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Underwater Noise Assessment for the Proposed Rampion Offshore Wind Farm

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A handwritten signature in black ink, which appears to be 'J R Nedwell', written over a circular stamp or seal.

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Executive Summary

Subacoustech Environmental has undertaken a study on behalf of RSK Environmental Ltd to assess the impact of underwater noise produced during pile driving operations during the installation of wind turbines at Rampion Offshore Wind Farm site, situated off the south coast of England.

The levels of underwater noise from the installation of two different wind turbine foundations have been taken into consideration. Noise from the installation of jacket pile and monopile foundations have been assessed and estimated using a proprietary underwater sound propagation model, INSPIRE (currently version 3.4.2), that enables the behaviour of noise with range from the piling to be estimated for varying water depths, pile sizes, blow energies and piling locations based on an existing database of measurements of piling noise. The model is validated against Subacoustech's existing database of measurements of piling noise. The INSPIRE model has been used to calculate the expected noise level on 180 transects radiating outwards from the piling location at the Rampion Wind Farm site and the results interpreted to yield impact range contours.

The modelled results suggest that marine species may suffer a lethal effect, where peak-to-peak pressure levels exceed 240 dB re. 1 μ Pa, to a range of up to 10 m. Physical injury, where peak-to-peak pressure levels exceed 220 dB re. 1 μ Pa, is predicted to occur out to a maximum range of 25, 35, 60 or 65 m depending on the piling scenario modelled.

The possibility of traumatic hearing injury has been assessed using the 130 dB_{ht}(Species) criteria, for which the largest estimated ranges are for humpback whale, used as a surrogate for minke whale, with 130 dB_{ht} ranges of up to 660 m and 720 m during the 6.5 m monopile scenario for west and east locations within the Rampion Wind Farm site boundary.

Behavioural impacts on marine species have been assessed using the 90 and 75 dB_{ht}(Species) criteria. The results show that the largest impact ranges are predicted for herring, harbour porpoise and humpback whale, with a maximum 90 dB_{ht} impact range for herring of 38.5 km, 19.1 km for the harbour porpoise and 36.6 km for the humpback whale for the 6.5 m monopile scenario positioned east in the Rampion Wind Farm site.

The accumulated exposure to sound for marine mammals has been assessed using M-Weighted SELs assuming an animal fleeing the noise source. The largest ranges are calculated for the 186 dB re 1 μ Pa²s criteria for pinnipeds. For piling operations at a single location a maximum range of 16.4 km is likely to be needed at the onset of the impact piling for the 6.5 m monopile scenario, located east in the Rampion Wind Farm site, to avoid a damaging exposure to sound using the Southall criteria. Lower ranges are predicted for all the cetacean criteria using the 198 dB re 1 μ Pa²s threshold.

The potential effects on divers in water has been estimated and assessed by using 130, 110 and 90 dB(UW) peak-to-peak levels to represent a range of possible effects. The maximum range to which 130 dB(UW) peak-to-peak level has been estimated to occur is 480 m and it is thought that this level may cause auditory damage to a diver. 'Startle' effects, when a diver is suddenly exposed to sufficiently high noise levels at the start of a piling procedure, may occur at levels of 110 dB(UW). The greatest range from the piling that this is calculated to occur is 2 km, and this is at the commencement of piling a 6.5 m monopile at the easternmost modelled position.

1 Introduction

1.1 Project description

Subacoustech Environmental have been tasked by the RSK Environmental Ltd, to investigate, by means of subsea noise modelling, the effect of proposed impact piling operations at the Rampion Offshore Wind Farm off the south coast of England. This has been undertaken by using preliminary engineering parameters to identify what impact this will have on marine species off the English south coast.

Subacoustech Environmental Ltd use a proprietary sub-sea acoustic modelling software package called INSPIRE, which calculates contours which show the approximate limits of the impact of underwater sound caused by an underwater noise source, in this case piling.

This report is intended to inform RSK Environmental Ltd of the potential zones of impact of the parameters to assist in the next stage of development.

The purpose of this report is to model the predicted noise levels during the construction of the turbines and determine impact ranges for species of fish and marine mammals.

1.2 Project objectives

This report has been compiled by Subacoustech Environmental Ltd to estimate the likely level of underwater noise during the installations of wind turbines using impact piling at the Rampion Offshore Wind Farm site. Subacoustech Environmental has completed the following project objectives:

- A review of background information on the units for measuring and assessing underwater noise;
- Subsea noise modelling to estimate the potential for physical injury or fatality to marine species based on predicted unweighted levels of underwater noise;
- Calculation of the source noise level from each pile size;
- Modelling of sound propagation in the $\text{dB}_{\text{ht}}(\text{Species})$ and M-Weighted SEL metrics for impact piling of jacket piles for two scenarios at two locations;
- A brief assessment on the airborne noise connected to the construction and operation; and
- Summary and conclusions.

This report quantifies the potential effects and impacts of the underwater noise that is likely to be generated by impact piling operations during the construction of the foundations for wind turbines at the Rampion site.

1.3 Impact piling

It has been proposed that impact piling is used to drive the piles into the seabed for part or all of the foundation installation scenarios modelled. This technique involves a large weight or “ram” being dropped or driven onto the top of the pile, driving it into the sea bed. Percussive impact piling has been established as a high level source of underwater impulsive noise (Wursig, 2000; Caltrans, 2001; Nedwell *et al*, 2003b; Parvin *et al*, 2006; Thomsen *et al*, 2006; Nedwell *et al*, 2007a).

Noise is created in air by the hammer, partly as a direct result of the impact of the hammer with the pile. Some of this airborne noise is transmitted into the water. Of more significance to the underwater noise, however, is the direct radiation of noise from the surface of the pile into the water as a consequence of the compressional, flexural or other complex structural waves that travel down the pile following the impact of the hammer on its head. As water is of similar density to steel and, in addition, due to its high sound speed (1,500 m/s, as opposed to 340 m/s for air), waves in the submerged section of the pile couple sound efficiently into the surrounding water. These waterborne waves will radiate outwards, usually providing the greatest contribution to the underwater noise.

At the end of the pile, force is exerted on the substrate not only by the mean force transmitted from the hammer by the pile, but also by the structural waves travelling down the pile which induce lateral waves in the seabed. These may travel as both compressional waves, in a similar manner to the sound in the water, or as a seismic wave, where the displacement travels as Rayleigh waves (Brekhovskikh, 1960). The waves can travel outwards through the seabed, or by reflection from deeper sediments. As they propagate, sound will tend to “leak” upwards into the water, contributing to the waterborne wave. Since the speed of sound is generally greater in consolidated sediments than in water, these waves usually arrive first as a precursor to the waterborne wave.

Generally, the level of the seismic wave is typically 10 – 20 dB below the waterborne arrival, and hence it is the latter that dominates the noise. In the context of this study, it should be noted that where mitigation measures such as pile cladding are used to attenuate the waterborne noise, the seismic wave may remain and limit the effectiveness of the technique.

2 Measurement of underwater noise

2.1 Introduction

Sound travels much faster in water (approximately 1,500 m/s) than in air (340 m/s). Since water is a relatively incompressible, dense medium, the pressures associated with underwater sound tend to be much higher than in air. As an example, background levels of sea noise of approximately 130 dB re 1 μ Pa for UK coastal waters are not uncommon (Nedwell *et al.*, 2003a and 2007a). This level equates to about 100 dB re 20 μ Pa in the units that would be used to describe a sound level in air. Such levels in air would be considered to be hazardous. However, marine mammals and fish have evolved to live in this environment and are thus relatively insensitive to sound pressure compared with terrestrial mammals. The most sensitive thresholds are often not below 100 dB re 1 μ Pa and typically not below 70 dB re 1 μ Pa (44 dB re 20 μ Pa using the reference unit that would be used in air).

2.2 Units of measurement

Sound measurements underwater are usually expressed using the decibel (dB) scale, which is a logarithmic measure of sound. A logarithmic scale is used because rather than equal increments of sound having an equal increase in effect, typically a constant ratio is required for this to be the case, that is, each *doubling* of sound level will cause a roughly equal increase in “loudness”.

Any quantity expressed in this scale is termed a “level”. If the unit is sound pressure, expressed on the dB scale, it will be termed a “Sound Pressure Level”. The fundamental definition of the dB scale is given by:

$$\text{Level} = 10 \times \log_{10}(Q/Q_{\text{ref}}) \quad \text{eqn. 2-1}$$

where Q is the quantity being expressed on the scale, and Q_{ref} is the reference quantity.

The dB scale represents a ratio and, for instance, 6 dB really means “twice as much as...”. It is, therefore, used with a reference unit, which expresses the base from which the ratio is expressed. The reference quantity is conventionally smaller than the smallest value to be expressed on the scale, so that any level quoted is positive. For instance, a reference quantity of 20 μ Pa is usually used for sound in air, since this is the threshold of human hearing.

A refinement is that the scale, when used with sound pressure, is applied to the pressure squared rather than the pressure. If this were not the case, if the acoustic power level of a source rose by 10 dB the Sound Pressure Level would rise by 20 dB. So that variations in the units agree, the sound pressure must be specified in units of RMS pressure *squared*. This is equivalent to expressing the sound as:

$$\text{Sound Pressure Level} = 20 \times \log_{10} (P_{\text{RMS}}/P_{\text{ref}}) \quad \text{eqn. 2-2}$$

For underwater sound, typically a unit of one microPascal (μ Pa) is used as the reference unit; a Pascal is equal to the pressure exerted by one Newton over one square metre. One microPascal equals one millionth of this.

2.3 Quantities of measurement

Sound may be expressed in many different ways depending upon the particular type of noise, and the parameters of the noise that allow it to be evaluated in terms of a biological effect. These are described in more detail below.

2.3.1 Peak level

The peak level is the maximum level of the acoustic pressure, usually a positive pressure. This form of measurement is often used to characterise underwater blasts where there is a clear

positive peak following the detonation of explosives. Examples of this type of measurement used to define underwater blast waves can be found in Bebb and Wright (1953 to 1955), Richmond *et al* (1973), Yelverton *et al* (1973) and Yelverton (1981). The data from these studies have been widely interpreted in a number of reviews on the impact of high level underwater noise causing fatality and injury in human divers, marine mammals and fish (see for example Rawlins, 1974; Hill, 1978; Goertner, 1982; Richardson *et al*, 1995; Cudahy and Parvin, 2001; Hastings and Popper, 2005). The peak sound level of a freely suspended charge of Tri-Nitro-Toluene (TNT) in water can be estimated from Arons (1954), as summarised by Urlick (1983). For offshore operations such as well head severance, typical charge weights of 40 kg may be used, giving a source peak pressure of 195 MPa or 285 dB re 1 μ Pa @ 1m (Parvin *et al*, 2007).

2.3.2 Peak-to-peak level

The peak-to-peak level is usually calculated using the maximum variation of the pressure from positive to negative within the wave. This represents the maximum change in pressure (differential pressure from positive to negative) as the transient pressure wave propagates. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak level will be twice the peak level, and hence 6 dB higher.

Peak-to-peak levels of noise are often used to characterise sound transients from impulsive sources such as percussive impact piling and seismic airgun sources. Measurements during offshore impact piling operations to secure tubular steel piles into the seabed have indicated peak-to-peak source level noise from 244 to 252dB re 1 μ Pa @ 1m for piles from 4.0 to 4.7 m diameter (Parvin *et al.*, 2006; Nedwell *et al.*, 2007a).

2.3.3 Sound pressure level (SPL)

The Sound Pressure Level is normally used to characterise noise and vibration of a continuous nature such as drilling, boring, continuous wave sonar, or background sea and river noise levels. To calculate the SPL, the variation in sound pressure is measured over a specific time period to determine the Root Mean Square (RMS) level of the time varying sound. The SPL can therefore be considered to be a measure of the average unweighted level of the sound over the measurement period.

As an example, small sea going vessels typically produce broadband noise at source SPLs from 170 – 180 dB re 1 μ Pa @ 1 m (Richardson *et al.*, 1995), whereas a supertanker generates source SPLs of typically 198 dB re 1 μ Pa @ 1 m (Hildebrand, 2004).

Where an SPL is used to characterise transient pressure waves such as that from seismic airguns, underwater blasting or piling, it is critical that the time period over which the RMS level is calculated is quoted. For instance, in the case of a pile strike lasting say a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean taken over one second.

2.3.4 Sound exposure level (SEL)

When assessing the noise from transient sources such as blast waves, impact piling or seismic airgun noise, the issue of the time period of the pressure wave (highlighted above) is often addressed by measuring the total acoustic energy (energy flux density) of the wave. This form of analysis was used by Bebb and Wright (1953 to 1955), and later by Rawlins (1987) to explain the apparent discrepancies in the biological effect of short and long range blast waves on human divers. More recently, this form of analysis has been used to develop an interim exposure criterion for assessing the injury range for fish from impact piling operations (Hastings and Popper, 2005; Popper *et al.*, 2006).

The Sound Exposure Level (SEL) sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound source and the duration the sound is present in the acoustic environment. Sound Exposure (SE) is defined by the equation:

$$SE = \int_0^T p^2(t)dt \quad \text{eqn. 2-3}$$

where p is the acoustic pressure in Pascals, T is the duration of the sound in seconds and t is time in seconds.

The Sound Exposure is a measure of the acoustic energy and, therefore, has units of Pascal squared seconds (Pa^2s).

To express the Sound Exposure on a logarithmic scale by means of a dB, it is compared with a reference acoustic energy level of $1 \mu\text{Pa}^2$ (P_{ref}^2) and a reference time (T_{ref}).

The SEL is then defined by:

$$SEL = 10 \log_{10} \left(\frac{\int_0^T p^2(t) dt}{P_{\text{ref}}^2 T_{\text{ref}}} \right) \quad \text{eqn. 2-4}$$

By selecting a common reference pressure P_{ref} of $1 \mu\text{Pa}$ for assessments of underwater noise, the SEL and SPL can be compared using the expression:

$$SEL = SPL + 10 \log_{10} T \quad \text{eqn. 2-5}$$

where the SPL is a measure of the average level of the broadband noise, and the SEL sums the cumulative broadband noise energy.

Therefore, for continuous sounds of duration less than one second, the SEL will be lower than the SPL. For periods of greater than one second the SEL will be numerically greater than the SPL (i.e. for a sound of ten seconds duration the SEL will be 10 dB higher than the SPL, for a sound of 100 seconds duration the SEL will be 20 dB higher than the SPL and so on).

2.3.5 The dB_{HT} (Species)

Measurement of sound using electronic recording equipment provides an overall linear level of that sound. The level that is obtained depends upon the recording bandwidth and sensitivity of the equipment used. This, however, does not provide an indication of the impact that the sound will have upon a particular fish or marine mammal species. This is of fundamental importance when considering the behavioural impact of underwater sound, as this is associated with the perceived loudness of the sound by the species. Therefore, the same underwater sound will affect marine species in a different manner depending upon the hearing sensitivity of that species.

This scale incorporates the concept of “loudness” for a species. The metric incorporates hearing ability by referencing the sound to the species’ hearing threshold, and hence evaluates the level of sound a species can perceive. In Figure 2-1, the same noise spectrum is perceived at a different loudness level depending upon the particular fish or marine mammal receptor. The aspect of the noise that can be heard is represented by the ‘hatched’ region in each case. The receptors also hear different parts (components) of the noise spectrum. In the case shown, Fish 1 has the poorest hearing (highest threshold) and only hears the noise over a limited low frequency range. Fish 2 has very much better hearing and hears the main dominant components of the noise. Although having the lowest threshold to the sound, the marine mammal only hears the very high components of the noise and so it may be perceived as relatively quiet.

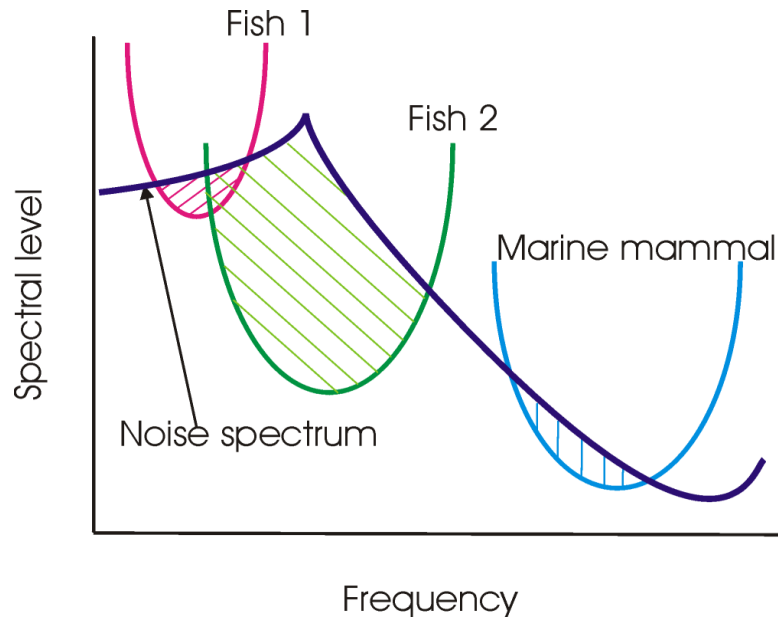


Figure 2-1 Illustration of perceived sound level (dB_{ht}) for representative fish and marine mammal species.

Since any given sound will be perceived differently by different species (since they have differing hearing abilities) the species name must be appended when specifying a level. For instance, the same sound might have a level of $70\text{ dB}_{ht}(\textit{Gadus morhua})$ for a cod and $40\text{ dB}_{ht}(\textit{Salmo salar})$ for a salmon.

The perceived noise levels of sources measured in $dB_{ht}(\textit{Species})$ are usually much lower than the un-weighted (linear) levels, both because the sound will contain frequency components that the species cannot detect, and also because most aquatic and marine species have high thresholds of perception to (are relatively insensitive to) sound.

2.4 The INSPIRE model

The Impulse Noise Sound Propagation and Impact Range Estimator (INSPIRE) model has been developed by Subacoustech specifically to model the propagation of impulsive broadband underwater noise in shallow waters. It uses a combined geometric and energy flow/hysteresis loss model to conservatively predict propagation in relatively shallow coastal water environments, and has been tested against actual results from a large number of other offshore wind farm piling operations.

The model is able to provide a wide range of physical outputs, including the peak pressure, impulse, SEL and dB_{ht} . Transmission Losses are calculated by the model on a fully range and depth dependent basis. The INSPIRE model imports electronic bathymetry data as a primary input to determine the transmission losses along transects extending from the pile location which has been input in addition to other simple physical data.

INSPIRE has a model of mitigation built in, which allows the effect of bubble curtains, cladding, and other mitigation methods to be estimated. It should be noted that when the frequency-dependent behaviour of these methods is considered, they are often found to be less effective than if simple measures of overall sound level such as peak pressure are used.

3 Impact of underwater sound on marine species

3.1 Introduction

3.1.1 Anthropogenic Noise and the Marine Environment

Over the past 20 years it has become increasingly evident that noise from human activities in and around underwater environments may have an impact on the marine species in the area. The extent to which intense underwater sound might cause an adverse environmental impact in a particular species is dependent upon the incident sound level, frequency content, duration and/or repetition rate of the sound wave (see, for example Hastings and Popper, 2005). As a result, scientific interest in the hearing abilities of aquatic animal species has increased. These studies are generally based on evidence from high level sources of underwater noise such as blast or impact piling, as these sources are likely to have the greatest environmental impact and therefore the clearest observable effects. In the absence of direct evidence from other sources these reviews have been used to inform assessments of lower level underwater noise sources such as drilling.

The impacts of underwater sound can be broadly summarised into three categories:

- Physical injury and fatality
- Auditory damage (either permanent or temporary)
- Behavioural avoidance

The levels of underwater noise associated with these impacts are briefly reviewed in section 3.2, and various criteria against which to assess the likelihood of these occurring presented.

Because of the profound effect of underwater noise on marine life, there is now a significant amount of legislation, guidelines and policies pertaining to their protection. In assessing the levels of anthropogenic noise, it is important to refer to the latest legislation. There are a number of policies which a development must comply with in order to best protect the marine environment. Of particular relevance are:

- Marine and Coastal Access Act (2009)
- Conservation (Natural Habitat) Regulations (2004)
- EU Habitat Directive (1992)
- JNCC marine SACs

Joint Nature Conservation Committee (JNCC), Natural England and Scottish Natural Heritage (SNH) have collaborated in producing guidance for the protection of marine European Protected Species (EPS) from injury and disturbance. The guidance can be used in conjunction with the marine area in England and Scotland as well as the UK offshore marine area, and is intended to be used when assessing likely impact of offshore activities in terms of committing an offence of disturbing, injuring or killing a marine EPS. The guidance highlights a number of offshore activities that could be associated with the disturbance or injury of marine EPS as a result of the emission of anthropogenic sound. Of particular note are piling operations, seismic surveys and the use of explosives. General protocols have been written by the JNCC for these three activities offering suggestions for mitigation measures in order to minimise the risk of injury to marine mammals. These are included in the annex in “The protection of marine EPS from injury and disturbance guidance” (2010) document.

3.1.2 Marine Mammals and Piling Noise

The “Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise” (JNCC, 2010) document is primarily concerned with the reduction of the likelihood of potential risk of injury or death to marine mammals in close proximity to piling operations, and does not discuss measures to mitigate disturbance effects. The standard piling protocol outlined is recommended to developers and instructs them to undertake the best available technique in an affordable, practical and established approach and consider producing an Environmental Management Plan. The standard piling protocol that is described discusses the use of Marine Mammal Observers (MMO’s), Passive Acoustic Monitoring (PAM), PAM operatives and implementing a mitigation zone which the MMO/PAM operative will monitor. The use of a soft-start is also advised at the start of a piling operation along with other mitigation measures. Variation to the given standard piling protocol may be possible but the developer would be required to justify any reasons for deviating from this.

3.2 Impacts and their associated sound levels

3.2.1 Physical injury and fatality

The data currently available relating to the levels of underwater noise likely to cause physical injury or fatality are primarily based on studies of blast injury at close range to explosives with an additional small amount of information on fish kill as a result of impact piling. All the data concentrates on impulsive underwater noise sources as other sources of noise are rarely of a sufficient level to cause these effects.

Parvin *et al.* (2007) presents a comprehensive review of information on lethal and physical impacts of underwater noise and proposes the following criteria to assess the likelihood of these effects occurring;

- Lethal effect may occur where peak-to-peak noise levels exceed 240dB re 1µPa; and
- Physical injury may occur where peak-to-peak noise levels exceed 220dB re 1µPa.

It might be noted however that for smaller fish sizes of mass 0.01 g, an interim “no injury” criteria has been proposed for fish exposed to impact piling noise of 208 dB re 1 µPa peak level (equivalent to 214 dB re 1 µPa peak-to-peak level) or a Sound Exposure Level of 187 dB re 1 µPa²s. In view of the very small fish size that this limit addresses, and the fact that it is extrapolated from limited data, it has not been used in this study.

3.2.2 Auditory Damage

Parvin *et al.* (2007) also suggests that for continuous sound, direct injury to gas-containing structures or auditory mechanisms may occur at lower incident sound levels depending on duration and frequency content of the noise. Several studies have been carried out relating to the onset of auditory damage in terms of Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS) (see, for example Nedwell *et al.* (2007b) and Southall *et al.* (2007) for a review of these studies).

Nedwell *et al.* (2007b) suggests the use of species specific weighting metrics (the dB_{ht}) similar to the approach used to assess human response to noise. The study suggests the perceived level by a particular species of 130 dB_{ht}(*Species*) will cause instantaneous hearing damage from a single event. As the assessment using this metric uses sound filtered for a specific marine species to determine if it is above 130 dB_{ht}(*Species*), this approach takes into the account the varying hearing abilities of marine species.

Southall *et al.* (2007) present another set of criteria for the levels of underwater noise that may cause auditory injury to marine mammals based on the M-weighted Sound Exposure Level (SEL) and peak Sound Pressure Level (see Section 2). These criteria are presented in Table 3-1. In order to obtain the weighted sound exposure levels the data are first filtered using the proposed filter responses presented in Southall *et al.* (2007) for either high, low or mid-frequency cetaceans or pinnipeds in water, then the sound exposure level is calculated.

Table 3-2 presents a summary of the various marine mammal groups, the suggested frequency range of hearing of each and example species.

Marine mammal group	Sound Type		
	Single pulses	Multiple pulses	Nonpulses
Low frequency cetaceans			
Sound Pressure Level	230 dB re. 1 μ Pa (peak)	230 dB re. 1 μ Pa (peak)	230 dB re. 1 μ Pa (peak)
Sound Exposure Level	198 dB re. 1 μ Pa ² -s (M_{lf})	198 dB re. 1 μ Pa ² -s (M_{lf})	215 dB re. 1 μ Pa ² -s (M_{lf})
Mid frequency cetaceans			
Sound Pressure Level	230 dB re. 1 μ Pa (peak)	230 dB re. 1 μ Pa (peak)	230 dB re. 1 μ Pa (peak)
Sound Exposure Level	198 dB re. 1 μ Pa ² -s (M_{mf})	198 dB re. 1 μ Pa ² -s (M_{mf})	215 dB re. 1 μ Pa ² -s (M_{mf})
High-frequency cetaceans			
Sound Pressure Level	230 dB re. 1 μ Pa (peak)	230 dB re. 1 μ Pa (peak)	230 dB re. 1 μ Pa (peak)
Sound Exposure Level	198 dB re. 1 μ Pa ² -s (M_{hf})	198 dB re. 1 μ Pa ² -s (M_{hf})	215 dB re. 1 μ Pa ² -s (M_{hf})
Pinnipeds (in water)			
Sound Pressure Level	218 dB re. 1 μ Pa (peak)	218 dB re. 1 μ Pa (peak)	218 dB re. 1 μ Pa (peak)
Sound Exposure Level	186 dB re. 1 μ Pa ² -s (M_{pw})	186 dB re. 1 μ Pa ² -s (M_{pw})	203 dB re. 1 μ Pa ² -s (M_{pw})

Table 3-1 Proposed injury criteria for various marine mammals groups (after Southall et al, 2007)

Functional hearing group	Estimated auditory bandwidth	Genera represented	Example species
Low frequency cetaceans	7 Hz to 22 kHz	Balaena, Caperea, Eschrichtius, Megaptera, Balaenoptera (13 species/subspecies)	Gray whale, Right whale, Humpback whale, Minke whale
Mid frequency cetaceans	150 Hz to 160 kHz	<i>Steno</i> , <i>Sousa</i> , <i>Sotalia</i> , <i>Tursiops</i> , <i>Stenella</i> , <i>Delphinus</i> , <i>Lagenodelphis</i> , <i>Lagenorhynchus</i> , <i>Lissodelphis</i> , <i>Grampus</i> , <i>Peponocephala</i> , <i>Feresa</i> , <i>Pseudorca</i> , <i>Orcinus</i> , <i>Globicephala</i> , <i>Orcaella</i> , <i>Physeter</i> , <i>Delphinapterus</i> , <i>Monodon</i> , <i>Ziphius</i> , <i>Berardius</i> , <i>Tasmacetus</i> , <i>Hyperoodon</i> , <i>Mesoplodon</i> (57 species/subspecies)	Bottlenose dolphin, striped dolphin, killer whale, sperm whale
High frequency cetaceans	200 Hz to 180 kHz	<i>Phocoena</i> , <i>Neophocaena</i> , <i>Phocoenoides</i> , <i>Platanista</i> , <i>Inia</i> , <i>Kogia</i> , <i>Lipotes</i> , <i>Pontoporia</i> , <i>Cephalorhynchus</i> (20 species/subspecies)	Harbour porpoise, river dolphins, Hector's dolphin
Pinnipeds (in water)	75 Hz to 75 kHz	<i>Arctocephalus</i> , <i>Callorhinus</i> , <i>Zalophus</i> , <i>Eumetopias</i> , <i>Neophoca</i> , <i>Phocartos</i> , <i>Otaria</i> , <i>Erignathus</i> , <i>Phoca</i> , <i>Pusa</i> , <i>Halichoerus</i> , <i>Histiophoca</i> , <i>Pagophilus</i> , <i>Cystophora</i> , <i>Monachus</i> , <i>Mirounga</i> , <i>Leptonychotes</i> , <i>Ommatophoca</i> , <i>Lobodon</i> , <i>Hydrurga</i> , and <i>Odobenus</i> (41 species/subspecies)	Fur seal, harbour (common seal), grey seal

Table 3-2 Functional marine mammal groups, their assumed auditory bandwidth of hearing and genera presented in each group (reproduced from Southall et al. (2007))

A further study was carried out by Lucke *et al* (2009) who looked at the effect of impulsive noise on a single harbour porpoise. The work was intended to serve as a basis for the definition of noise exposure criteria for harbour porpoises. Following measurement of baseline hearing data, the animal was exposed to increasing noise impulses from an airgun stimuli and after each its hearing threshold was tested. The study found that the temporary threshold shift (TTS) criterion was exceeded at a received sound pressure level of 199.7 dB_{pk-pk} re 1 µPa and a sound exposure level (SEL) of 164.3 dB re. 1 µPa²s, although this is not currently used in the UK.

It is worth noting that the dB SEL limit proposed by Lucke does not take the hearing capability of the harbour porpoise into account. Additionally, the study was carried out using an airgun stimulus, which has a somewhat different spectrum to a pile strike. These limitations may lead to a restriction that could potentially over- or under-estimate the impact of piling on harbour porpoise.

3.2.3 Behavioural response

At levels lower than those that cause auditory injury, noise may nevertheless have important behavioural effects on a species, of which the most significant is avoidance of the insonified area (the region within which noise from the source is above ambient underwater noise levels). The significance of the effect requires an understanding of its consequences; for instance, avoidance may be significant if it causes a migratory species to be delayed or diverted. However, in other cases, the movement of species from one area to another may be of no consequence.

Various metrics have been proposed to assess the possibility of auditory damage and behavioural avoidance response occurring to marine species. On the basis of a large body of measurements of fish avoidance of noise (Maes *et al*, 2004), and from re-analysis of marine mammal behavioural response to underwater sound, using the $dB_{ht}(\text{Species})$ metric, the following assessment criteria was published by the Department of Business, Enterprise and Regulatory Reform (BERR) (Nedwell *et al*, 2007b) to assess the potential impact of the underwater noise on marine species:

Level in $dB_{ht}(\text{Species})$	Effect
0 – 50	Low likelihood of disturbance
75 and above	Significant avoidance reaction by the majority of individuals but habituation or context may limit effect
90 and above	Strong avoidance reaction by virtually all individuals
Above 130	Possibility of traumatic hearing damage from single event

Table 3-3 Assessment criteria used in this study to assess the potential impact of underwater noise on marine species

3.2.4 Overview of hearing in fish and marine mammals

Behavioural impacts in fish following their exposure to underwater sound relate to the way in which they hear and how they may subsequently respond to the sound. Variation in the anatomy and physiology of the ears and associated structures in fish is extensive, indicating that different species detect sound in different ways (Popper and Fay, 1993). Furthermore, published data also indicates that there is a considerable variation in the hearing abilities of fish sensitive to sound, both in terms of the minimum levels of sound perceptible and the frequency range over which they can hear (e.g. Hawkins, 1981; Lovell *et al*, 2005; Popper *et al*, 2004; Hastings and Popper, 2005; Thomsen *et al*, 2006; Madsen *et al*, 2006). Any assessment of potential impacts on a particular species must therefore take this into account. The dB_{ht} , which is a probabilistic model, takes this into account by estimating the proportion of a population that will react, rather than trying to estimate whether an individual will.

This variation appears to be linked to particular physiological adaptations in the distance of the swim bladder to the inner ear. The herring for example has an extension of the swim bladder that terminates within the inner ear (Blaxter *et al*, 1981; Popper *et al*, 2004). Species such as dab and plaice do not have a swim bladder and thus tend to have a lower hearing ability than many other species of fish.

A recent study on behalf of COWRIE (Mueller-Blenkle *et al*, (2010)) investigated the reaction of cod and sole to recordings of impact pile driving noise played back on an underwater loudspeaker. The results of the study are interesting, but are difficult to interpret as the fish were well within the acoustic near field of the loudspeaker. In addition, the spectra presented for the reproduced insonifying field differ greatly from actual measured data, particularly at the low frequencies perceived by fish.

Sensitivity to underwater noise in marine mammals is considerably more developed than in fish due to the use of sound in these species for hunting, echolocation and communication. Although there is also considerable variation in the hearing abilities of marine mammals, the data suggest that, in general, they are able to perceive both a wider range of frequencies and also to lower levels than fish.

3.2.5 Audiograms of underwater species

The metric that has been used in this study to estimate the effect of noise, the dB_{ht} , is based on the audiogram of a species. When measuring the audiogram of an animal, it is necessary to determine the response to the sound by a technique that does not require cognitive compliance. Two principal techniques have been used to determine the audiogram of fish and marine mammal species, these involve either a behavioural response technique or auditory evoked potential measurements (monitoring of the electrical activity of the animals hearing mechanism) see for example Lovell *et al* (2005).

The audiogram data highlights that species of fish hear at very low frequency (typically 10 Hz to 1000 Hz). Of the fish audiograms shown in Figure 3-1, the most sensitive to underwater sound is the herring (*Clupea harengus*) which is often defined as a hearing specialist. Audiogram data from Enger (1967) for the herring indicates that compared to most fish species it has a fairly broad response to the low frequency components of underwater sound, with hearing threshold at levels below 80 dB re 1 μPa , over the frequency range from 32 Hz to 1000 Hz. The data suggests that the cod is also sensitive to underwater sound, but over a narrower, low frequency range. According to Chapman and Hawkins (1973) peak hearing sensitivity for the cod is at a frequency of 160 Hz, where hearing threshold is at a level of 75 dB re 1 μPa , and at this frequency the data suggests that cod hearing sensitivity is comparable with the herring.

Data for dab (Chapman and Sand, 1974) suggests that this species is less sensitive to underwater sound than the species above. They are therefore likely to perceive a given underwater sound at a lower loudness level. In the case of the seahorse (*Hippocampus erectus*), a key species in the English Channel, tentative audiological presented by Anderson and Mann (2011) show sensitivity to underwater sound typical of a 'hearing generalist' fish.

In comparison, marine mammal species such as the bottlenose dolphin (*Tursiops truncatus*) and the harbour porpoise (*Phocoena phocoena*) are sensitive to a very broad bandwidth of sound. The audiogram data presented in Figure 3-2 indicates that they are responsive at frequencies from 100 Hz to 170 kHz. Peak hearing sensitivity occurs over the frequency range from 20 kHz to 150 kHz, where for example the audiogram for the harbour porpoise (Kastelein *et al.*, 2002) indicates that it is able to hear sounds below 40 dB re 1 μPa . This typically corresponds to sea noise levels at these frequencies. The audiogram from Johnson (1967) indicates that the bottlenose dolphin also hears over the same broad frequency band, but that peak sensitivity is of the order of 10 dB less sensitive.

Figure 3-3 presents the underwater audiogram for several species of seal (airborne noise data are also available, but are not relevant in the context of underwater sound perception). The data for the common (harbour) seal (*Phocoena vitulina*) from Kastak and Schusterman (1998) indicates that this species has better low and mid-frequency hearing than the harbour porpoise and bottlenose dolphin (frequency range from 100 Hz to approximately 5 kHz), but that their hearing is not as sensitive at very high frequency.

Where good quality audiogram data for a species does not exist or is not available, it is possible that the audiogram data for another surrogate species having a similar hearing morphology may be used to provide an indicative assessment of potential impact. The surrogate audiogram data is usually selected on the basis of having similar auditory morphology, and therefore hearing abilities, as the species of interest. A surrogate may also be used to provide a conservative estimate of potential impact ranges by selecting a suitable representative audiogram for a species having sensitive hearing, that is, the lowest auditory threshold. For example, in this study an audiogram for red sea bream (*Pagrus major*) has been used to conduct the analysis for black sea bream (*Spondyliosoma cantharus*), for which there is no available audiogram data.

As there is no single published dataset for seal species that covers the full audiometric range, the FIR filter used for the common seal uses the data of Kastak and Schusterman (1998) for the frequency range from 100 Hz to 6.4 kHz, and the data from Mohl (1968) over the higher frequency range from 8 to 128 kHz. As the data in Figure 3-3 suggests that the hearing of the grey seal (*Halichoerus grypus*) and harp seal (*Pagophilus groenlandicus*) are marginally less

sensitive than that for the harbour (common) seal, the data for the harbour seal presented in this report represents a conservative estimate of the perceived sound levels for the other seal species. Predicted impact ranges would therefore be considered as conservatively long for these other seal species.

3.2.6 Selection of species

The species upon which the dB_{nt} analysis has been conducted in this study have been selected based upon regional significance and also crucially upon the availability of a good quality peer-reviewed audiogram shown in Figures 3-1 to 3-4. It should be noted that the analysis undertaken for black sea bream and shad are to be taken as tentative only as limited data is available.

The species of fish considered in this study are:

- Bass (*Dicentrarchus labrax*), a fish with generalist hearing capability (Lovell, 2003);
- Cod (*Gadus morhua*), (Chapman and Hawkins, 1973) a fish hearing generalist that is relatively sensitive to underwater sound;
- Dab (*Limanda limanda*), a flatfish species with generalist hearing capability, but that based on current peer reviewed audiogram data (Chapman and Sand, 1974) is the most sensitive flatfish to underwater sound, used as a surrogate to represent sole and plaice;
- Herring (*Clupea harengus*), a fish hearing specialist that, based on current peer reviewed audiogram data (Enger, 1967) is the most sensitive marine fish to underwater sound;
- Red sea bream (*Pagrus major*), a fish hearing generalist part of the family *Sparidae* (Ishioka et al, 1988), used as a surrogate to represent black sea bream.
- Sandeels or sand lances lack a swim bladder and generally have poor sensitivity to sound (Suga et al, 2005). They are capable of hearing low frequencies typically less than about 500 Hz;
- Seahorses (generalised from the lined seahorse, *Hippocampus erectus*) demonstrate a hearing sensitivity typical of a hearing generalist fish with an evoked potential audiogram (Anderson and Mann, 2011);
- Shad are related to herring as both are part of the family *Clupeidae*. Shad are thought to be less sensitive to underwater sound although no reliable data exists.

The species of marine mammal considered in this study are:

- Harbour (common) seal (*Phoca vitulina*), a pinniped that based on current peer reviewed audiogram data (Mohl, 1968, Kastak and Shustermann, 1998) is the most sensitive seal species to underwater sound and may be representative of other marine mammals that are sensitive to mid-frequency underwater sound;
- Harbour porpoise (*Phocoena phocoena*), a marine mammal (toothed whale) that based on current peer reviewed audiogram data (Kastelein, 2002) is the most sensitive marine mammal to high frequency underwater sound;
- Bottlenose dolphin (*Tursiops truncatus*), (Johnson, 1967) a marine mammal (toothed whale) with good high frequency hearing sensitivity. Also used as a surrogate for white-sided dolphin;
- Humpback Whale (*Megaptera novaeangliae*). There is very little information available about the hearing of large mysticetes, so in this case an approximation of the hearing sensitivities of humpback whales made by Erbe (2002), including an upper and lower range audiogram, for which Erbe states that the true audiogram is likely to be somewhere in between these two bands. Due to the similar frequency ranges involved a modified harbour seal audiogram with increased sensitivity to sound has been used to estimate the noise level perceived by large whales, as a best fit between the upper and lower

audiograms. This process is illustrated in Figure 3-4. This audiogram has also been used as a surrogate for minke whale.

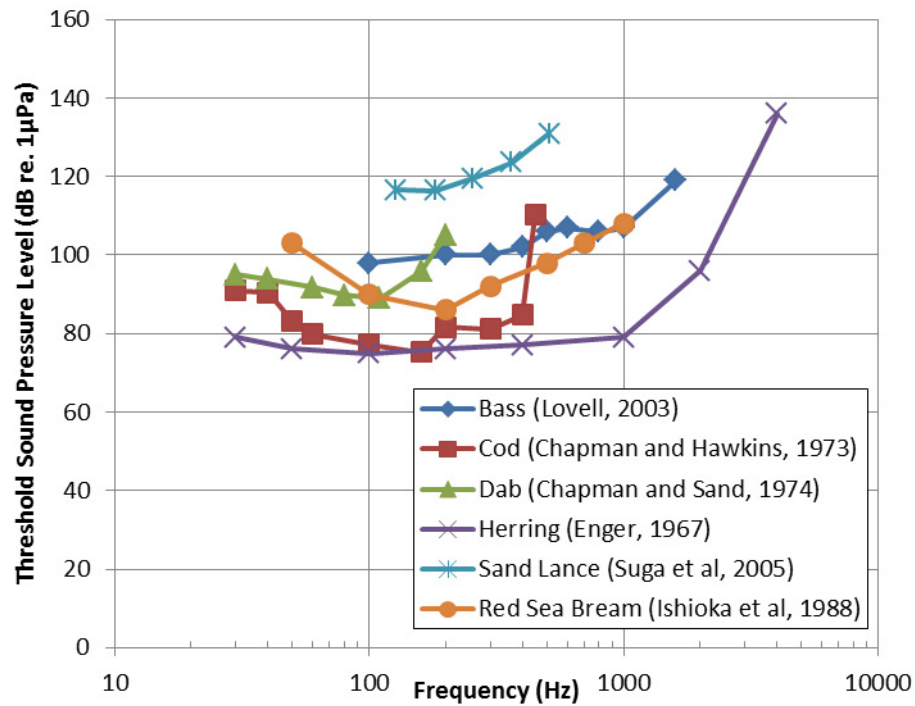


Figure 3-1 Comparison of hearing thresholds for species of fish

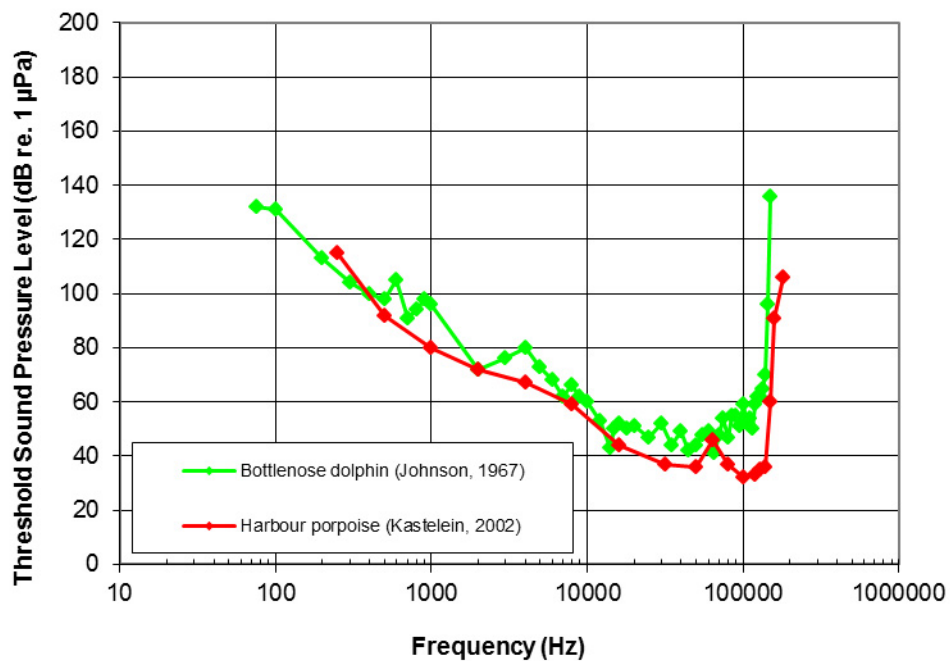


Figure 3-2 Comparison of hearing thresholds for species of marine mammal

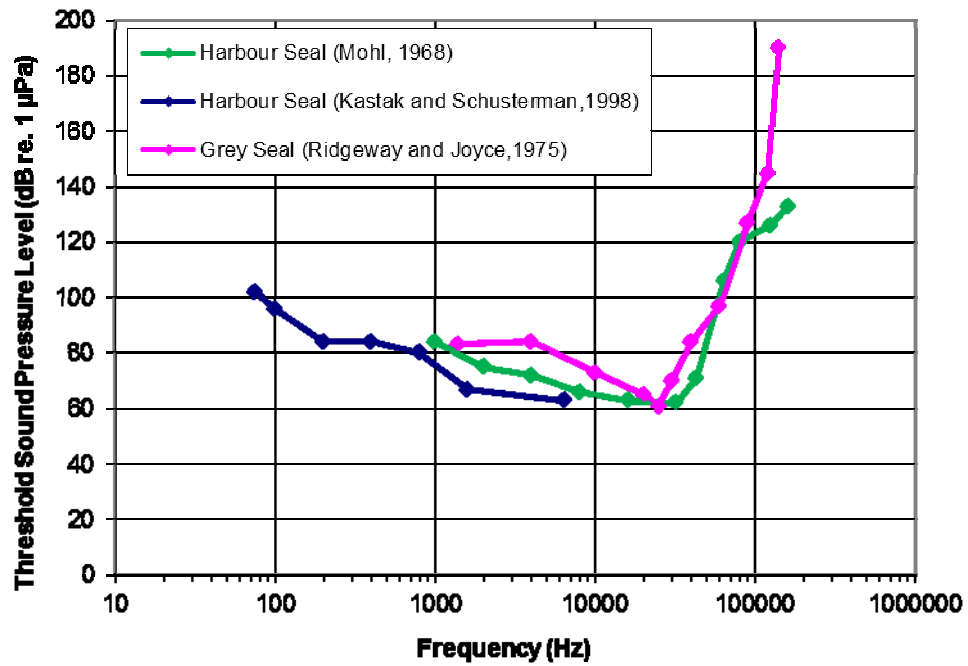


Figure 3-3 Comparison of auditory threshold levels of various species of seal

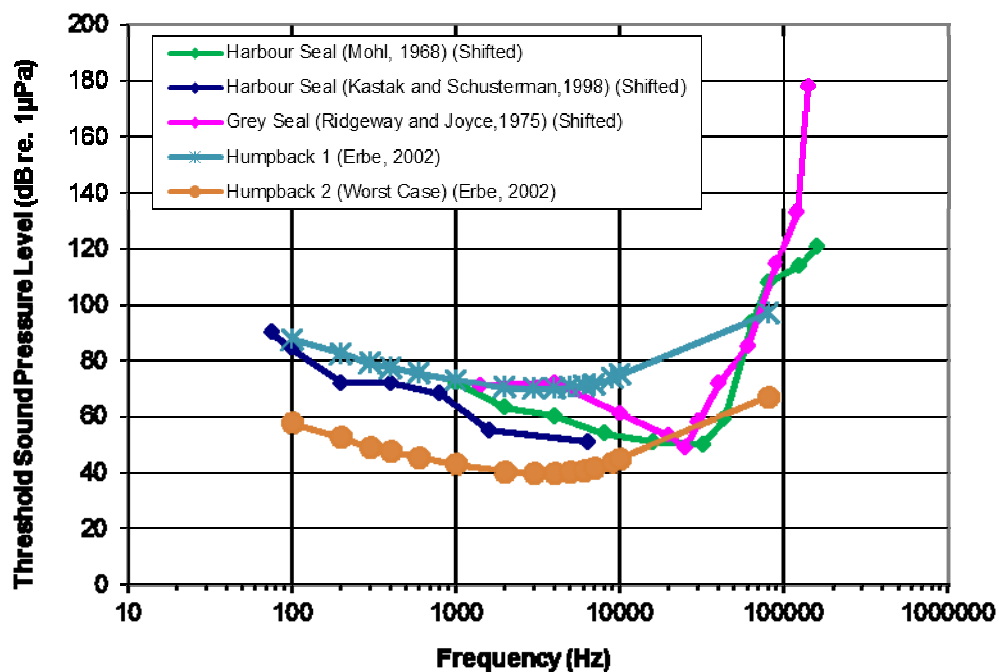


Figure 3-4 Audiograms for the Humpback Whale, presented in Erbe (2002), presented with the shifted seal audiograms used for the calculations in this study

A number of fish species are locally important but have no significant audiological information available. Table 3-4 below provides a list of these species alongside tentative surrogates, generally along taxonomic lines. These should be considered only as very speculative suggestions, as without any formal study their capabilities are unknown.

Species	Latin name	Comment
Smelt	<i>Osmerus eperlanus</i>	Of superorder Protacanthopterygii which includes salmon
Sea trout	<i>Salmo trutta</i> (similar to brown trout)	Audiogram available - Less sensitive than salmon
European eel	<i>Anguilla anguilla</i>	Audiogram available, similar to dab (Jerko et al 1989)
Atlantic mackerel, Horse mackerel (scad)	<i>Scomber scombrus</i> , <i>Decapterus macarellus</i>	Japanese jack mackerel audiogram available, similar to seahorse
European conger	<i>Conger conger</i>	See European eel
Red mullet	<i>Mullus barbatus</i>	Of the order perciformes, as wrasse and mackerel
Pollock Saithe (coley)	<i>Pollachius pollachius</i> <i>Pollachius virens</i>	Audiogram available for walleye pollock, like bass
Bib (pouting)	<i>Trisopterus luscus</i>	Cod
Whiting	<i>Merlangius merlangus</i>	Cod
Monkfish (angler)	<i>Lophius piscatorius</i>	Of superorder paracanthopterygii, also including gadiformes (cod)
Wrasse (various species)	e.g. <i>Labrus mixtus</i>	Blue headed wrasse audiogram: Tavalga, W.N. & Wodinsky, J. 1963. Less sensitive than bass
Gurnards (various species)	e.g. East Atlantic red gurnard <i>Chelidonichthys cuculus</i>	Hearing generalist; no clear link for surrogate species.
Turbot	<i>Scophthalmus maximus</i>	Flatfish (dab)
Brill	<i>Scophthalmus rhombus</i>	Flatfish (dab)
Plaice	<i>Pleuronectes platessa</i>	Flatfish (dab)
Lemon sole	<i>Microstomus kitt</i>	Flatfish (dab)
Flounder	<i>Platichthys flesus</i>	Flatfish (dab)

Table 3-4 Suggested surrogate species for locally important species, to be used with caution

3.2.7 Other concerns

3.2.7.1 Cephalopods

There is a specific concern in the Rampion Offshore Wind Farm region regarding the risk to cephalopods, particularly cuttlefish and squid, from noise during the piling. Relatively little is

known about their sensitivity to noise, but indications are that they have a low sensitivity compared to most fish.

Williamson & Budelmann (1985) states that the statocyst (otolith) of the northern octopus, *Eledone cirrosa*, is sensitive to vibration (~20-200 Hz) although it is 3-4 orders of magnitude less sensitive than fish (say, cod or salmon). It is of the same order as other aquatic invertebrates, e.g. crayfish (*Cherax destructor*, *Procambarus clarkii*).

Following the ABR experiments on the European prawn (*Palaemon serratus*) by Lovell et al (2005), Hu et al (2009) were prompted to formulate a hypothesis as to whether such a technique would be successful with cephalopods, despite these animals having no real brainstem. They recorded Acoustically Evoked Potentials (AEPs) from two cephalopods (oval squid *Sepioteuthis lessoniana* and octopus *Octopus vulgaris*) indicating a measurable sensitivity to sound in excess of 400 Hz and up to 1000 Hz (octopus) and 1600 Hz (squid), well above their previously known low frequency sensitivity.

Most recently, André et al (2011) studied the effects of noise on adults of four cephalopod species (*Loligo vulgaris* [n=5], *Sepia officinalis* [n=76], *Octopus vulgaris* [n=4], and *Illex coindetii* [n=2]) over a period of two years, using two hours of exposure at levels of 157 dB re 1 µPa rms (175 dB re 1 µPa peak). Lesions in all of the species were identified at this relatively low sound level exposure with nothing on the controls, which are generally only found in other species at much higher intensities of sound. There has been some scepticism (Madsen at Aarhus University in Denmark and Mooney at Woods Hole Oceanographic Institution, Massachusetts, Kessler (2011)) levelled at André's results, primarily over the experimental methodology, although Mooney noted that their research is a "good first step" in determining whether anthropogenic noise harms cephalopods.

To date, there are no large scale studies that show evidence that cephalopods in the wild will be harmed by piling noise, and no criteria that could be used to provide an objective assessment of its potential impact specifically on these species. There is evidence that their audiological sensitivity, and therefore the risk to their audiological systems through exposure to noise, is likely to be somewhat lower than the least sensitive fish species assessed here.

3.2.7.2 Life cycle

The assessments on the potential effects of piling noise produced during wind farm installation on fish have largely focussed on the audiological capabilities of adults of the various fish species of concern in the development region. Concern has been expressed as to the potential effects on these species at different stages in their life cycle, such as at larval and juvenile stages. If it was found that they were more sensitive to sound than adults, it might imply that the effects of noise on them during wind farm construction could have a proportionally greater effect than on adult fish.

A number of different studies have been undertaken, although the number of studies available on this subject overall is limited, and they pertain only to a very small number of species.

For the more sensitive 'hearing specialist' fish, Higgs *et al* (2003) found the zebrafish (*Danio rerio*) displayed no significant shift in auditory sensitivity during early development, although the frequency bandwidth of sound detectable to the zebrafish was found to increase over time. Zeddies and Fay (2005) noted no response to auditory stimuli in the same species for four days post-fertilisation, but no significant change in sensitivity from five days to adult. Lechner et al (2010) studied ontogenetic development of hearing and sound production in the otophysine mochokid catfish (*Synodontis schoutedeni*) and found that hearing sensitivity increased slightly in adults at low frequency (50 Hz - 1 kHz), but decreased at higher frequencies (5-6 kHz). Studies by Mann et al (2009) into the walleye pollock (*Theragra chalcogramma*) at three different age groups (ranging from 15 grams to 700 grams) found no significant difference in hearing sensitivity between the age groups.

For 'hearing generalist' fish, with a generally lower sensitivity to sound than the specialists, Iwashita *et al* (1999) studied ontogenetic development in 0 to 2 year-old red sea bream (*Pagrus major*). The authors report that as the fish grew, thresholds at the lower frequencies between 100 to 200 Hz significantly decreased. It is considered that hearing sensitivity of red sea bream improves as they grow from juvenile to adult. Following this, Wysocki & Ladich (2001) studied ontogenetic development in the croaking gourami (*Trichopsis vittata*). As the size of the developing juveniles increased from 0.18 g to 0.30 g, the authors found indications that the frequency bandwidth of auditory thresholds decreases with age whilst hearing sensitivity improves.

Kenyon (1996) investigated the effects of increasing age from juvenile to adult damselfishes (*Pomacentridae*). Young juveniles were found to exhibit poor hearing compared to previously identified adult audiograms, and the hearing progressively improved with age as the fish approached adulthood. Sisneros & Bass (2005) found the same result with midshipmanfish (*Porichthys notatus*).

Bolle *et al* (2012) studied the lethality of pile driving sound on common sole (*Solea solea*) larvae. The highest cumulative sound exposure level applied was 206 dB re 1 $\mu\text{Pa}^2\text{s}$, which corresponds to 100 strikes at a distance of 100 m from a typical North Sea pile-driving site. The results showed no statistically significant differences in mortality between exposure and control groups at sound exposure levels, which were well above the US interim criteria for non-auditory tissue damage in fish.

Cott *et al* (2012) assessed hearing damage to northern pike (*Esox lucius*), a hearing generalist, both juvenile and adults, when exposed to seismic airgun blasts. No evidence of hearing loss (temporary) to the young specimens was detected, although the adults showed a marked variation in auditory sensitivity following exposure under the same conditions.

The above evidence suggests that there appears to be a limited effect from noise on young fish when compared with mature counterparts. Generally the juvenile fish were found to have a lower sensitivity to noise than adults, possibly indicating a greater degree of resistance to injury as a result of exposure to high noise levels. This hypothesis appears to be borne out by the results of Bolle *et al* (2012) and Cott *et al* (2012), although the limited information available means that their results should not be extrapolated to other species without further research.

3.3 Impact of underwater noise on humans

The impact of excessive levels of noise in air is well known to cause deafness and legislation is in place to control the effects of noise as a pollutant and as a hazard in the case of occupational noise exposure. The effects of waterborne noise have not been widely investigated, with most research and analysis having been conducted for the military sector. However, where there has been a great deal of attention given to exposure of noise to humans in air then the possibility of waterborne noise exposure should be taken into consideration. In the case of impact piling for the installation of offshore wind turbines which are in the vicinity of popular diving sites or are situated close to the coast, the potential risk of adverse effects exists.

The effects of exposure of humans to underwater impulsive sound depends on the level of exposure, and may be divided into three categories – *primary*, or life threatening physical injury, including death and severe physical injury; *secondary*, or non-life threatening physical injury, and in particular auditory damage; and tertiary injury, due to behavioural effects.

3.3.1 Physical injury and death

Much of the available information on underwater effects on humans concerns blast injuries and was carried out during the 1940s and 1950s. Bebb and Wright (1951 to 1955) conducted experiments using animals and volunteer divers which demonstrated that severe symptoms of

blast occurred for blast waves with peak pressures of about 246 dB re 1 μ Pa and above. These results suggested underwater blast waves with a level of 246 dB re 1 μ Pa peak pressure or above could prove lethal to unprotected divers. Further existing information on the effects of underwater blasts arise from accidental exposure to blast summarized by Cudahy and Parvin (2001), however in these instances no record of the pressure wave parameters is available.

Measurements of underwater bolt guns have been undertaken previously. Underwater bolt guns contain an explosive propellant and which exposes the operator to significant levels of blast pressures. Sterba (1987a) investigated the potential for hearing damage due to a Ramset Stud Gun. The impulse resulting from firing the gun was measured to be 10.76 psi-ms (74.19 Pa-s). Two of the five divers operating the gun reported tinnitus which resolved within one hour. Measurements undertaken in July 1993 recorded the noise exposure experienced by divers when using a Cox's Bolt Gun and a Tornado Stud Gun (Nedwell *et al.*, 1993). Measurements were taken at the diver's ear and a peak pressure of 350,000 Pa, with a corresponding impulse of 500 Pa-s were recorded for the Cox's Bolt Gun. The divers described the experience as "unpleasant" leading to the guns being fired at arm's length.

3.3.2 Auditory injury

Exposure to underwater sounds that are not high enough to cause physical injury could still potentially cause auditory damage. This could occur as a result of a single traumatic exposure to a high level of noise. Also, and more commonly, is the effect of cumulative exposure of noise over a longer period in the same manner as airborne noise. Such exposure may result in TTS, and if continued at a high enough level could lead to significant hearing loss in the long term.

3.3.3 Criteria for assessing human audiological injury to exposure of underwater sound

Existing criteria are defined in the Control of Noise at Work Regulations (2005) and are utilised to judge the hazard from airborne noise exposure. It has been determined that where exposure to a sound level equivalent of 85 dB(A) re 20 μ Pa (111 dB re 1 μ Pa) for an eight hour period is exceeded, a significant risk of long term hearing loss exists; for each halving of the duration of exposure an increase in level of 3 dB is permitted. Peaks in excess of 130 dB re 20 μ Pa (166 dB re 1 μ Pa) are also hazardous and can cause traumatic injury, in which permanent damage can be caused by a single exposure.

A significant experimental programme reported by Nedwell (1998) indicates that the ear is inefficient in perceiving sound in water due to water's high acoustical impedance and the consequent mismatch of acoustical impedance. The degree of reduction in efficiency is frequency dependent.

Measurements of underwater hearing threshold were made in a water tank. The subject was submerged in the experimental facility with their sternal notch at mid water depth, breathing from a diving valve from a cylinder of air placed within the tank, but away from the diver. Measurements of hearing threshold in air and in water were taken at all of the audiometric test frequencies: measurements were made of the hearing threshold of pure tones at 1/3-octave centre frequencies from 20 Hz to 20 kHz.

Figure 3-5 illustrates the results. Whereas human hearing in air is most sensitive at about 2 kHz, in water the results indicate it is most sensitive at about 800 Hz. Underwater hearing is inefficient at low frequencies, but increases in sensitivity at about 40 dB per decade (12 dB per doubling of frequency) in the range from 20 Hz to about 600 Hz. There is a broad and fairly flat threshold of underwater hearing at about 48 dB re 1 μ Pa from about 600 Hz to 1.2 kHz. At higher frequencies the sensitivity generally decreases at about 40 dB per octave. It may be seen that at all frequencies the sensitivity of underwater hearing is significantly lower than in air. The difference is smallest at the lowest frequencies measured, of the order of 20 dB, and increases to about 70 dB at 4 kHz.

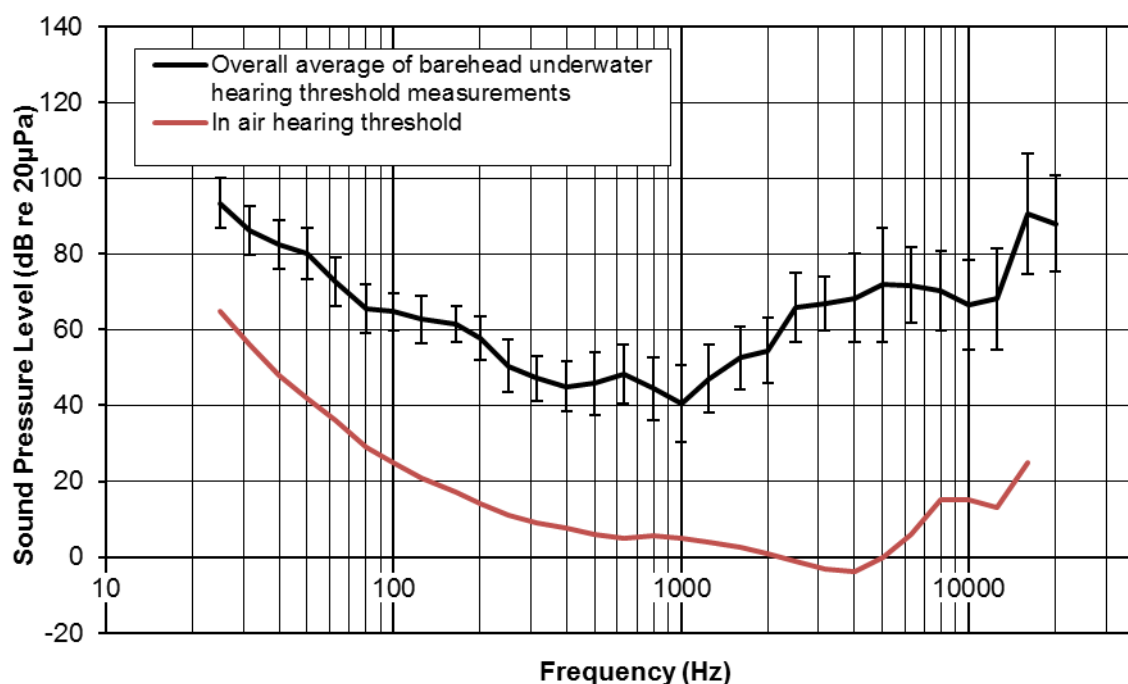


Figure 3-5 Results of underwater hearing threshold measurements (Nedwell, 1998)

The implication of this result is that a significant degree of protection from the effects on hearing of underwater impulsive sound is conferred by the inefficiency of the hearing process, and this effect can be used to modify the criteria indicated above for application to divers. The corrected level is termed the dB(UW) level, and a level of 85 dB(UW) for an eight hour period could indicate a risk of hearing loss. However, if the time of exposure is reduced to 15 minutes a level of 100 dB(UW) is permitted. Peaks in excess of 130 dB(UW) are assumed to be capable of causing permanent traumatic auditory injury. It should be noted that the link between the airborne noise exposure criteria as noted in the Control of Noise at Work Regulations 2005 and the dB(UW) is only at a preliminary stage, and further study in this area is required before confident assertions with respect to underwater noise impacts on humans can be made.

3.3.4 Startle

A further effect that divers could experience from exposure to underwater noise is significant behavioural effects that could lead to injury. This could occur in the case of diver who is subjected to a sudden exposure of sound resulting in the diver being startled. Adverse effects to a diver may include a reaction of panic and rapid surfacing leading to a risk of decompression injury or death, or the spitting out his diving valve heightening the attendant risk of drowning.

There are no existing guidelines as to acceptable levels of noise in respect of startle. However, a level of 90 dB(A) in air is judged to be “very loud” and probably forms a suitable criterion. It was recommended in a previous Subacoustech Report E356R0105 that until better information is available, a level of 90 dB(UW) peak level is adopted as a criterion for a level of noise above which strong aversive reaction or avoidance may occur.

4 Modelling of underwater sound levels as a function of range

4.1 Introduction to subsea noise propagation modelling using INSPIRE

As part of this study, the propagation of underwater noise from the pile driving operations has been modelled, in order to provide estimates of underwater sound levels as a function of range from selected positions at the Rampion Offshore Wind Farm site.

Transmission of sound in the underwater environment is highly variable from region to region, and can also vary considerably with the local bathymetry and physical conditions. Some frequency components of piling noise can be more rapidly attenuated than others in very shallow water regions typical of the silt and sandbank regions located around European coasts in which wind farms are often constructed.

In general, in shallow coastal environments, the lower the frequency of sound, the more efficiently the sound propagates. High frequency components, by contrast, are more heavily attenuated in shallow water, especially when the water depth decreases with range. In these conditions there is also a greater interaction of the sound with the seabed, and the sound is therefore more rapidly absorbed than would be the case in the deep ocean. In shallow water geometric spreading can also be important. Sound may spread not only through the water but also through the underlying sediments, resulting in attenuation of its level as a result of energy being lost into the underlying rock.

In the conditions typical of those in which wind farms are installed (estuaries and shoals), the underwater sound may vary considerably temporally and spatially due to these factors. The approach used in this and previous studies is, therefore, to base the modelling and assessment on a suitable acoustic model, which has been validated against a database of measured data in similar operations.

The Impulse Noise Sound Propagation and Impact Range Estimator (INSPIRE) model has been developed by Subacoustech Environmental Ltd specifically for the estimation of marine impact piling operations. It uses a combined geometric and energy flow/hysteresis loss model to model subsea noise propagation. The INSPIRE model (currently version 3.4.0) has also been tested “blind” against measured impact piling noise data from several offshore construction operations, as well as a range of shallow water estuarine piling operations, and has been found to provide accurate results.

One hundred and eighty transects have been modelled for each pile location using INSPIRE. These transects are equally spaced at two degree intervals (taken from grid north) for 360 degrees around the pile position and are generally taken to the extent of any impact ranges or until land is reached. The bathymetry along each of these transects has been recorded and depth profiles have been generated using digital bathymetry data and input into the INSPIRE model. In order to provide a balanced estimate of the likely impacts of underwater noise during piling at Rampion in terms of water depth, the varying tidal states that may be encountered have been taken into account. Modelling has been carried out for water depth at Mean High Water Springs (MHWS) as a worst case, which in this case has been given as 5.5 m above LAT.

4.2 Modelling Locations

The following locations were considered in the noise modelling exercise:

Location ID	Coordinates
East (E)	50.6606; -0.0488
West (W)	50.6849; -0.3607

Table 4-1 Coordinates of modelling locations

4.3 Modelling scenarios

Three scenarios have been modelled in two positions in the Rampion wind farm site. This includes two scenarios involving jacket structures, and one scenario involving monopiles.

For the jacket structure scenarios, the foundation consists of either four 1.53 m or 2.6 m diameter pin piles. The hammer that has been estimated to be used to drive these piles is to have a maximum hammer capacity of 600 kJ for the 1.53 m pin pile and 900 kJ for the 2.6 m pin pile. The piles would be installed consecutively, although there has to be a delay between the installation of each pile to allow the piling rig to move, which for the purposes of the study has been modelled to be two hours. The ramp-up details shown in Table 4-2 have been used for each pile modelled. The modelling run takes into account a 24-hour period; hence within this period only three piles will be installed as part of the jacket structure since each pile has been modelled to take four hours, with the addition of the time it takes in between each pile. The installation of any more than three piles in a 24-hour period would be considered extremely unlikely.

For the 6.5 m diameter monopile scenario the maximum hammer capacity of 1500 kJ is estimated to be used. The ramp-up in blow energy has been modelled to follow the same percentage increases as used for each pin pile in the jacket structure.

	Total piling duration	% of maximum hammer capacity
Ramp-up details	10 minutes	10%
	10 minutes	25%
	5 minutes	50%
	5 minutes	75%
	210 minutes	100%

Table 4-2 Summary of the modelled ramp-up details for Rampion

This is likely to be a 'worst case' piling scenario, as the average time for pile installation is predicted to be typically of the order of two hours.

4.4 Unweighted levels

Table 4-3 shows the estimated ranges out to which lethal and physical injury may occur in marine species based on unweighted peak-to-peak sound levels and the criteria presented in Section 3.2.1. The data indicate that marine species may suffer a lethal effect out to a range of less than 10 m at maximum blow energy, and that physical injury is likely to occur out to between 25 m and 65 m.

It should be noted that these impact ranges are based on the extrapolation of data from measurements taken at considerably greater ranges since it is generally not possible to carry out measurements this close to impact piling operations. “Near field” acoustic effects are likely to occur at close range to the piling operations so the levels of underwater noise may be lower than those estimated by the INSPIRE model.

	Range to 240 dB re. 1 µPa (Lethal effect) (m)	Range to 220 dB re. 1 µPa (Physical injury) (m)
1.53 m Pin pile (West)	10	25
1.53 m Pin pile (East)	10	25
2.6 m Pin pile (West)	10	40
2.6 m Pin pile (East)	10	40
6.5 m Monopile (West)	10	65
6.5 m Monopile (East)	10	65

Table 4-3 Summary of ranges out to which lethal effect and physical injury are expected to occur in marine species

4.5 dB_{ht}(Species)

The 130 dB_{ht} perceived level is used to indicate traumatic hearing damage over a very short exposure time of only a few pile strikes at most. Tables 4-4 and 4-5 present a summary of the maximum ranges to which traumatic hearing damage is likely to occur in marine species.

The largest estimated ranges out to which hearing damage may occur are for humpback whale, with 130 dB_{ht} ranges of up to 630 m during the 2.6 m pin pile jacket structure scenario and 690 m during the 6.5 m monopile scenario.

	1.53 m Pin pile (W)	2.6 m Pin pile (W)	6.5 m Monopile (W)
Bass	20	20	60
Cod	50	120	390
Dab	20	30	90
Herring	110	210	480
Red Sea Bream	20	30	50
Sand Lance	<5	< 5	< 5
Seahorse	20	20	60
Shad	20	20	60
Bottlenose Dolphin	230	280	360
Harbour Porpoise	420	500	600
Harbour Seal	110	140	180
Humpback Whale	470	590	630

Table 4-4 Summary of ranges out to which traumatic hearing damage are expected to occur in marine species at the most westerly position in Rampion

	1.53 m pin pile (E)	2.6 m pin pile (E)	6.5 m monopile (E)
Bass	20	20	60
Cod	50	130	450
Dab	20	30	90
Herring	120	220	510
Red Sea Bream	20	30	50
Sand Lance	< 5	<5	< 5
Seahorse	20	20	60
Shad	20	20	60
Bottlenose Dolphin	240	290	360
Harbour Porpoise	430	520	600
Harbour Seal	120	150	180
Humpback Whale	500	630	690

Table 4-5 Summary of ranges out to which traumatic hearing damage are expected to occur in marine species at the most easterly position in Rampion

Tables 4-6 to 4-13 present a comparison of estimated 90 dB_{ht}(Species) and 75 dB_{ht}(Species) impact ranges for behavioural response for the species of interest at high tide. Maximum, minimum and mean ranges are presented for all the impact piling scenarios at both locations.

It can be seen that the largest impact ranges are predicted for herring, harbour porpoise and humpback whale. With a maximum 90 dB_{ht} impact range for herring of 39 km, 20 km for the harbour porpoise and 37 km for the humpback whale, for the 6.5 m scenario of the installation of a monopile east in the Rampion offshore wind farm site.

It should be noted that for a number of species the minimum ranges presented correspond to the minimum distance between the wind turbine position and the coastline. This is because the sound has not attenuated to below 90 or 75 dB_{ht} before reaching the coastline. Hence why, for example the majority of the minimum 75 dB_{ht} ranges for the 6.5 m monopile scenario, positioned in the east of the Rampion offshore wind farm site, are calculated to be 14 km from the pile position.

As the mean values quote in the tables take into account all of the transects, these apparently reduced impact ranges are also used when calculating the average. It is therefore suggested that the maximum values quoted and the contour plots presented later are also considered along with these results

1.53 m pin pile (W)	Range to 90 dB _{ht} (km)			Range to 75 dB _{ht} (km)		
	Max	Min	Mean	Max	Min	Mean
Bass	0.8	0.8	0.8	5.7	4.9	5.3
Cod	7.9	6.2	7.1	31.1	12.8	21.5
Dab	0.7	0.7	0.7	4.4	4.0	4.2
Herring	13.5	8.8	11.0	41.7	13.5	27.8
Red Sea Bream	2.4	2.3	2.3	14.1	9.0	11.4
Sand Lance	0.1	0.1	0.1	0.6	0.6	0.6
Seahorse	2.1	2.0	2.1	14.5	8.7	11.3
Shad	0.9	0.9	0.9	5.1	4.6	4.8
Bottlenose Dolphin	8.6	7.2	7.9	26.6	13.4	20.2
Harbour Porpoise	13.6	10.1	11.9	38.5	13.5	27.5
Harbour Seal	9.8	7.5	8.7	33.6	13.5	23.6
Humpback Whale	28.0	13.1	20.4	63.5	13.5	38.1

Table 4-6 Summary of 90 and 75 dB_{ht} ranges for the 1.53m pin pile jacket structure scenario at the most westerly point in the Rampion offshore wind farm

1.53 m pin pile (E)	Range to 90 dB _{ht} (km)			Range to 75 dB _{ht} (km)		
	Max	Min	Mean	Max	Min	Mean
Bass	1.0	0.9	0.9	7.5	6.3	6.9
Cod	10.8	8.3	9.6	37.4	14.1	27.0
Dab	0.9	0.8	0.8	6.1	5.2	5.7
Herring	17.1	11.9	14.5	48.9	14.1	32.8
Red Sea Bream	3.0	2.8	2.9	18.1	12.4	15.3
Sand Lance	0.1	0.1	0.1	0.7	0.6	0.6
Seahorse	2.6	2.4	2.5	18.6	12.2	15.4
Shad	1.0	0.9	0.9	6.1	5.4	5.7
Bottlenose Dolphin	9.7	8.4	9.1	29.2	14.1	23.2
Harbour Porpoise	15.2	12.4	13.9	42.2	14.1	30.7
Harbour Seal	12.0	9.5	10.7	38.1	14.1	27.7
Humpback Whale	32.0	14.1	24.4	71.9	14.1	43.1

Table 4-7 Summary of 90 and 75 dB_{ht} ranges for the 1.53m pin pile jacket structure scenario at the most easterly point in the Rampion offshore wind farm

2.6 m pin pile (W)	Range to 90 dB _{ht} (km)			Range to 75 dB _{ht} (km)		
	Max	Min	Mean	Max	Min	Mean
Bass	1.5	1.5	1.5	9.7	7.3	8.5
Cod	16.7	9.5	12.8	46.6	13.5	30.0
Dab	2.6	2.5	2.6	14.2	9.2	11.5
Herring	21.7	11.3	16.1	53.8	13.5	33.9
Red Sea Bream	4.4	4.0	4.2	22.9	11.6	16.8
Sand Lance	0.1	0.1	0.1	1.0	1.0	1.0
Seahorse	4.0	3.6	3.8	23.0	11.0	16.5
Shad	1.3	1.3	1.3	7.0	5.9	6.4
Bottlenose Dolphin	10.3	8.1	9.2	30.4	13.5	22.5
Harbour Porpoise	16.0	11.2	13.6	43.1	13.5	29.9
Harbour Seal	11.9	8.5	10.1	37.7	13.5	25.9
Humpback Whale	31.7	13.5	22.6	68.7	13.5	40.3

Table 4-8 Summary of 90 and 75 dB_{ht} ranges for the 2.6 m pin pile jacket structure scenario at the most westerly point in the Rampion offshore wind farm

2.6 m pin pile (E)	Range to 90 dB _{ht} (km)			Range to 75 dB _{ht} (km)		
	Max	Min	Mean	Max	Min	Mean
Bass	1.9	1.8	1.8	12.9	9.8	11.3
Cod	21.5	13.4	17.4	55.6	14.1	35.6
Dab	3.5	3.2	3.3	19.3	12.9	16.2
Herring	26.2	14.1	20.7	63.1	14.1	39.1
Red Sea Bream	5.7	5.0	5.4	28.0	14.1	21.9
Sand Lance	0.1	0.1	0.1	1.2	1.2	1.2
Seahorse	5.2	4.5	4.8	27.9	14.1	21.5
Shad	1.4	1.4	1.4	8.5	7.1	7.8
Bottlenose Dolphin	11.6	9.8	10.7	33.2	14.1	25.5
Harbour Porpoise	17.8	13.8	15.9	47.4	14.1	33.3
Harbour Seal	14.3	10.9	12.6	42.8	14.1	30.1
Humpback Whale	36.0	14.1	26.7	77.9	14.1	45.5

Table 4-9 Summary of 90 and 75 dB_{ht} ranges for the 2.6 m pin pile jacket structure scenario at the most easterly point in the Rampion offshore wind farm

6.5 m monopile (W)	Range to 90 dB _{ht} (km)			Range to 75 dB _{ht} (km)		
	Max	Min	Mean	Max	Min	Mean
Bass	3.2	3.0	3.1	18.0	10.2	13.8
Cod	32.6	13.0	22.3	69.0	13.5	40.0
Dab	6.7	5.6	6.2	29.6	13.2	21.1
Herring	32.9	13.3	22.8	70.1	13.5	40.7
Red Sea Bream	8.9	6.9	7.9	36.2	13.5	24.7
Sand Lance	0.3	0.3	0.3	2.1	2.0	2.1
Seahorse	7.8	6.1	6.9	34.4	13.1	23.2
Shad	1.8	1.7	1.8	9.1	7.1	8.1
Bottlenose Dolphin	11.4	8.7	10.1	32.7	13.5	23.8
Harbour Porpoise	17.5	11.8	14.7	46.0	13.5	31.3
Harbour Seal	12.3	8.6	10.4	38.5	13.5	26.4
Humpback Whale	32.3	13.5	22.9	69.4	13.5	40.7

Table 4-10 Summary of 90 and 75 dB_{ht} ranges for the 6.5 m monopile scenario at the most westerly point in the Rampion offshore wind farm

6.5 m monopile (E)	Range to 90 dB _{ht} (km)			Range to 75 dB _{ht} (km)		
	Max	Min	Mean	Max	Min	Mean
Bass	4.1	3.7	3.9	22.7	14.0	18.4
Cod	39.2	14.1	27.9	81.1	14.1	46.1
Dab	9.4	7.6	8.4	36.9	14.1	27.0
Herring	38.5	14.1	27.7	81.2	14.1	46.4
Red Sea Bream	11.8	9.2	10.5	43.1	14.1	30.0
Sand Lance	0.3	0.3	0.3	2.6	2.5	2.5
Seahorse	10.4	8.1	9.2	40.6	14.1	28.5
Shad	2.0	1.9	2.0	11.2	8.9	10.0
Bottlenose Dolphin	12.9	10.6	11.8	35.6	14.1	26.9
Harbour Porpoise	19.4	14.1	17.2	50.6	14.1	34.8
Harbour Seal	14.8	11.2	13.0	43.7	14.1	30.6
Humpback Whale	36.6	14.1	27.0	78.8	14.1	45.8

Table 4-11 Summary of 90 and 75 dB_{ht} ranges for the 6.5 m monopile scenario at the most easterly point in the Rampion offshore wind farm

These results are presented graphically as contour plots in Figures 4-1 to 4-71, with each group of images showing the 130, 90 and 75 dB_{ht} impact ranges for the scenarios for each marine species of interest.

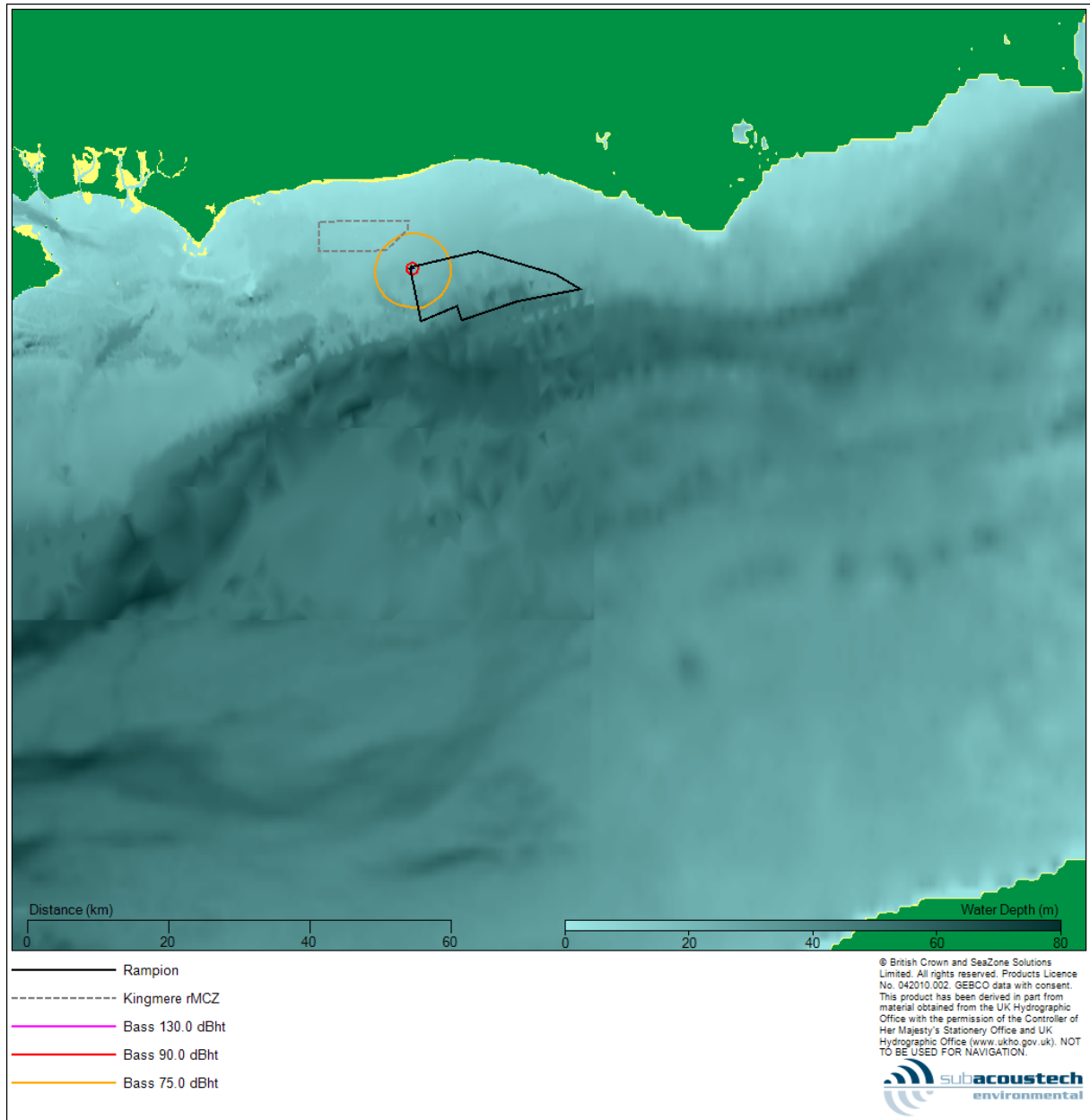


Figure 4-1 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Bass for the installation of a 1.53m pin pile, positioned west in the Rampion offshore wind farm site

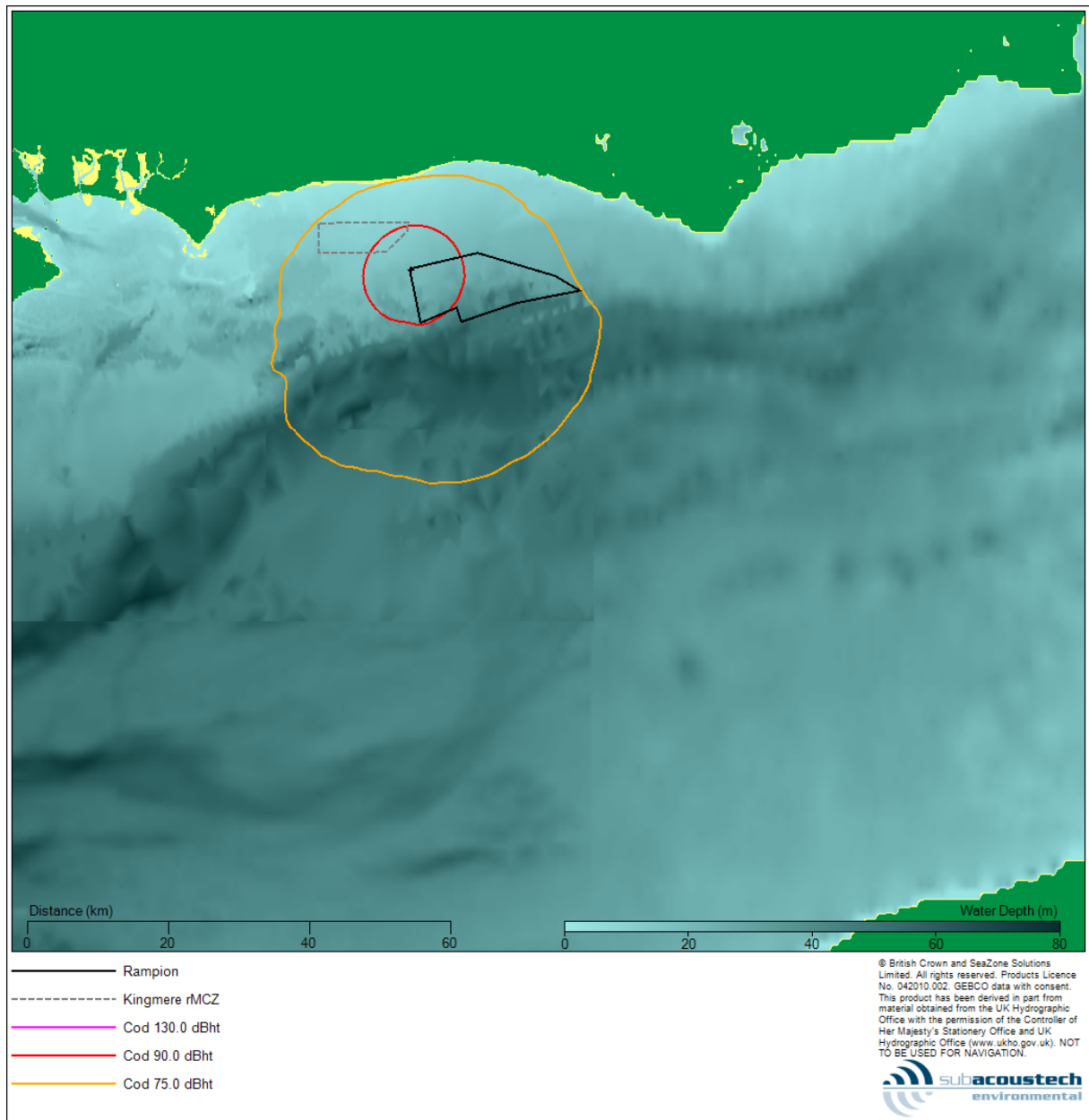


Figure 4-2 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Cod for the installation of a 1.53m pin pile, positioned west in the Rampion offshore wind farm site

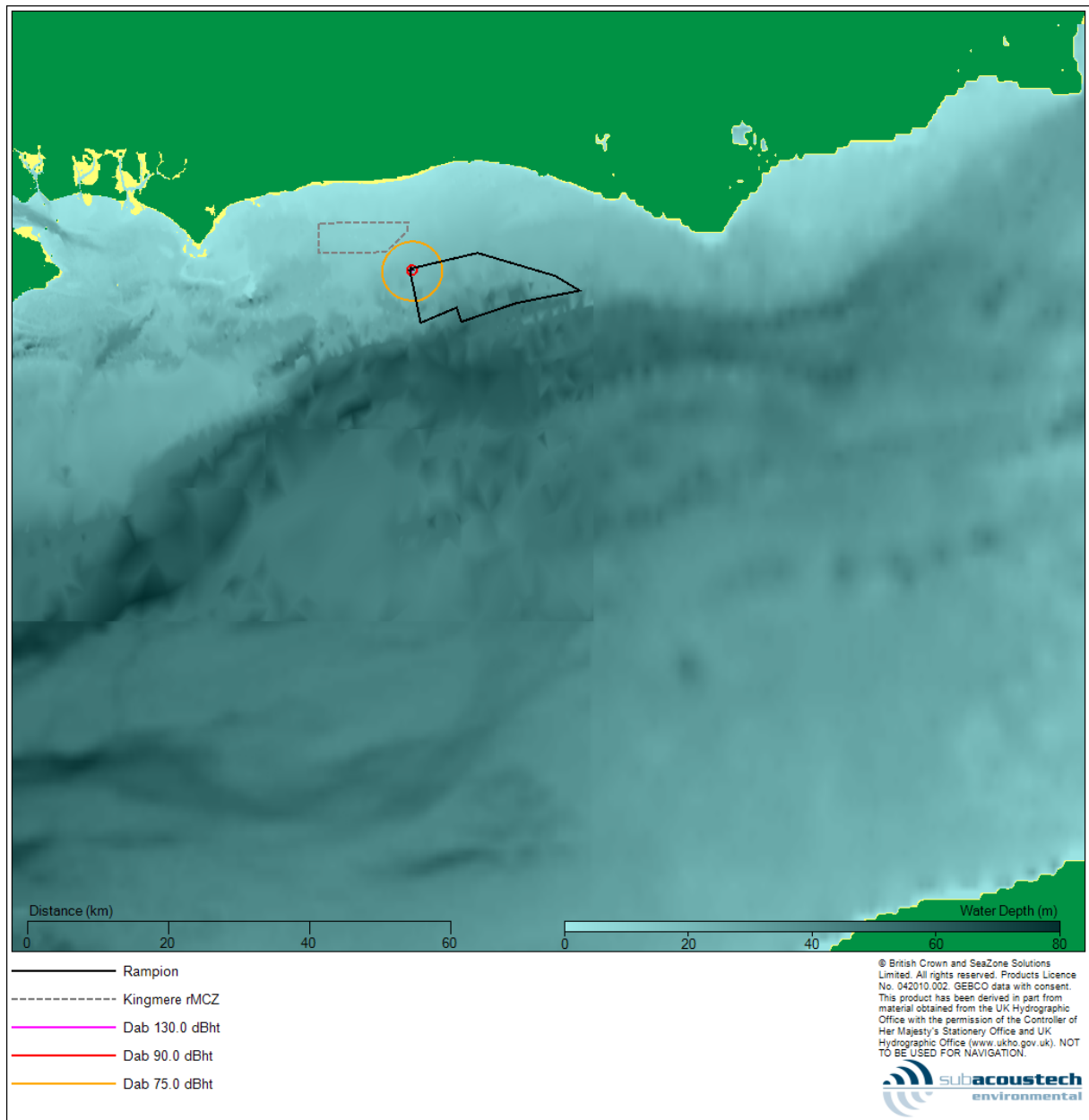


Figure 4-3 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Dab for the installation of a 1.53m pin pile, positioned west in the Rampion offshore wind farm site

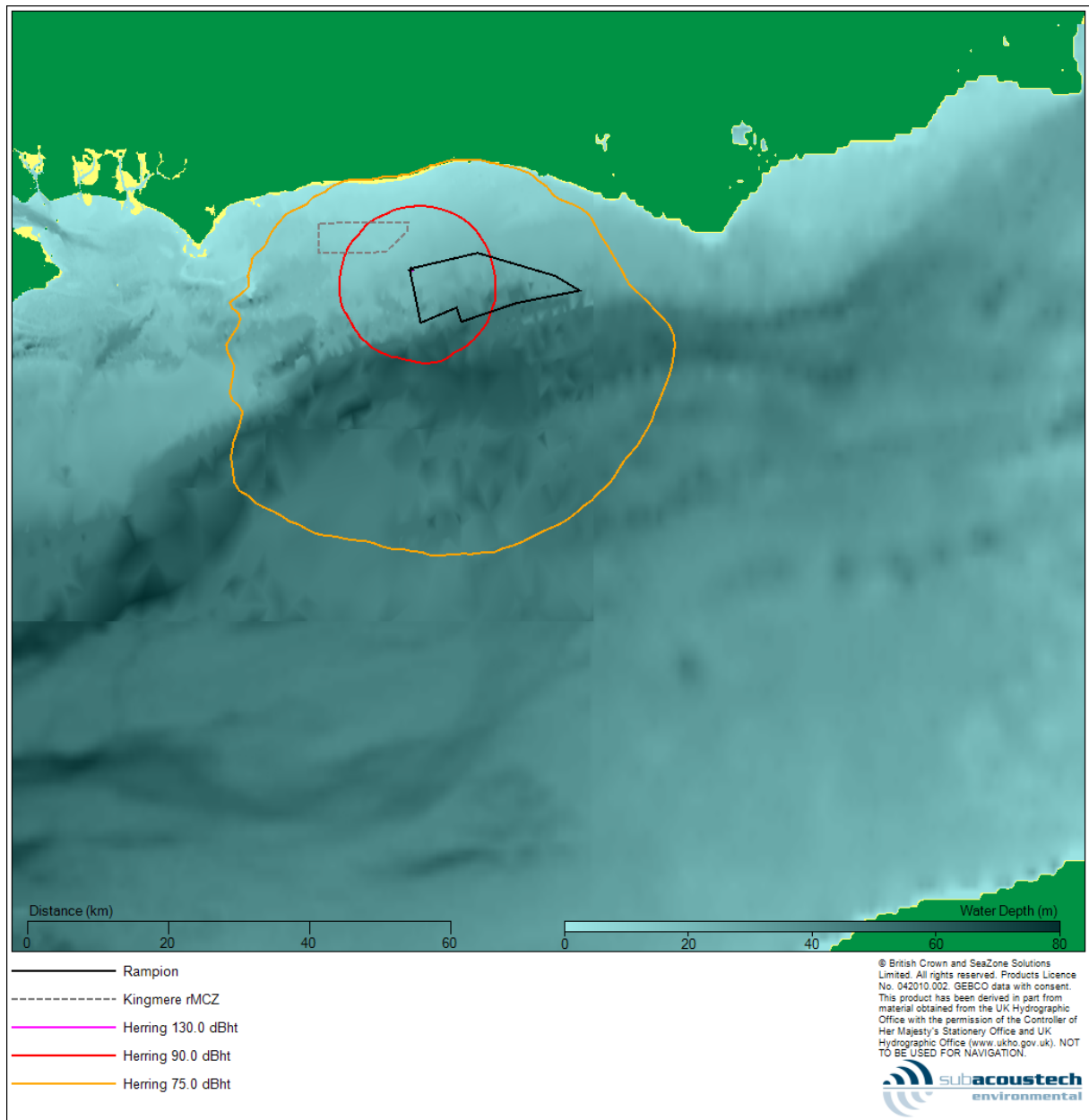


Figure 4-4 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Herring for the installation of a 1.53m pin pile, positioned west in the Rampion offshore wind farm site

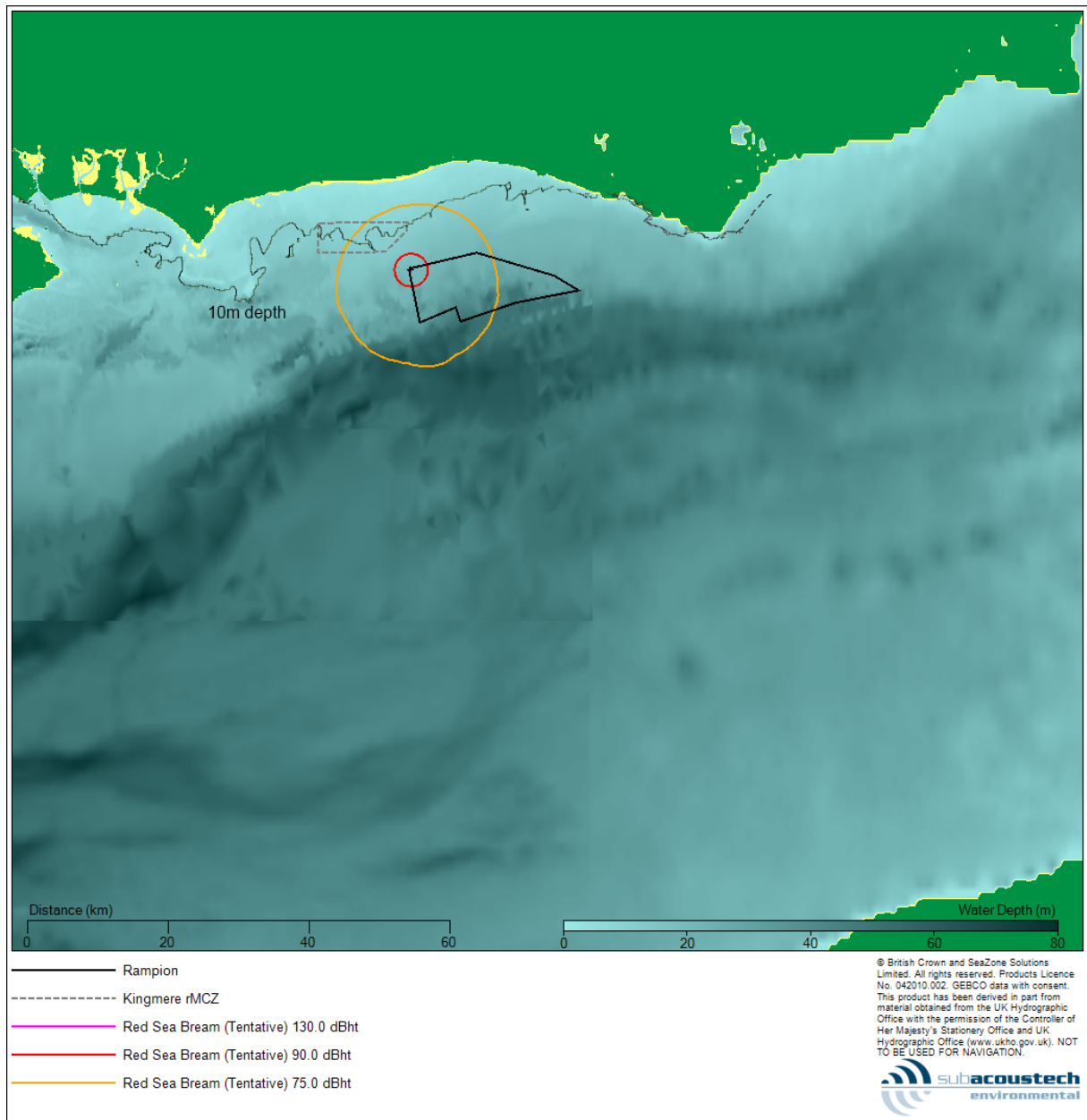


Figure 4-5 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Red Sea Bream for the installation of a 1.53m pin pile, positioned west in the Rampion offshore wind farm site

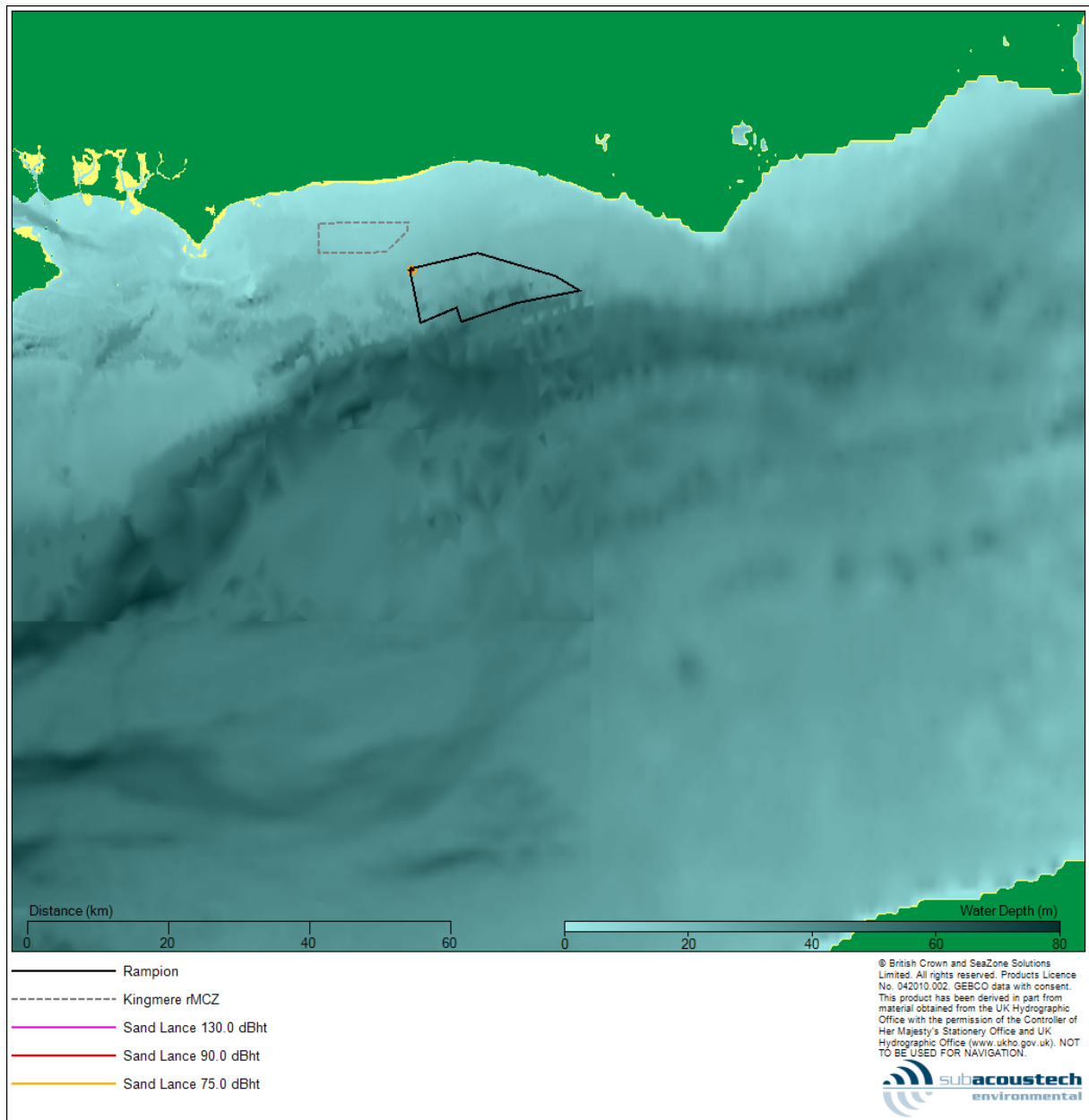


Figure 4-6 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Sand Lance for the installation of a 1.53m pin pile, positioned west in the Rampion offshore wind farm site

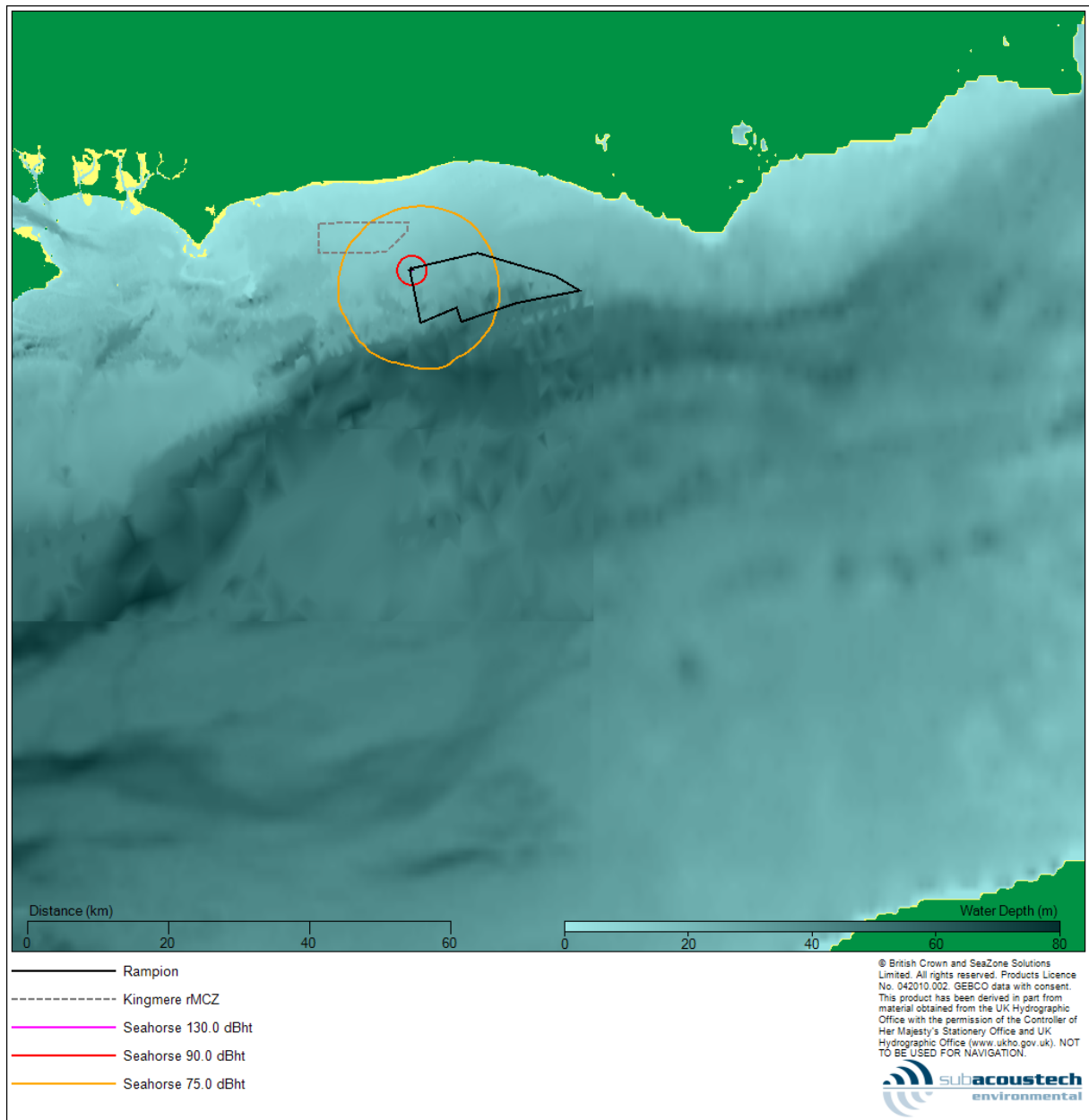


Figure 4-7 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Seahorse for the installation of a 1.53m pin pile, positioned west in the Rampion offshore wind farm site

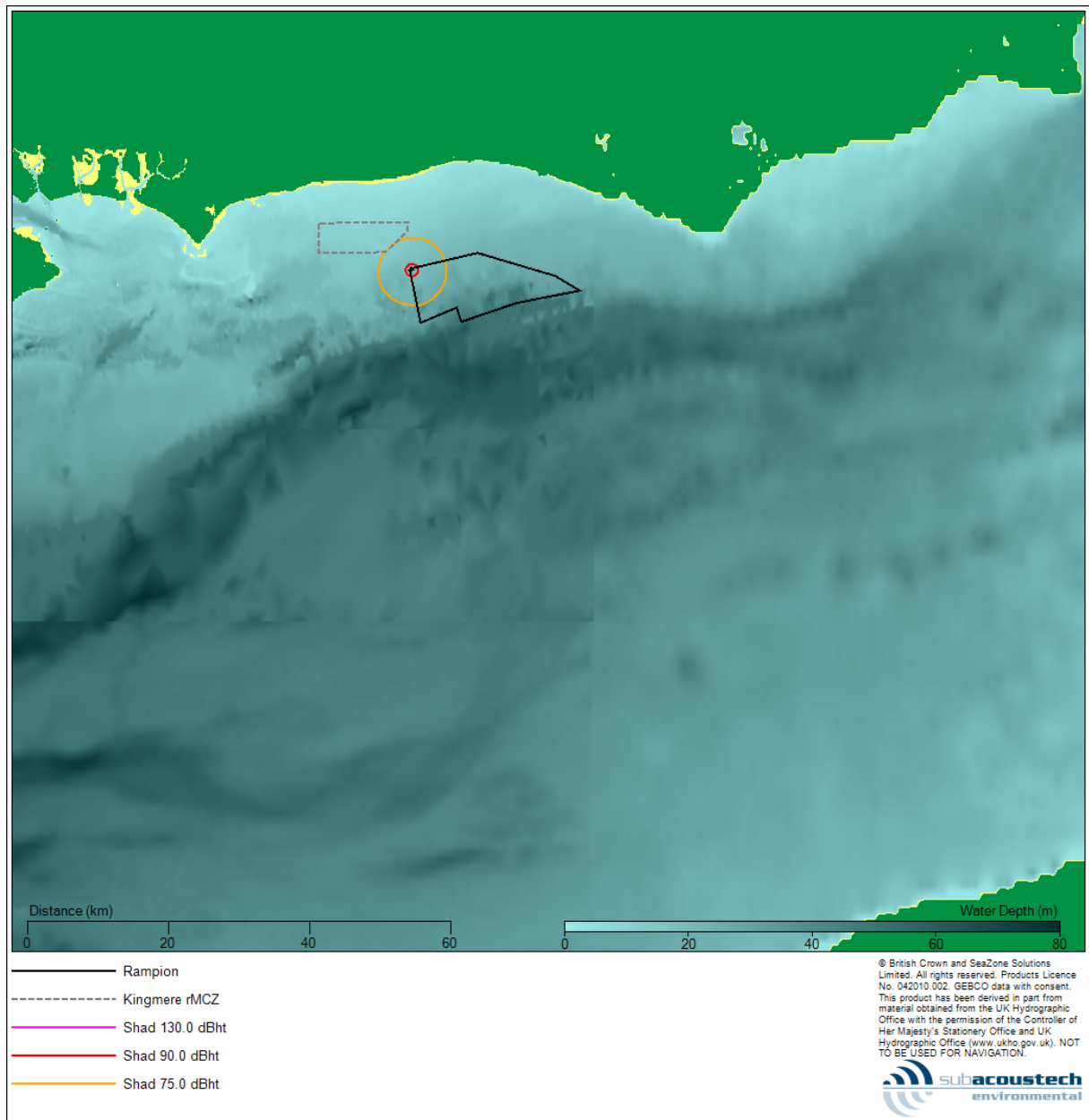


Figure 4-8 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Shad for the installation of a 1.53m pin pile, positioned west in the Rampion offshore wind farm site

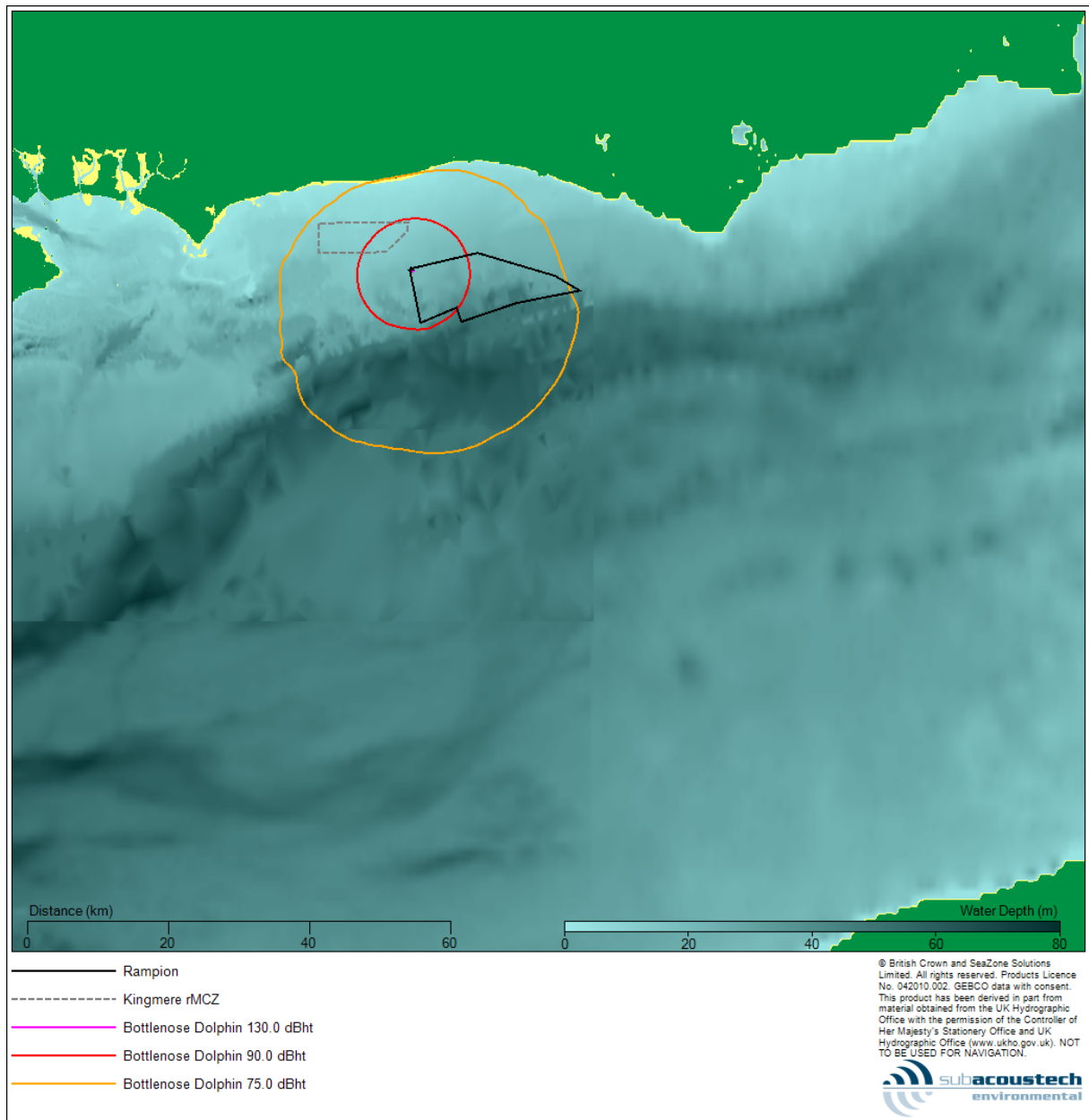


Figure 4-9 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Bottlenose Dolphin for the installation of a 1.53m pin pile, positioned west in the Rampion offshore wind farm site

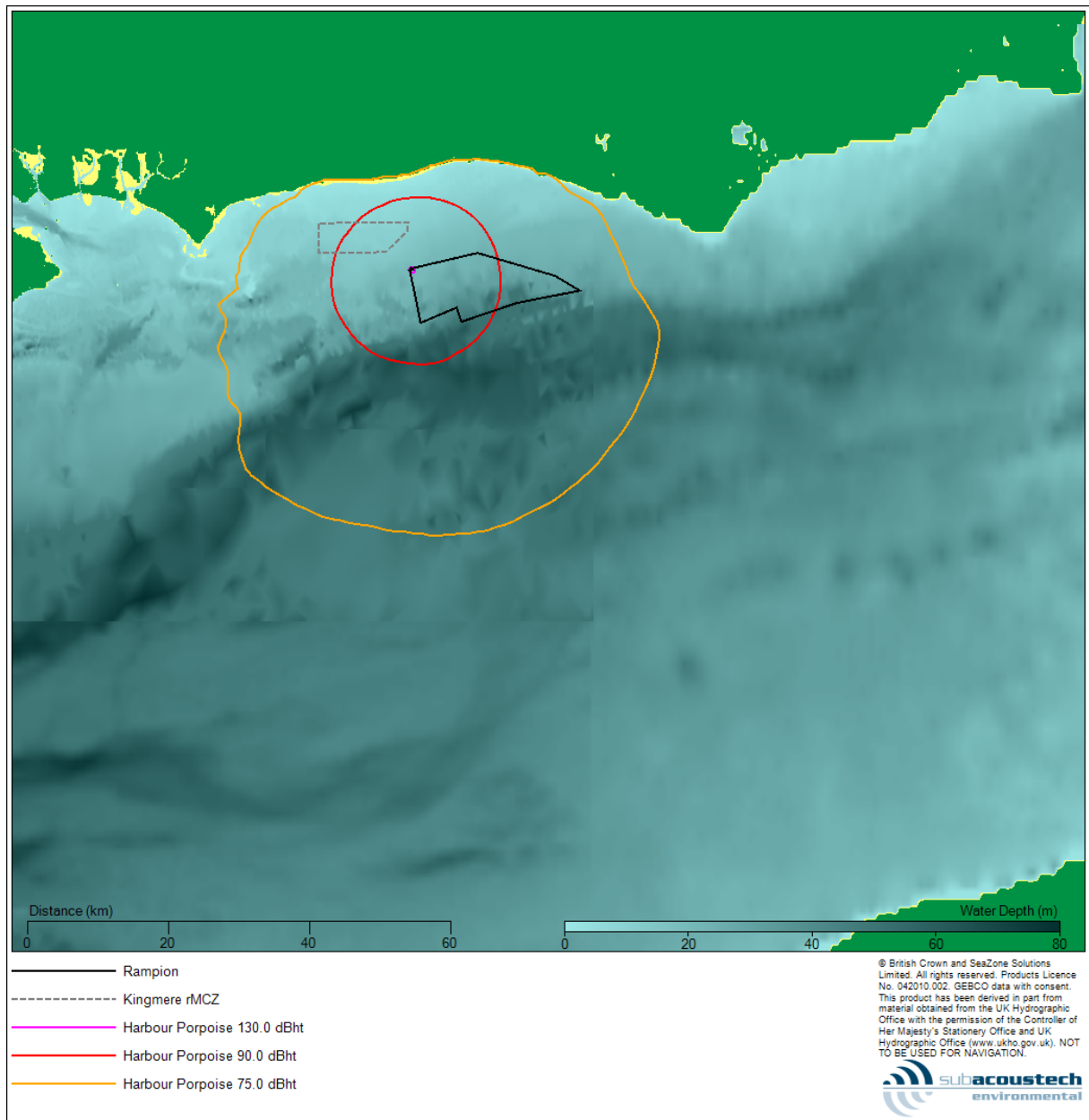


Figure 4-10 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Harbour Porpoise for the installation of a 1.53m pin pile, positioned west in the Rampion offshore wind farm site

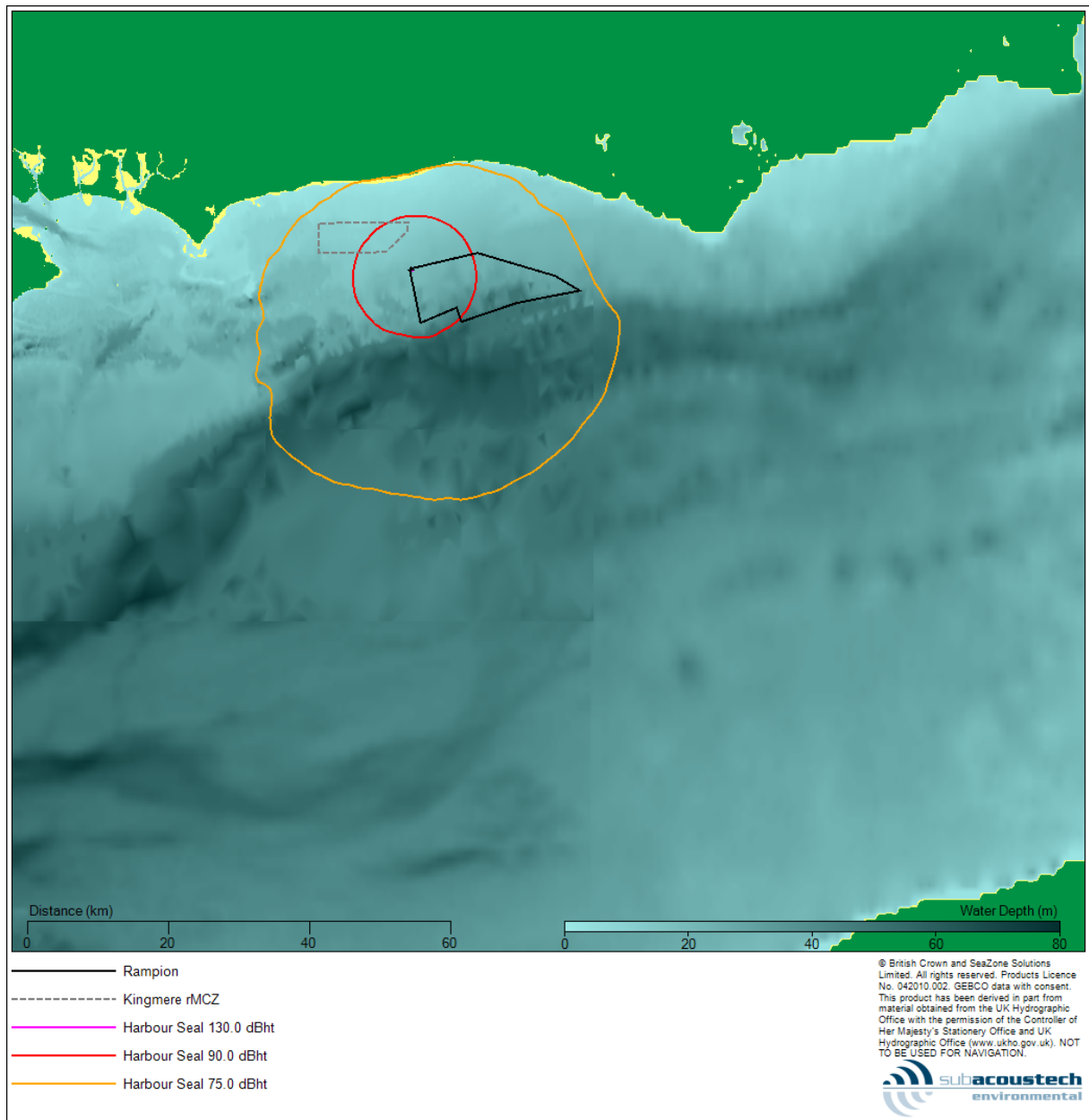


Figure 4-11 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Harbour Seal for the installation of a 1.53m pin pile, positioned west in the Rampion offshore wind farm site

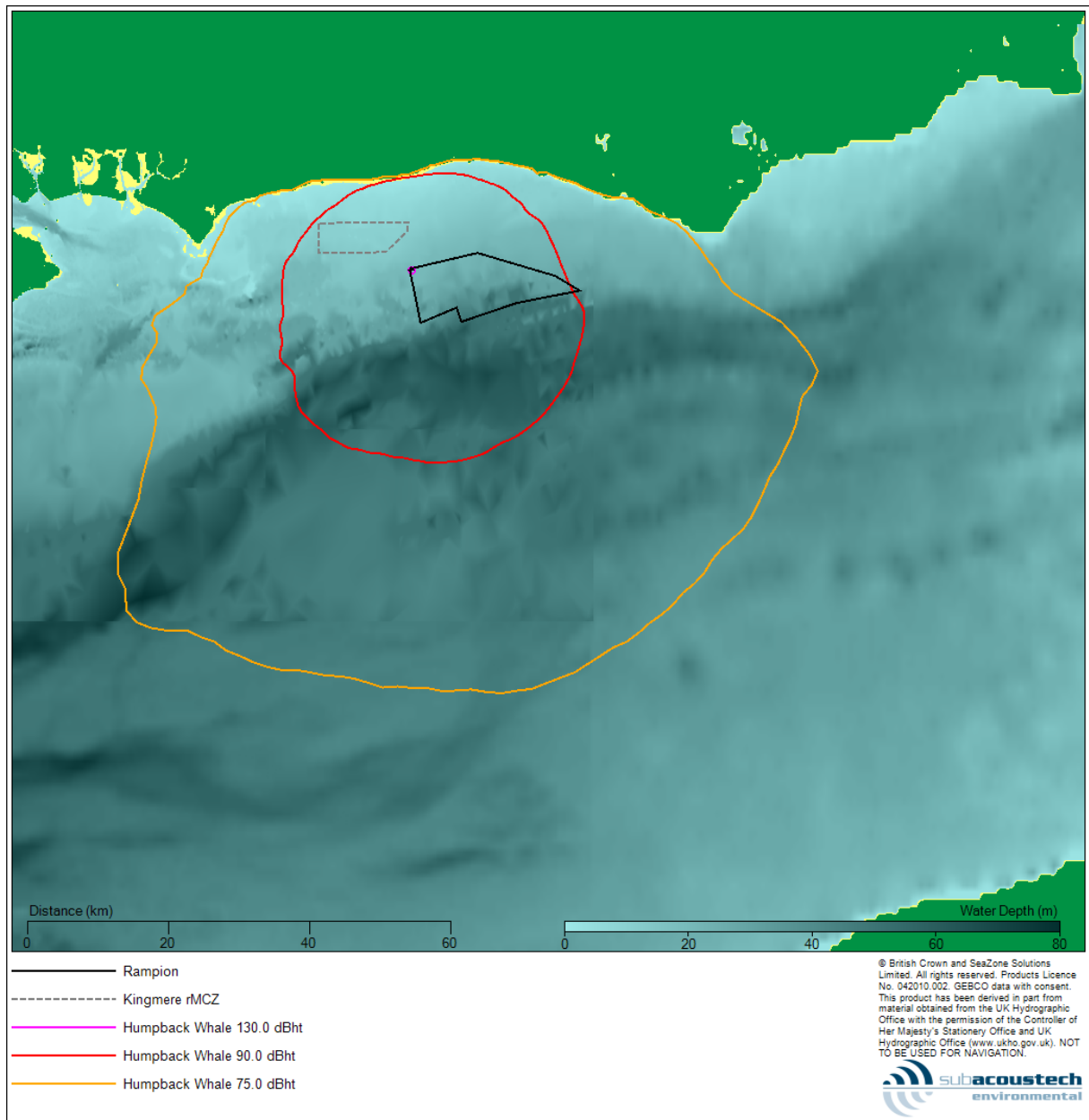


Figure 4-12 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Humpback Whale for the installation of a 1.53m pin pile, positioned west in the Rampion offshore wind farm site

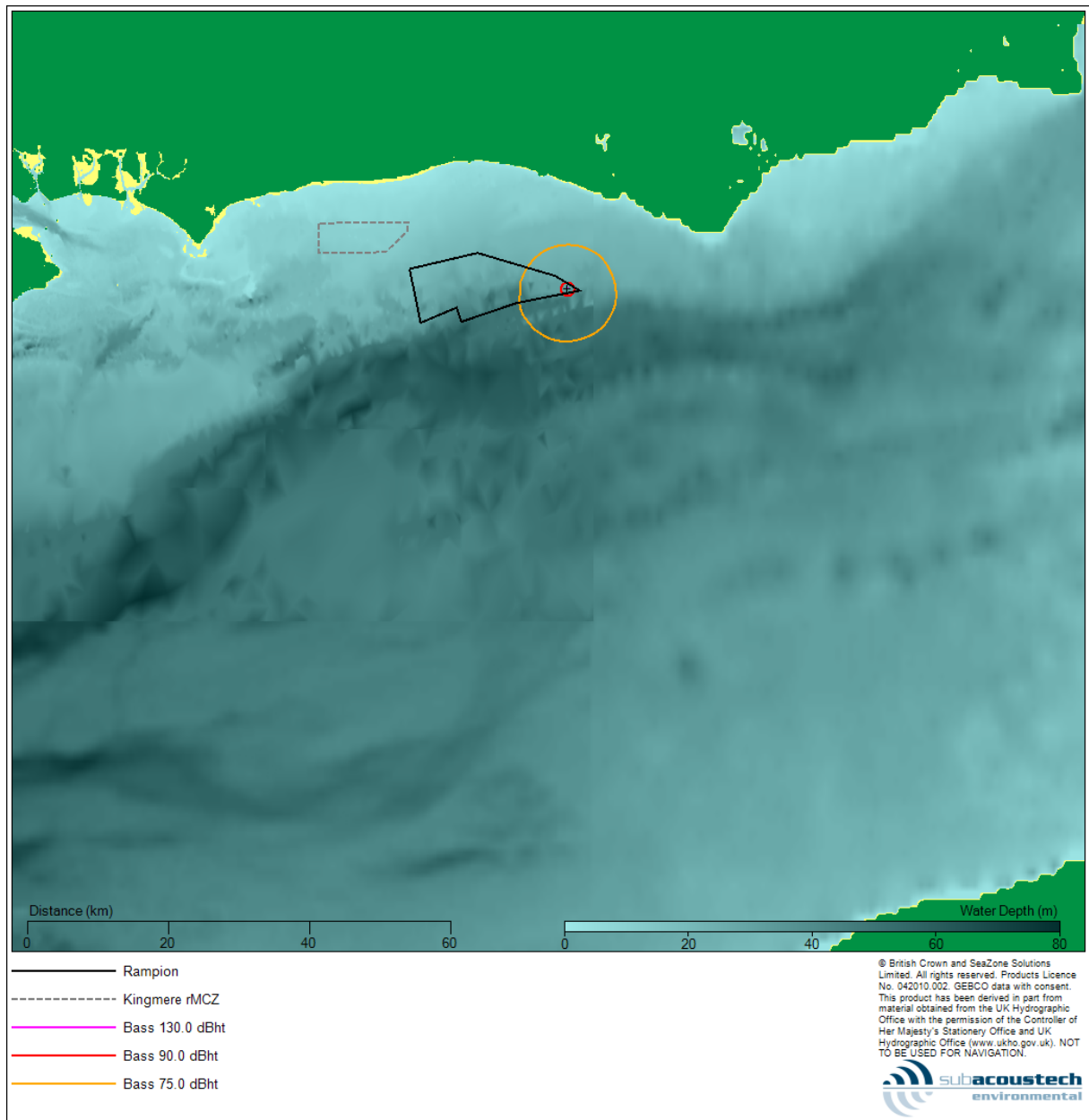


Figure 4-13 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Bass for the installation of a 1.53m pin pile, positioned east in the Rampion offshore wind farm site

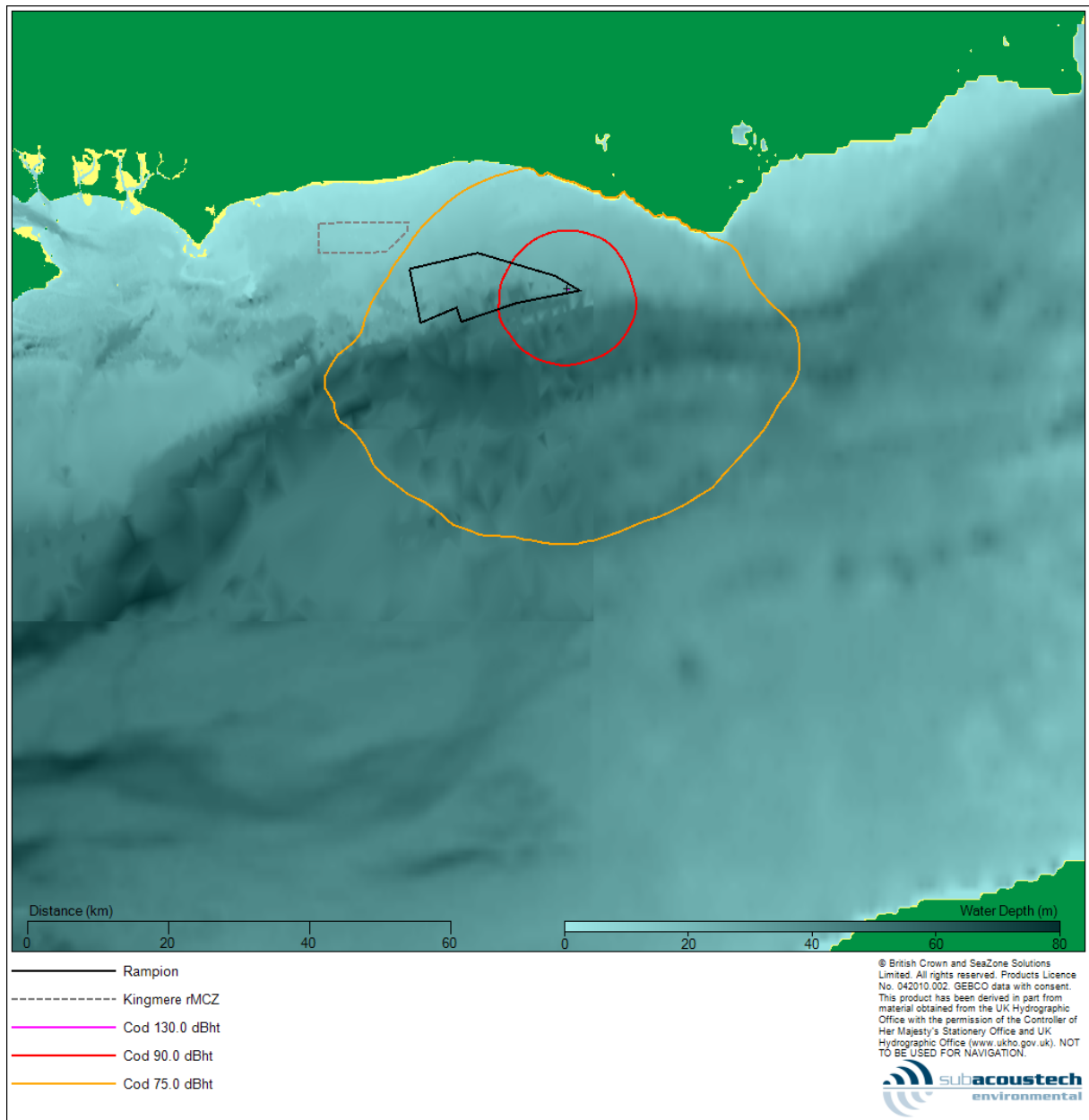


Figure 4-14 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Cod for the installation of a 1.53m pin pile, positioned east in the Rampion offshore wind farm site

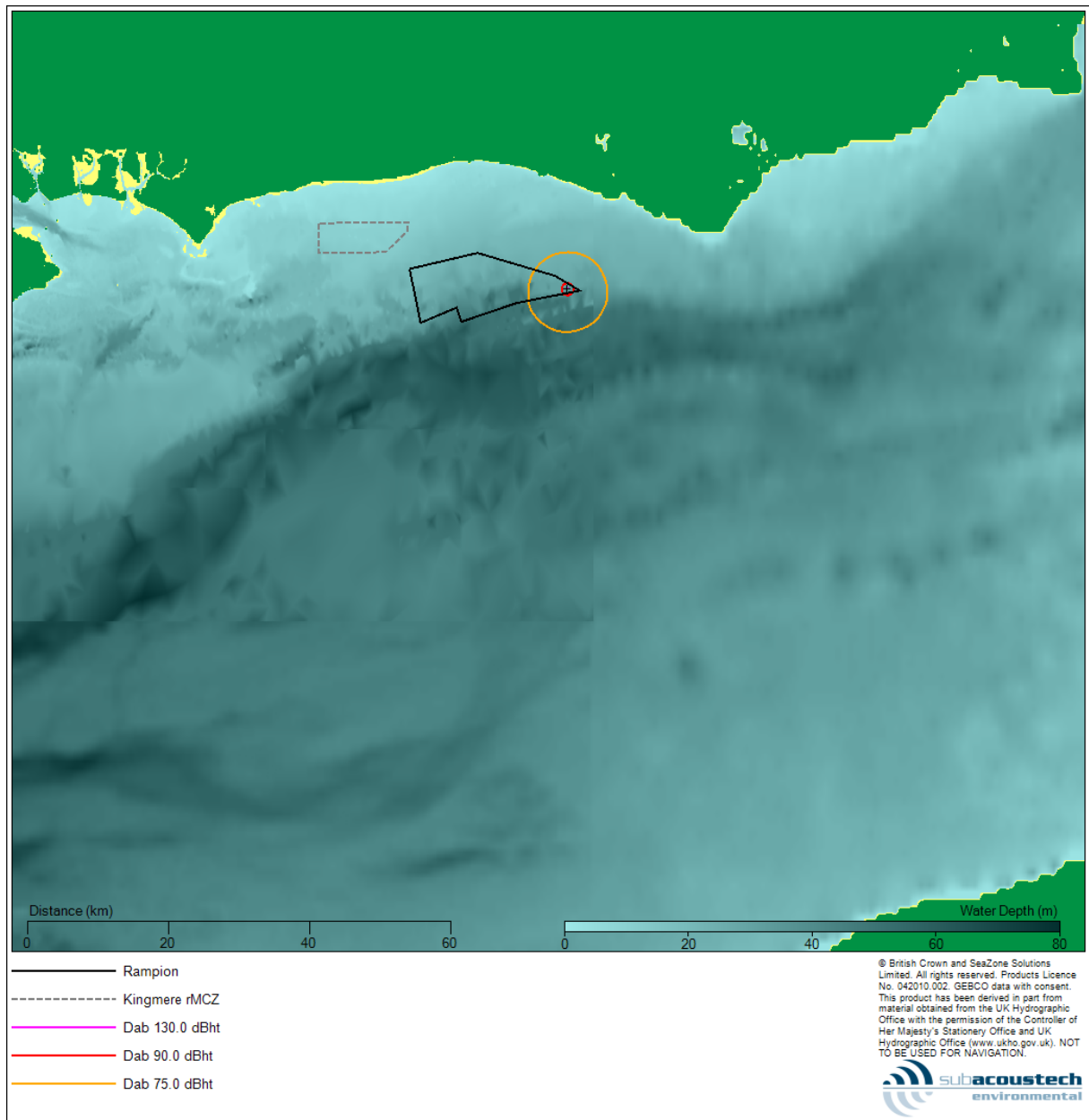


Figure 4-15 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Dab for the installation of a 1.53m pin pile, positioned east in the Rampion offshore wind farm site

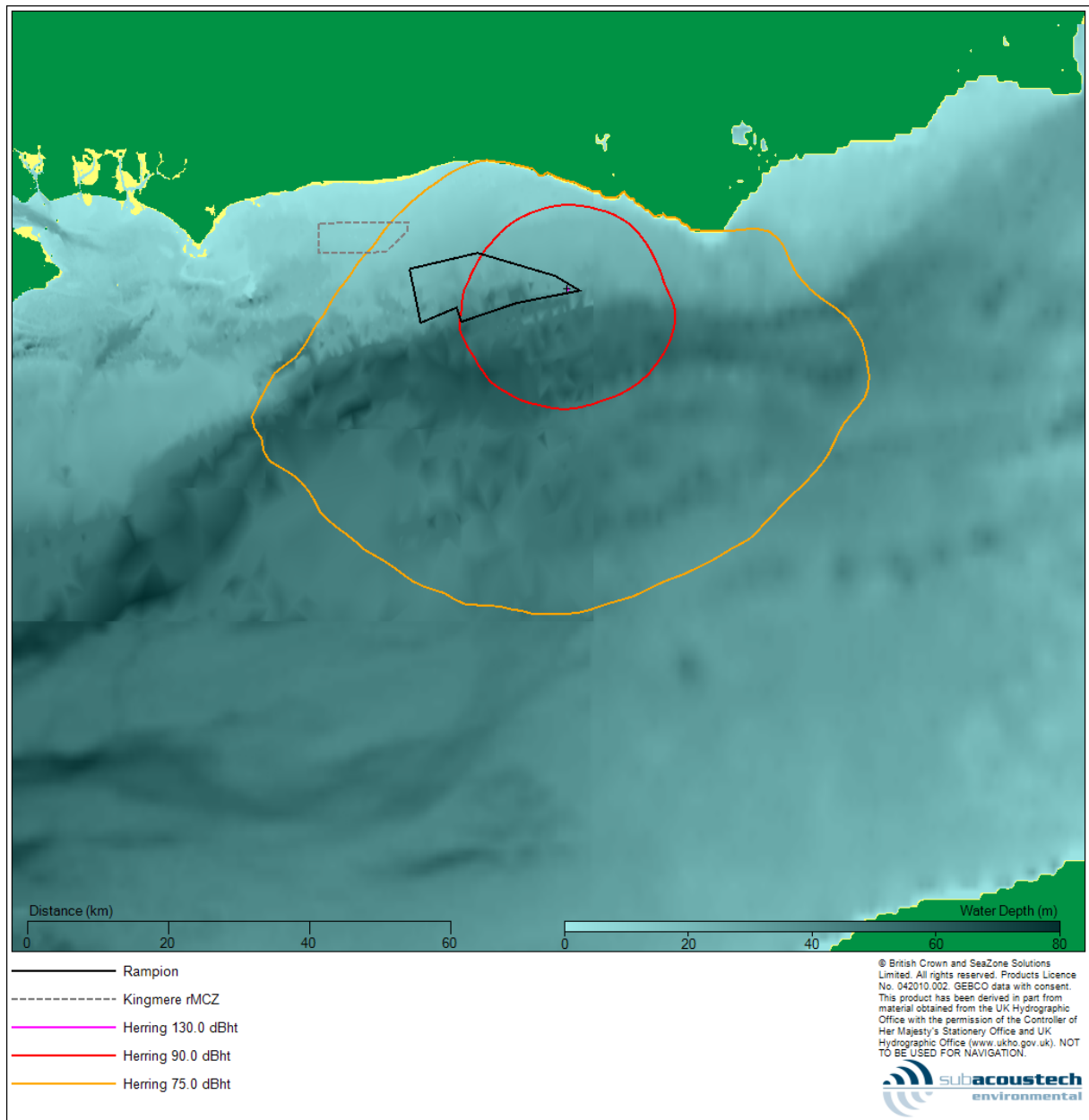


Figure 4-16 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Herring for the installation of a 1.53m pin pile, positioned east in the Rampion offshore wind farm site

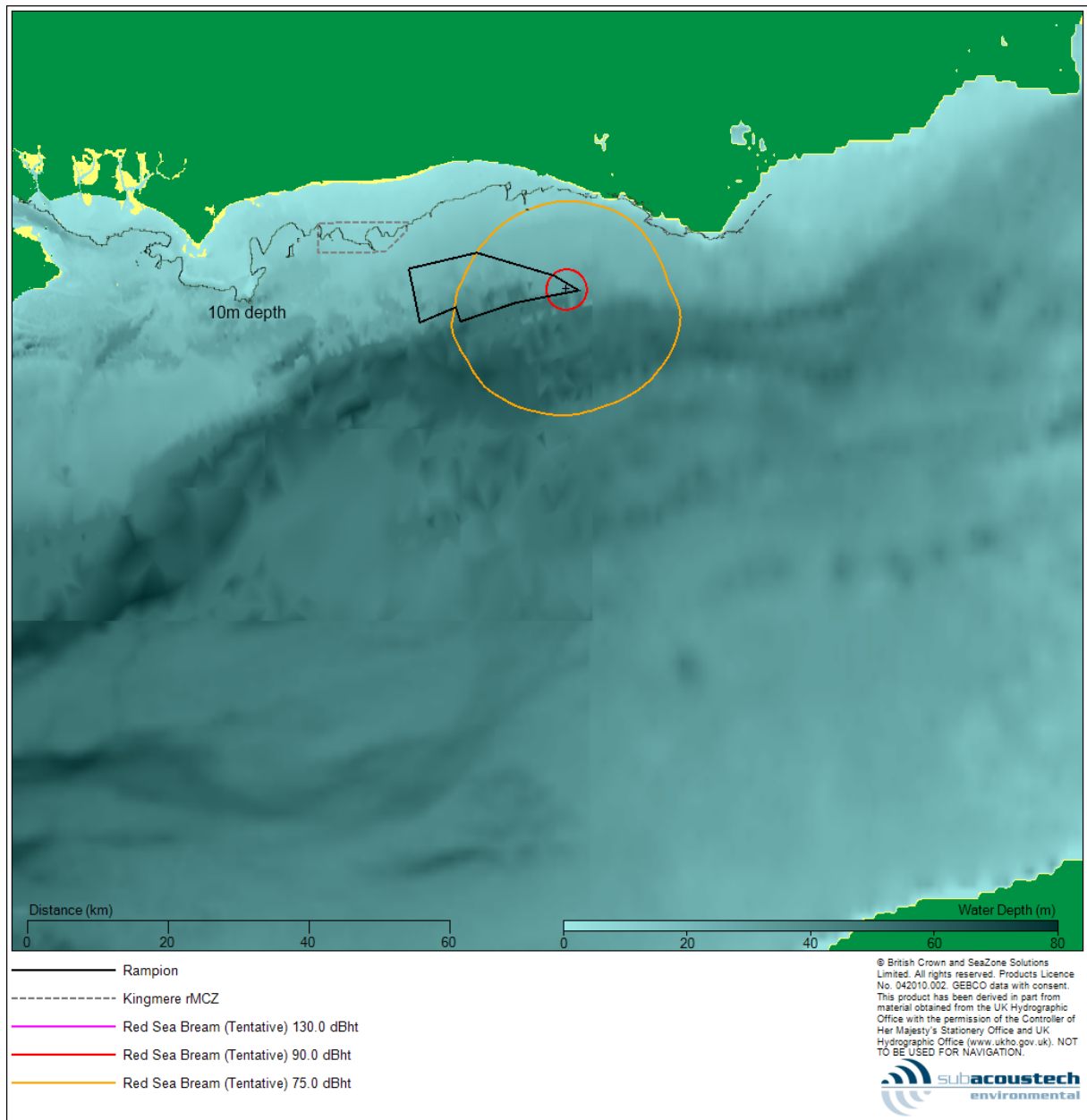


Figure 4-17 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Red Sea Bream for the installation of a 1.53m pin pile, positioned east in the Rampion offshore wind farm site

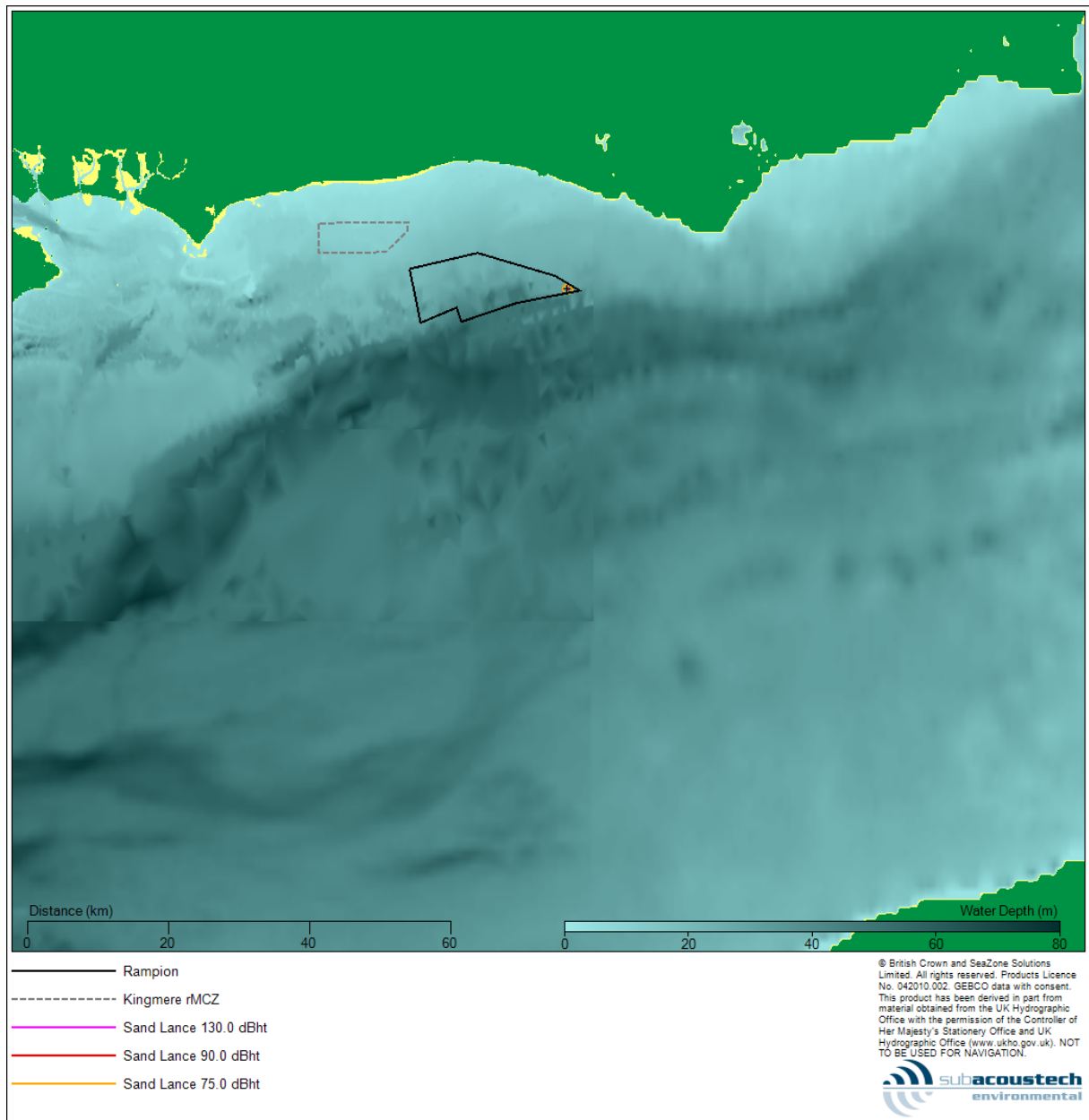


Figure 4-18 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Sand Lance for the installation of a 1.53m pin pile, positioned east in the Rampion offshore wind farm site

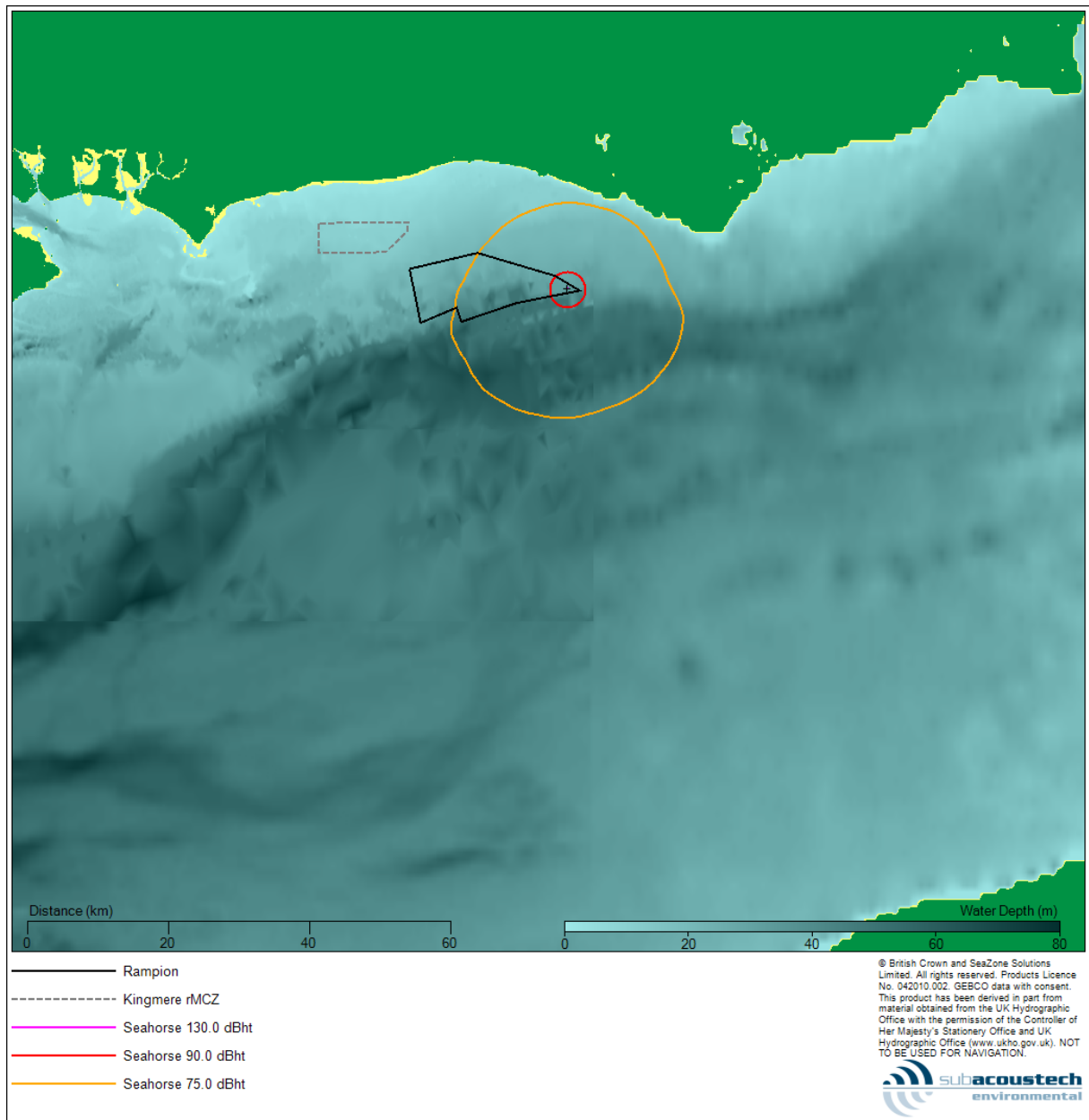


Figure 4-19 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Seahorse for the installation of a 1.53m pin pile, positioned east in the Rampion offshore wind farm site

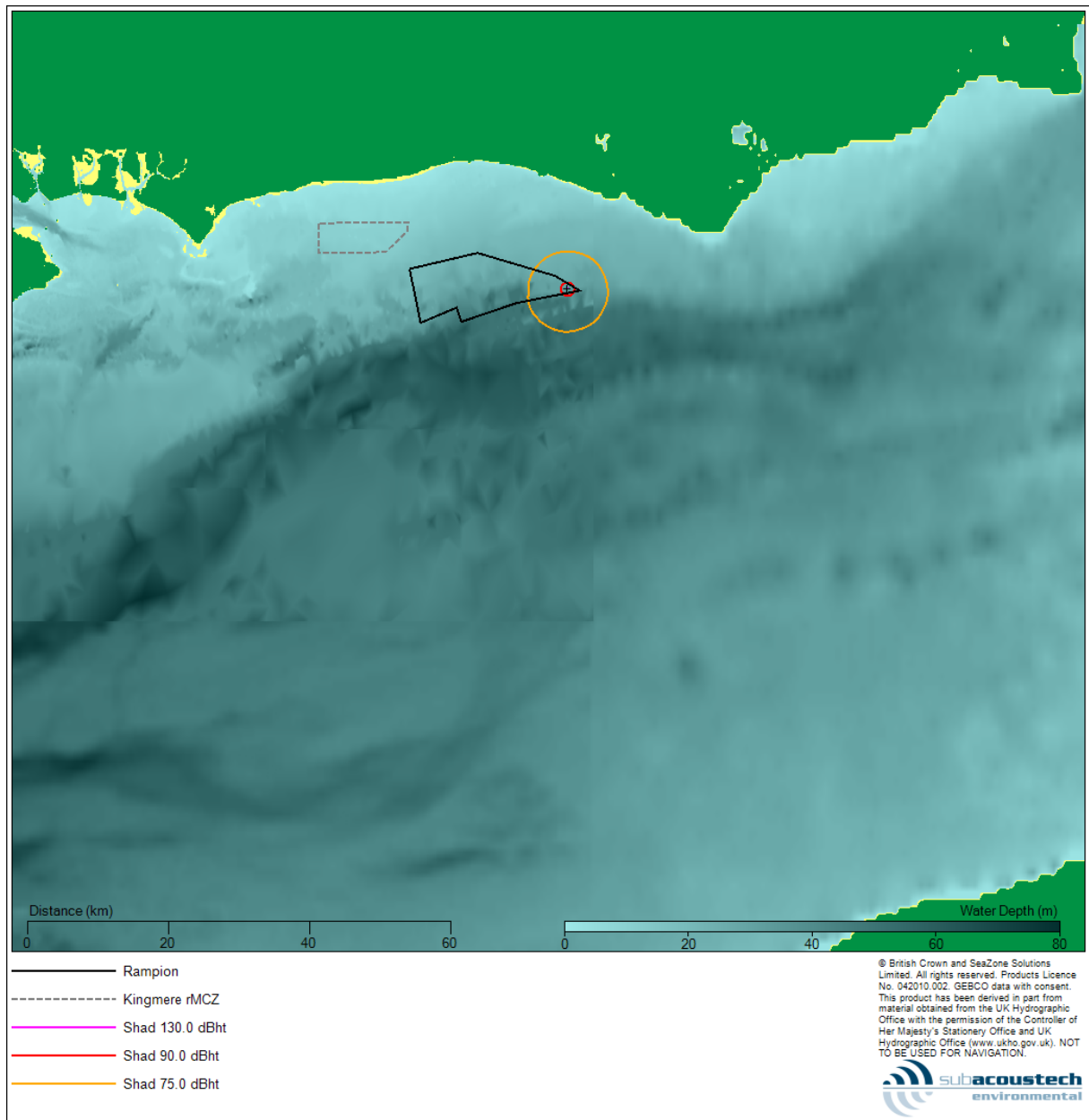


Figure 4-20 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Shad for the installation of a 1.53m pin pile, positioned east in the Rampion offshore wind farm site

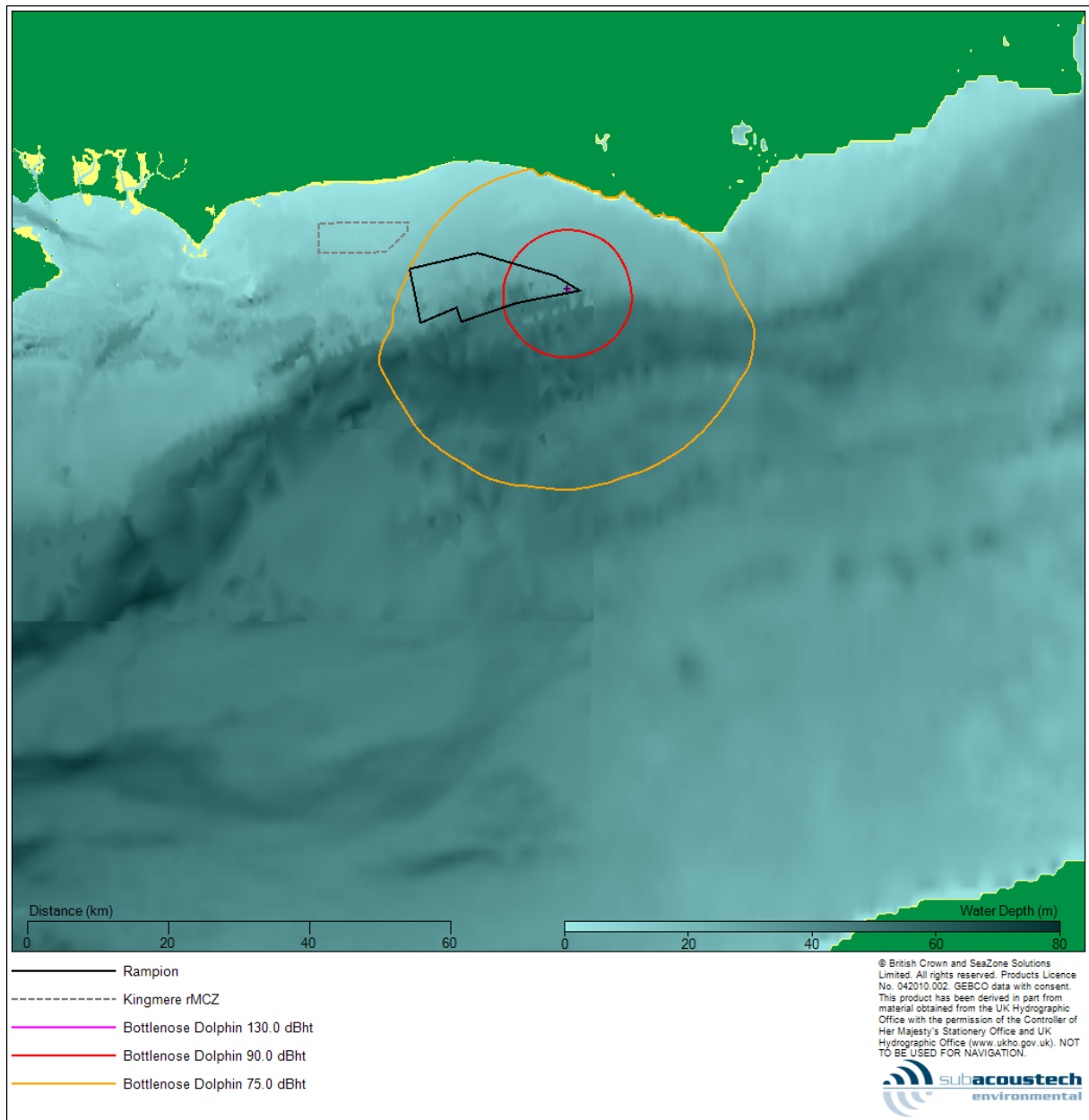


Figure 4-21 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Bottlenose Dolphin for the installation of a 1.53m pin pile, positioned east in the Rampion offshore wind farm site

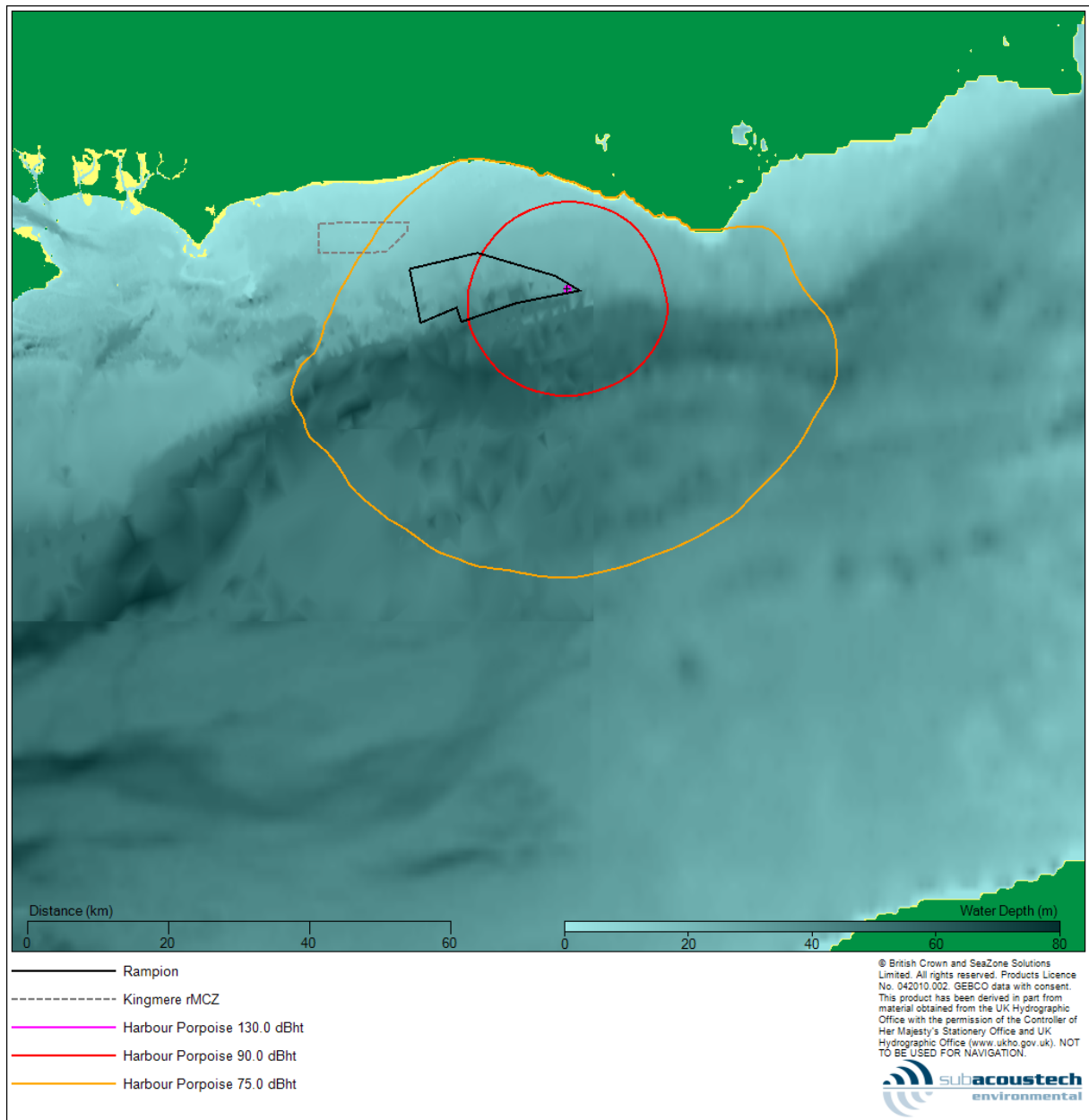


Figure 4-22 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Harbour Porpoise for the installation of a 1.53m pin pile, positioned east in the Rampion offshore wind farm site

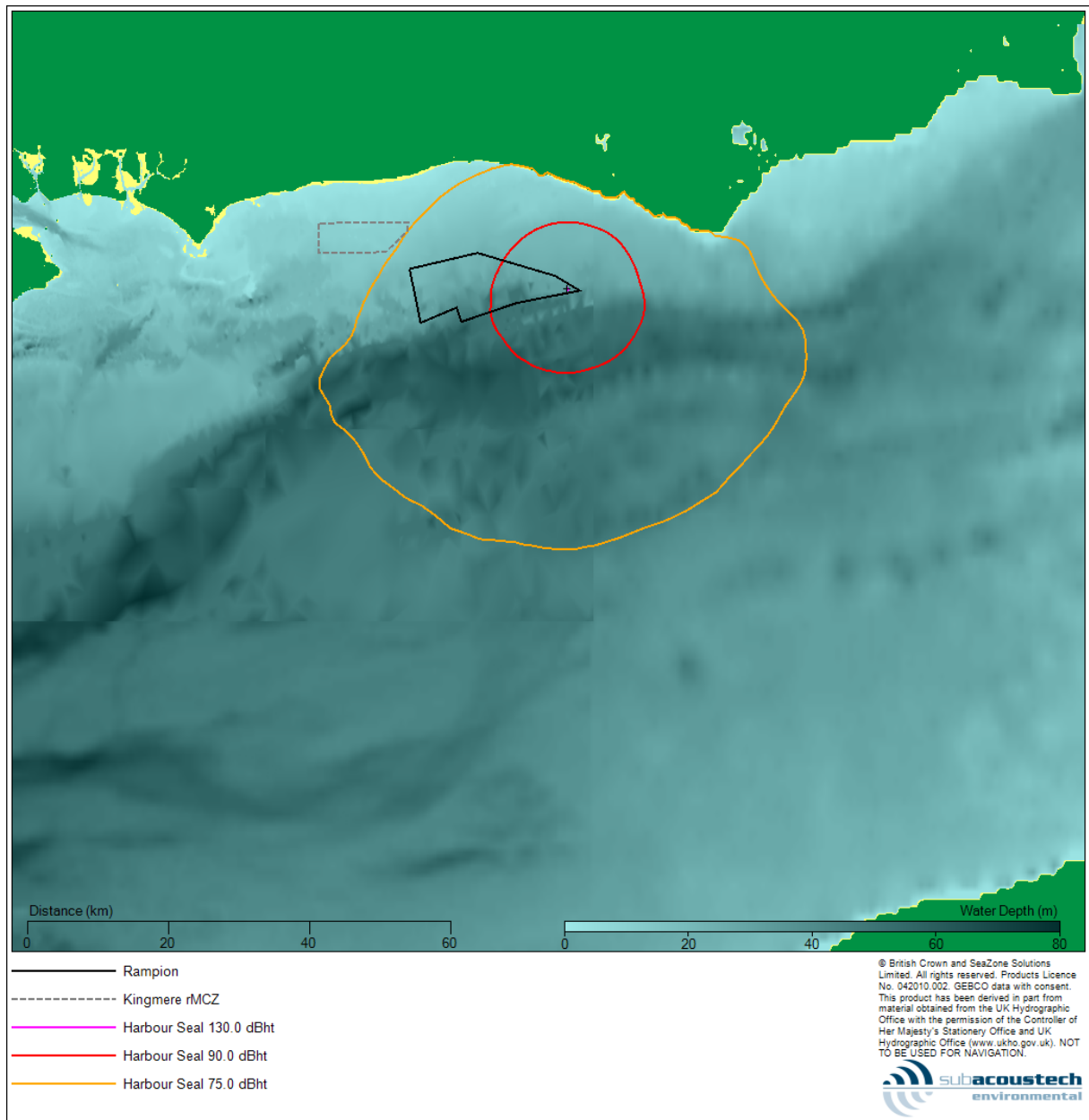


Figure 4-23 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Harbour Seal for the installation of a 1.53m pin pile, positioned east in the Rampion offshore wind farm site

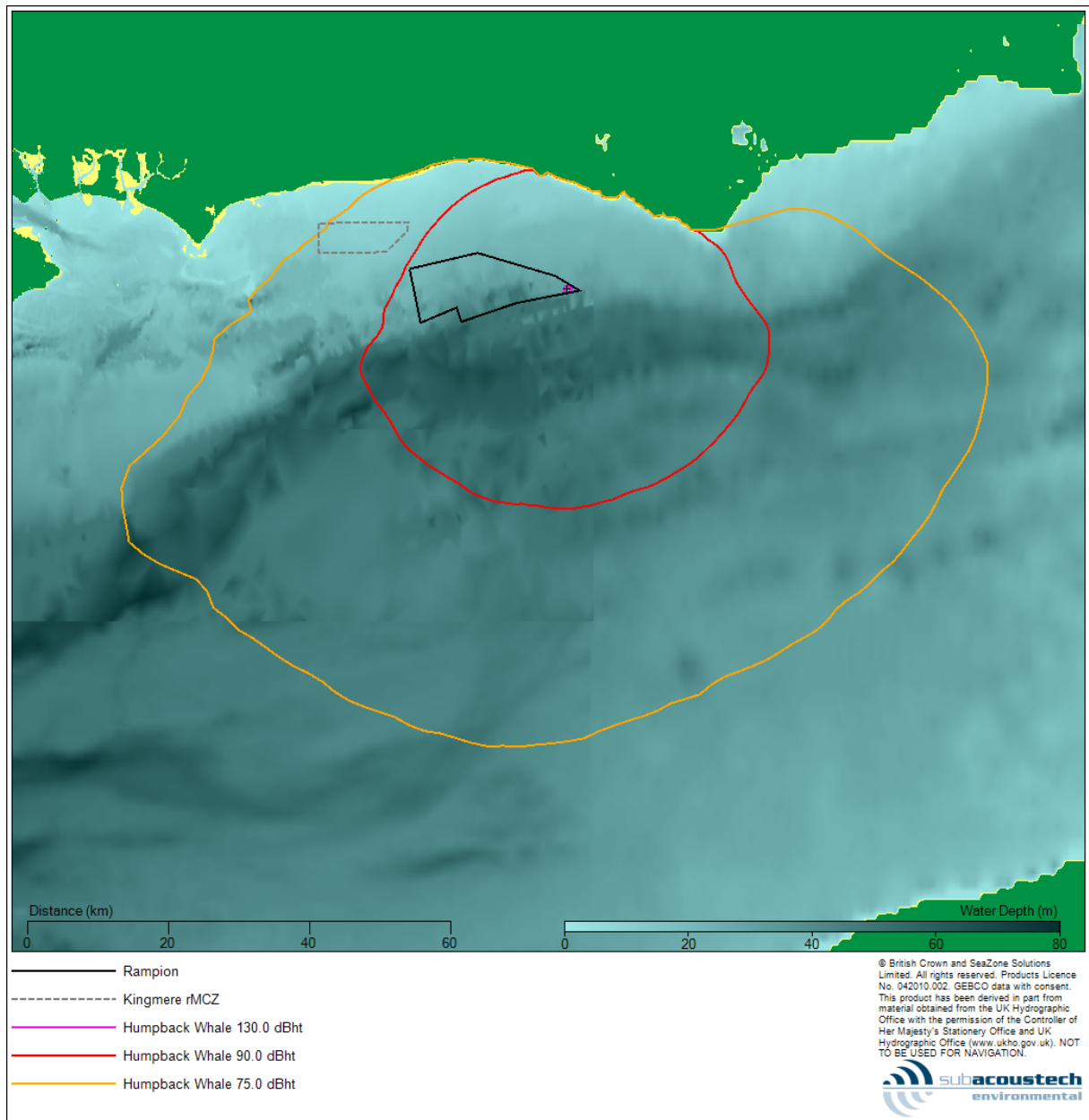


Figure 4-24 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Humpback Whale for the installation of a 1.53m pin pile, positioned east in the Rampion offshore wind farm site

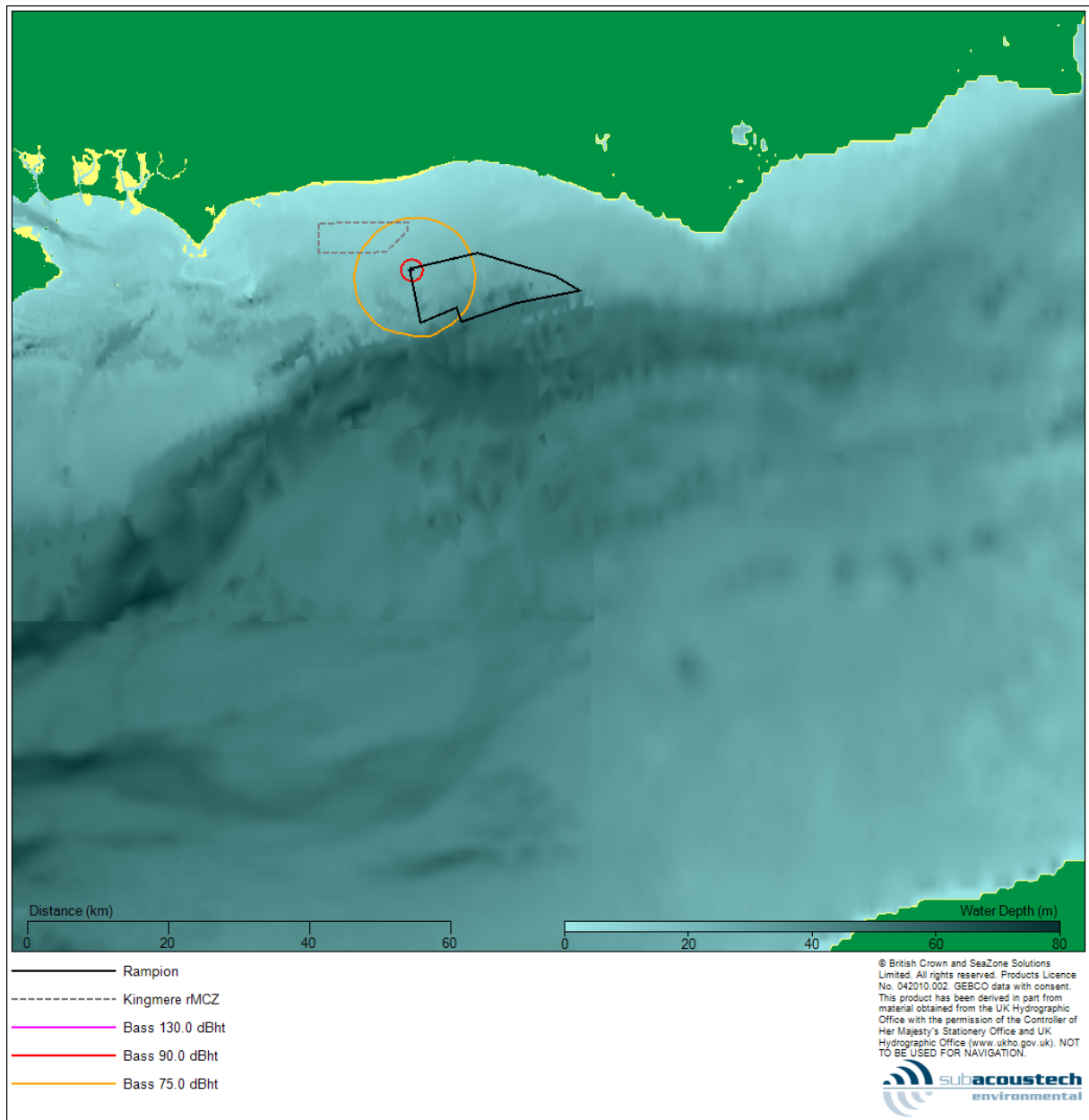


Figure 4-25 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Bass for the installation of a 2.6m pin pile, positioned west in the Rampion offshore wind farm site

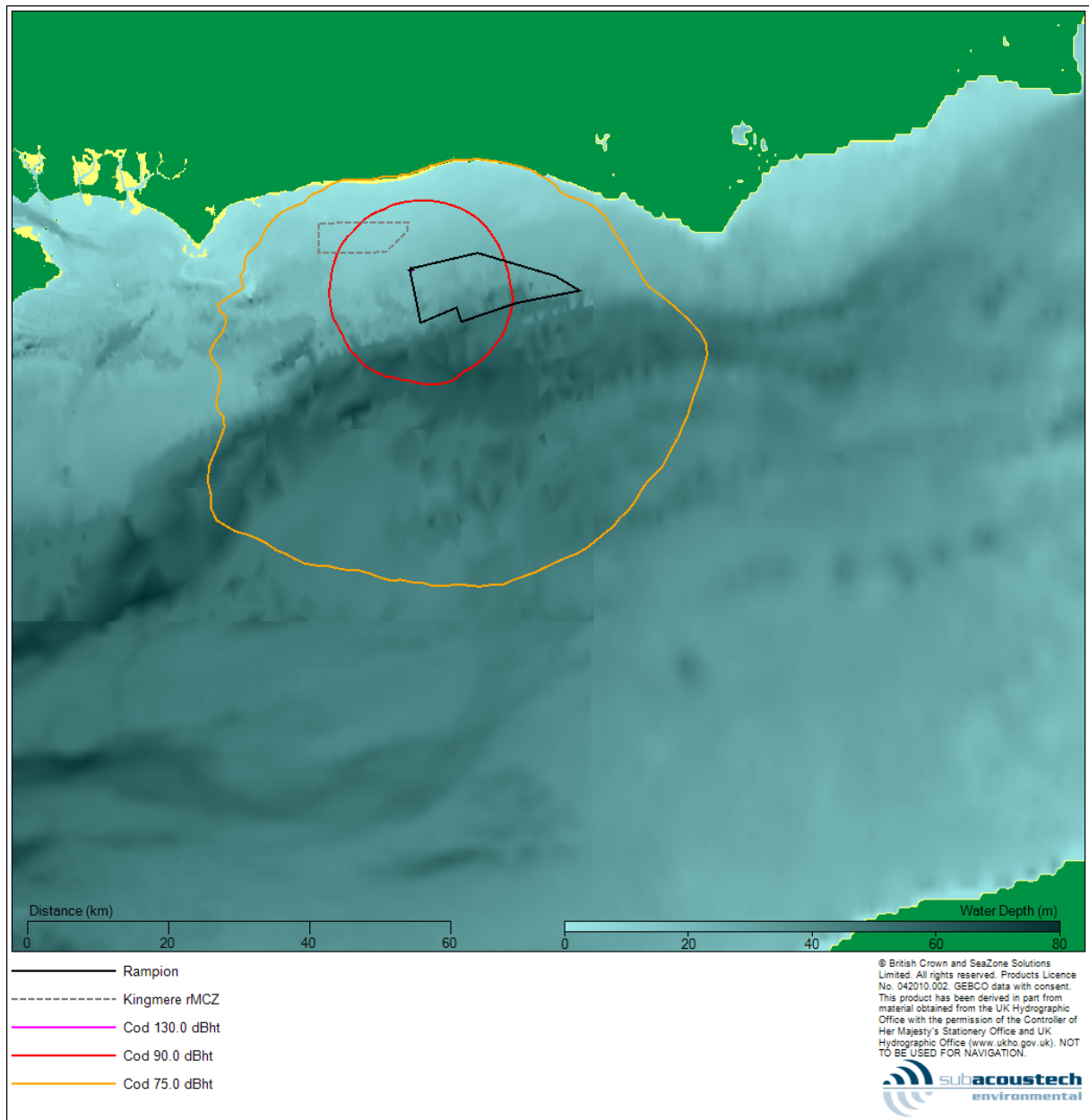


Figure 4-26 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Cod for the installation of a 2.6m pin pile, positioned west in the Rampion offshore wind farm site

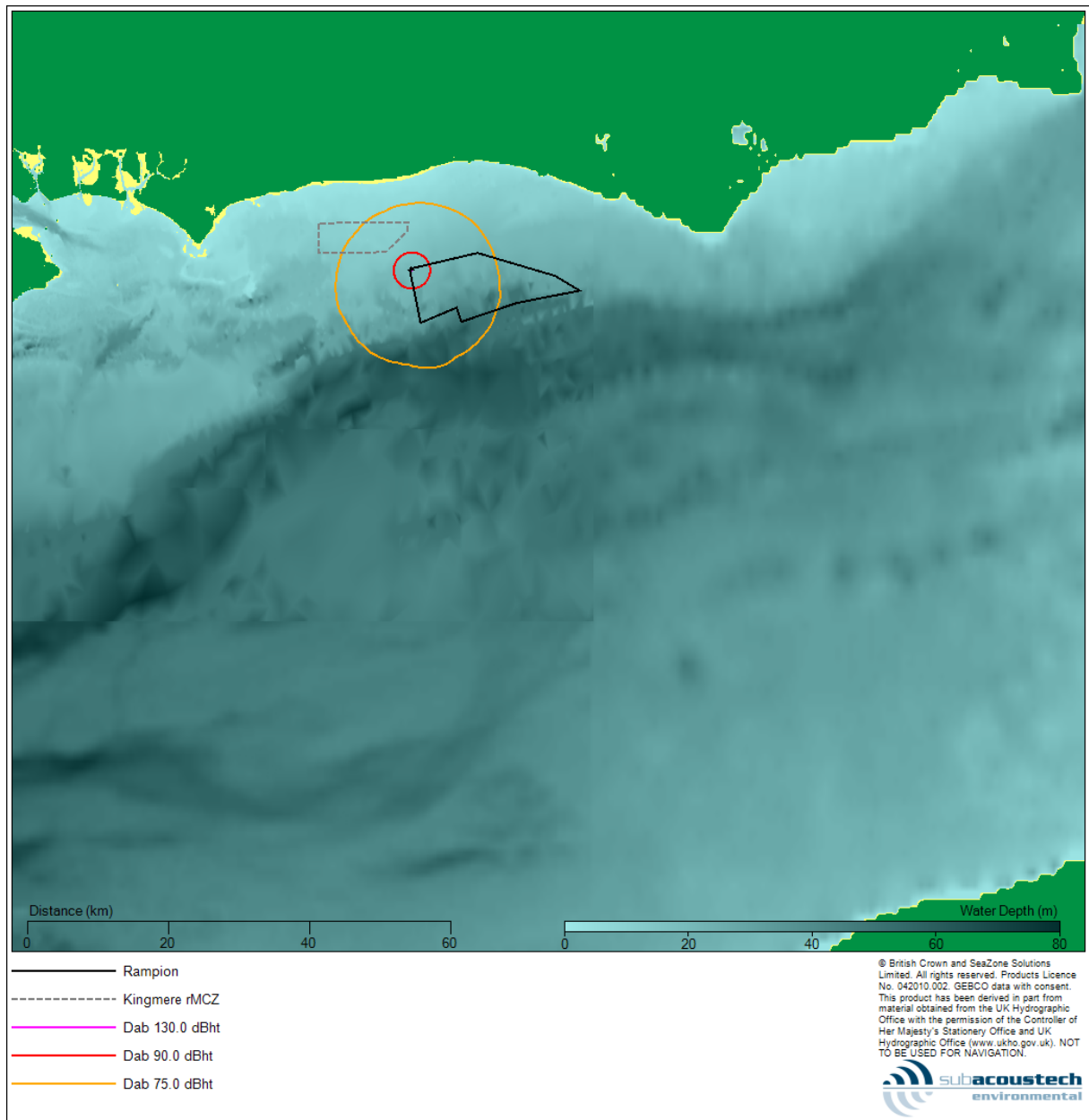


Figure 4-27 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Dab for the installation of a 2.6m pin pile, positioned west in the Rampion offshore wind farm site

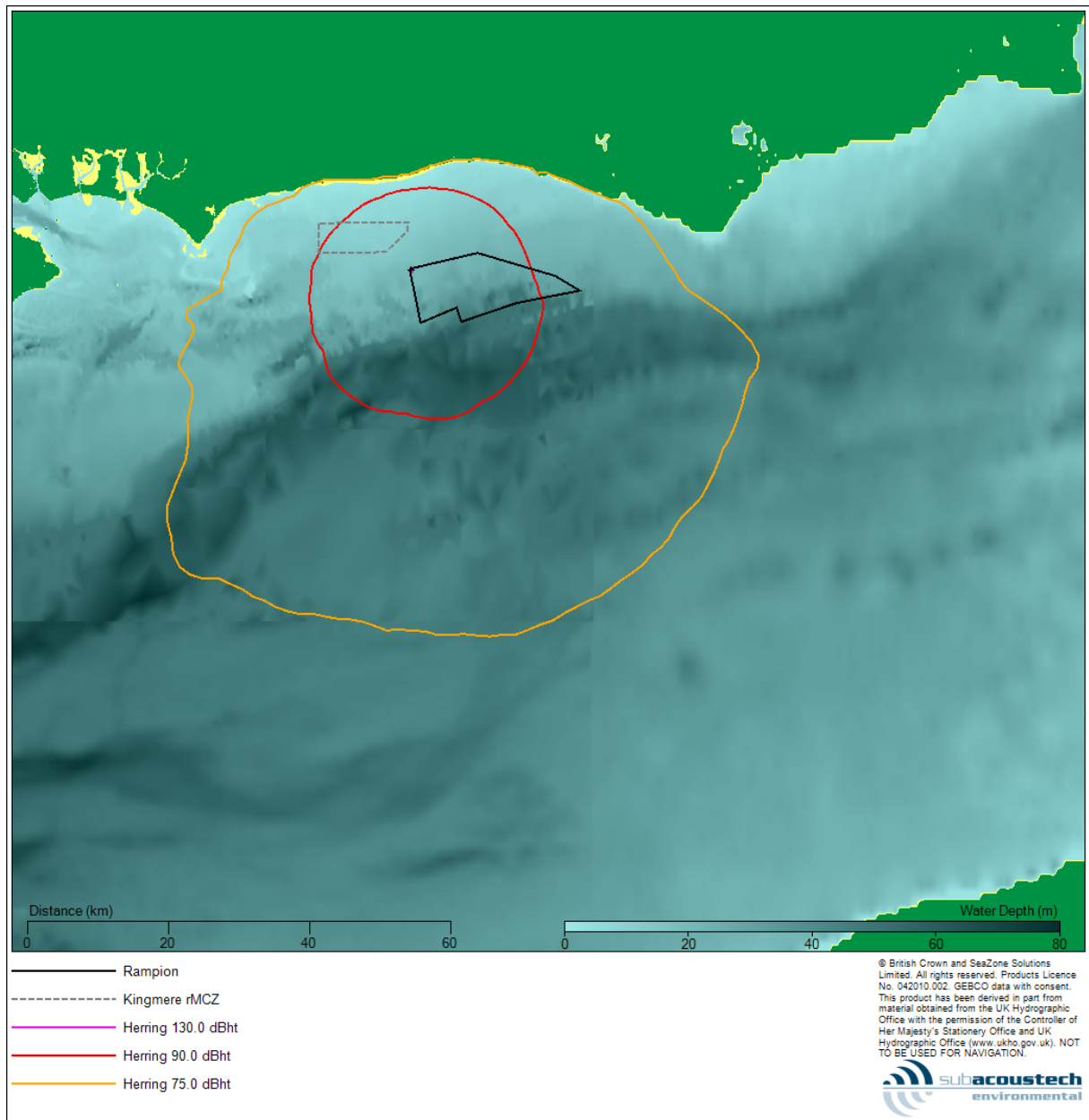


Figure 4-28 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Herring for the installation of a 2.6m pin pile, positioned west in the Rampion offshore wind farm site

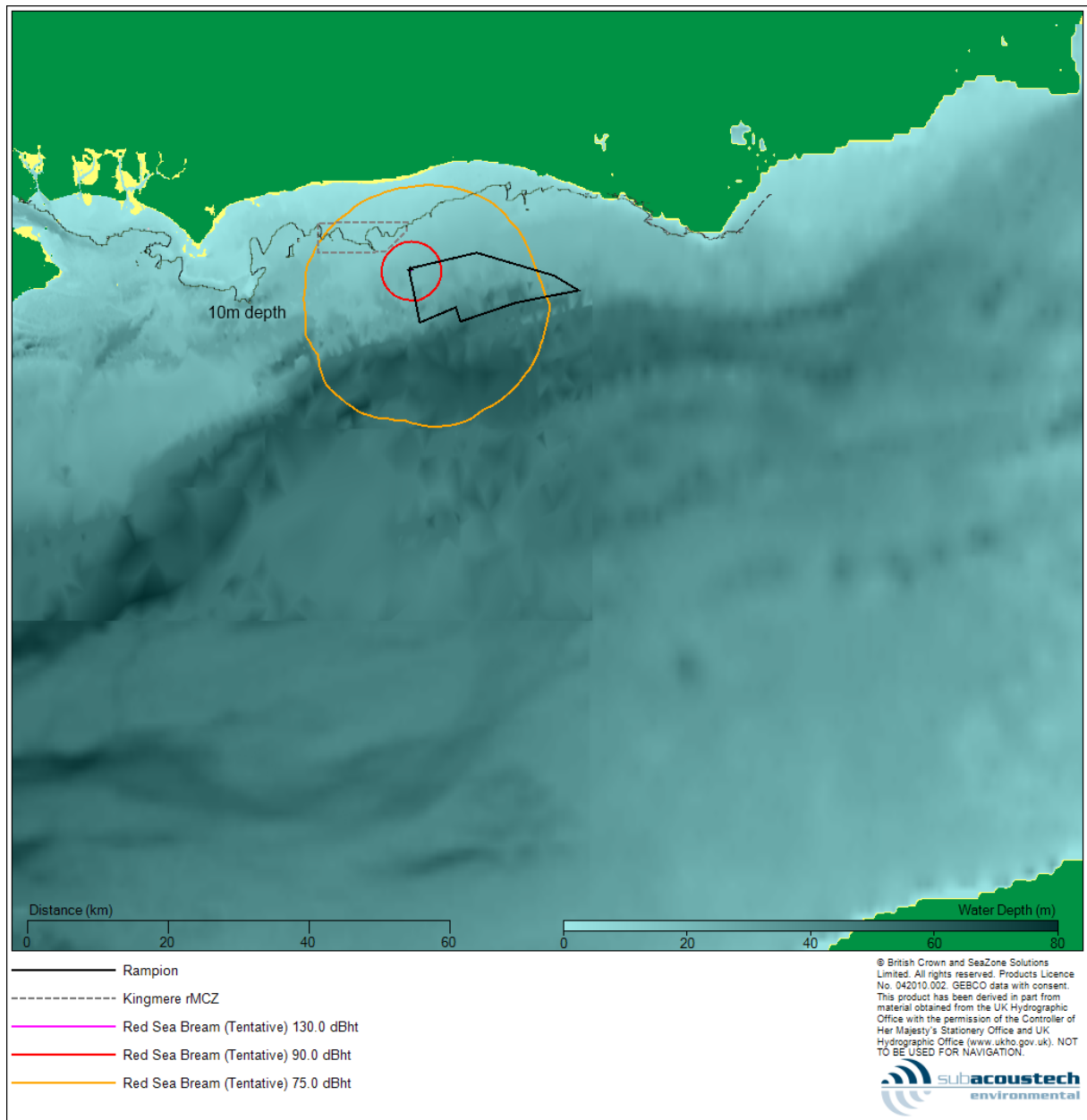


Figure 4-29 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Red Sea Bream for the installation of a 2.6m pin pile, positioned west in the Rampion offshore wind farm site

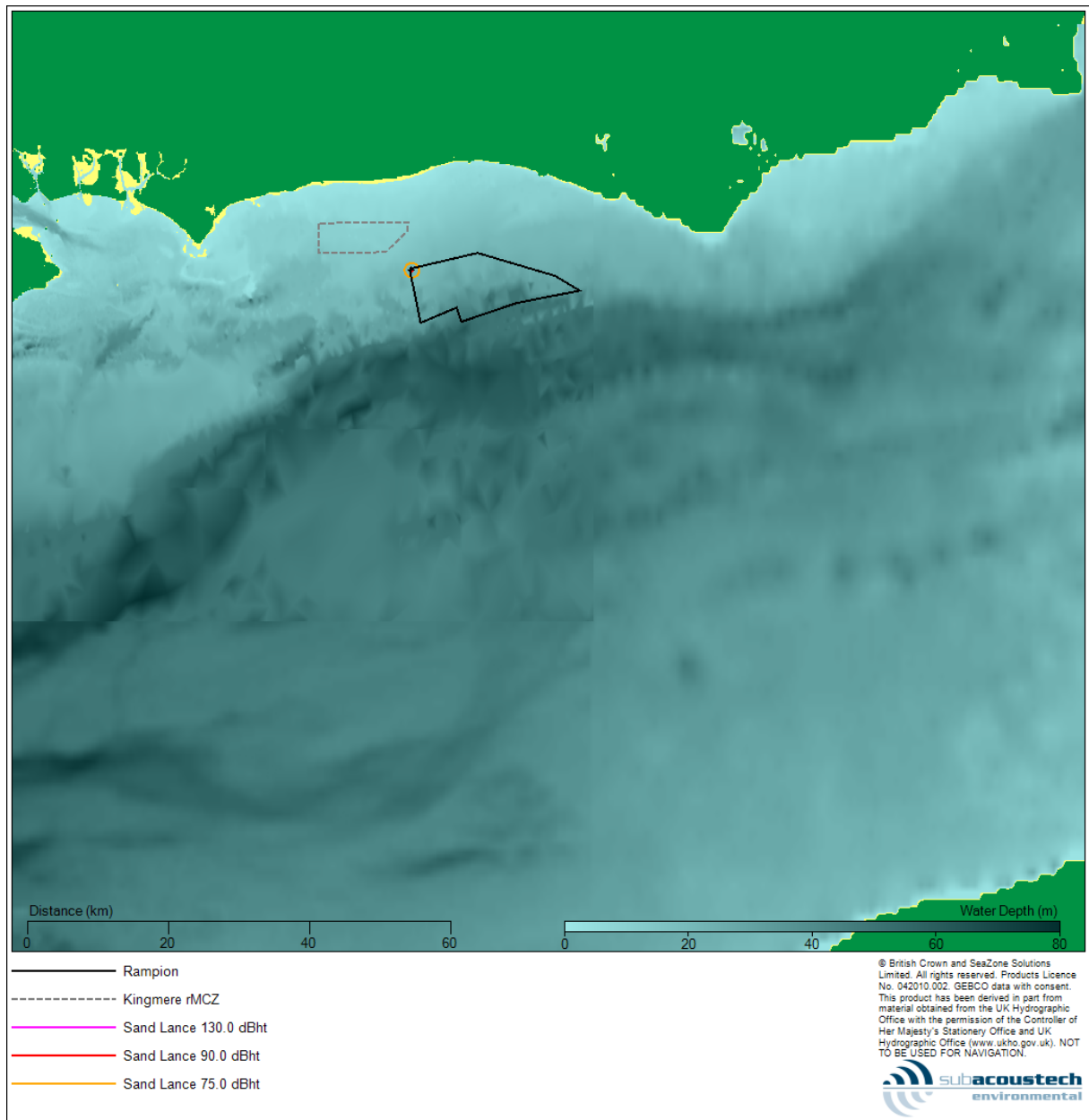


Figure 4-30 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Sand Lance for the installation of a 2.6m pin pile, positioned west in the Rampion offshore wind farm site

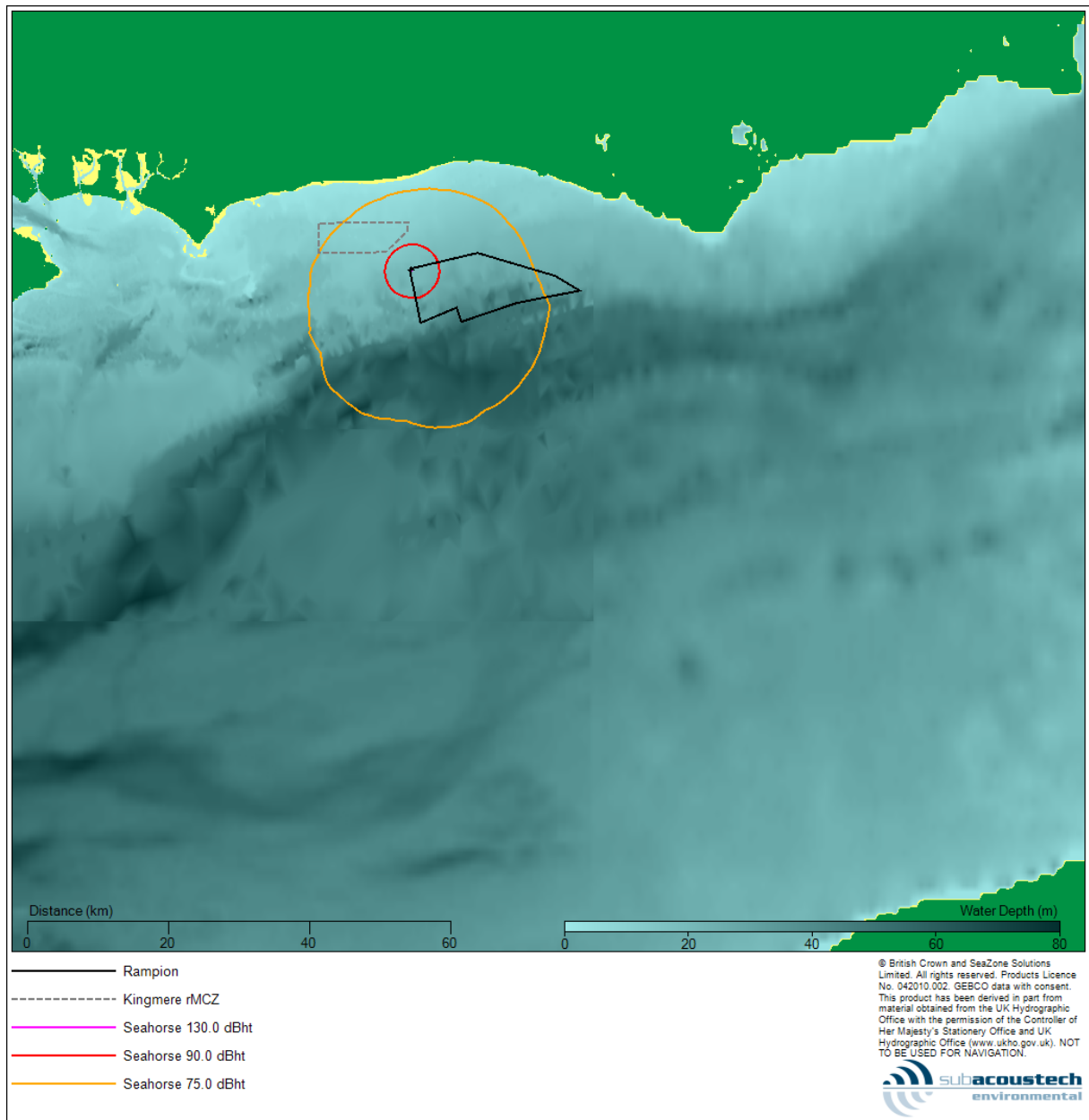


Figure 4-31 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Seahorse for the installation of a 2.6m pin pile, positioned west in the Rampion offshore wind farm site

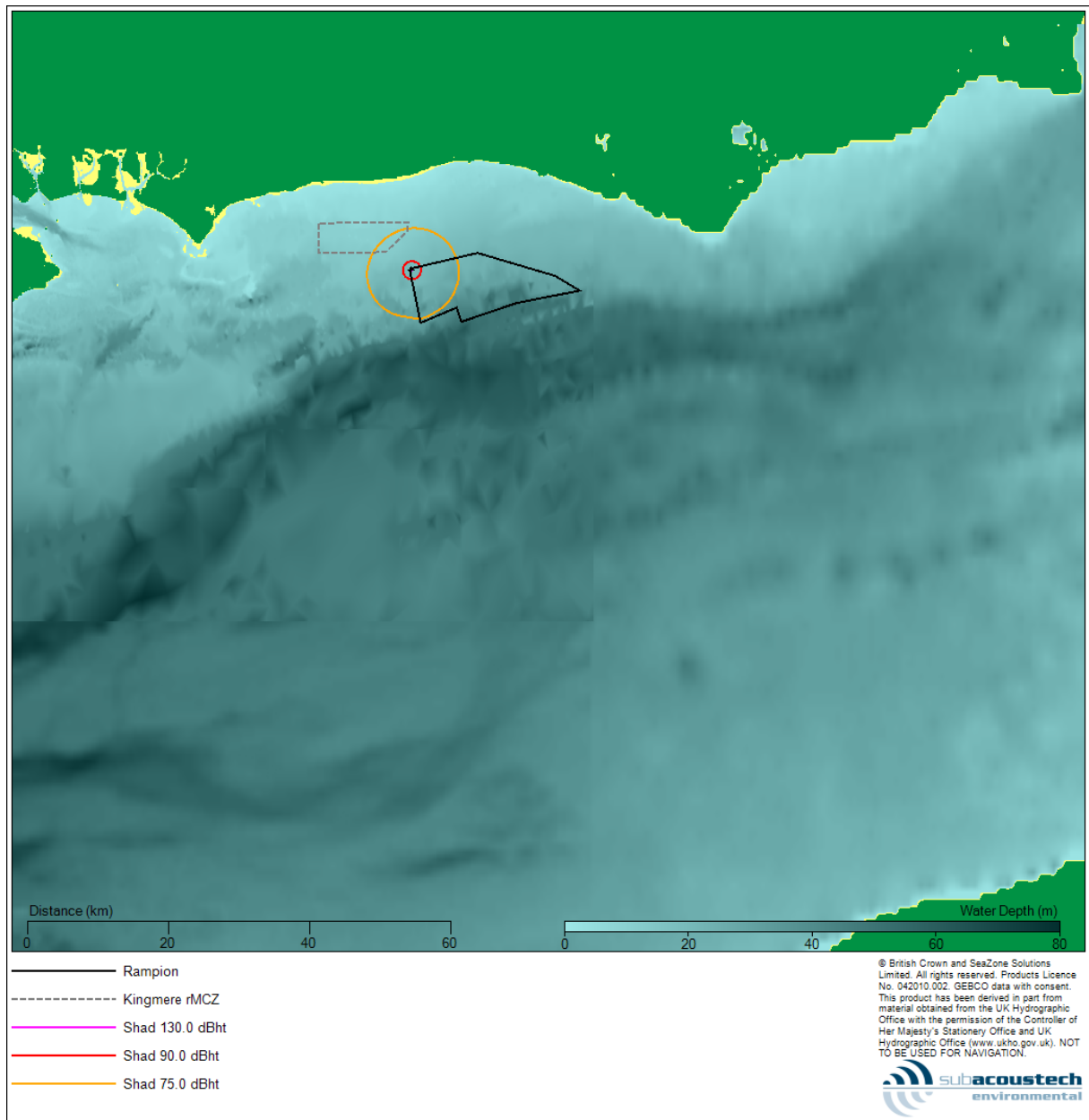


Figure 4-32 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Shad for the installation of a 2.6m pin pile, positioned west in the Rampion offshore wind farm site

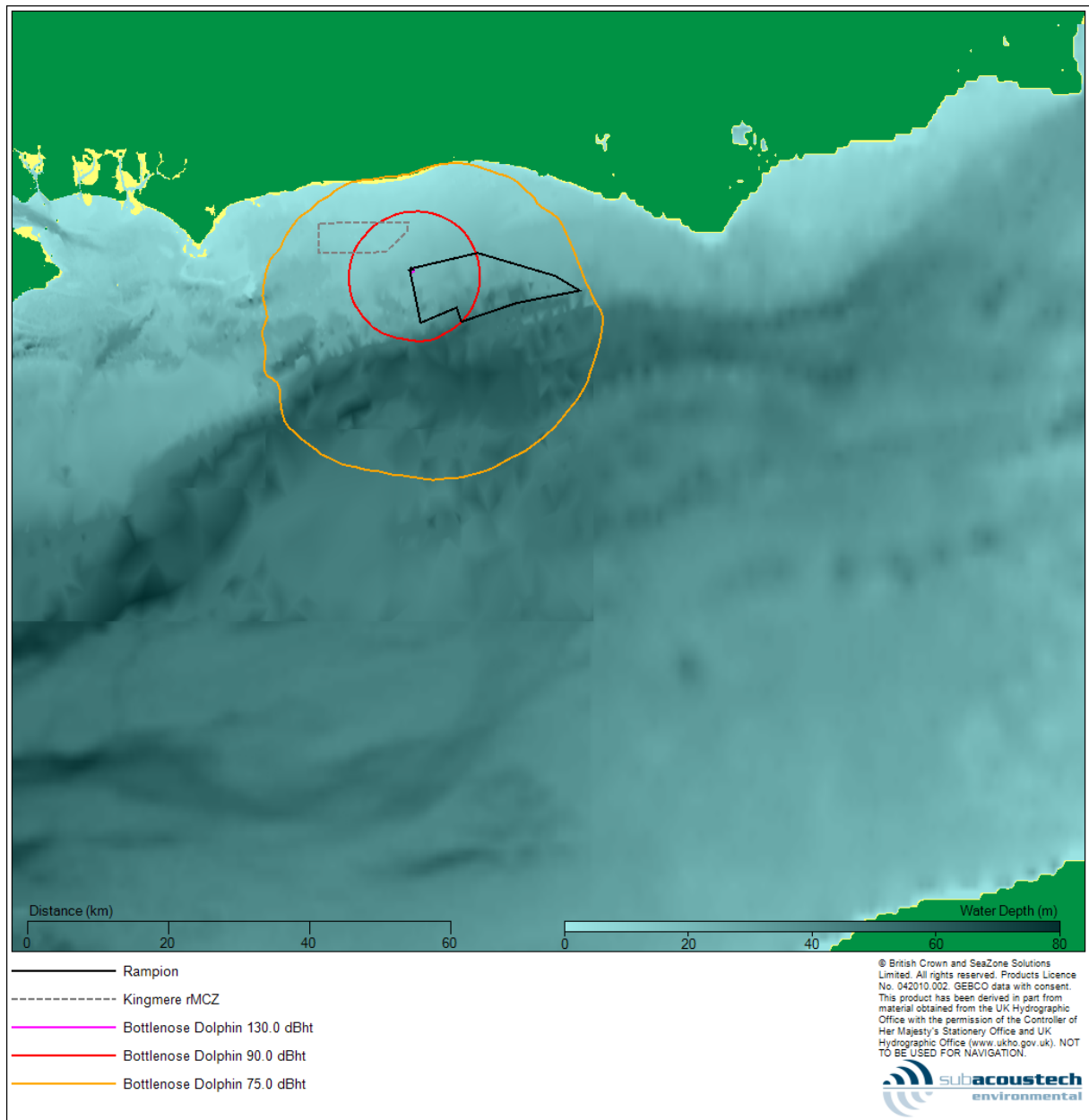


Figure 4-33 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Bottlenose Dolphin for the installation of a 2.6m pin pile, positioned west in the Rampion offshore wind farm site

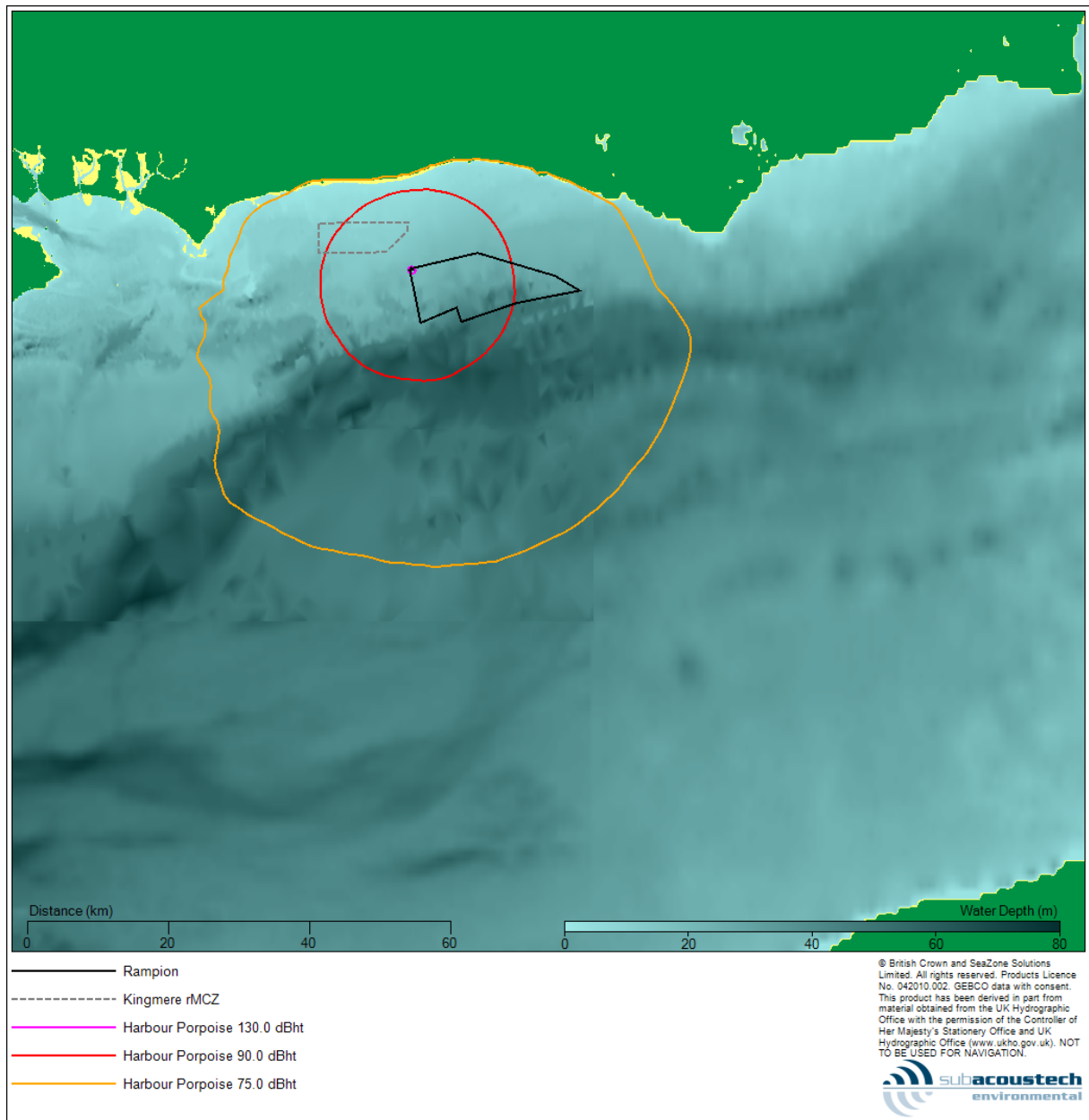


Figure 4-34 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Harbour Porpoise for the installation of a 2.6m pin pile, position west in the Rampion offshore wind farm site

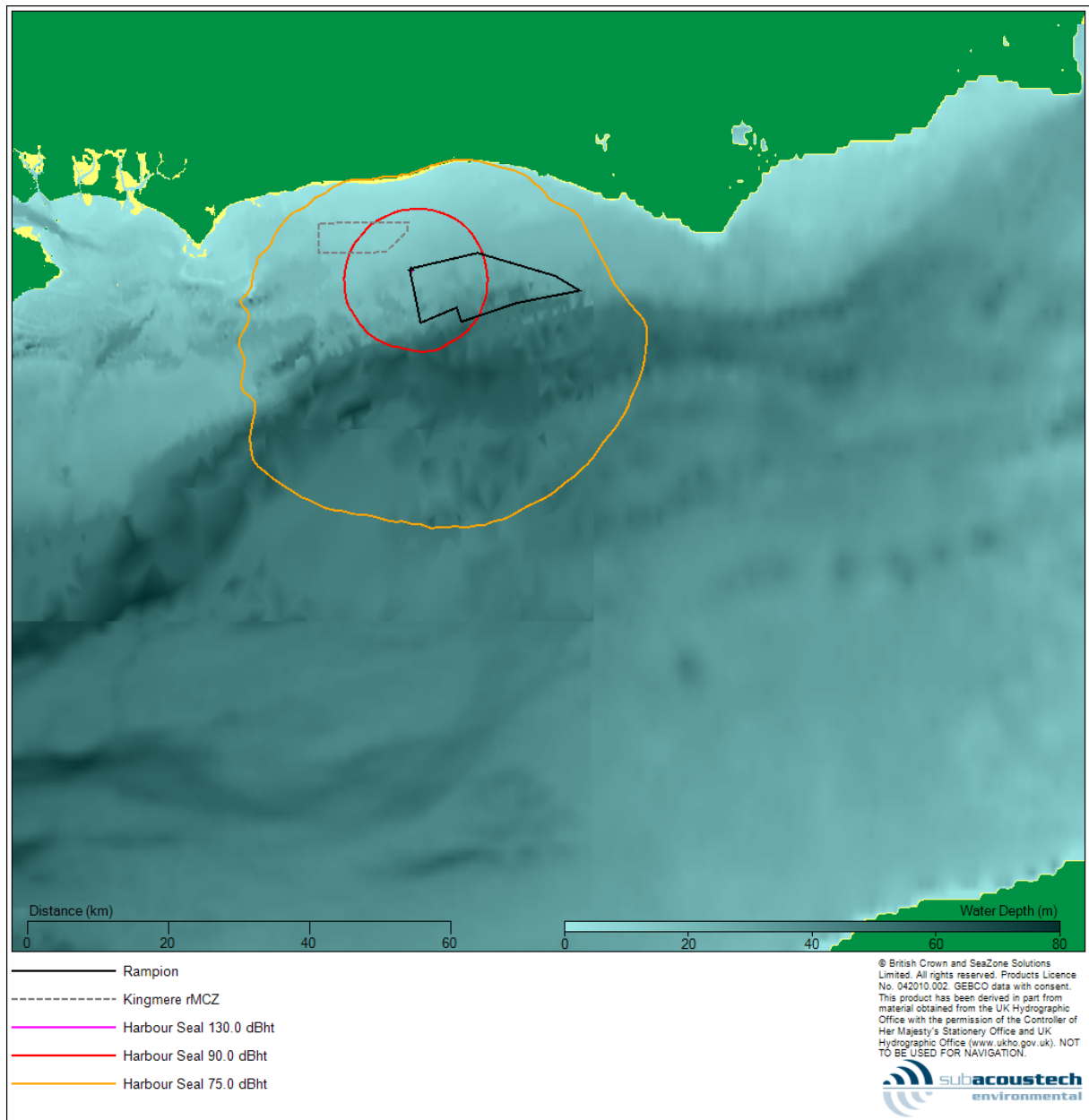


Figure 4-35 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Harbour Seal for the installation of a 2.6m pin pile, positioned west in the Rampion offshore wind farm site

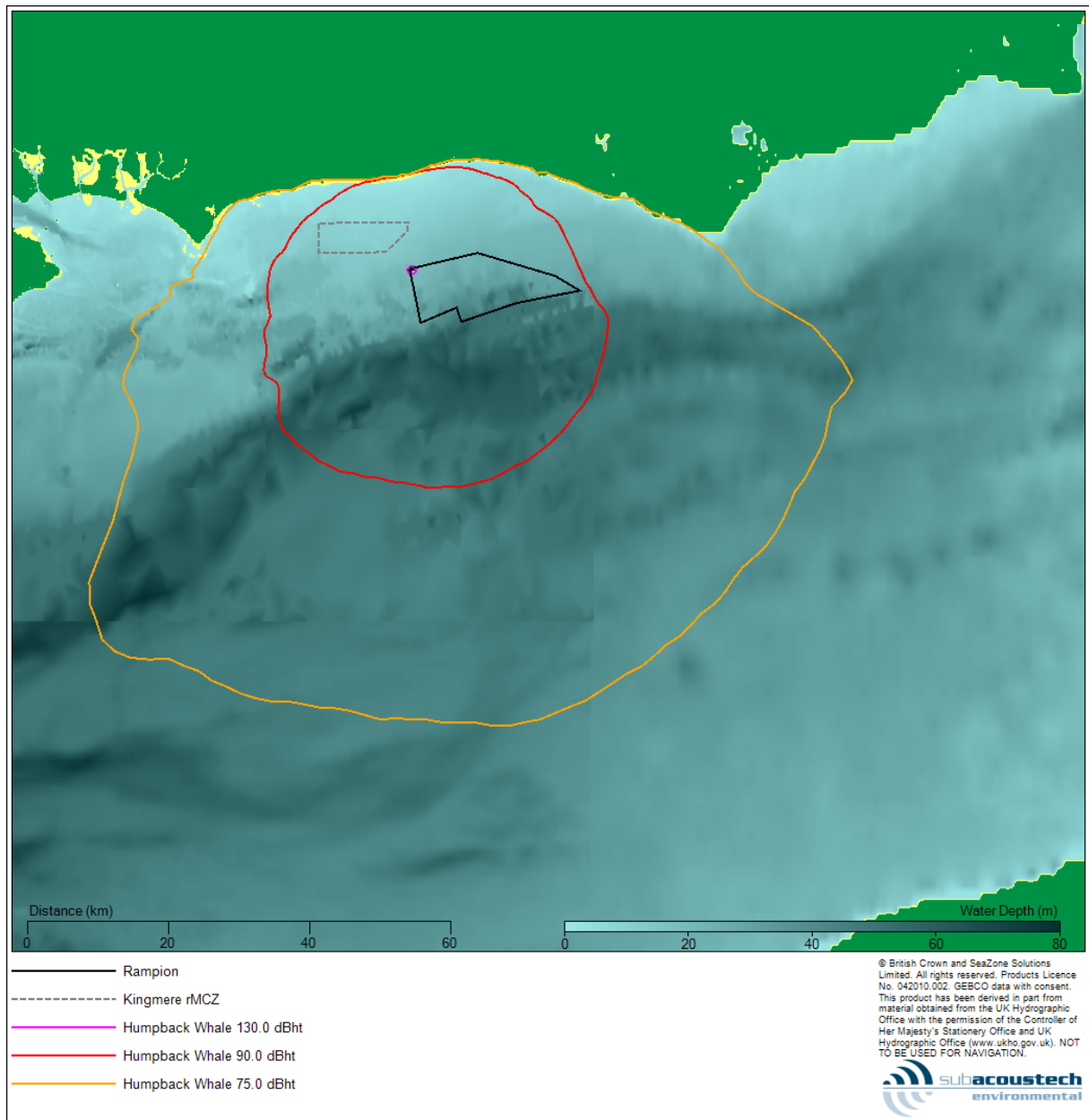


Figure 4-36 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Humpback Whale for the installation of a 2.6m pin pile, positioned west in the Rampion offshore wind farm site

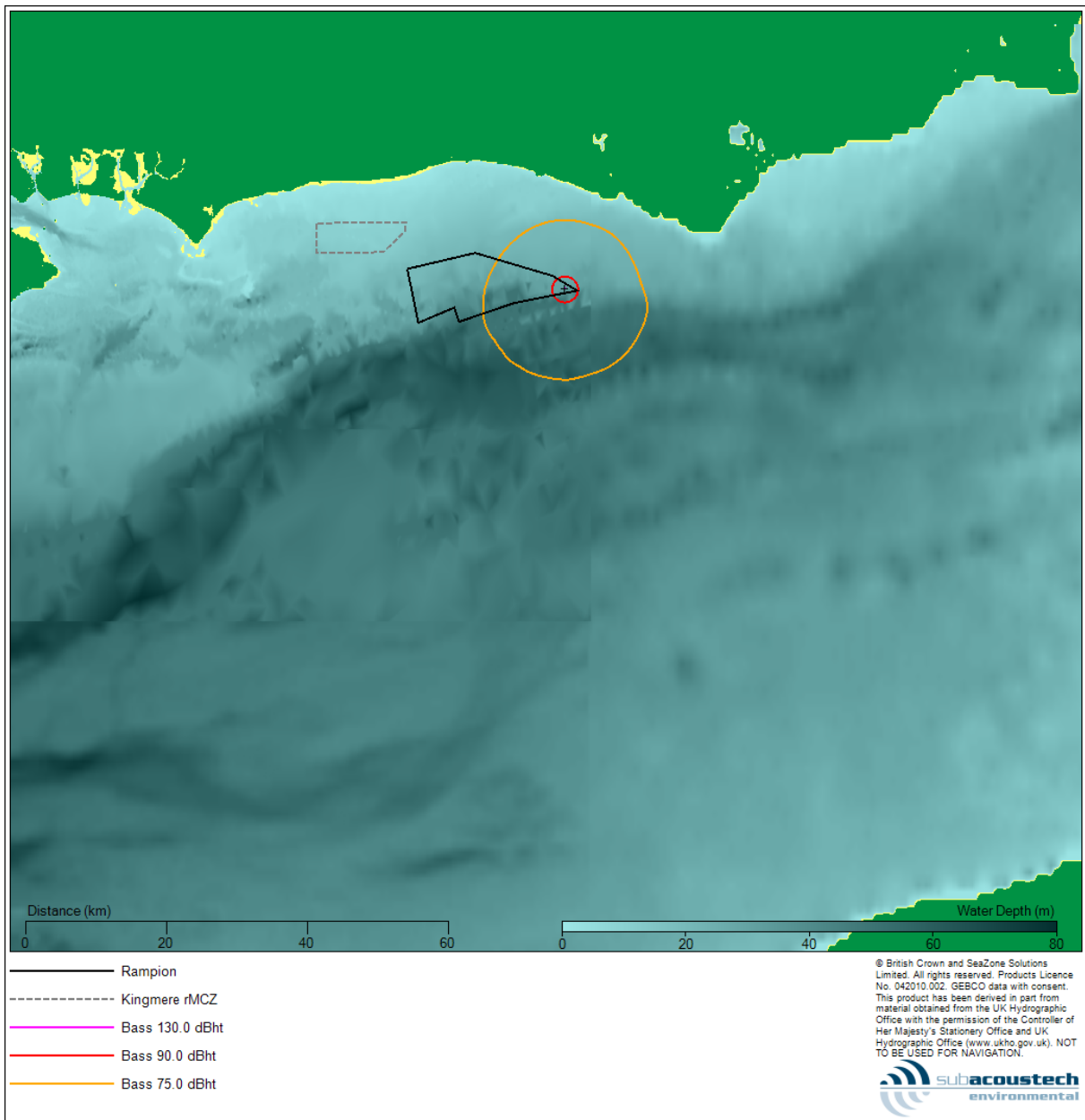


Figure 4-37 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Bass for the installation of a 2.6m pin pile, positioned east in the Rampion offshore wind farm site

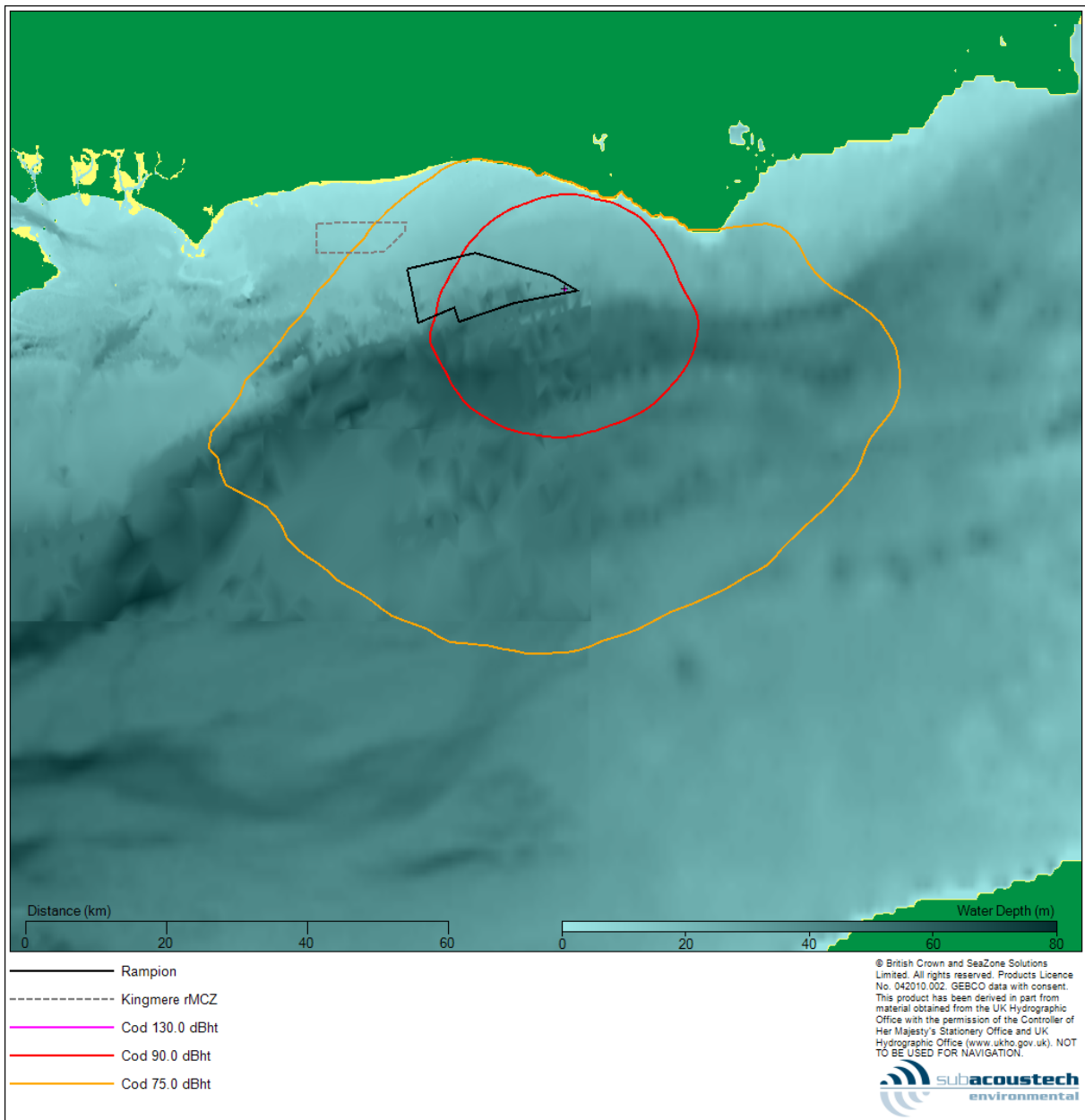


Figure 4-38 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Cod for the installation of a 2.6m pin pile, positioned east in the Rampion offshore wind farm site

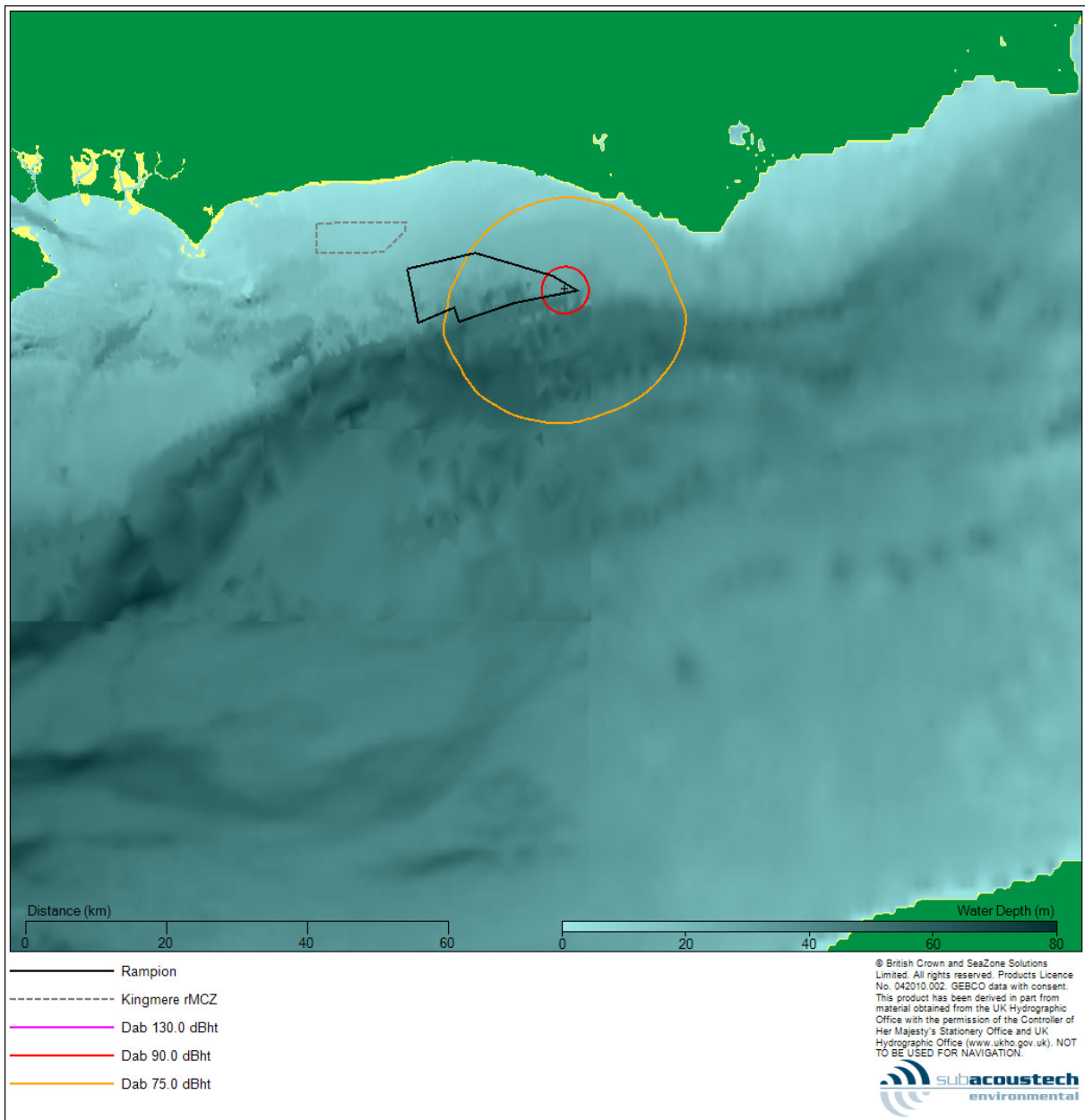


Figure 4-39 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Dab for the installation of a 2.6m pin pile, positioned east in the Rampion offshore wind farm site

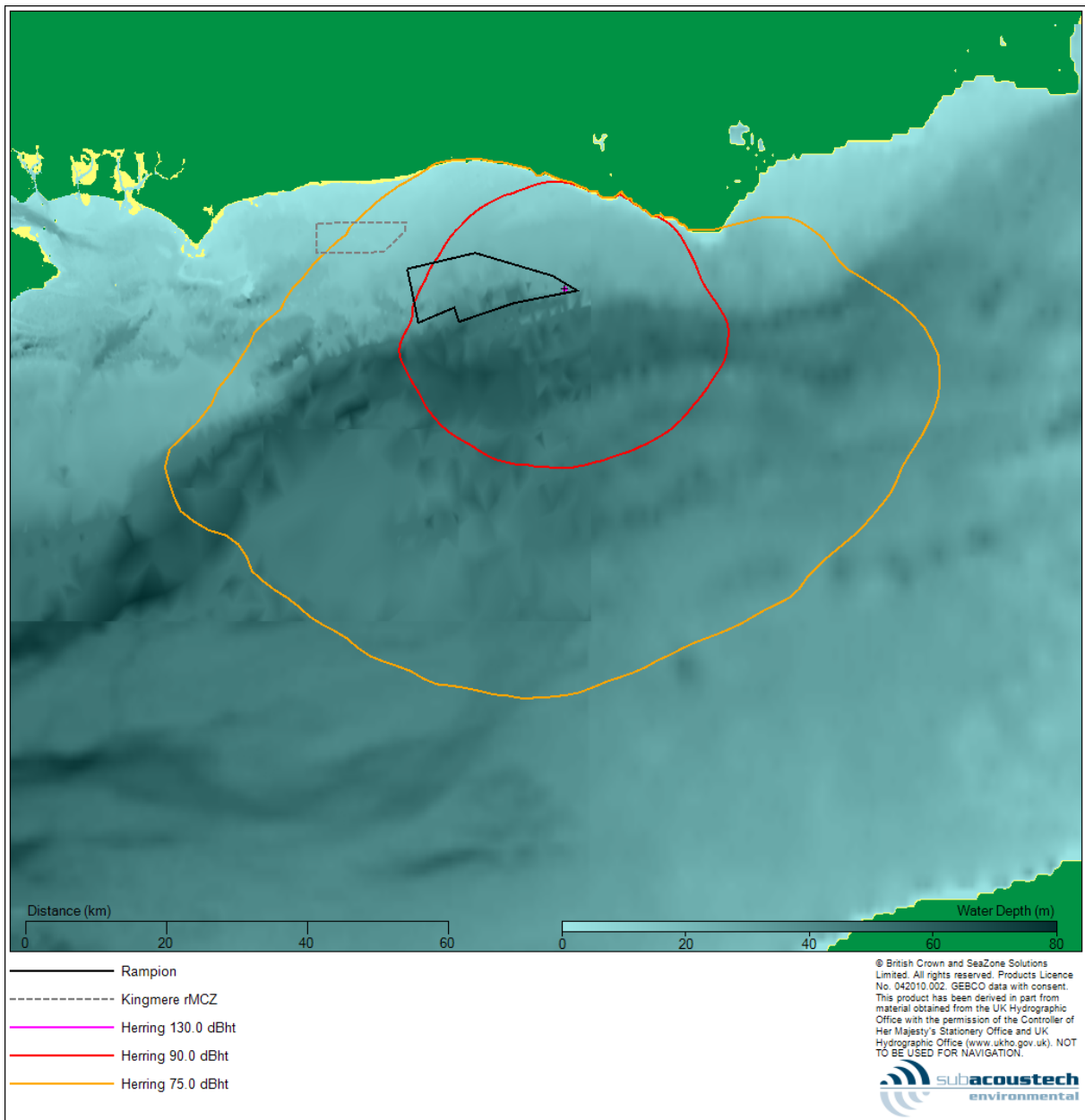


Figure 4-40 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Herring for the installation of a 2.6m pin pile, positioned east in the Rampion offshore wind farm site

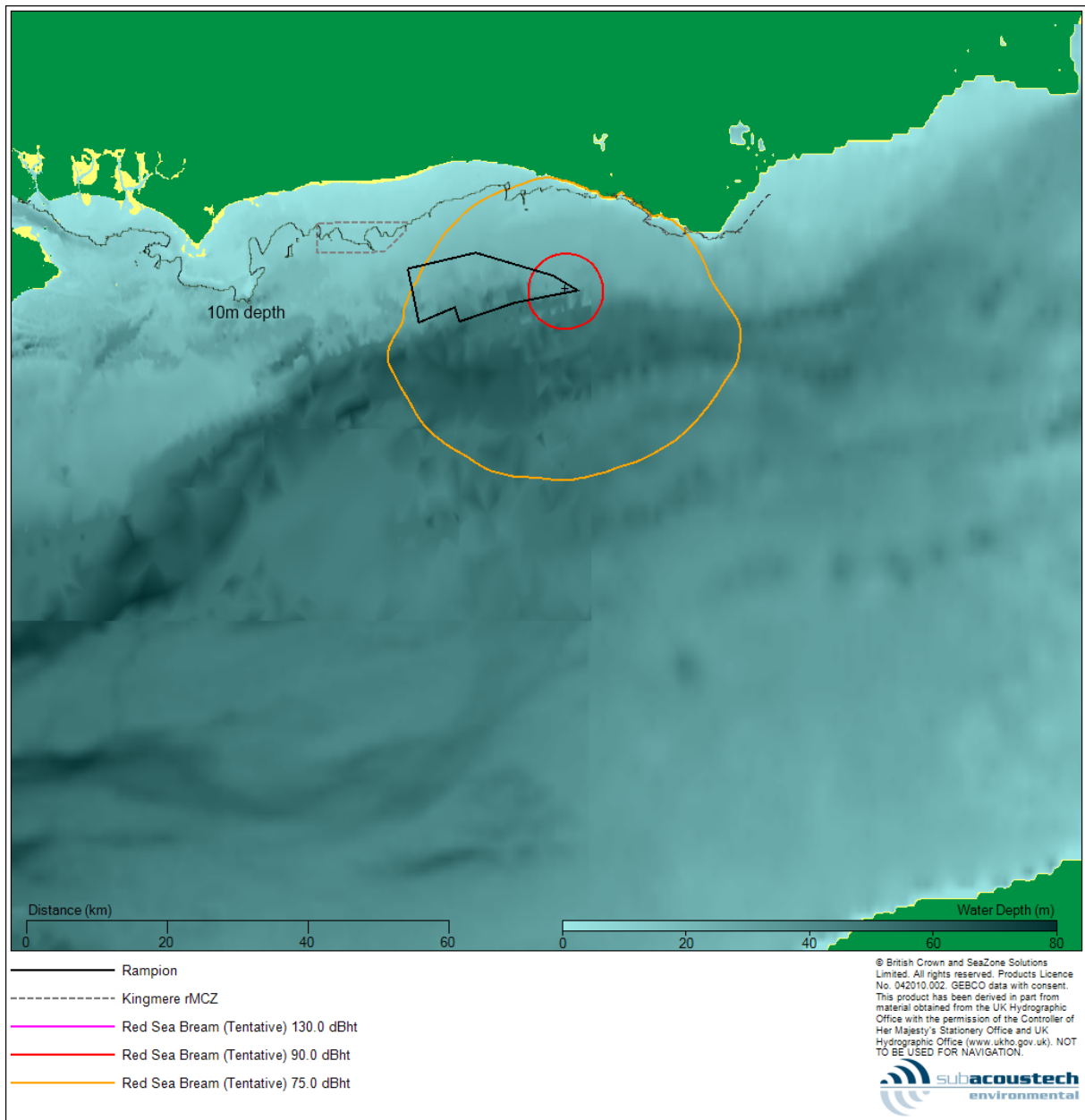


Figure 4-41 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Red Sea Bream for the installation of a 2.6m pin pile, positioned east in the Rampion offshore wind farm site

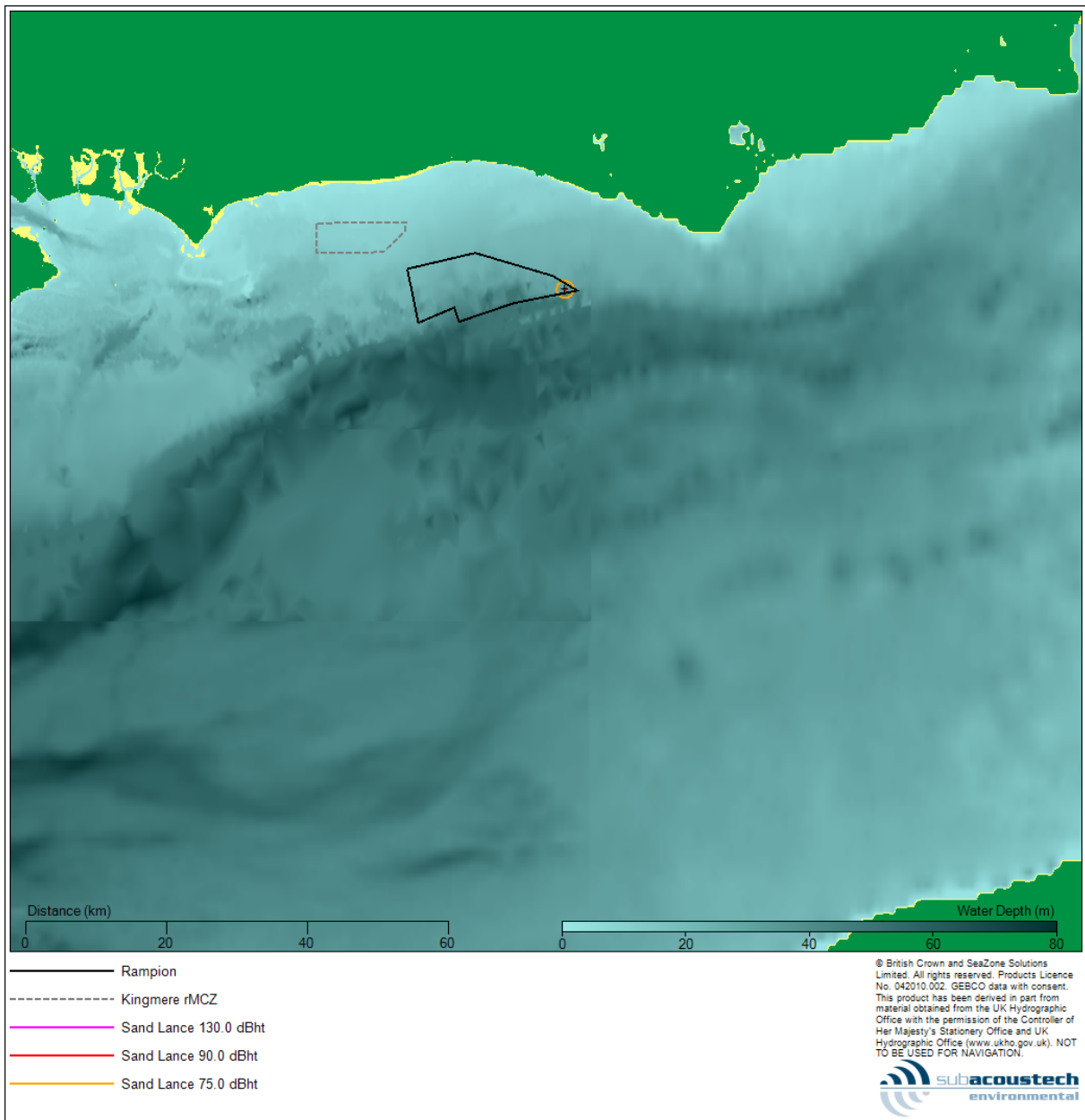


Figure 4-42 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Sand Lance for the installation of a 2.6m pin pile, positioned east in the Rampion offshore wind farm site

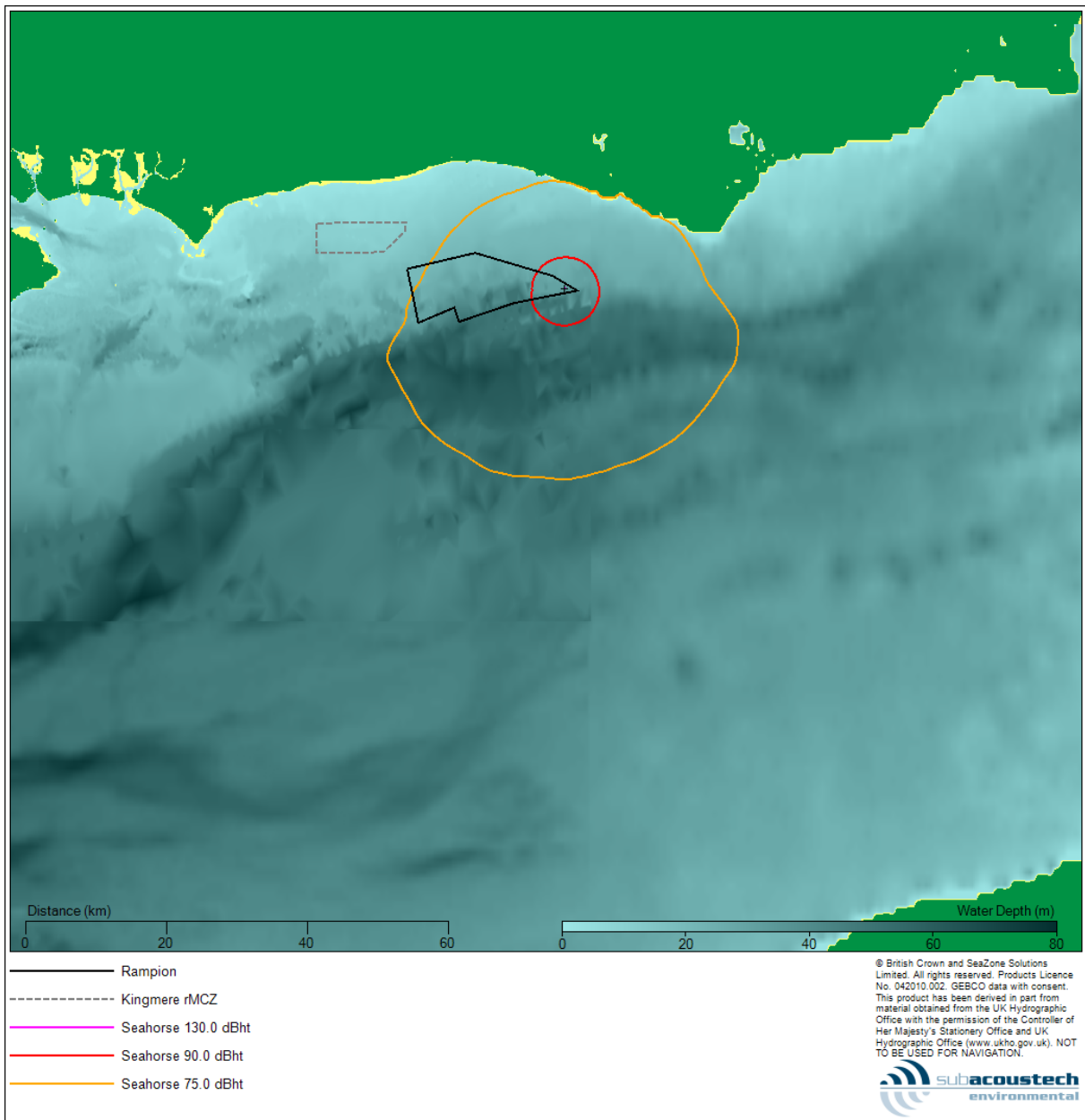


Figure 4-43 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Seahorse for the installation of a 2.6m pin pile, positioned east in the Rampion offshore wind farm site

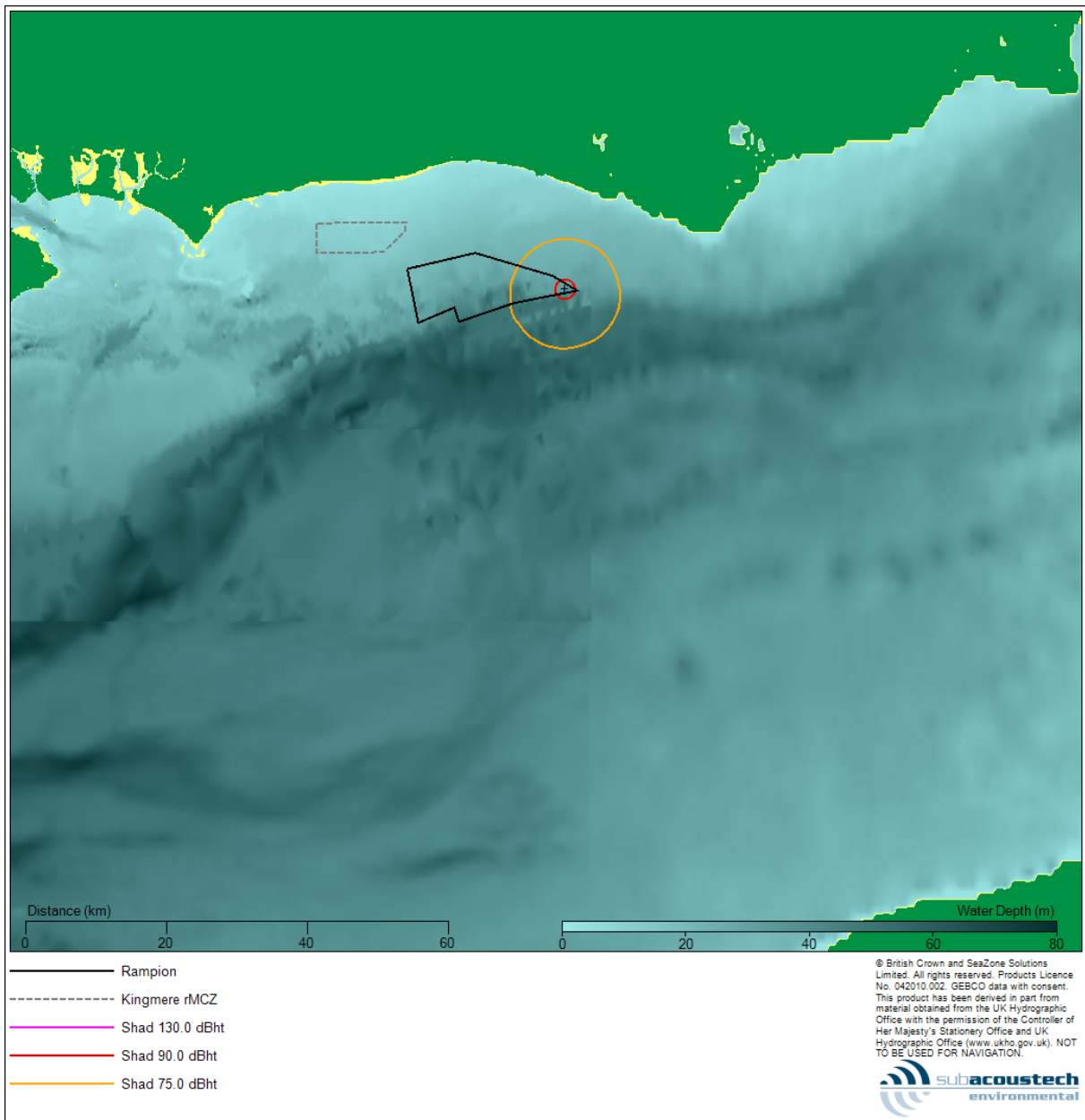


Figure 4-44 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Shad for the installation of a 2.6m pin pile, positioned east in the Rampion offshore wind farm site

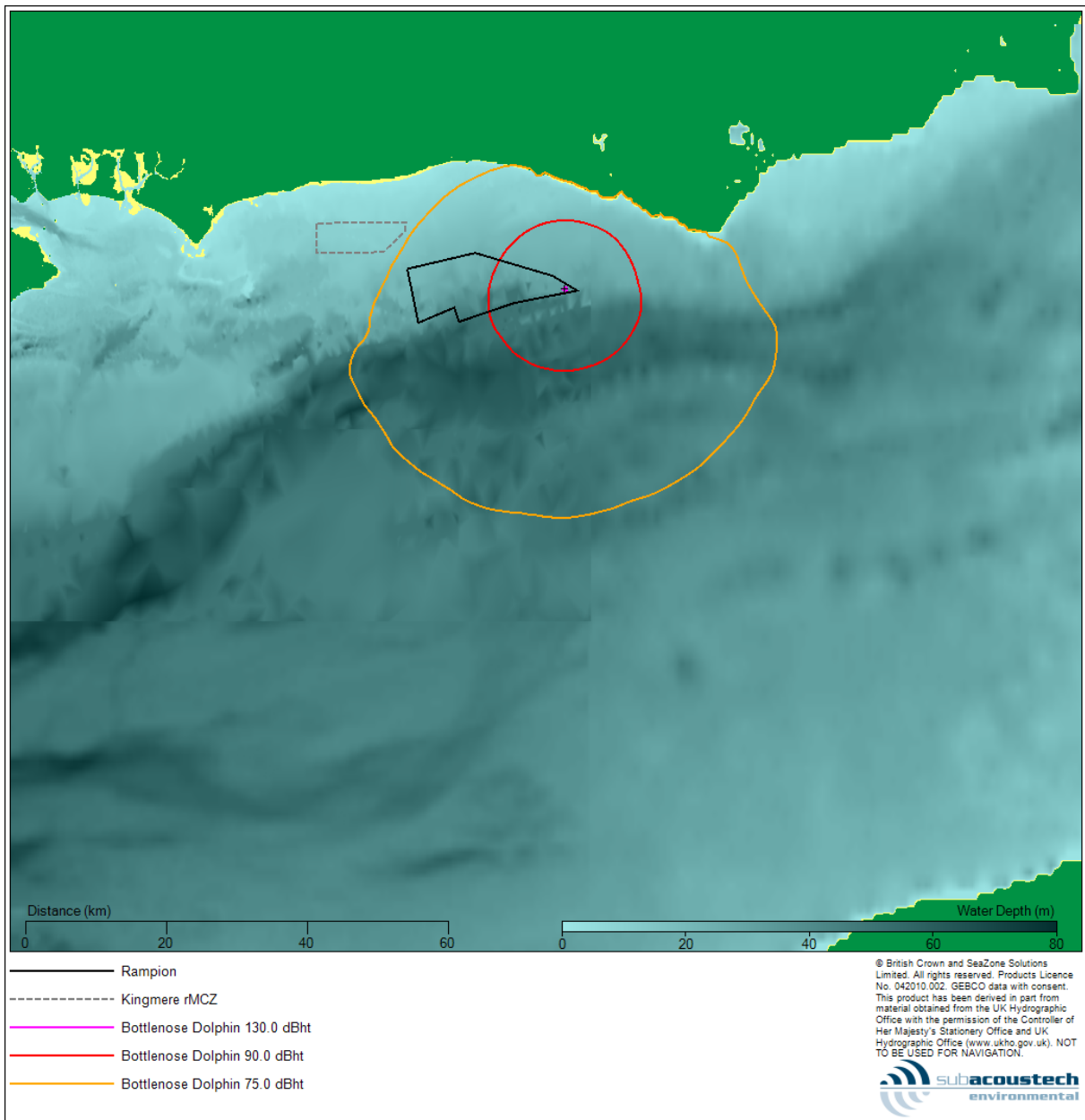


Figure 4-45 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Bottlenose Dolphin for the installation of a 2.6m pin pile, positioned east in the Rampion offshore wind farm site

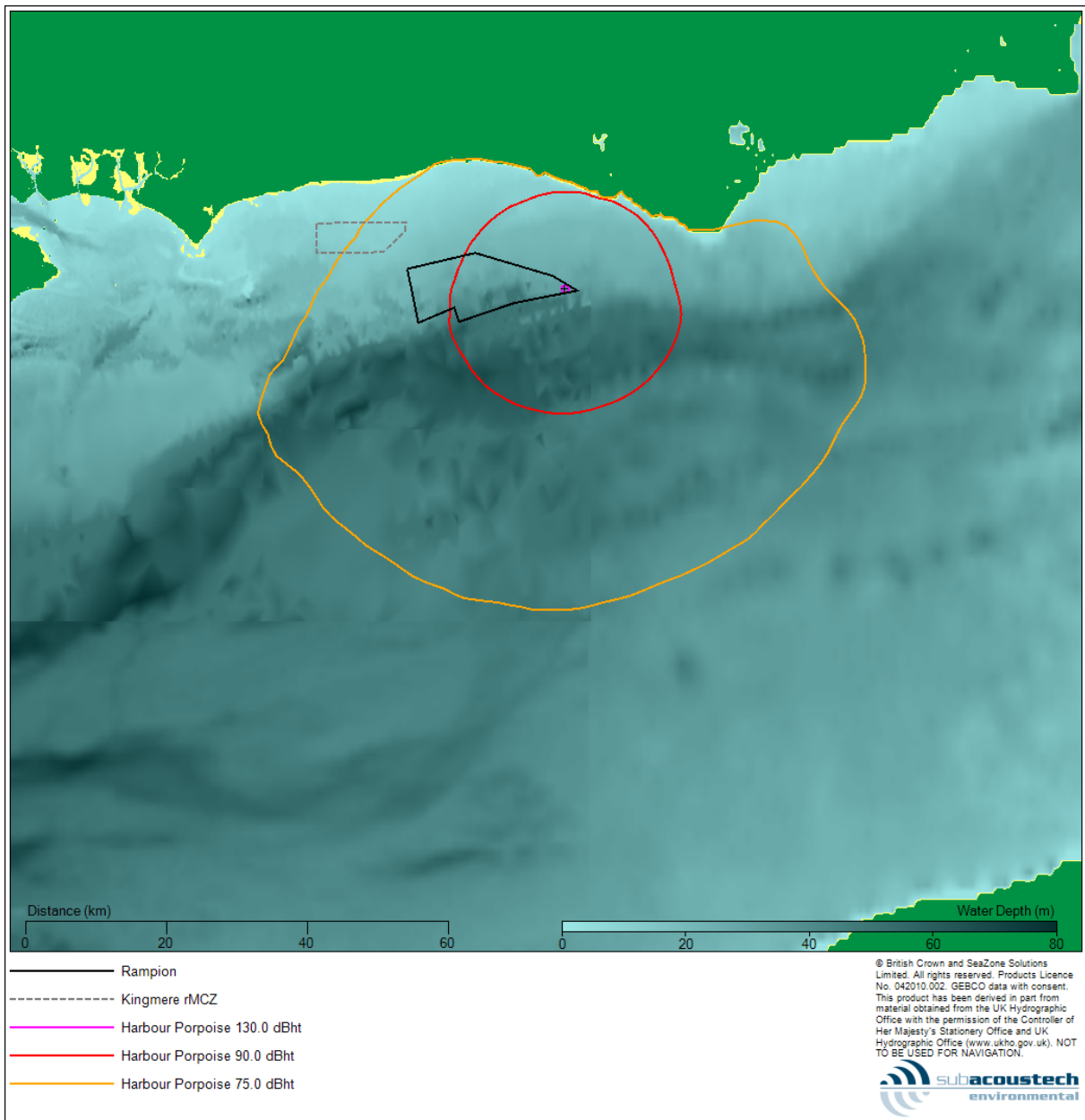


Figure 4-46 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Harbour Porpoise for the installation of a 2.6m pin pile, positioned east in the Rampion offshore wind farm site

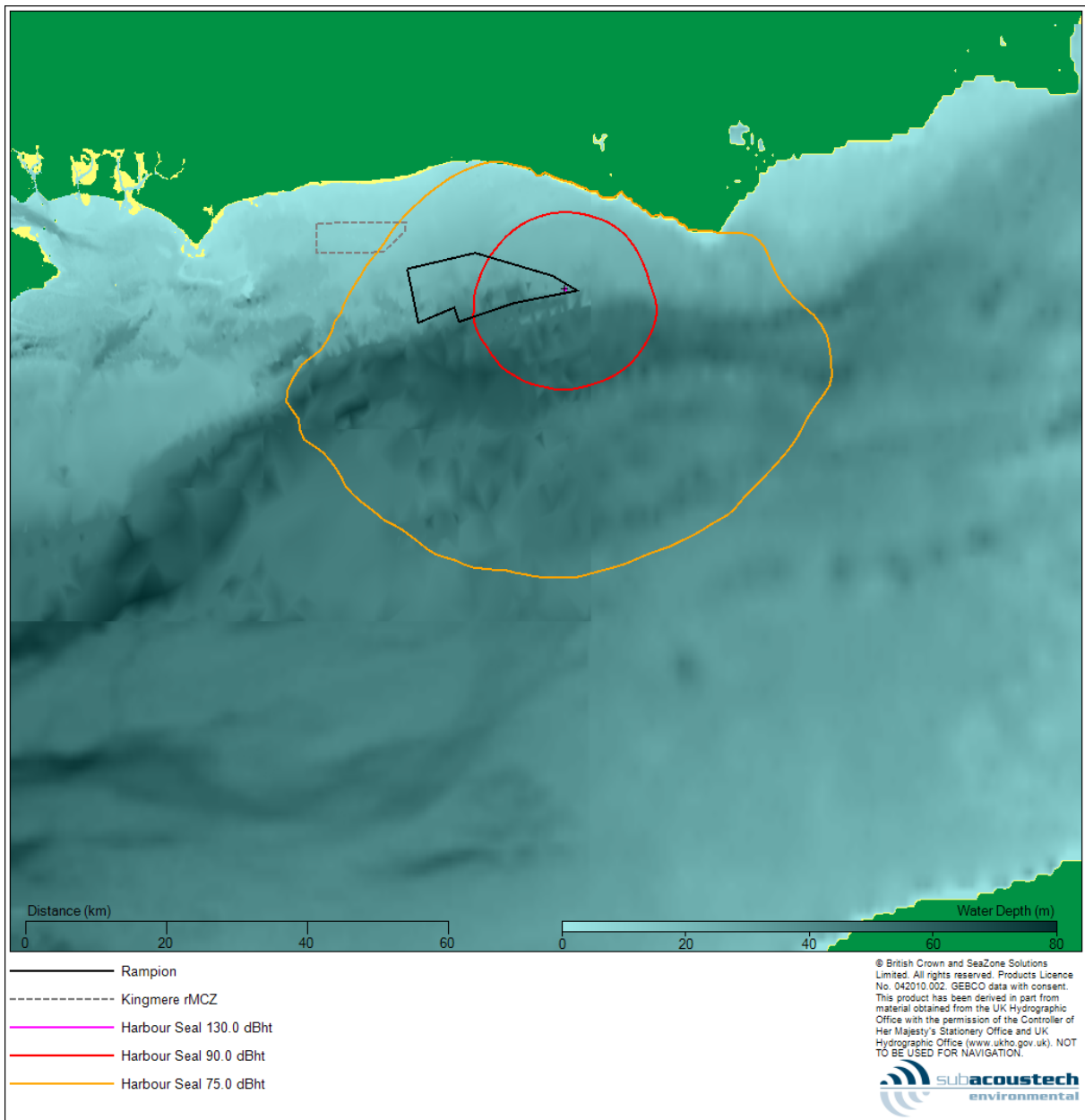


Figure 4-47 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Harbour Seal for the installation of a 2.6m pin pile, positioned east in the Rampion offshore wind farm site

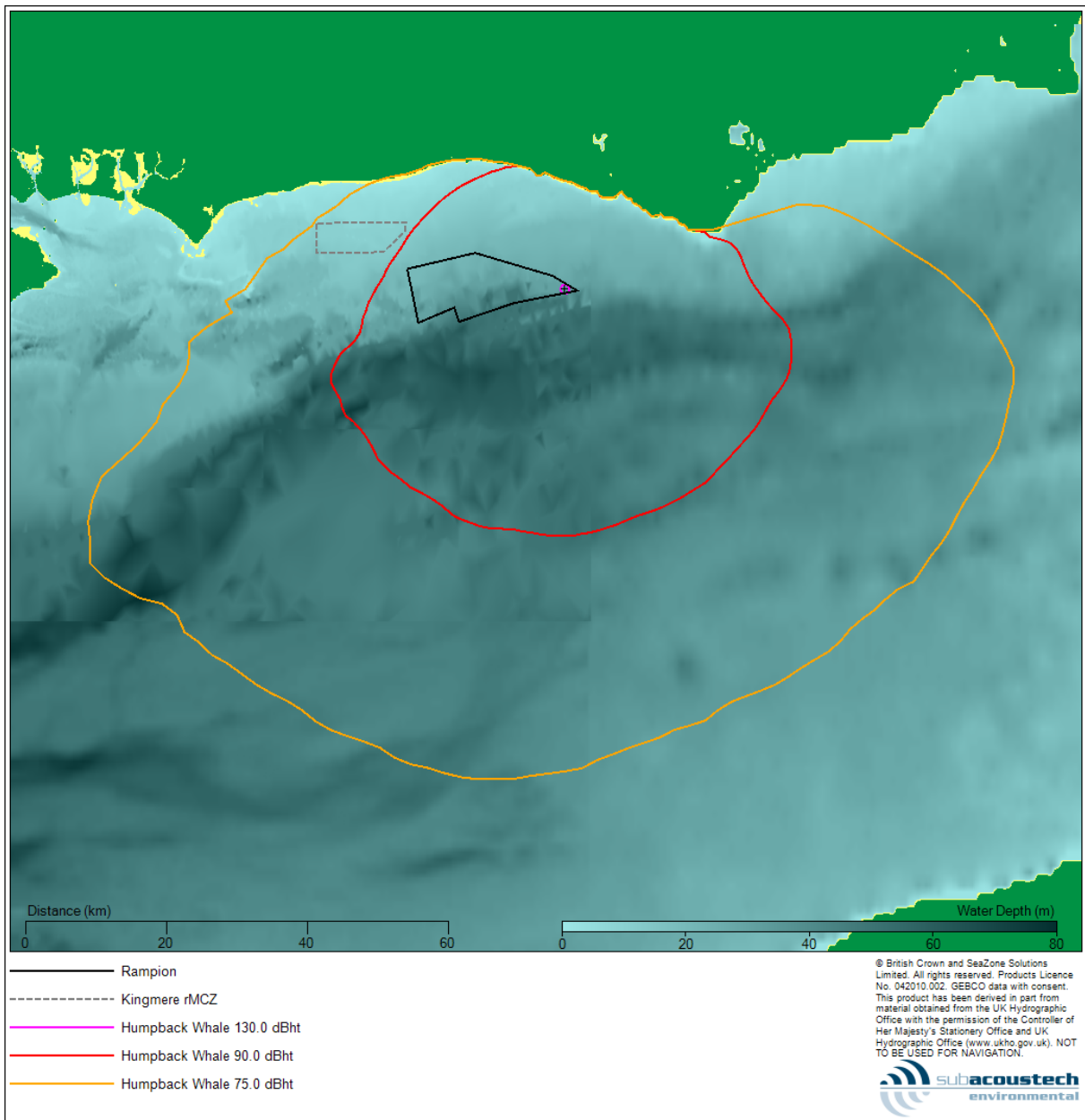


Figure 4-48 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Humpback Whale for the installation of a 2.6m pin pile, positioned east in the Rampion offshore wind farm site

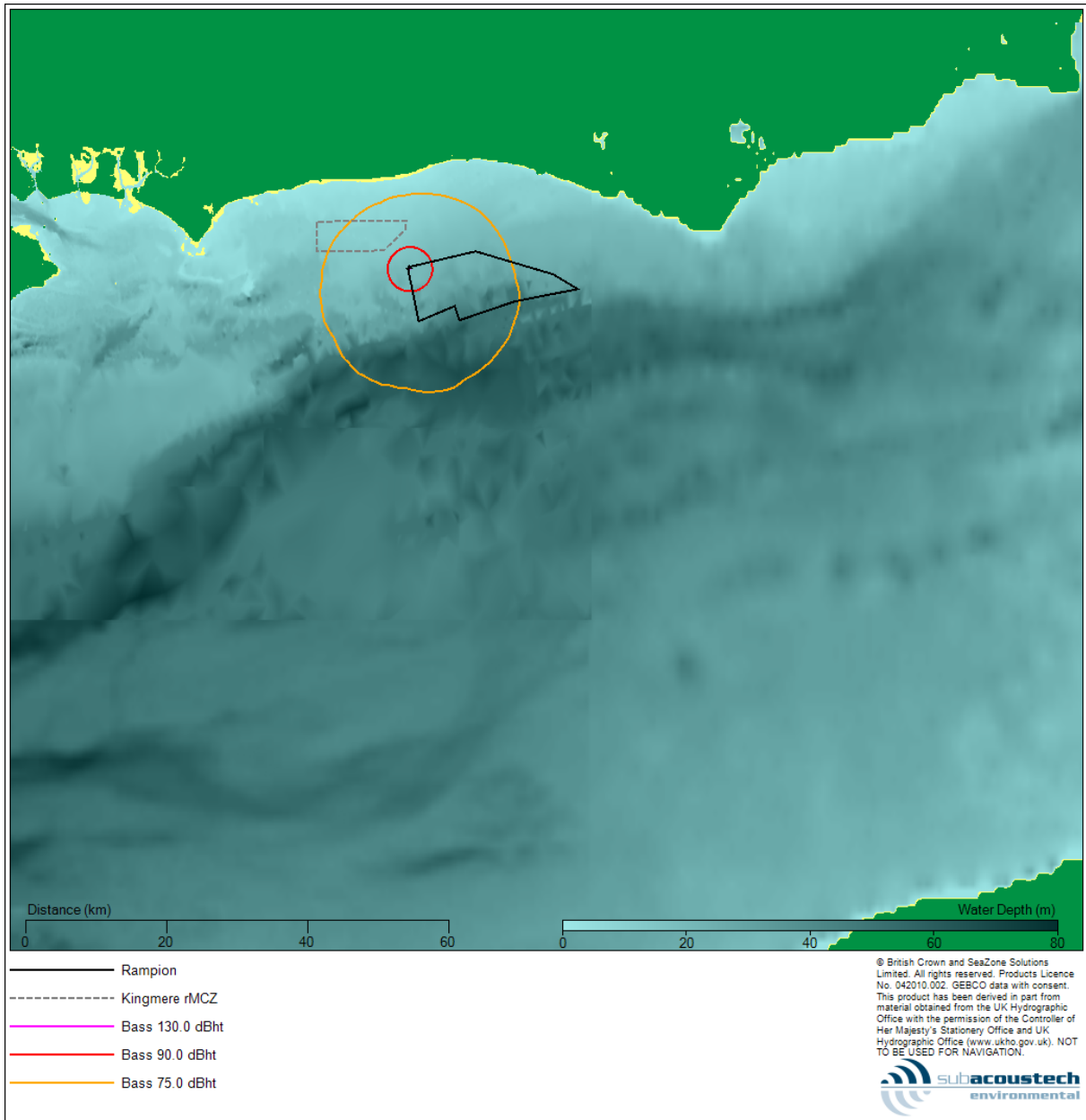


Figure 4-49 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Bass for the installation of a 6.5m monopile, positioned west in the Rampion offshore wind farm site

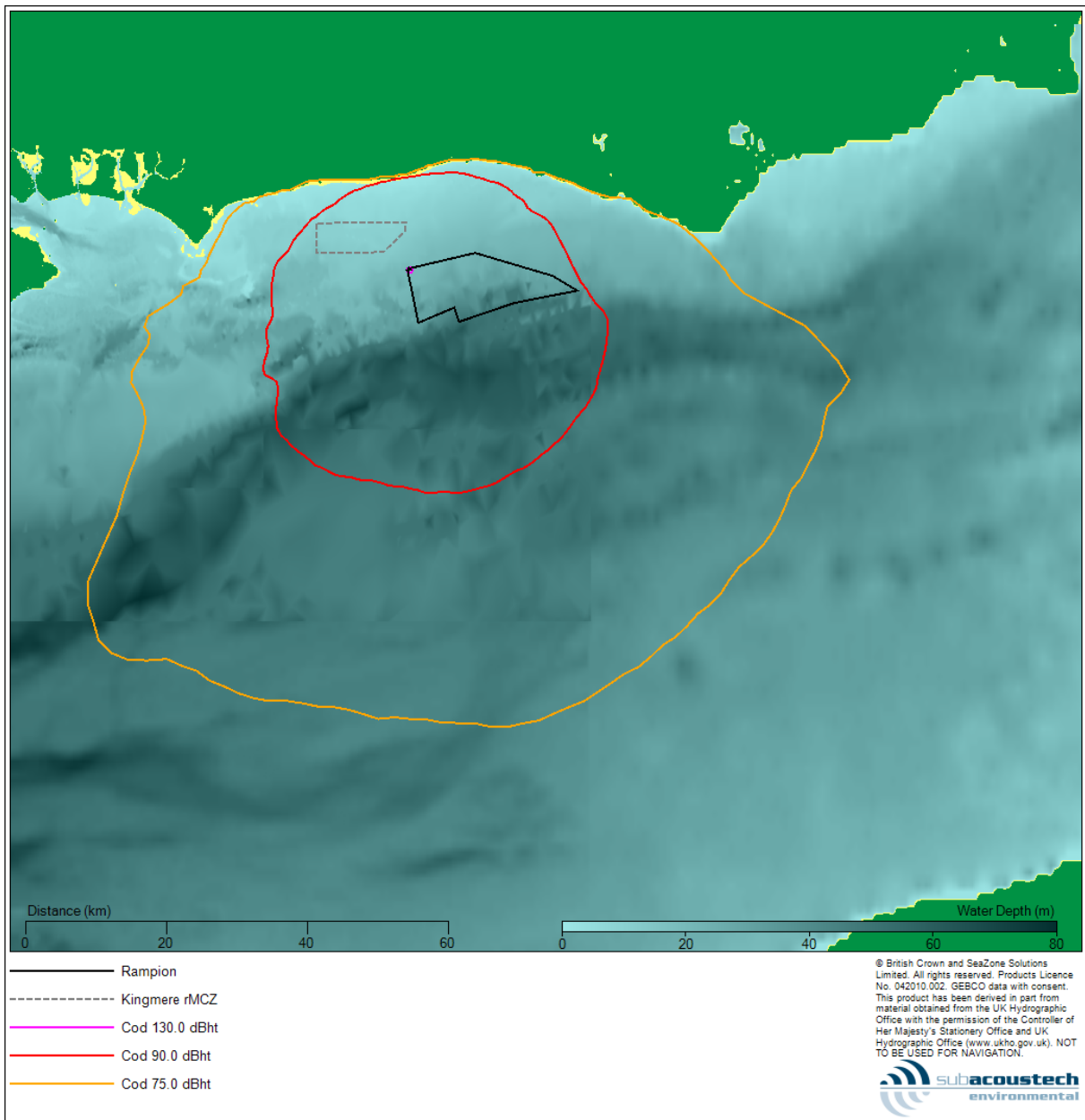


Figure 4-50 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Cod for the installation of a 6.5m monopile, positioned west in the Rampion offshore wind farm site

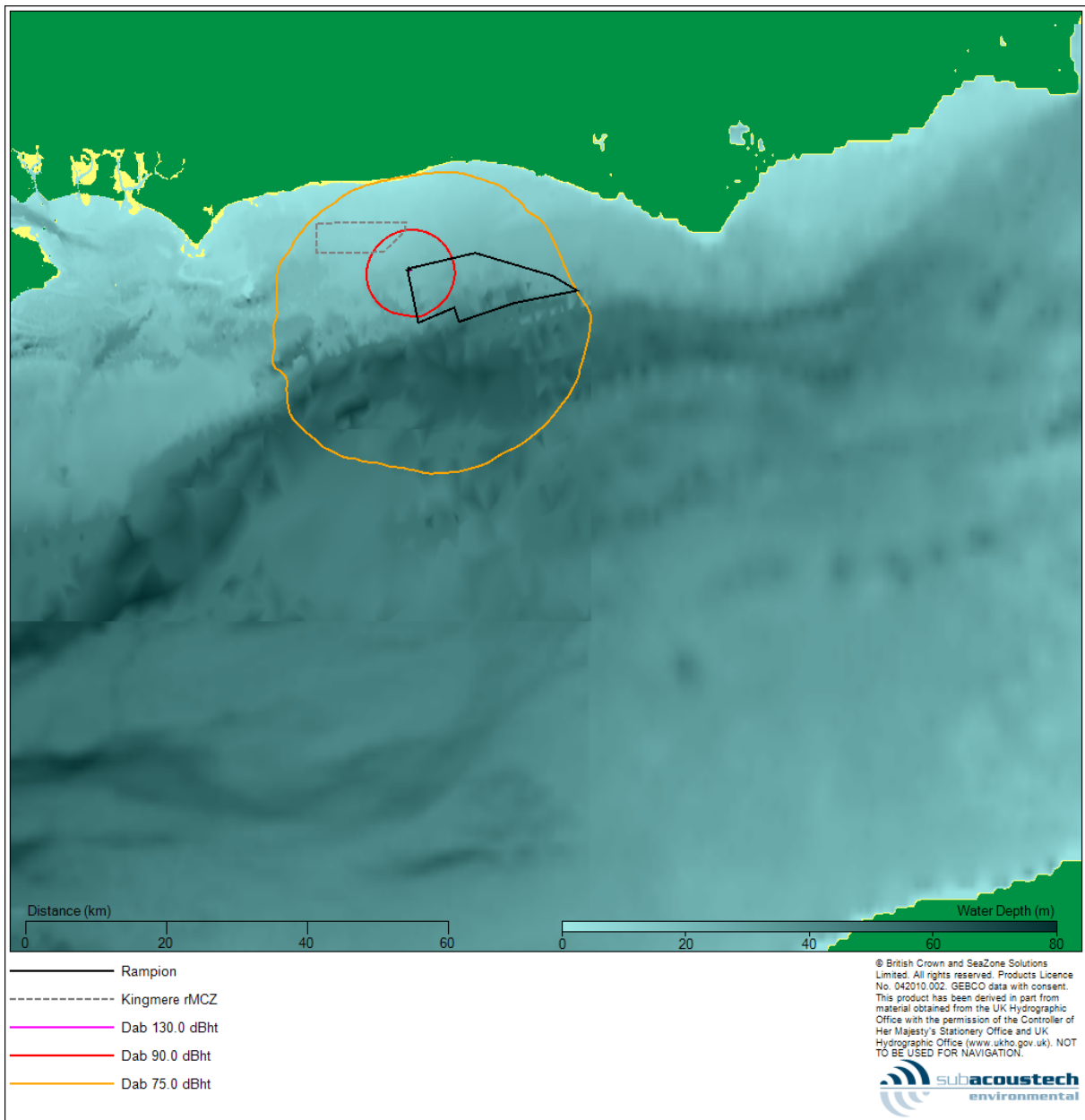


Figure 4-51 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Dab for the installation of a 6.5m monopile, positioned west in the Rampion offshore wind farm site

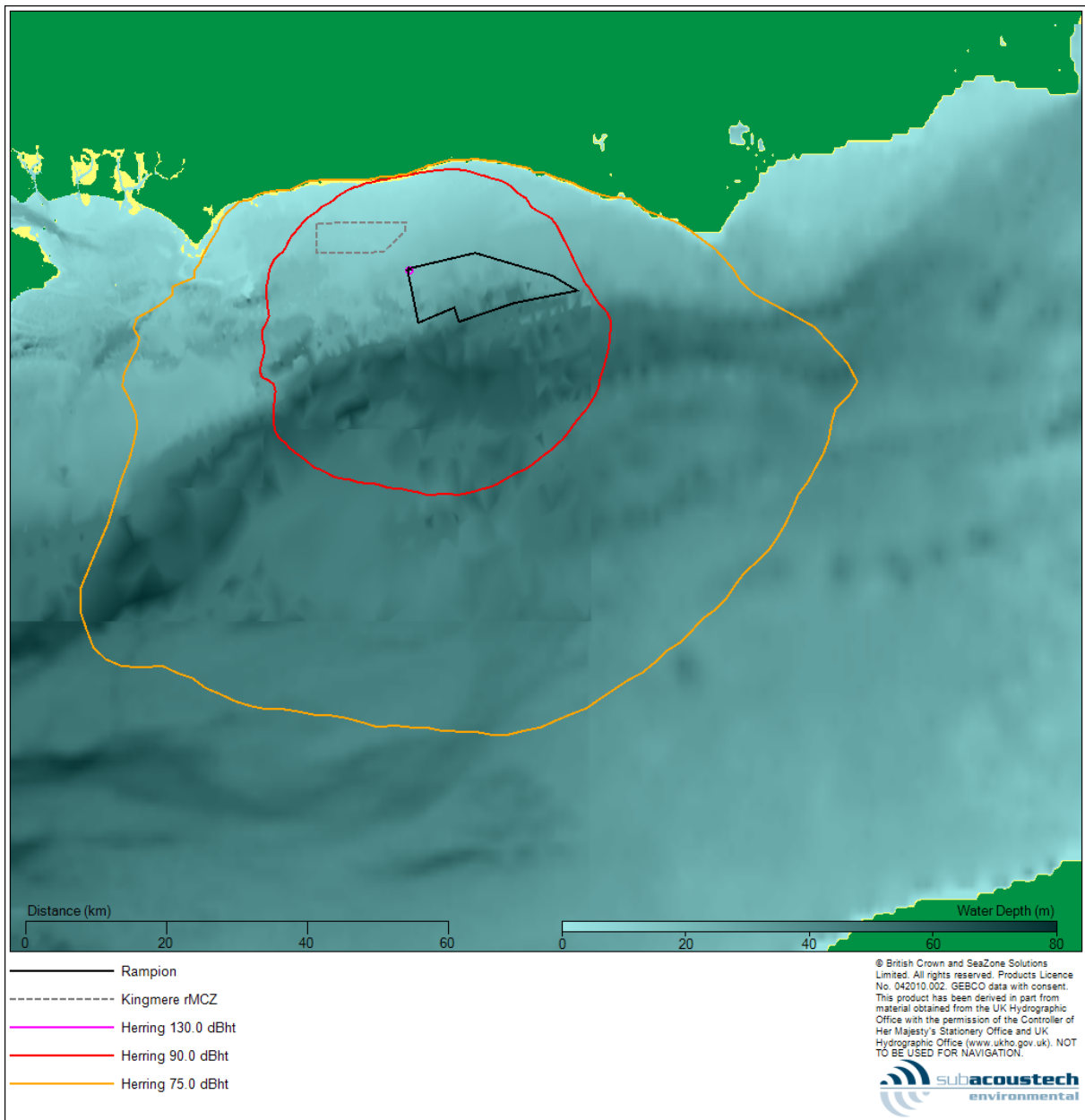


Figure 4-52 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Herring for the installation of a 6.5m monopile, positioned west in the Rampion offshore wind farm site

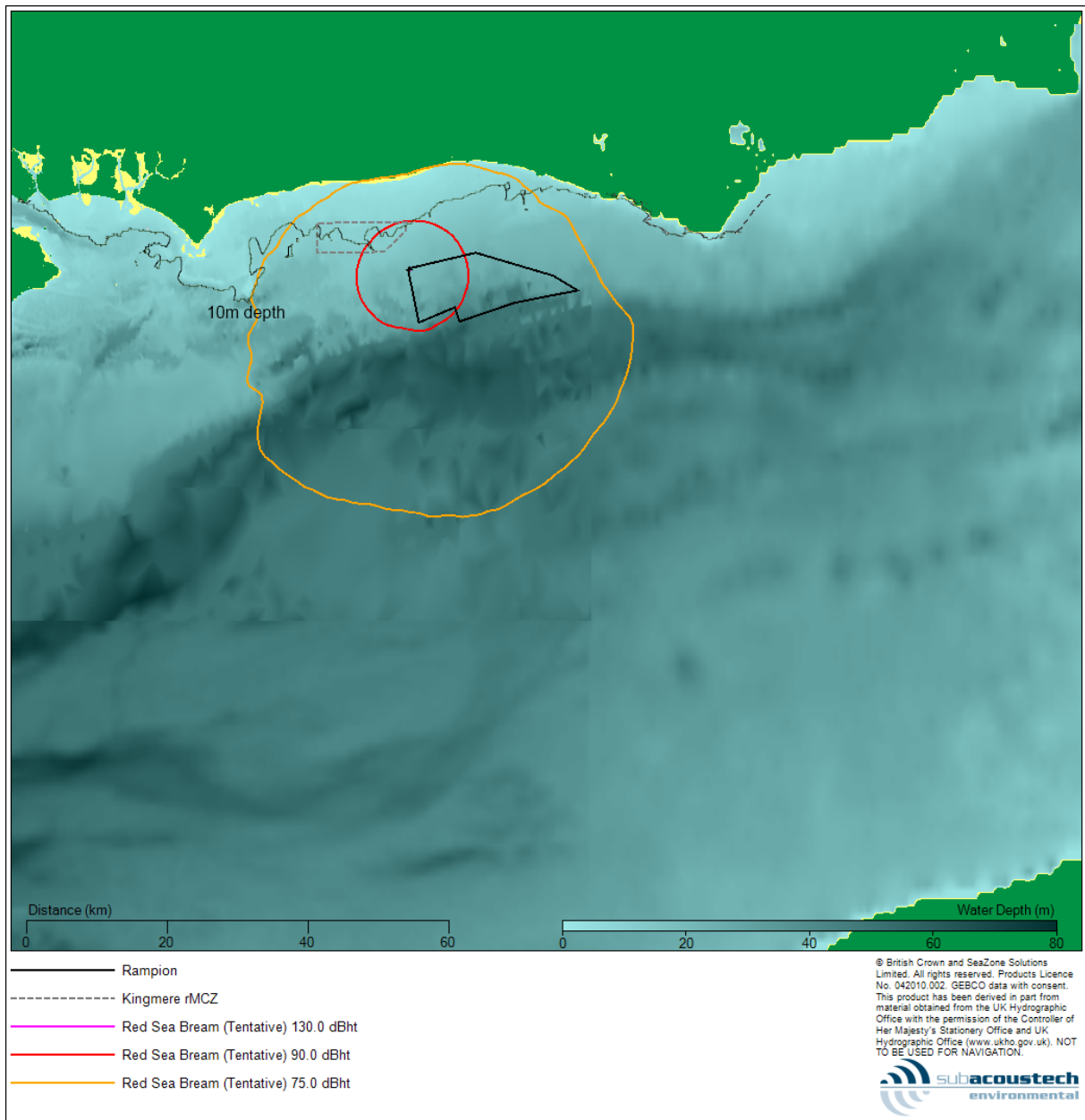


Figure 4-53 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Red Sea Bream for the installation of a 6.5m monopile, positioned west in the Rampion offshore wind farm site

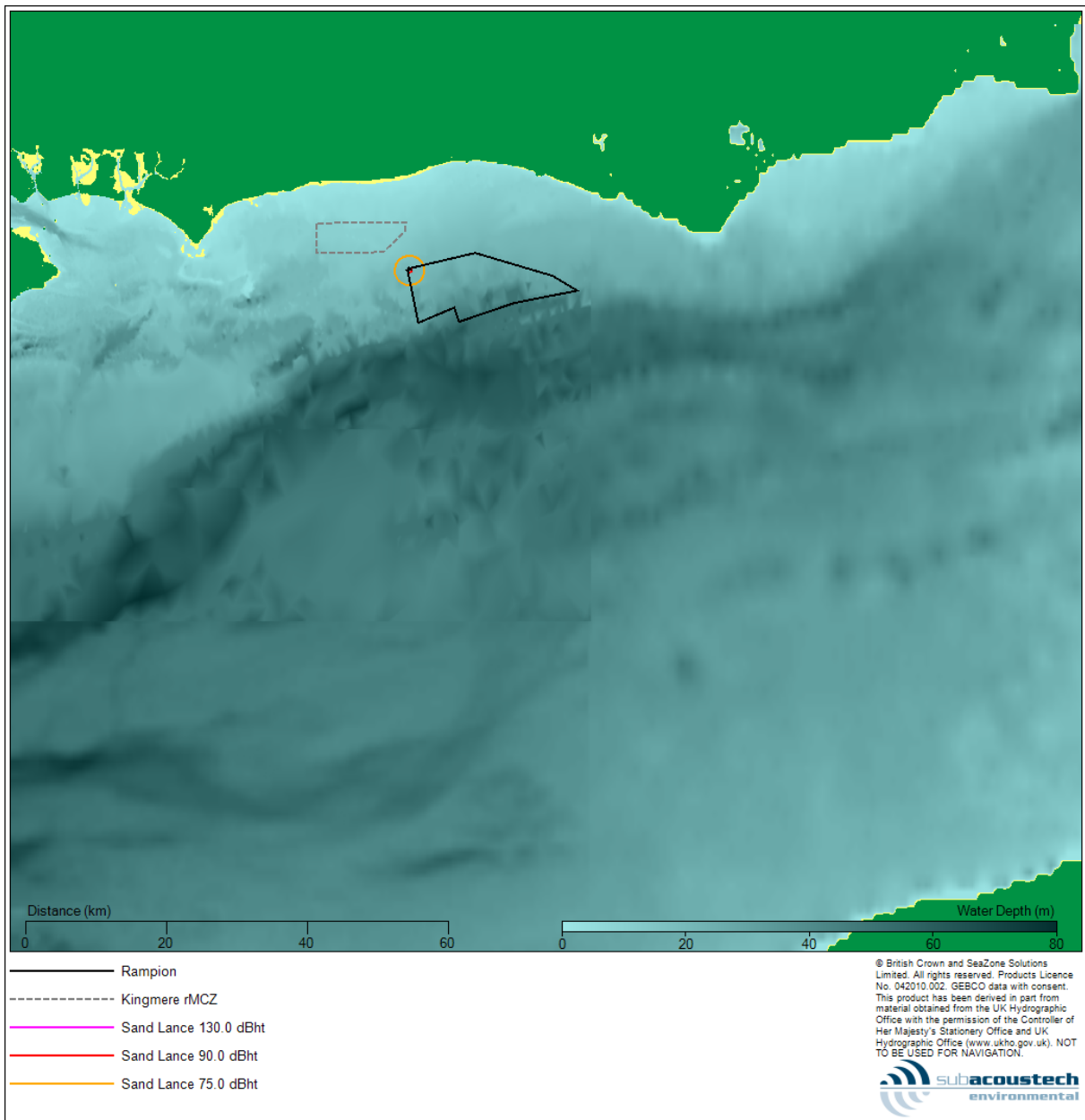


Figure 4-54 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Sand Lance for the installation of a 6.5m monopile, positioned west in the Rampion offshore wind farm site

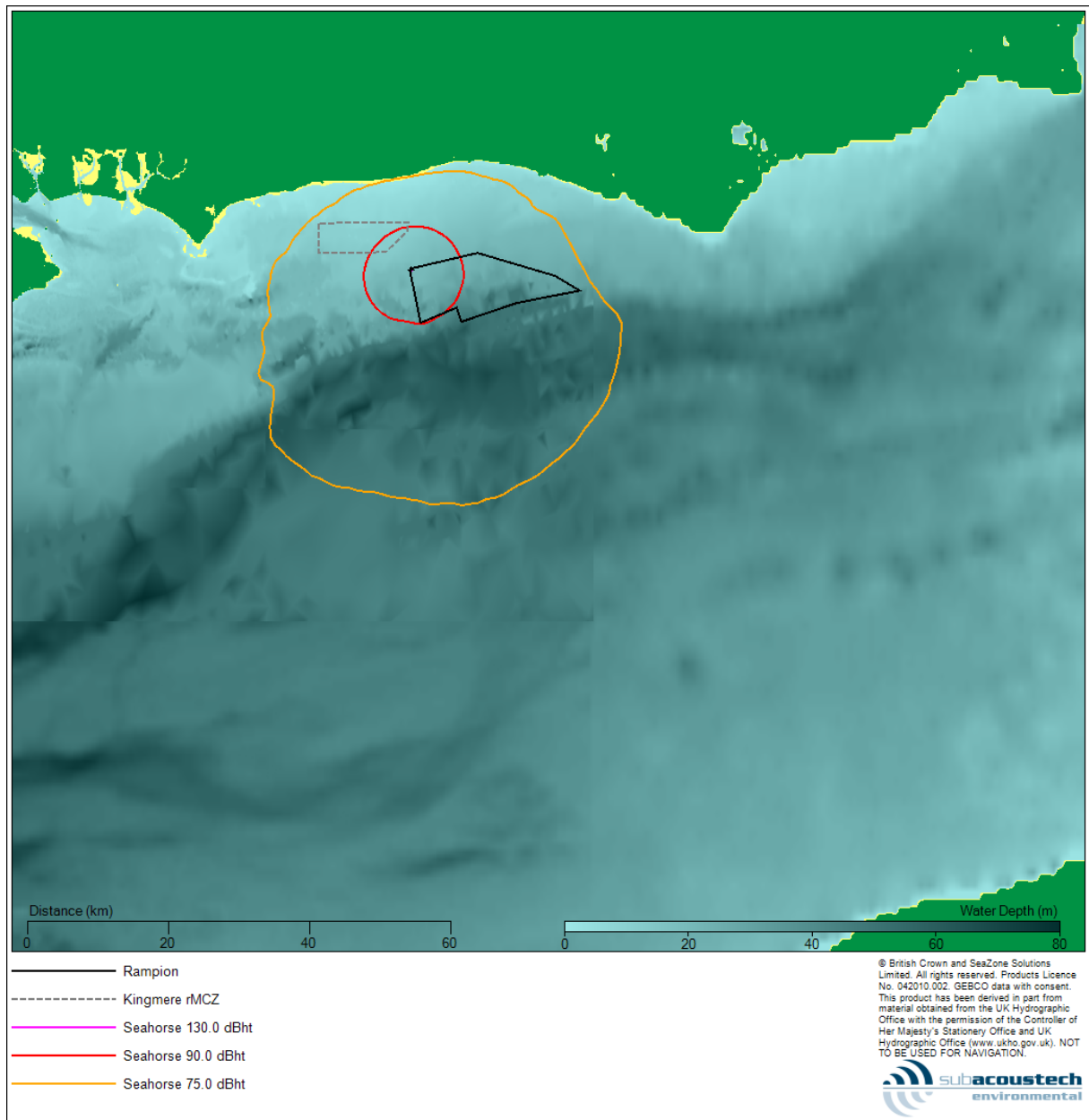


Figure 4-55 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Seahorse for the installation of a 6.5m monopile, positioned west in the Rampion offshore wind farm site

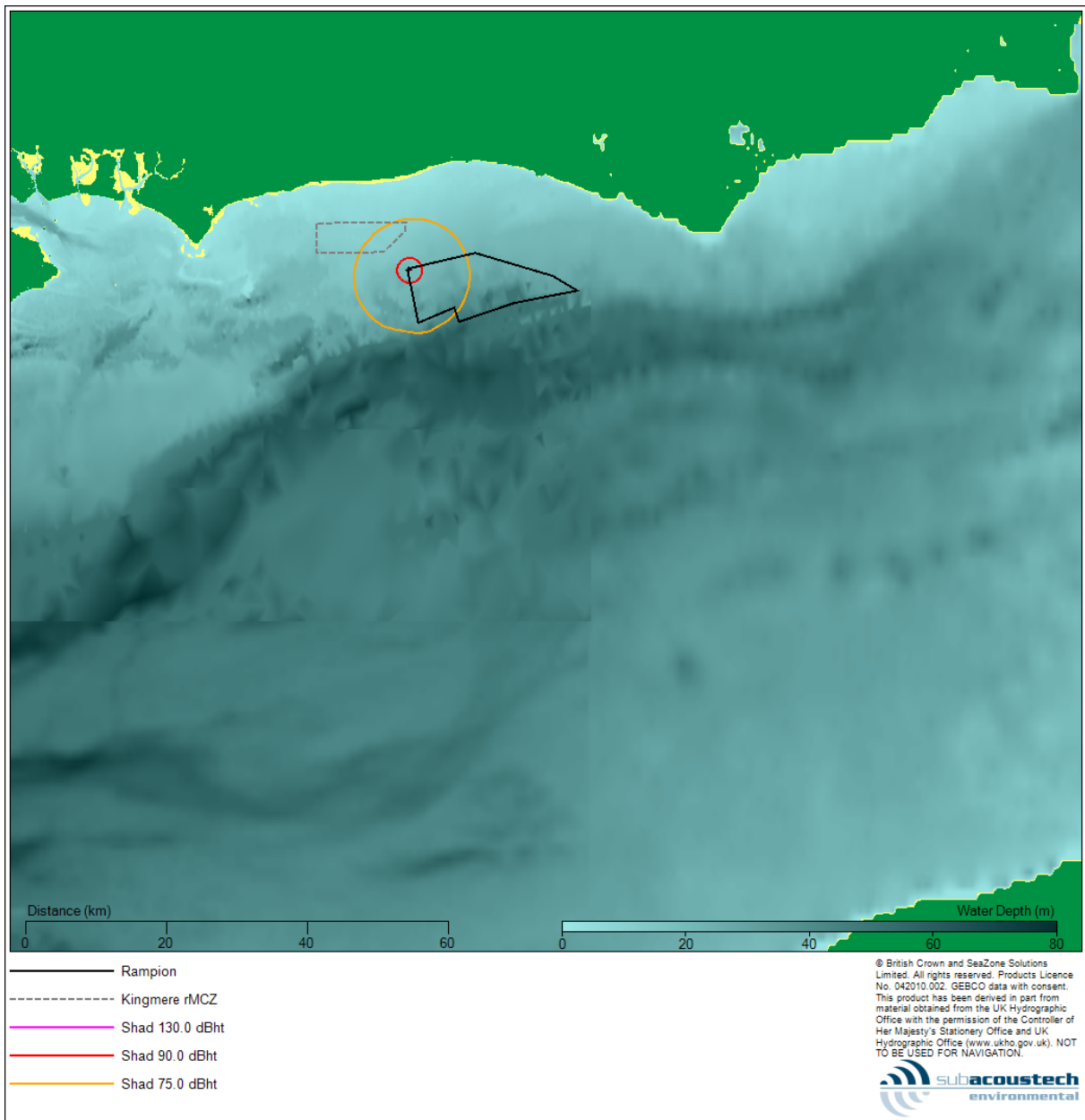


Figure 4-56 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Shad for the installation of a 6.5m monopile, positioned west in the Rampion offshore wind farm site

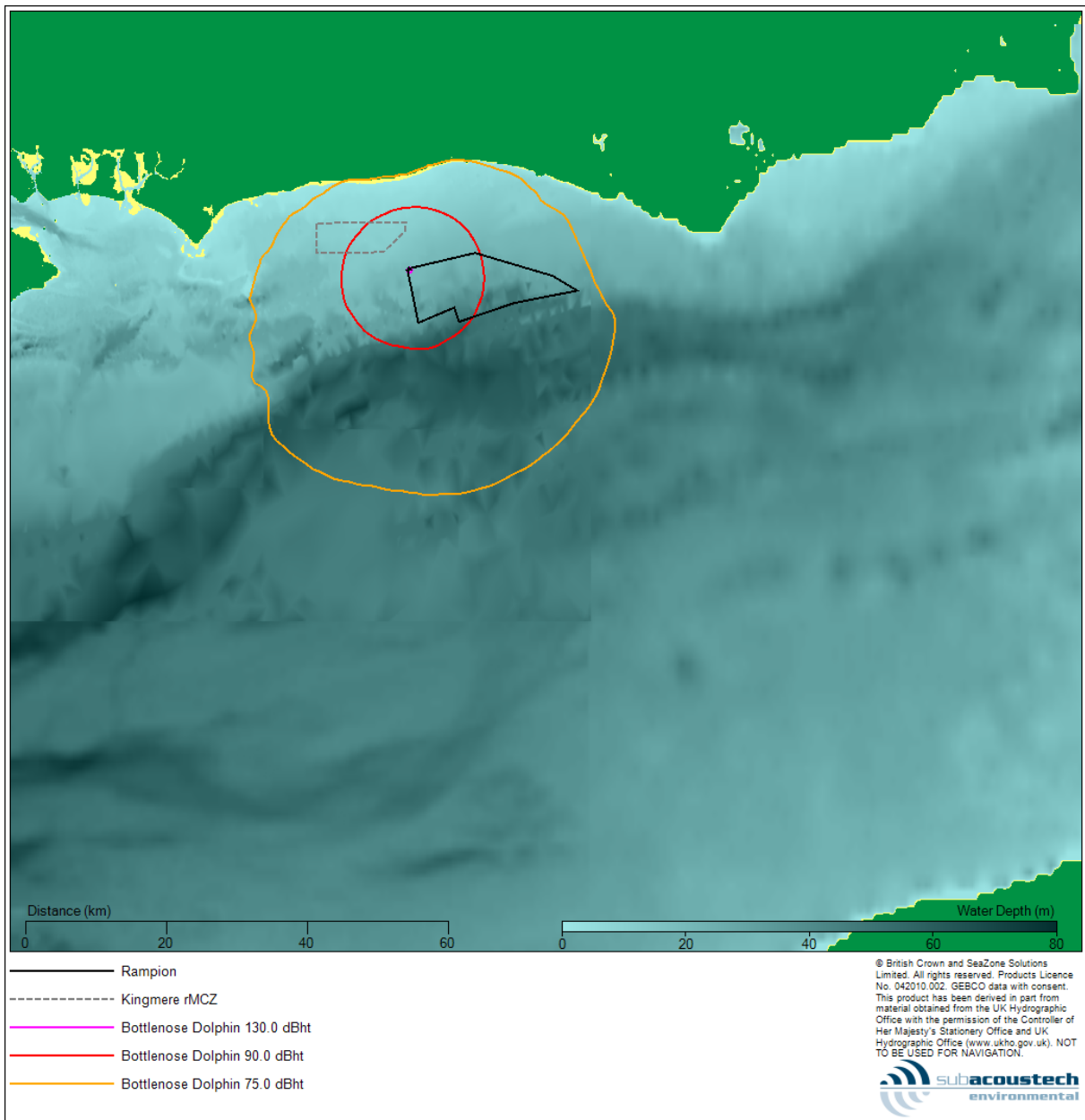


Figure 4-57 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Bottlenose Dolphin for the installation of a 6.5m monopile, positioned west in the Rampion offshore wind farm site

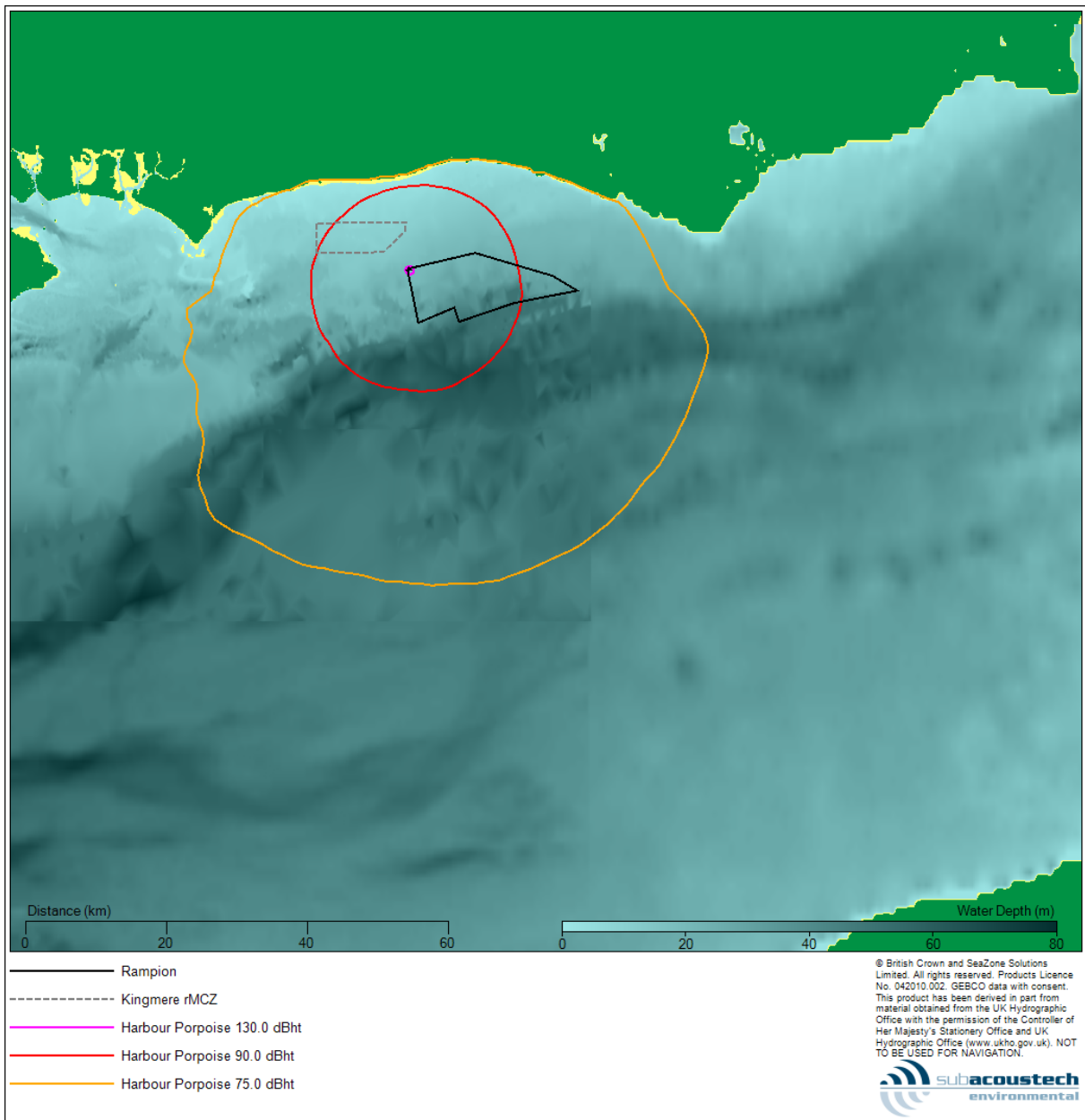


Figure 4-58 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Harbour Porpoise for the installation of a 6.5m monopile, positioned west in the Rampion offshore wind farm site

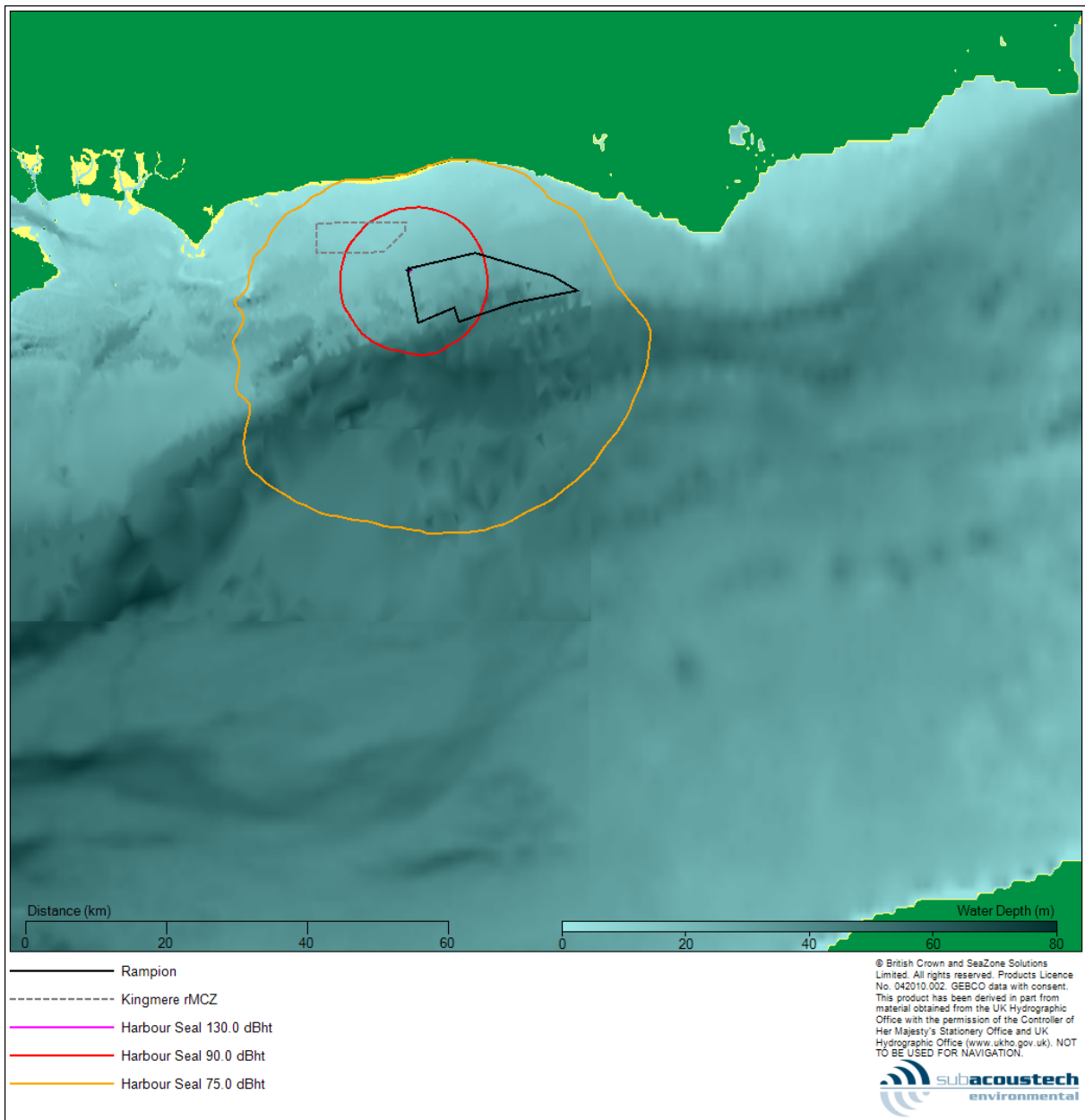


Figure 4-59 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Harbour Seal for the installation of a 6.5m monopile, positioned west in the Rampion offshore wind farm site

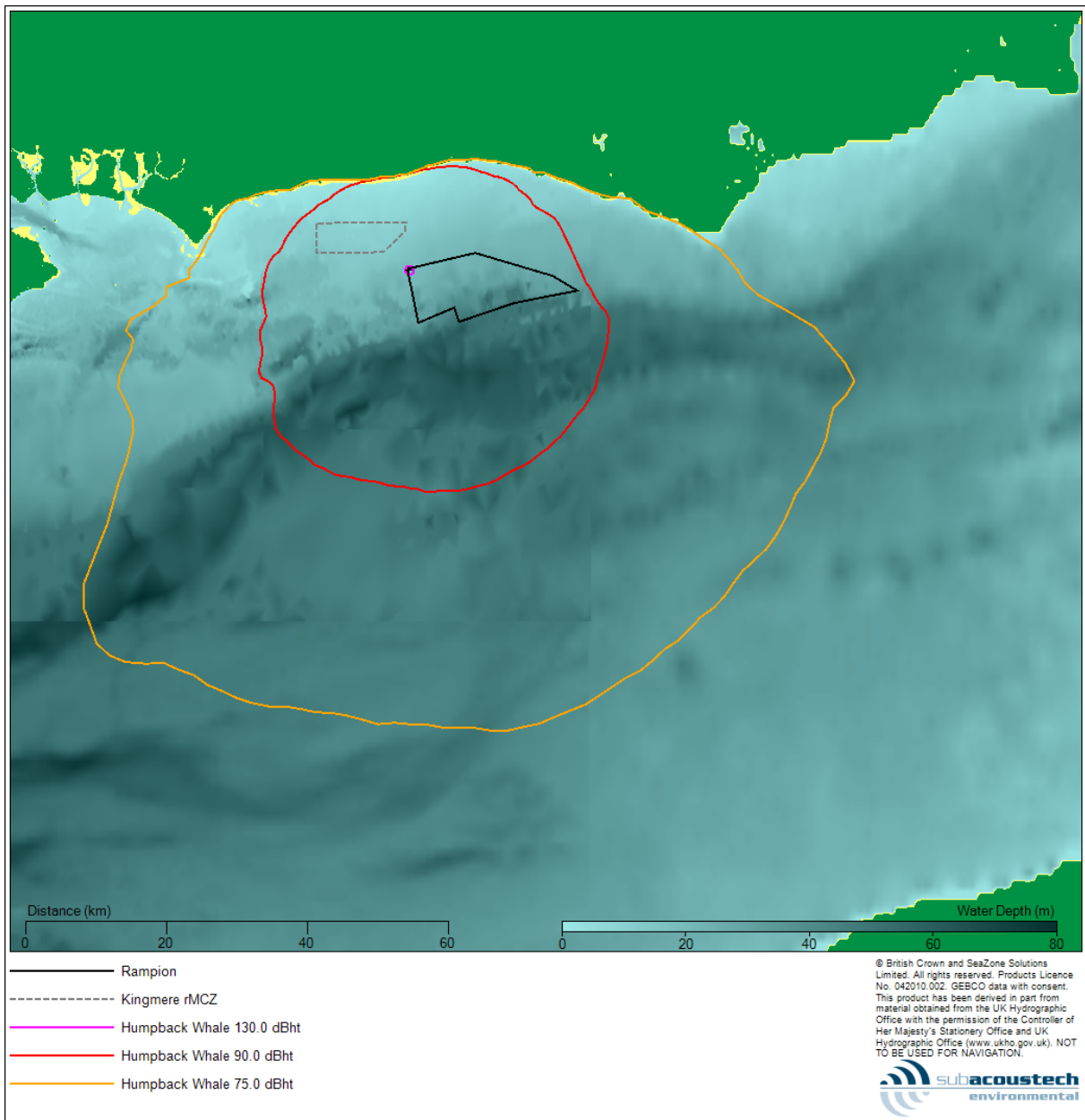


Figure 4-60 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Humpback Whale for the installation of a 6.5m monopile, positioned west in the Rampion offshore wind farm site

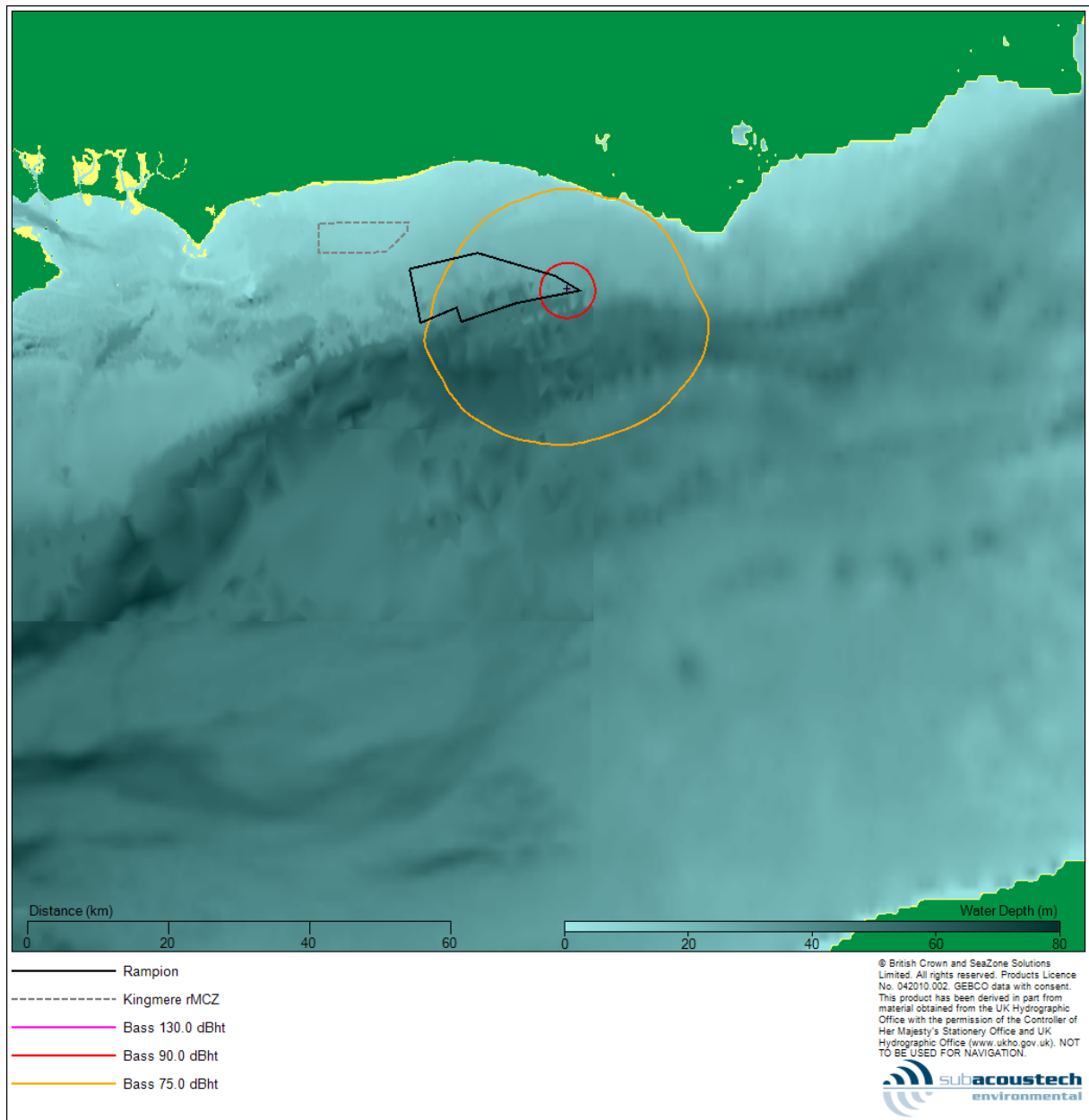


Figure 4-61 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Bass for the installation of a 6.5m monopile, positioned east in the Rampion offshore wind farm site

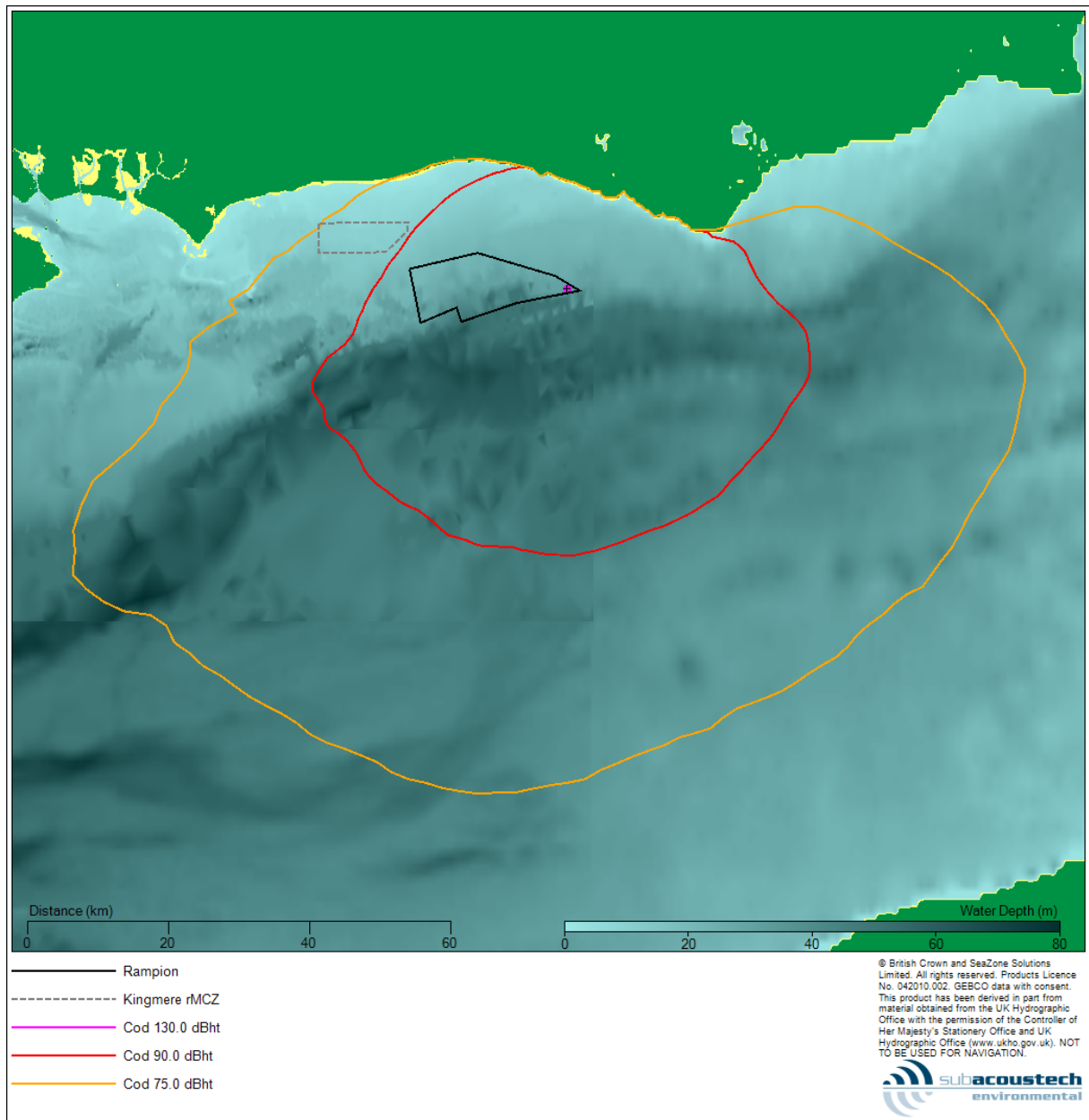


Figure 4-62 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Cod for the installation of a 6.5m monopile, positioned east in the Rampion offshore wind farm site

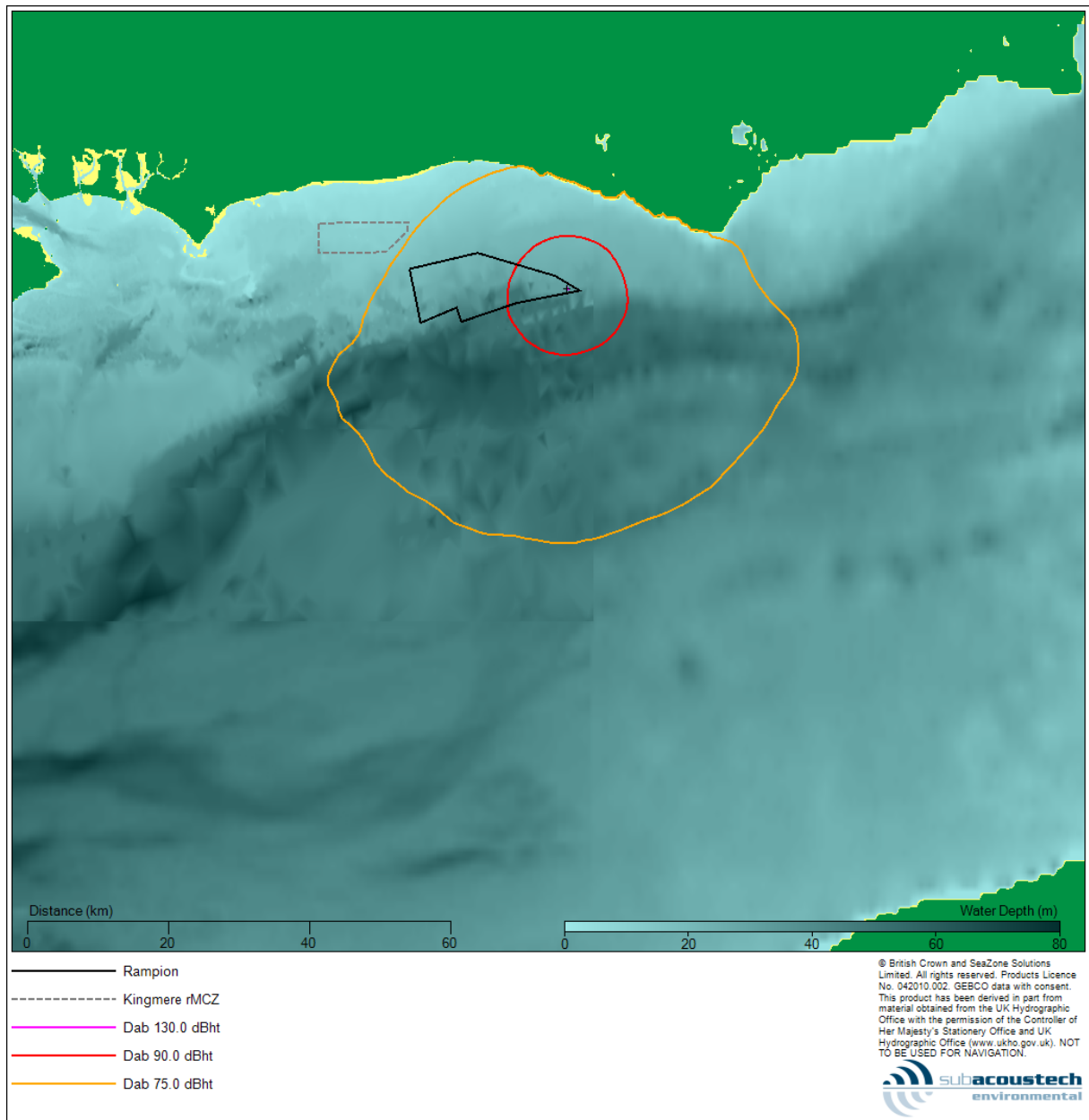


Figure 4-63 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Dab for the installation of a 6.5m monopile, positioned east in the Rampion offshore wind farm site

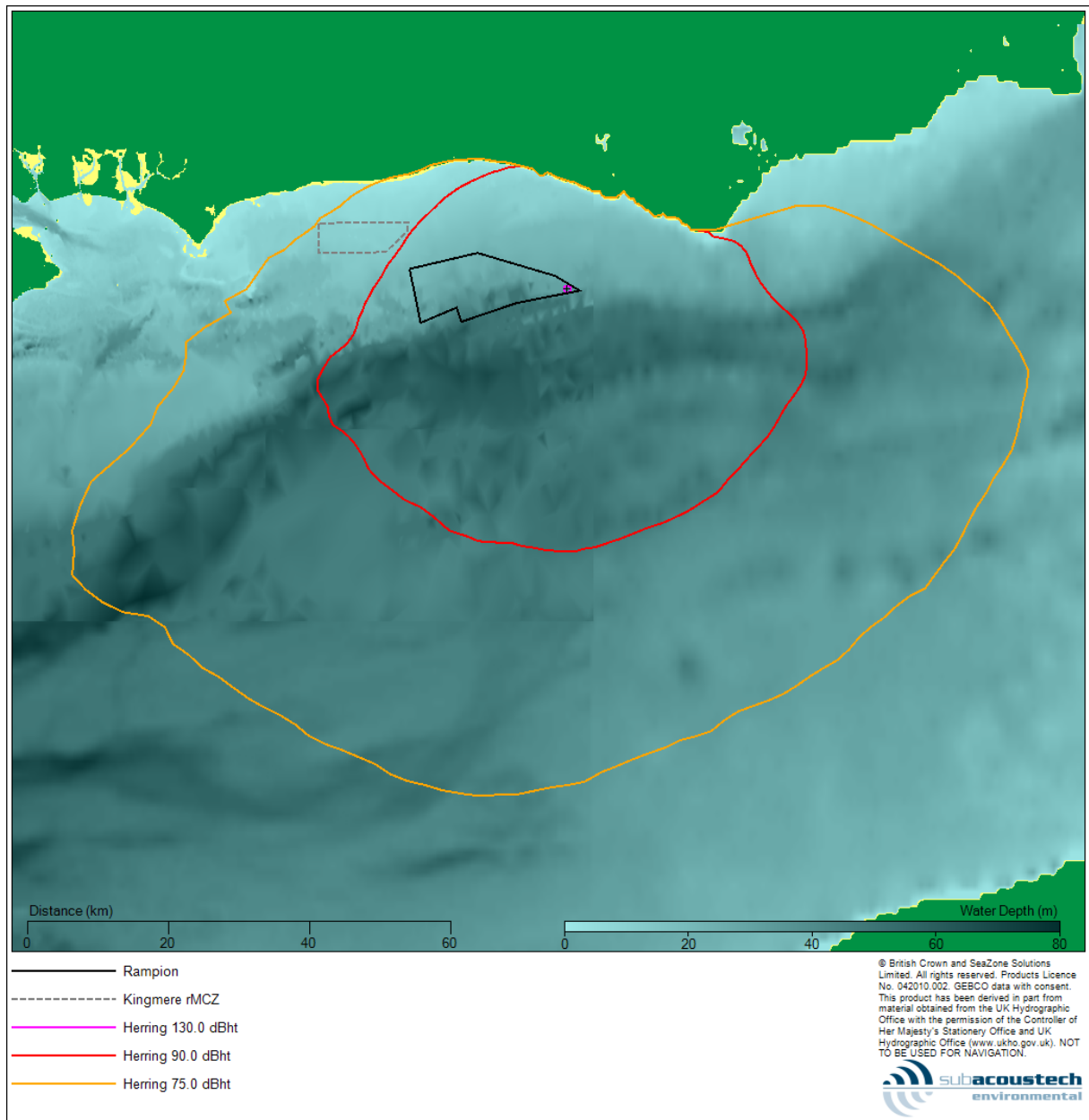


Figure 4-64 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Herring for the installation of a 6.5m monopile, positioned east in the Rampion offshore wind farm site

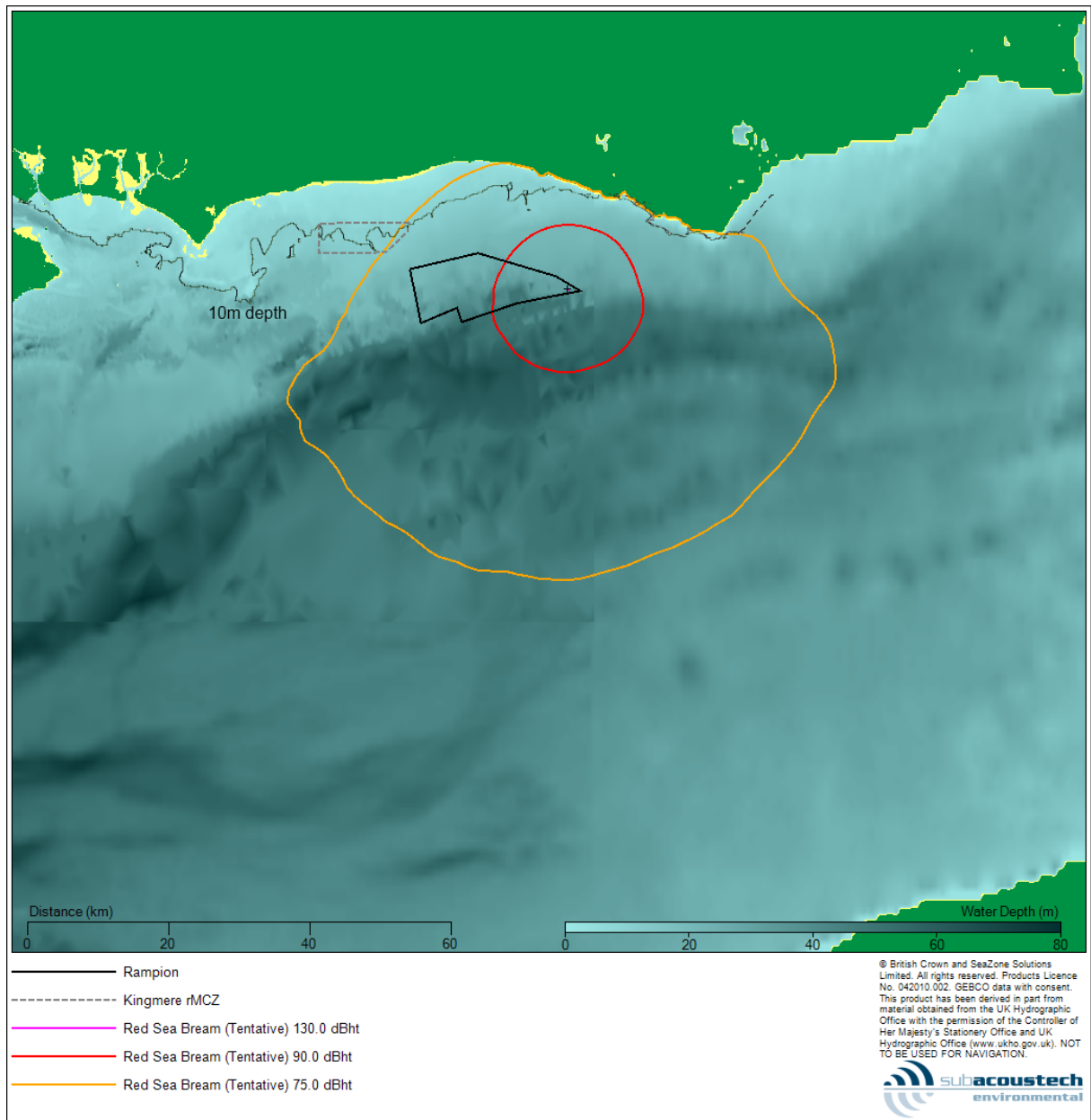


Figure 4-65 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Red Sea Bream for the installation of a 6.5m monopile, positioned east in the Rampion offshore wind farm site

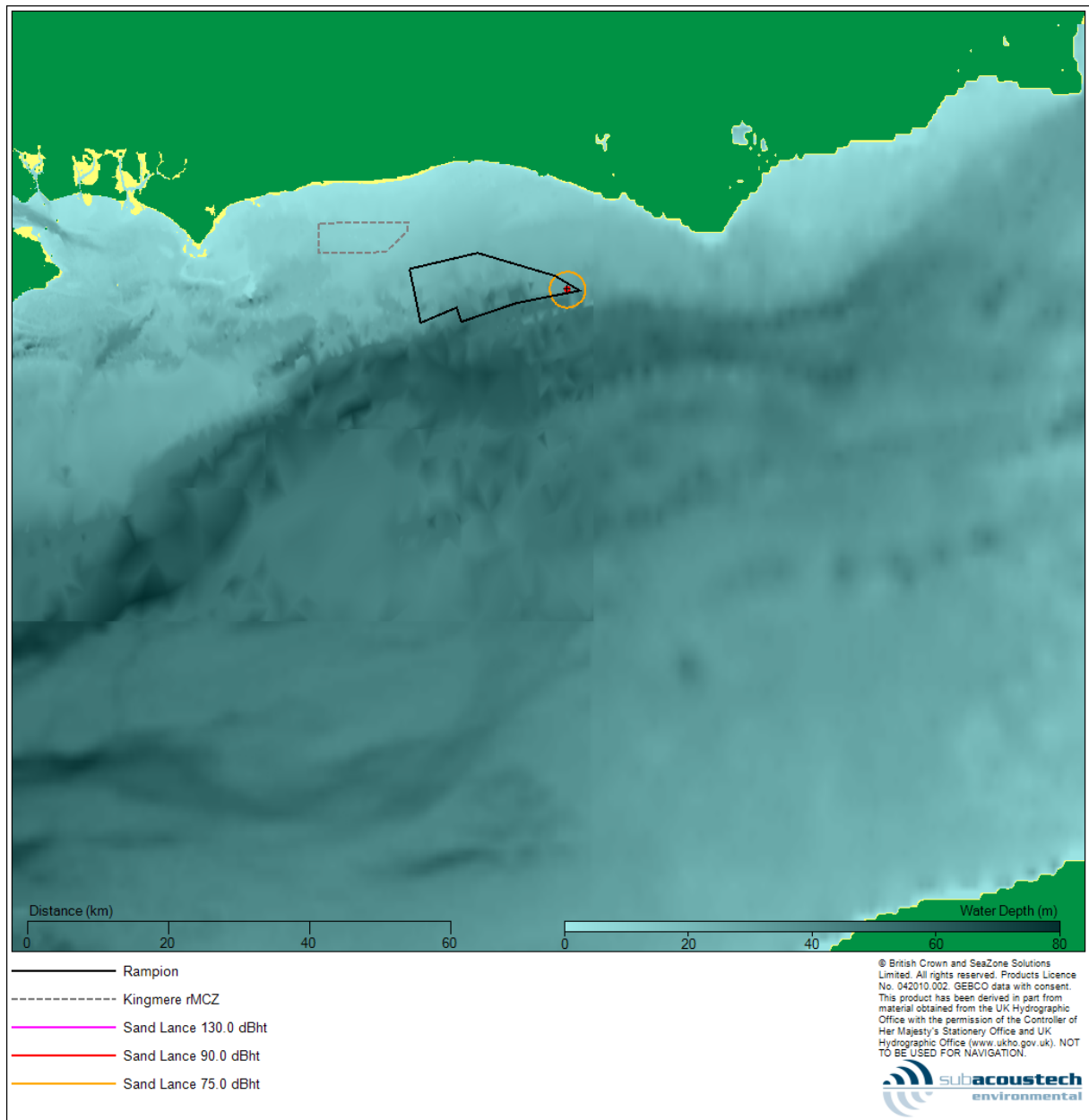


Figure 4-66 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Sand Lance for the installation of a 6.5m monopile, positioned east in the Rampion offshore wind farm site

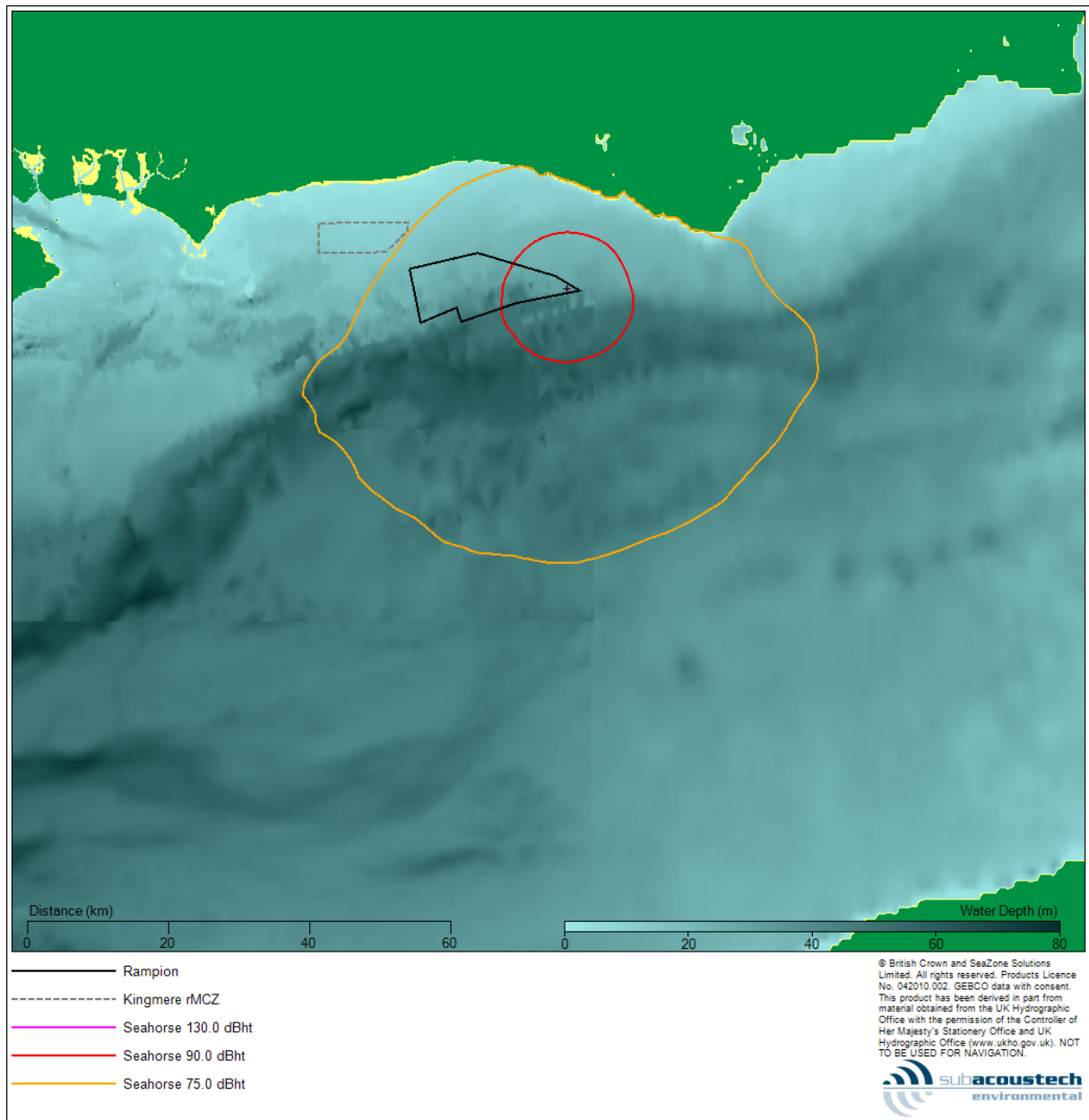


Figure 4-67 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Seahorse for the installation of a 6.5m monopile, positioned east in the Rampion offshore wind farm site

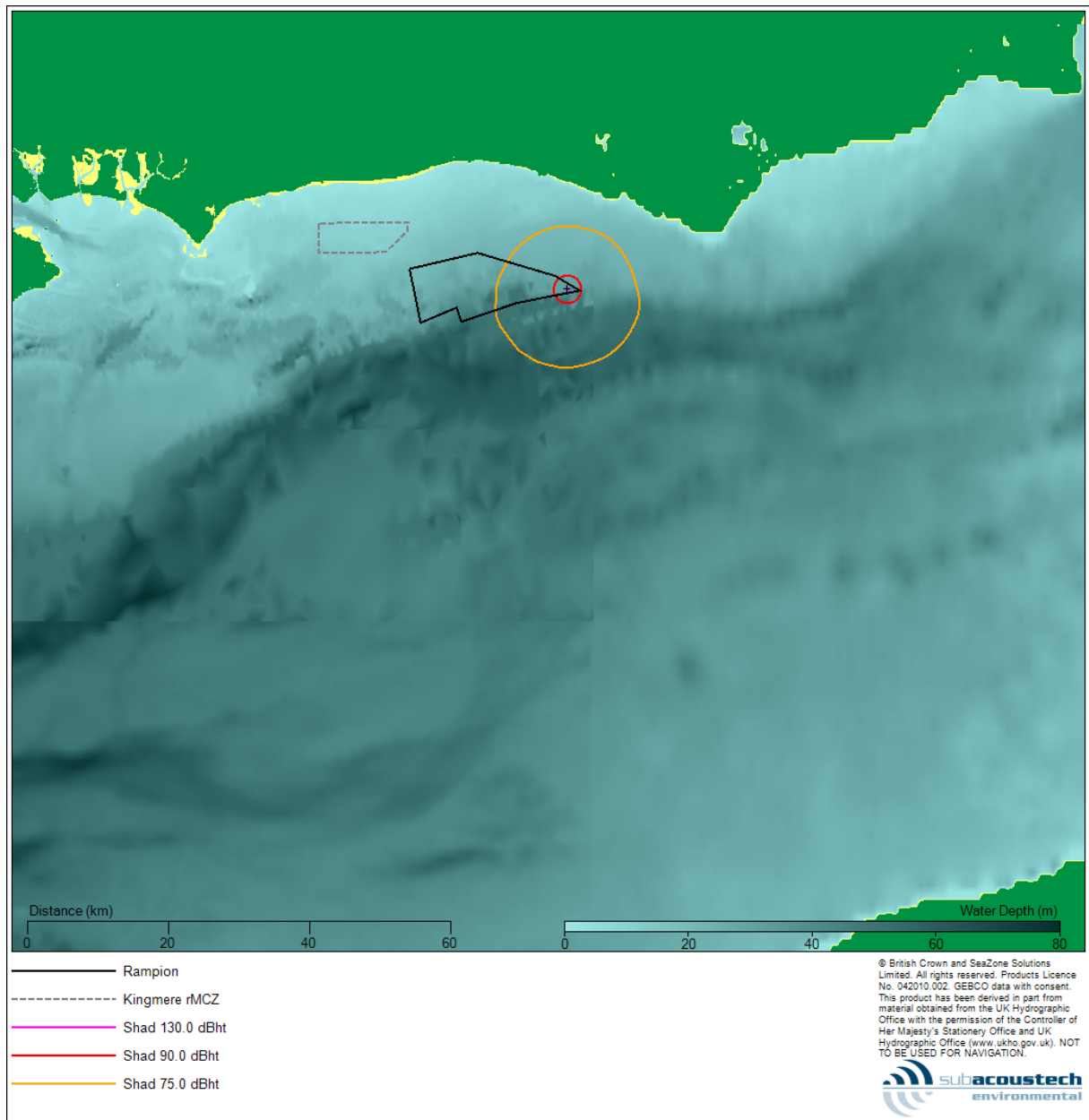


Figure 4-68 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Shad for the installation of a 6.5m monopile, positioned east in the Rampion offshore wind farm site

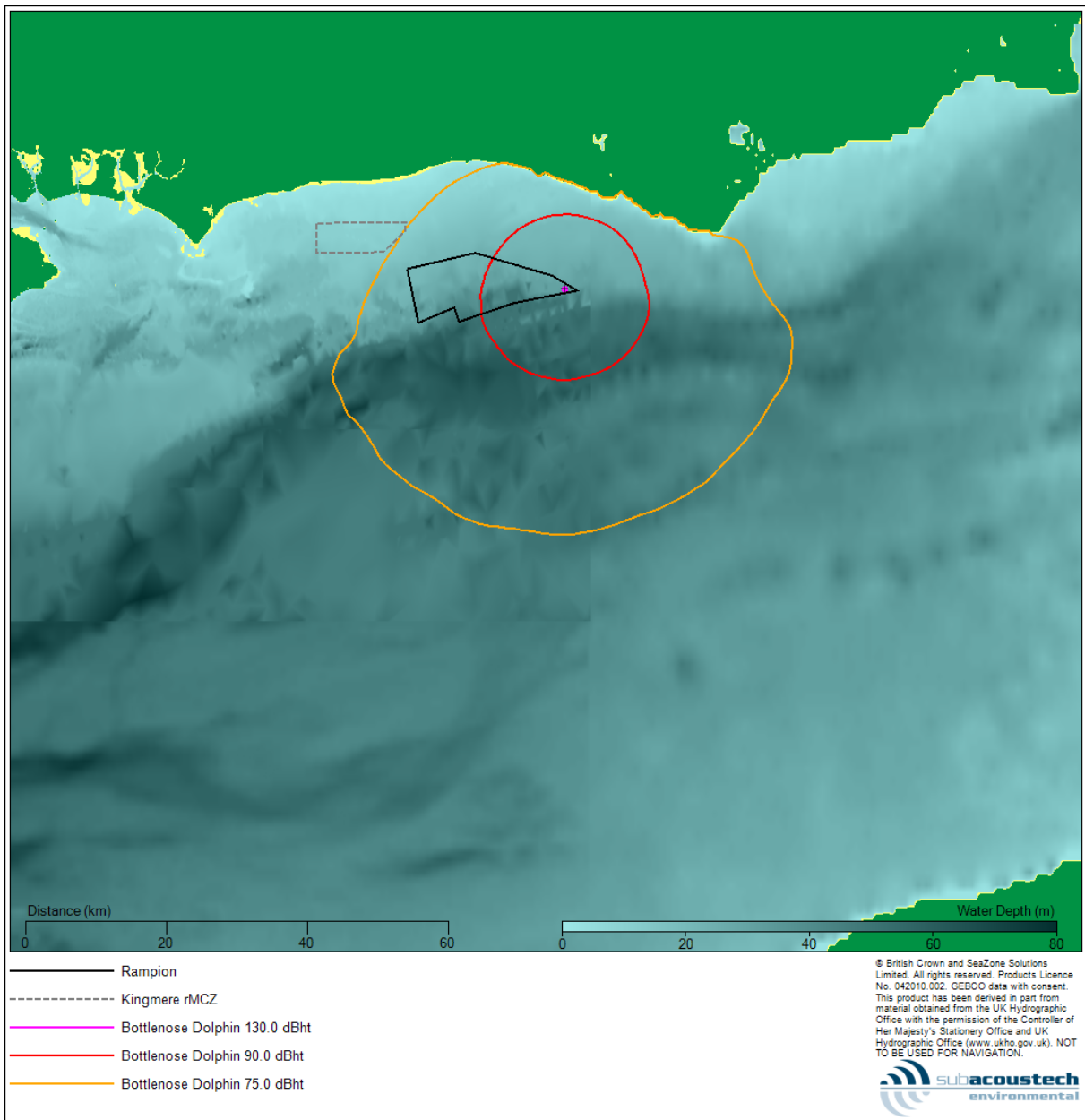


Figure 4-69 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Bottlenose Dolphin for the installation of a 6.5m monopile, positioned east in the Rampion offshore wind farm site

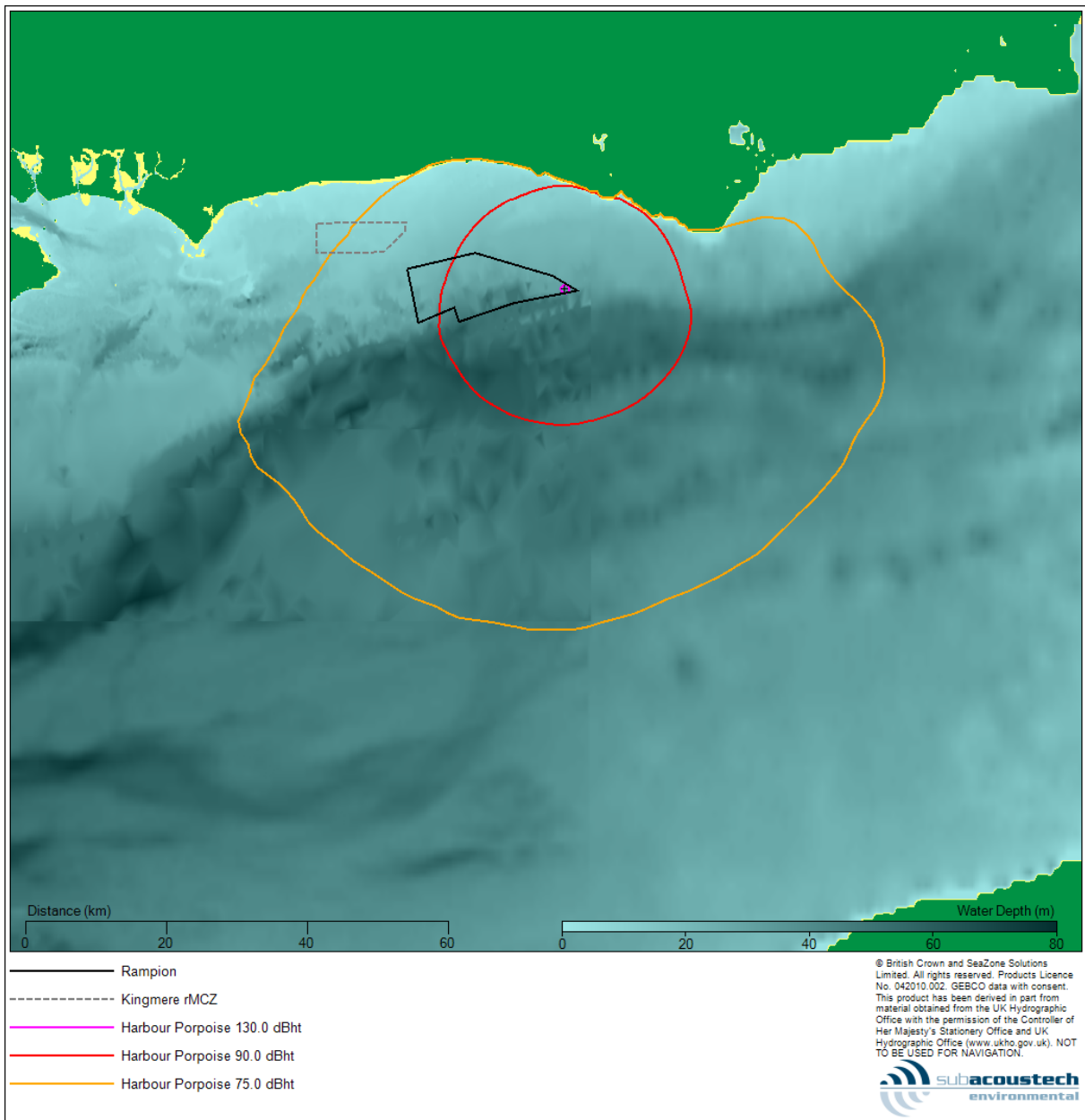


Figure 4-70 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Harbour Porpoise for the installation of a 6.5m monopile, positioned east in the Rampion offshore wind farm site

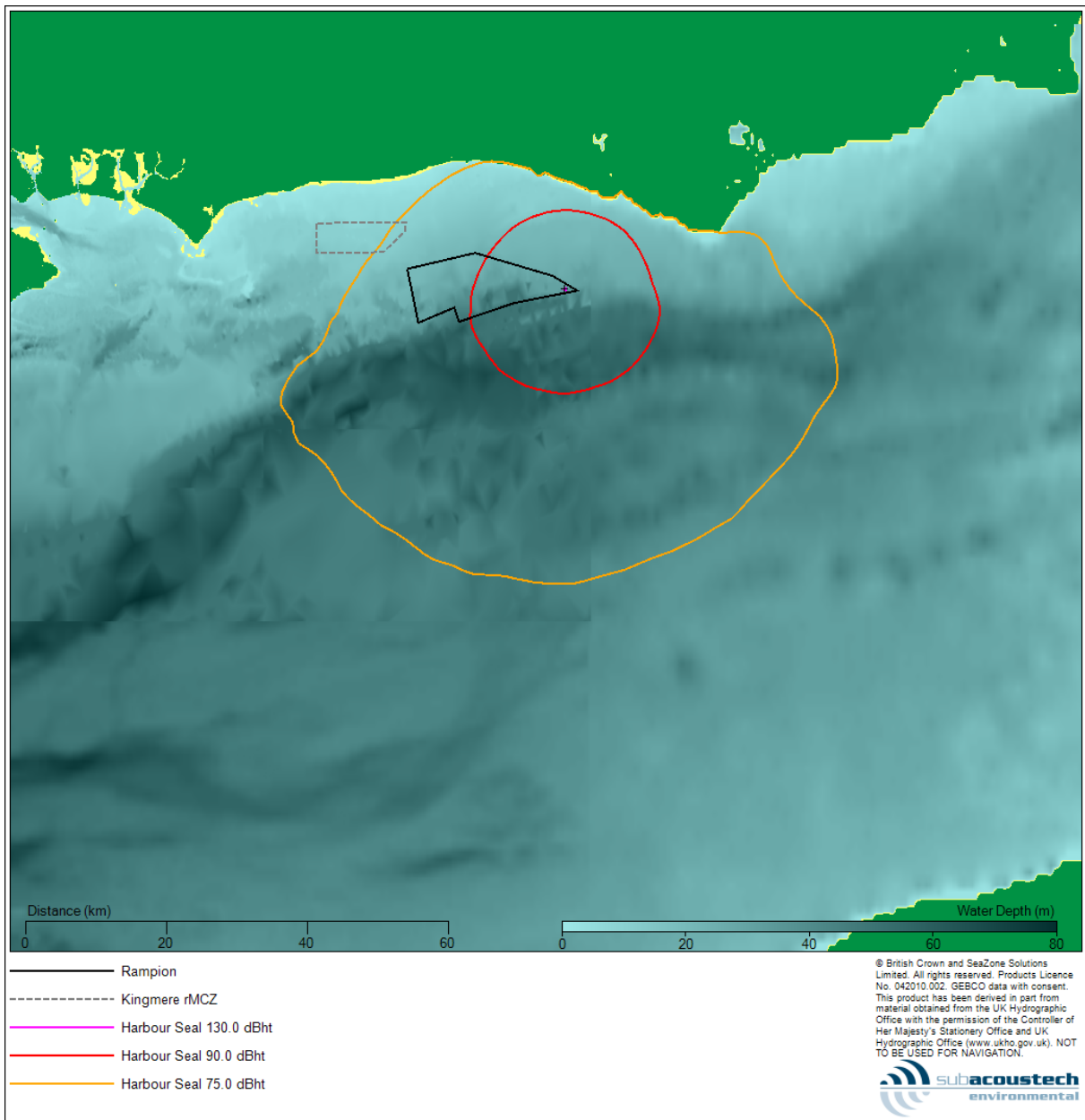


Figure 4-71 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak-to-peak impact ranges for Harbour Seal for the installation of a 6.5m monopile, positioned east in the Rampion offshore wind farm site

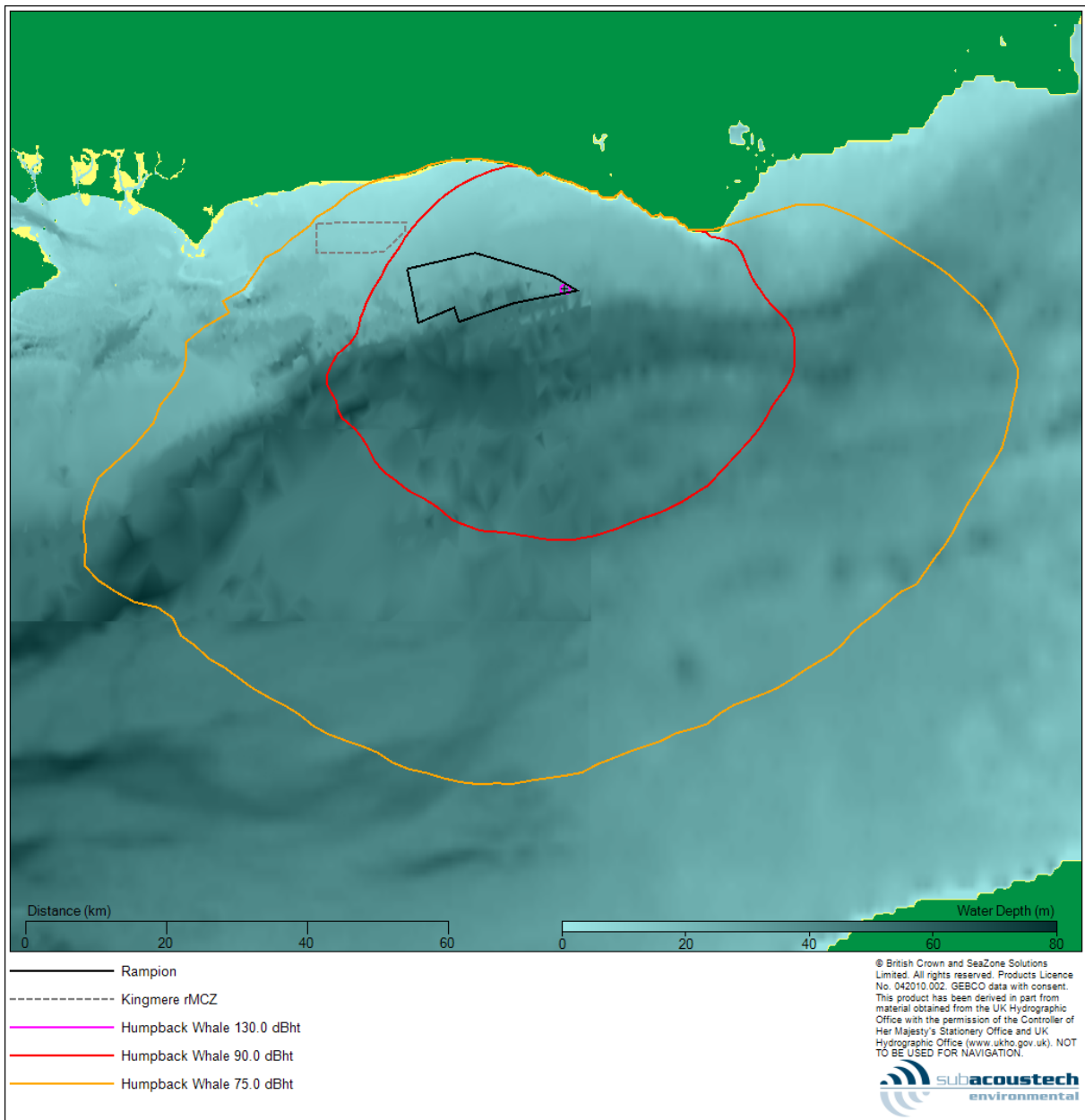


Figure 4-72 Contour plot showing the estimated 130, 90 and 75 dB_{nt} peak-to-peak impact ranges for Humpback Whale for the installation of a 6.5m monopile, positioned east in the Rampion offshore wind farm site

4.6 M-Weighted SELs

The accumulated exposure to sound for marine mammals has been assessed using the criteria proposed by Southall *et al* (2007), using M-Weighted SELs. This has been done by calculating a starting range for each marine mammal group, whereby the receptor would be able to escape the affected area without receiving the specified level of sound where auditory injury is expected to occur. Tables 4-12 to 4-17 show a summary of these ranges, assuming a swim speed of 1.5 ms^{-1} , an average cruising speed for a harbour porpoise. The largest ranges are calculated for the 186 dB criteria for pinnipeds (in water). For piling operations of a 6.5 m monopile located east in the Rampion offshore wind farm site a maximum range of 16.7 km is likely to be needed at the onset of the impact piling to avoid a damaging exposure to sound using the Southall criteria.

Figures 4-73 to 4-96 show contour plots for pinnipeds (in water). The contours represent the modelled starting ranges for a fleeing animal to receive a level of 186 dB re $1 \mu\text{Pa}^2/\text{s}$ (M_{pw}) over the total installation time of the pile, i.e. animals within this range at the start of piling will receive a dose of 186 dB re $1 \mu\text{Pa}^2/\text{s}$ SEL or greater.

Jacket structure (W) 1.53m pin pile	Range to auditory injury criteria		
	Max	Min	Mean
Low Frequency Cetacean (198 dB re. $1 \mu\text{Pa}^2/\text{s}$ (M_{lf}))	<100 m	<100 m	<100 m
Mid Frequency Cetacean (198 dB re. $1 \mu\text{Pa}^2/\text{s}$ (M_{mf}))	<100 m	<100 m	<100 m
High Frequency Cetacean (198 dB re. $1 \mu\text{Pa}^2/\text{s}$ (M_{hf}))	<100 m	<100 m	<100 m
Pinnipeds (in water) (186 dB re. $1 \mu\text{Pa}^2/\text{s}$ (M_{pw}))	600 m	200 m	370 m

Table 4-12 Summary of the ranges out to which auditory injury is predicted during the installation of 1.53m pin pile jacket structure for a fleeing animal using the M-Weighted SEL criteria

Jacket structure (E) 1.53m pin pile	Range to auditory injury criteria		
	Max	Min	Mean
Low Frequency Cetacean (198 dB re. $1 \mu\text{Pa}^2/\text{s}$ (M_{lf}))	<100 m	<100 m	<100 m
Mid Frequency Cetacean (198 dB re. $1 \mu\text{Pa}^2/\text{s}$ (M_{mf}))	<100 m	<100 m	<100 m
High Frequency Cetacean (198 dB re. $1 \mu\text{Pa}^2/\text{s}$ (M_{hf}))	<100 m	<100 m	<100 m
Pinnipeds (in water) (186 dB re. $1 \mu\text{Pa}^2/\text{s}$ (M_{pw}))	1900 m	800 m	1300 m

Table 4-13 Summary of the ranges out to which auditory injury is predicted during the installation of 1.53m pin pile jacket structure for a fleeing animal using the M-Weighted SEL criteria

Jacket structure (W) 2.6 m pin pile	Range to auditory injury criteria		
	Max	Min	Mean
Low Frequency Cetacean (198 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{lf}))	<100 m	<100 m	<100 m
Mid Frequency Cetacean (198 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{mf}))	<100 m	<100 m	<100 m
High Frequency Cetacean (198 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{hf}))	<100 m	<100 m	<100 m
Pinnipeds (in water) (186 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{pw}))	4200 m	1700 m	2800 m

Table 4-14 Summary of the ranges out to which auditory injury is predicted during the installation of 2.6 m pin pile jacket structure for a fleeing animal using the M-Weighted SEL criteria

Jacket structure (E) 2.6 m pin pile	Range to auditory injury criteria		
	Max	Min	Mean
Low Frequency Cetacean (198 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{lf}))	<100 m	<100 m	<100 m
Mid Frequency Cetacean (198 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{mf}))	<100 m	<100 m	<100 m
High Frequency Cetacean (198 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{hf}))	<100 m	<100 m	<100 m
Pinnipeds (in water) (186 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{pw}))	7800 m	3500 m	5700 m

Table 4-15 Summary of the ranges out to which auditory injury is predicted during the installation of 2.6 m pin pile jacket structure for a fleeing animal using the M-Weighted SEL criteria

6.5 m Monopile (W)	Range to auditory injury criteria		
	Max	Min	Mean
Low Frequency Cetacean (198 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{lf}))	200 m	100 m	170 m
Mid Frequency Cetacean (198 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{mf}))	<100 m	<100 m	<100 m
High Frequency Cetacean (198 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{hf}))	<100 m	<100 m	<100 m
Pinnipeds (in water) (186 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{pw}))	11200 m	3900 m	7050 m

Table 4-16 Summary of the ranges out to which auditory injury is predicted during the installation of 6.5 m monopile for a fleeing animal using the M-Weighted SEL criteria

6.5 m Monopile (E)	Range to auditory injury criteria		
	Max	Min	Mean
Low Frequency Cetacean (198 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{lf}))	500 m	200 m	370 m
Mid Frequency Cetacean (198 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{mf}))	<100 m	<100 m	<100 m
High Frequency Cetacean (198 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{hf}))	<100 m	<100 m	<100 m
Pinnipeds (in water) (186 dB re. 1 $\mu\text{Pa}^2/\text{s}$ (M_{pw}))	16400 m	6600 m	11600 m

Table 4-17 Summary of the ranges out to which auditory injury is predicted during the installation of 6.5 m monopile for a fleeing animal using the M-Weighted SEL criteria

Contour plots for 198 dB re 1 $\mu\text{Pa}^2/\text{s}$ M-weighting filters are not always visible as they are too small to display on a figure at this scale.

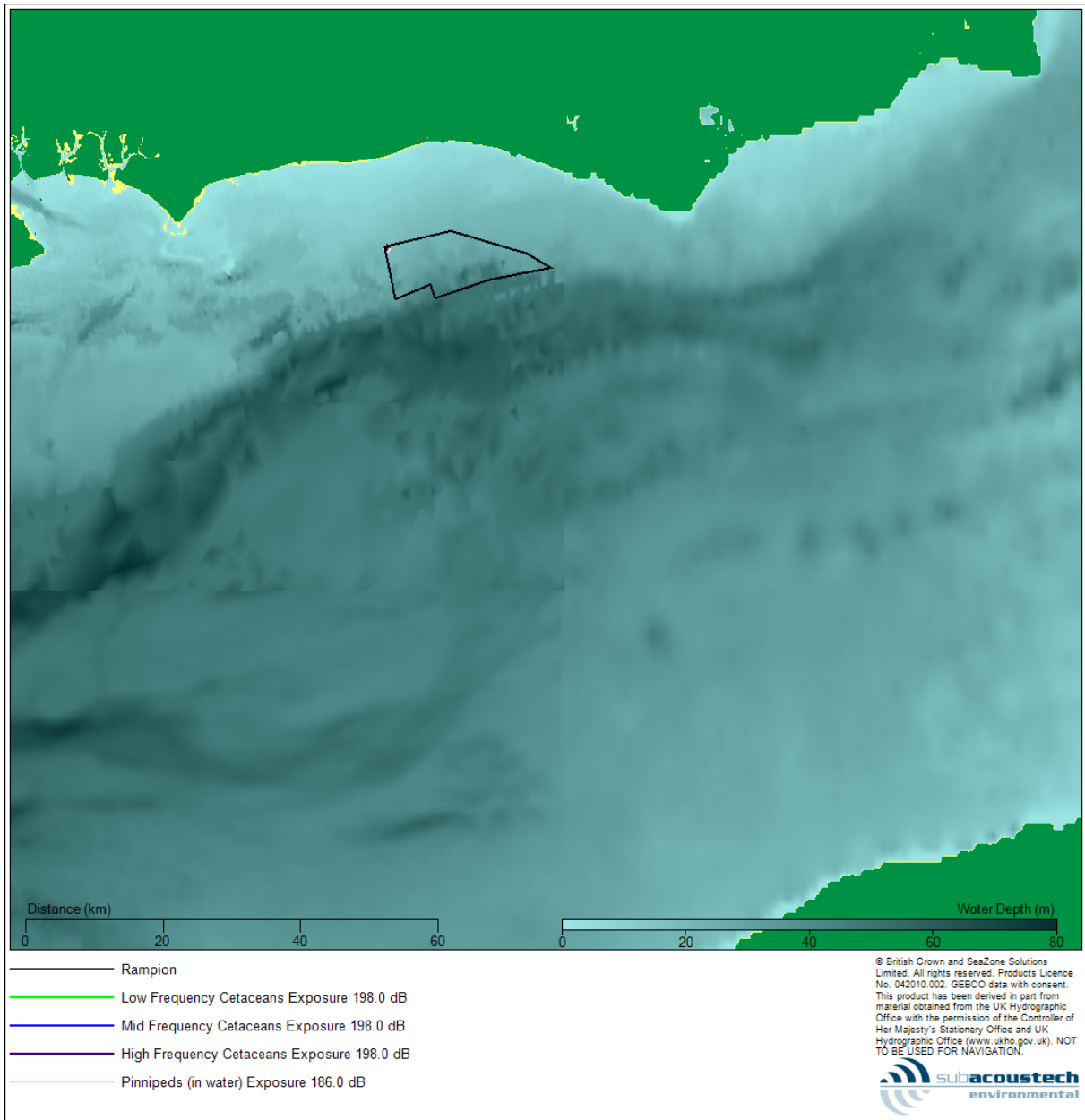


Figure 4-73 Contour plot showing the estimated M-Weighted SEL impact ranges for marine mammals for the 1.53m pin pile jacket structure scenario located west in the Rampion wind farm site

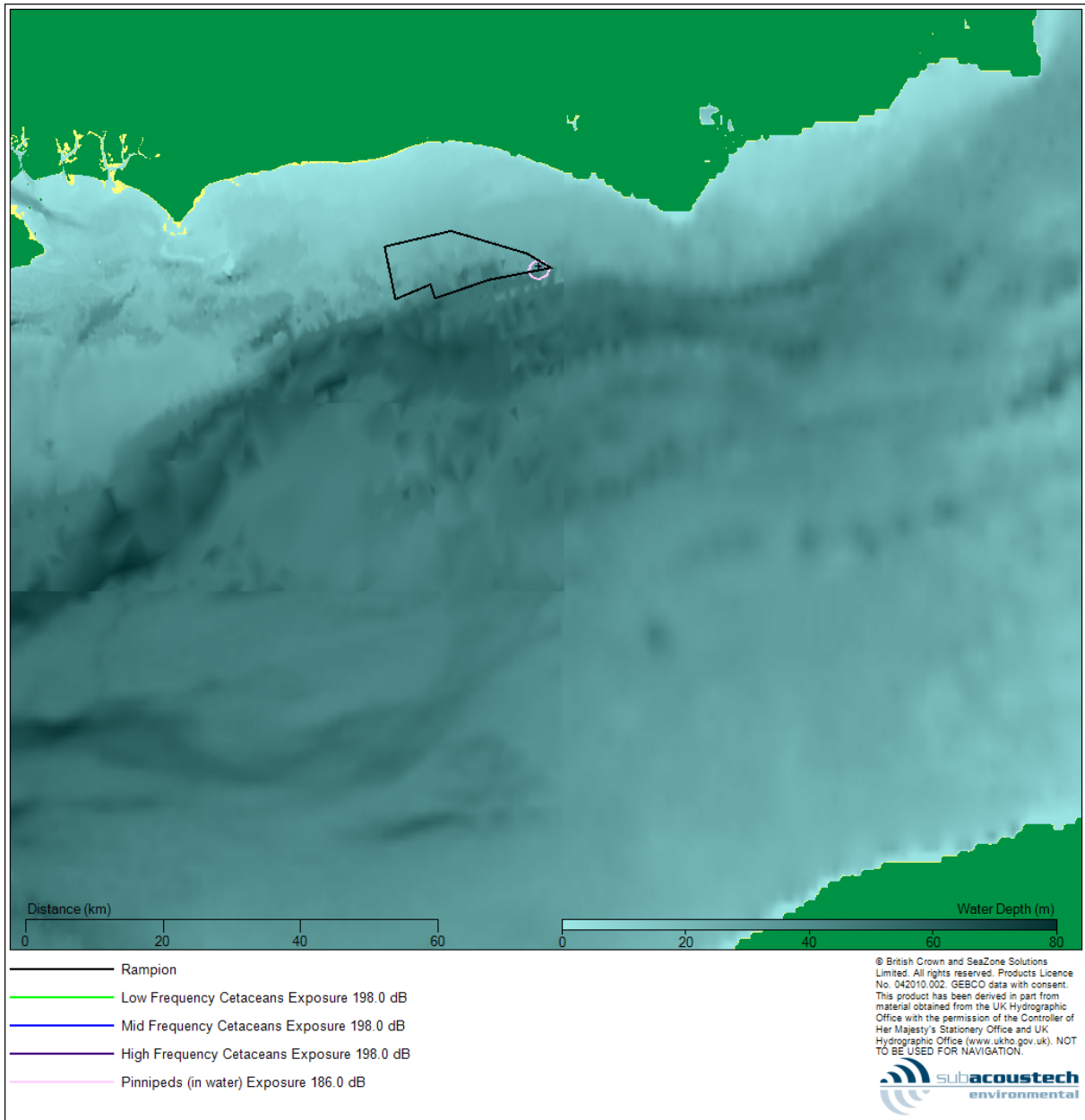


Figure 4-74 Contour plot showing the estimated M-Weighted SEL impact ranges for marine mammals for the 1.53m pin pile jacket structure scenario located east in the Rampion wind farm site

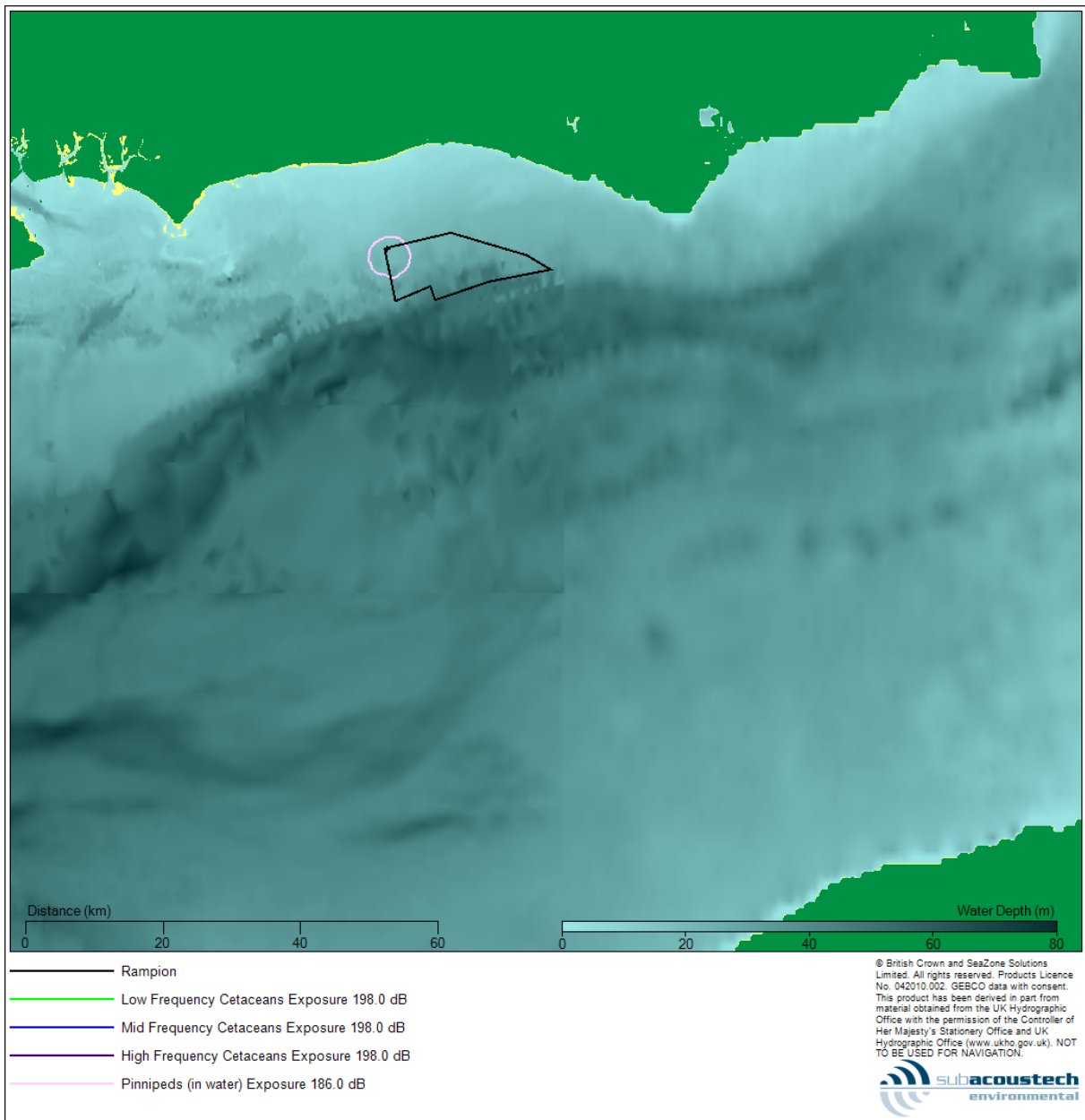


Figure 4-75 Contour plot showing the estimated M-Weighted SEL impact ranges for marine mammals for the 2.6m pin pile jacket structure scenario located west in the Rampion wind farm site

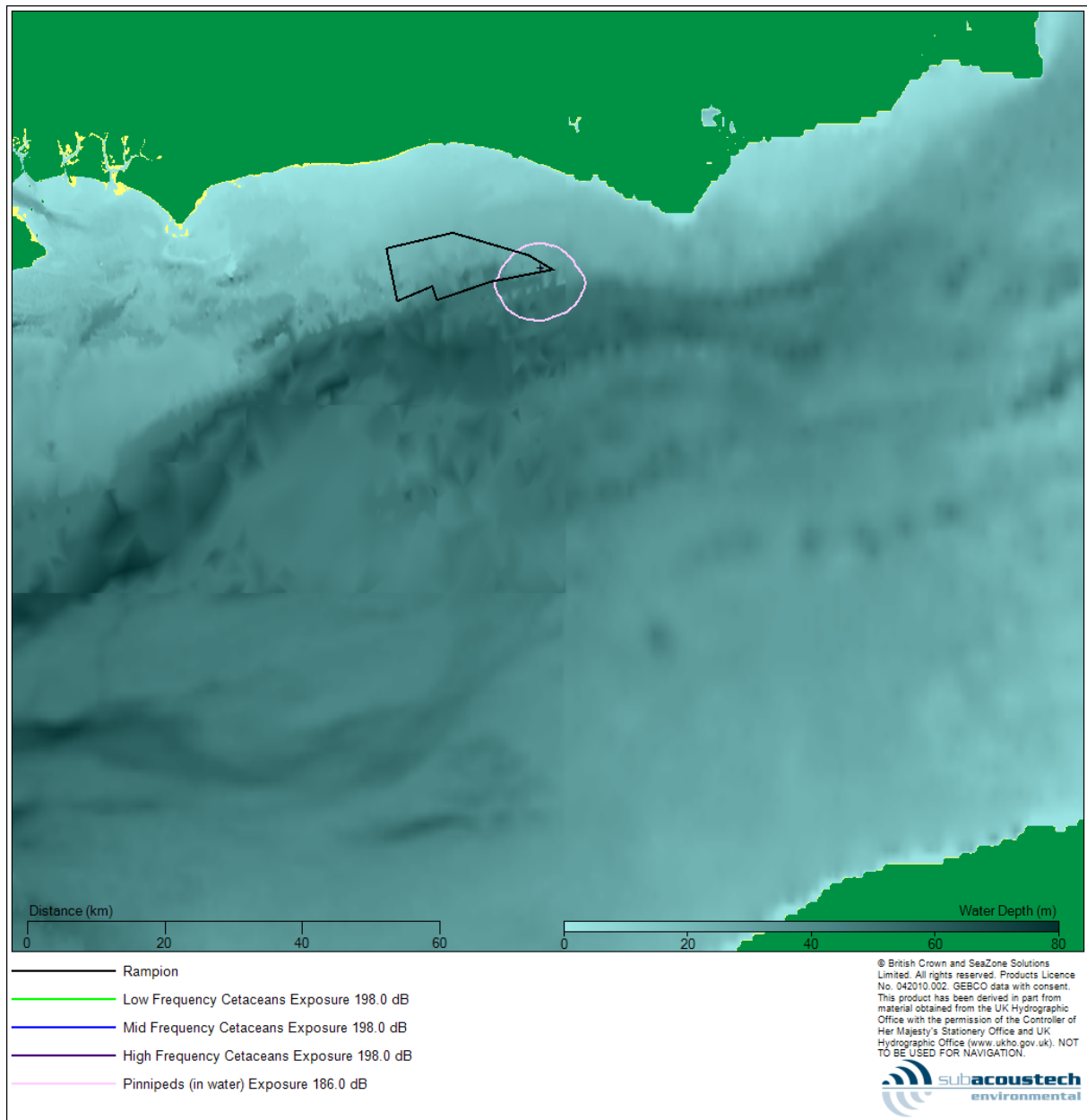


Figure 4-76 Contour plot showing the estimated M-Weighted SEL impact ranges for marine mammals for the 2.6m pin pile jacket structure scenario located east in the Rampion wind farm site

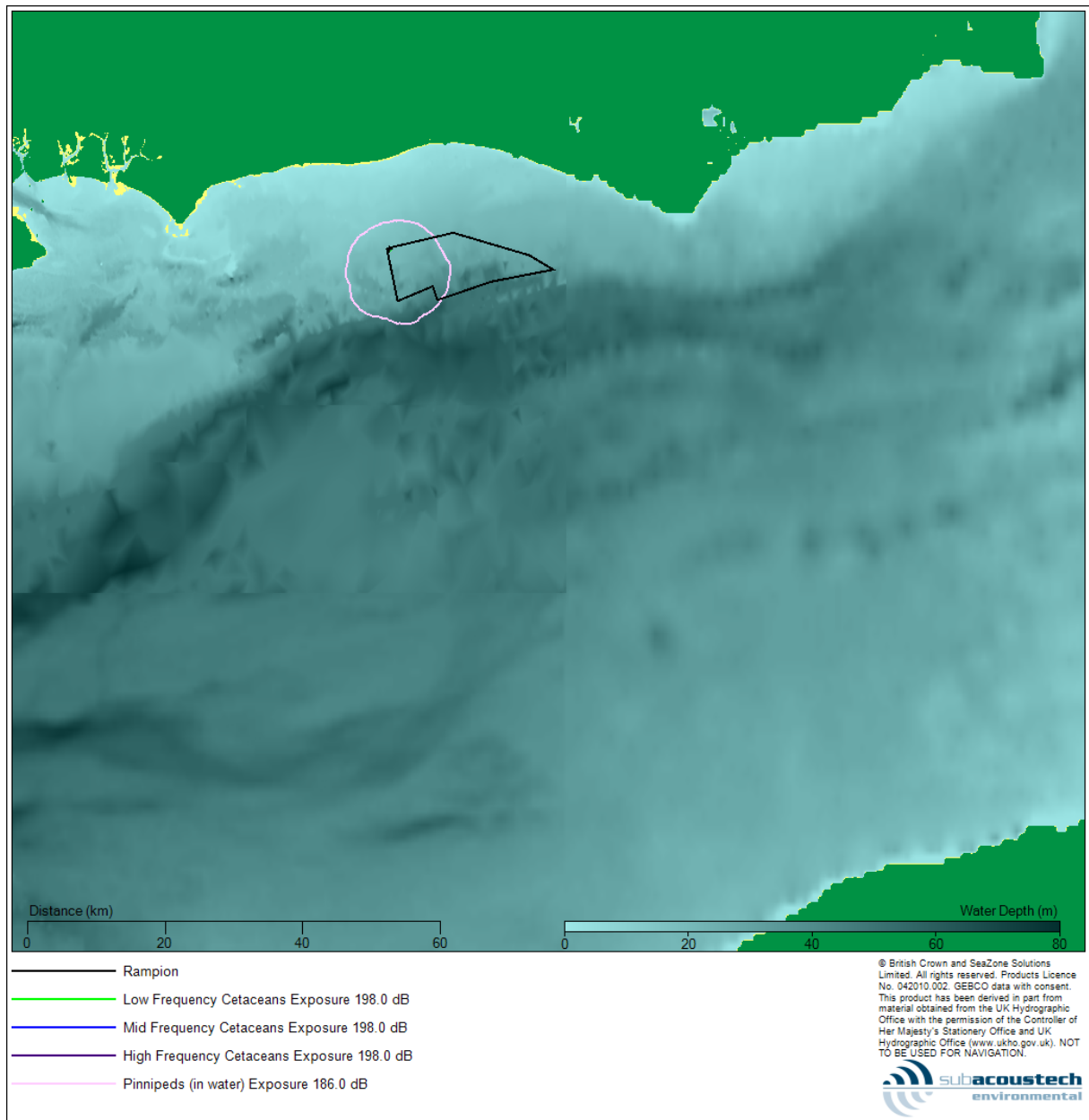


Figure 4-77 Contour plot showing the estimated M-Weighted SEL impact ranges for marine mammals for the 6.5 m monopile scenario located west in the Rampion wind farm site

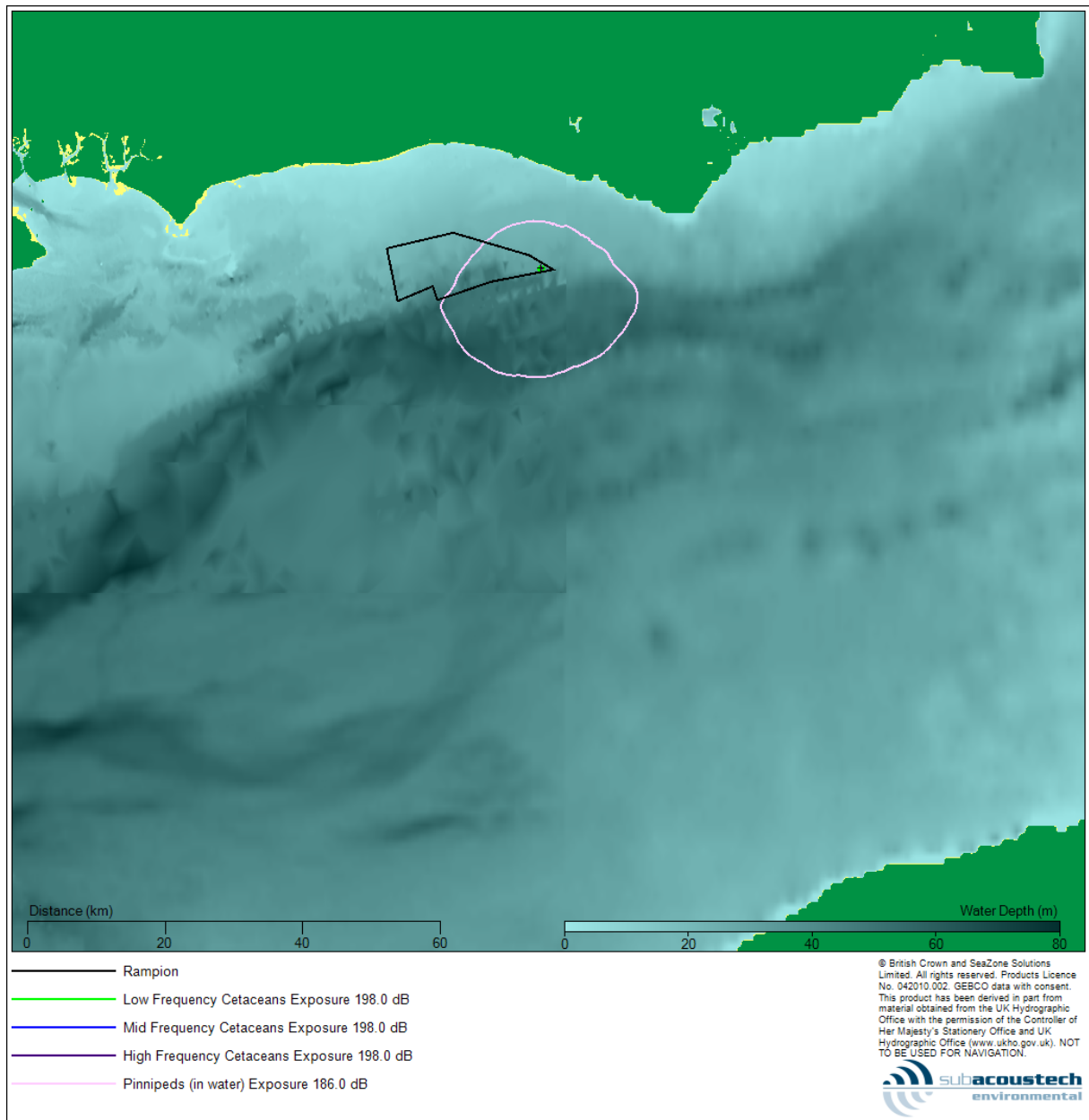


Figure 4-78 Contour plot showing the estimated M-Weighted SEL impact ranges for marine mammals for the 6.5 m monopile scenario located east in the Rampion wind farm site

4.7 Impact on divers and swimmers, dB(UW)

4.7.1 Maximum ranges

Tables 4-18 and 4-19 show the various ranges for which humans underwater would hear various levels to. A maximum range of 480 m for 130 dB(UW) peak-to-peak has been estimated to occur when a 6.5 m monopile is driven in the most eastern part of Rampion wind farm site. For 110 dB(UW) peak-to-peak level a max range of 7.5 km has been estimated and for 90 dB(UW) peak-to-peak level a maximum range of 39 km has been calculated. Figures 4-81 to 4-86 present the data in Tables 4-18 and 4-19 in graphical form.

Piling parameters	Range to 130 dB(UW) (m)		
	Max	Min	Mean
1.53 m pin pile (W)	260	250	255
1.53 m pin pile (E)	270	260	265
2.6 m pin pile (W)	360	350	355
2.6 m pin pile (E)	380	360	370
6.5 m monopile (W)	450	420	435
6.5 m monopile (E)	480	450	465

Table 4-18 Ranges to which 130 dB(UW) peak-to-peak levels are estimated to occur for the modelled scenarios

Piling parameters	110 dB(UW) (km)			90 dB(UW) (km)		
	Max	Min	Mean	Max	Min	Mean
1.53 m pin pile (W)	4.2	3.8	4.0	28	12	19
1.53 m pin pile (E)	5.1	4.4	4.7	32	14	24
2.6 m pin pile (W)	5.4	4.6	4.9	32	13	22
2.6 m pin pile (E)	6.7	5.6	6.1	36	14	26
6.5 m monopile (W)	6.0	5.0	5.5	34	13	23
6.5 m monopile (E)	7.5	6.1	6.8	39	14	27

Table 4-19 Ranges to which 110 and 90 dB(UW) peak-to-peak levels are estimated to occur for the modelled scenarios

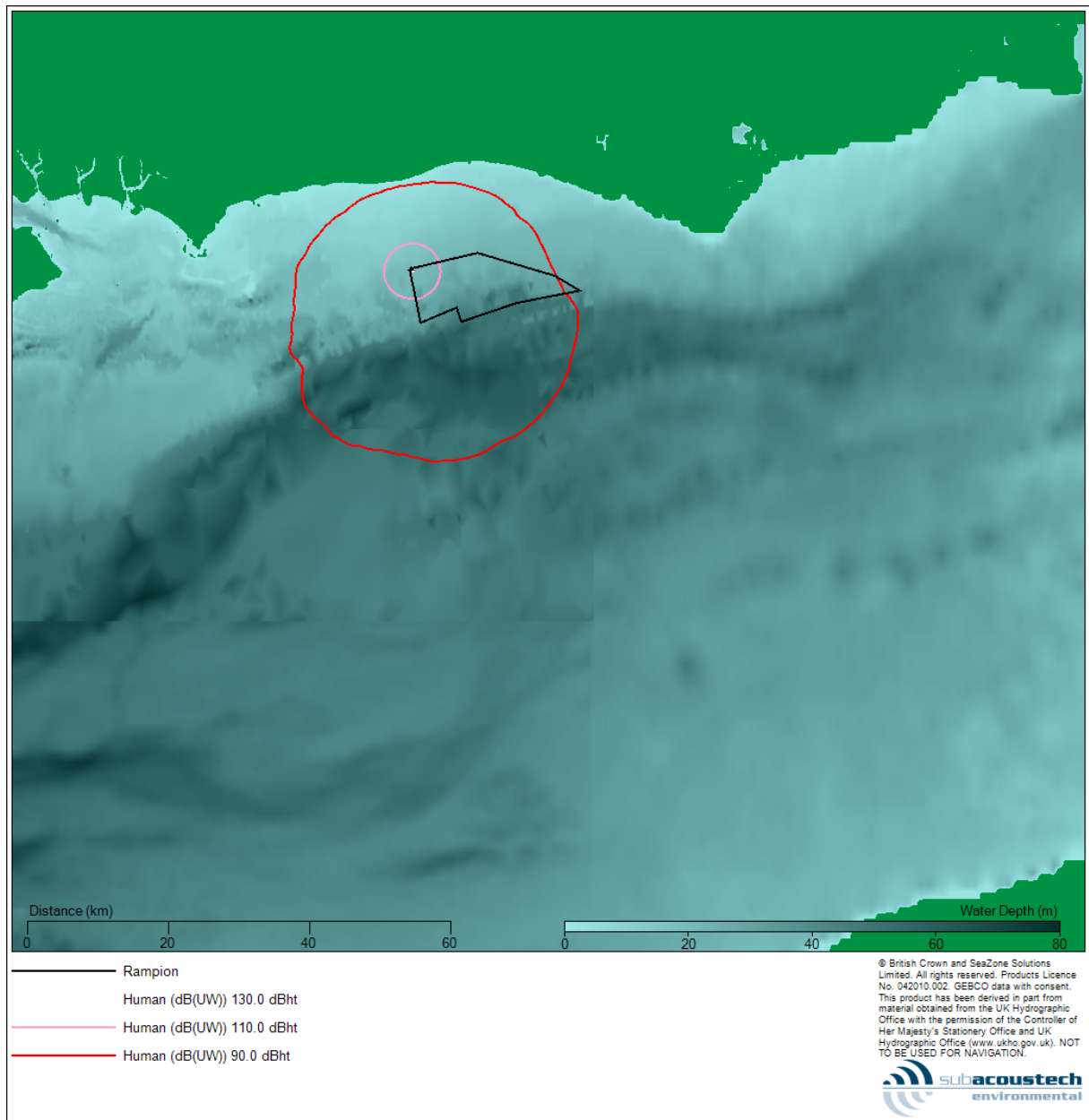


Figure 4-79 Contour plot showing the estimated 130, 110 and 90 dB(UW) peak-to-peak impact ranges for humans underwater during the installation of a 1.53m pin pile, positioned west in the Rampion offshore wind farm site

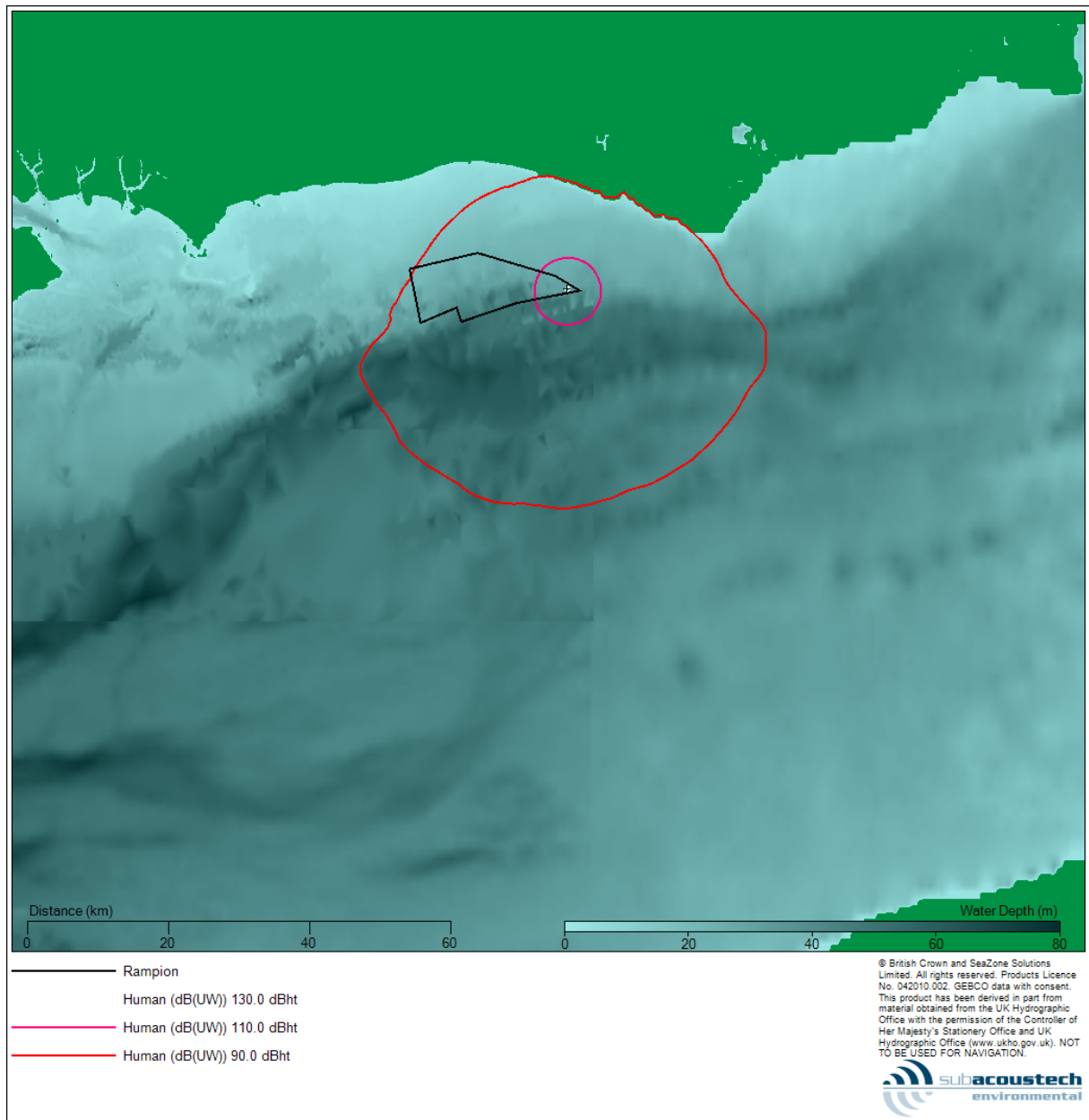


Figure 4-80 Contour plot showing the estimated 130, 110 and 90 dB(UW) peak-to-peak impact ranges for humans underwater during the installation of a 1.53 m pin pile, positioned east in the Rampion offshore wind farm site

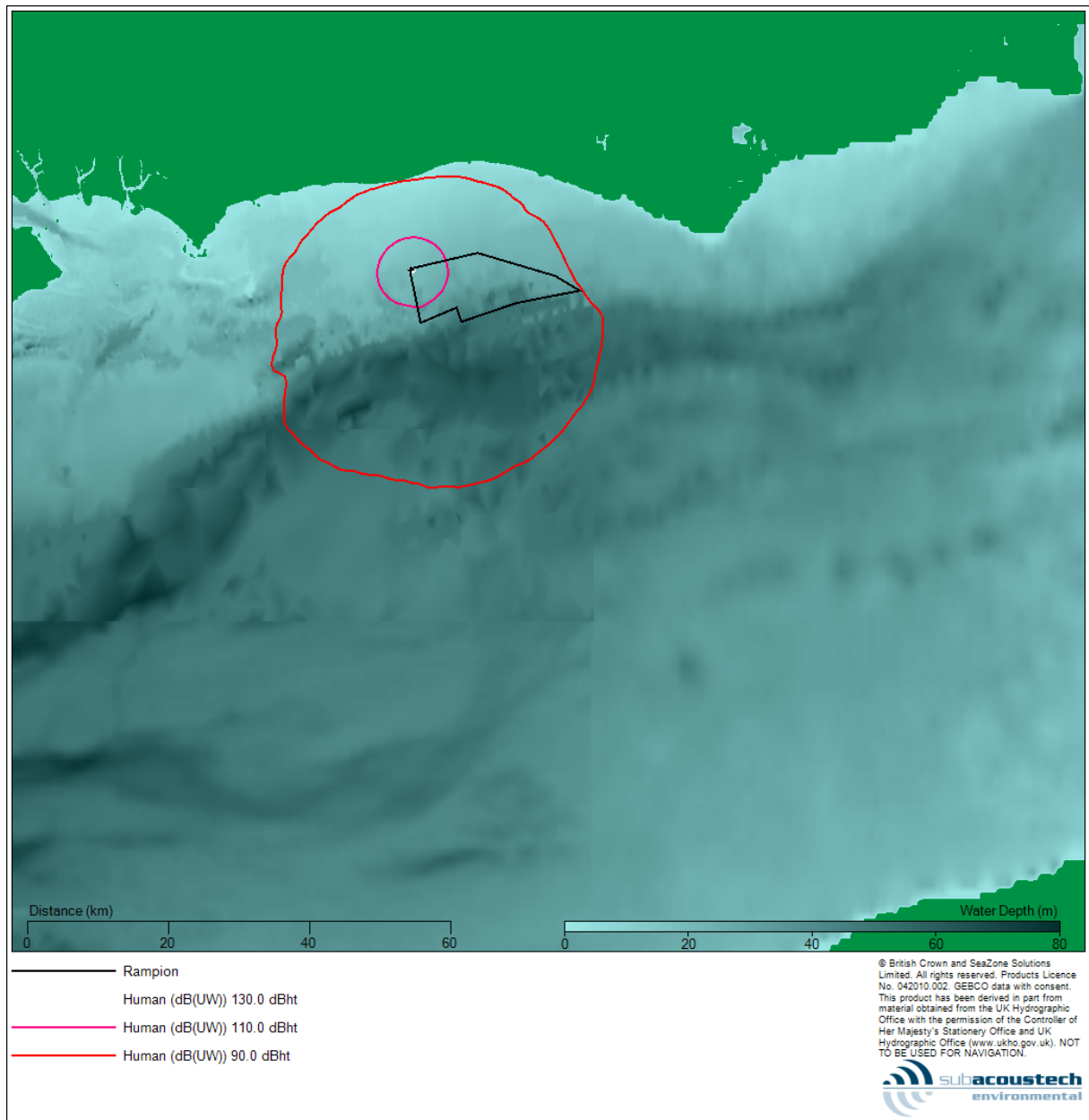


Figure 4-81 Contour plot showing the estimated 130, 110 and 90 dB(UW) peak-to-peak impact ranges for humans underwater during the installation of a 2.6 m pin pile, positioned west in the Rampion offshore wind farm site

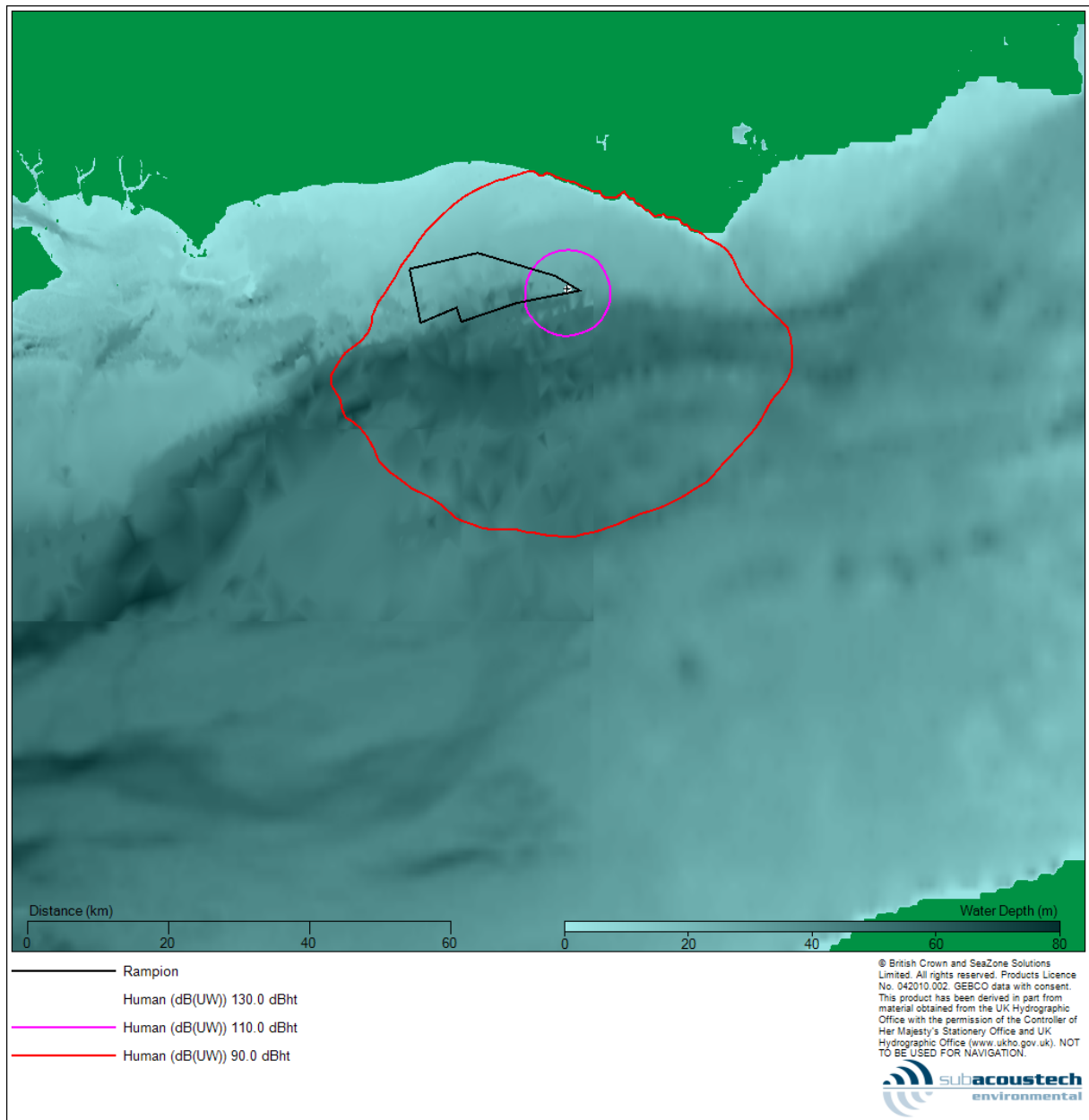


Figure 4-82 Contour plot showing the estimated 130, 110 and 90 dB(UW) peak-to-peak impact ranges for humans underwater during the installation of a 2.6 m pin pile, positioned east in the Rampion offshore wind farm site

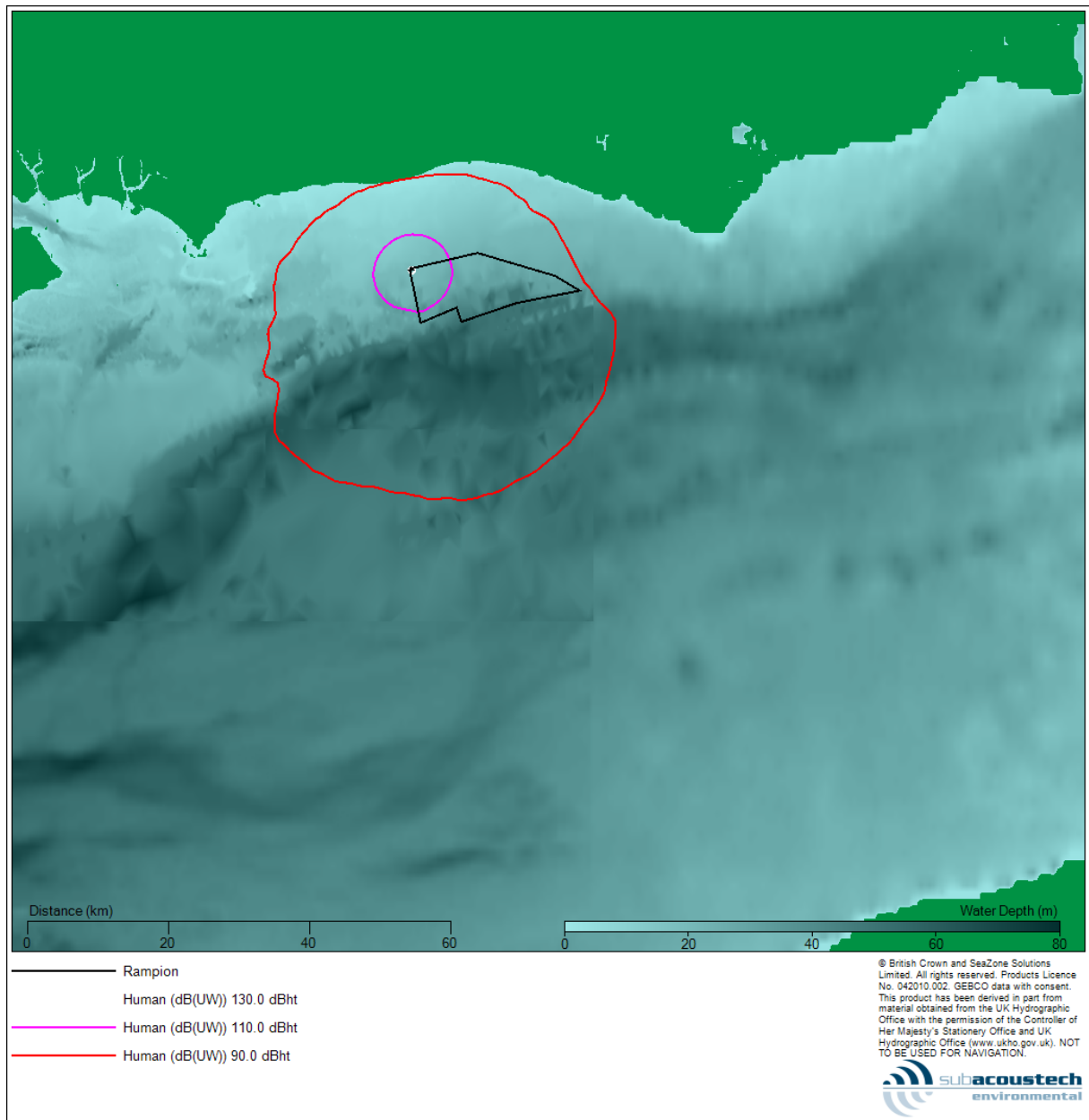


Figure 4-83 Contour plot showing the estimated 130, 110 and 90 dB(UW) peak-to-peak impact ranges for humans underwater during the installation of a 6.5 m monopile, positioned west in the Rampion offshore wind farm site

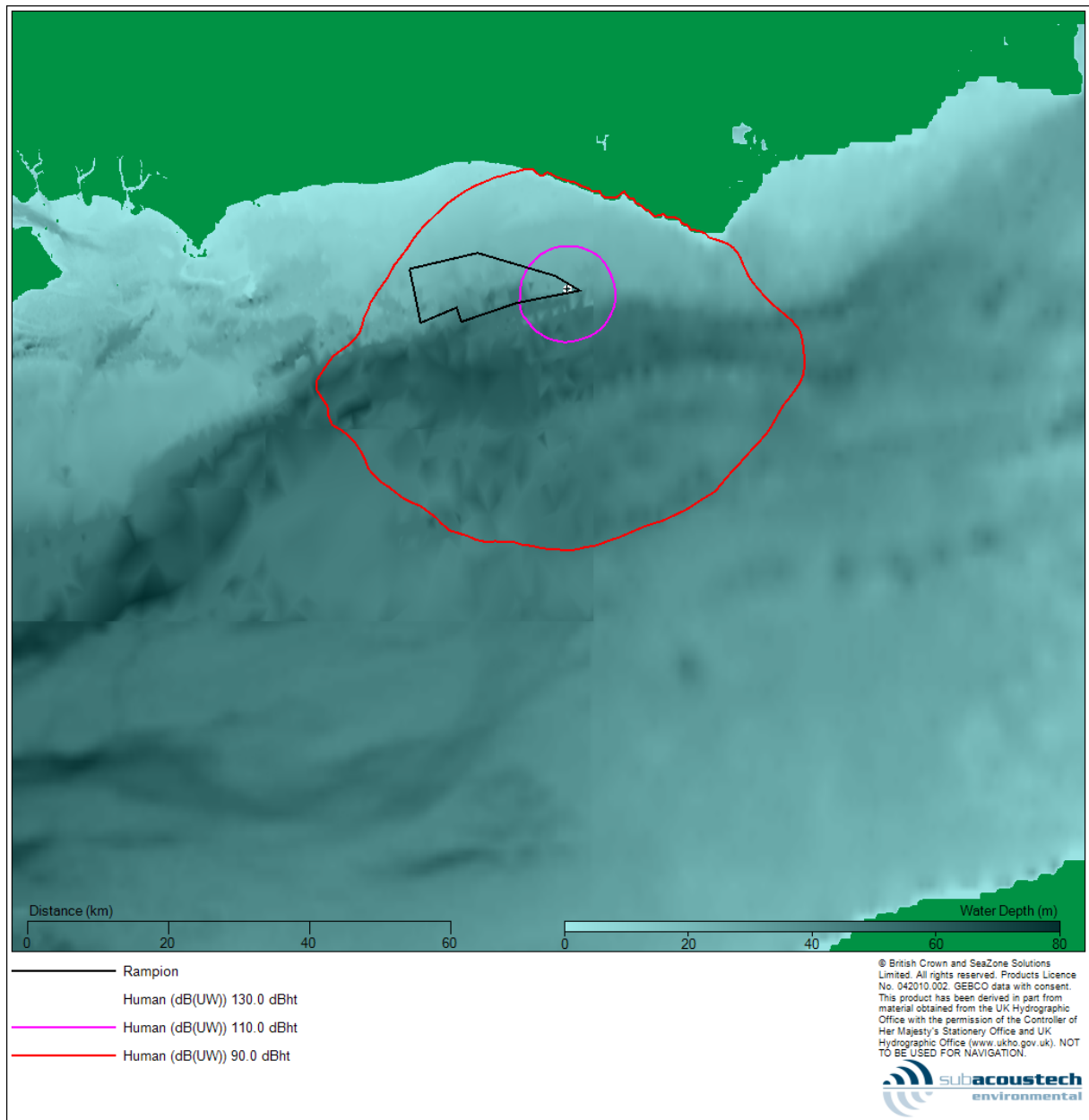


Figure 4-84 Contour plot showing the estimated 130, 110 and 90 dB(UW) peak-to-peak impact ranges for humans underwater during the installation of a 6.5 m monopile, positioned east in the Rampion offshore wind farm site

4.7.2 Startle range during 'soft start'

The ranges provided in Section 4.7.1 above concern the worst case impact from the piling at the maximum blow energy. However, the risk from the tertiary effect of startle will be greatest at the commencement of piling when a diver who may be in the vicinity of the piling would be suddenly and unexpected exposed to the noise. This will be at the beginning of the 'soft start' procedure and consequently the lowest blow energies will be in use.

Table 4-20 shows the ranges at which 110 dB(UW) have been calculated and the energy that is expected at the beginning of the 'soft start' procedure for each size of pile.

Piling parameters	Range to 110 dB(UW) (m)		
	Max	Min	Mean
1.53 m pin pile (W) 60kJ	1130	1110	1120
1.53 m pin pile (E) 60 kJ	1250	1210	1230
2.6 m pin pile (W) 90 kJ	1520	1490	1510
2.6 m pin pile (E) 90 kJ	1730	1650	1680
6.5 m monopile (W) 150 kJ	1740	1700	1723
6.5 m monopile (E) 150 kJ	2000	1890	1940

Table 4-20 Ranges to which 110 dB(UW) peak-to-peak (startle) levels may occur at commencement of soft start

The following figures show the 110 dB(UW) ranges. Note this is at a larger scale than the figures previously to show detail.

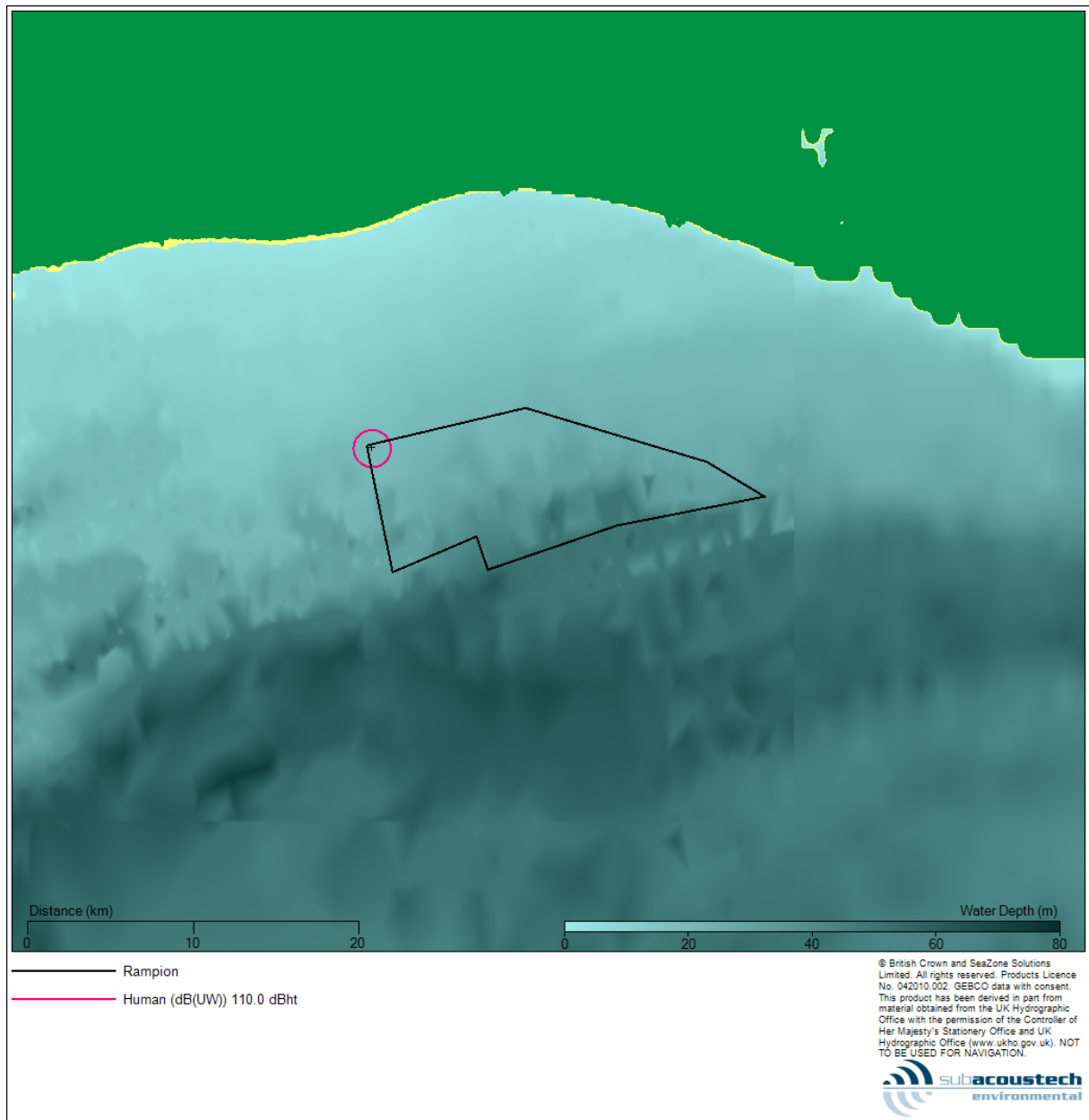


Figure 4-85 Contour plot showing the calculated 110 dB(UW) peak-to-peak impact ranges for humans underwater during the installation of a 1.53 m pile (west position) at commencement of the 'soft start' procedure

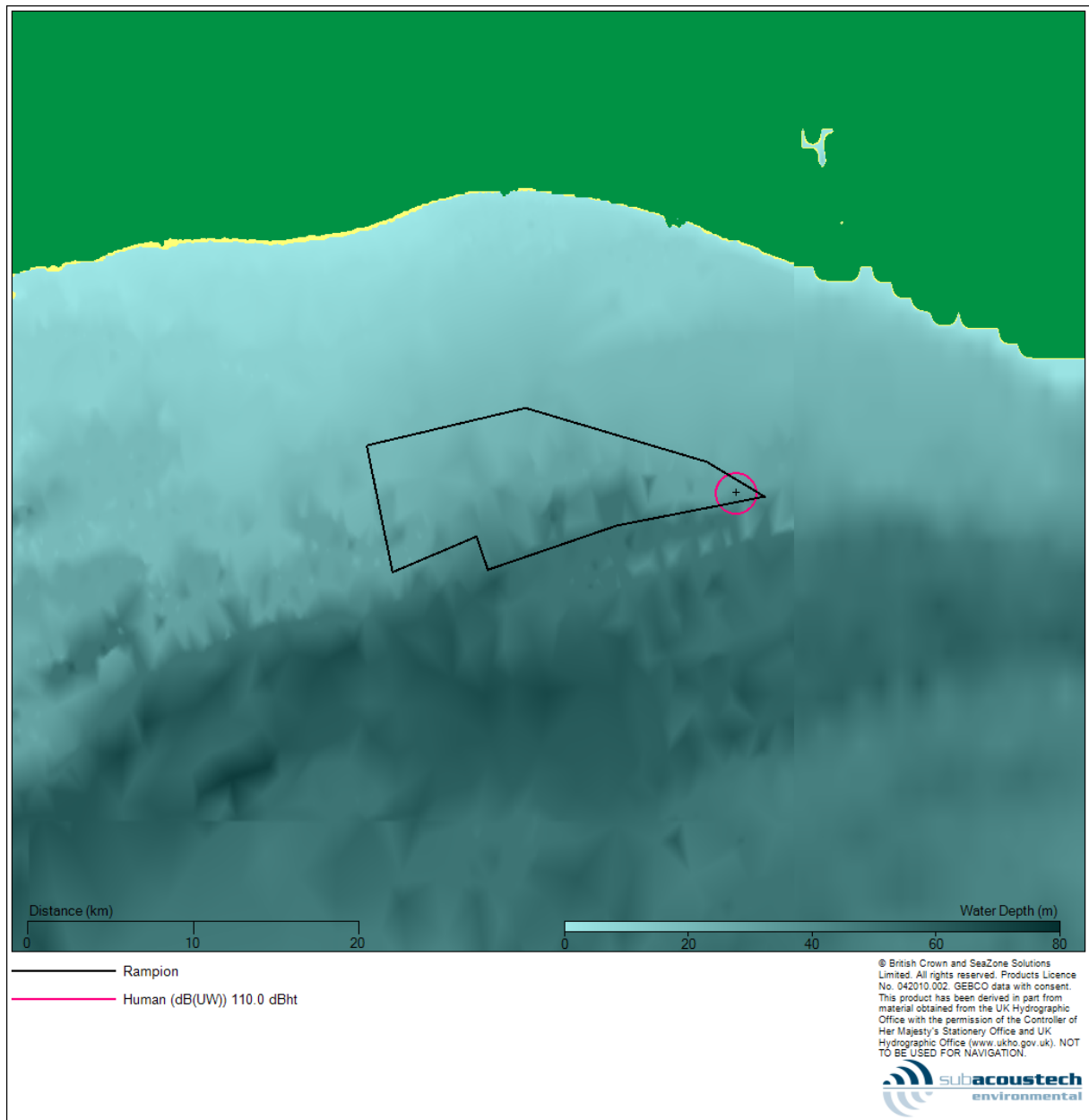


Figure 4-86 Contour plot showing the calculated 110 dB(UW) peak-to-peak impact ranges for humans underwater during the installation of a 1.53 m pile (east position) at commencement of the 'soft start' procedure

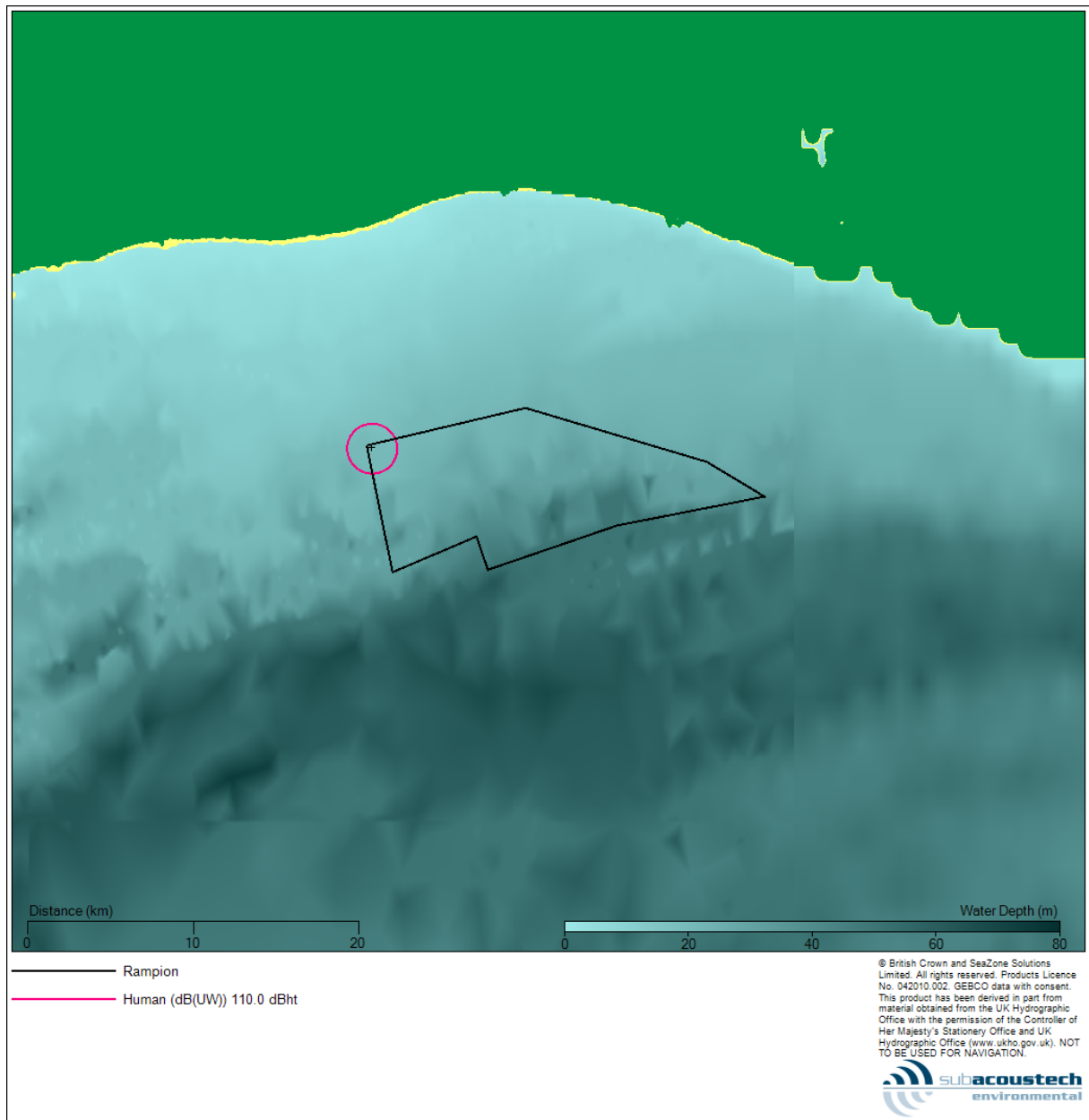


Figure 4-87 Contour plot showing the calculated 110 dB(UW) peak-to-peak impact ranges for humans underwater during the installation of a 2.6 m pile (west position) at commencement of the 'soft start' procedure

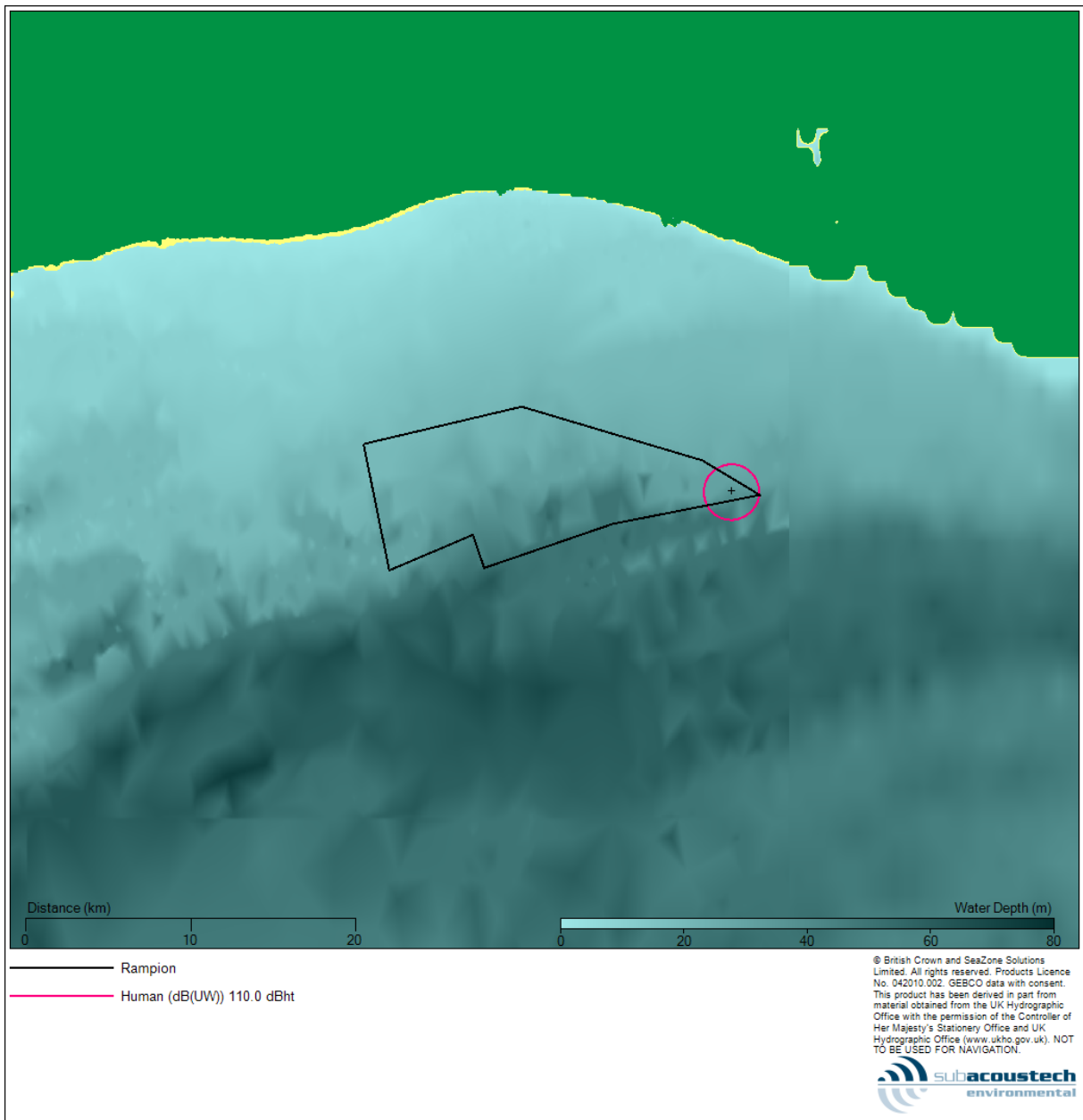


Figure 4-88 Contour plot showing the calculated 110 dB(UW) peak-to-peak impact ranges for humans underwater during the installation of a 2.6 m pile (west position) at commencement of the 'soft start' procedure

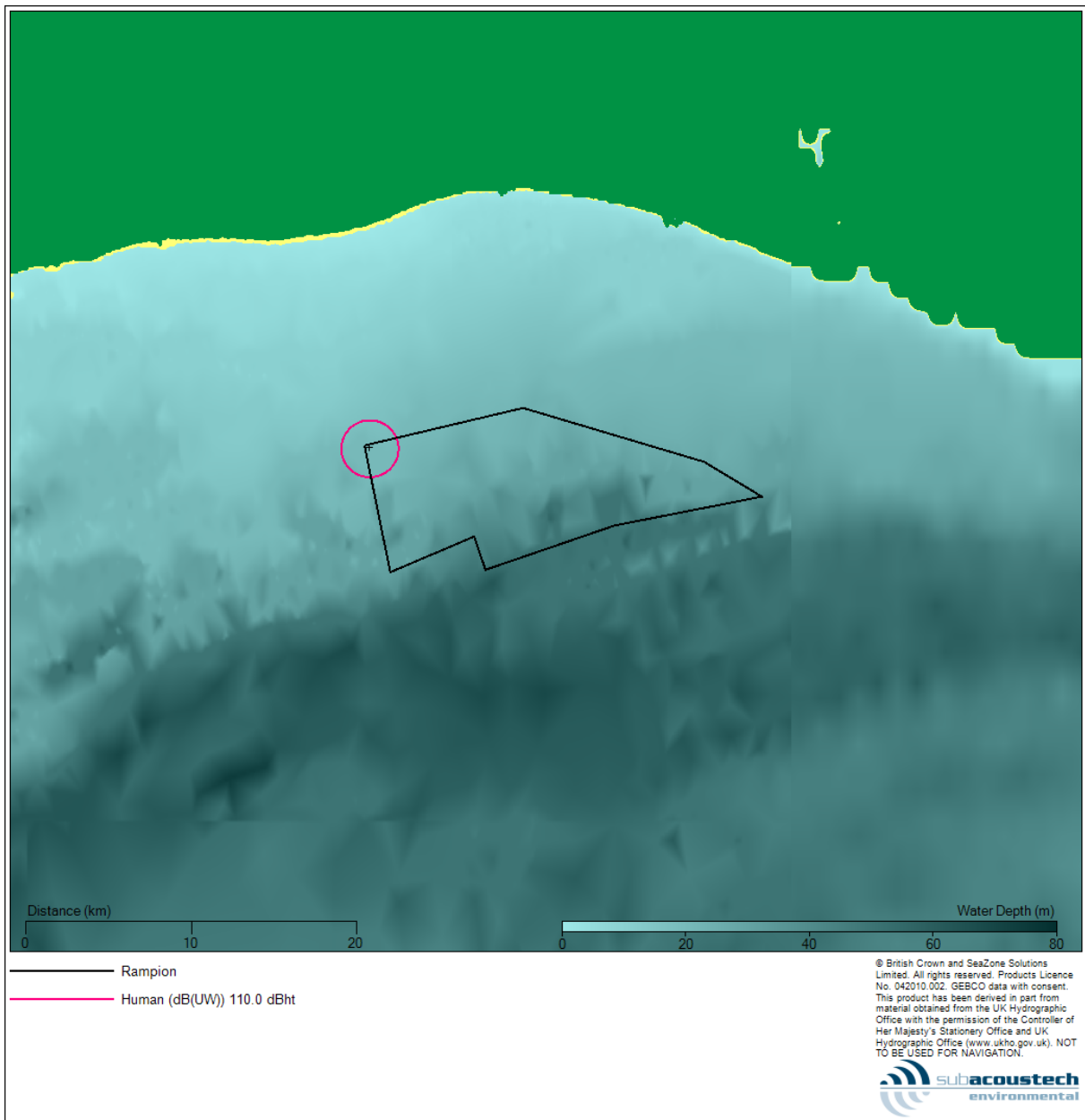


Figure 4-89 Contour plot showing the calculated 110 dB(UW) peak-to-peak impact ranges for humans underwater during the installation of a 6.5 m monopile (west position) at commencement of the 'soft start' procedure

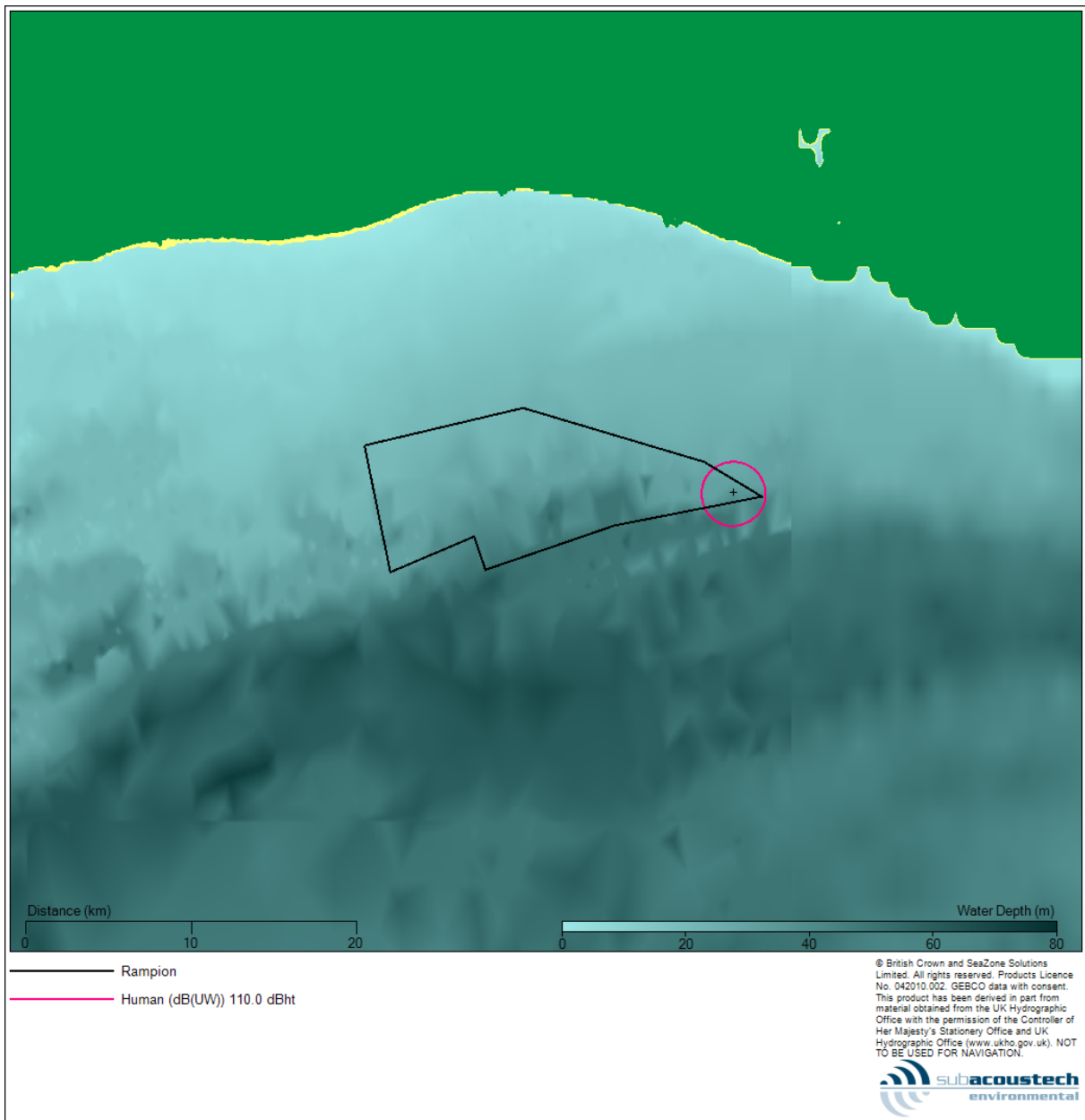


Figure 4-90 Contour plot showing the calculated 110 dB(UW) peak-to-peak impact ranges for humans underwater during the installation of a 6.5 m pile (east position) at commencement of the 'soft start' procedure

5 Subsea operational and decommissioning noise

5.1 Operational

The nature of the underwater-noise generated by an operational wind farm tends to be relatively broadband in nature with a few dominant tonals. The sound generating mechanisms are believed to be gearbox mesh vibrations that are transmitted via the tower structure and then radiate out to the water. The airborne noise of the rotors above the water are not expected to influence the underwater noise levels significantly since the transfer of sound energy through the air-water interface is extremely inefficient.

Subacoustech's underwater noise database contains recordings of operational wind turbines. The measurements have been shown to have little influence over a distance of more than a few hundred metres. These measurements of underwater noise from operational turbines have generally been on wind farms with up to 60 turbines. Therefore, with a greater number of larger turbines the noise level is likely to increase however it is not thought this would be greatly significant.

Cefas (2010) reviewed the monitoring of underwater sound around wind farm sites around the UK coast, with a view to establishing the compliance with licensing requirements. The review concluded, *inter alia*, that in the operational phase the sound generated was only slightly above ambient noise levels and would be expected to have a negligible effect on marine fauna.

5.2 Decommissioning

Considerations of decommissioning noise may be considered a little premature in light of the expected 20+ years of operational life. With present technologies it is likely that decommissioning techniques will resemble that currently used by the oil industry.

In effect there are two approaches:

- Shaped explosives;
- Grinding/drilling techniques.

The effects of underwater explosions on fish, birds and mammals has been fairly well documented (Yelverton et al 1981 and Rawlins 1987) and are touched on in Section 3.2. The effects of grinding techniques are likely to be relatively unimportant.

For explosive techniques the peak sound level of a freely suspended charge of Tri-Nitro-Toluene (TNT) in water can be estimated from Arons (1954). For offshore operations such as well head severance, typical charge weights of 40 kg may be used, giving a source peak pressure of 195 MPa or 285 dB re 1 μ Pa @ 1m (Parvin et al, 2007). This is considerably larger than the levels produced by present piling techniques.

It is noteworthy that the grinding techniques would be at a much lower and less intrusive levels but would be present for longer periods of time. Therefore, only at the time of decommissioning when local marine life is known and understood can a realistic and useful assessment of the effects and the appropriate mitigation be carried out. Consequently, it seems clear that a separate and new impact assessment will be required and no further discussion will be made of these approaches.

6 Summary and Conclusions

Subacoustech Environmental has undertaken a study on behalf of RSK Environmental Ltd to assess the impact of underwater noise and most notably the effect of impact piling scenarios at the Rampion Wind Farm site off the south coast of England.

The level of underwater noise from the installation of jacket piles and monopiles have been estimated by using a proprietary underwater sound propagation model that enables the behaviour of noise with range from the piling to be estimated for varying water depths, pile sizes, blow energies and piling locations based on an existing database of measurements of piling noise.

The modelled results suggest that marine species may suffer a lethal effect out to a range of less than 10 m and that physical injury is likely to occur out to a maximum range of up to 25 or 65 m, depending on the piling scenario modelled.

The possibility of traumatic hearing injury has been assessed using the 130 dB_{ht}(*Species*) criteria, for which the largest estimated ranges are for humpback whale, with 130 dB_{ht} ranges for the humpback whale of up to 630 m for the 2.6 m pin pile jacket structure scenario and 690 m for the 6.5 m monopile scenario located east in the wind farm site.

Behavioural impacts on marine species have been assessed using the 90 dB_{ht}(*Species*) and 75 dB_{ht}(*Species*) criteria and show that the largest impact ranges are predicted for herring, harbour porpoise and humpback whale. A maximum 90 dB_{ht} impact range for herring of 38.5 km, 19.1 km for the harbour porpoise and 36.6 km for the humpback whale, for the 6.5 m monopile scenario positioned east in the wind farm site, was calculated.

The accumulated exposure to sound for marine mammals has been assessed using M-Weighted SELs assuming an animal fleeing the noise source. The largest ranges are calculated for the 186 dB criteria for pinnipeds (in water). For piling operations at the easterly location a maximum range of 16.7 km is likely to be needed at the onset of the impact piling for the installation of a monopile to avoid a damaging exposure to sound using the Southall criteria. Lower ranges are predicted for all the species and criteria using the 198 dB threshold.

The potential effects on divers in water has been assessed by using the dB(UW) metric. 130, 110 and 90 dB(UW) peak-to-peak levels have been presented. The maximum range to which 130 dB(UW) peak-to-peak level has been estimated to occur is 480 m and is thought that this level is likely to cause auditory damage to a diver exposed to this level. At commencement of the 'soft start' procedure at the beginning of piling, the greatest range at which a diver may be exposed to levels of 110 dB(UW) for 'startle' is 2,000 m for installation of a 6.5 m pile at 10% of the maximum blow energy. All other modelled locations and pile sizes have a smaller impact range.

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Issue	Date	Details of changes
E356R0301	29/05/2012	Initial draft and internal review
E356R0302- E356R0304		Internal revisions
E356R0305	09/08/2012	Revised pile sizes
E356R0306- E356R0307	23/10/2012	Revised pile sizes, easterly location, inclusion of seahorse data, inclusion of research on cephalopods and life cycle. Draft, awaiting SEL modelling data.
E356R0308	25/10/2012	Including SEL data and surrogate list. Other minor revisions.
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