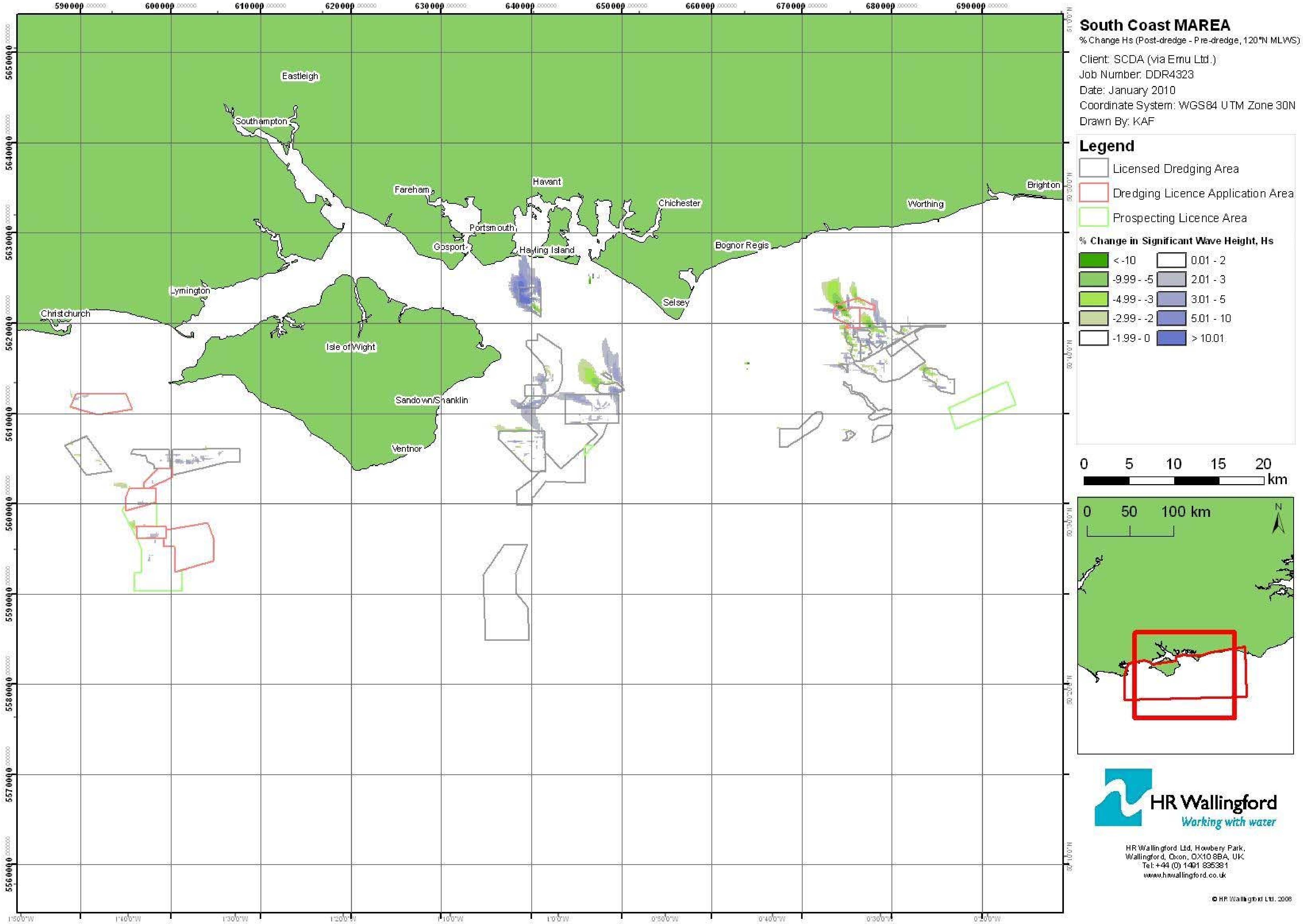

Figure 20 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 120ºN at MLWS

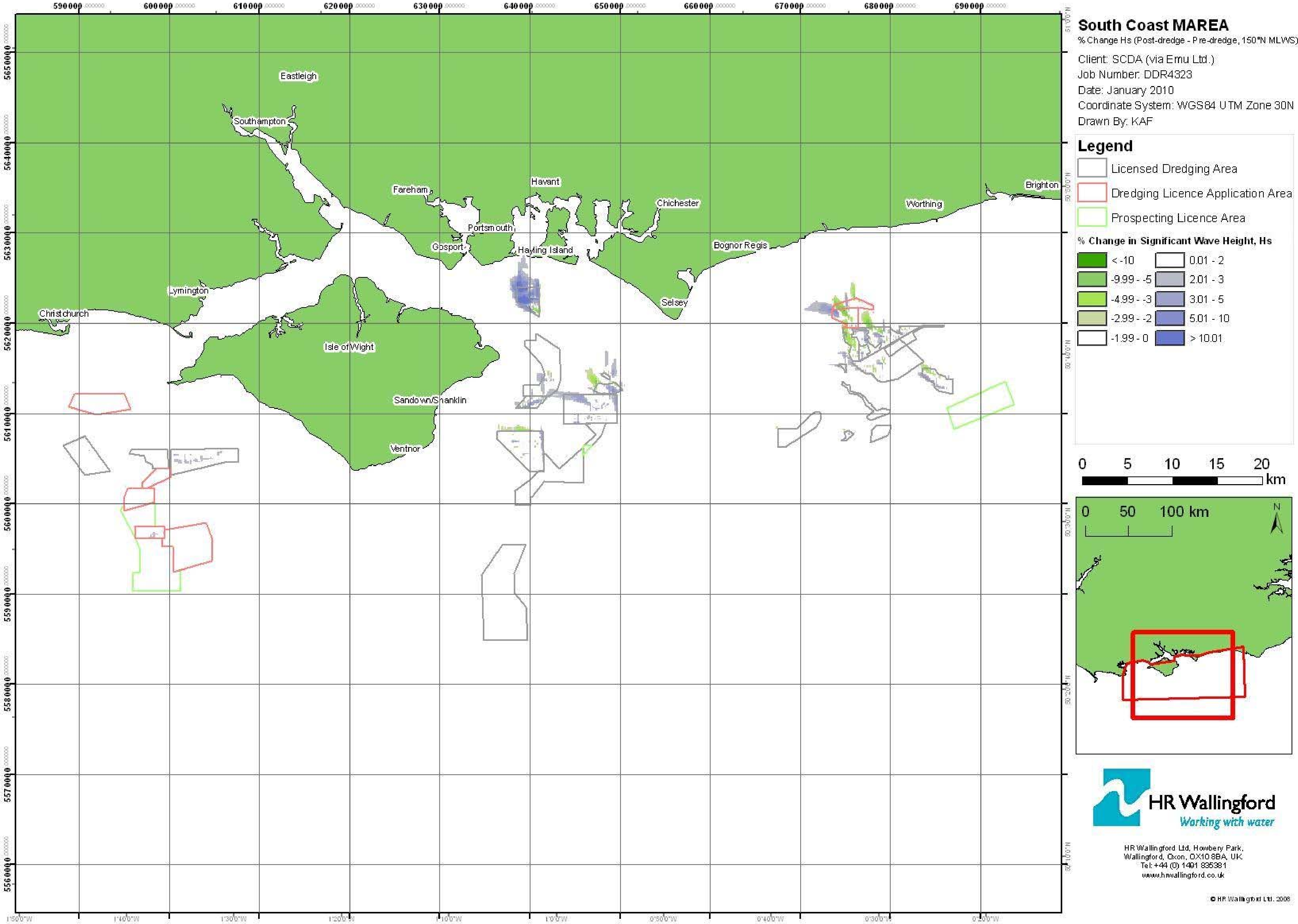

Figure 21 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 150ºN at MLWS

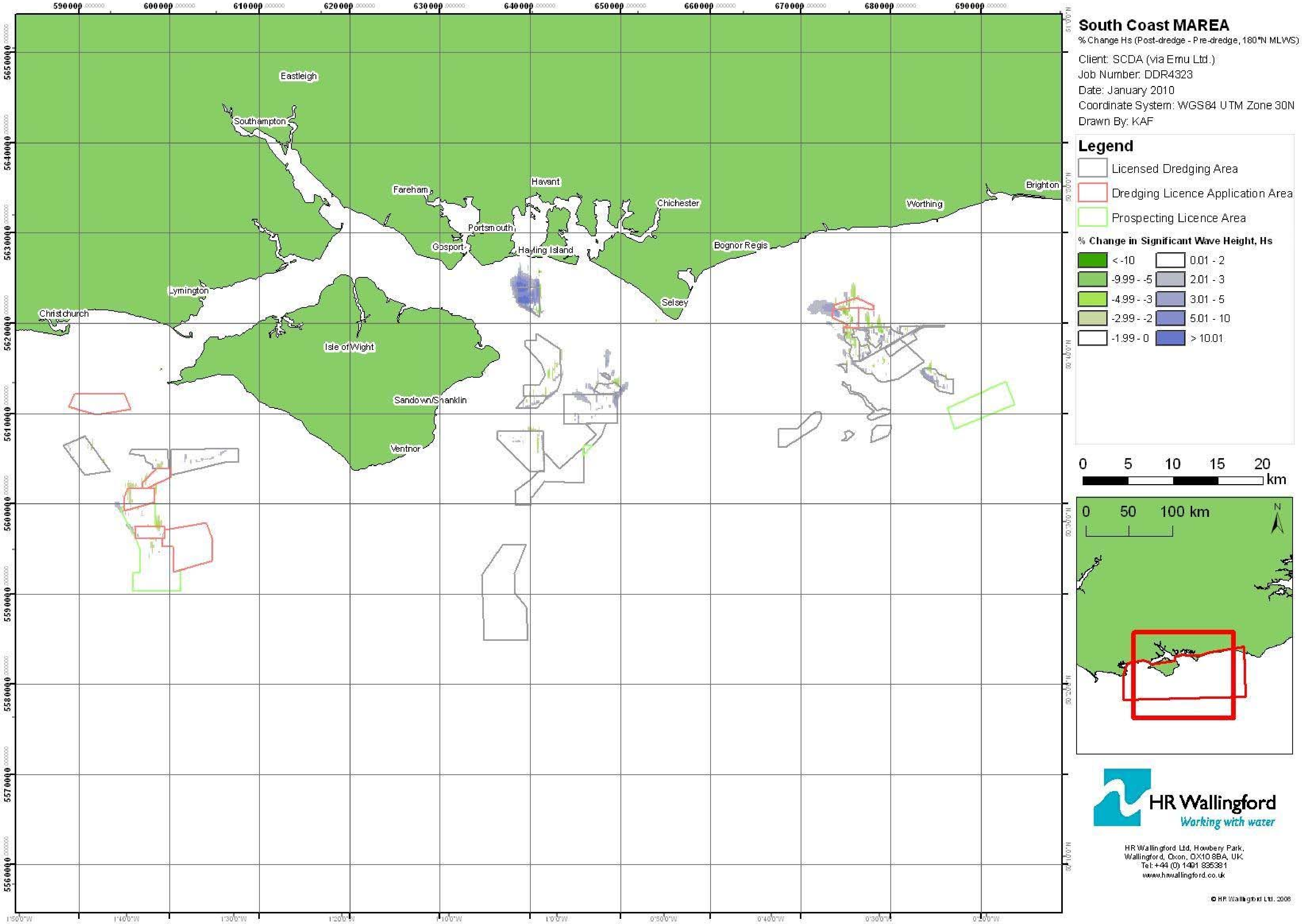

Figure 22 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 180ºN at MLWS

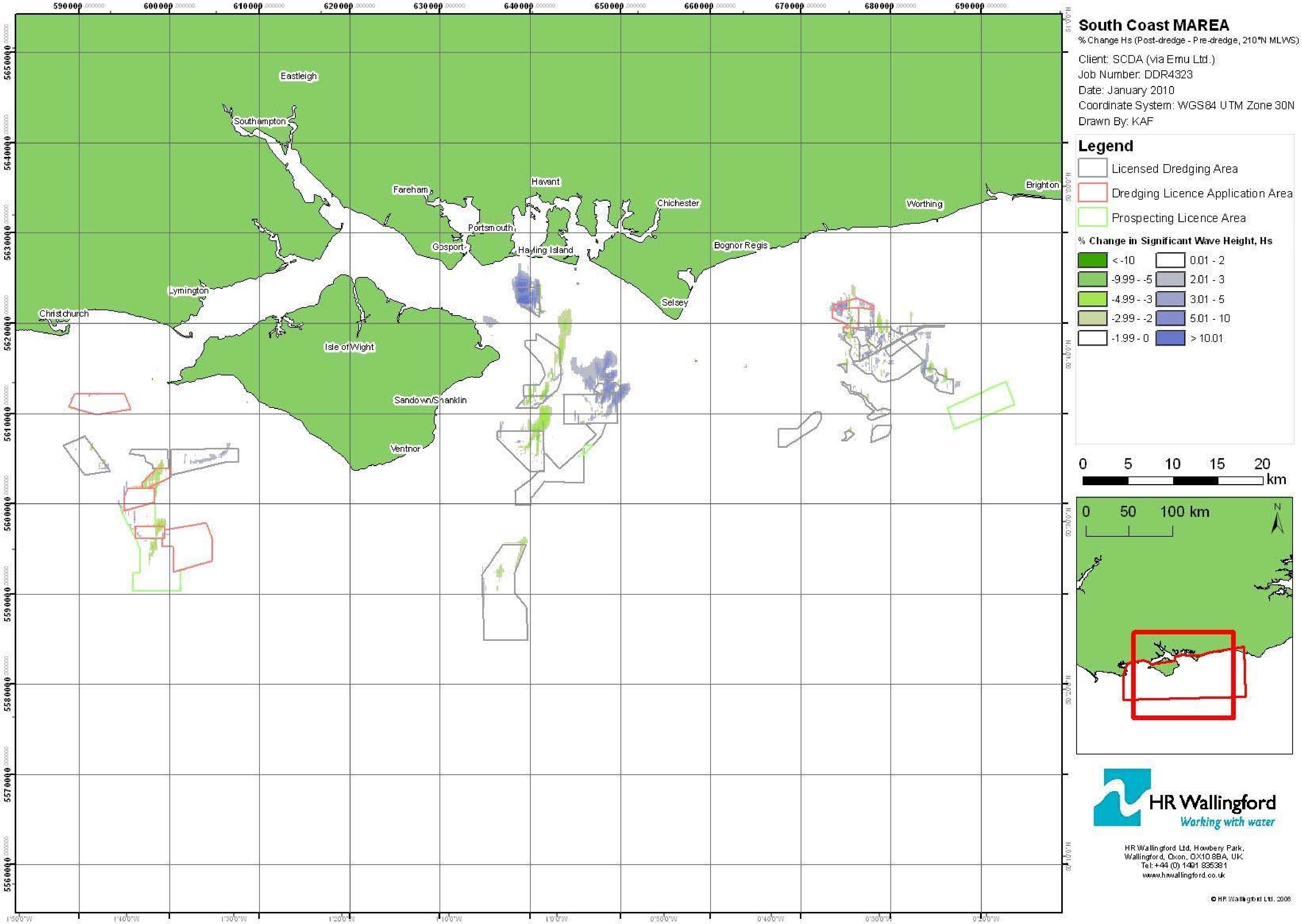

Figure 23 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 210ºN at MLWS

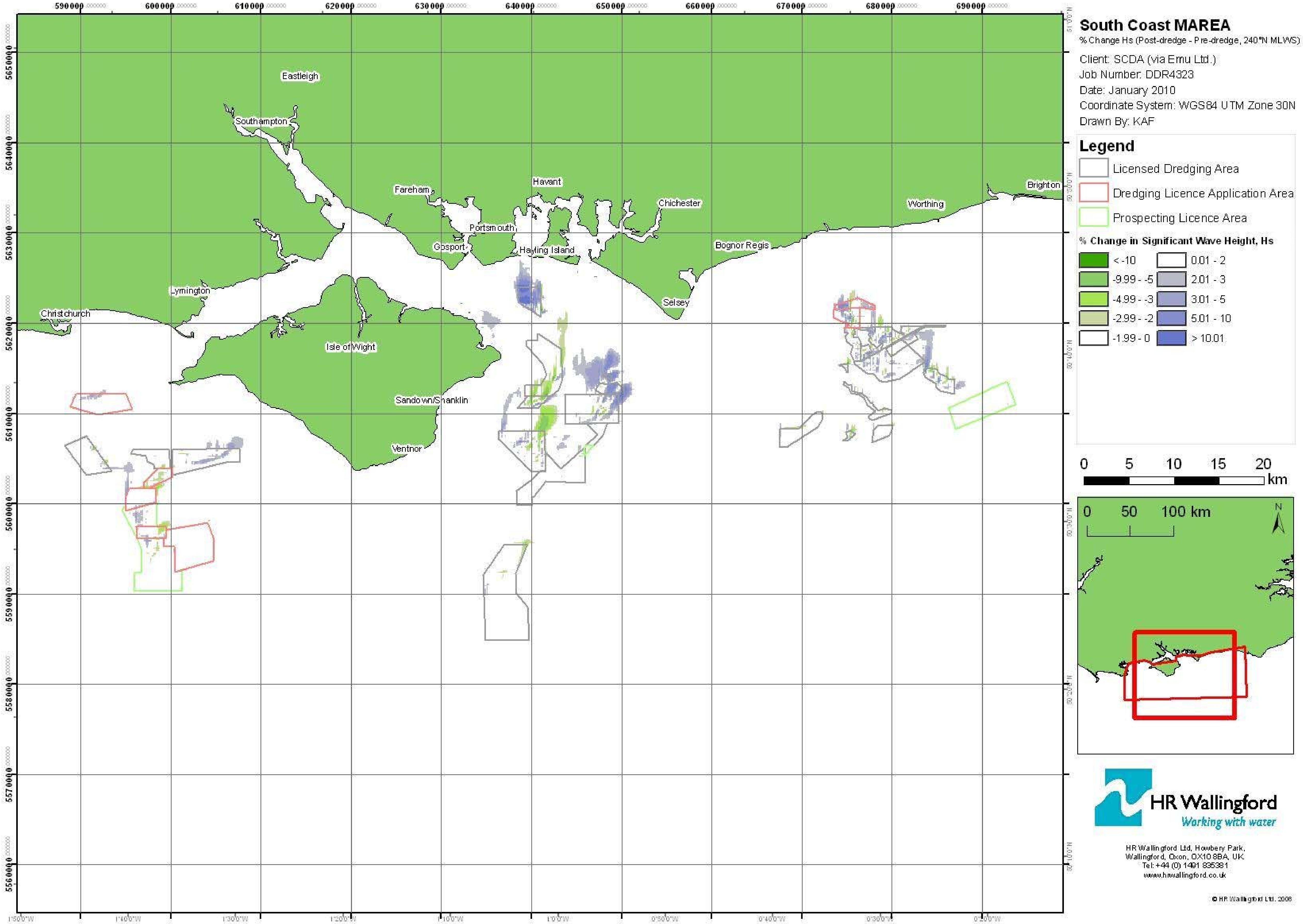

Figure 24 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 240ºN at MLWS

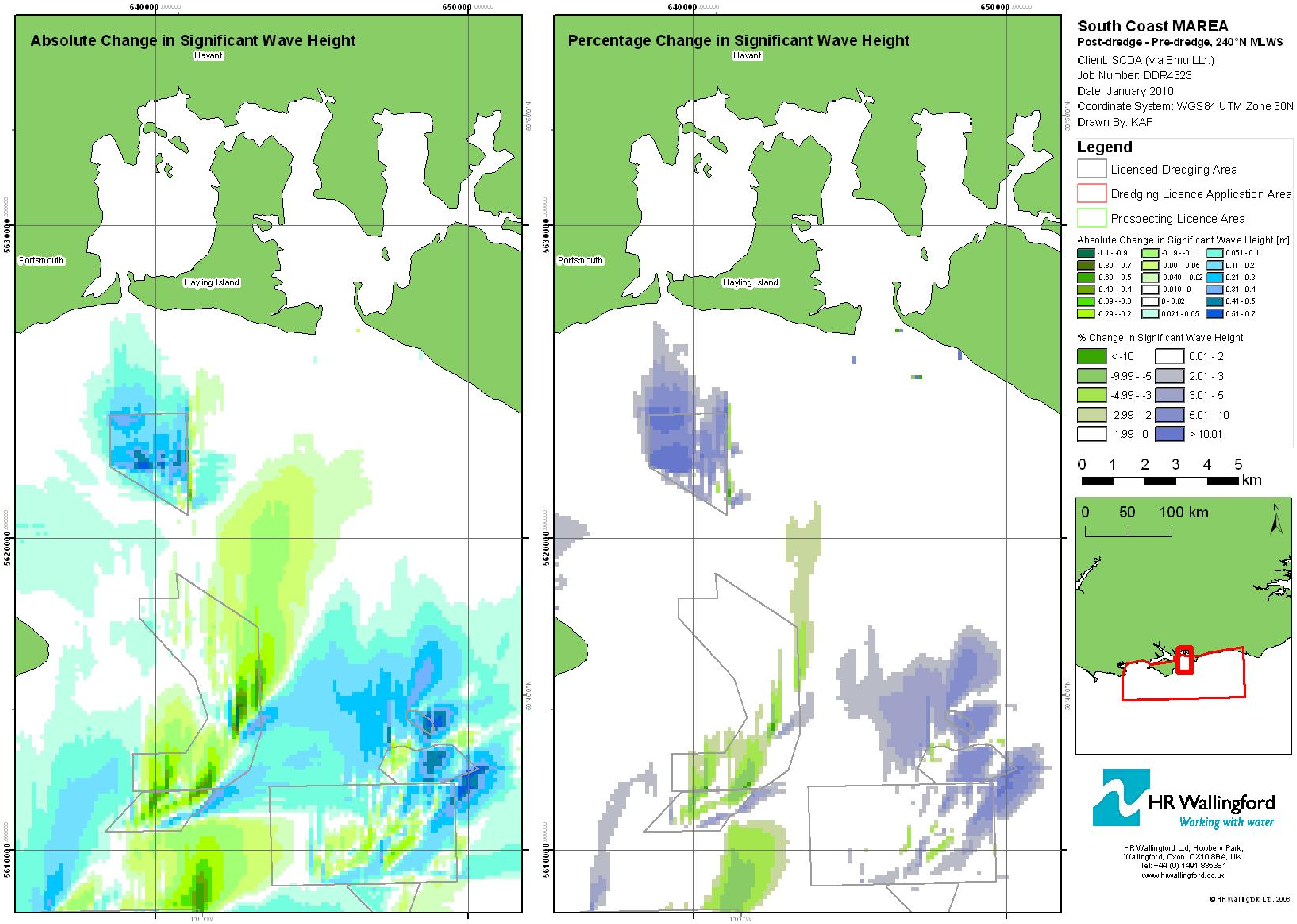

Figure 25 Wave height differences for past and future dredging (absolute and percentage changes) around Area 122/2 for 200 year return condition from 240ºN at MLWS

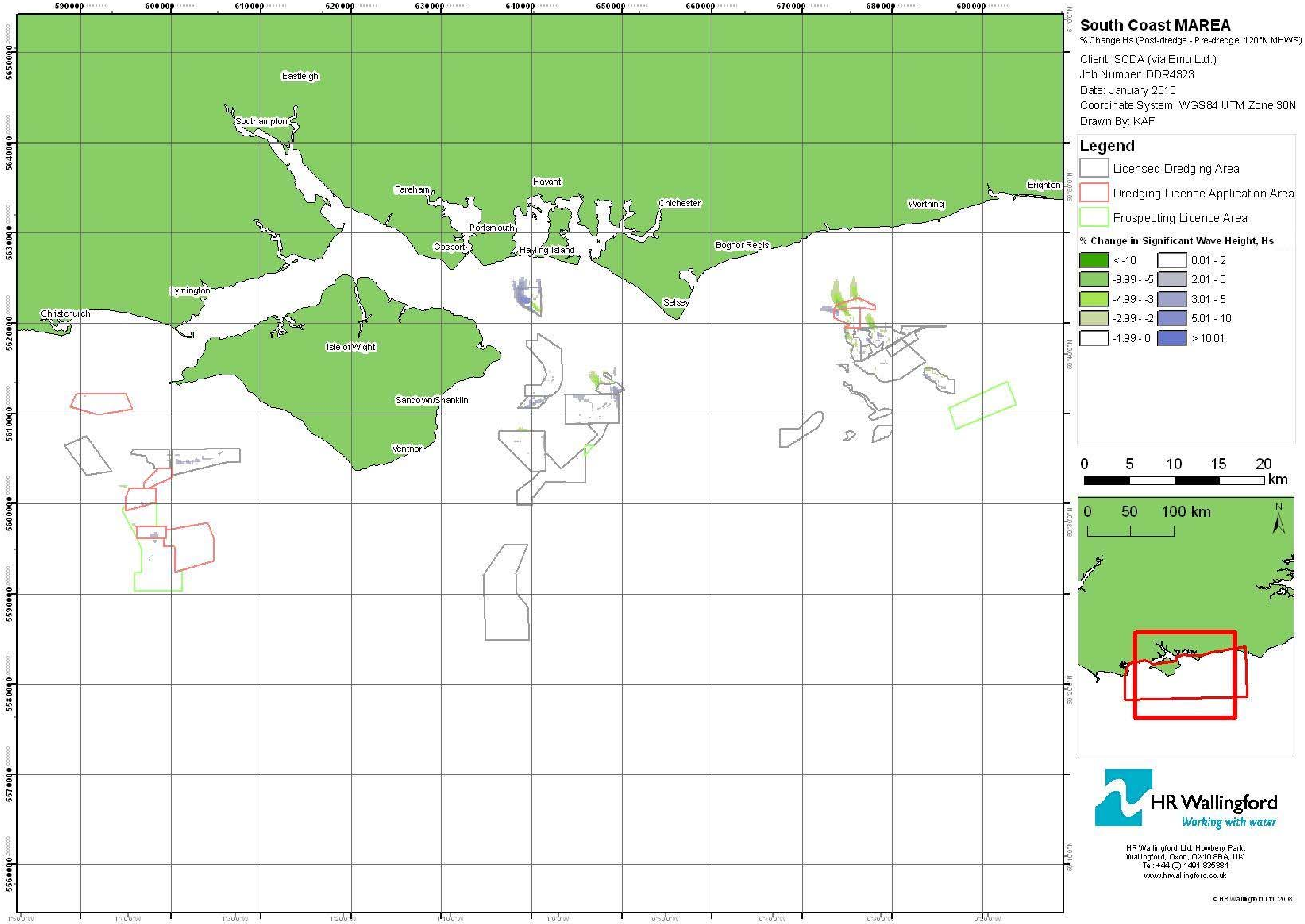

Figure 26 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 120ºN at MHWS

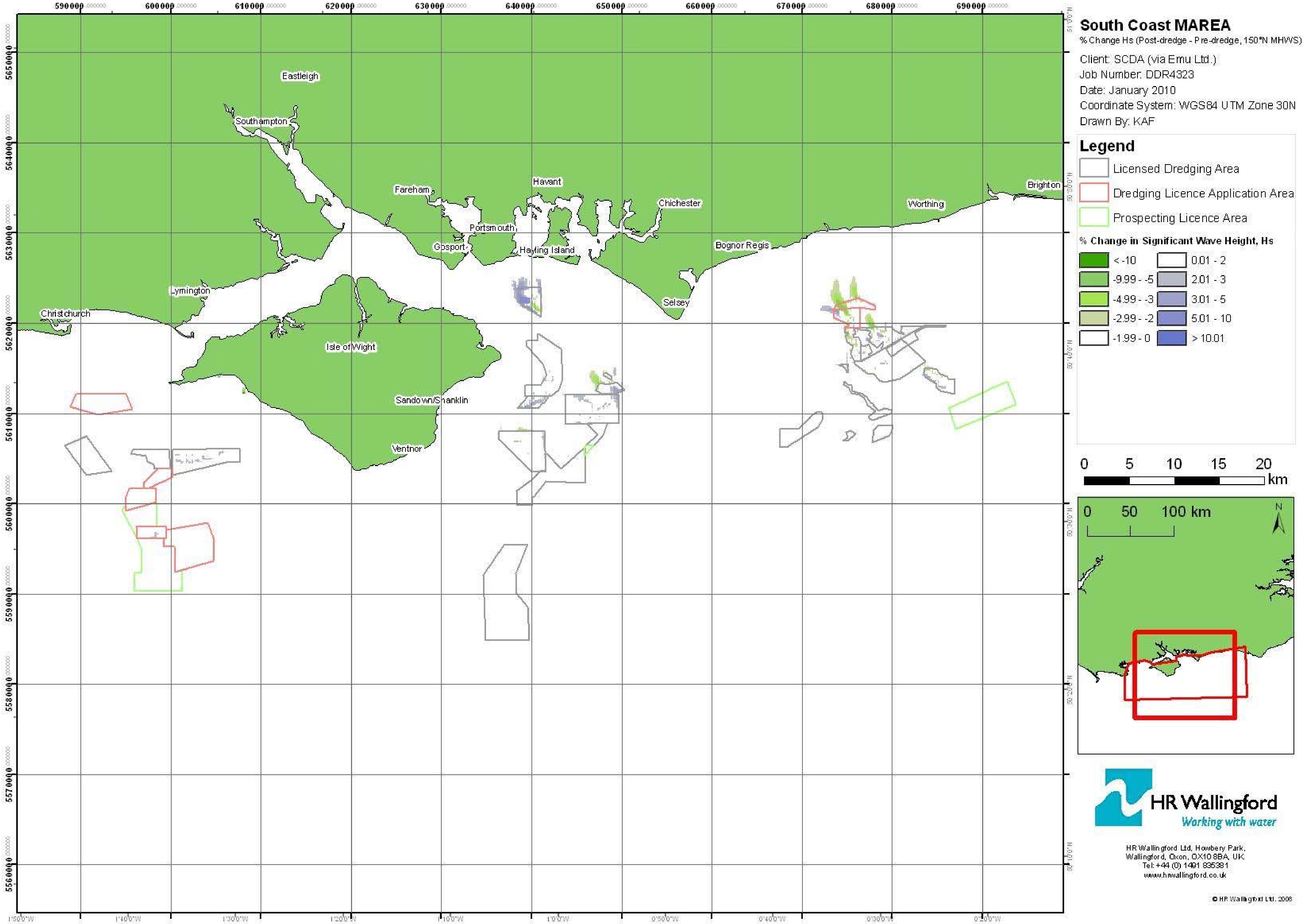

Figure 27 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 150ºN at MHWS

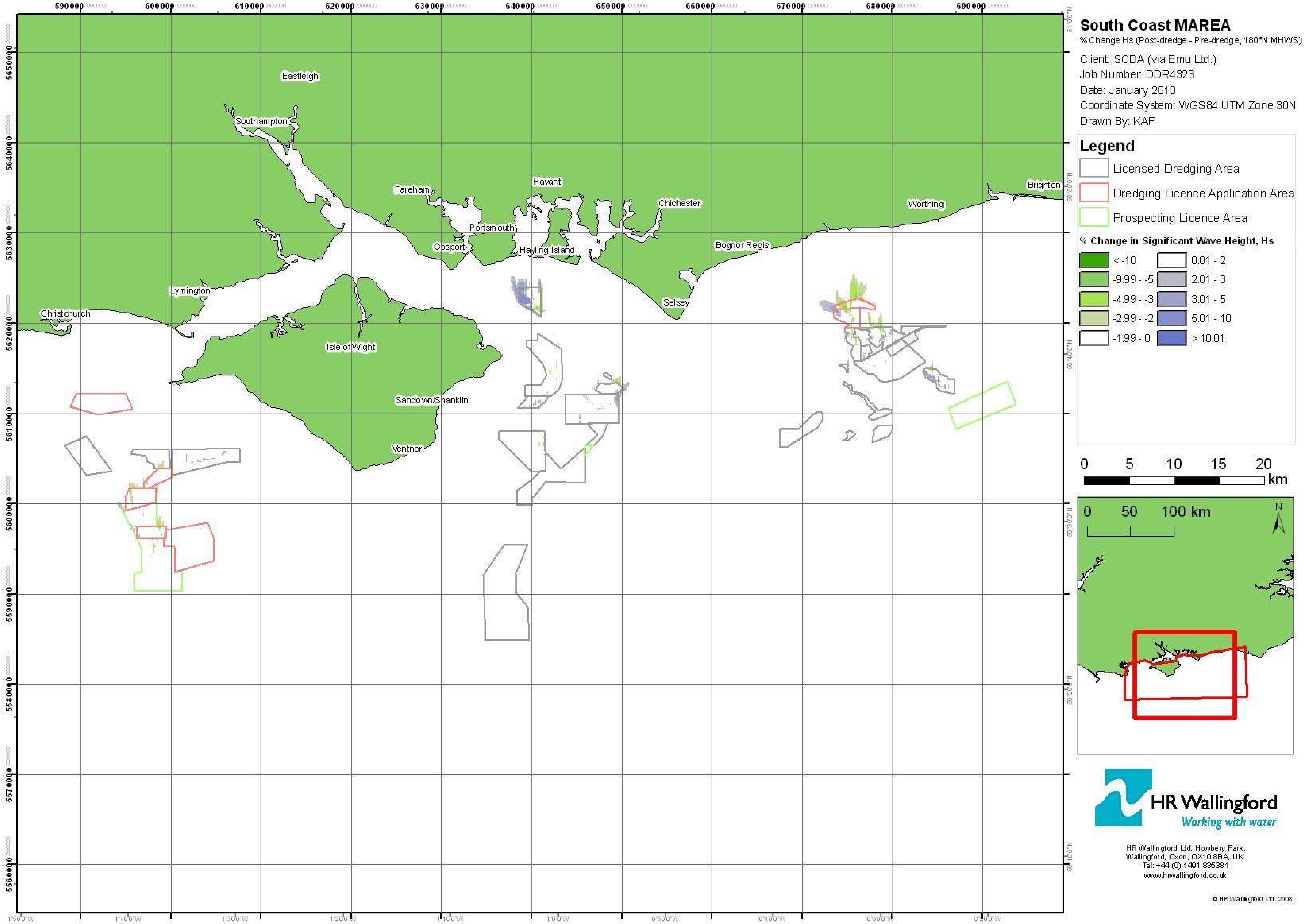

Figure 28 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 180ºN at MHWS

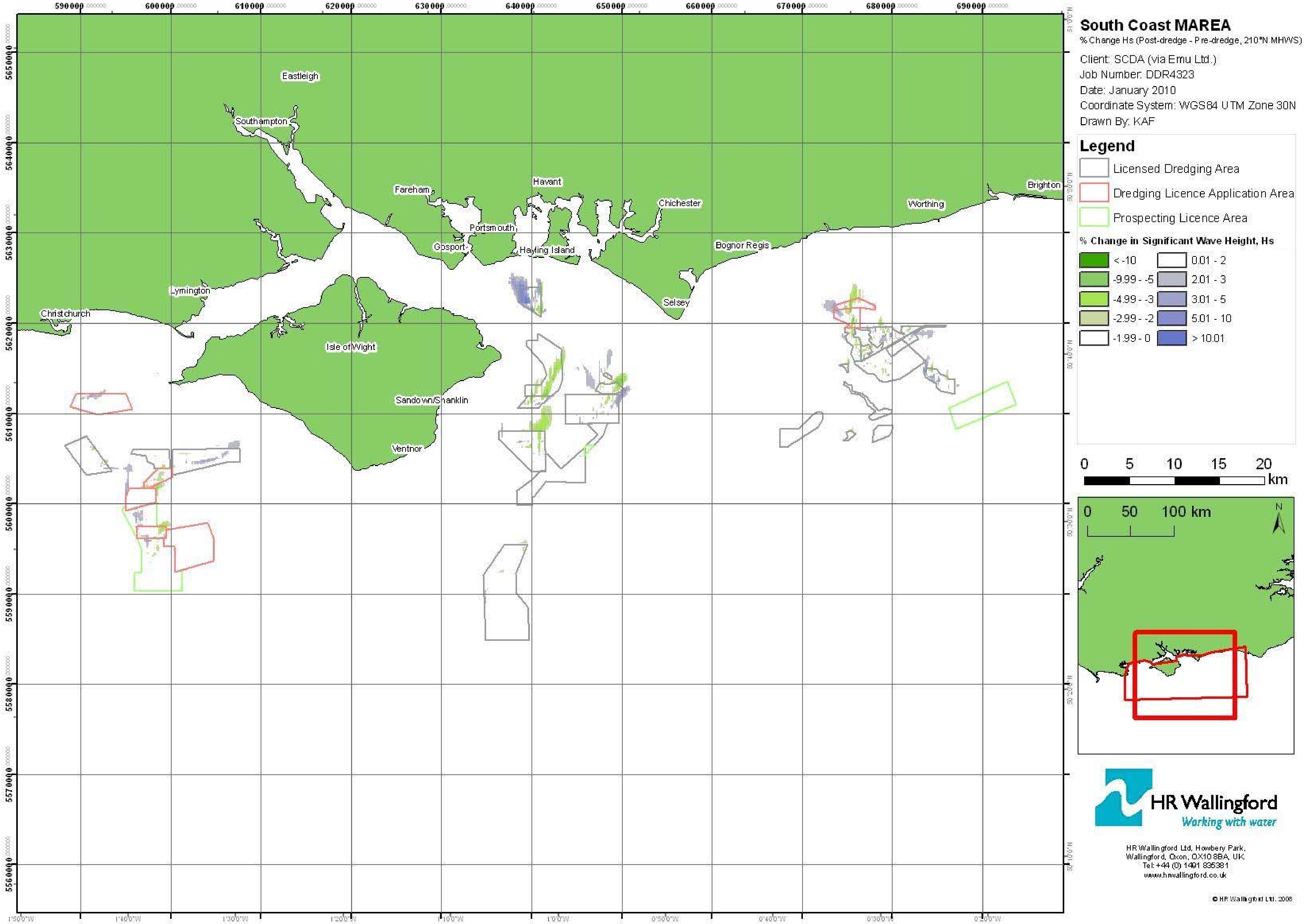

Figure 29 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 210ºN at MHWS

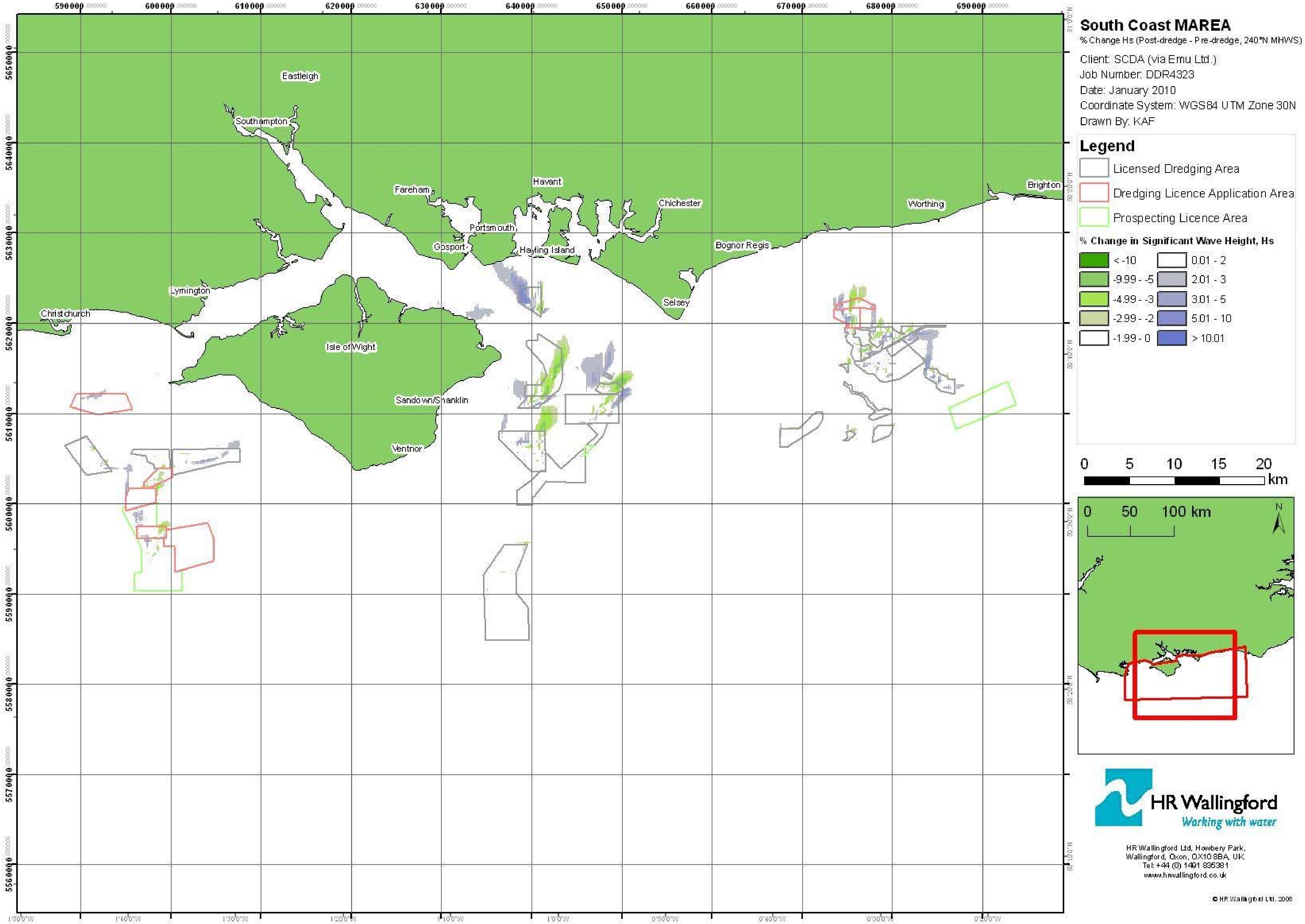

Figure 30 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 240ºN at MHWS

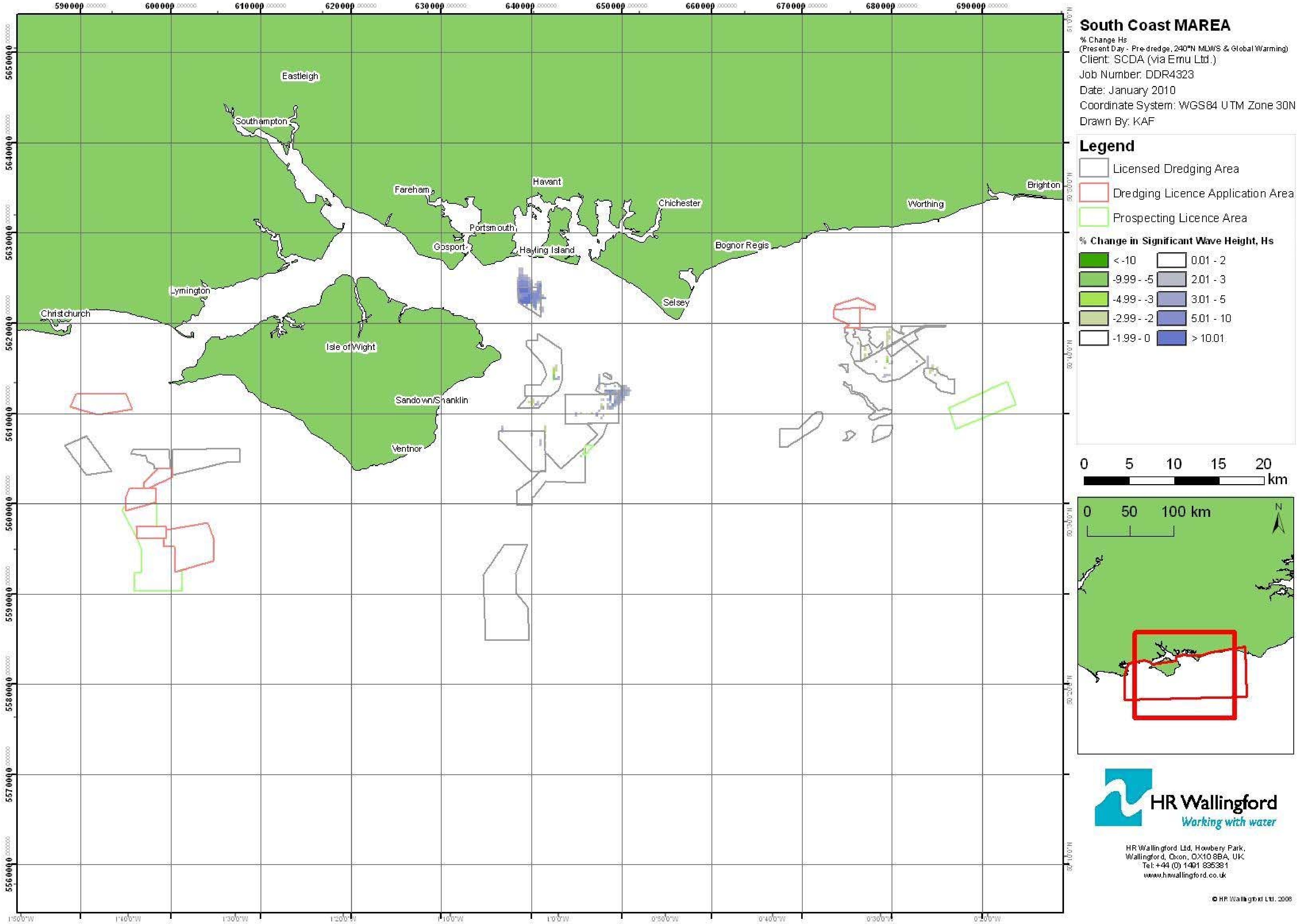

Figure 31 Changes (%) in wave height due to past dredging for 200 year return wave condition from 240ºN at MLWS and global warming (10% greater wave height and 5% greater wave period offshore)

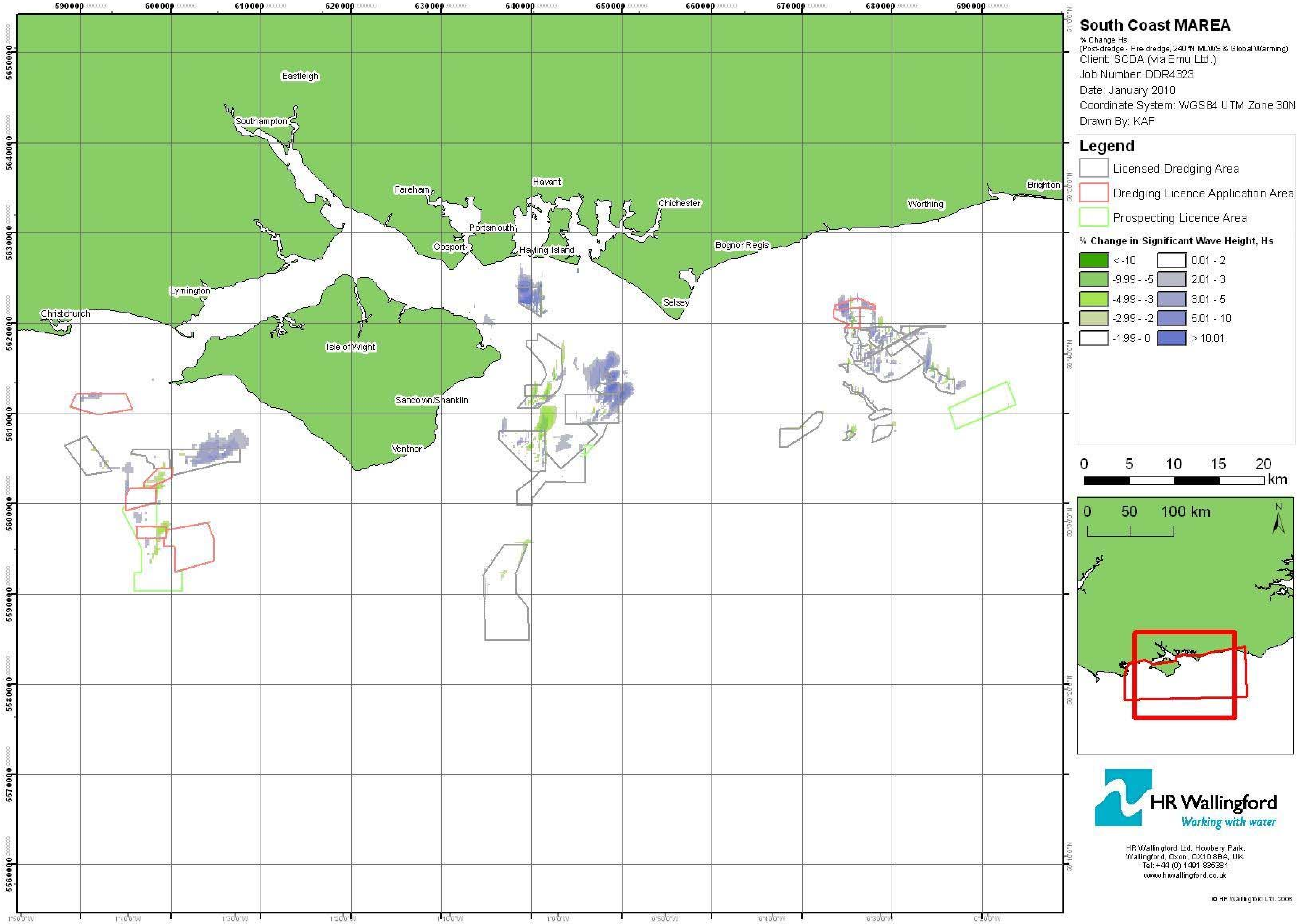

Figure 32 Changes (%) in wave height due to past and future dredging for 200 year return wave condition from 240ºN at MLWS and global warming (10% greater wave height and 5% greater wave period offshore)

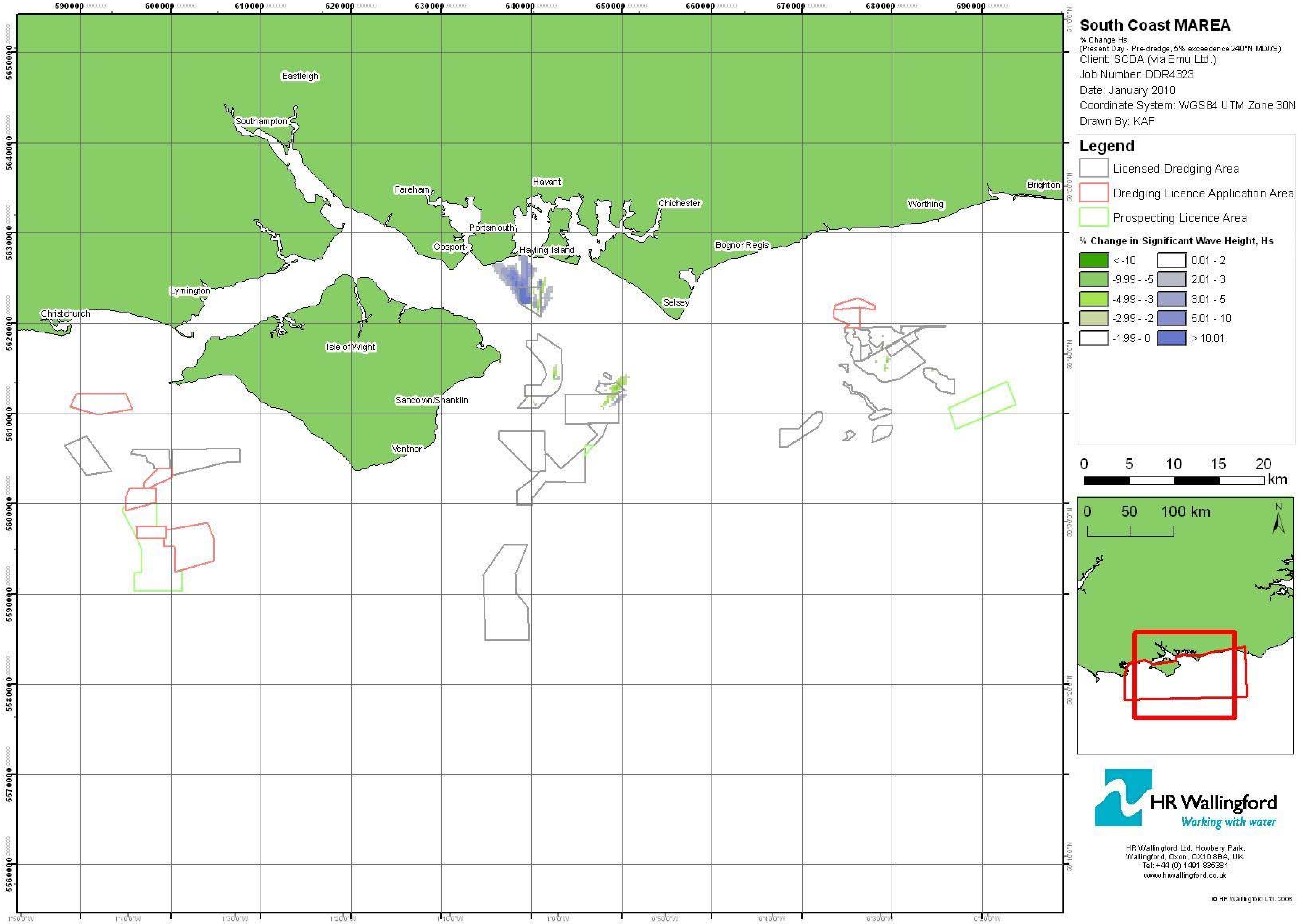

Figure 33 Changes (%) in wave height due to past dredging for 5% exceedence wave condition from 240ºN at MLWS

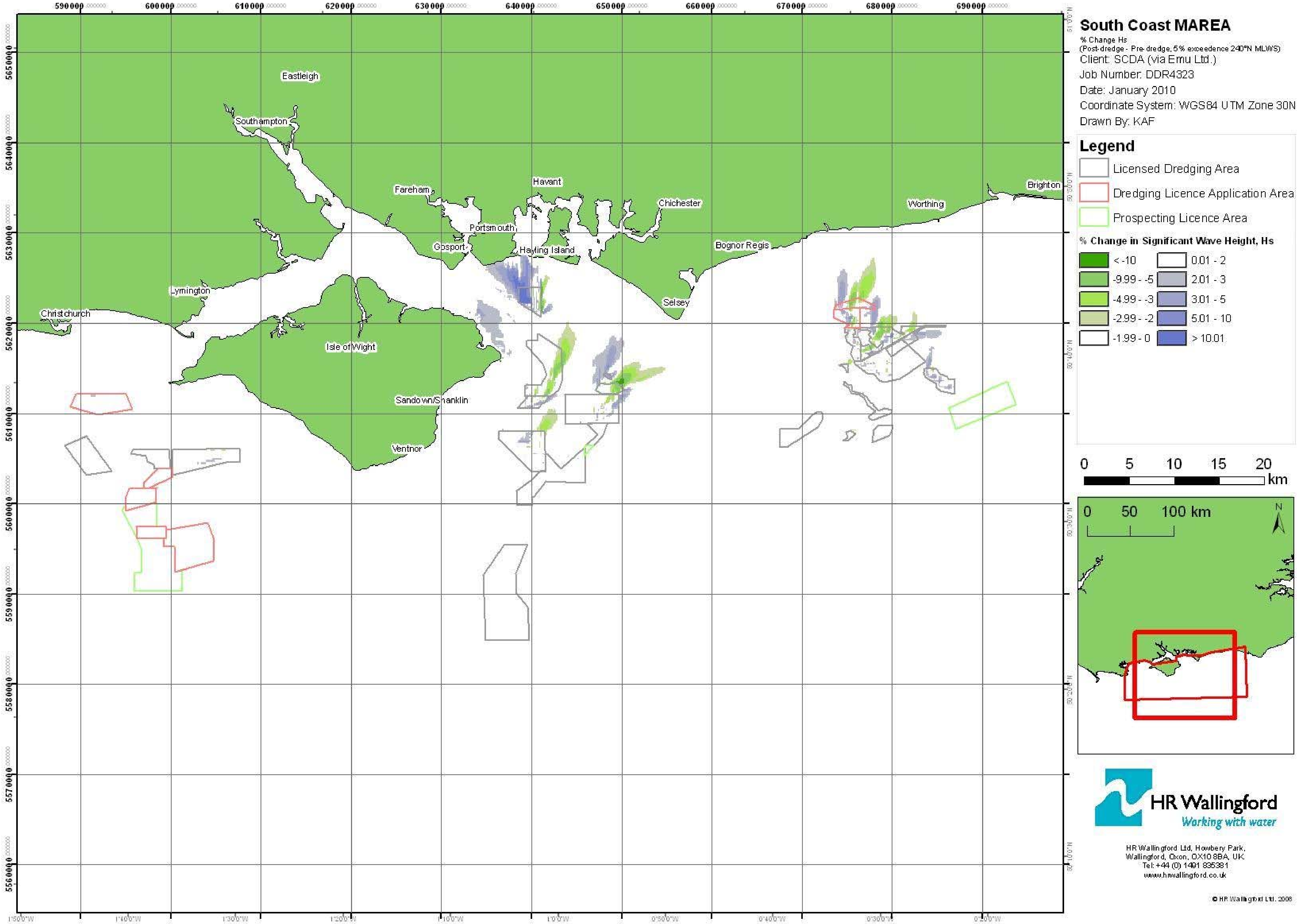

Figure 34 Changes (%) in wave height due to past and future dredging for 5% exceedence wave condition from 240ºN at MLWS

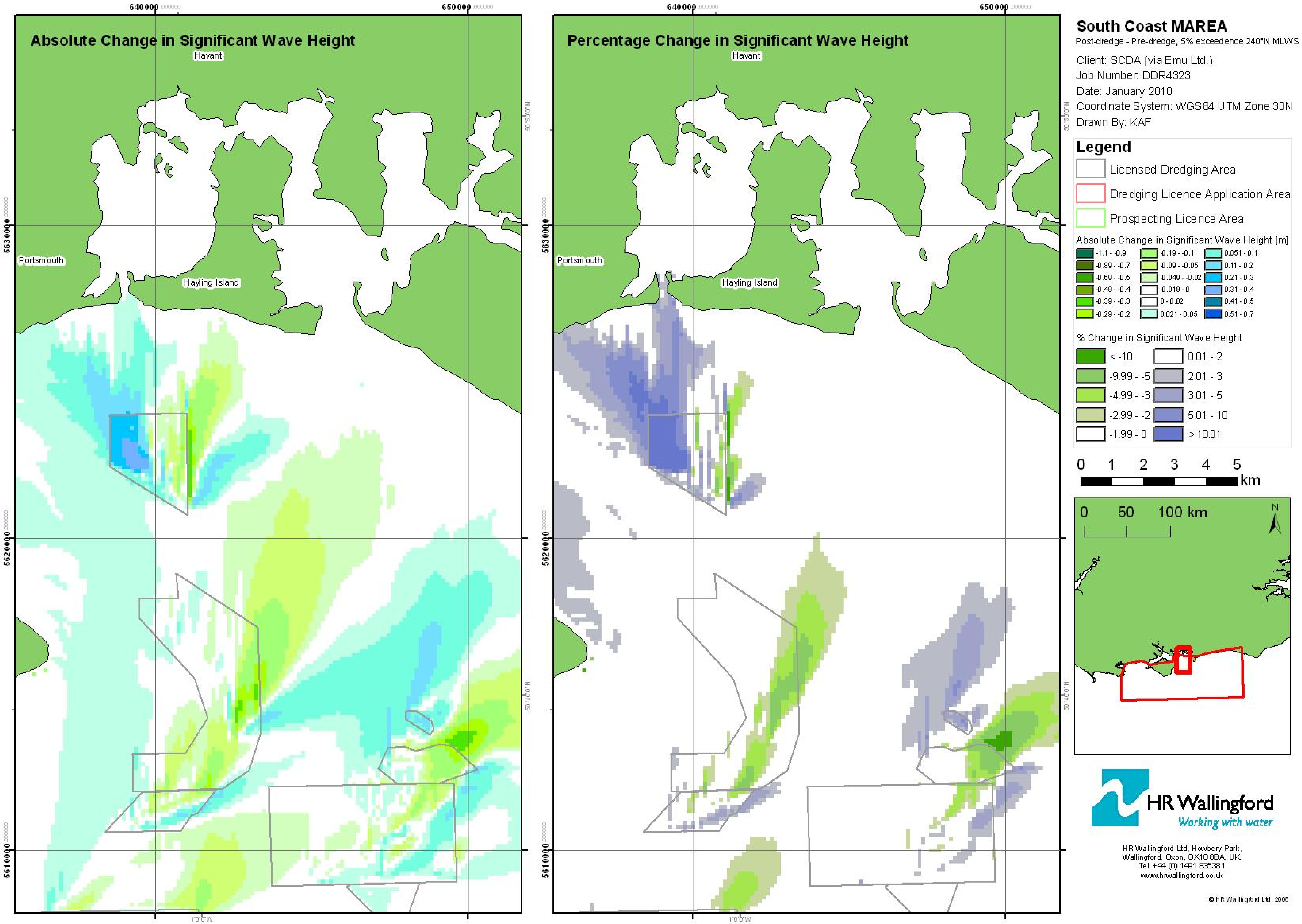

Figure 35 Changes (percentage and absolute) in wave height around Area 122/2 due to past and future dredging for 5% exceedence wave condition from 240ºN at MLWS

Appendices

Appendix 1 The SWAN wave 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):

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

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:

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

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):

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

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. A large number of models has 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 downwave side of the breakwater over the (significant) wave height at the upwave 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 Annually averaged wave climates for the three offshore prediction points

For all the tables presented in this Appendix, the wave climates have been compiled using data from April 1990 to March 2006.

In the body of each table, the distribution is expressed in parts per hundred thousand.

H is the significant wave height in metres; $P(H>H_1)$ is the probability of H exceeding H_1. Wave (from) direction is given in degrees relative to North.

Table A2.1 Summary of offshore wave climate at Point W (50.5N 2.07W) off Purbeck (from UKMO European Wave Model)

Wave direction in degrees North

H1 to H2		$P(H>H_1)$	-15 to 15	15 to 45	45 to 75	75 to 105	105 to 135	135 to 165	**165 to 195**	**195 to 225**	**225 to 255**	255 to 285	285 to 315	315 to 345
0.00	0.50	0.98804	173	180	231	468	567	503	**875**	**4466**	**4584**	828	400	229
0.50	1.00	0.85301	804	935	1110	1508	1358	1119	**1985**	**7367**	**9001**	2575	1360	1095
1.00	1.50	0.55084	501	736	1144	1750	1226	1093	**1531**	**5957**	**5865**	1842	871	496
1.50	2.00	0.32073	141	293	515	1121	637	445	**963**	**4246**	**3382**	1102	295	148
2.00	2.50	0.18786	47	53	173	714	338	165	**503**	**3136**	**2293**	554	75	26
2.50	3.00	0.10710	6	41	26	406	158	56	**338**	**2250**	**1536**	272	21	2
3.00	3.50	0.05598	2	0	6	101	30	34	**222**	**1623**	**915**	56	2	2
3.50	4.00	0.02603	0	0	0	6	11	13	**139**	**926**	**409**	30	0	0
4.00	4.50	0.01069	0	0	0	0	4	0	**34**	**436**	**167**	13	0	0
4.50	5.00	0.00415	0	0	0	0	0	0	**24**	**186**	**66**	2	0	0
5.00	5.50	0.00137	0	0	0	0	0	0	**4**	**60**	**32**	0	0	0
5.50	6.00	0.00041	0	0	0	0	0	0	**2**	**19**	**4**	0	0	0
6.00	6.50	0.00015	0	0	0	0	0	0	**0**	**2**	**4**	0	0	0
6.50	7.00	0.00009	0	0	0	0	0	0	**0**	**4**	**2**	0	0	0
7.00	7.50	0.00002	0	0	0	0	0	0	**0**	**0**	**2**	0	0	0
Parts per thousand for each direction			17	22	32	61	43	34	66	307	283	73	30	20

Table A2.2 Summary of offshore wave climate at Point M (50.5N 1.27W) off Ventor (from UKMO European Wave Model)

Wave direction in degrees North

H1	to H2	P(H>H_1)	-15	15	45	75	105	135	165	**195**	**225**	255	285	315
			15	45	75	105	135	165	195	**225**	**255**	285	315	345
0.00	0.50	0.98791	156	184	355	567	582	505	1067	**4173**	**4490**	813	349	235
0.50	1.00	0.85316	843	1010	1339	1692	1234	1117	1904	**7219**	**9642**	2483	1303	1078
1.00	1.50	0.54453	528	798	1298	1673	1046	1044	1726	**5195**	**6656**	1968	789	505
1.50	2.00	0.31226	152	329	650	892	552	424	734	**3549**	**4120**	1281	312	193
2.00	2.50	0.18040	32	73	255	684	274	171	394	**2657**	**2971**	687	83	64
2.50	3.00	0.09696	15	17	39	332	122	47	248	**1874**	**1940**	278	24	13
3.00	3.50	0.04748	0	0	4	58	43	30	122	**1309**	**1176**	77	0	2
3.50	4.00	0.01927	0	0	0	0	4	0	49	**625**	**505**	32	0	0
4.00	4.50	0.00712	0	0	0	0	4	2	24	**257**	**201**	2	0	0
4.50	5.00	0.00222	0	0	0	0	0	0	6	**83**	**49**	0	0	0
5.00	5.50	0.00083	0	0	0	0	0	0	0	**28**	**36**	0	0	0
5.50	6.00	0.00019	0	0	0	0	0	0	0	**6**	**6**	0	0	0
6.00	6.50	0.00006	0	0	0	0	0	0	0	**2**	**2**	0	0	0
6.50	7.00	0.00002	0	0	0	0	0	0	0	**0**	**2**	0	0	0
Parts per thousand for each direction			17	24	39	59	39	33	63	**270**	**318**	76	29	21

Table A2.3 Summary of offshore wave climate at Point E (50.5N 0.46W) off Littlehampton (from UKMO European Wave Model)

Wave direction in degrees North

H1 to H2		$P(H>H_1)$	-15 15	15 45	45 75	75 105	105 135	135 165	165 195	195 225	225 255	255 285	285 315	315 345
0.00	0.50	0.98772	216	319	667	911	441	370	586	2212	5865	1134	329	229
0.50	1.00	0.85494	935	1112	1805	1906	980	892	1277	3739	13030	3221	1529	1206
1.00	1.50	0.53861	535	963	1658	1589	948	856	1341	2997	8678	2652	834	584
1.50	2.00	0.30228	182	317	911	836	351	325	597	2199	4990	1777	299	195
2.00	2.50	0.17248	34	66	396	612	133	133	353	1561	3373	1080	133	45
2.50	3.00	0.09330	26	15	88	169	62	81	173	1245	2135	607	49	26
3.00	3.50	0.04654	0	9	13	49	6	6	88	727	1467	284	9	0
3.50	4.00	0.01996	0	0	0	6	0	6	26	376	742	68	2	0
4.00	4.50	0.00768	0	0	0	0	0	4	11	190	257	26	0	0
4.50	5.00	0.00280	0	0	0	0	0	0	4	51	118	11	0	0
5.00	5.50	0.00096	0	0	0	0	0	0	0	26	32	6	0	0
5.50	6.00	0.00032	0	0	0	0	0	0	0	4	13	0	0	0
6.00	6.50	0.00015	0	0	0	0	0	0	0	0	9	0	0	0
6.50	7.00	0.00006	0	0	0	0	0	0	0	0	2	0	0	0
7.00	7.50	0.00004	0	0	0	0	0	0	0	0	4	0	0	0
Parts per thousand			19	28	55	61	29	27	45	153	407	109	32	23

Table A2.4 Summary of offshore wave climate at Point M (50.5N 1.27W) off Ventor (from HINDWAVE Model)

Wave direction in degrees North

H1 to H2		$P(H>H_1)$	-15 15	15 45	45 75	75 105	**105 135**	**135 165**	**165 195**	195 225	225 255	255 285	285 315	315 345
0.00	0.50	0.99327	804	1400	1900	1705	**1207**	**1000**	**935**	1184	1925	2348	2875	1962
0.50	1.00	0.80083	600	2411	4479	2658	**776**	**356**	**420**	1176	2100	3674	2475	940
1.00	1.50	0.58018	16	350	2128	3558	**1574**	**1667**	**1838**	2094	4604	4207	890	24
1.50	2.00	0.35068	0	19	640	1199	**262**	**796**	**970**	1434	1877	1537	135	0
2.00	2.50	0.26199	0	0	111	2143	**498**	**243**	**395**	1118	8412	1303	25	0
2.50	3.00	0.11951	0	0	5	707	**190**	**36**	**201**	820	2324	680	0	0
3.00	3.50	0.06987	0	0	0	210	**37**	**42**	**40**	127	1543	53	0	0
3.50	4.00	0.04935	0	0	0	1	**0**	**0**	**0**	123	2910	130	0	0
4.00	4.50	0.01770	0	0	0	10	**0**	**0**	**0**	4	463	67	0	0
4.50	5.00	0.01226	0	0	0	0	**0**	**0**	**0**	0	945	15	0	0
5.00	5.50	0.00266	0	0	0	0	**0**	**0**	**0**	0	91	16	0	0
5.50	6.00	0.00158	0	0	0	0	**0**	**0**	**0**	0	123	0	0	0
6.00	6.50	0.00036	0	0	0	0	**0**	**0**	**0**	0	24	0	0	0
6.50	7.00	0.00012	0	0	0	0	**0**	**0**	**0**	0	11	1	0	0
Parts per thousand for each direction			14	42	93	122	45	41	48	81	274	140	64	29

Table A2.5 Summary of offshore wave climate at Point E (50.5N 0.46W) off Littlehampton (from HINDWAVE Model)

Wave direction in degrees North

			-15	15	45	75	**105**	**135**	**165**	195	225	255	285	315
			15	45	75	105	**135**	**165**	**195**	225	255	285	315	345
H1 to H2		**P(H>H_1)**												
0.00	0.50	0.99324	1199	1430	1385	1409	**1137**	**915**	**900**	1173	1653	2113	1578	1255
0.50	1.00	0.83176	1466	2048	3324	2358	**433**	**331**	**367**	599	1994	3124	2519	2610
1.00	1.50	0.62004	390	1610	2067	2161	**1464**	**1569**	**1867**	2977	4142	3847	1041	294
1.50	2.00	0.38575	108	139	2160	2627	**566**	**571**	**1119**	2275	2829	1795	243	38
2.00	2.50	0.24105	0	28	928	1068	**181**	**169**	**487**	826	6149	2218	24	0
2.50	3.00	0.12027	0	0	197	133	**11**	**50**	**229**	807	1800	294	6	0
3.00	3.50	0.08499	0	0	9	157	**0**	**4**	**41**	332	2013	886	0	0
3.50	4.00	0.05059	0	0	0	9	**0**	**0**	**0**	42	2771	64	0	0
4.00	4.50	0.02172	0	0	0	0	**0**	**0**	**0**	13	407	190	0	0
4.50	5.00	0.01562	0	0	0	0	**0**	**0**	**0**	0	1181	66	0	0
5.00	5.50	0.00315	0	0	0	0	**0**	**0**	**0**	0	210	12	0	0
5.50	6.00	0.00093	0	0	0	0	**0**	**0**	**0**	0	46	21	0	0
6.00	6.50	0.00026	0	0	0	0	**0**	**0**	**0**	0	11	0	0	0
6.50	7.00	0.00015	0	0	0	0	**0**	**0**	**0**	0	2	6	0	0
7.00	7.50	0.00006	0	0	0	0	**0**	**0**	**0**	0	4	2	0	0
Parts per thousand for each direction			32	53	101	99	38	36	50	90	252	146	54	42

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 (Reference 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.

Extreme Value Distribution

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

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

Weibull Scales

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

$y = \log\{-\log(1-P(H_s))\}$ 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.

Reference

1. Alcock G A. Parameterizing extreme still water levels and waves in design level studies. Report 183, Institute of Oceanographic Sciences, 1984.