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Modelling of Noise during Impact Piling Operations at the Neart na Gaoithe Offshore Wind Farm in the Firth of Forth

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Executive Summary

Subacoustech Environmental has undertaken a study on behalf of Mainstream Renewable Power to assess the impact of underwater noise produced during pile driving operations during the installation of wind turbines at the Neart na Gaoithe (NNG) Wind Farm site, situated in the Firth of Forth.

The levels of underwater noise from the installation of jacket piles have been assessed and estimated using a proprietary underwater sound propagation model, INSPIRE (currently version 3.3.0), 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 NNG 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 µPa, out to a range of less than 10 m. Physical injury, where peak to peak pressure levels exceed 220 dB re. 1 µPa, is likely to occur out to a maximum range of 50 m or 60 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 of up to 780 m during the fully driven scenario and 690 m during the drill-drive scenario.

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 34 km, 20 km for the harbour porpoise and 41 km for the humpback whale for the worst case fully driven NNG scenario.

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. For piling operations at a single location a maximum range of 8.4 km is likely to be needed at the onset of the impact piling for the NNG drill-drive scenario to avoid a damaging exposure to sound using the Southall criteria. Lower ranges are predicted for all the criteria using the 198 dB threshold. The largest impact range calculated was found to be 47.3 km for the 186 dB criteria for Pinnipeds for the cumulative scenario of NNG drill-drive, Inch Cape and Seagreen.

1 Introduction

1.1 Project description

Subacoustech Environmental have been tasked by the Mainstream Renewable Power, as part of the Forth and Tay Offshore Developer's Group, to investigate, by means of subsea noise modelling, the impact of proposed impact piling operations at the Neart na Gaoithe (NNG) offshore wind farm in the Forth and Tay area. This will be undertaken by using preliminary engineering parameters to identify what effect this will have on marine species in the Firth of Forth.

The FTOWDG development site includes three sites:

- NNG;
- Inch Cape;
- Seagreen (Phases 1 to 3).

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 Mainstream RP 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 Limited to estimate the likely level of underwater noise during the installations of wind turbines using impact piling at the NNG 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 dB_{ht}(*Species*) and M-Weighted SEL metrics for impact piling of jacket piles for two scenarios;
- The cumulative effects of simultaneous piling that could potentially occur at two or all three of the above fields;
- 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 NNG 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 µPa for UK coastal waters are not uncommon (Nedwell *et al,* 2003a and 2007a). This level equates to about 100 dB re 20 µPa 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 µPa and typically not below 70 dB re 1 µPa (44 dB re 20 µPa 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:

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

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 µPa 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:

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

For underwater sound, typically a unit of one microPascal (µPa) 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 Urick (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 µPa @ 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 1µPa @ 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 µPa @ 1 m (Richardson *et al*, 1995), whereas a supertanker generates source SPLs of typically 198 dB re 1 µPa @ 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:

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

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 μPa^2 (P^2_{ref}) and a reference time (T_{ref}).

The SEL is then defined by:

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

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

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

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.

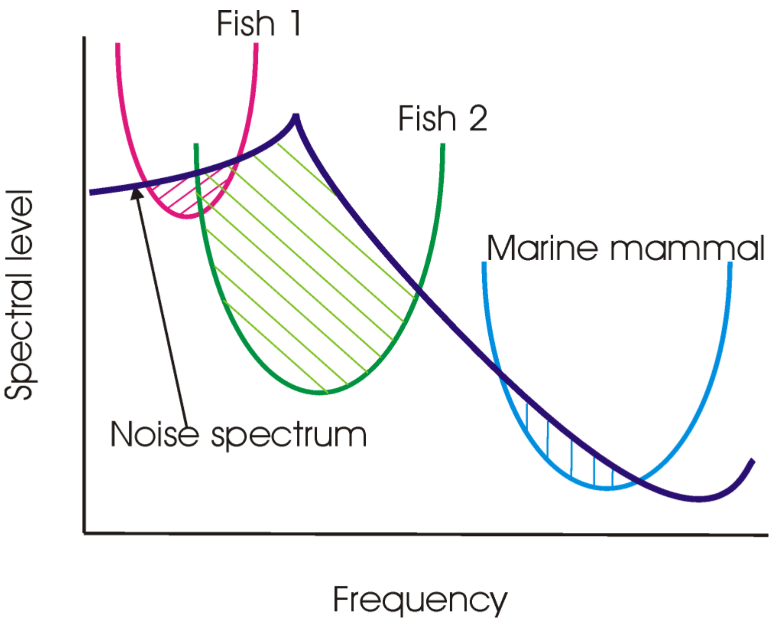

Figure 2-1. Illustration of perceived sound level (dB$_{ht}$) for representative fish and marine mammal species.

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 dB$_{ht}$(*Gaddus morhua*) for a cod and 40 dB$_{ht}$(*Salmo salar*) for a salmon.

The perceived noise levels of sources measured in dB$_{ht}$(*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. Concerning the NGG Offshore Wind Farm there are a number of Scottish policies which a development must comply with in order to best protect the marine environment. Of particular relevance are:

- Marine (Scotland) Act (2010)
- 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 Legislation and Marine Developments

Under guidance of the JNCC, Special Areas of Conservation (SAC) are established at locations to protect the species outlined in EU Habitats Directive. Currently there are around 28 marine

SACs (or derivatives) within Scotland, all of which all aim to limit the effects of anthropogenic noise underwater. Their management is overseen via Regulation 33. Dolman & Simmonds (2010) outlined other Scottish legislation which was aimed at providing significant protection to its intrinsic fauna, including the Conservation (Natural habitats) Regulations (2004; as amended). These guidelines offer protection to individual marine mammals up to 12 nautical miles from the Scottish coast, and deem it an offence to disturb or harass any mammals to such an extent that their abundance or distribution within that area is affected. The EU Habitat Directive requires strict protection of Scotland's 24 cetacean species; a list which includes harbour porpoises, bottlenose dolphins, grey seals, and common seals. Most recently, the Marine (Scotland) Act (2010) has been introduced to provide a legal mechanism to help ensure clean, productive and biologically diverse marine and coastal environments. It was introduced with the long term goals in mind, and aims to achieve this through improved management and protection of marine and coastal areas. One of the particular goals of the Act is improved measures for the protection of seals via a more comprehensive and less complex licensing system. Seal species now account for a high percentage of the Scottish marine SACs, with only one SAC for the bottlenose dolphin. Any developments within Scottish waters are heavily weighted towards protection of the native seal species.

3.1.3 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 µPa^{2}s. 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.

	Sound Type		
Marine mammal group	**Single pulses**	**Multiple pulses**	**Nonpulses**
Low frequency cetaceans			
Sound Pressure Level	230 dB re. 1 µPa (peak)	230 dB re. 1 µPa (peak)	230 dB re. 1 µPa (peak)
Sound Exposure Level	198 dB re. 1 μPa^2-s (M_{lf})	198 dB re. 1 μPa^2-s (M_{lf})	215 dB re. 1 μPa^2-s (M_{lf})
Mid frequency cetaceans			
Sound Pressure Level	230 dB re. 1 µPa (peak)	230 dB re. 1 µPa (peak)	230 dB re. 1 µPa (peak)
Sound Exposure Level	198 dB re. 1 μPa^2-s (M_{mf})	198 dB re. 1 μPa^2-s (M_{mf})	215 dB re. 1 μPa^2-s (M_{mf})
High-frequency cetaceans			
Sound Pressure Level	230 dB re. 1 µPa (peak)	230 dB re. 1 µPa (peak)	230 dB re. 1 µPa (peak)
Sound Exposure Level	198 dB re. 1 μPa^2-s (M_{hf})	198 dB re. 1 μPa^2-s (M_{hf})	215 dB re. 1 μPa^2-s (M_{hf})
Pinnipeds (in water)			
Sound Pressure Level	218 dB re. 1 µPa (peak)	218 dB re. 1 µPa (peak)	218 dB re. 1 µPa (peak)
Sound Exposure Level	186 dB re. 1 μPa^2-s (M_{pw})	186 dB re. 1 μPa^2-s (M_{pw})	203 dB re. 1 μPa^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	*Steno, Sousa, Sotalia, Tursiops, Stenella, Delphinus, Lagenodelphis, Lagenorhynchus, Lissodelphis, Grampus, Peponocephala, Feresa, Pseudorca, Orcinus, Globicephala, Orcaella, Physeter, Delphinapterus, Monodon, Ziphius, Berardius, Tasmacetus, Hyperoodon, Mesoplodon* (57 species/subspecies)	Bottlenose dolphin, striped dolphin, killer whale, sperm whale
High frequency cetaceans	200 Hz to 180 kHz	*Phocoena, Neophocaena, Phocoenoides, Platanista, Inia, Kogia, Lipotes, Pontoporia, Cephalorhynchus* (20 species/subspecies)	Harbour porpoise, river dolphins, Hector’s dolphin
Pinnipeds (in water)	75 Hz to 75 kHz	*Arctocephalus, Callorhinus, Zalophus, Eumetopias, Neophoca, Phocarctos, Otaria, Erignathus, Phoca, Pusa, Halichoerus, Histriophoca, Pagophilus, Cystophora, Monachus, Mirounga, Leptonychotes, Ommatophoca, Lobodon, Hydrurga,* and *Odobenus* (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 multiple pulse criterion of 198 dB re 1 µPa^2-s (M_{pw}) for Pinnipeds (in water) has been proposed by Thompson and Hastie (in prep.), as the 186 dB re 1 µPa^2-s (M_{pw}) criterion was found to lead to paradoxical values. This new criterion is based on seal distribution data and its correlation to estimated noise levels from impact piling, and has also been used herein.

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 $dB_{pk\text{-}pk}$ re 1 µPa and a sound exposure level (SEL) of 164.3 dB re. 1 µPa^{2}s, although this has 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}(*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}(*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). By comparison, the swim bladder in salmon is not in close proximity to the ear anatomy and, as such, this species has poorer hearing. 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.

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 species upon which the dB_{ht} 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 3-3.

The species of fish considered in this study are:

- 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;
- 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;
- The Atlantic salmon (*Salmo salar*) possess a substantial swimbladder but, as it is not in close proximity to the inner ear, they are therefore less sensitive to underwater noise and vibration.
- Trout are represented by the brown trout (*Salmo trutta*), which, although salmonids, have been found to be significantly less sensitive than the Atlantic salmon (Nedwell *et al*, 2006).
- 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.

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.

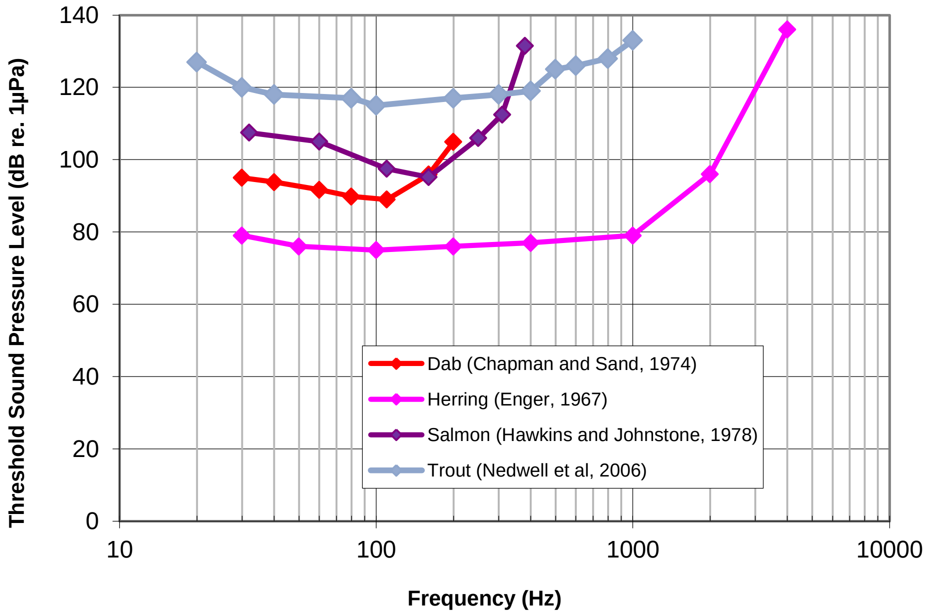

Figure 3-1 Comparison of hearing thresholds for species of fish

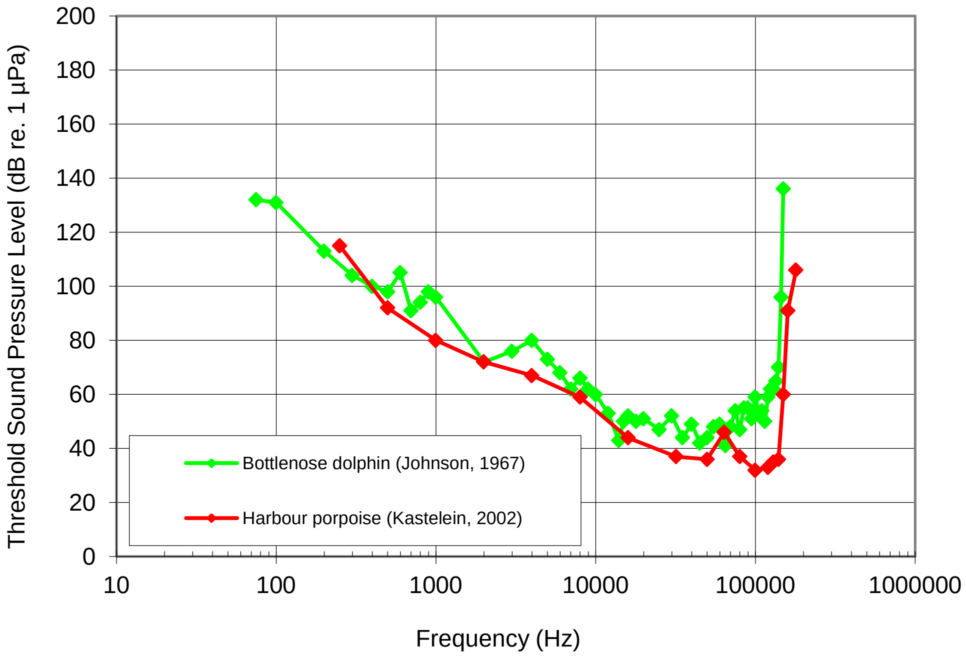

Figure 3-2 Comparison of hearing thresholds for species of marine mammal

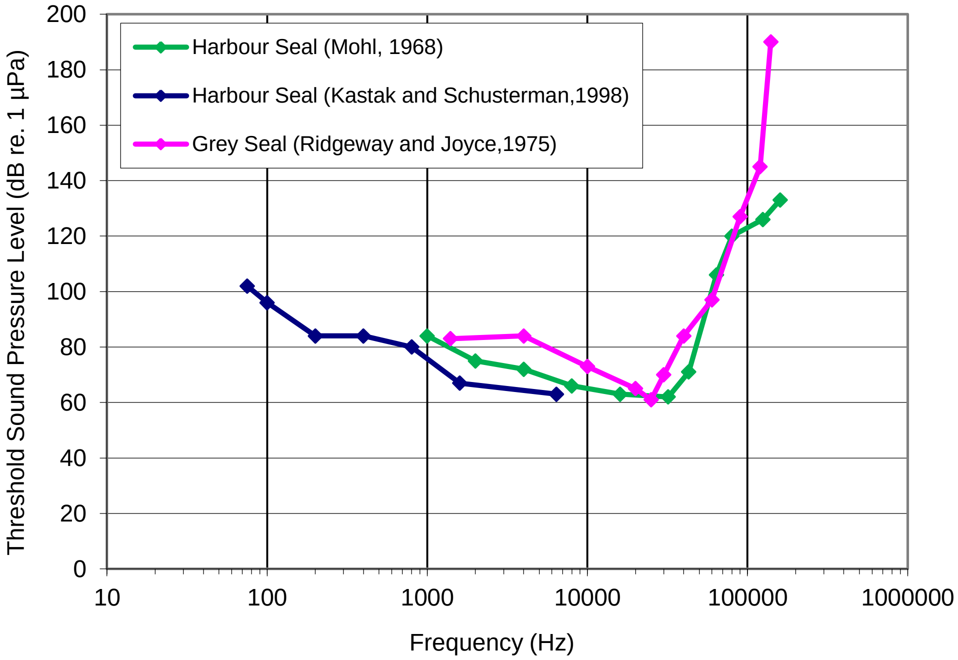

Figure 3-3 Comparison of auditory threshold levels of various species of seal

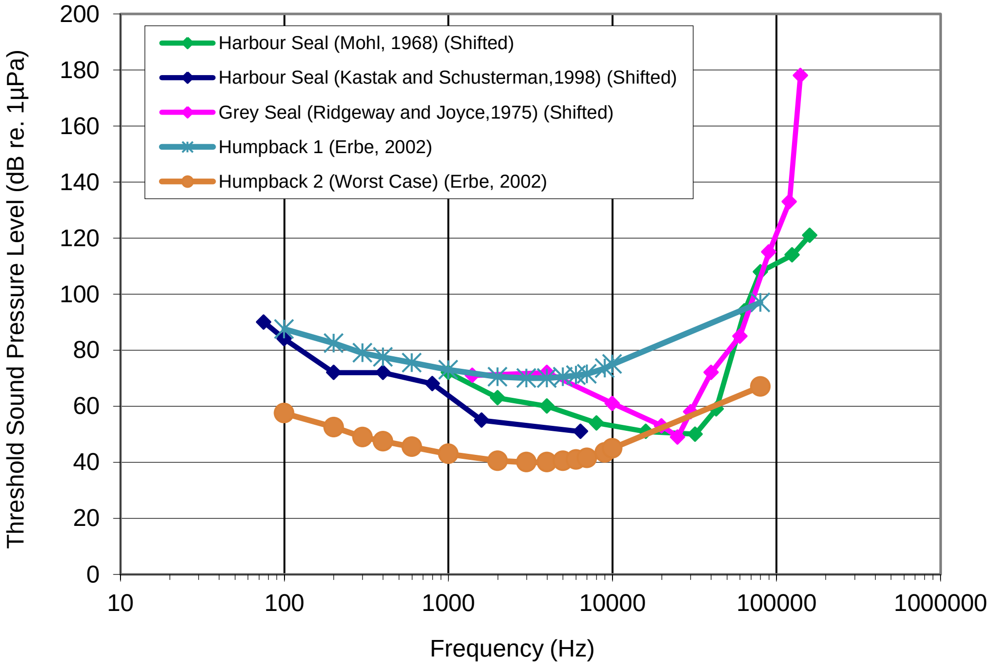

Figure 3-4 The audiograms for Humpback Whale, presented in Erbe (2002), presented with the shifted seal audiograms used for the calculations in this study

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 a selected position at the NNG site and the cumulative effects to include additional piling from other nearby wind farm construction sites.

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 3.3.0) 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 NNG 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
F1 – Seagreen (Firth of Forth) Phase 1	56.6718; -1.9314
F4 – Inch Cape	56.4583; -2.2579
F5 – NNG	56.3139; -2.2803
F6 – NNG	56.2461; -2.3040

4.3 Modelling scenarios

Two scenarios were modelled for at two positions in the NNG wind farm site. This includes two scenarios involving jacket structures: the most likely being a drill and drive operation and the worst case being impact piling. These scenarios are outlined in Table 4-1a and 4-1b below.

	Total piling duration	% of maximum hammer capacity
Ramp-up details (max. 1200 kJ)	20 minutes	20%
	180 minutes	83%

Table 4-1a Summary of the most likely drill-drive scenario, 2.5 m diameter pile

	Total piling duration	% of maximum hammer capacity
Ramp-up details (max. 1635 kJ)	114 minutes	20%
	85 minutes	57%
	17 minutes	85%

Table 4-1b Summary of the worst case fully driven scenario, 3.5 m diameter pile

There are four piles installed consecutively in each of these scenarios, although there is a delay between the installation of each pile to allow the piling rig to move.

The following scenario was modelled for Inch Cape for the purposes of the cumulative assessment:

	Total piling duration	% of maximum hammer capacity
Ramp-up details (max. 1200 kJ)	27 minutes	20%
	27 minutes	40%
	27 minutes	60%
	45 minutes	80%
	54 minutes	100%

Table 4-1c Summary of the Inch Cape scenario, 2.438 m diameter pile

The following scenario was modelled for Seagreen Phase 1 for the purposes of the cumulative assessment:

	Total piling duration	**% of maximum hammer capacity**
Ramp-up details (max. 1800 kJ)	15 minutes	20%
	15 minutes	40%
	15 minutes	60%
	25 minutes	80%
	50 minutes	95%

Table 4-1d Summary of the Seagreen Phase 1 scenario, 2 m diameter pile

4.4 Unweighted levels

Table 4-2 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 metres at maximum blow energy, and that physical injury is likely to occur out to less than 50 metres or 60 metres.

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)	**Range to 220 dB re. 1 µPa (Physical injury)**
F5 NNG Drill-drive	< 10 m	< 50 m
F5 NNG Fully driven	< 10 m	< 60 m
F1 Seagreen Phase 1	< 10 m	< 50 m
F4 Inch Cape	< 10 m	< 50 m

Table 4-2 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.

The largest estimated ranges out to which hearing damage may occur are for humpback whale, with 130 dB_{ht} ranges of up to 690 m during the drill-drive scenario and 780 m during the fully driven scenario.

Tables 4-3 to 4-6 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 four impact piling scenarios.

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 34 km, 20 km for the harbour porpoise and 41 km for the humpback whale, for the fully driven NNG modelling scenario.

It should be noted that the minimum ranges presented below are for transects heading into deeper water, and in some cases, reach the coastline before the sound has attenuated to below 90 or 75 dB$_{ht}$. Hence why, for example all the minimum 75 dB$_{ht}$ ranges for the worst case scenario are calculated to be, for example, 19 km for NNG, as this is the minimum distance between the wind turbine position and the coastline.

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.

NNG Drill-drive	**Range to 90 dB$_{ht}$ (km)**			**Range to 75 dB$_{ht}$ (km)**		
	Max	**Min**	**Mean**	**Max**	**Min**	**Mean**
Dab	3.8	3.7	3.7	20	16	19
Herring	27	19	25	65	19	47
Salmon	1.5	1.4	1.5	9.2	8.8	9.0
Sand Lance	0.2	0.2	0.2	1.4	1.3	1.3
Trout	0.3	0.2	0.2	1.8	1.8	1.8
Bottlenose Dolphin	12	12	12	34	19	31
Harbour Porpoise	18	16	18	50	19	40
Harbour Seal	15	14	15	46	19	37
Humpback Whale	38	19	33	82	19	54

Table 4-3 Summary of dB$_{ht}$ ranges for the NNG drill-drive scenario

NNG Fully driven	**Range to 90 dB$_{ht}$ (km)**			**Range to 75 dB$_{ht}$ (km)**		
	Max	**Min**	**Mean**	**Max**	**Min**	**Mean**
Dab	7.0	6.9	7.0	30	19	28
Herring	34	19	30	76	19	52
Salmon	2.6	2.6	2.6	14	13	14
Sand Lance	0.2	0.2	0.2	2.0	2.0	2.0
Trout	0.4	0.4	0.4	2.7	2.6	2.7
Bottlenose Dolphin	14	13	13	37	19	33
Harbour Porpoise	20	18	19	53	19	42
Harbour Seal	17	15	16	58	19	39
Humpback Whale	41	19	35	85	19	56

Table 4-4 Summary of dB$_{ht}$ ranges for the NNG fully driven scenario

Seagreen	**Range to 90 dB$_{ht}$ (km)**			**Range to 75 dB$_{ht}$ (km)**		
	Max	**Min**	**Mean**	**Max**	**Min**	**Mean**
Dab	3.3	3.2	3.3	19	16	18

Herring	33	26	28	81	27	56
Salmon	1.5	1.5	1.5	9.4	8.8	9.1
Sand Lance	0.2	0.2	0.2	1.6	1.6	1.6
Trout	0.3	0.3	0.3	2.0	2.0	2.0
Bottlenose Dolphin	15	14	14	45	27	37
Harbour Porpoise	23	20	22	63	27	48
Harbour Seal	20	17	18	61	27	45
Humpback Whale	52	27	40	110	27	69

Table 4-5 Summary of dB$_{ht}$ ranges for the Seagreen Phase 1 scenario

Inch Cape	**Range to 90 dB$_{ht}$ (km)**			**Range to 75 dB$_{ht}$ (km)**		
	Max	**Min**	**Mean**	**Max**	**Min**	**Mean**
Dab	4.0	3.8	3.9	21	16	19
Herring	28	20	25	70	21	48
Salmon	16	16	16	96	85	93
Sand Lance	0.2	0.2	0.2	1.5	1.4	1.5
Trout	0.3	0.3	0.3	20	19	19
Bottlenose Dolphin	13	11	13	36	21	31
Harbour Porpoise	20	16	19	51	21	41
Harbour Seal	16	13	15	46	21	37
Humpback Whale	39	21	33	89	21	56

Table 4-6 Summary of dB$_{ht}$ ranges for the Inch Cape scenario

These results are presented graphically as contour plots in Figures 4-1 to 4-54, with each group of images showing the 90 and 75 dB$_{ht}$ impact ranges for the scenarios for each marine species of interest.

F5 – Most likely (2 piles) (2.5 m 996 kJ)

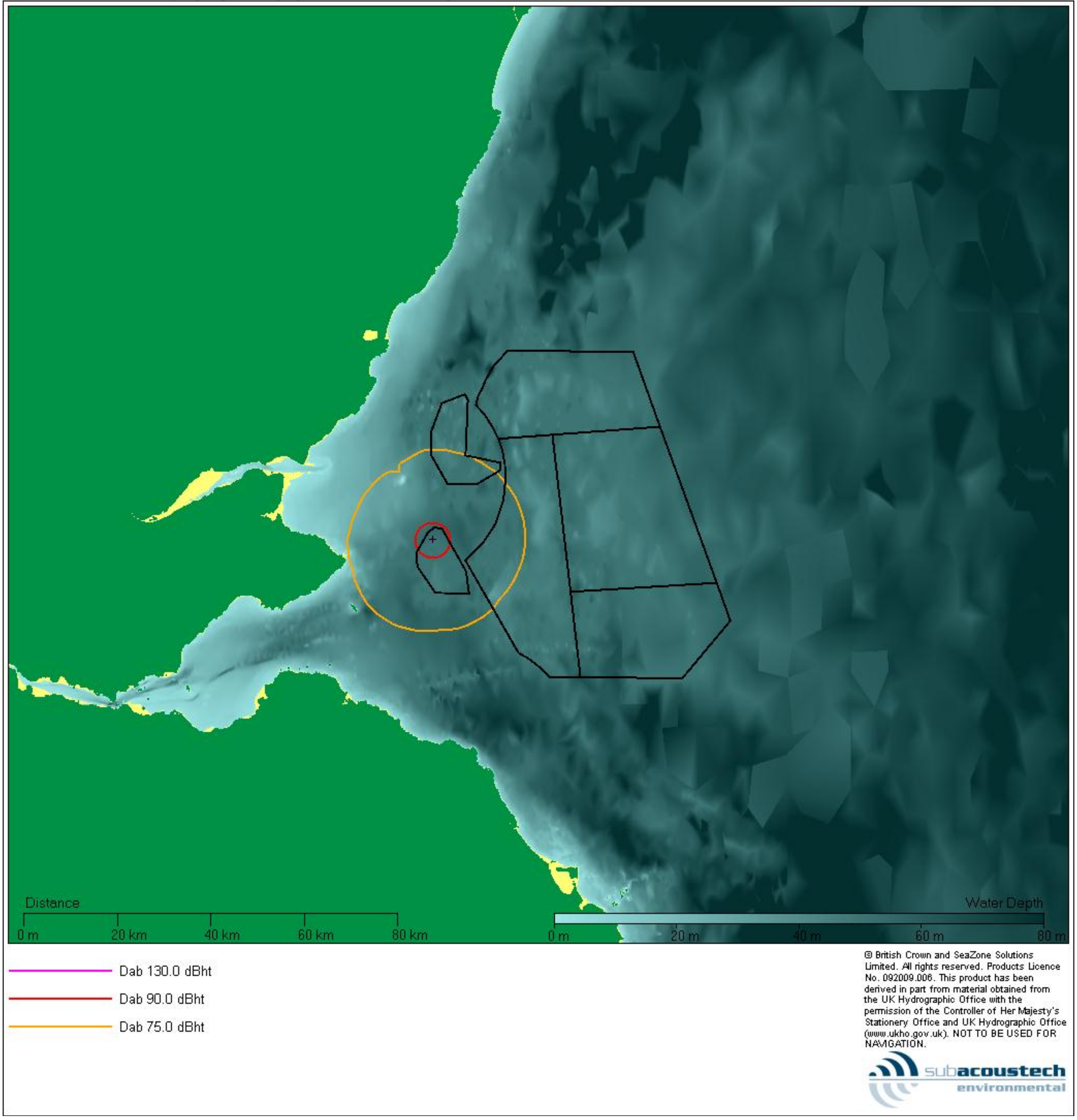

Figure 4-1 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the installation of a jacket pile at NNG

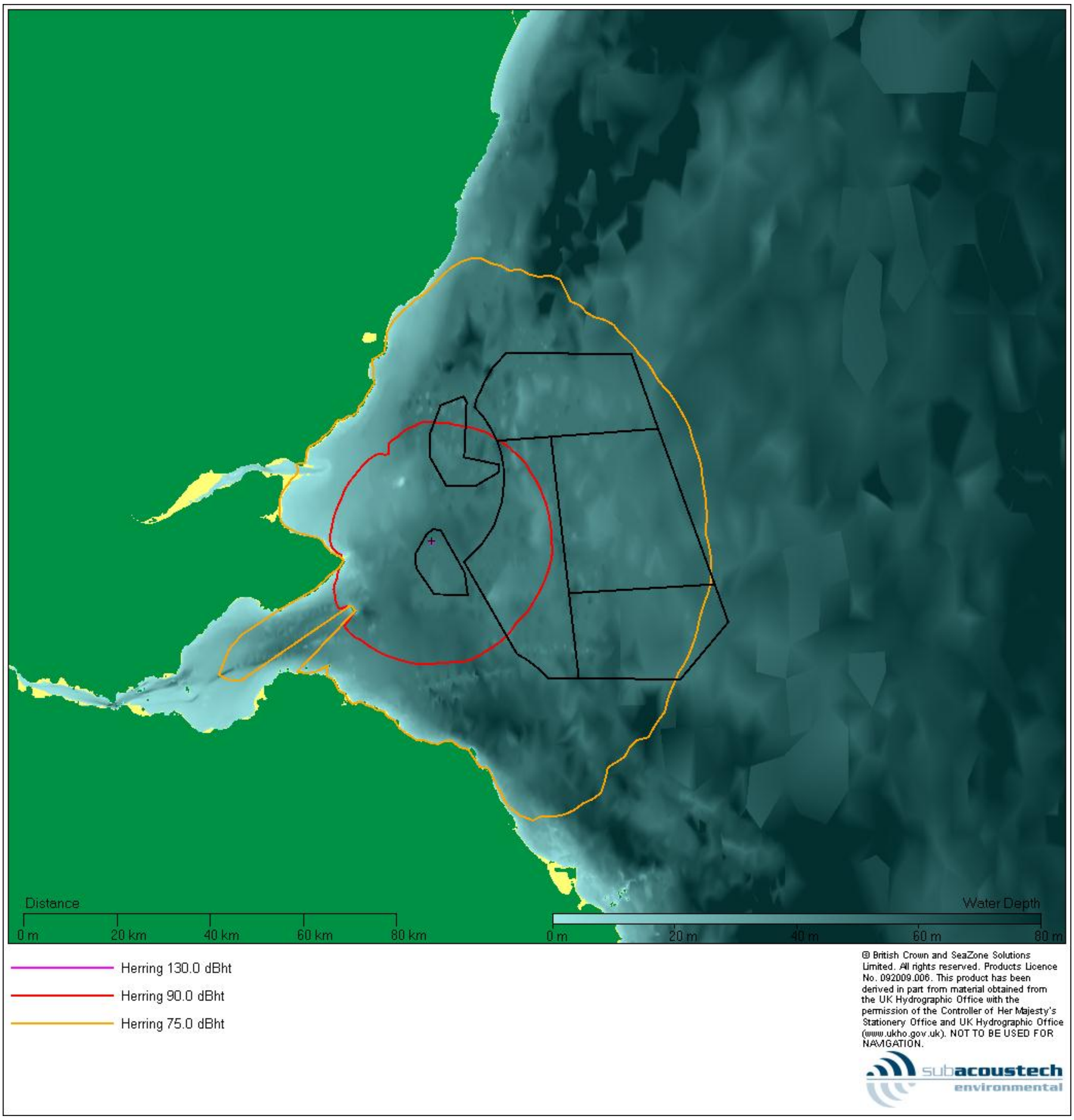

Figure 4-2 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the installation of a jacket pile at NNG

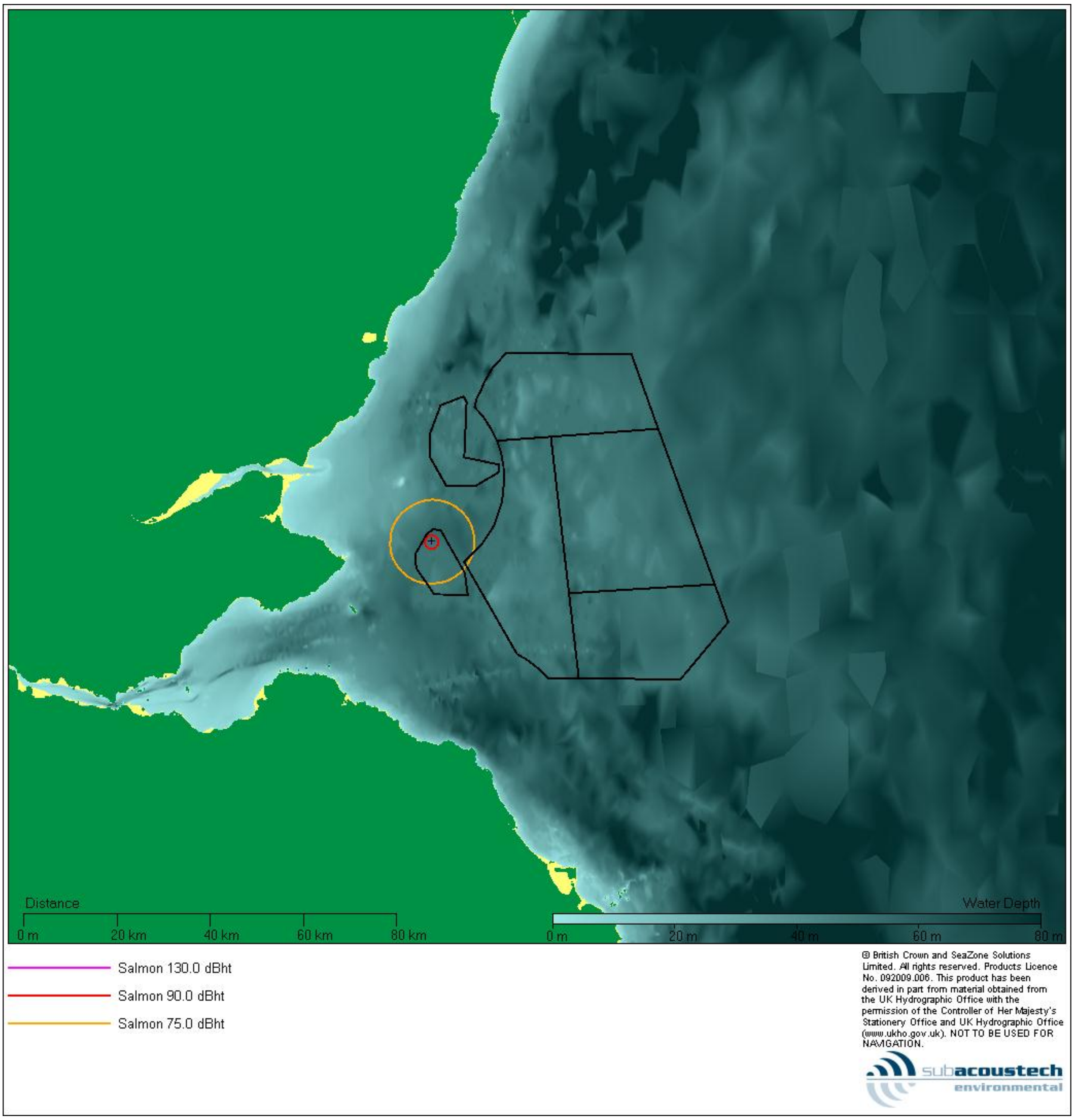

Figure 4-3 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the installation of a jacket pile at NNG

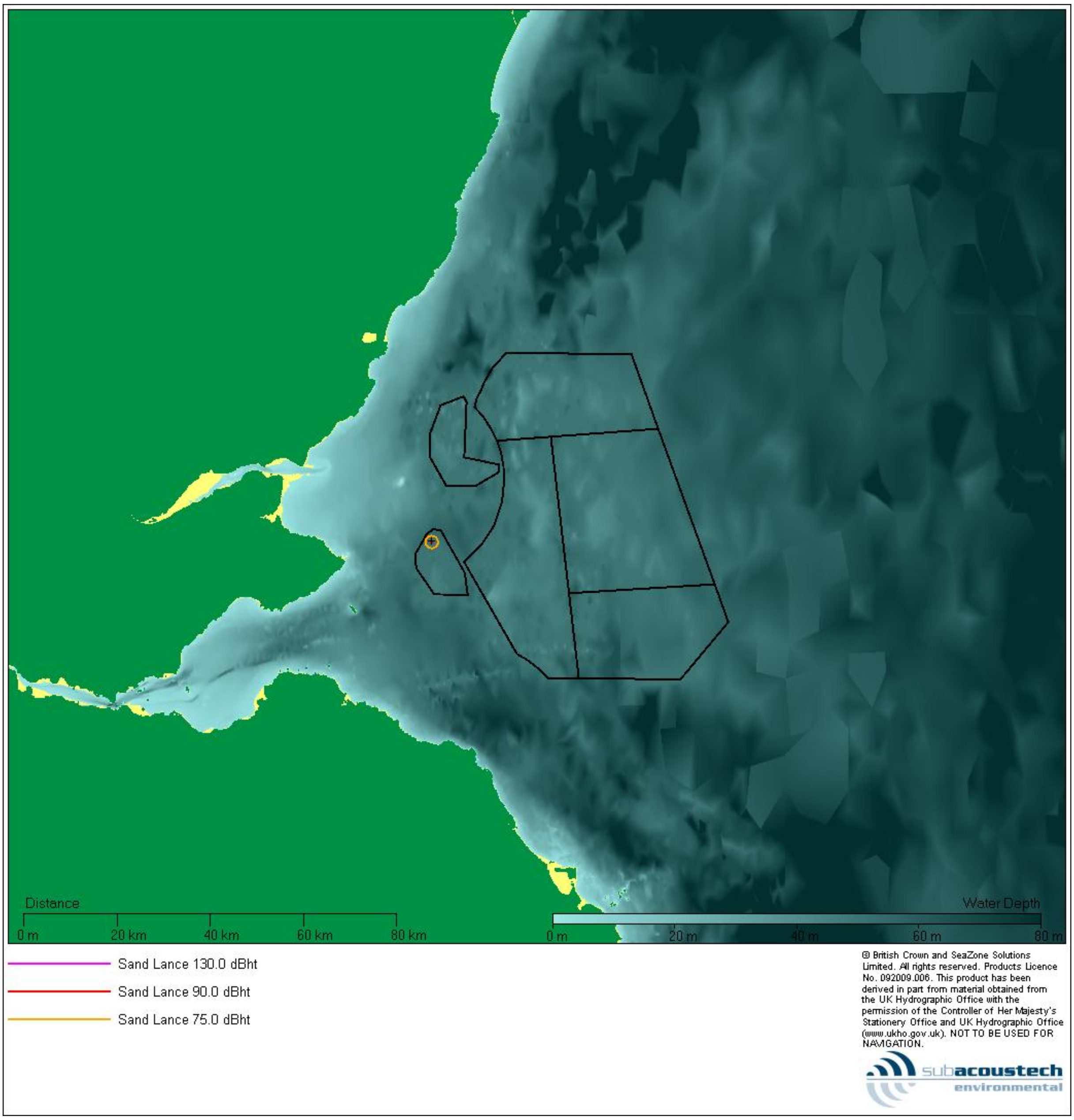

Figure 4-4 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the installation of a jacket pile at NNG

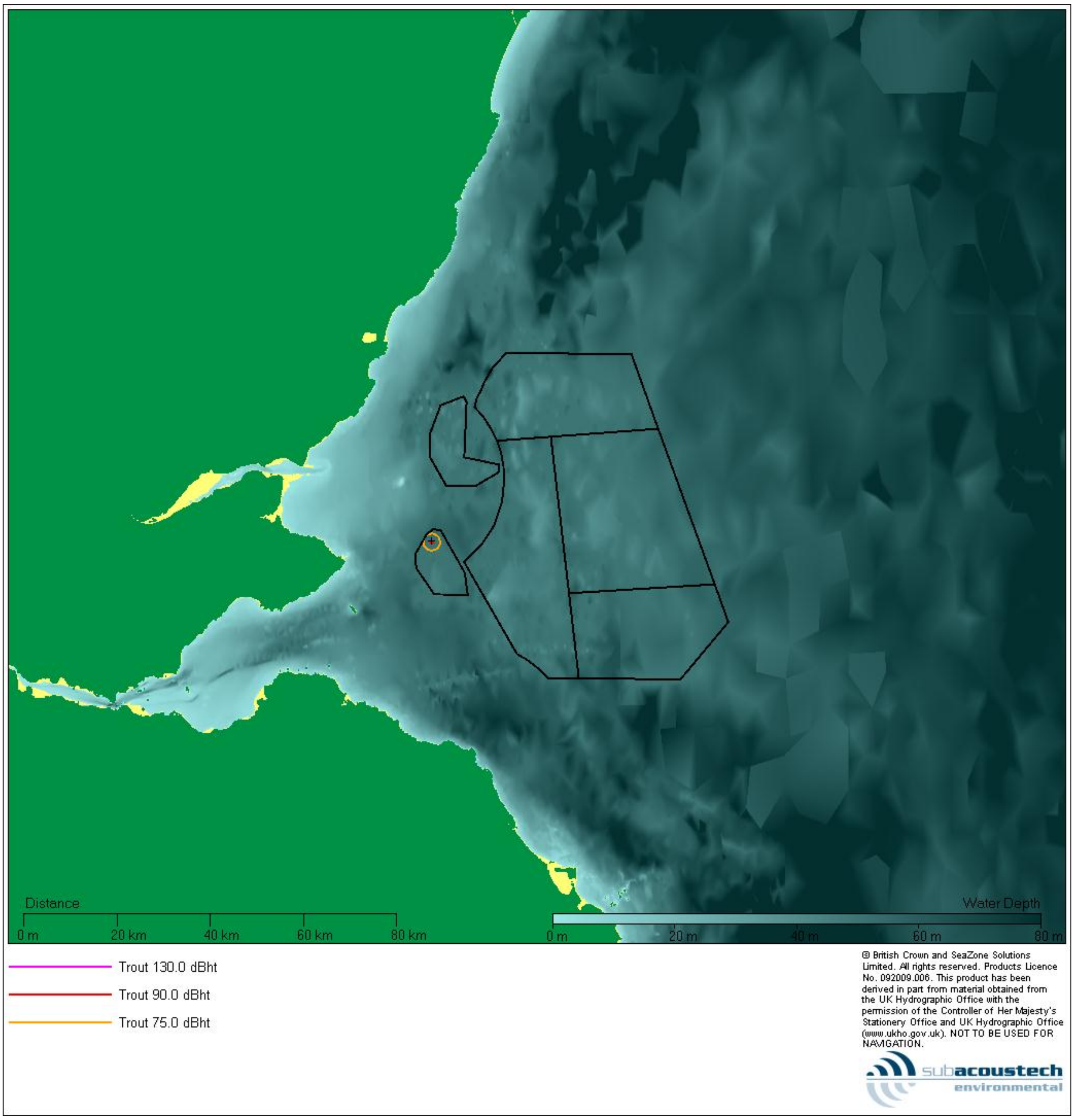

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Figure 4-5 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the installation of a jacket pile at NNG

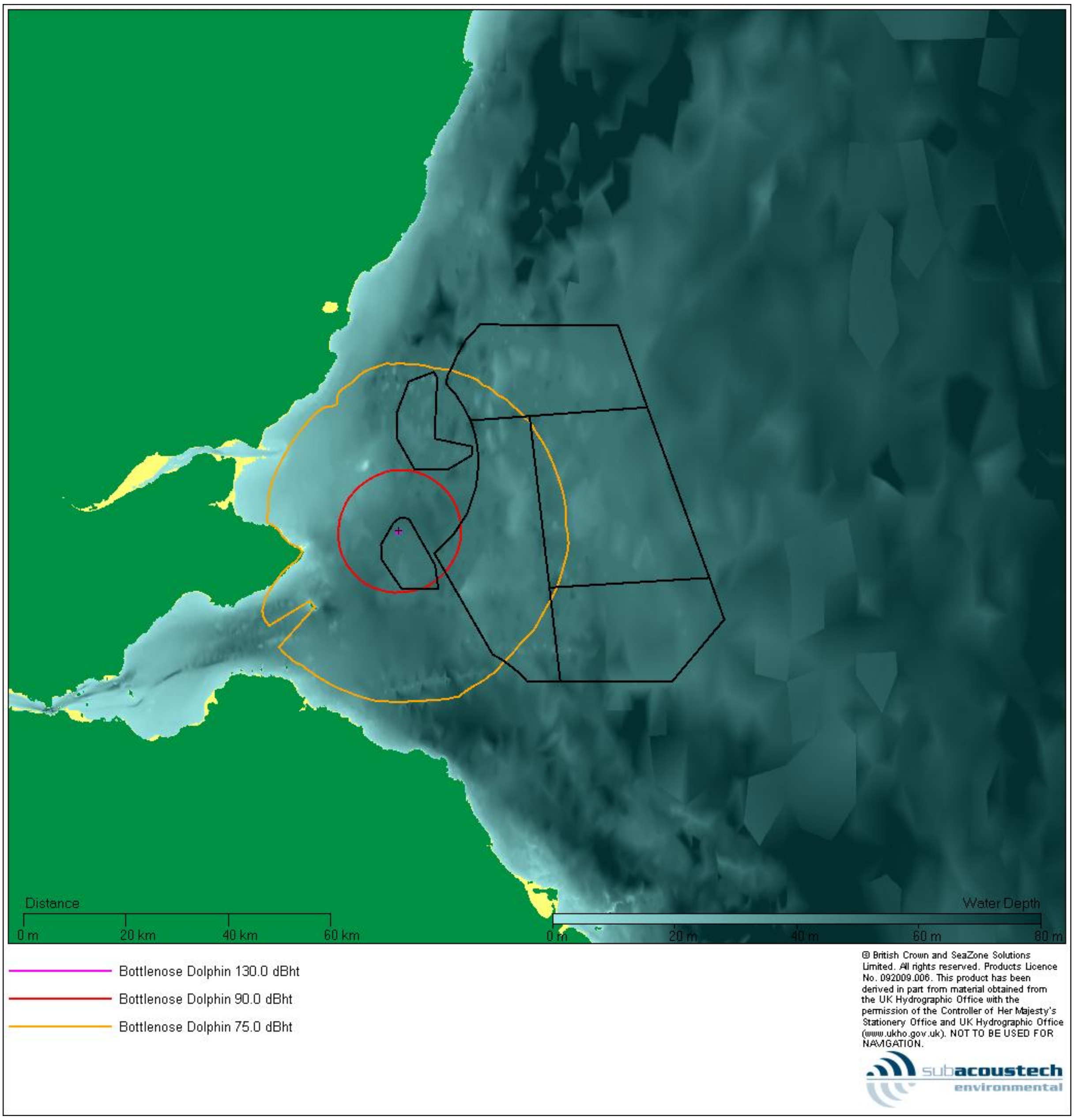

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Figure 4-6 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the installation of a jacket pile at NNG

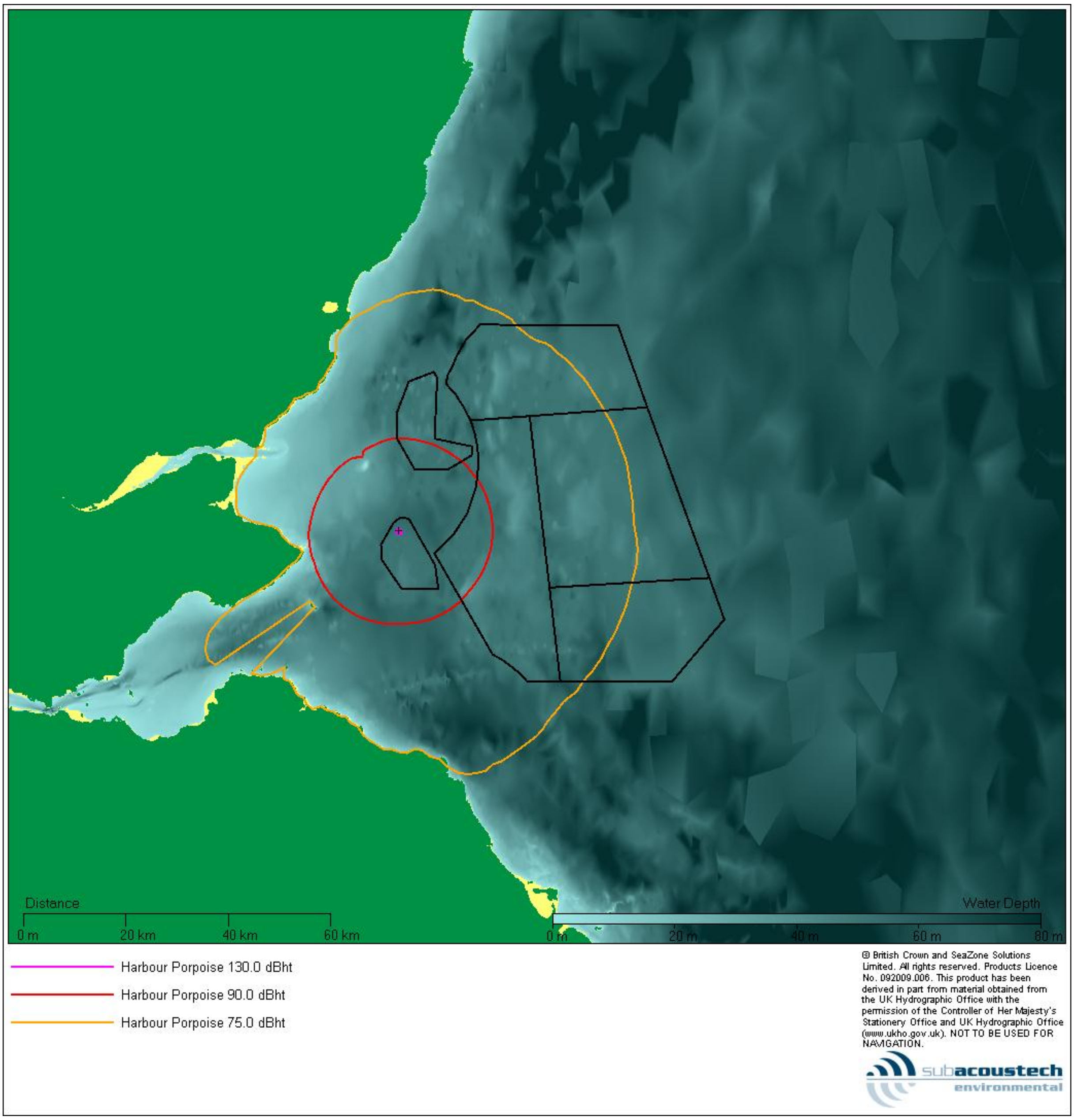

Figure 4-7 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the installation of a jacket pile at NNG

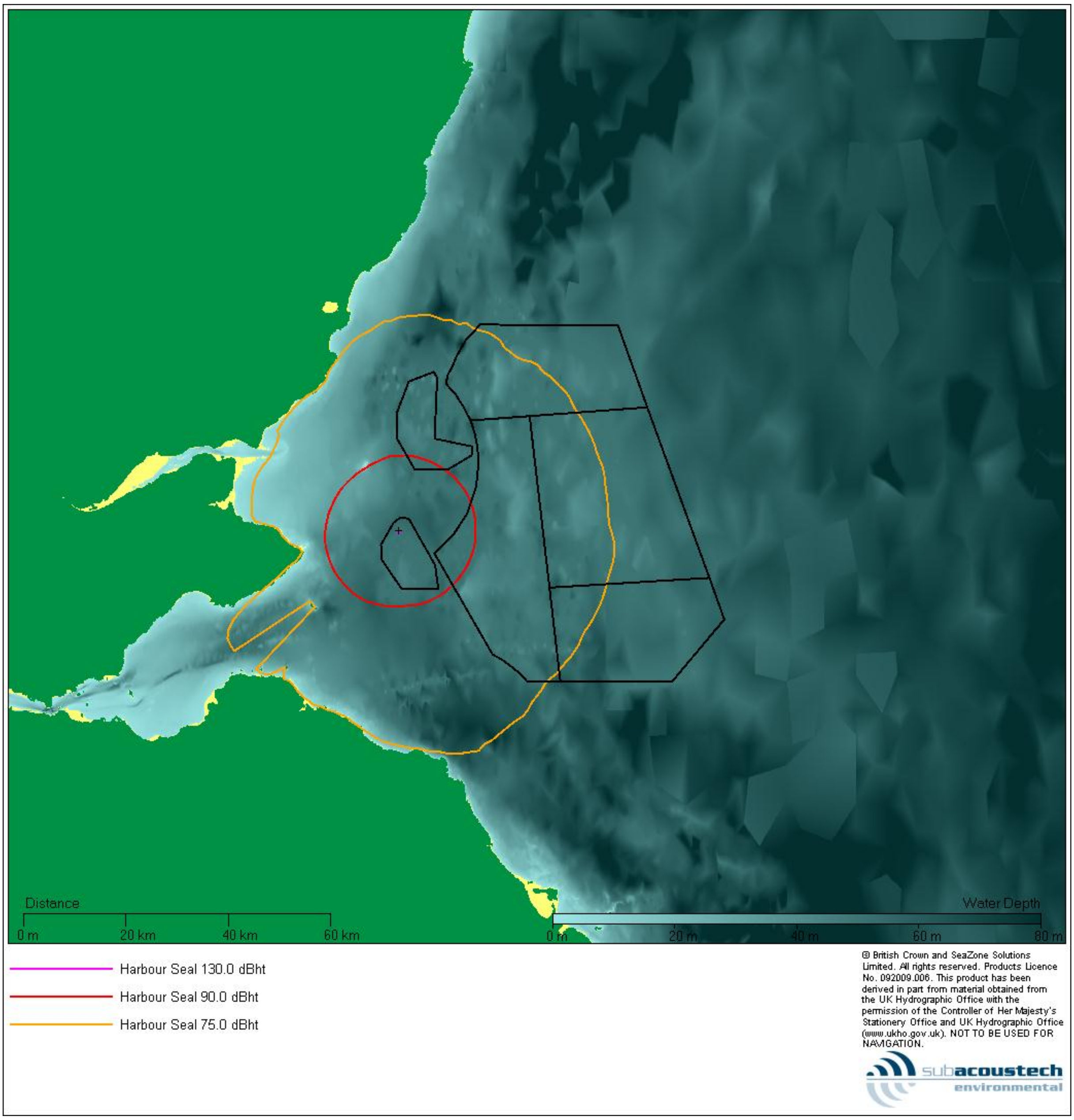

Figure 4-8 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the installation of a jacket pile at NNG

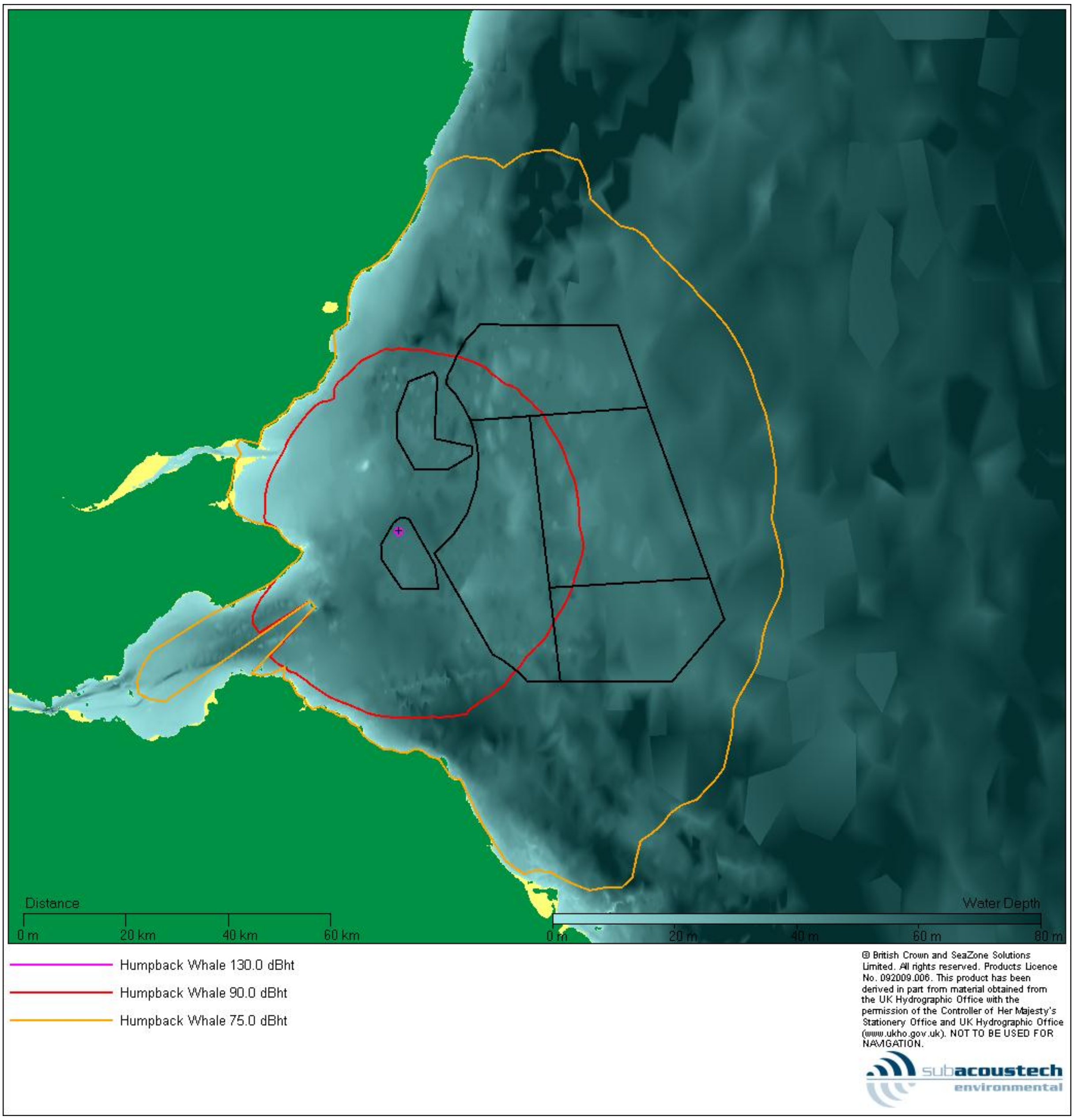

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Figure 4-9 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the installation of a jacket pile at NNG

F5 - Worst case (3.5 m 1390 kJ)

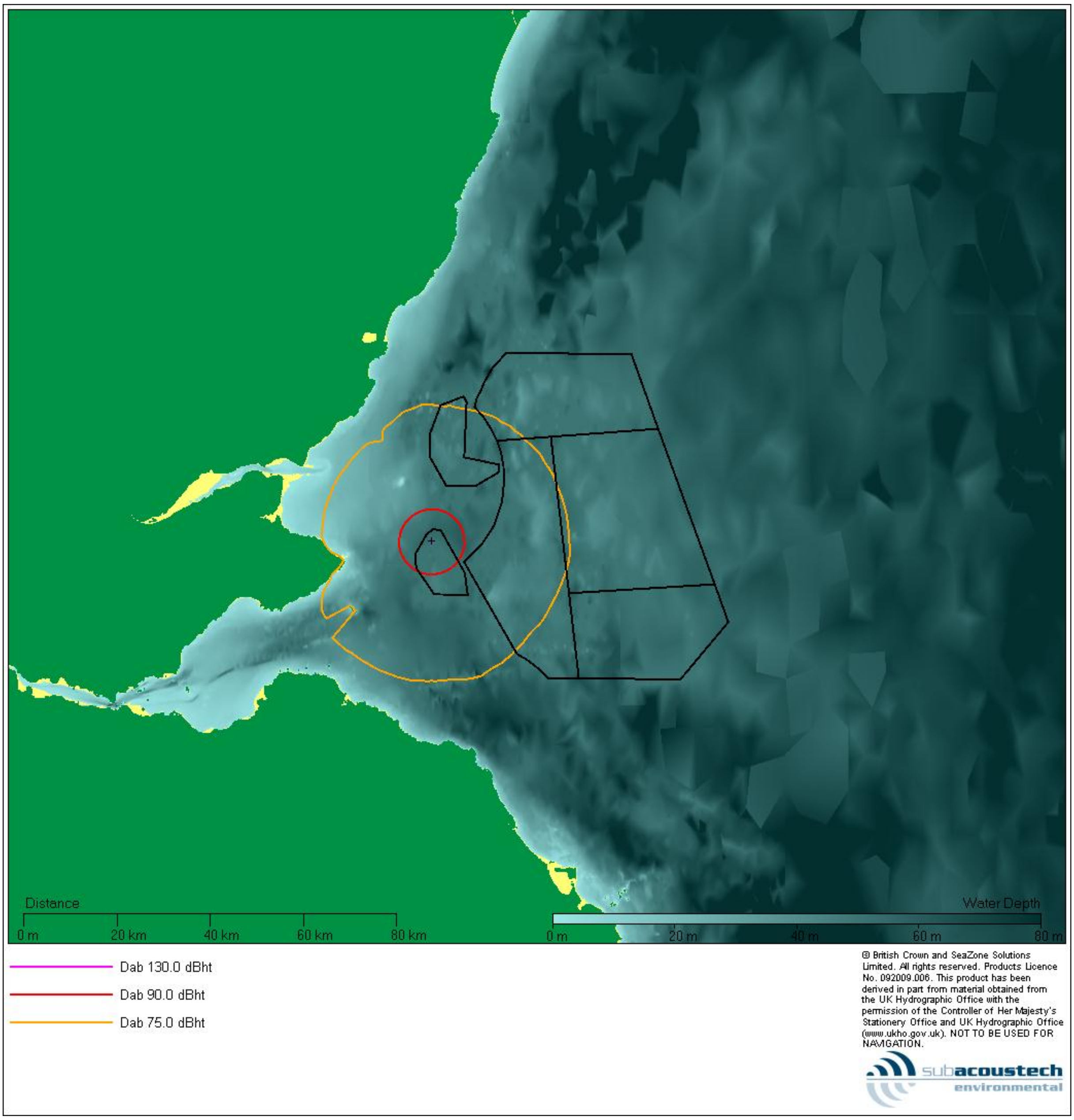

Figure 4-10 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the installation of a 3.5 m diameter pile at NNG

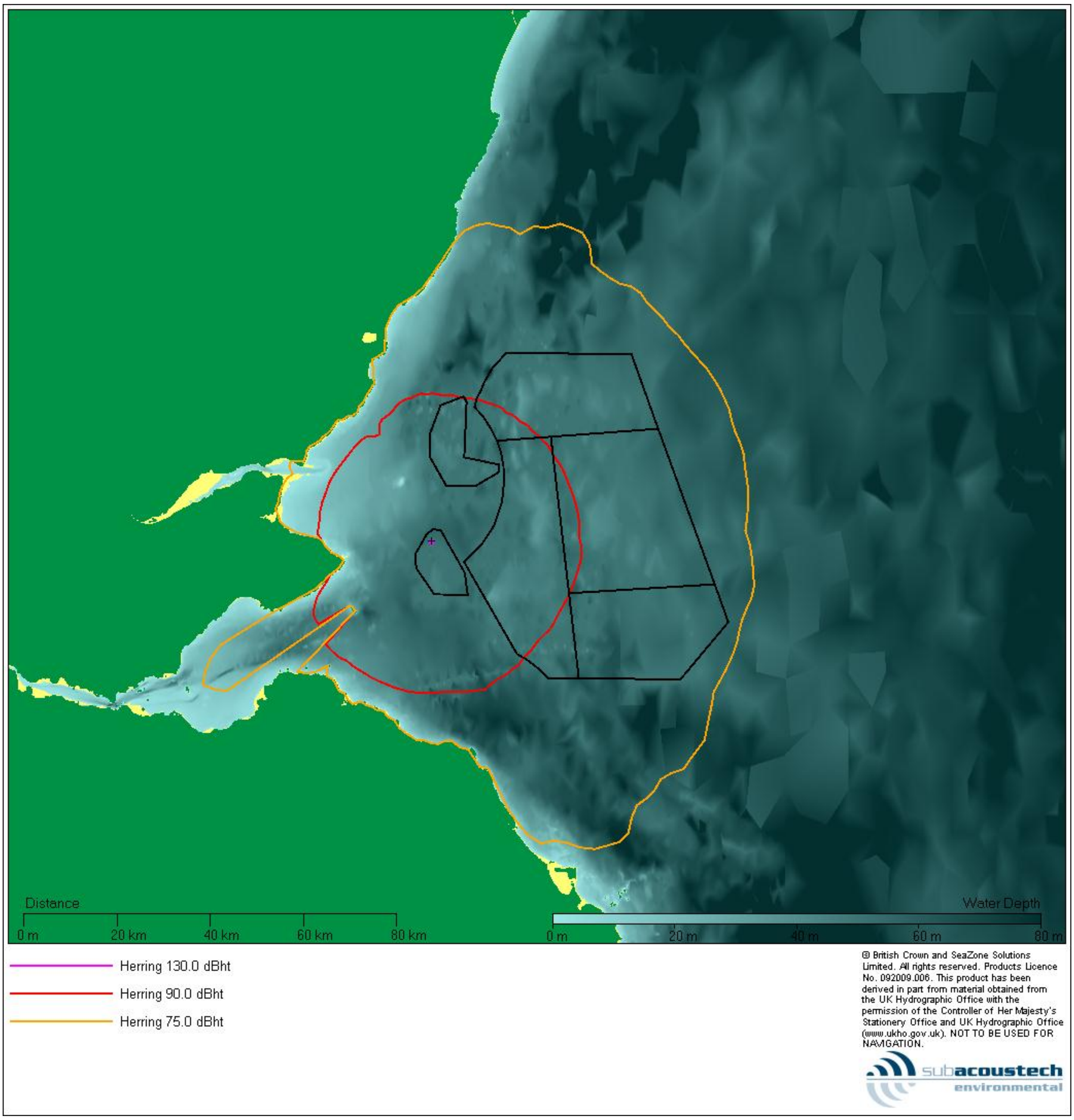

Figure 4-11 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the installation of a 3.5 m diameter pile at NNG

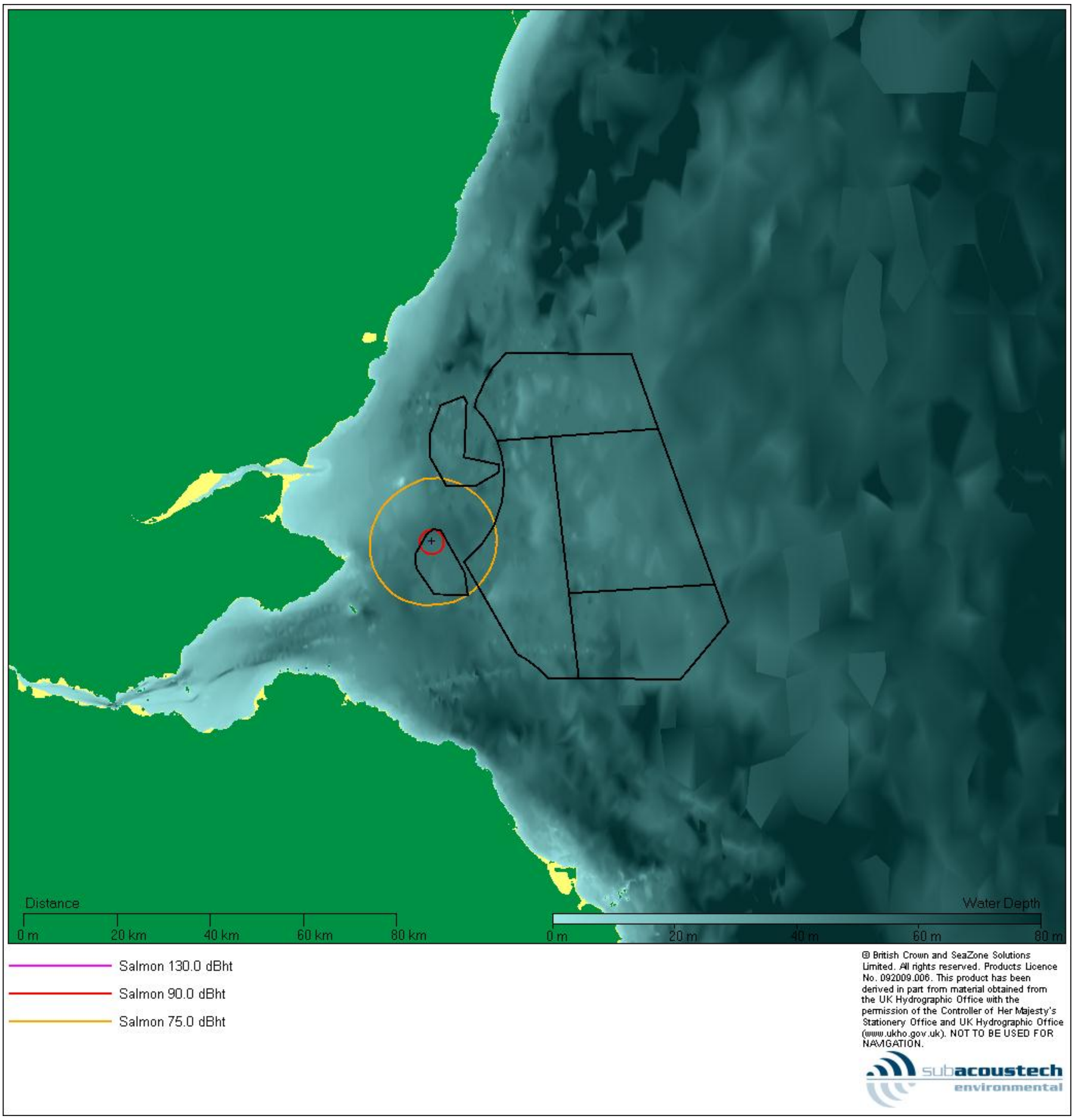

Figure 4-12 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the installation of a 3.5 m diameter pile at NNG

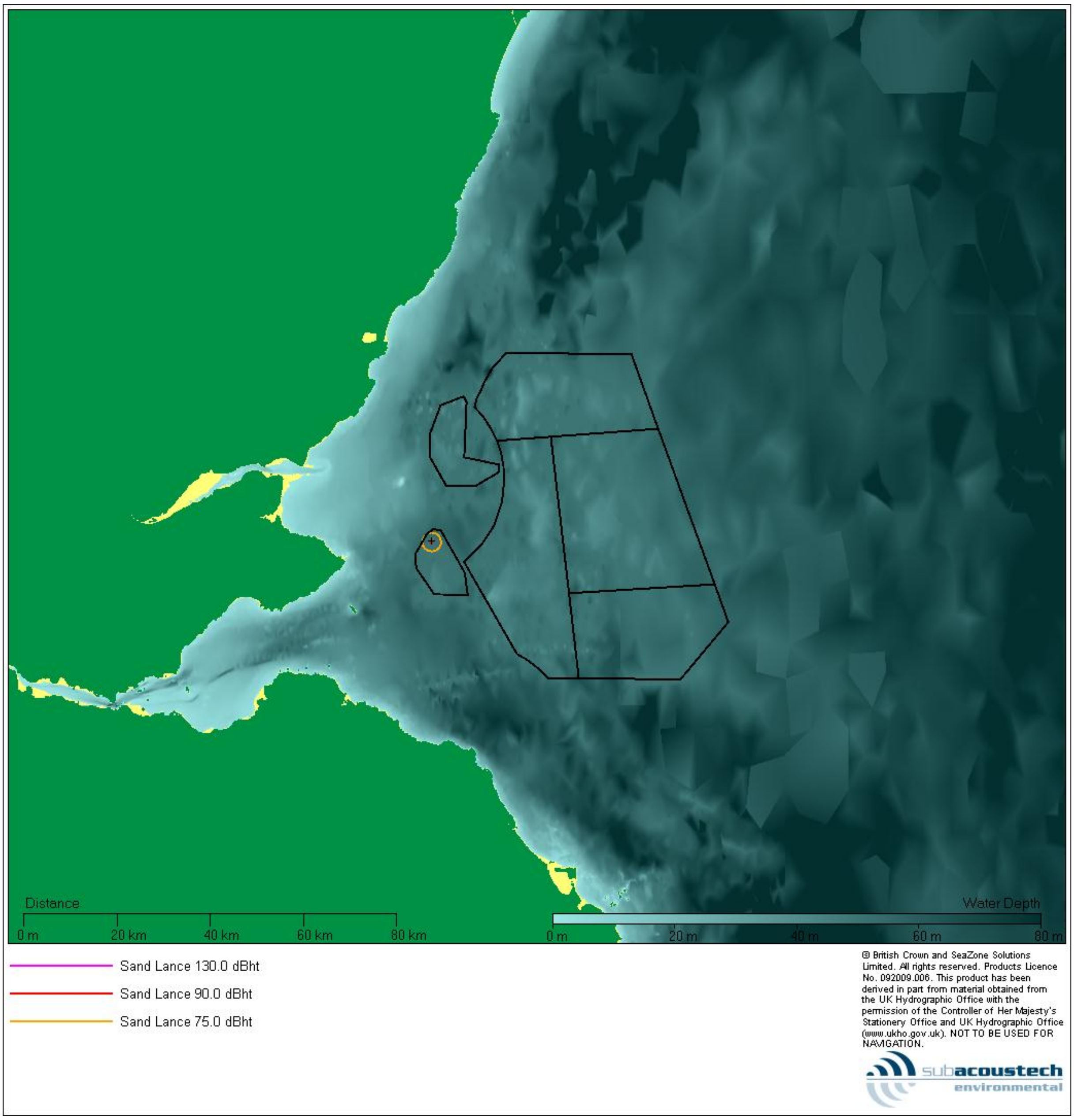

Figure 4-13 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the installation of a 3.5 m diameter pile at NNG

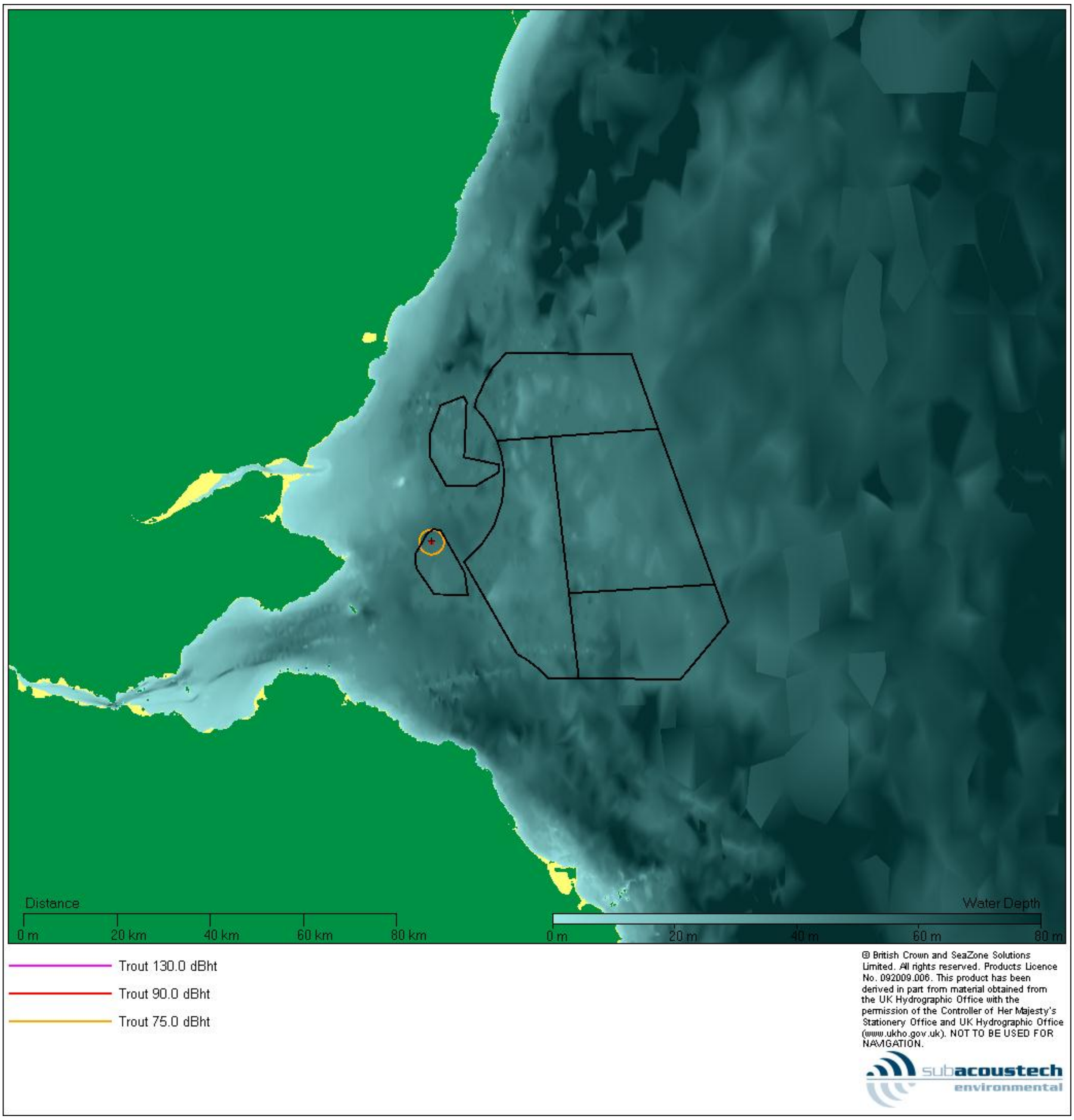

Figure 4-14 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the installation of a 3.5 m diameter pile at NNG

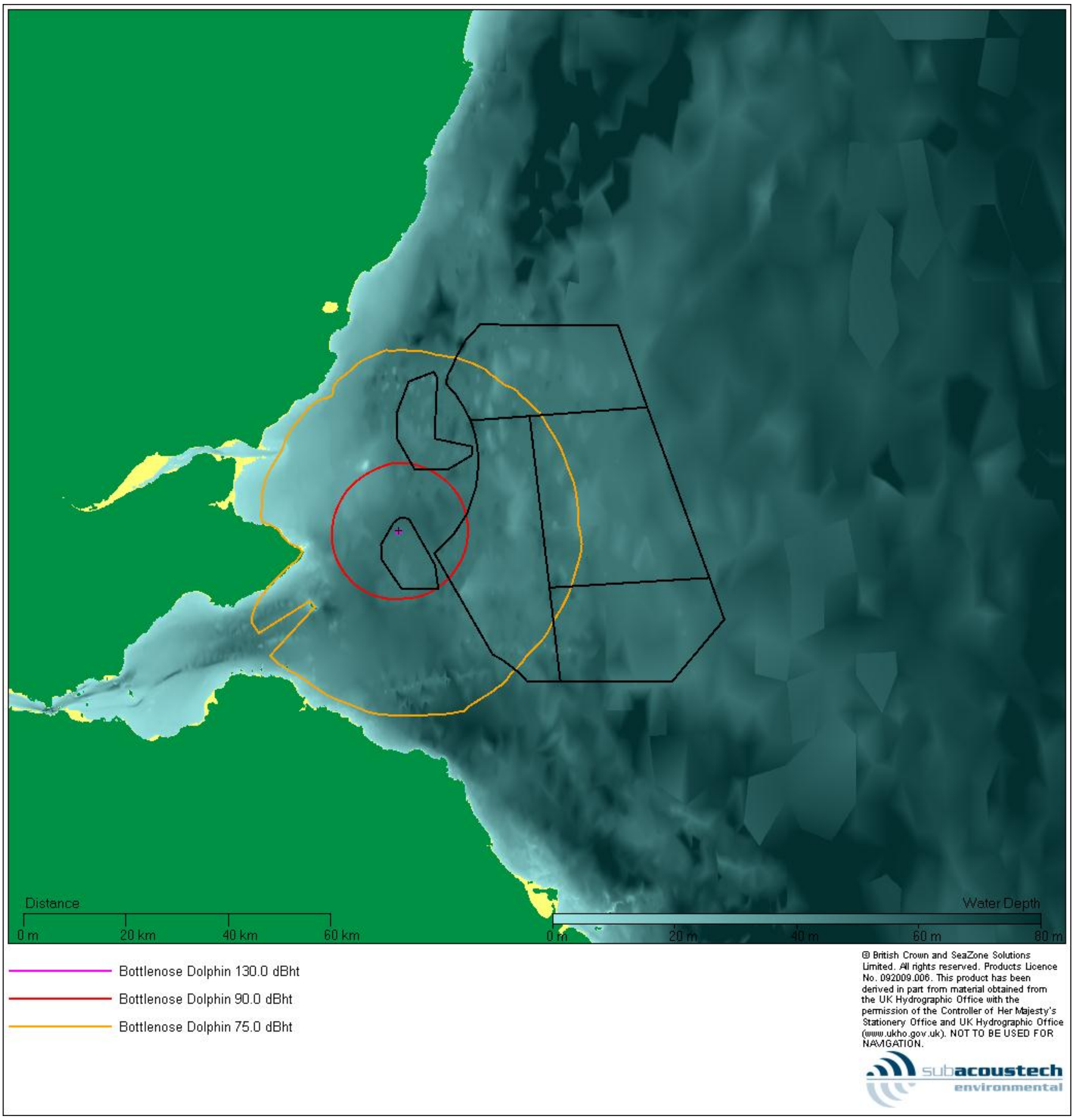

Figure 4-15 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the installation of a 3.5 m diameter pile at NNG

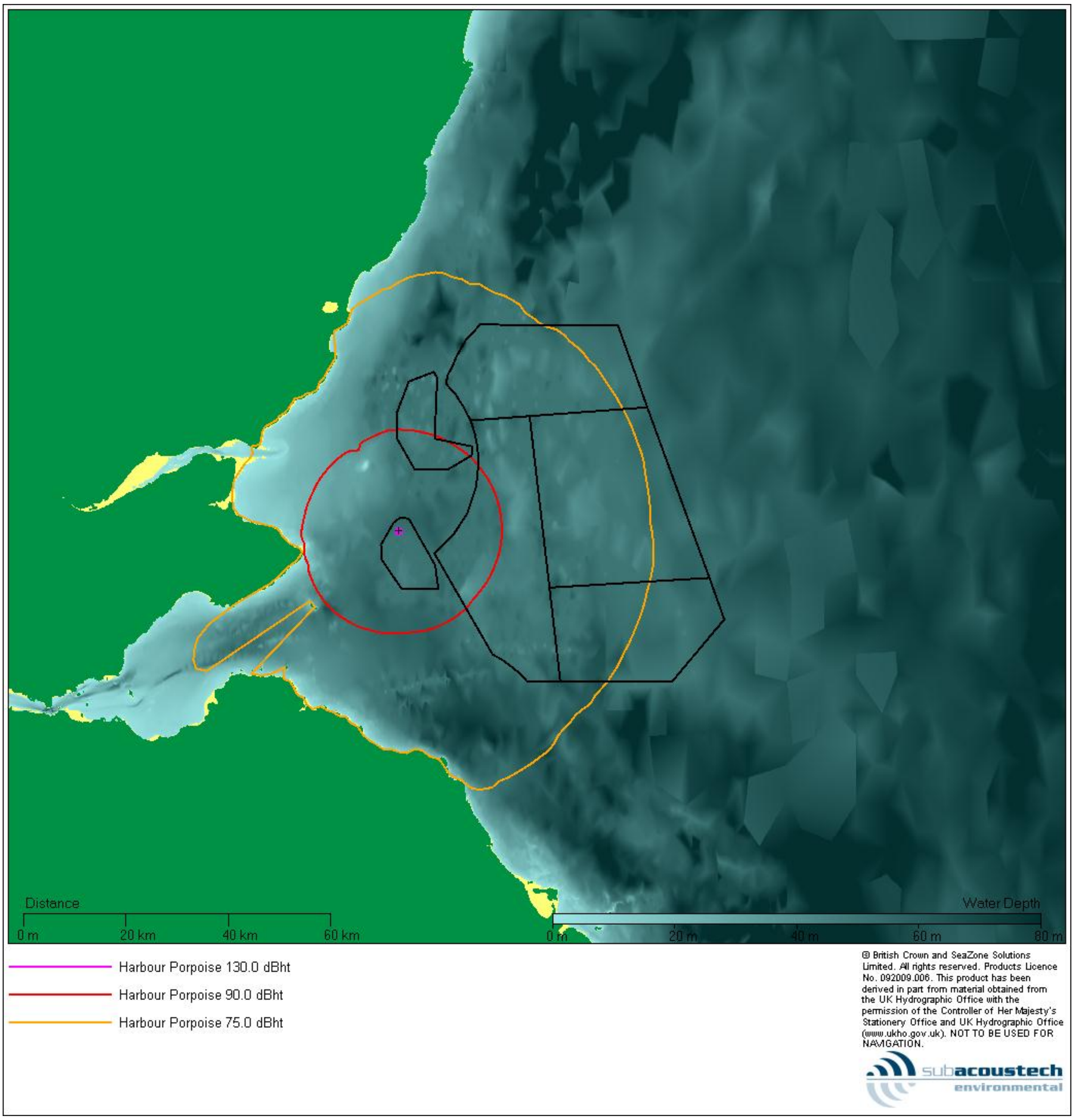

Figure 4-16 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the installation of a 3.5 m diameter pile at NNG

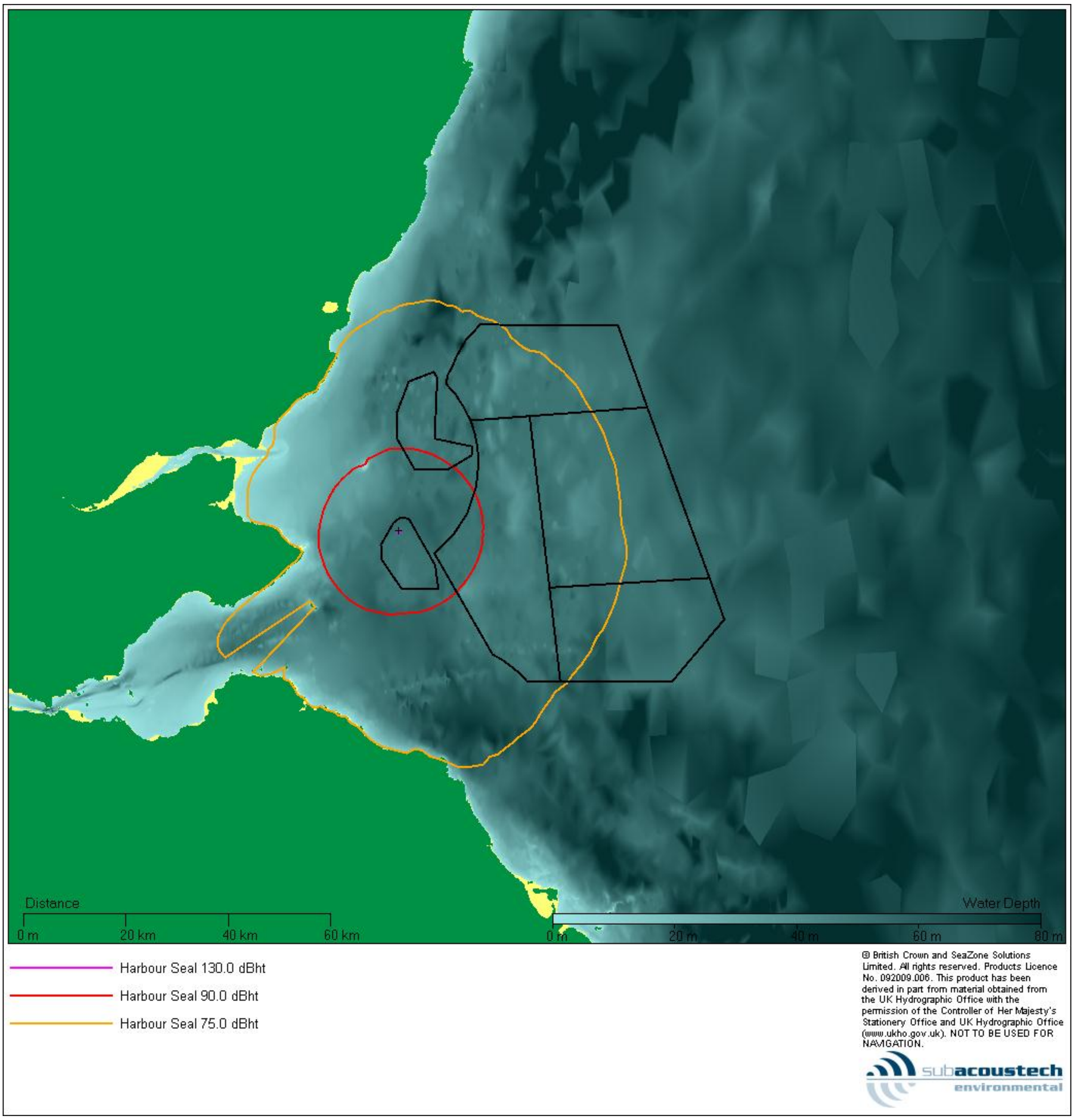

Figure 4-17 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the installation of a 3.5 m diameter pile at NNG

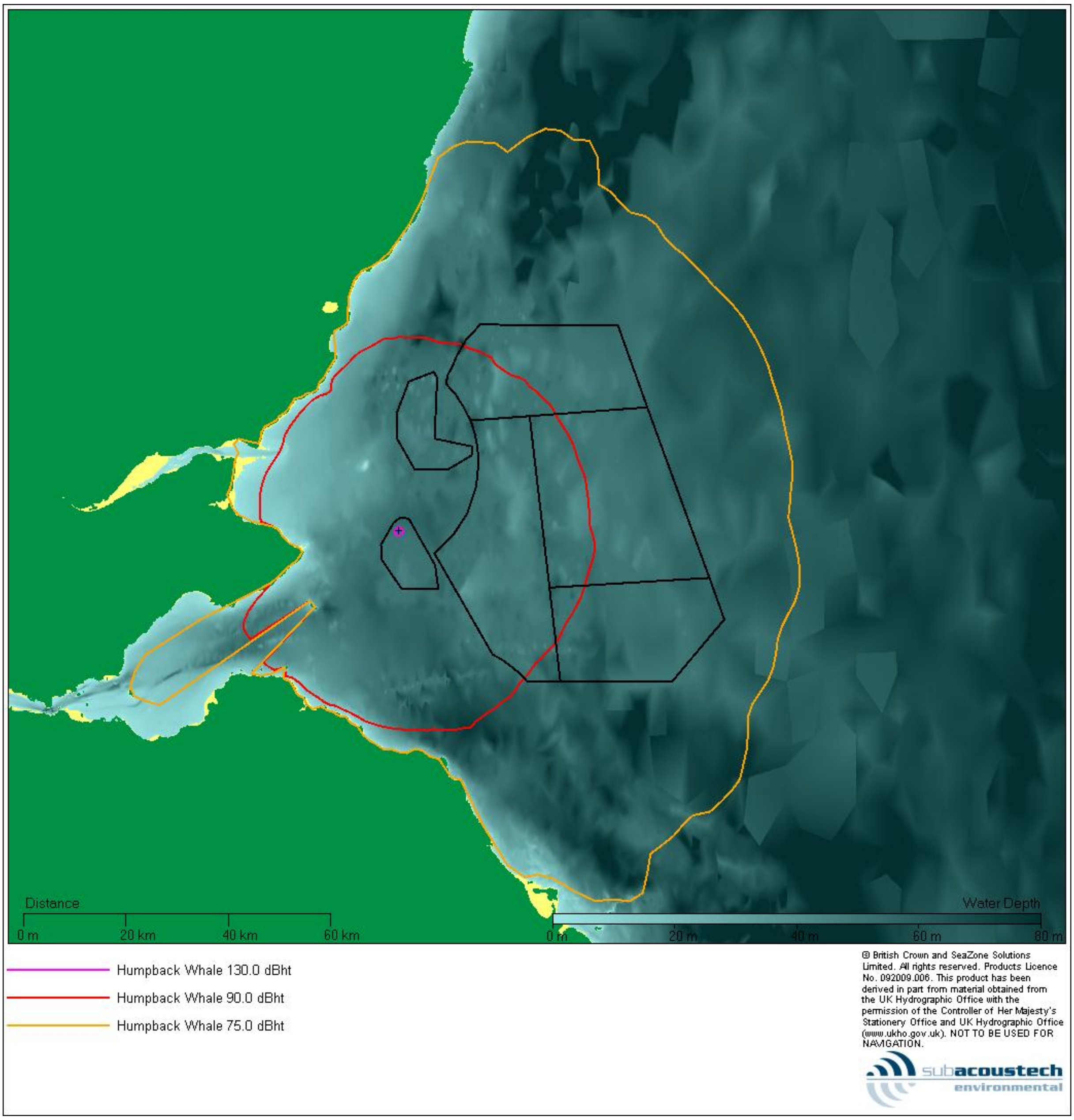

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Figure 4-18 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the installation of a 3.5 m diameter pile at NNG

F5 and F1 Most likely (simultaneous)

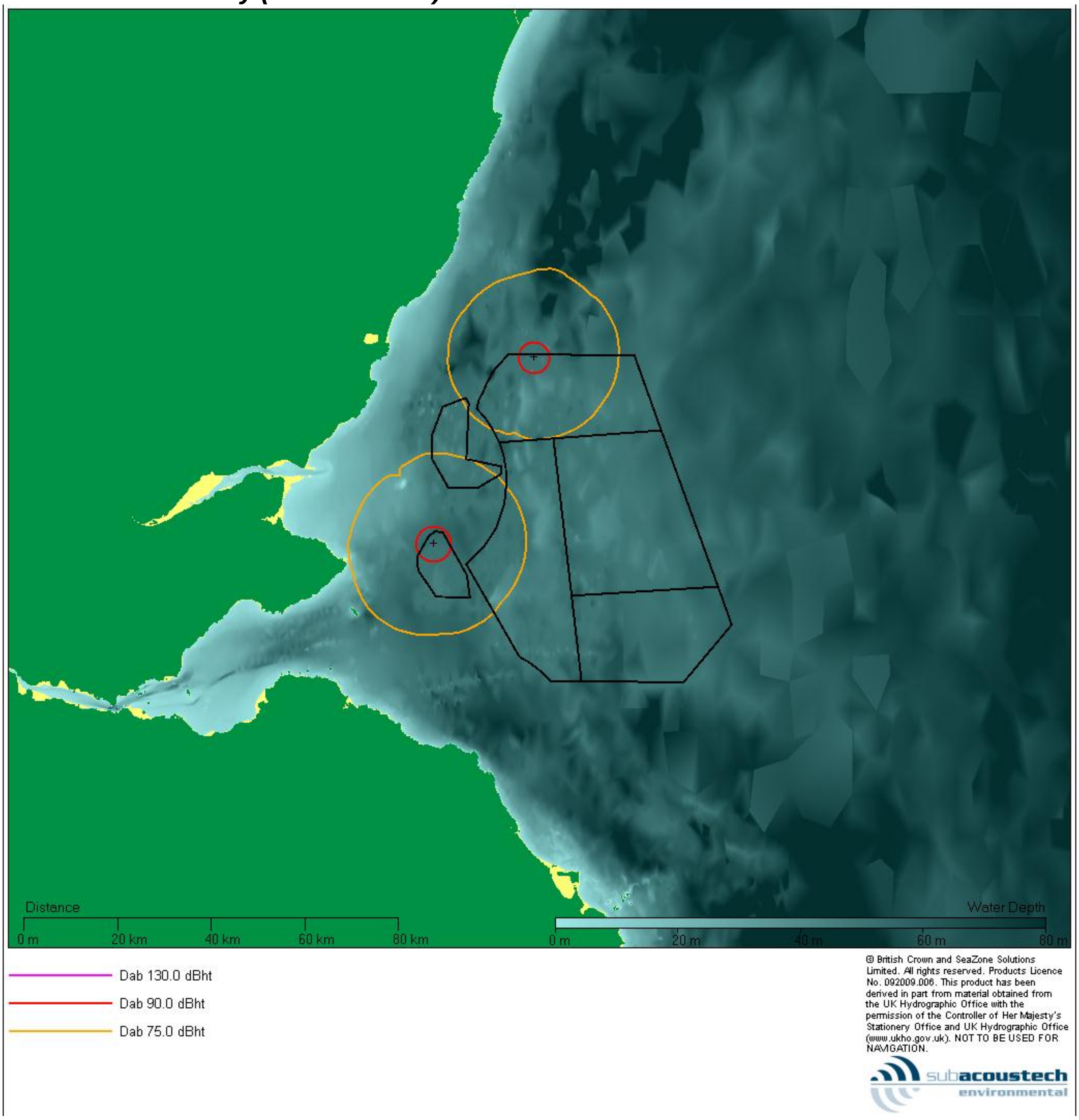

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Figure 4-19 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the installation of simultaneous piles at NNG and Seagreen

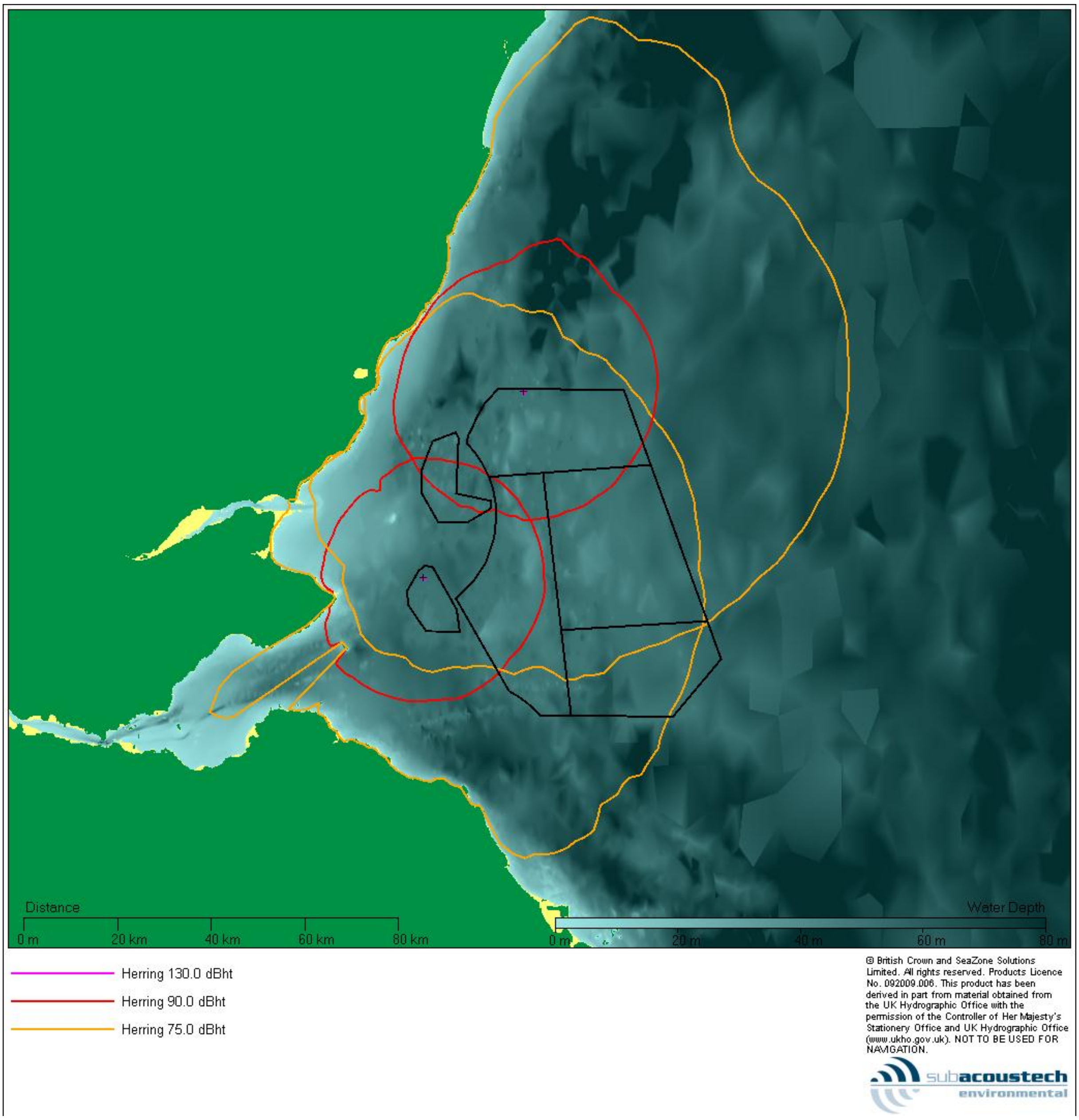

Figure 4-20 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the installation of simultaneous piles at NNG and Seagreen

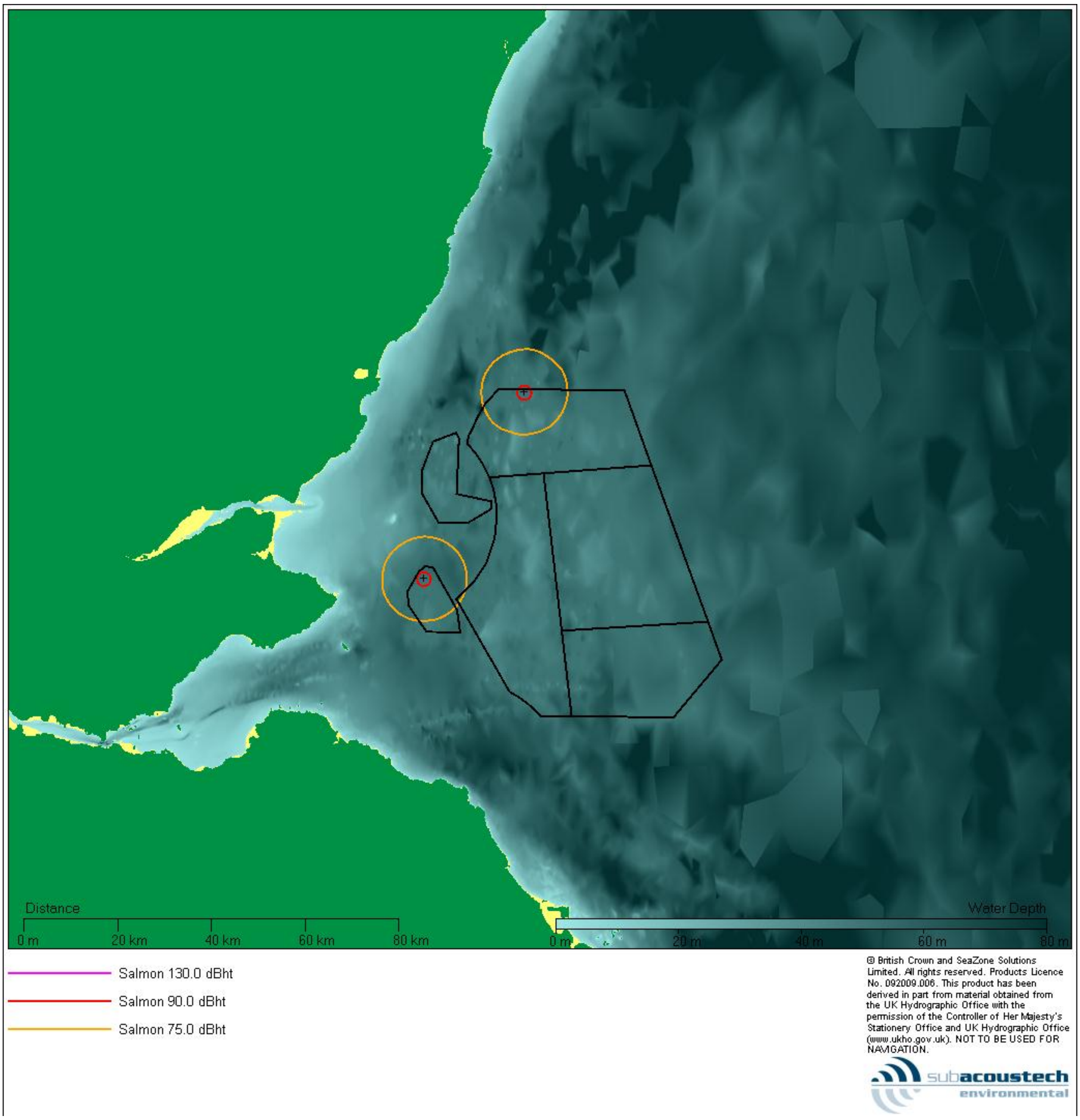

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Figure 4-21 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the installation of simultaneous piles at NNG and Seagreen

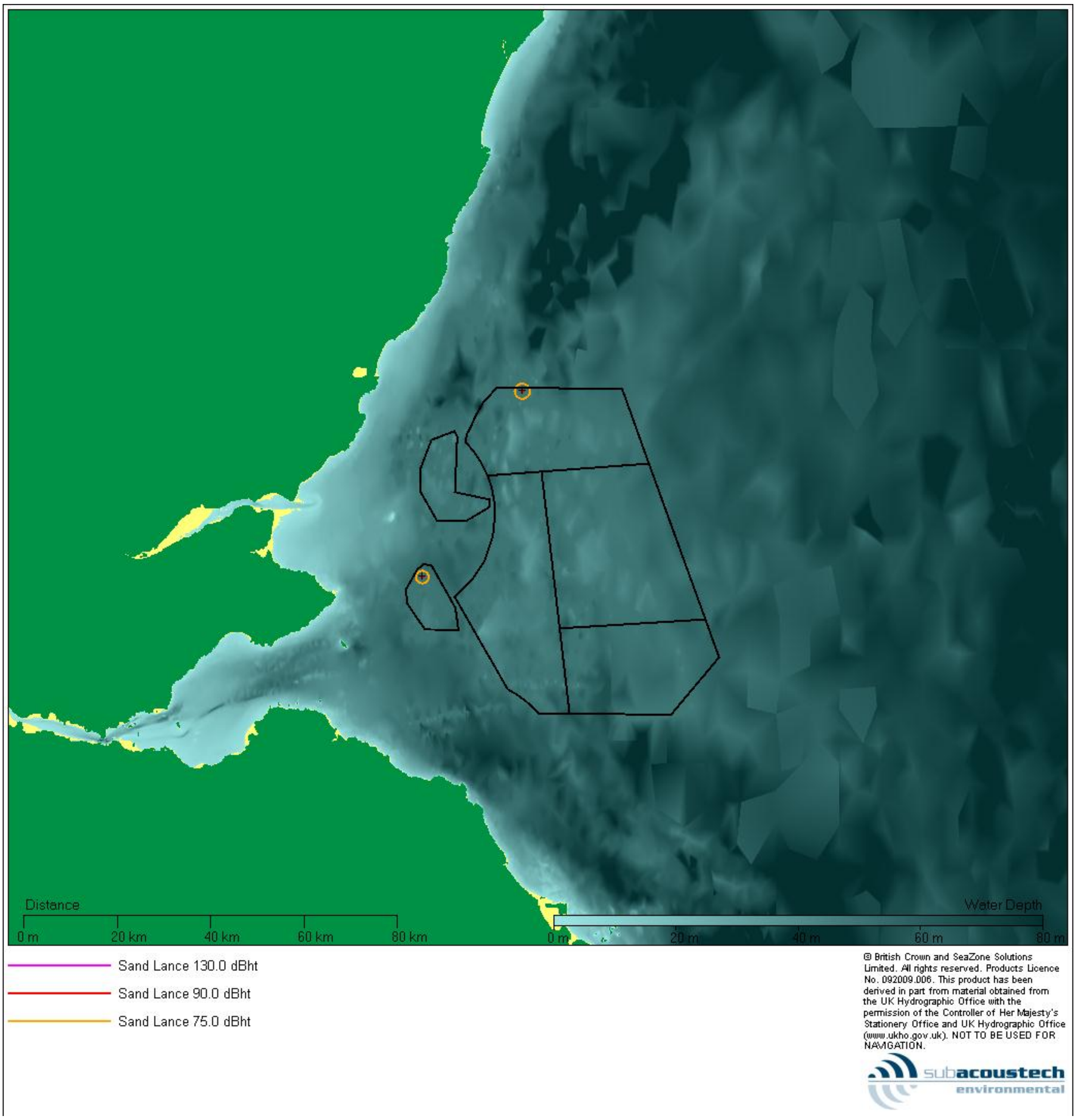

Figure 4-22 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the installation of simultaneous piles at NNG and Seagreen

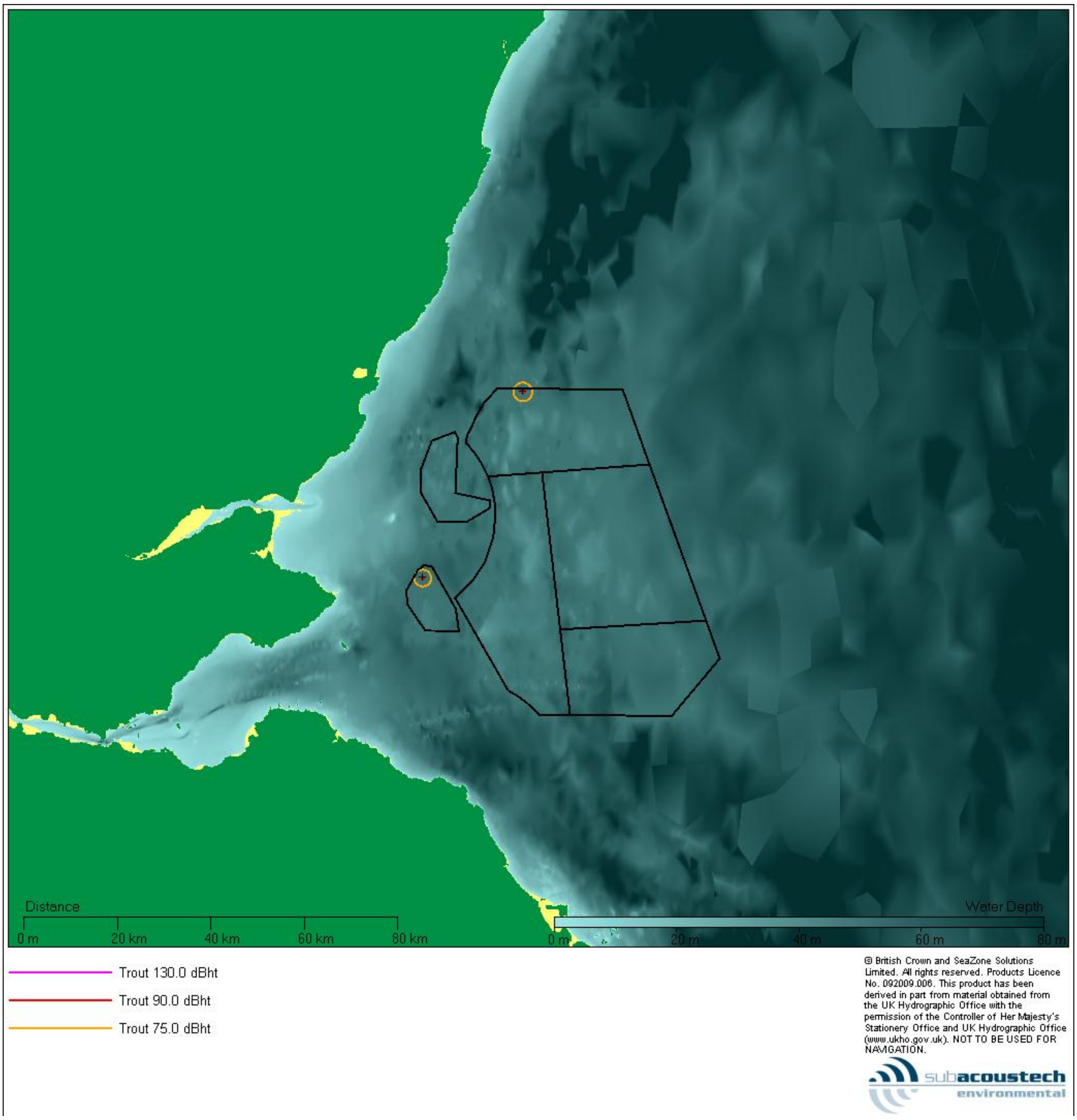

Figure 4-23 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the installation of simultaneous piles at NNG and Seagreen

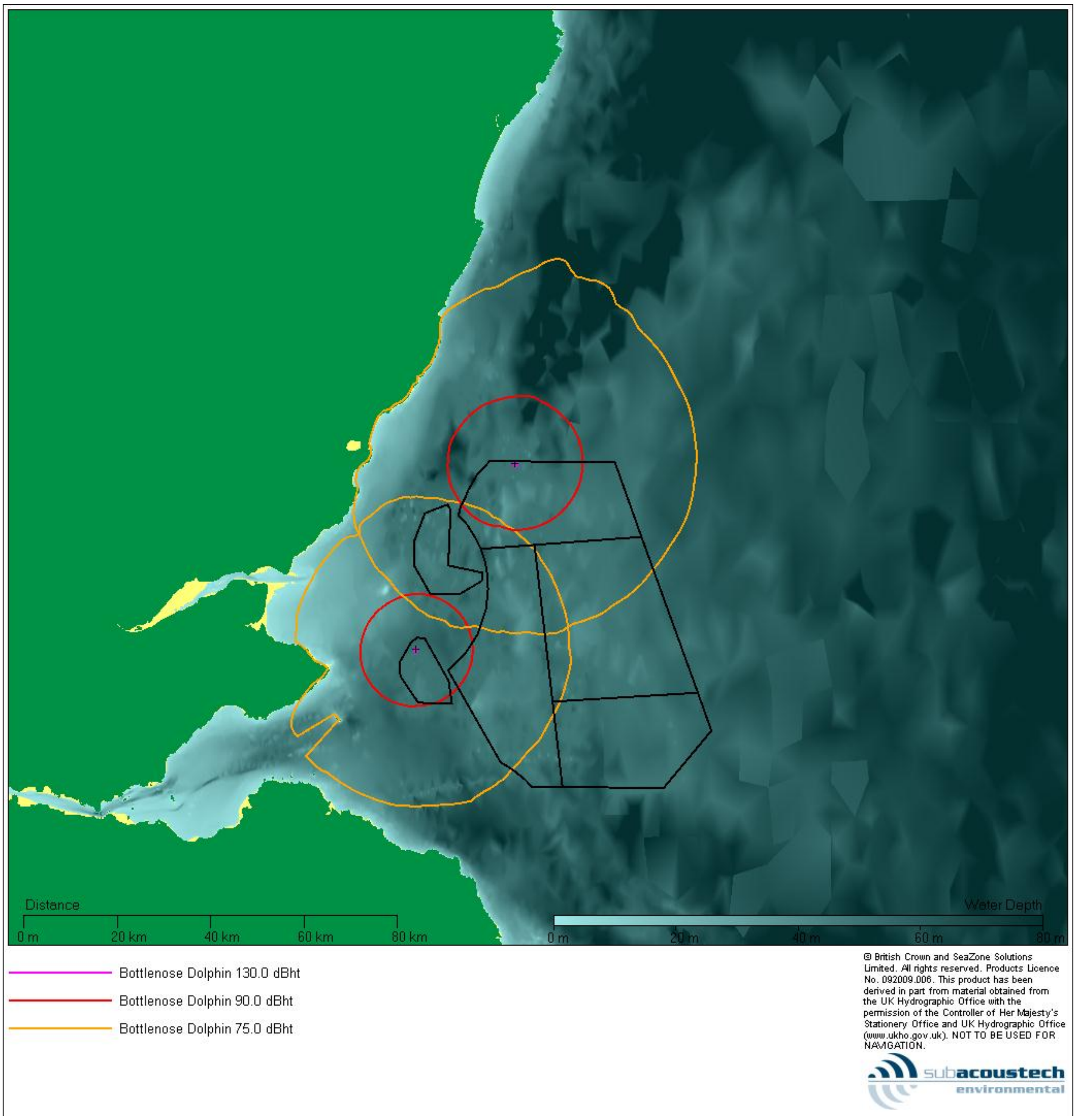

Figure 4-24 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the installation of simultaneous piles at NNG and Seagreen

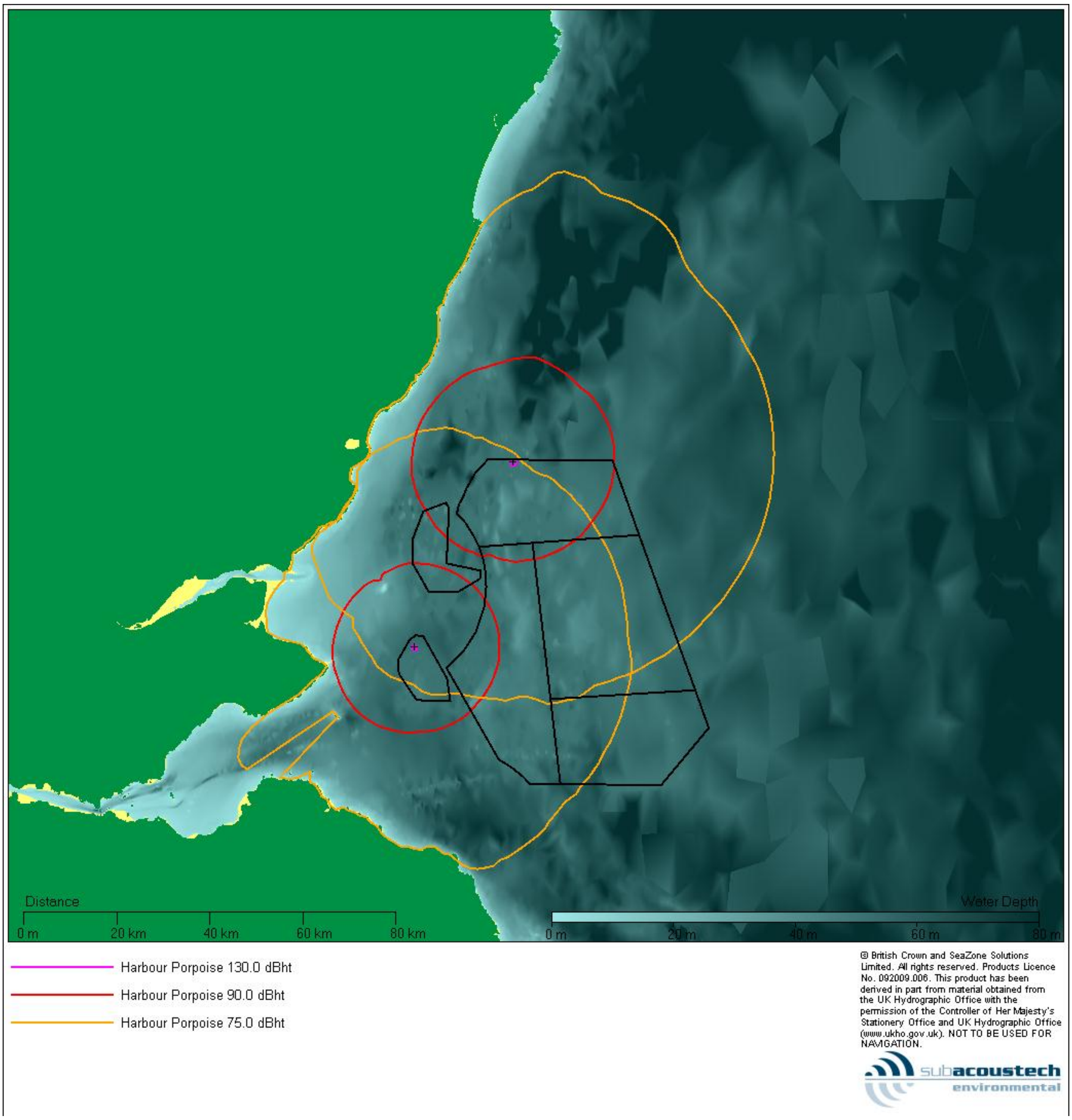

Figure 4-25 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the installation of simultaneous piles at NNG and Seagreen

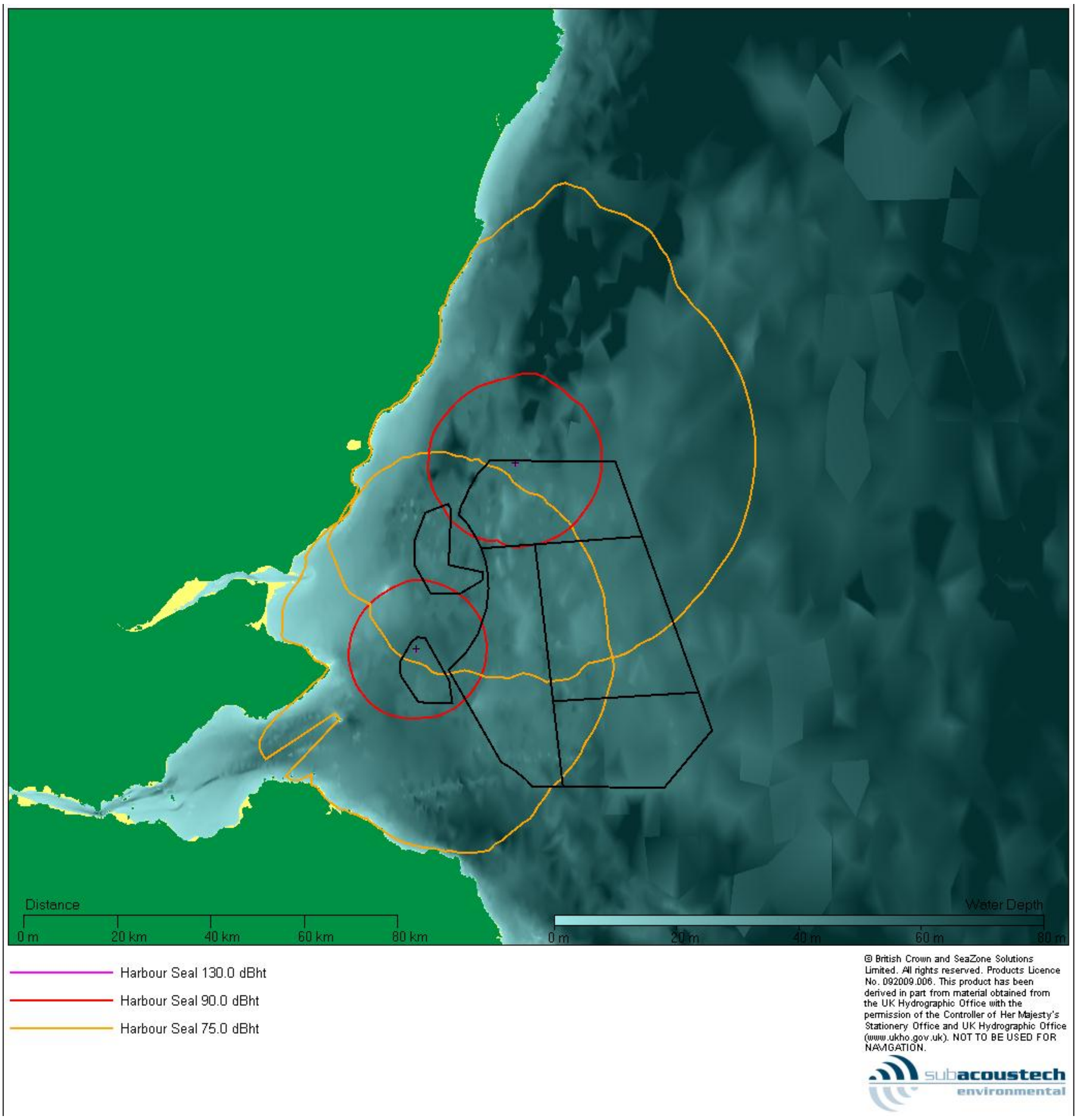

Figure 4-26 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the installation of simultaneous piles at NNG and Seagreen

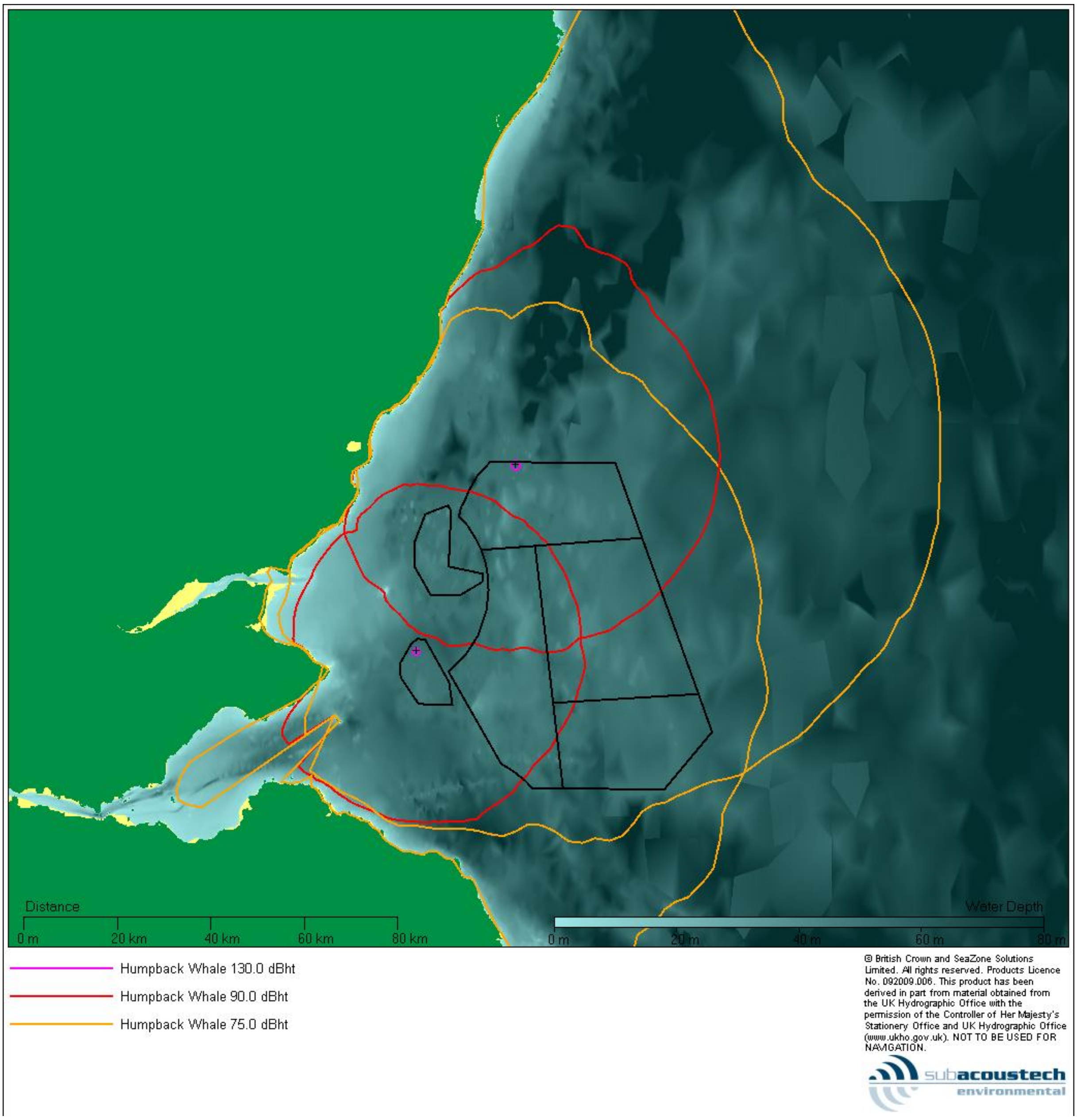

Figure 4-27 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the installation of simultaneous piles at NNG and Seagreen

F5 and F4 most likely (simultaneous)

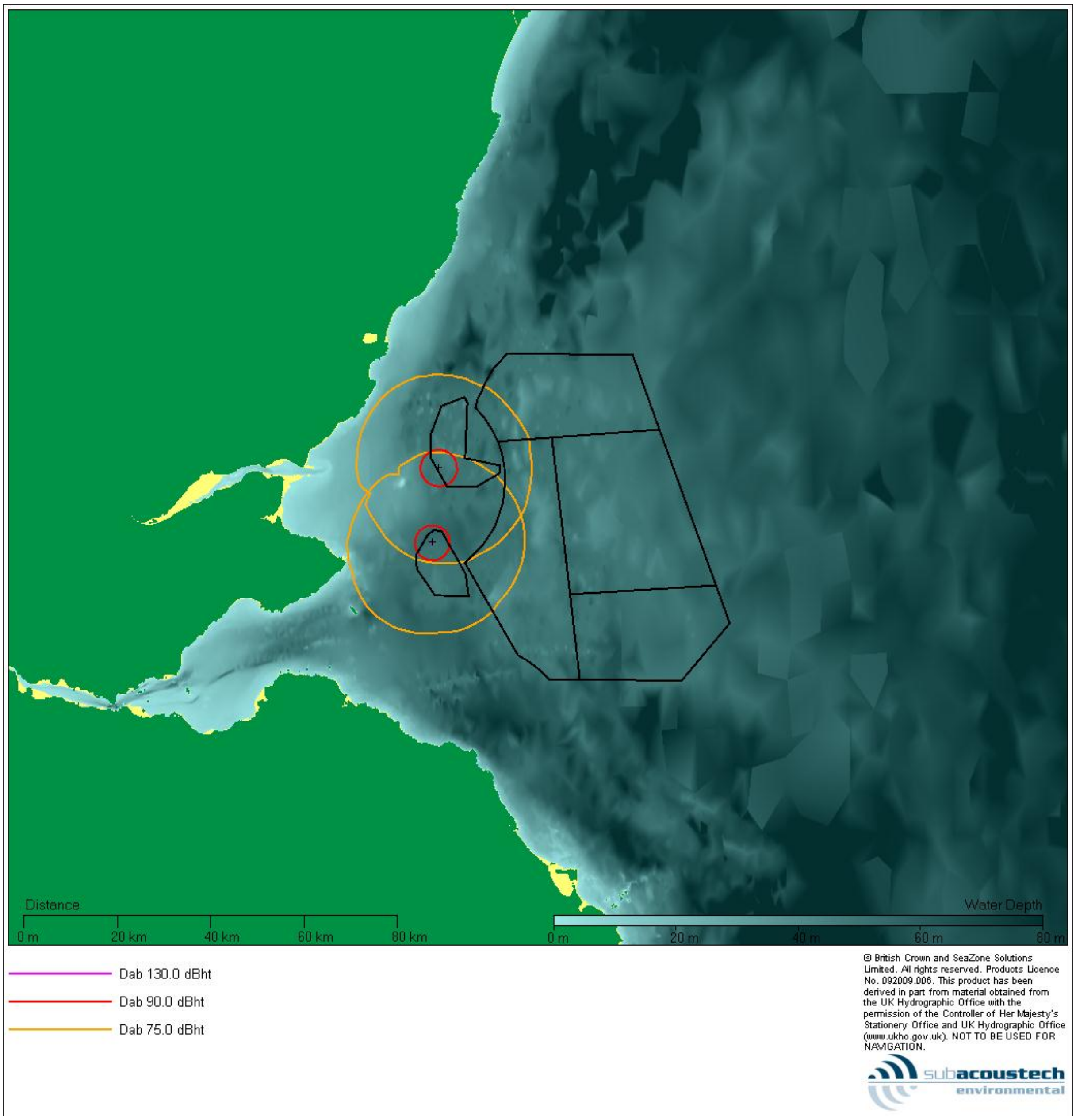

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Figure 4-28 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the installation of simultaneous piles at NNG and Inch Cape

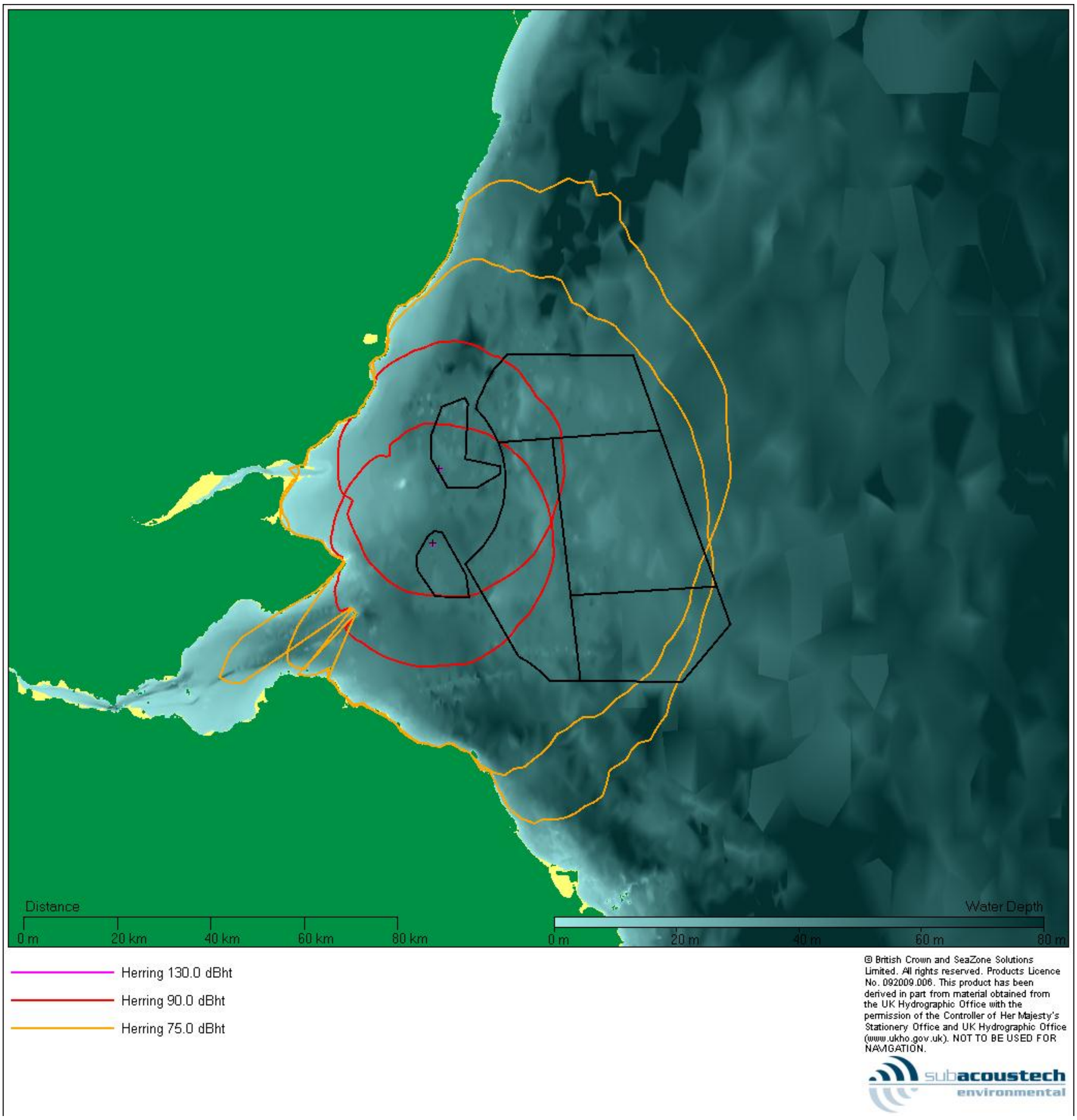

Figure 4-29 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the installation of simultaneous piles at NNG and Inch Cape

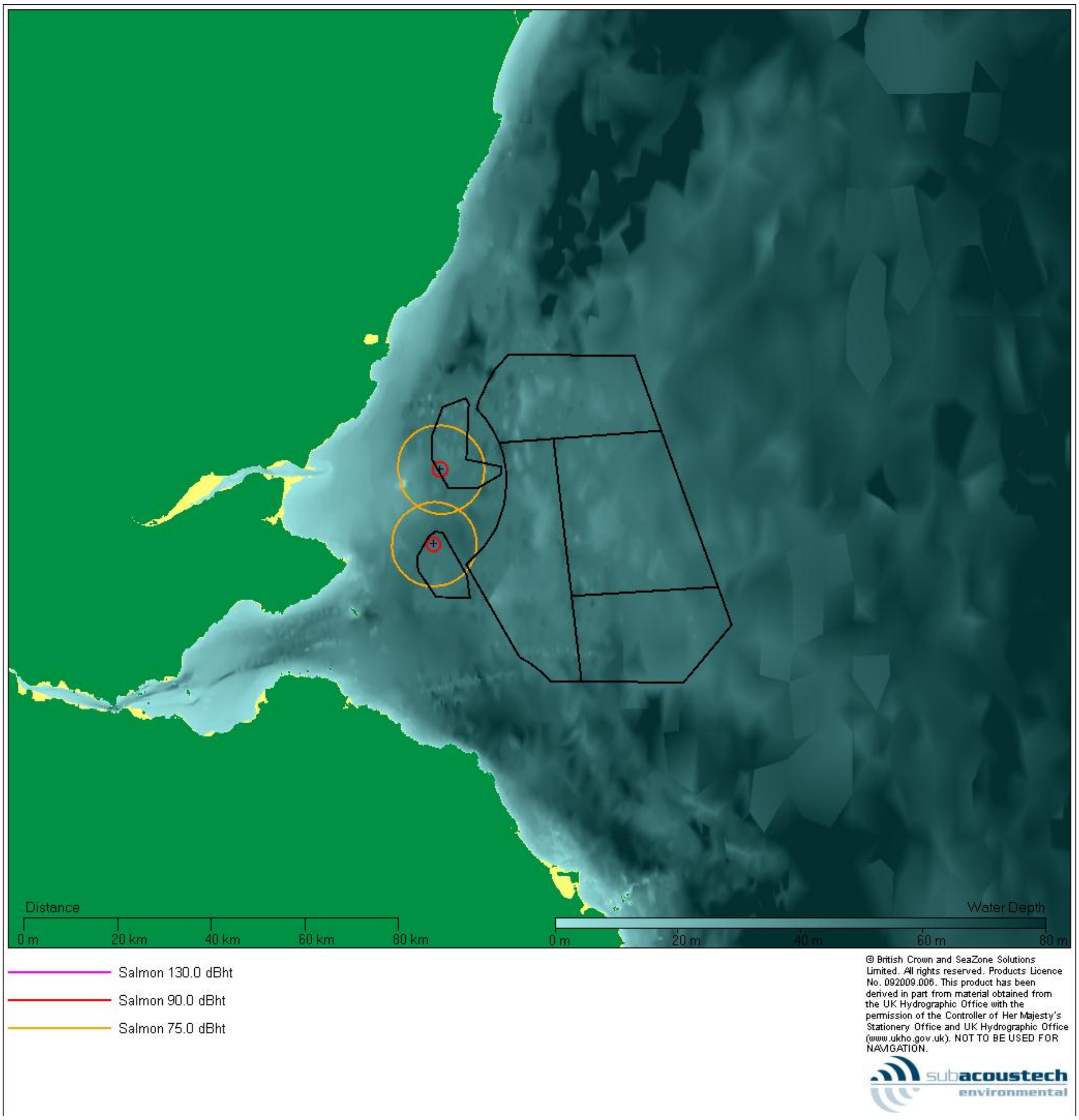

Figure 4-30 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the installation of simultaneous piles at NNG and Inch Cape

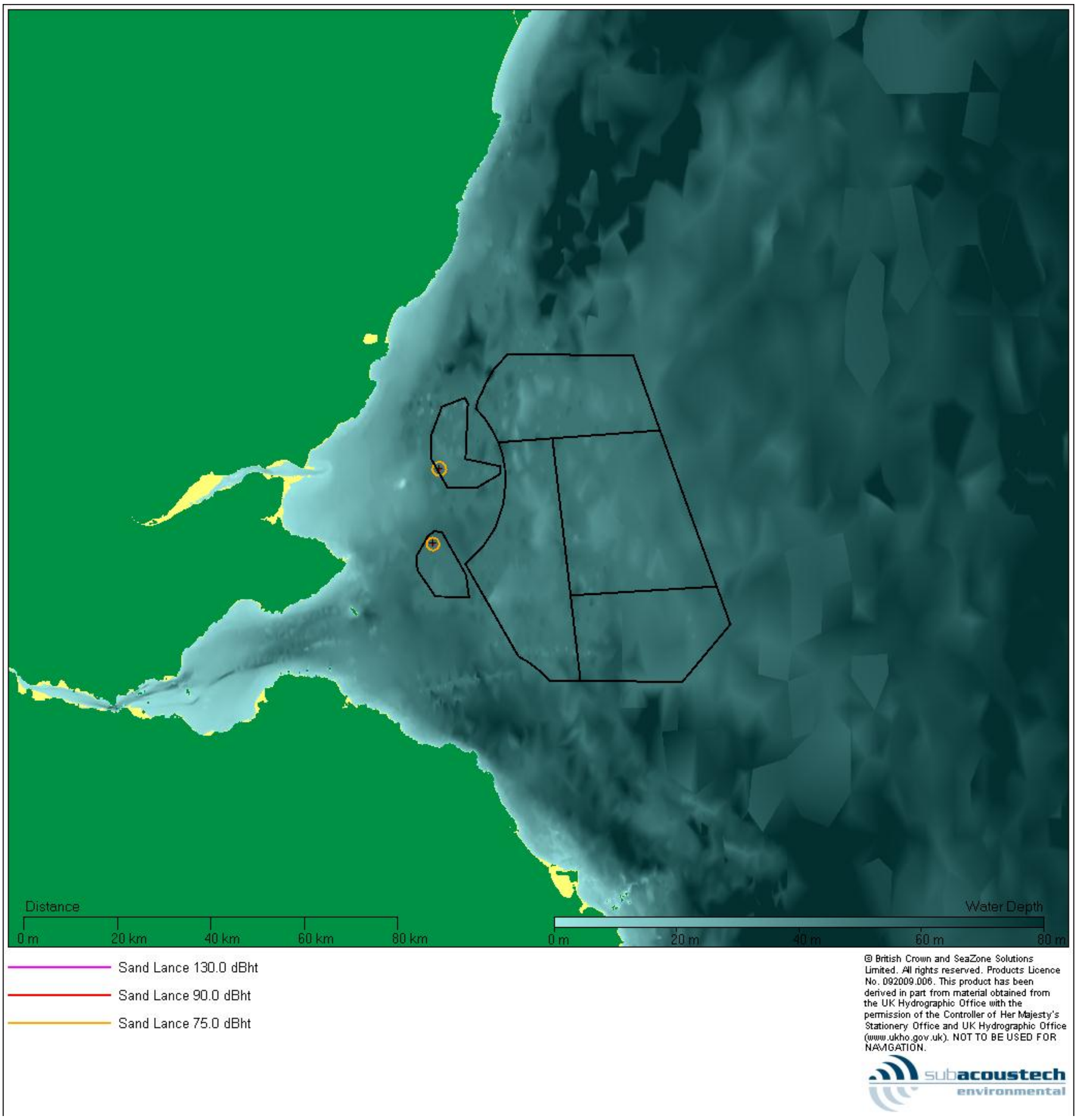

Figure 4-31 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the installation of simultaneous piles at NNG and Inch Cape

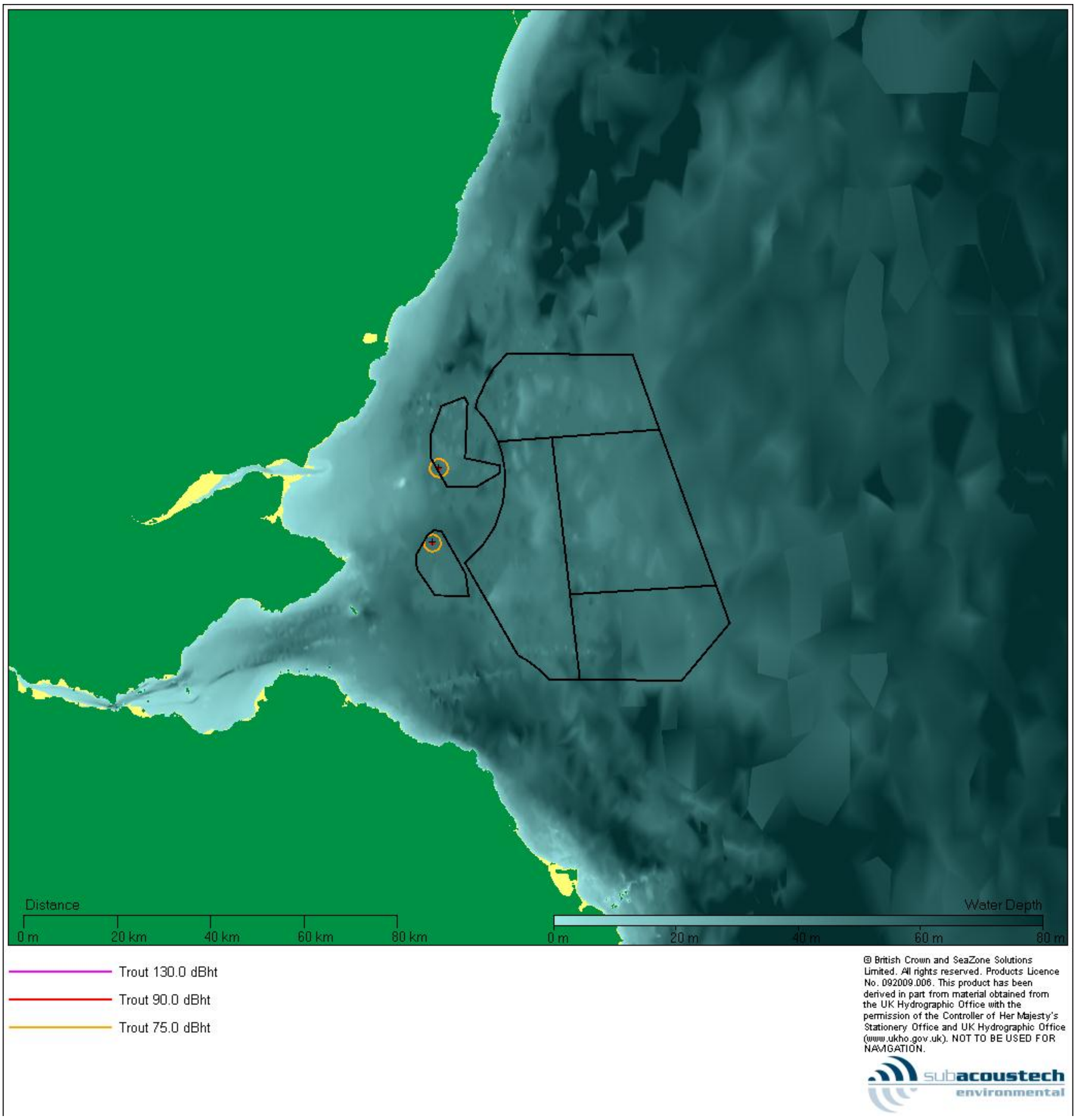

Figure 4-32 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the installation of simultaneous piles at NNG and Inch Cape

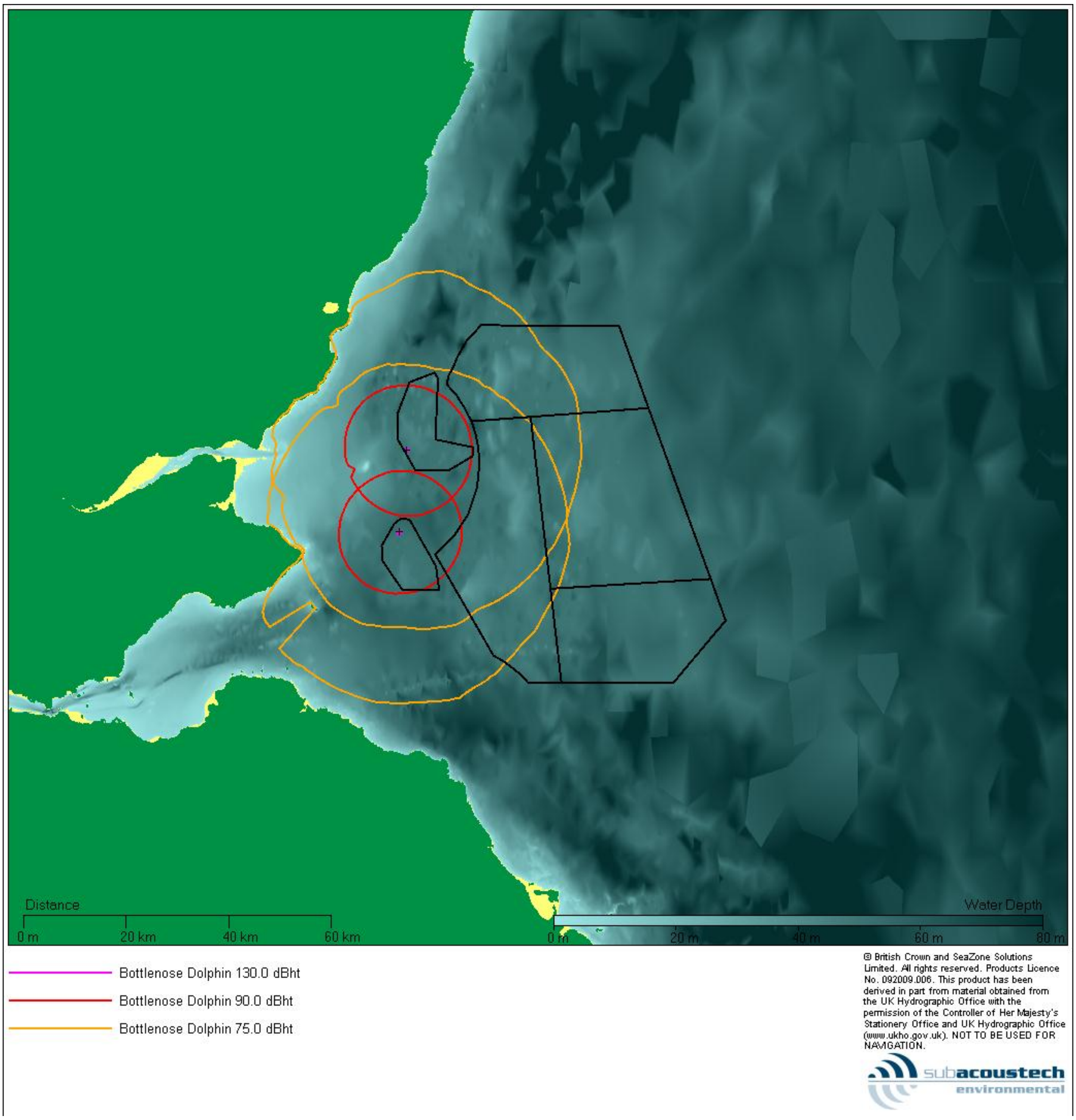

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Figure 4-33 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the installation of simultaneous piles at NNG and Inch Cape

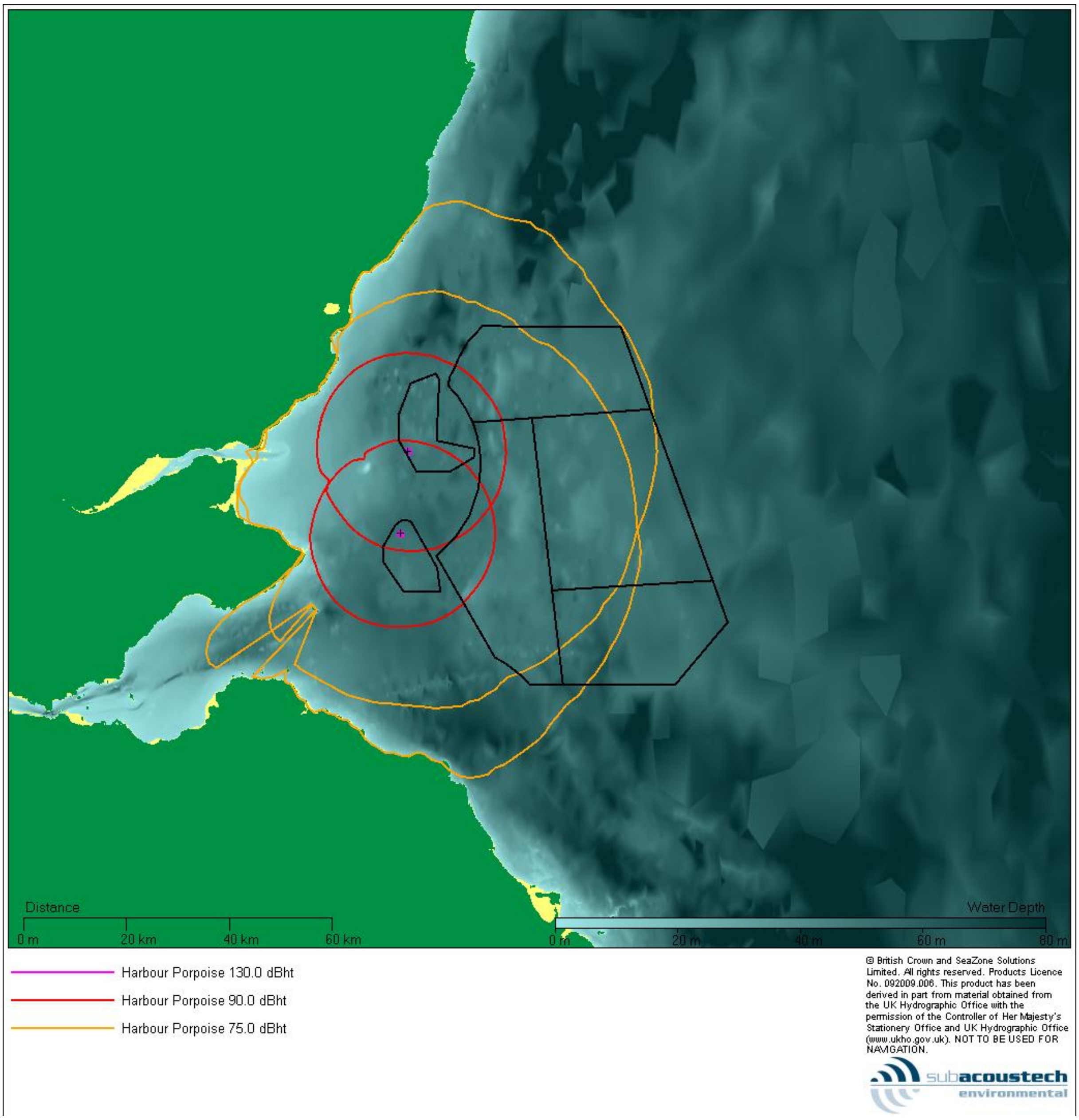

Figure 4-34 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Harbour Porpoise for the installation of simultaneous piles at NNG and Inch Cape

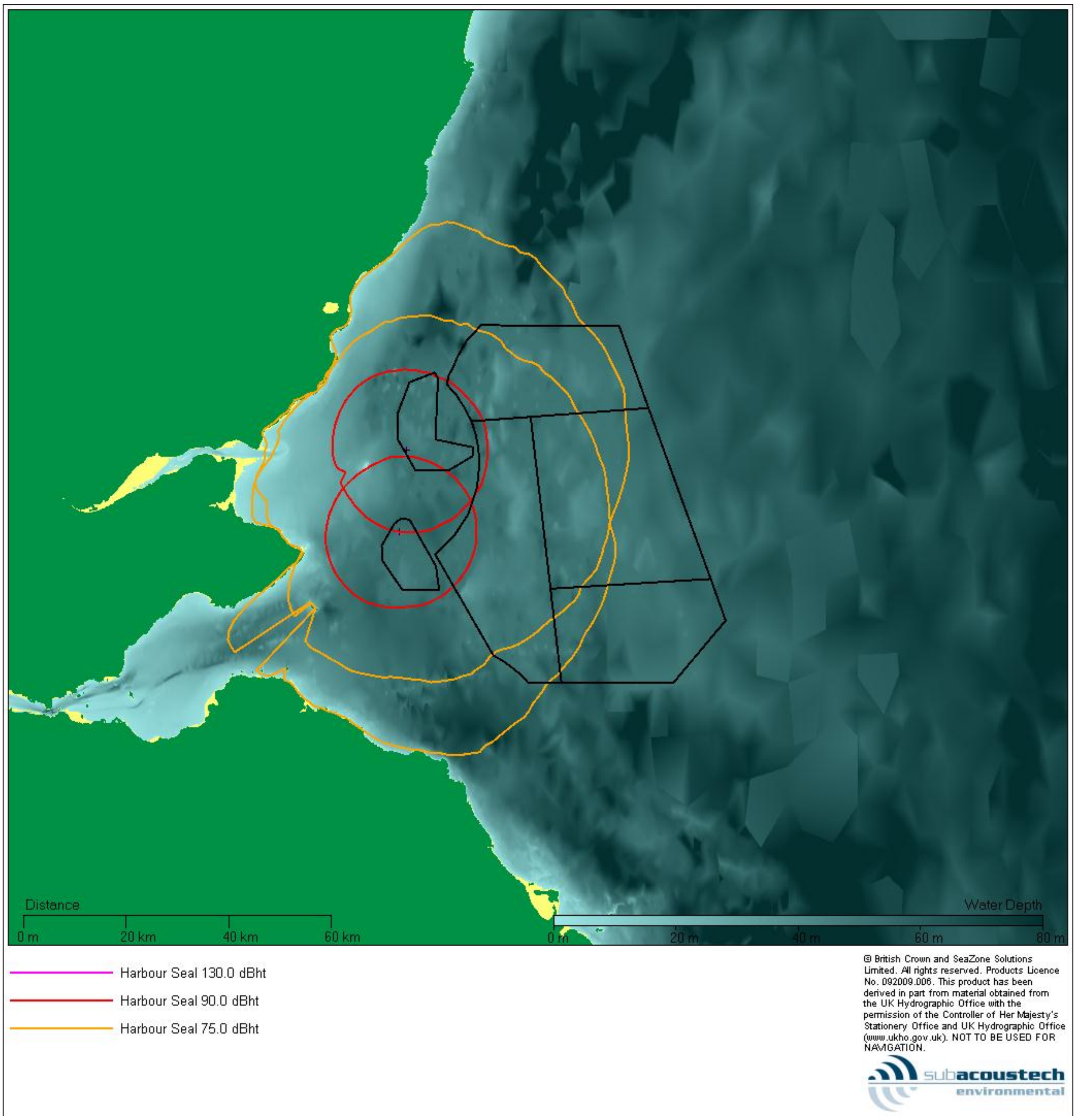

Figure 4-35 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the installation of simultaneous piles at NNG and Inch Cape

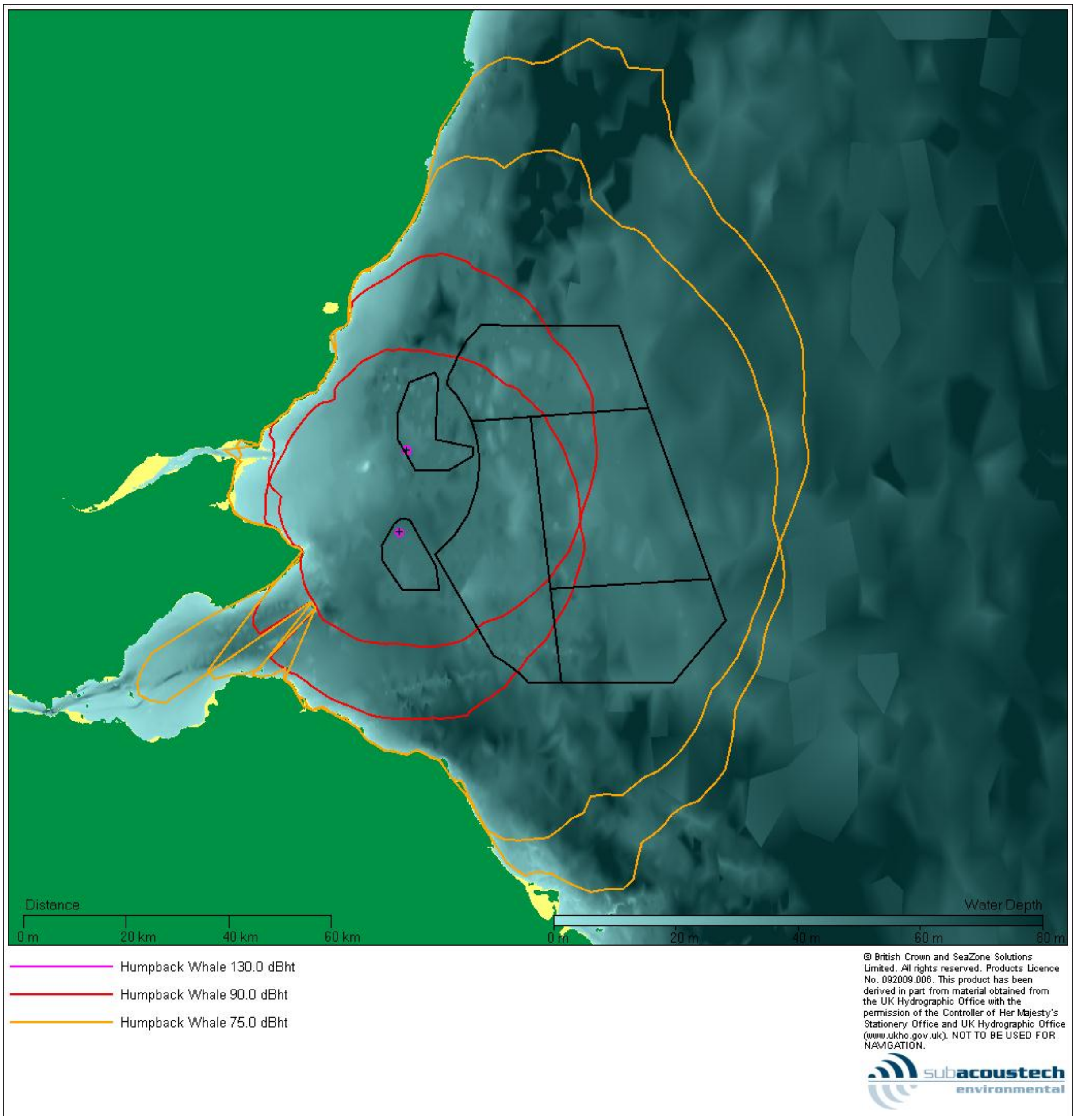

Figure 4-36 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the installation of simultaneous piles at NNG and Inch Cape

F5 and F6 most likely

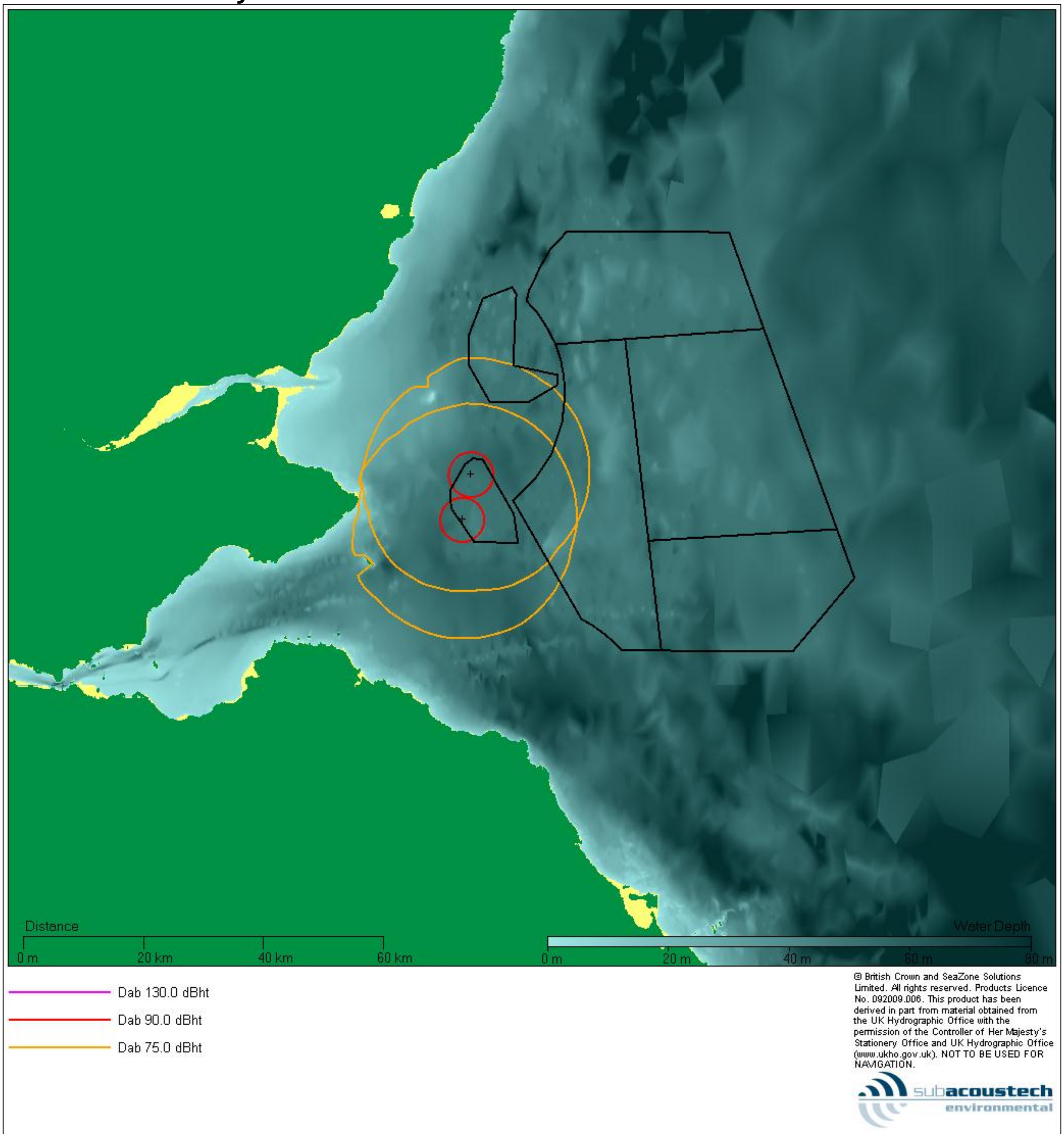

Figure 4-37 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the installation of simultaneous piles at NNG

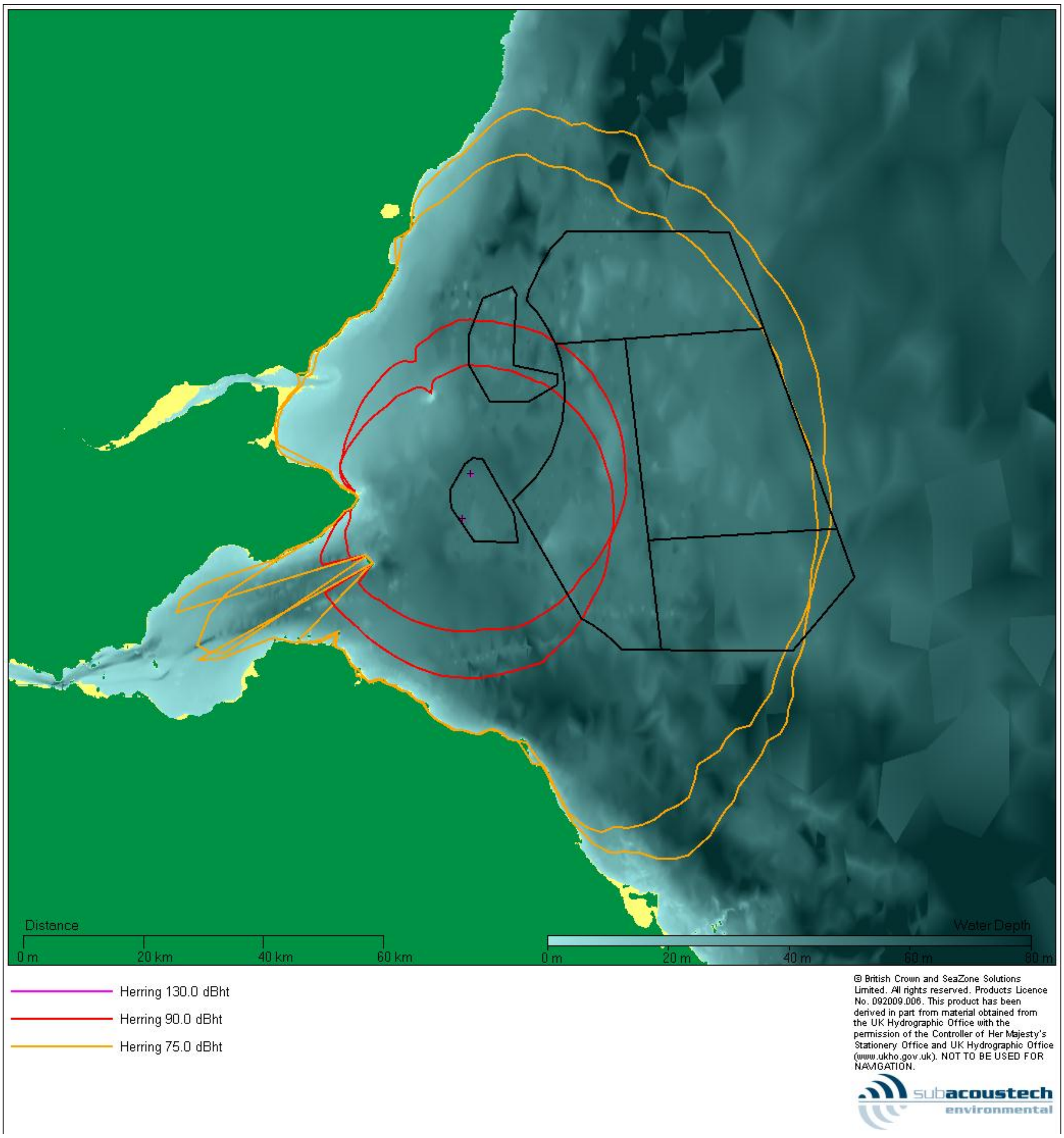

Figure 4-38 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the installation of simultaneous piles at NNG

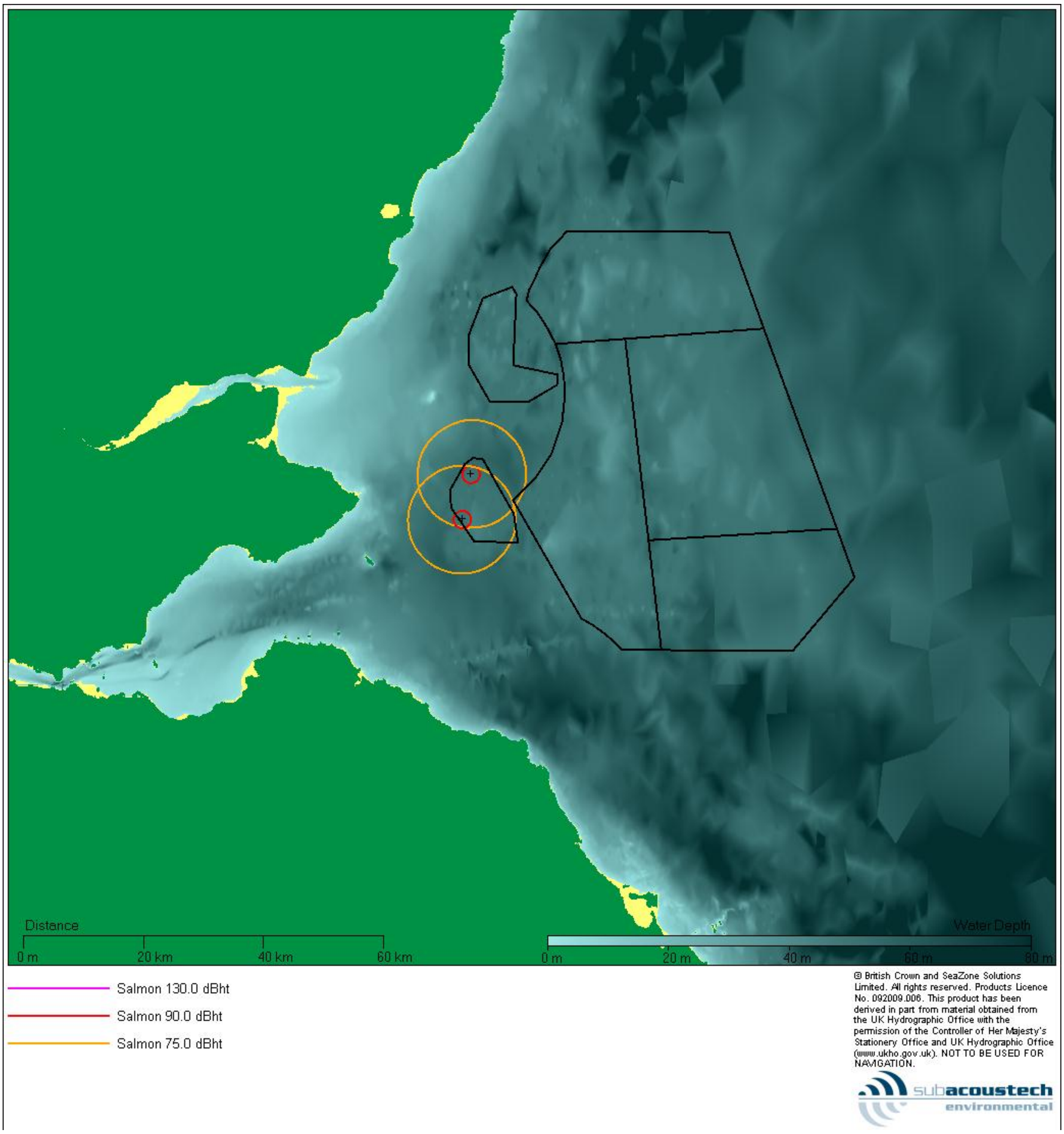

Figure 4-39 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the installation of simultaneous piles at NNG

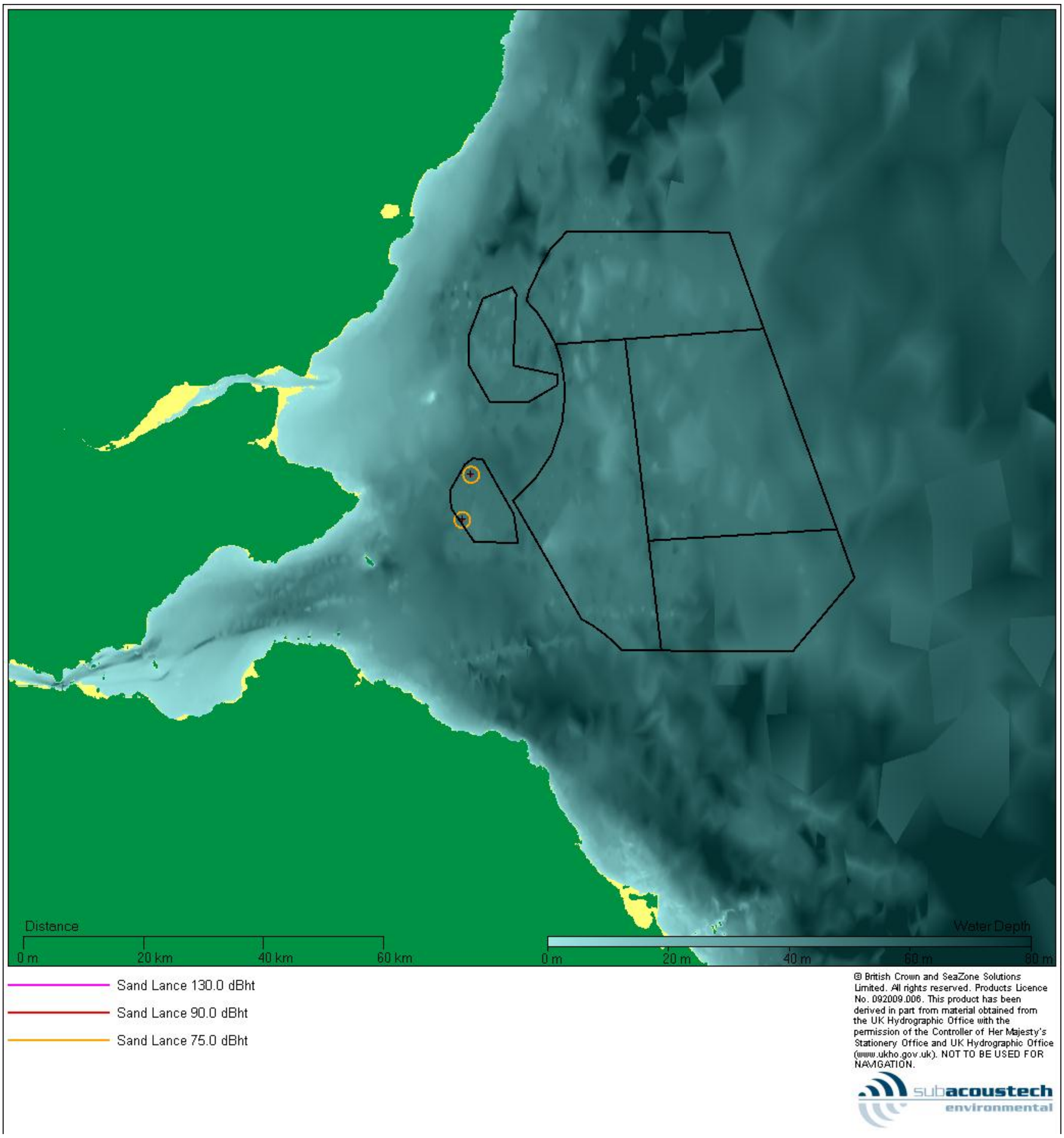

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Figure 4-40 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the installation of simultaneous piles at NNG

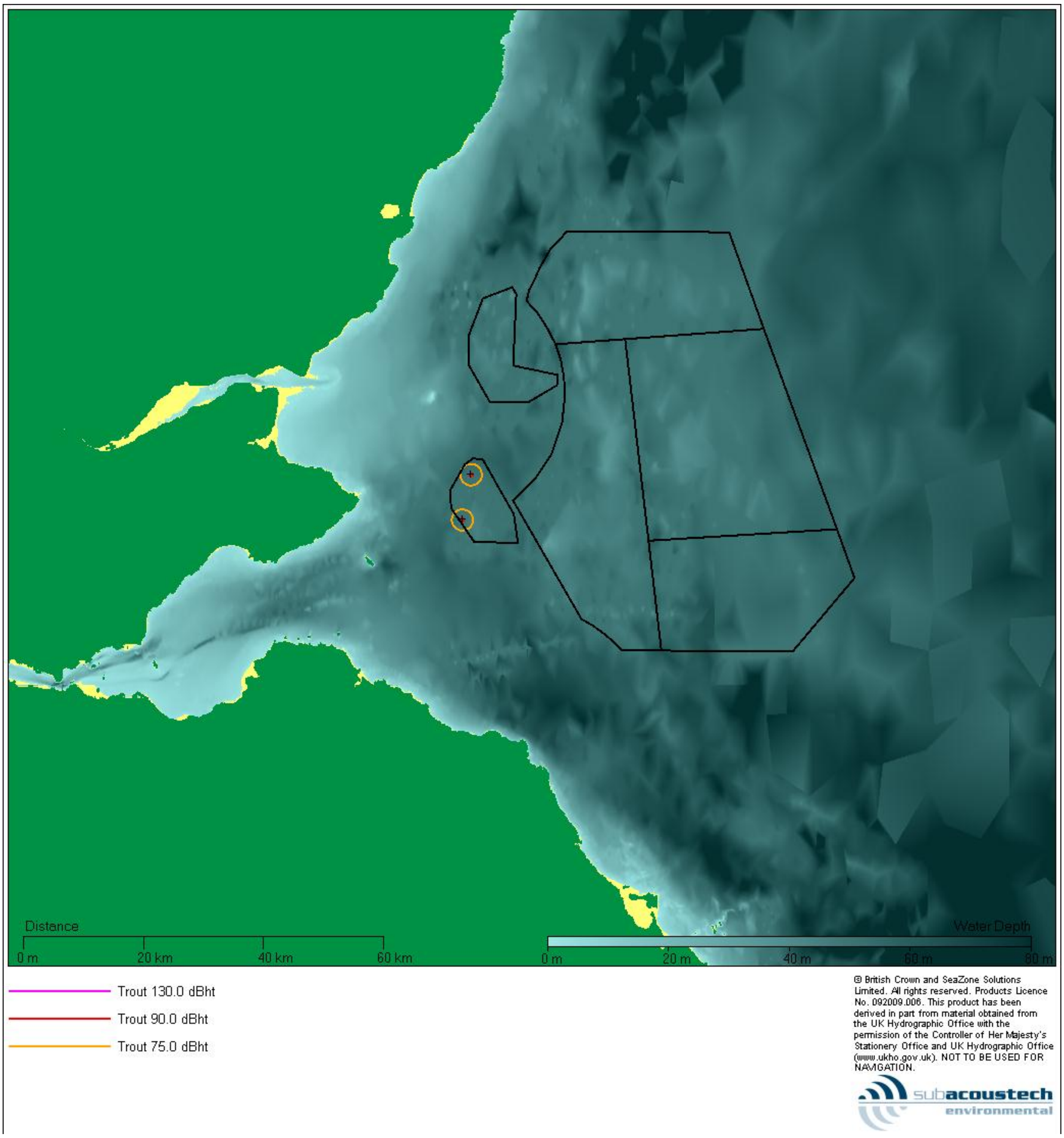

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Figure 4-41 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the installation of simultaneous piles at NNG

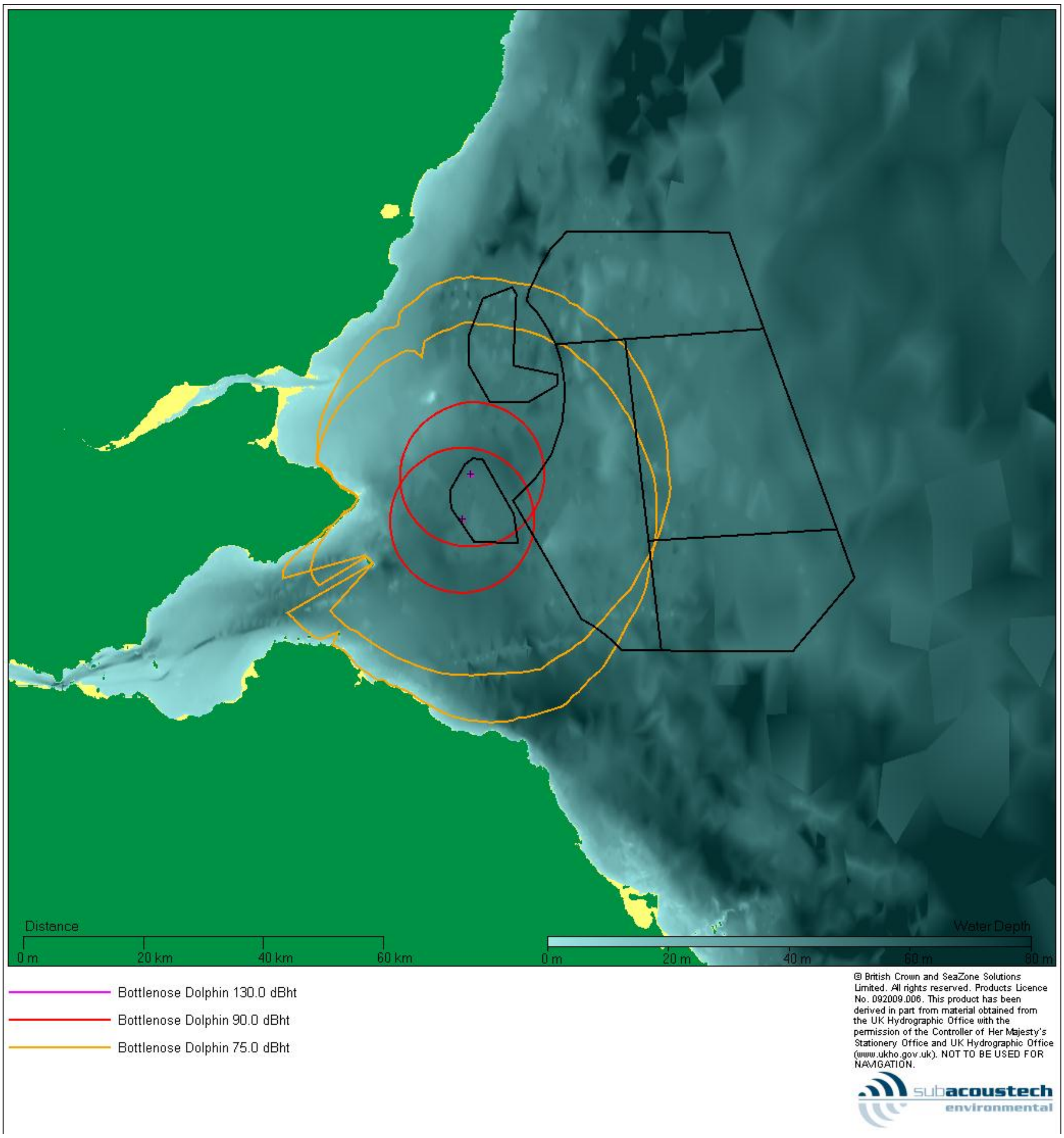

Figure 4-42 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the installation of simultaneous piles at NNG

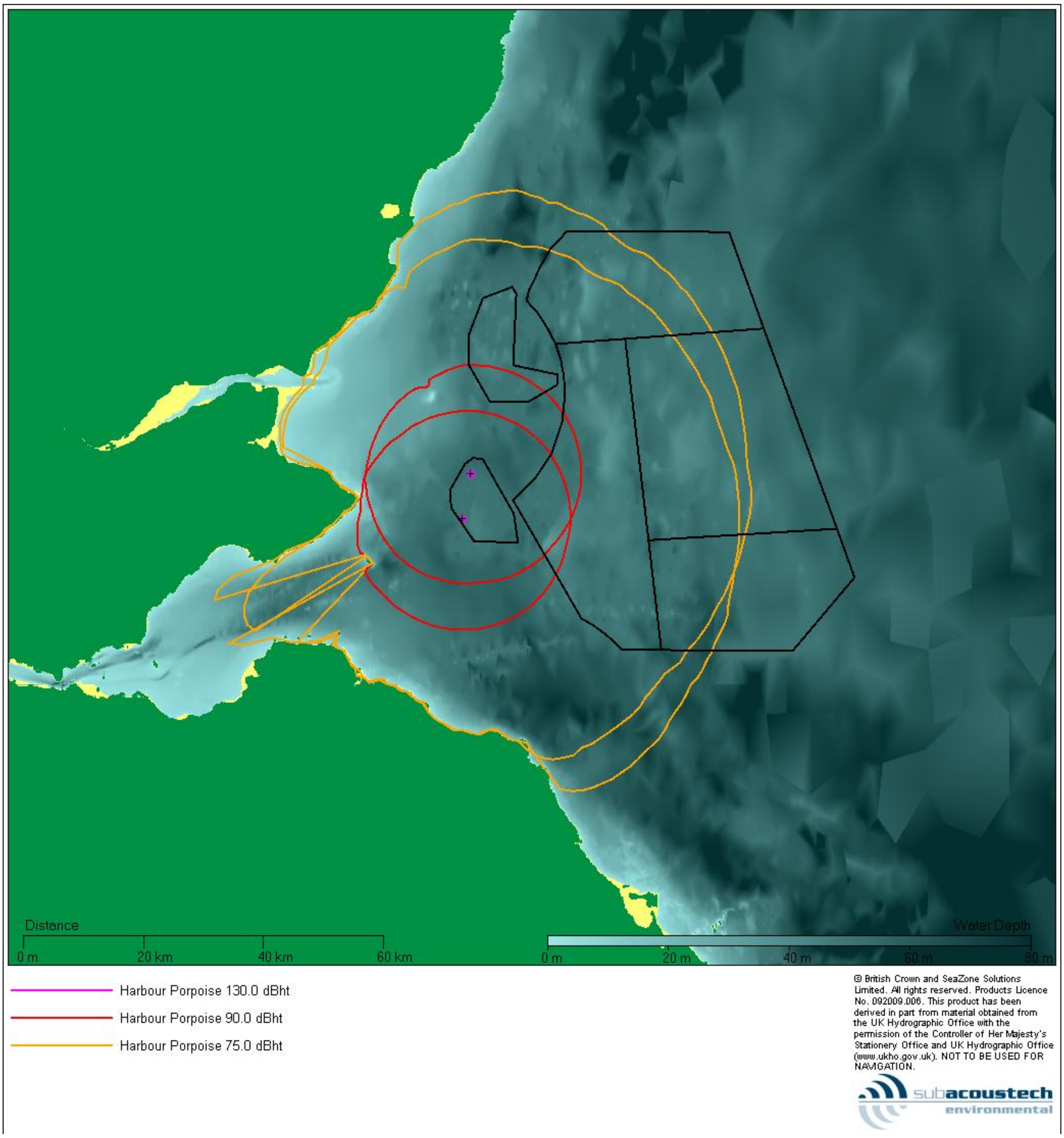

Figure 4-43 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the installation of simultaneous piles at NNG

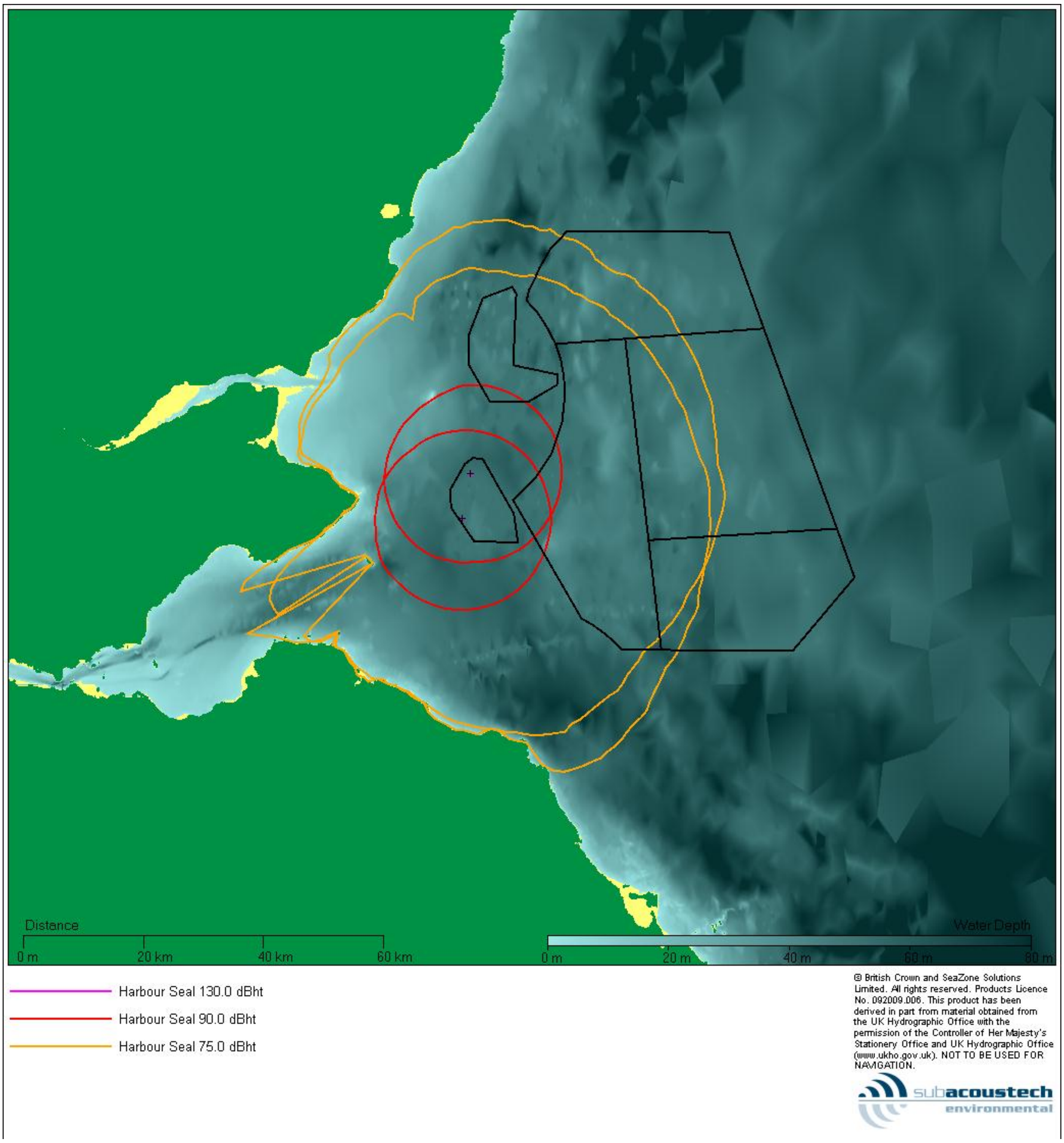

Figure 4-44 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Harbour Seal for the installation of simultaneous piles at NNG

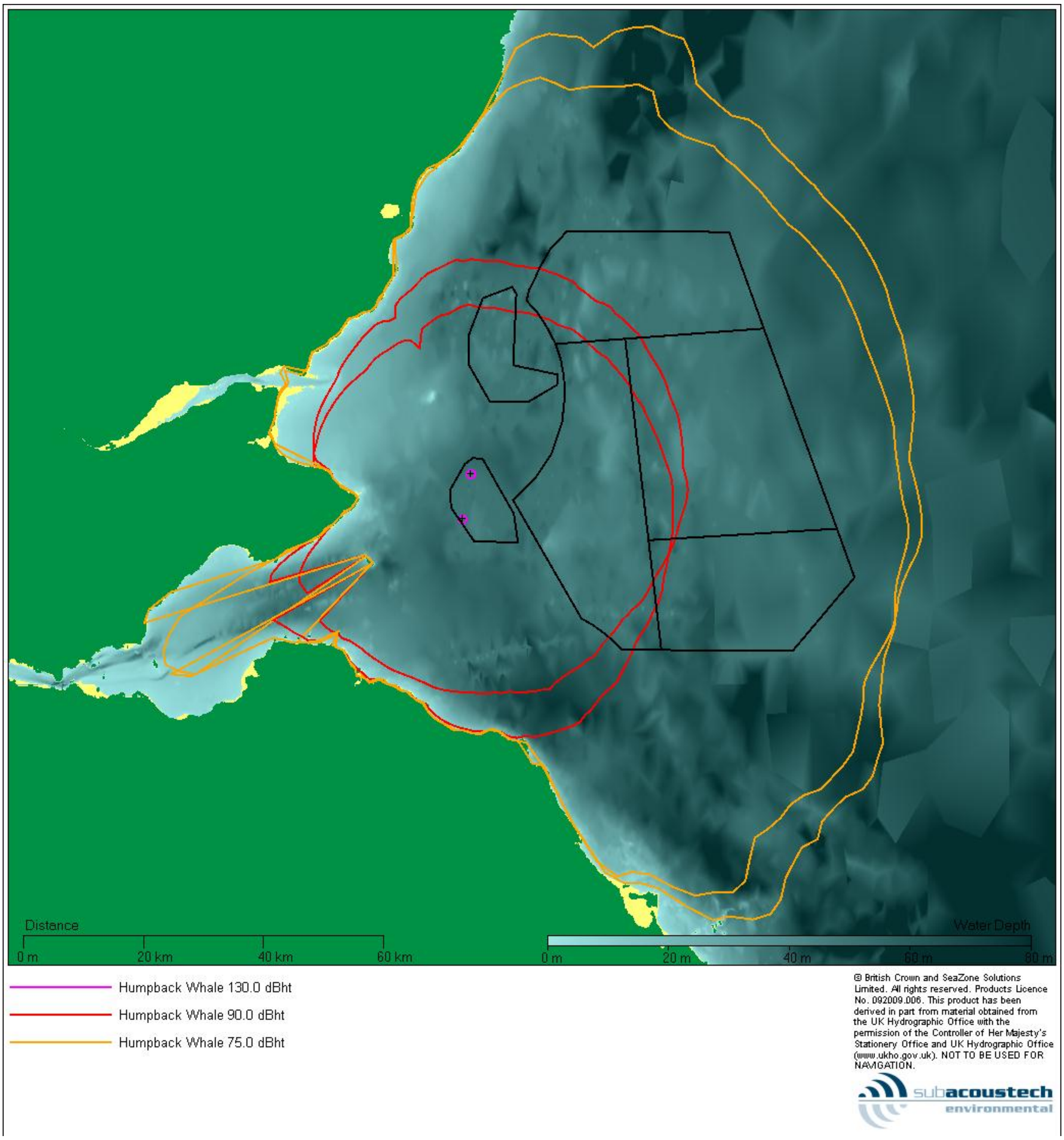

Figure 4-45 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the installation of simultaneous piles at NNG

F5, F4 and F1 most likely (simultaneous)

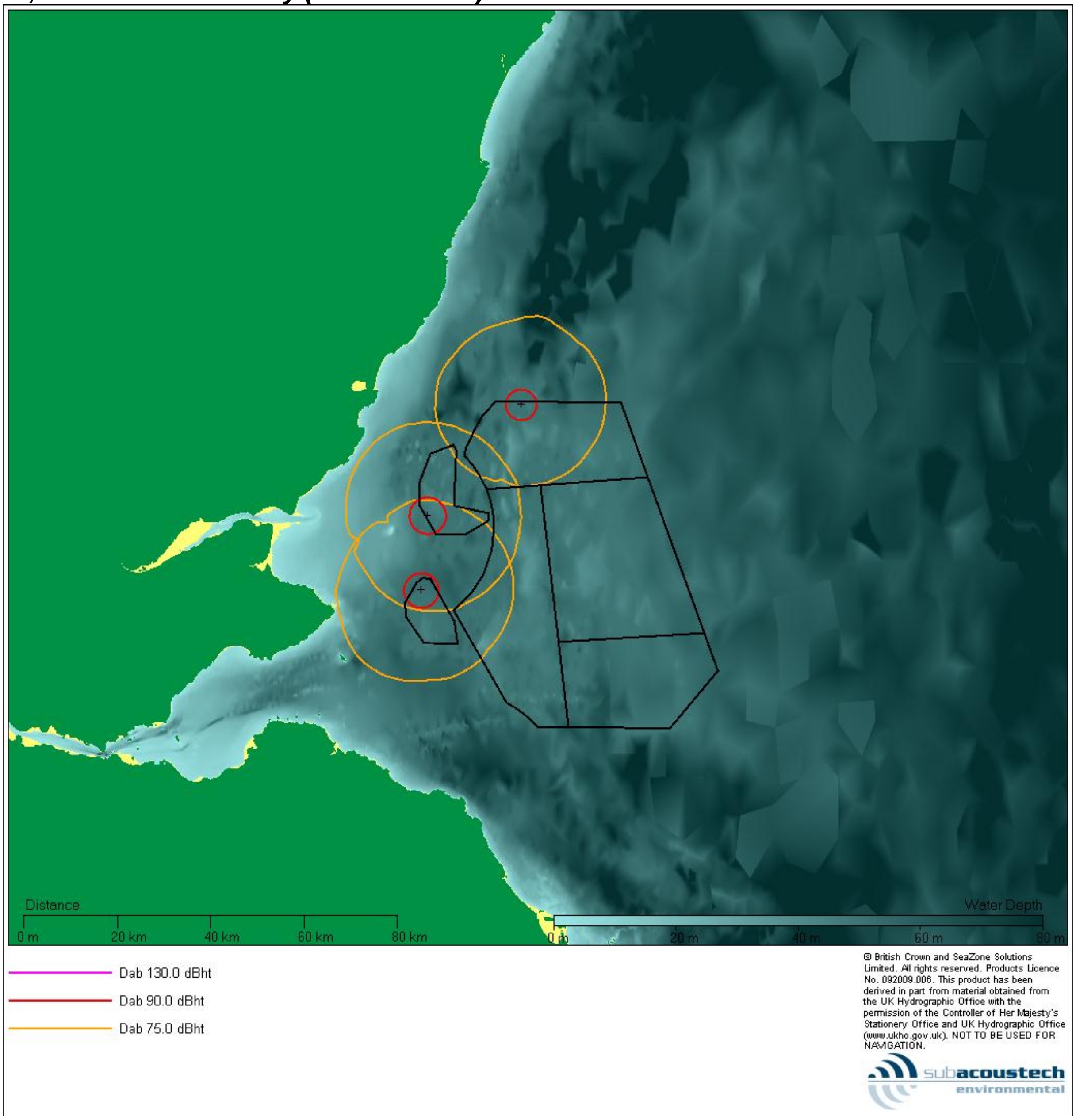

Figure 4-46 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the installation of simultaneous piles at NNG, Inch Cape and Seagreen

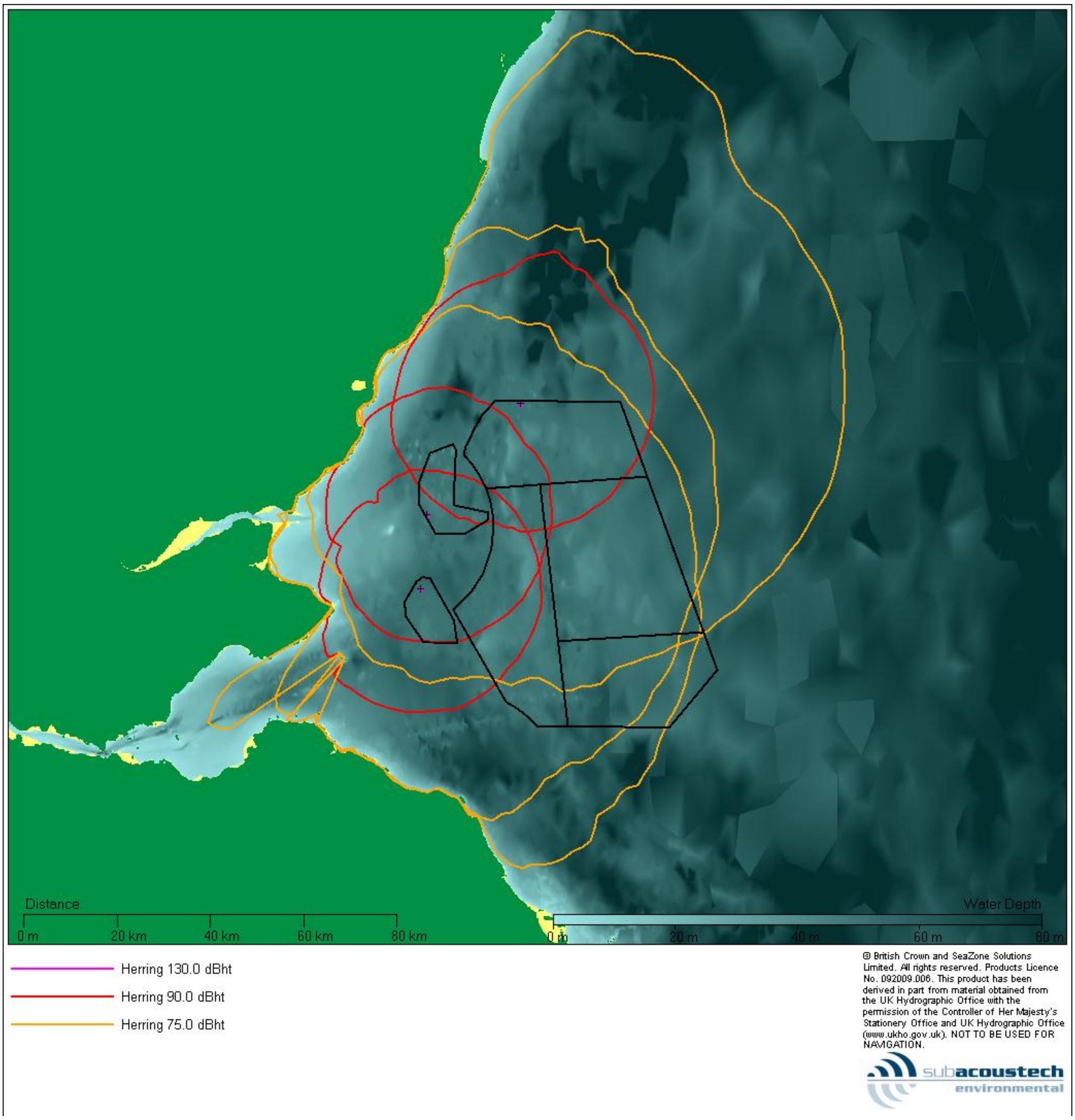

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Figure 4-47 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the installation of simultaneous piles at NNG, Inch Cape and Seagreen

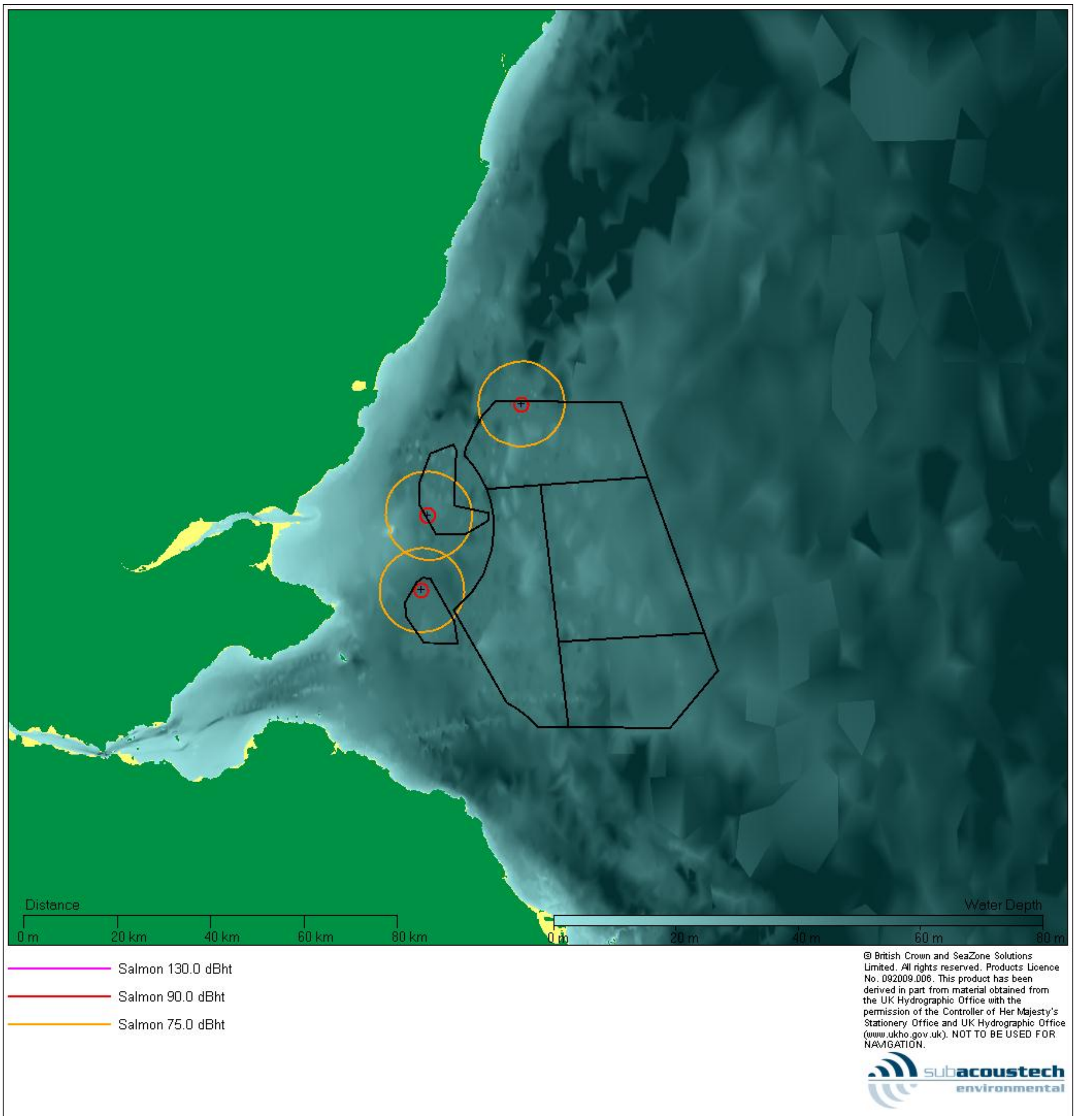

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Figure 4-48 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the installation of simultaneous piles at NNG, Inch Cape and Seagreen

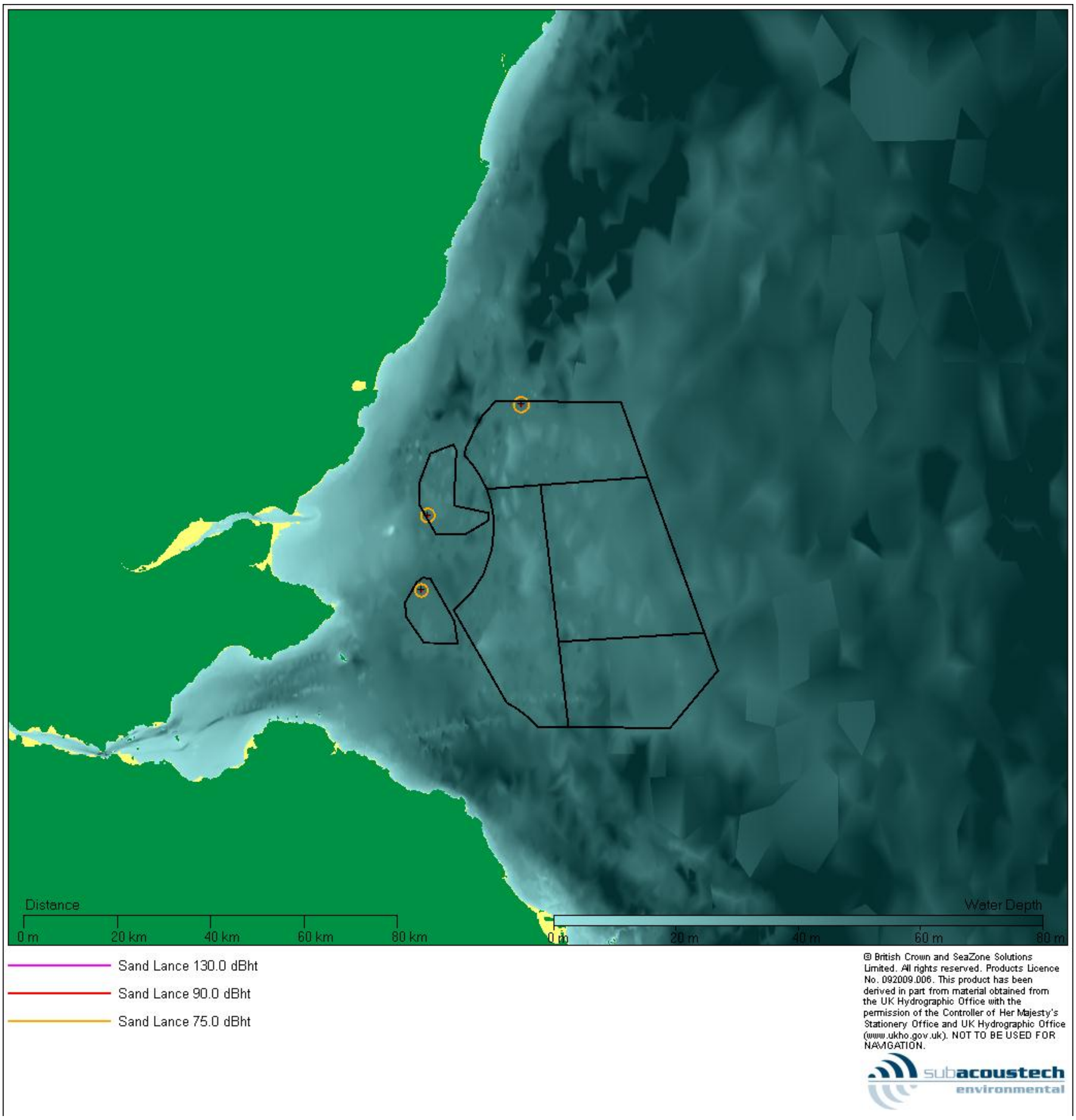

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Figure 4-49 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the installation of simultaneous piles at NNG, Inch Cape and Seagreen

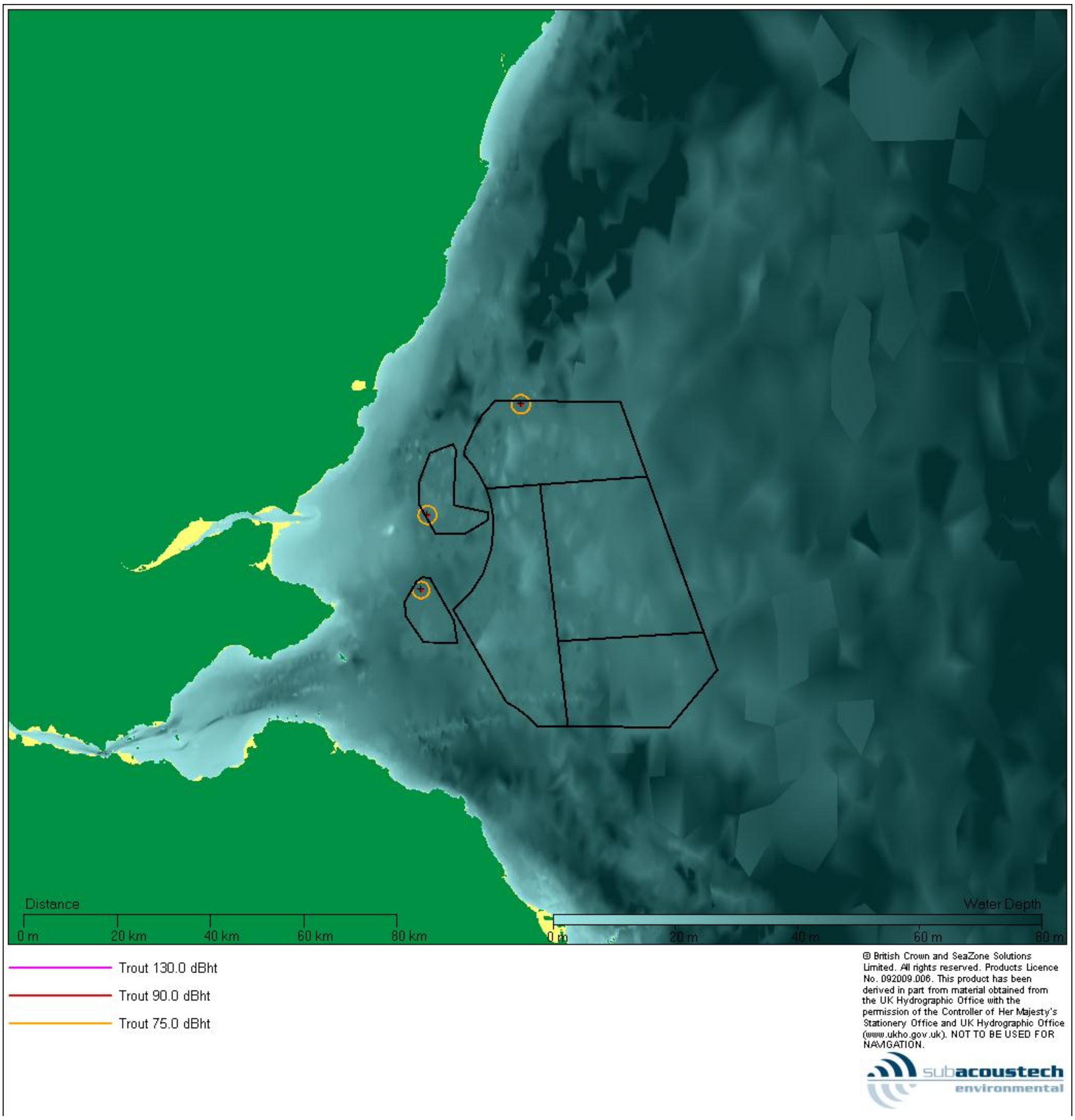

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Figure 4-50 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the installation of simultaneous piles at NNG, Inch Cape and Seagreen

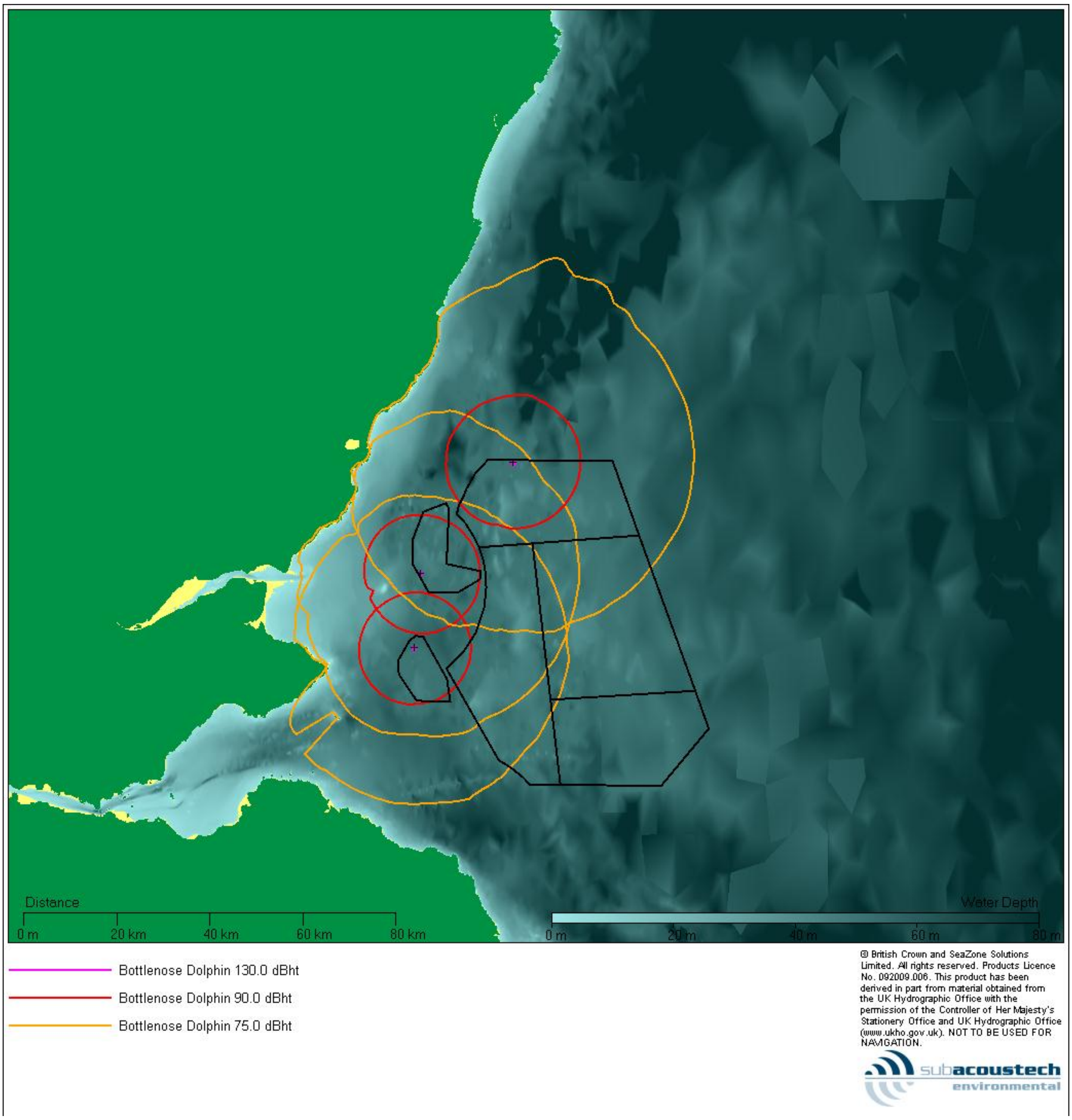

Figure 4-51 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the installation of simultaneous piles at NNG, Inch Cape and Seagreen

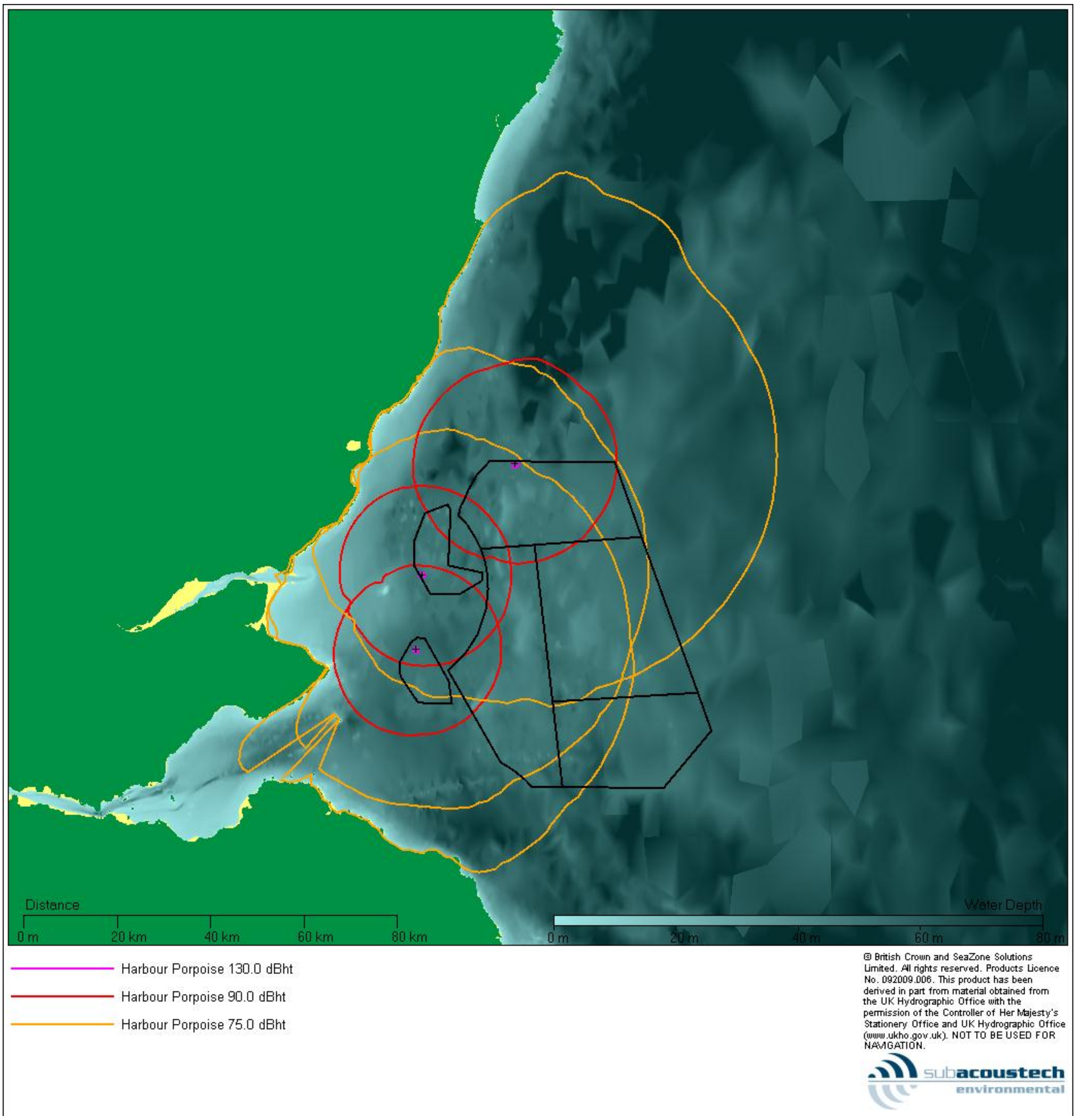

Figure 4-52 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the installation of simultaneous piles at NNG, Inch Cape and Seagreen

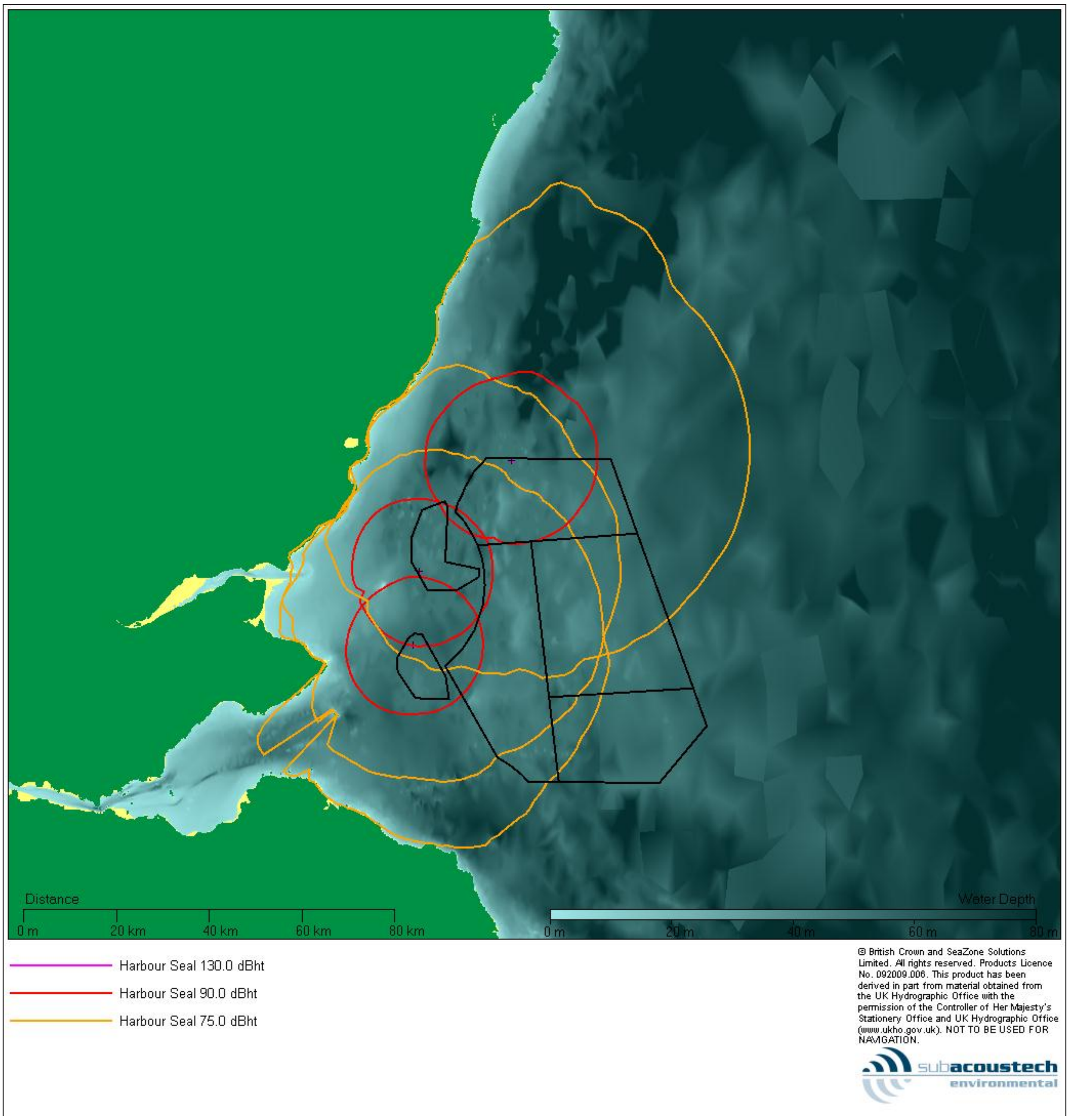

Figure 4-53 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the installation of simultaneous piles at NNG, Inch Cape and Seagreen

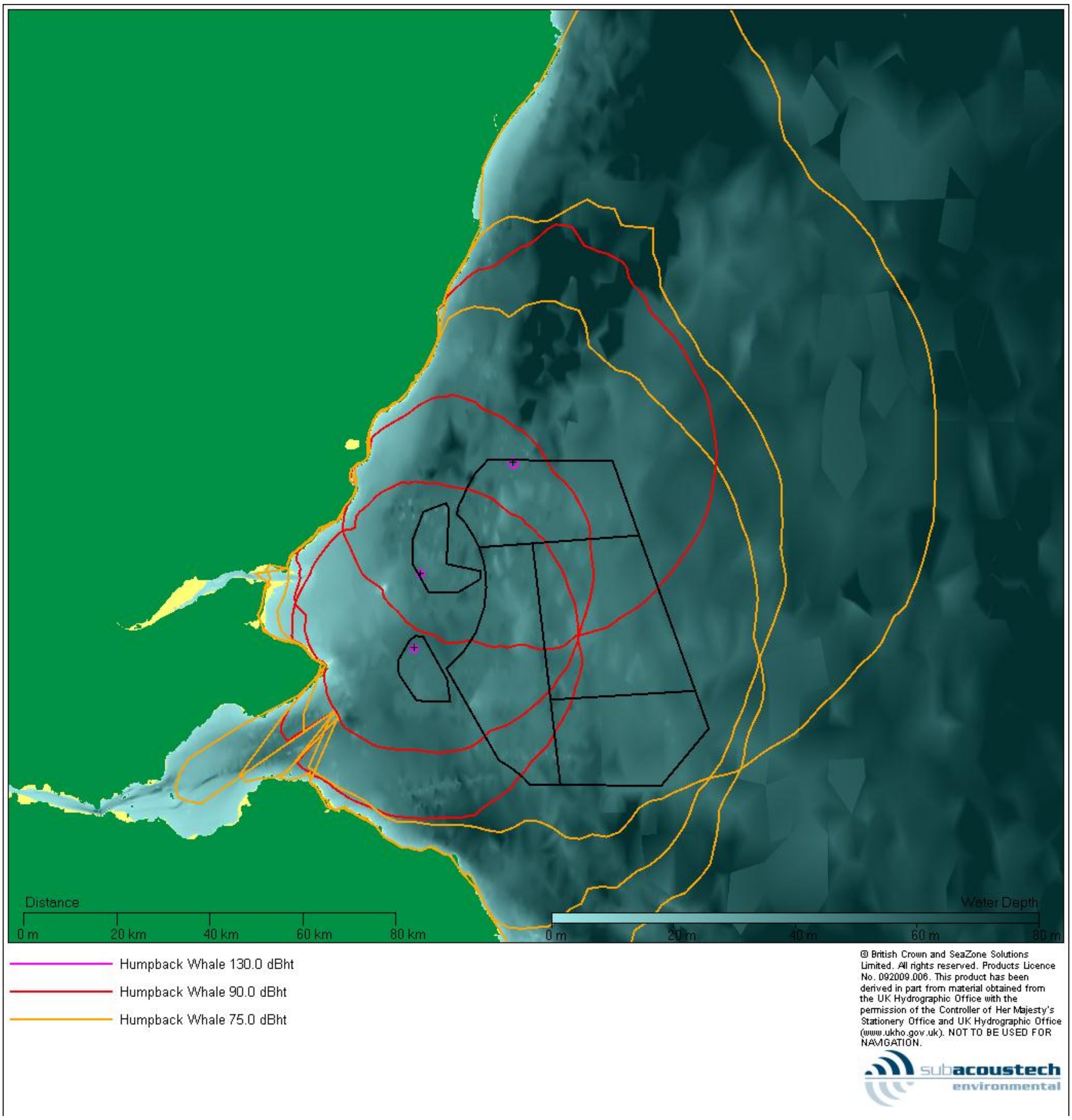

Figure 4-54 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the installation of simultaneous piles at NNG, Inch Cape and Seagreen

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 4-7 to 4-11 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 at a single location a maximum range of 8.4 km is likely to be needed at the onset of the impact piling for the NNG drill-drive scenario to avoid a damaging exposure to sound using the Southall criteria.

The maximum range for a cumulative scenario of NNG drill-drive, Inch Cape and Seagreen, is seen to be 47.3 km for the 186 dB criteria for Pinnipeds (in water). Low ranges of less than 100 m are typically predicted for all the criteria using the 198 dB threshold. Some very high ranges are predicted for some of the cetacean plots, which are calculated on the transect of an animal starting between the piles and ‘fleeing’ in a straight line directly through the path of the piling. This can be considered an unrealistic situation.

Figures 4-55 to 4-60 show contour plots for Pinnipeds (in water), for the NNG scenarios and simultaneous piling alongside the other Firth of Forth sites. The contours represent the modelled starting ranges for a fleeing animal to receive a level of 186 dB re 1 $\mu Pa^2/s$ (M_{pw}) over the total installation time of the pile.

NNG Drill-drive	**Range to auditory injury criteria**		
	Max	**Min**	**Mean**
Low Frequency Cetacean (198 dB re. 1 $\mu Pa^2/s$ (M_{lf})	<100 m	<100 m	<100 m
Mid Frequency Cetacean (198 dB re. 1 $\mu Pa^2/s$ (M_{mf})	<100 m	<100 m	<100 m
High Frequency Cetacean (198 dB re. 1 $\mu Pa^2/s$ (M_{hf})	<100 m	<100 m	<100 m
Pinnipeds (in water) (186 dB re. 1 $\mu Pa^2/s$ (M_{pw})	8400 m	6800 m	7900 m
Pinnipeds (in water) (198 dB re. 1 $\mu Pa^2/s$ (M_{pw})	<100 m	<100 m	<100 m

Table 4-7 Summary of the ranges out to which auditory injury is predicted during the installation of jacket for a fleeing animal using the M-Weighted SEL criteria

NNG Drill-drive and Seagreen	**Range to auditory injury criteria**		
	Max	**Min**	**Mean**
Low Frequency Cetacean (198 dB re. 1 $\mu Pa^2/s$ (M_{lf})	<100 m	<100 m	<100 m
Mid Frequency Cetacean (198 dB re. 1 $\mu Pa^2/s$ (M_{mf})	<100 m	<100 m	<100 m
High Frequency Cetacean (198 dB re. 1 $\mu Pa^2/s$ (M_{hf})	<100 m	<100 m	<100 m
Pinnipeds (in water) (186 dB re. 1 $\mu Pa^2/s$ (M_{pw})	44100 m	5500 m	21100 m

Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	<100 m	<100 m	<100 m

Table 4-8 Summary of the ranges out to which auditory injury is predicted during the installation of simultaneous piles for a fleeing animal using the M-Weighted SEL criteria

NNG Drill-drive and Inch Cape	**Range to auditory injury criteria**		
	Max	**Min**	**Mean**
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{lf})	8400 m	<100 m	1120 m
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{mf})	8100 m	<100 m	500 m
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{hf})	8100 m	<100 m	460 m
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M_{pw})	23500 m	10900 m	17300 m
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	8500 m	<100 m	1280 m

Table 4-9 Summary of the ranges out to which auditory injury is predicted during the installation of simultaneous piles for a fleeing animal using the M-Weighted SEL criteria

NNG Drill-drive, two locations within NNG	**Range to auditory injury criteria**		
	Max	**Min**	**Mean**
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{lf})	3900 m	<100 m	480 m
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{mf})	2500 m	<100 m	230 m
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{hf})	2200 m	<100 m	190 m
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M_{pw})	14800 m	9700 m	13190 m
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	3900 m	<100 m	540 m

Table 4-10 Summary of the ranges out to which auditory injury is predicted during the installation of simultaneous piles for a fleeing animal using the M-Weighted SEL criteria

NNG Drill-drive, Inch Cape and Seagreen	**Range to auditory injury criteria**		
	Max	**Min**	**Mean**
Low Frequency Cetacean	20200 m	<100 m	1310 m

(198 dB re. 1 $\mu Pa^2/s$ (M_{lf})			
Mid Frequency Cetacean (198 dB re. 1 $\mu Pa^2/s$ (M_{mf})	6800 m	<100 m	360 m
High Frequency Cetacean (198 dB re. 1 $\mu Pa^2/s$ (M_{hf})	6800 m	<100 m	340 m
Pinnipeds (in water) (186 dB re. 1 $\mu Pa^2/s$ (M_{pw})	47300 m	15700 m	26400 m
Pinnipeds (in water) (198 dB re. 1 $\mu Pa^2/s$ (M_{pw})	20200 m	<100 m	1510 m

Table 4-11 Summary of the ranges out to which auditory injury is predicted during the installation of simultaneous piles for a fleeing animal using the M-Weighted SEL criteria

Contour plots for the other M-weighting filters are not always visible as they are too small to display on a figure at this scale.

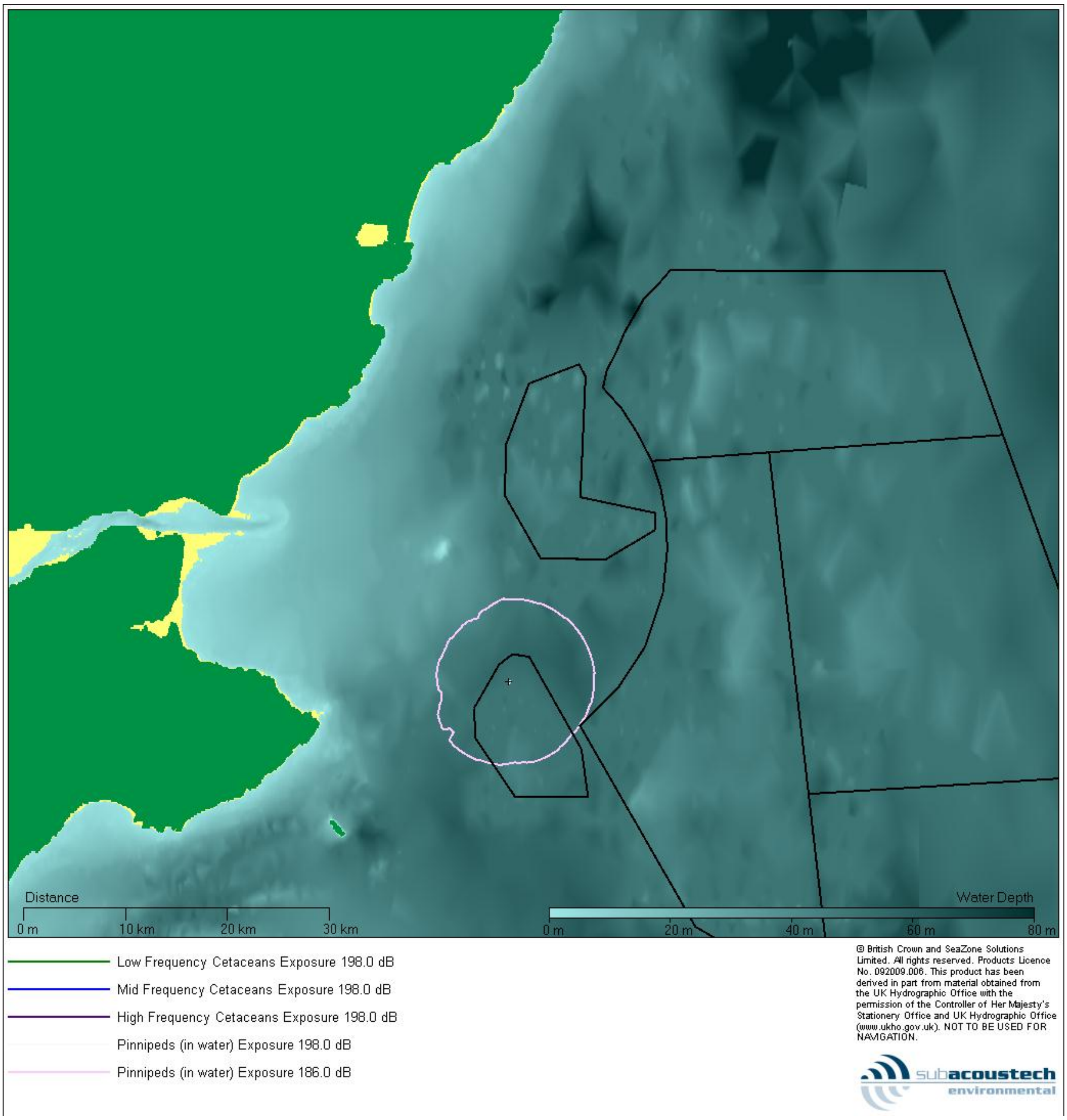

Figure 4-55 Contour plot showing the estimated M-Weighted SEL impact ranges for marine mammals for the NNG drill-drive scenario

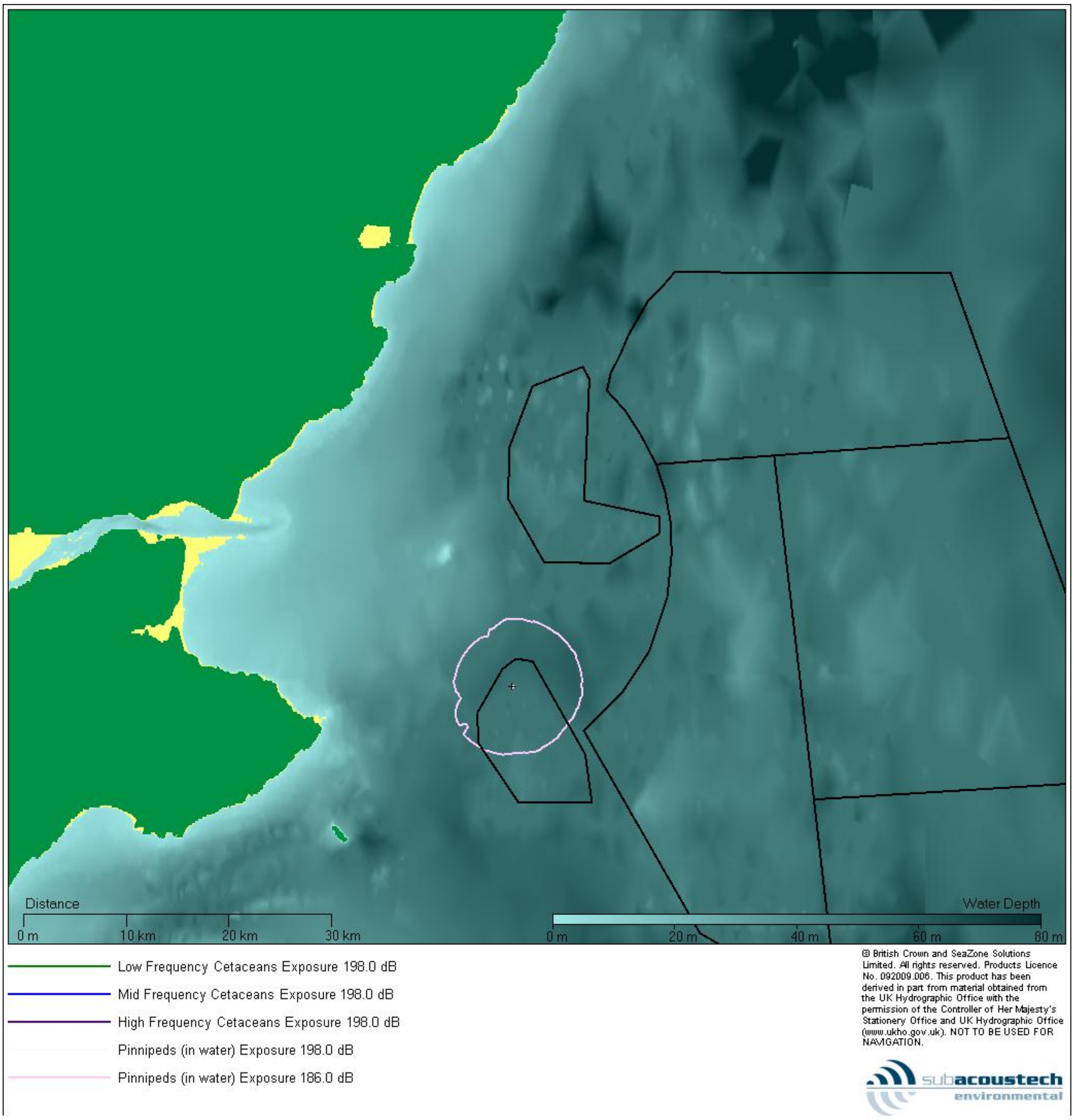

Figure 4-56 Contour plot showing the estimated M-Weighted SEL impact ranges for marine mammals for the NNG fully driven scenario

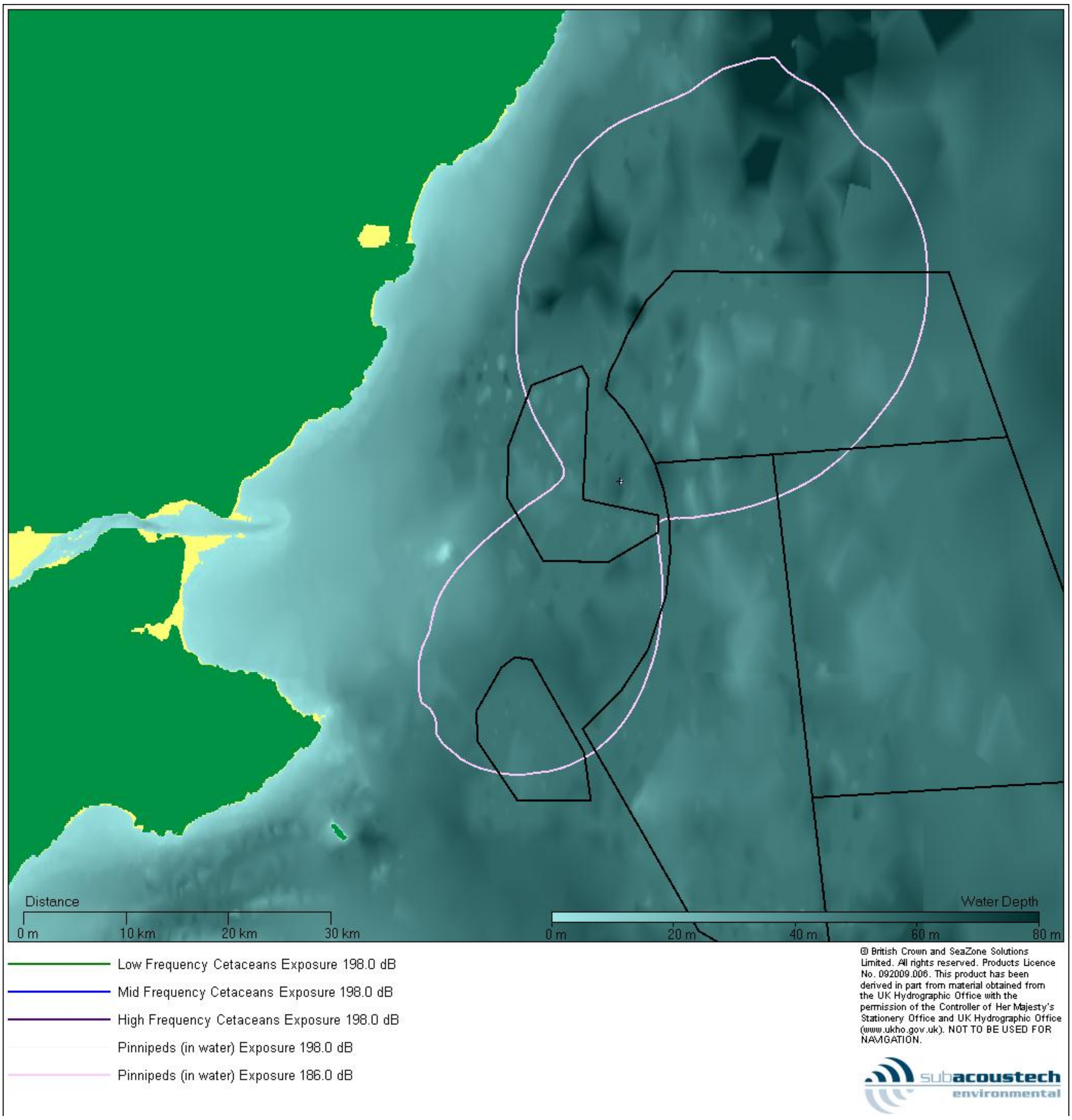

Figure 4-57 Contour plot showing the estimated M-Weighted SEL impact ranges for marine mammals for a cumulative scenario NNG drill-drive and Seagreen

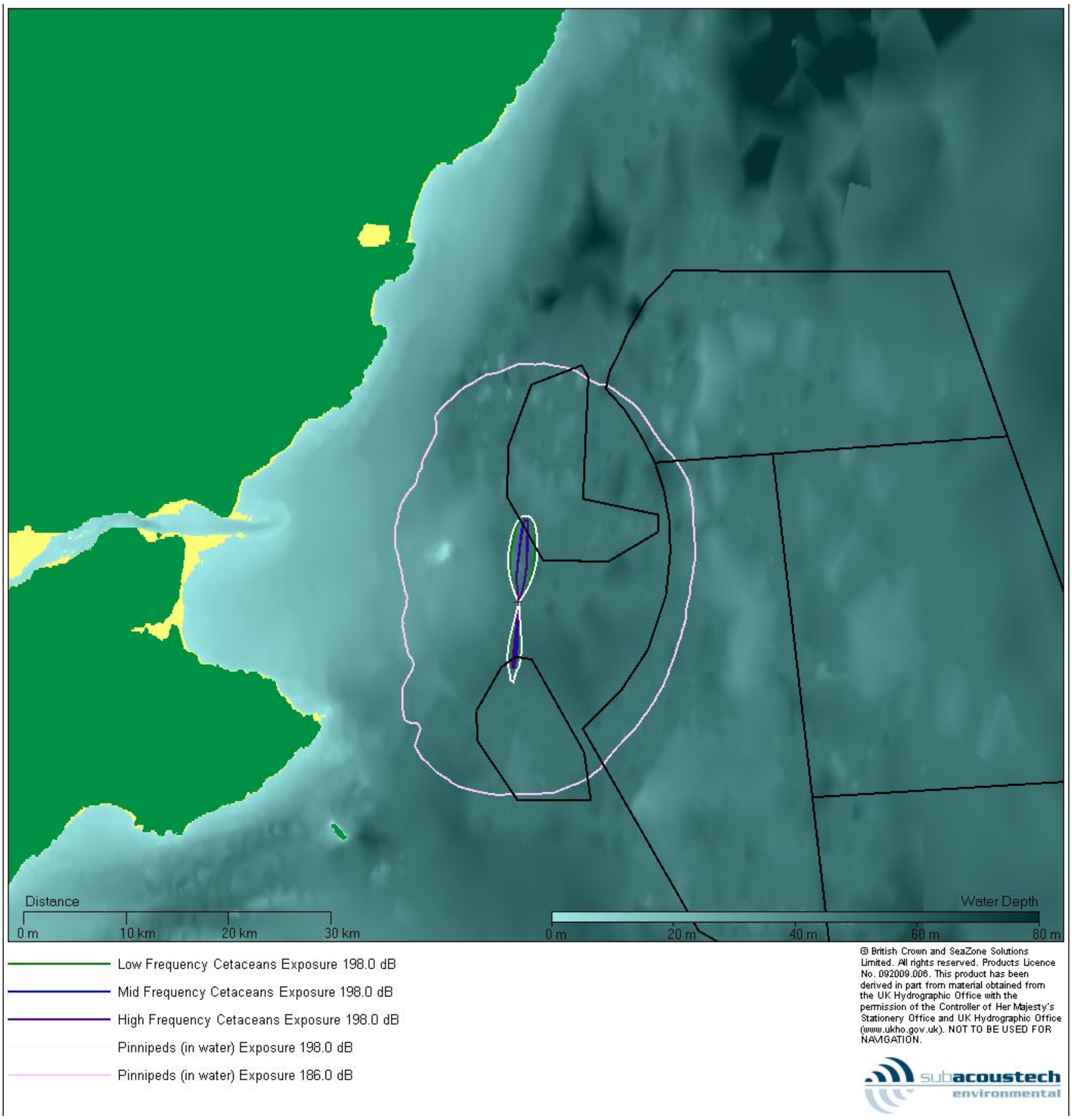

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Figure 4-58 Contour plot showing the estimated M-Weighted SEL impact ranges for marine mammals for a cumulative scenario NNG drill-drive and Inch Cape

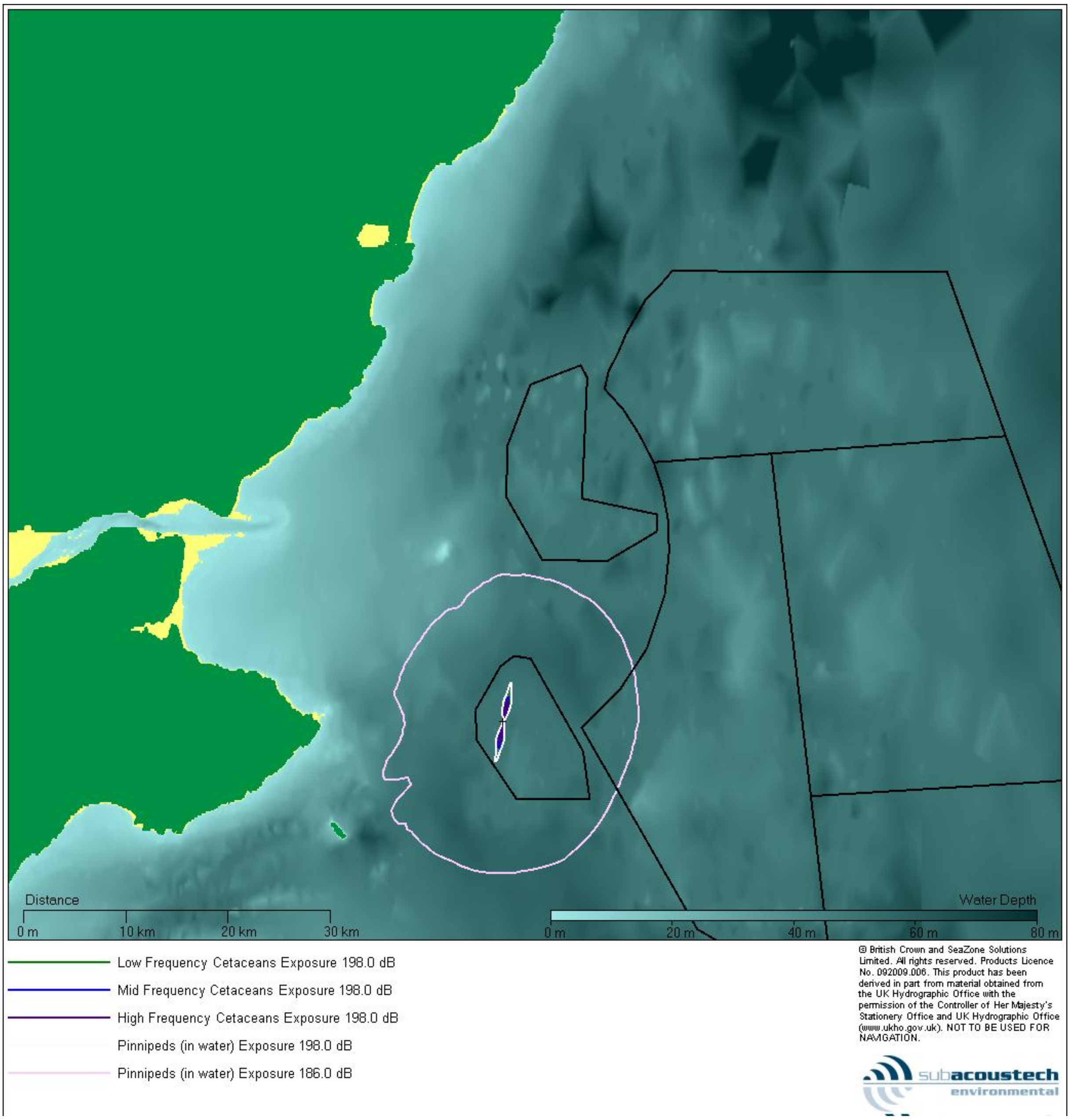

Figure 4-59 Contour plot showing the estimated M-Weighted SEL impact ranges for marine mammals for a cumulative scenario NNG drill-drive, two locations within NNG

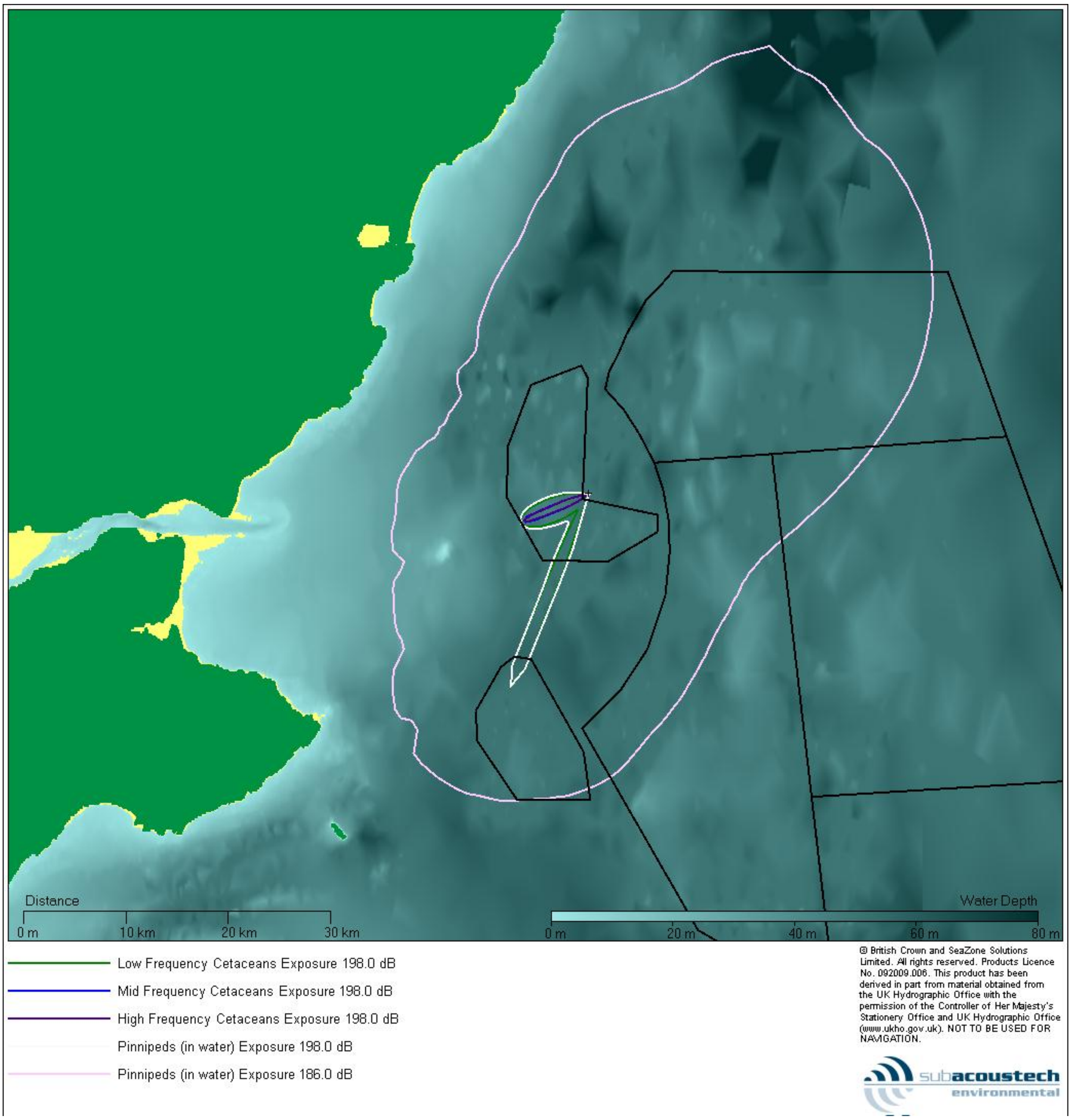

Figure 4-60 Contour plot showing the estimated M-Weighted SEL impact ranges for marine mammals for a cumulative scenario NNG drill-drive, Seagreen and Inch Cape

5 Summary and Conclusions

Subacoustech Environmental has undertaken a study on behalf of Mainstream Renewable Power to assess the impact of a range of impact piling scenarios at the NNG Wind Farm site in the Firth of Forth.

The level of underwater noise from the installation of jacket piles 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 less than 40 or 50 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 harbour porpoise and humpback whale, with 130 dB_{ht} ranges for the humpback whale of up to 690 m for the drill-drive scenario and 780 m for the fully driven scenario.

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 34 km, 20 km for the harbour porpoise and 41 km for the humpback whale worst case NNG fully driven scenario 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 a single location a maximum range of 8.4 km is likely to be needed at the onset of the impact piling for the NNG drill-drive scenario to avoid a damaging exposure to sound using the Southall criteria. Lower ranges are predicted for all the criteria using the 198 dB threshold. The maximum range for a cumulative scenario of NNG drill-drive, Inch Cape and Seagreen, has been found to be 47.3 km for the 186 dB criteria for Pinnipeds (in water).

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