Appendix H6

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Modelling of Noise during Impact Piling Operations at the Firth of Forth Phase 1 Offshore Wind Farm

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List of Contents

Executive Summary

Subacoustech Environmental has undertaken a study on behalf of Seagreen Wind Energy Limited to calculate the range of effect of underwater noise produced during pile driving operations during the installation of wind turbines at the Seagreen Wind Farm site, situated in the Firth of Forth.

The levels of underwater noise from the installation of monopiles and 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 based on and 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 Firth of Forth Phase 1 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, may occur out to a range of less than 40 m. Physical injury, where peak to peak pressure levels exceed 220 dB re. µPa, may occur out to a maximum range of 60 or 80 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 820 m during the fully driven scenario and 740 m during the drill-drive scenario. It should be noted that the auditory data available for the humpback whale (based on Erbe, 2002) is only theoretical and should be regarded as tentative only.

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 35 km, 21 km for the harbour porpoise and 45 km for the humpback whale for the worst case fully driven 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 (in water). For piling operations at a single location, a maximum range of 9.2 km is likely to be needed at the onset of the impact piling for the GM1 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 simultaneous piling occurring at Firth of Forth Phase 1 (GM1 scenario), Inch Cape Offshore Wind Farm and Neart Na Gaoithe Wind Farm, is seen to be 31 km for the 186 dB SEL M-Weighted criteria for Pinnipeds (in water).

1 Introduction

1.1 Project description

Subacoustech Environmental have been tasked by the Seagreen Wind Energy Limited, as part of the Forth and Tay Offshore Developer's Group, to investigate, by means of subsea noise modelling, the impact of proposed piling operations at the Seagreen 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 site is situated in the North Sea in water depths typically between 30 and 70 metres.

The FTOWDG development site includes three sites:

- Seagreen (Phases 1 to 3);
- Inch Cape; and
- Neart Na Gaoithe (NNG).

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

This report is intended to inform Seagreen Wind Energy 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 Limited to estimate the likely level of underwater noise during the installations of wind turbines using impact piling at the Seagreen 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 Seagreen 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.

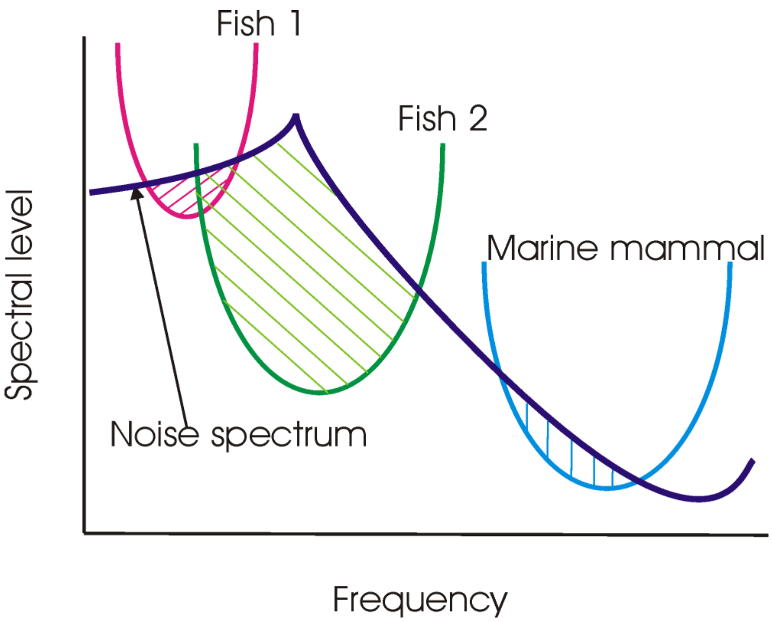

Figure 2-1. Illustration of perceived sound level (dB$_{ht}$) for representative fish and marine mammal species.

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); and
- 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 Firth of Forth 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); and
- 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 harbour 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.). 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-pk} re 1 µPa and a sound exposure level (SEL) of 164.3 dB re. 1 µPa^{2}s, 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}(*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
50 - 75	Avoidance is unlikely
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 lless 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. The grey seal has similar auditory capabilities to the harbour seal and so the harbour seal has been used as a surrogate species in the modelling;
- 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 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 been used as a surrogate for minke whale.

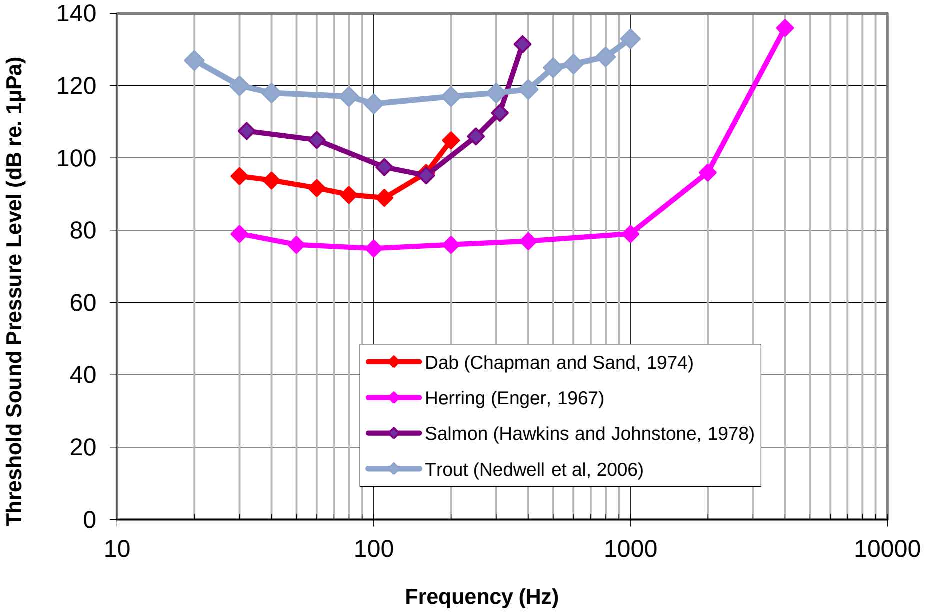

Figure 3-1 Comparison of hearing thresholds for species of fish

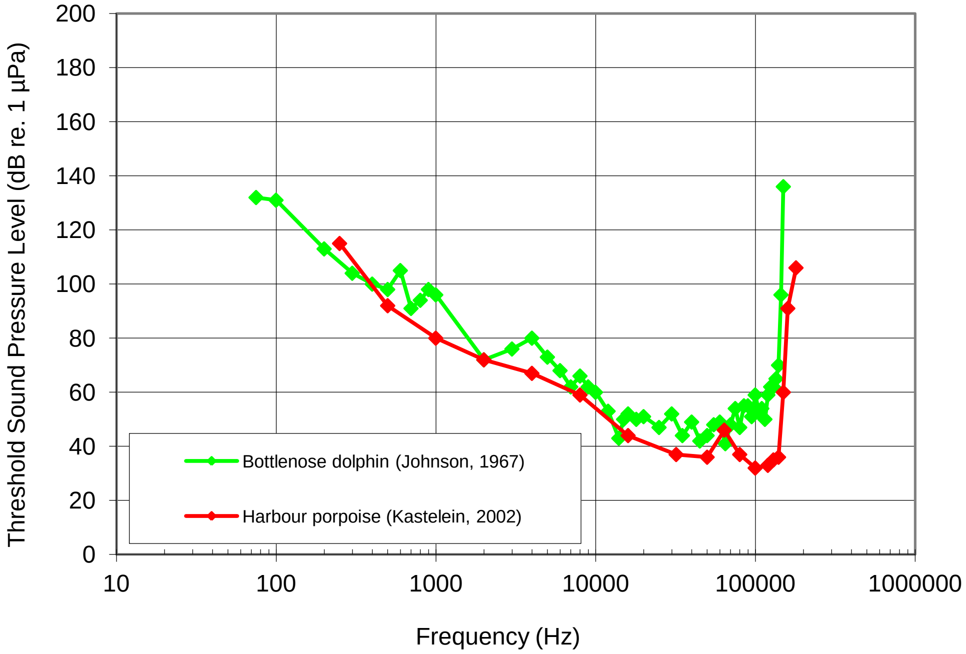

Figure 3-2 Comparison of hearing thresholds for species of marine mammal

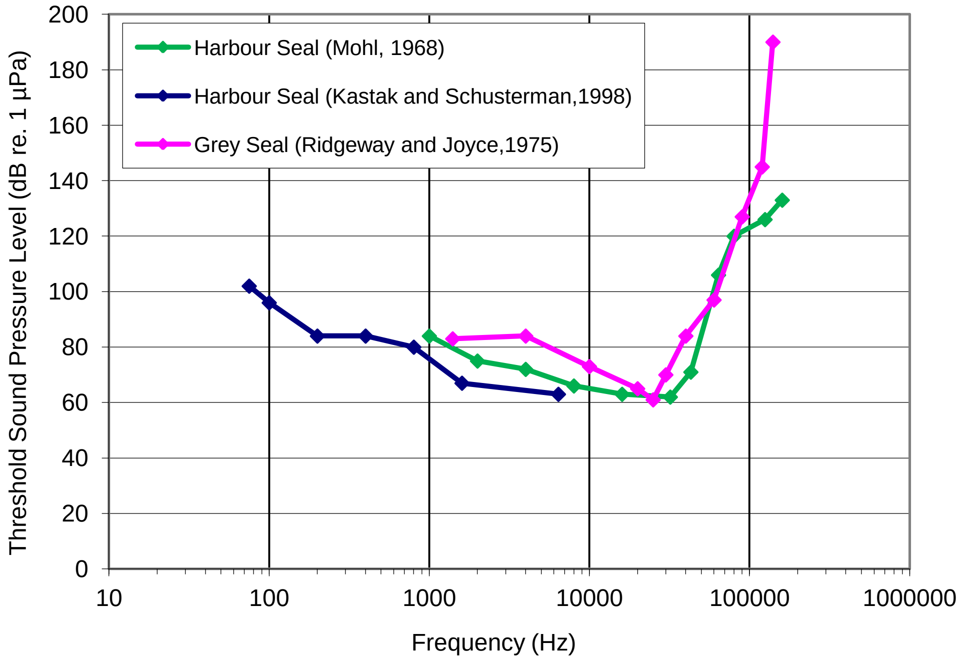

Figure 3-3 Comparison of auditory threshold levels of various species of seal

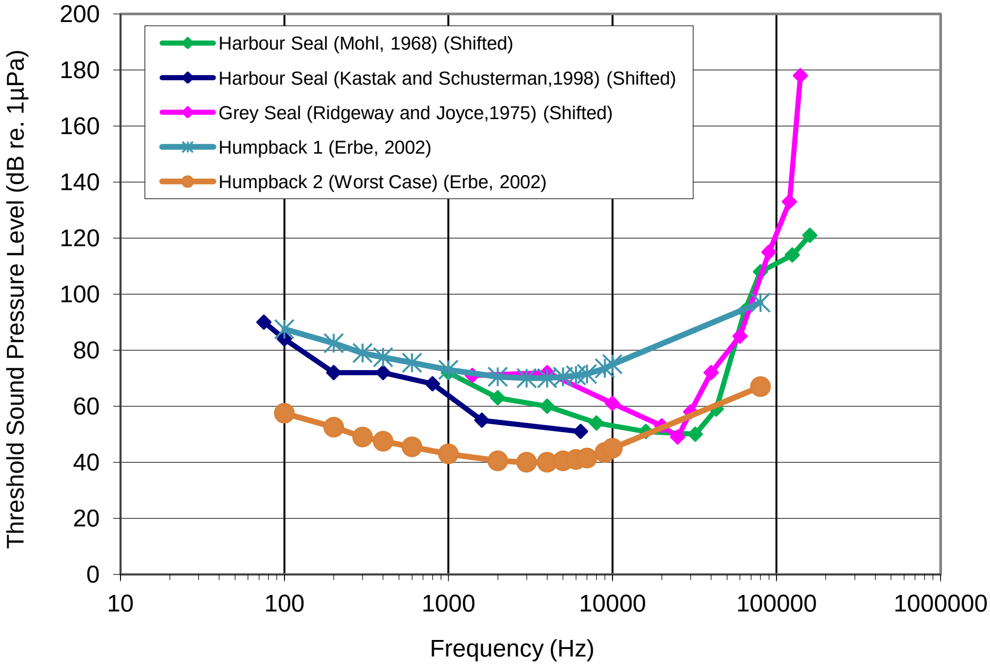

Figure 3-4 The audiograms for Humpback Whale, presented in Erbe (2002), presented with the shifted seal audiograms used for the calculations in this study

3.3 JNCC Guidelines

Joint Nature Conservation Committee (JNCC), Natural England and Countryside Council for Wales 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 Wales 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 seismic surveys, piling operations and the use of explosives. General protocols have been written, by the JNCC, for these three activities offering mitigation measures in order to minimise the risk of injury to marine mammals and are annexed in the protection of marine EPS from injury and disturbance guidance document.

The JNCC document outlining protocol for minimising the risk of injury to marine mammals from piling noise 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, 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 averting to the standard protocol.

4 Baseline Environment

As a result of military research oceanic ambient noise is relatively well understood. However, the information from these studies may not be directly relevant to coastal waters, where ambient underwater noise can be more variable and significantly louder or quieter than in the deep oceans. In the underwater acoustics field it is commonly considered that shallow water is any water depth less than 200 m. However, it may be argued that a more useful definition of deep water should be related to the wavelength of the sound. Using this approach, assuming a frequency of 50 Hz, water may be considered shallow in depths of about 30 m or less, which corresponds more closely to the sort of water depths in areas where offshore wind farms are built.

Over the past 20 years Subacoustech Ltd has taken several thousand noise measurements of background underwater noise during offshore construction projects in United Kingdom (UK) territorial waters. The set of measurements is unique, in that they all span a broad frequency range from 1 Hz to over 100 kHz, and also have a wide dynamic range in excess of 70 dB. All of the measurements are traceable to International Standards. These measurements have been conducted in a large range of different geographical locations and sea states around UK waters, and may be regarded as giving a realistic representation of background sound in UK territorial waters.

Some of this data have been analysed to yield typical spectra for underwater coastal background sound. Analyses have been made of recordings of underwater noise taken at 10 different sites, all of which are between 1 km and 20 km from the UK coast. These are shown on a map of the UK in Figure 4-1.

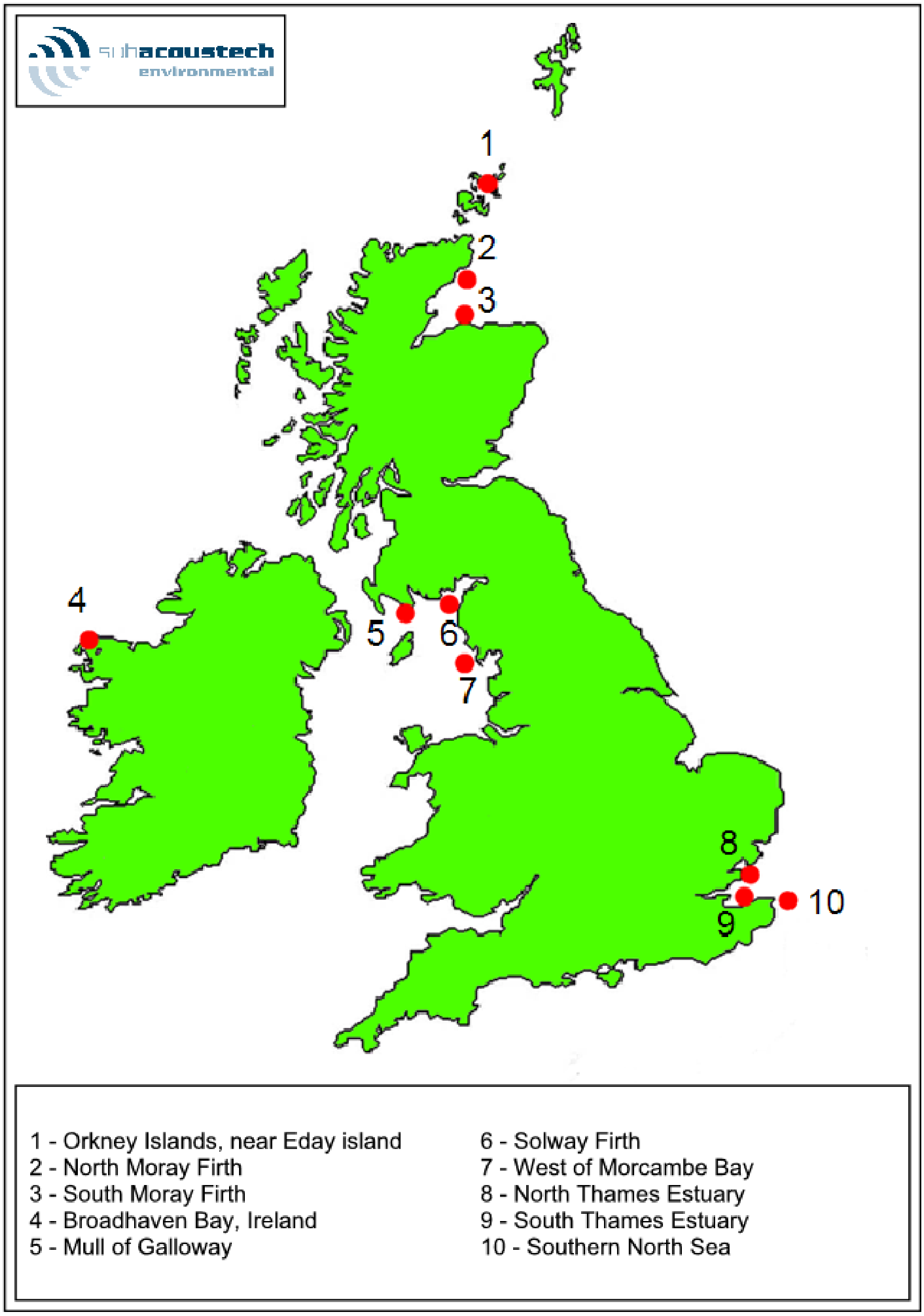

Figure 4-1. Map of the UK showing sites where background sound measurements have been collected and analysed.

All of these underwater noise measurements were made using a Bruel & Kjaer Type 8106 hydrophone, connected to a proprietary Subacoustech hydrophone power supply/amplifier. This amplifier provided power to, as well as conditioning and amplifying the acoustic signal from, the hydrophone, and also could pre-emphasise recordings where this was required in order to achieve an adequate dynamic range. The measurements presented in this study are based on analysis over the frequency range from 1 Hz to 120 kHz. All of the measurements presented were taken in the absence of precipitation, with no other noticeable sources of underwater noise, such as nearby shipping, and at either Sea State 1 or 3, with the hydrophone at half water depth (typically 10 m to 15 m below the surface).

Figures 4-2 and 4-3 below present a summary of the Power Spectral Density levels of underwater noise measured at the various sites, with the data from the Moray Firth highlighted, being the only data we have along the eastern Scottish coast, the closest to the Firth of Forth site, along with an average of all the data also shown. Figure 4-2 presents data for measurements during Sea State 1 conditions and Figure 4-3 presents data for slightly rougher Sea State 3 conditions.

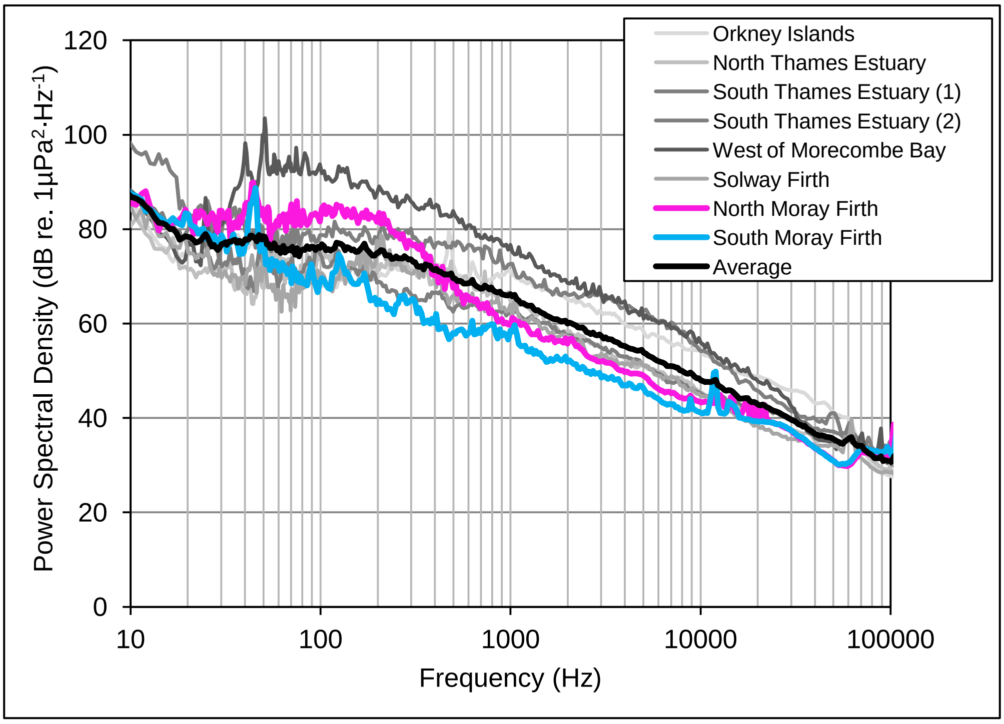

Figure 4-2. Summary of Power Spectral Density levels of background underwater noise at Sea State 1 at sites around the UK coast

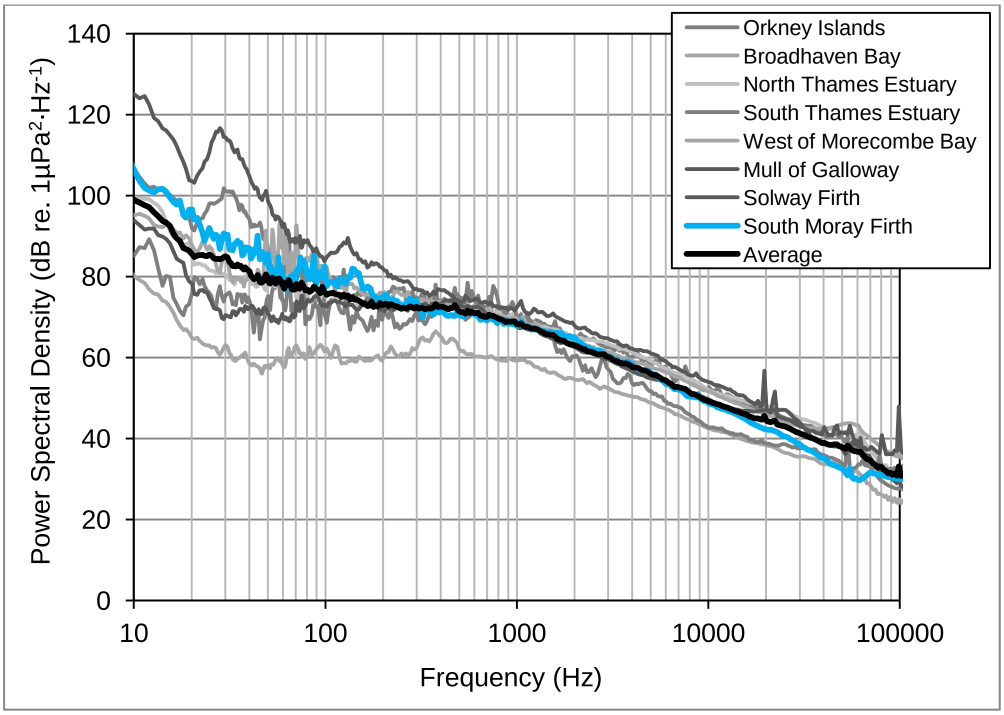

Figure 4-3 Summary of Power Spectral Density levels of background underwater noise at Sea State 3 at sites around the UK coast

It can be seen from these figures that the typical levels of background underwater noise in the Moray Firth region are very close to the overall average for the UK coast. In order to provide an estimate of the typical levels of background noise levels that may occur in the Moray Firth taking into account natural variation, it is therefore appropriate to use the averages, in terms of both weighted and unweighted metrics, presented in Table 4-1 below.

	Unweighted dB re.1 µPa	Bass dB$_{ht}$ (*Micropeterus salmoides*)	Cod dB$_{ht}$ (*Gadius Morhua*)	Dab dB$_{ht}$ (*Limanda limanda*)	Herring dB$_{ht}$ (*Clupea Harengus*)	Salmon dB$_{ht}$ (*Salmo salar*)	Bottlenose Dolphin dB$_{ht}$ (*Tursiops truncatus*)	Harbour Porpoise dB$_{ht}$ (*Phocoena phocoena*)	Harbour Seal dB$_{ht}$ (*Phoca vitulina*)	Killer Whale dB$_{ht}$ (*Orcinus orca*)
Overall Average Background Noise Levels – Sea State 1										
Max	126	15	39	26	42	17	66	74	43	66
Min	92	0	1	0	9	0	36	44	21	37
Mean	111	5	23	10	28	5	44	54	31	47
Overall Average Background Noise Levels – Sea State 3										
Max	132	15	42	31	47	19	50	60	38	53
Min	94	0	3	0	11	0	30	42	7	29
Mean	112	4	22	11	28	5	41	52	27	43

Table 4-1. Summary of average background levels of noise around the UK at Sea States 1 and 3

5 Modelling of underwater sound levels as a function of range

5.1 Introduction to rank-ordering of noise sources using the SPEAR model

The first phase of the underwater noise modelling was carried out using the simple yet realistic broad-brush Source Level-Transmission Loss (SL-TL) model, SPEAR. The model is based on Subacoustech Environmental's substantial database of noise sources, and provides an indication of the typical levels of underwater noise generated by wind farm related activities. The model allows the significance of a wide range of sources of underwater noise to be rank-ordered for a wide range of marine animals.

The results provided by this model allowed the elimination of most of the construction activities from further consideration as they were shown to have a negligible likelihood of causing an environmental impact when compared with impact piling.

5.2 Summary of noise scenarios for SPEAR modelling

Table 5-1 below provides a summary of the various parameters that have been input into the SPEAR model to account for the various scenarios presented above. Detailed information relating to the exact amount of time that activities will be carried out, for example duration of time a vessel will be on site or how long rock dumping will be taking place per day, is not available at this stage. It has therefore been necessary to take a very worst case estimation in terms of noise generation.

Activity	Parameters used for SPEAR modelling
Impact Piling	• Just over half an hour install per pile • 2000 mm and 3000 mm piles being considered
Rock Breaking	• Required for the cable installation at the Arbroath landfall out to below the 7 m water depth mark.
Rock Dumping	• Required on site for installation of the export cable • Also required if Gravity Base structures are to be used
Cable Laying	• Required during the export cable installation
Vessel Noise	• Jack-up barges for piling, substructure and WTG installation • Other large and medium sized vessel will be on site to carry out other construction tasks, diving support and anchor handling • Other small vessels for crew transport and survey work on site

Table 5-1. Summary of parameters taken into account in the SPEAR modelling

5.3 Results from SPEAR modelling

The SPEAR programme produced as output an 'index figure' which represents the area of ocean which is rendered unusable by a species as a result of a particular activity. The results shown below show 90 dB_{ht} impact ranges which illustrate the differences between all the species for a single activity (pile driving a 3 metre diameter pile) and the differences between different noise source for a single species of interest.

It is clear from the figures that impact piling is the dominant noise source and hence the activity that will have the greatest impact. This activity has therefore been studied in more detail using the INSPIRE model; the results from that are presented in the following sections.

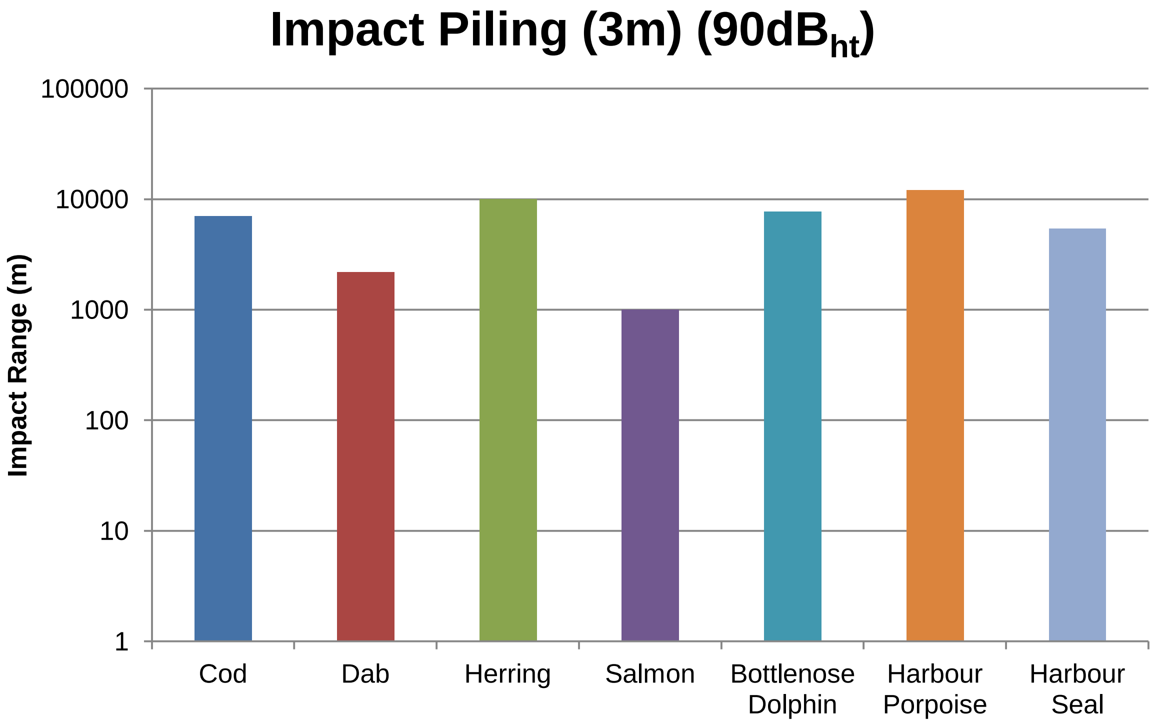

Figure 5-1. Spatial extent of impact of impact piling a 3m diameter pile, on various species of importance

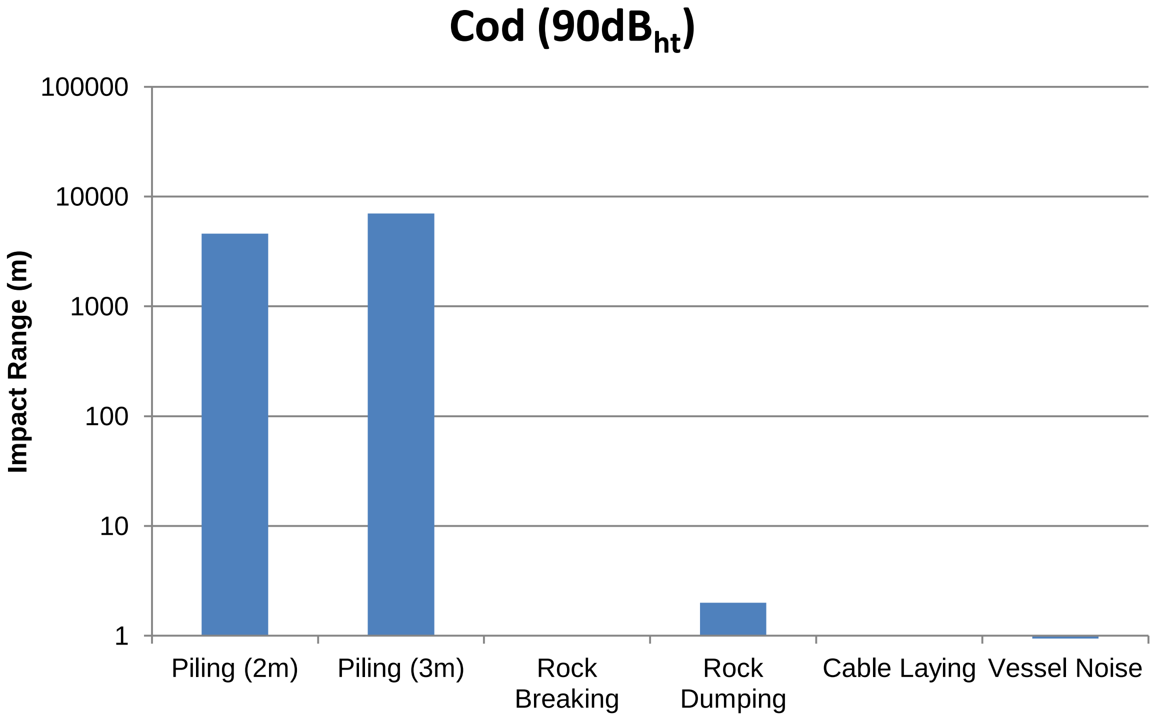

Figure 5-2. Spatial extent of impact of various activities on cod

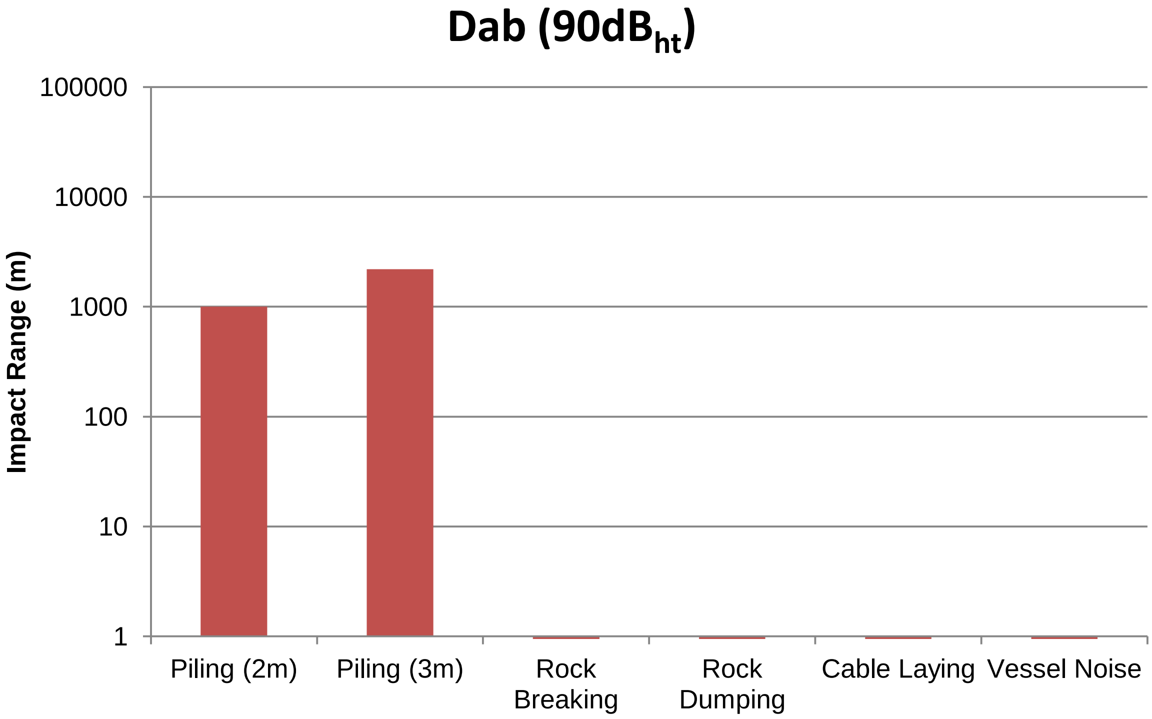

Figure 5-3. Spatial extent of impact of various activities on dab

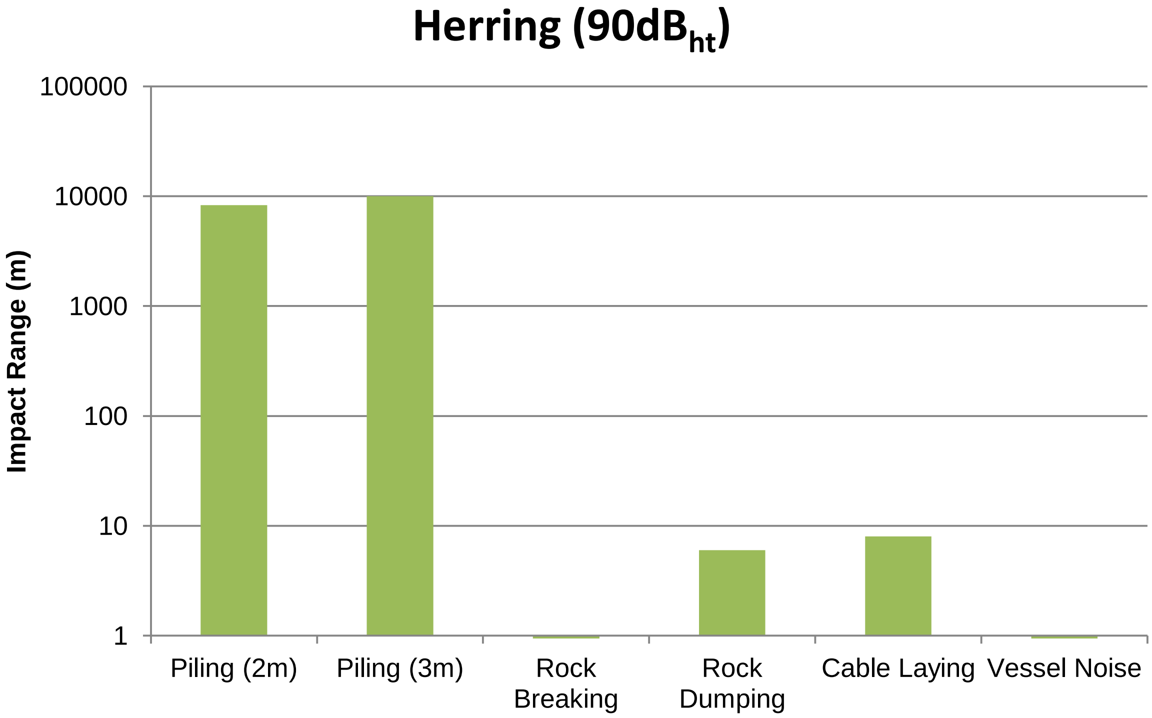

Figure 5-4. Spatial extent of impact of various activities on herring

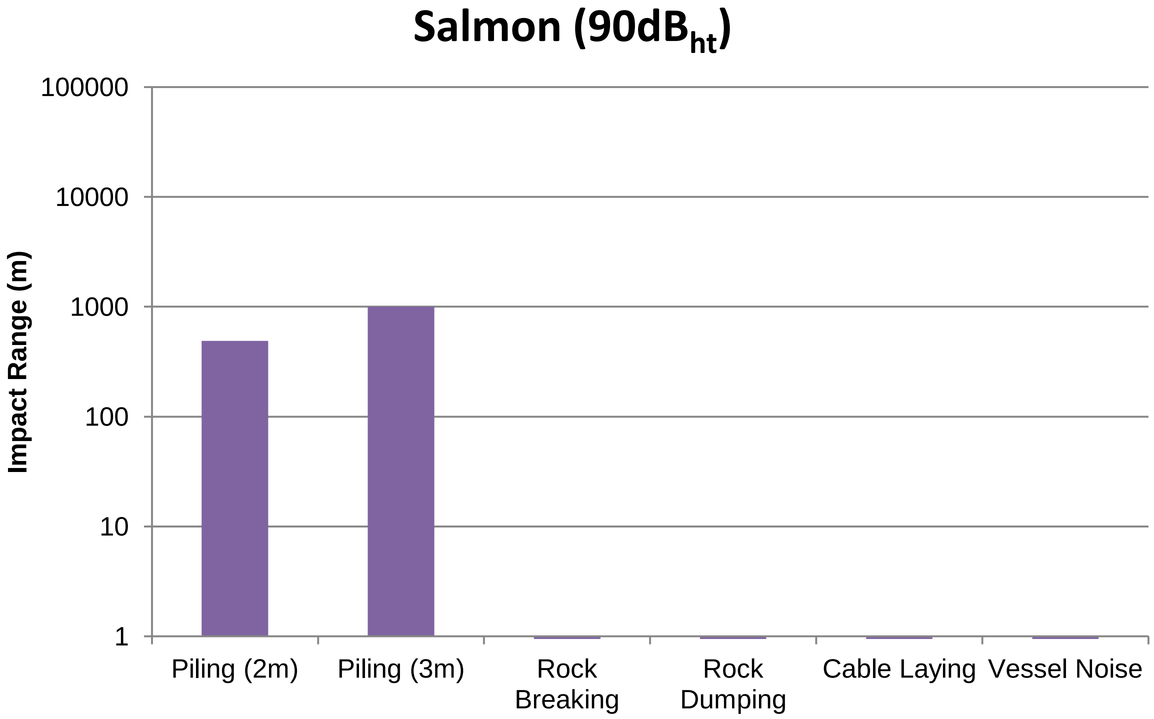

Figure 5-5. Spatial extent of impact of various activities on salmon

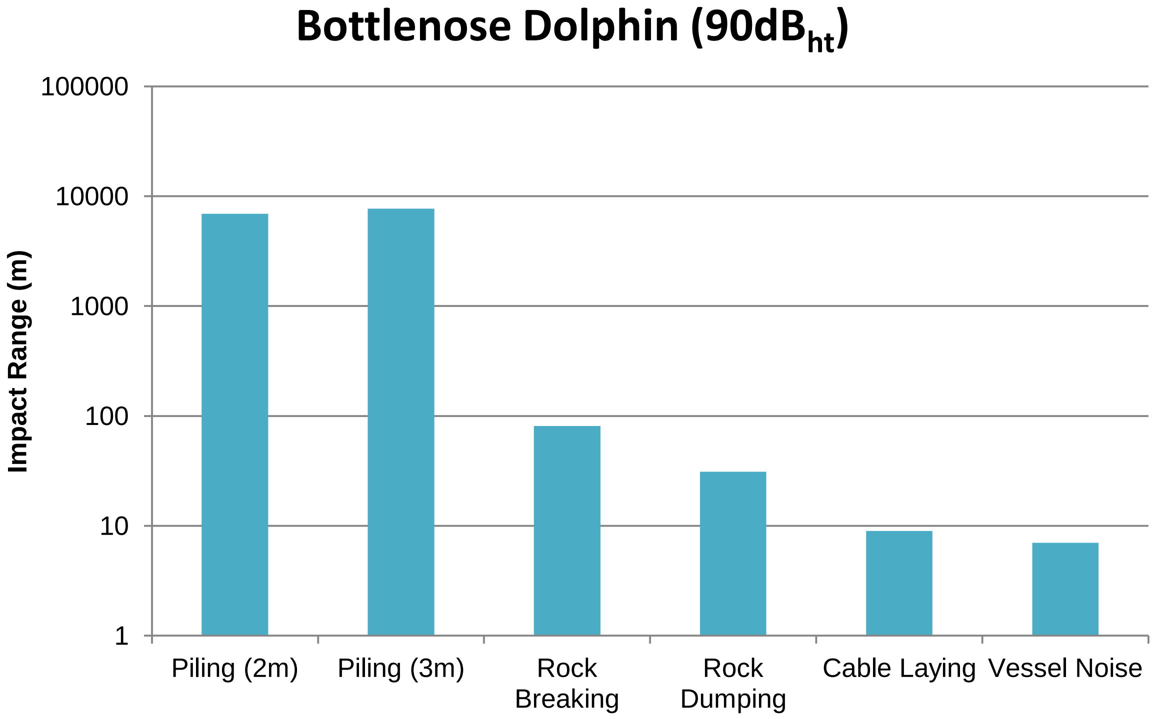

Figure 5-6. Spatial extent of impact of various activities on bottlenose dolphin

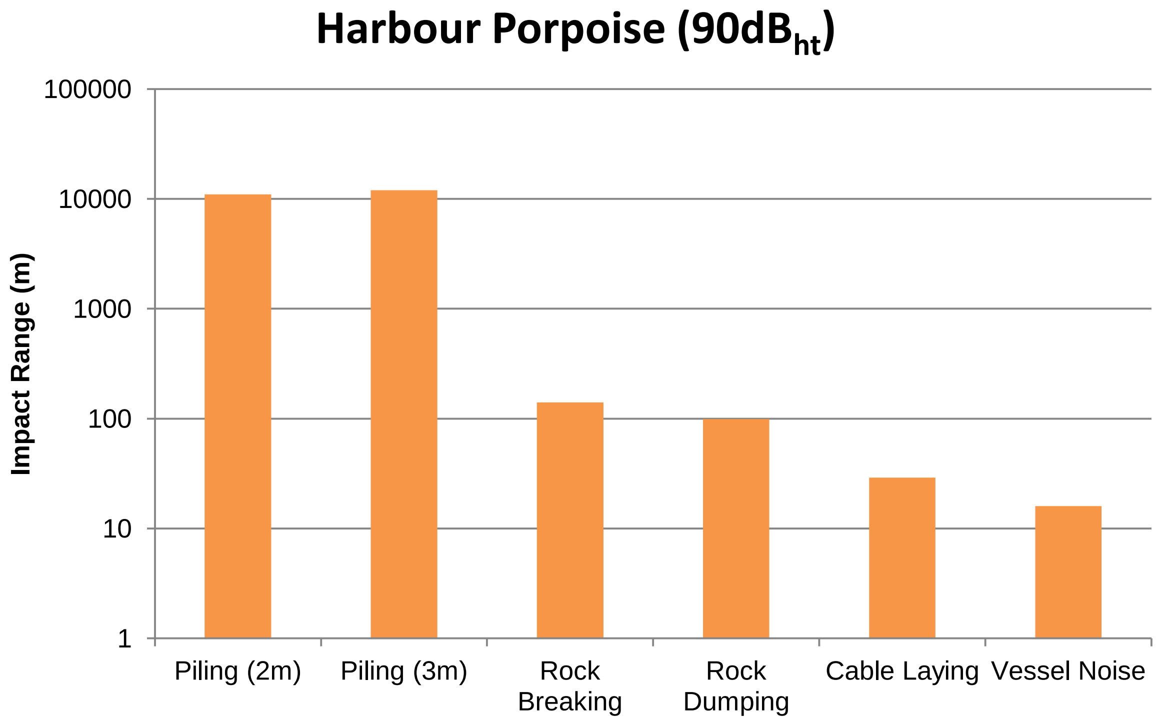

Figure 5-7. Spatial extent of impact of various activities on harbour porpoise

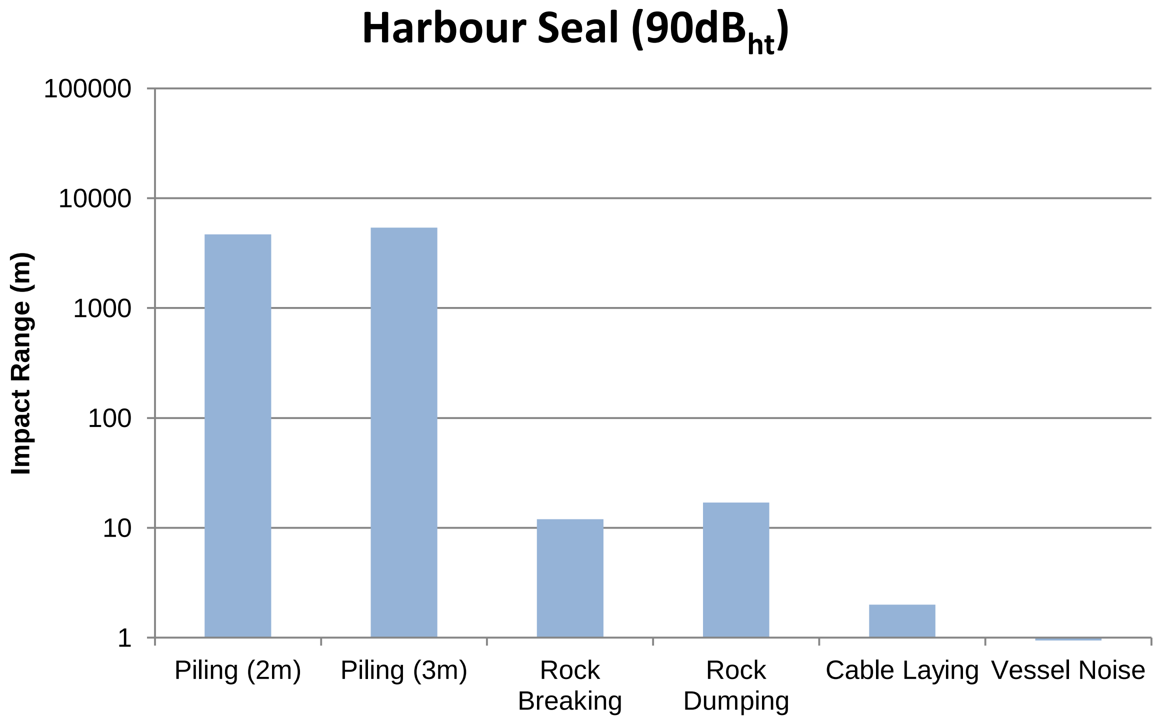

Figure 5-8. Spatial extent of impact of various activities on harbour seal

6 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 Seagreen 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 Seagreen 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.

6.1 Modelling Locations

The following locations were considered in the noise modelling exercise:

Location ID	Coordinates
Seagreen – (alpha)	56.6718; -1.9314
Seagreen – (bravo)	56.5897; -1.7328
Inch Cape	56.4583; -2.2579
NNG	56.3139; -2.2803

Table 6-1 Piling locations for each modelling scenario

6.2 Modelling scenarios

Four scenarios were modelled at two positions in the Seagreen 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 Tables 6-2 to 6-5 below.

	Total piling duration	% of maximum hammer capacity
Ramp-up details for GM1 (max. 1800 kJ)	6 minutes	15%
	4 minutes	35%
	5 minutes	55%
	10 minutes	75%
	30 minutes	95%

Table 6-2 Summary of the GM1 fully driven scenario, 2 m diameter pile

	Total piling duration	% of maximum hammer capacity
Ramp-up details for GM2 (max. 1800 kJ)	7 minutes	15%
	9 minutes	35%
	6 minutes	55%
	4 minutes	75%
	7 minutes	95%

Table 6-3 Summary of the GM2 fully driven scenario, 3 m diameter pile

	Total piling duration	% of maximum hammer capacity
Ramp-up details for GM3 (max. 1200 kJ)	5 minutes	15%
	12 minutes	35%
	11 minutes	55%
	5 minutes	75%

Table 6-4 Summary of the GM3 drill-drive scenario, 2 m diameter pile

	Total piling duration	% of maximum hammer capacity
Ramp-up details for GM4 (max. 1200 kJ)	13 minutes	15%
	14 minutes	35%
	10 minutes	55%
	6 minutes	75%
	4 minutes	95%

Table 6-5 Summary of the GM4 drive-drill scenario, 2 m diameter pile

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 for Inch Cape (max. 1200 kJ)	47 minutes	20%
	27 minutes	40%
	27 minutes	60%
	27 minutes	80%
	27 minutes	100%

Table 6-6 Summary of the Inch Cape scenario, 2.438 m diameter pile

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

	Total piling duration	% of maximum hammer capacity
Ramp-up details for NNG (max. 996 kJ)	20 minutes	24%
	80 minutes	100%
	20 minutes	24%
	100 minutes	100%

Table 6-7 Summary of the NNG scenario, 2.5 m diameter pile

6.3 Unweighted levels

Table 6-8 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 40 metres at maximum blow energy, and that physical injury is likely to occur out to less than 60 metres or 80 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)
GM1 (alpha)	< 40 m	< 60 m
GM1 (bravo)	< 40 m	< 60 m
GM2 (alpha)	< 40 m	< 80 m
GM2 (bravo)	< 40 m	< 80 m
GM3 (alpha)	< 40 m	< 60 m
GM3 (bravo)	< 40 m	< 60 m
GM4 (alpha)	< 40 m	< 60 m
GM4 (bravo)	< 40 m	< 60 m
Inch Cape	< 40 m	< 80 m
NNG	< 40 m	< 60 m

Table 6-8 Summary of ranges out to which lethal effect and physical injury are expected to occur in marine species

6.4 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 820 m during the fully driven scenario and 740 m during the drill-drive scenario. It should be reiterated that these figures are based on the theoretical humpback whale audiogram, which is very tentative and has a large potential error.

Tables 4-9 to 4-18 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 at each location (alpha and bravo). The predicted behavioural responses have also been presented for piling at the Inch Cape and NNG offshore wind farm sites.

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 35 km, 21 km for the harbour porpoise and 45 km for the humpback whale for the GM2 (bravo) fully driven 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 some of the minimum 75 dB$_{ht}$ ranges calculated for the alpha location at the Seagreen wind farm site are seen to be 33 km, as this is the minimum distance between the wind turbine position and the coastline.

As the mean values quoted 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.

Seagreen – GM1 (alpha)	**Range to 130 dB$_{ht}$ (km)**			
	Max	**Min**	**Mean**	**Area**
Dab	<0.1	<0.1	<0.1	0
Herring	0.25	0.25	0.25	0.2
Salmon	<0.1	<0.1	<0.1	0
Sand Lance	n/a	n/a	n/a	n/a
Trout	n/a	n/a	n/a	n/a
Bottlenose Dolphin	0.4	0.3	0.35	0.4
Harbour Porpoise	0.6	0.6	0.6	1.2
Harbour Seal	0.2	0.2	0.2	0.1
Humpback Whale	0.8	0.8	0.8	2.2

Table 6-9a Summary of dB$_{ht}$ ranges for the GM1 (alpha) fully driven scenario

Seagreen – GM1 (alpha)	**Range to 90 dB$_{ht}$ (km)**				**Range to 75 dB$_{ht}$ (km)**			
	Max	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**	**Area**
Dab	2.9	2.7	2.8	25	16	15	16	785
Herring	28	25	26	2100	77	33	55	10,000
Salmon	1.3	1.3	1.3	5.5	8.4	8.0	8.2	210
Sand Lance	0.2	0.2	0.2	0.1	1.4	1.4	1.4	6
Trout	0.3	0.2	0.3	0.2	1.8	1.7	1.8	10
Bottlenose Dolphin	13	13	13	550	39	33	35	3900
Harbour Porpoise	21	20	20	1260	59	33	47	7173.5
Harbour Seal	17	16	17	870	55	33	44	6028.1
Humpback Whale	45	33	38	4600	99	33	68	15878.2

Table 6-10b Summary of dB$_{ht}$ ranges for the GM1 (alpha) fully driven scenario

Seagreen – GM1 (bravo)	Range to 130 dB$_{ht}$ (km)			
	Max	Min	Mean	Area
Dab	0.04	0.02	0.03	0
Herring	0.26	0.24	0.25	0.2
Salmon	0.04	0.02	0.03	0
Sand Lance	0	0	0	0
Trout	0	0	0	0
Bottlenose Dolphin	0.36	0.34	0.35	0.38
Harbour Porpoise	0.64	0.62	0.63	1.24
Harbour Seal	0.2	0.18	0.19	0.11
Humpback Whale	0.84	0.82	0.83	2.15

Table 6-11a Summary of dB$_{ht}$ ranges for the GM1 (bravo) fully driven scenario

Seagreen – GM1 (bravo)	Range to 90 dB$_{ht}$ (km)				Range to 75 dB$_{ht}$ (km)			
	Max	Min	Mean	Area	Max	Min	Mean	Area
Dab	2.9	2.8	2.9	25.5	17	16	16	810.6
Herring	28	25	26	2164.4	74	43	60	11458.6
Salmon	1.3	1.3	1.3	5.5	8.4	8.2	8.3	216.5
Sand Lance	0.2	0.2	0.2	0.1	1.4	1.4	1.4	6.21
Trout	0.3	0.2	0.3	0.2	1.8	1.8	1.8	9.8
Bottlenose Dolphin	14	13	13	557.2	40	34	36	4125.3
Harbour Porpoise	21	20	20	1276.1	57	43	51	8120.7
Harbour Seal	17	16	17	885	53	42	47	6827
Humpback Whale	45	37	40	5053.5	99	42	75	18195

Table 6-12b Summary of dB$_{ht}$ ranges for the GM1 (bravo) fully driven scenario

Seagreen – GM2 (alpha)	Range to 130 dB$_{ht}$ (km)			
	Max	Min	Mean	Area
Dab	0.06	0.04	0.05	0.01
Herring	0.34	0.32	0.33	0.34
Salmon	0.04	0.02	0.03	0
Sand Lance	0	0	0	0
Trout	0.04	0.02	0.03	0
Bottlenose Dolphin	0.36	0.34	0.35	0.38
Harbour Porpoise	0.64	0.62	0.63	1.24
Harbour Seal	0.2	0.18	0.19	0.11
Humpback Whale	0.82	0.8	0.81	2.05

Table 6-13a Summary of dB$_{ht}$ ranges for the GM2 (alpha) fully driven scenario

Seagreen – GM2 (alpha)	Range to 90 dB$_{ht}$ (km)				Range to 75 dB$_{ht}$ (km)			
	Max	Min	Mean	Area	Max	Min	Mean	Area
Dab	5.8	5.5	5.7	100.7	28	25	26	2123.5
Herring	34	29	30	2897.2	85	33	60	11965.3
Salmon	2.2	2.2	2.2	15.2	12	12	12	456.2
Sand Lance	0.2	0.2	0.2	0.1	1.8	1.8	1.8	10.4
Trout	0.4	0.3	0.4	0.4	2.4	2.4	2.4	18.3
Bottlenose Dolphin	14	13	13	562.9	40	33	36	3957.7
Harbour Porpoise	21	20	20	1273.3	59	33	48	7215.4

Harbour Seal	17	16	17	850.7	54	33	43	5961
Humpback Whale	45	33	39	4535	98	33	68	15701.7

Table 6-14b Summary of dB$_{ht}$ ranges for the GM2 (alpha) fully driven scenario

Seagreen – GM2 (bravo)	Range to 130 dB$_{ht}$ (km)			
	Max	**Min**	**Mean**	**Area**
Dab	0.06	0.04	0.05	0.01
Herring	0.34	0.32	0.33	0.34
Salmon	0.04	0.02	0.03	0
Sand Lance	0	0	0	0
Trout	0.04	0.02	0.03	0
Bottlenose Dolphin	0.36	0.34	0.35	0.38
Harbour Porpoise	0.64	0.62	0.63	1.24
Harbour Seal	0.2	0.18	0.19	0.11
Humpback Whale	0.82	0.8	0.81	2.05

Table 6-15a Summary of dB$_{ht}$ ranges for the GM2 (bravo) fully driven scenario

Seagreen – GM2 (bravo)	Range to 90 dB$_{ht}$ (km)				Range to 75 dB$_{ht}$ (km)			
	Max	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**	**Area**
Dab	5.9	5.7	5.8	104.6	28	26	27	2201.3
Herring	35	29	31	3034.7	82	43	65	13694
Salmon	2.2	2.2	2.2	15.4	13	12	12	467
Sand Lance	0.2	0.2	0.2	0.14	1.9	1.8	1.8	10.51
Trout	0.4	0.3	0.4	0.4	2.5	2.4	2.4	18.6
Bottlenose Dolphin	14	13	14	570.8	40	34	37	4200
Harbour Porpoise	21	20	20	1286.2	57	43	51	8162.4
Harbour Seal	17	16	17	865.7	53	42	46	6737.5
Humpback Whale	45	37	40	4949.8	98	43	74	17971

Table 6-16b Summary of dB$_{ht}$ ranges for the GM2 (bravo) fully driven scenario

Seagreen – GM3 (alpha)	Range to 130 dB$_{ht}$ (km)			
	Max	**Min**	**Mean**	**Area**
Dab	0.04	0.02	0.03	0
Herring	0.2	0.18	0.19	0.11
Salmon	0.04	0.02	0.03	0
Sand Lance	0	0	0	0
Trout	0	0	0	0
Bottlenose Dolphin	0.3	0.28	0.29	0.26
Harbour Porpoise	0.54	0.52	0.53	0.88
Harbour Seal	0.16	0.14	0.15	0.07
Humpback Whale	0.66	0.64	0.65	1.32

Table 6-17a Summary of dB$_{ht}$ ranges for the GM3 (alpha) drill-drive scenario

Seagreen – GM3 (alpha)	Range to 90 dB$_{ht}$ (km)				Range to 75 dB$_{ht}$ (km)			
	Max	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**	**Area**
Dab	2.2	2.1	2.2	15	13	13	13	534.8
Herring	23	22	22	1574.8	70	33	52	8572.7
Salmon	1.0	1.0	1.0	3.31	6.8	6.5	6.7	138.9
Sand Lance	0.1	0.1	0.1	0.1	1.1	1.0	1.1	3.5

Trout	0.2	0.2	0.2	0.1	1.4	1.3	1.4	5.9
Bottlenose Dolphin	12	11	11	406.4	35	31	32	3167.6
Harbour Porpoise	18	17	17	951.1	52	33	44	5994.7
Harbour Seal	14	14	14	622.4	48	33	40	5019.3
Humpback Whale	40	32	35	3755.5	91	33	64	13905.8

Table 6-18b Summary of dB$_{ht}$ ranges for the GM3 (alpha) drill-drive scenario

Seagreen – GM3 (bravo)	**Range to 130 dB$_{ht}$ (km)**			
	Max	**Min**	**Mean**	**Area**
Dab	0.04	0.02	0.03	0
Herring	0.2	0.18	0.19	0.11
Salmon	0.04	0.02	0.03	0
Sand Lance	0	0	0	0
Trout	0	0	0	0
Bottlenose Dolphin	0.3	0.28	0.29	0.26
Harbour Porpoise	0.54	0.52	0.53	0.88
Harbour Seal	0.16	0.14	0.15	0.07
Humpback Whale	0.66	0.64	0.65	1.32

Table 6-19a Summary of dB$_{ht}$ ranges for the GM3 (bravo) drill-drive scenario

Seagreen – GM3 (bravo)	**Range to 90 dB$_{ht}$ (km)**				**Range to 75 dB$_{ht}$ (km)**			
	Max	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**	**Area**
Dab	2.2	2.2	2.2	15.37	14	13	13	552.9
Herring	24	22	23	1610.3	68	43	56	9827.7
Salmon	1.0	1.0	1.0	3.3	6.8	6.7	6.8	142.6
Sand Lance	0.1	0.1	0.1	0.1	1.1	1.1	1.1	3.6
Trout	0.2	0.2	0.2	0.1	1.4	1.4	1.4	5.9
Bottlenose Dolphin	12	11	11	412.3	35	31	32	3293.3
Harbour Porpoise	18	17	18	960.6	51	43	46	6713
Harbour Seal	15	14	14	635	48	39	42	5557.8
Humpback Whale	40	33	36	3999.5	90	43	70	15873

Table 6-20b Summary of dB$_{ht}$ ranges for the GM3 (bravo) drill-drive scenario

Seagreen – GM4 (alpha)	**Range to 130 dB$_{ht}$ (km)**			
	Max	**Min**	**Mean**	**Area**
Dab	0.04	0.02	0.03	0
Herring	0.22	0.2	0.21	0.14
Salmon	0.04	0.02	0.03	0
Sand Lance	0	0	0	0
Trout	0	0	0	0
Bottlenose Dolphin	0.32	0.3	0.31	0.3
Harbour Porpoise	0.58	0.56	0.57	1.02
Harbour Seal	0.18	0.16	0.17	0.09
Humpback Whale	0.74	0.72	0.73	1.67

Table 6-21a Summary of dBht ranges for the GM4 (alpha) drill-drive scenario

Seagreen – GM4 (alpha)	**Range to 90 dB$_{ht}$ (km)**				**Range to 75 dB$_{ht}$ (km)**			
	Max	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**	**Area**
Dab	2.5	2.4	2.4	18.5	14	14	14	628

Herring	25	23	24	1778.3	73	33	53	9150.5
Salmon	1.2	1.1	1.2	4.1	7.4	7.1	7.3	165.3
Sand Lance	0.2	0.1	0.2	0.1	1.2	1.2	1.2	4.4
Trout	0.2	0.2	0.2	0.1	1.5	1.5	1.5	7.2
Bottlenose Dolphin	12	12	12	460.5	37	32	33	3456.1
Harbour Porpoise	19	18	19	1070	55	33	45	6458.9
Harbour Seal	15	15	15	715.4	51	33	41	5420.6
Humpback Whale	42	33	36	4101.5	94	33	66	14709.7

Table 6-22 Summary of dBht ranges for the GM4 (alpha) drill-drive scenario

Seagreen – GM4 (bravo)	**Range to 130 dB$_{ht}$ (km)**			
	Max	**Min**	**Mean**	**Area**
Dab	0.04	0.02	0.03	0
Herring	0.22	0.2	0.21	0.14
Salmon	0.04	0.02	0.03	0
Sand Lance	0	0	0	0
Trout	0	0	0	0
Bottlenose Dolphin	0.32	0.3	0.31	0.3
Harbour Porpoise	0.58	0.56	0.57	1.02
Harbour Seal	0.18	0.16	0.17	0.09
Humpback Whale	0.74	0.72	0.73	1.67

Table 6-23a Summary of dB$_{ht}$ ranges for the GM4 (bravo) drill-drive scenario

Seagreen – GM4 (bravo)	**Range to 90 dB$_{ht}$ (km)**				**Range to 75 dB$_{ht}$ (km)**			
	Max	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**	**Area**
Dab	2.5	2.4	2.5	18.9	15	14	14	648.8
Herring	26	23	24	1822.2	71	43	58	10478.3
Salmon	1.2	1.1	1.2	4.1	7.5	7.3	7.4	169.6
Sand Lance	0.2	0.1	0.2	0.1	1.2	1.2	1.2	4.4
Trout	0.2	0.2	0.2	0.1	1.5	1.5	1.5	7.3
Bottlenose Dolphin	12	12	12	467.1	37	32	34	3616.6
Harbour Porpoise	19	18	19	1080.4	53	43	48	7271.8
Harbour Seal	16	15	15	728.9	50	41	44	6062.9
Humpback Whale	42	35	38	4413.6	93	43	72	16795.7

Table 6-24b Summary of dB$_{ht}$ ranges for the GM4 (bravo) drill-drive scenario

Inch Cape	**Range to 130 dB$_{ht}$ (km)**			
	Max	**Min**	**Mean**	**Area**
Dab	0.04	0.02	0.03	0
Herring	0.28	0.26	0.27	0.23
Salmon	0.04	0.02	0.03	0
Sand Lance	0	0	0	0
Trout	0	0	0	0
Bottlenose Dolphin	0.34	0.32	0.33	0.34
Harbour Porpoise	0.6	0.58	0.59	1.09
Harbour Seal	0.18	0.16	0.17	0.09
Humpback Whale	0.76	0.74	0.75	1.76

Table 6-25a Summary of dBht ranges for the Inch Cape scenario

Inch Cape	**Range to 90 dB$_{ht}$ (km)**				**Range to 75 dB$_{ht}$ (km)**			
	Max	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**	**Area**
Dab	3.9	3.8	3.9	47.4	21	16	19	1176.8
Herring	28	20	25	2003	70	21	48	8099.9
Salmon	1.6	1.6	1.6	7.7	9.6	8.5	9.3	271.5
Sand Lance	0.2	0.2	0.2	0.1	1.5	1.4	1.5	6.6
Trout	0.3	0.3	0.3	0.2	1.9	1.9	1.9	11.5
Bottlenose Dolphin	13	11	13	492.1	36	21	31	3093.1
Harbour Porpoise	20	16	19	1101.9	51	21	41	5514.6
Harbour Seal	16	13	15	747.3	46	21	37	4585.4
Humpback Whale	39	21	33	3539.5	89	21	56	11389.5

Table 6-26 Summary of dBht ranges for the Inch Cape scenario

NNG	**Range to 130 dB$_{ht}$ (km)**			
	Max	**Min**	**Mean**	**Area**
Dab	0.04	0.02	0.03	0
Herring	0.26	0.24	0.25	0.2
Salmon	0.04	0.02	0.03	0
Sand Lance	0	0	0	0
Trout	0	0	0	0
Bottlenose Dolphin	0.32	0.3	0.31	0.3
Harbour Porpoise	0.56	0.54	0.55	0.95
Harbour Seal	0.18	0.16	0.17	0.09
Humpback Whale	0.7	0.68	0.69	1.49

Table 6-27a Summary of dB$_{ht}$ ranges for the NNG scenario

NNG	**Range to 90 dB$_{ht}$ (km)**				**Range to 75 dB$_{ht}$ (km)**			
	Max	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**	**Area**
Dab	3.7	3.7	3.7	42.8	20	16	19	1130.6
Herring	27	19	25	1898.6	65	19	47	7588.4
Salmon	1.5	1.4	1.5	6.6	9.2	8.8	9.0	252.8
Sand Lance	0.2	0.1	0.2	0.1	1.3	1.3	1.3	5.4
Trout	0.3	0.2	0.3	0.2	1.8	1.8	1.8	9.8
Bottlenose Dolphin	12	12	12	448.7	34	19	31	2999.2
Harbour Porpoise	18	16	18	1006.9	50	19	40	5304.5
Harbour Seal	15	14	15	676.9	46	19	37	4501.1
Humpback Whale	38	19	33	3446.7	82	19	54	10496.3

Table 6-28b Summary of dB$_{ht}$ ranges for the NNG scenario

These results are presented graphically as contour plots in Figures 6-1 to 6-135, with each group of images showing the 90 and 75 dB$_{ht}$ impact ranges for the scenarios for each marine species of interest.

6.4.1 FIGURES

6.4.1.1 GM1 (alpha)

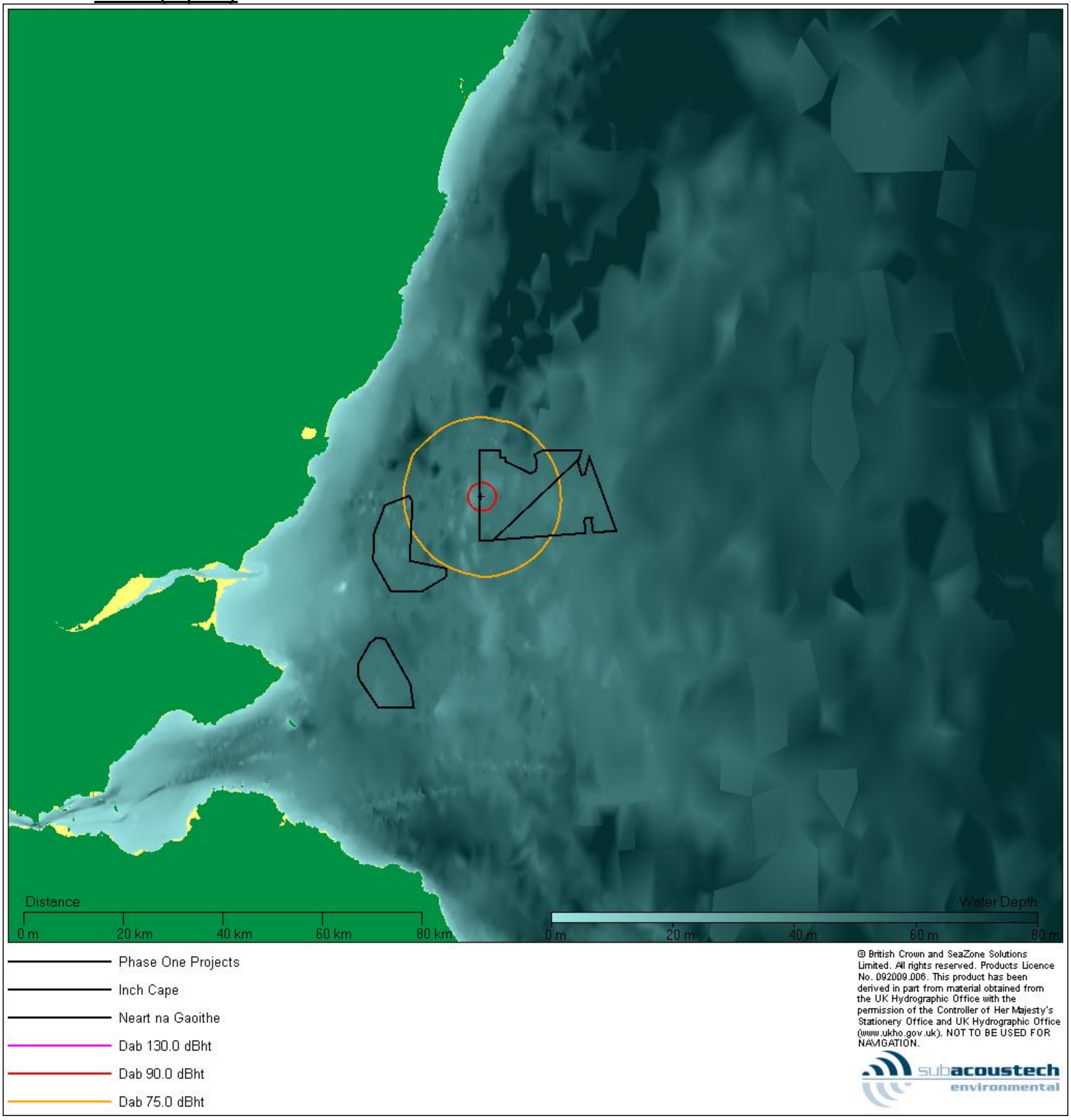

Figure 6-1 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM1 (alpha) scenario

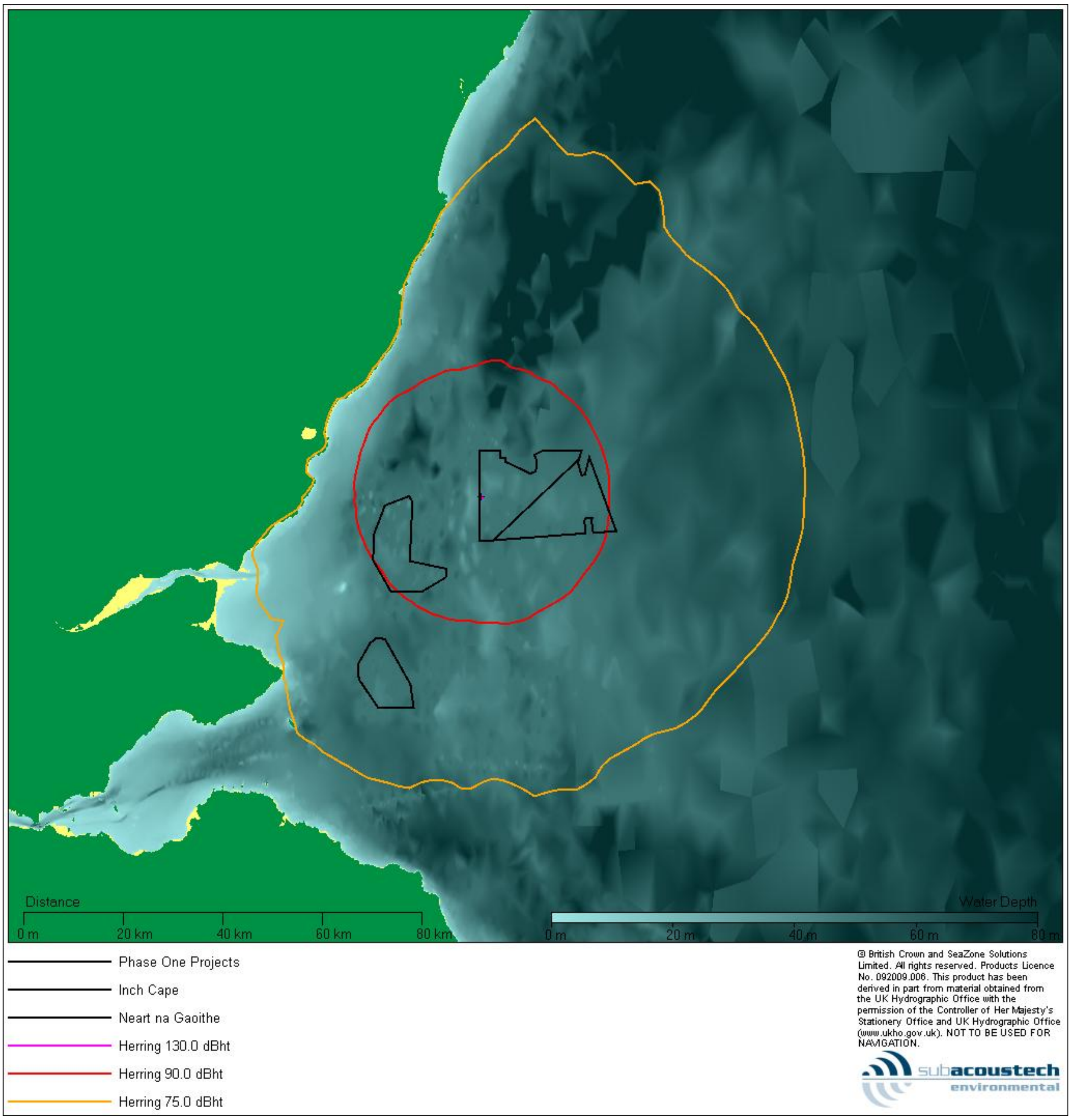

Figure 6-2 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the GM1 (alpha) scenario

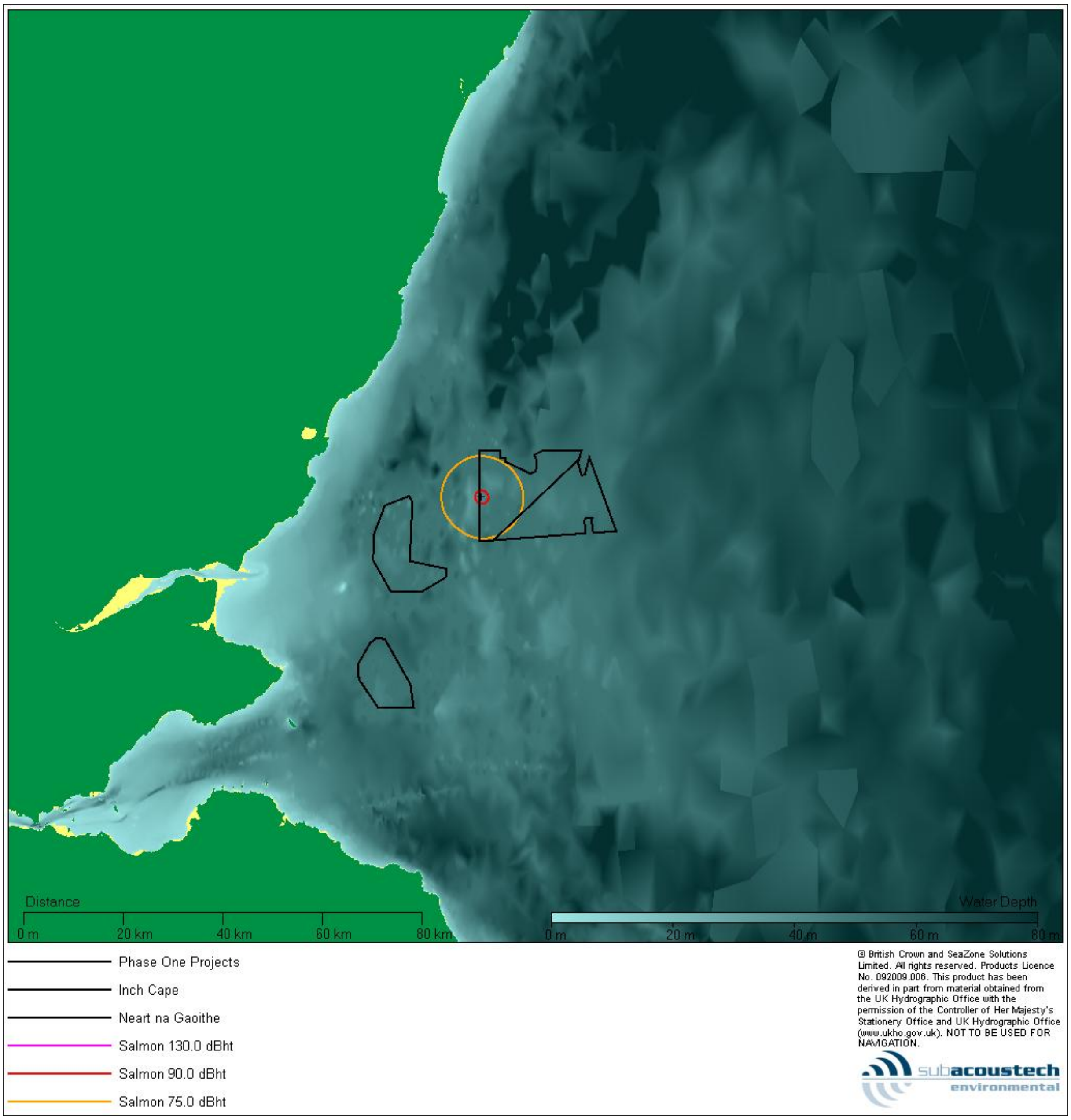

Figure 6-3 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Salmon for the GM1 (alpha) scenario

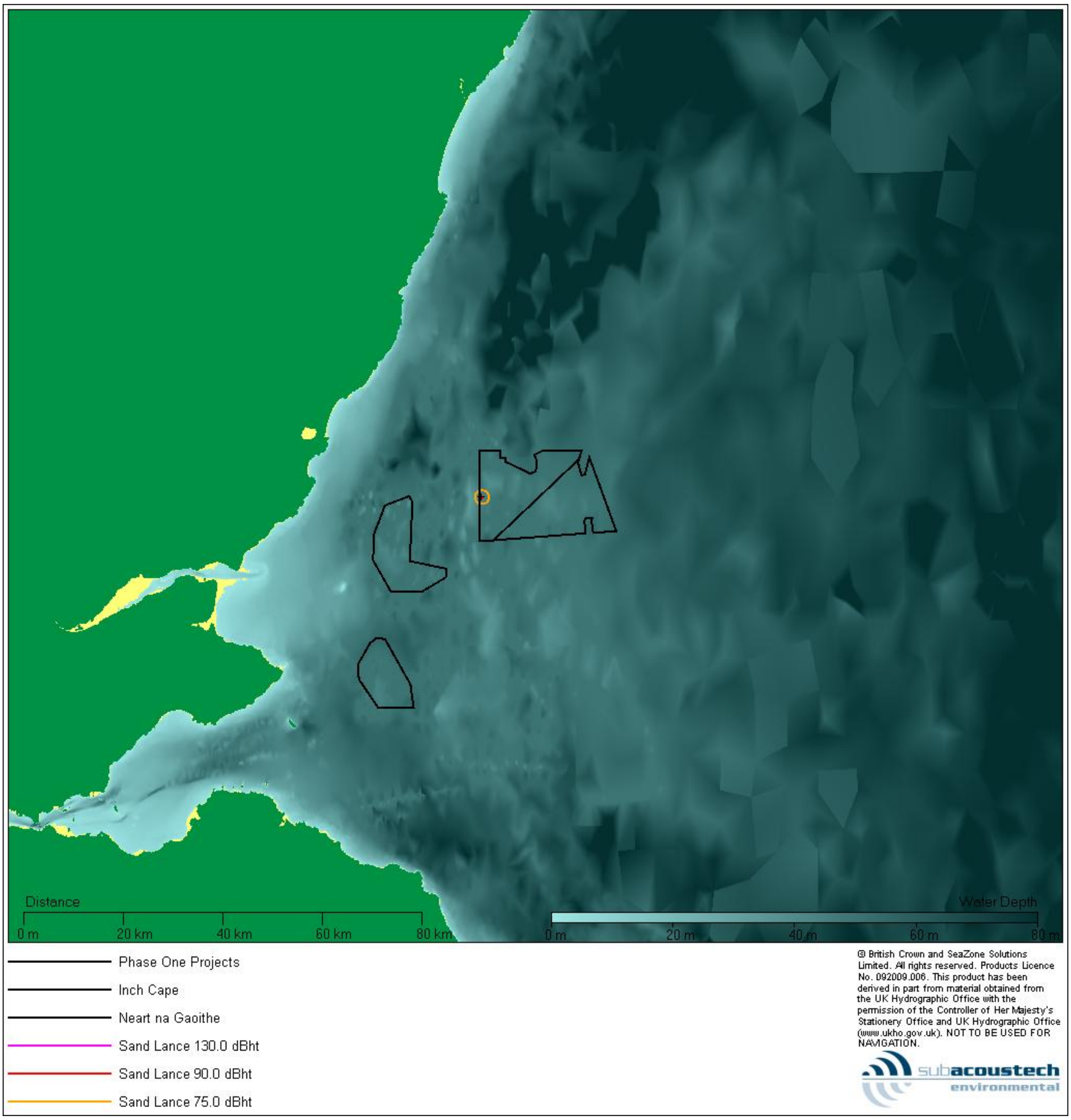

Figure 6-4 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the GM1 (alpha) scenario

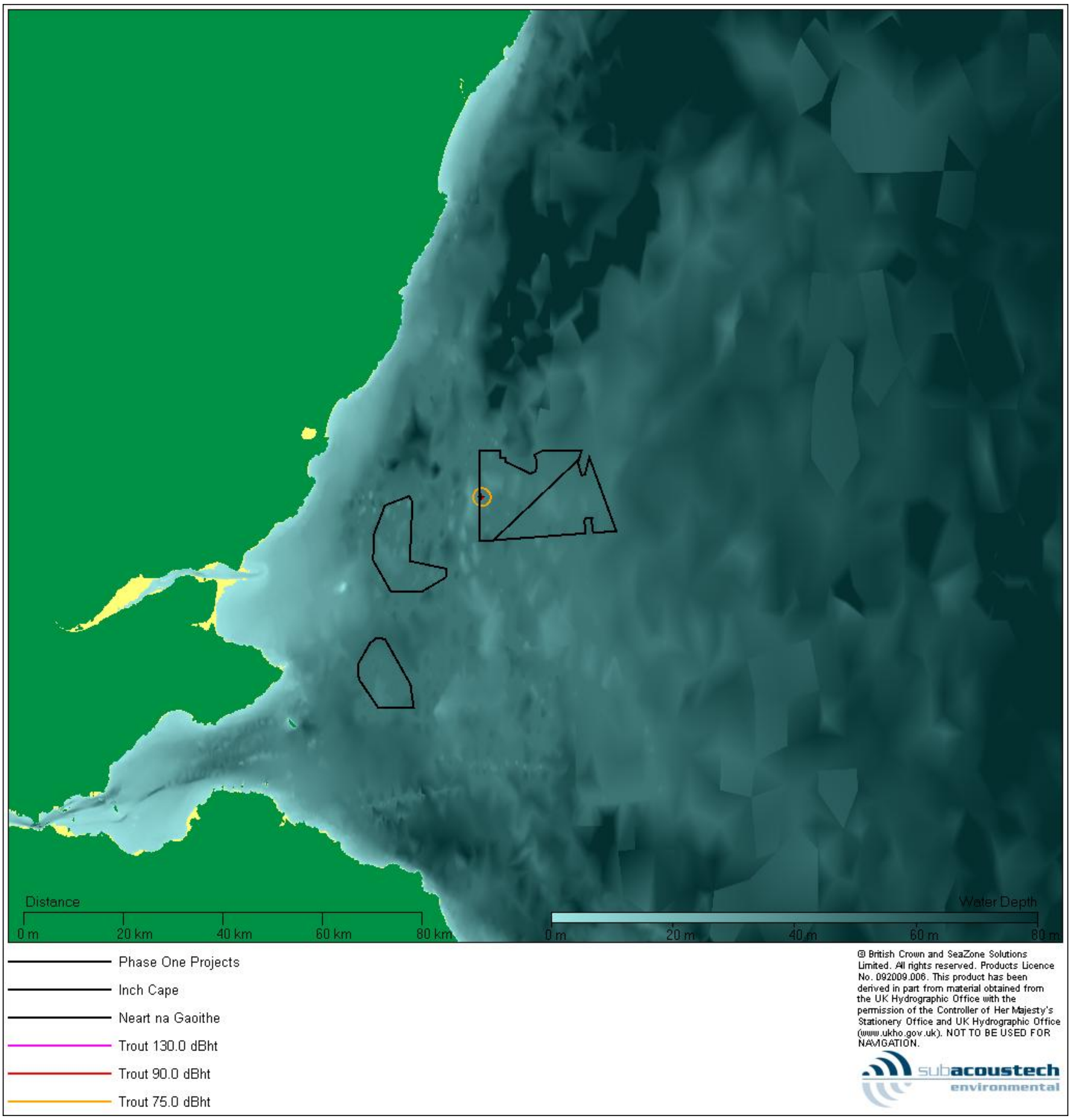

Figure 6-5 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the GM1 (alpha) scenario

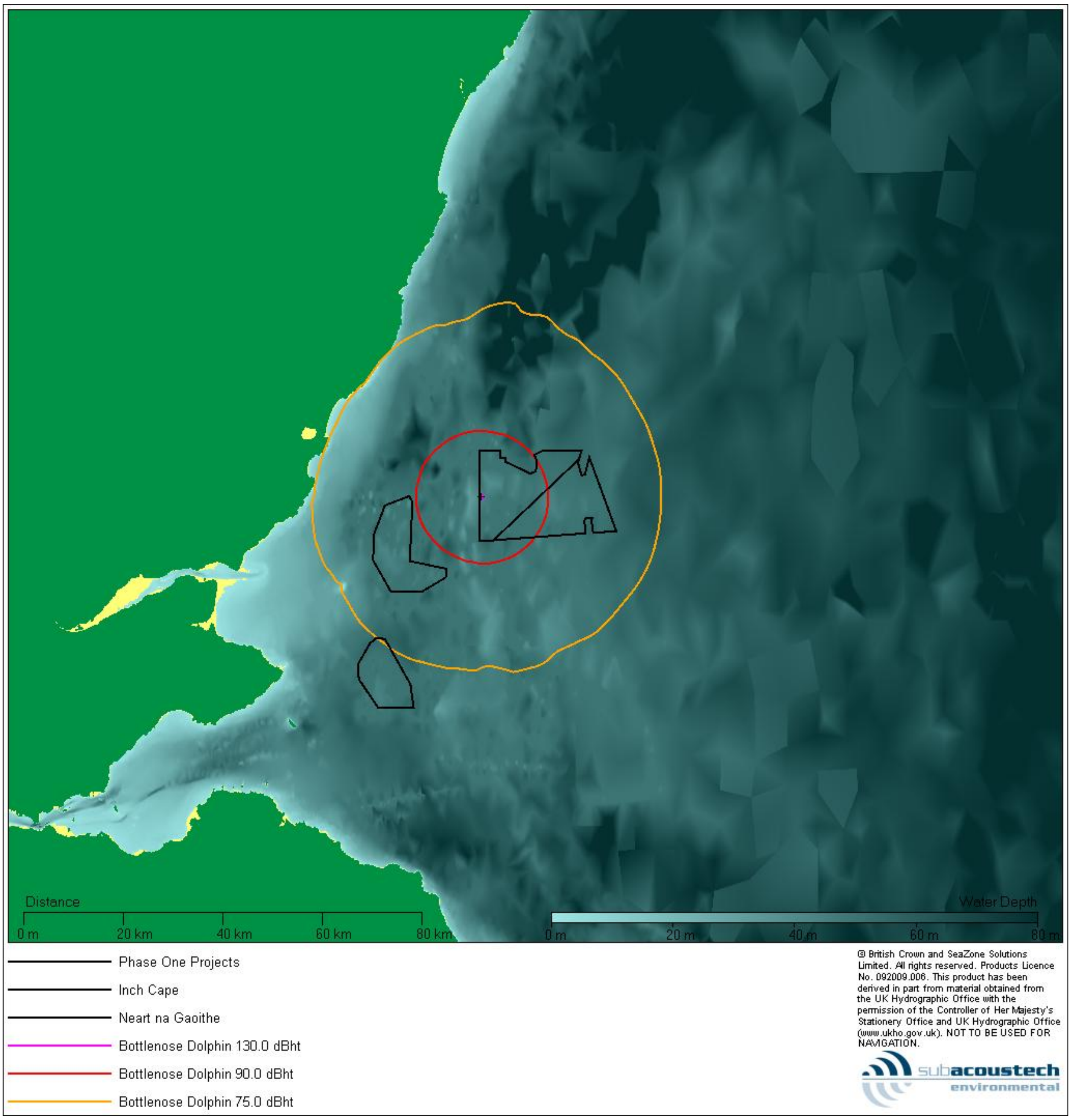

Figure 6-6 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the GM1 (alpha) scenario

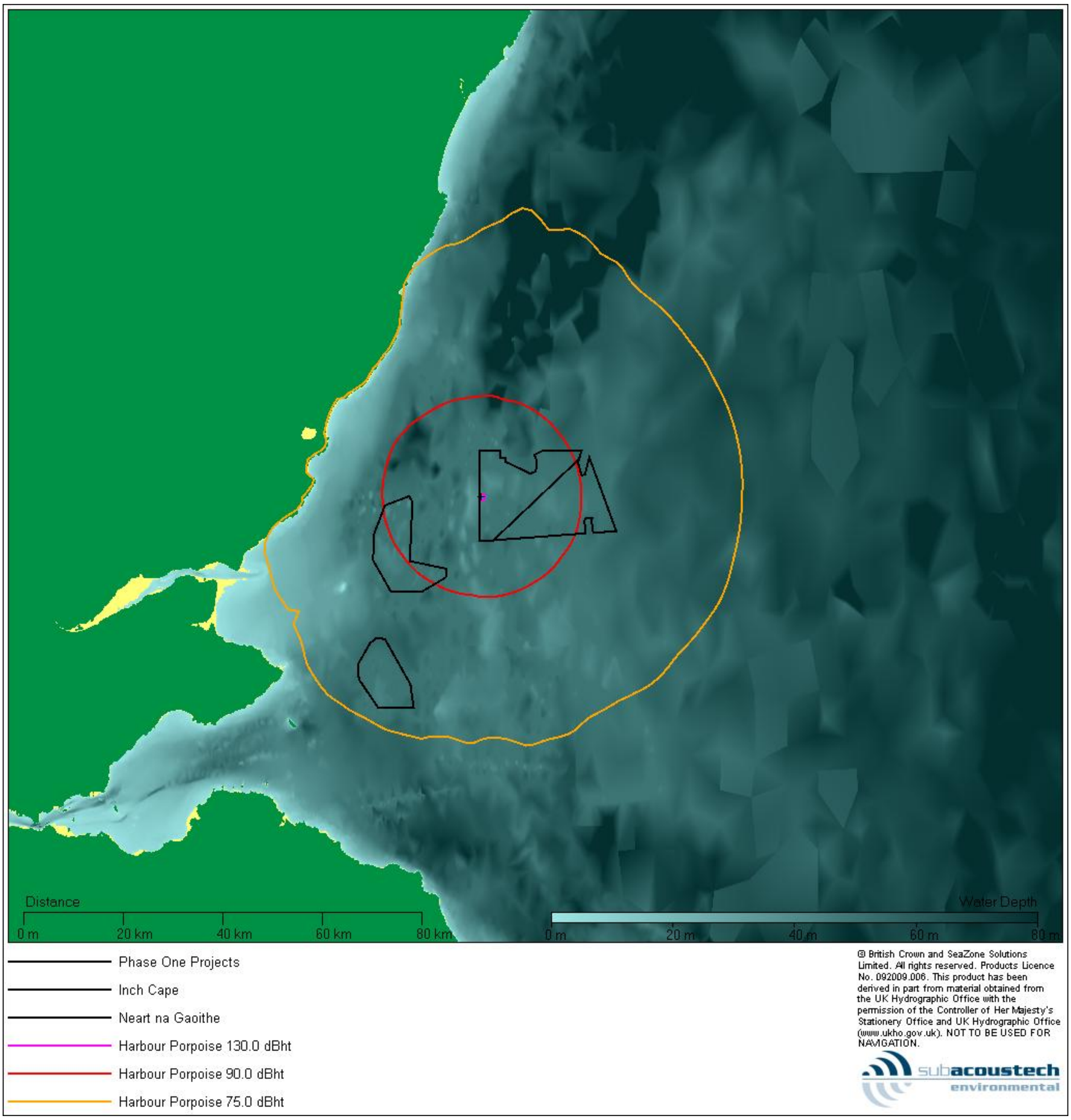

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Figure 6-7 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM1 (alpha) scenario

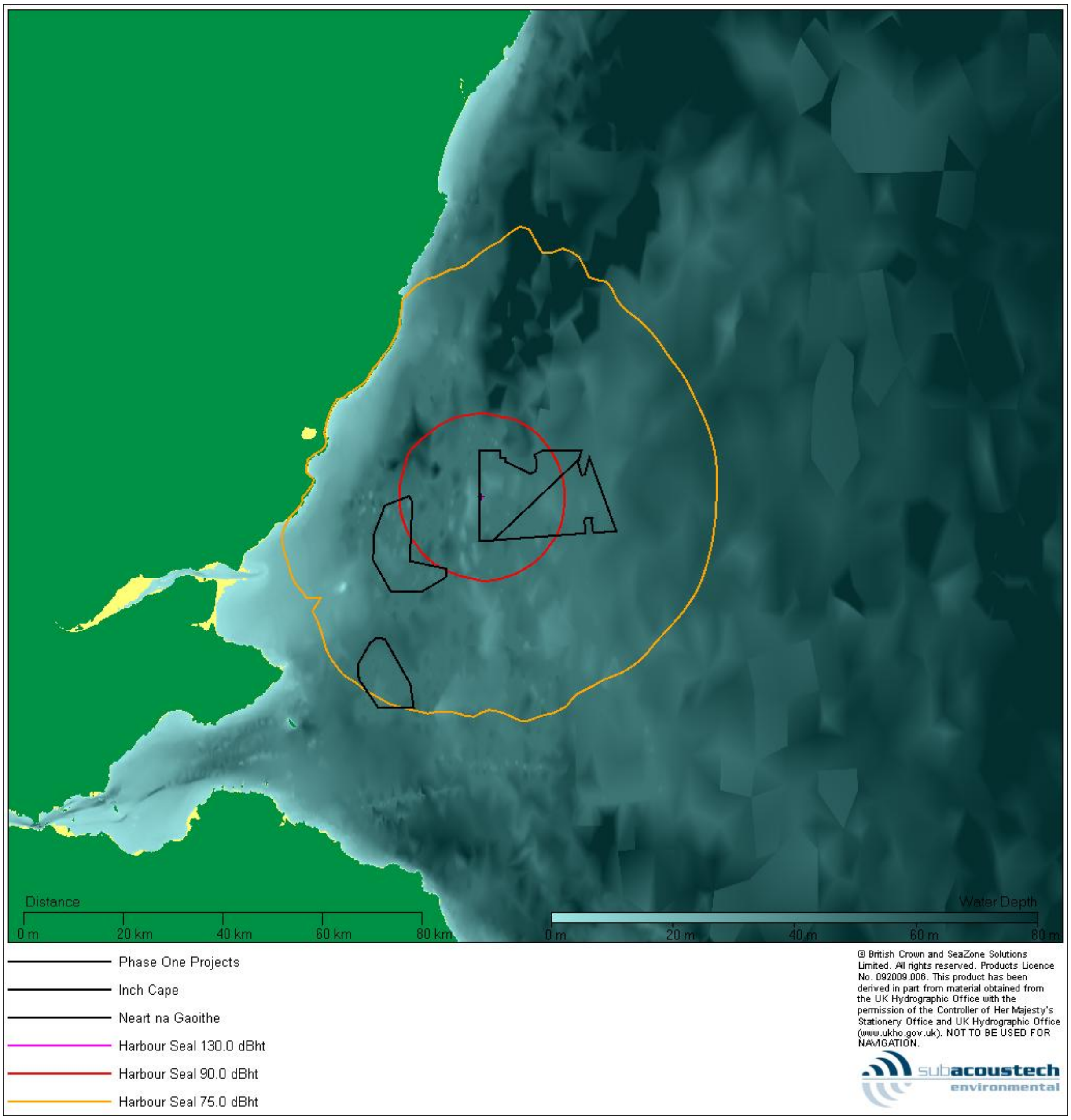

Figure 6-8 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM1 (alpha) scenario

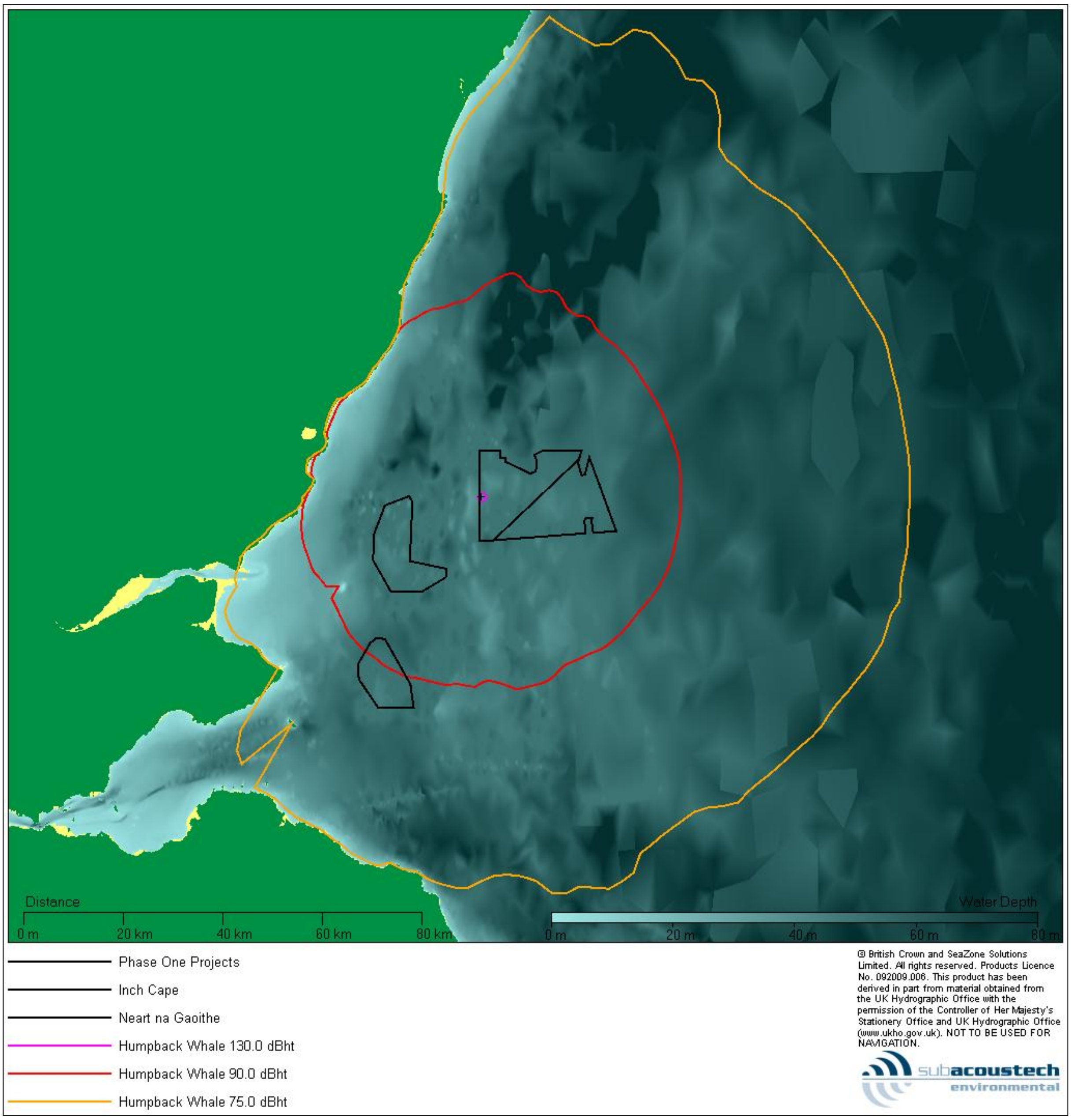

Figure 6-9 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the GM1 (alpha) scenario

6.4.1.2 GM1 (bravo)

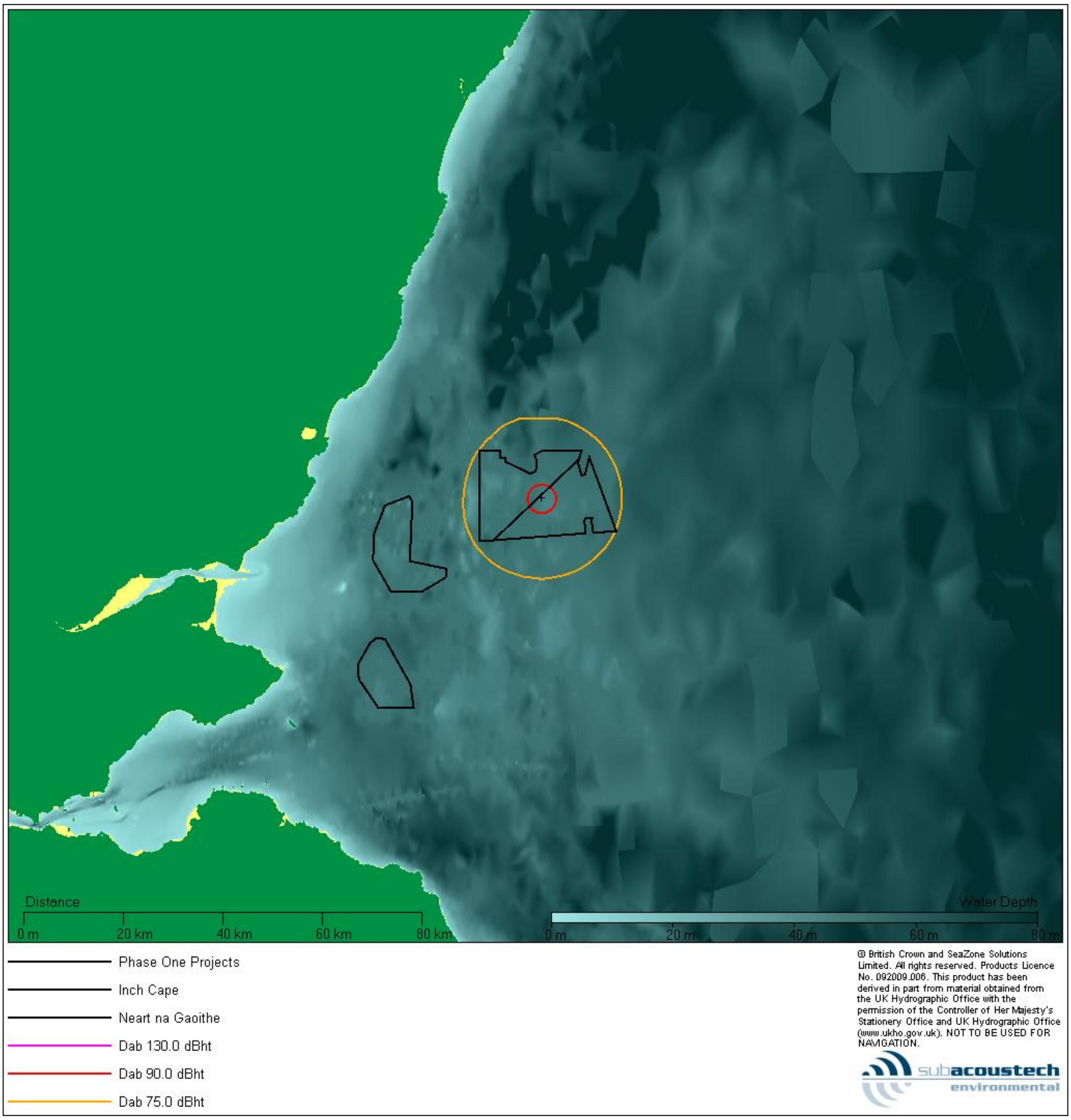

Figure 6-10 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM1 (bravo) scenario

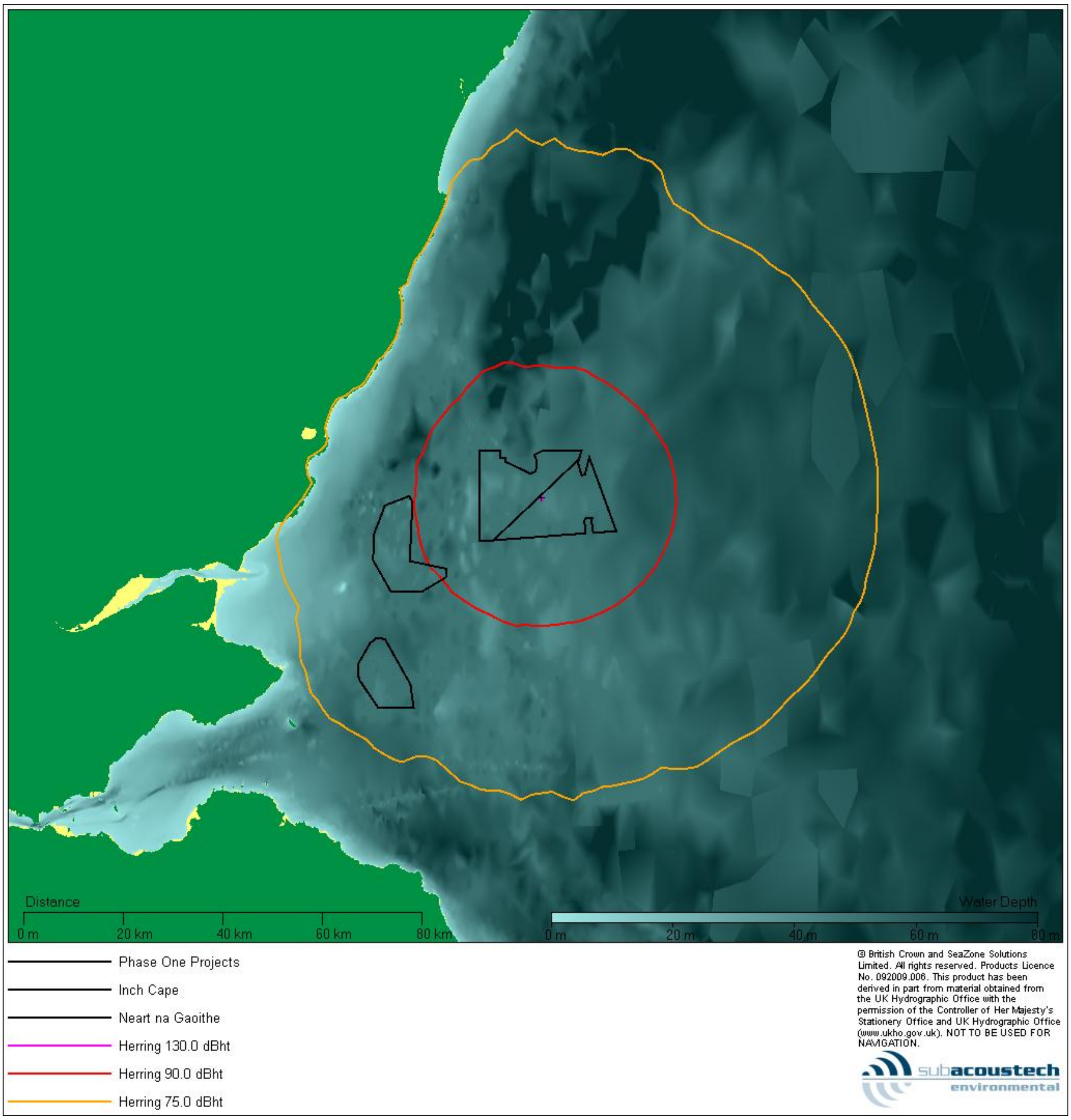

Figure 6-11 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the GM1 (bravo) scenario

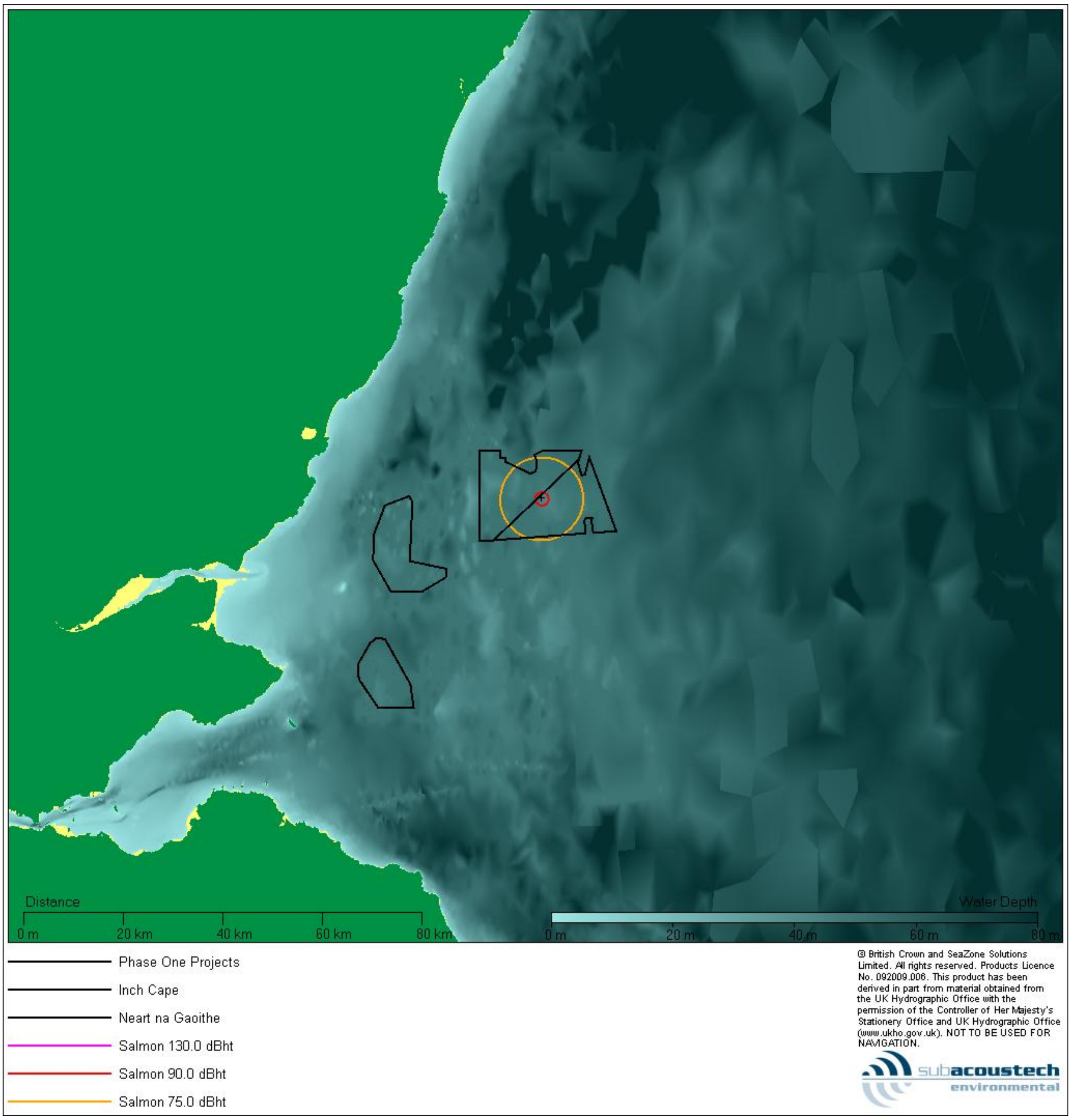

Figure 6-12 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the GM1 (bravo) scenario

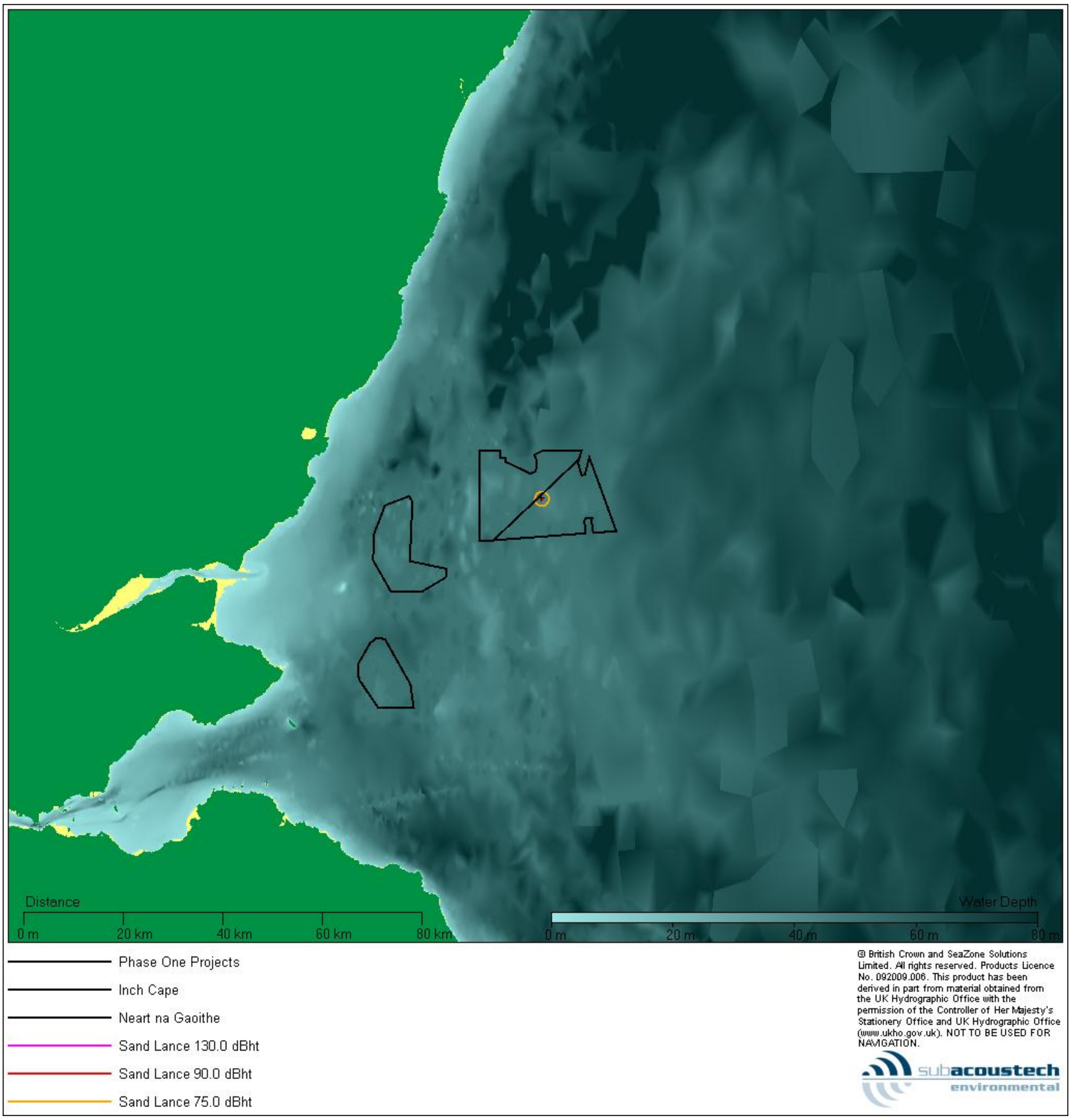

Figure 6-13 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the GM1 (bravo) scenario

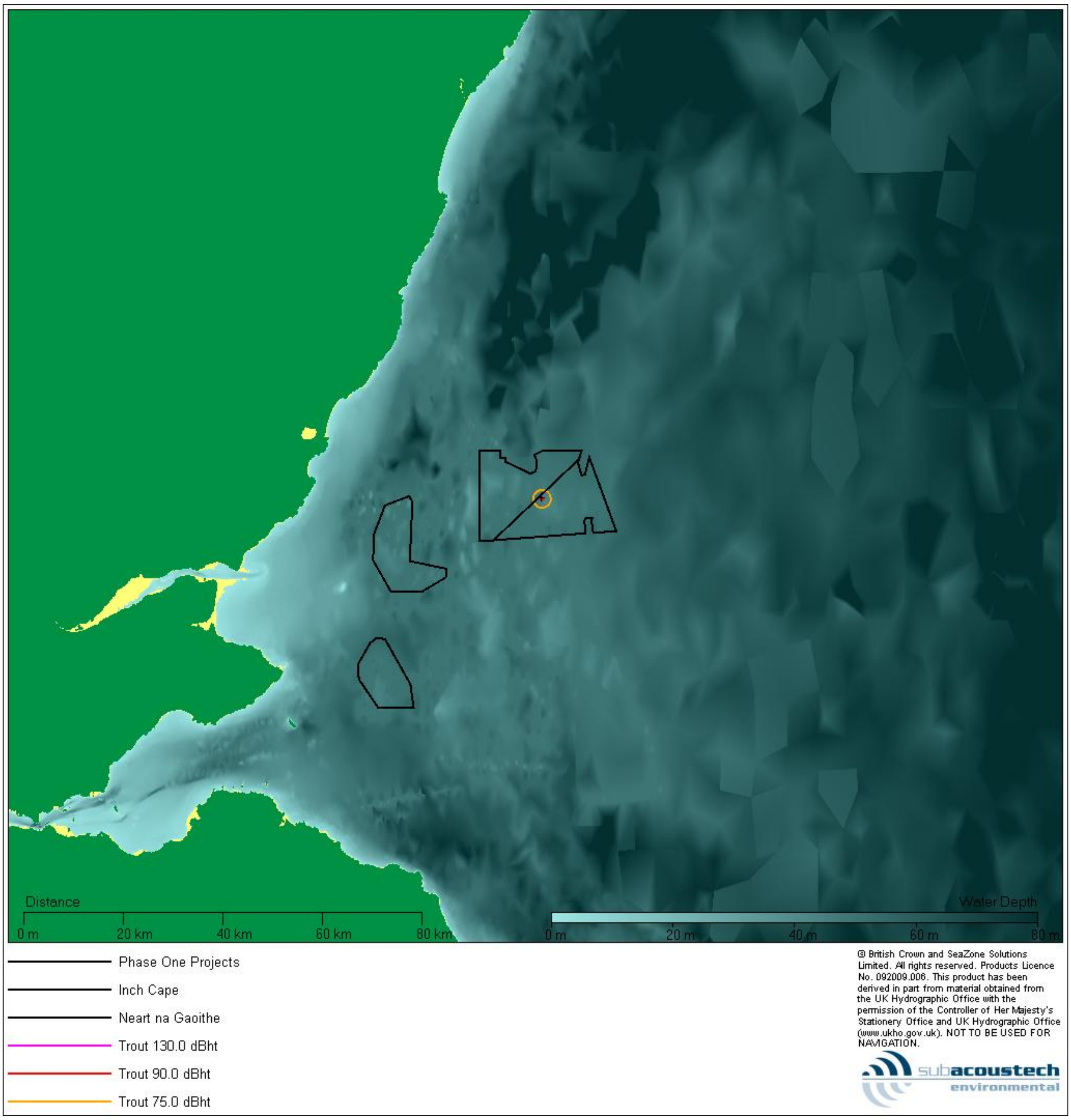

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Figure 6-14 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the GM1 (bravo) scenario

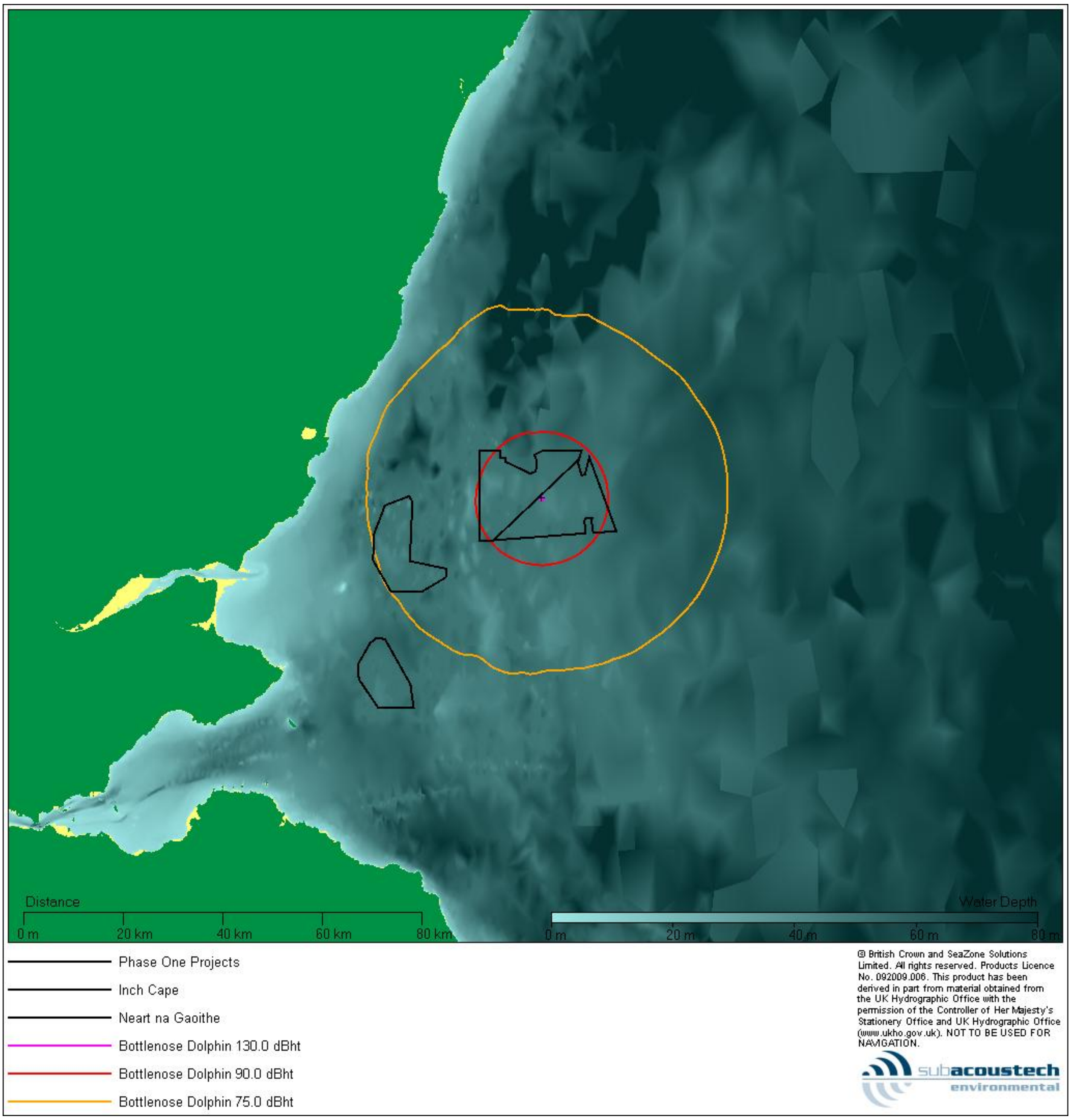

Figure 6-15 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the GM1 (bravo) scenario

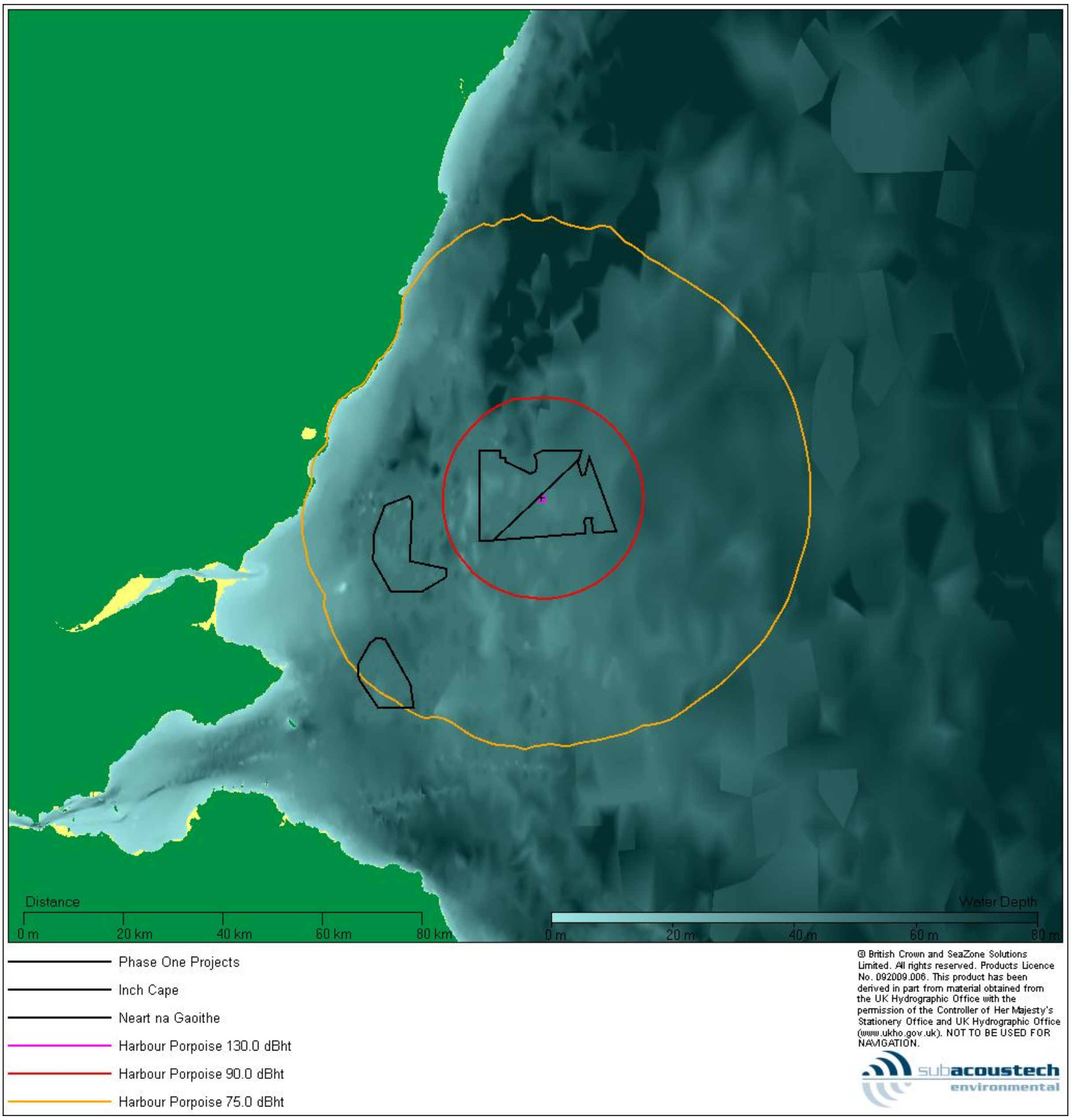

Figure 6-16 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM1 (bravo) scenario

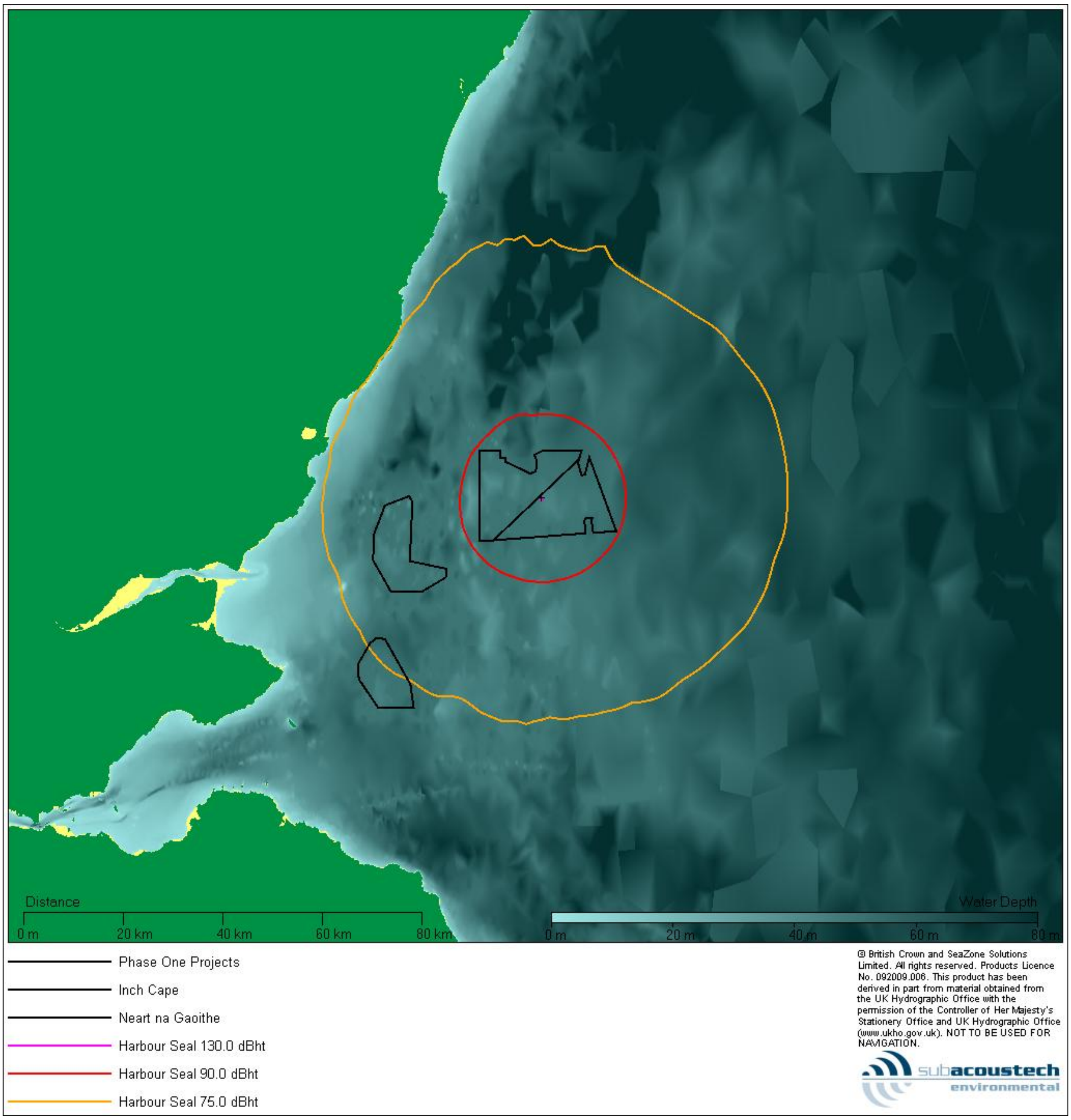

Figure 6-17 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM1 (bravo) scenario

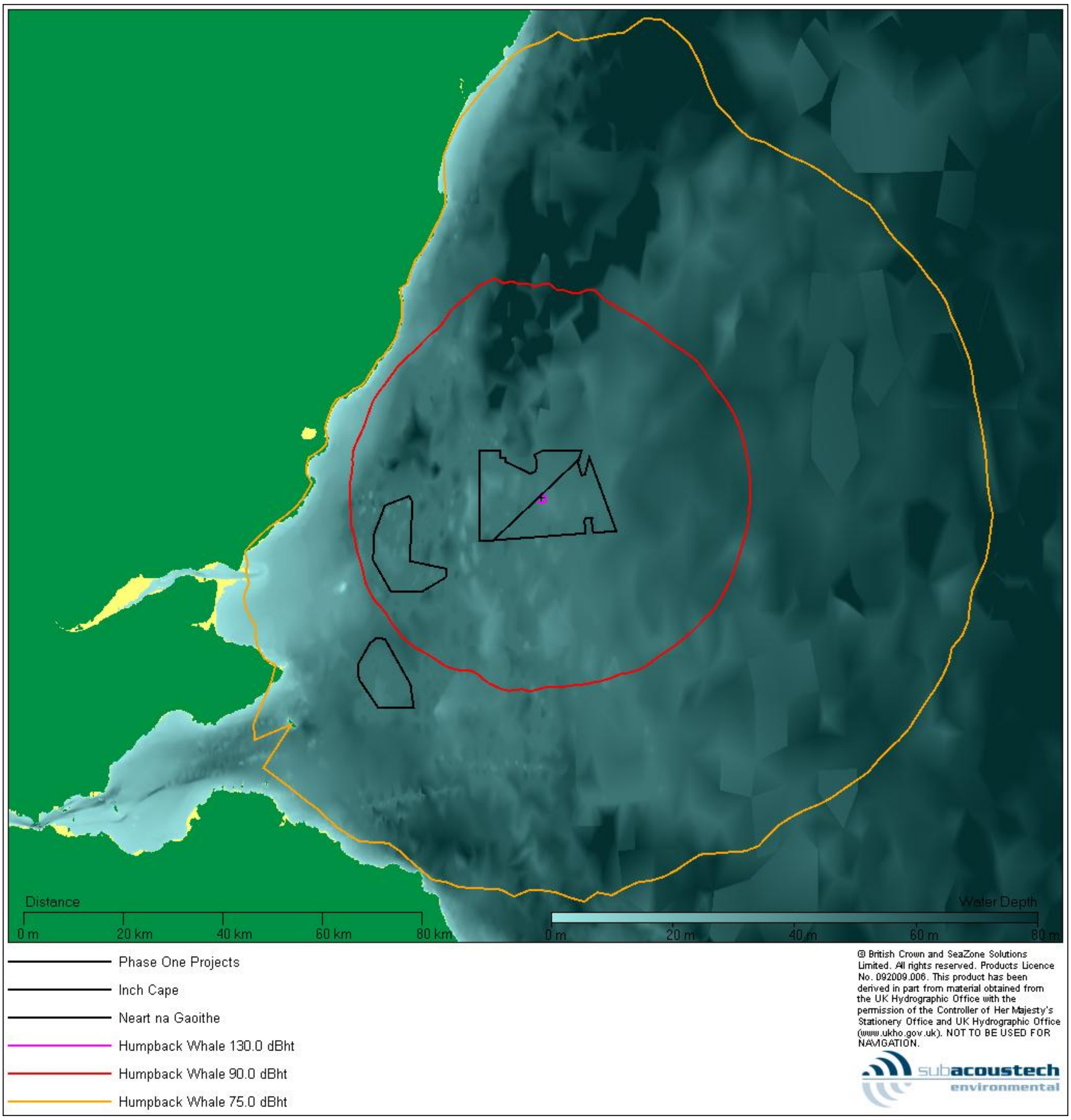

Figure 6-18 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the GM1 (bravo) scenario

6.4.1.3 GM2 (alpha)

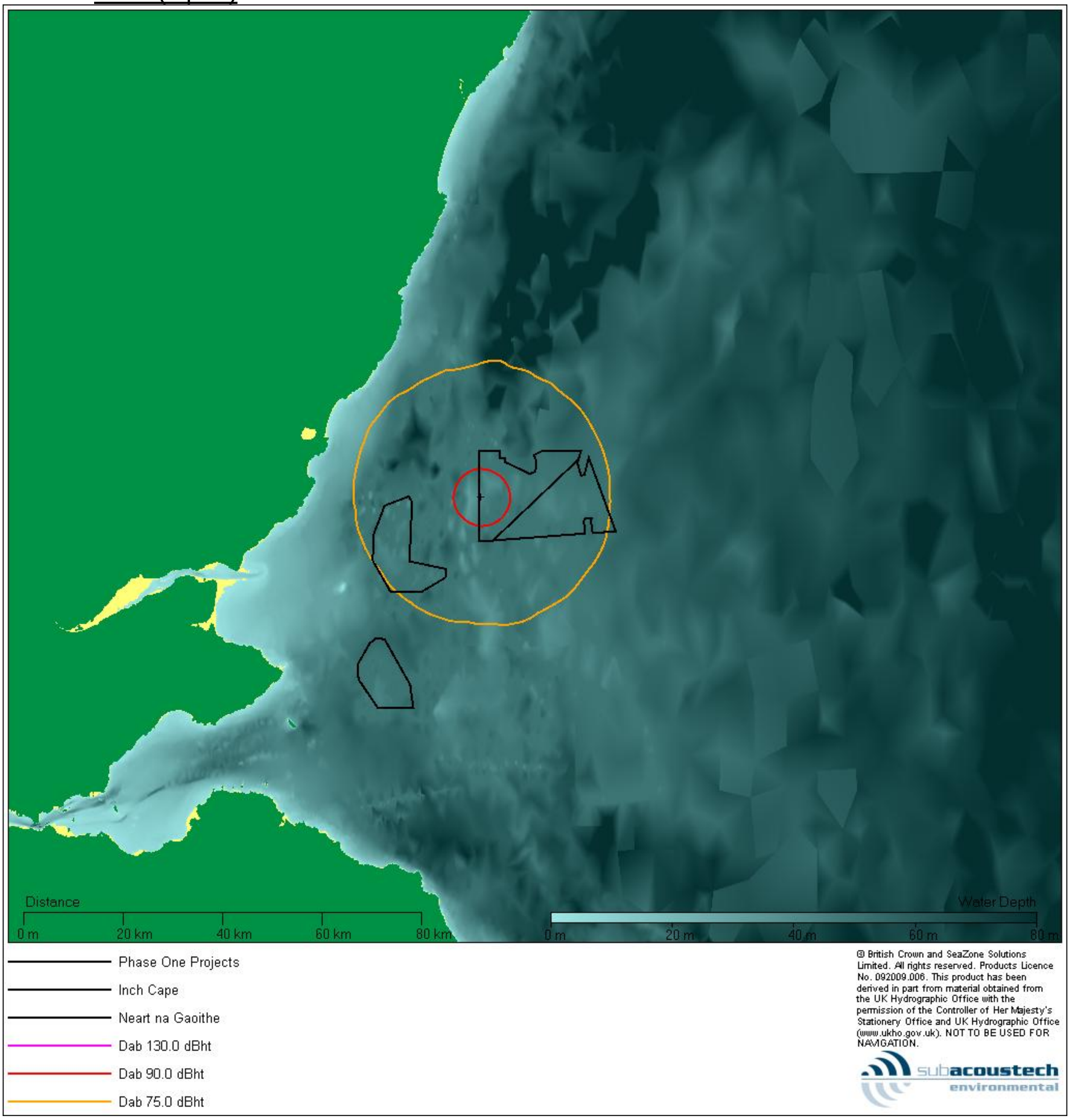

Figure 6-19 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM2 (alpha) scenario

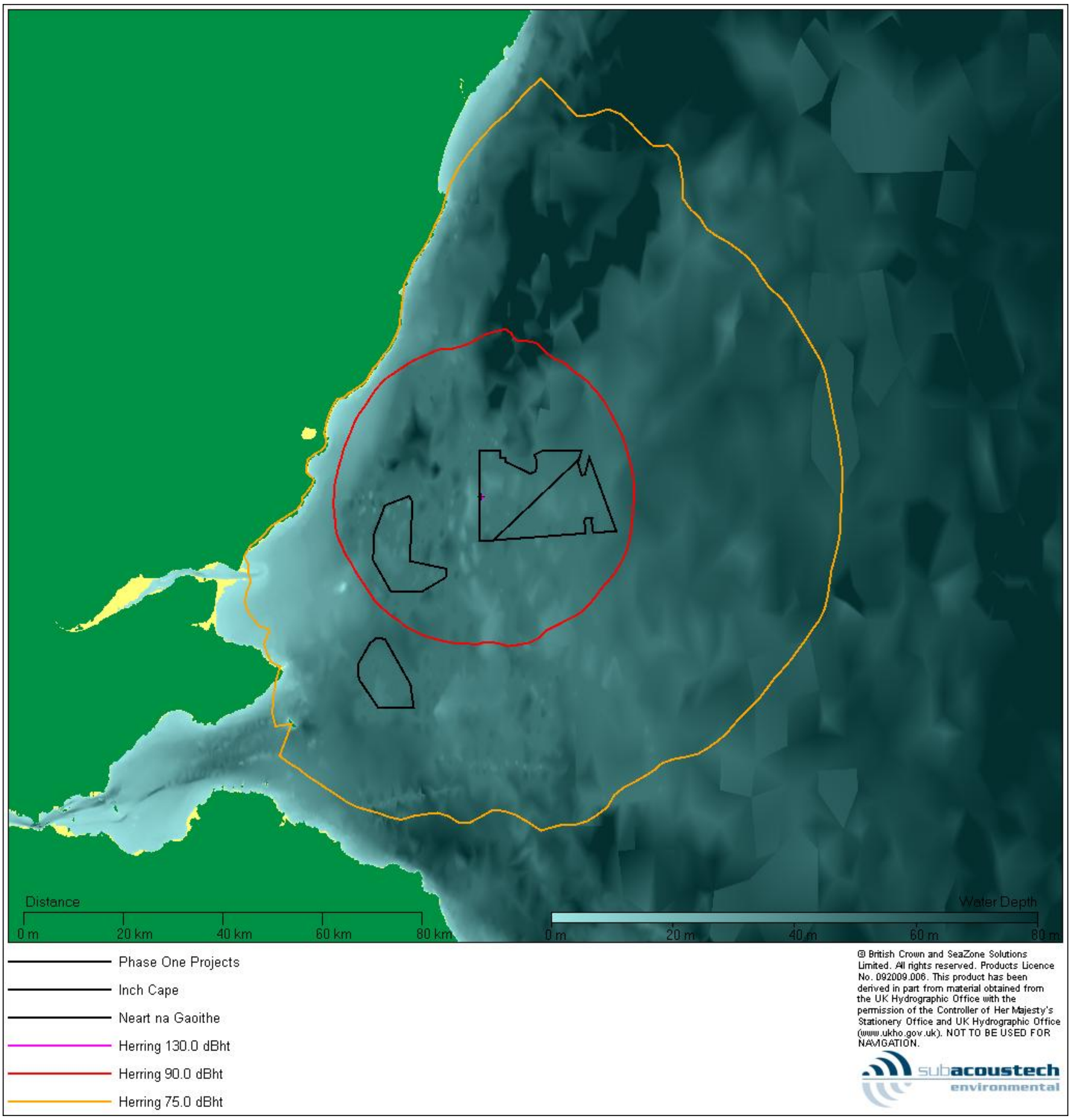

Figure 6-20 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the GM2 (alpha) scenario

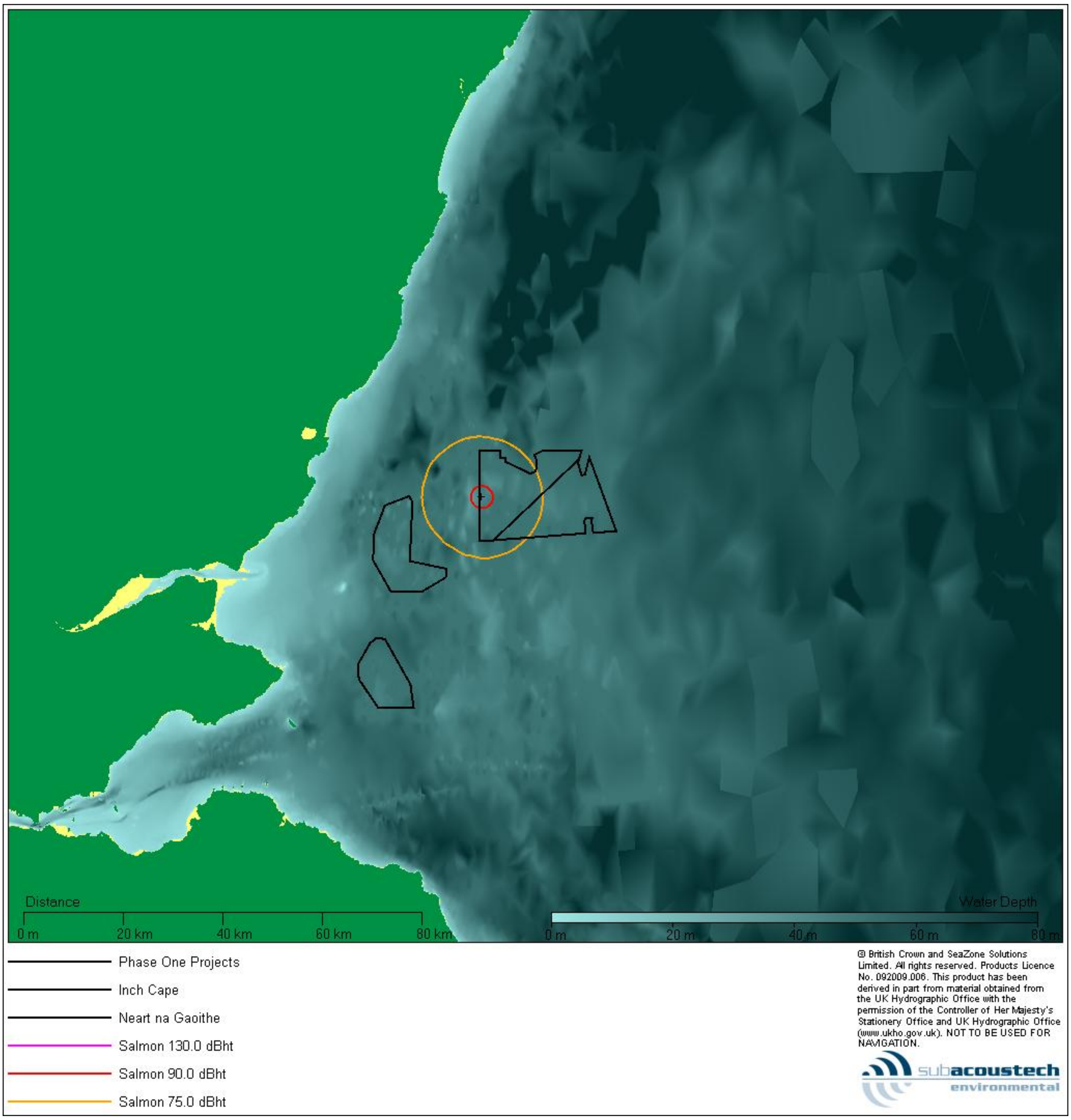

Figure 6-21 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the GM2 (alpha) scenario

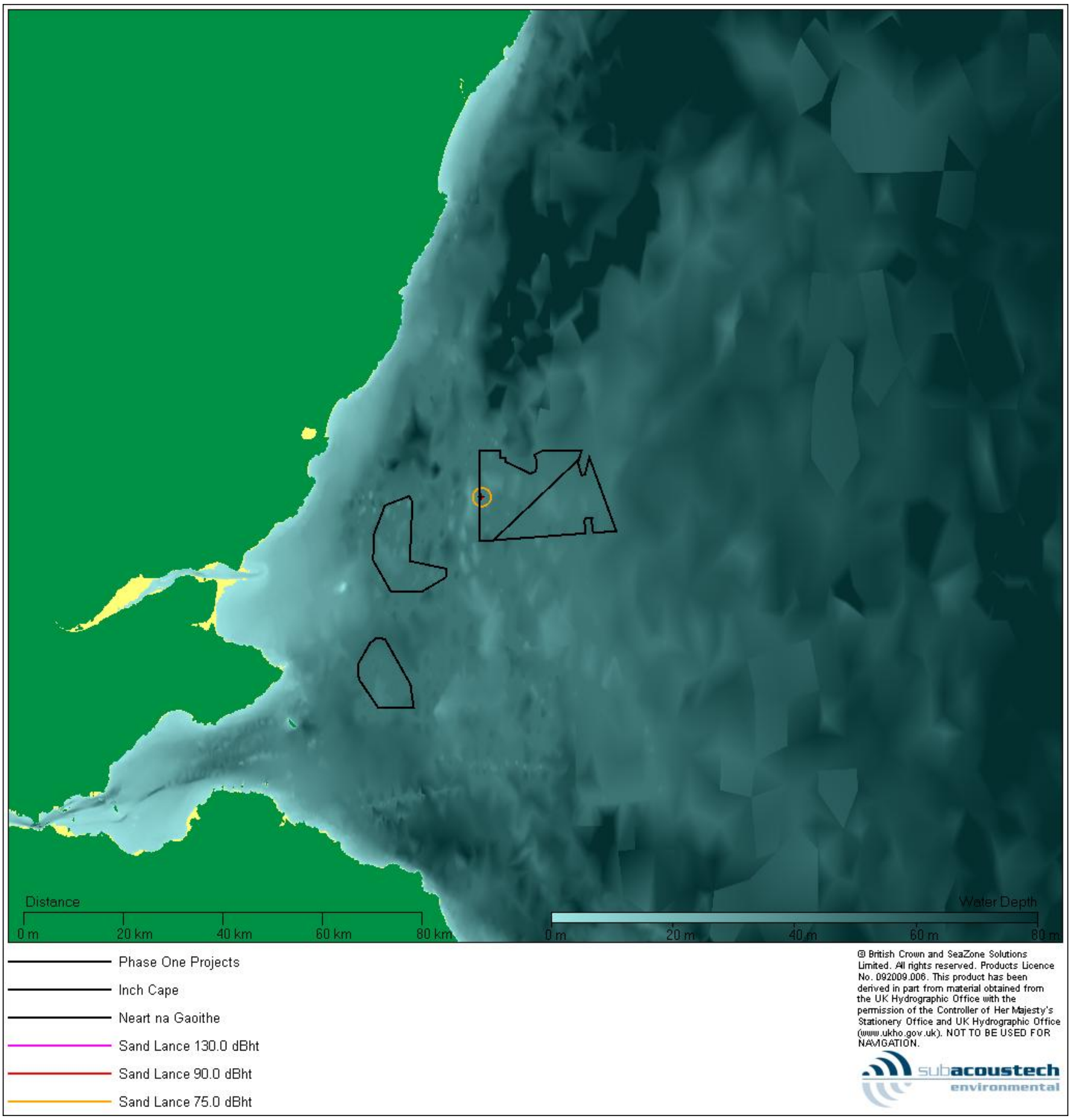

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Figure 6-22 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the GM2 (alpha) scenario

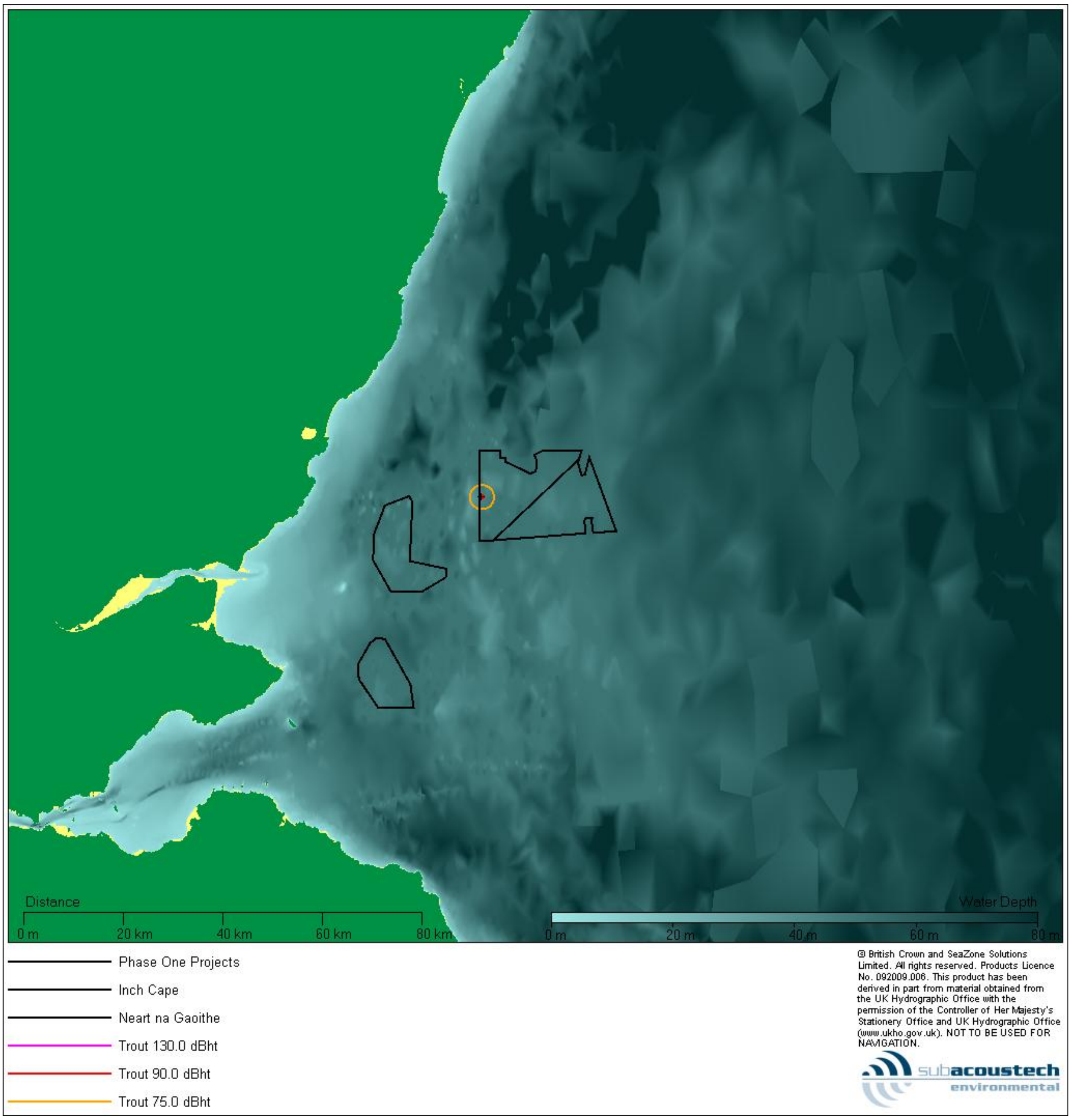

Figure 6-23 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Trout for the GM2 (alpha) scenario

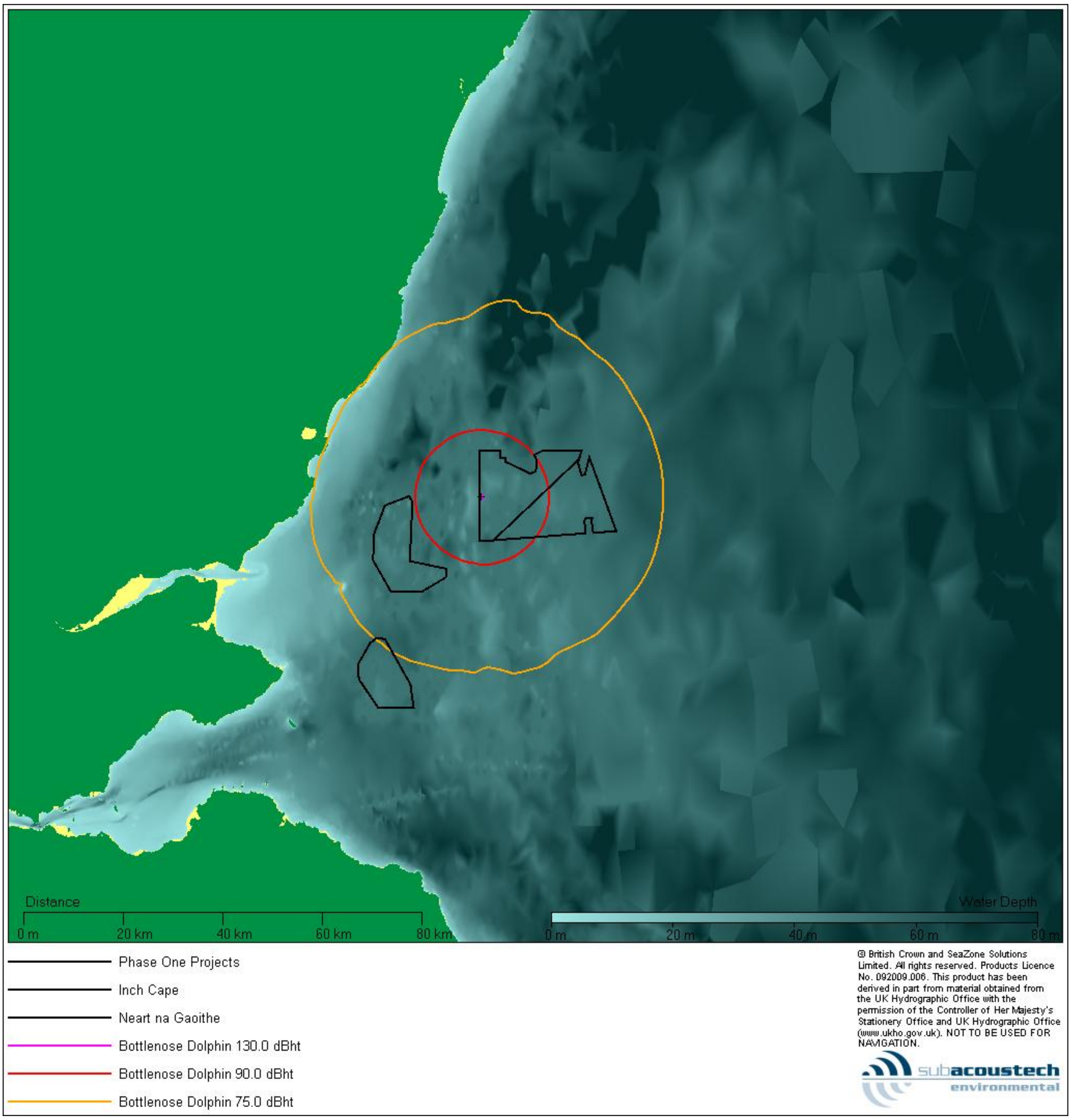

Figure 6-24 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the GM2 (alpha) scenario

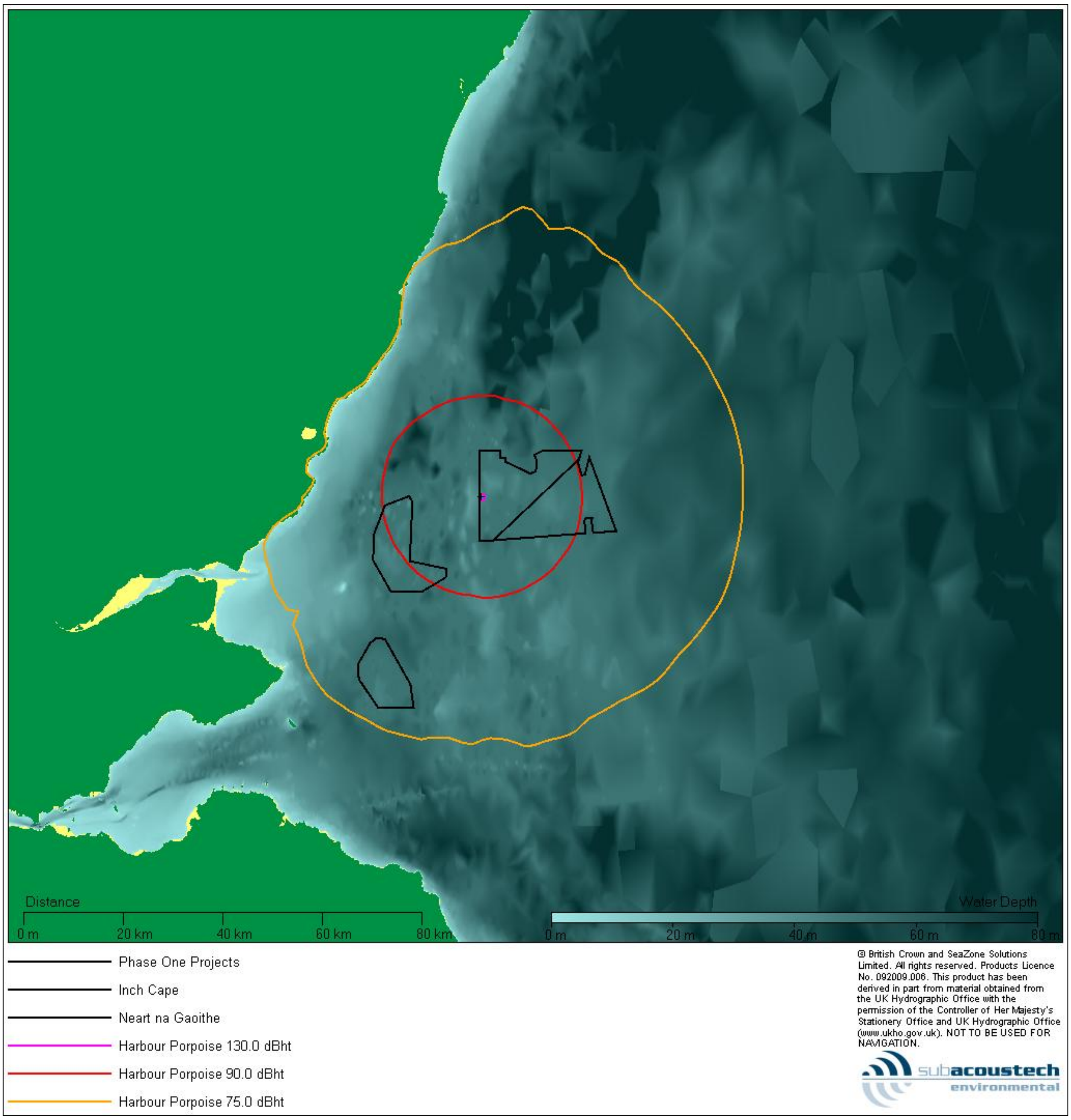

Figure 6-25 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Harbour Porpoise for the GM2 (alpha) scenario

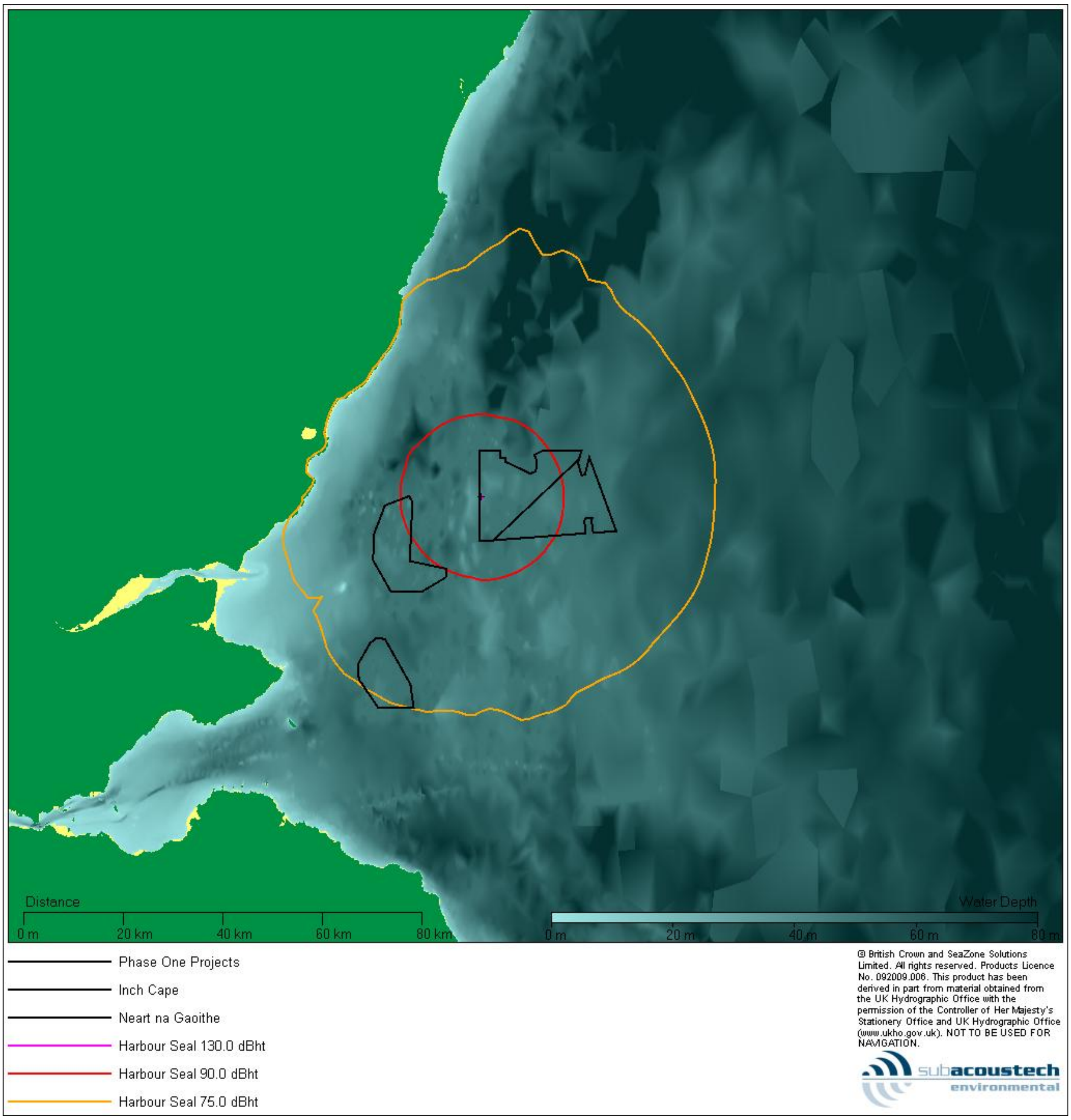

Figure 6-26 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM2 (alpha) scenario

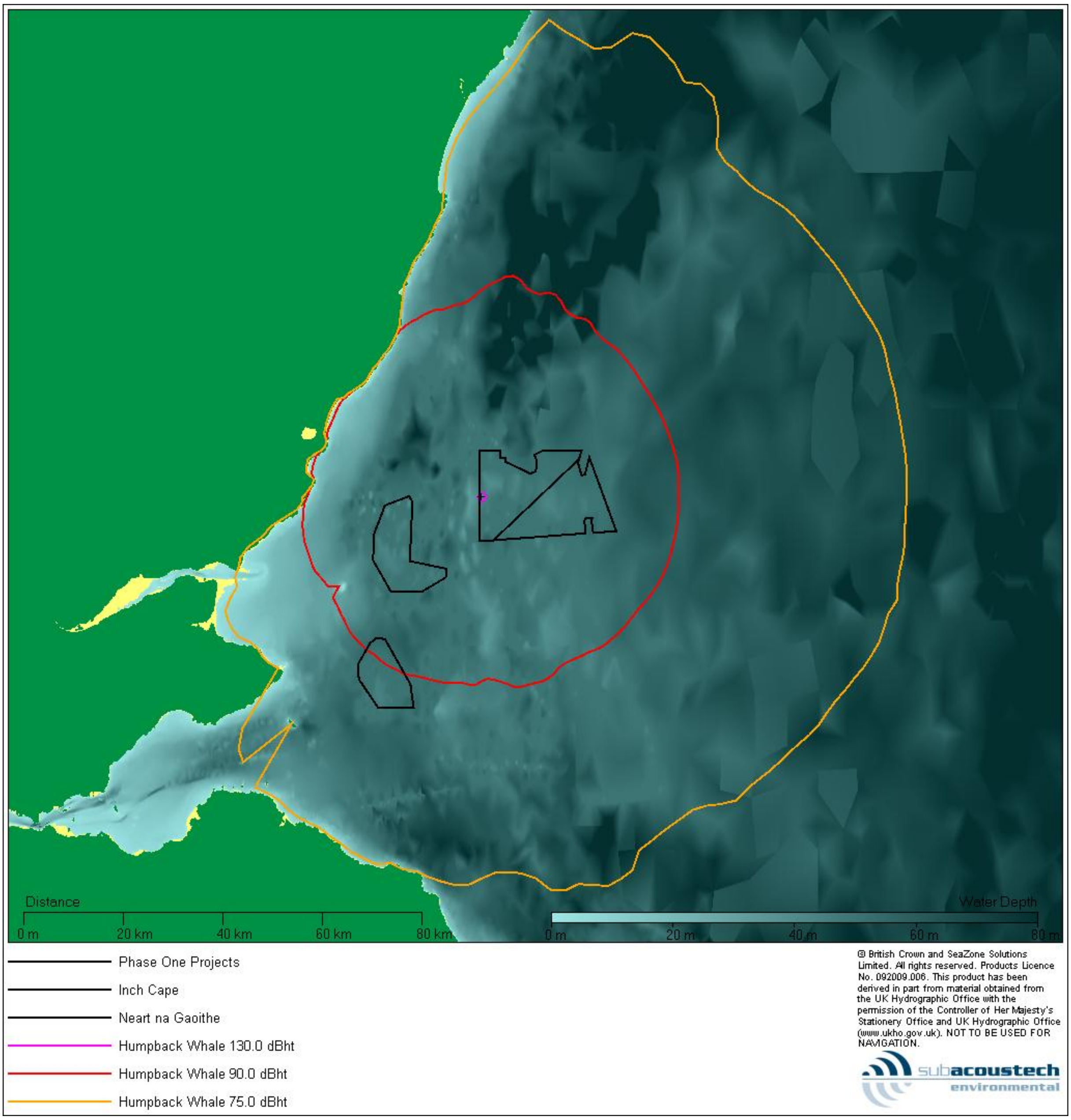

Figure 6-27 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the GM2 (alpha) scenario

6.4.1.4 GM2 (bravo)

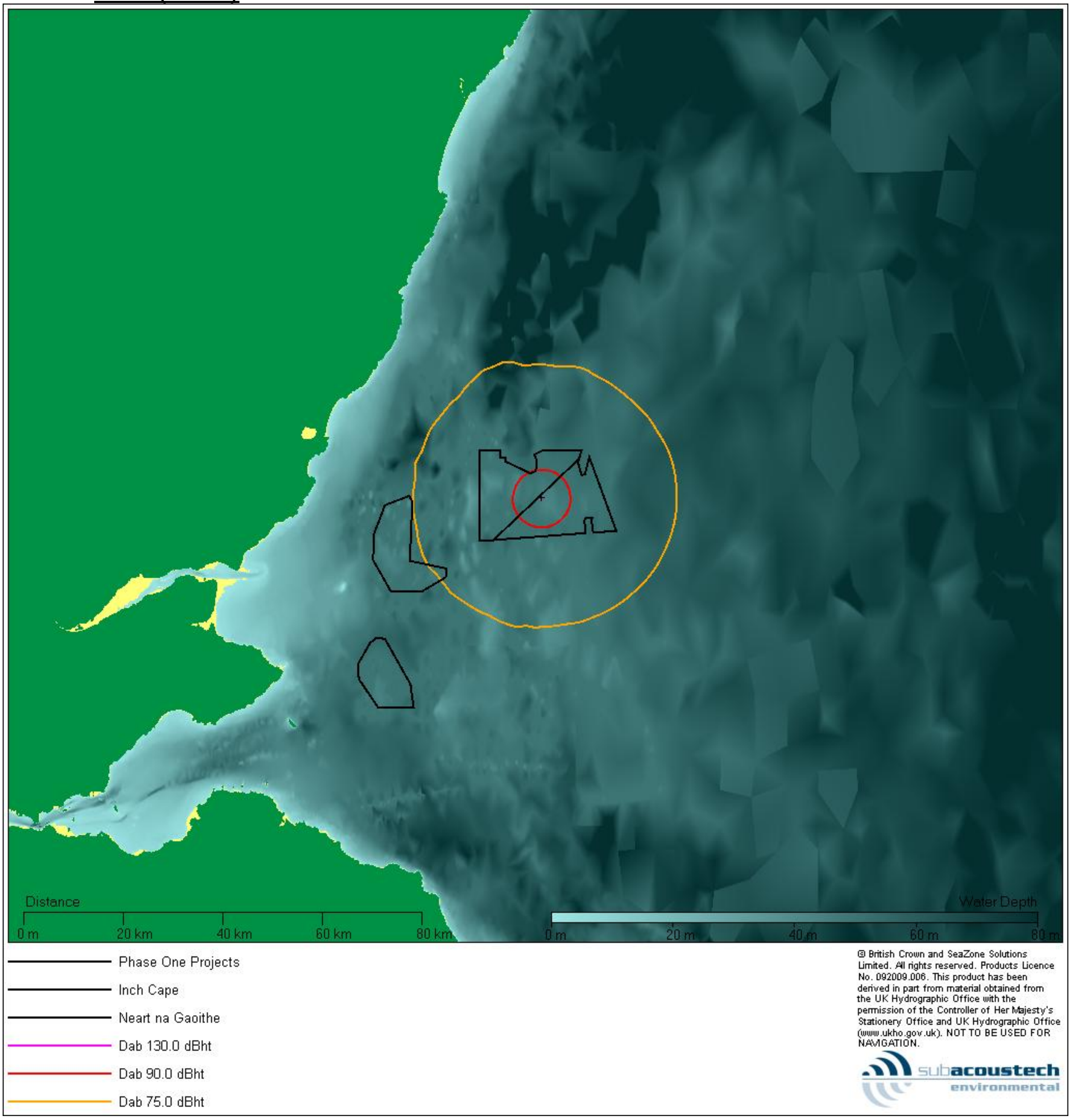

Figure 6-28 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM2 (bravo) scenario

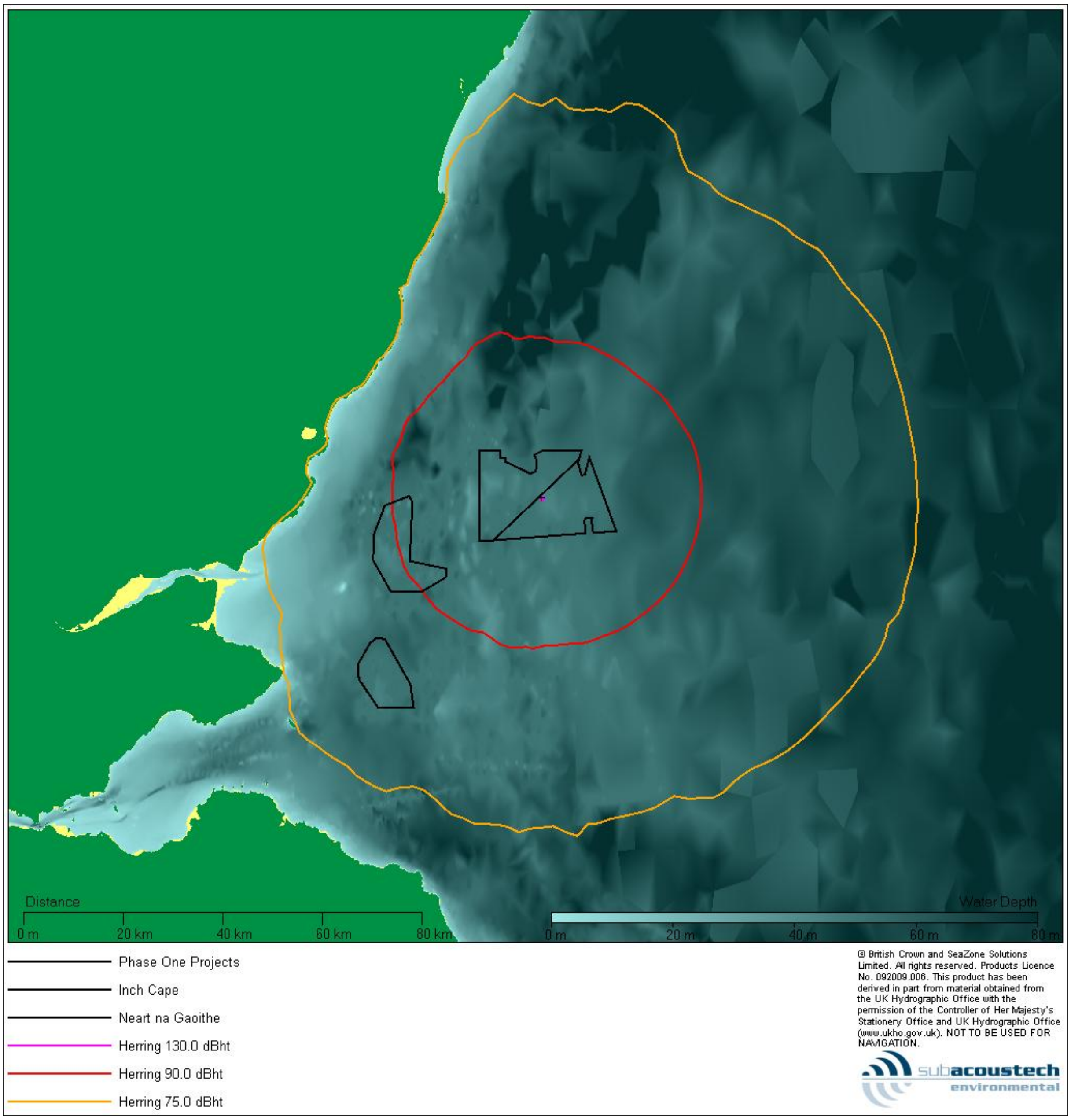

Figure 6-29 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the GM2 (bravo) scenario

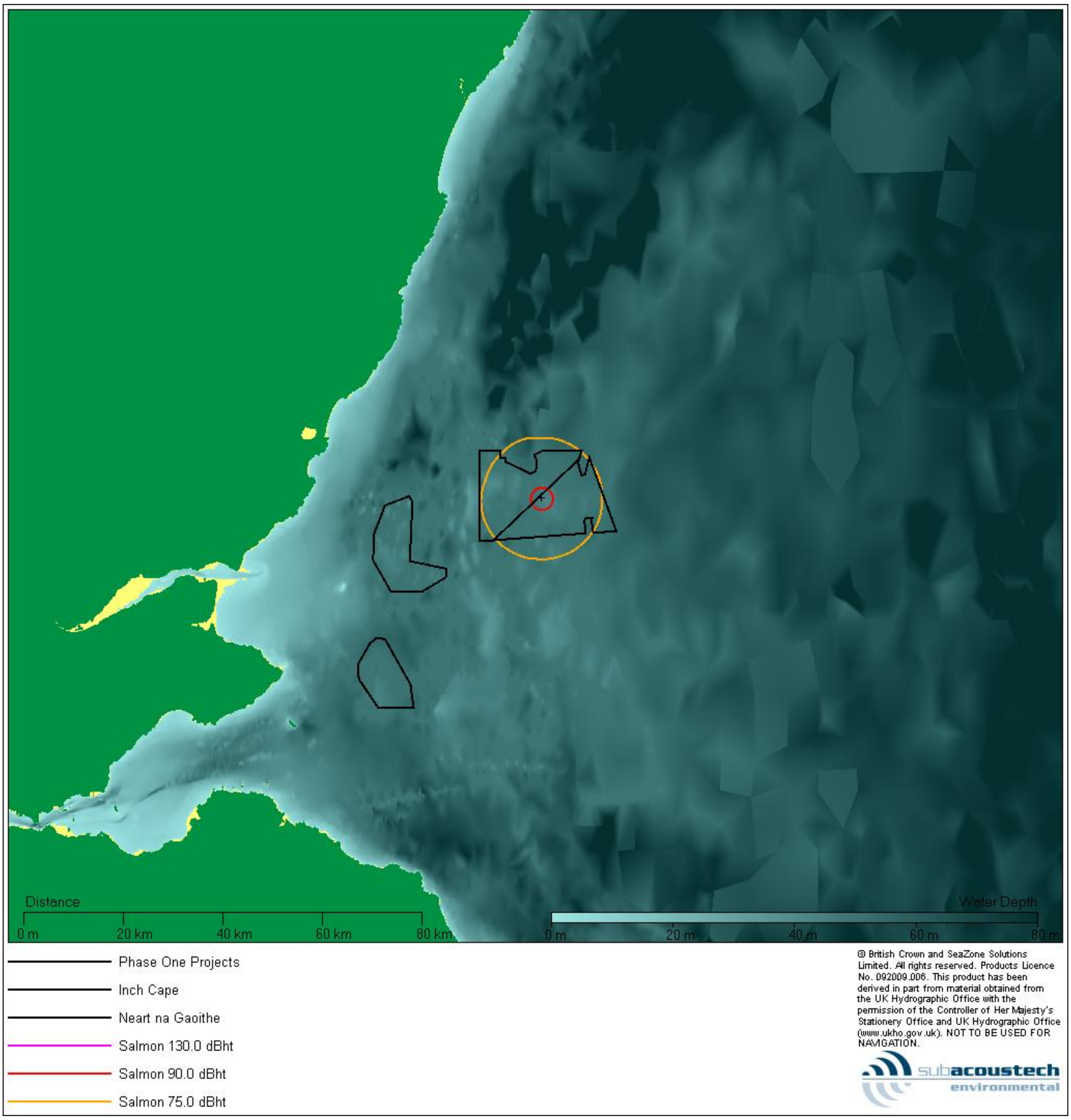

Figure 6-30 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Salmon for the GM2 (bravo) scenario

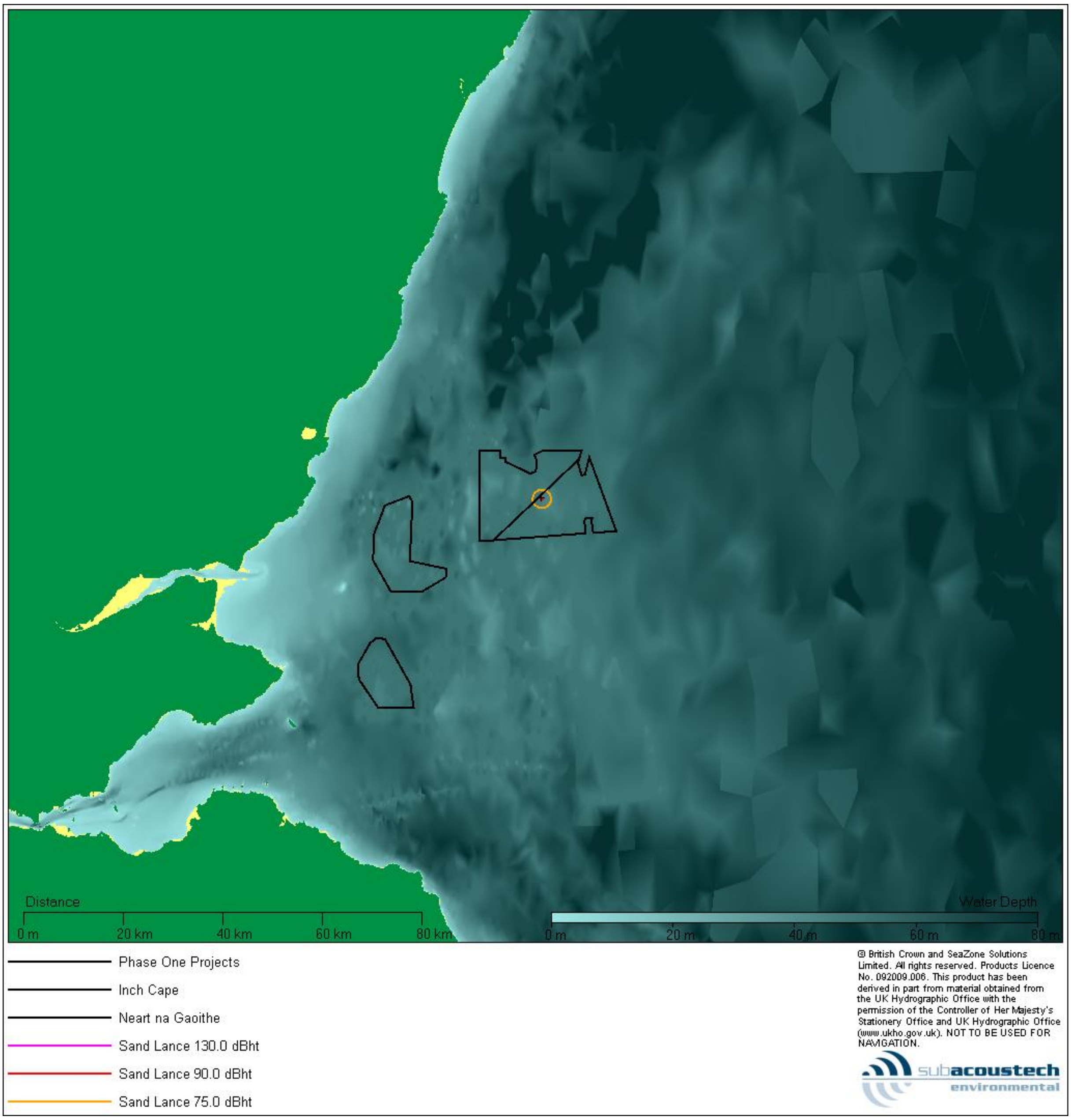

Figure 6-31 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the GM2 (bravo) scenario

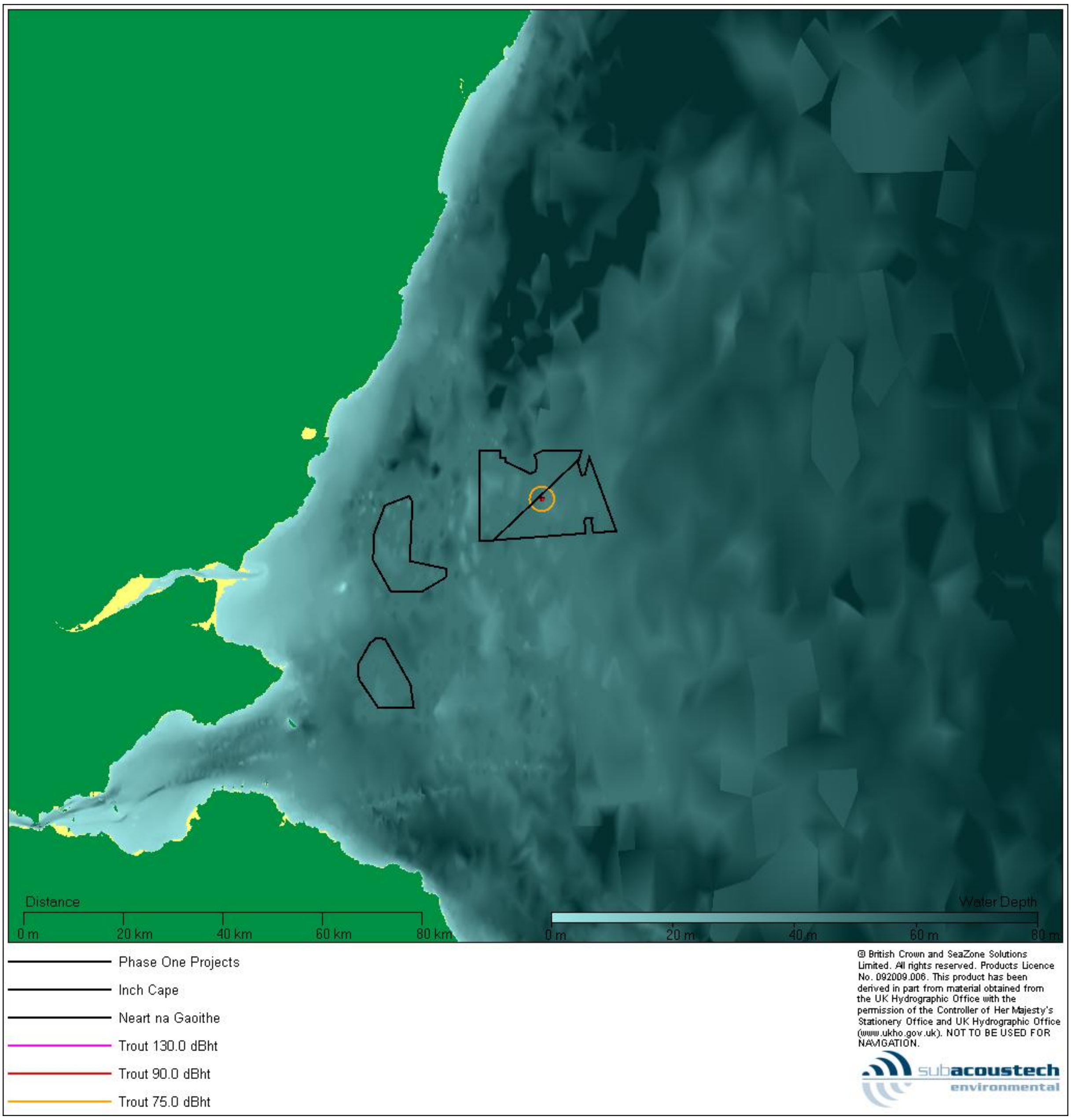

Figure 6-32 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the GM2 (bravo) scenario

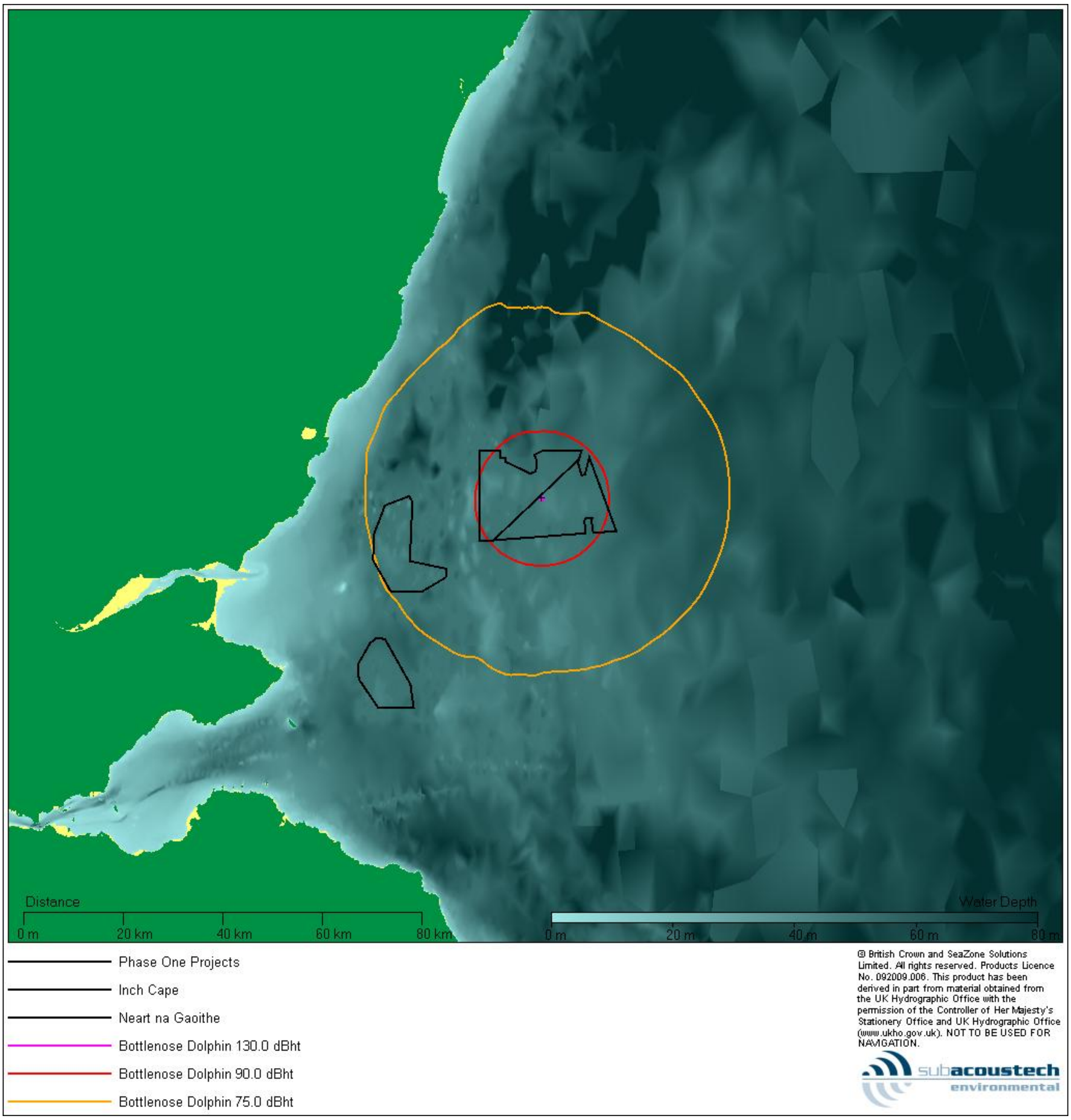

Figure 6-33 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the GM2 (bravo) scenario

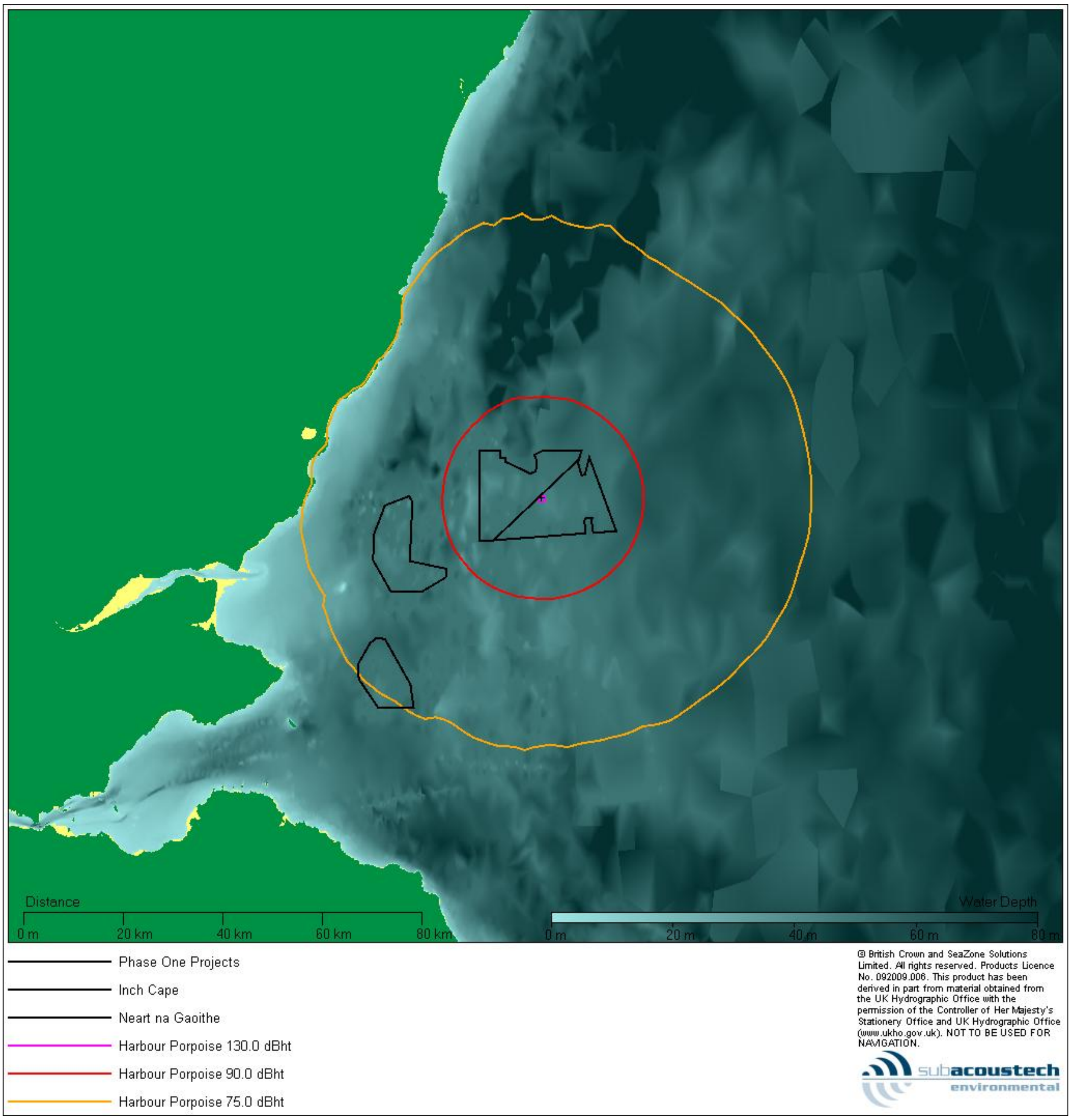

Figure 6-34 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM2 (bravo) scenario

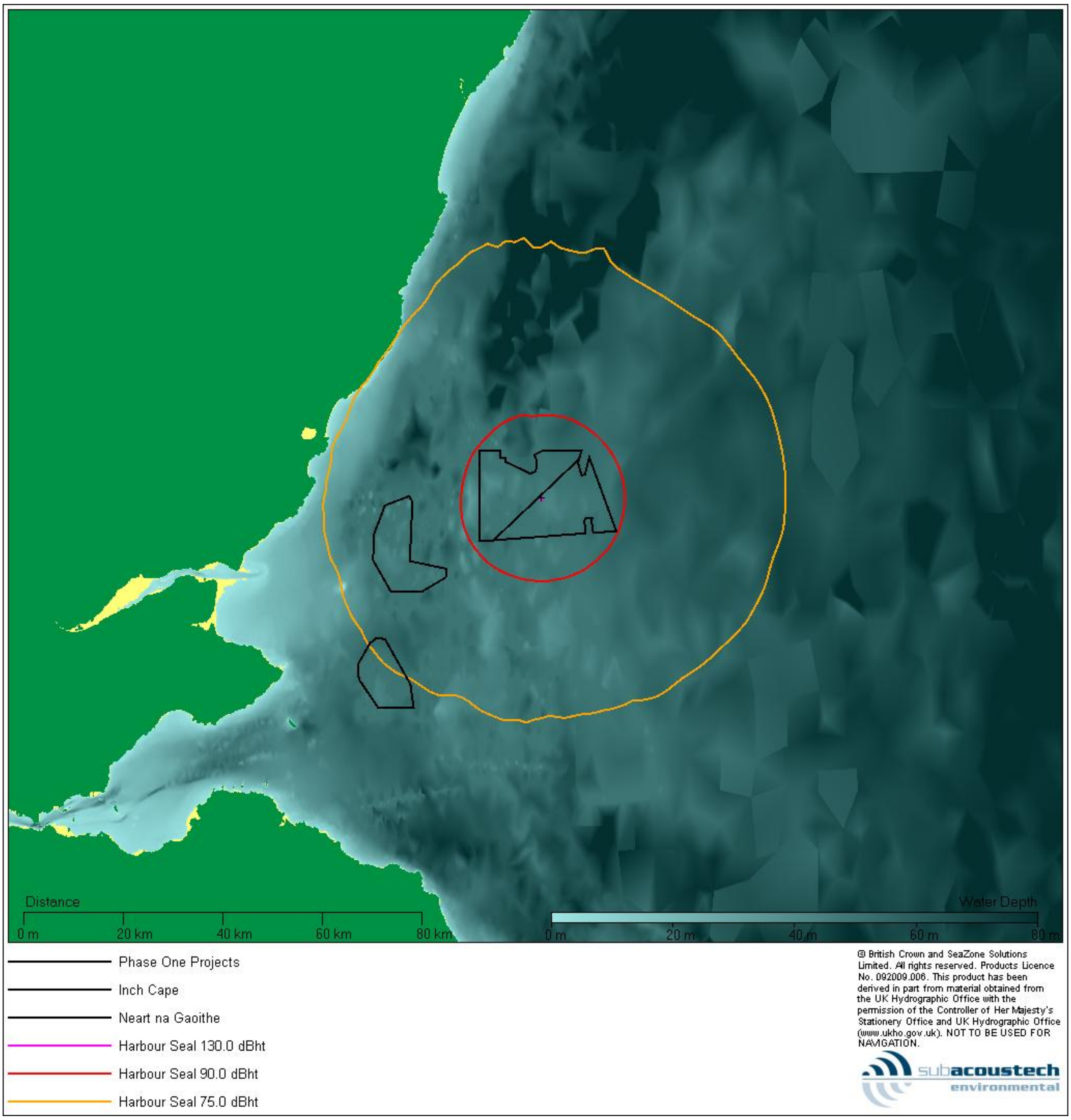

Figure 6-35 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM2 (bravo) scenario

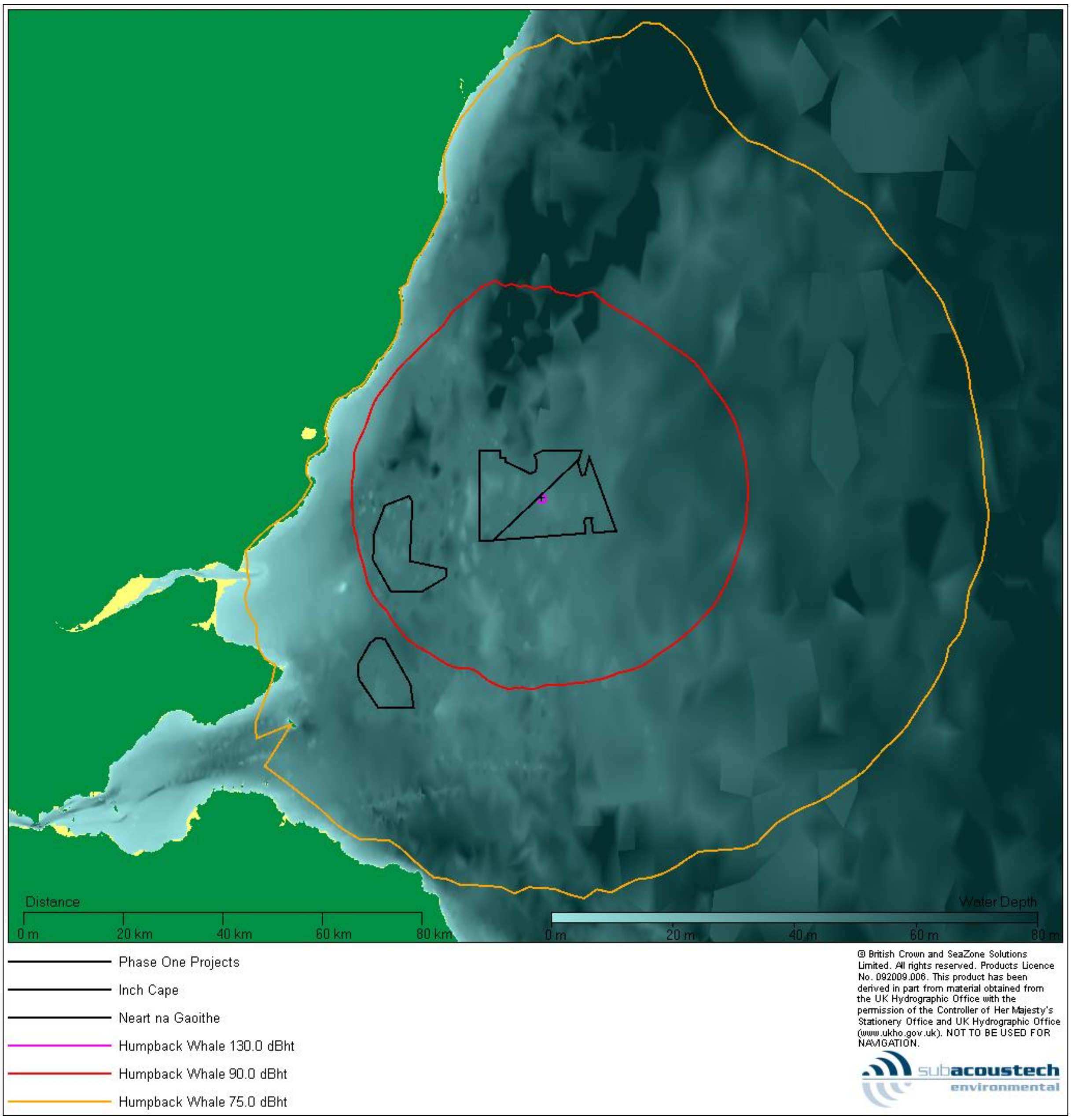

Figure 6-36 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the GM2 (bravo) scenario

6.4.1.5 GM3 (alpha)

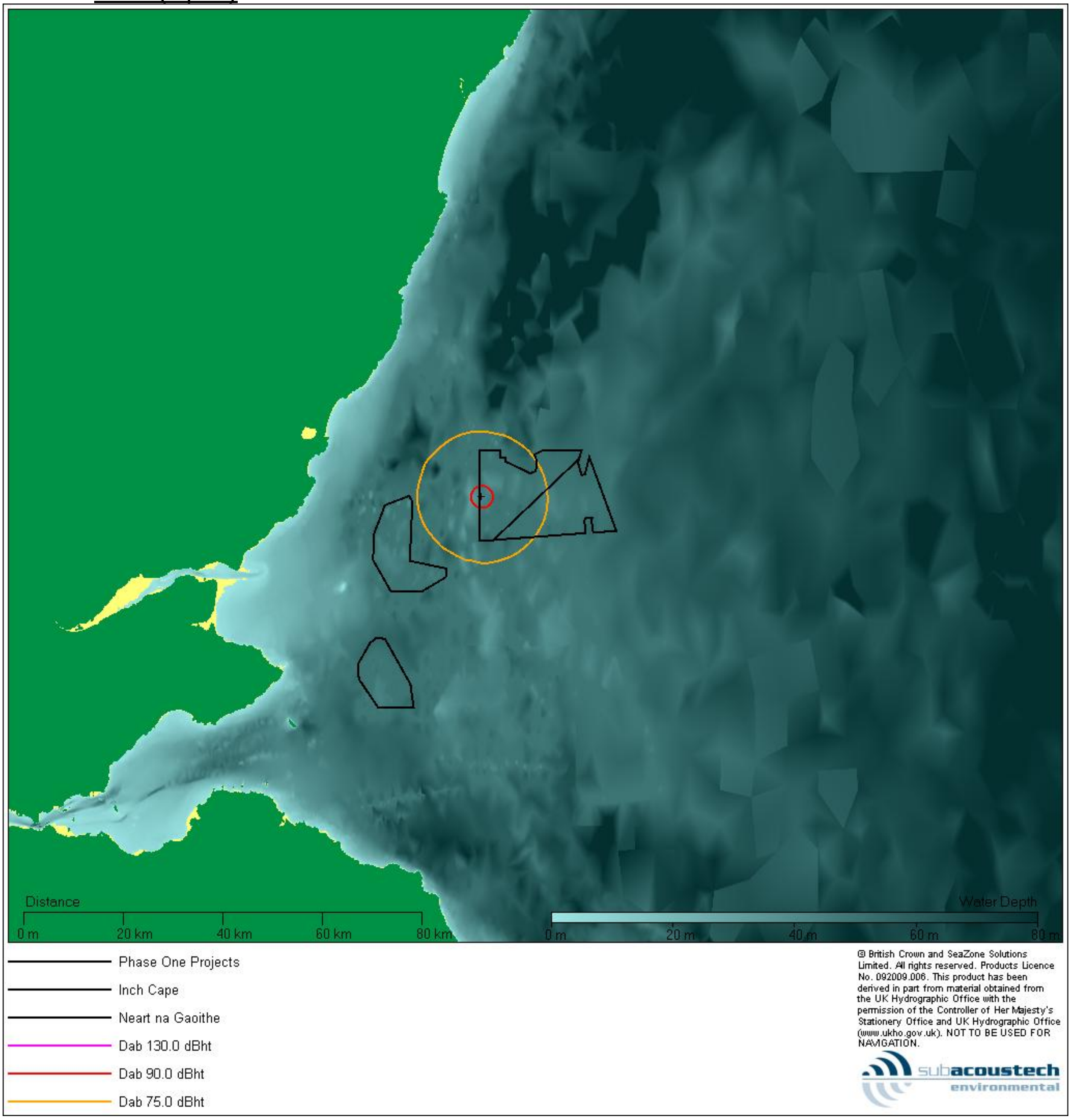

Figure 6-37 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM3 (alpha) scenario

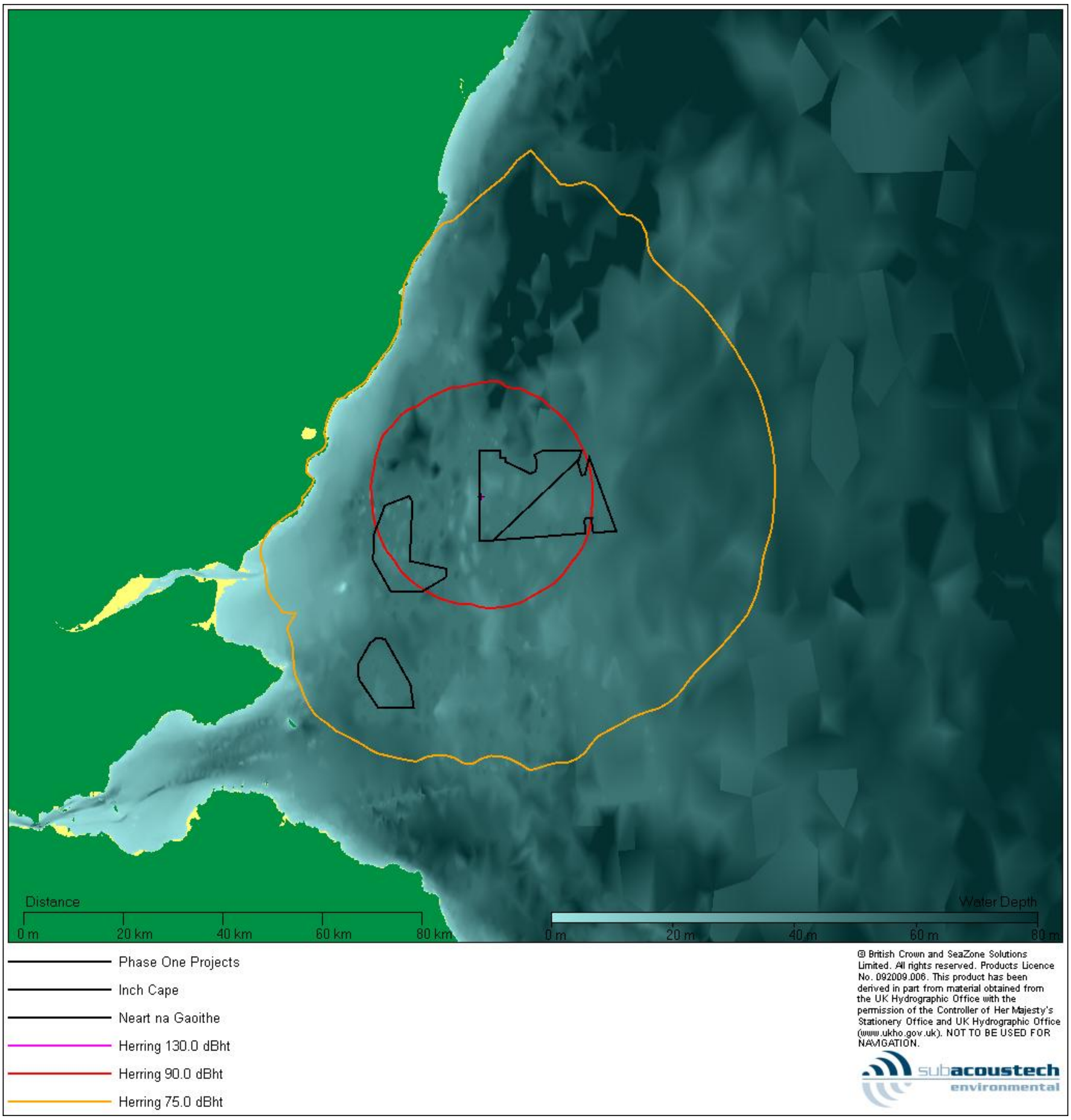

Figure 6-38 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Herring for the GM3 (alpha) scenario

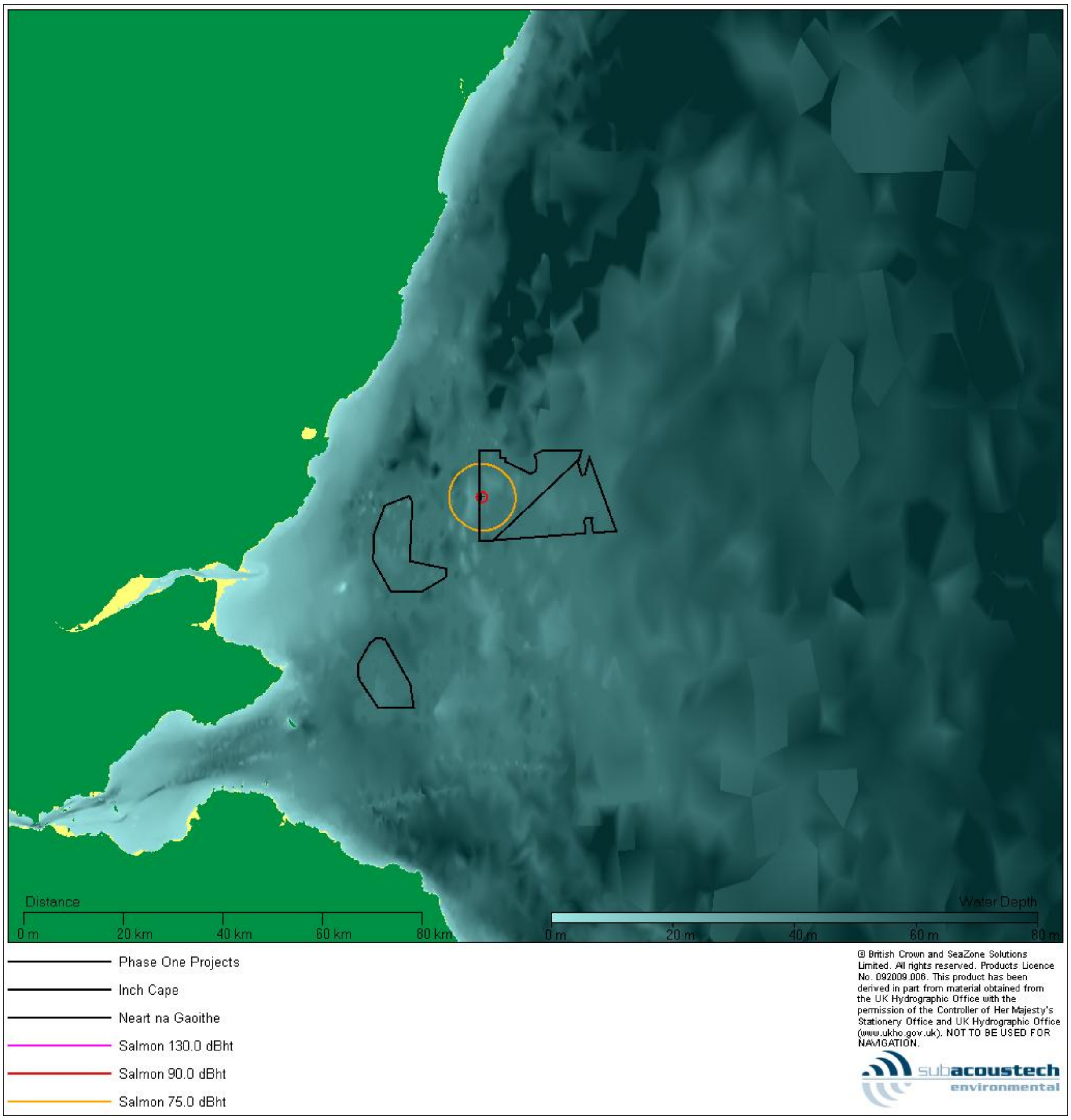

Figure 6-39 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Salmon for the GM3 (alpha) scenario

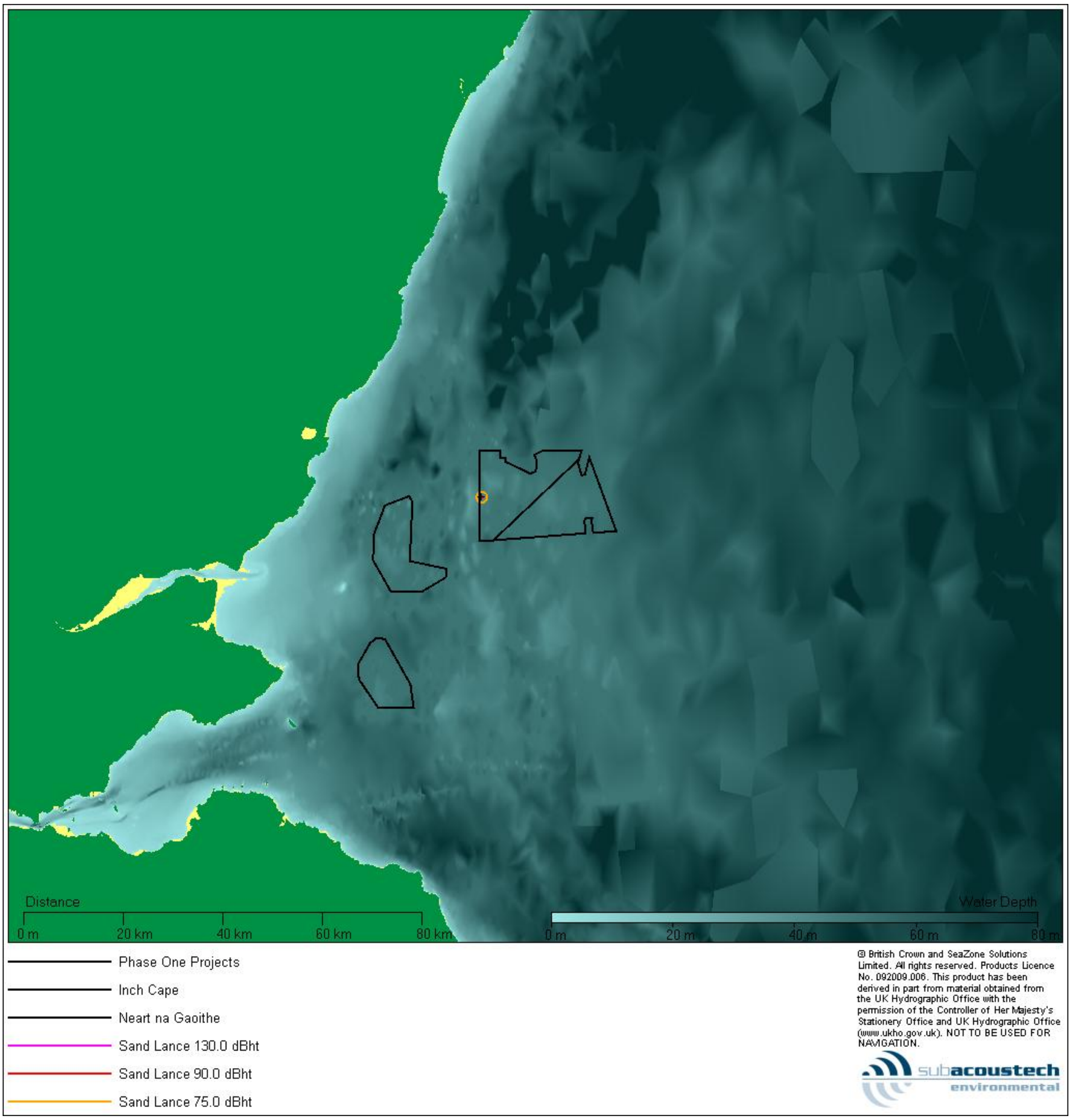

Figure 6-40 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the GM3 (alpha) scenario

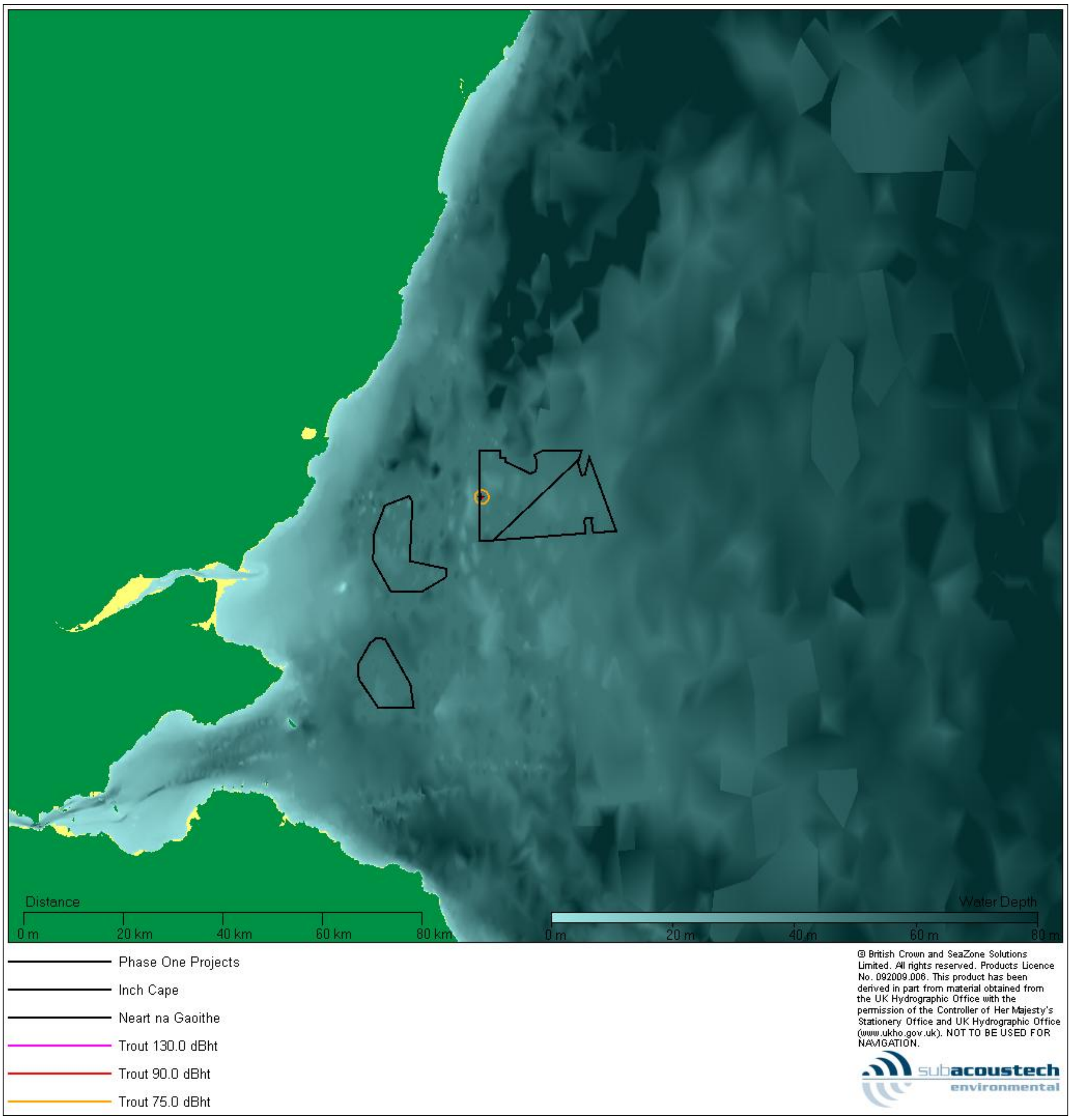

Figure 6-41 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Trout for the GM3 (alpha) scenario

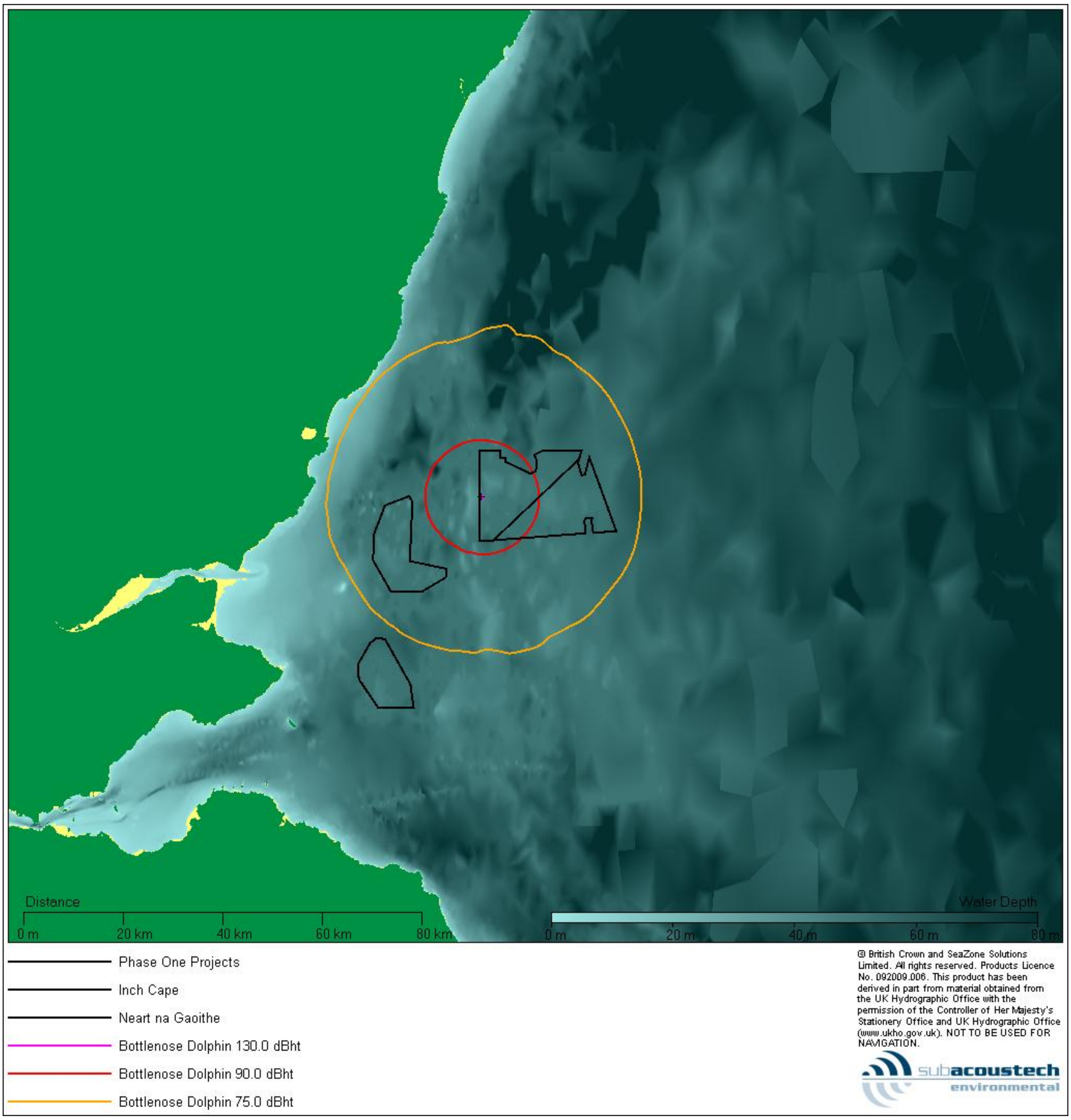

Figure 6-42 Contour plot showing the estimated 130, 90 and 75 $\mathrm{dB_{ht}}$ peak to peak impact ranges for Bottlenose Dolphin for the GM3 (alpha) scenario

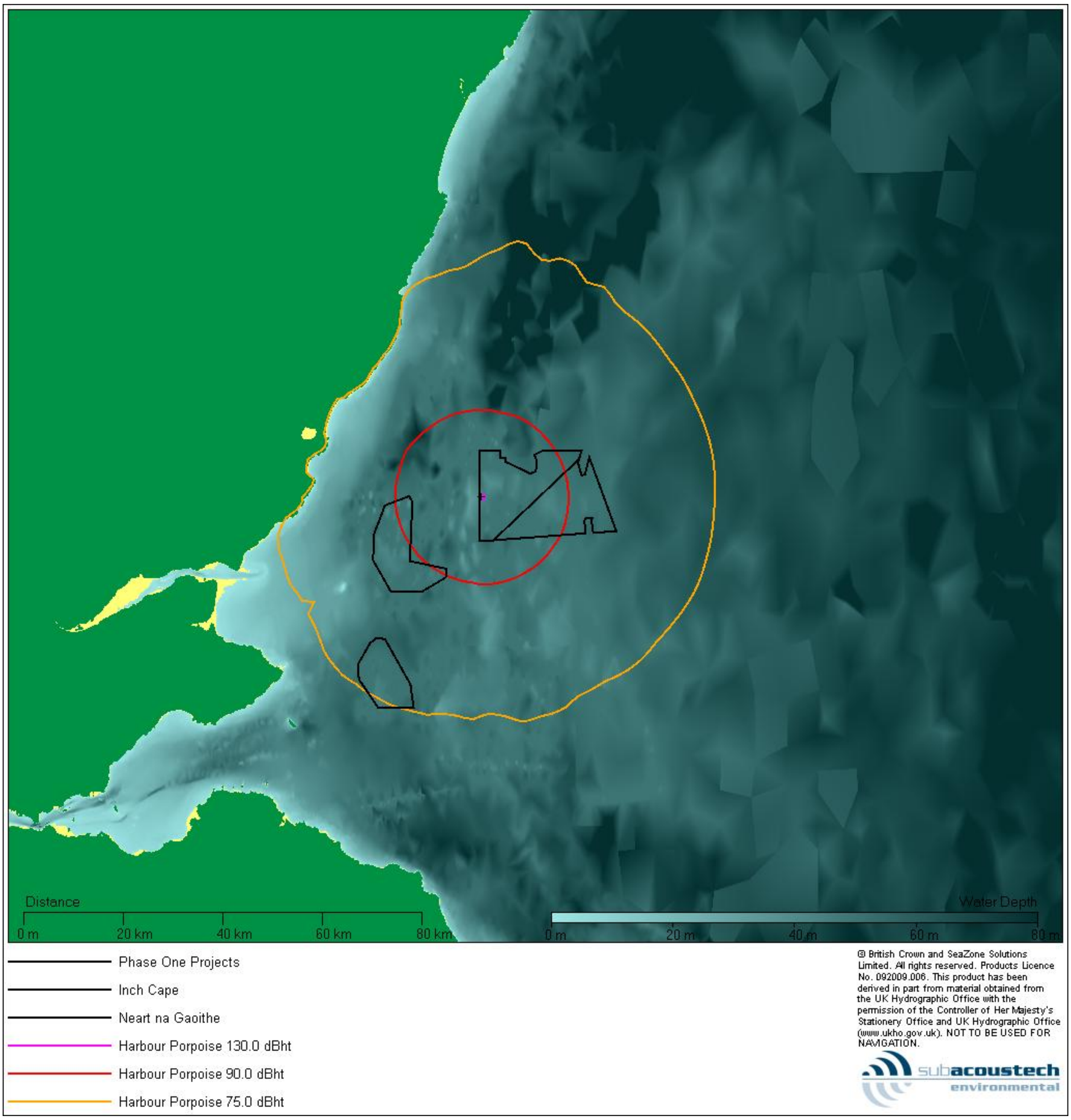

Figure 6-43 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM3 (alpha) scenario

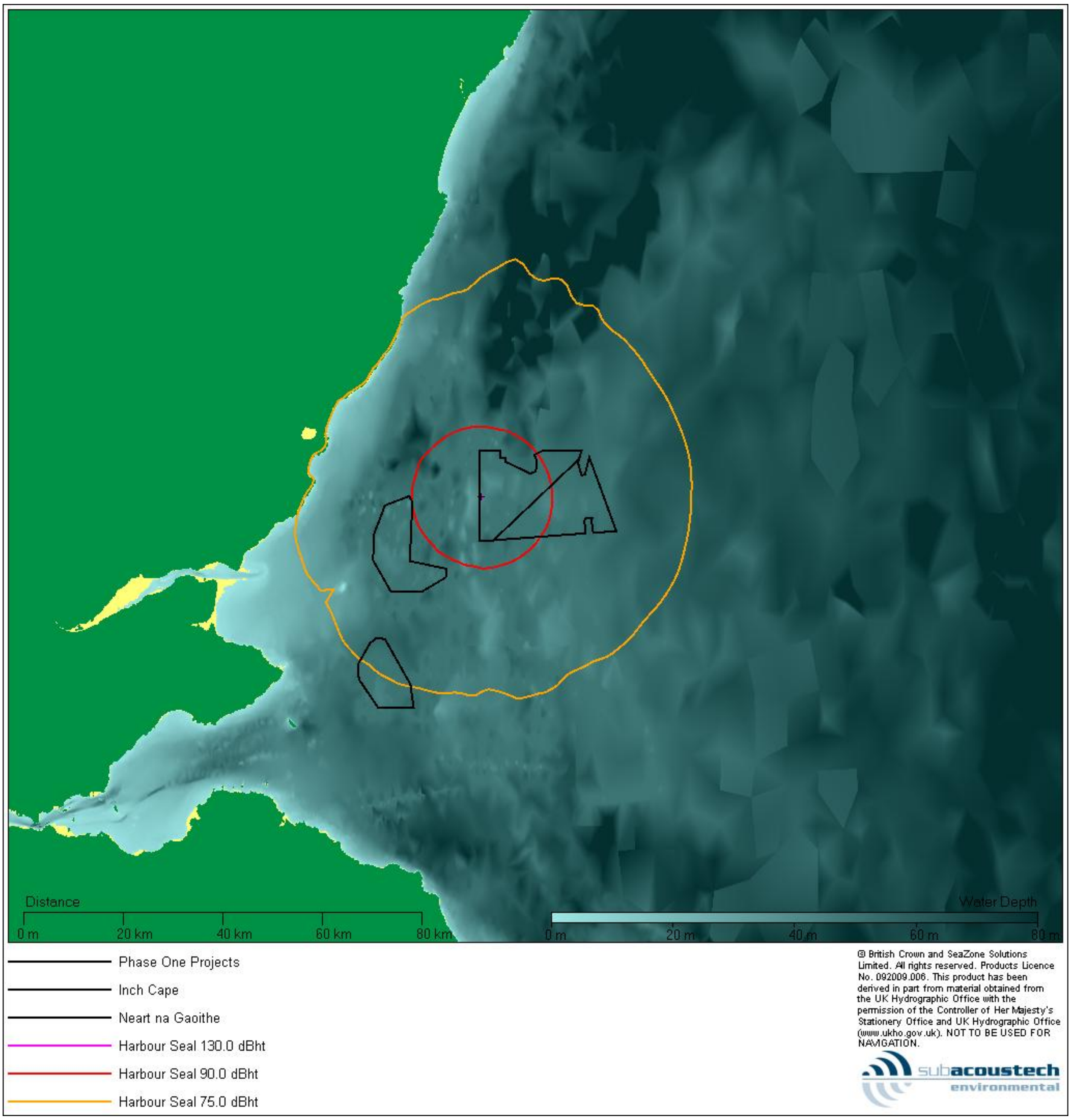

Figure 6-44 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM3 (alpha) scenario

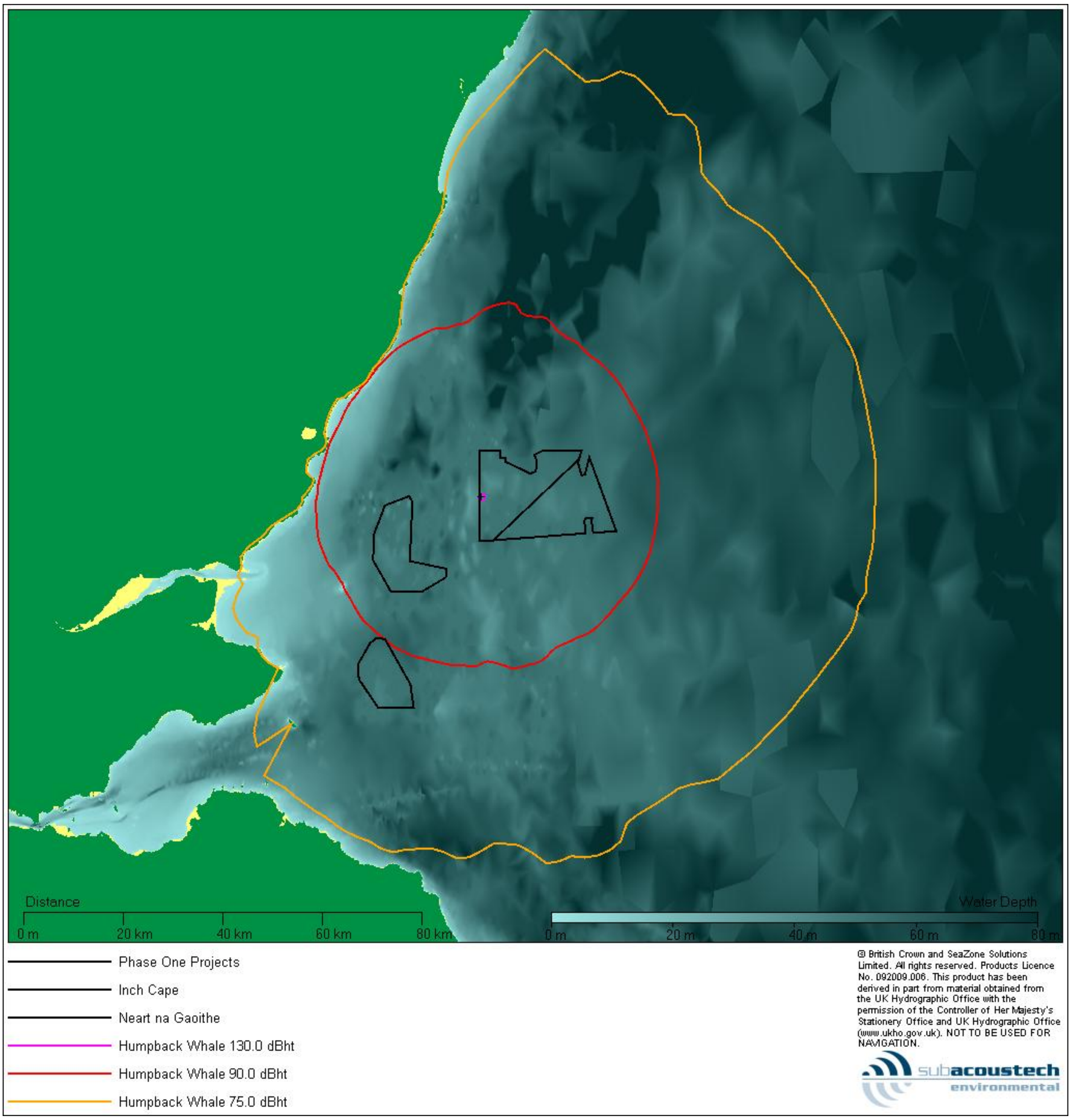

Figure 6-45 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Humpback Whale for the GM3 (alpha) scenario

6.4.1.6 GM3 (bravo)

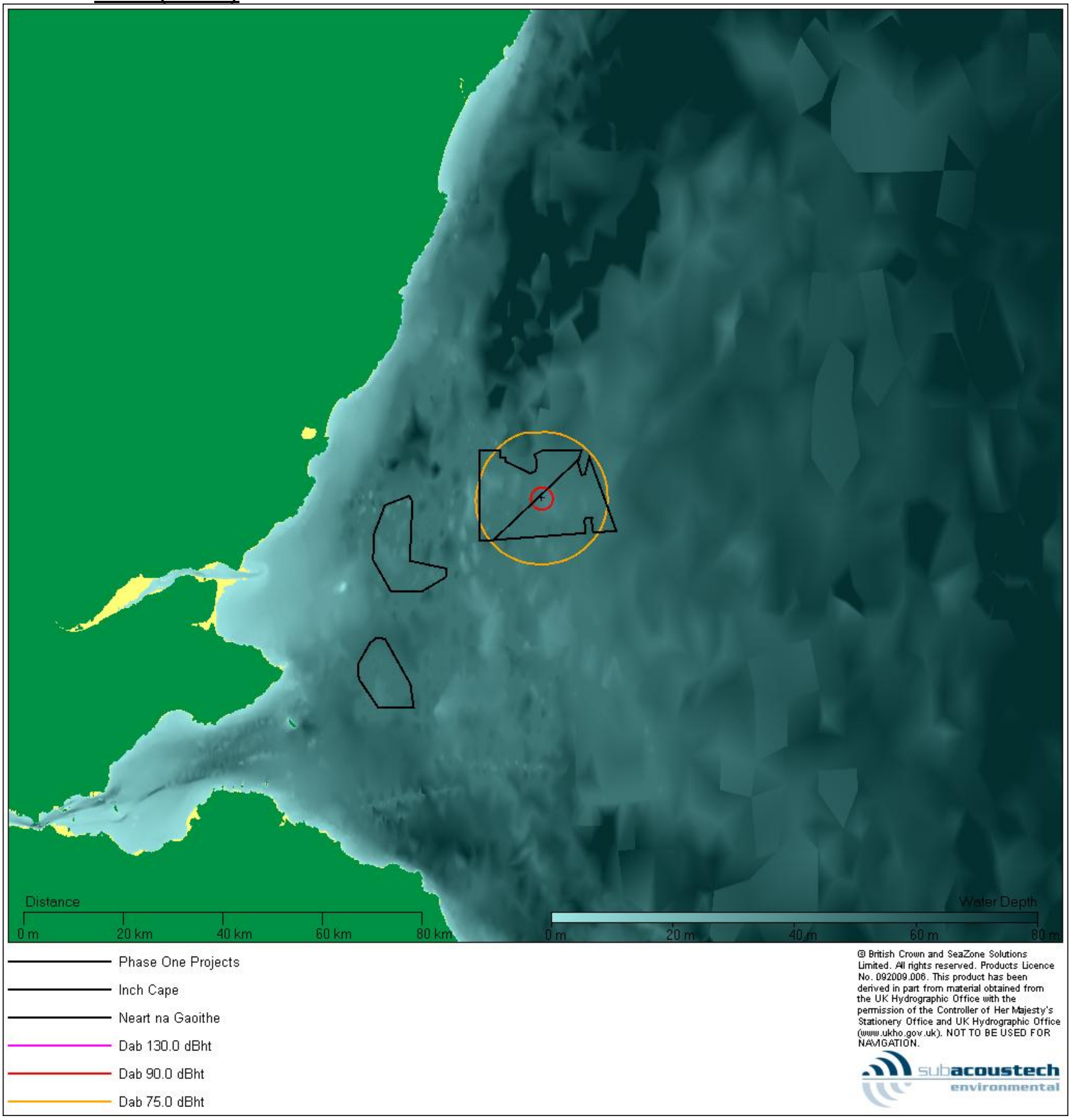

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Figure 6-46 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM3 (bravo) scenario

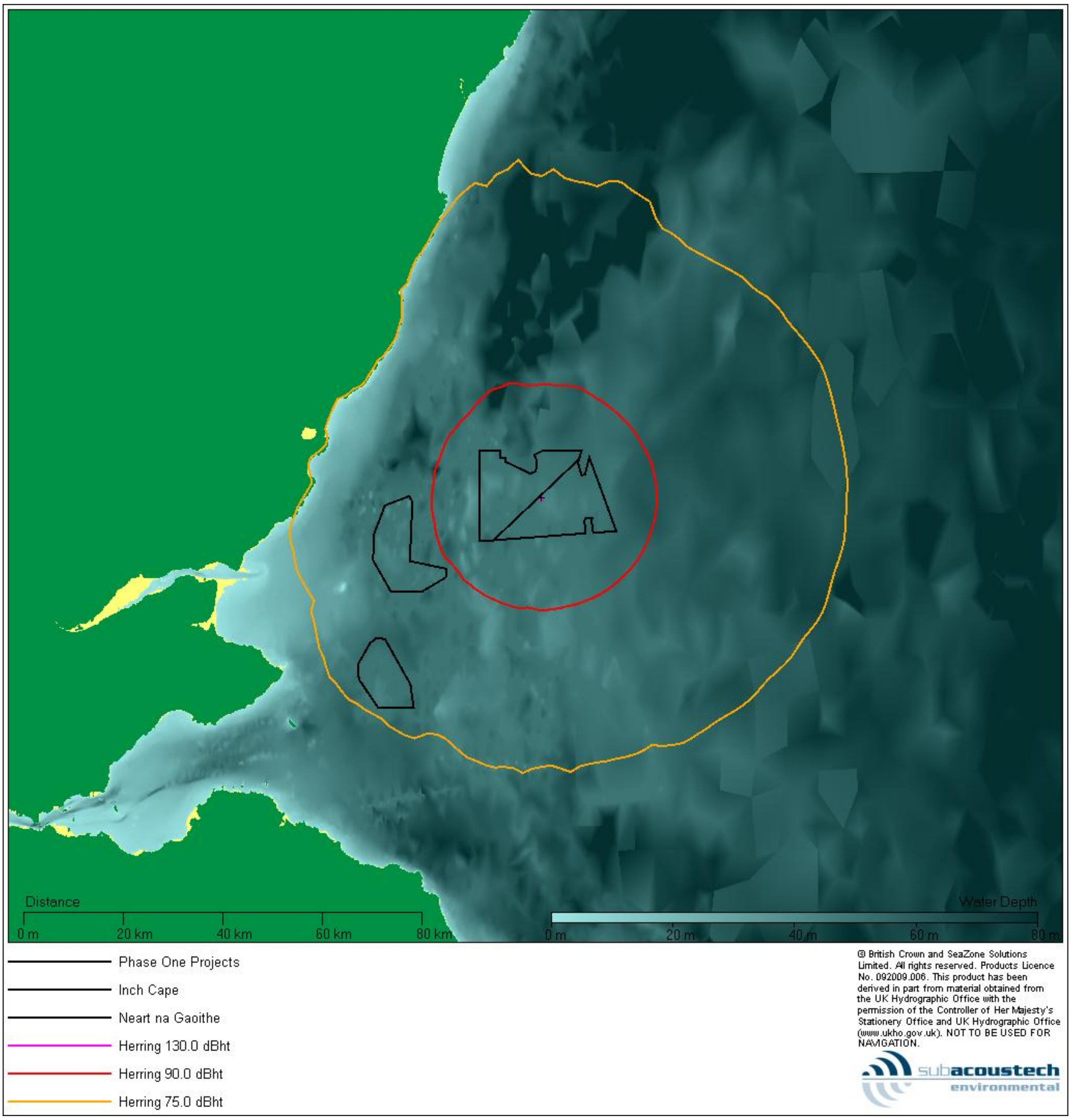

Figure 6-47 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Herring for the GM3 (bravo) scenario

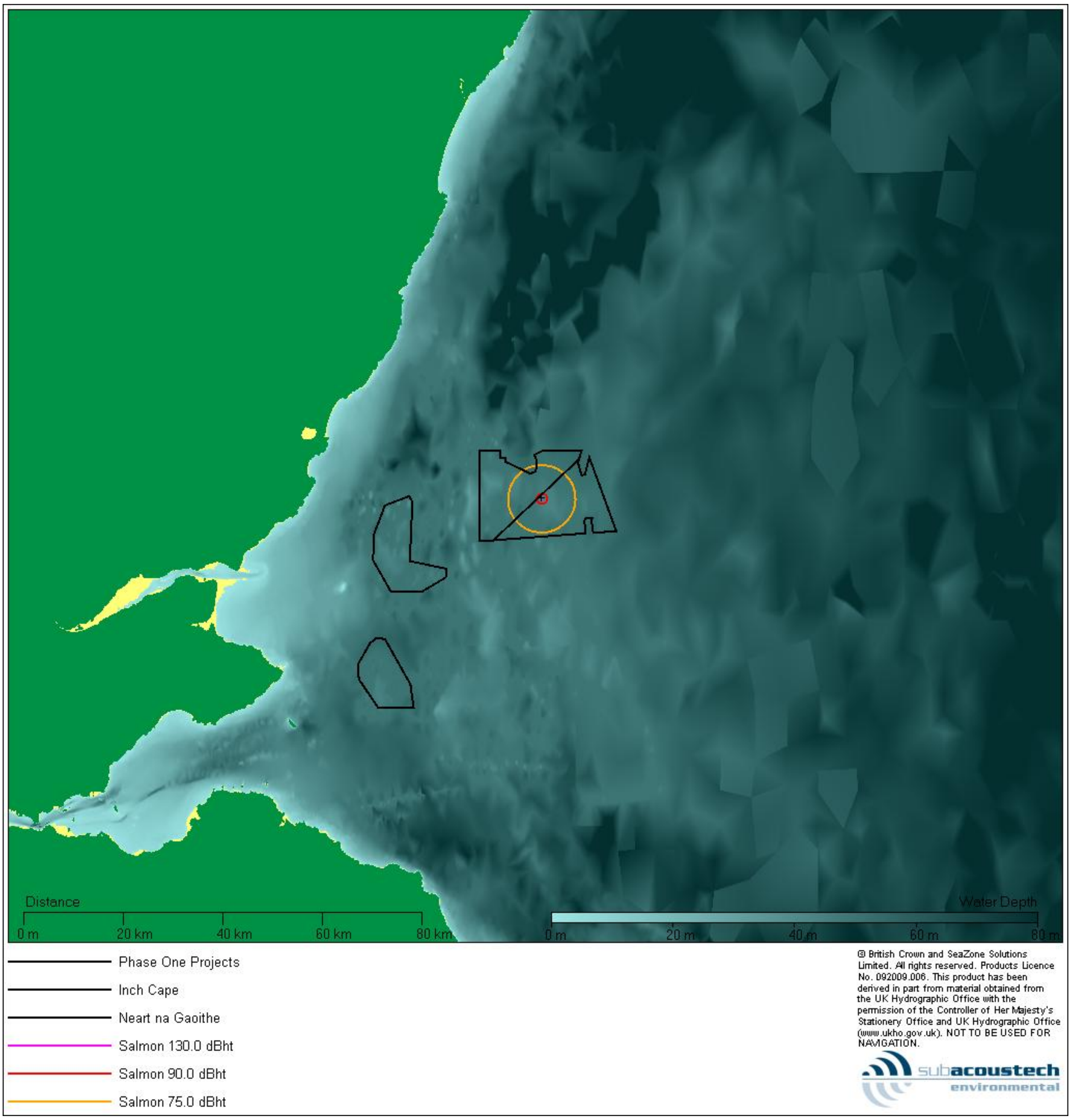

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Figure 6-48 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Salmon for the GM3 (bravo) scenario

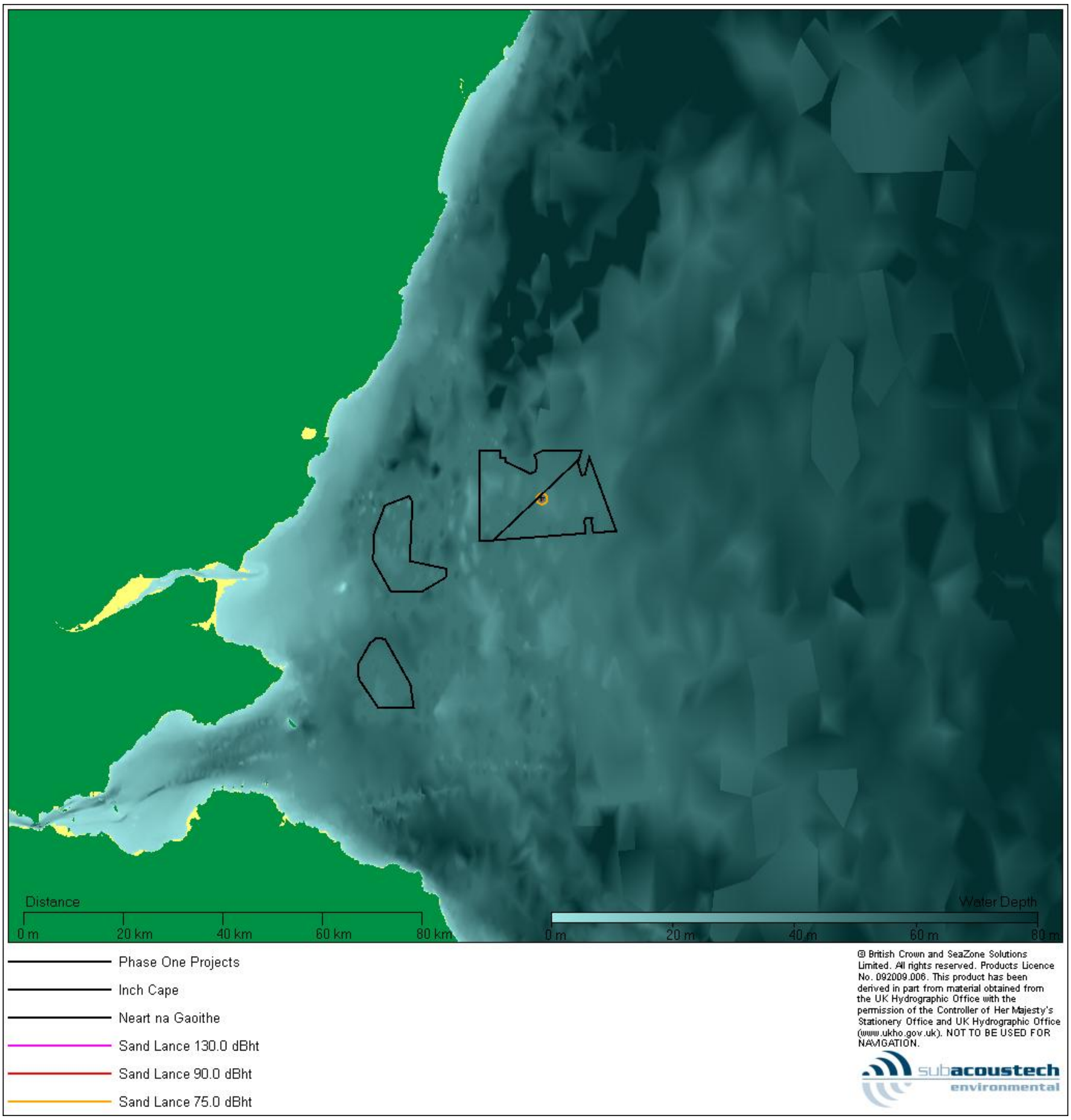

Figure 6-49 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Sand Lance for the GM3 (bravo) scenario

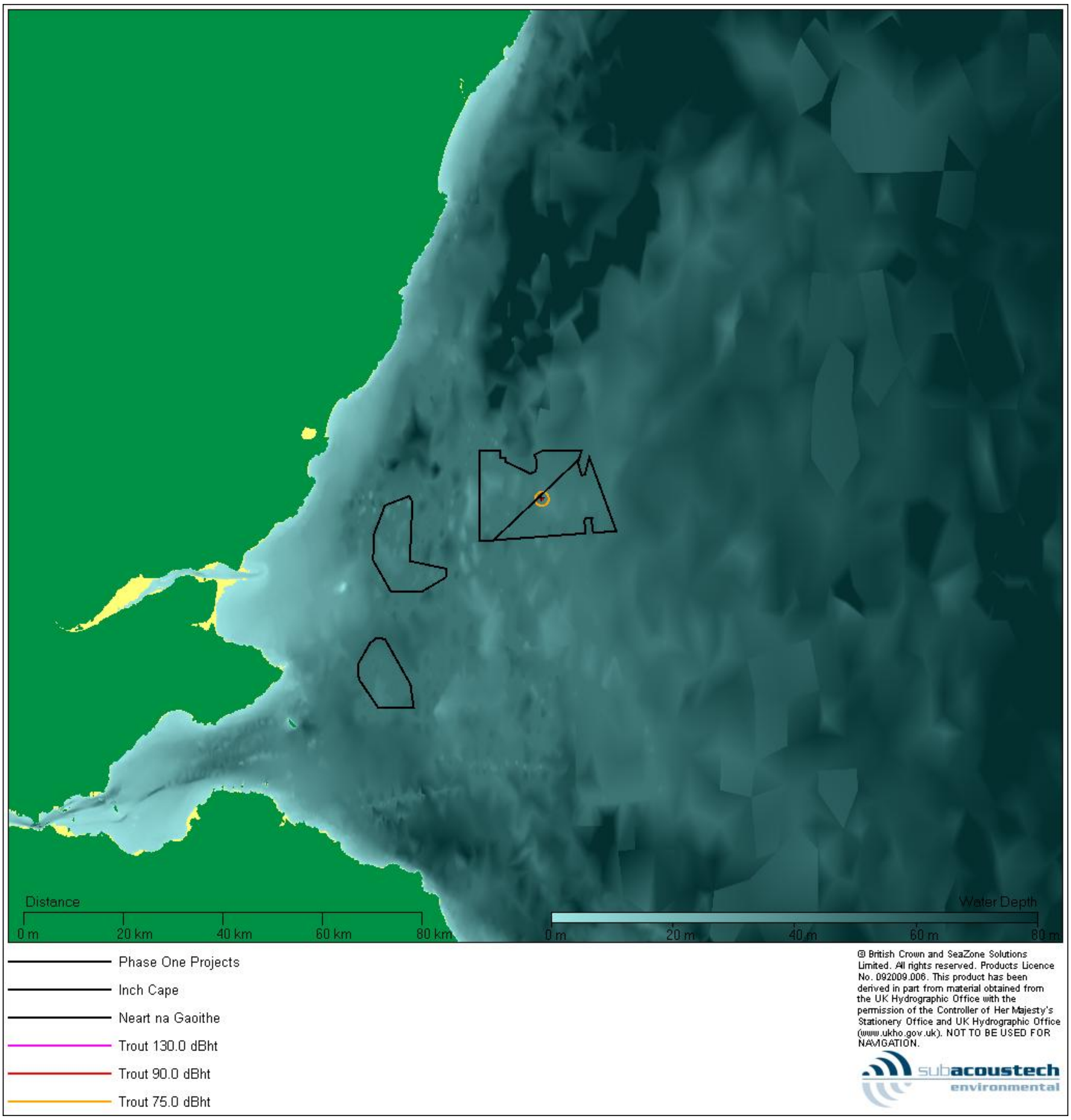

Figure 6-50 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Trout for the GM3 (bravo) scenario

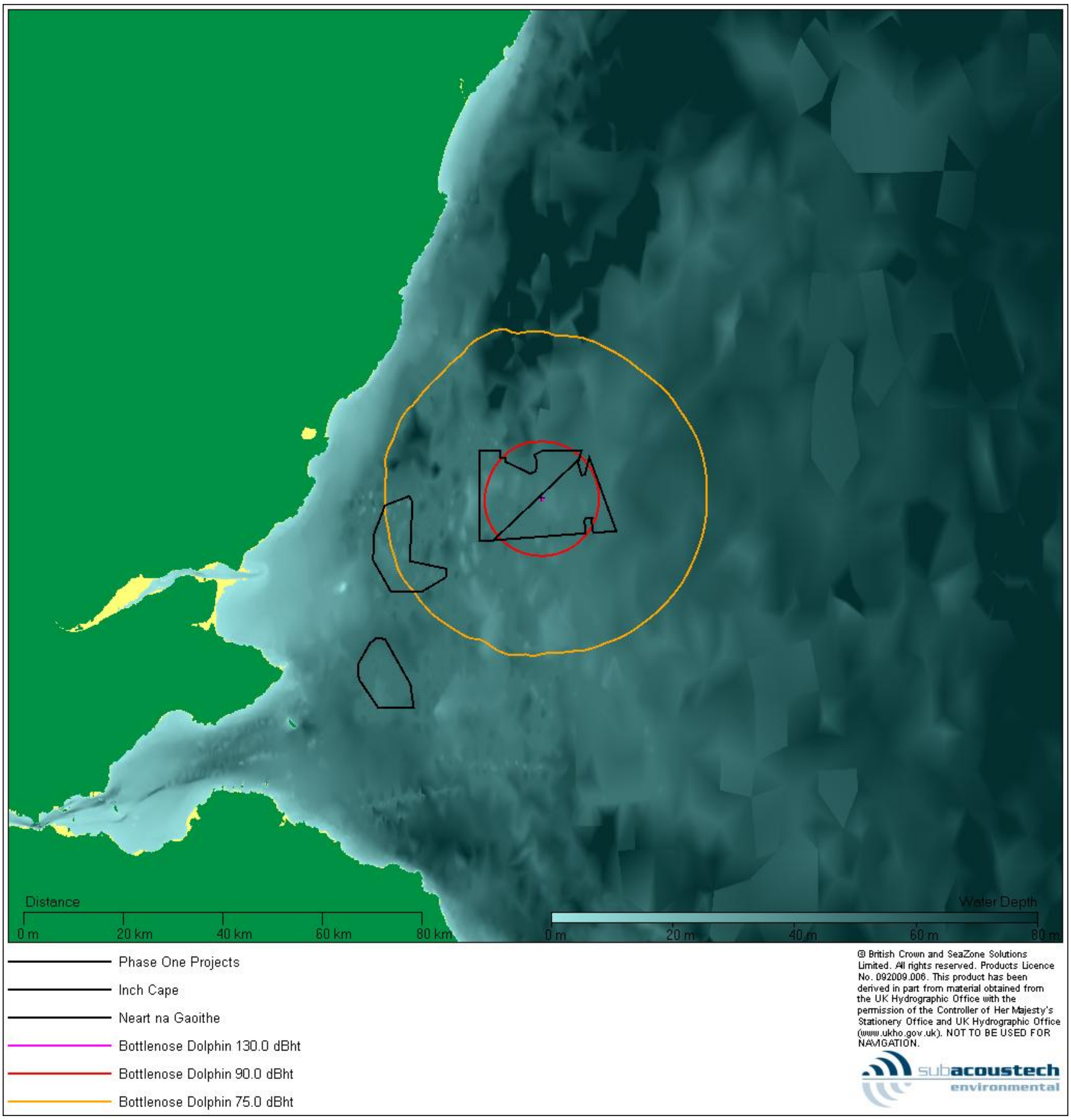

Figure 6-51 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the GM3 (bravo) scenario

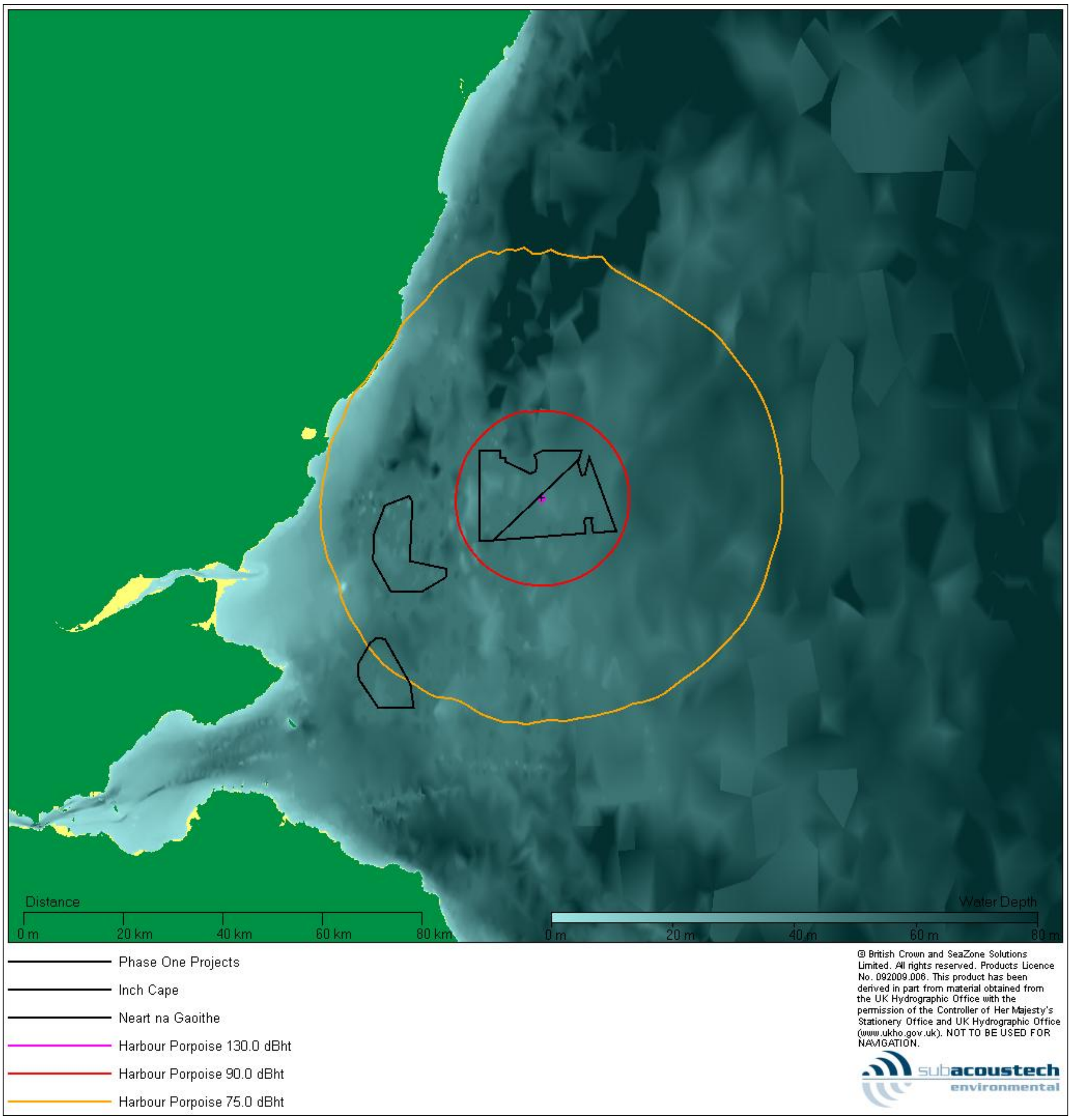

Figure 6-52 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM3 (bravo) scenario

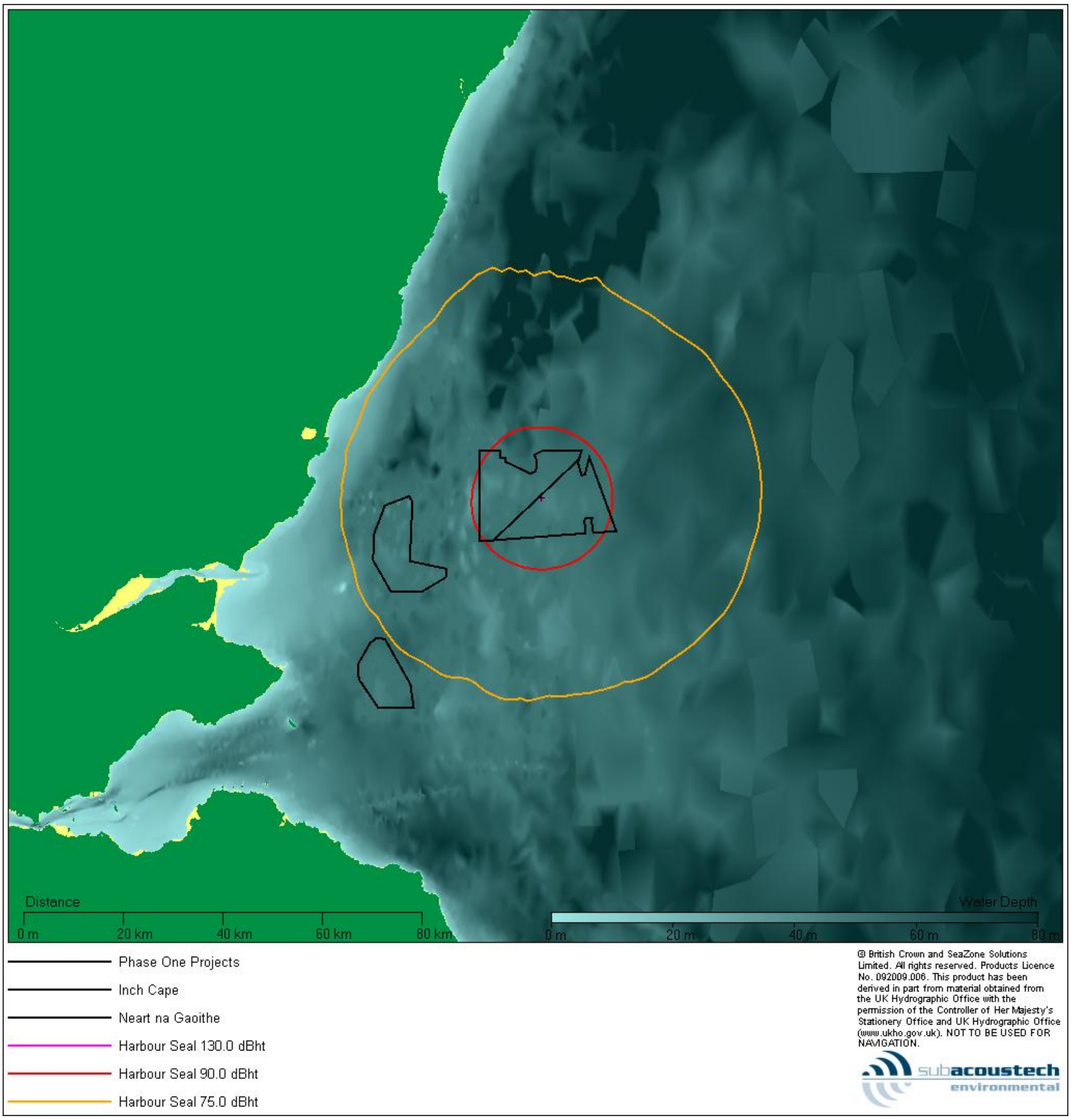

Figure 6-53 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM3 (bravo) scenario

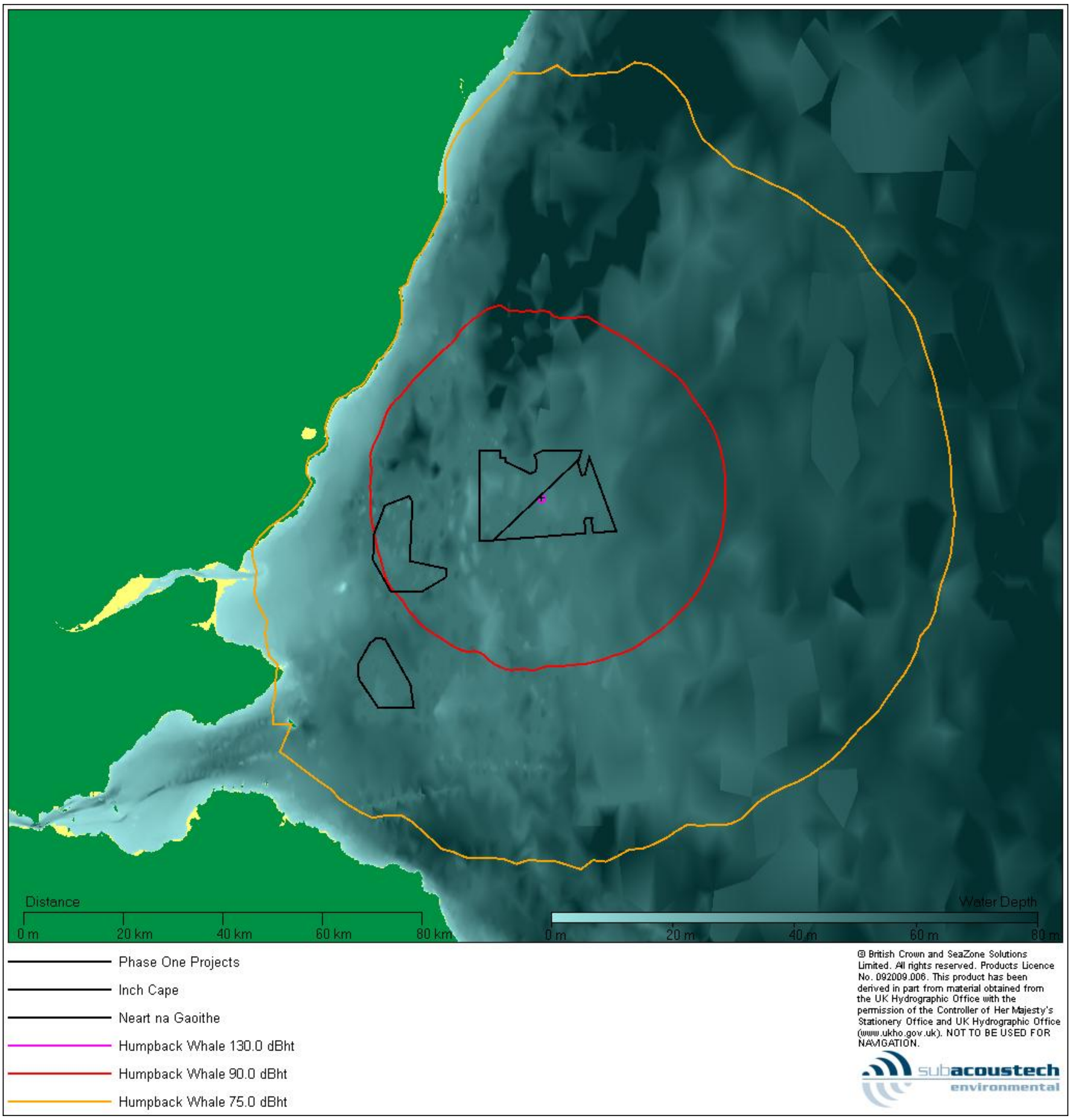

Figure 6-54 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Humpback Whale for the GM3 (bravo) scenario

6.4.1.7 GM4 (alpha)

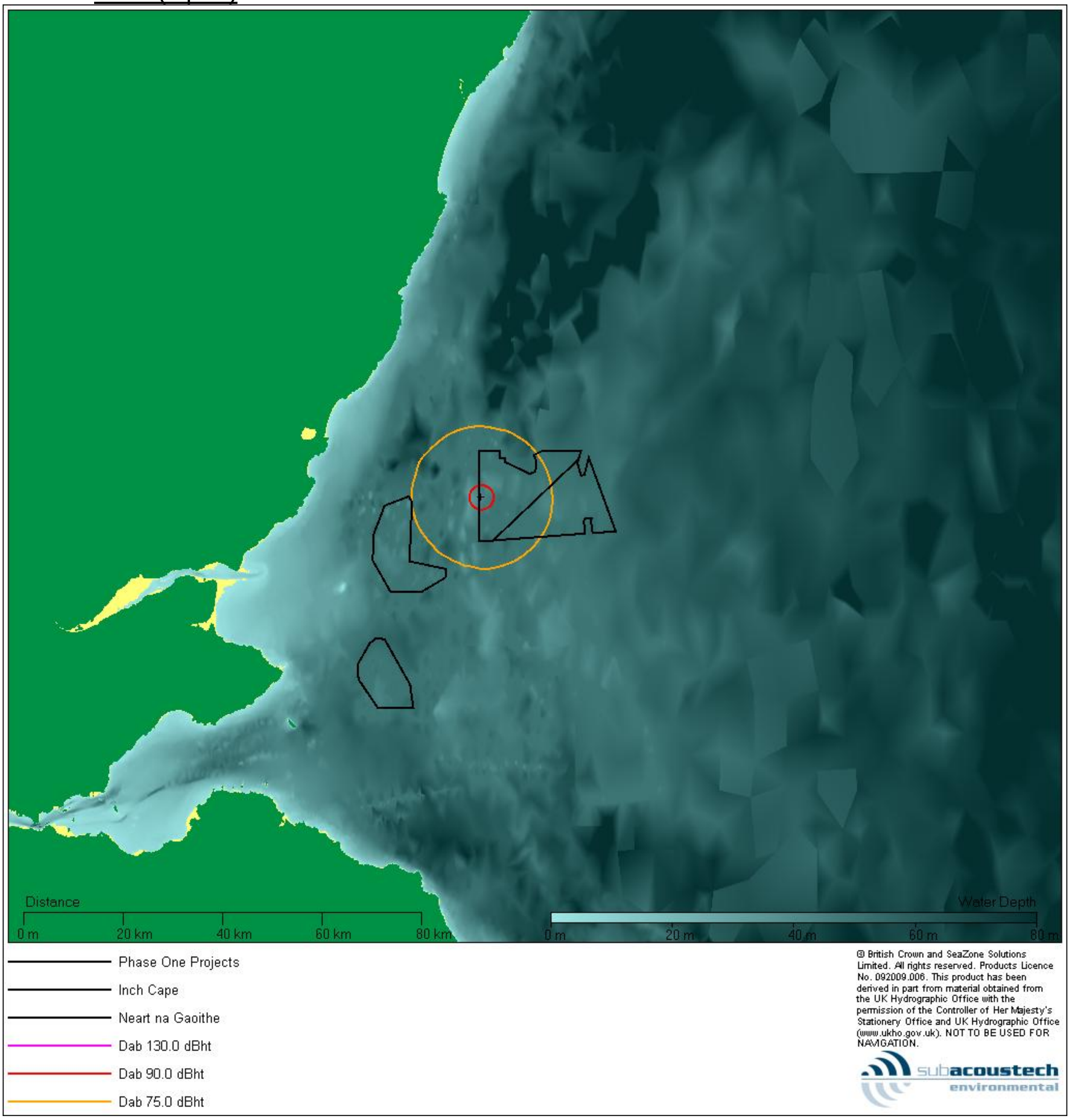

Figure 6-55 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM4 (alpha) scenario

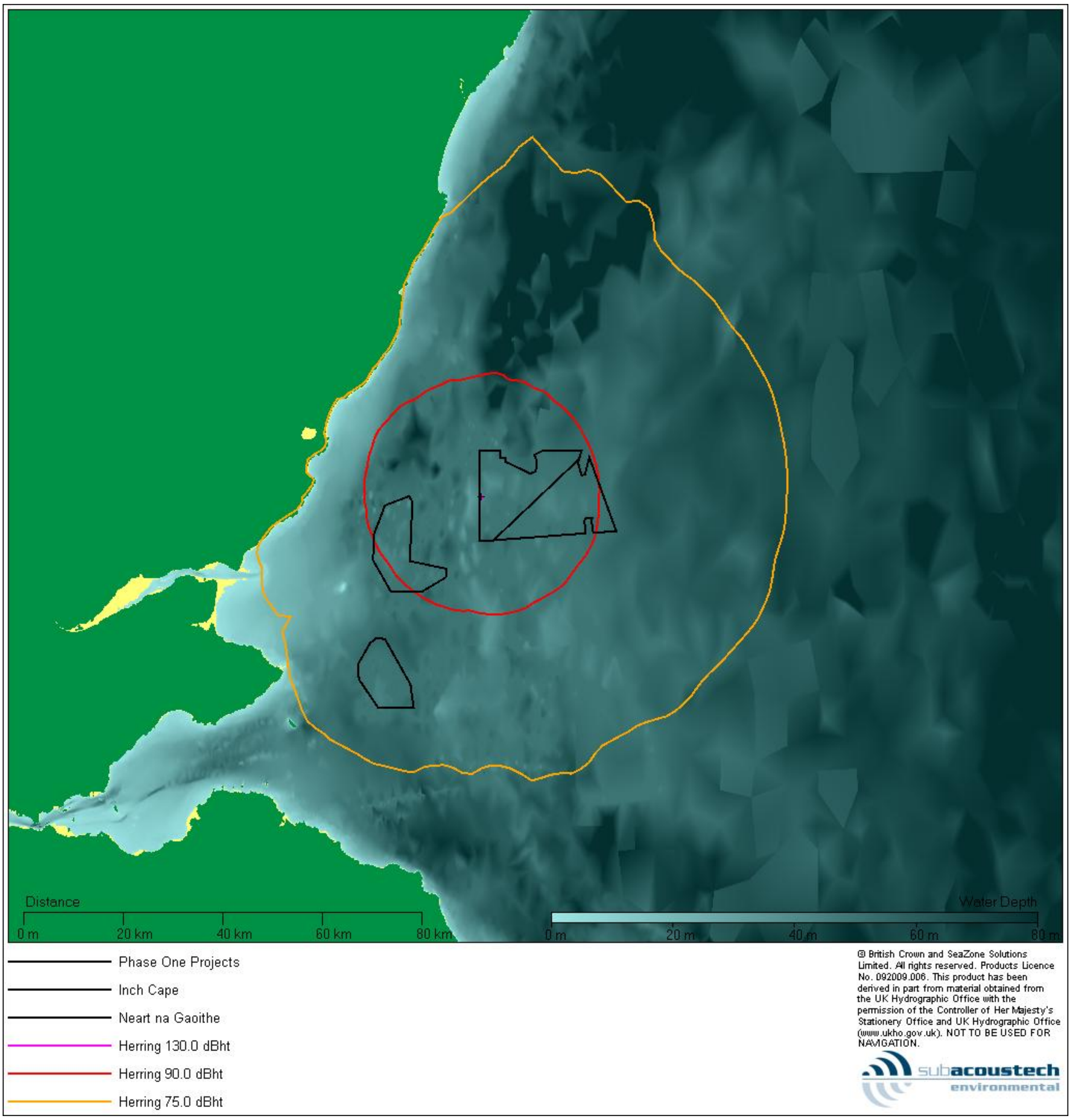

Figure 6-56 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the GM4 (alpha) scenario

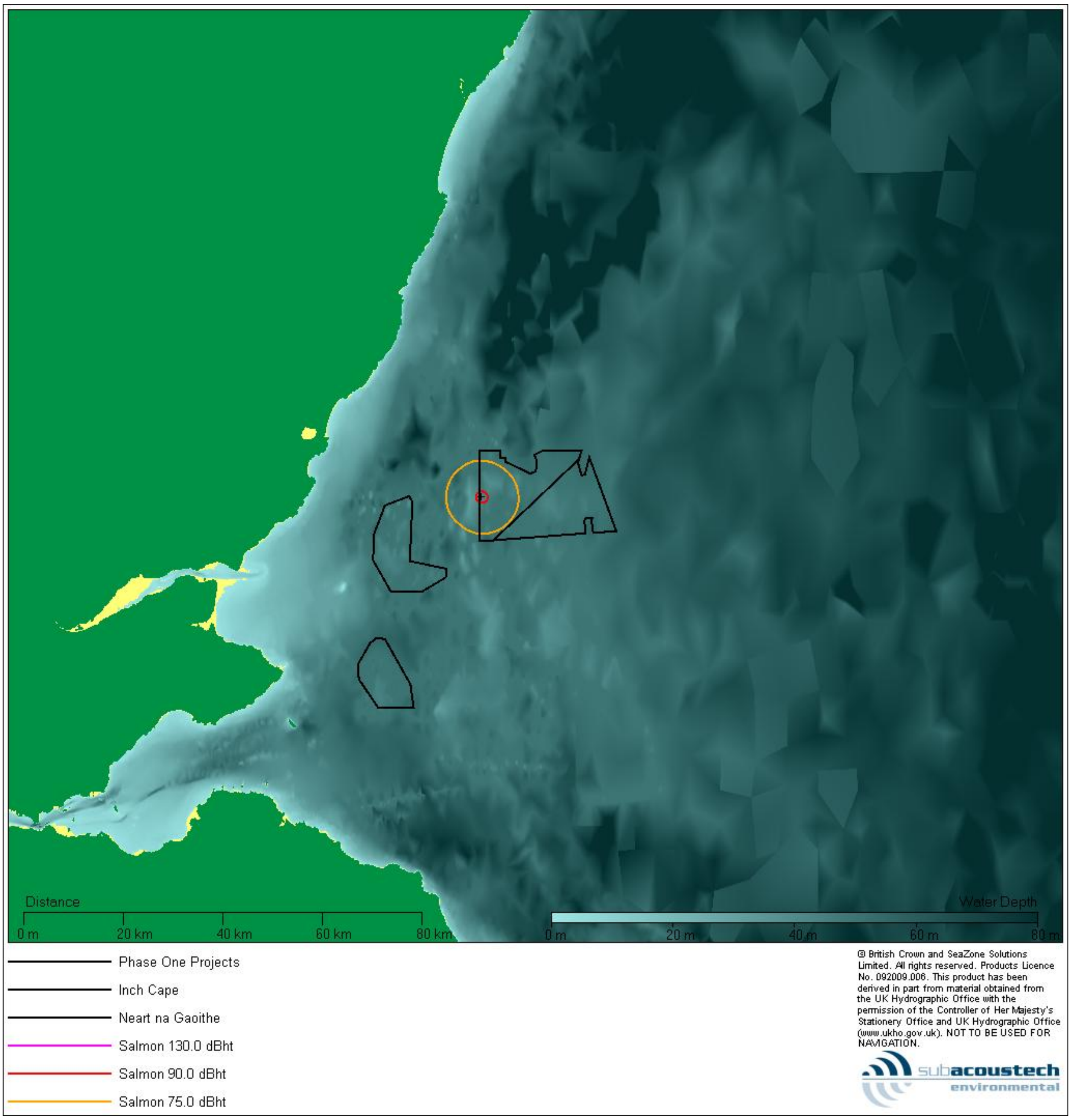

Figure 6-57 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the GM4 (alpha) scenario

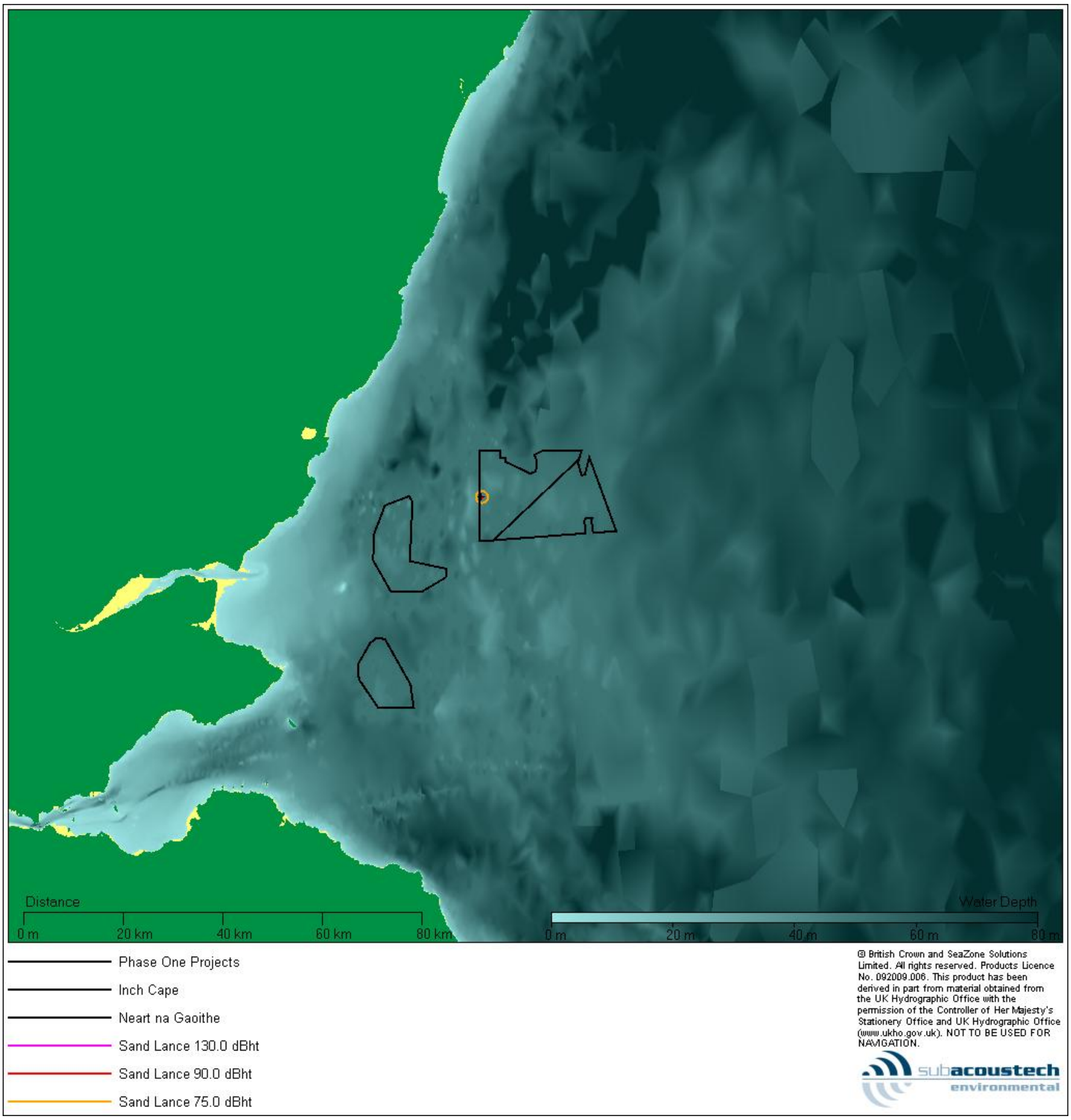

Figure 6-58 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the GM4 (alpha) scenario

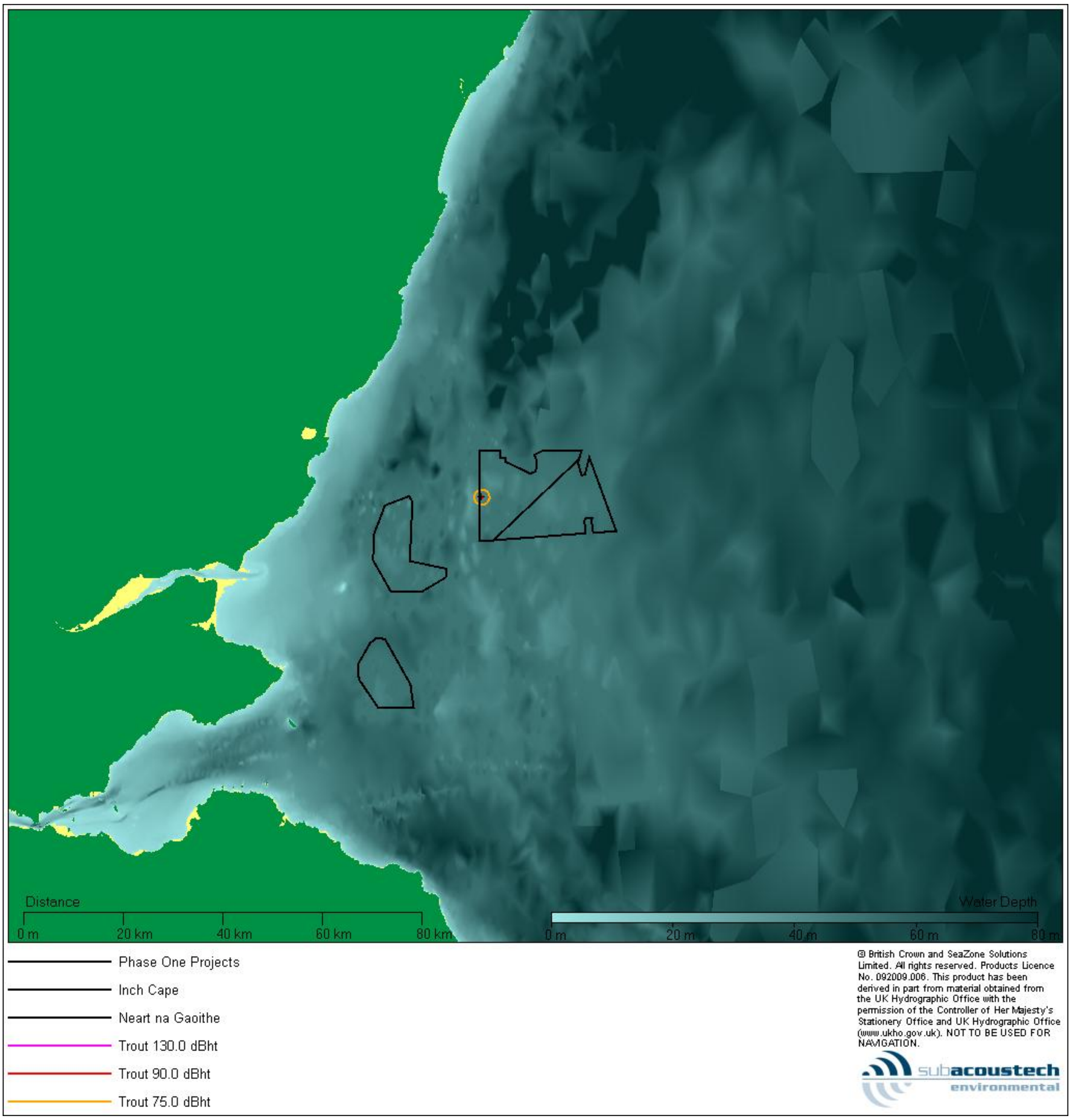

Figure 6-59 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the GM4 (alpha) scenario

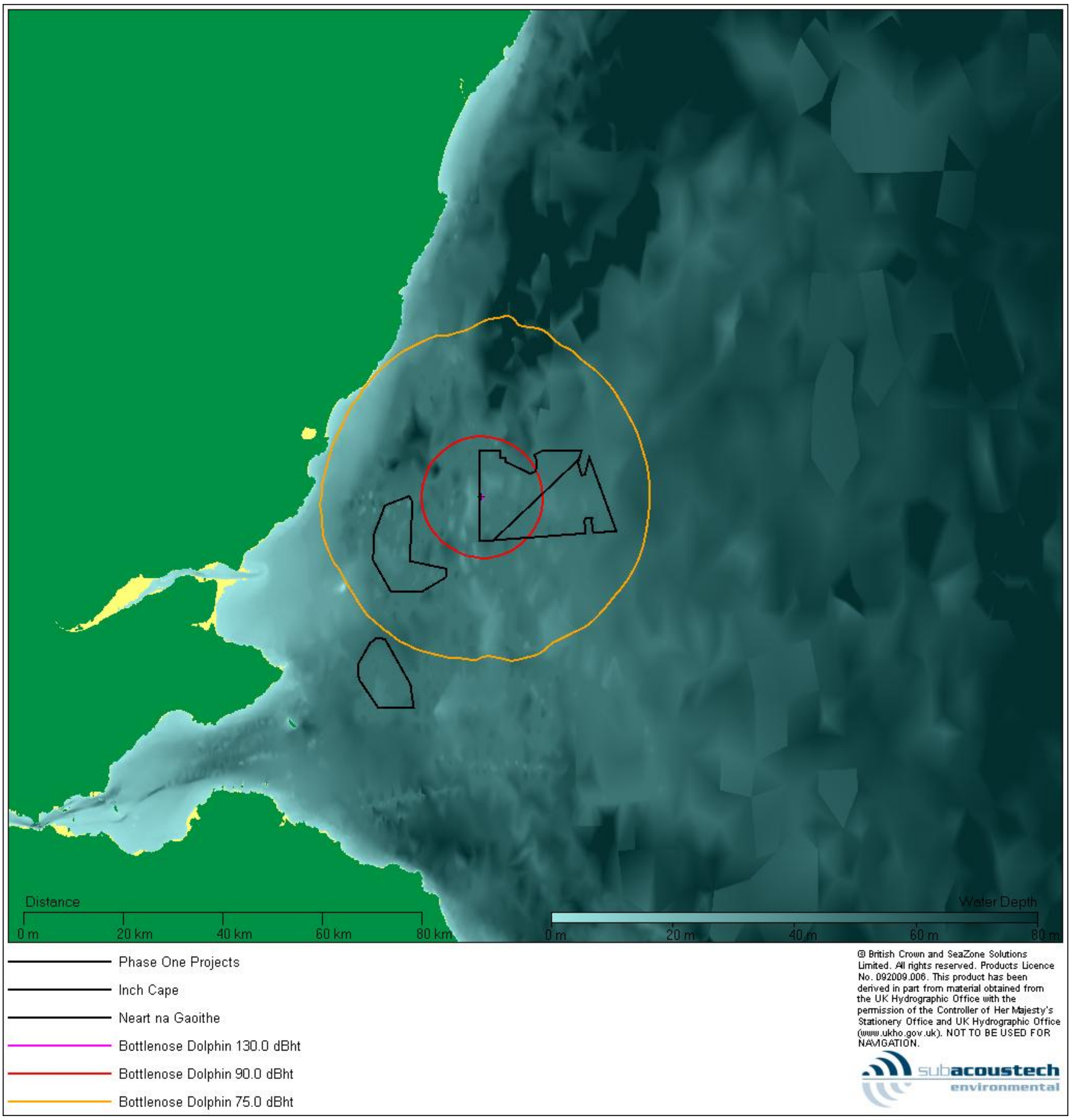

Figure 6-60 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the GM4 (alpha) scenario

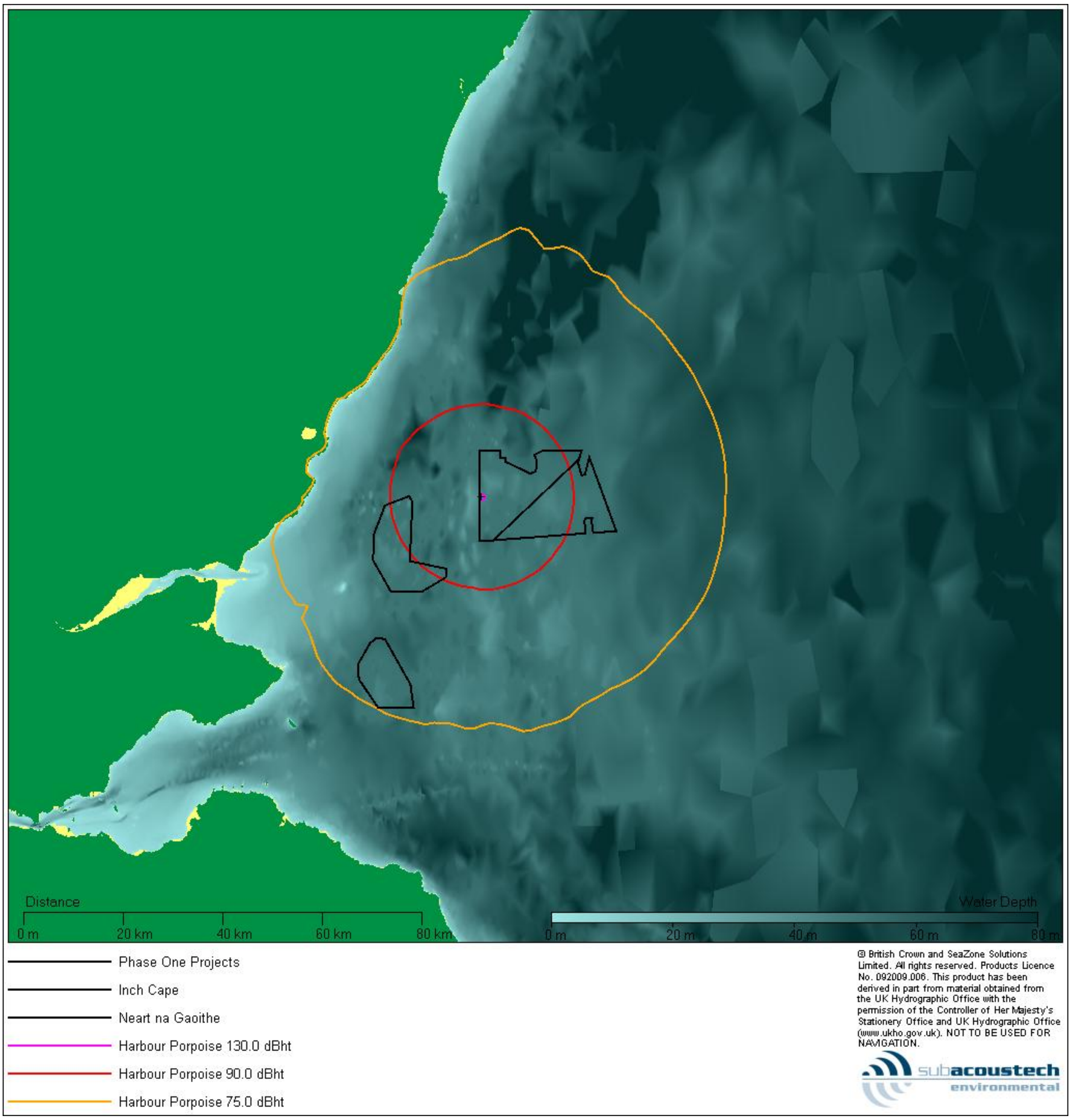

Figure 6-61 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM4 (alpha) scenario

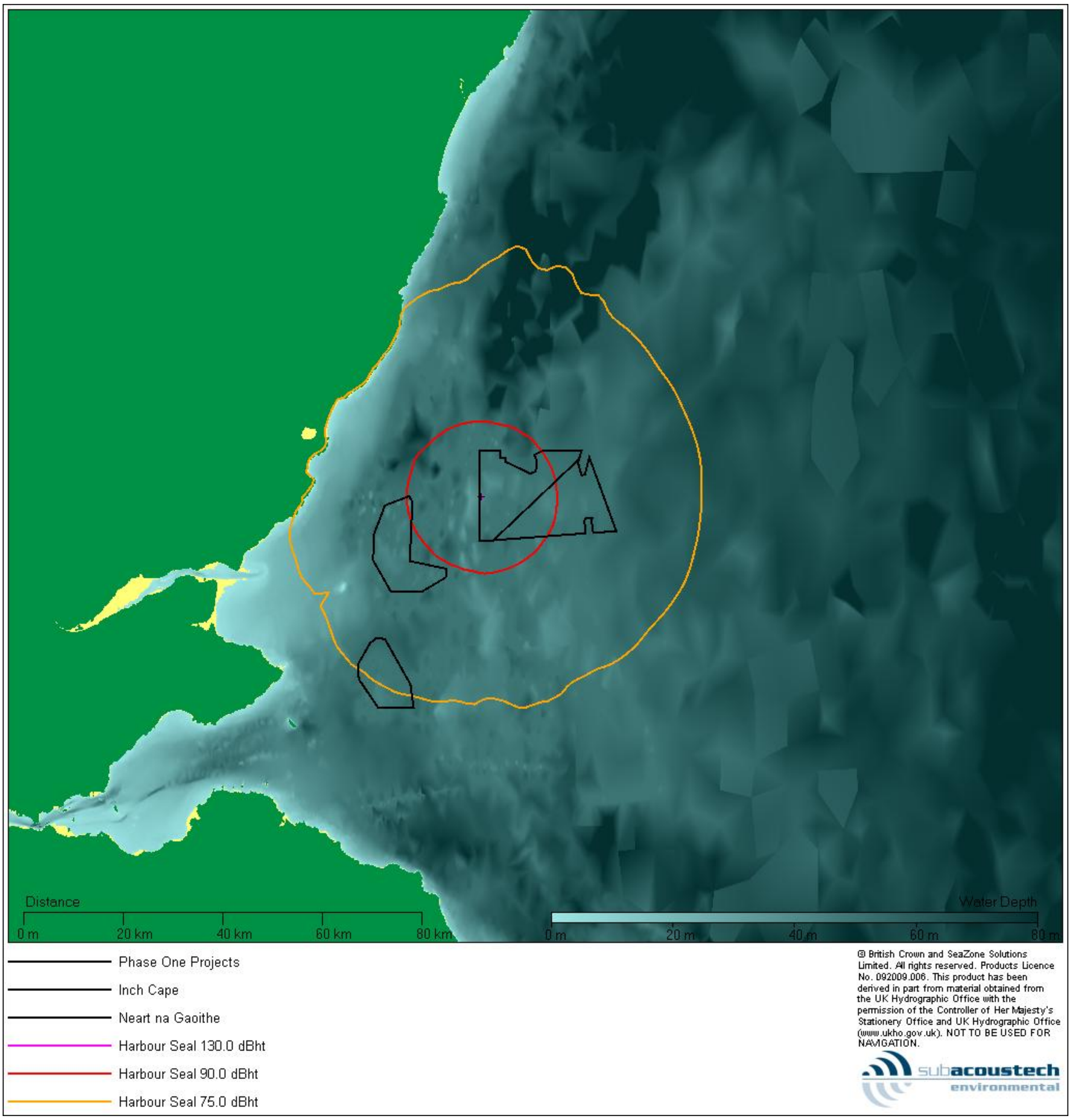

Figure 6-62 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM4 (alpha) scenario

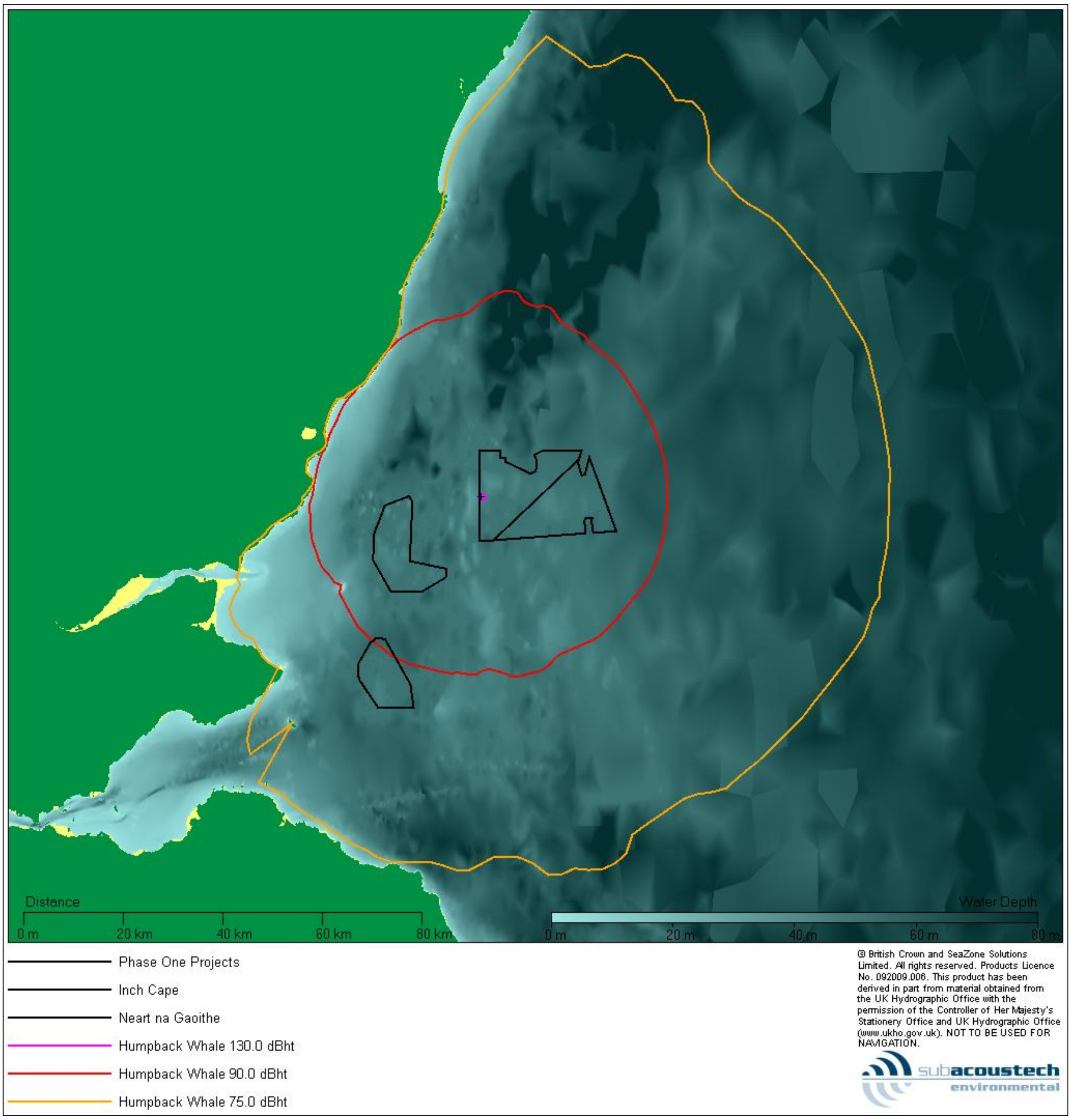

Figure 6-63 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the GM4 (alpha) scenario

6.4.1.8 GM4 (bravo)

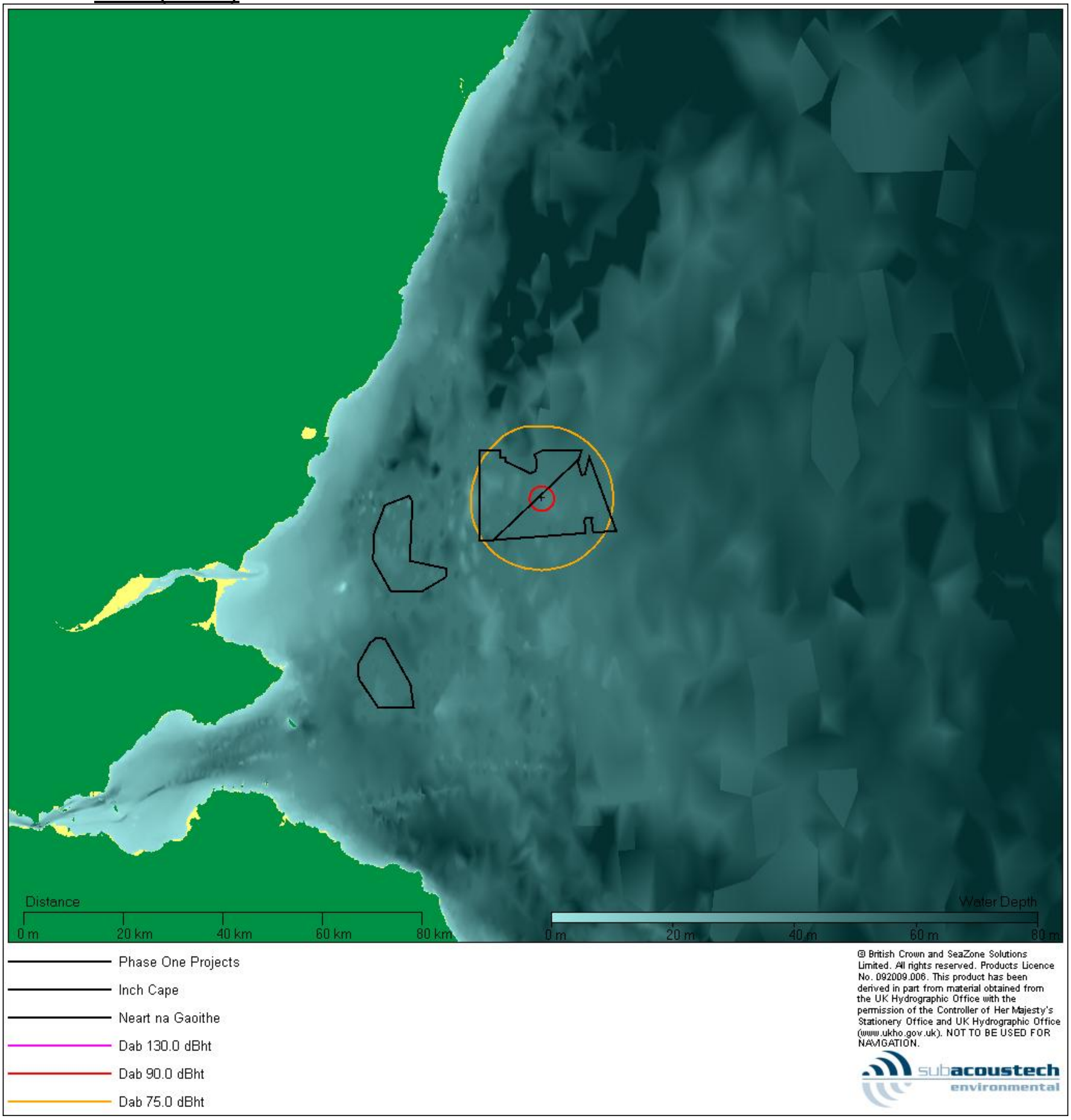

Figure 6-64 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM4 (bravo) scenario

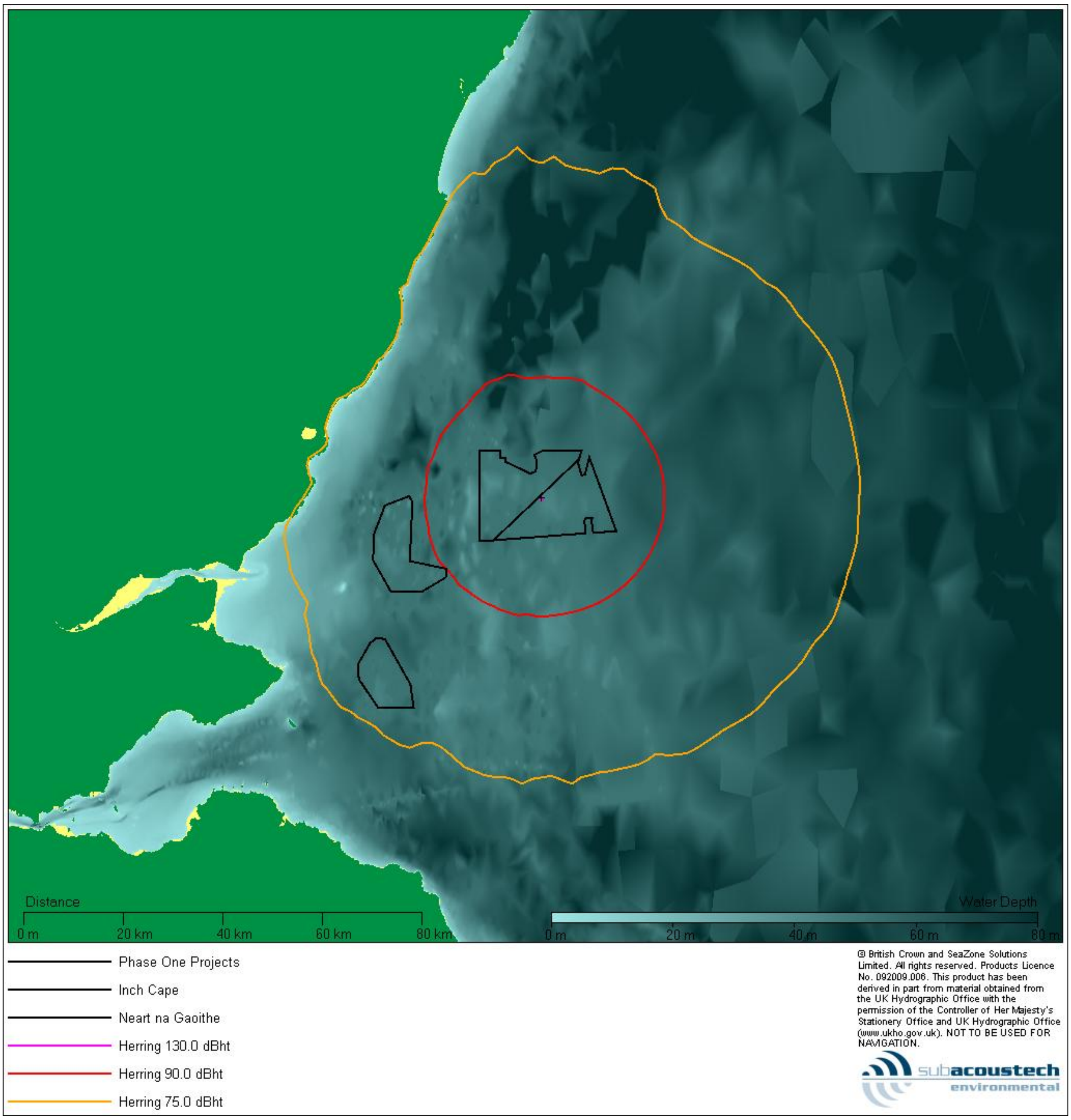

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Figure 6-65 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Herring for the GM4 (bravo) scenario

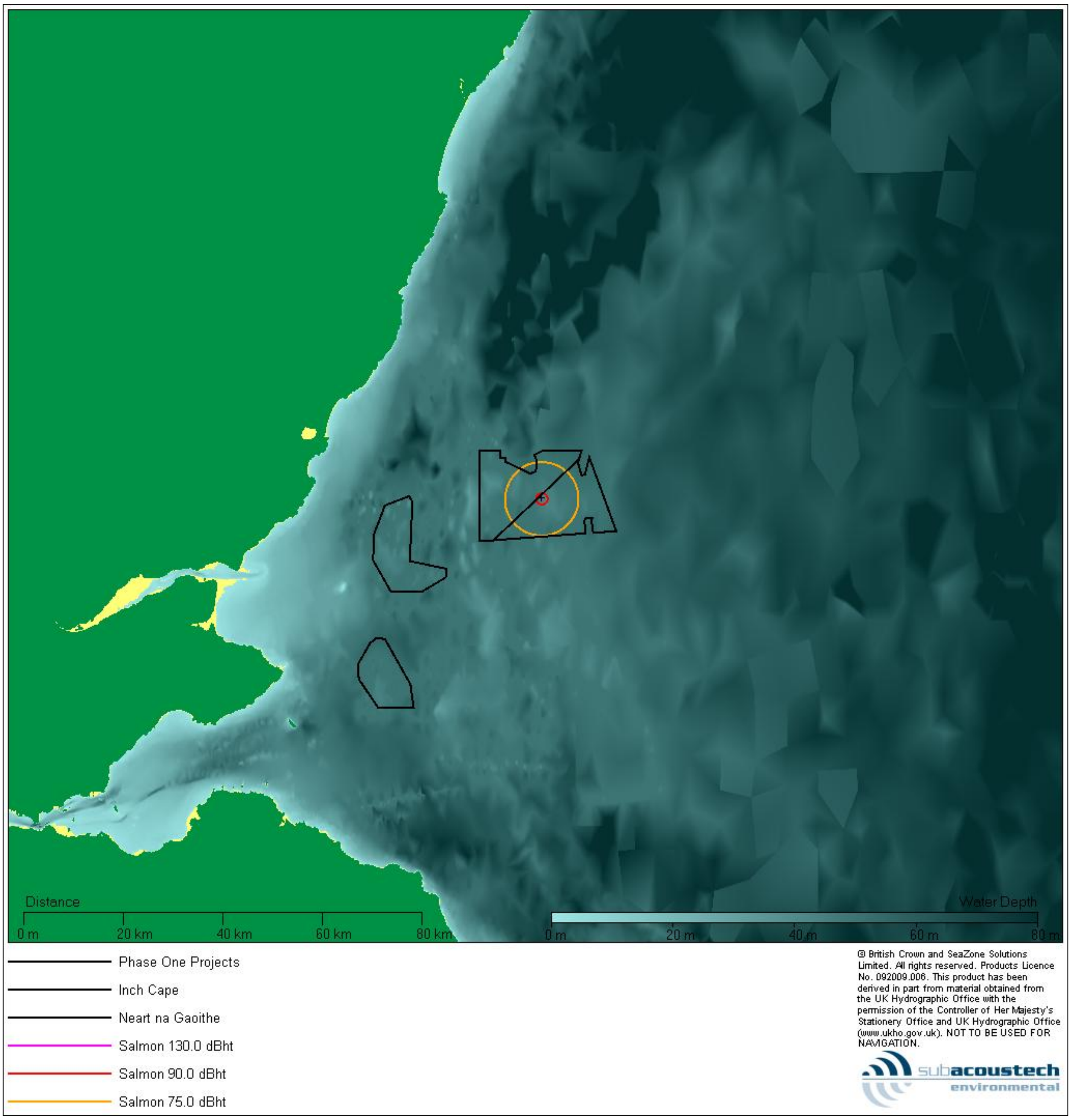

Figure 6-66 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Salmon for the GM4 (bravo) scenario

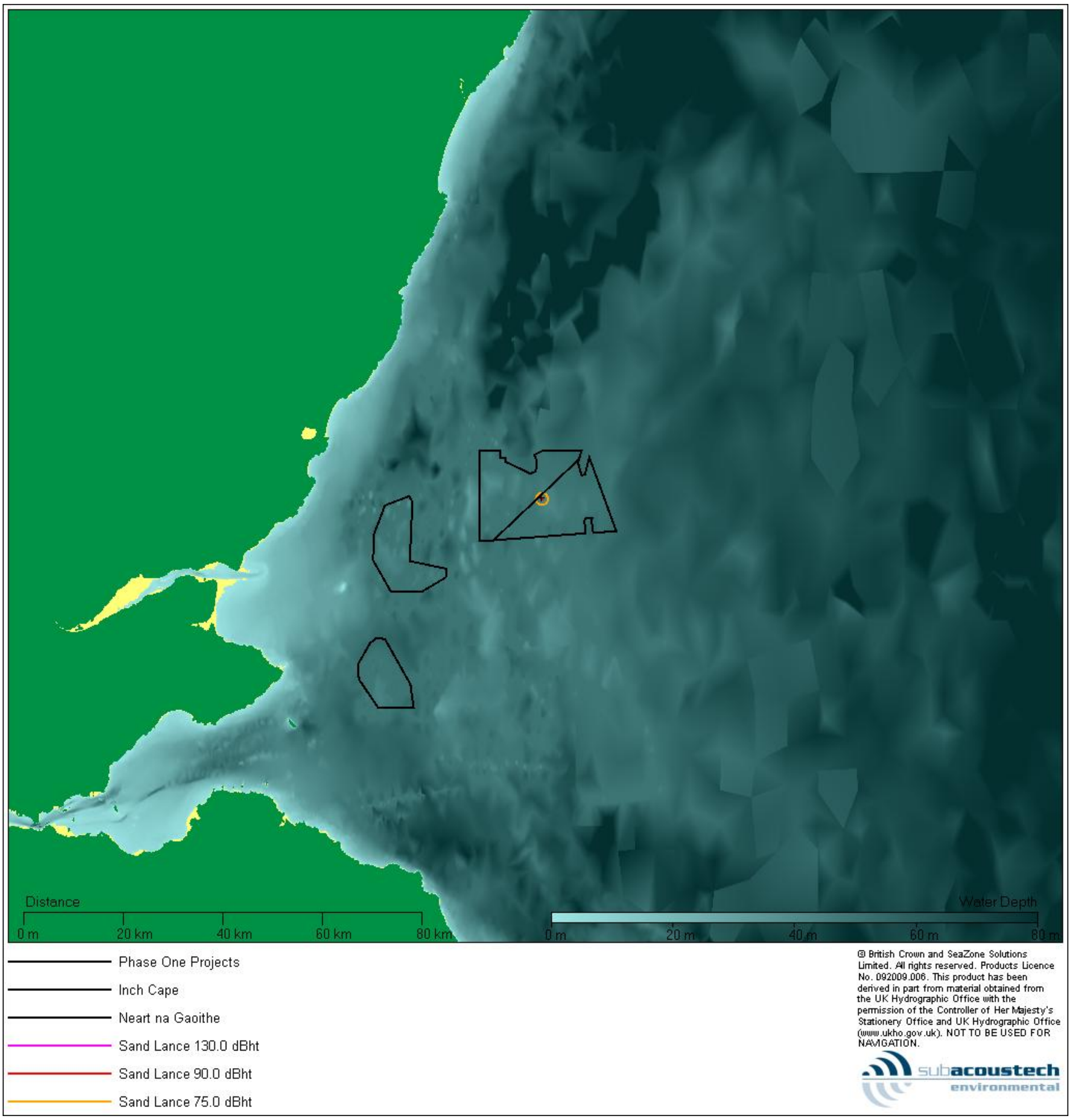

Figure 6-67 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the GM4 (bravo) scenario

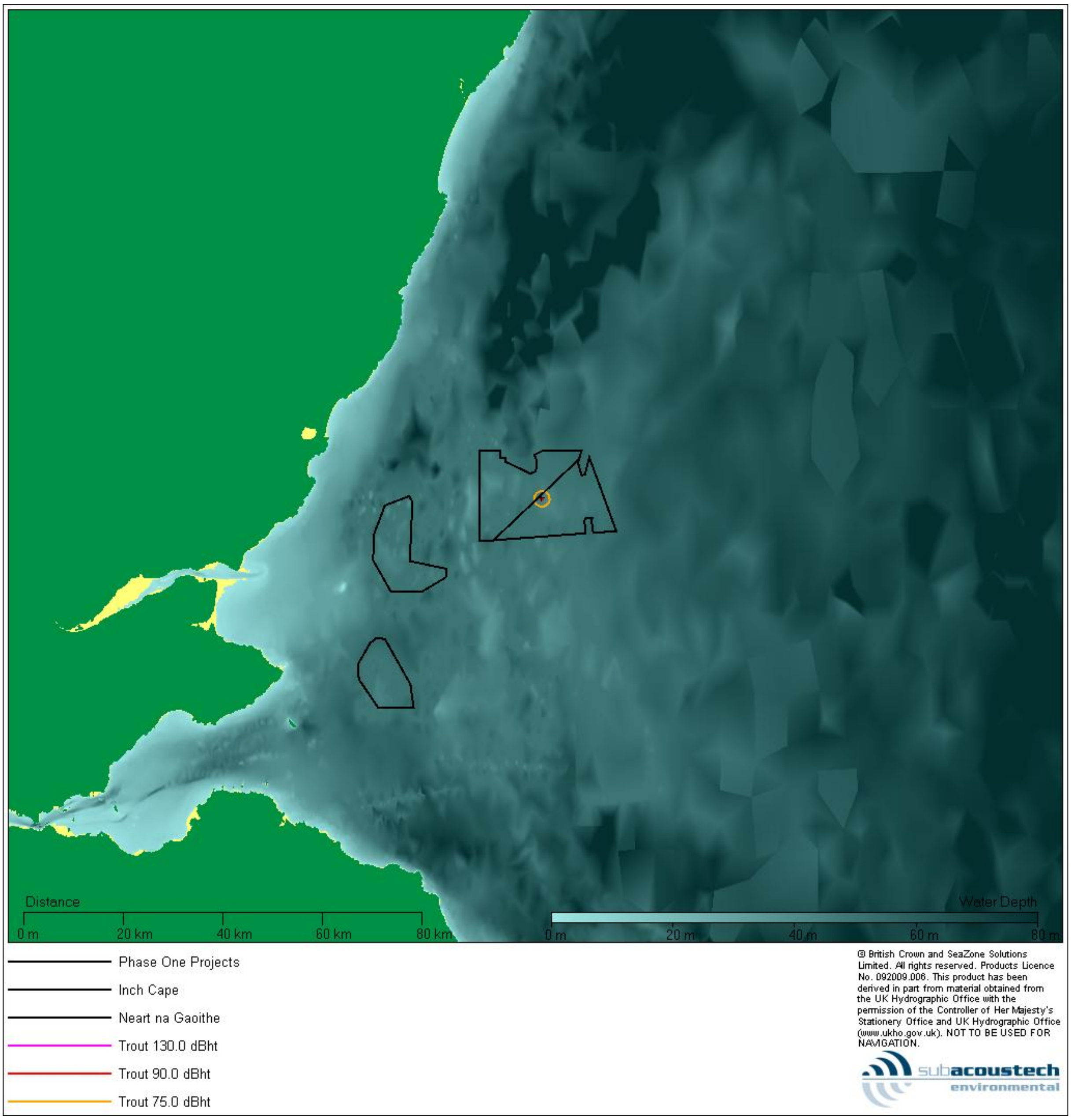

Figure 6-68 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the GM4 (bravo) scenario

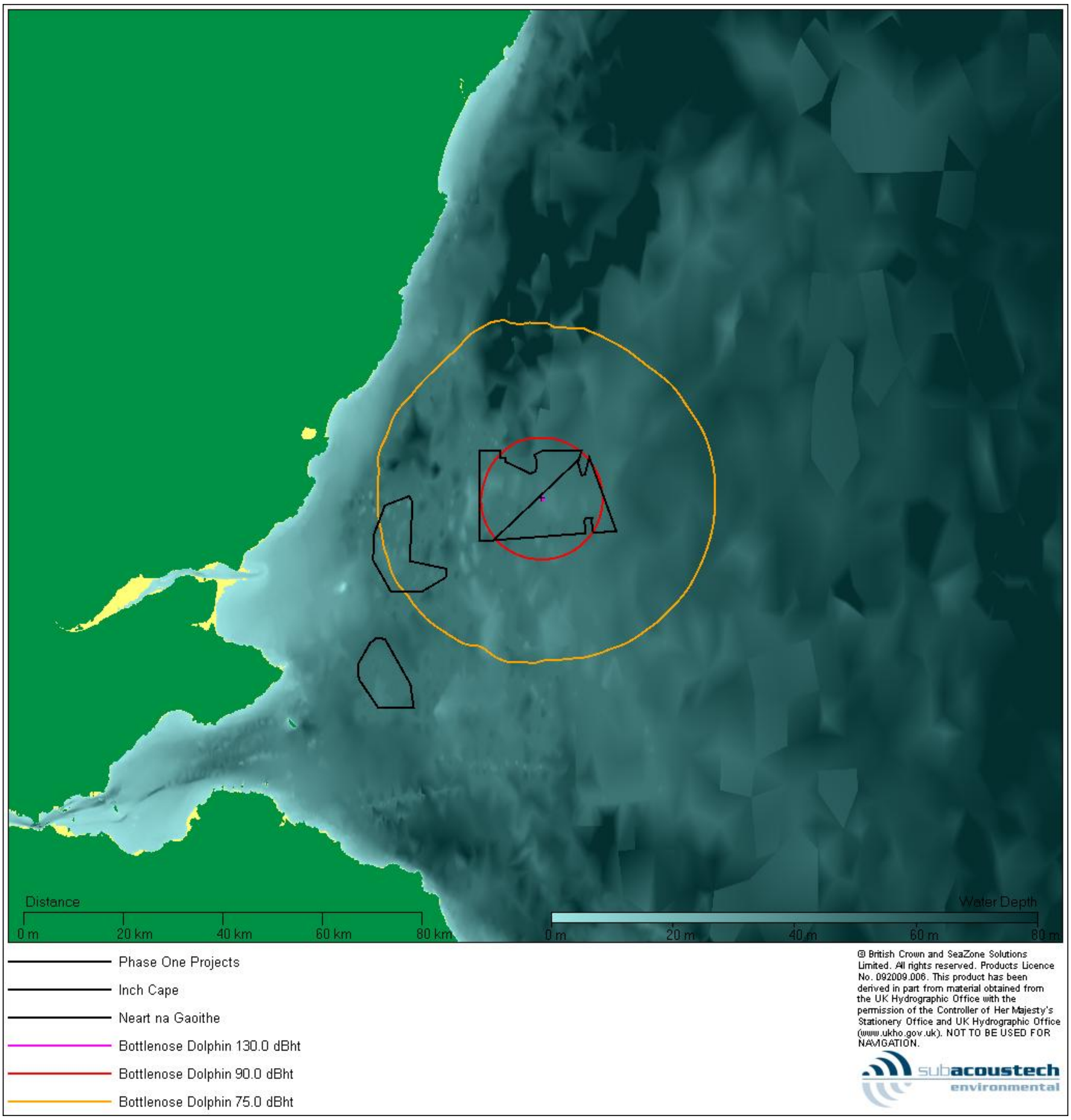

Figure 6-69 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the GM4 (bravo) scenario

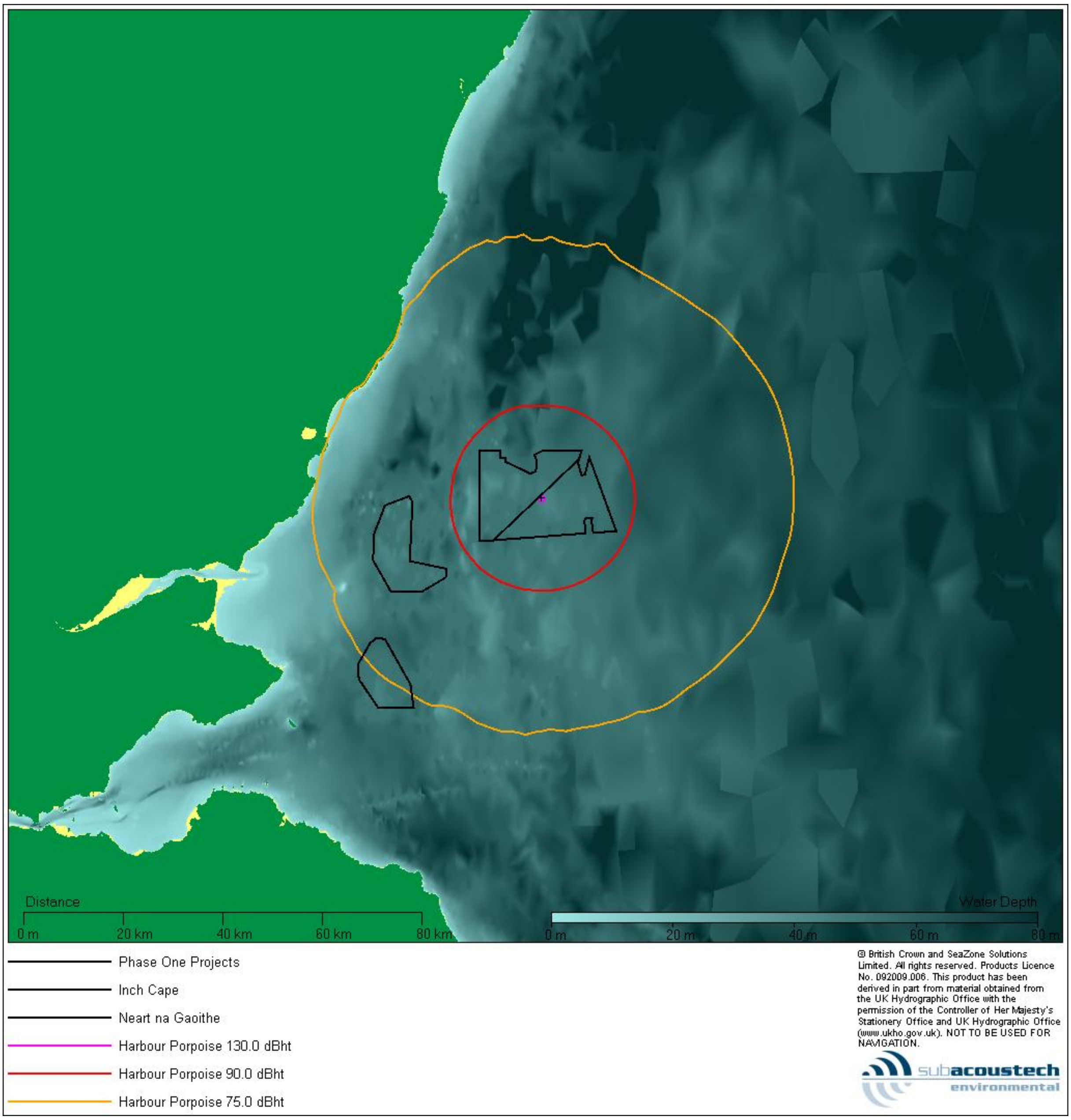

Figure 6-70 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM4 (bravo) scenario

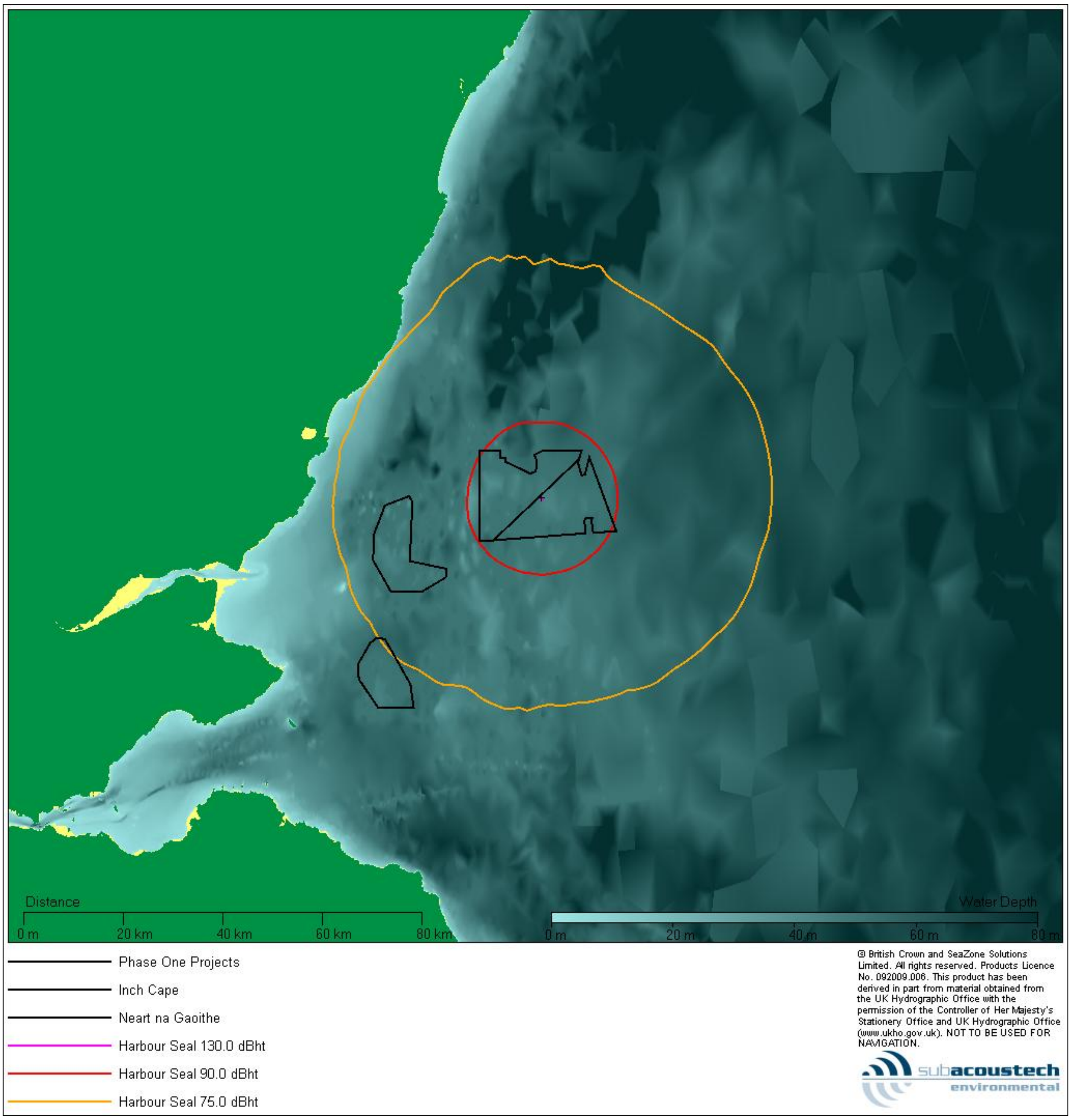

Figure 6-71 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM4 (bravo) scenario

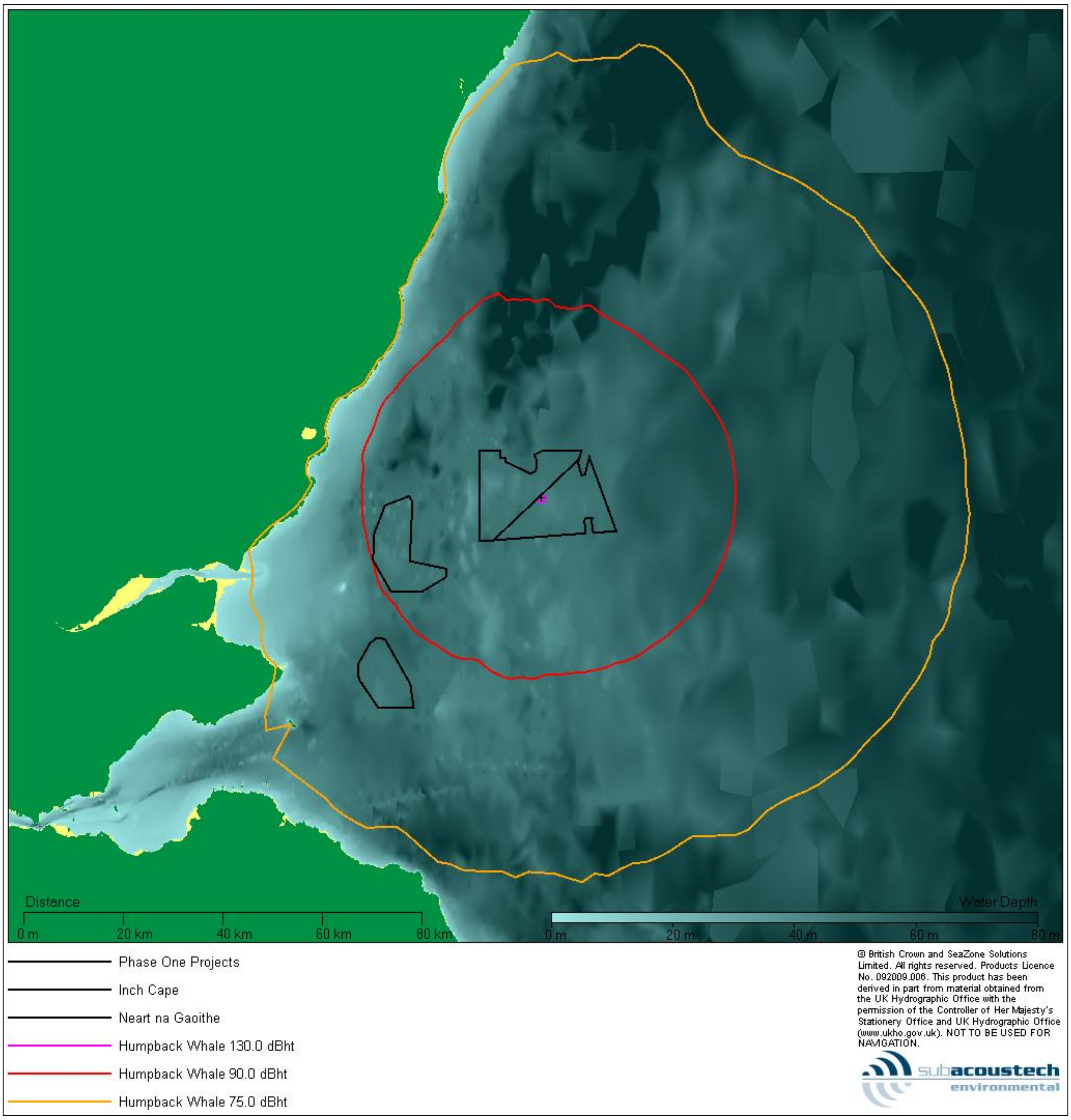

Figure 6-72 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the GM4 (bravo) scenario

6.4.1.9 Multiple Locations – GM1 (alpha) and GM1 (bravo)

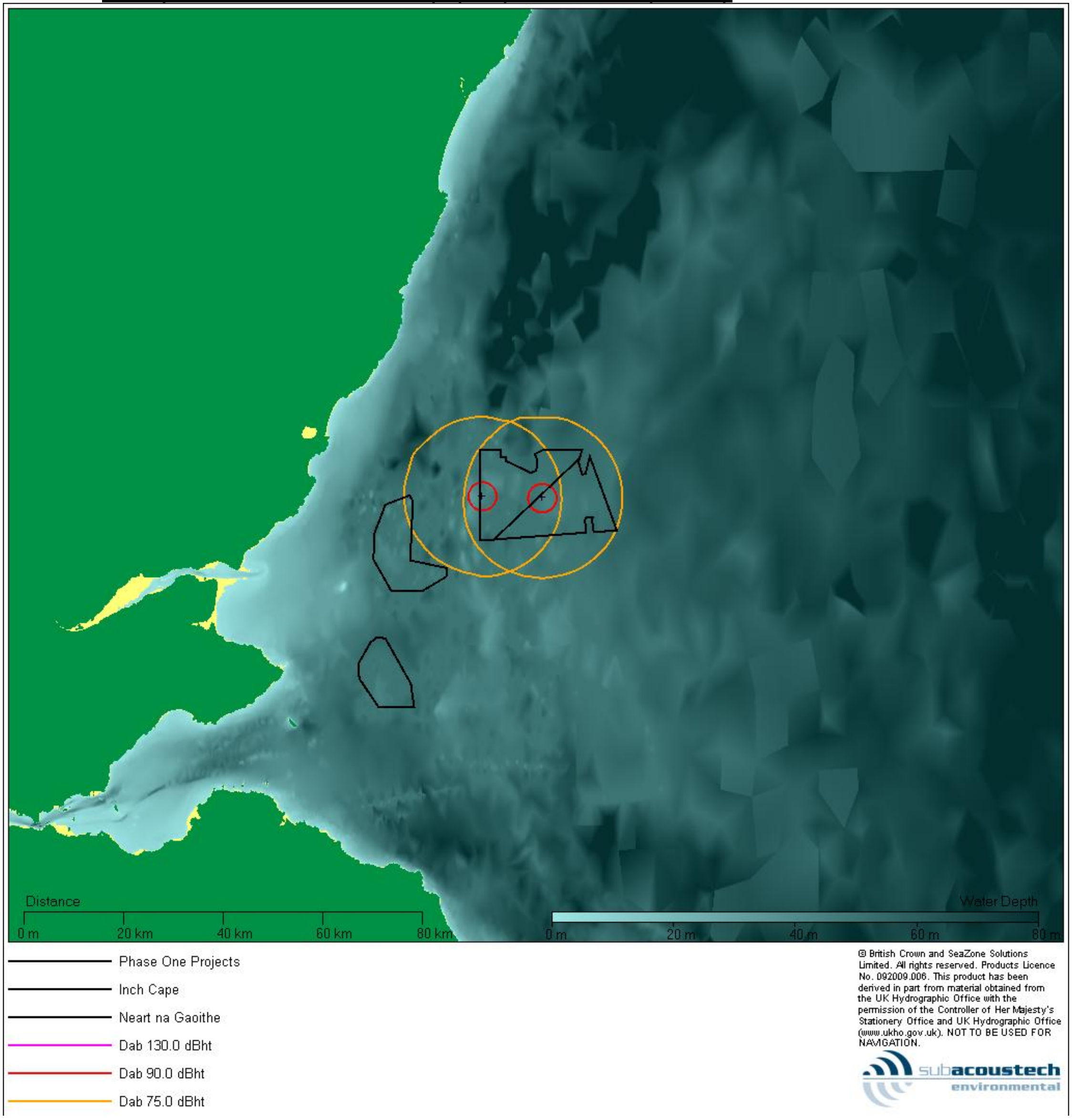

Figure 6-73 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM1 (alpha) and GM1 (bravo) scenarios

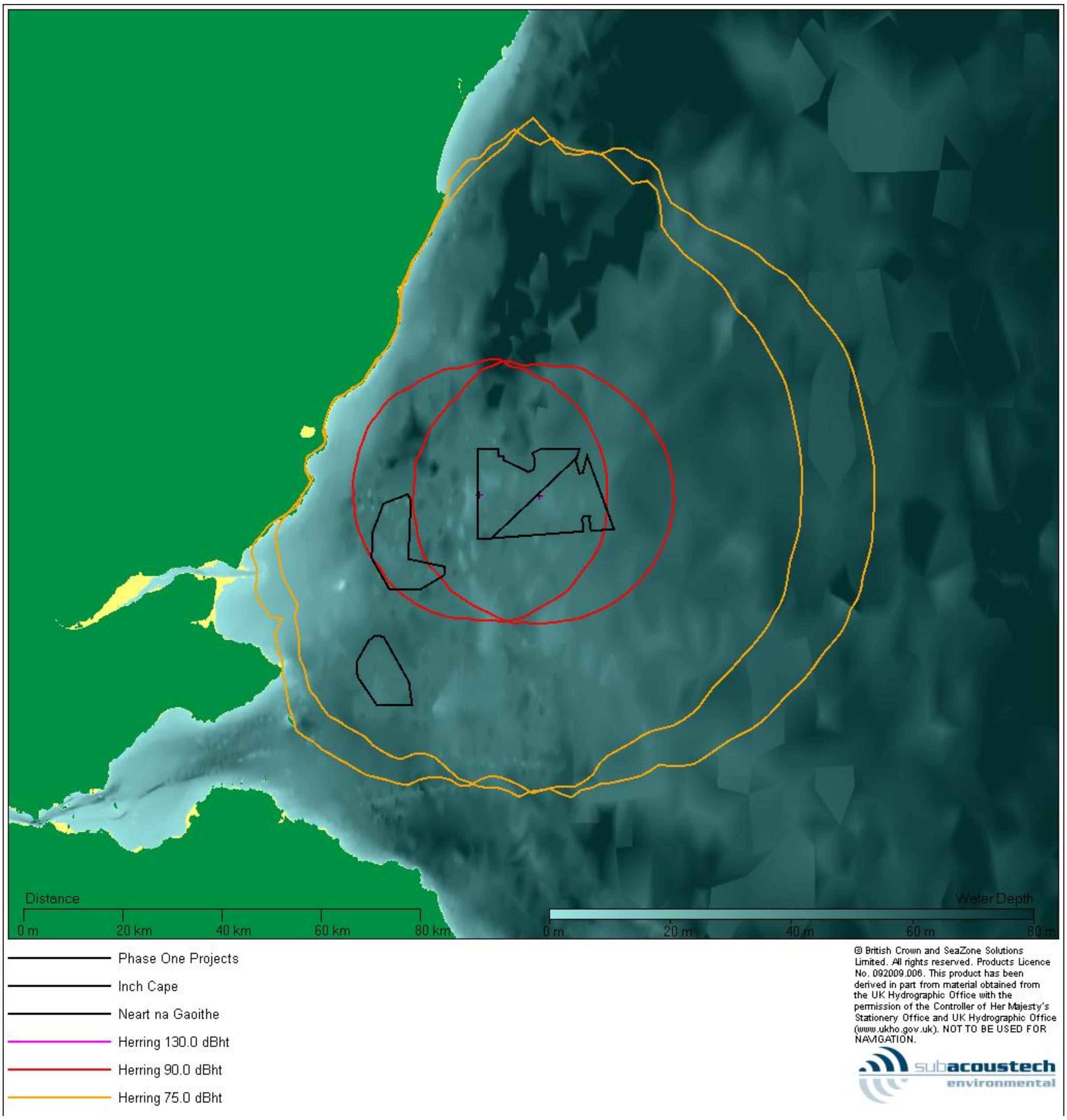

Figure 6-74 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the GM1 (alpha) and GM1 (bravo) scenarios

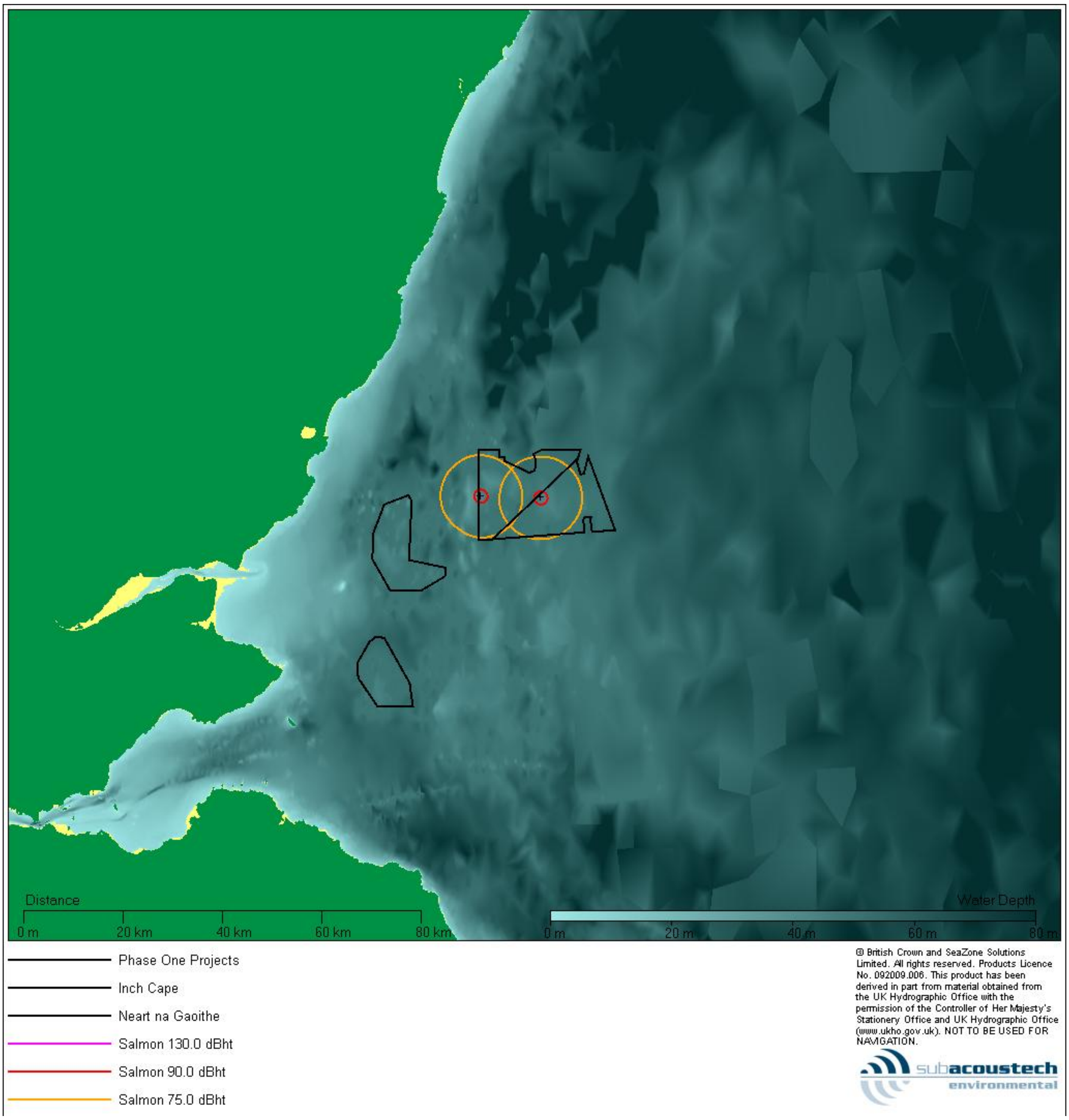

Figure 6-75 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the GM1 (alpha) and GM1 (bravo) scenarios

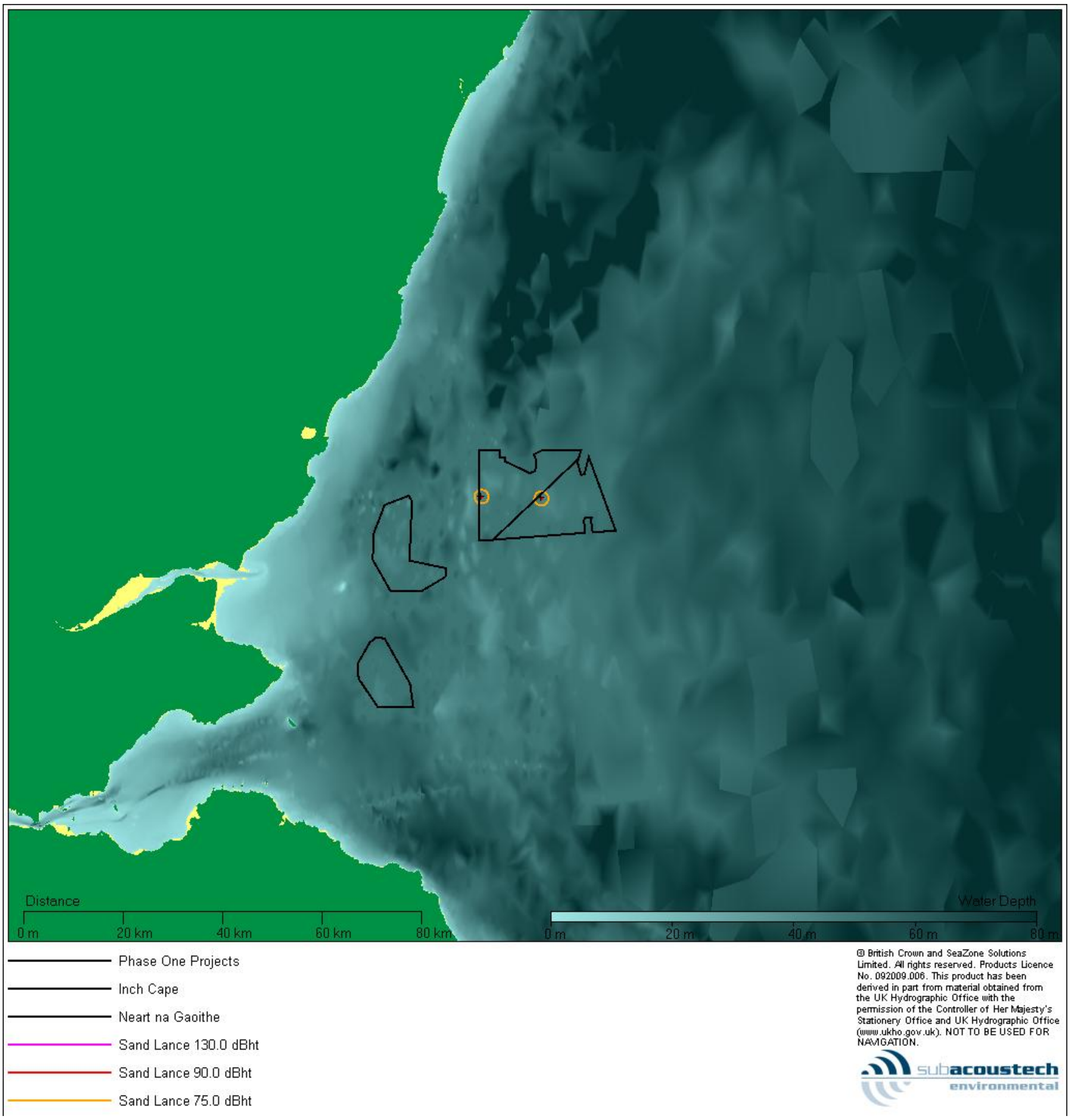

Figure 6-76 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the GM1 (alpha) and GM1 (bravo) scenarios

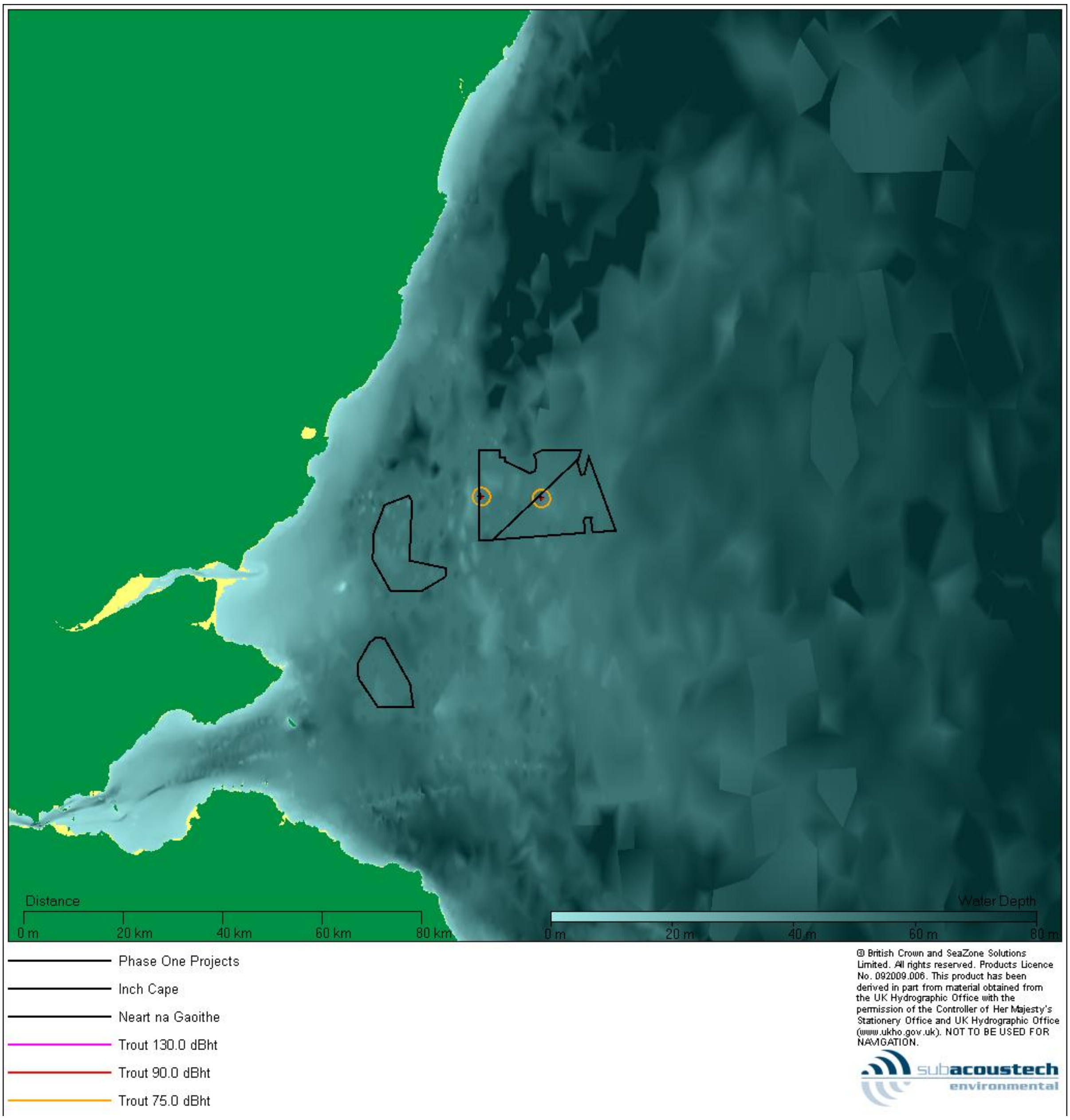

Figure 6-77 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the GM1 (alpha) and GM1 (bravo) scenarios

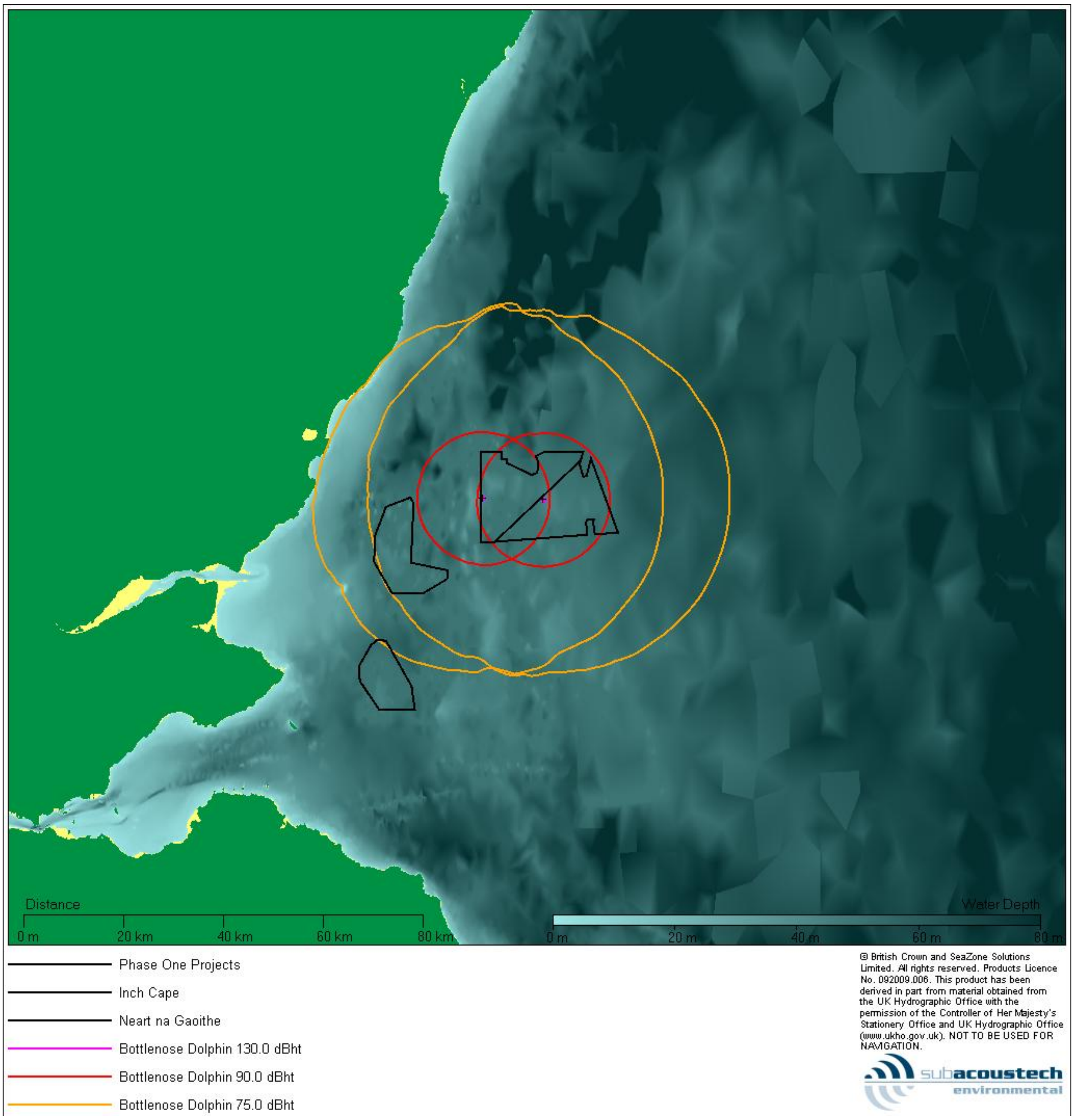

Figure 6-78 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the GM1 (alpha) and GM1 (bravo) scenarios

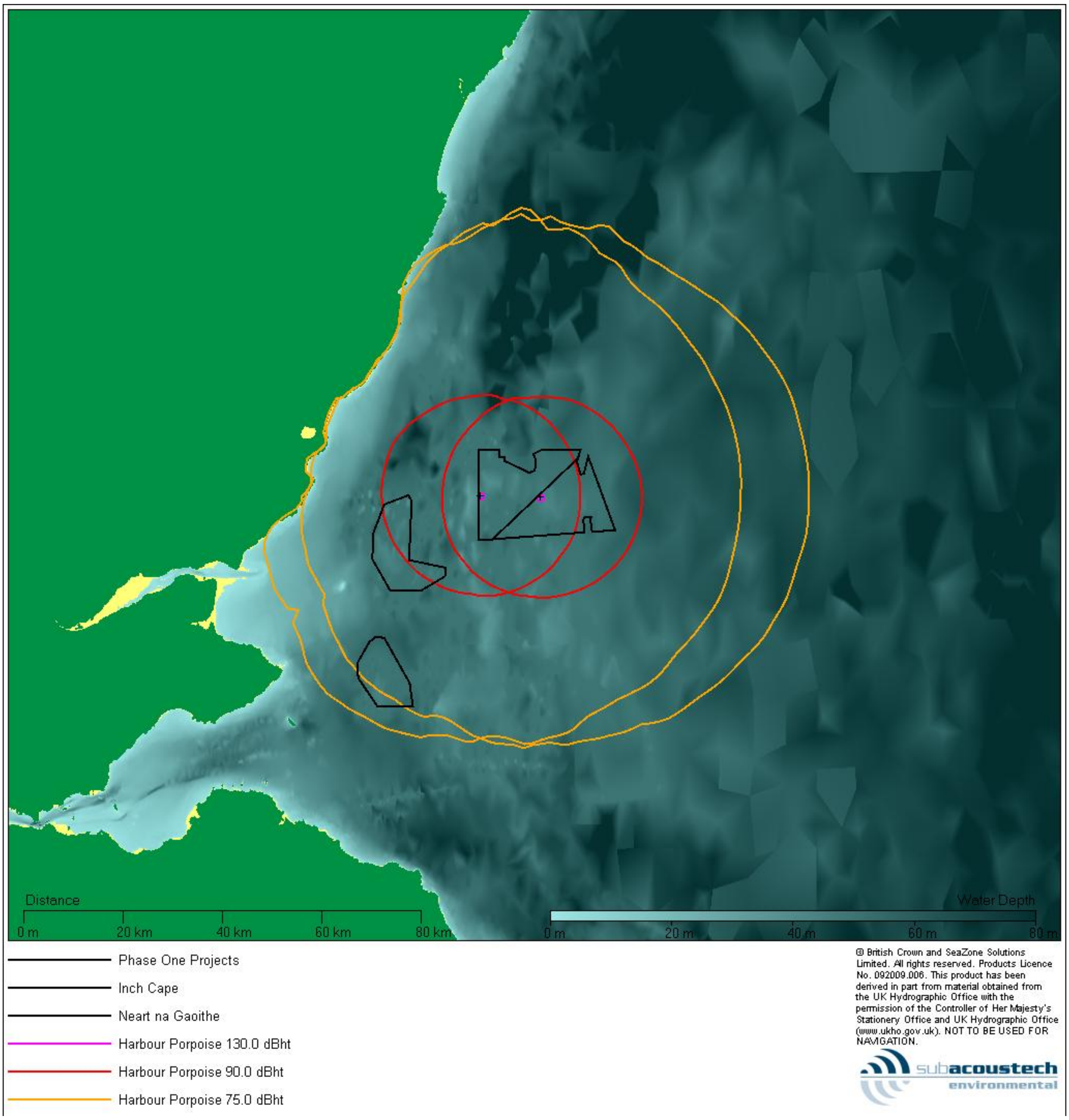

Figure 6-79 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM1 (alpha) and GM1 (bravo) scenarios

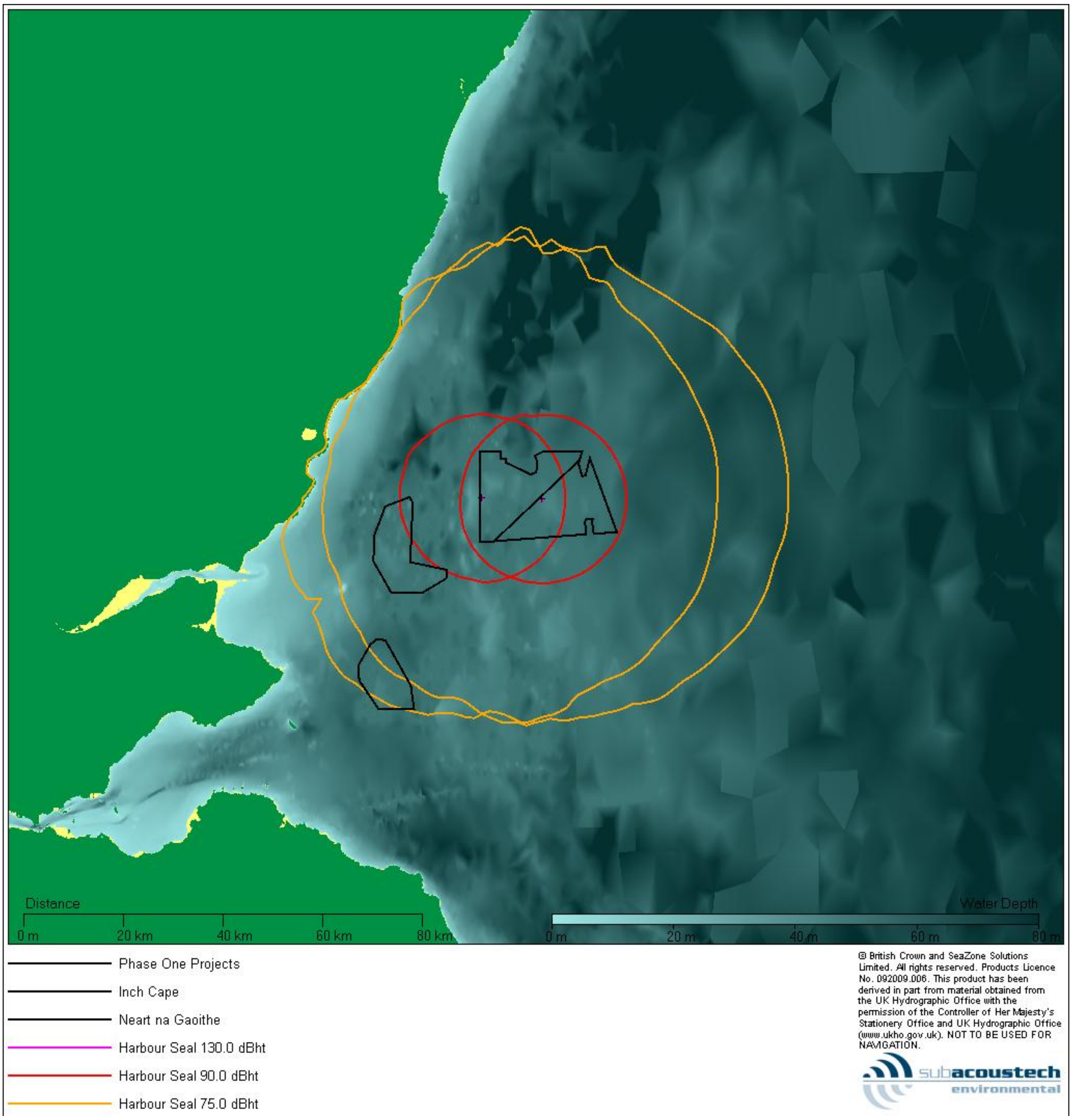

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Figure 6-80 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM1 (alpha) and GM1 (bravo) scenarios

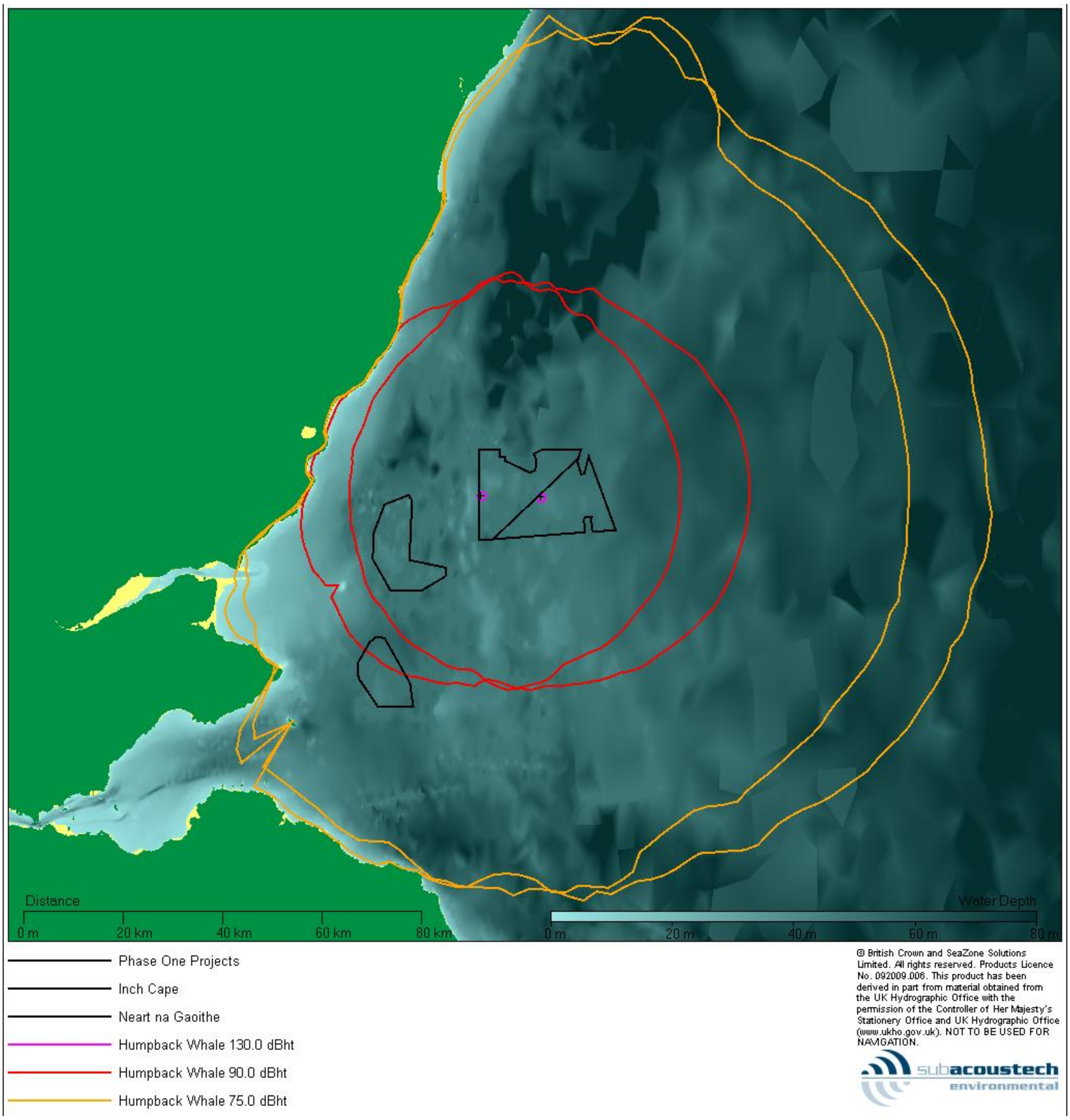

Figure 6-81 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the GM1 (alpha) and GM1 (bravo) scenarios

6.4.1.10 Multiple Locations - GM1 (alpha) and Inch Cape

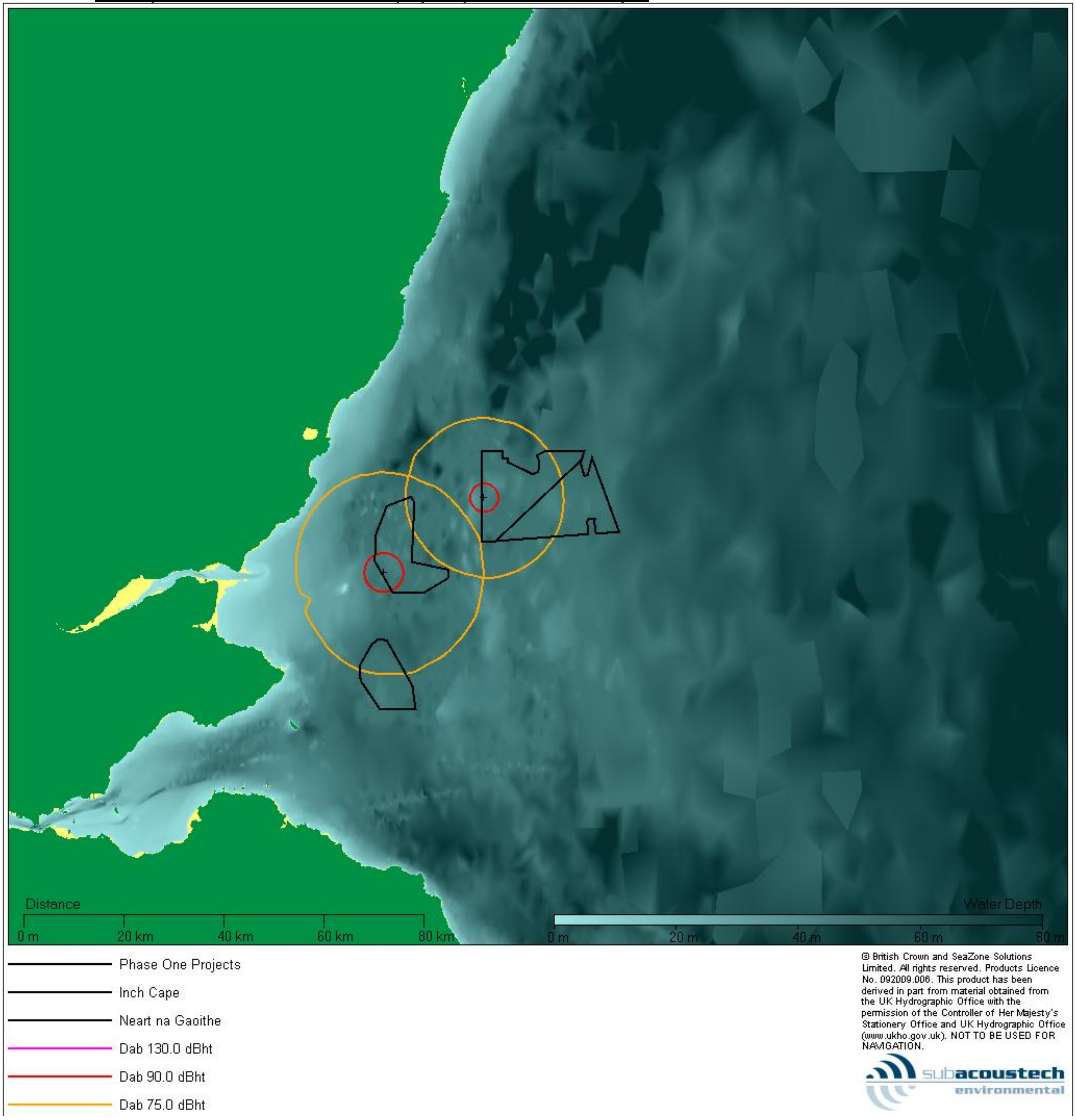

Figure 6-82 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM1 (alpha) and Inch Cape scenarios

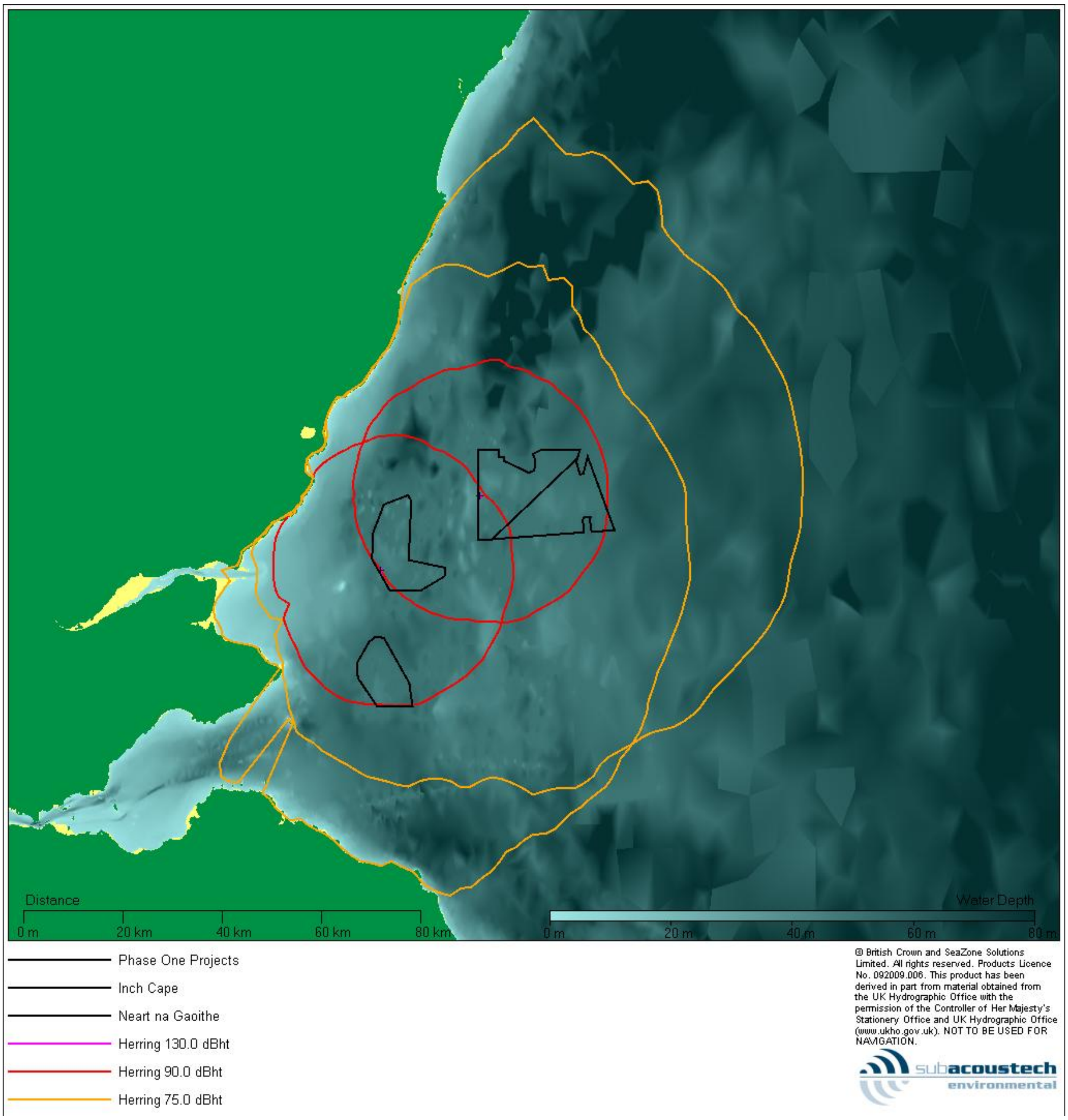

Figure 6-83 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the GM1 (alpha) and Inch Cape scenarios

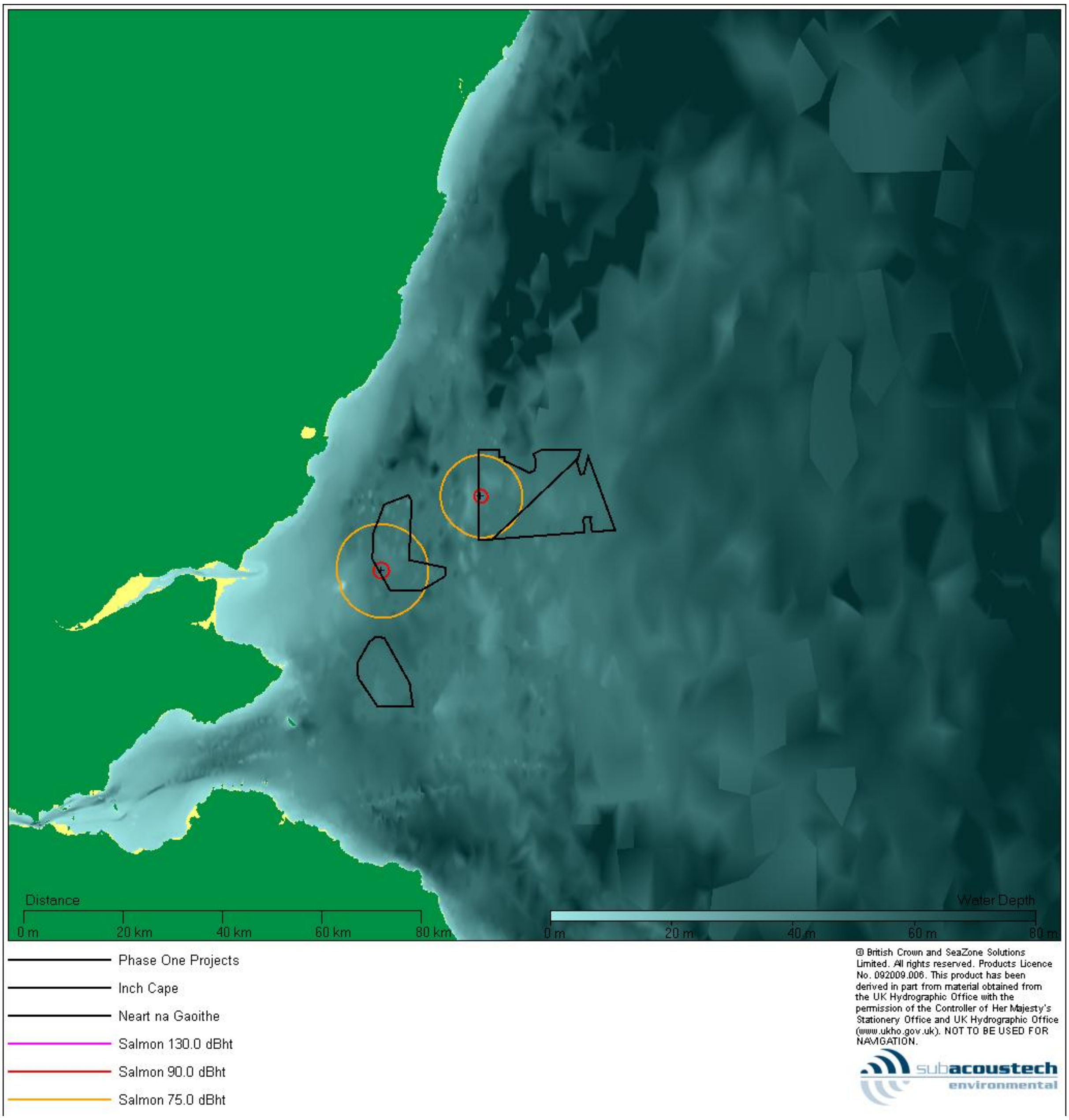

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Figure 6-84 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the GM1 (alpha) and Inch Cape scenarios

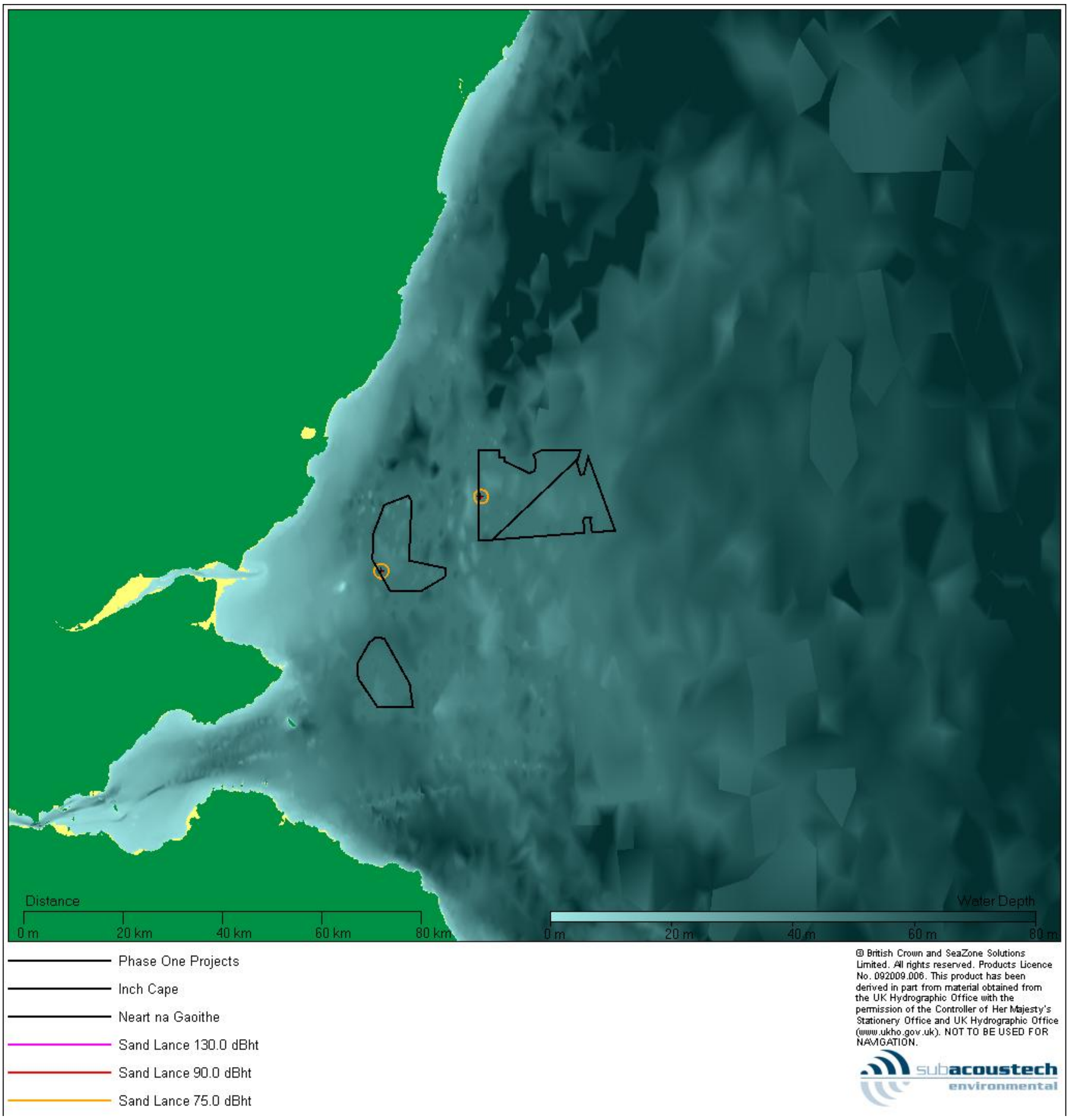

Figure 6-85 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the GM1 (alpha) and Inch Cape scenarios

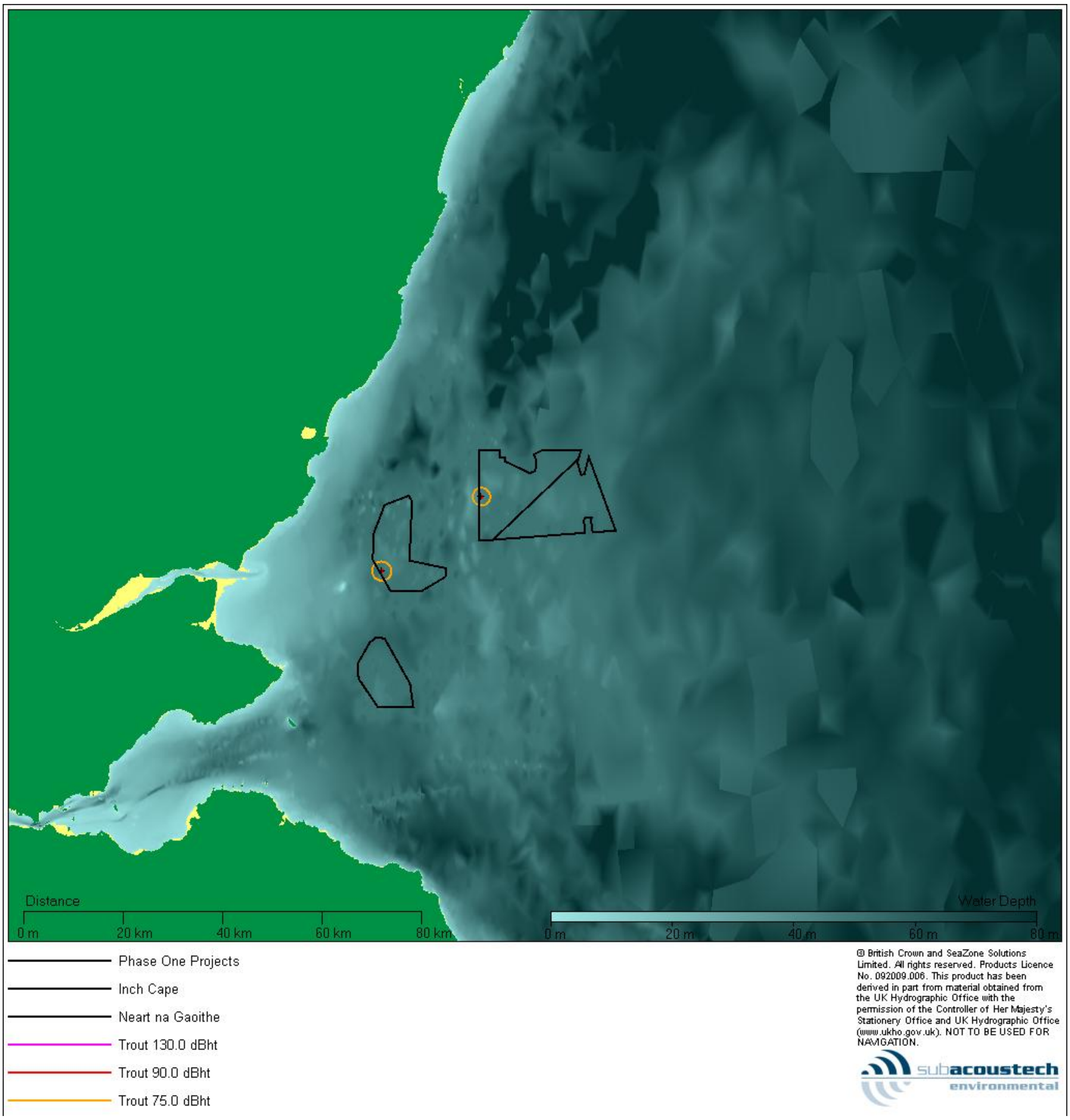

Figure 6-86 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the GM1 (alpha) and Inch Cape scenarios

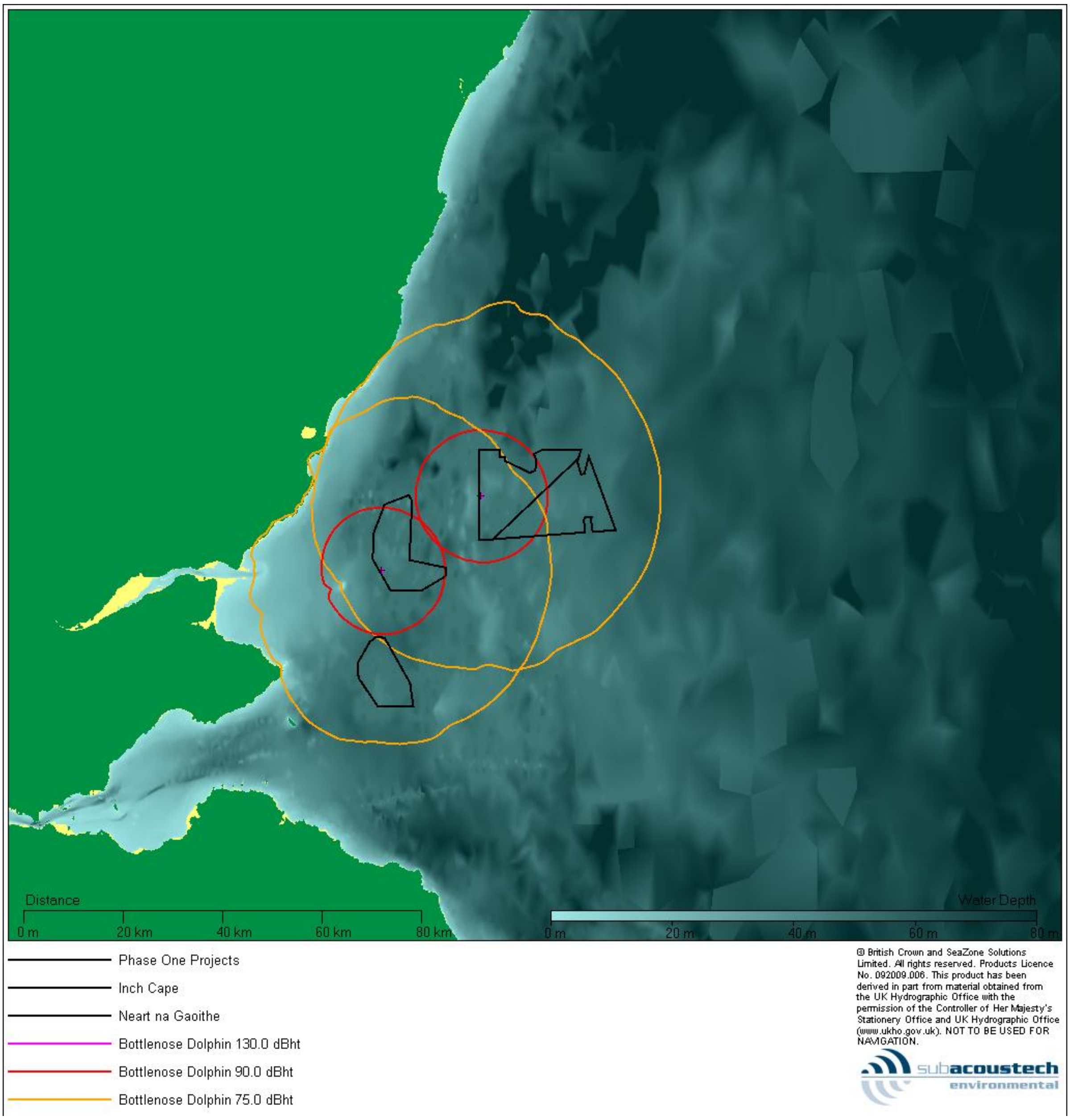

Figure 6-87 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the GM1 (alpha) and Inch Cape scenarios

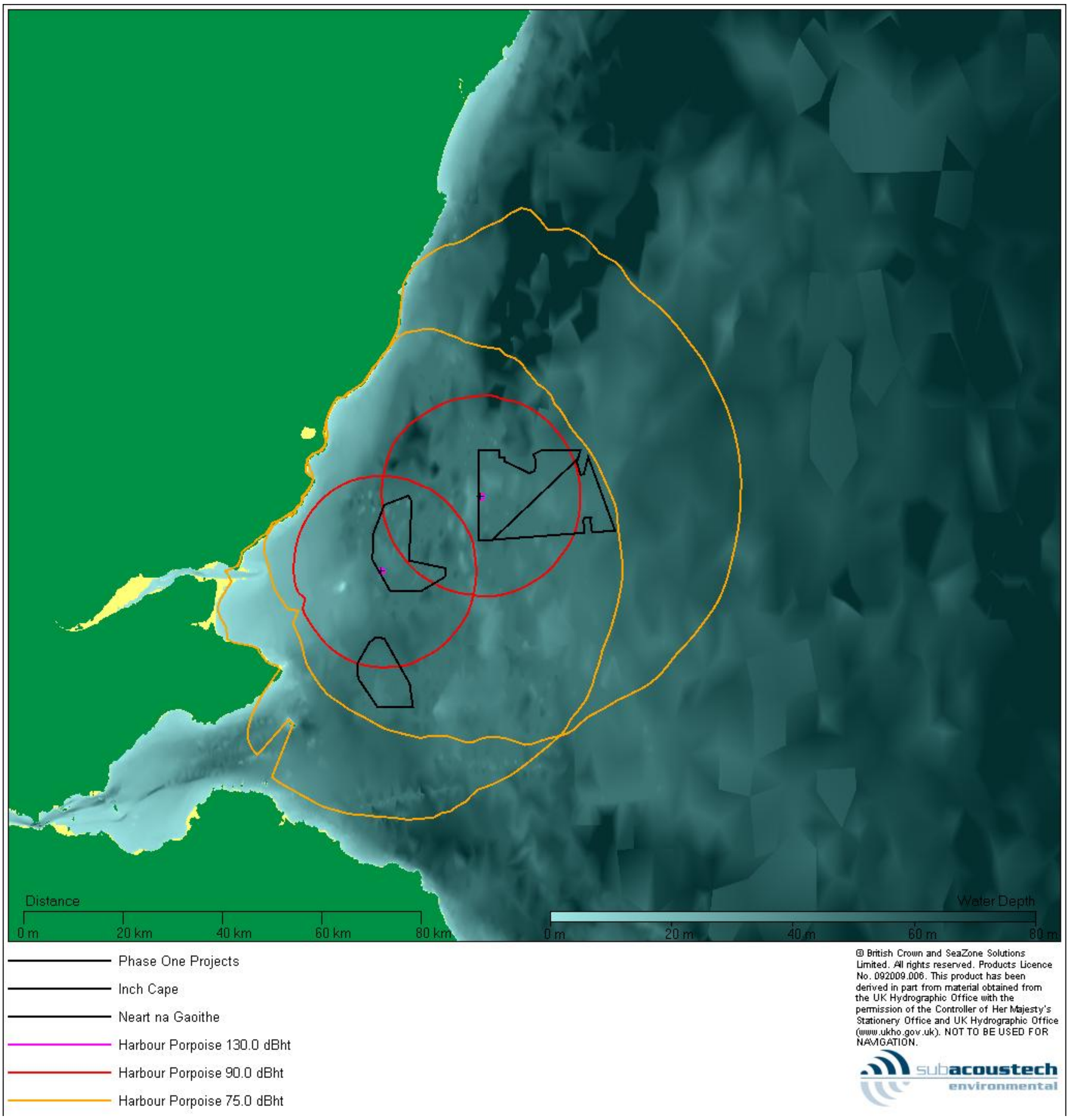

Figure 6-88 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM1 (alpha) and Inch Cape scenarios

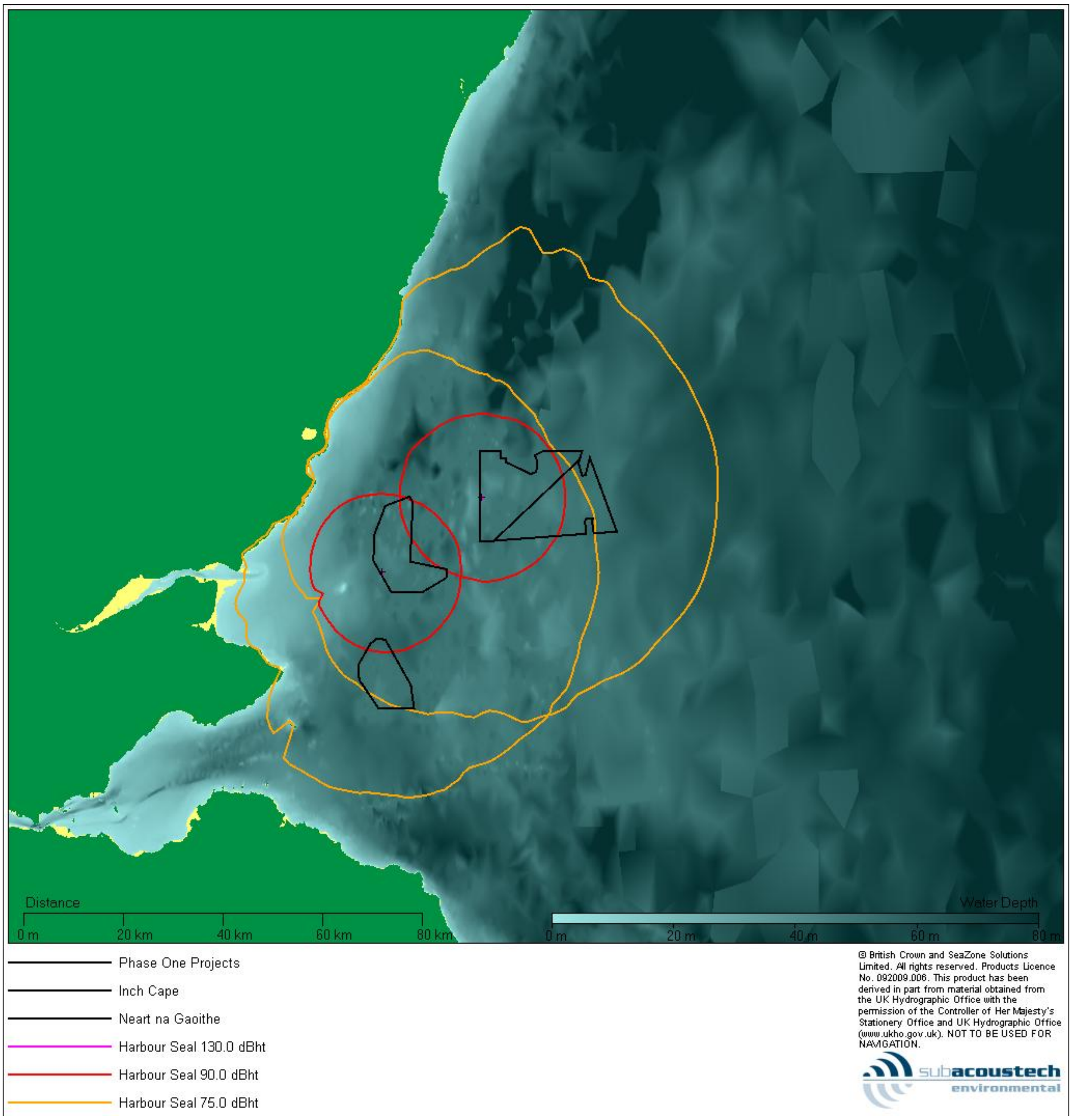

Figure 6-89 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM1 (alpha) and Inch Cape scenarios

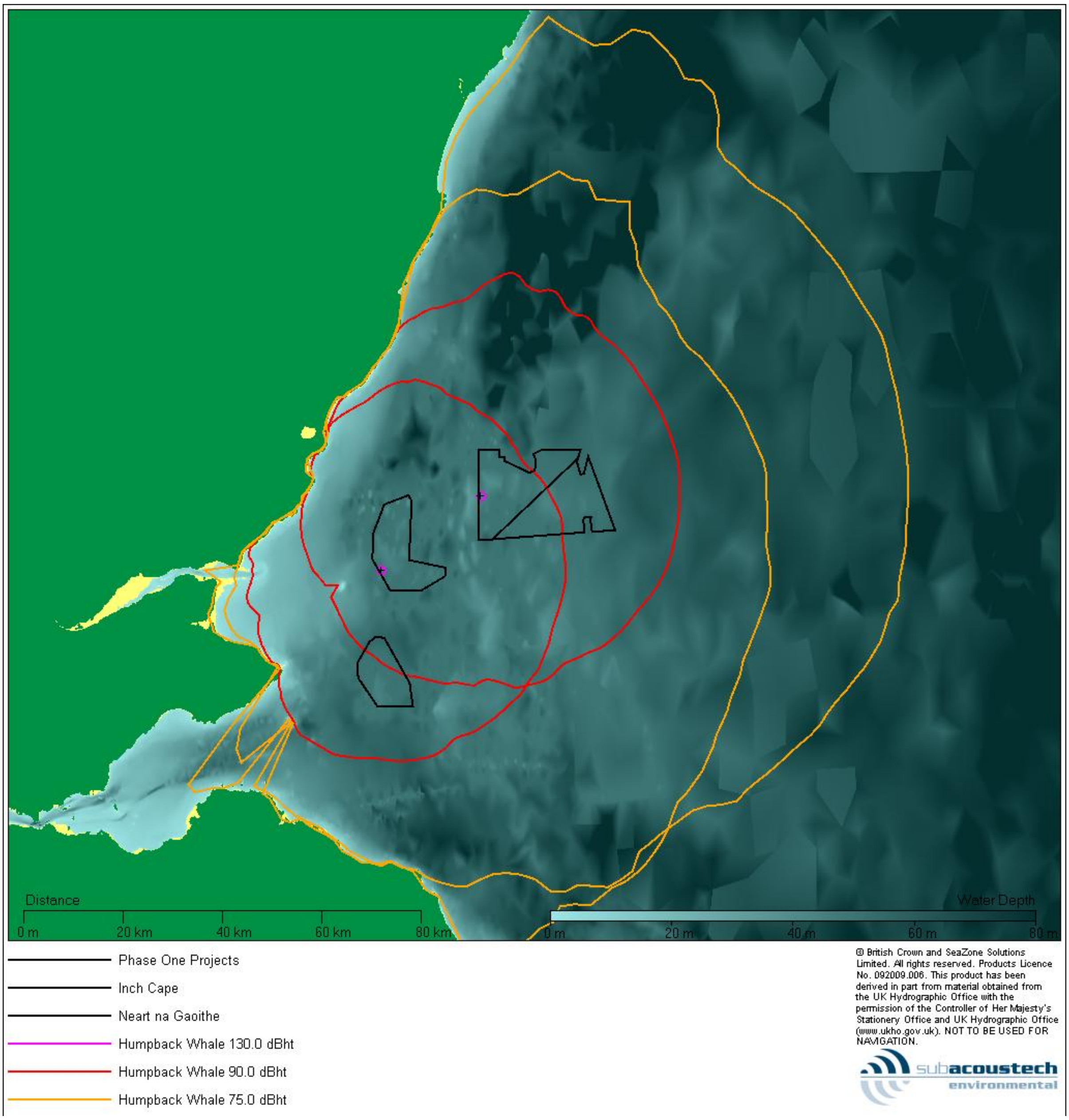

Figure 6-90 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the GM1 (alpha) and Inch Cape scenarios

6.4.1.11 Multiple Locations - GM1 (alpha) and NNG

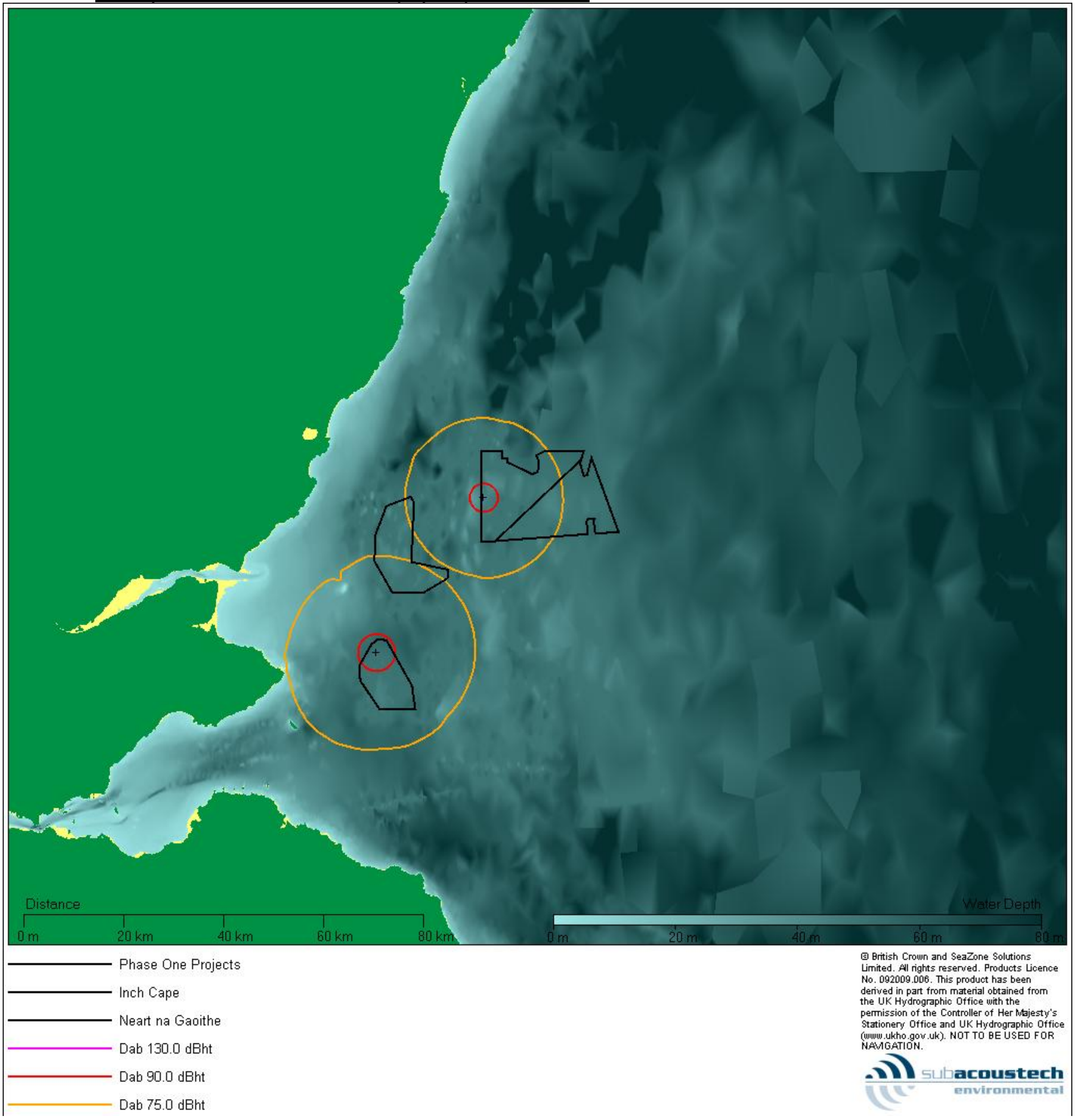

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Figure 6-91 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Dab for the GM1 (alpha) and NNG scenarios

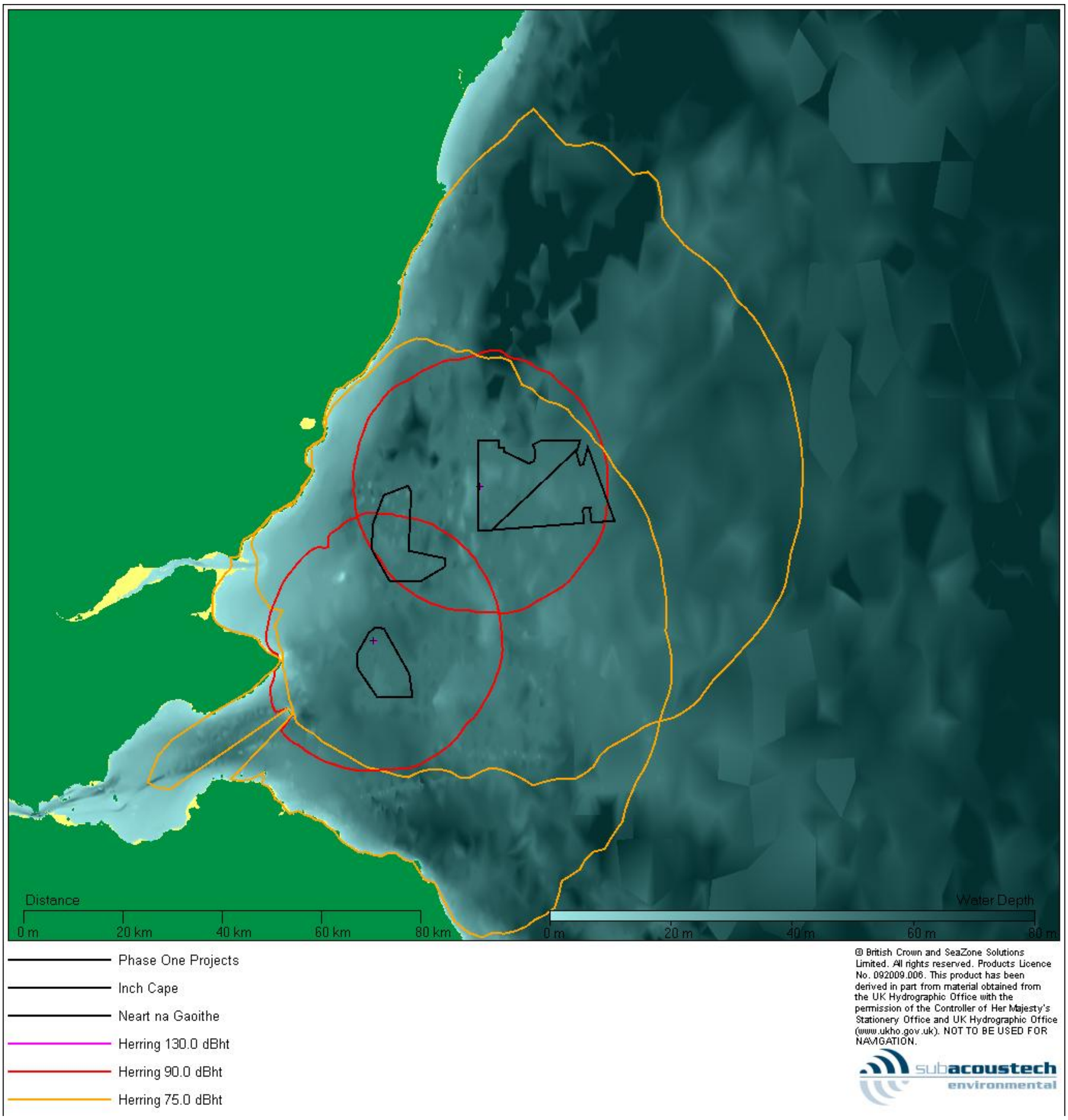

Figure 6-92 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Herring for the GM1 (alpha) and NNG scenarios

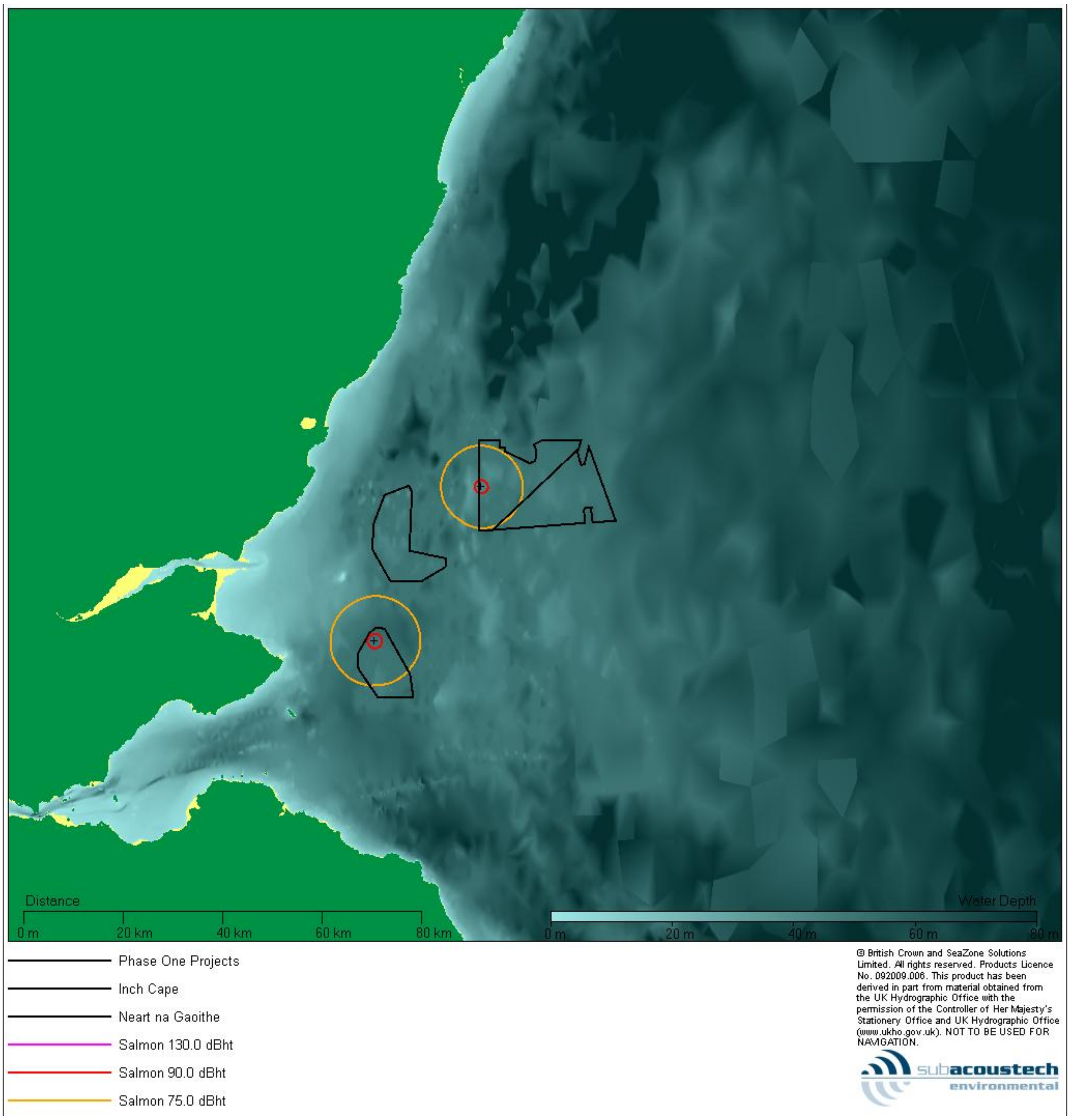

Figure 6-93 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the GM1 (alpha) and NNG scenarios

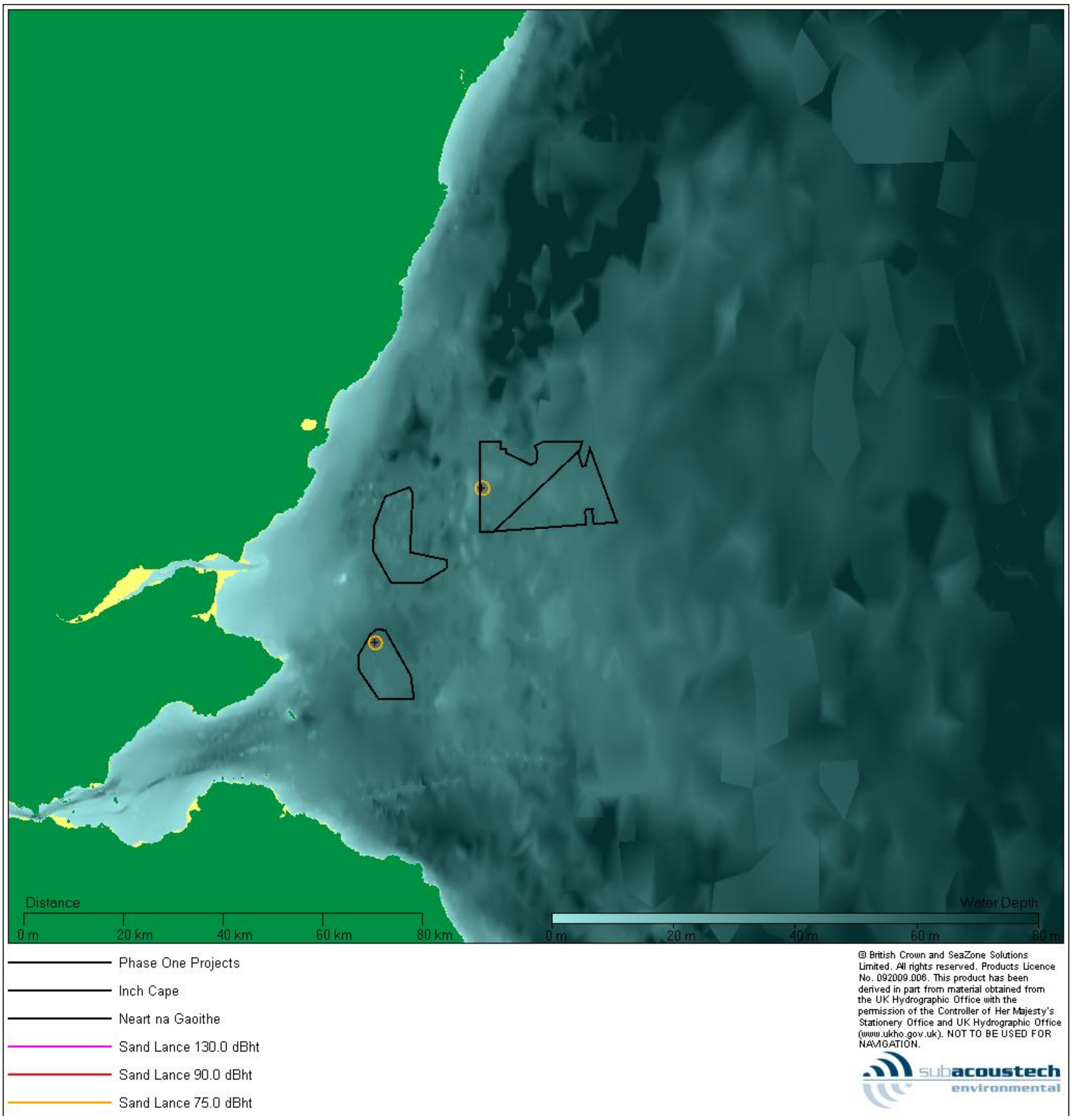

Figure 6-94 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the GM1 (alpha) and NNG scenarios

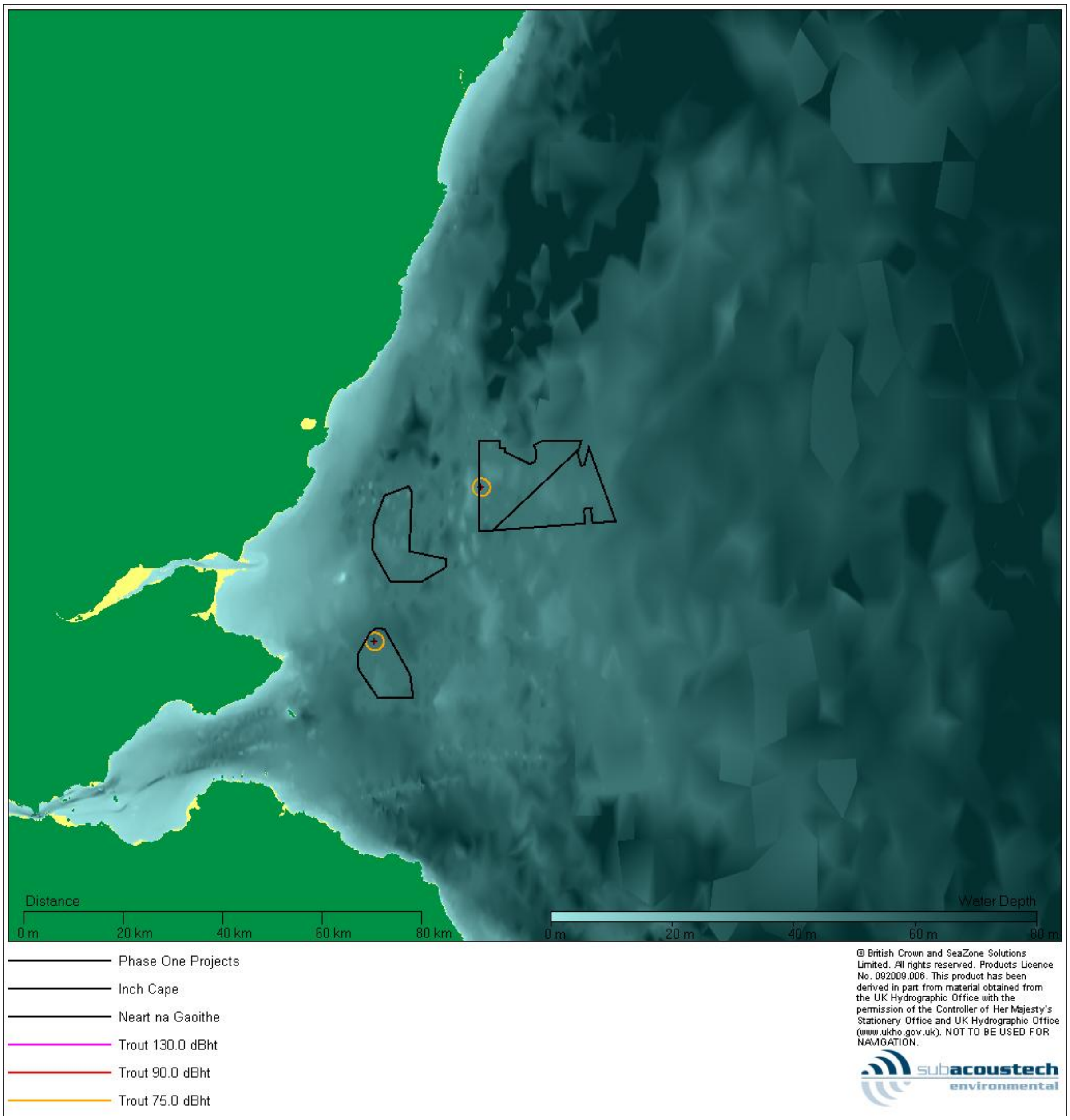

Figure 6-95 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Trout for the GM1 (alpha) and NNG scenarios

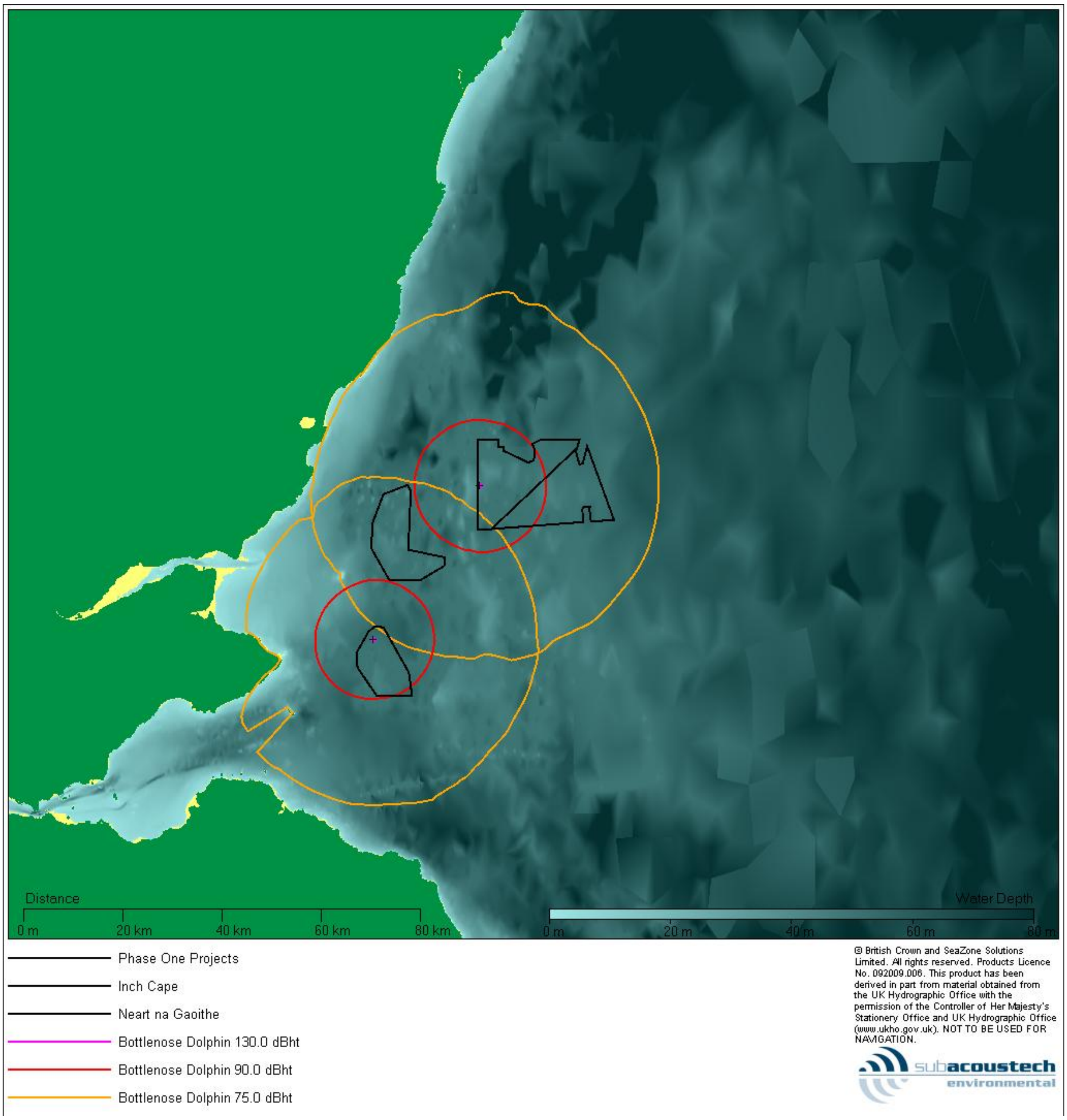

Figure 6-96 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the GM1 (alpha) and NNG scenarios

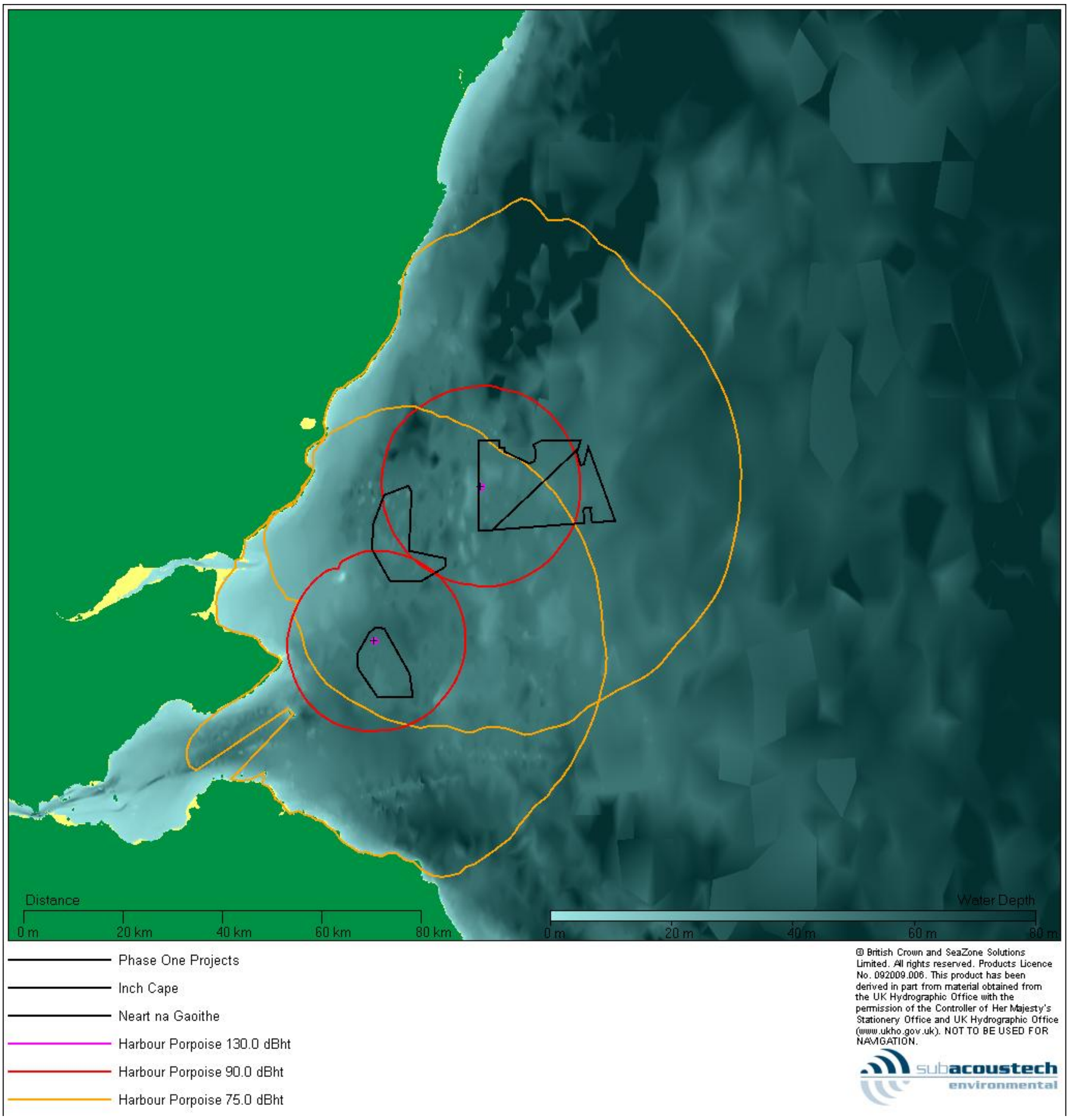

Figure 6-97 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM1 (alpha) and NNG scenarios

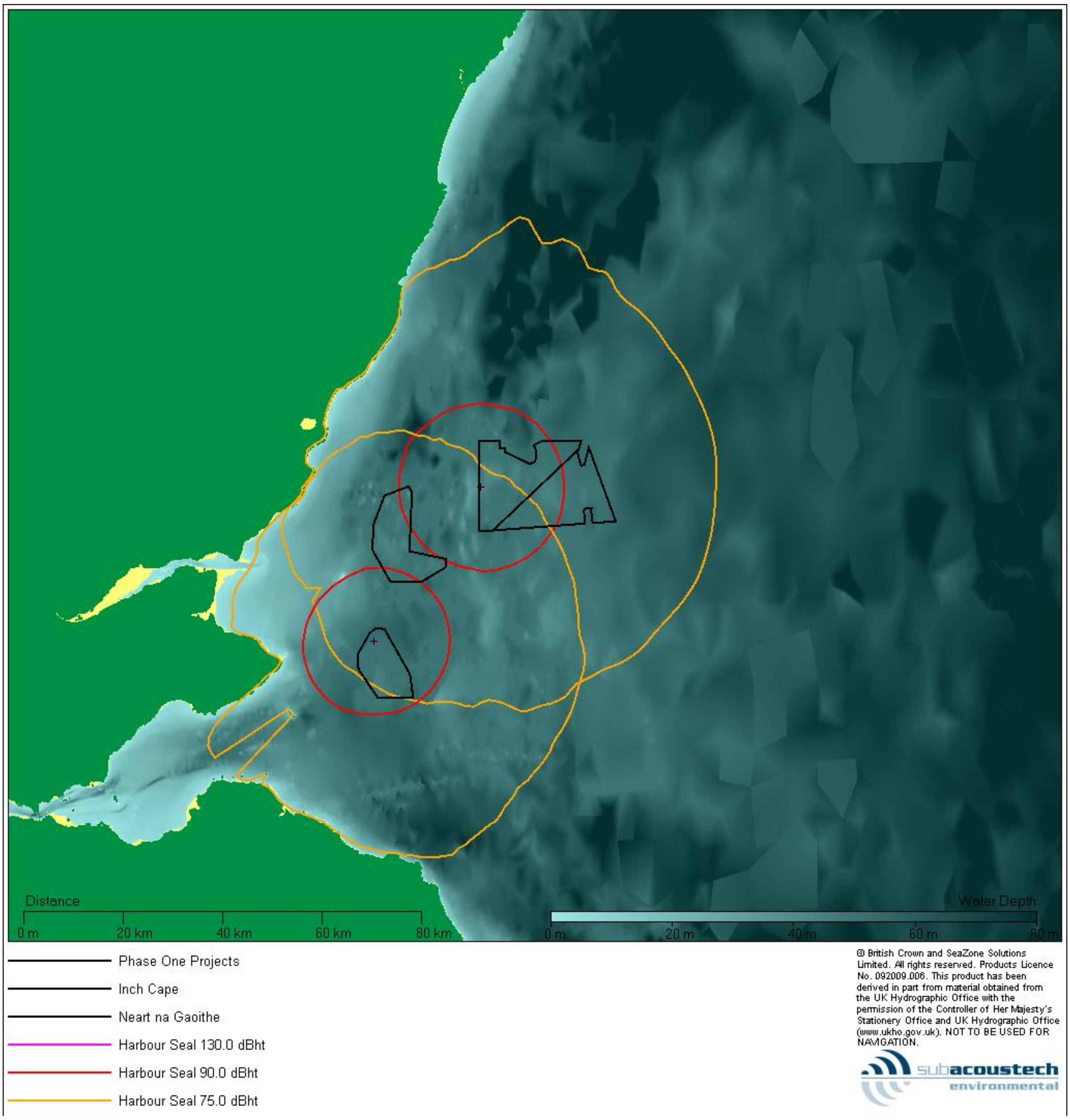

Figure 6-98 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM1 (alpha) and NNG scenarios

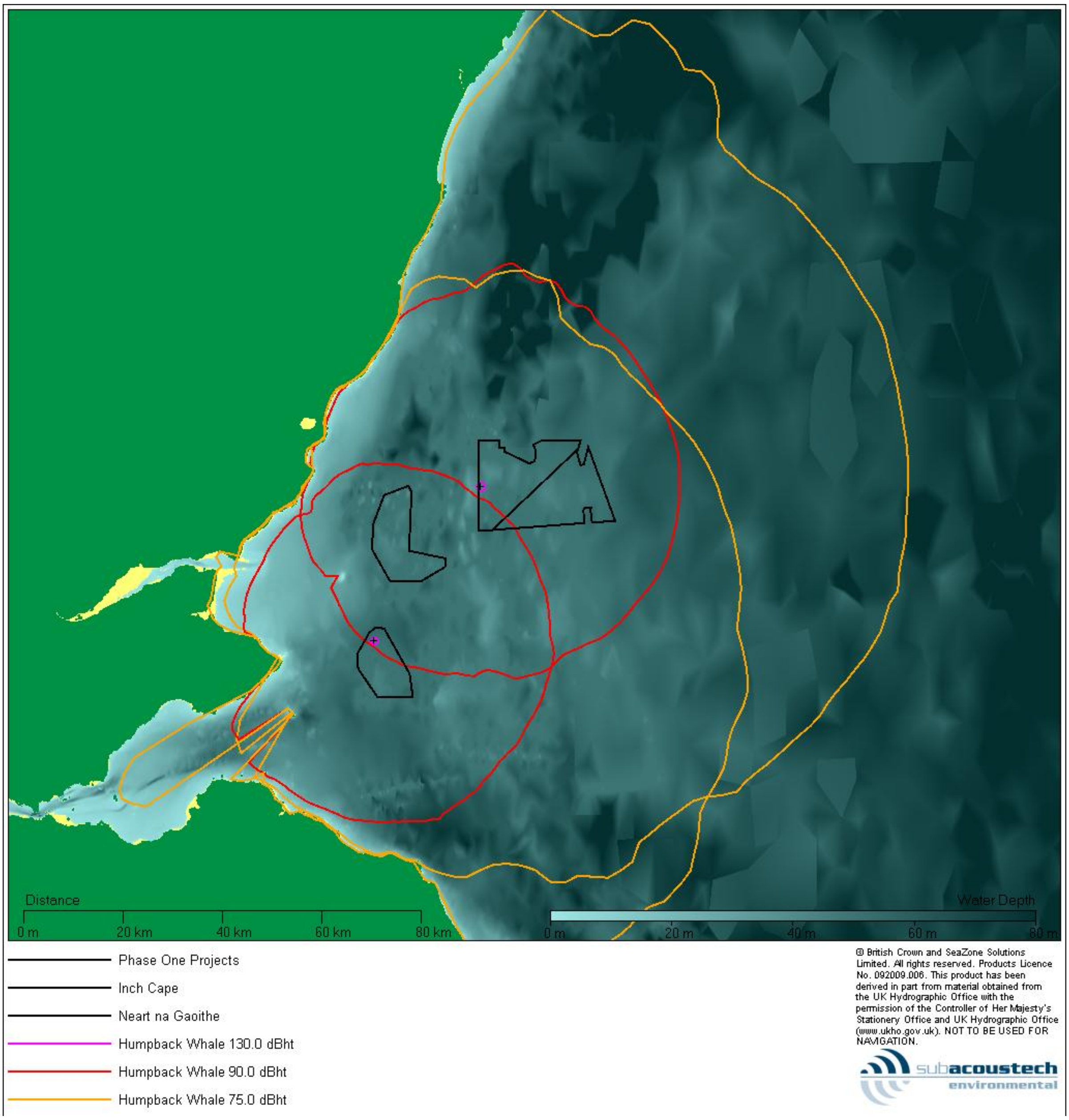

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Figure 6-99 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the GM1 (alpha) and NNG scenarios

6.4.1.12 Multiple Locations - GM1 (alpha), Inch Cape and NNG

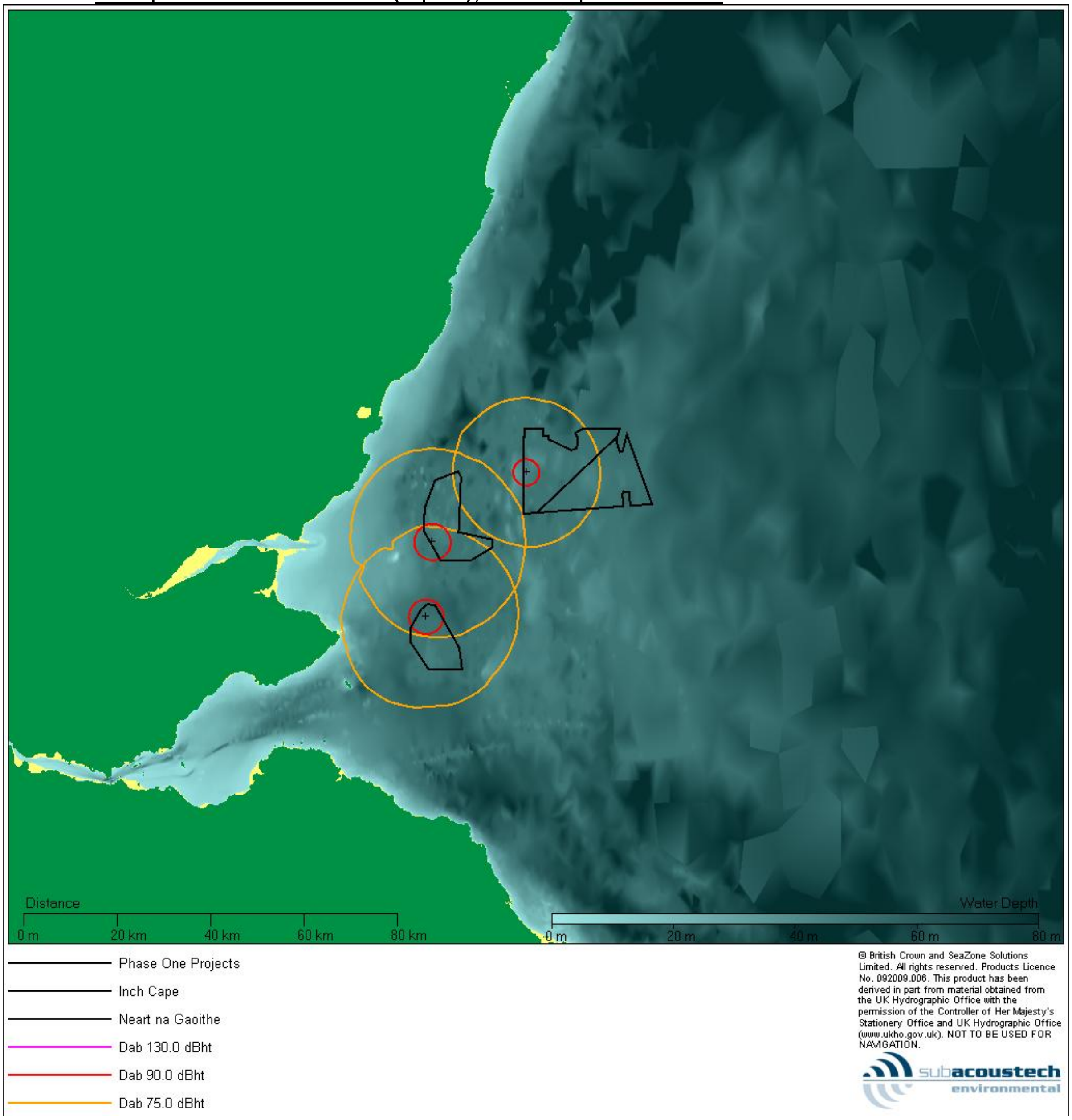

Figure 6-100 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM1 (alpha), Inch Cape and NNG scenarios

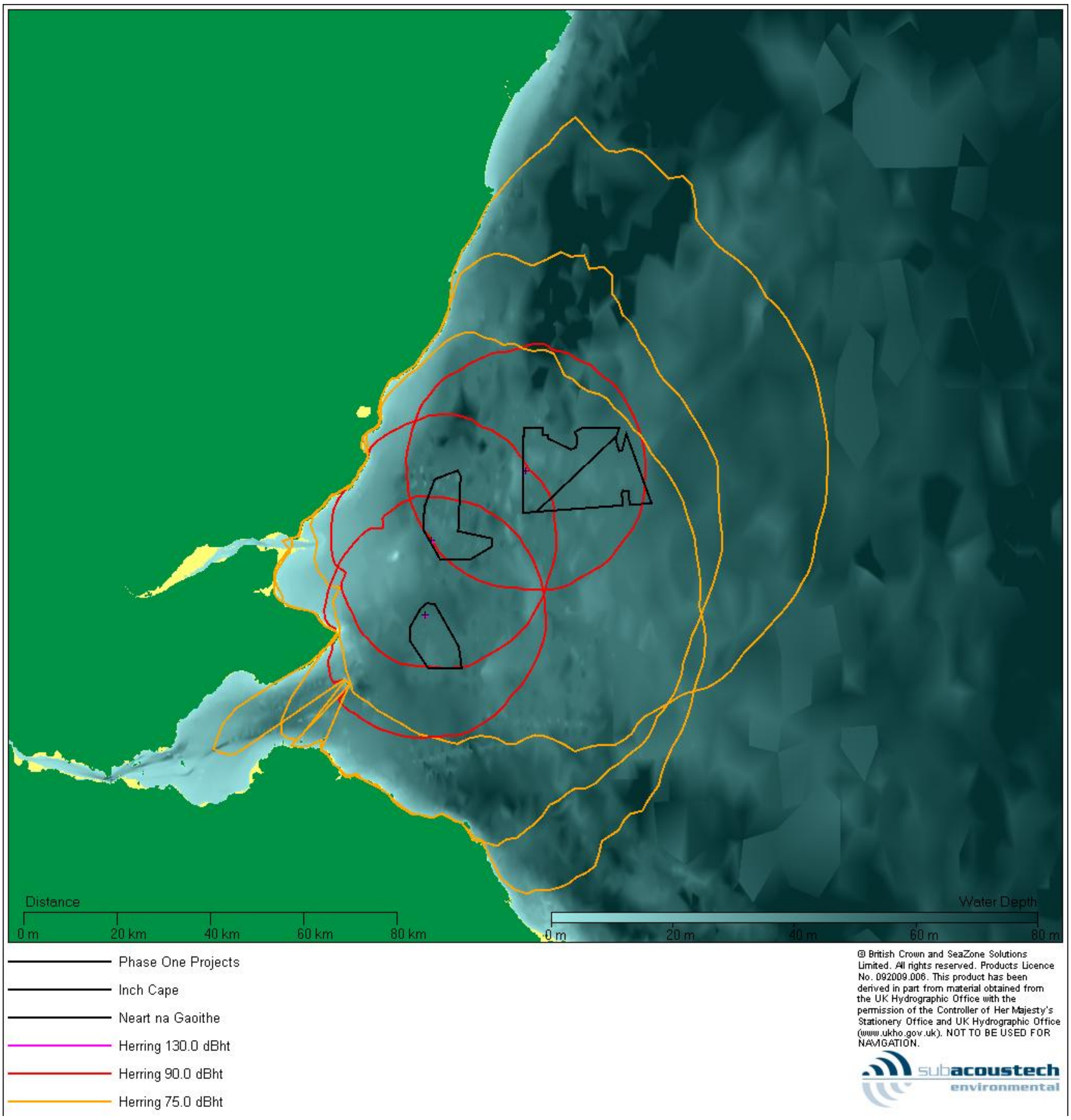

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Figure 6-101 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the GM1 (alpha), Inch Cape and NNG scenarios

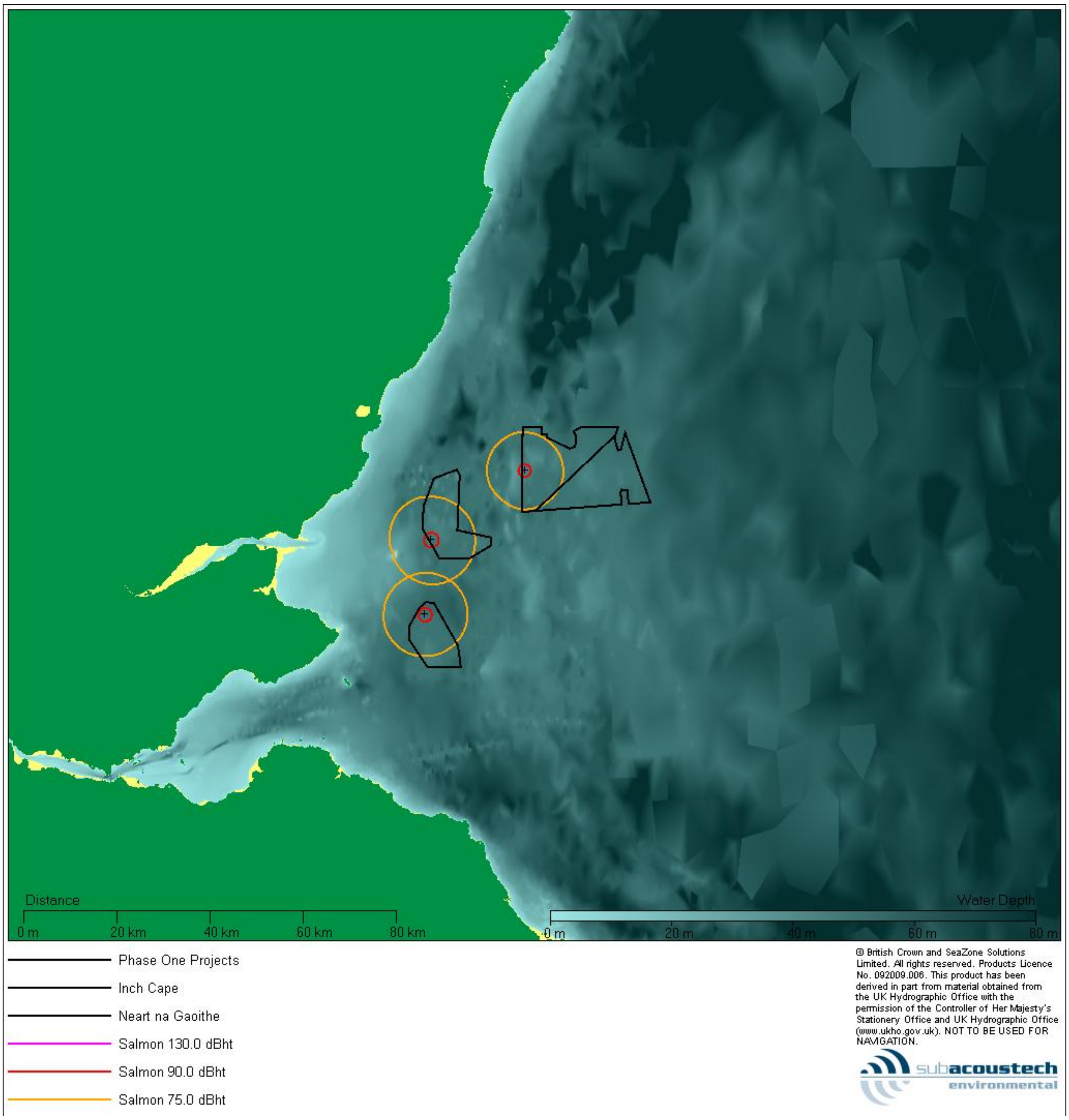

Figure 6-102 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the GM1 (alpha), Inch Cape and NNG scenarios

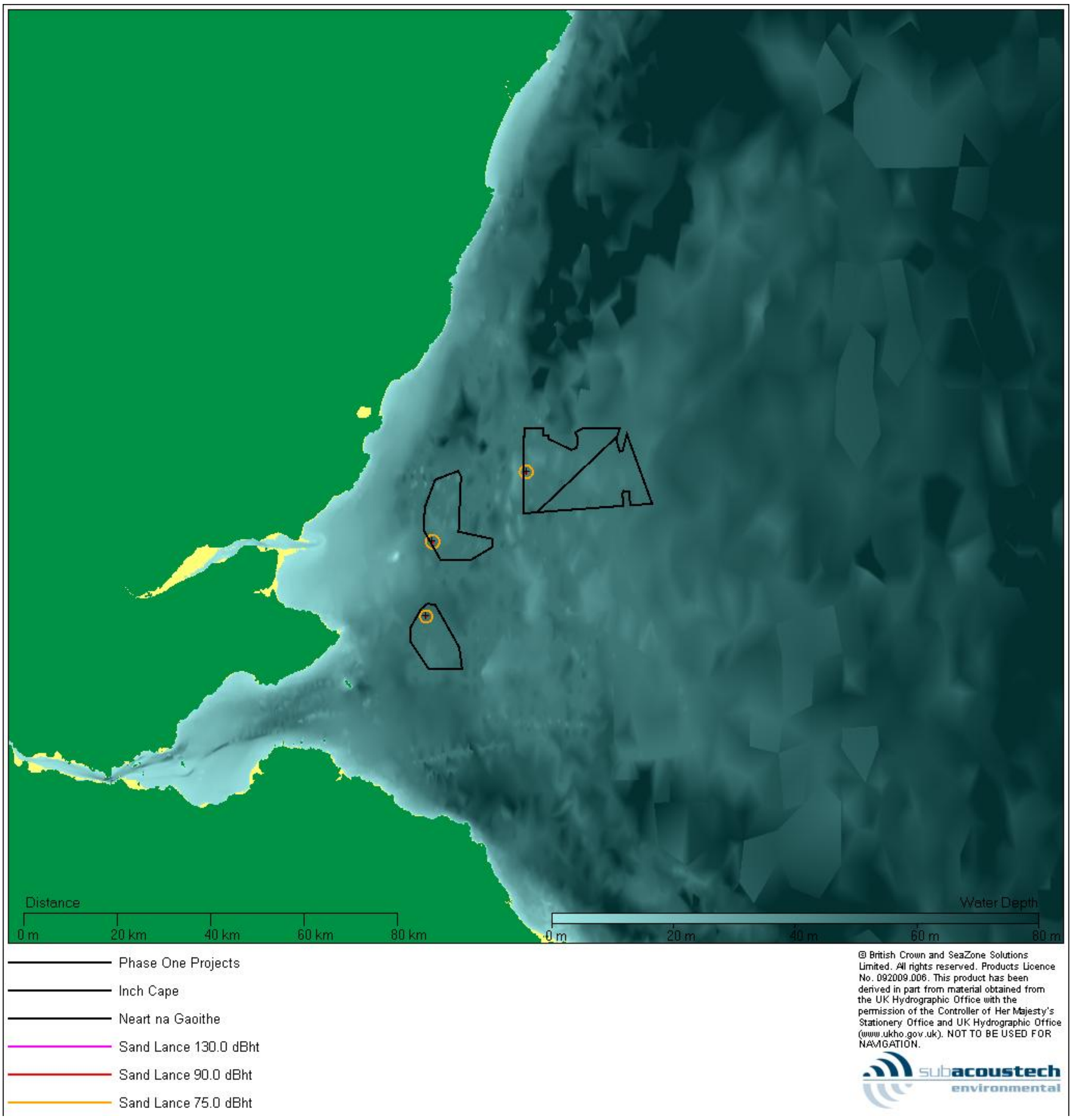

Figure 6-103 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the GM1 (alpha), Inch Cape and NNG scenarios

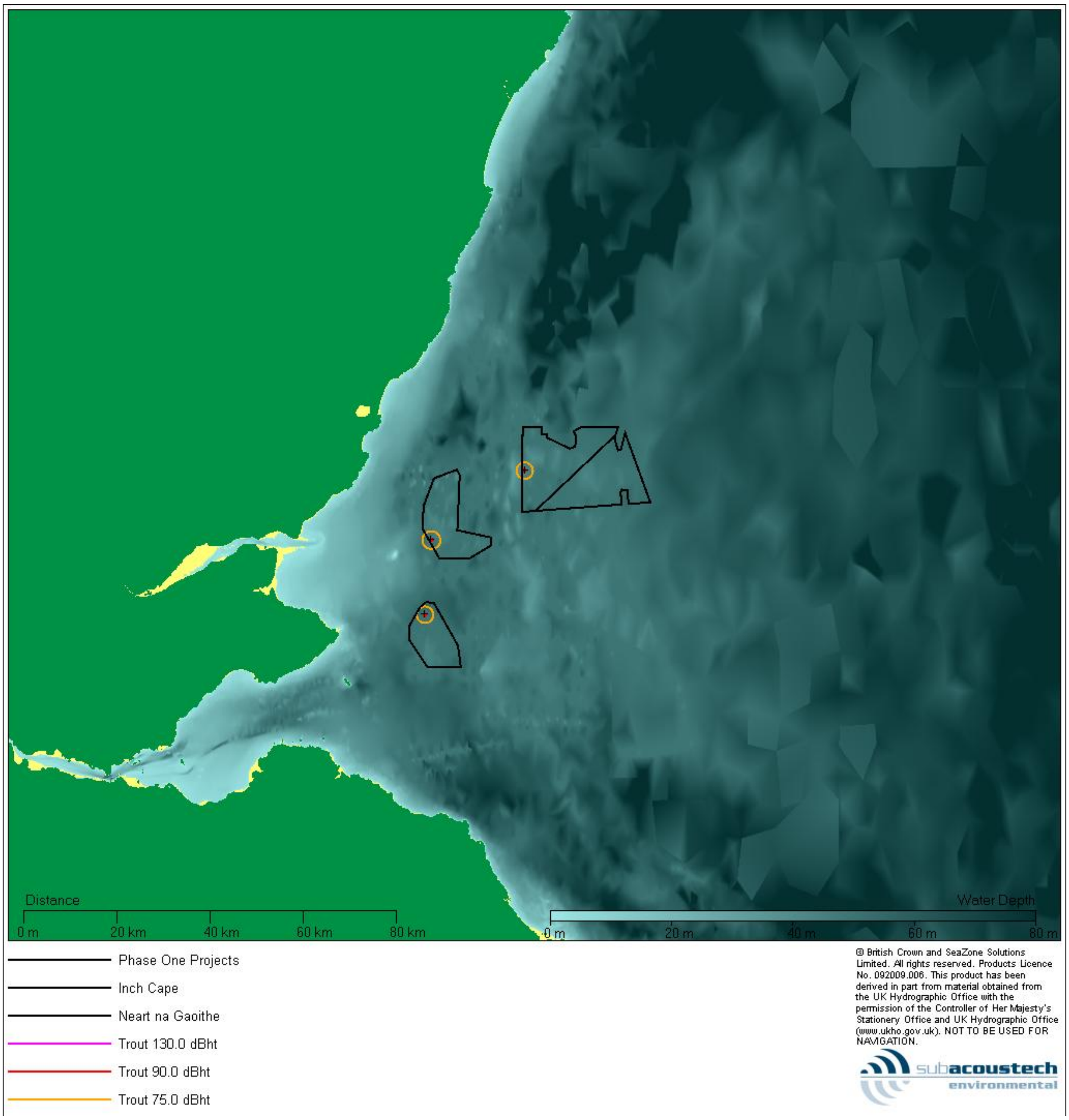

Figure 6-104 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the GM1 (alpha), Inch Cape and NNG scenarios

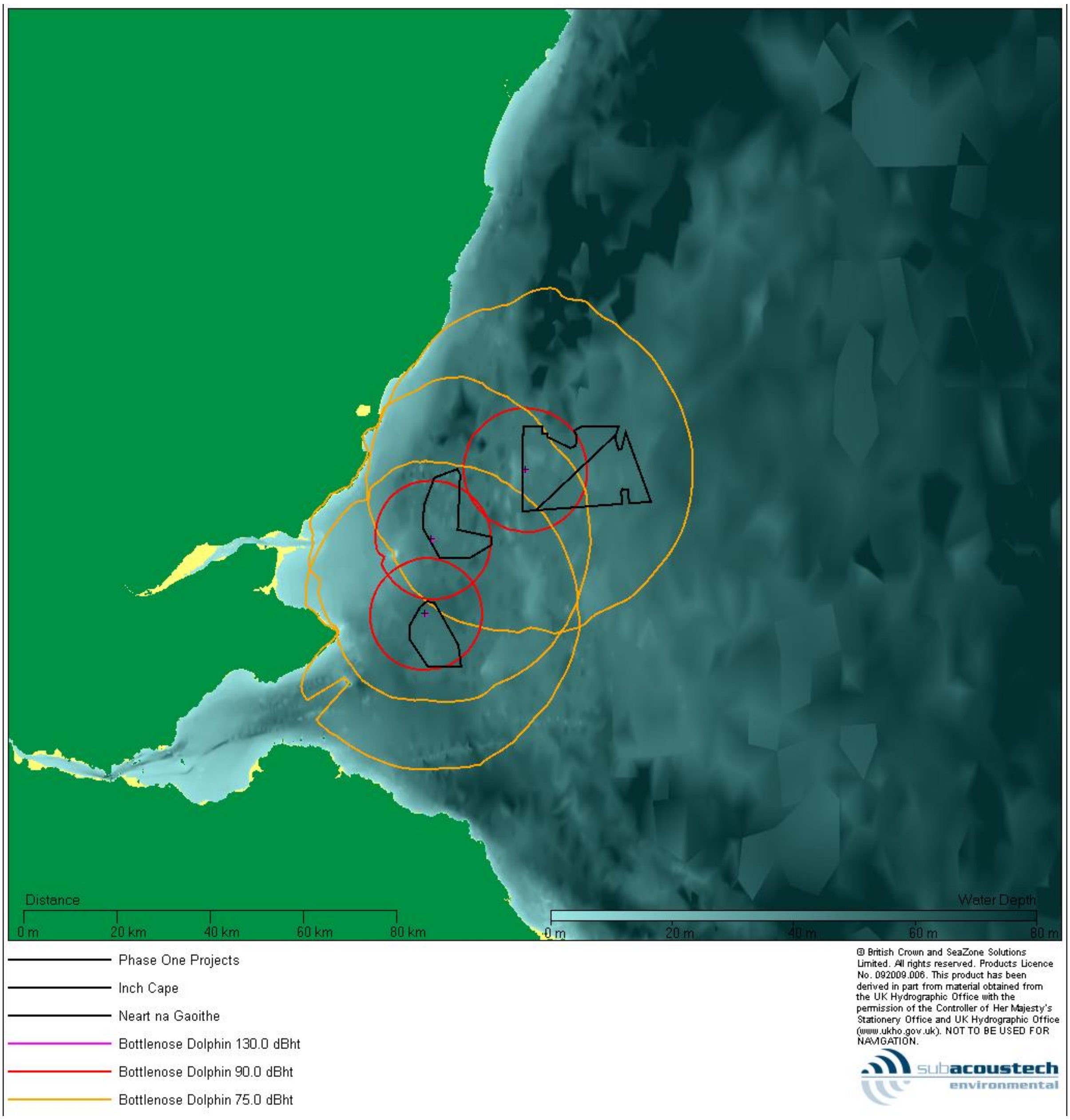

Figure 6-105 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the GM1 (alpha), Inch Cape and NNG scenarios

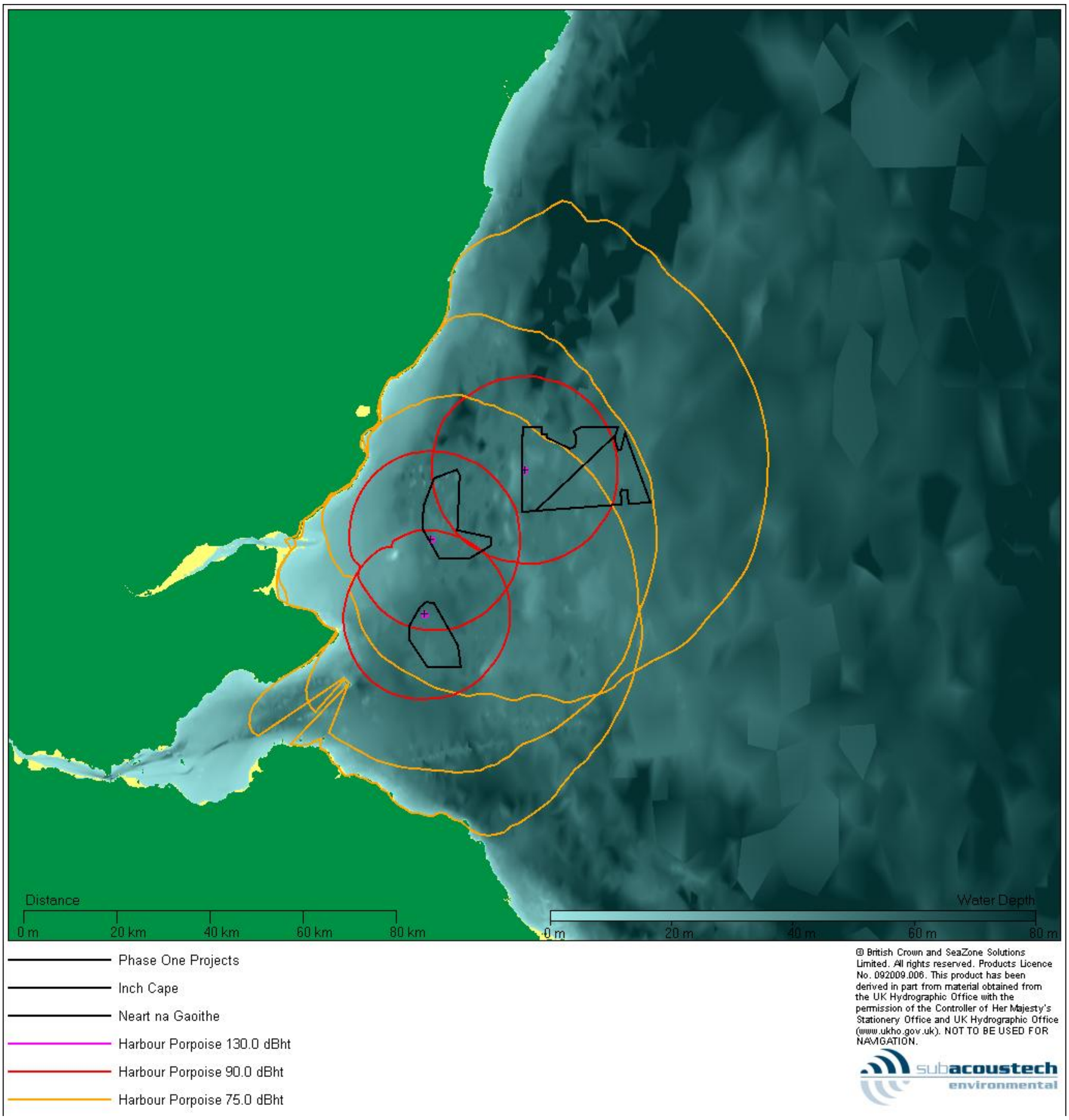

Figure 6-106 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM1 (alpha), Inch Cape and NNG scenarios

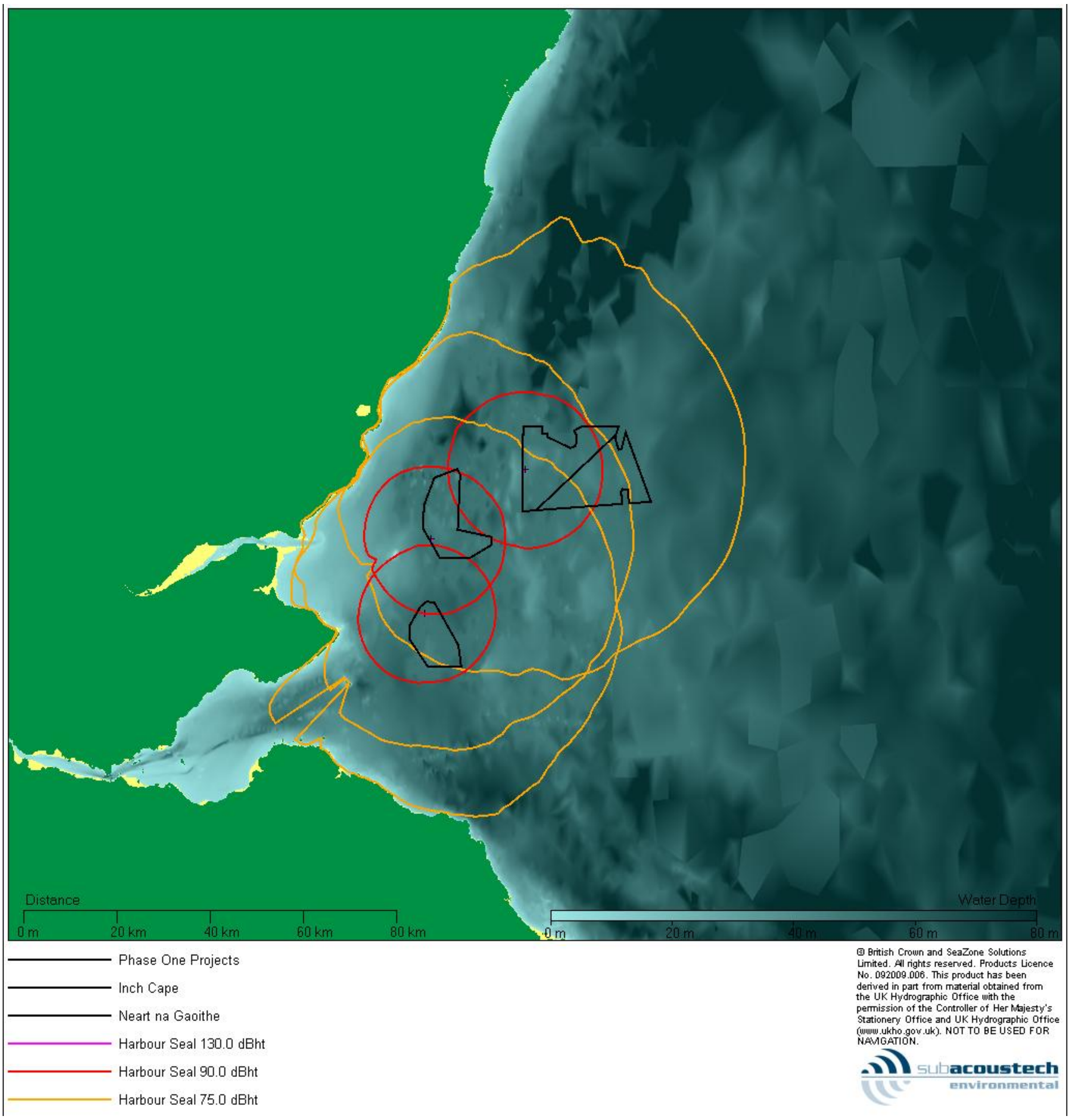

Figure 6-107 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM1 (alpha), Inch Cape and NNG scenarios

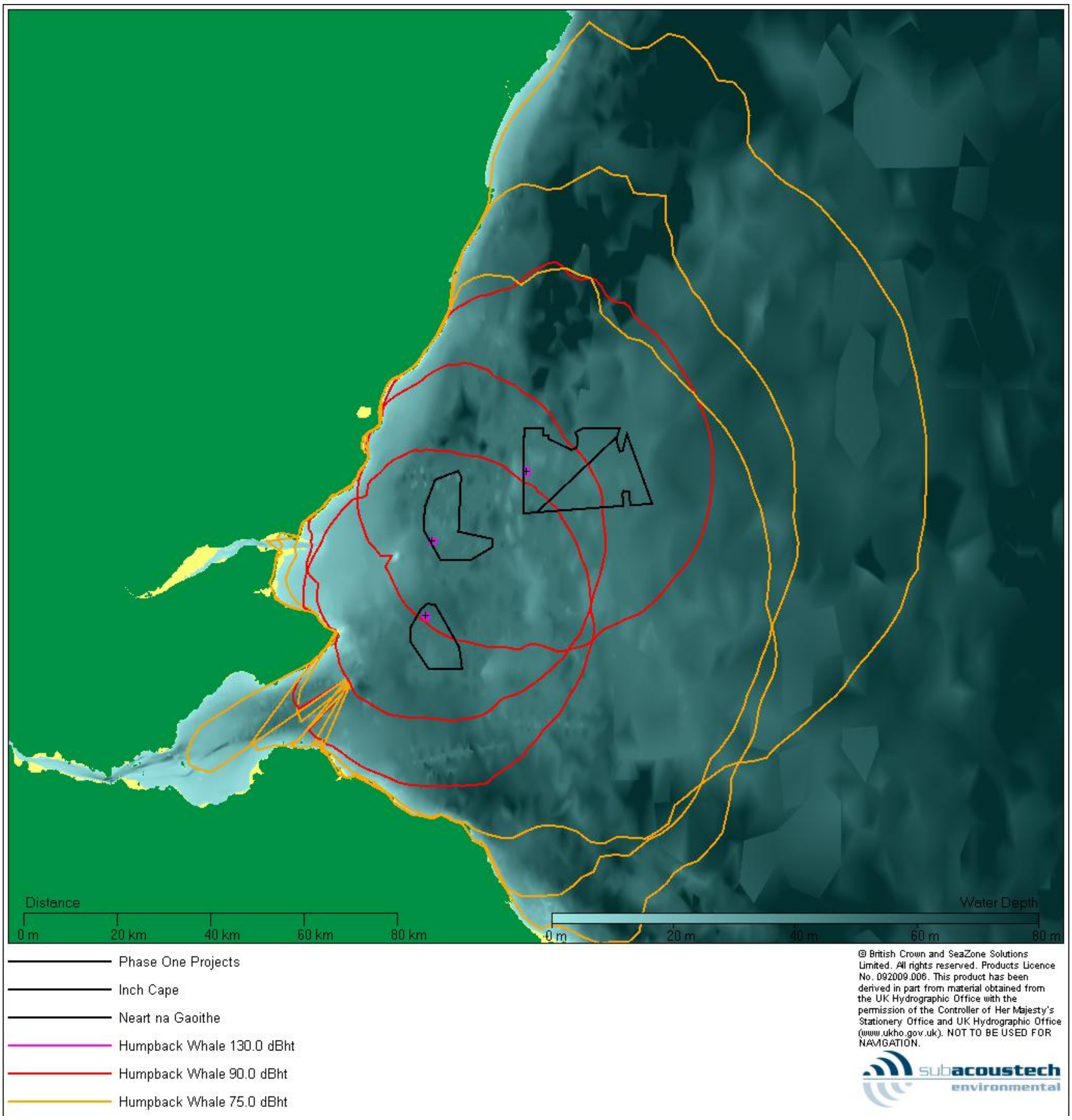

Figure 6-108 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Humpback Whale for the GM1 (alpha), Inch Cape and NNG scenarios

6.4.1.13 Multiple Locations - GM3 (alpha) and Inch Cape

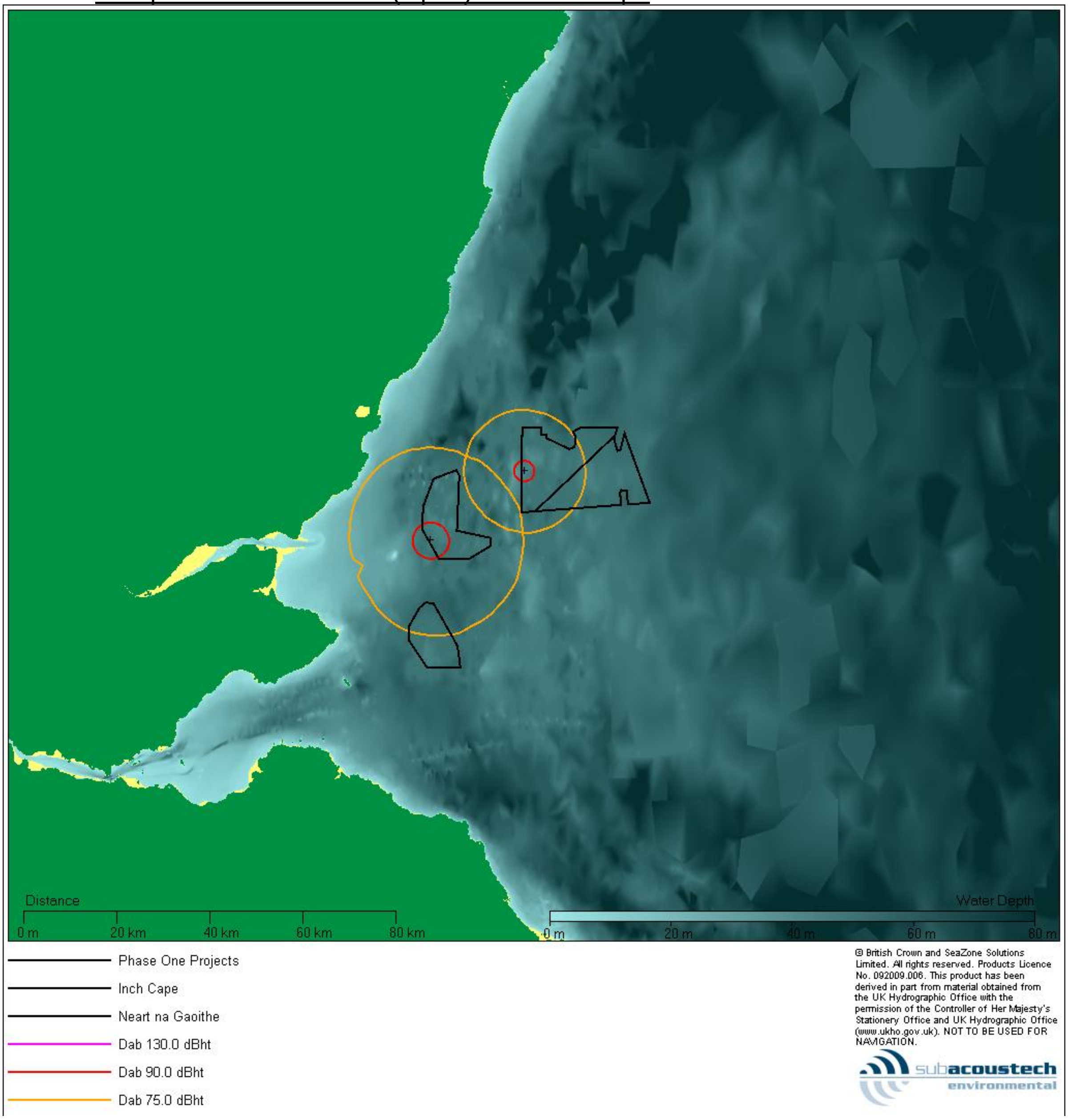

Figure 6-109 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM3 (alpha) and Inch Cape scenarios

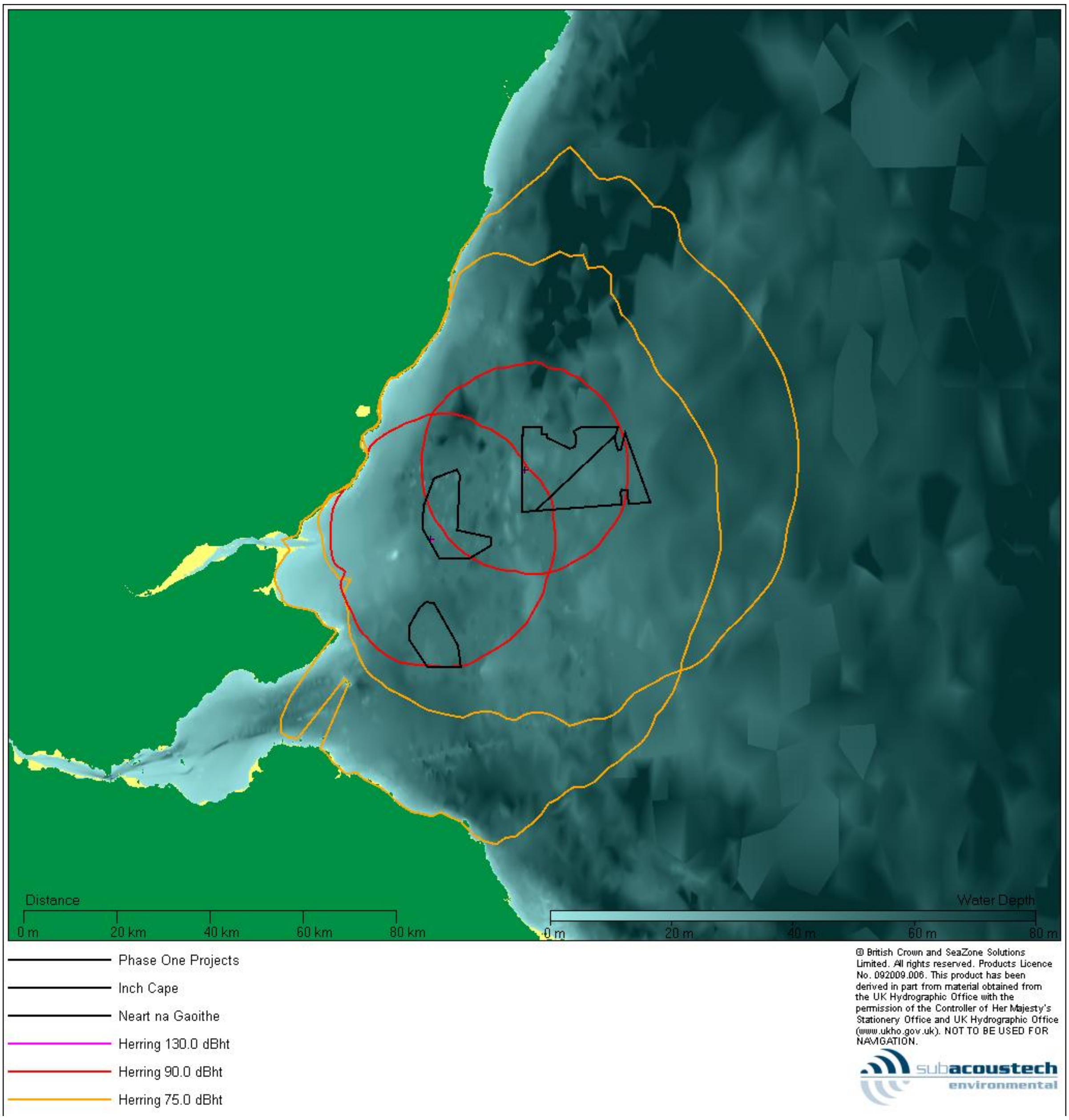

Figure 6-110 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the GM3 (alpha) and Inch Cape scenarios

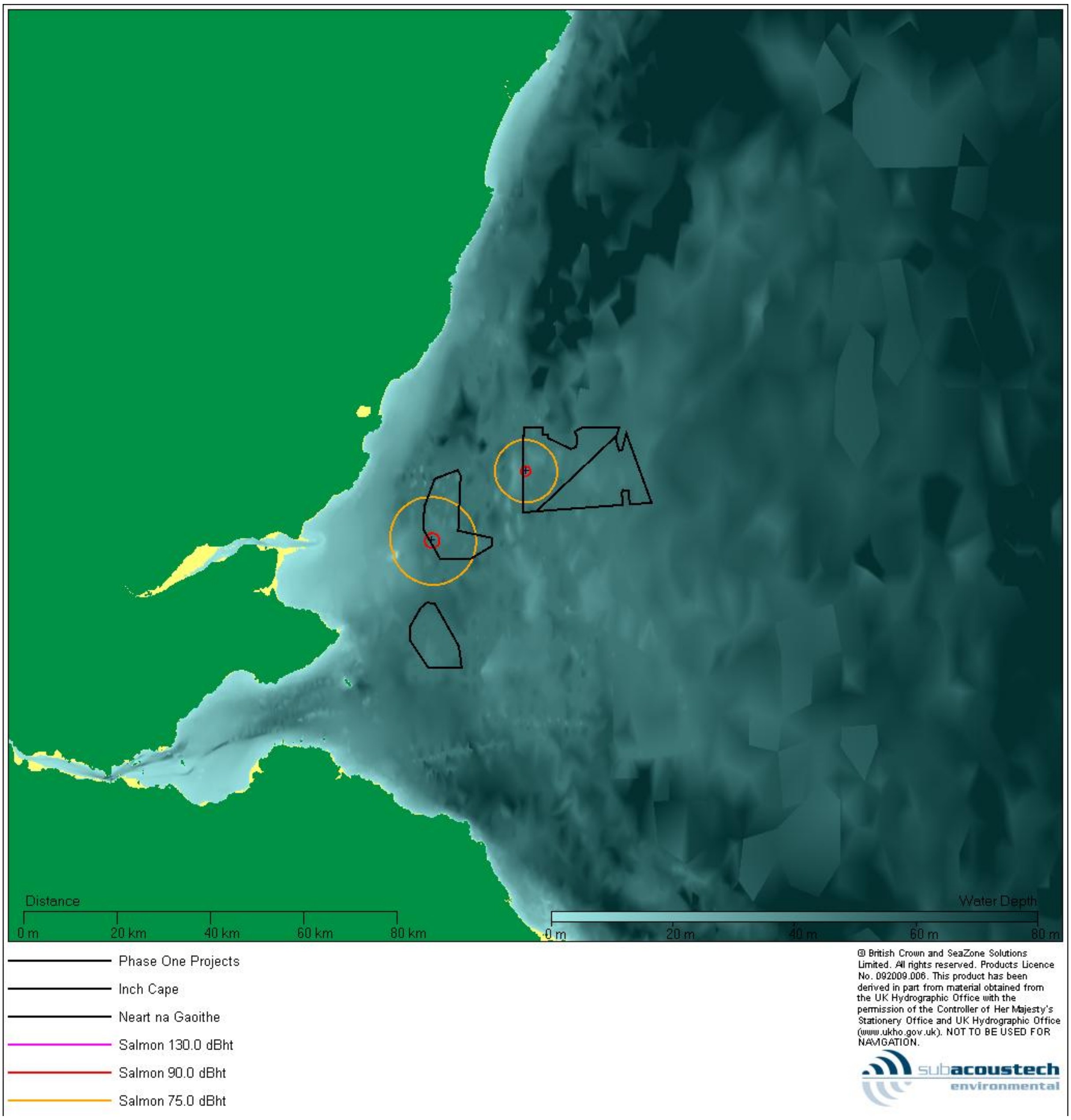

Figure 6-111 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the GM3 (alpha) and Inch Cape scenarios

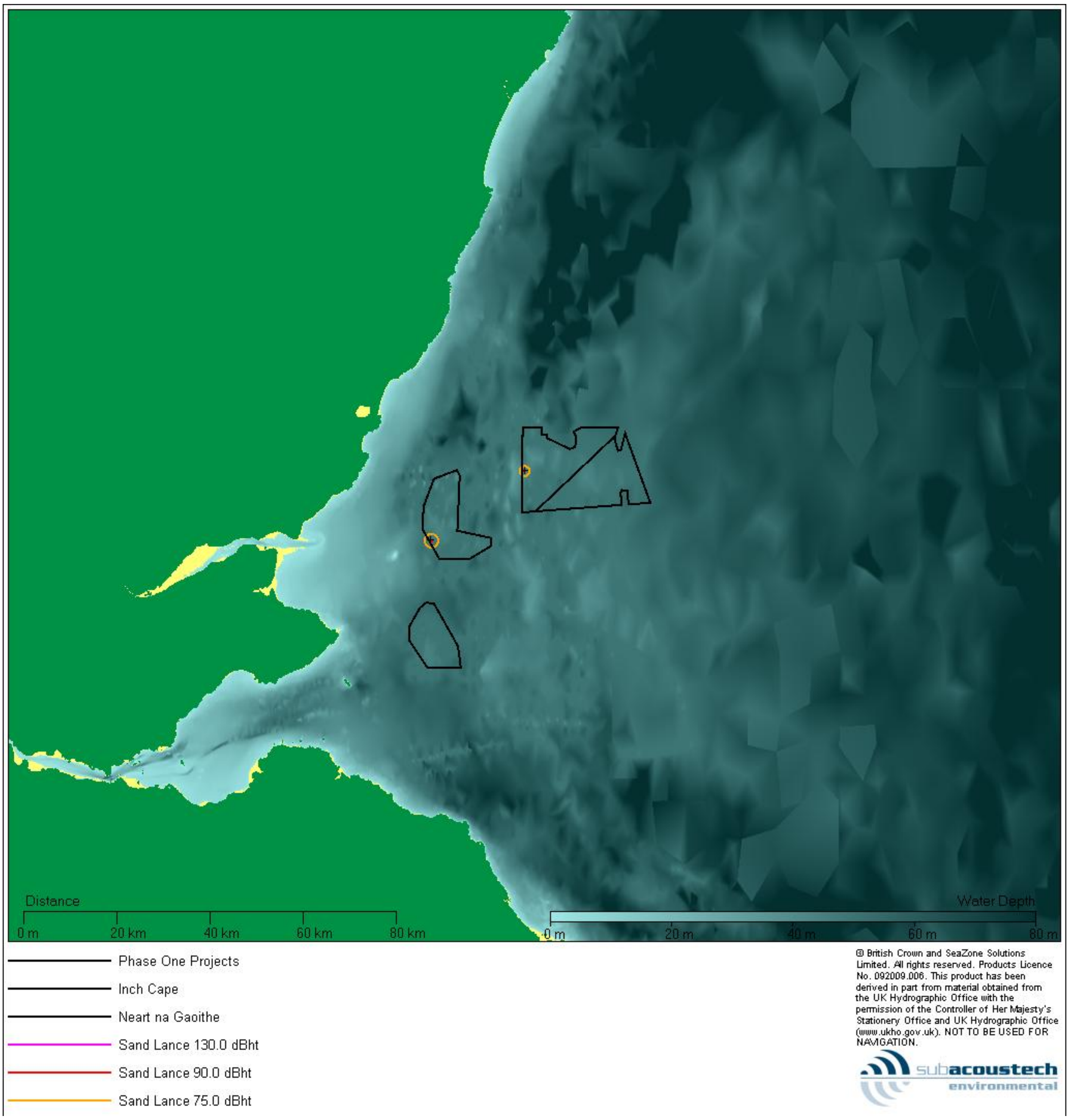

Figure 6-112 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the GM3 (alpha) and Inch Cape scenarios

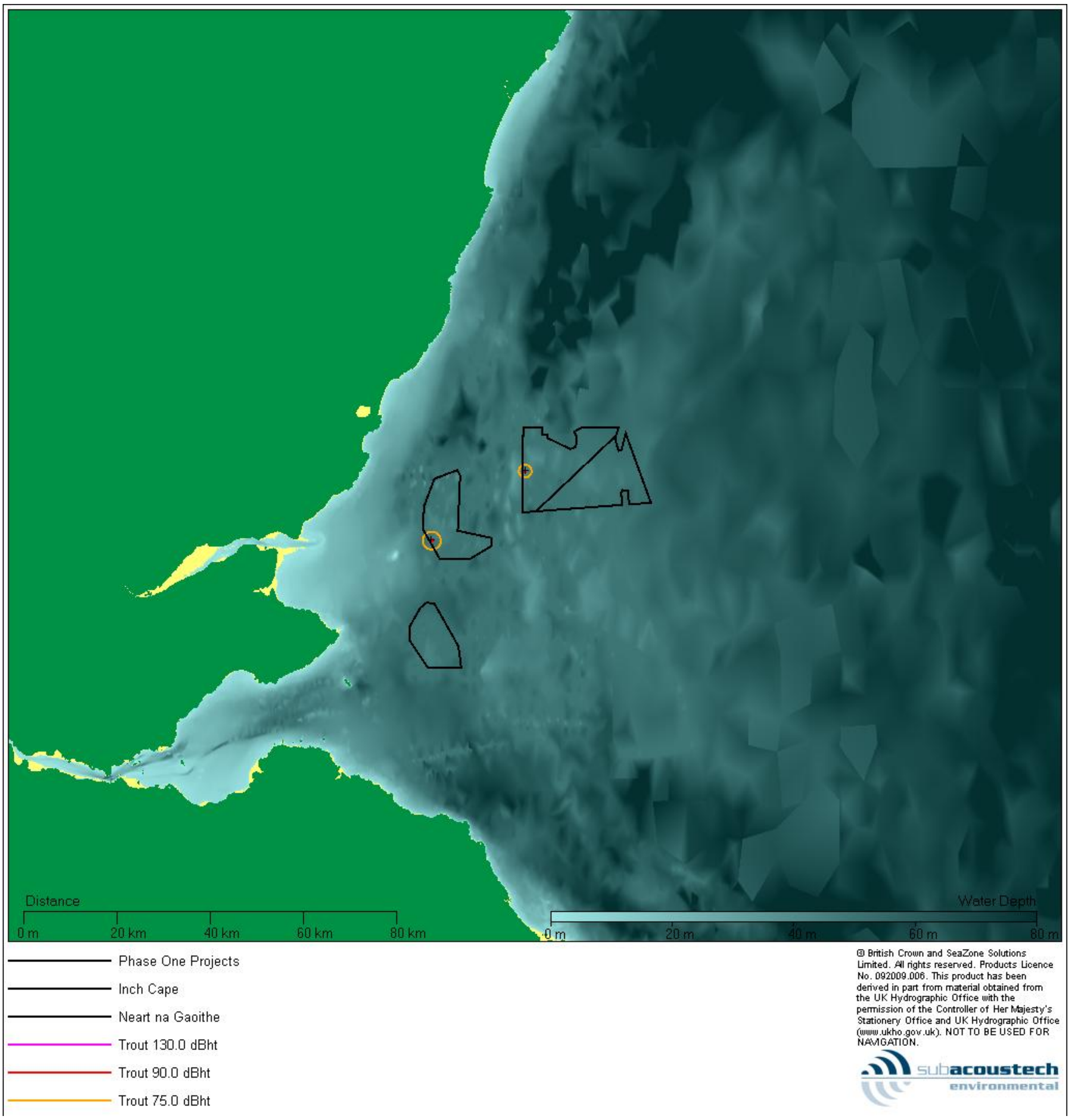

Figure 6-113 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the GM3 (alpha) and Inch Cape scenarios

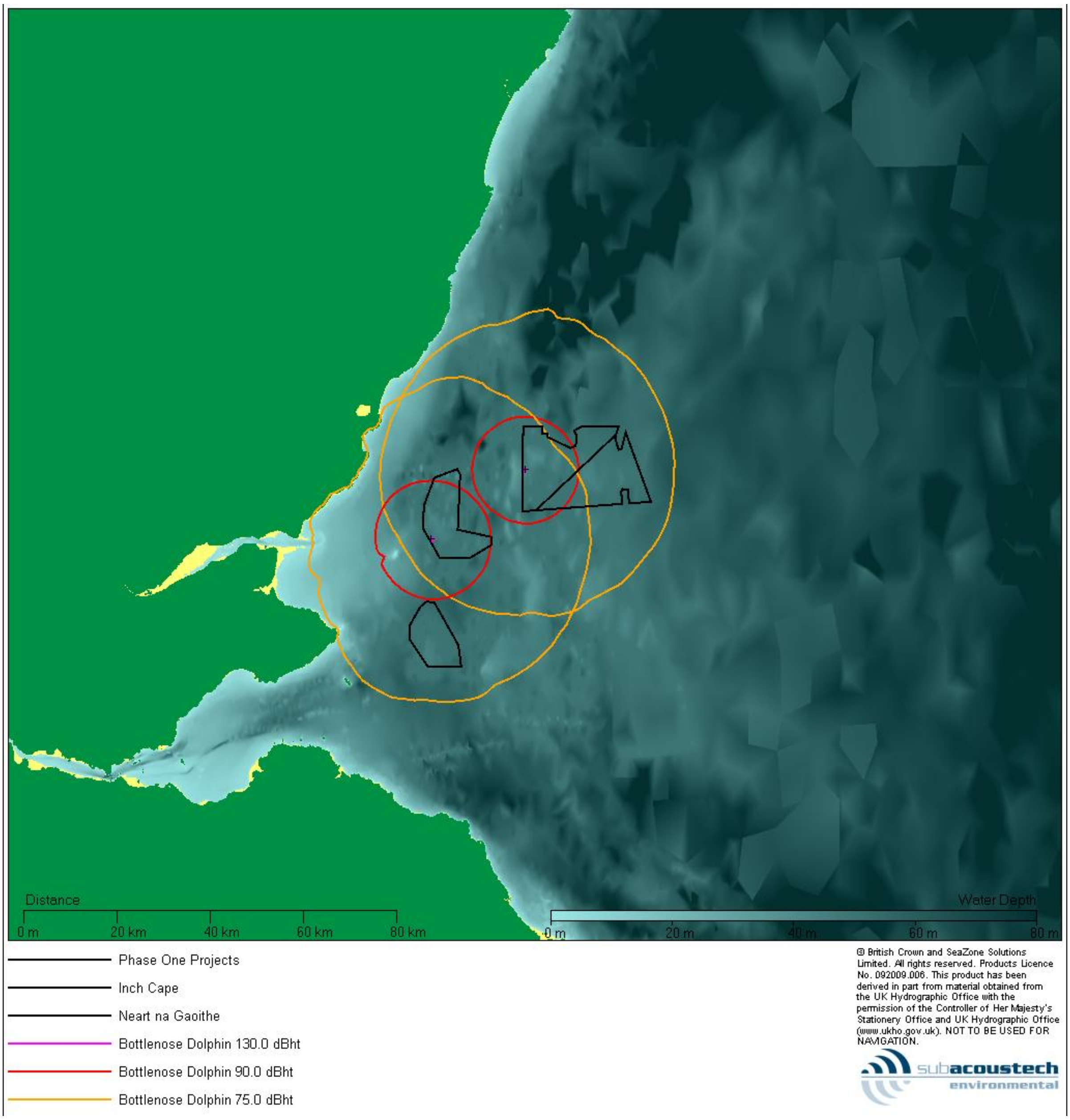

Figure 6-114 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphins for the GM3 (alpha) and Inch Cape scenarios

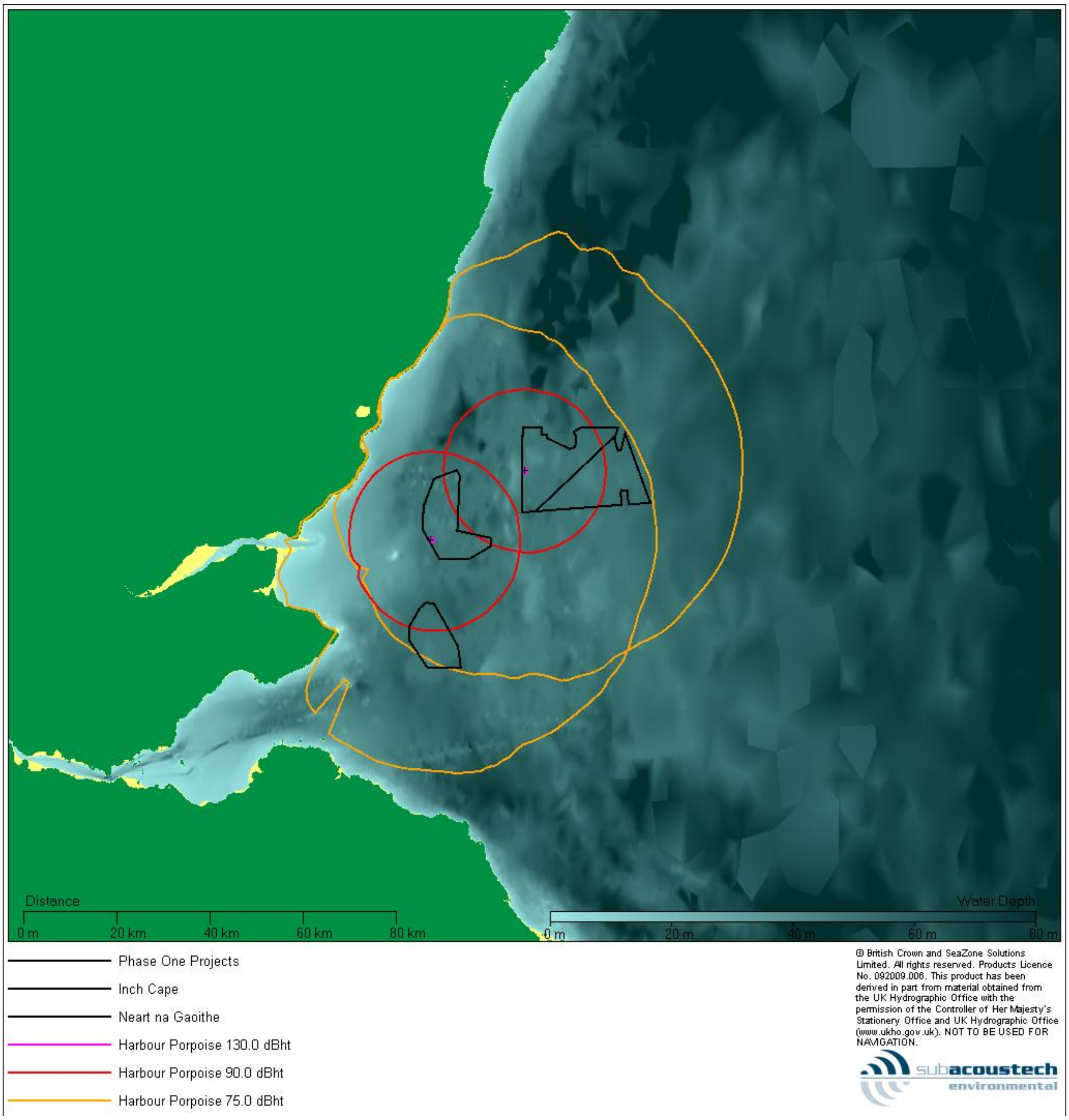

Figure 6-115 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM3 (alpha) and Inch Cape scenarios

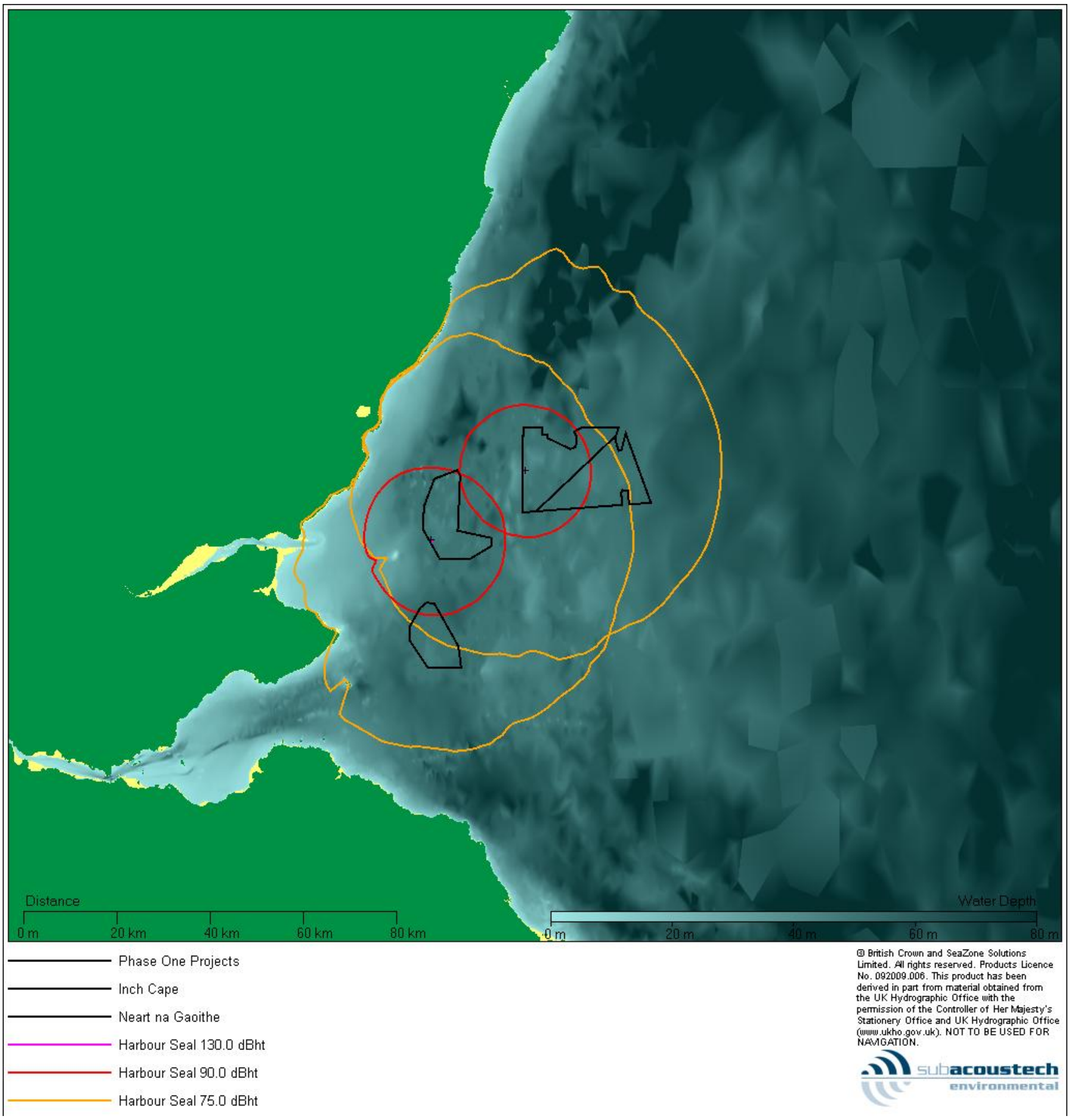

Figure 6-116 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM3 (alpha) and Inch Cape scenarios

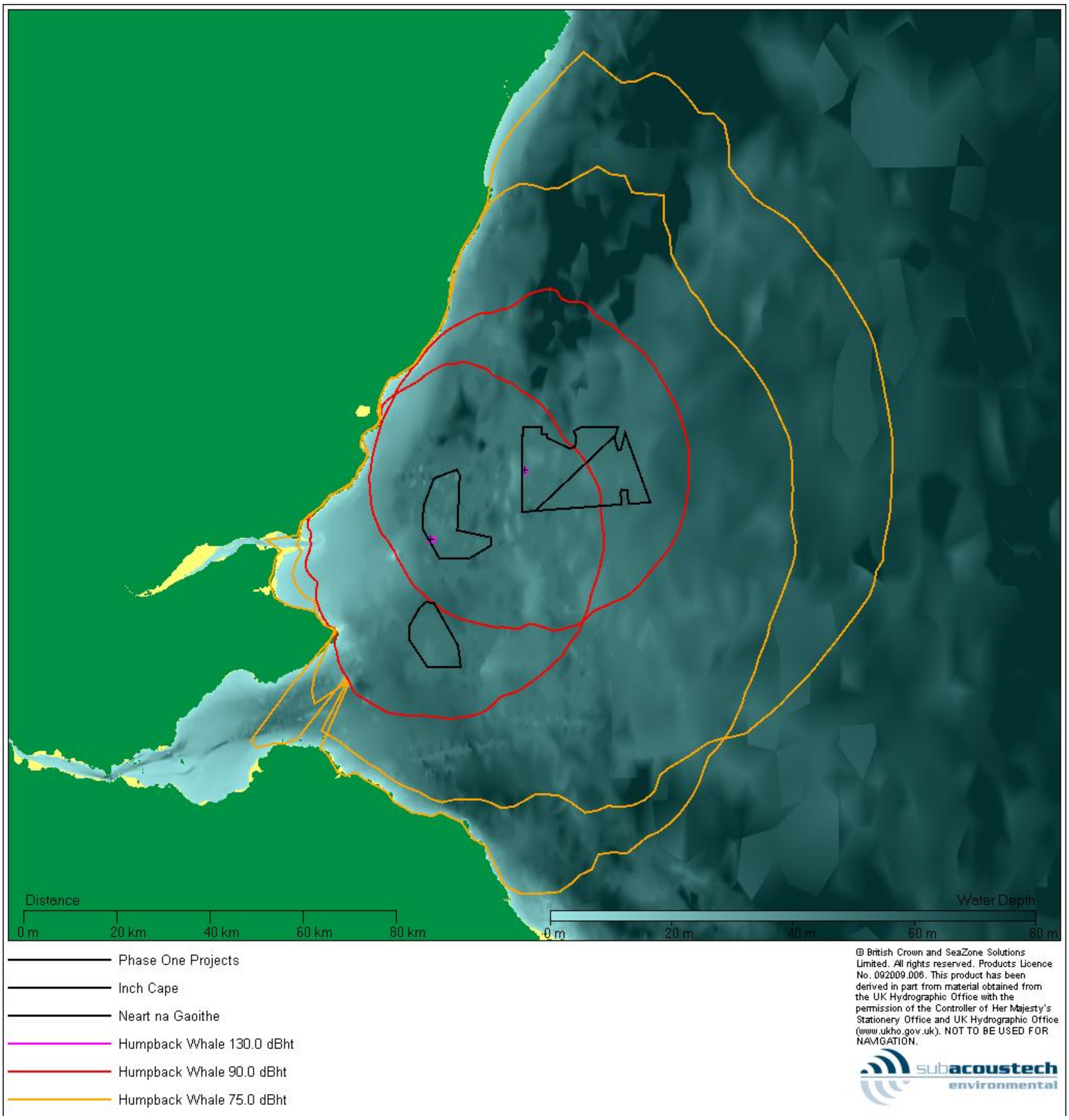

Figure 6-117 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Humpback Whale for the GM3 (alpha) and Inch Cape scenarios

6.4.1.14 Multiple Locations - GM3 (alpha) and NNG

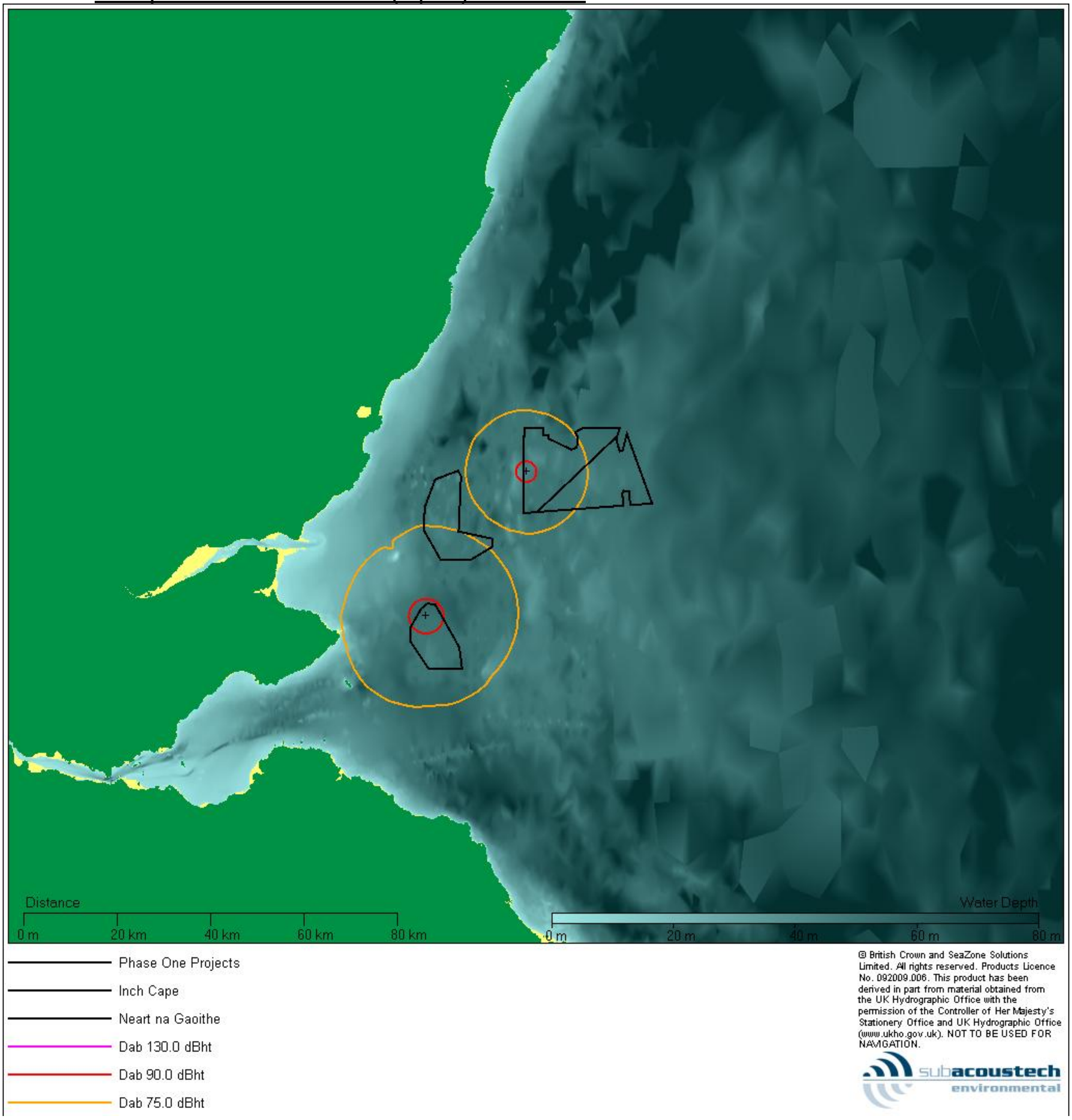

Figure 6-118 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM3 (alpha) and NNG scenarios

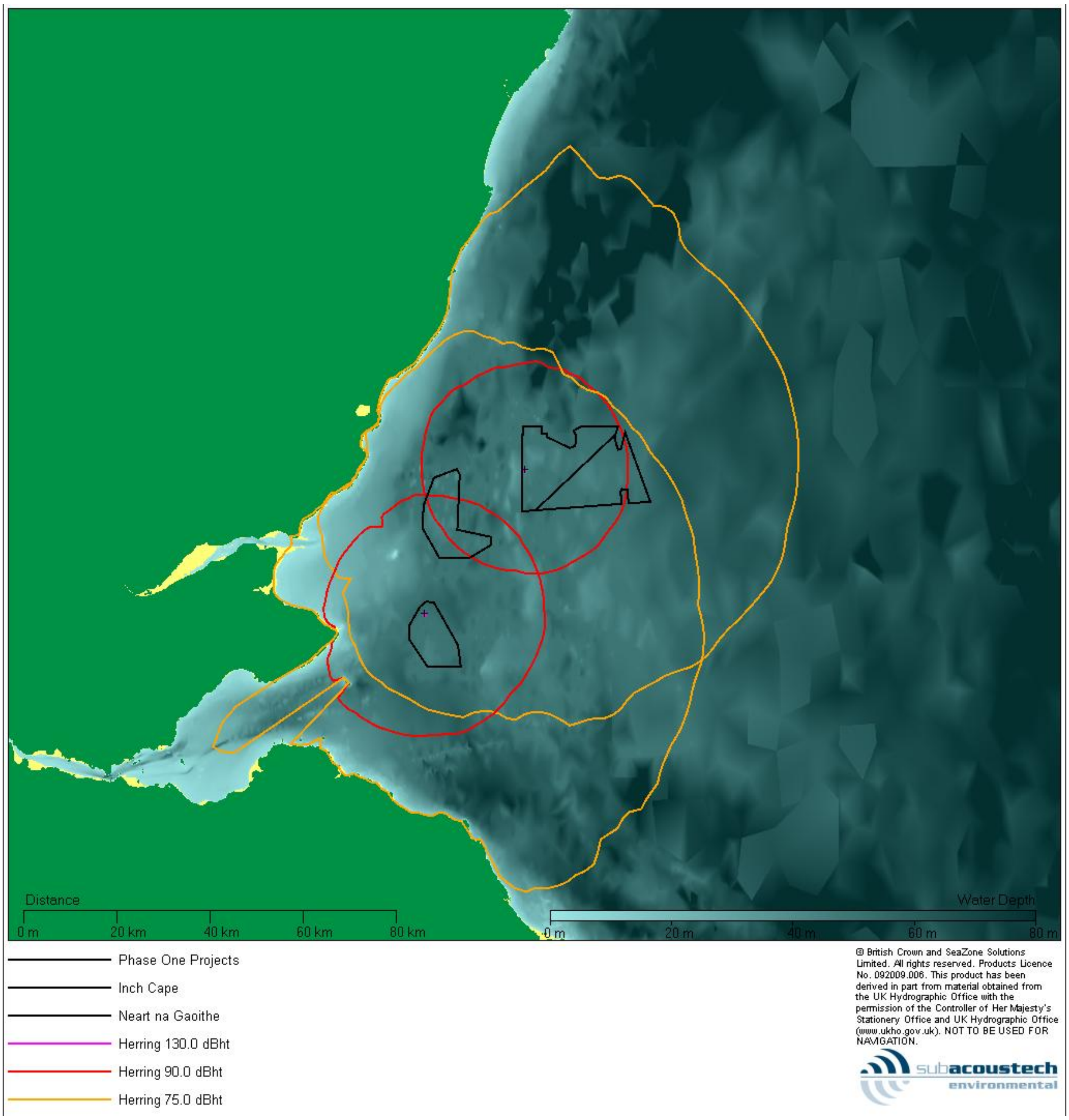

Figure 6-119 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the GM3 (alpha) and NNG scenarios

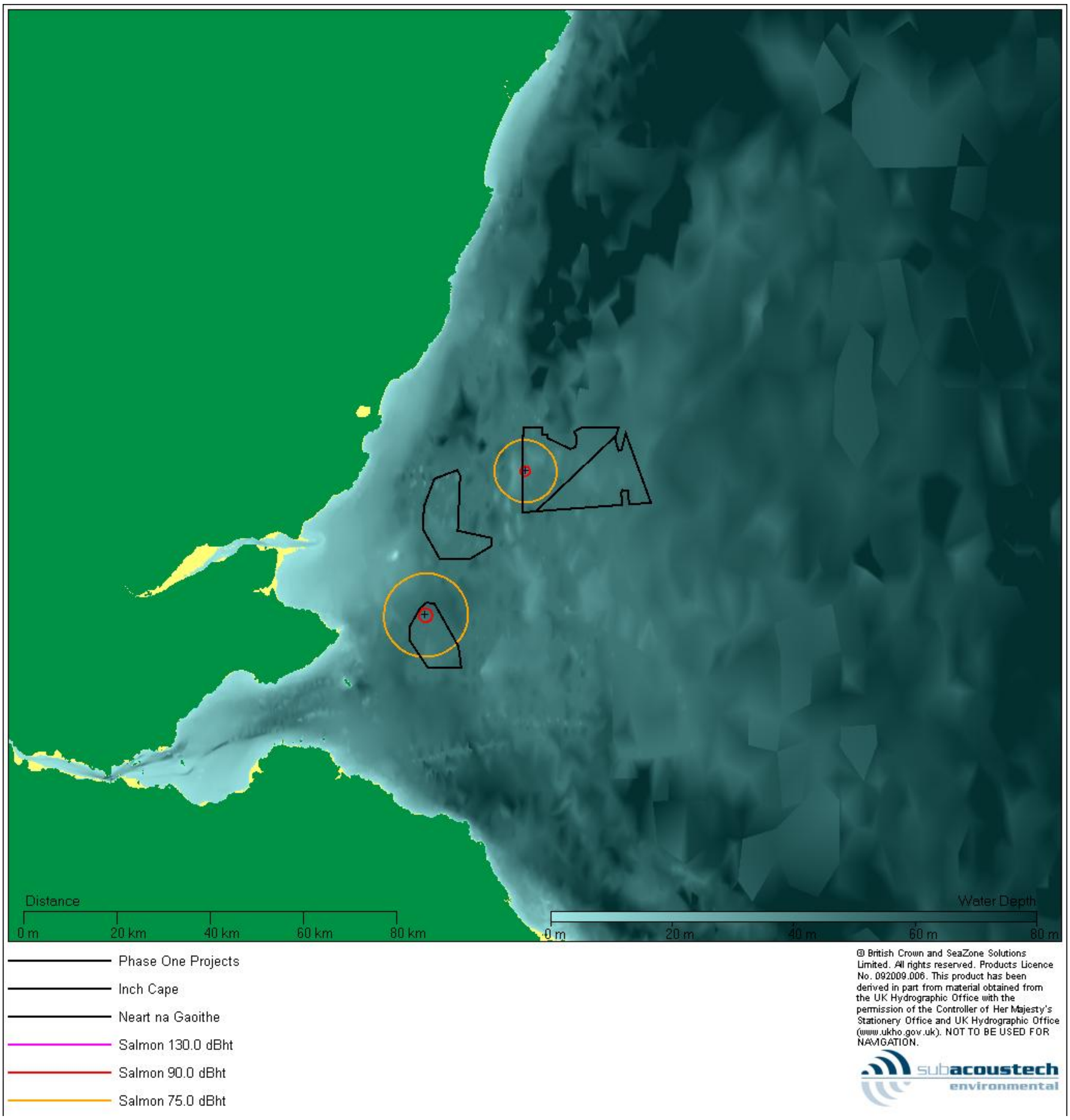

Figure 6-120 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the GM3 (alpha) and NNG scenarios

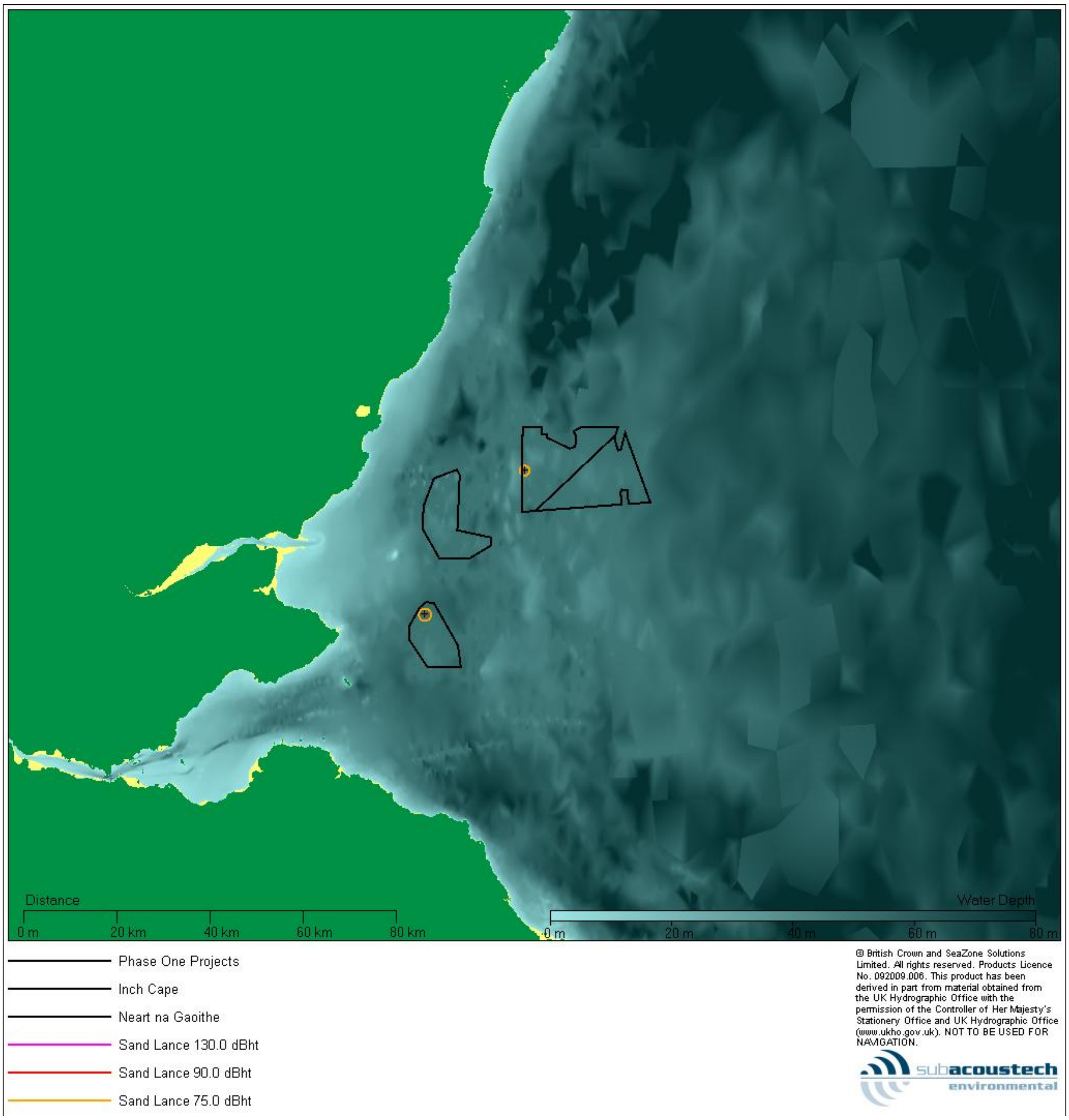

Figure 6-121 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Sand Lance for the GM3 (alpha) and NNG scenarios

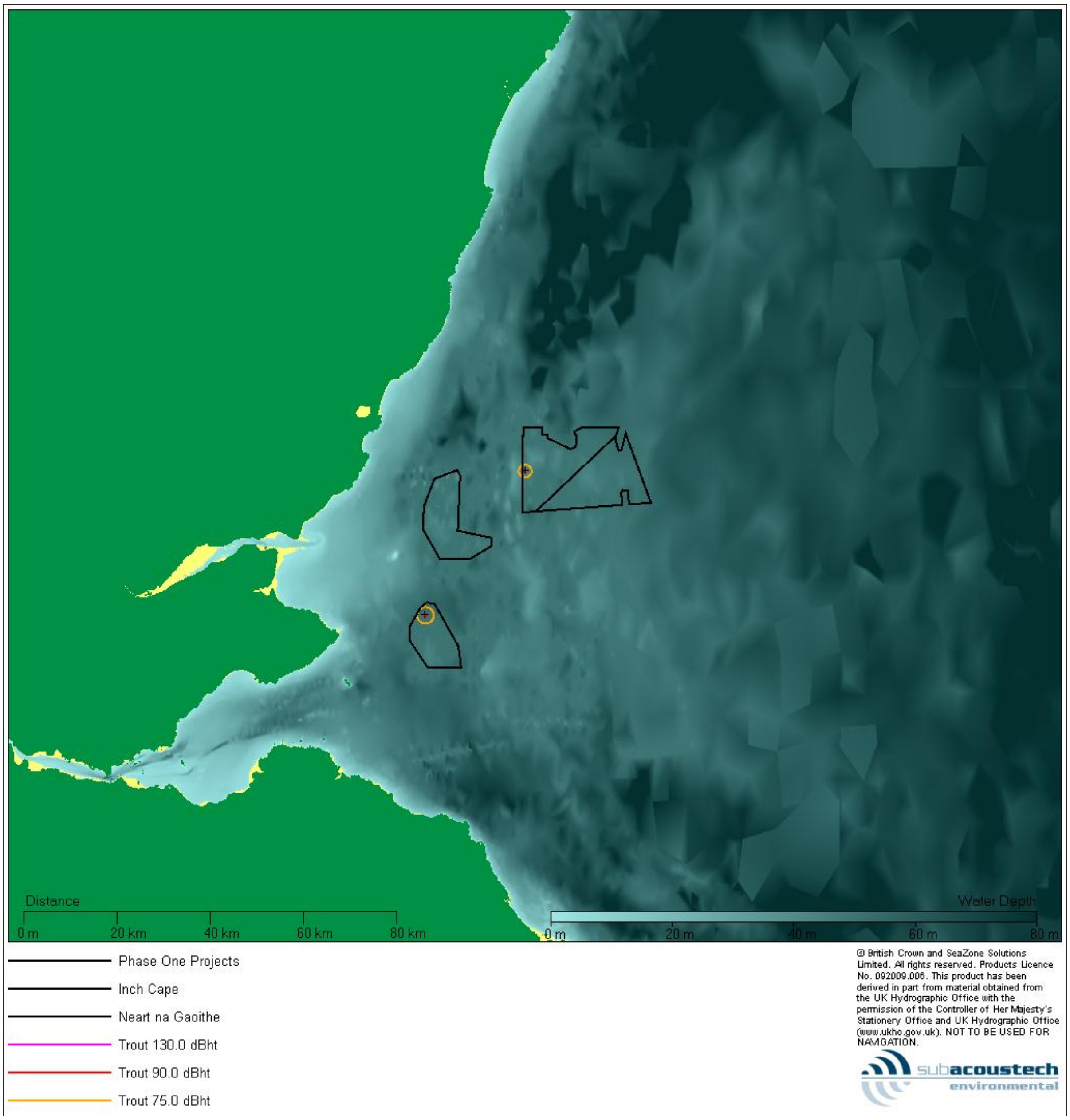

Figure 6-122 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the GM3 (alpha) and NNG scenarios

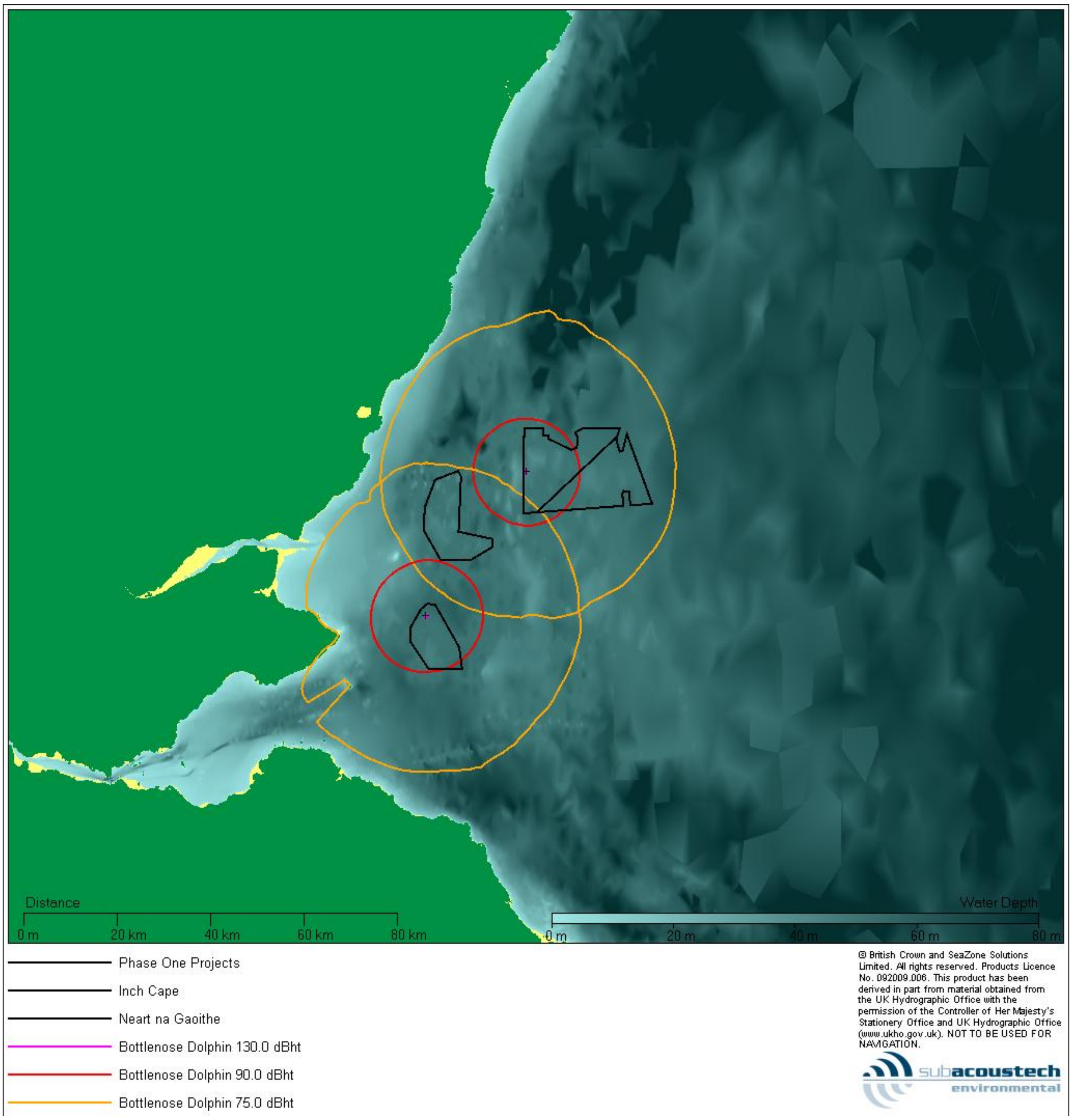

Figure 6-123 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the GM3 (alpha) and NNG scenarios

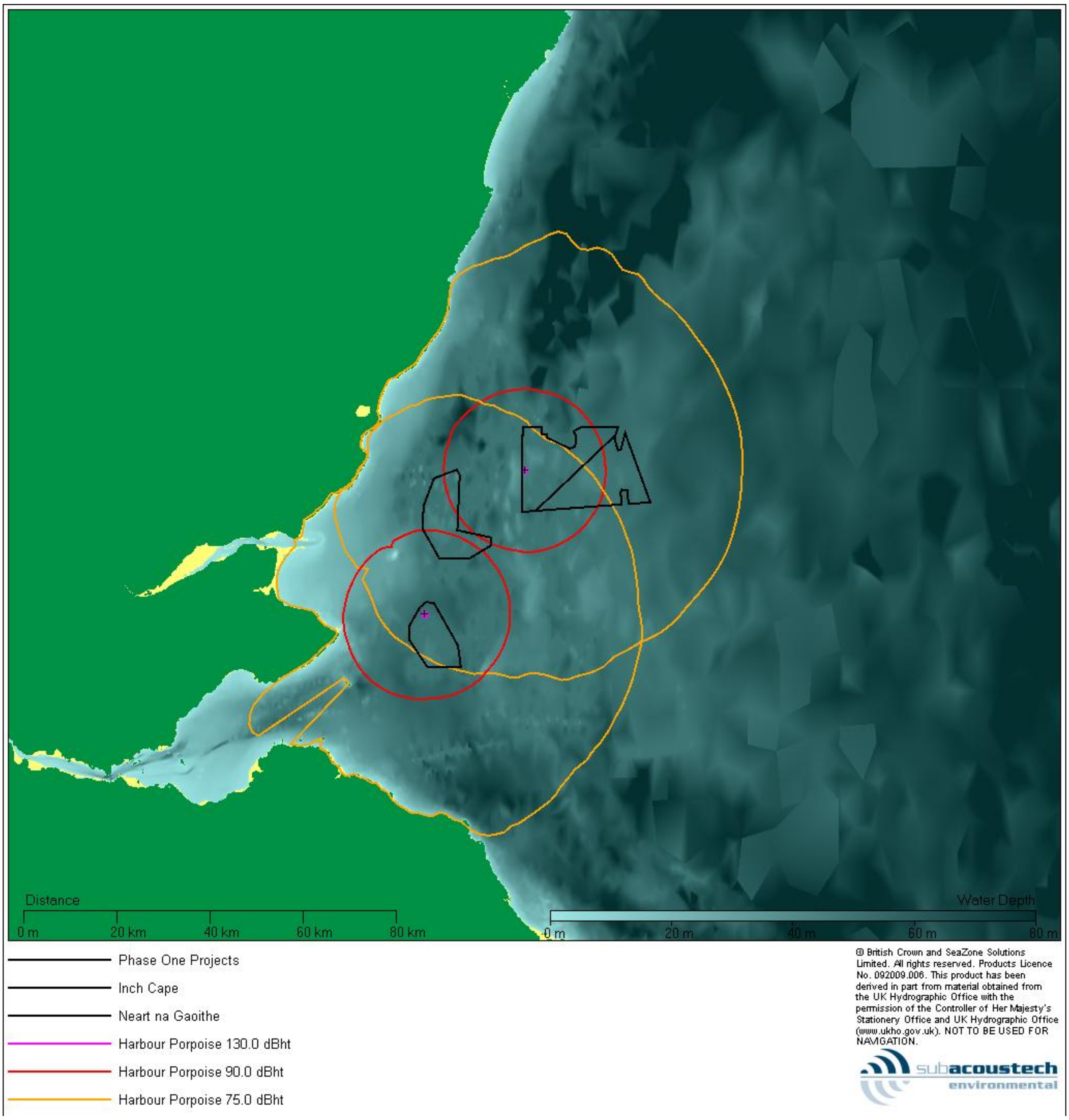

Figure 6-124 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM3 (alpha) and NNG scenarios

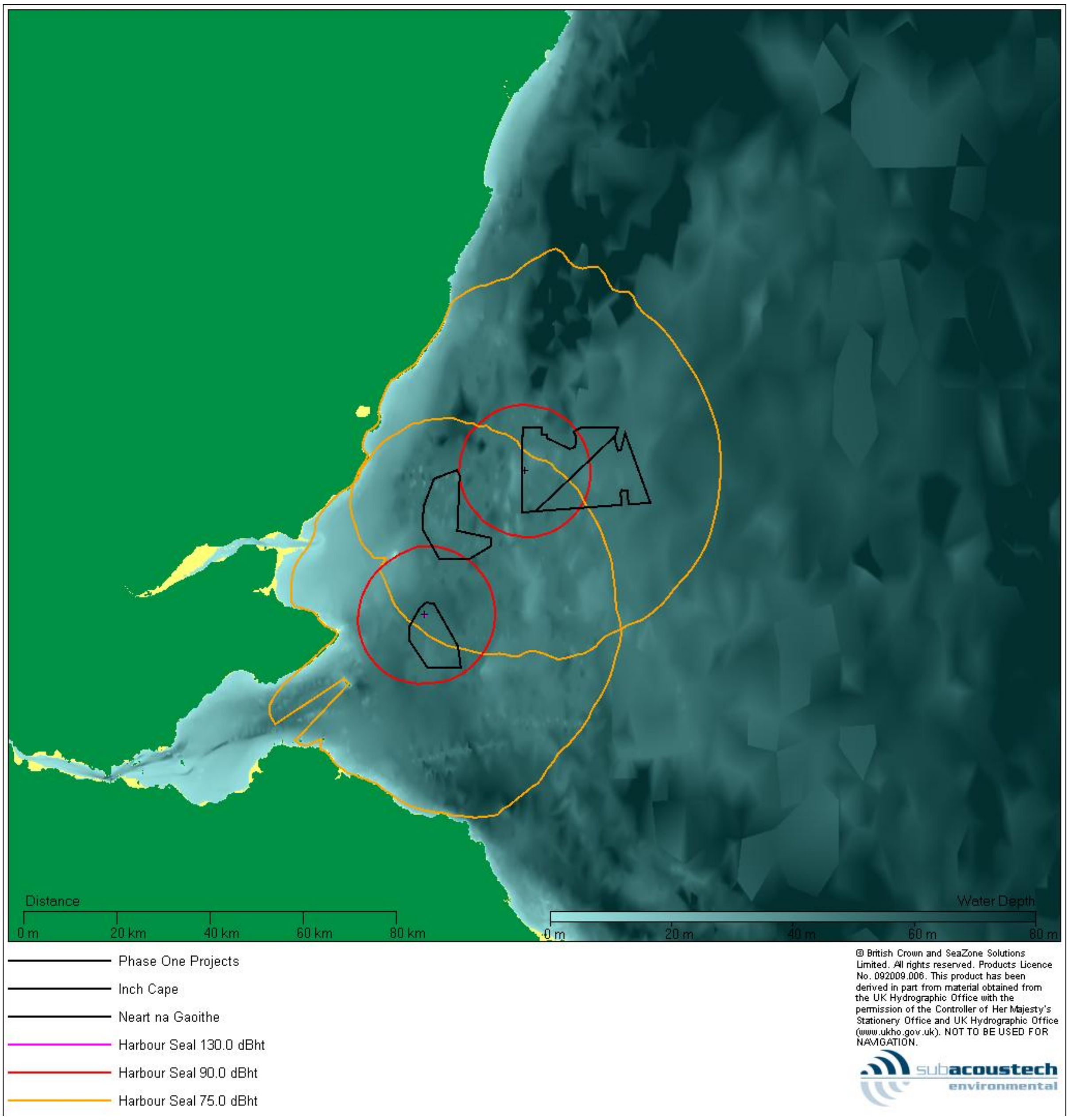

Figure 6-125 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM3 (alpha) and NNG scenarios

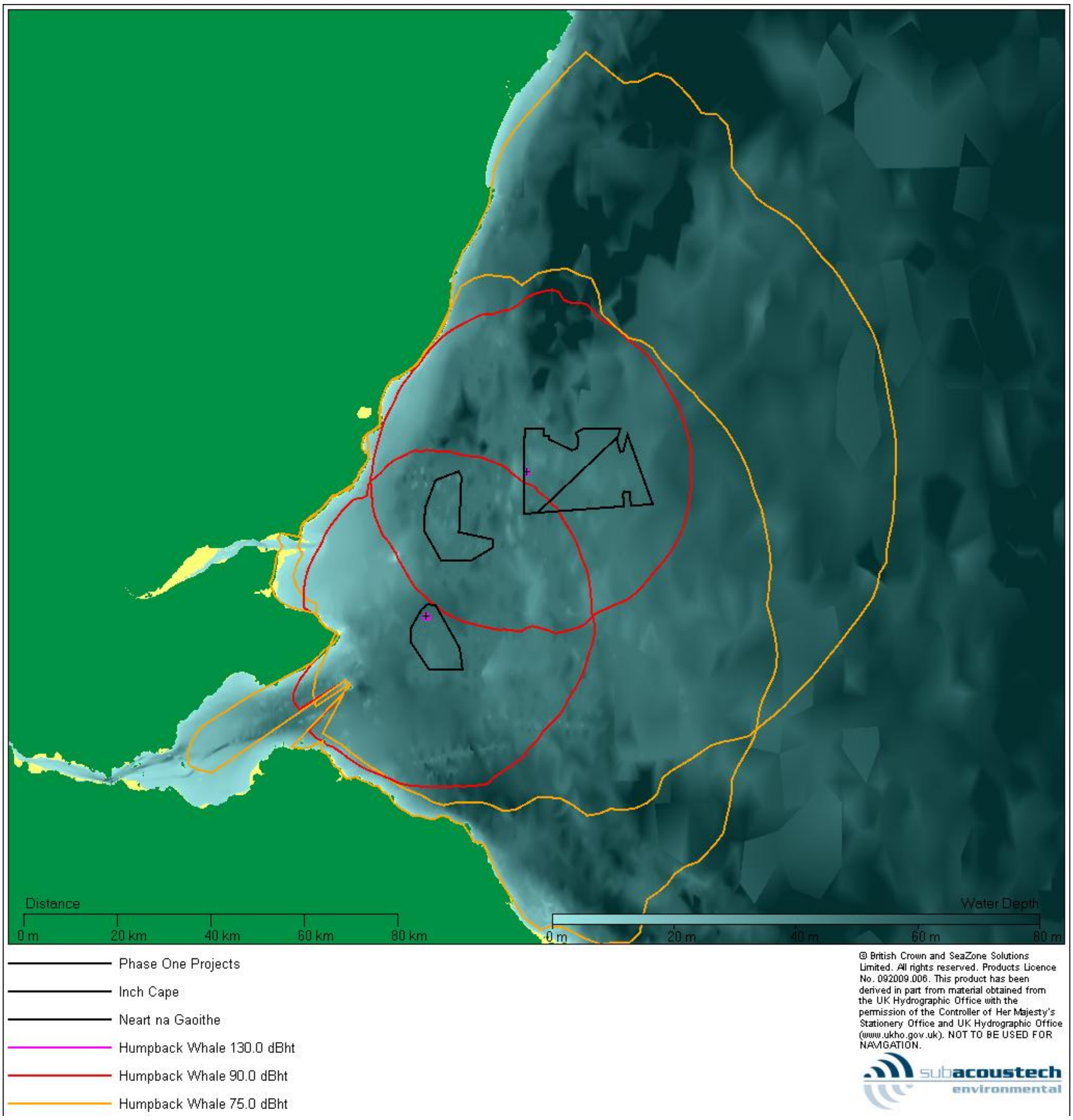

Figure 6-126 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the GM3 (alpha) and NNG scenarios

6.4.1.15 GM3 (alpha), Inch Cape and NNG

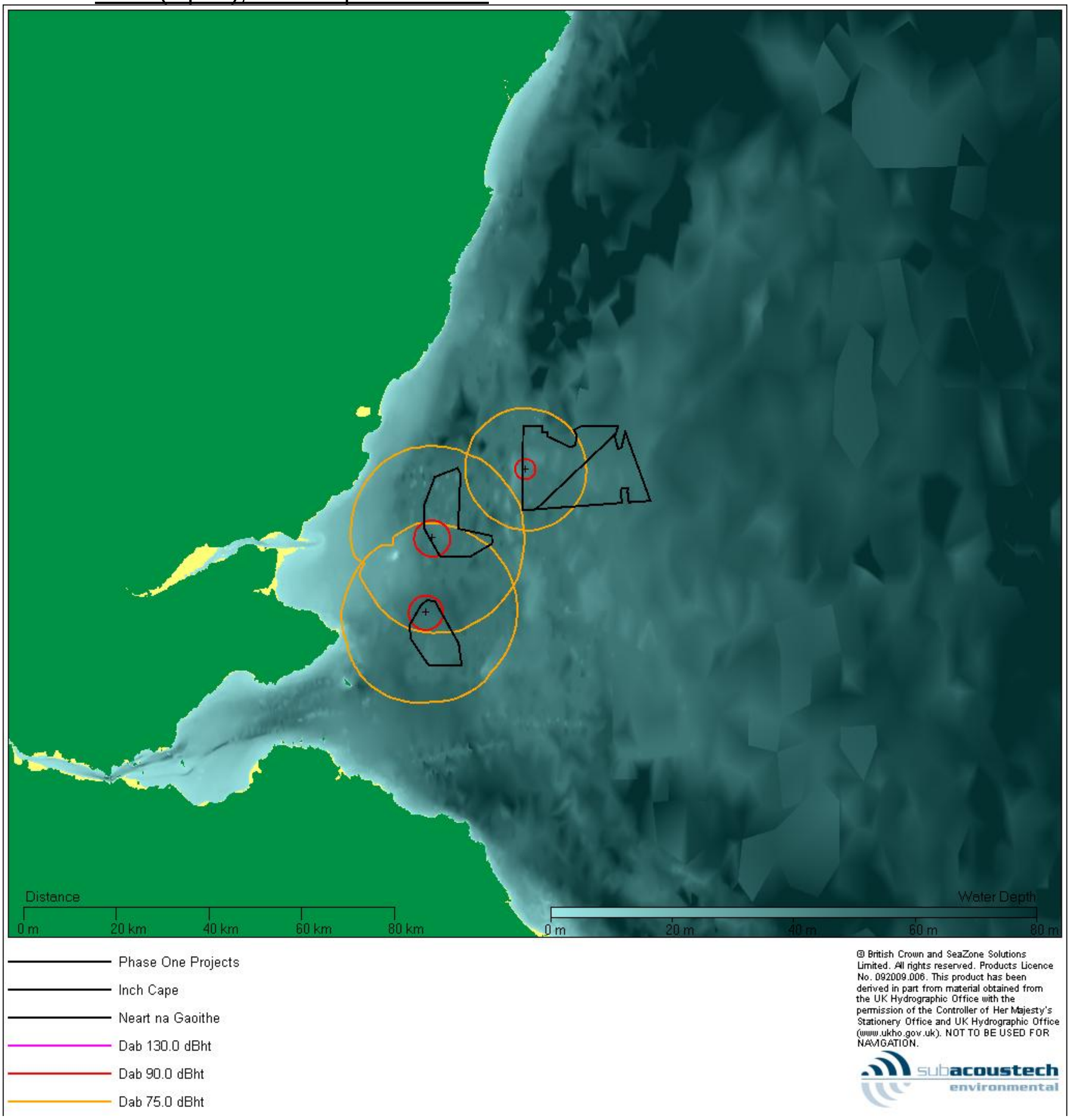

Figure 6-127 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Dab for the GM3 (alpha), Inch Cape and NNG scenarios

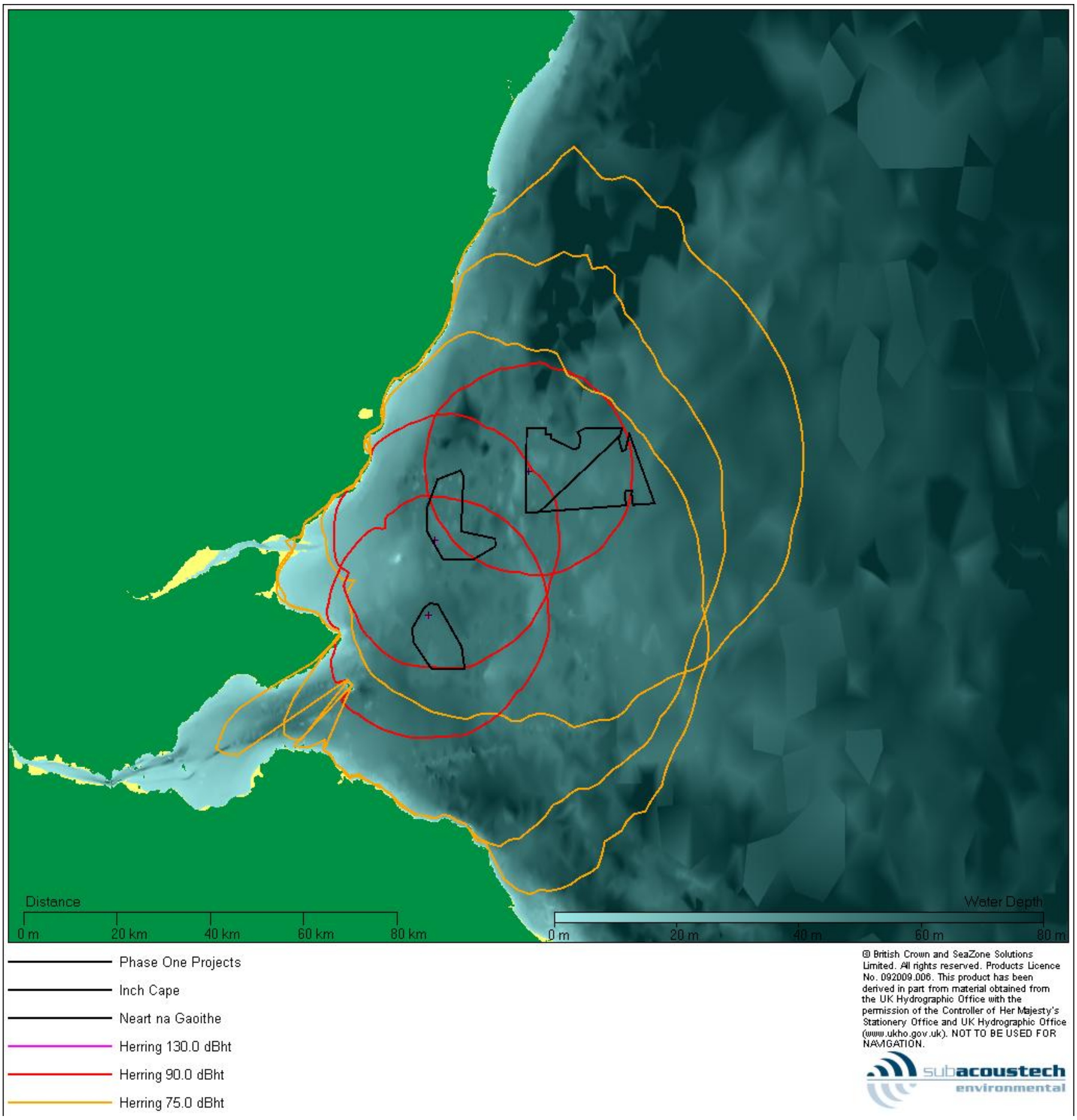

Figure 6-128 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Herring for the GM3 (alpha), Inch Cape and NNG scenarios

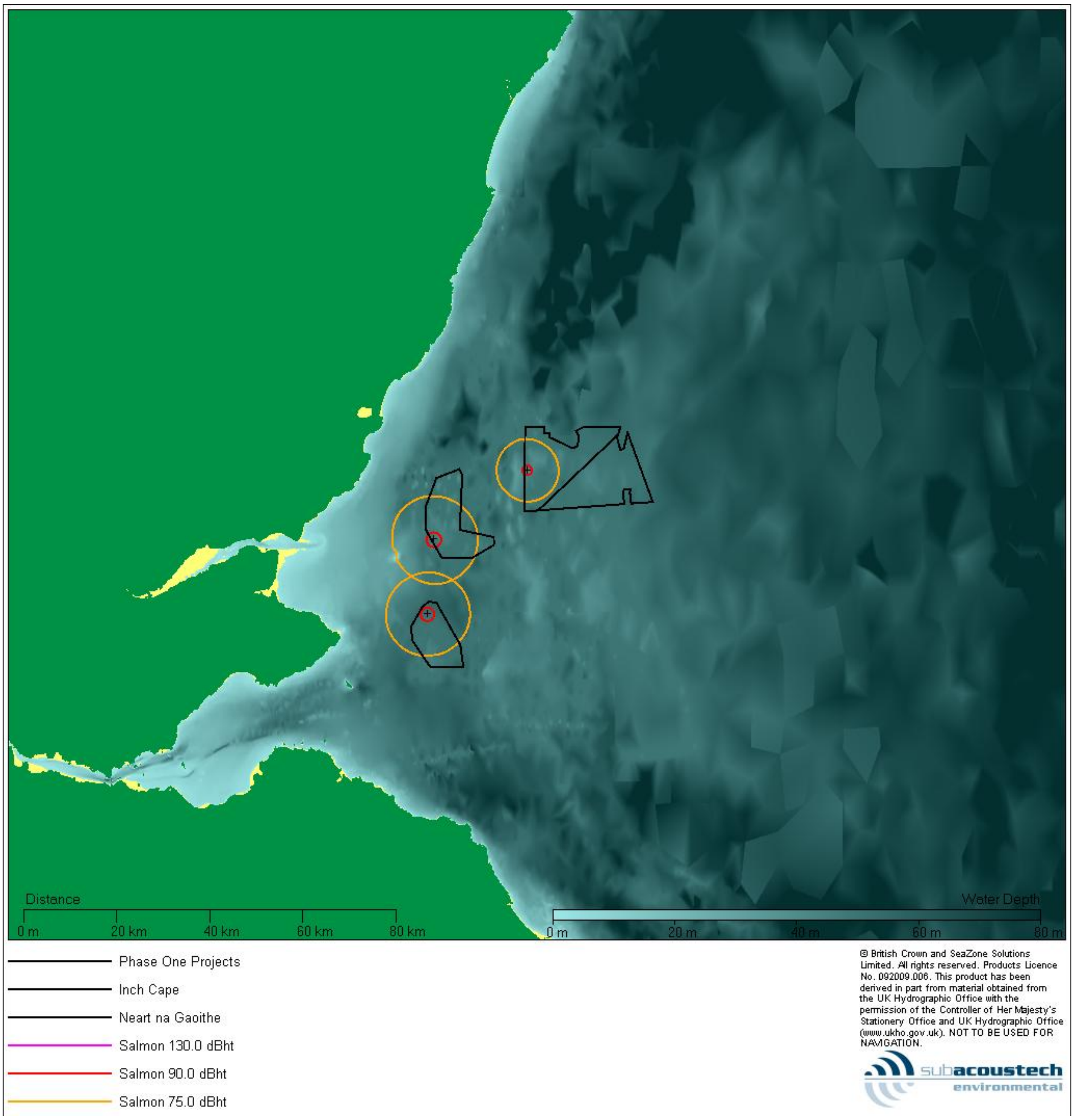

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Figure 6-129 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Salmon for the GM3 (alpha), Inch Cape and NNG scenarios

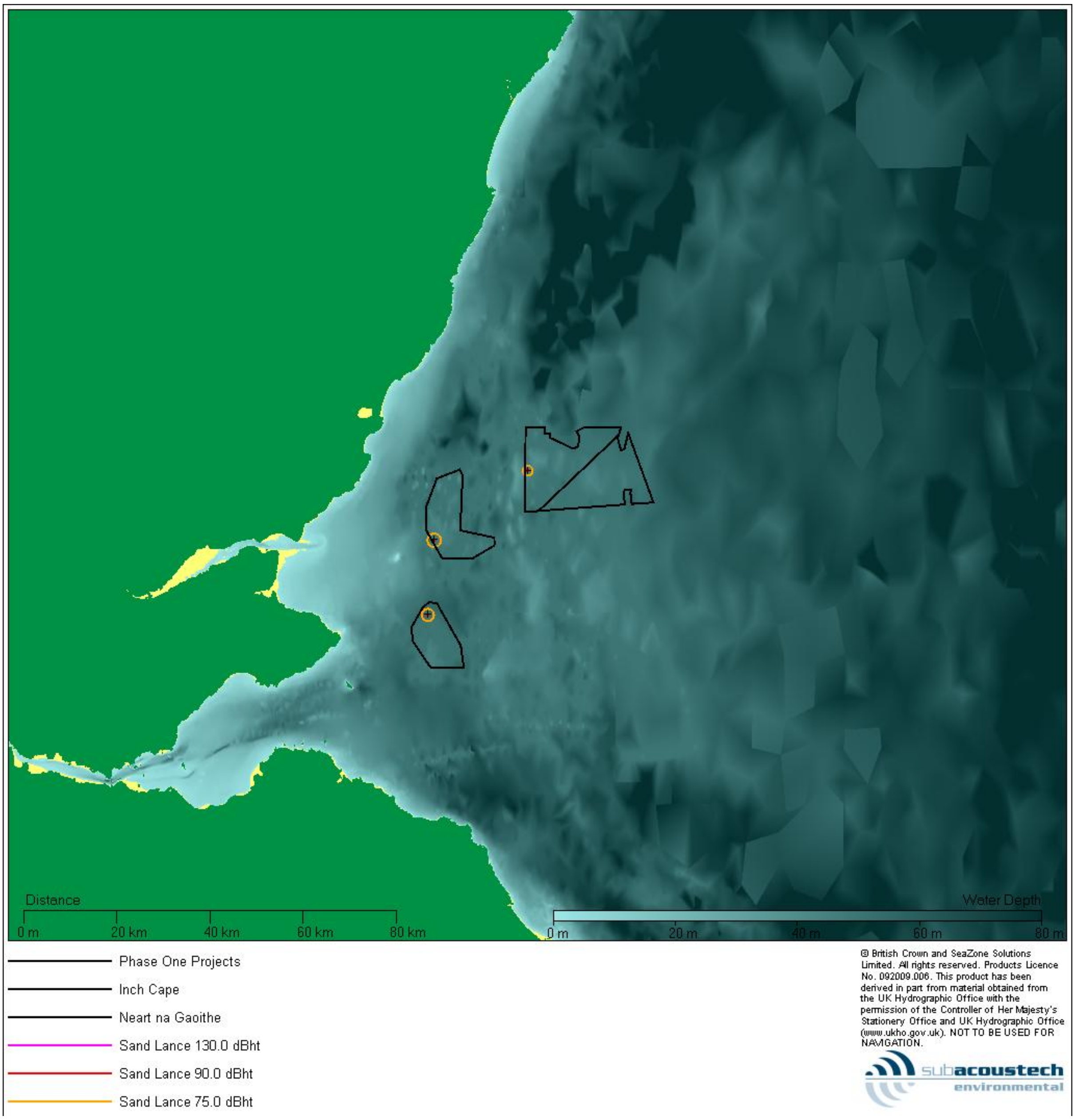

Figure 6-130 Contour plot showing the estimated 130, 90 and 75 dB_{ht} peak to peak impact ranges for Sand Lance for the GM3 (alpha), Inch Cape and NNG scenarios

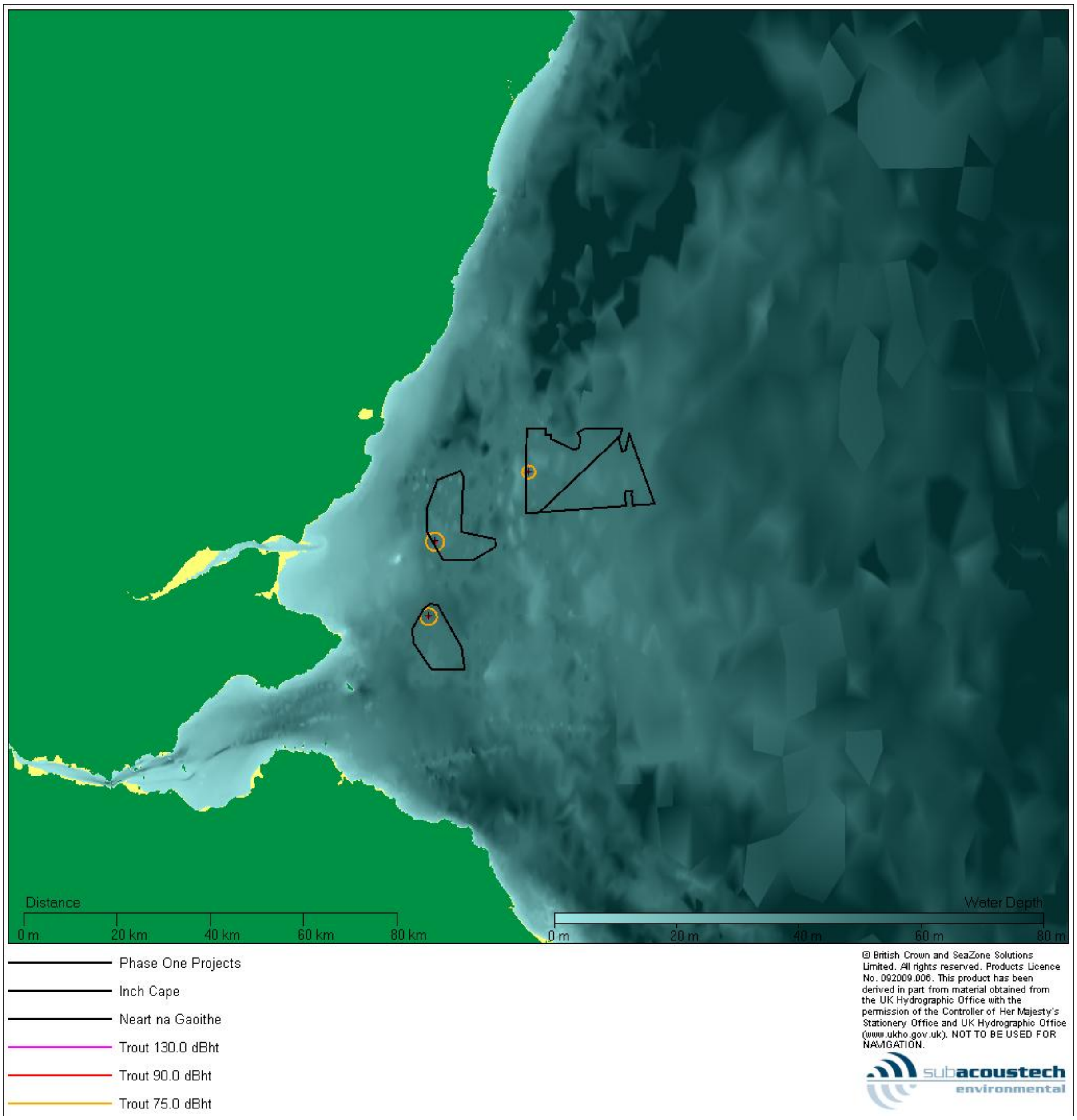

Figure 6-131 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Trout for the GM3 (alpha), Inch Cape and NNG scenarios

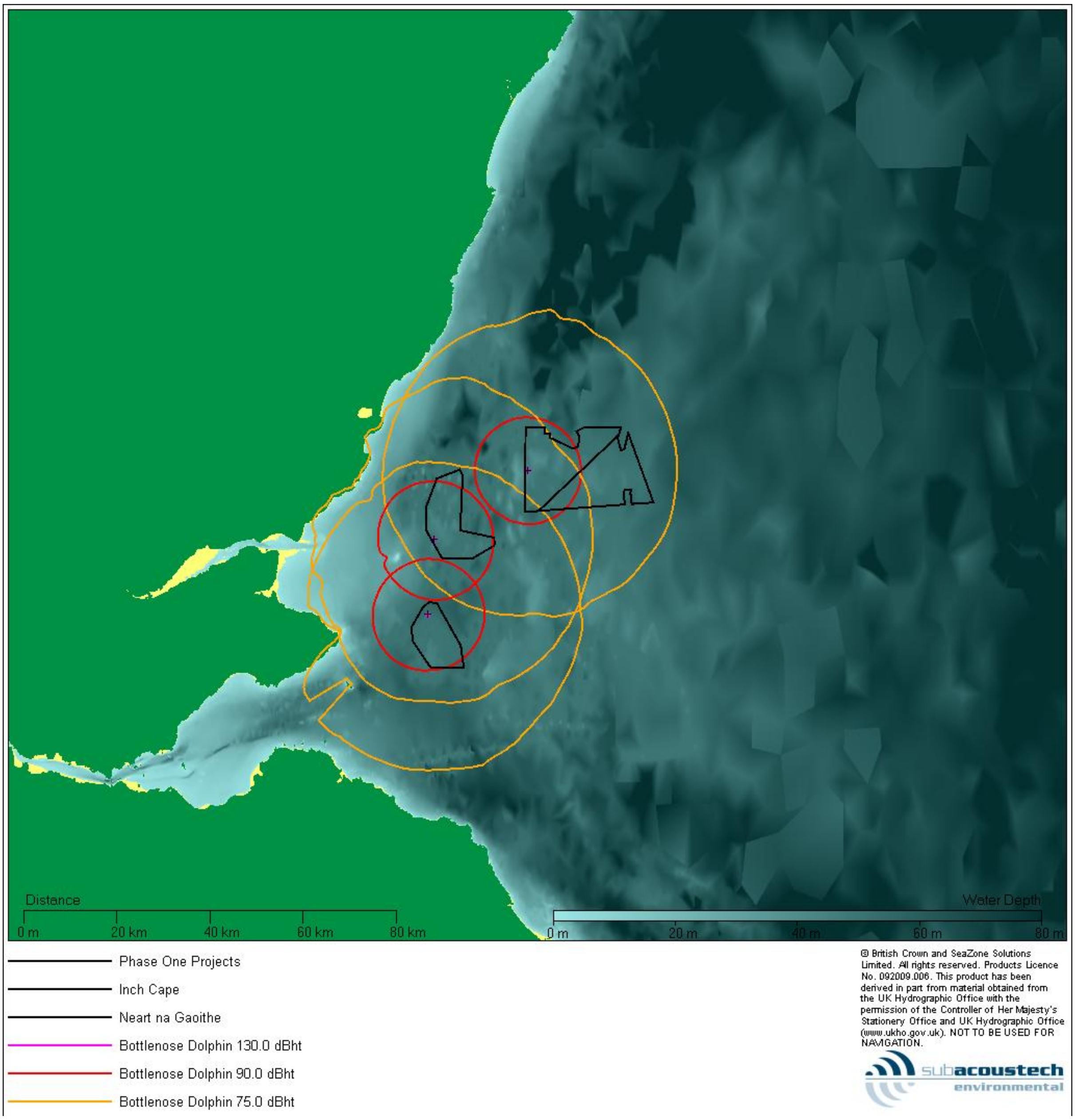

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Figure 6-132 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Bottlenose Dolphin for the GM3 (alpha), Inch Cape and NNG scenarios

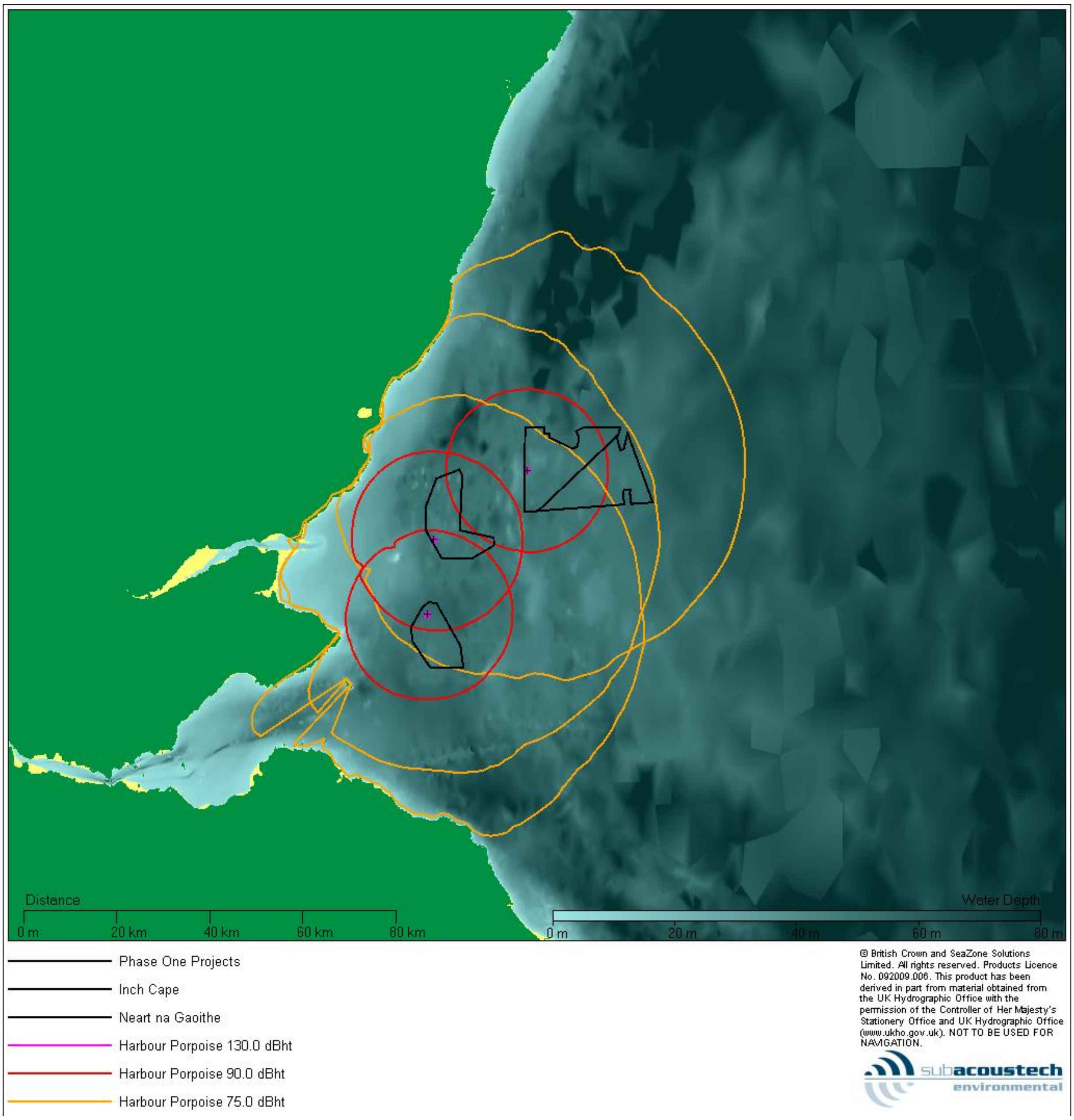

Figure 6-133 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Porpoise for the GM3 (alpha), Inch Cape and NNG scenarios

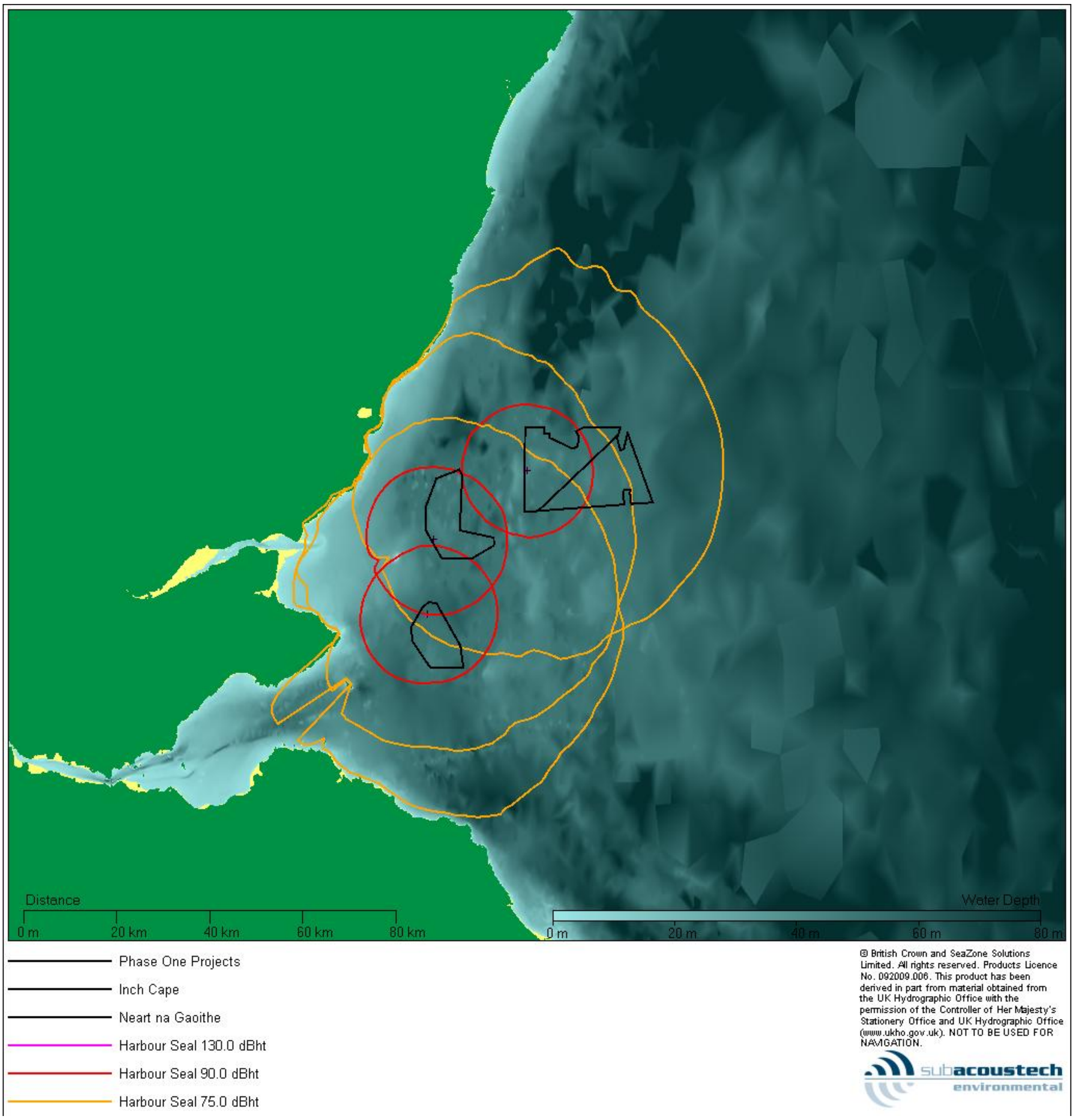

Figure 6-134 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Harbour Seal for the GM3 (alpha), Inch Cape and NNG scenarios

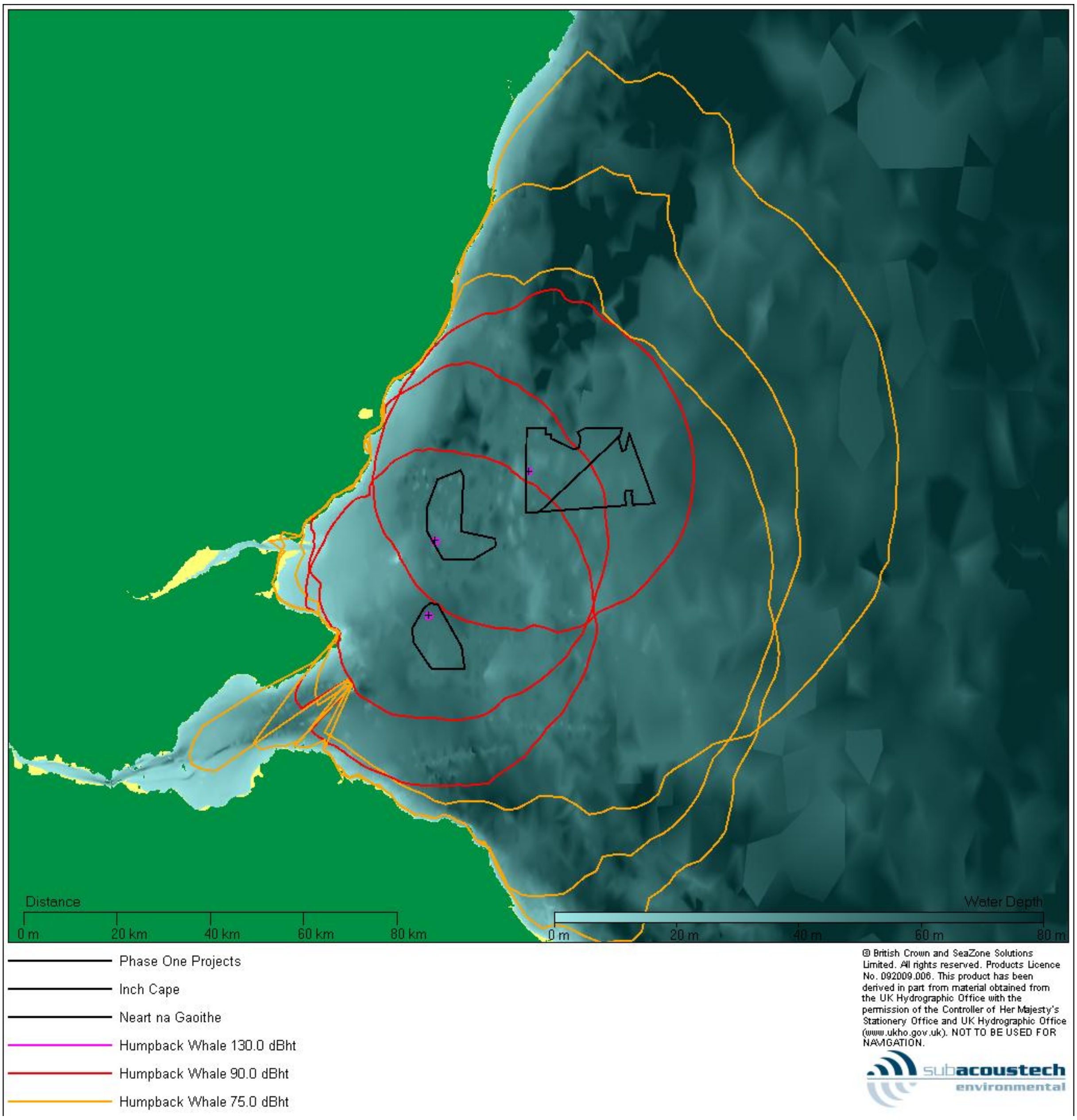

Figure 6-135 Contour plot showing the estimated 130, 90 and 75 dB$_{ht}$ peak to peak impact ranges for Humpback Whale for the GM3 (alpha), Inch Cape and NNG scenarios

6.5 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 6-19 to 6-34 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. For piling operations at a single location a maximum range of 9.2 km is likely to be needed at the onset of the impact piling for the GM1 (bravo) scenario to avoid a damaging exposure to sound using the Southall criteria.

The maximum range for a cumulative scenario of GM1 (alpha), Inch Cape and NNG, is seen to be 31 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. The sea area affected under these conditions is considered to be negligible and defined as “n/a” in the tables below.

GM1 (alpha)	**Range to auditory injury criteria**			**Sea area**
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{lf}$))	200 m	200 m	200 m	~0.1 km^2
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{mf}$))	<100 m	<100 m	<100 m	<0.05 km^2
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{hf}$))	<100 m	<100 m	<100 m	<0.05 km^2
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M$_{pw}$))	9100 m	6500 m	8800 m	240 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M$_{pw}$))	200 m	200 m	200 m	~0.1 km^2

Table 6-29 Summary of the ranges out to which auditory injury is predicted during the GM1 (alpha) scenario for a fleeing animal using the M-Weighted SEL criteria

GM1 (bravo)	**Range to auditory injury criteria**			**Sea area**
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{lf}$))	200 m	200 m	200 m	~0.1 km^2
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{mf}$))	<100 m	<100 m	<100 m	<0.05 km^2
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{hf}$))	<100 m	<100 m	<100 m	<0.05 km^2
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M$_{pw}$))	9200 m	8800 m	9000 m	250 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M$_{pw}$))	200 m	200 m	200 m	~0.1 km^2

Table 6-30 Summary of the ranges out to which auditory injury is predicted during the GM1 (bravo) scenario for a fleeing animal using the M-Weighted SEL criteria

GM2 (alpha)	**Range to auditory injury criteria**			**Sea area**
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{lf})	300 m	300 m	300 m	0.3 km^2
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{mf})	<100 m	<100 m	<100 m	<0.05 km^2
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{hf})	<100 m	<100 m	<100 m	<0.05 km^2
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M_{pw})	7600 m	7200 m	7400 m	175 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	300 m	300 m	300 m	0.3 km^2

Table 6-31 Summary of the ranges out to which auditory injury is predicted during the GM2 (alpha) scenario for a fleeing animal using the M-Weighted SEL criteria

GM2 (bravo)	**Range to auditory injury criteria**			**Sea area**
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{lf})	300 m	300 m	300 m	0.3 km^2
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{mf})	<100 m	<100 m	<100 m	<0.05 km^2
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{hf})	<100 m	<100 m	<100 m	<0.05 km^2
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M_{pw})	7700 m	7500 m	7600 m	180 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	300 m	300 m	300 m	0.3 km^2

Table 6-32 Summary of the ranges out to which auditory injury is predicted during the GM2 (bravo) scenario for a fleeing animal using the M-Weighted SEL criteria

GM3 (alpha)	**Range to auditory injury criteria**			**Sea area**
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{lf})	<100 m	<100 m	<100 m	<0.05 km^2
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{mf})	<100 m	<100 m	<100 m	<0.05 km^2
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{hf})	<100 m	<100 m	<100 m	<0.05 km^2
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M_{pw})	4300 m	4100 m	4200 m	55 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	<100 m	<100 m	<100 m	<0.05 km^2

Table 6-33 Summary of the ranges out to which auditory injury is predicted during the GM3 (alpha) scenario for a fleeing animal using the M-Weighted SEL criteria

GM3 (bravo)	**Range to auditory injury criteria**			**Sea area**
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{lf})	<100 m	<100 m	<100 m	<0.05 km^2
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{mf})	<100 m	<100 m	<100 m	<0.05 km^2
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{hf})	<100 m	<100 m	<100 m	<0.05 km^2
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M_{pw})	4300 m	4200 m	4300 m	55 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	<100 m	<100 m	<100 m	<0.05 km^2

Table 6-34 Summary of the ranges out to which auditory injury is predicted during the GM3 (bravo) scenario for a fleeing animal using the M-Weighted SEL criteria

GM4 (alpha)	**Range to auditory injury criteria**			**Sea area**
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{lf})	<100 m	<100 m	<100 m	<0.05 km^2
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{mf})	<100 m	<100 m	<100 m	<0.05 km^2
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{hf})	<100 m	<100 m	<100 m	<0.05 km^2
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M_{pw})	4600 m	4300 m	4500 m	60 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	<100 m	<100 m	<100 m	<0.05 km^2

Table 6-35 Summary of the ranges out to which auditory injury is predicted during the GM4 (alpha) scenario for a fleeing animal using the M-Weighted SEL criteria

GM4 (bravo)	**Range to auditory injury criteria**			**Sea area**
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{lf})	<100 m	<100 m	<100 m	<0.05 km^2
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{mf})	<100 m	<100 m	<100 m	<0.05 km^2
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{hf})	<100 m	<100 m	<100 m	<0.05 km^2
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M_{pw})	4600 m	4500 m	4500 m	60 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	<100 m	<100 m	<100 m	<0.05 km^2

Table 6-36 Summary of the ranges out to which auditory injury is predicted during the GM4 (bravo) scenario for a fleeing animal using the M-Weighted SEL criteria

Inch Cape	**Range to auditory injury criteria**			**Sea area**
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{lf})	400 m	300 m	350 m	0.4 km^2
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{mf})	<100 m	<100 m	<100 m	<0.05 km^2
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{hf})	<100 m	<100 m	<100 m	<0.05 km^2
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M_{pw})	15100 m	9200 m	13300m	560 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	400 m	400 m	400 m	0.5 km^2

Table 6-37 ***Summary of the ranges out to which auditory injury is predicted during the Inch Cape cumulative scenario for a fleeing animal using the M-Weighted SEL criteria***

NNG	**Range to auditory injury criteria**			**Sea area**
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{lf})	<100 m	<100 m	<100 m	<0.05 km^2
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{mf})	<100 m	<100 m	<100 m	<0.05 km^2
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{hf})	<100 m	<100 m	<100 m	<0.05 km^2
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M_{pw})	8400 m	6800 m	7900 m	200 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	<100 m	<100 m	<100 m	<0.05 km^2

Table 6-38 ***Summary of the ranges out to which auditory injury is predicted during the NNG cumulative scenario for a fleeing animal using the M-Weighted SEL criteria***

GM1 (alpha) and GM1 (bravo)	**Range to auditory injury criteria**			**Sea area**
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{lf})	<100 m	<100 m	<100 m	<0.05 km^2
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{mf})	<100 m	<100 m	<100 m	<0.05 km^2
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{hf})	<100 m	<100 m	<100 m	<0.05 km^2
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M_{pw})	16200 m	12600 m	14400 m	660 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	<100 m	<100 m	<100 m	<0.05 km^2

Table 6-39 Summary of the ranges out to which auditory injury is predicted during the GM1 (alpha) and GM1 (bravo) cumulative scenario for a fleeing animal using the M-Weighted SEL criteria

GM1 (alpha) and Inch Cape	**Range to auditory injury criteria**			**Sea area**
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{lf})	12900 m	<100 m	1000 m	n/a
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{mf})	12600 m	<100 m	500 m	n/a
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{hf})	12500 m	<100 m	500 m	n/a
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M_{pw})	25700 m	13100 m	18600m	1100 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	12900 m	<100 m	1000 m	n/a

Table 6-40 Summary of the ranges out to which auditory injury is predicted during the GM1 (alpha) and Inch Cape cumulative scenario for a fleeing animal using the M-Weighted SEL criteria

GM1 (alpha) and NNG	**Range to auditory injury criteria**			**Sea area**
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{lf})	17700 m	<100 m	300 m	n/a
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{mf})	8100 m	<100 m	150 m	n/a
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M_{hf})	7900 m	<100 m	150 m	n/a
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M_{pw})	27300 m	<100 m	6400 m	n/a
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M_{pw})	17800 m	<100 m	300 m	n/a

Table 6-41 Summary of the ranges out to which auditory injury is predicted during the GM1 (alpha) and NNG cumulative scenario for a fleeing animal using the M-Weighted SEL criteria

GM1 (alpha), Inch Cape and NNG	Range to auditory injury criteria			Sea area
	Max	Min	Mean	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{lf}$)	17600 m	<100 m	1000 m	n/a
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{mf}$)	17600 m	<100 m	400 m	n/a
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{hf}$)	17600 m	<100 m	400 m	n/a
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M$_{pw}$)	30700 m	14000 m	21600 m	1500 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M$_{pw}$)	17600 m	<100 m	1400 m	n/a

Table 6-42 Summary of the ranges out to which auditory injury is predicted during the GM1 (alpha), Inch Cape and NNG cumulative scenario for a fleeing animal using the M-Weighted SEL criteria

GM3 (alpha) and GM3 (bravo)	Range to auditory injury criteria			Sea area
	Max	Min	Mean	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{lf}$)	<100 m	<100 m	<100 m	n/a
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{mf}$)	<100 m	<100 m	<100 m	n/a
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{hf}$)	<100 m	<100 m	<100 m	n/a
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M$_{pw}$)	10800 m	4700 m	7800 m	200 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M$_{pw}$)	<100 m	<100 m	<100 m	n/a

Table 6-43 Summary of the ranges out to which auditory injury is predicted during the GM3 (alpha) and GM3 (bravo) cumulative scenario for a fleeing animal using the M-Weighted SEL criteria

GM3 (alpha) and Inch Cape	Range to auditory injury criteria			Sea area
	Max	Min	Mean	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{lf}$)	12900 m	<100 m	1000 m	n/a
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{mf}$)	12600 m	<100 m	500 m	n/a
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{hf}$)	12500 m	<100 m	500 m	n/a
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M$_{pw}$)	25400 m	8700 m	15600 m	860 km^2
Pinnipeds (in water)	12900 m	<100 m	1000 m	n/a

(198 dB re. 1 μPa^2/s (M$_{pw}$)				

Table 6-44 Summary of the ranges out to which auditory injury is predicted during the GM3 (alpha) and Inch Cape cumulative scenario for a fleeing animal using the M-Weighted SEL criteria

GM3 (alpha) and NNG	Range to auditory injury criteria			Sea area
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{lf}$)	17700 m	<100 m	300 m	n/a
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{mf}$)	8100 m	<100 m	150 m	n/a
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{hf}$)	7900 m	<100 m	150 m	n/a
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M$_{pw}$)	27200 m	<100 m	6000 m	n/a
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M$_{pw}$)	17800 m	<100 m	300 m	n/a

Table 6-45 Summary of the ranges out to which auditory injury is predicted during the GM3 (alpha) and NNG cumulative scenario for a fleeing animal using the M-Weighted SEL criteria

GM3 (alpha), Inch Cape and NNG	Range to auditory injury criteria			Sea area
	Max	**Min**	**Mean**	
Low Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{lf}$)	17600 m	<100 m	1100 m	n/a
Mid Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{mf}$)	17600 m	<100 m	400 m	n/a
High Frequency Cetacean (198 dB re. 1 μPa^2/s (M$_{hf}$)	17600 m	<100 m	400 m	n/a
Pinnipeds (in water) (186 dB re. 1 μPa^2/s (M$_{pw}$)	28600 m	11600 m	19300 m	1250 km^2
Pinnipeds (in water) (198 dB re. 1 μPa^2/s (M$_{pw}$)	17600 m	<100 m	1300 m	n/a

Table 6-46 Summary of the ranges out to which auditory injury is predicted during the GM3 (alpha), Inch Cape and NNG cumulative scenario for a fleeing animal using the M-Weighted SEL criteria

Figures 6-136 and 6-163 show contour plots for marine mammals, for each scenario modelled. The contours represent the modelled starting ranges for a fleeing animal to receive a level of 198 dB or 186 dB re 1 μPa^2/s (M$_{pw}$) over the total installation time of the pile.

All SEL calculations assume the animal starts from the position of and flees from the source of noise where a single piling location is considered. Where multiple piling locations are considered, the calculations assume that the animal starts from the central position in between the two or three piling locations and flees in a straight line from this position.

Not all contour plots for each species and scenario are presented as they are too small to display on a figure at this scale.

6.5.1 FIGURES

6.5.1.1 Single location pinniped multiple pulse SEL

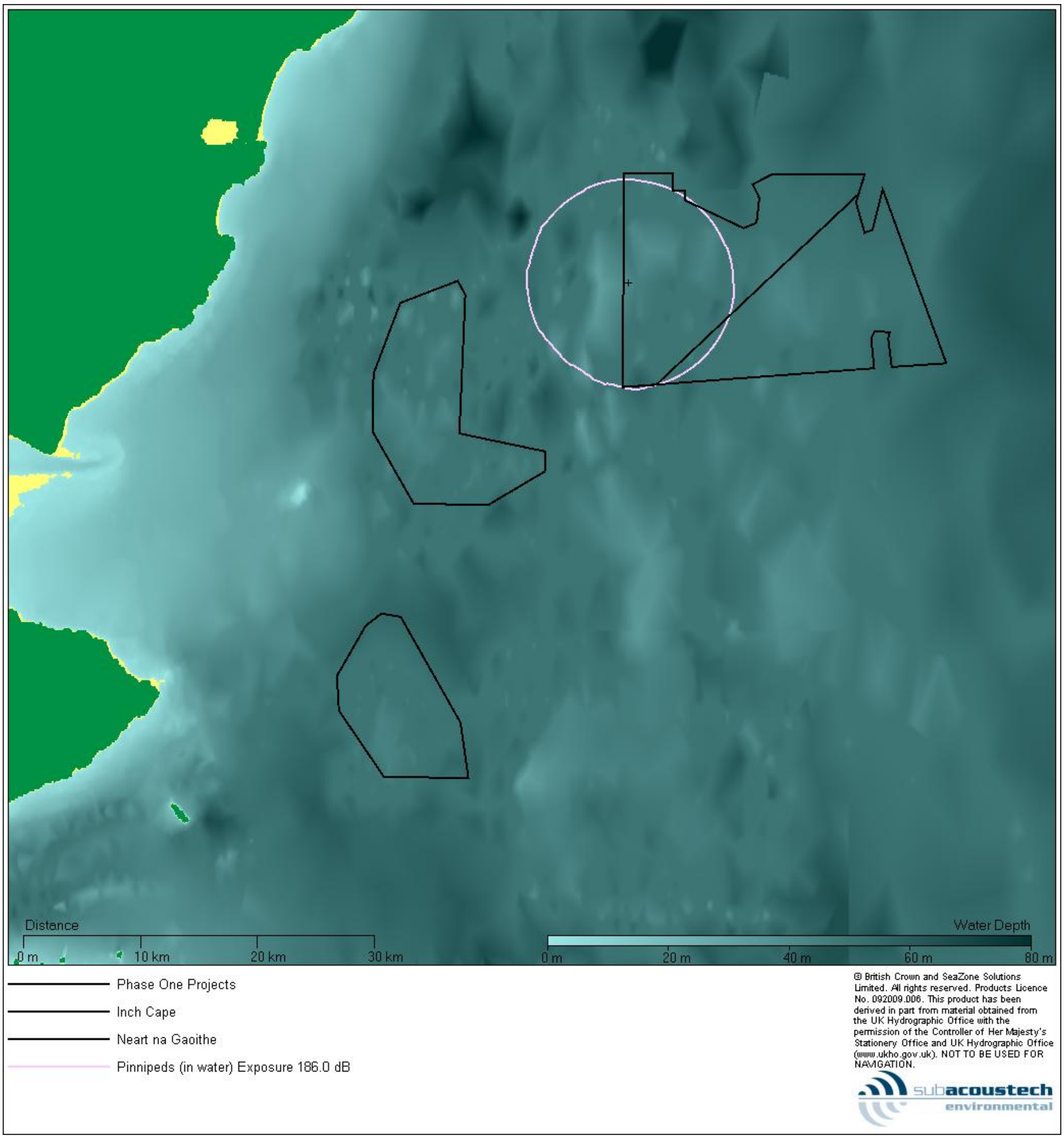

Figure 6-136 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM1 (alpha) fully driven scenario

The M-weighted 198 dB SEL (pinniped in water) contour is not visible at this range.

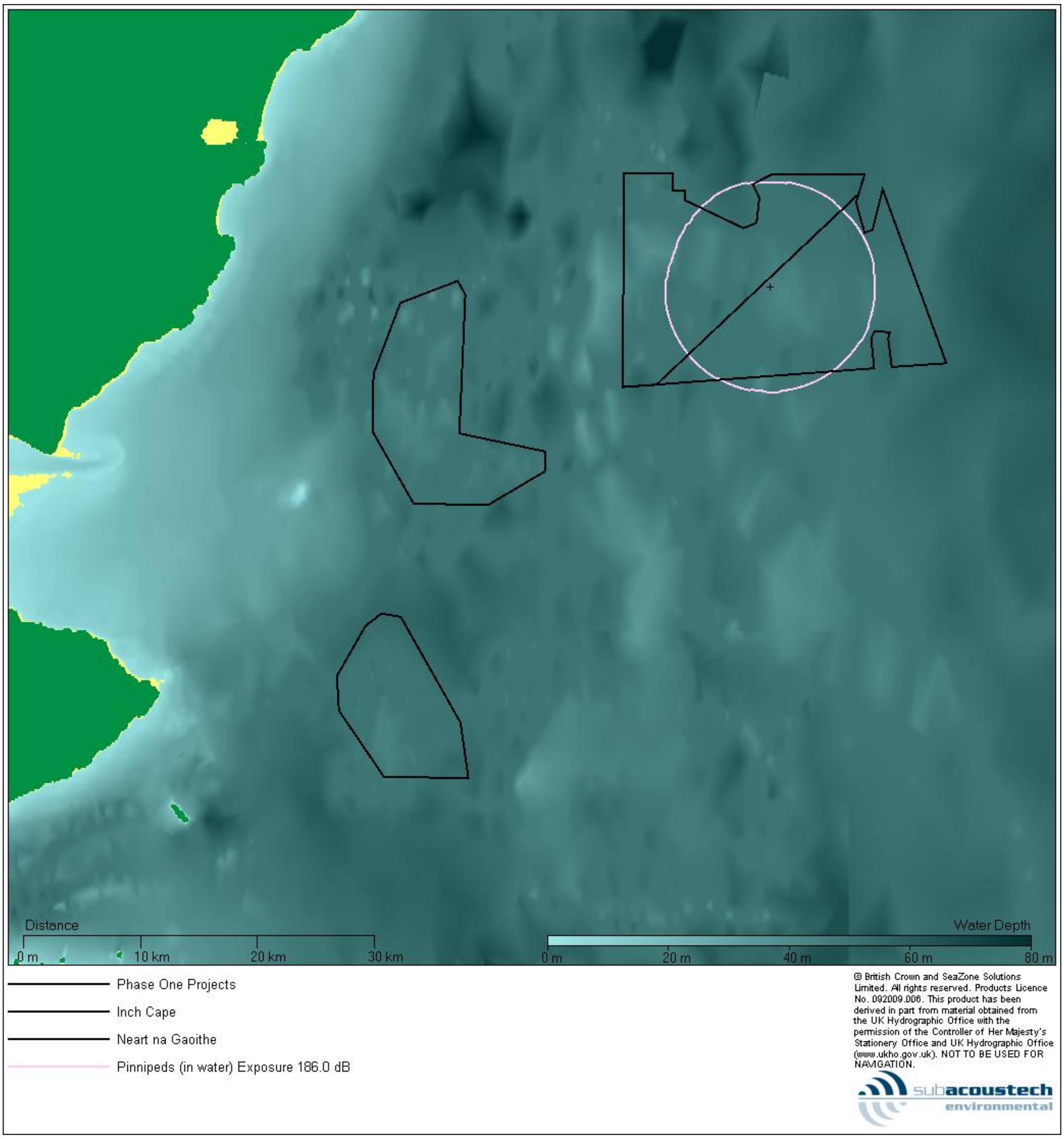

Figure 6-137 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM1 (bravo) fully driven scenario

The M-weighted 198 dB SEL (pinniped in water) contour is not visible at this range.

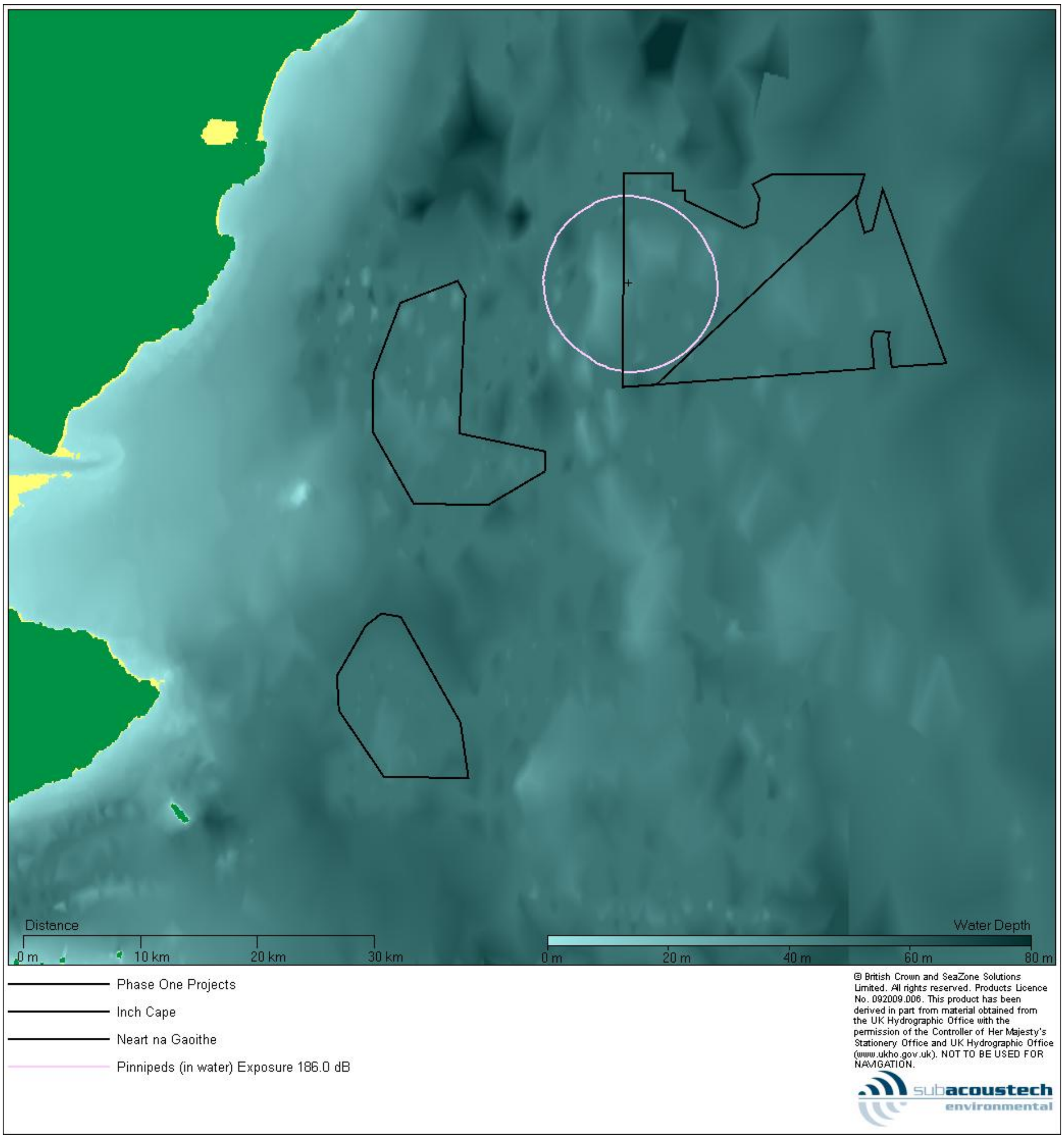

Figure 6-138 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM2 (alpha) fully driven scenario

The M-weighted 198 dB SEL (pinniped in water) contour is not visible at this range.

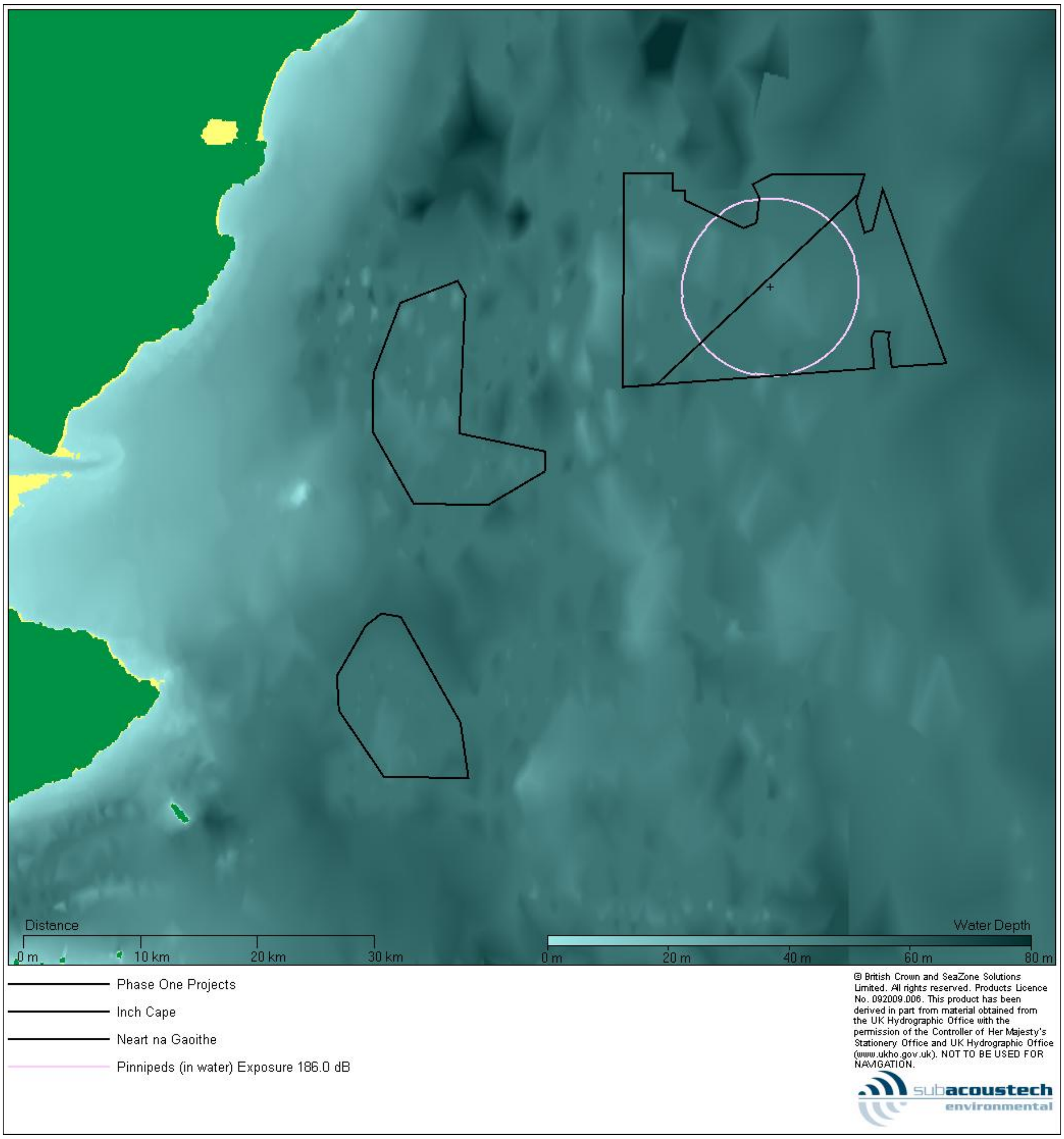

Figure 6-139 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM2 (bravo) fully driven scenario

The M-weighted 198 dB SEL (pinniped in water) contour is not visible at this range.

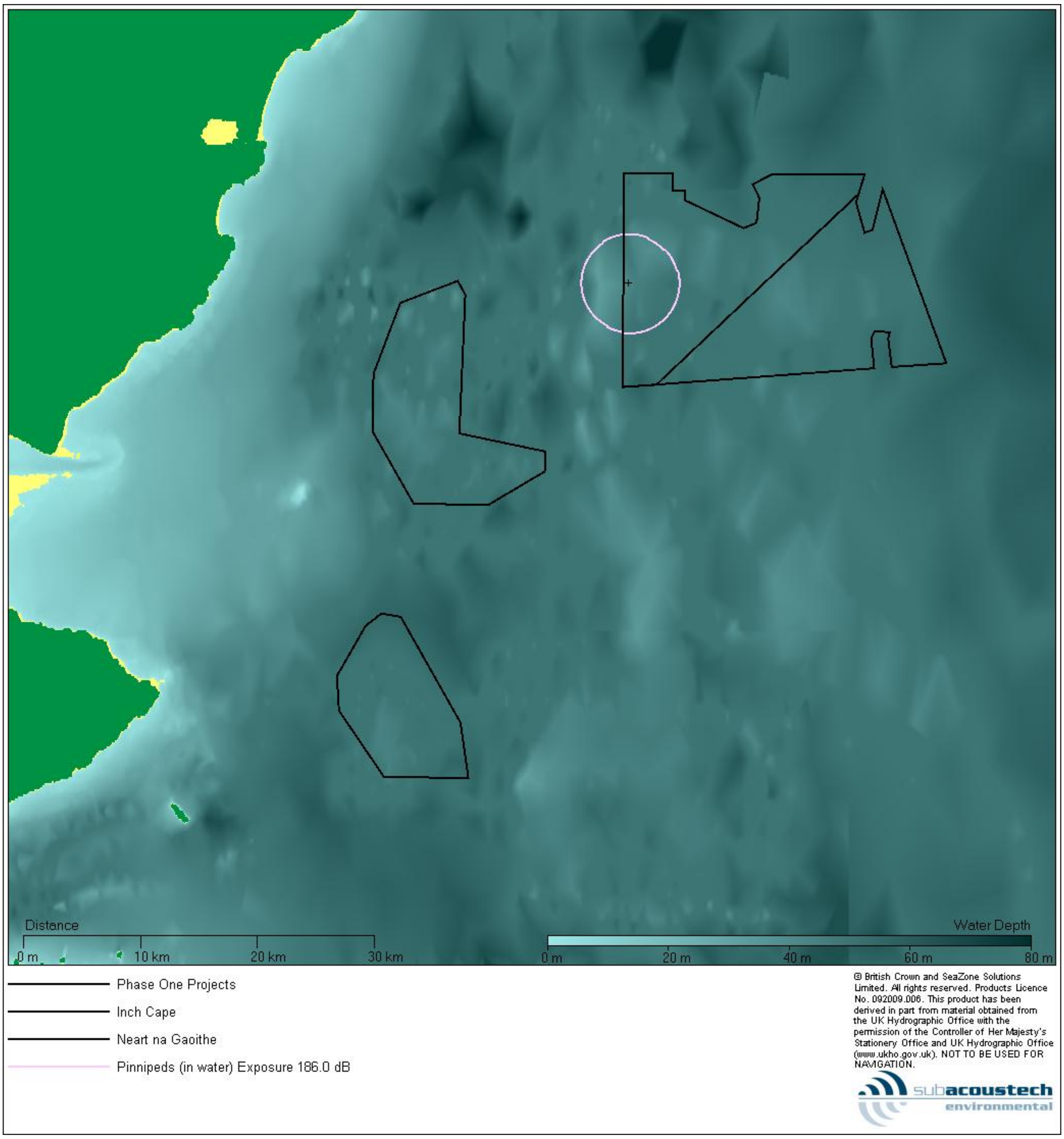

Figure 6-140 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM3 (alpha) drill-drive scenario

The M-weighted 198 dB SEL (pinniped in water) contour is not visible at this range.

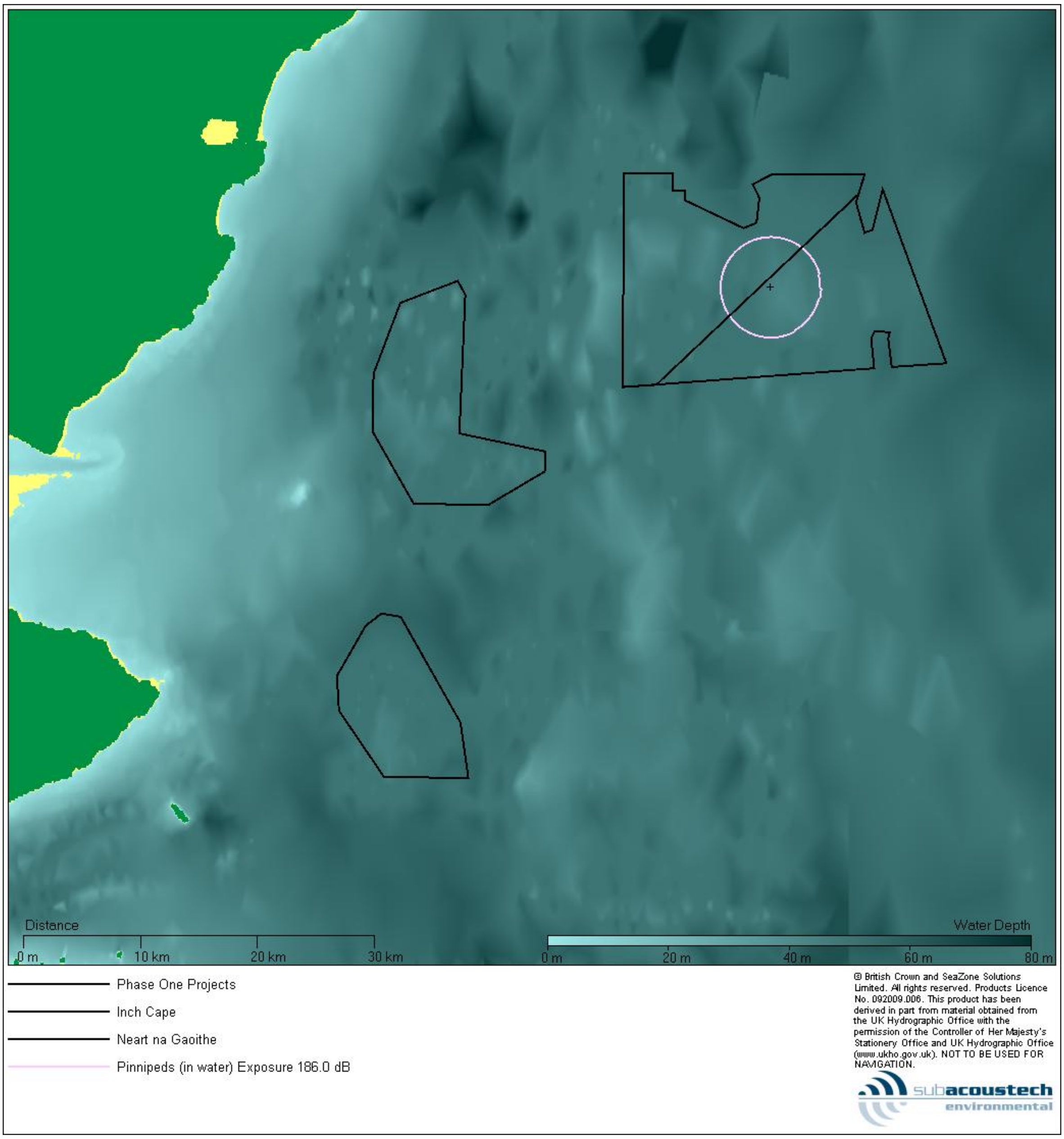

Figure 6-141 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM3 (bravo) drill-drive scenario

The M-weighted 198 dB SEL (pinniped in water) contour is not visible at this range.

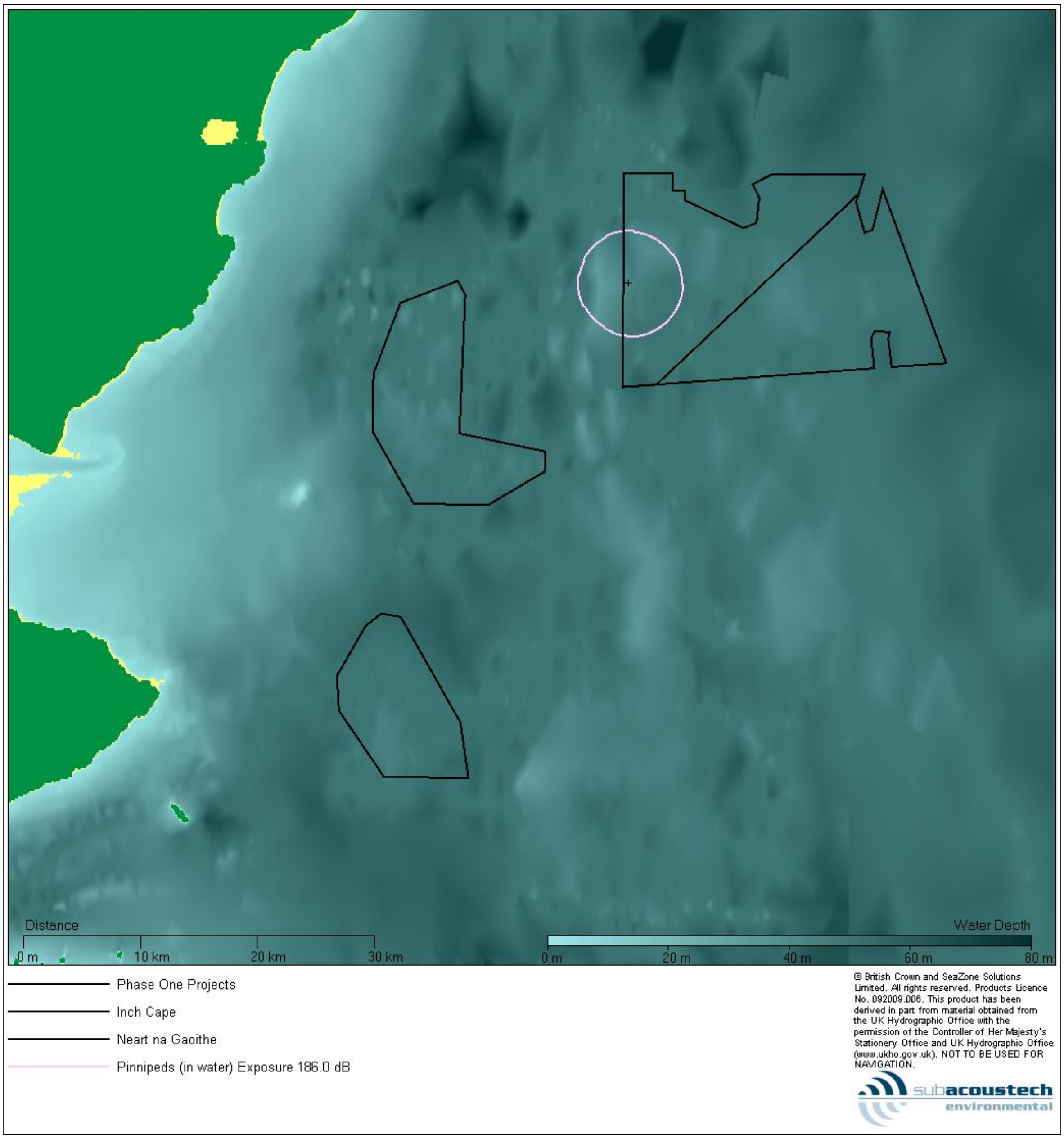

Figure 6-142 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM4 (alpha) drill-drive scenario

The M-weighted 198 dB SEL (pinniped in water) contour is not visible at this range.

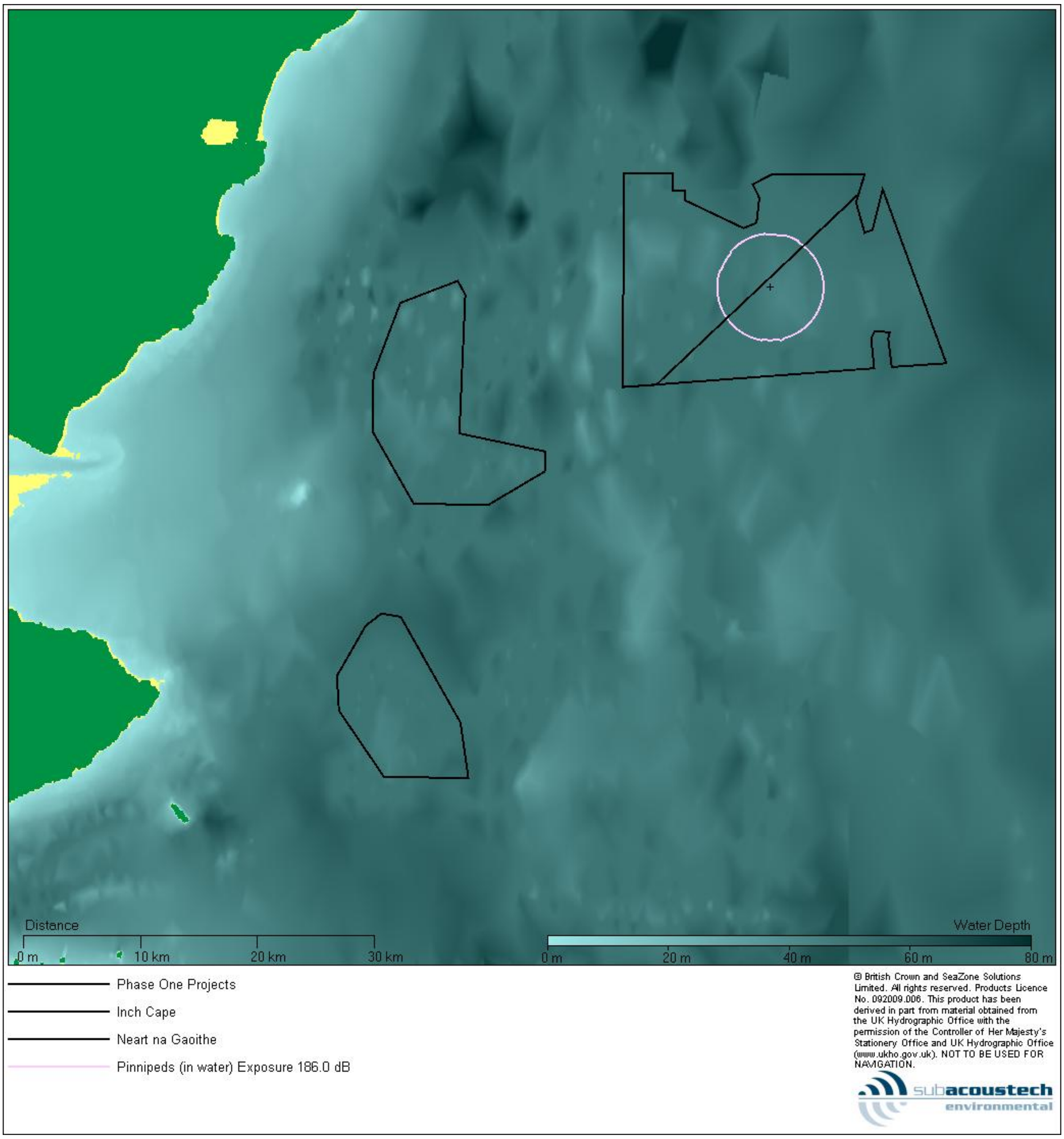

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Figure 6-143 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM4 (bravo) drill-drive scenario

The M-weighted 198 dB SEL (pinniped in water) contour is not visible at this range.

6.5.1.2 Multiple – GM1 (alpha) and GM1 (bravo)

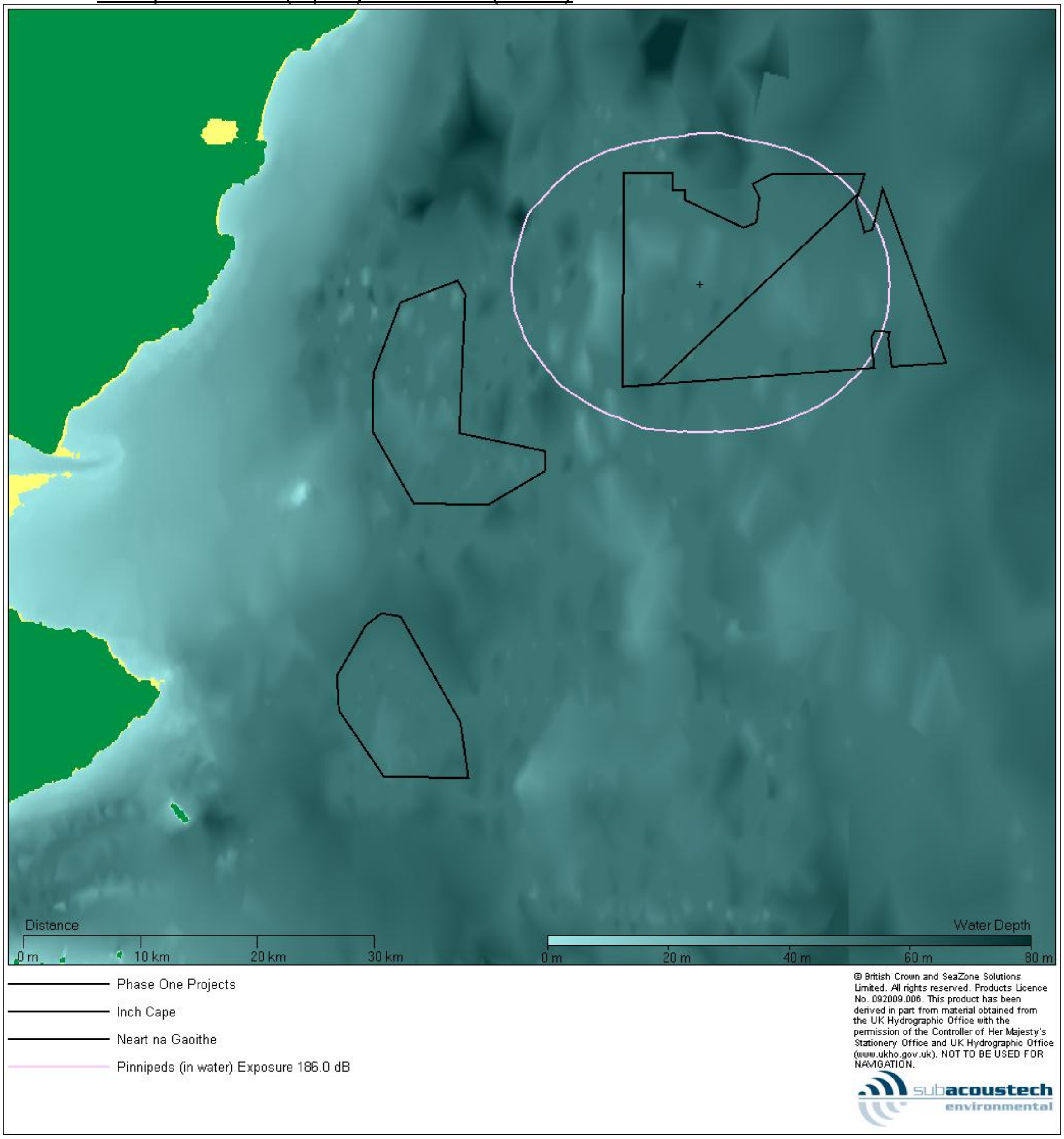

Figure 6-144 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM1 (alpha) and GM1 (bravo) cumulative scenario

The M-weighted 198 dB SEL (pinniped in water) contour is not visible at this range.

GM1 (alpha) and Inch Cape

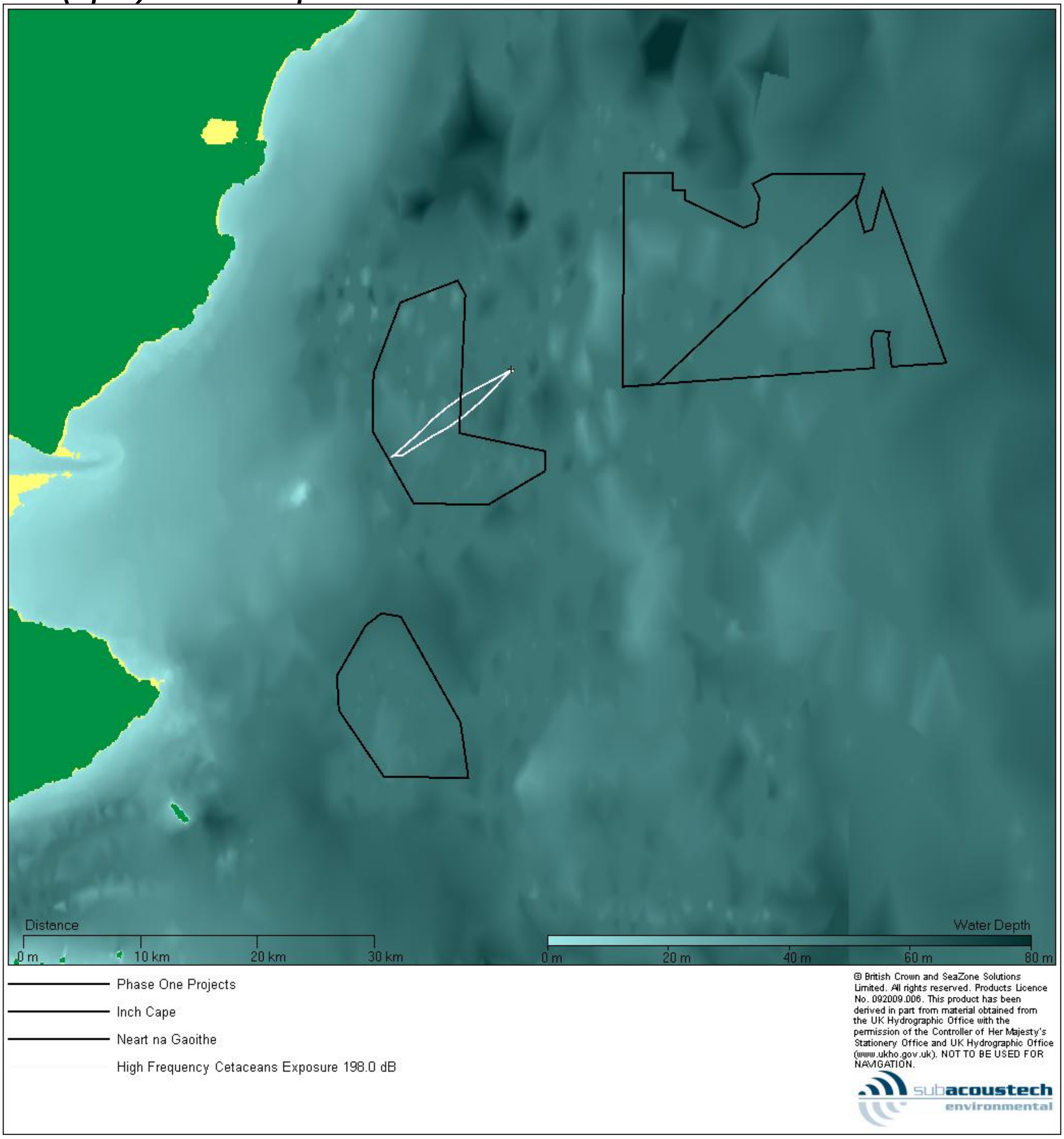

Figure 6-145 Contour plot showing the estimated M-Weighted SEL impact range for High Frequency Cetaceans for the GM1 (alpha) and Inch Cape cumulative scenario

It should be noted again that the start position for the animal is central to the two piling locations here and the animal flees in a straight line from this position. This leads to the unlikely scenario where the animal flees into an area of high noise (primarily towards the Inch Cape piling location) and out again instead of avoiding the piling as would be expected. The thin contours connecting with the central + position above and on the following figures therefore represent an extreme worst case for animal behaviour.

The lack of a contour in the direction of Seagreen is representative of the relatively low effect of the noise output from the Seagreen wind farm, indicating a fleeing animal would not be able to flee fast enough in that direction to be subject to an exposure in excess of the criterion.

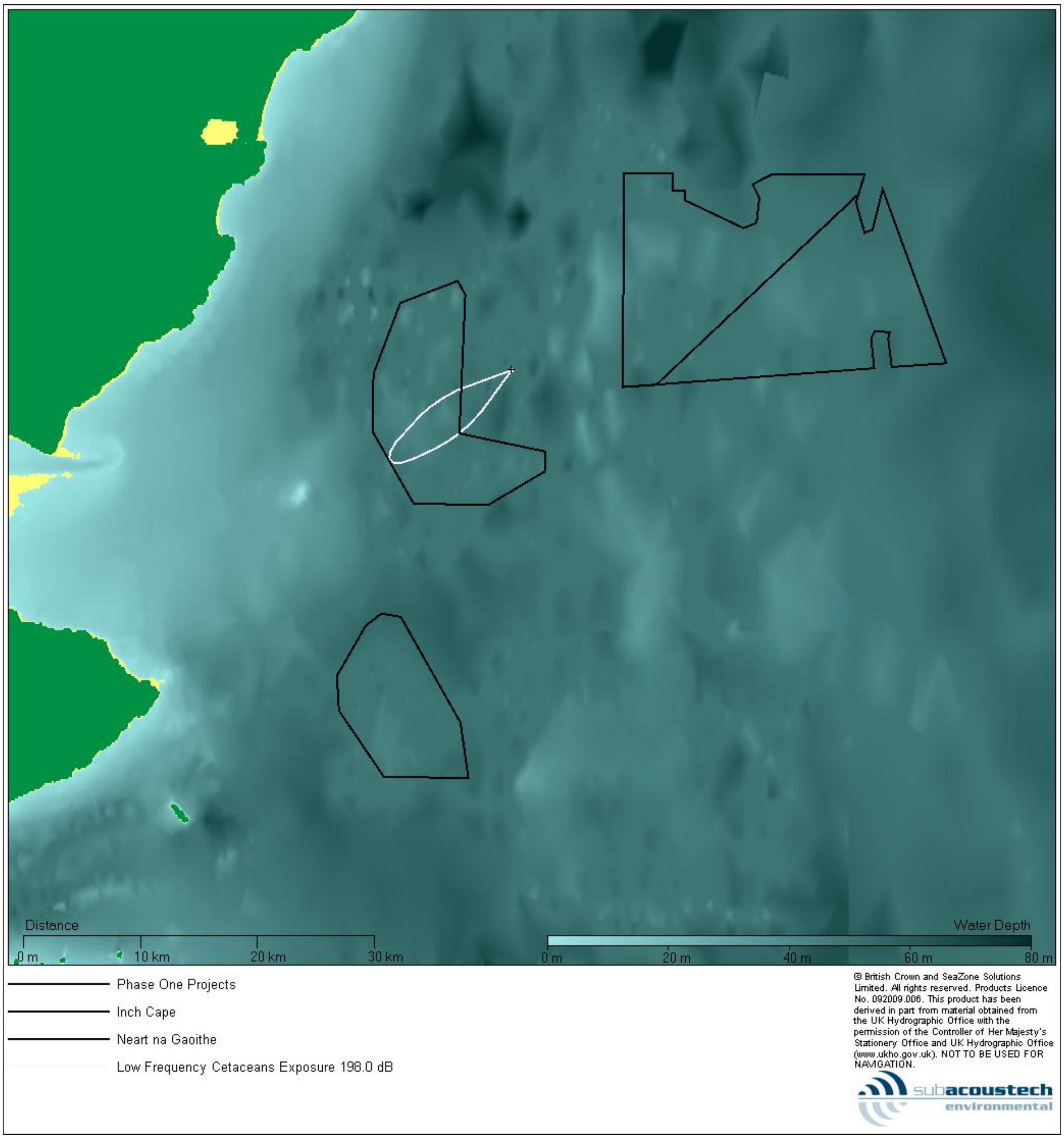

Figure 6-146 Contour plot showing the estimated M-Weighted SEL impact range for Low Frequency Cetaceans for the GM1 (alpha) and Inch Cape cumulative scenario

Please note description at Figure 6-145.

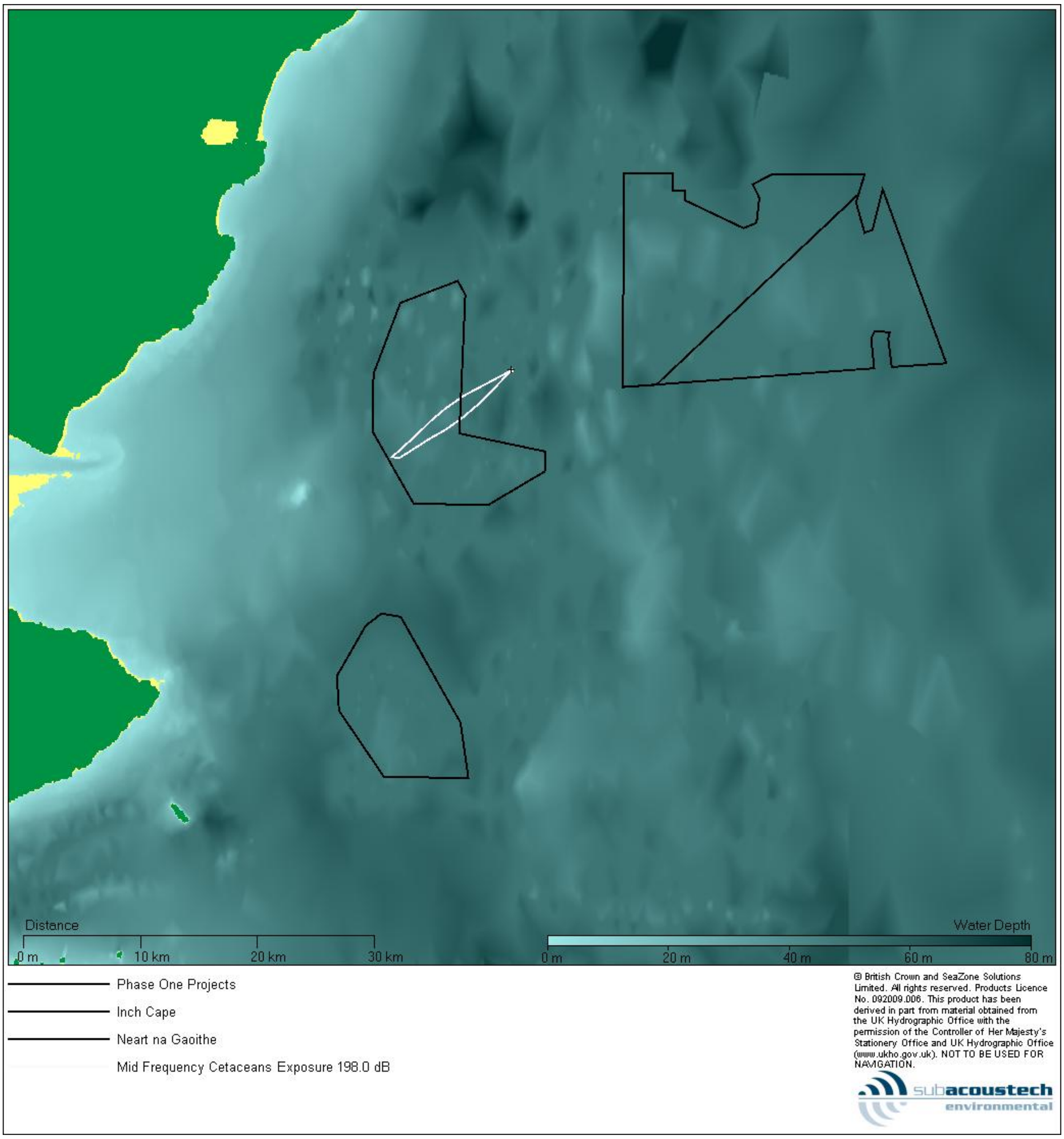

Figure 6-147 Contour plot showing the estimated M-Weighted SEL impact range for Mid Frequency Cetaceans for the GM1 (alpha) and Inch Cape cumulative scenario

Please note description at Figure 6-145.

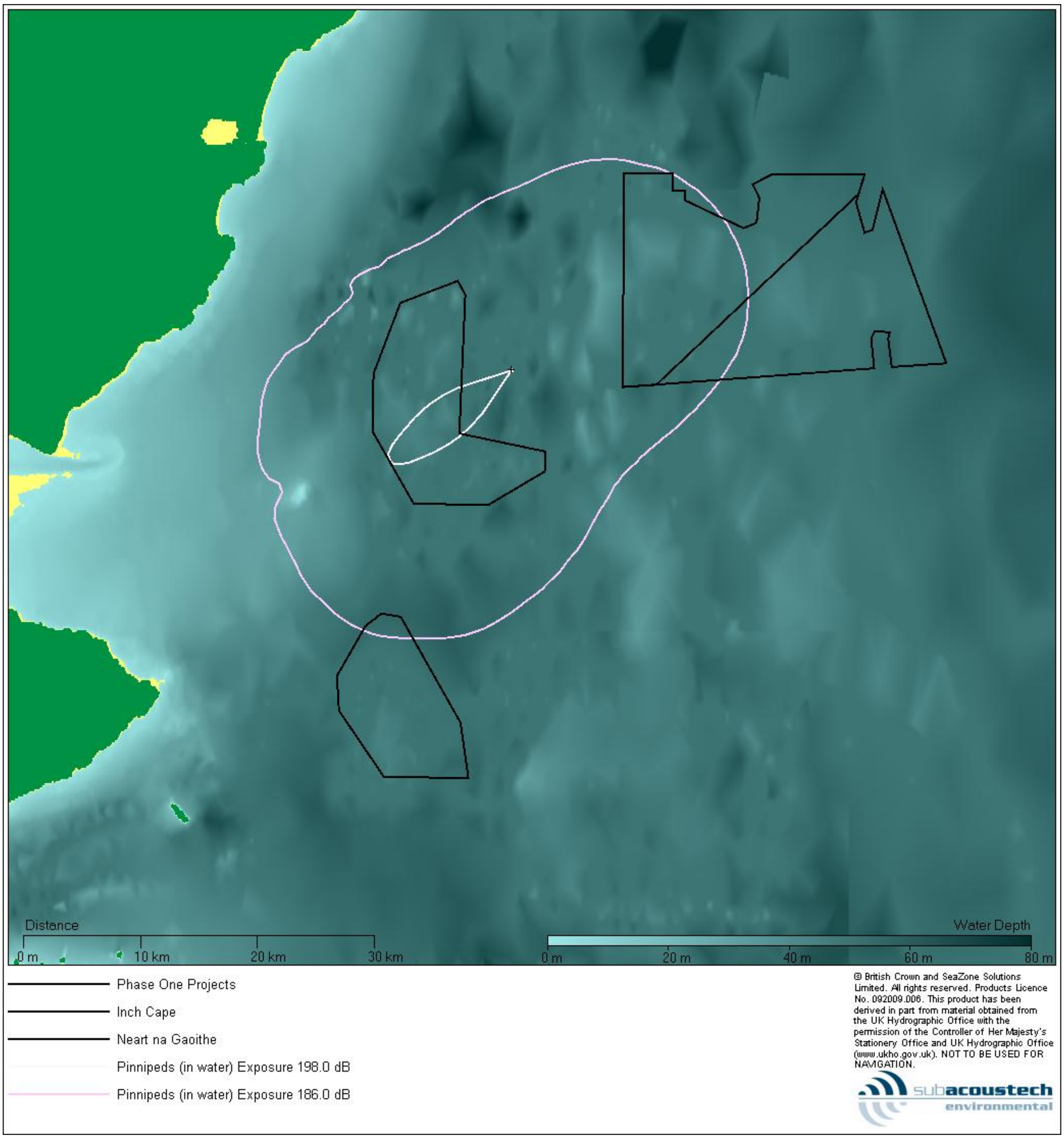

Figure 6-148 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM1 (alpha) and Inch Cape cumulative scenario

Please note description at Figure 6-145.

GM1 (alpha) and NNG

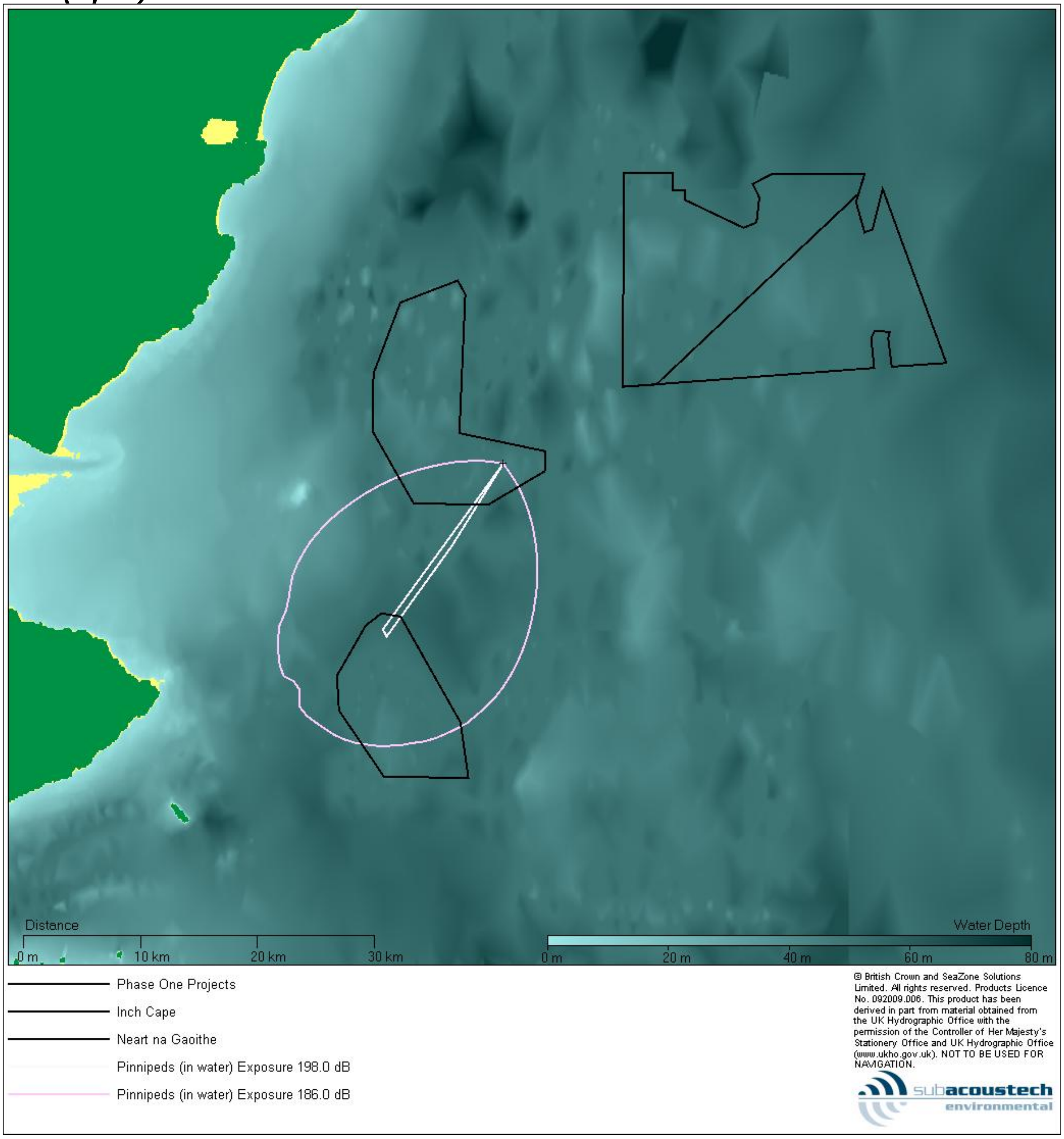

Figure 6-149 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM1 (alpha) and NNG cumulative scenario

Please note description at Figure 6-145.

GM1 (alpha), Inch Cape and NNG

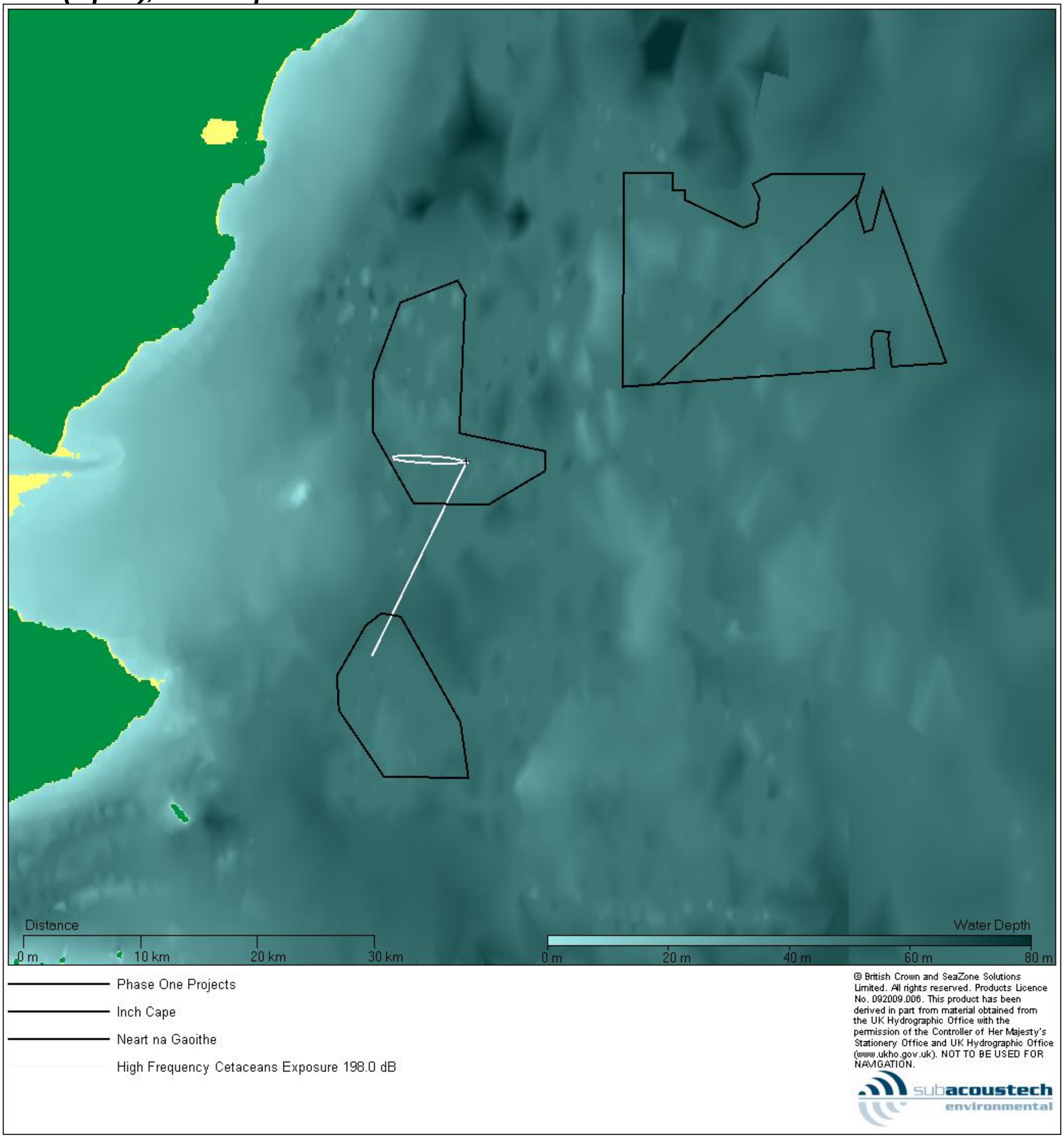

Figure 6-150 Contour plot showing the estimated M-Weighted SEL impact range for High Frequency Cetaceans for the GM1 (alpha), Inch Cape and NNG cumulative scenario

Please note description at Figure 6-145.

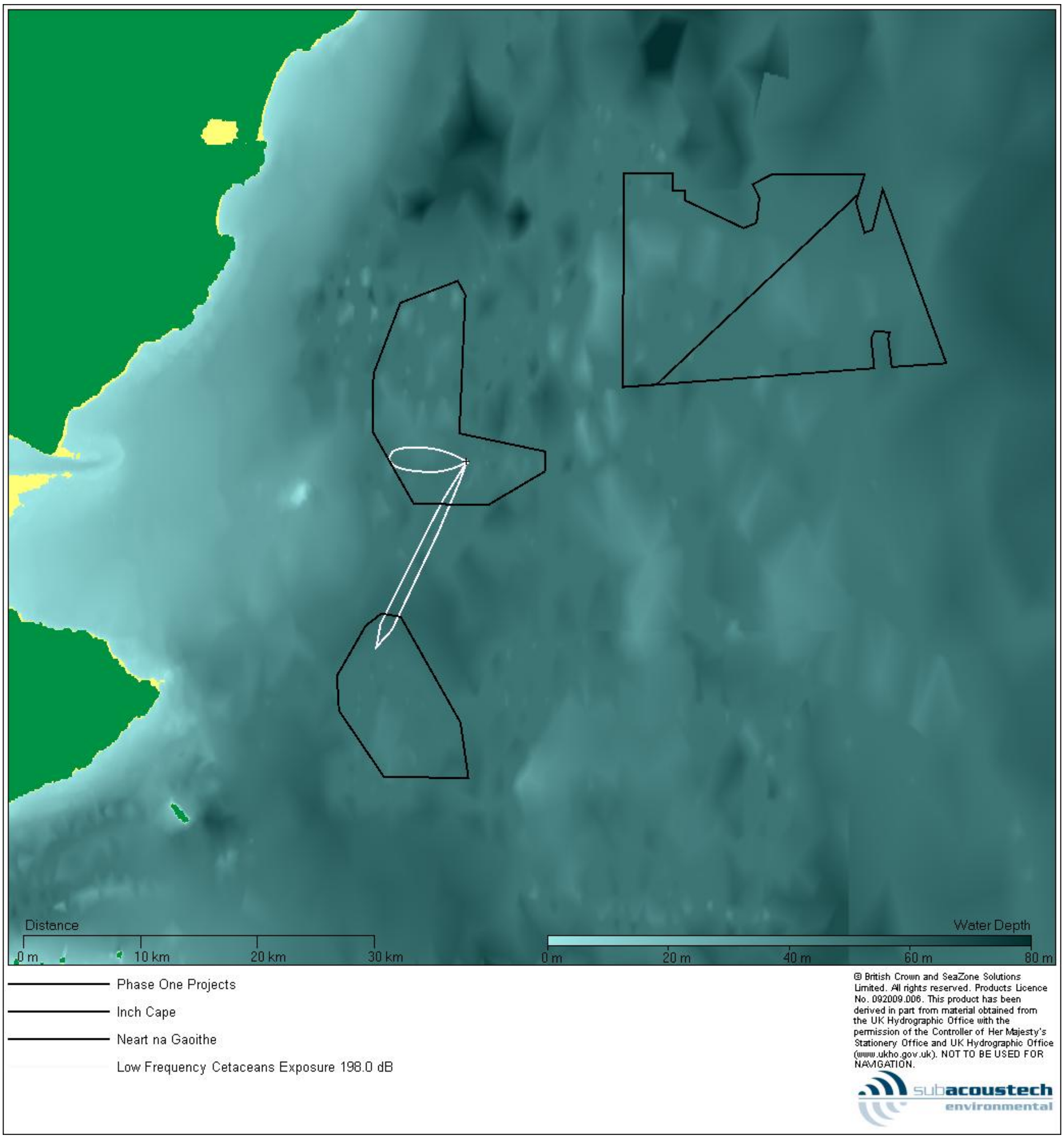

Figure 6-151 Contour plot showing the estimated M-Weighted SEL impact range for Low Frequency Cetaceans for the GM1 (alpha), Inch Cape and NNG cumulative scenario

Please note description at Figure 6-145.

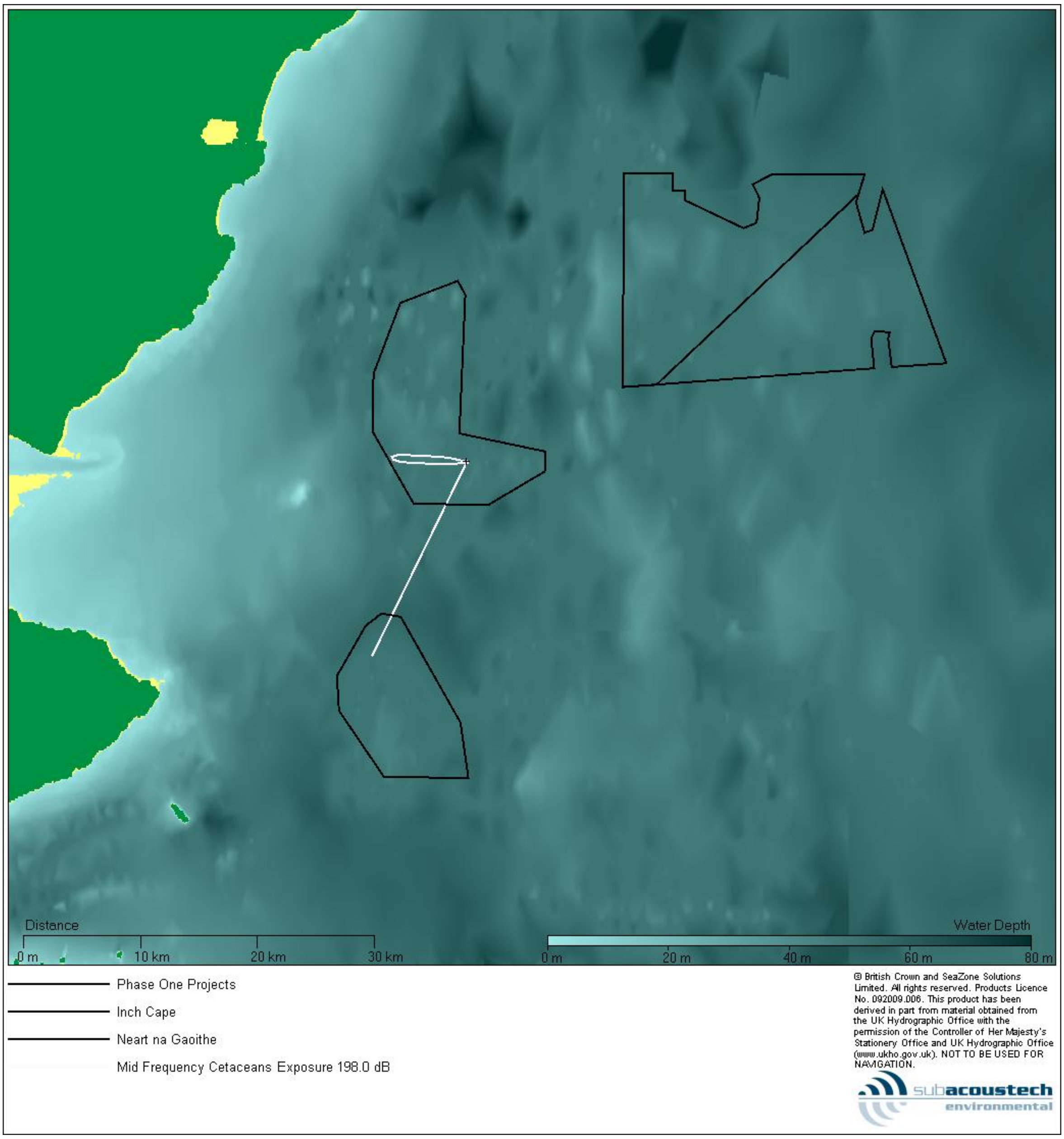

Figure 6-152 Contour plot showing the estimated M-Weighted SEL impact range for Mid Frequency Cetaceans for the GM1 (alpha), Inch Cape and NNG cumulative scenario

Please note description at Figure 6-145.

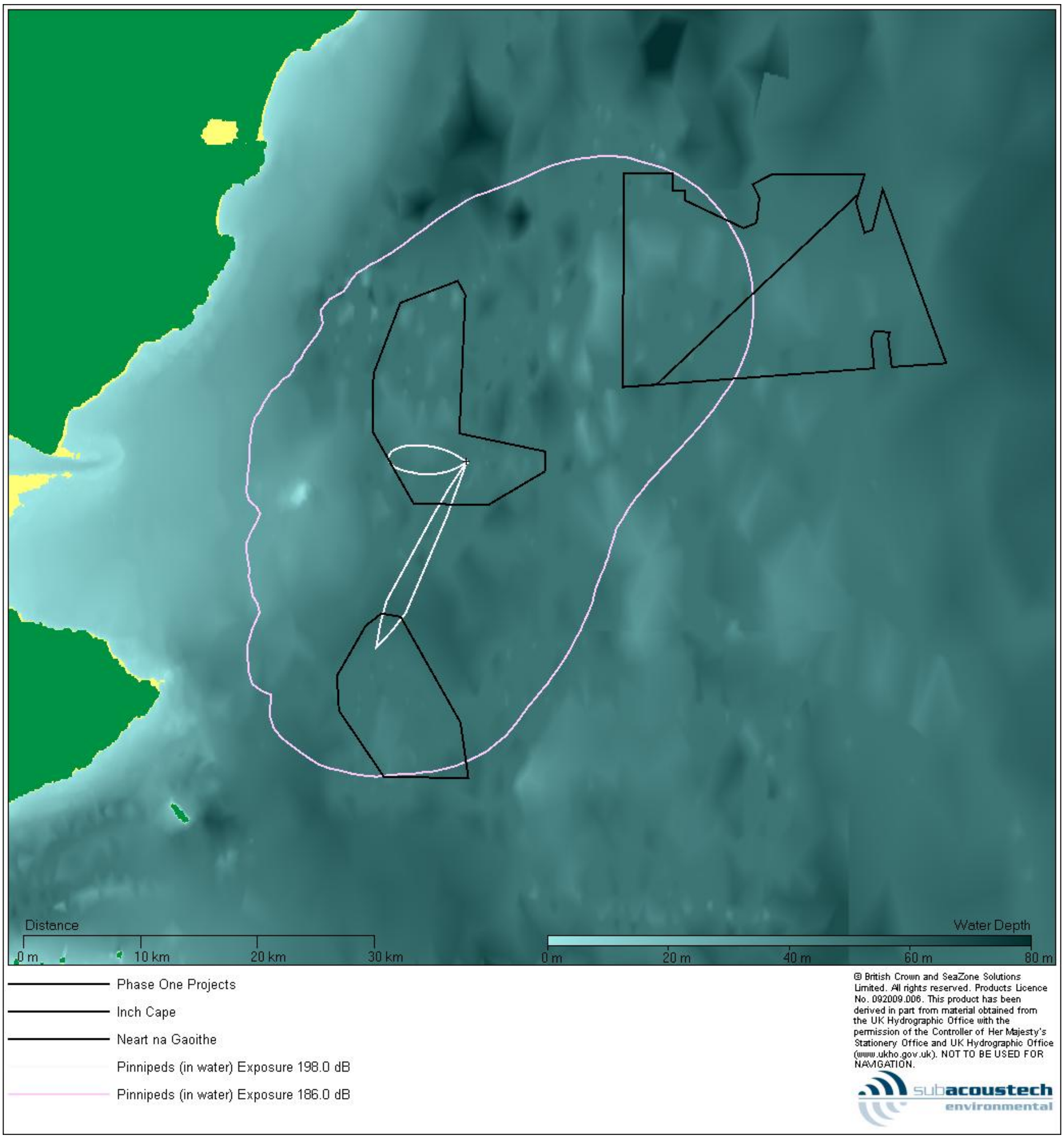

Figure 6-153 Contour plot showing the estimated M-Weighted SEL impact ranges for Pinnipeds (in water) for the GM1 (alpha), Inch Cape and NNG cumulative scenario

Please note description at Figure 6-145.

6.5.1.3 Multiple – GM3 (alpha) and GM3 (bravo)

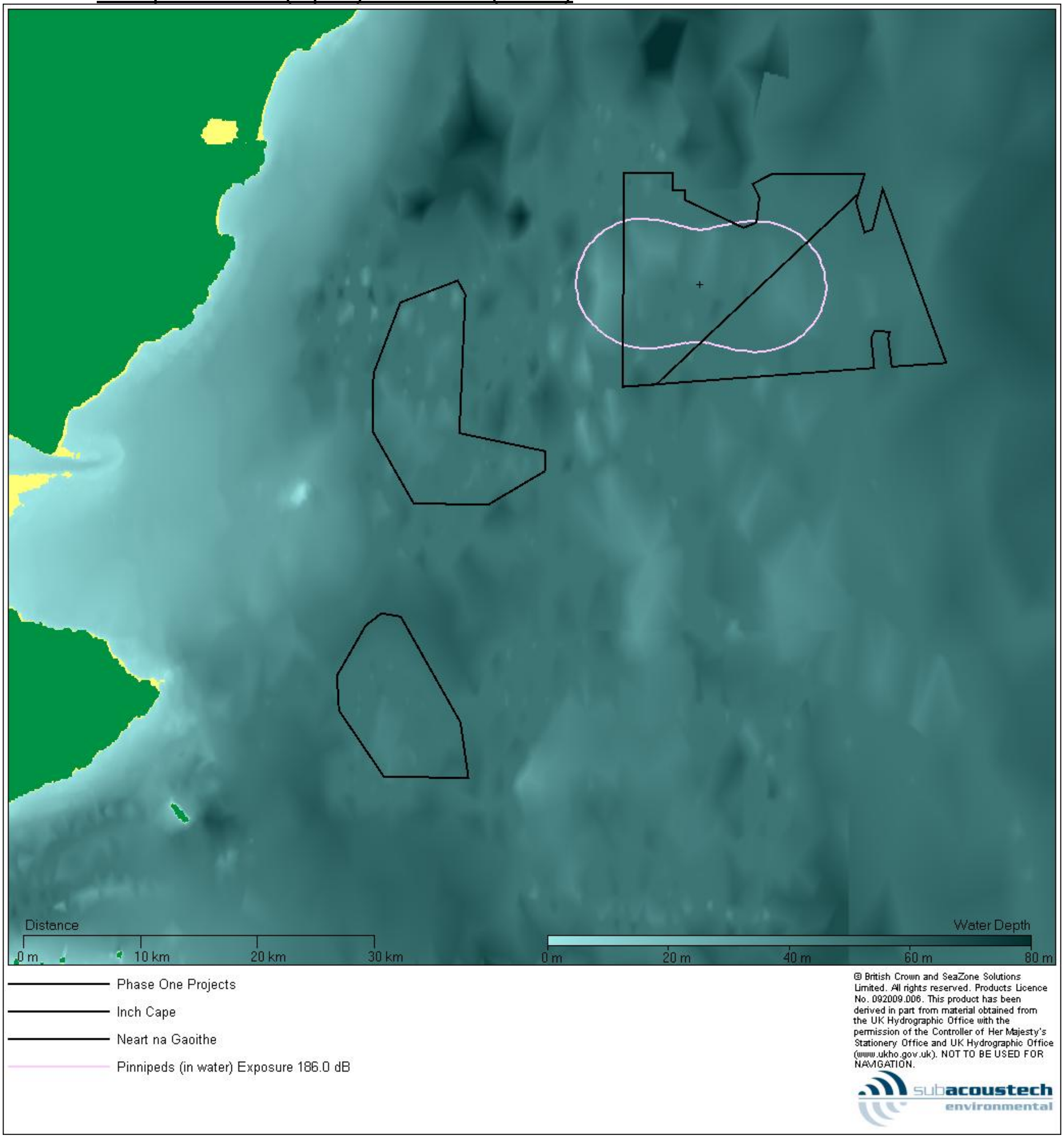

Figure 6-154 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM3 (alpha) and GM3 (bravo) cumulative scenario

The M-weighted 198 dB SEL (pinniped in water) contour is not visible at this range.

GM3 (alpha) and Inch Cape

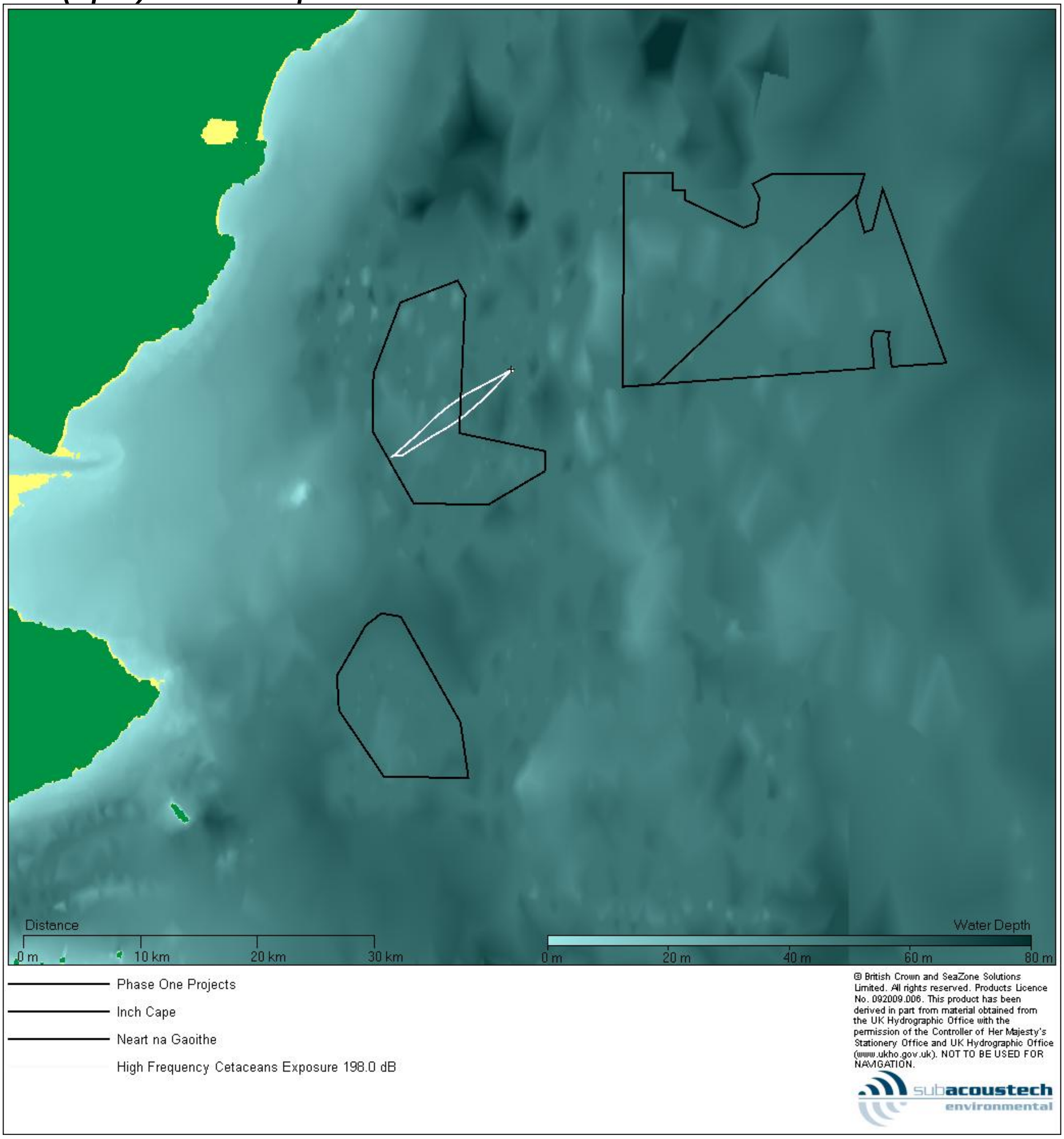

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Figure 6-155 Contour plot showing the estimated M-Weighted SEL impact range for High Frequency Cetaceans for the GM3 (alpha) and Inch Cape cumulative scenario

Please note description at Figure 6-145.

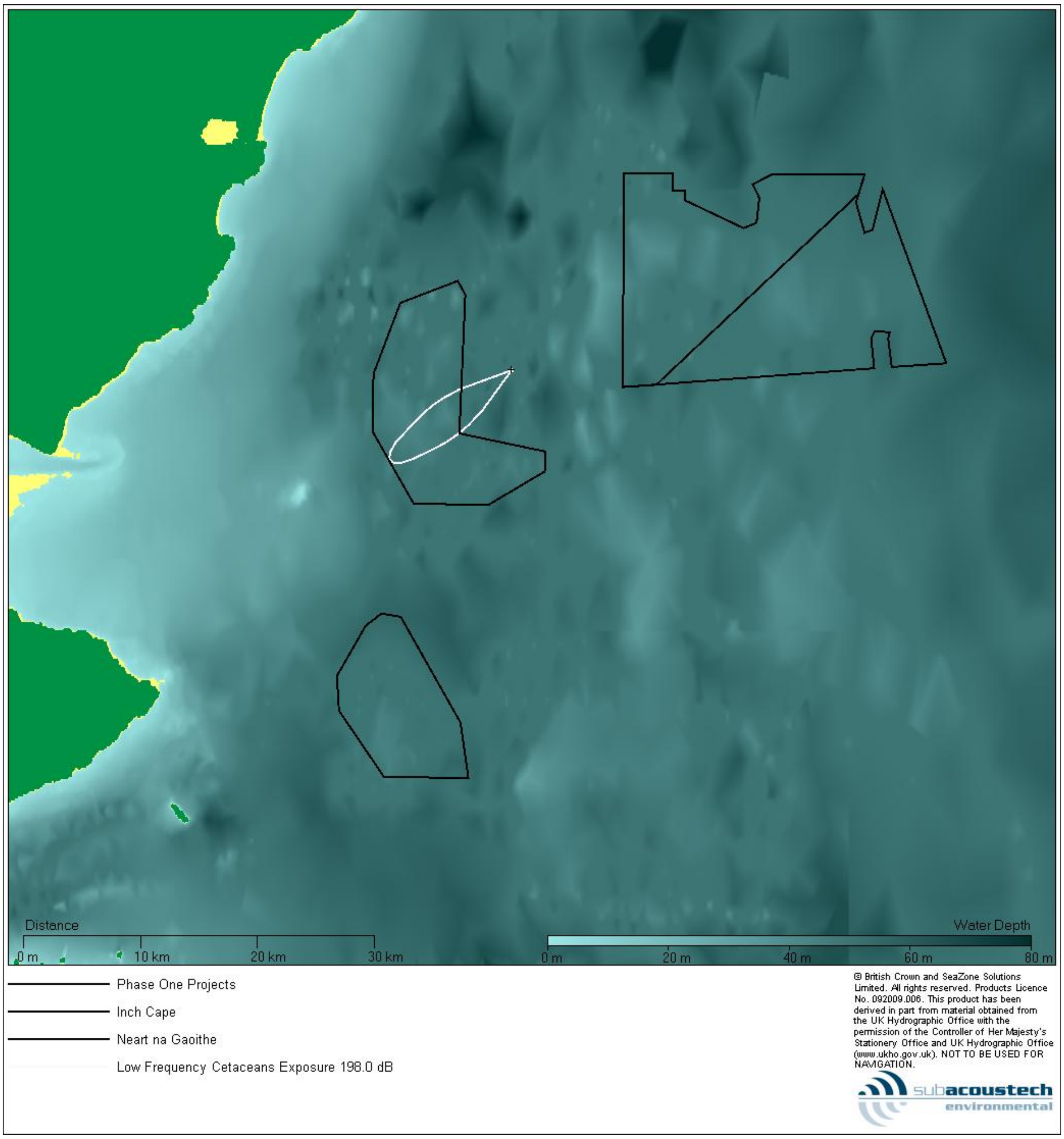

Figure 6-156 Contour plot showing the estimated M-Weighted SEL impact range for Low Frequency Cetaceans for the GM3 (alpha) and Inch Cape cumulative scenario

Please note description at Figure 6-145.

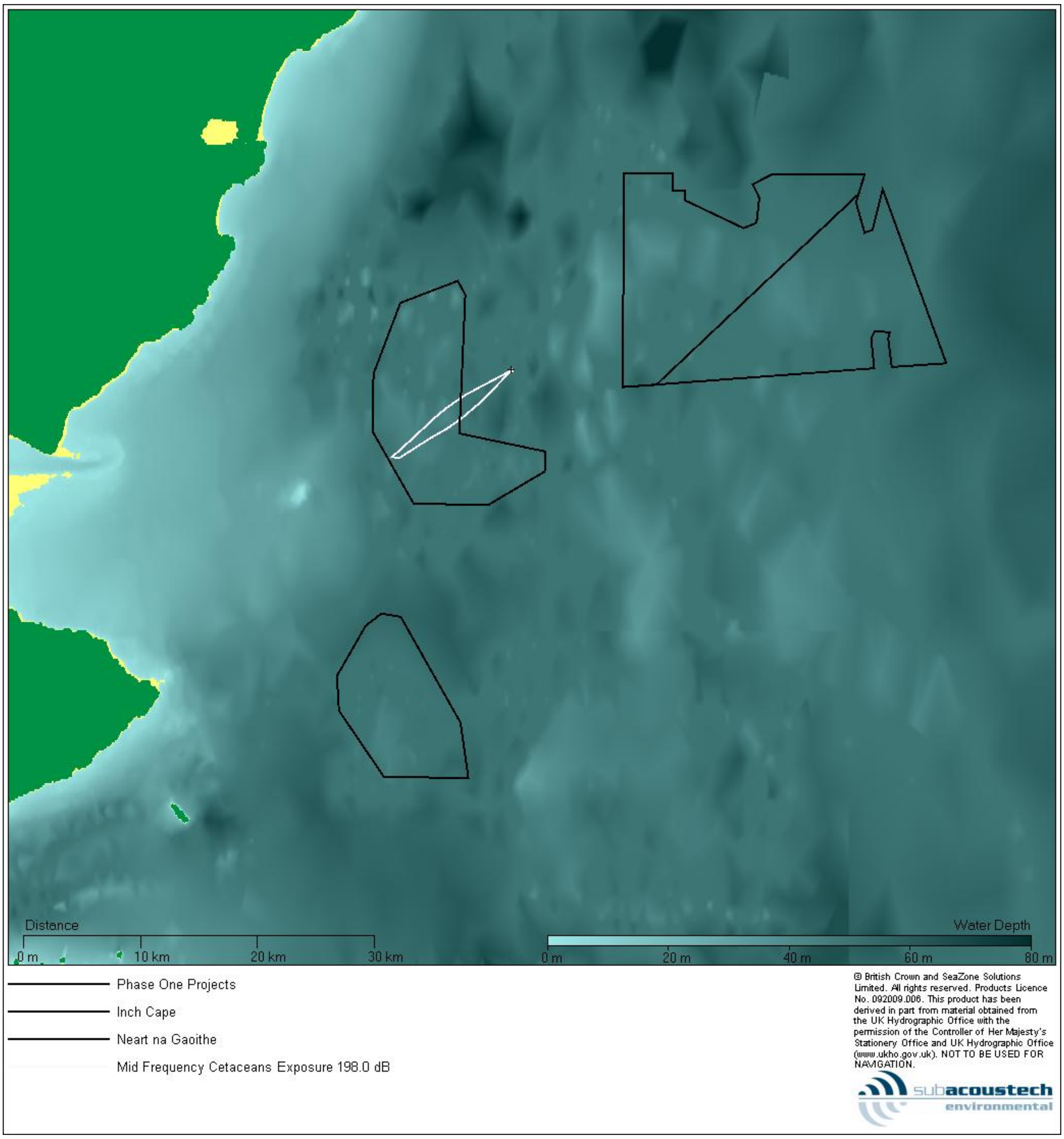

Figure 6-157 Contour plot showing the estimated M-Weighted SEL impact range for Mid Frequency Cetaceans for the GM3 (alpha) and Inch Cape cumulative scenario

Please note description at Figure 6-145.

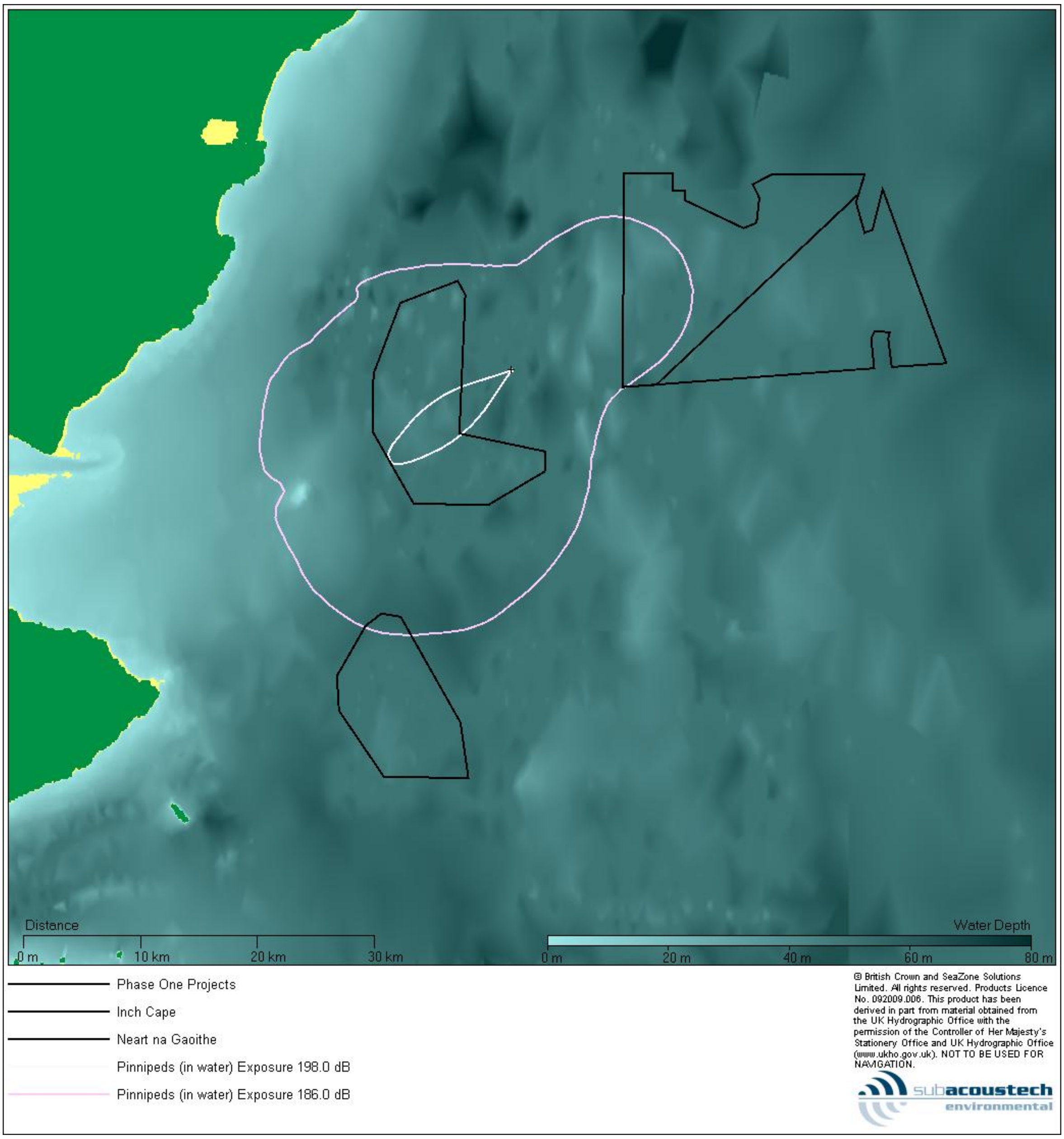

Figure 6-158 Contour plot showing the estimated M-Weighted SEL impact ranges for Pinnipeds (in water) for the GM3 (alpha) and Inch Cape cumulative scenario

Please note description at Figure 6-145.

GM3 (alpha) and NNG

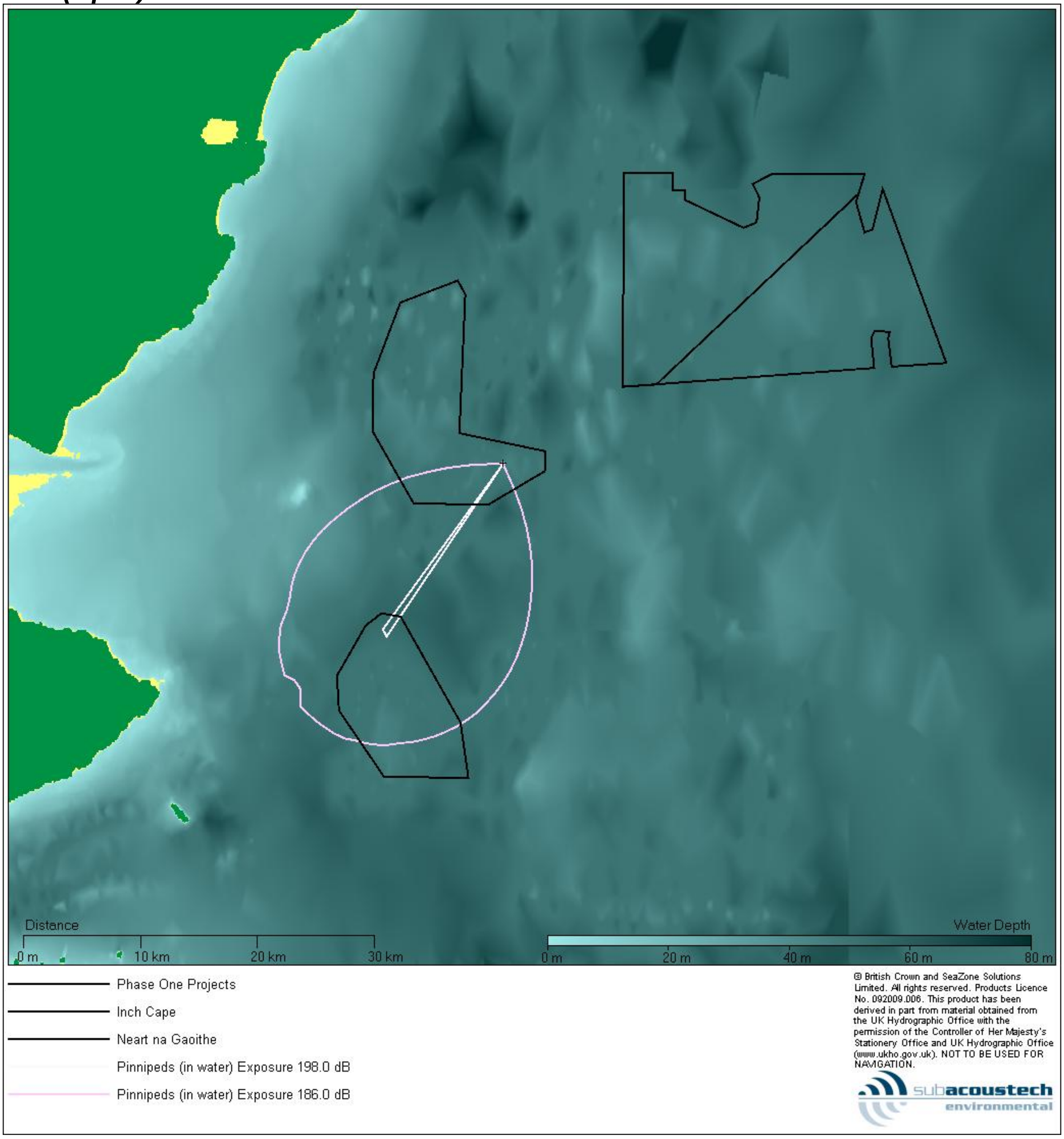

Figure 6-159 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM3 (alpha) and NNG cumulative scenario

Please note description at Figure 6-145.

GM3 (alpha), Inch Cape and NNG

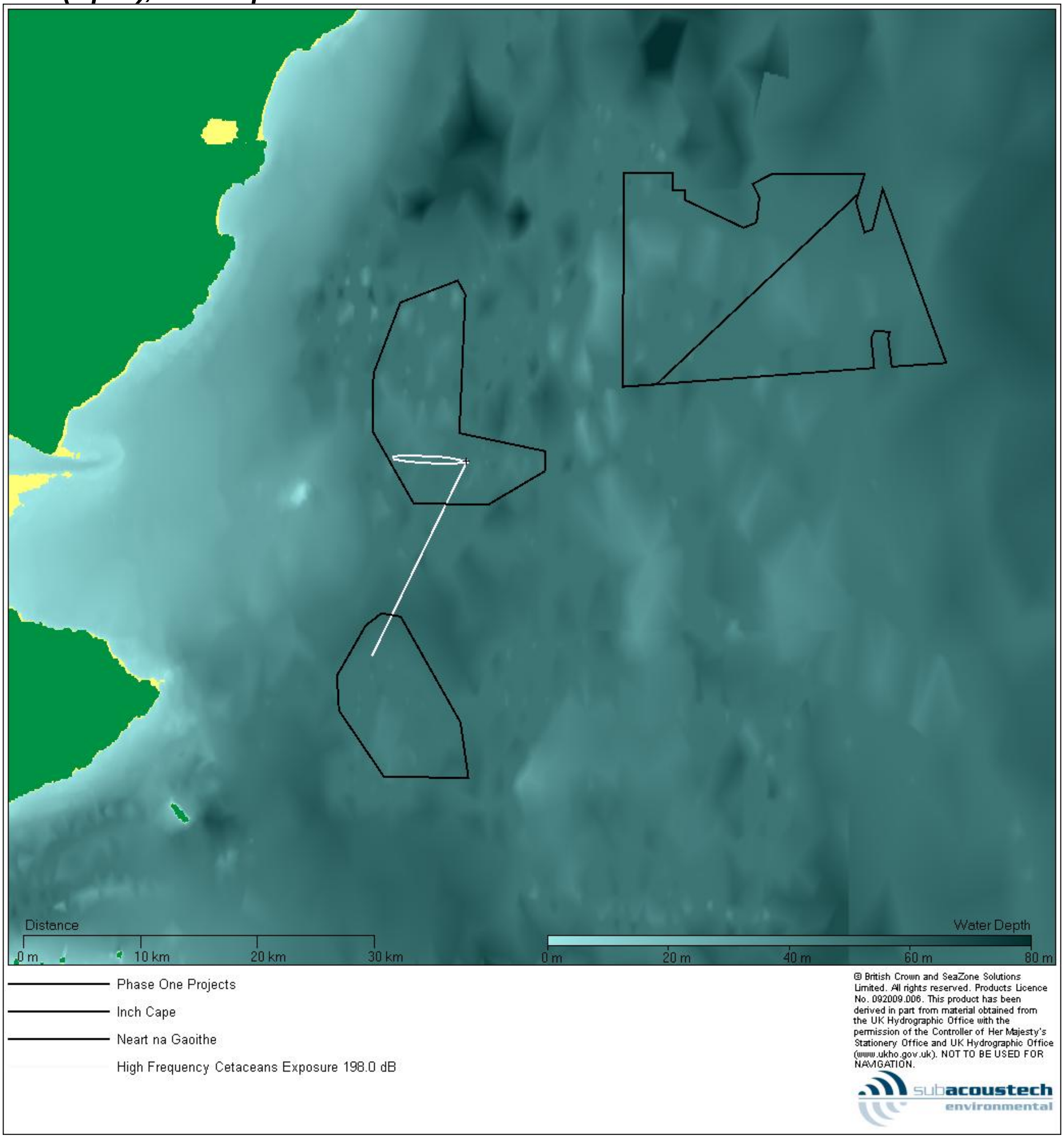

Figure 6-160 Contour plot showing the estimated M-Weighted SEL impact range for High Frequency Cetaceans for the GM3 (alpha), Inch Cape and NNG cumulative scenario

Please note description at Figure 6-145.

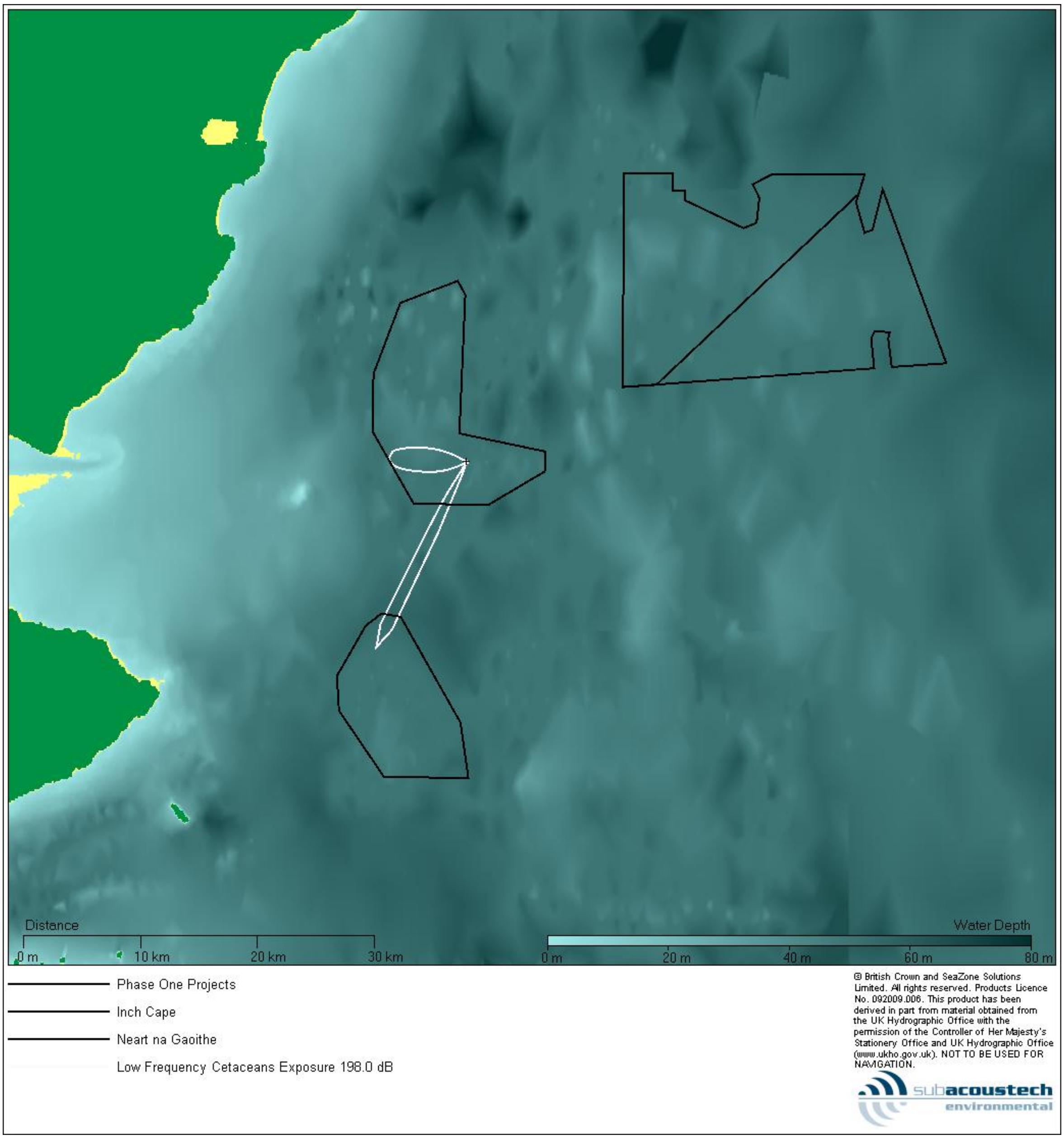

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Figure 6-161 Contour plot showing the estimated M-Weighted SEL impact range for Low Frequency Cetaceans for the GM3 (alpha), Inch Cape and NNG cumulative scenario

Please note description at Figure 6-145.

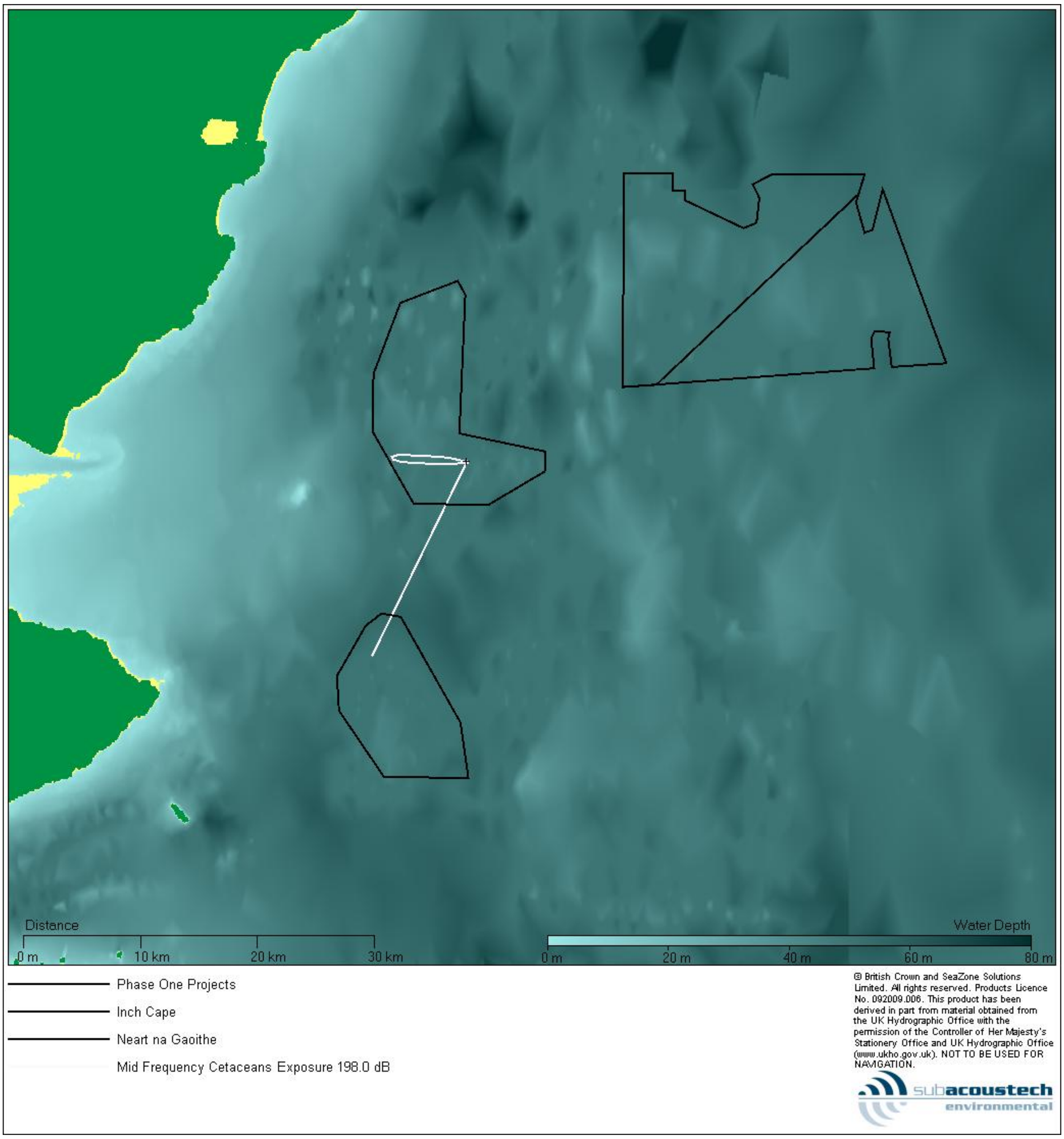

Figure 6-162 Contour plot showing the estimated M-Weighted SEL impact range for Mid Frequency Cetaceans for the GM3 (alpha), Inch Cape and NNG cumulative scenario

Please note description at Figure 6-145.

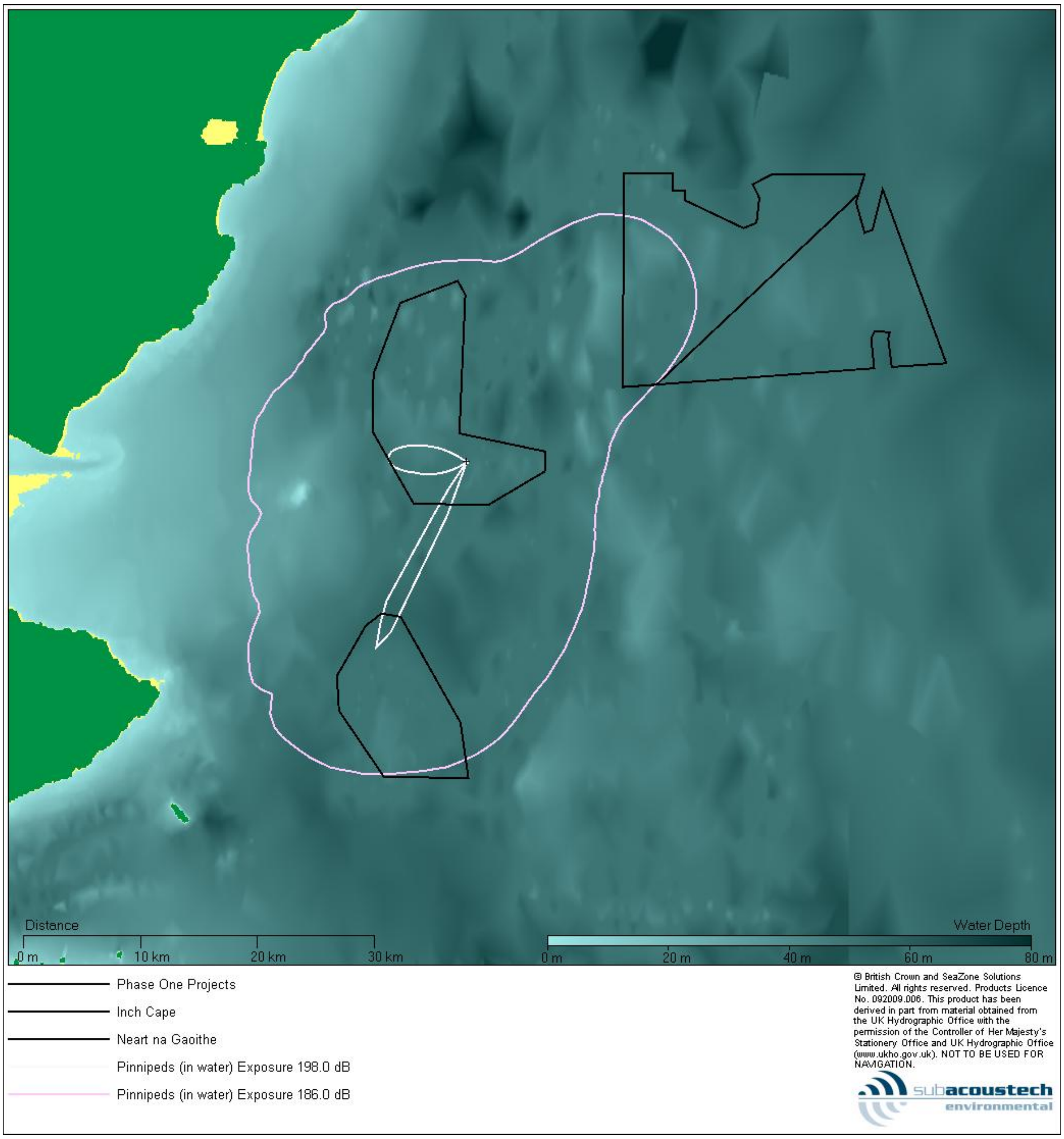

Figure 6-163 Contour plot showing the estimated M-Weighted SEL impact range for Pinnipeds (in water) for the GM3 (alpha), Inch Cape and NNG cumulative scenario

Please note description at Figure 6-145.

6.6 Mitigation

To investigate the effect that different degrees of attenuation have on impact ranges, additional modelling has been undertaken. This modelling uses similar piling parameters to the scenario previously presented as GM1 (alpha). Tables 6-35 and 6-36 present impact ranges and impact areas respectively for harbour seal 90 and 75 dB$_{ht}$ and for pinnipeds (in water) M-weighted SEL 186 dB and are only intended to provide an indication of ranges for different levels of attenuation should it be achieved.

	Mean Impact Ranges (km)		
Reduction	Harbour Seal 90 dB$_{ht}$	Harbour Seal 75 dB$_{ht}$	Pinnipeds (in water) Exposure 186 dB
0 dB	18	46	18
-1 dB	17	44	16
-2 dB	15	42	14
-3 dB	14	40	12
-5 dB	12	36	8.8
-7 dB	9.7	32	5.9
-10 dB	7.1	26	2.6
-15 dB	4.2	18	<0.1
-20 dB	2.4	12	<0.1
-23 dB	1.7	8.8	<0.1

Table 6-47 Summary of impact ranges for estimated attenuation of piling noise

	Impact areas (km^2)		
Reduction	Harbour Seal 90 dB$_{ht}$	Harbour Seal 75 dB$_{ht}$	Pinnipeds (in water) Exposure 186 dB
0 dB	1000	6600	1000
-1 dB	870	6000	810
-2 dB	730	5500	620
-3 dB	610	5000	460
-5 dB	430	4100	240
-7 dB	290	3200	110
-10 dB	160	2200	21
-15 dB	54	1000	<0.1
-20 dB	17	430	<0.1
-23 dB	8.5	240	<0.1

Table 6-48 Summary of impact areas for estimated attenuation of piling noise

Figures 6-164 to 6-166 show contour plots of impact ranges, illustrating the effect of increasing levels of attenuation.

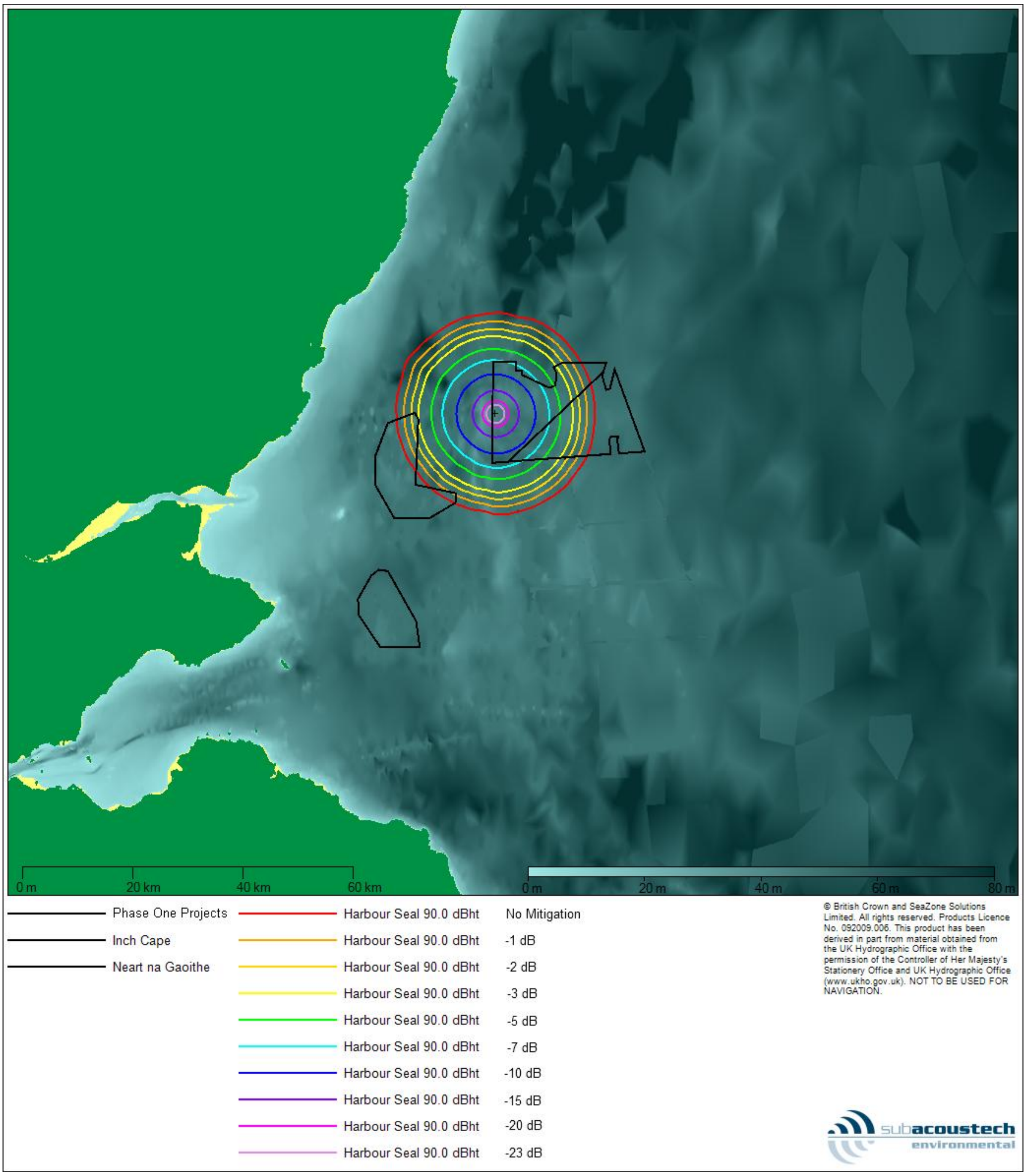

Figure 6-164 Contour plot showing the estimated impact ranges of Harbour Seal 90 dB$_{ht}$ for increasing levels of attenuation of noise from piling at the alpha position

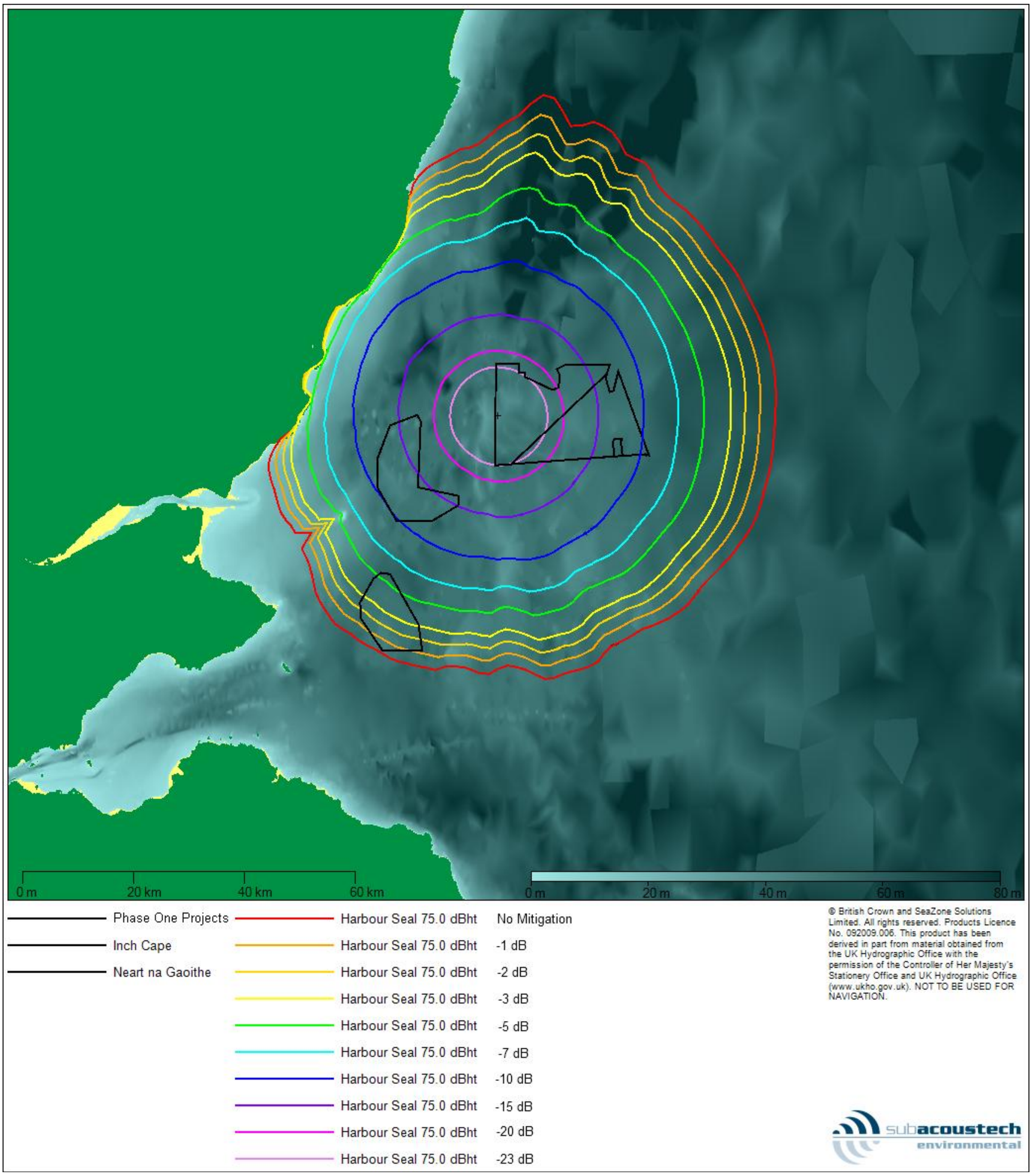

Figure 6-165 Contour plot showing the estimated impact ranges of Harbour Seal 75 dB$_{ht}$ for increasing levels of attenuation of noise from piling at the alpha position

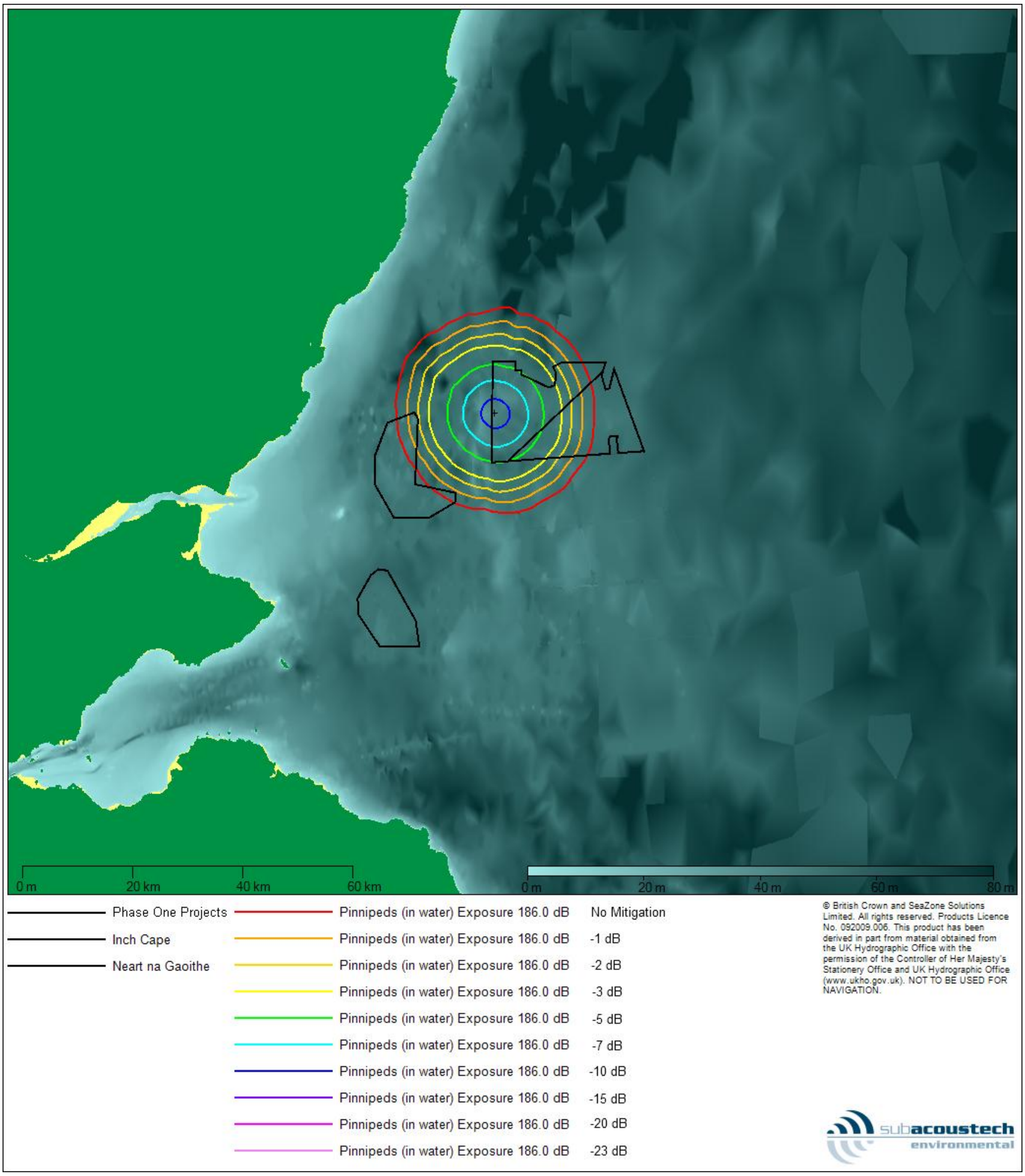

Figure 6-166 Contour plot showing the estimated M-weighted SEL 186 dB impact ranges for Pinnipeds (in water) for increasing levels of attenuation of noise from piling at the alpha position

7 Summary and Conclusions

Subacoustech Environmental has undertaken a study on behalf of Seagreen Wind Energy Ltd to assess the impact of a range of impact piling scenarios at the Firth of Forth Phase 1 Wind Farm site.

The level of underwater noise from the installation of monopiles and 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 40 m, and that physical injury is likely to occur out to a maximum range of 60 or 80 m, depending on the piling scenario modelled.

The possibility of traumatic auditory (hearing) injury has been assessed using the 130 dB$_{\text{ht}}$(*Species*) criteria, for which the largest estimated ranges are for humpback whale, with 130 dB$_{\text{ht}}$ ranges for the humpback whale of up to 820 m during the fully driven scenario and 740 m during the drill-drive scenario.

Behavioural impacts on marine species have been assessed using the 90 and 75 dB$_{\text{ht}}$(*Species*) criteria and show that the largest impact ranges are predicted for herring, harbour porpoise and humpback whale, with a maximum 90 dB$_{\text{ht}}$ impact range for herring of 35 km, 21 km for harbour porpoise and 45 km for the humpback whale for the worst case fully driven scenario, GM2.

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 9.2 km is likely to be needed at the onset of the impact piling for the GM1 (bravo) scenario to avoid a damaging exposure to sound, using the Southall *et al* (2007) criteria. Lower ranges are predicted for all the criteria using the 198 dB threshold. The maximum range for a cumulative scenario of simultaneous piling at Neart Na Gaoithe Wind Farm (drill-drive), Inch Cape Wind Farm and Firth of Forth Phase 1 has been found to be 31 km for the 186 dB SEL M-weighted criteria for pinnipeds (in water).

Further modelling has been undertaken to offer an indication on the effect of mitigation on impact ranges, by attenuation of the piling noise at the source.

Bibliography and references

1. Arons A.B. (1954). *Underwater explosion shock wave parameters at large distances from the charge.* JASA, 26, 3, p3143.
2. Bebb A H and Wright H C. (1953). *Injury to animals from underwater explosions.* Medical Research Council, Royal Navy Physiological Report 53/732, Underwater Blast Report 31, January 1953.
3. Bebb A H and Wright H C. (1954a). *Lethal conditions from underwater explosion blast.* RNP Report 51/654, RNPL 3/51, National archives reference ADM 298/109, March 1954.
4. Bebb A H and Wright H C. (1954b). *Protection from underwater explosion blast. III Animal experiments and physical measurements.* RNP Report 54/792, RNPL 2/54, March 1954
5. Bebb A H and Wright H C. (1955). *Underwater explosion blast Data from the Royal Navy Physiological Labs 1950/55.* Medical Research Council, April 1955
6. Blaxter J H S, Denton E J and Gray J A B. (1981). *Acousticolateralis system in clupeid fishes.* Ed’s Tavolga W; Popper A; Fay R. *Hearing and sound communication in fishes*. Springer Verlag. New York. pp 39-61
7. Brekhovskikh L M. (1960). *Propagation of surface Rayleigh waves along the uneven boundary of an elastic body.* Sov. Phys. Acoust
8. Caltrans (2001). *Pile Installation Demonstration Project, San Francisco – Oakland Bay Bridge, East Span Seismic Safety Project*, PIPD EA 01281, Caltrans contract 04A0148, August 2001.
9. Chapman C J and Sand O. (1974). *Field studies of hearing in two species of flatfish Pleuronectes platessa (L.) and Limanda limanda (L.) (Family Pleuronectidae).* Comp. Biochem. Physiol. 47A, 371-385.
10. Cudahy E and Parvin S (2001). *The effects of underwater blast on divers.* Naval Submarine Medical Research Laboratory Report 1218, Groton, CT 06349 62 p
11. Enger P S and Andersen R A (1967). *An electrophysiological field study of hearing in fish.* Comp. Biochem. Physiol. 22, 517-525.
12. Erbe C. (2002). *Hearing abilities of Baleen Whales.* Defence R&D Canada. Atlantic report CR 2002-065.
13. Goertner J F. (1982) *Prediction of underwater explosion safe ranges for sea mammals.* NSWC/WOL TR-82-188. Naval surface Weapons Centre, White Oak Laboratory, Silver Spring, MD, USA, NTIS AD-A139823
14. Hastings M C and Popper A N. (2005). *Effects of sound on fish.* Report to the California Department of Transport, under contract No. 43A01392005, January 2005.
15. Hawkins A D. (1981). *The hearing abilities of fish.* Ed’s Tovolga W; Popper A; Fay R. *Hearing and sound communication in fishes.* Springer Verlag. New York. pp 109-139.
16. Hildebrand J (2004). *Impacts of anthropometric sound on cetaceans.* International Whaling Commission. IWC/SC/56/E13 report, Sorrento, Italy. Available at http://cetus.ucsd.edu/projects/pub/SC-56-E13Hilde.pdf.
17. Hill, S.H. (1978). *A guide to the effects of underwater shock waves in arctic marine mammals and fish.* Pacific Mar. Sci. Rep.78-26. Inst. Ocean Sciences, Patricia Bay, Sidney, B.C. 50 pp
18. Johnson C S. (1967). *Sound detection thresholds in marine mammals.* In Tavolga W N (ed), *Marine bioacoustics*, Vol 2, Pergamon, Oxford, UK.

19. Kastak D and Schustermann R J. (1998). *Low frequency amphibious hearing in pinnipeds: methods measurements, noise and ecology.* Journal of the Acoustical Society of America, 103(4), 2216-2228.

20. Kastelein R A, Bunskoek P, Hagedoorn M, Au W W L and Haan D. (2002). *Audiogram of the harbour porpoise (Phocoena phocoena) measured with narrow-band frequency-modulated signals.* J.Acoust.Soc.Am., Vol 113 (2), pp1130-1137

21. Lovell J M, Findlay M M, Moate R M, Nedwell J R and Pegg M A. (2005). *The inner ear morphology and hearing abilities of the paddlefish (Polyodon spathula) and the lake sturgeon (Acipenser fulvescens).* Comp. Biochem. Physiol. A: Mol. Integr. Physiol. 142, 286–296

22. Madsen P T, Wahlberg M, Tougard J, Lucke K and Tyack P. (2006). *Wind turbine underwater noise and marine mammals: Implications of current knowledge and data needs.* Marine Ecology Progress Series, Vol. 309: pp279-295, March 2006.

23. Maes J, Turnpenny A W H, Lambert D R, Nedwell J R, Parmentier A and Olivier F (2004). *Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet*. J.Fish.Biol. 64, pp938 – 946.

24. Mohl B. (1968). *Auditory sensitivity of the common seal in air and water.* Journal of Auditory Research, 8, 27-38.

25. Nedwell J R, Langworthy J and Howell D. (2003a). *Assessment of sub-sea acoustic noise and vibration from offshore wind turbines and its impact on marine wildlife; initial measurements of underwater noise during construction of offshore wind farms, and comparison with background noise.* Subacoustech Report ref: 544R0423, published by COWRIE, May 2003.

26. Nedwell J R, Turnpenny A W H, Lovell J, Langworthy J W., Howell D M & Edwards B. (2003b). *The effects of underwater noise from coastal piling on salmon (Salmo salar) and brown trout (Salmo trutta).* Subacoustech report to the Environment Agency, reference 576R0113, December 2003.

27. Nedwell J R, Parvin S J, Edwards B, Workman R, Brooker A G and Kynoch J E (2007a) *Measurement and interpretation of underwater noise during construction and operation of offshore windfarms in UK waters.* Subacoustech Report No. 544R0738 to COWRIE. ISBN: 978-09554279-5-4.

28. Nedwell J R, Turnpenny A W H, Lovell J, Parvin S J, Workman R, Spinks J A L, Howell D (2007b). *A validation of the dB*$_{ht}$ *as a measure of the behavioural and auditory effects of underwater noise.* Subacoustech Report Reference: 534R1231, Published by Department for Business, Enterprise and Regulatory Reform.

29. Parvin S J, Nedwell J R and Workman R. (2006). *Underwater noise impact modelling in support of the London Array, Greater Gabbard and Thanet offshore wind farm developments*. Report to CORE Ltd by Subacoustech Ltd Report No. 710R0517

30. Parvin S J, Nedwell J R and Harland E (2007). *Lethal and physical injury of marine mammals, and requirements for Passive Acoustic Monitoring.* Subacoustech Report 565R0212, report prepared for the UK Government Department for Business, Enterprise and Regulatory Reform.

31. Popper A N and Fay R R. (1993). *Sound detection and processing by fish: critical review and major research questions.* Brain Behav. Evol. 41, 14-38.

32. Popper A N, Fewtrell J, Smith M E and McCauley R D. (2004). *Anthropogenic sound: Effects on the behaviour and physiology of fishes.* Marine Technology Soc. J. 37(4). pp 35-40.

33. Popper A N, Carlson T J, Hawkins A D, Southall B L and Gentry R L. (2006) *Interim Criteria for injury of fish exposed to pile driving operations*: A white paper.
34. Rawlins J S P. (1974). *Physical and patho-physiological effects of blast.* Joint Royal Navy Scientific service. Volume 29, No. 3, pp124 – 129, May 1974.
35. Rawlins J S P. (1987). *Problems in predicting safe ranges from underwater explosions.* Journal of Naval Science, Volume 14, No.4 pp235 – 246
36. Richardson W J, Greene, C R, Malme C I and Thompson D H. (1995). *Marine mammals and noise*. Academic Press Inc, San Diego, 1995.
37. Richmond D R, Yelverton J T and Fletcher E R. (1973). *Far-field underwater blast injuries produced by small charges.* Defense Nuclear Agency, Department of Defense Washington, D.C. Technical Progress Report, DNA 3081
38. Ridgeway S H and Joyce P L (1975). *Studies on the seal brain by radiotelemetry.* Rapp. P.V. Reun. Cons. Int. Explor. Mer, 169, 81-91.
39. Southall B L, Bowles A E, Ellison W T, Finneran J J, Gentry R L, Greene C R, Kastak D, Ketten D R, Miller J H, Nachtigall P E, Richardson W J, Thomas J A, Tyack P L. (2007) *Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations*. Aquatic Mammals.
40. Thomsen F, Lüdemann K, Kafemann R and Piper W. (2006). *Effects of offshore wind farm noise on marine mammals and fish*, on behalf of COWRIE Ltd
41. Turnpenny A W H and Nedwell J R. (1994). *The effects on marine fish, diving mammals and birds of underwater sound generated by seismic surveys.* Report to the UK Offshore Operators Association (UKOOA). No. FRR 089/94, Fawley Aquatic Research Laboratories Ltd, Southampton, UK, 1994.
42. Urick, R., (1983). *Principles of underwater sound*, New York: McGraw Hill.
43. Wursig B, Greene C R and Jefferson T A. (2000). *Development of an air bubble curtain to reduce underwater noise of percussive piling.* Mar.Environ.Res. 49, pp 79 – 93.
44. Yelverton J T, Richmond D R, Fletcher E R and Jones R K. (1973). *Safe distances from underwater explosions for mammals and birds.* DNA 3114T, Lovelace Foundation for Medical Education and Research, Final Technical Report, July 1973.
45. Yelverton J T, Richmond D R, Hicks W, Saunders K and Fletcher E R. (1975). *The relationship between fish size and their response to underwater blast.* DNA 3677T, Lovelace Foundation for Medical Education and Research, Final Technical Report, June 1975.
46. Yelverton J, et al., (1981). *Underwater explosion damage risk criteria for fish, birds and mammals,* presented at 102nd Meet. Acoust. Soc. Am., Miami Beach, FL

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