Annex A

Underwater Noise Modelling Technical Report

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10 TECHNICAL REPORT

10.1 INTRODUCTION

10.1.1 This annex presents in detail the results of modelling undertaken to provide a prediction of the likely extent of impacts on marine fauna as a result of underwater noise generated during the construction and operation of the Beatrice Offshore Wind Farm. It also provides a summary of the technical background to underwater noise, the various metrics used to assess its impact and any additional details relating to the noise modelling methodology.

10.2 MEASUREMENT OF UNDERWATER NOISE

Introduction

10.2.1 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[1] and 2007a[2]). 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).

Units of Measurement

10.2.2 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".

10.2.3 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 the "Sound Pressure Level".

10.2.4 The fundamental definition of the dB scale is:

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

(1) 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.

(2) 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 Ltd. ISBN: 978-09554279-5-4.

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

10.2.5 The dB scale represents a ratio and 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.

10.2.6 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 (SPL) 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:

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

10.2.7 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). For the SPL, an increase in level of 6 dB means a doubling of pressure.

Quantities of Measurement

10.2.8 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.

Peak Level

10.2.9 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, 1955)[1&2], Richmond *et al* (1973)[3], Yelverton *et al* (1973)[4] and Yelverton (1981)[5]. 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)[6];

(1) 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.

(2) 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

(3) 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

(4) 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.

(5) 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

(6) 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.

Hill (1978)[(1)]; Goertner (1982)[(2)]; Richardson *et al (*1995)[(3)]; Cudahy and Parvin (2001)[(4)]; Hastings and Popper (2005)[(5)]). The peak sound level of a freely suspended charge of Tri-Nitro-Toluene (TNT) in water can be estimated from Arons (1954)[(6)], as summarised by Urick (1983)[(7)]. 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 @ 1 m (Parvin *et al (*2007))[(8)].

Peak-to-peak Level

10.2.10 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.

10.2.11 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)[(9)], Nedwell *et al* (2007a)) [(10)].

Sound Pressure Level

10.2.12 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.

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(1) 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

(2) 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

(3) Richardson W J, Greene, C R, Malme C I and Thompson D H. (1995). **Marine mammals and noise**. Academic Press Inc, San Diego.

(4) 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

(5) 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.

(6) Arons A B. (1954). **Underwater explosion shock wave parameters at large distances from the charge**. JASA, 26, 3, p3143.

(7) Urick R. (1983). **Principles of underwater sound**, New York: McGraw Hill.

(8) 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.

(9) Parvin S J and Nedwell J R. (2006b). Underwater **noise survey during impact piling to construct the Barrow Offshore Wind Farm**. COWRIE Project ACO-04-2002, Subacoustech Report 544R0602.

(10) 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 Ltd. ISBN: 978-09554279-5-4.

10.2.13 As an example, small sea going vessels typically produce broadband noise at source SPLs from 170 to 180 dB re 1 μPa @ 1 m (Richardson *et* al (1995))(1), whereas a supertanker generates source SPLs of typically 198 dB re 1 μPa @ 1 m (Hildebrand (2004))(2).

10.2.14 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.

Sound Exposure Level

10.2.15 When assessing the noise from transient sources such as blast waves, impact piling or seismic airguns, the issue of the time duration of the pressure wave (highlighted above) is often addressed by measuring the energy flux density of the wave. This form of analysis was used by Bebb and Wright (1951 to 1955)(3), and later by Rawlins (1987)(4) 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(5); Popper *et al*, 2006(6)).

10.2.16 The Sound Exposure sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound and the length of time the sound is present in the acoustic environment.

10.2.17 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.

10.2.18 Sound Exposure is a proportional to the acoustic energy and has units of Pascal squared seconds (Pa^2s).

10.2.19 To express the Sound Exposure on a logarithmic scale by means of a dB, it is compared with a reference acoustic energy $(P_{ref})^2T_{ref}$, using 1 μPa for P_{ref} and 1 sec for T_{ref}. The Sound Exposure Level (SEL) is then defined by:

(1) Richardson W J, Greene, C R, Malme C I and Thompson D H. (1995). **Marine mammals and noise**. Academic Press Inc, San Diego.

(2) 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.

(3) 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

(4) Rawlins J S P. (1987). **Problems in predicting safe ranges from underwater explosions**. Journal of Naval Science, Volume 14, No.4 pp235 – 246

(5) 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.

(6) 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.**

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

10.2.20 By selecting a common reference pressure for the SPL and the SEL (ie 1 μPa) for assessments of underwater noise, the SEL and SPL can be compared using the expression:

$SEL = SPL + 10\log_{10}T$ .... 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.

10.2.21 Therefore, for continuous sounds of duration less than one second, the SEL will be numerically lower than the SPL. For periods greater than one second the SEL will be numerically greater than the SPL. For example, for a sound of 10 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.

Impulse

10.2.22 The Impulse (I) is defined as the integral of pressure over time and is given by the equation:

$I = \int_0^\infty P(t)dt$ .... eqn. 2-6

where *I* is the impulse in Pascal-seconds (Pa.s), *P(t)* is the acoustic pressure in Pa of the blast wave at time *t* and *t* is time. Impulse may be thought of as the average pressure of the wave multiplied by its duration. The importance of Impulse is that in many cases a wave acting for a given time will have the same effect as one of twice the pressure acting for half the time. The Impulse of both these waves would be the same.

10.3 OVERVIEW OF HEARING IN FISH AND MARINE MAMMALS

Introduction

10.3.1 The ways fish react following their exposure to underwater sound relate to the way in which they hear. 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))[(1)]. Furthermore, published data also indicate that, for fish which are sensitive to sound, there is a considerable variation in the hearing abilities, both in terms of the minimum levels of sound perceptible and the frequency range over which they can hear (e.g. Hawkins (1981)[(2)];

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(1) 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

(2) Hawkins A D. (1981). **The hearing abilities of fish**. Eds Tovolga W; Popper A; Fay R. Hearing and sound communication in fishes. Springer Verlag. New York. pp 109 - 139.

10.3.2 Lovell *et al* (2005)[1]; Popper *et al* (2004)[2]; Hastings and Popper (2005)[3]; Thomsen *et al* (2006)[4]; Madsen *et al* (2006)[5]). Any assessment of potential impacts on a particular species must therefore take this into account.

10.3.3 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)[6]; Popper *et al* (2004)[7]). 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.

10.3.4 In general, fish that are considered hearing specialists, such as the herring, are able to perceive sounds in the frequency range 30 Hz to 4 kHz, though at the higher frequencies sensitivity is very low. Threshold levels for these species are at approximately 75 dB re 1 µPa at frequencies between 30 Hz and 1 kHz.

10.3.5 In comparison, the less sensitive group, termed hearing generalists, including the dab and the bass, are only able to perceive sounds between 30 Hz and 400 Hz, with peak sensitivity at 118 dB re 1 µPa over this range, though the salmon, representing one of the more sensitive hearing generalists, has a threshold level of 95 dB re 1 µPa at 160 Hz. In comparison, the dab, a hearing generalist, has a threshold level of approximately 90 dB re 1 µPa at frequencies between 30 Hz and 200 Hz.

10.3.6 In contrast to fish, marine mammal species, such as the bottlenose dolphin, *Tursiops truncatus*, and harbour porpoise, *Phocoena phocoena*, are sensitive to a very broad bandwidth of sound. Audiogram data for the porpoise indicate that they are responsive at frequencies from 100 Hz to 170 kHz. Peak hearing sensitivity occurs over the frequency range 20 kHz to 150 kHz, where, for example, the audiogram for the harbour porpoise (Kastelein *et al* (2002))[8] indicates that it is able to hear sounds below 40 dB re 1 µPa. This typically corresponds to sea noise levels at these frequencies.

Introduction to Audiograms

10.3.7 An audiogram is a means of showing a species' sensitivity to sound; it is the variation of hearing threshold level with frequency of sound stimulus. The principle of measuring an audiogram is that sound at a single frequency and a

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(1) Lovell, J.M, Findlay, M.M, Moate, R.M & Yan H.Y (2005). **The hearing abilities of the prawn (Palaemon serratus).** Comp. Biochem. Physiol. A Mol. Integr. Physiol. Vol 140/1 pp 89-100

(2) 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). pp35-40.

(3) 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.

(4) Thomsen F, Lüdemann K, Kafemann R, Piper W. (2006). **Effects of offshore wind farm noise on marine mammals and fish**, on behalf of COWRIE Ltd.

(5) Madsen P T, Wahlberg M, Tougaard 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.

(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) 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). pp35-40.

(8) Kastelein R A, Bunskoek P, Hagedoornm, 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

known level is presented to the test subject, typically in the form of a pulsed tone. A uniform, calibrated sound field is created, in air, by means of a loudspeaker or headphones, and in water by underwater projectors. A protocol is required to determine whether the subject has heard the sound stimulus. For humans this is normally in the form of the subject pressing a button if it has detected the sound (a behavioural response). The level of the stimulus is then reduced and the test repeated. (This method is generally known as the 'staircase method'). Eventually a level is reached at which the subject can no longer detect the sound, which is therefore below the subject's threshold of hearing. The actual threshold is taken to be the last level that evoked a repeatable response. The measurement is typically repeated at a range of frequencies.

Audiograms of Underwater Species

10.3.8 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 audiograms 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 animal's hearing mechanism) (see, for example, Lovell *et al* (2005)(1)).

10.3.9 Behavioural response techniques rely on training an animal to provide a specific response when an auditory stimulus is heard. This can take the form of a reward-based procedure, usually involving the feeding of an animal, or obtaining a conditioned response by some form of aversion response — for example electric shocks have been used. When the animal hears the sound it is usually required to move into or out of a predetermined area. The disadvantage of this type of technique is that it relies upon the compliance of the subject and can only be used with animals that can easily be trained.

10.3.10 An alternative approach involves direct measurement of the Auditory Evoked Potential (AEP), a bio-electric impulse in the auditory nerves that results from stimulation of the sensory hair cells within the ear. In this approach either subcutaneous or cutaneous electrodes are attached to the animal to measure the response to the sound directly. This latter technique is referred to as the Auditory Brainstem Response, or ABR, method.

10.3.11 Audiograms for a number of species considered in this assessment are given in Figures 10.1 to 10.3 below.

(1) Lovell, J.M, Findlay, M.M, Moate, R.M & Yan H.Y (2005). **The hearing abilities of the prawn (Palaemon serratus).** Comp. Biochem. Physiol. A Mol. Integr. Physiol. Vol 140/1 pp 89-100

Figure 10.1 Audiograms for species of cetacean

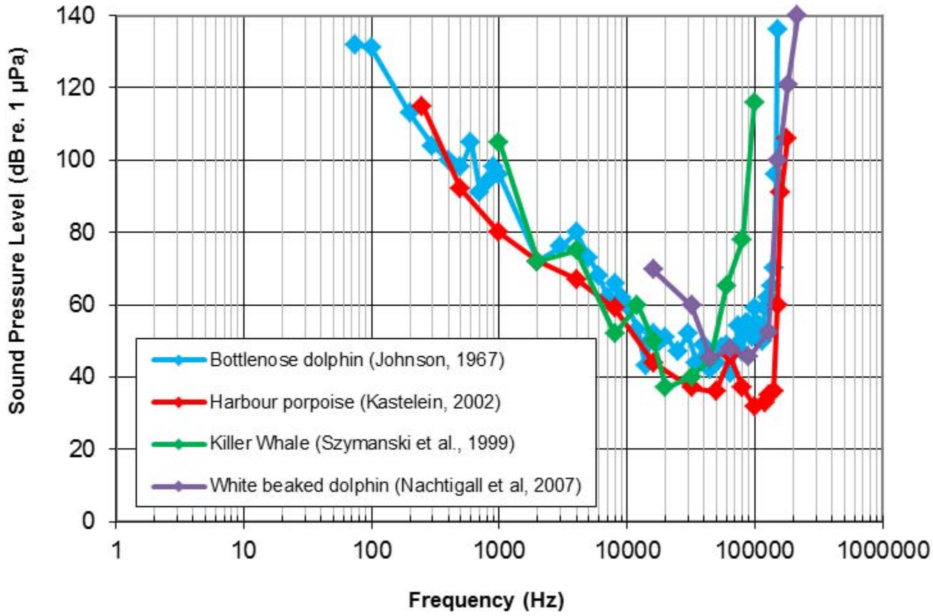


Figure 10.2 Audiograms for species of seal

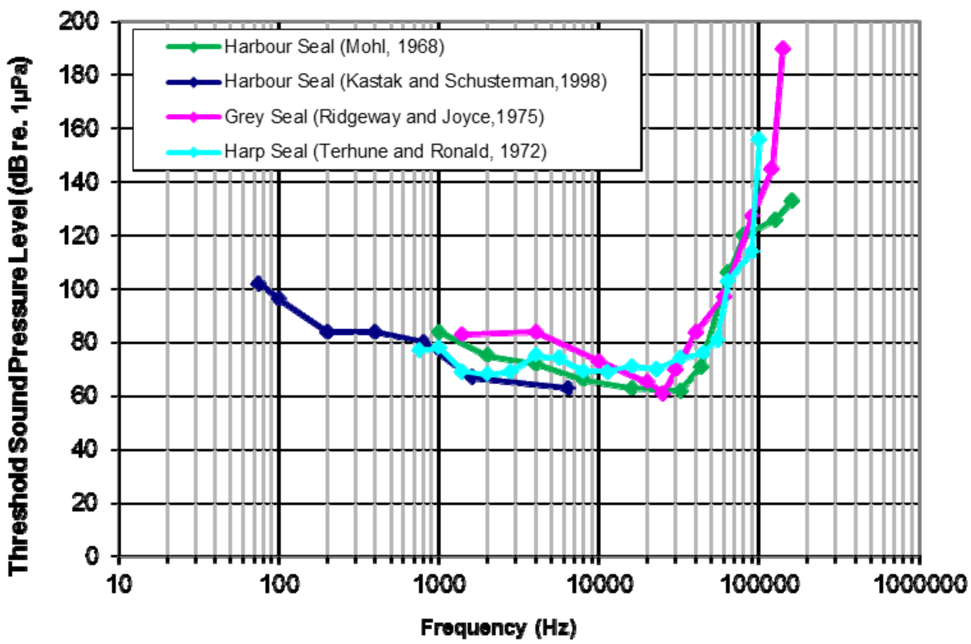
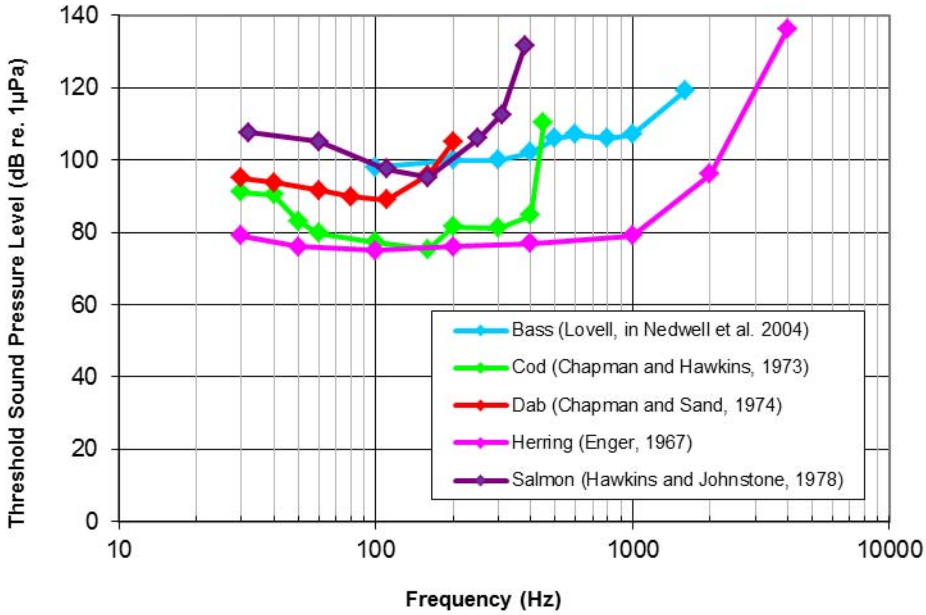


Figure 10.3 Audiograms for species of fish



A metric which take into account a species' hearing sensitivity — the dB_{ht}

10.3.12 Measurements of noise are frequently made using an unweighted RMS level of that sound, or its peak pressure. 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 response of animals to activities generating underwater noise, as avoidance is associated with the perceived level of loudness and vibration of the sound by the animals. Therefore, the same underwater noise may have a different impact on different species with different hearing sensitivities.

10.3.13 Where the intention is to estimate these more subtle behavioural or audiological effects of noise, caused by "loudness", hearing ability has to be taken into account and simple metrics based on unweighted measures are inadequate. For instance, it has been determined that in humans a metric incorporating a frequency weighting that parallels the sensitivity of the human ear is required to accurately assess the behavioural effects of noise, hence the use of frequency weighted measures by regulatory bodies worldwide, such as the Health and Safety Executive in the UK, as a method off assessing the impacts of noise in the workplace. The most widely used metric in this case is the dB(A), which incorporates a frequency weighting (the A-weighting), based on the 40-phon human hearing curve.

10.3.14 The dB_{ht} (*Species*) metric (Nedwell *et al* (2007b)[(1)]) has been developed as a means for quantifying the potential for a behavioural impact of a sound on a

(1) 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.

species in the underwater environment. It is similar to the dB(A) in that it uses a species' audiogram in its calculation.

10.3.15 As 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 using this metric. For instance, the same construction event might have a level of 70 dB_{ht}(*Salmo salar*) for a salmon, and 110 dB_{ht}(*Tursiops truncatus)* for a bottlenose dolphin.

10.3.16 The perceived noise levels of sounds measured in dB_{ht}(*Species*) are usually much lower than the unweighted levels, both because the sound will contain frequency components that the species cannot detect, and also because most species that live in the underwater environment have high thresholds of perception (i.e. are relatively insensitive) of sound.

The M-weighting curves for marine mammals

10.3.17 Based on the evidence from numerous studies of auditory damage Southall *et al* (2007)(1) proposed a procedure for assessing the possible effects of sound on marine mammals when using the Sound Exposure metric. They proposed that the sound should be filtered into 'generic' frequency ranges or passbands for four groups of mammals, viz low, mid and high frequency cetaceans, and pinnipeds in water. The four passbands are shown in Figure 10.4 below. The levels resulting from employing these are termed by the authors 'M-weighted Sound Exposure Levels', and are given in dB re 1 $\mu Pa^2.s$ (M_{lf}) for the low frequency hearers. The 'M_{lf}' is replaced by 'M_{mf}' and 'M_{hf}' for the other cetaceans as appropriate, and 'M_{pw}' for the pinnipeds. It should be noted that strictly the nomenclature is inaccurate as the sound is not *weighted* but rather *filtered* to remove low and high frequencies. Between these frequencies the sound is unweighted. The distinction is important as most marine animals have highly sloped audiograms, and an unweighted measure may tend to overestimate the effects of sound at low frequencies and underestimate it at high frequencies.

(1) Southall, Brandon L.; Bowles, Ann E.; Ellison, William T.; Finneran, James J.; Gentry, Roger L.; Greene, Charles R.; Kastak, David; Ketten, Darlene R.; Miller, James H.; Nachtigall, Paul E.; Richardson, W. John; Thomas, Jeanette A.; Tyack, Peter L, (2007). **Marine Mammal Noise Exposure Criteria Aquatic Mammals**, Vol 33 (4).

Figure 10.4 The M weighting curves for cetaceans

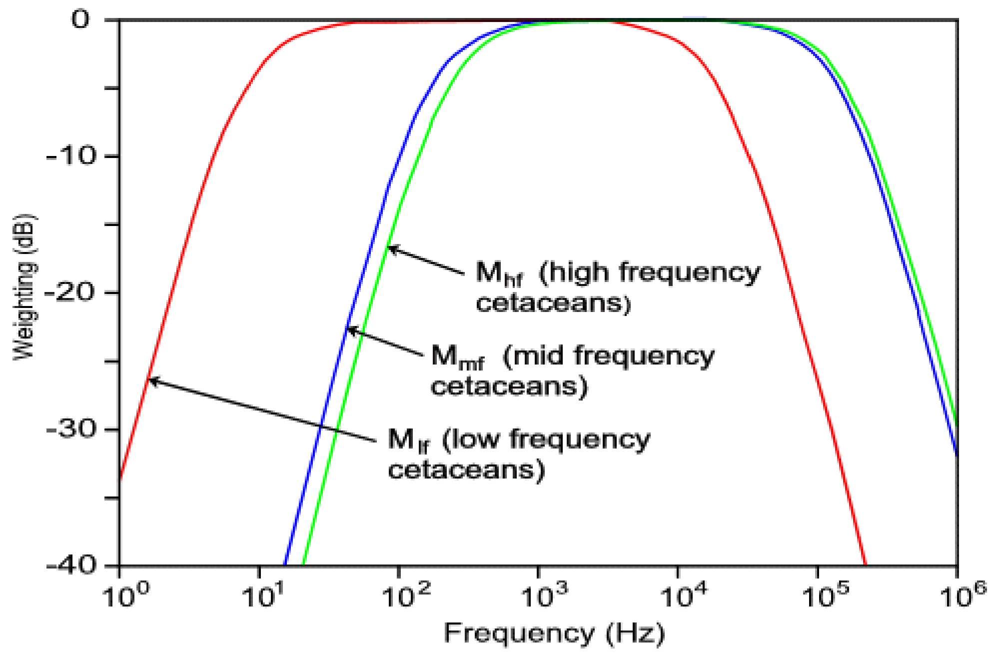
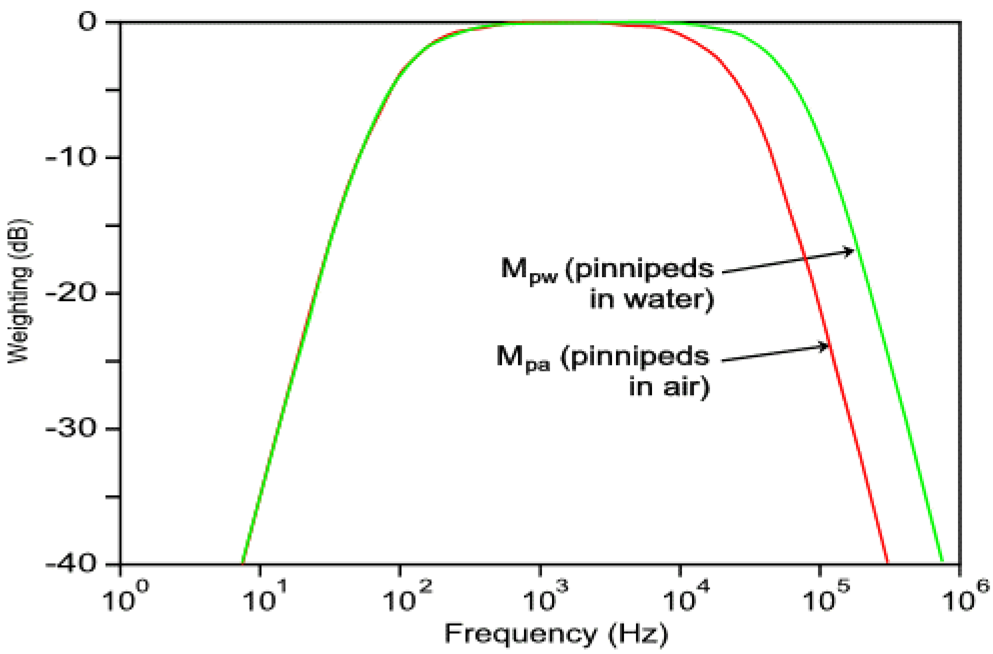


Figure 10.5 The M-weighting curves for pinnipeds



10.4 *IMPACT OF UNDERWATER SOUND ON MARINE SPECIES: ASSESSMENT CRITERIA*

Introduction

10.4.1 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 on a particular species is dependent upon the level of the incident sound, its frequency content, its duration and/or its repetition rate (see, for example Hastings and Popper (2005)(1)). As a result scientific interest in the hearing abilities of aquatic animal species has increased.

10.4.2 A review by Popper *et al* (2006)(2) suggests the use of unweighted sound exposure metrics, such as the peak level and the SEL of the noise, to develop interim guidance for estimating the injury range for fish from pile driving operations. Similarly, a review of the effects of underwater noise from offshore wind farms on marine mammals (Madsen *et al* (2006)(3)) discusses the use of frequency weighting of the underwater noise in assessing its impact. The authors comment that the impact of underwater sound on the auditory system is frequency dependent and, ideally, noise levels should (as for humans) be weighted using the defined frequency responses of the auditory system of the animal in question.

10.4.3 The approach that has been adopted in this study has been to use unweighted sound level metrics to define the potential for gross damage, such as fatality, swim bladder rupture or tissue damage, since hearing is not involved in those impacts. To assess ranges at which an aversive response to the piling would be expected frequency weighted measures of the sound, based on the hearing thresholds of the affected species, have been used.

Lethality and Physical Injury Impacts and their Associated Sound Levels

Introduction

10.4.4 At the highest level, typically during underwater blast from explosives, sound has the ability to cause injury and, in extreme cases, the death of exposed animals.

10.4.5 Due to the current lack of information on potential lethal and physical injury effects from impact piling, this study has used the data from blast exposures to estimate impact zones. The waveforms from these two noise sources are rather different. The transient pressure wave from an impact piling operation has roughly equal positive and negative pressure amplitude components and a relatively long duration of up to a few hundred milliseconds. By contrast, blast waves have a very high positive pressure peak followed by a much lower amplitude, negative wave due to the momentum imparted to the water surrounding the explosive gas bubble. The pressure of a blast wave is normally quantified therefore in terms of the peak level, due to the dominance of the positive peak of the waveform. There is, therefore, a level of uncertainty as to whether a blast wave criterion can be directly applied to a transient waveform arising from an impact piling operation.

(1) 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.

(2) 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.**

(3) Madsen P T, Wahlberg M, Tougaard 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.

Criteria for Assessing Lethality and Physical Injury

10.4.6 The following criteria have been applied in this study for levels of noise likely to cause physical effects (Parvin *et al* (2007)[(1)]), based on data in the studies of Yelverton (1975)[(2)], Turnpenny *et al* (1994)[(3)] and Hastings and Popper (2005)[(4)]:

- lethal effect may occur where peak-to-peak levels exceed 240 dB re 1 µPa, or an impulse of 100 Pa.s; and
- physical injury may occur where peak-to-peak levels exceed 220 dB re 1 µPa, or an impulse of 35 Pa.s.

10.4.7 It should be noted however that for smaller fish sizes of mass 0.01 g Hastings and Popper (2005)[(5)], and Popper *et al* (2006)[(6)] recommend an interim "no injury" criteria 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^2s. 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 the present study.

Audiological Injury and its Associated Sound Levels

Introduction

10.4.8 The concept of auditory injury from exposure to noise is well established for airborne sound exposure of humans. At a high enough level of sound traumatic hearing injury may occur even where the duration of exposure is short. Injury also occurs at lower levels of noise where the duration of exposure is long. In this case the degree of hearing damage depends on both the level of the noise and the duration of exposure to it.

Criteria for the Assessment of Audiological Injury

10.4.9 On the basis of a large body of measurements of fish avoidance of noise (Maes *et al* (2004)[(7)]), and from re-analysis of marine mammal behavioural response to underwater sound, Nedwell *et al* (2007)[(8)] has suggested that the use of a level of 130 dB_{ht}, similar to that used for human exposure in air, provides a suitable criterion for predicting the onset of traumatic hearing damage (i.e.

(1) 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.

(2) 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.

(3) Turnpenny A W H, Thatcher K P and Nedwell J R. (1994). **The effects on fish and other marine animals of high-level underwater sound.** Report FRR 127/94, Fawley Aquatic Research Laboratories, Ltd., Southampton, UK.

(4) 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.

(5) 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.

(6) 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.**

(7) 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.

(8) 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.

where immediate traumatic and irreversible damage occurs), which recognises the varying hearing sensitivity of differing species.

10.4.10 Another set of criteria, based on the evidence from numerous studies of auditory damage, has been proposed by Southall *et al* (2007)(1). That study, however, considers the likelihood of hearing damage (permanent threshold shift, or PTS) caused by accumulated noise exposure, rather than occurring as a result of a single event. Their auditory injury criteria, for various groups of marine mammals, are based on Peak Pressure Levels and M-weighted Sound Exposure Levels (dB re 1 µPa^2.s (M)). The criteria are given in Table 10.1. The results of the present study have also been presented in terms of this metric.

Table 10.1 Proposed injury criteria for various marine mammal groups

	Sound type	
Marine mammal group	**Single pulse**	**Multiple pulses**
Low Frequency Cetaceans		
Peak Pressure Level	230 dB re 1 µPa	230 dB re 1 µPa
Sound Exposure Level	198 dB re 1 µPa^2.s (M_{lf})	198 dB re 1 µPa^2.s (M_{lf})
Mid Frequency Cetaceans		
Peak Pressure Level	230 dB re 1 µPa	230 dB re 1 µPa
Sound Exposure Level	198 dB re 1 µPa^2.s (M_{mf})	198 dB re 1 µPa^2.s (M_{mf})
High Frequency Cetaceans		
Peak Pressure Level	230 dB re 1 µPa	230 dB re 1 µPa
Sound Exposure Level	198 dB re 1 µPa^2.s (M_{hf})	198 dB re 1 µPa^2.s (M_{hf})
Pinnipeds (in water)		
Peak Pressure Level	218 dB re 1 µPa	218 dB re 1 µPa
Sound Exposure Level	186 dB re 1 µPa^2.s (M_{pw})	186 dB re 1 µPa^2.s (M_{pw})
Proposed pinniped SEL	198 dB re 1 µPa^2.s (M_{pw})	198 dB re 1 µPa^2.s (M_{pw})
Source: Southall *et al* (2007)		

10.4.11 The Southall study criteria can be used for both single pulse noise sources and multiple pulse sources. This report presents estimated ranges of effect for impact pile driving using Southall *et al*'s multiple impact SEL criteria. This modelling is carried out by assuming a swim speed and starting range for the animals and hence calculating the accumulated exposure as the animal moves away from the noise source. The M-weighted Sound Exposure Level at each range as the animal moves is calculated using the INSPIRE model.

10.4.12 Recent research undertaken by Thompson and Hastie(2) has suggested that although the 186 dB re 1 µPa^2.s SEL injury criterion is generally used at present, there is a shortage of evidence for this criterion for pinnipeds. Their research suggests that based on the available research, 198 dB re 1 µPa^2.s SEL as per cetaceans, is also appropriate for pinnipeds based on current knowledge. This criterion has also been included in the noise exposure modelling.

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(1) Southall, Brandon L.; Bowles, Ann E.; Ellison, William T.; Finneran, James J.; Gentry, Roger L.; Greene, Charles R.; Kastak, David; Ketten, Darlene R.; Miller, James H.; Nachtigall, Paul E.; Richardson, W. John; Thomas, Jeanette A.; Tyack, Peter L, (2007). **Marine Mammal Noise Exposure Criteria Aquatic Mammals**, Vol 33 (4).

(2) Thompson, P and Hastie, G. **Proposed revision of noise exposure criteria for auditory injury in pinnipeds.** (In prep)

10.4.13 For marine mammal exposures, two techniques are used to assess overall noise exposure over the duration of piling: a stationary and a 'fleeing animal' model. These two techniques are used to cover two eventualities based on an uncertainty in how the animals in question are likely to react following a sudden exposure to a high noise source. With a stationary model, the calculation assumes the animal will not move once

Behavioural Impacts and their Associated Sound Levels

Introduction

10.4.14 At levels lower than those that cause physical injury or permanent threshold shift (PTS), 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 of interest 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 impedes the migration of a species. However, in other cases the movement of species from one area to another may be of no consequence.

10.4.15 Avoidance appears to be associated with a sensation of "unbearable loudness". Hence, in order to judge the potential of a noise to cause avoidance, it is necessary to be able to ascertain the perception of the sound by the species, i.e. how loud the sound appears to individuals of that species. Individuals of species having poor hearing may perceive the level as low, and hence not react to the noise, whereas a species that is sensitive may find the level unbearably loud and react by swimming away. Therefore, of key importance in the process is an understanding of the hearing ability of the species that may be affected.

Criteria for Assessing Behavioural Response

10.4.16 If the level of sound is sufficiently high on the dB_{ht}(*Species*) scale, it is likely that an avoidance reaction will occur. The response from a species will be probabilistic in nature (e.g. at 75 dB_{ht}(*Species*) one individual from a species may react, whereas another individual may not: the metric indicates the *probability* of an individual reacting), and may also vary depending upon the type of signal. A level of 0 dB_{ht}(*Species*) represents a sound that is at the hearing threshold for that species and is, therefore, at a level at which sound will start to be 'heard'. At this and lower perceived sound levels no response occurs as the receptor cannot hear the sound.

10.4.17 Currently, on the basis of a large body of measurements of fish avoidance of noise (Maes *et al* (2004)[(1)]), and from re-analysis of marine mammal behavioural response to underwater sound, the following assessment criteria were published by the Department of Business, Enterprise and Regulatory

(1) 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.

Reform (BERR) (Nedwell *et al* (2007b)[1]) to assess the potential impact of the underwater noise on marine species:

Table 10.2 ***Assessment criteria used to assess the potential impact of underwater noise on marine species***

Level in dB_{ht}(*Species*)	Effect
90 and above	Strong avoidance reaction by virtually all individuals.
Above 110	Tolerance limit of sound; unbearably loud.
Above 130	Possibility of traumatic hearing damage from single event.
Source: Nedwell *et al* (2007)	

10.4.18 In addition, a lower level of 75 dB_{ht} has been used for analysis as a level of "significant avoidance". At this level about Nedwell *et al*[2] found that 85% of fish were found to initially react to a sound of this level in a study of short-term noise. The effect will probably be transient and limited by habituation: another study by Thompson and Hastie[2] found 50% of marine mammal individuals were found to react to an equivalent level of noise.

Species considered in the assessment

10.4.19 Table 10.3 below presents a summary of the species of interest to this study, along with some information regarding the availability of data concerning their sensitivity to underwater sound.

Table 10.3 ***Summary of marine species relevant to the Moray Firth region***

Species common to area	Audiogram available?	Surrogate used	Comments	Reference
Common (Harbour) seal	Yes	-	No single audiogram dataset covering full audiometric range available. Data from two studies used	Kastak and Schusterman (1998)[3]; Mohl (1968)[4]
Grey seal	Partial – only upper frequencies	Harbour seal	No single audiogram dataset covering full audiometric range available. Data from two studies used	Kastak and Schusterman (1998)[1]; Mohl (1968)[2]
Harbour porpoise	Yes	-	-	Kastelein (2002)[5]
Minke whale	No	None	No surrogate data available for large mysticetes	-

(1) 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.

(2) Thompson P and Hastie G (2011) **Proposed revision of noise exposure criteria for auditory injury in pinnipeds.** Awaiting publication.

(3) Kastak D and Schusterman 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

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

(5) Kastelein R A, Bunskoek P, Hagedoornm, 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

Species common to area	Audiogram available?	Surrogate used	Comments	Reference
Killer whale	Yes	-	-	Szymanski et al., (1999)(1)
Risso's dolphin	Yes	Striped dolphin	Existing audiogram data indicates higher threshold than other dolphin species but high background noise levels during audiogram tests	Risso's dolphin – Nachtigall et al., (1995)(2) Striped dolphin – Kastelein (2003)(3)
White-sided dolphin	No	Bottlenose dolphin	Audiogram data suggest bottlenose dolphin are most sensitive dolphin species to sound so may provide conservative indication of impacts	Johnson (1967)(4)
White beaked dolphin	Partial – only upper frequencies	Striped dolphin	Partial audiogram data for white-beaked dolphin indicates close match to striped dolphin data	White beaked dolphin – Nachtigall et al., (2008)(5) Striped dolphin - Kastelein (2003)(1)
Bottlenose dolphin	Yes	-	-	Johnson (1967)(2)
Herring	Yes	-	-	Enger (1967)(6)
Plaice	No	Dab		Chapman and Sand (1974)(7)
Whiting	No	Cod	Of the same taxonomical family as cod so the audiogram data for cod is the best available information on which to base the impact assessment for this species.	
Cod	Yes	-	-	Chapman and Hawkins (1973)(8)
Salmon	Yes	-	-	Hawkins and Johnstone (1978)(9)
Sandeels	No			

(1) Szymanski M D, Bain D E, Kiehl K, Pennington S, Wong S & Henry K R. (1999). **Killer whale (Orcinusorca) hearing: Auditory brainstem response and behavioral audiograms.** J. Acoust. Soc. Am. **106**, 1134–1141.

(2) Nachtigall P E, Au W W L, Pawloski J L and Moore P W B. (1995). Risso's **dolphin (Grampus griseus) hearing thresholds in Kaneohe Bay, Hawaii**. In 'Sensory Systems of Aquatic Mammals,' 49-53. R A Kastelein et al (eds. De Spil Publ., Woerden, Netherlands.

(3) Kastelein R A, Hagedoornm, Au W W L and Haan D. (2003). **Audiogram of the striped dolphin (Stenella coeruleoalba).** J.Acoust.Soc.Am., Vol 113 (2), pp1130-1137

(4) Johnson C S. (1967) **Sound detection thresholds in marine mammals.** In W N Tavolga (ed), Marine bioacoustics, Vol 2, Pergamon, Oxford, UK

(5) Nachtigall, PE, Mooney, TA, Taylor, KA, Miller, LA, Rasmussen, MH, Akamatsu, T, Teilmann, J, Linnenschmidt, M, and Vikingsson, G. (2008). **Shipboard measurements of the hearing of the white-beaked dolphin, *Lagenorhynchus albirostris*.** 211(4): 642-647 Journal of Experimental Biology.

(6) Enger P S and Andersen RA. (1967). **An electrophysiological field study of hearing in fish.** Comp. Biochem. Physiol. 22, 517-525.

(7) 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.

(8) Chapman C J and Hawkins A D. (1973). **A field study of hearing in the cod, Gadus morhua** L. Journal of comparative physiology, 85: pp147 – 167.

(9) Hawkins and Johnstone (1976) (full details of ref. not available in photocopy of Hawkins and Myrberg seen).

Species common to area	Audiogram available?	Surrogate used	Comments	Reference
Mackerel	No			
Ling	No			
Sea lamprey	No			
Elasmobranchs	Yes - various			
Guillemot	No			
Razorbill	No			
Puffin	No			
Gannet	No			
Arctic tern	No			
Species specific assessment		Inferred hearing abilities or species grouped		Not assessed

10.4.20 Audiograms for the species listed in the table, where available, have been presented in Figures 10.1 to 10.3 above.

The use of surrogates

10.4.21 In the table it is shown that, for instance, there is no known audiogram for the plaice and the audiogram for the dab has been used when making calculations for the plaice.

10.4.22 The dab is in the family *Pleuronectidae*. It is common in the shell grit and sandy seabeds surrounding Great Britain and Ireland towards Scandinavia. It is able to live in water depths of a few metres to around 100 m. The dab is found in temperate waters and usually grows to around 35 cm in length and weighs up to a kilogram. Spawning depends on water temperature and occurs during early summer. It is known to prey on crustaceans, small fishes, brittlestars, sea urchins and molluscs. The audiogram for the dab (*L. Limanda*), (from Chapman & Sand (1974)[(1)]) is presented in Figure 10.3, converted to units of sound pressure by Popper & Fay (1993)[(2)]. As can be seen in the figure, dab detect frequencies from below 30 Hz up to around 200 Hz, with sensitivities of around 90 dB re 1 µPa at 110 Hz. This indicates that dab have relatively poor hearing sensitivity compared to clupeids and therefore, in common with plaice and lemon sole, they may be classed as hearing generalists.

10.4.23 The plaice, too, is in the family *Pleuronectidae.* The geographical range of the European plaice is off all coasts from the Barents Sea to the Mediterranean. It is a common flatfish, occurring on the sandy and muddy bottoms of the European shelf, usually at depths between 10 and 50 m, where they tend to burrow in sediment during day time and remain stationary for long periods. They can be found at depths up to approximately 200 m. Young fish in particular come right inshore in very shallow water. Its maximum length is about 1 m, but adults, caught in fishing nets, are usually between 50 and 60 cm in length. Its maximum published weight is 7 kg.

(1) 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.

(2) 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.

10.4.24 Because of the similarities between the two species, the dab has been used as a surrogate for the plaice.

10.5 UNDERWATER NOISE MODELLING METHODOLOGY

Introduction

10.5.1 The general approach to estimating the levels of subsea noise from offshore wind farm developments has been undertaken in two phases. In the first a broad-brush modelling approach has been used to rank order a wide range of offshore wind farm-related sources of underwater noise. This was done using the proprietary Simple Propagation Estimator and Ranking model (SPEAR) developed specifically for the Moray Firth developers. In the main, the information used to validate this model has come from the very substantial database of recordings of various noise sources compiled by Subacoustech Environmental over the last 20 years. The model uses estimates from this database of the typical frequency content, source level and transmission losses associated with each type of noise source. These data have been used to determine the impact of each noise source on the marine environment, by using the estimate of noise level and a suitable criterion for a level above which it will have an effect to estimate the area which is affected by the noise source for each class or species of marine animal.

10.5.2 The rank ordering showed that most of the activities had a negligible adverse effect, so they could be eliminated from further consideration in the second phase of the assessment, where the focus was on sources of noise that have the capacity to cause a significant adverse effect. Results are shown in Figure 10.12. The activity that generated the highest noise levels (impact piling) was modelled in detail to provide an assessment of the area which would be affected. These results are shown in Section 10.7 (Phase 2). The results of this detailed modelling were combined with population and behavioural data to allow a biological assessment of the significance of any effects on fish, marine mammals and birds to be made.

10.5.3 It may be noted, however, that although most of the relatively low level noise sources could be eliminated from detailed modelling in the second phase of the assessment, their significance has been re-assessed in the context of the cumulative impact assessment, where they may be considered of greater importance.

Modelling of Sound Propagation

10.5.4 Sound levels underwater are usually quantified in terms of the Source Level, which is a measure of the sound energy released by the source, and the Transmission Loss, which is a measure of the rate at which that energy is lost. Sound propagation is thus described by the simple equation:

$$L(r) = SL - TL \quad \text{.......... eqn. 2-6}$$

where $L(r)$ is the Sound Pressure Level at distance r from a source in metres, SL is the source level, which may be thought of as the "effective" level of sound at one metre from the source, and *TL* is the transmission loss (Kinsler *et al* (1982)[(1)]). Transmission Loss (TL) is defined as:

$$TL = 20\log\left(\frac{P_0}{P_R}\right)$$ .... eqn. 2-7

where P_o is the effective acoustic pressure at a point at 1 m from the source, as per the Source Level above, and P_R is the acoustic pressure at range R away from it. The Transmission Loss is therefore a measure of the rate at which the sound energy decreases with increasing range.

10.5.5 Frequently a simplification is made by assuming that the Transmission Loss may be approximated due to spreading and absorption losses such that:

$TL = N\log(r) + \alpha$ .... eqn. 2-8

where *r* is the distance from the source in metres, *N* is the constant factor for attenuation due to geometric spreading, and α is a factor for the absorption of sound in water and at boundaries in dB/m (Urick (1983)[(2)]; Kinsler *et al* (1982)[(3)]).

10.5.6 For instance, spherical spreading gives a value of N=20. By combining equations 2-6 and 2-8 the level of sound at any point in the water space can be estimated from the expression:

$L(r) = SL - N\log_{10}(r) - ar$ .... eqn. 2-9

10.5.7 Over short distances absorption effects have little influence on the Transmission Loss and can often be ignored. The Source Level itself may be quoted in any physical quantity, e.g. a piling source may be expressed as having a "peak-to-peak Source Level of 200 dB re 1 µPa @ 1m".

10.5.8 This simple but convenient formulation ignores the practical difficulty of estimating the Source Level. Since the measurements are usually made at some distance from the source (in the acoustic far field) and extrapolated back to the source, the true level at 1 metre may actually be very different from the Source Level used in these equations.

10.5.9 It is often not realised that, since the value of Source Level quoted for a particular source is obtained by extrapolation, the value will depend on the model that is used to perform the extrapolation. Figure 2-1 illustrates this point. The diagram illustrates a set of measurements made of the noise from piling. In the simplest case, in order to draw conclusions about the data, a straight-line model may be fitted to it — this is shown in the figure by the green line. Such a model effectively assumes that the noise level, NL, behaves as $L(r) = SL - N\log_{10}(r)$. This, however, will generally over-estimate the levels for low and high ranges, since it ignores the effects of absorption of the noise. The improved model including absorption, $L(r) = SL - N\log_{10}(r) - ar$ (red line in the figure), gives a better fit to the data, and indeed this simple form is usually adequate for modelling sound propagation from a source in deep

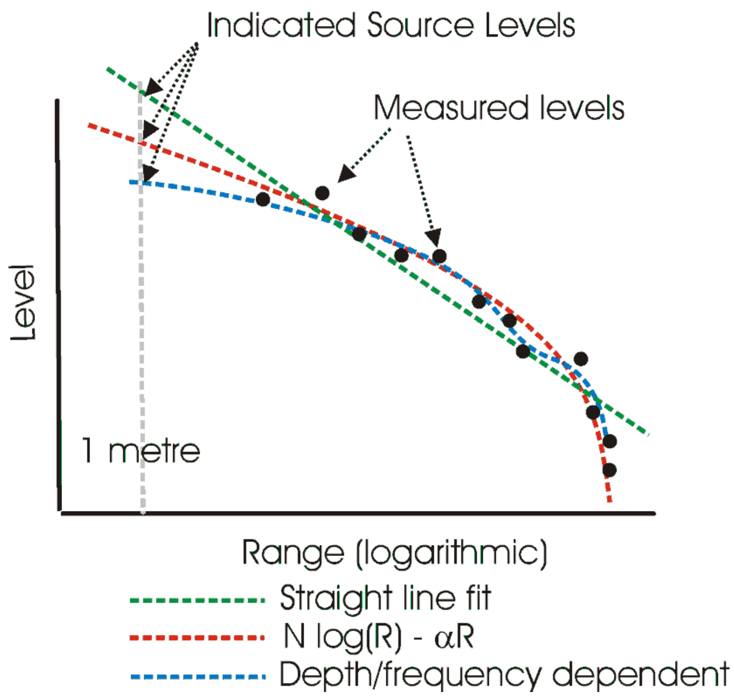
(1) Kinsler L E, Frey A R, Coppens A B, Sanders J V. (1982). **Fundamentals of Acoustics.** John Wiley and Sons, New York

(2) Urick R. (1983). **Principles of underwater sound**, New York: McGraw Hill.

(3) Kinsler L E, Frey A R, Coppens A B, Sanders J V. (1982). **Fundamentals of Acoustics.** John Wiley and Sons, New York

water of roughly constant depth. However, in the case of the shallow coastal waters where wind farms are typically situated, the depth may rapidly fluctuate between shallow water of a few metres and deeper water of tens of metres or more. In these circumstances the Transmission Loss becomes a more complex function of depth that depends heavily on the local bathymetry and hence must be calculated using a more sophisticated model, such as INSPIRE. Where these effects are included, as illustrated by the blue line in the figure, yet another value of Source Level may result; typically, lower levels of noise may be predicted near to the pile.

Figure 10.6 ***Differences in Source Level estimation based on various models***



10.5.10 Source Levels can also be expressed in the dB_{ht} metric, e.g. 170 dB_{ht} (*Clupea harengus*) @ 1 m.

10.5.11 This approach is very convenient, as it allows the relative significance of various sources to be easily compared for different species or pile sizes. The levels can be analysed using the SPEAR and/or INSPIRE models to determine impact ranges for fish and marine mammal species.

Phase 1 of the Modelling: Rank-ordering of Noise Sources

10.5.12 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 has been developed as part of the MFOWDG projects and allows the significance of a wide range of sources of underwater noise to be rank-ordered for a wide range of marine animals.

10.5.13 As has been previously noted, as sound propagates through water it reduces in level as a result of losses relating to energy dissipation (absorption) and to geometric spreading. The latter is the acoustician's terminology for the effect of the area of the notional surface surrounding the sound source increasing as distance from the source increases; the sound energy consequently is flowing through a larger area and its intensity will accordingly reduce.

10.5.14 At a particular point in the water space the level to which an animal is subjected, the Received Level (*RL*), is, in logarithmic terms, the Source Level minus the Transmission Loss:

$$RL = SL - TL \qquad \text{eqn. 2-10}$$

10.5.15 Over short distances absorption effects have little influence on the Transmission Loss and can often be ignored, and in that case, and over a defined spread of range, it is reasonably accurate to use a linear fit of the form:

$$RL = SL - N\log_{10}(r) \qquad \text{eqn. 2-11}$$

where *N* is generally characterised as being a term associated with the spreading of sound. The Source Level itself may be quoted in any physical quantity, for instance, a piling source may be expressed as having a "peak-to-peak Source Level of 200 dB re 1 µPa @ 1 m". It may be also specified in terms of a frequency weighted level for a particular animal species, allowing the "loudness" or effect of the sound to be evaluated. This approach is inherent in both the Nedwell dB_{ht} formulation and the Southall SEL approach.

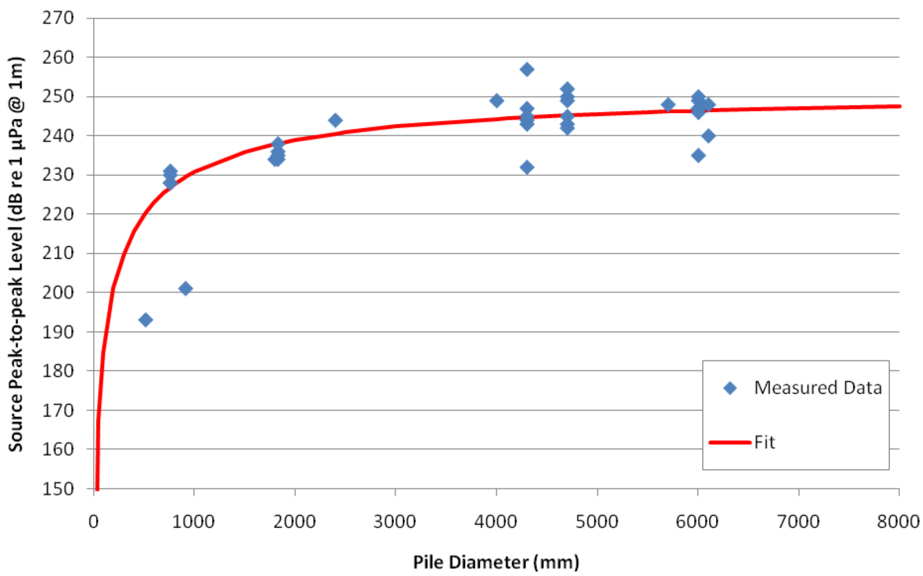
10.5.16 It will therefore be appreciated that this simple model has been chosen in the main because it allows the evaluation of the significance of the noise for a wide range of marine animals having greatly varying acuity of hearing and frequency range over which they can hear. This is critical to any realistic investigation, because noise sources with a significant content of high frequency sound will tend to selectively affect high frequency hearers, such as the harbour porpoise, while sources with a significant content of low frequency sound will tend to affect low frequency hearers, such as fish. The effect of any given noise source may therefore be greatly different for different species, and it is therefore essential to use a modelling process that considers the hearing acuity of the affected species.

10.5.17 Although the formula is simple, obtaining accurate values to insert into it from actual data from a wide range of experimental measurements requires processing of the data for a large range of animal types, and is both complex and onerous. For instance, consideration must be given to the factors detailed earlier in this Annex relating to the estimation of source levels using different models.

10.5.18 For the purposes of the methodology of this assessment, the calculations in Phase 1 used a simple $L(r)=N\log_{10}(r)-ar$ formulation.

10.5.19 The simple model also takes into account variations in the parameters affecting the source level. For instance, currently available information suggests that the level of underwater noise from impact piling operations is closely related to the pile diameter, with sound levels increasing with diameter. The blow energy applied to the pile also influences the noise levels produced. Figure 10.7 shows a summary of Source Levels extrapolated from measured data obtained on a number of impact piling operations which used various pile sizes. It can be seen that as the diameter of the pile increases the Source Level also increases, although it may be commented that two results for small pile diameters that lie beneath the general curve are now believed to be anomalous. The fitted curve has been used as an input to the SPEAR model to provide a reasonably accurate estimation of the sound energy generated by striking of different sized piles. This is adequate for the purposes of ranking the significance of the various noise sources required in Phase 1. In the SPEAR model this information is included explicitly, whereas in the INSPIRE model, where it is also used, it is taken into account via an inbuilt source function.

Figure 10.7 ***Plot showing the asymptotic best fit to Source Level calculated from measured piling noise data for various pile sizes***



10.5.20 In summary, the initial ranking process was based on the simple yet representative SPEAR model, which enabled an evaluation to be made of the impact of a wide range of noise sources on a range of marine species in terms of the level of the noise, the area affected and the duration of activity.

10.5.21 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. Thus in Phase 2 of the modelling programme only impact piling was considered.

Phase 2 of the Modelling: Detailed Modelling of Impact Piling

10.5.22 Impact piling is known to generate high levels of underwater noise. It is therefore important to make an accurate estimate of its likely level so that its impact can be accurately assessed. There are a variety of acoustic models for the estimation of underwater noise propagation in coastal and offshore regions, mainly developed as a result of military interests. However, the authors are not aware of any underwater broadband noise propagation models suitable for the much shallower environments typical of wind farm construction, or for the highly impulsive time histories encountered from impact piling. In these environments and with these source types there is a greater capacity for underwater sound to be affected by absorptive processes in the seabed, resulting in propagation losses which typically increase with frequency but decrease with depth.

10.5.23 The Impulse Noise Sound Propagation and Impact Range Estimator (INSPIRE) model has been developed 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 measurements from a large number of other offshore wind farm piling operations (Nedwell *et al* (2012)[(1)]).

10.5.24 Transmission Losses are calculated by the model on a fully range and depth dependent basis. The model imports electronic bathymetry data as a primary input to allow it to calculate the transmission losses along transects extending from the pile location. Other simple physical data are also supplied as input to the model. The model is able to provide a wide range of outputs, including the peak pressure, impulse, dB_{ht}, SEL, etc. of the noise.

10.5.25 As well as calculating the SEL variation with range, the model incorporates a "fleeing animal receptor" extension which enables the noise dose an animal receives as it is moves away from a piling operation to be calculated. This feature permits the calculation of the nearest distance from a pile from which an animal must start fleeing such that its noise dose just reaches the criterion value at the cessation of the piling operation.

10.5.26 In Phase 2 the INSPIRE model was used to assess in detail the ranges at which fatality, physical injury, auditory injury and behavioural avoidance was likely to occur for a range of animal species.

10.5.27 Further studies using INSPIRE were also undertaken to assess the detailed impact of the noise on populations of marine mammals in the Moray Firth. A graduated approach to the calculation of noise, where noise levels are calculated in bands, was used to estimate its effect on animal populations[(2)].

10.6 BASELINE ENVIRONMENT

10.6.1 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

(1) Nedwell J R, Brooker A G, Barham R J. **The INSPIRE Piling Noise Model and its Test Against Actual Data**. In prep.

(2) Thompson, P and Hastie, G. **Proposed revision of noise exposure criteria for auditory injury in pinnipeds.** In prep.

closely to the sort of water depths in areas where offshore wind farms are built.

10.6.2 A review has been undertaken of currently available information relating to background sea noise around UK coastal waters. Public domain sources of information were searched and some sources relevant to the Moray Firth were found (see, for example, Kongsberg[(1] and Senior *et al*[(2)]). However, very little information was available and, in the case of the two references cited, the data presented are from measurements taken by Subacoustech Ltd.

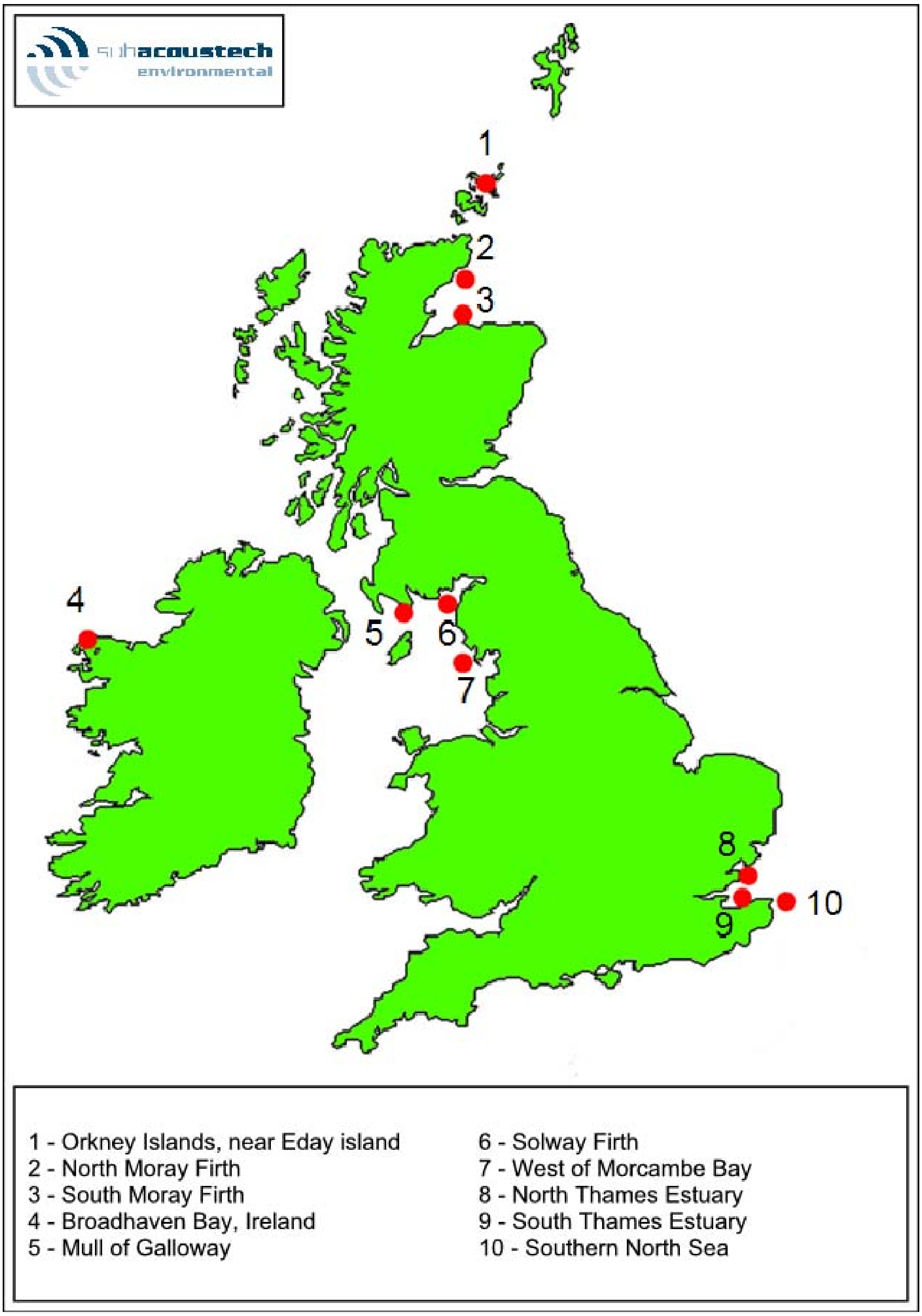
10.6.3 Over the past 20 years Subacoustech Ltd has taken several thousand noise measurements of background underwater noise during offshore construction projects in United Kingdom (UK) territorial waters. The set of measurements is unique, in that they all span a broad frequency range from 1 Hz to over 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.

10.6.4 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 10.8.

(1) Kongsberg (2010). **Underwater noise propagation modelling and estimate of impact zones for seismic operations in the Moray Firth**. Final report 37399 – FR1

(2) Senior, B., Bailey, H., Lusseau, D., Foote, AD. & Thompson, PM. (2008). **Anthropogenic noise in the Moray Firth SAC: Potential sources and impacts on bottlenose dolphins.** vol. Commissioned Report No 256, Scottish Natural Heritage.

Figure 10.8 Map of the UK showing sites where background sound measurements have been collected and analysed.



10.6.5 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).

10.6.6 Figures 10.9 and 10.10 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 and an average of all the data also shown. Figure 10.9 presents data for measurements during Sea State 1 conditions and Figure 10.10 presents data for slightly rougher Sea State 3 conditions.

Figure 10.9 Summary of Power Spectral Density levels of background underwater noise at Sea State 1 at sites around the UK coast

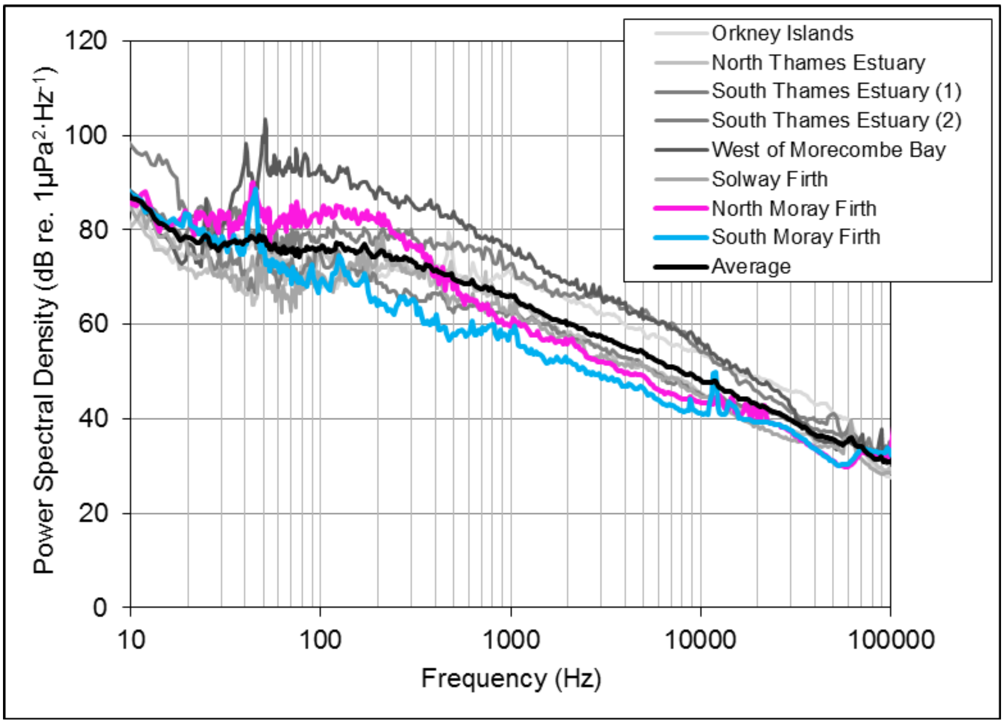
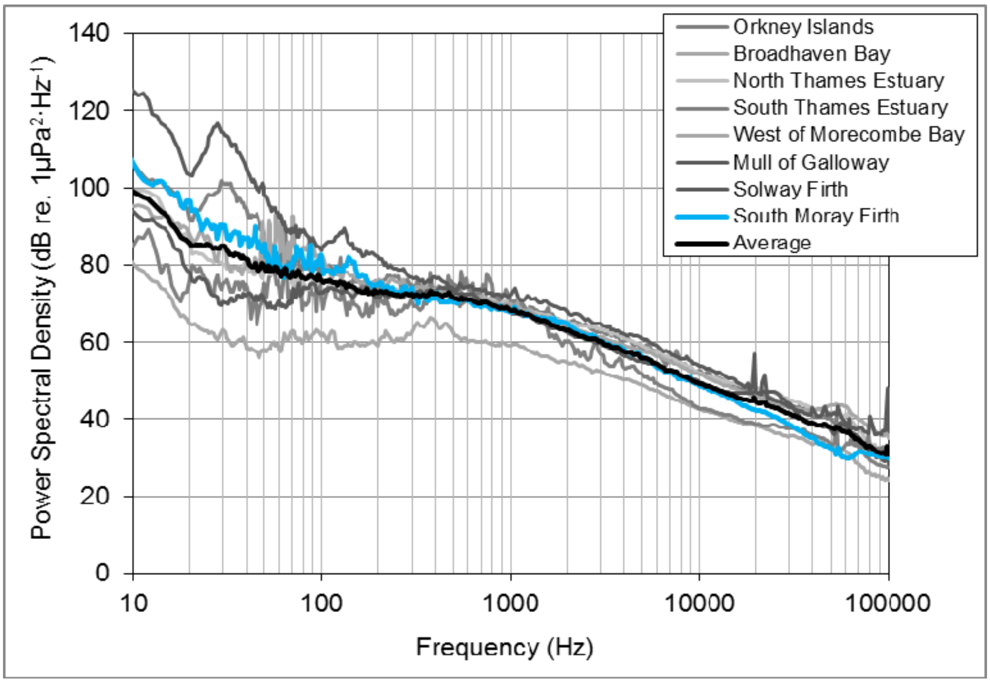


Figure 10.10 Summary of Power Spectral Density levels of background underwater noise at Sea State 3 at sites around the UK coast



10.6.7 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 10.4 below.

Table 10.4 Summary of average background levels of noise around the UK coast and in the Moray Firth at Sea State 1

	Unweighted	Bass	Cod	Dab	Herring	Salmon	Bottlenose Dolphin	Harbour Porpoise	Harbour Seal	Killer Whale
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
South Moray Firth Averages – Sea State 1										
Max	115	5	30	20	36	8	40	53	27	44
Min	103	1.5	23	7	27	2	38	53	24	41
Mean	106	3.5	26	11	29	5	39	53	25	42
North Moray Firth Averages – Sea State 1										
Max	111	3	27	17	33	6	42	54	31	47
Min	92	0	5	0	10	0	39	53	21	41
Mean	99	0	15	2	20	0	40	53	24	42

Table 10.5 ***Summary of average background levels of noise around the UK coast and in the Moray Firth at Sea State 3***

	Unweighted	Bass	Cod	Dab	Herring	Salmon	Bottlenose Dolphin	Harbour Porpoise	Harbour Seal	Killer Whale
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
South Moray Firth Averages – Sea State 3										
Max	120	15	42	30	45	19	44	54	38	50
Min	101	0	15	0	21	0	40	53	29	46
Mean	109	4	26	11	30	4	42	53	32	47

10.7 PREDICTED IMPACTS

Phase 1: Rank-ordering of Noise Sources

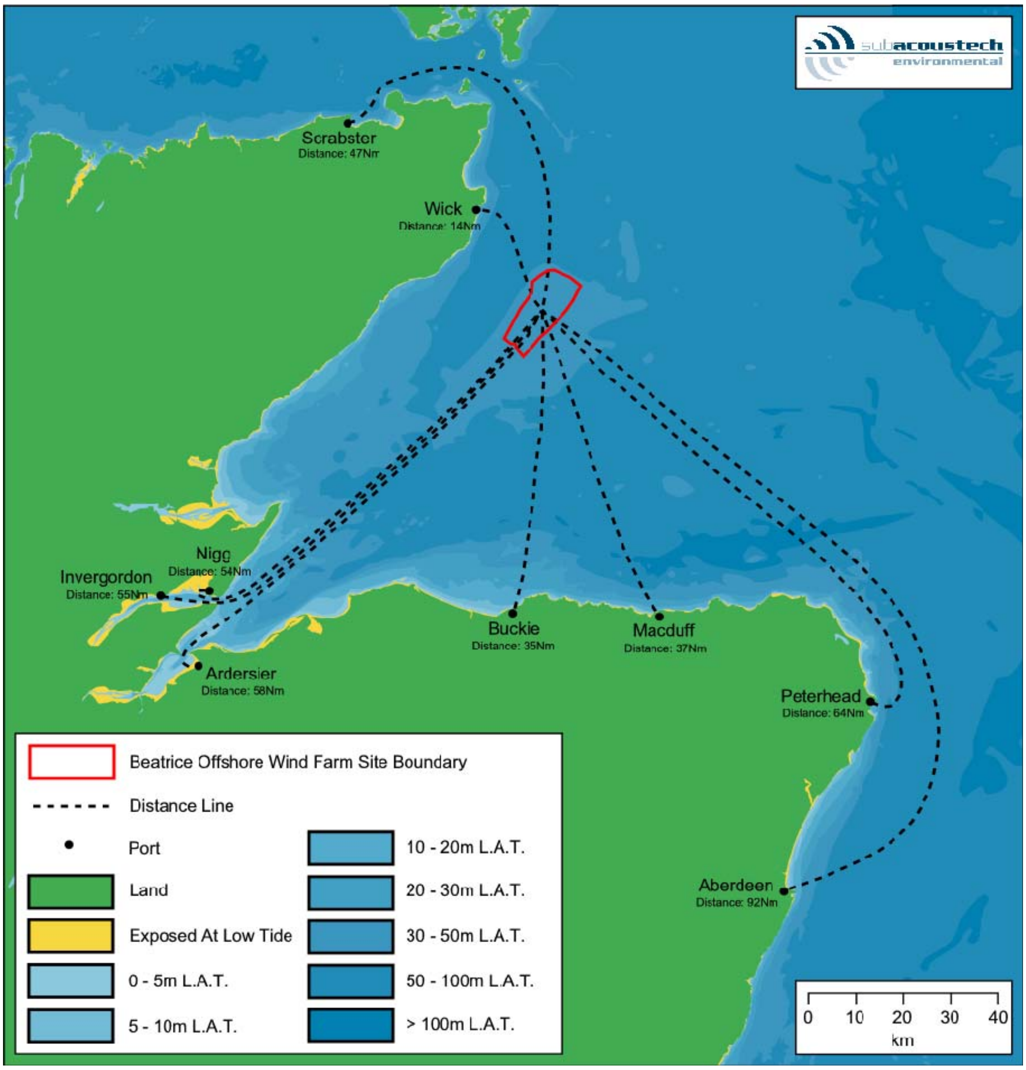
10.7.1 The SPEAR model has been used to make prediction runs for a number of representative scenarios for the various activities related to offshore wind farms. A summary of the various considerations relating to construction activity is given below.

Vessel Types and Ports

10.7.2 The ports identified in the Rochdale Envelope information for the BOWL project that may be used by the wind farm during the construction and operational phases are:

- Nigg
- Ardersier
- Wick
- Buckie
- Invergordon
- Aberdeen
- Peterhead
- Scrabster (emergency or lay-by option only)
- McDuff (emergency or lay-by option only)

Figure 10.11 Site location and potential ports that may be used



10.7.3 Consideration has been given to the extent of vessel noise generated for vessels using each of these ports. In addition, the specification presented in the Rochdale Envelope for the type of vessels that may be used is:

- jack-up barges;
- crane barges;
- supply vessels;
- anchor handling tugs;
- cable laying vessel;
- crew transfer vessels;
- remotely operated vehicles (ROVs)/construction vessels;
- dredging vessels; and
- rock placement vessels.

These are the vessels identified in Section 7 of the Offshore Environmental Statement.

10.7.4 The worst case scenario for movement of these vessels is for all movement to be between ports within the inner Moray Firth and the site, except for the dredging vessels and rock dumping vessels, which will move to locations outside of the Moray Firth. Movement of vessels to ports not within the inner

Moray Firth (i.e. Scrabster, Wick, Buckie, MacDuff, Peterhead and Aberdeen) has therefore not been considered further in this assessment.

Foundation Options

10.7.5 Three foundation options for turbines are being considered. These are:

- jacket foundation with pin piles;
- Gravity Base structures (GBS); and
- suction piles.

Other Noise Sources

10.7.6 In addition to the above considerations, the following noise sources are also considered in the initial Phase 1 modelling:

- cable laying and trenching;
- dredging; and
- scour protection (rock placing).

Worst Case Scenarios for each Foundation Option

10.7.7 For each of the three foundation options listed above a worst case scenario for the purposes of the EIA process has been provided based on the expected installation requirements. These are outlined in the following sections. A three metre pin pile for the OSP and a five metre monopile for the met mast are also specified. However, given the number of piling events associated with the turbines this is taken to be the worst case for assessment of impacts on fish and marine mammals.

Scenario 1: Driven Piles and Steel Jacket Foundation Turbines

10.7.8 The worst case scenario in terms of underwater noise for the jacket foundation with pin pile foundation option must consider the following:

- 277 WTGs in total;
- dynamically positioned (DP) jack-up vessel required for piling and jacket installation;
- barge towed by anchor handling tugs (AHTs) with up to 32 piles brought to site on each trip during piling and up to eight jackets per trip during jacket installation;
- additional AHT on site for positioning of barge;
- impact piling of 2400 mm diameter piles;
- DP jack-up vessel to return to port for each wind turbine generator (WTG) installation (277 trips); and
- 1 AHT on site for one day per turbine location for grouting.

Scenario 2: Suction Piles and Steel Jacket

10.7.9 It is expected that this will involve similar vessels to those described above for the driven piles and jacket foundation, but with fewer vessel movements. It is therefore considered that this falls into the same envelope as that described above.

Scenario 3: Gravity Base Structure and Integrated Substructure

10.7.10 This foundation option requires preparation of the seabed prior to the foundation arriving and scour protection.

- Five visits of a vessel similar in size to the TSHD *Brabo* for seabed preparation, per turbine location (50,000 m^3 removed per turbine location).
- Visit of fall pipe rock dump vessel similar in size to the Van Oord *Nordnes* 70 times for seabed preparation (assuming 277 WTGs – can carry enough load for preparation of up to four turbine locations.
- Visit of fall pipe rock dump vessel similar in size to the Van Oord *Nordnes* 139 times for scour protection (assuming 277 WTGs – can carry enough load for scour protection of two WTGs).
- Two AHTs to tow GBS to site.
- Anchored semi-submersible crane vessel (SSCV) to install GBS.
- DP jack-up vessel to return to port for each WTG installation (277 trips).

Scenario 4: Gravity Base and Steel Jacket

10.7.11 This scenario will be as described for the gravity base and integrated substructure with the addition of:

- requirements for pre-driven piles as for the steel jacket installation above (DP jack-up vessel, AHTs and pontoon barge).

Scenario 5: Additional Activities

10.7.12 In addition to the activities relating to the foundation installations outlined above, the laying of inter-array cables must also be considered. Inter-array cables will be buried or protected wherever feasible. However, due to the uncertainty regarding seabed and underlying geological conditions it is not possible to specify what proportion of inter-array cables will be buried or protected. There may also be areas where it is necessary to surface-lay inter-array cables but this will be minimised.

10.7.13 In order to provide a worst case scenario for this aspect of the project the following have been looked at in terms of underwater noise:

- cable vessel visits inner Moray Firth port for each cable;
- cable to be trenched and buried;
- 1.5 days required for each 1 km of cable (includes cable lay, trenching and burial where required;
- total inter-array cabling 350 km of which 325 km will require trenching, based on the 277 WTG layout option (the additional 25 km is allowed for jointing into WTG);
- the possibility of up to 50% of inter-array cables requiring protection was taken into account.

10.7.14 If harder substrates are encountered drilling may also be required where impact piling is not sufficient to drive the piles to the required depth. Drilling operations have therefore also been considered with regard to underwater noise.

Summary of noise scenarios for SPEAR modelling

10.7.15 Table 10.6 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 dredging may take, is not available at this stage. It has therefore been necessary to take a very worst case estimation in terms of noise generation.

Table 10.6 Summary of parameters used in the SPEAR modelling

Activity	Parameters used for SPEAR modelling
Impact piling[1]	• 5 hours driving per pile • 2400 mm diameter piles • 4 piles per foundation • 277 foundations in total (1108 piles) • **5540 hours of impact piling in total for wind farm construction**
DP Vessels	• DP jack up barges for piling, substructure and WTG installation • DP operational for 100% of total time on site • DP vessels on site for entire construction schedule (2014 – 2019) • **Total operational DP vessel time 43,800hrs**
Trenching	• 325 km maximum trenched length • 1 km/12 hours trenching speed • **Total of 650hrs on site**
Cable laying	• Inter array cables only • 325 km basic cable length based on trenching requirements • 25 km additional cable length for around turbines where trenching not possible • Total of 375 km cable laying length • 1 km/12 hours laying speed • **750hrs on site in total**
Drilling	• Assume worst case every foundation drilled • Each pile requires 5 hours drilling • 4 piles per foundation • 400kW drill • **5,540hrs total drilling (277 foundations)**
Rock placing	• Required intermittently on site for total of 5 years • **43,800hrs in total**
Dredging	• Trailer Suction Hopper Dredger required on site for full 5 years • **43,800hrs total time on site**
Operational noise	• Assume typical 20 year operational lifespan • **Total of 175,200hrs total operational noise**

[1] Modelling was also undertaken for 5 metre monopile for the met mast.

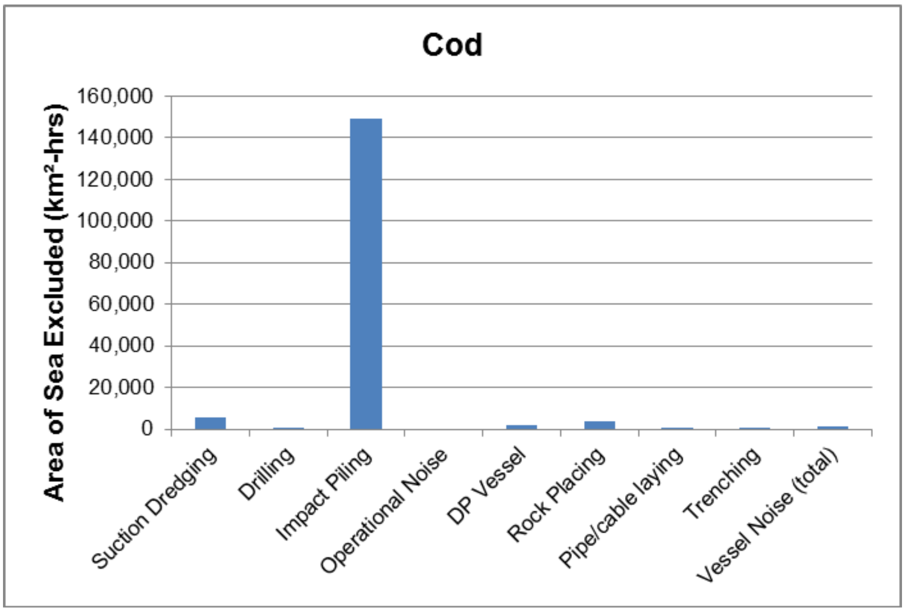
Activity	Parameters used for SPEAR modelling
Other vessel noise	• Two medium sized vessels (e.g. Anchor Handling Tugs. Dive Support Vessel, etc) required throughout construction • **Total of 87,600hrs of medium vessel time on site** • One large vessel (SSCV) required on site during GBS installation • Assume this will commence one year after construction begins and continue for 4 years • **Total of 35,040hrs of large vessel on site**

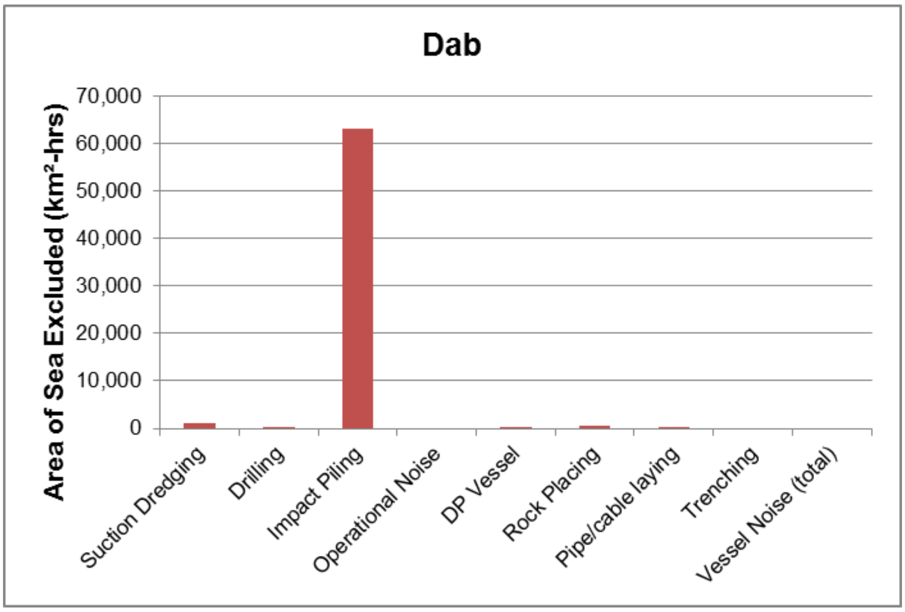
Results of the Phase 1, SPEAR, modelling

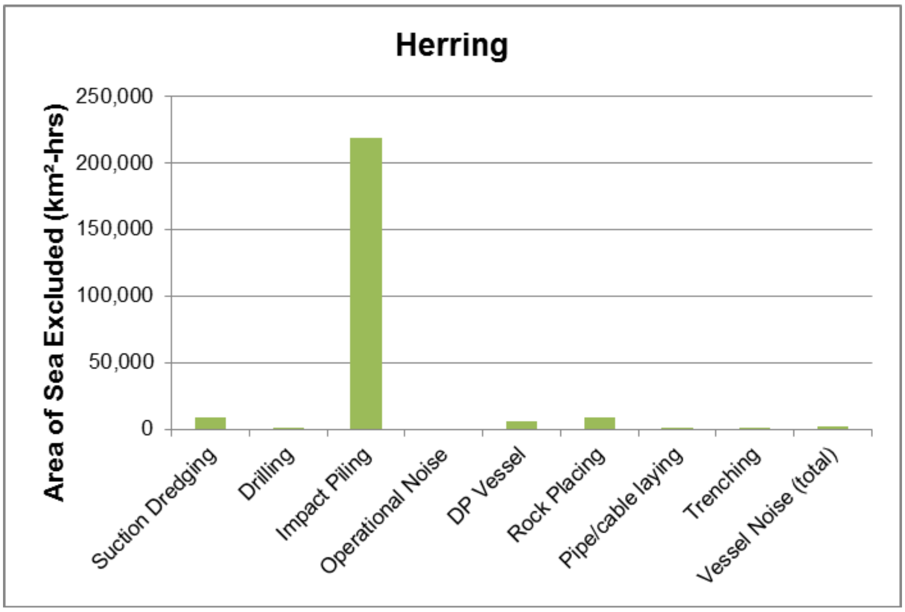
10.7.16 The SPEAR programme produced as output an 'index figure' which represents the area of ocean which is rendered unusable by a species as a result of a particular activity. The results for the species of interest are given in Figure 10.12 below.

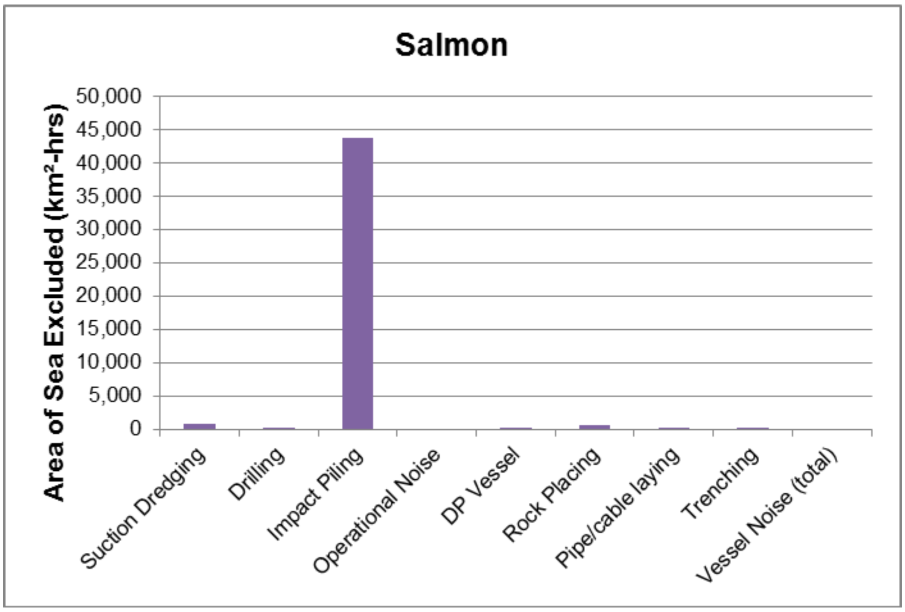
10.7.17 It is clear from the figures that impact piling is the dominant noise source and hence the activity that will have the greatest impact. This activity has therefore been studied in more detail using the INSPIRE model; the results from that are presented in the following section. It is worth noting that the effect of operational noise is zero in all instances below despite its long term nature, due to its low level.

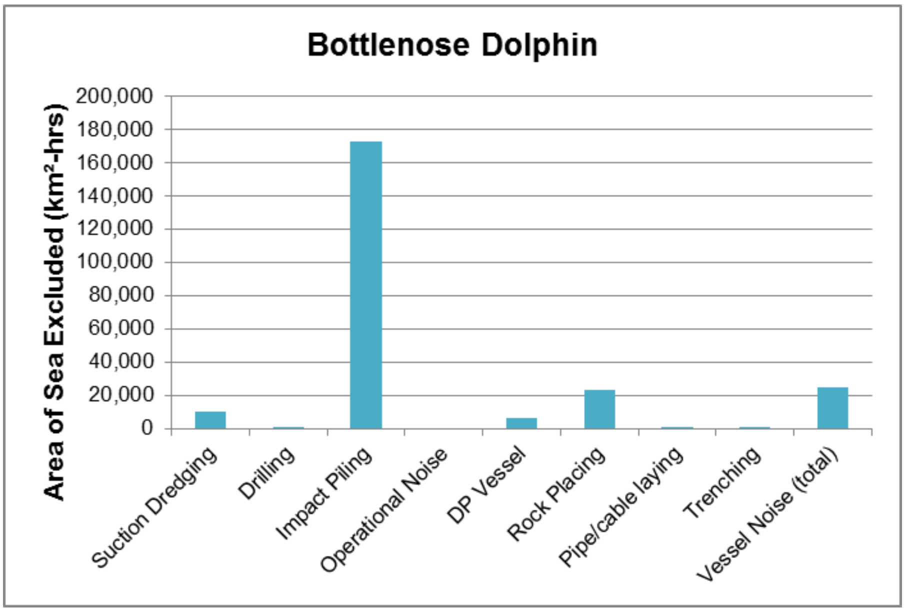
Figure 10.12 Relative importance with regard to extent of impact of various activities, on various species of animal

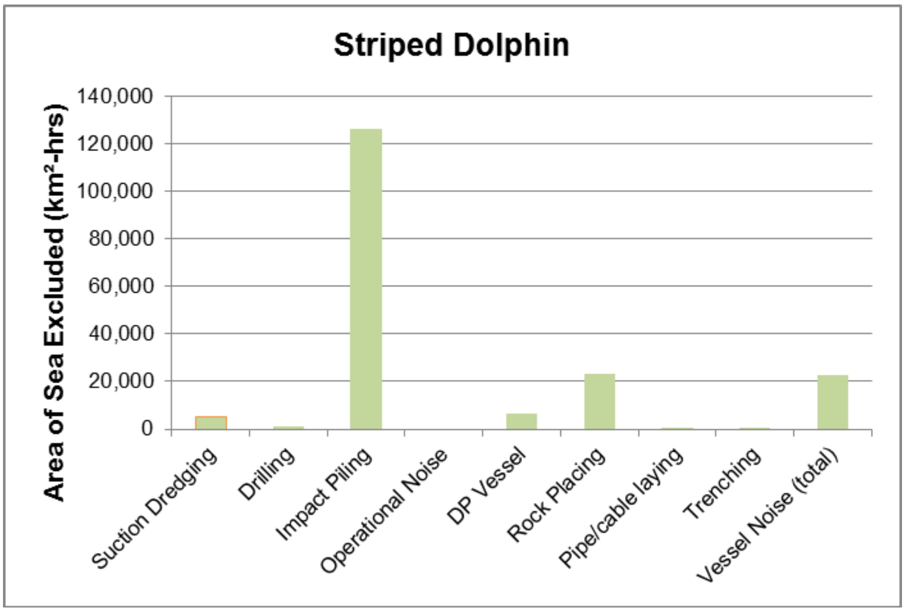


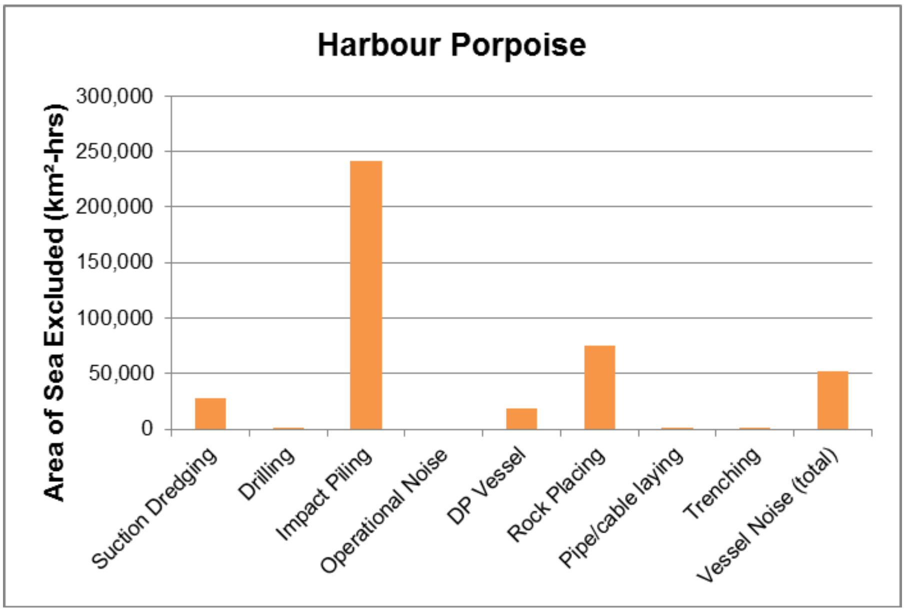

Dab
Area of Sea Excluded (km²-hrs)
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Suction Dredging
Drilling
Impact Piling
Operational Noise
DP Vessel
Rock Placing
Pipe/cable laying
Trenching
Vessel Noise (total)

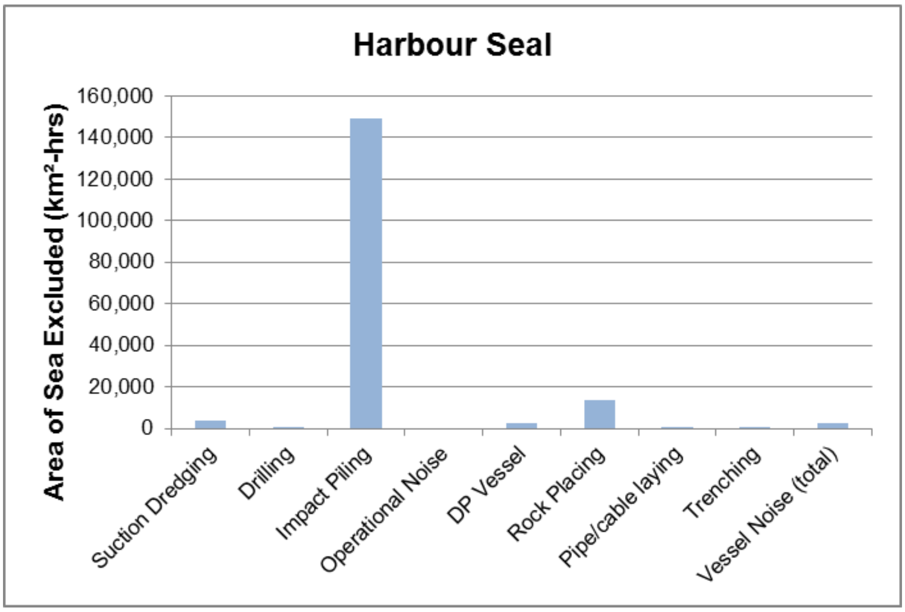

Herring
Area of Sea Excluded (km²-hrs)
250,000
200,000
150,000
100,000
50,000
0
Suction Dredging
Drilling
Impact Piling
Operational Noise
DP Vessel
Rock Placing
Pipe/cable laying
Trenching
Vessel Noise (total)

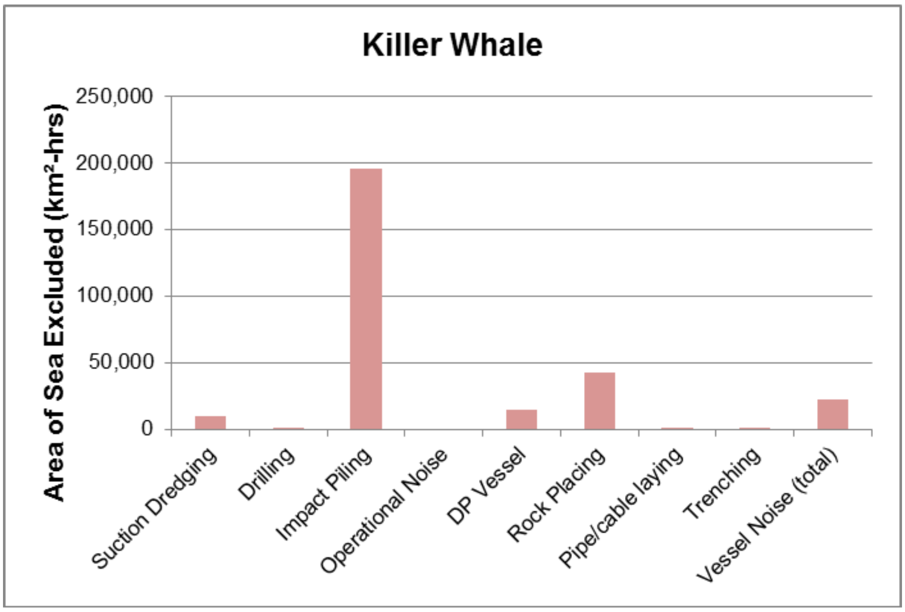

Salmon
Area of Sea Excluded (km²-hrs)
50,000
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
Suction Dredging
Drilling
Impact Piling
Operational Noise
DP Vessel
Rock Placing
Pipe/cable laying
Trenching
Vessel Noise (total)


Bottlenose Dolphin
Area of Sea Excluded (km²-hrs)
200,000
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
Suction Dredging
Drilling
Impact Piling
Operational Noise
DP Vessel
Rock Placing
Pipe/cable laying
Trenching
Vessel Noise (total)


Striped Dolphin
Area of Sea Excluded (km²-hrs)
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
Suction Dredging
Drilling
Impact Piling
Operational Noise
DP Vessel
Rock Placing
Pipe/cable laying
Trenching
Vessel Noise (total)


Harbour Porpoise
Area of Sea Excluded (km²-hrs)
300,000
250,000
200,000
150,000
100,000
50,000
0
Suction Dredging
Drilling
Impact Piling
Operational Noise
DP Vessel
Rock Placing
Pipe/cable laying
Trenching
Vessel Noise (total)





Phase 2: Modelling of Impact Piling

Details of cases modelled

10.7.18 The INSPIRE model has been used to make predictions for two broad categories of conditions.

- Predictions of ranges, *from a single pile*, at which specified noise criteria are met. One criterion is the dB_{ht}(*Species*) value. The second is the M-weighted SEL value, for mid-frequency and high-frequency cetaceans, and pinnipeds in water. For the SEL calculations there are two cases — the 'stationary animal' case, where the programme calculates the distance at which the criterion value is reached, and the 'fleeing animal' case, where the programme calculates the distance from the pile at which the animal must start to flee such that, at the cessation of the piling operation, its noise dose will just reach but not exceed the criterion value.

- Predictions of ranges, *for a number of piles being driven simultaneously*, to allow an estimation of the envelope of the area within which specified criteria are exceeded. Again, the criteria are the dB_{ht}(*Species*) value and the three M-weighted SEL values, and the latter includes stationary and fleeing animal cases as described above.

10.7.19 The results for the single pile cases are presented below, while the results for the multiple pile cases are presented later in the Cumulative Impacts section of the report.

10.7.20 Figure 10.13 is a sketch map of the Moray Firth area where the Beatrice Offshore Wind Farm is located. The location of the Moray Offshore Ltd Wind Farm is also shown. It shows the boundaries of the sites, and the locations of the piles for which modelling has been done.

10.7.21 The single pile cases were for the open circles (piles A to E). A summary of the cases considered is given in Tables 10.7 to 10.11.

Figure 10.13 Sketch map, showing locations and identifications of the piles whose driving has been modelled.

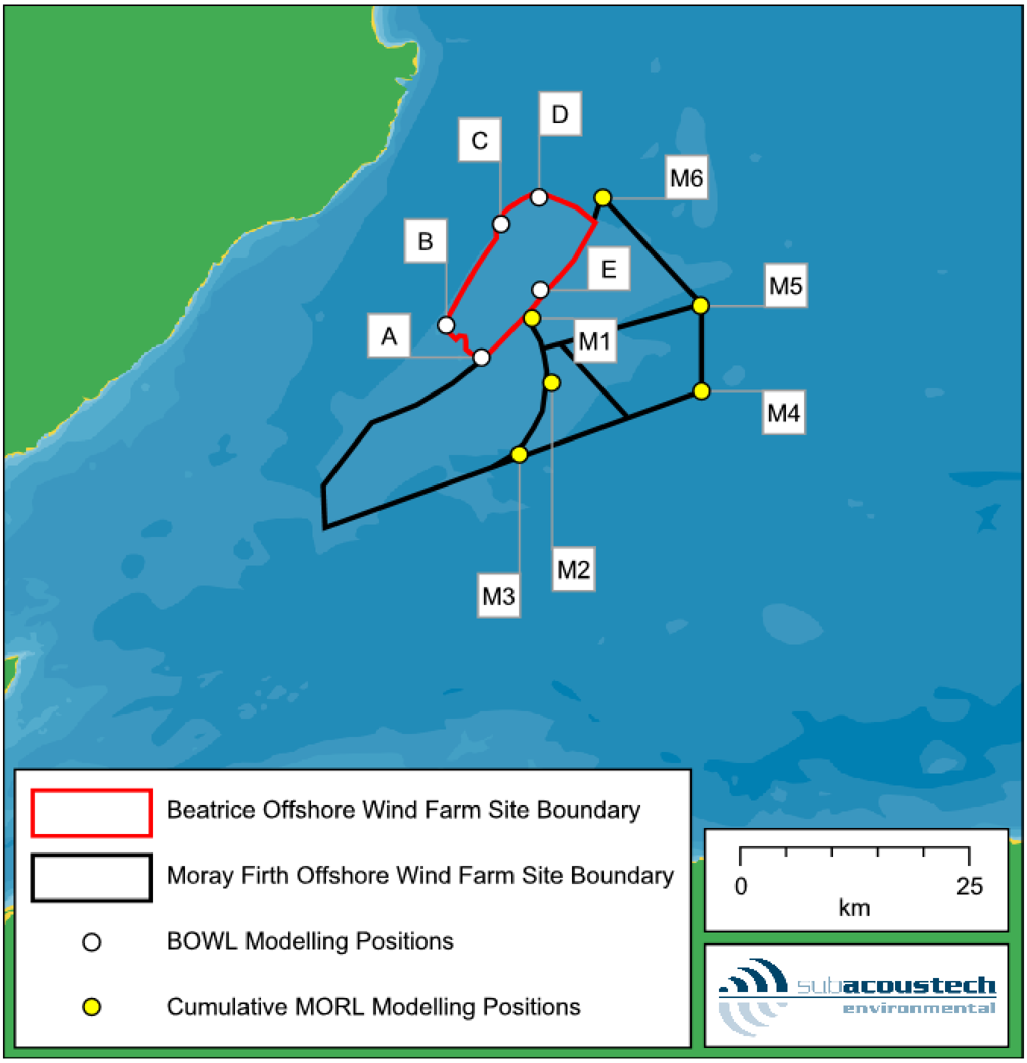


Table 10.7 Summary of conditions modelled for a single pile being driven at location A

Pile diameter (m)	Driving energy (kJ)	Species	Results shown	Figure
2.4	1800 and 2300	Cod	90 dBht and 75 dBht contours	Figure 10.14
2.4		Herring		Figure 10.15
2.4		Plaice		Figure 10.16
2.4		Salmon		Figure 10.17
2.4		Bottlenose dolphin		Figure 10.18
2.4		Harbour porpoise		Figure 10.19
2.4		Harbour seal		Figure 10.20
5	1800 and 2300	Cod	90 dBht and 75 dBht contours	Figure 10.21
5		Herring		Figure 10.22
5		Plaice		Figure 10.23
5		Salmon		Figure 10.24
5		Bottlenose dolphin		Figure 10.25
5		Harbour porpoise		Figure 10.26
5		Harbour seal		Figure 10.27
2.4	1800 and 2300	Mid-frequency cetacean	198 dB(M_{mf}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.41
2.4		High-frequency cetacean	198 dB(M_{hf}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.42
2.4		Pinniped in water	198 dB(M_{pw}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.43a
2.4		Pinniped in water	186 dB(M_{pw}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.43b
5	1800 and 2300	Mid-frequency cetacean	198 dB(M_{mf}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.44
5		High-frequency cetacean	198 dB(M_{hf}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.45
5		Pinniped in water	186 dB(M_{pw}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.46

Table 10.8 Summary of conditions modelled for a single pile being driven at location B

Pile diameter (m)	Driving energy (kJ)	Species	Results shown	Figure
2.4	1800 and 2300	Salmon	90 dBht and 75 dBht contours	Figure 10.28
2.4		Bottlenose dolphin		Figure 10.29
2.4		Harbour porpoise		Figure 10.30
2.4		Harbour seal		Figure 10.31
5	1800 and 2300	Salmon	90 dBht and 75 dBht contours	Figure 10.32
5		Bottlenose dolphin		Figure 10.33
5		Harbour porpoise		Figure 10.34
5		Harbour seal		Figure 10.35
2.4	1800 and 2300	Mid-frequency cetacean	198 dB(M_{mf}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.47
2.4		High-frequency cetacean	198 dB(M_{hf}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.48
2.4		Pinniped in water	198 dB(M_{pw}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.49a
2.4		Pinniped in water	186 dB(M_{pw}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.49b
5	1800 and 2300	Mid-frequency cetacean	198 dB(M_{mf}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.50
5		High-frequency cetacean	198 dB(M_{hf}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.51
5		Pinniped in water	186 dB(M_{pw}) contour for stationary animal, and locus of starting distances for fleeing animal	Figure 10.52

Table 10.9 Summary of conditions modelled for a single pile being driven at location C

Pile diameter (m)	Driving energy (kJ)	Species	Results shown	Figure
2.4	1800 and 2300	Herring	90 dBht and 75 dBht contours	Figure 10.36
2.4		Salmon		Figure 10.37

Table 10.10 Summary of conditions modelled for a single pile being driven at location D

Pile diameter (m)	Driving energy (kJ)	Species	Results shown	Figure
2.4	1800 and 2300	Herring	90 dBht and 75 dBht contours	Figure 10.38
5	1800 and 2300	Herring		Figure 10.39

Table 10.11 Summary of conditions modelled for a single pile being driven at location E

Pile diameter (m)	Driving energy (kJ)	Species	Results shown	Figure
2.4	1800 and 2300	Cod	90 dBht and 75 dBht contours	Figure 10.40

10.7.22 The pile driving is envisaged to use a 'soft start' procedure, in which the strike energy is increased in steps as the pile is driven. Table 10.12 sets out the assumptions which have been made in the modelling to account for this process.

Table 10.12 Details of 'soft start' procedure assumed for the piling

Single pile cases (locations A, B, C, D and E)		
Final driving energy	**1800 kJ**	**2300 kJ**
'Ramp up' steps	1200 strikes @ 360 kJ	1200 strikes @460 kJ
	3700 strikes @ 720 kJ	3700 strikes @ 920 kJ
	3700 strikes @ 1080 kJ	3700 strikes @ 1380 kJ
	3700 strikes @ 1440 kJ	3700 strikes @ 1840 kJ
	3700 strikes @ 1800 kJ	3700 strikes @ 2300 kJ
Two piles being driven simultaneously (locations A and B simultaneously, locations A and E simultaneously, and locations C and D simultaneously)		
Final driving energy	**1800 kJ**	**2300 kJ**
'Ramp up' steps	Same as for single pile case	Same as for single pile case
Two 2.4 m diameter piles driven simultaneously (locations A and B and M1, M2 and M3 simultaneously, and locations A and E and M1, M2 and M3 simultaneously)		
Pile diameter	**2.4 m**	
Final driving energy	**2300 kJ**	
'Ramp up' steps	1200 strikes @460 kJ	
	3700 strikes @ 920 kJ	
	3700 strikes @ 1380 kJ	
	3700 strikes @ 1840 kJ	
	3700 strikes @ 2300 kJ	

10.7.23 For the fleeing animal cases the animal was assumed to move away from the pile at 1.5 m/s.

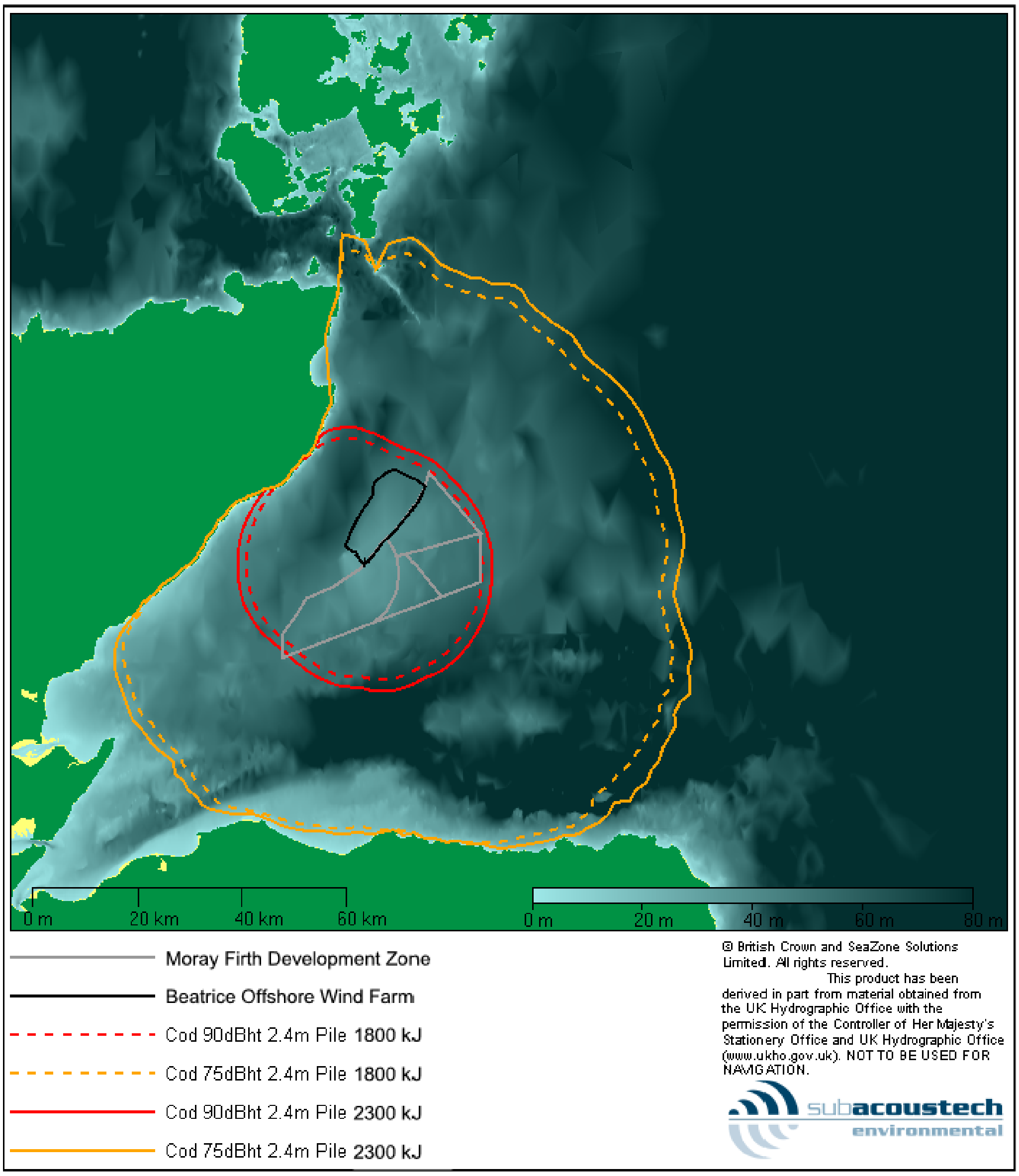
Results of INSPIRE modelling

10.7.24 The results of the calculations for the single pile cases are presented in Figures 10.14 to 10.52 below.

10.7.25 It will be seen that for some of the figures the contours are not closed lines (e.g. Figure 10.43). The reason for this is that the "fleeing animal" in the programme has 'encountered' the shore before it has arrived at the criterion value. The model only considers straight line fleeing, and is hence unable to calculate the exposure on transects where this condition occurs. In some cases a closed contour has been estimated by hand.

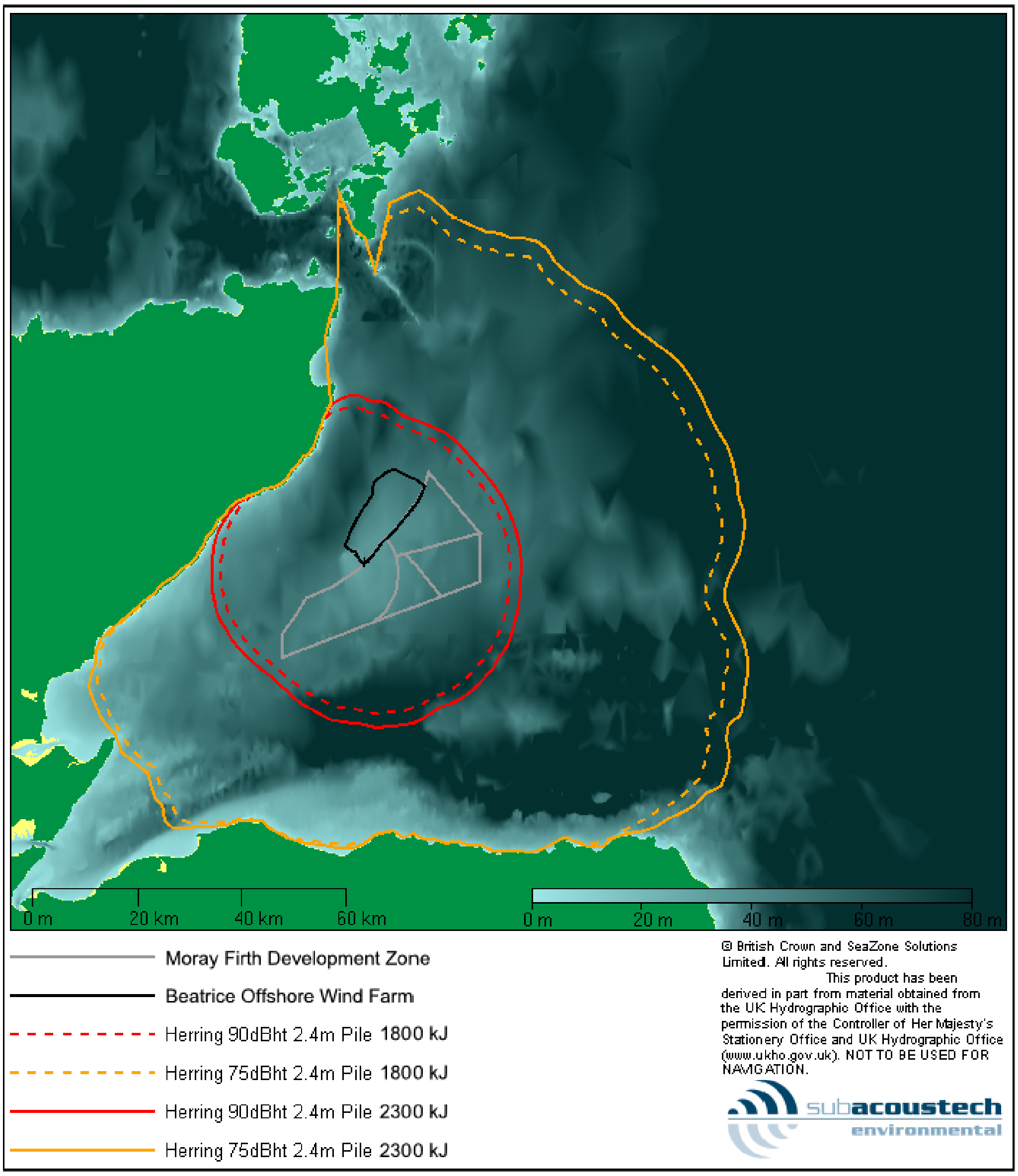
Results for a single pile being driven at location A

Figure 10.14 *90 dBht and 75 dBht contours for the cod. 2.4 m diameter pile being driven at location A. Results for two piling energies*



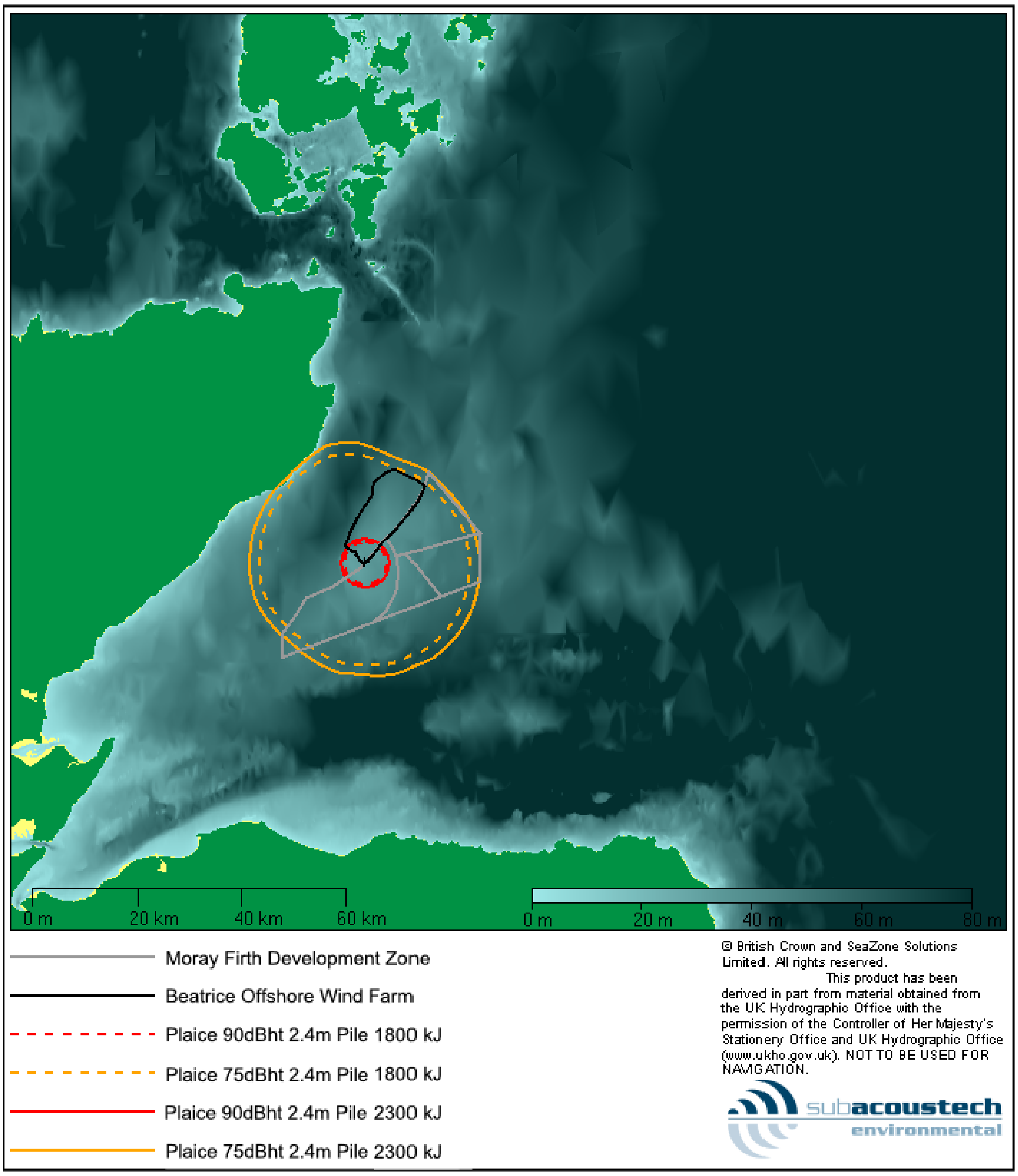
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Cod

Figure 10.15 90 dBht and 75 dBht contours for the herring. 2.4 m diameter pile being driven at location A. Results for two piling energies



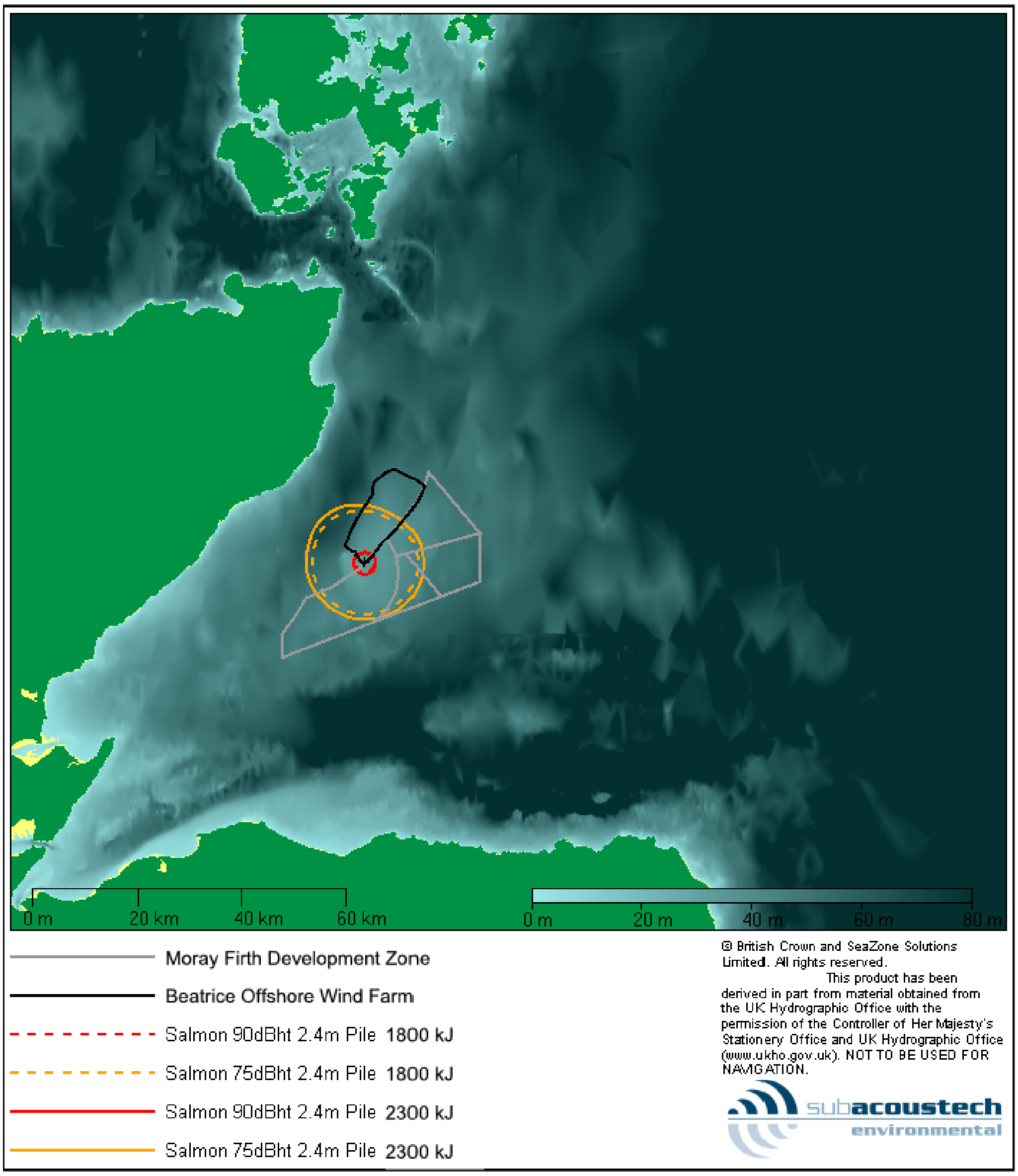
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Herring

Figure 10.16 90 dBht and 75 dBht contours for the plaice. 2.4 m diameter pile being driven at location A. Results for two piling energies



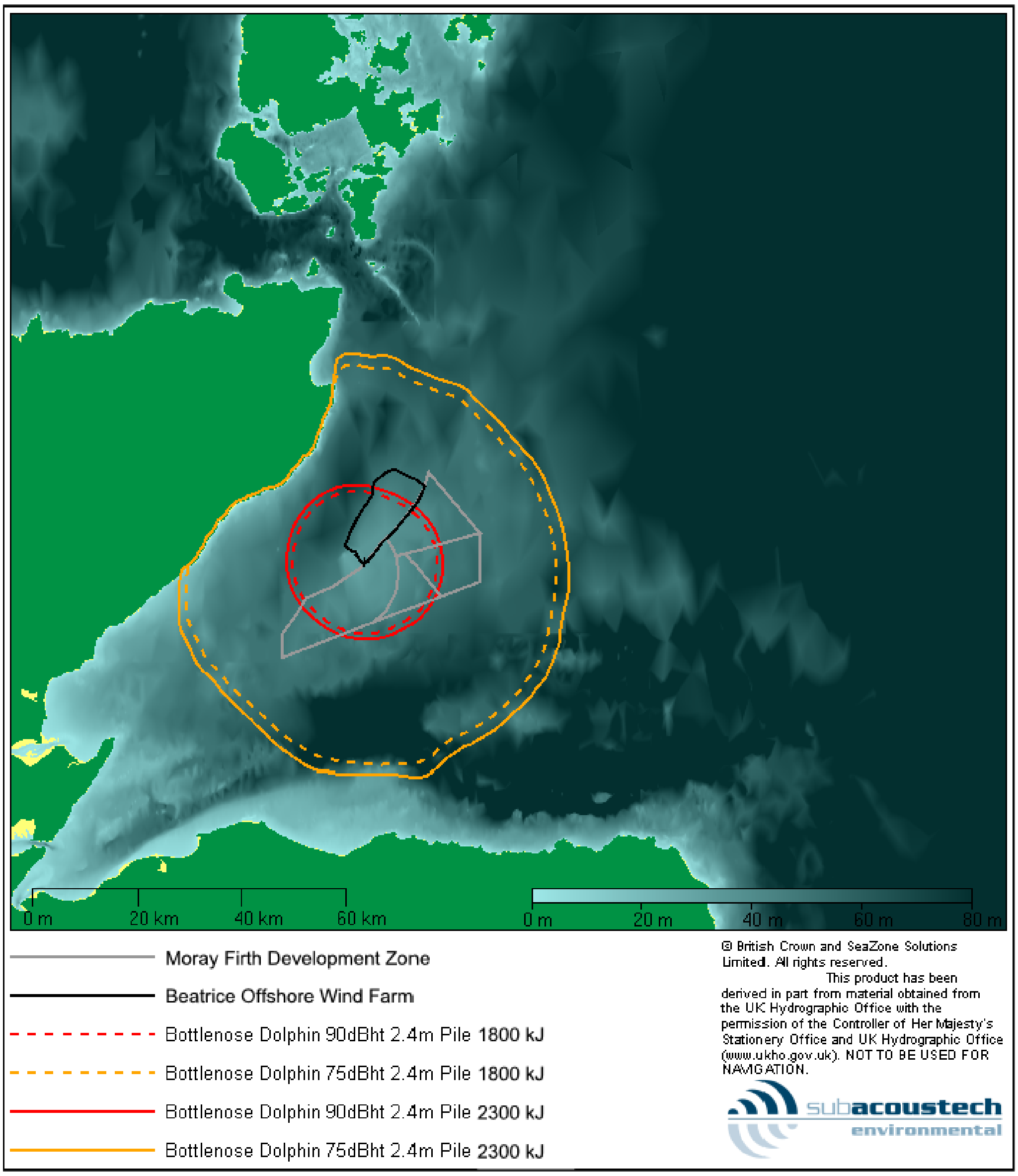
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Plaice

Figure 10.17 90 dBht and 75 dBht contours for the salmon. 2.4 m diameter pile being driven at location A. Results for two piling energies



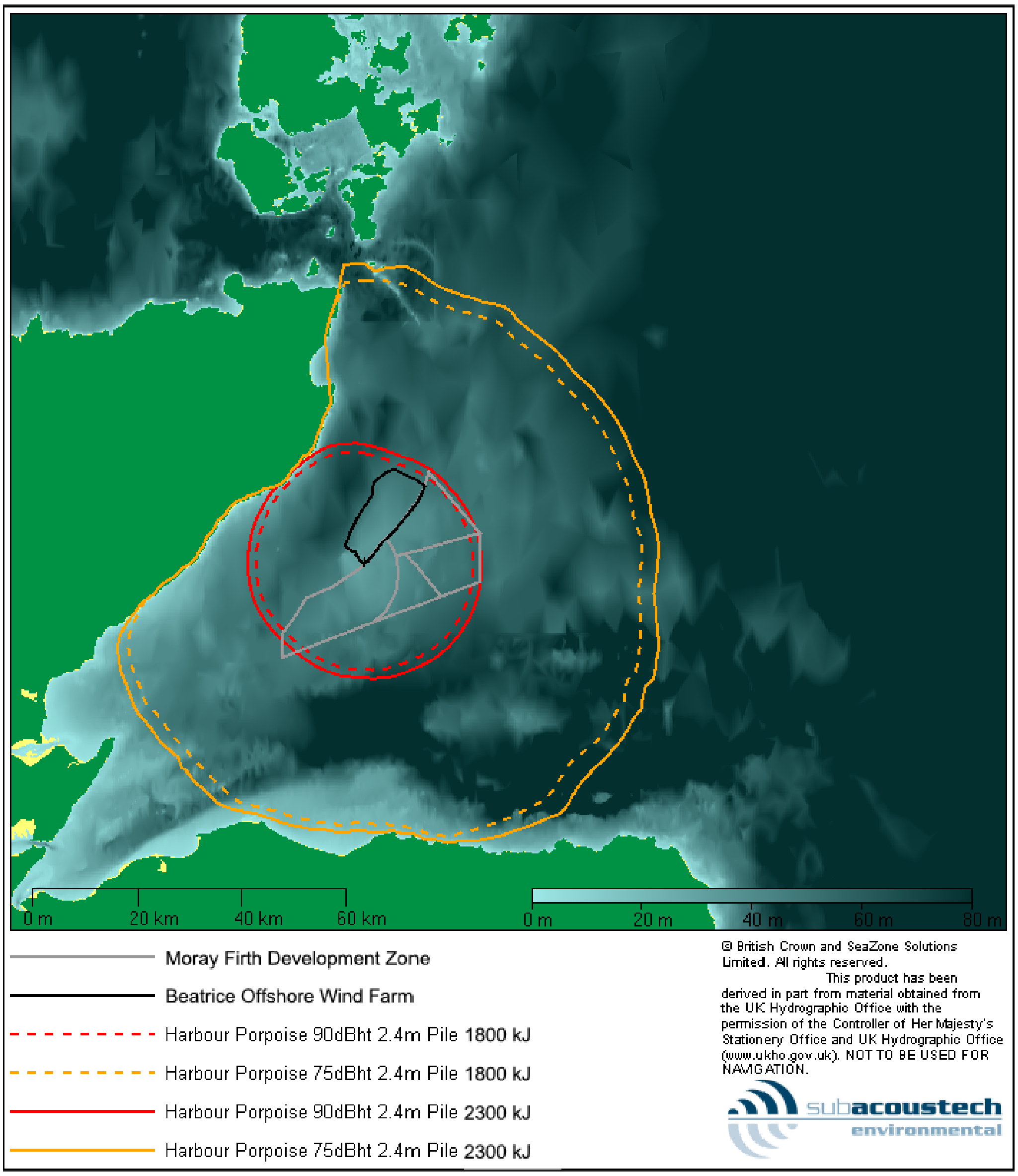
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Salmon

Figure 10.18 90 dBht and 75 dBht contours for the bottlenose dolphin. 2.4 m diameter pile being driven at location A. Results for two piling energies



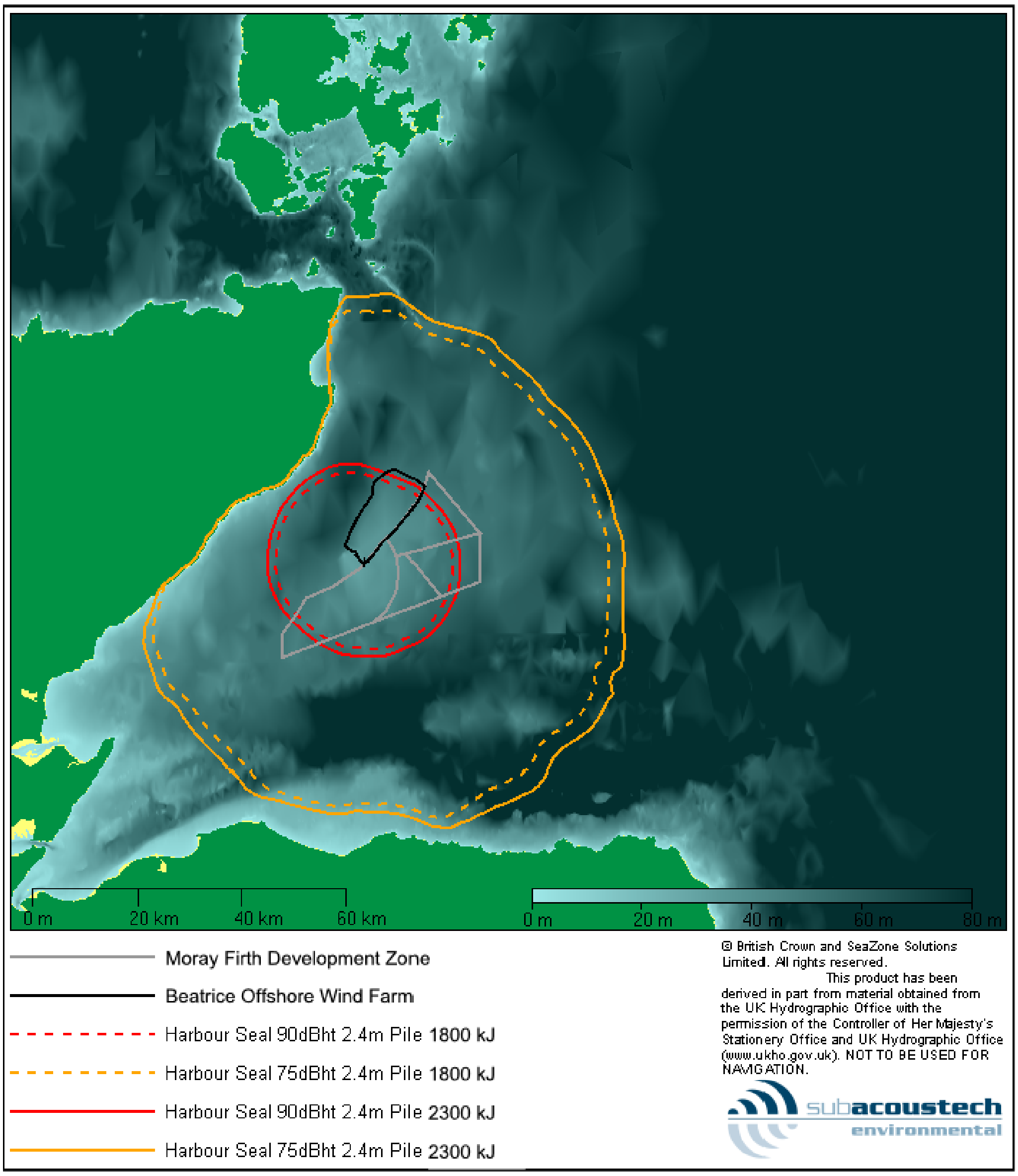
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Bottlenose dolphin

Figure 10.19 90 dBht and 75 dBht contours for the harbour porpoise. 2.4 m diameter pile being driven at location A. Results for two piling energies



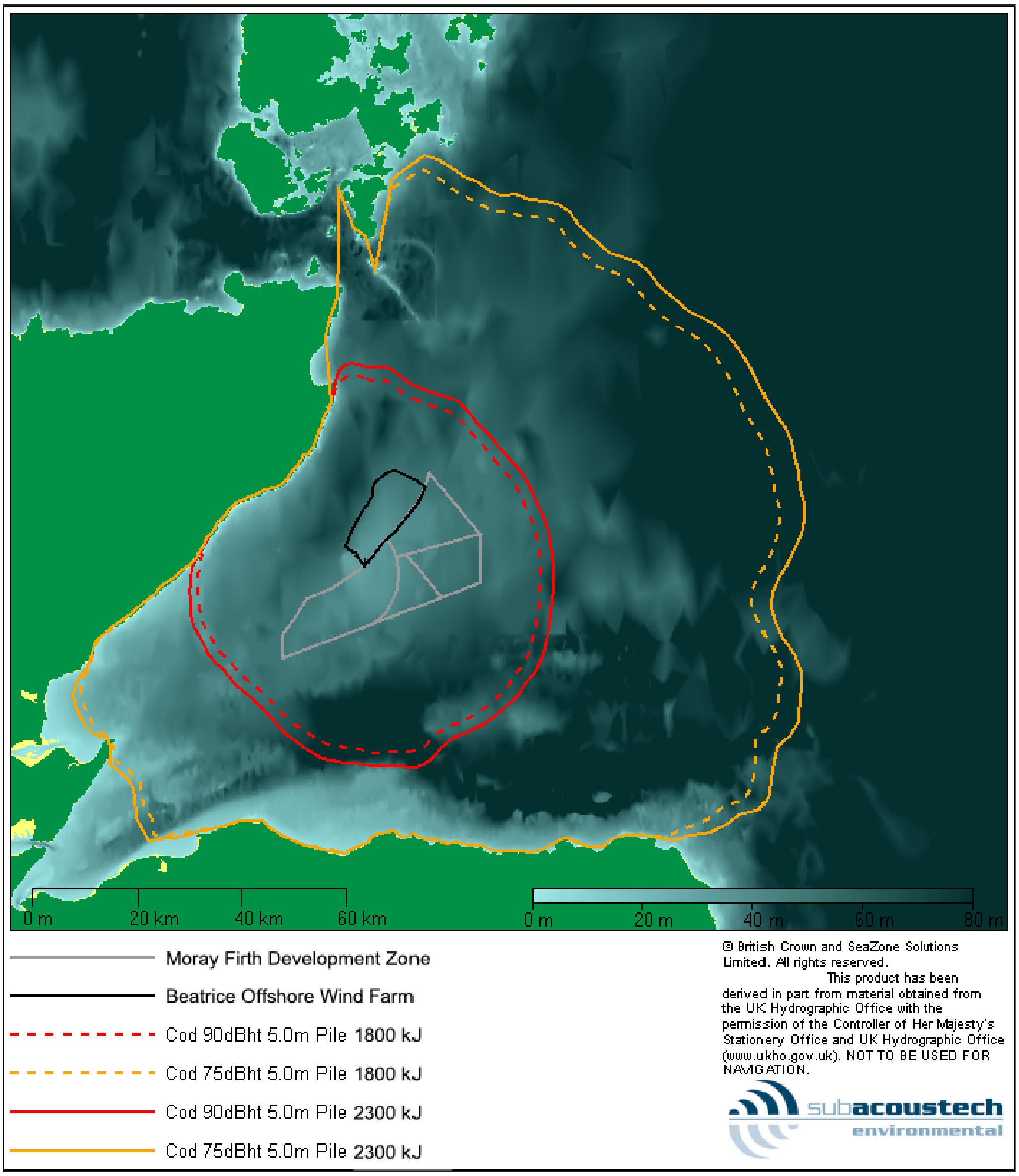
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Harbour porpoise

Figure 10.20 90 dBht and 75 dBht contours for the harbour seal. 2.4 m diameter pile being driven at location A. Results for two piling energies



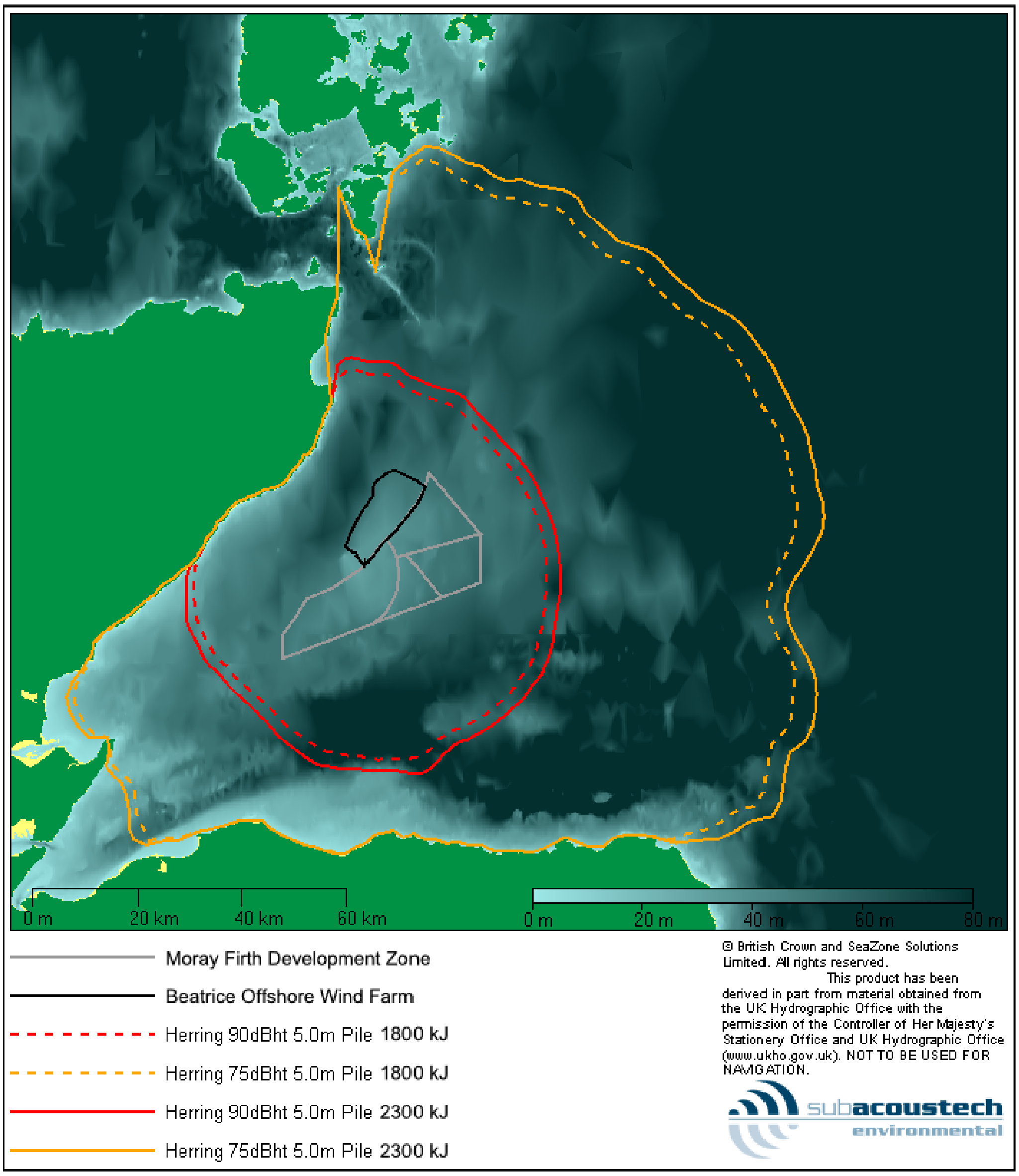
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Harbour seal

Figure 10.21 90 dBht and 75 dBht contours for the cod. 5 m diameter pile being driven at location A. Results for two piling energies



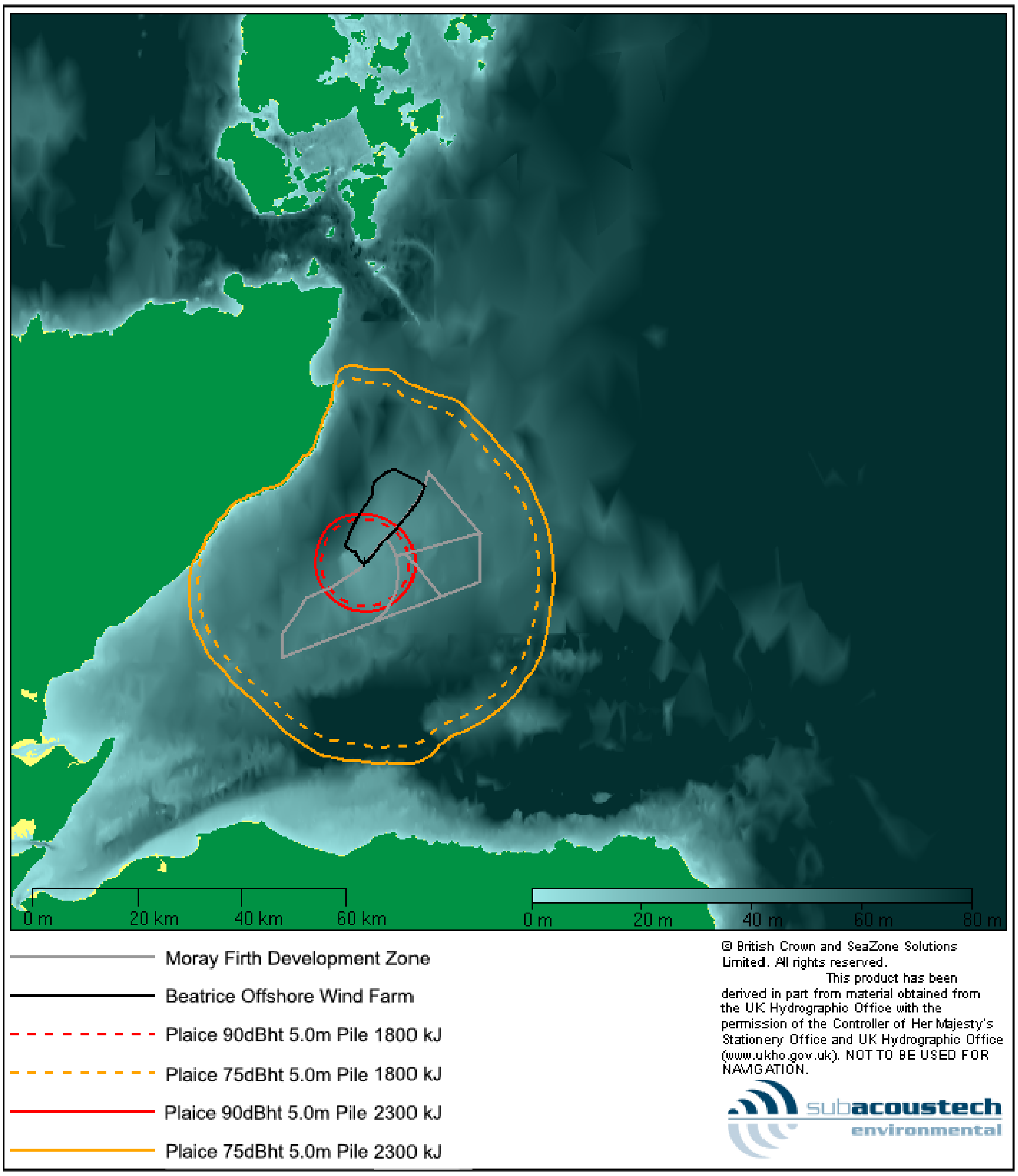
Pile diameter (m)	5
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Cod

Figure 10.22 90 dBht and 75 dBht contours for the herring. 5 m diameter pile being driven at location A. Results for two piling energies



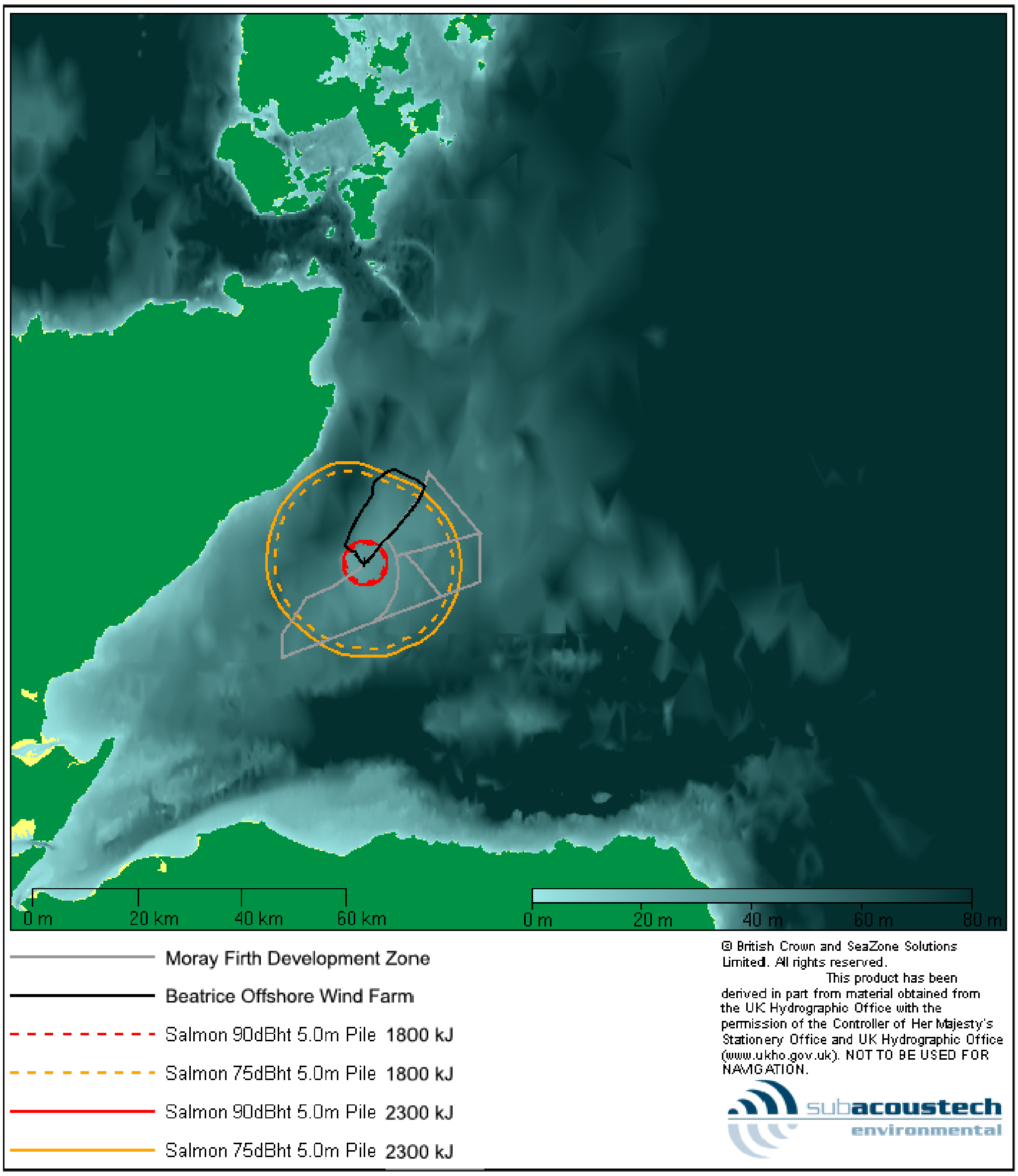
Pile diameter (m)	5
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Herring

Figure 10.23 90 dBht and 75 dBht contours for the plaice. 5 m diameter pile being driven at location A. Results for two piling energies



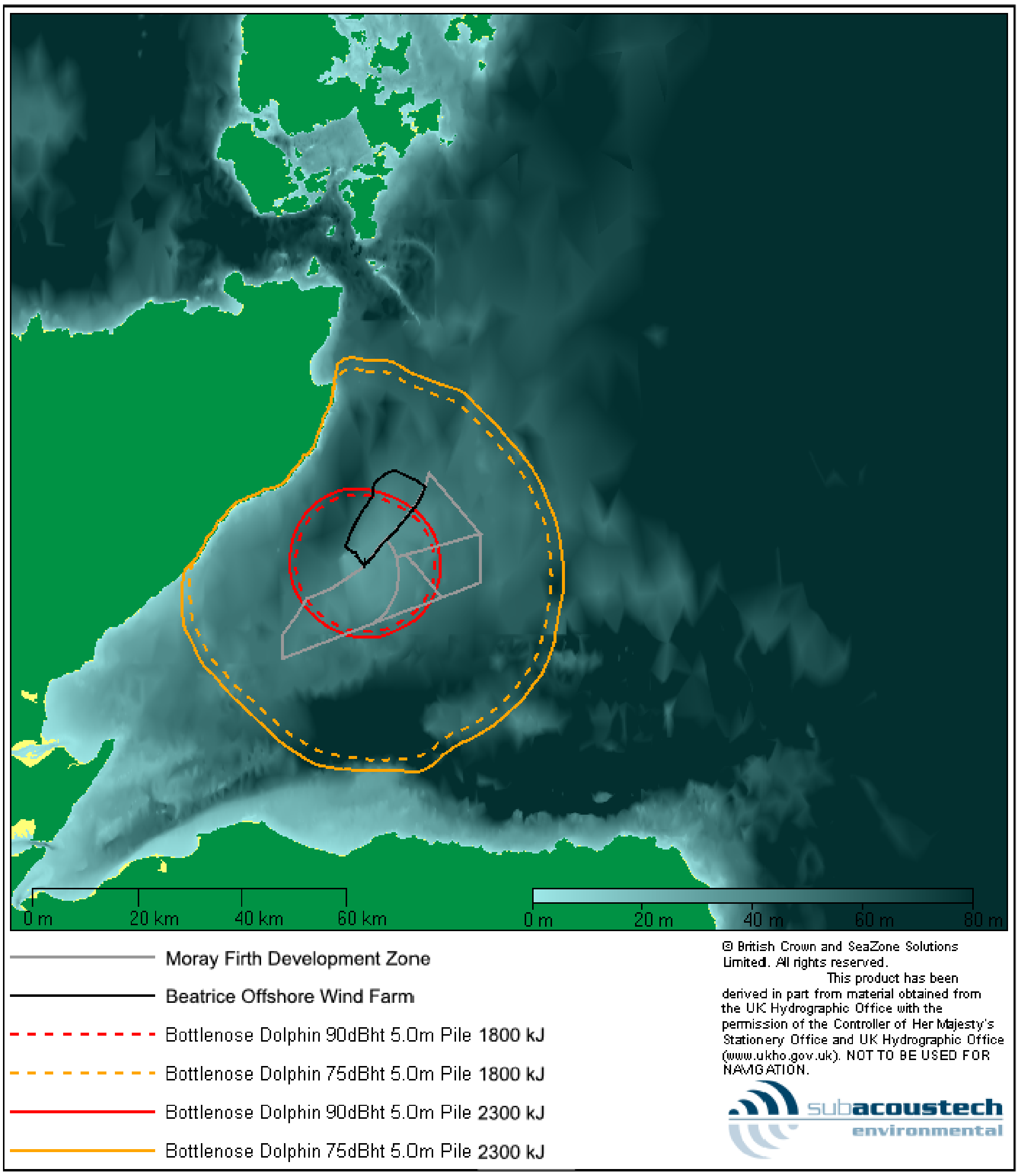
Pile diameter (m)	5
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Plaice

Figure 10.24 90 dBht and 75 dBht contours for the salmon. 5 m diameter pile being driven at location A. Results for two piling energies



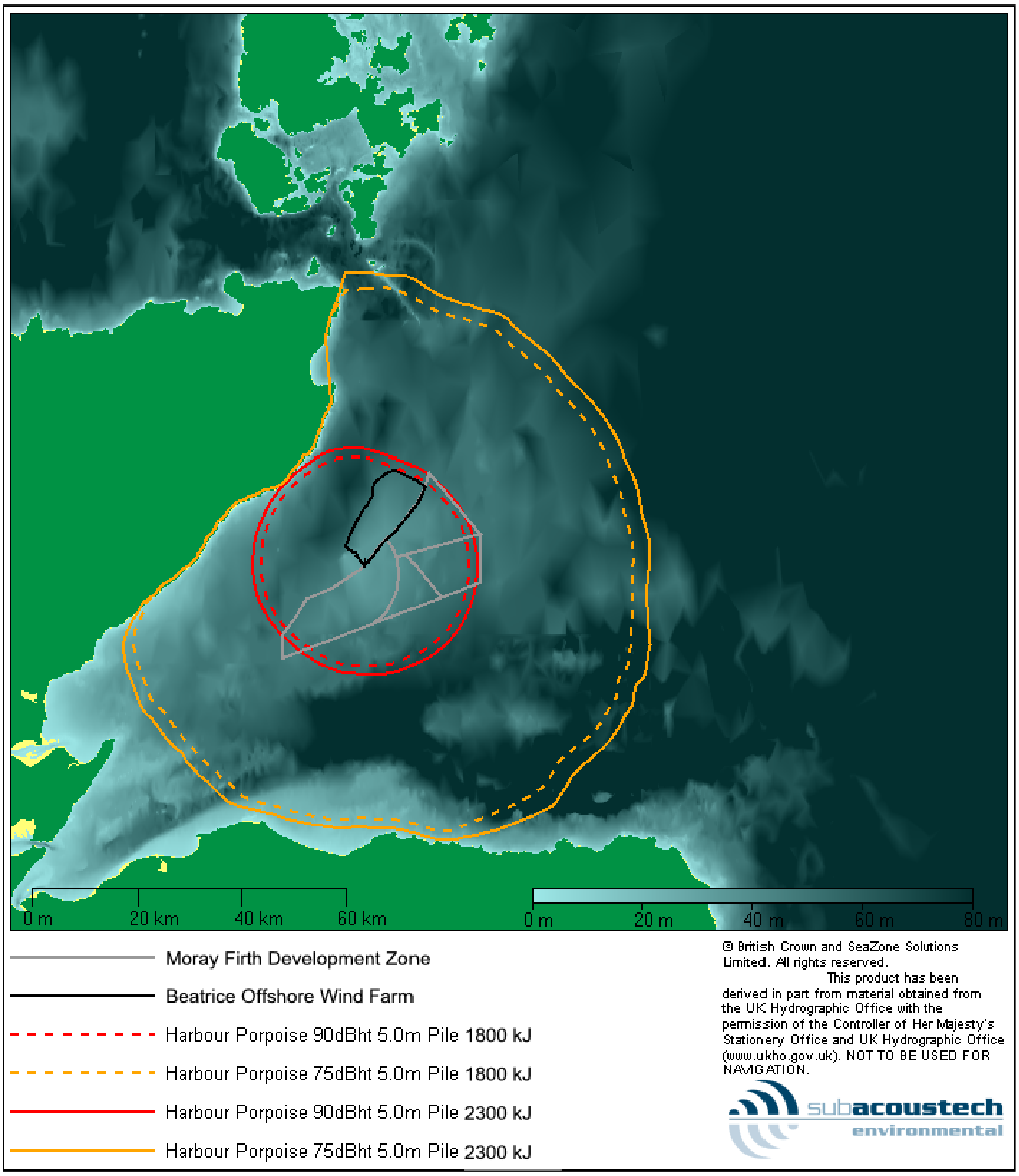
Pile diameter (m)	5
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Salmon

Figure 10.25 90 dBht and 75 dBht contours for the bottlenose dolphin. 5 m diameter pile being driven at location A. Results for two piling energies



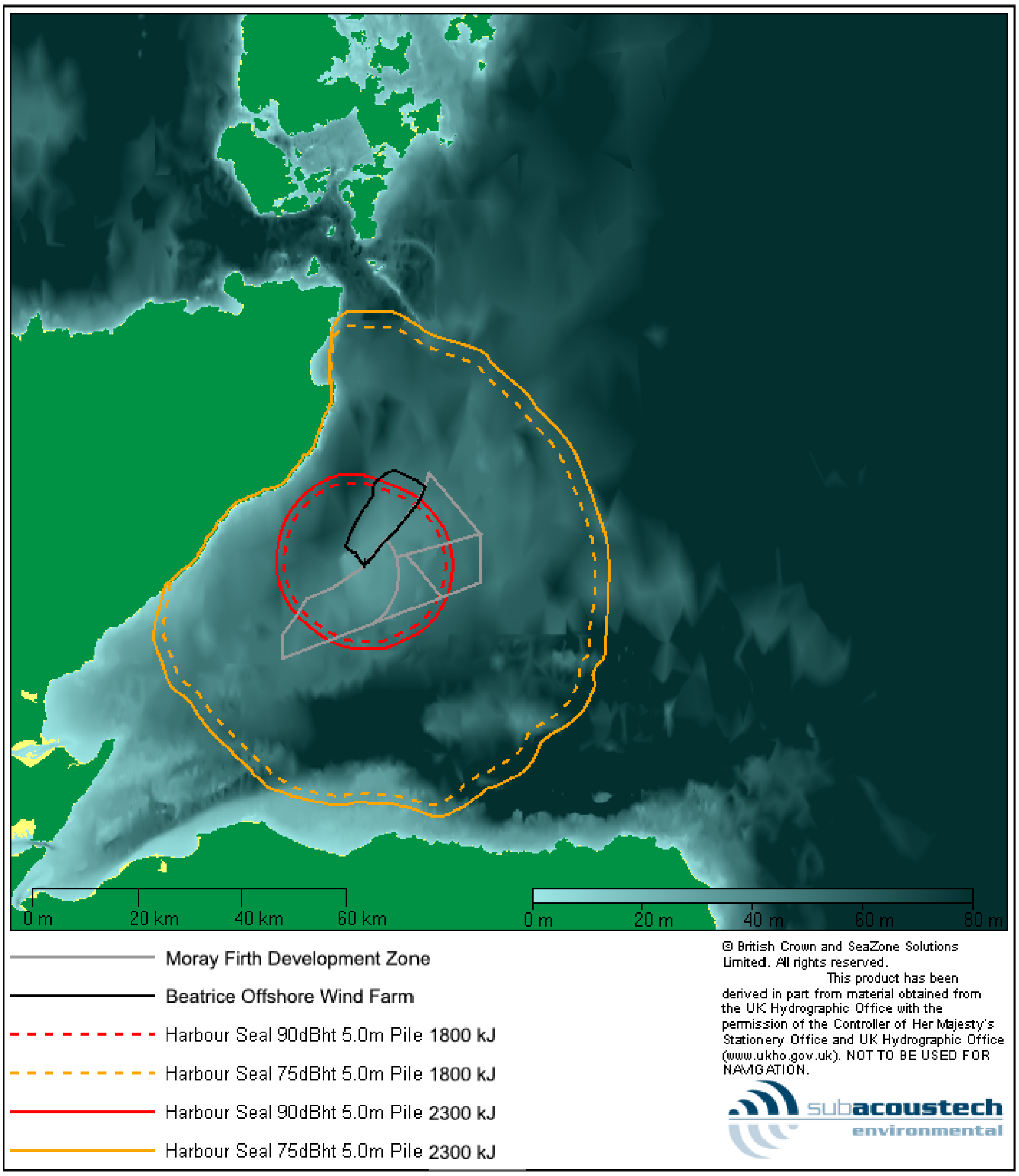
Pile diameter (m)	5
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Bottlenose dolphin

Figure 10.26 90 dBht and 75 dBht contours for the harbour porpoise. 5 m diameter pile being driven at location A. Results for two piling energies



Pile diameter (m)	5
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Harbour porpoise

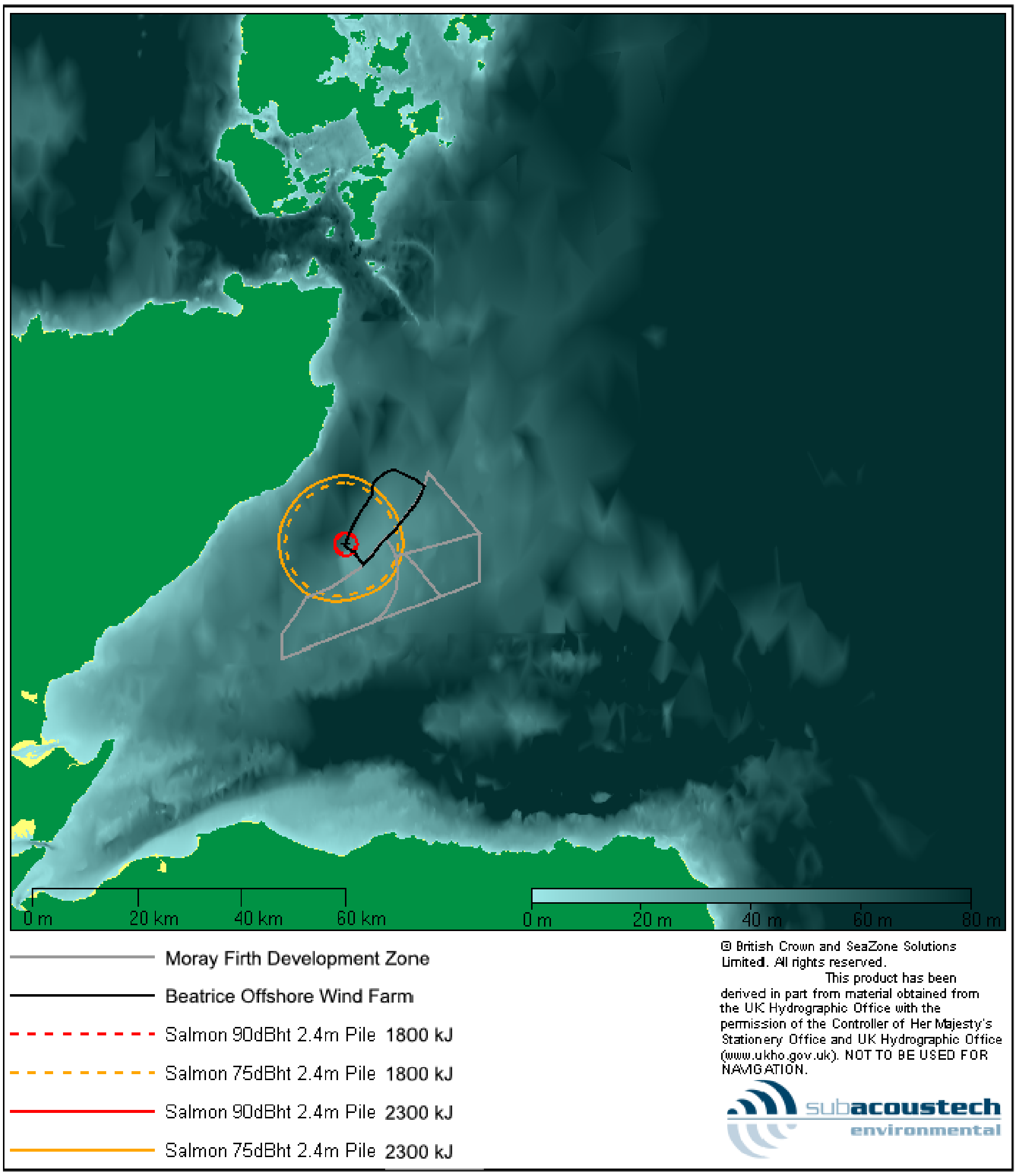
Figure 10.27 90 dBht and 75 dBht contours for the harbour seal. 5 m diameter pile being driven at location A. Results for two piling energies



Pile diameter (m)	5
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Harbour seal

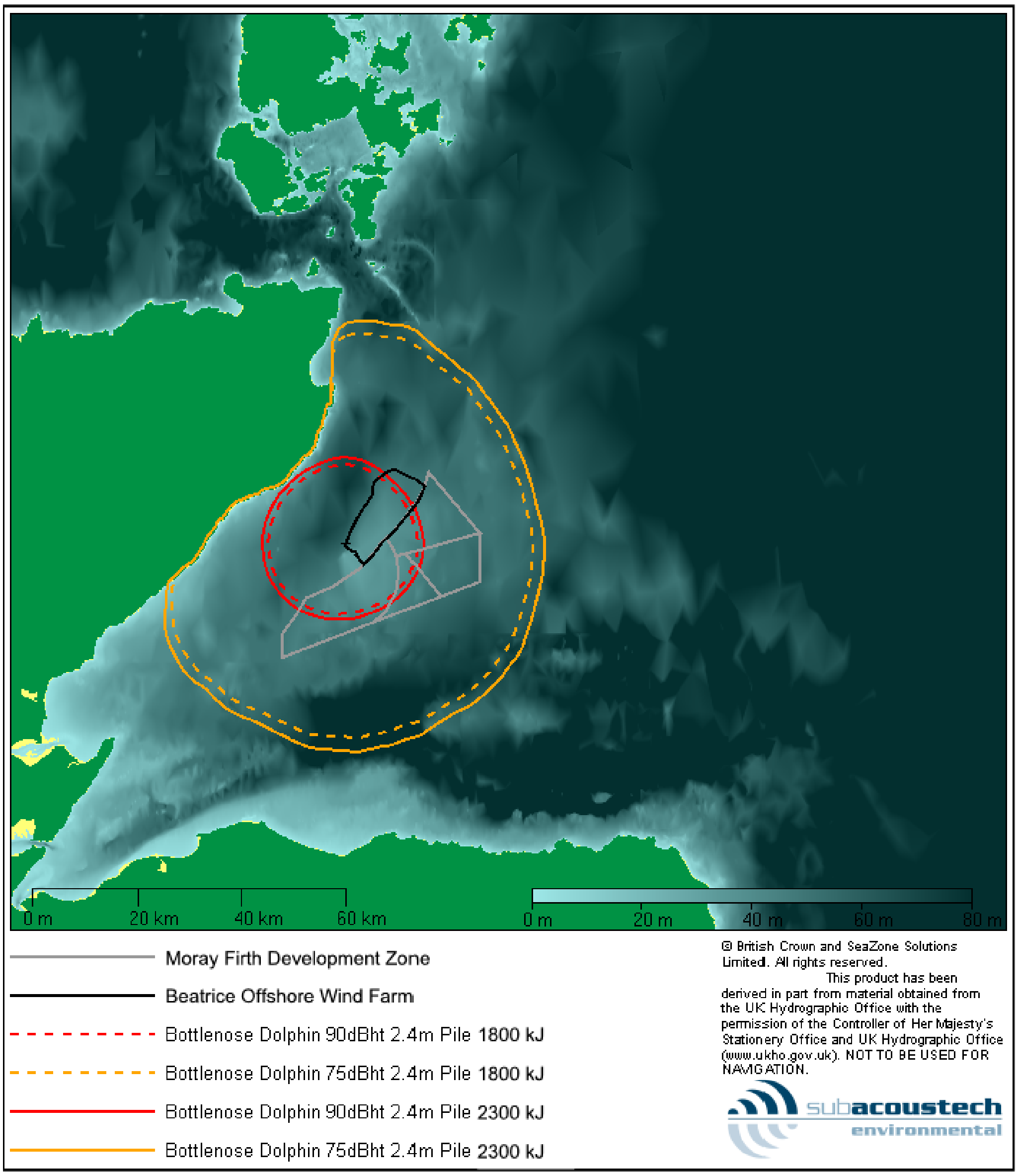
Results for a single pile being driven at location B

Figure 10.28 90 dBht and 75 dBht contours for the salmon. 2.4 m diameter pile being driven at location B. Results for two piling energies



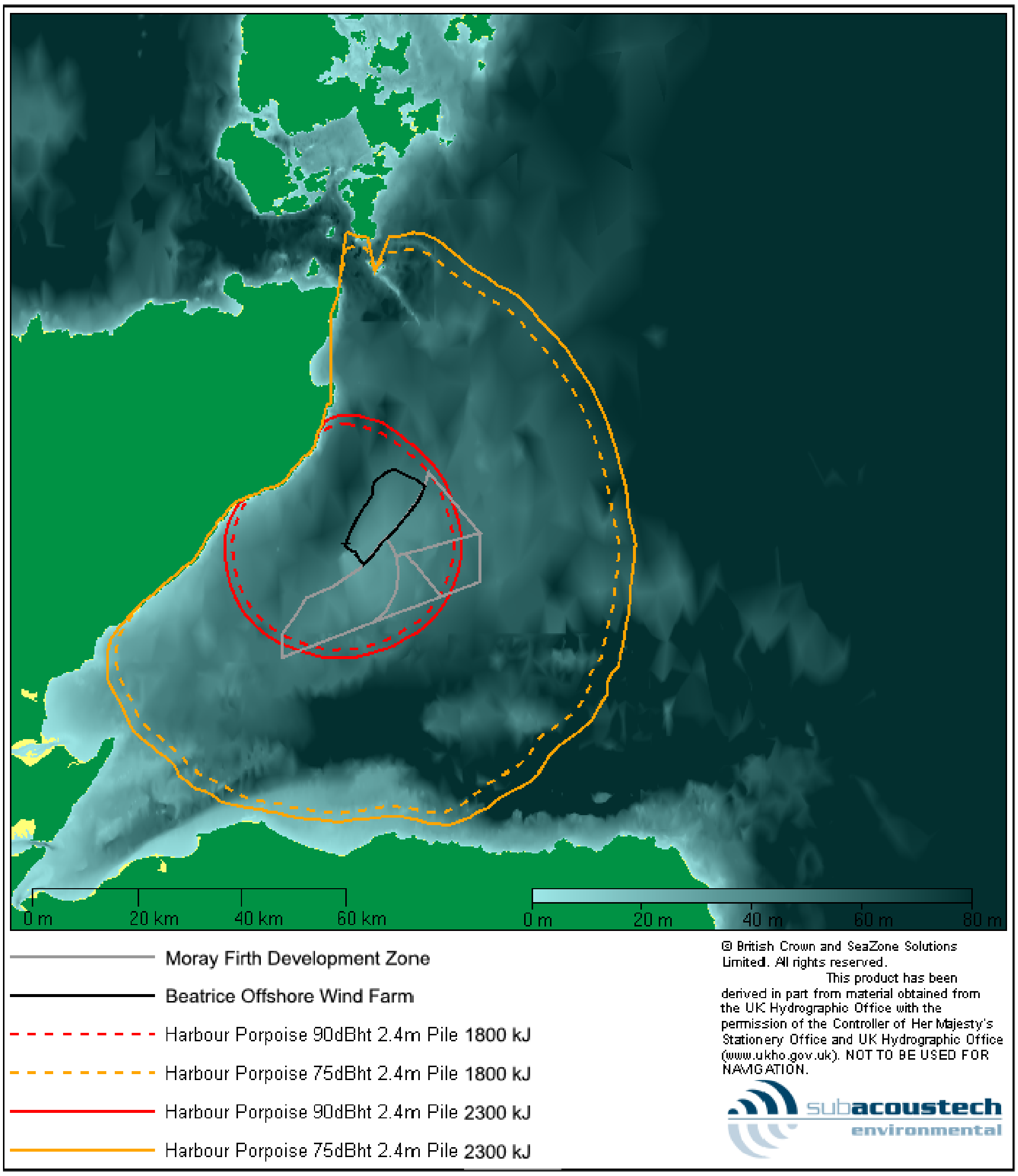
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	Cod

Figure 10.29 90 dBht and 75 dBht contours for the bottlenose dolphin. 2.4 m diameter pile being driven at location B. Results for two piling energies



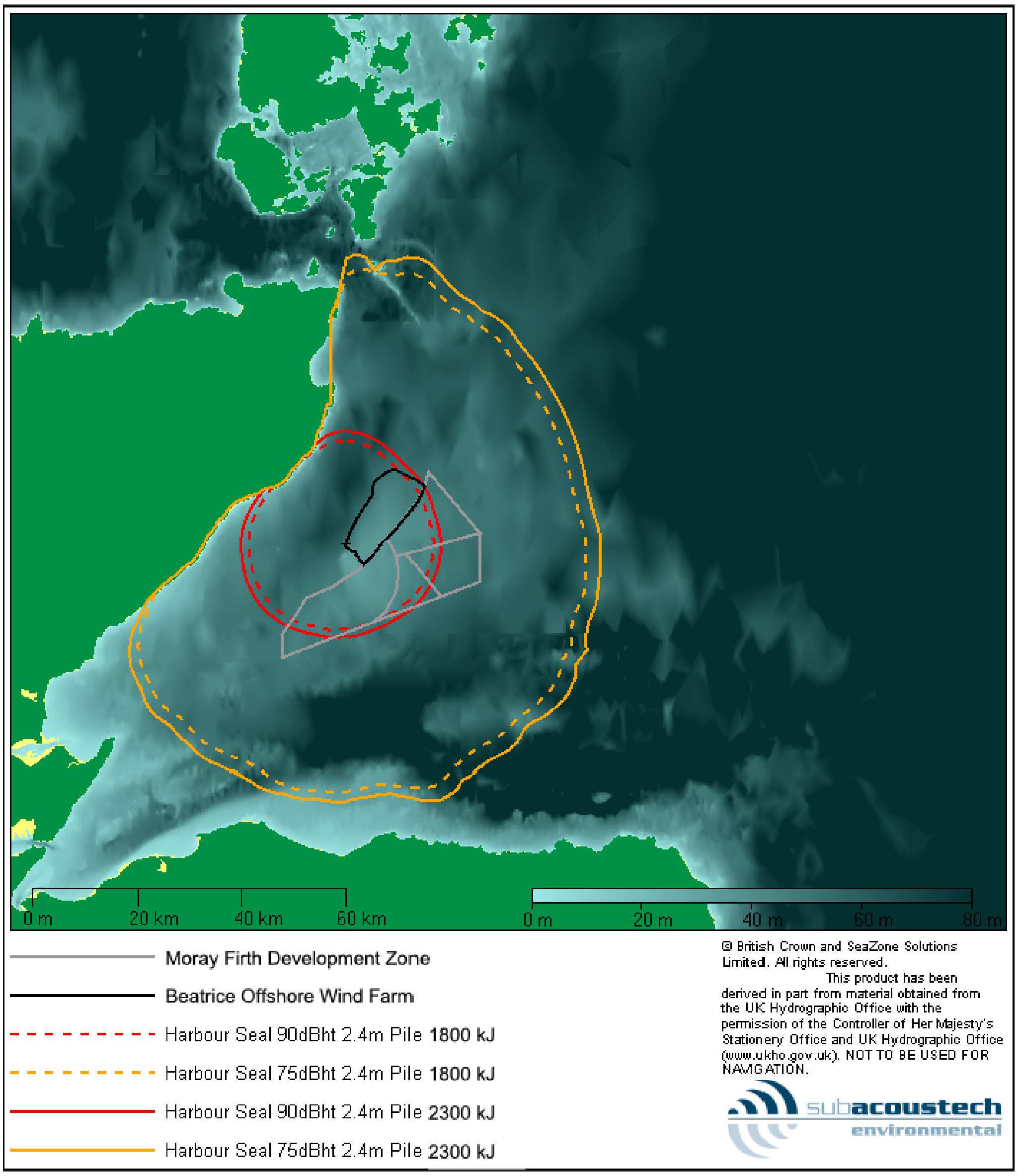
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	Bottlenose dolphin

Figure 10.30 90 dBht and 75 dBht contours for the harbour porpoise. 2.4 m diameter pile being driven at location B. Results for two piling energies



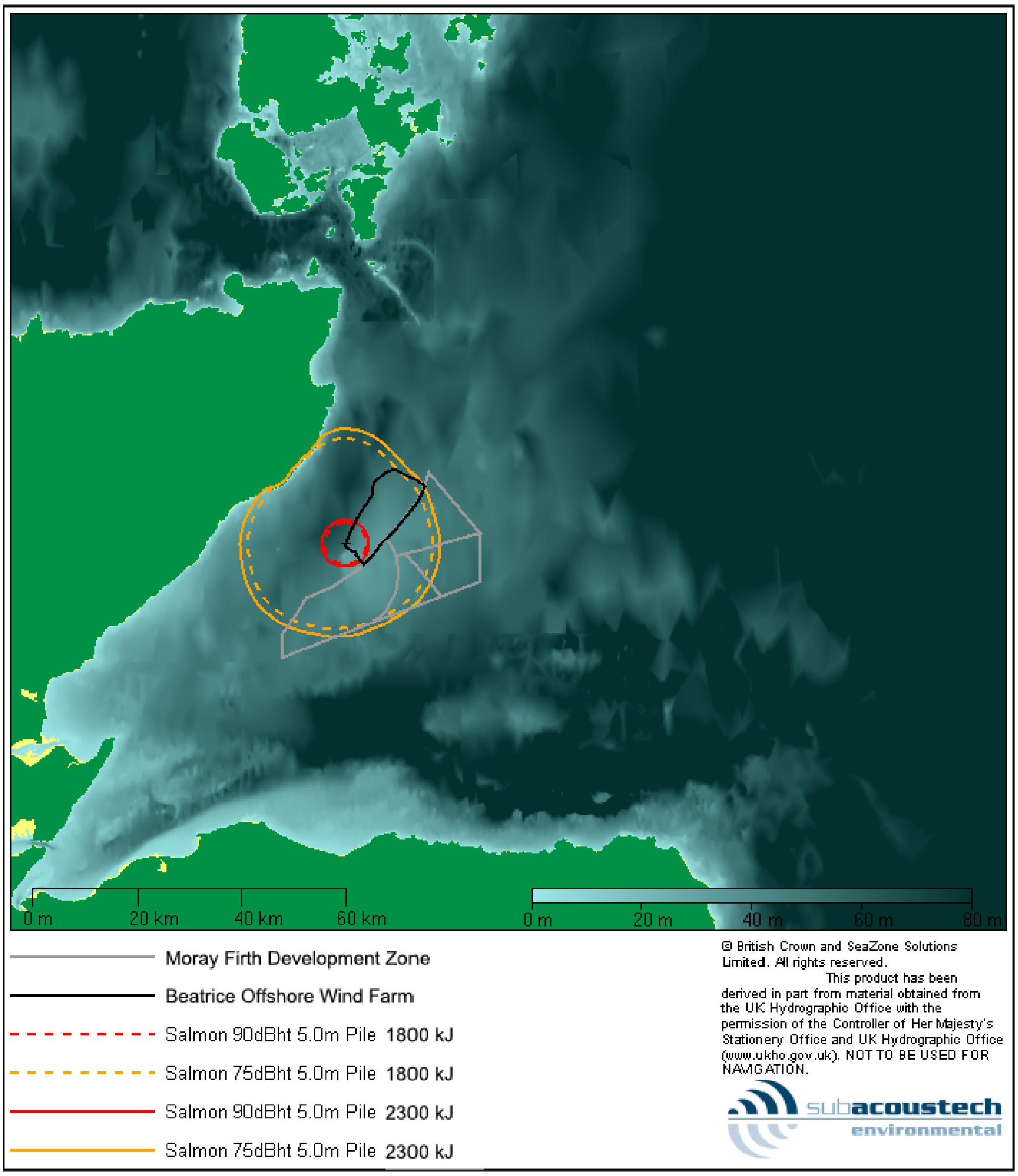
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	Harbour porpoise

Figure 10.31 90 dBht and 75 dBht contours for the harbour seal. 2.4 m diameter pile being driven at location B. Results for two piling energies



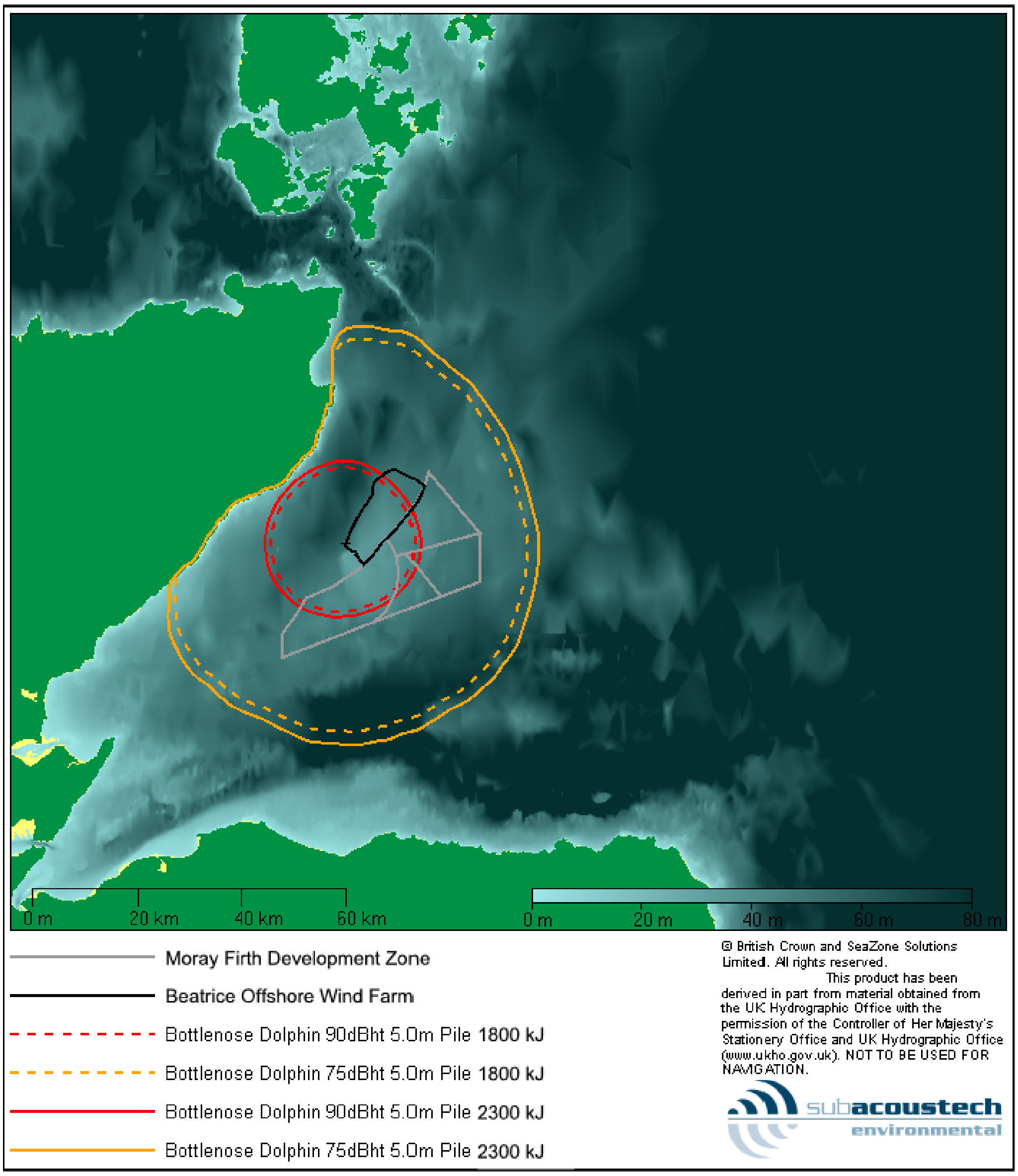
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	Harbour seal

Figure 10.32 90 dBht and 75 dBht contours for the salmon. 5 m diameter pile being driven at location B. Results for two piling energies



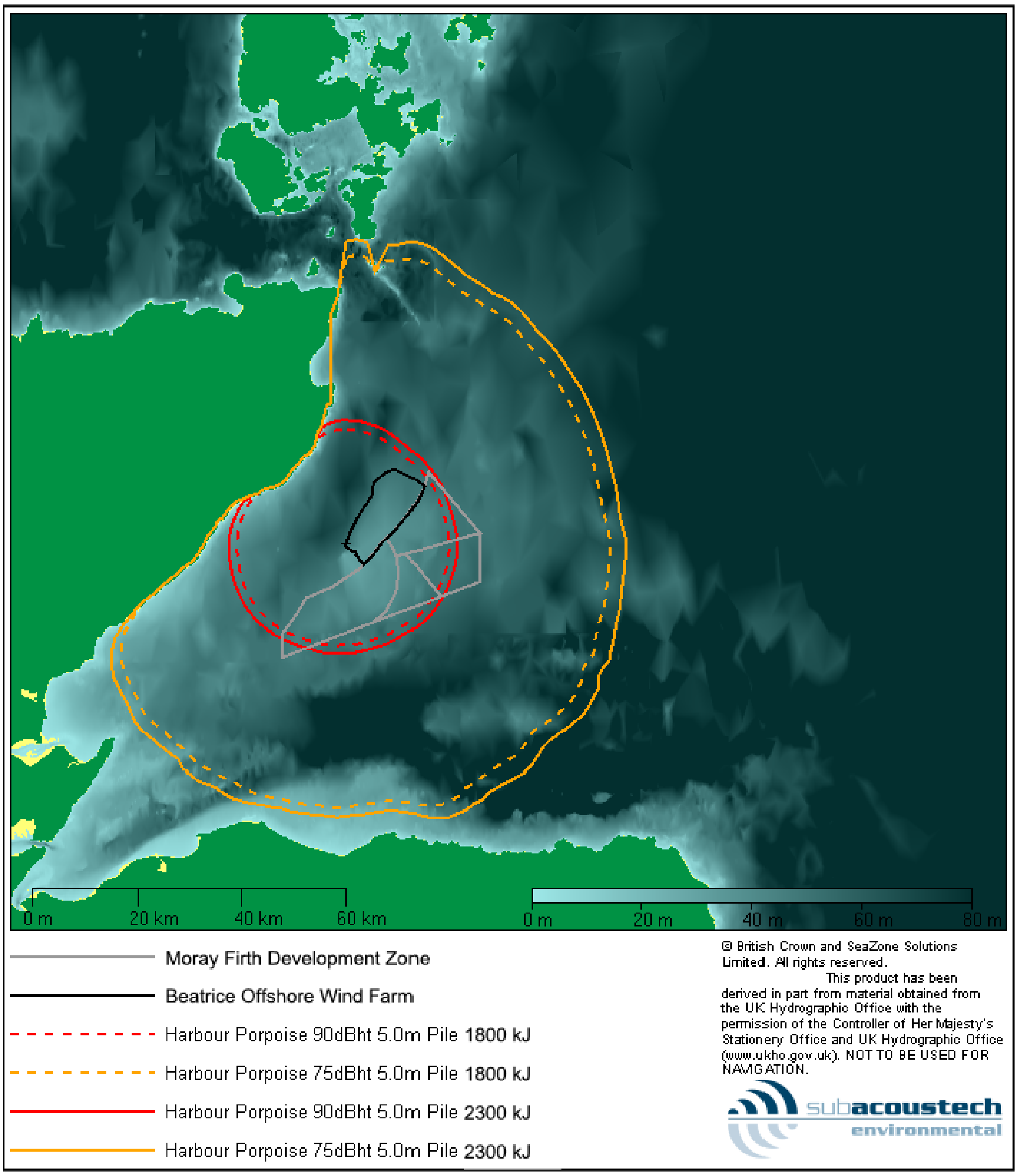
Pile diameter (m)	5
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	Salmon

Figure 10.33 90 dBht and 75 dBht contours for the bottlenose dolphin. 5 m diameter pile being driven at location B. Results for two piling energies



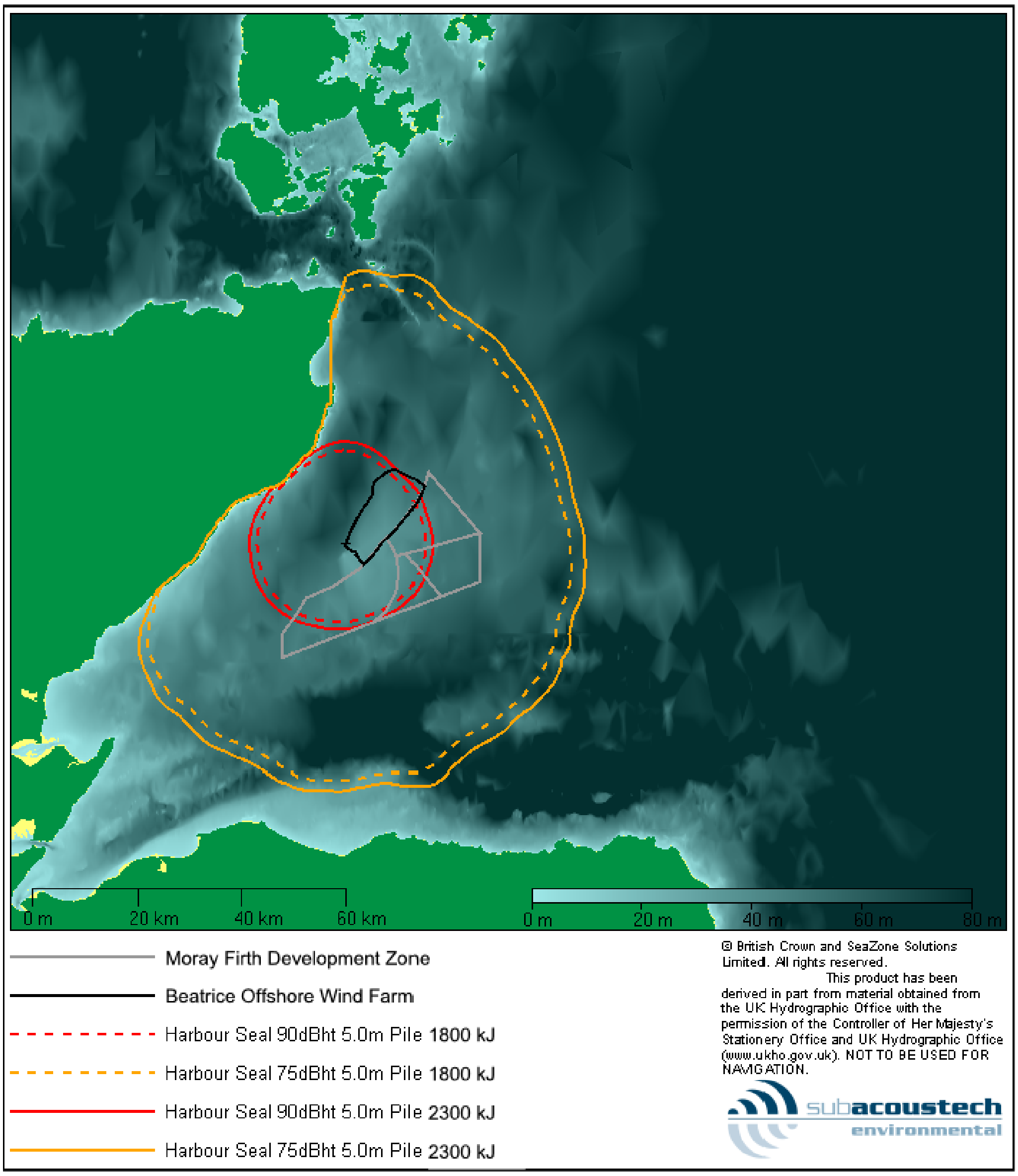
Pile diameter (m)	5
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	Bottlenose dolphin

Figure 10.34   90 dBht and 75 dBht contours for the harbour porpoise. 5 m diameter pile being driven at location B. Results for two piling energies



Pile diameter (m)	5
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	Harbour porpoise

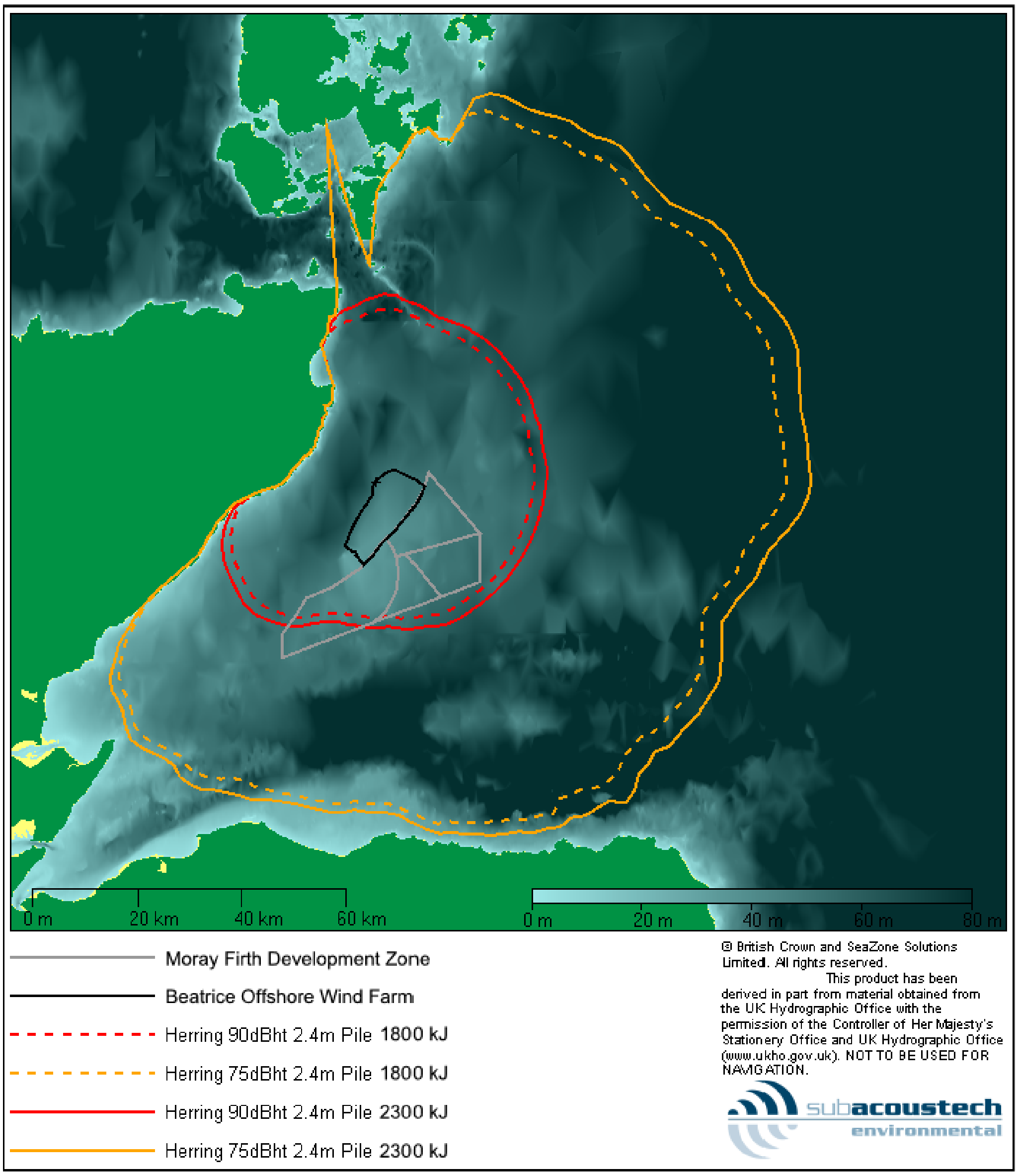
Figure 10.35 90 dBht and 75 dBht contours for the harbour seal. 5 m diameter pile being driven at location B. Results for two piling energies



Pile diameter (m)	5
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	Harbour seal

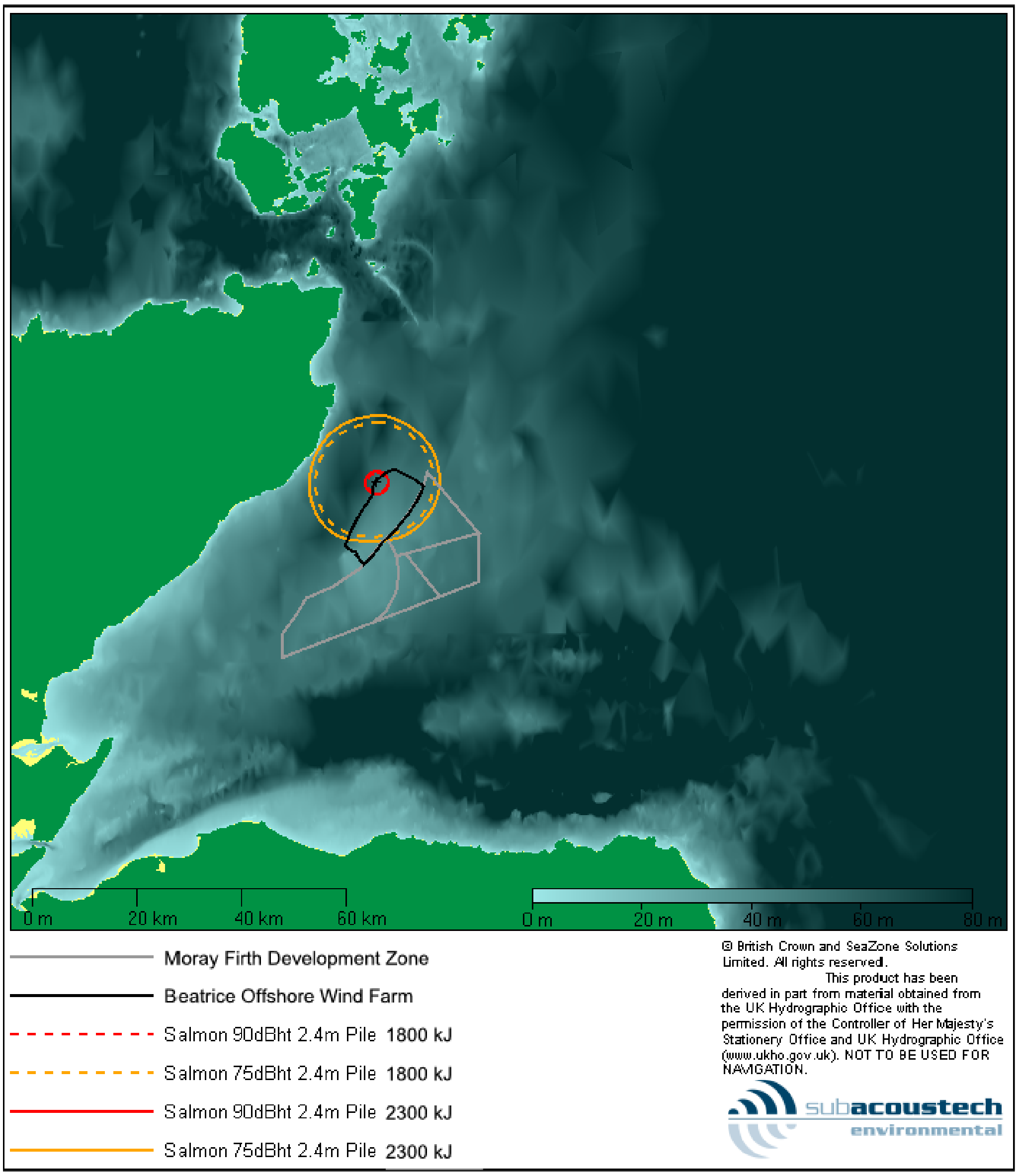
Results for a single pile being driven at location C

Figure 10.36 90 dBht and 75 dBht contours for the herring. 2.4 m diameter pile being driven at location C. Results for two piling energies



Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	C
Pile driving energy (kJ)	1800 and 2300
Species	Herring

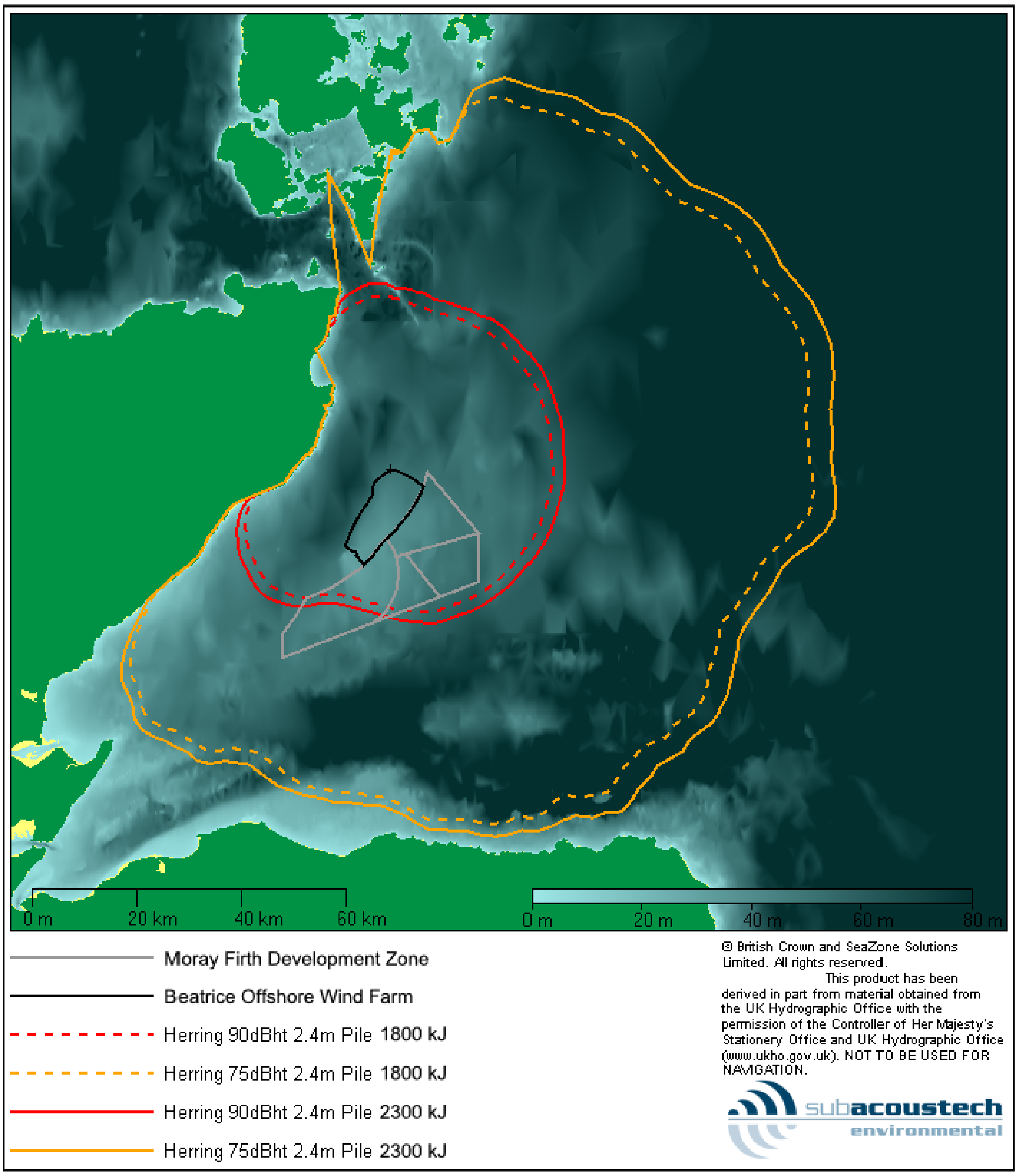
Figure 10.37 90 dBht and 75 dBht contours for the salmon. 2.4 m diameter pile being driven at location C. Results for two piling energies



Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	C
Pile driving energy (kJ)	1800 and 2300
Species	Salmon

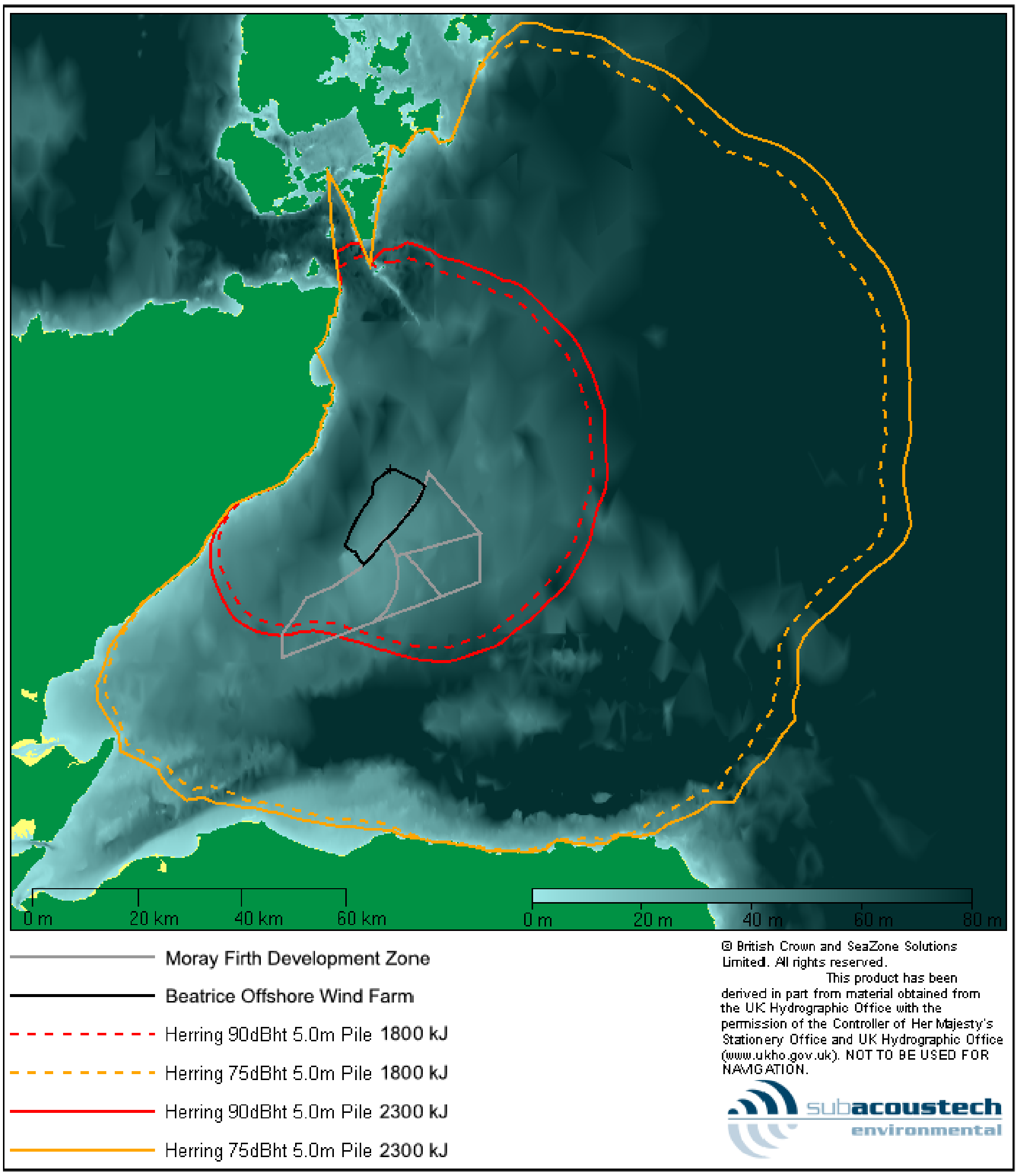
Results for a single pile being driven at location D

Figure 10.38 90 dBht and 75 dBht contours for the herring. 2.4 m diameter pile being driven at location D. Results for two piling energies



Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	D
Pile driving energy (kJ)	1800 and 2300
Species	Herring

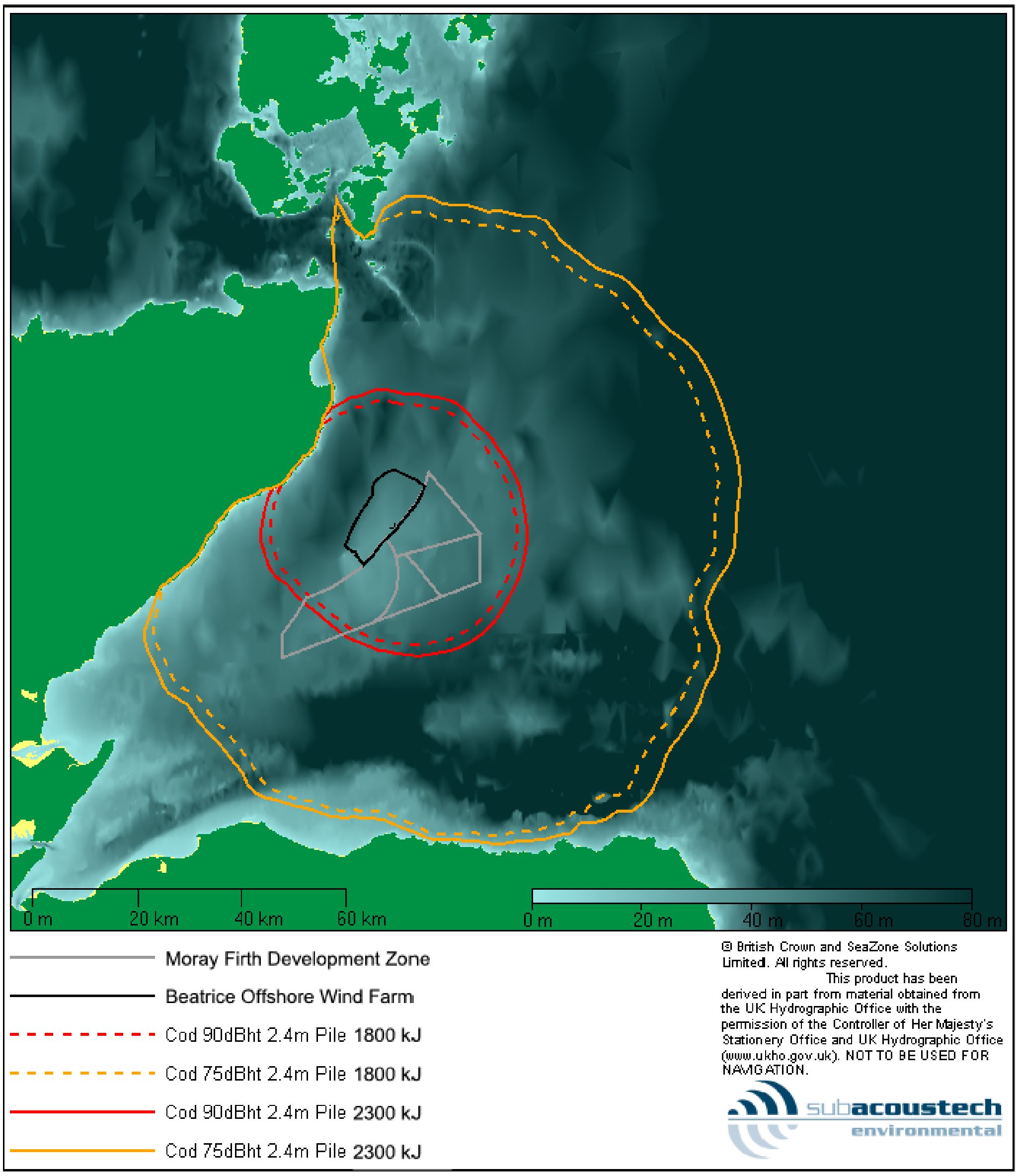
Figure 10.39   90 dBht and 75 dBht contours for the herring. 5 m diameter pile being driven at location D. Results for two piling energies



Pile diameter (m)	5
Pile location (see map, Figure 10.13)	D
Pile driving energy (kJ)	1800 and 2300
Species	Herring

Results for a single pile being driven at location E

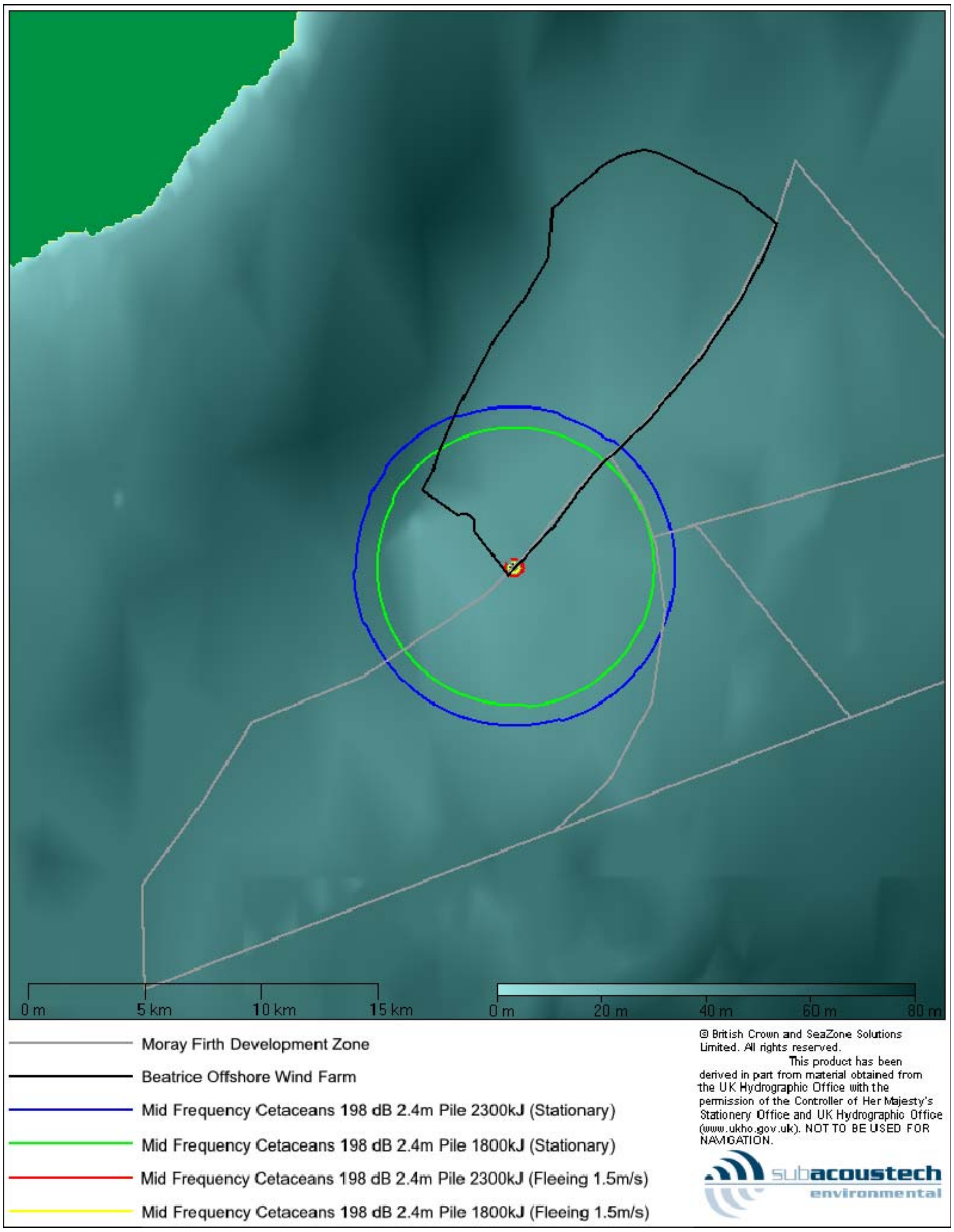
Figure 10.40 90 dBht and 75 dBht contours for the cod. 2.4 m diameter pile being driven at location E. Results for two piling energies



Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	E
Pile driving energy (kJ)	1800 and 2300
Species	Cod

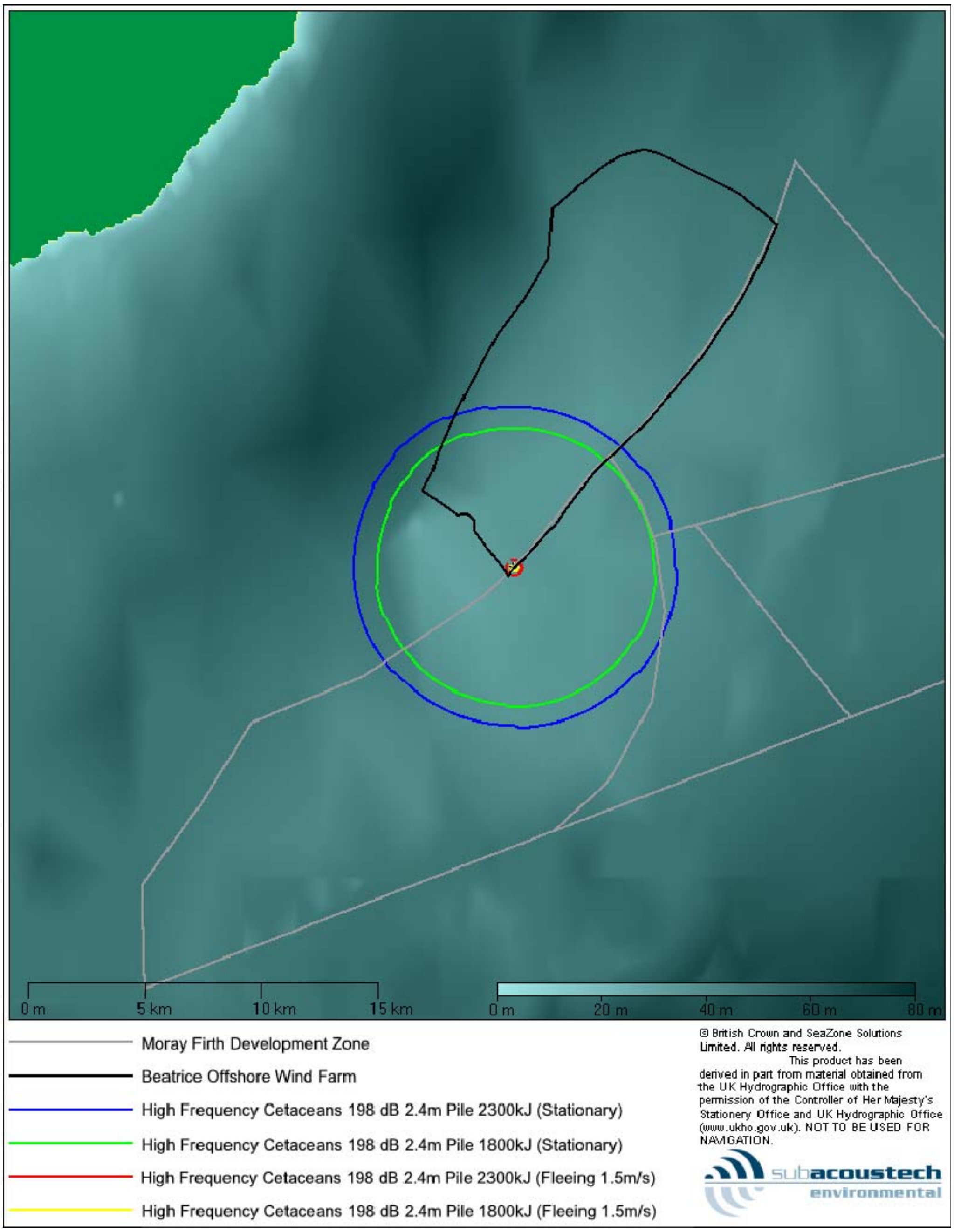
M-weighted results for a single pile being driven at location A

Figure 10.41 198 dB(Mmf) contour for a stationary mid-frequency cetacean, and locus of starting distances from which a fleeing mid-frequency cetacean would just reach 198 dB(Mmf) at the cessation of the driving of the pile. 2.4 m diameter pile being driven at location A. Results for two piling energies



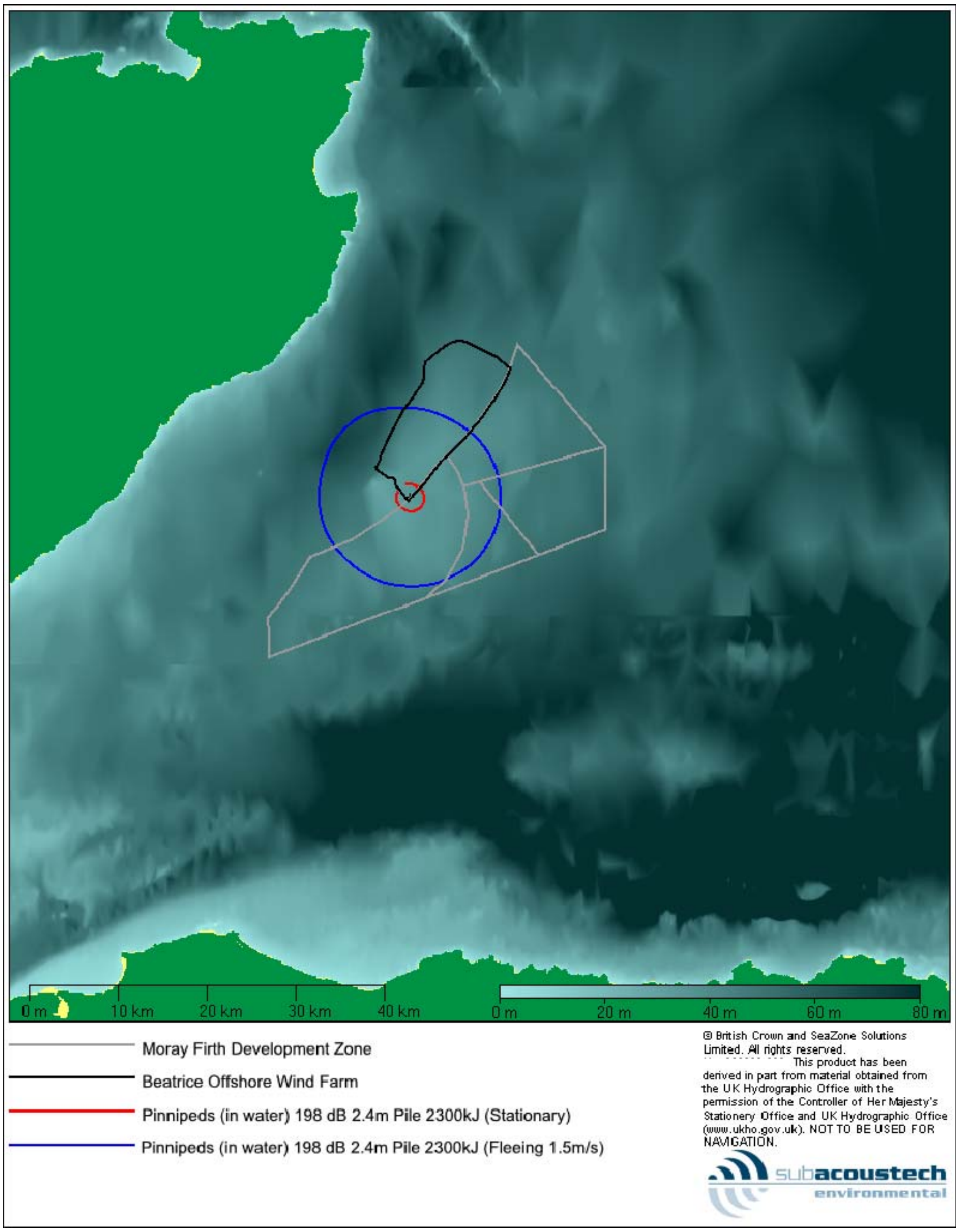
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Mid-frequency cetacean

Figure 10.42 198 dB(Mhf) contour for a stationary high-frequency cetacean, and locus of starting distances from which a fleeing high-frequency cetacean would just reach 198 dB(Mmf) at the cessation of the driving of the pile. 2.4 m diameter pile being driven at location A. Results for two piling energies



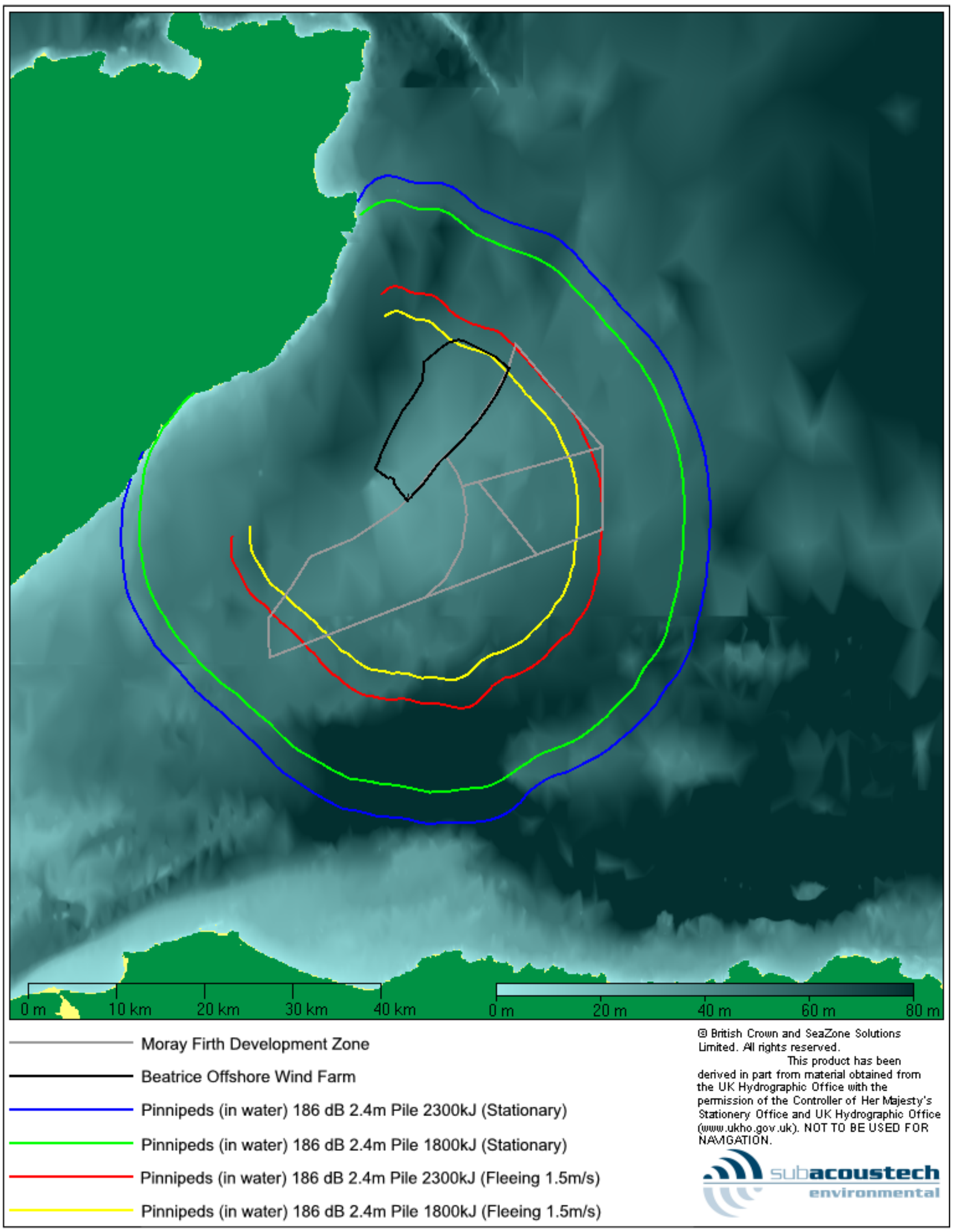
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	High-frequency cetacean

Figure 10.43a 198 dB(Mpw) contour for a stationary pinniped in water, and locus of starting distances from which a fleeing pinniped in water would just reach 198 dB(Mmf) at the cessation of the driving of the pile. 2.4 m diameter pile being driven at location A. Results for 2300 kJ piling energy



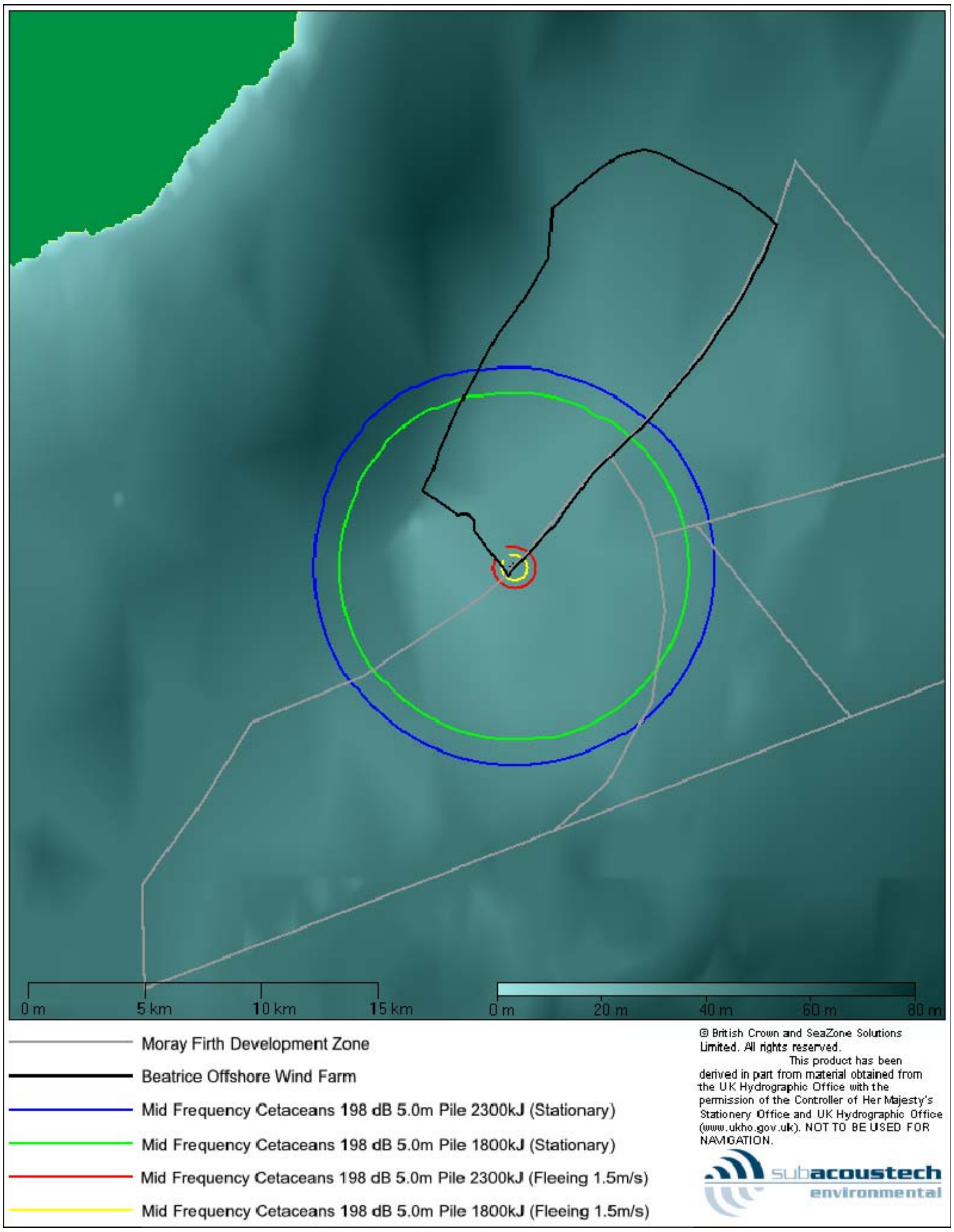
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	2300
Species	Pinniped in water

Figure 10.43b 186 dB(Mpw) contour for a stationary pinniped in water, and locus of starting distances from which a fleeing pinniped in water would just reach 186 dB(Mmf) at the cessation of the driving of the pile. 2.4 m diameter pile being driven at location A. Results for two piling energies



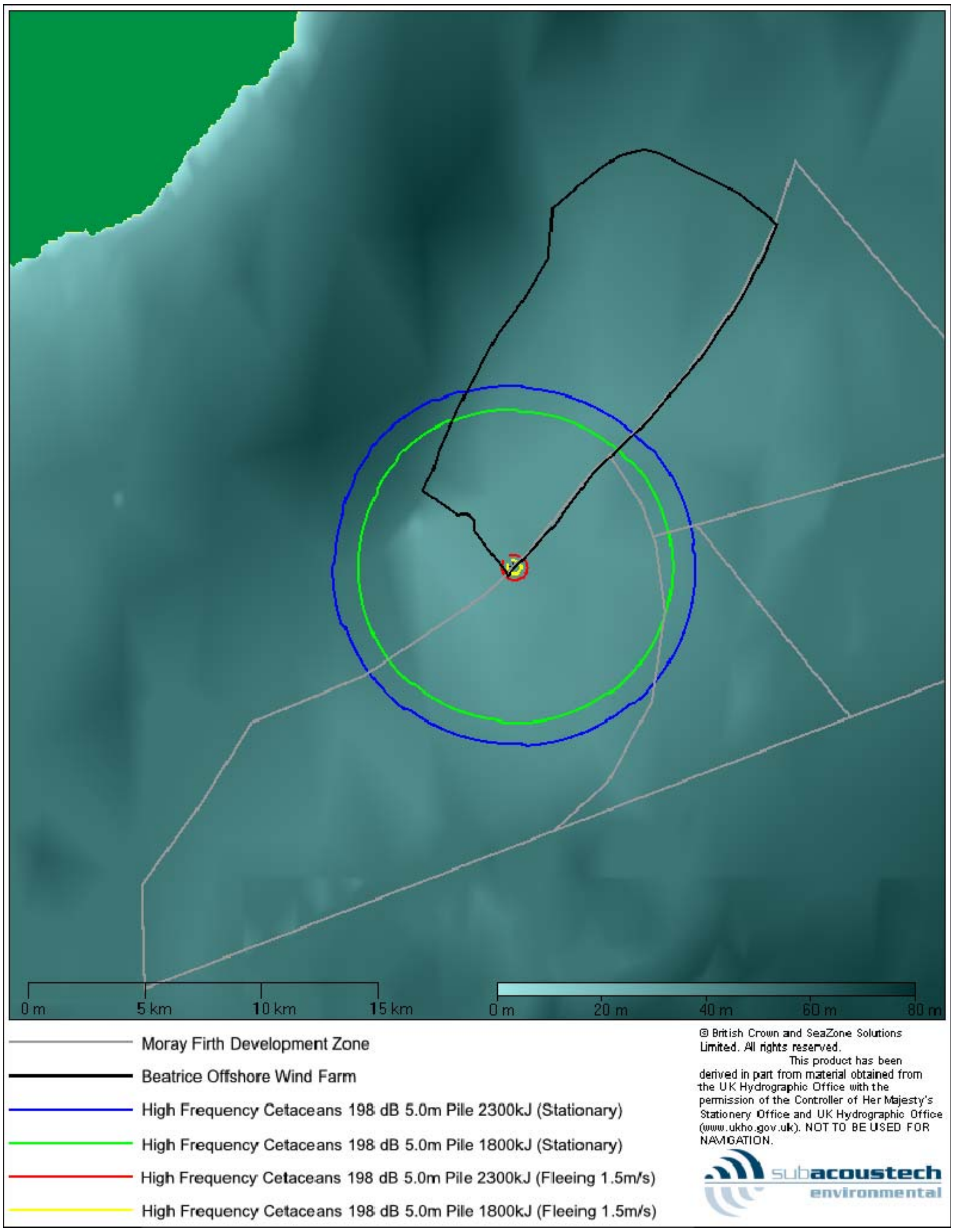
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Pinniped in water

Figure 10.44 198 dB(Mmf) contour for a stationary mid-frequency cetacean, and locus of starting distances from which a fleeing mid-frequency cetacean would just reach 198 dB(Mmf) at the cessation of the driving of the pile. 5 m diameter pile being driven at location A. Results for two piling energies



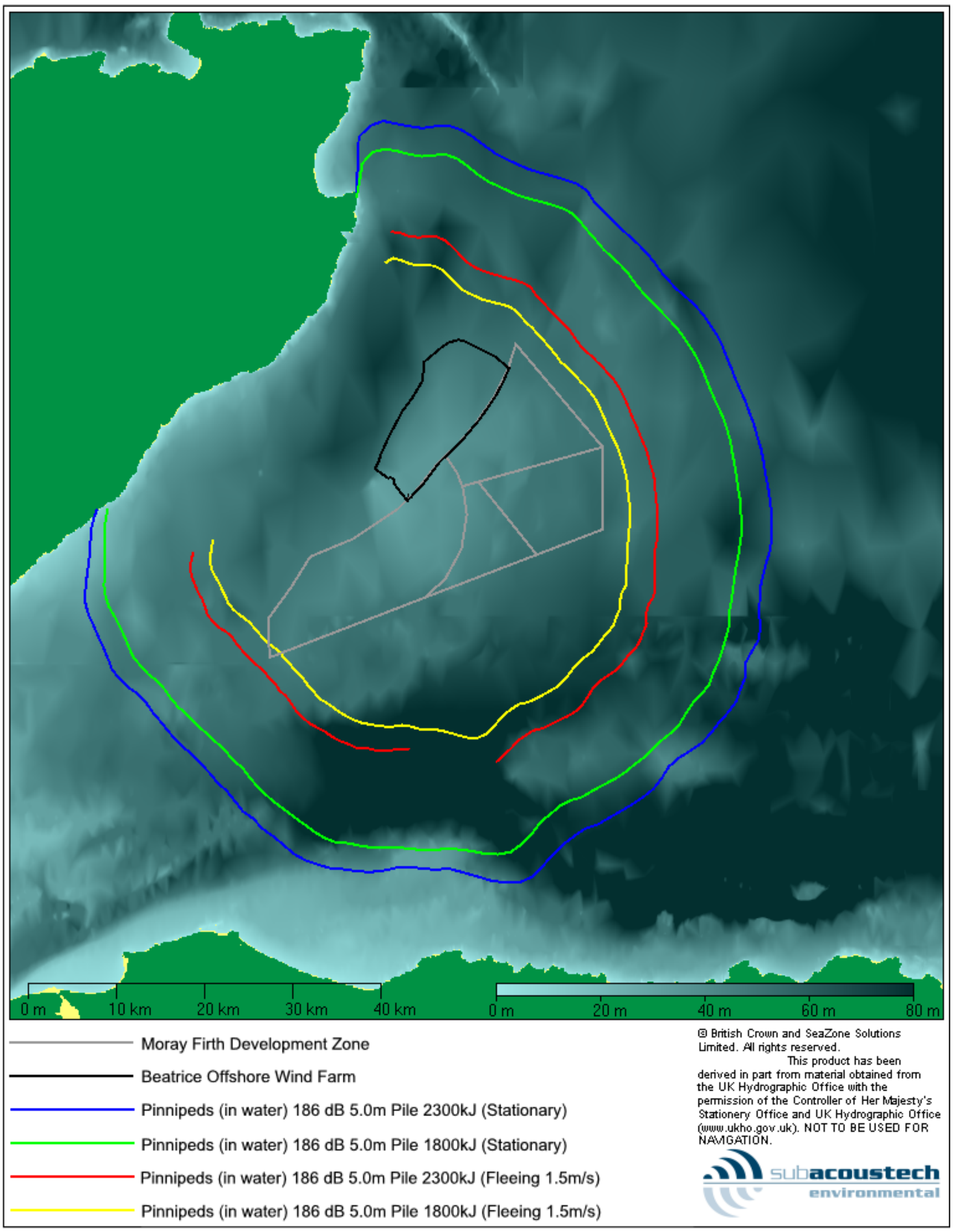
Pile diameter (m)	5
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Mid-frequency cetacean

Figure 10.45 198 dB(Mhf) contour for a stationary high-frequency cetacean, and locus of starting distances from which a fleeing high-frequency cetacean would just reach 198 dB(Mmf) at the cessation of the driving of the pile. 5 m diameter pile being driven at location A. Results for two piling energies



Pile diameter (m)	5
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	High-frequency cetacean

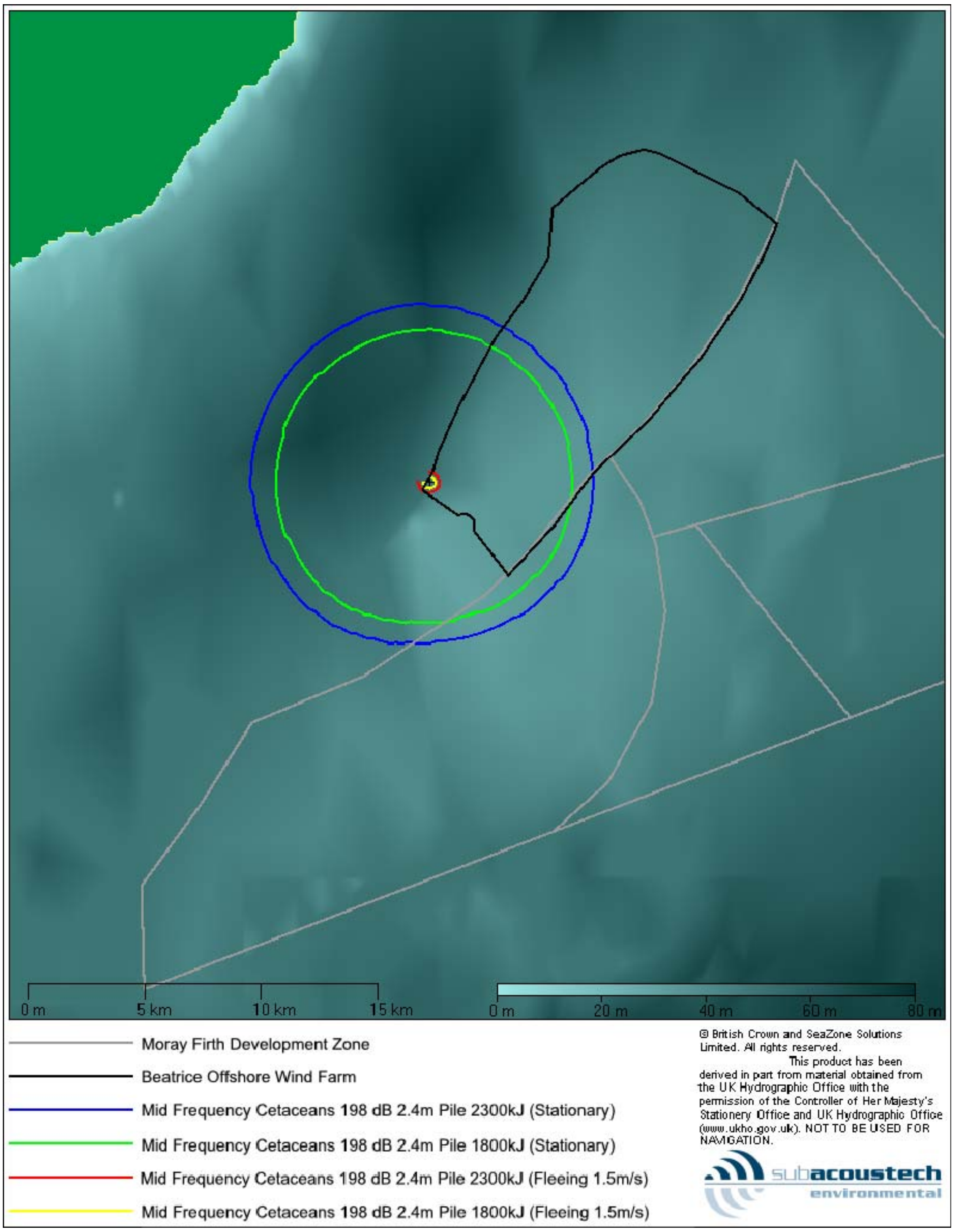
Figure 10.46 186 dB(Mpw) contour for a stationary pinniped in water, and locus of starting distances from which a fleeing pinniped in water would just reach 186 dB(Mmf) at the cessation of the driving of the pile. 5 m diameter pile being driven at location A. Results for two piling energies



Pile diameter (m)	5
Pile location (see map, Figure 10.13)	A
Pile driving energy (kJ)	1800 and 2300
Species	Pinniped in water

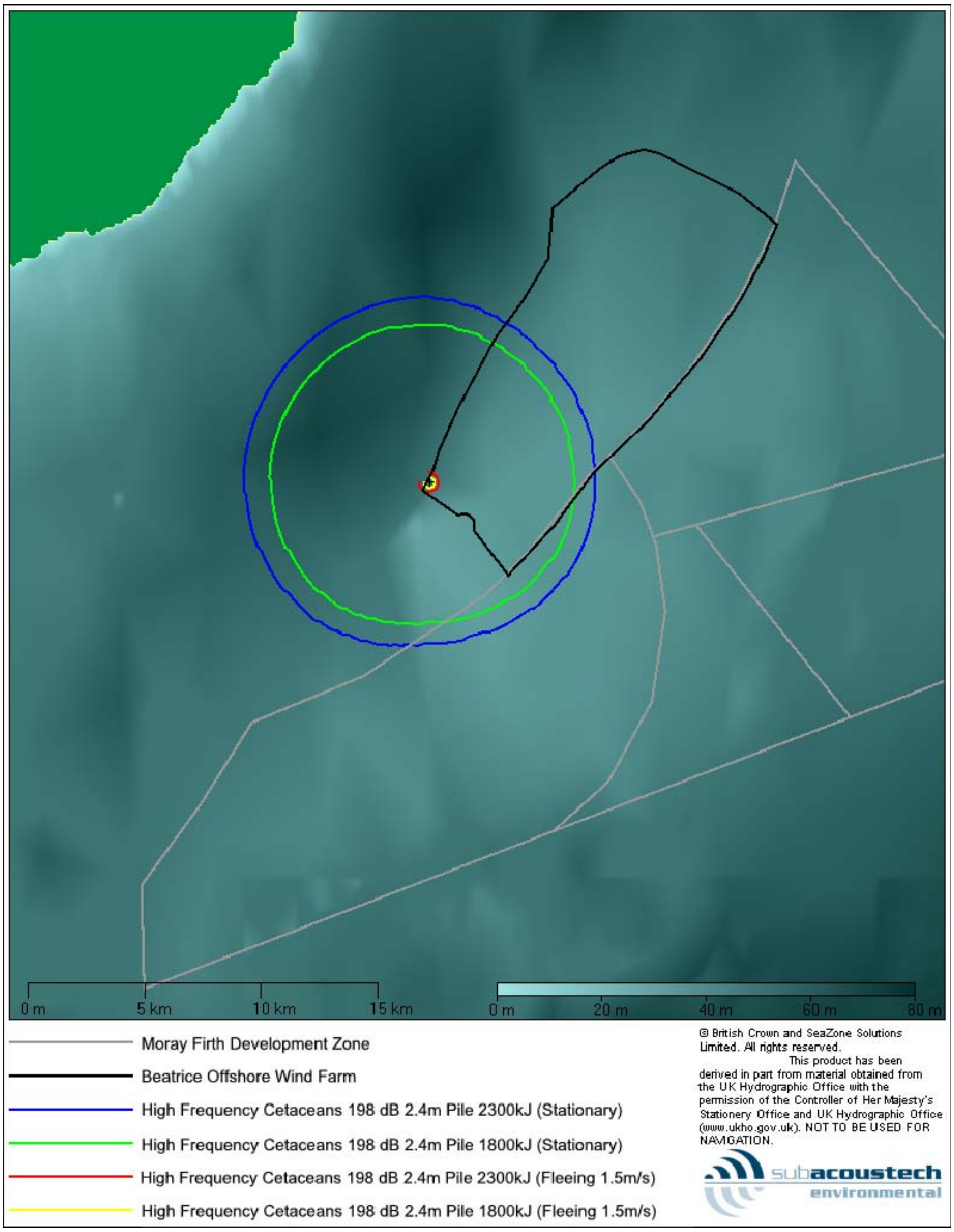
M-weighted results for a single pile being driven at location B

Figure 10.47 198 dB(Mmf) contour for a stationary mid-frequency cetacean, and locus of starting distances from which a fleeing mid-frequency cetacean would just reach 198 dB(Mmf) at the cessation of the driving of the pile. 2.4 m diameter pile being driven at location B. Results for two piling energies



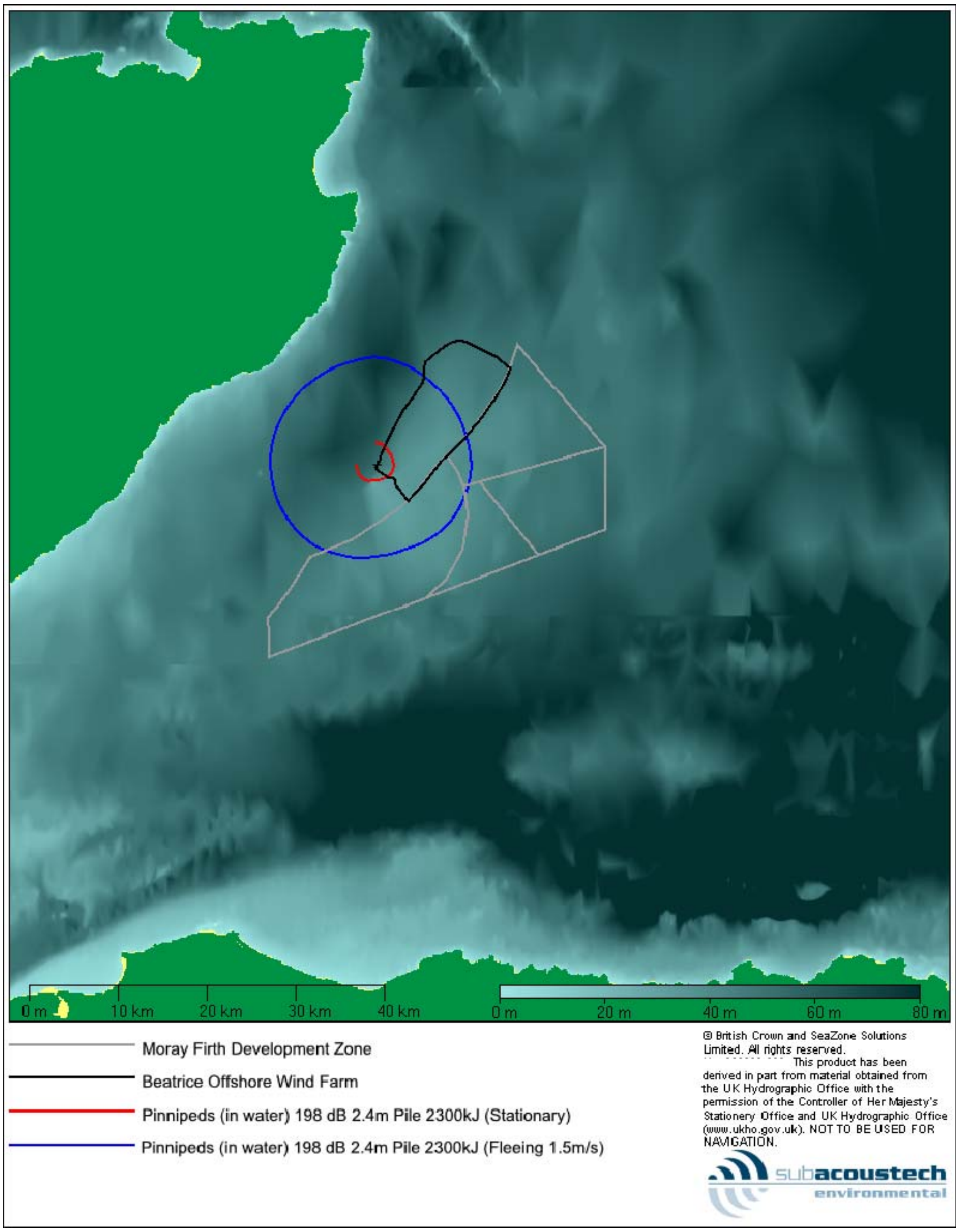
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	Mid-frequency cetacean

Figure 10.48 198 dB(Mhf) contour for a stationary high-frequency cetacean, and locus of starting distances from which a fleeing high-frequency cetacean would just reach 198 dB(Mmf) at the cessation of the driving of the pile. 2.4 m diameter pile being driven at location B. Results for two piling energies



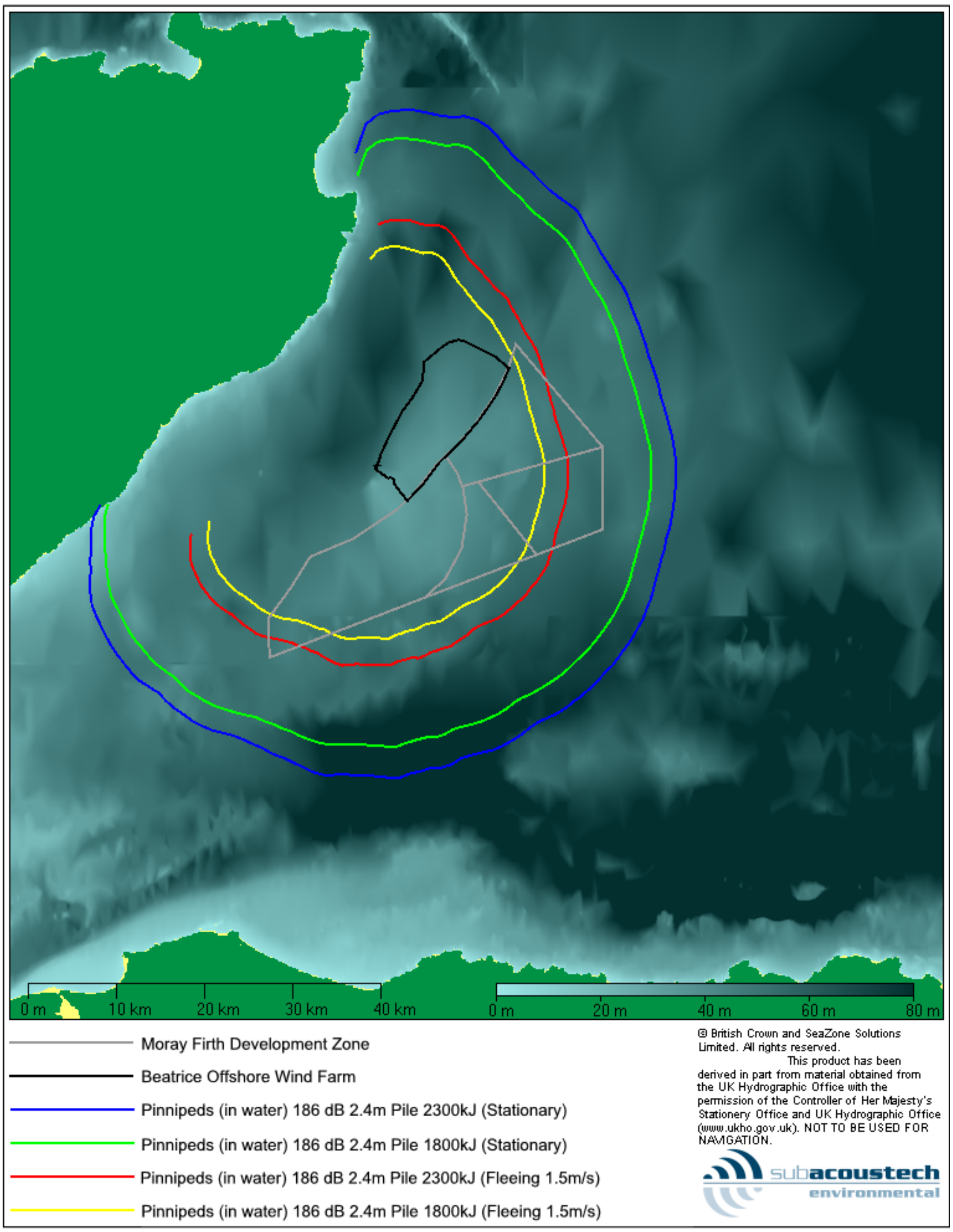
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	High-frequency cetacean

Figure 10.49a 198 dB(Mpw) contour for a stationary pinniped in water, and locus of starting distances from which a fleeing pinniped in water would just reach 198 dB(Mmf) at the cessation of the driving of the pile. 2.4 m diameter pile being driven at location B. Results for 2300 kJ piling energy



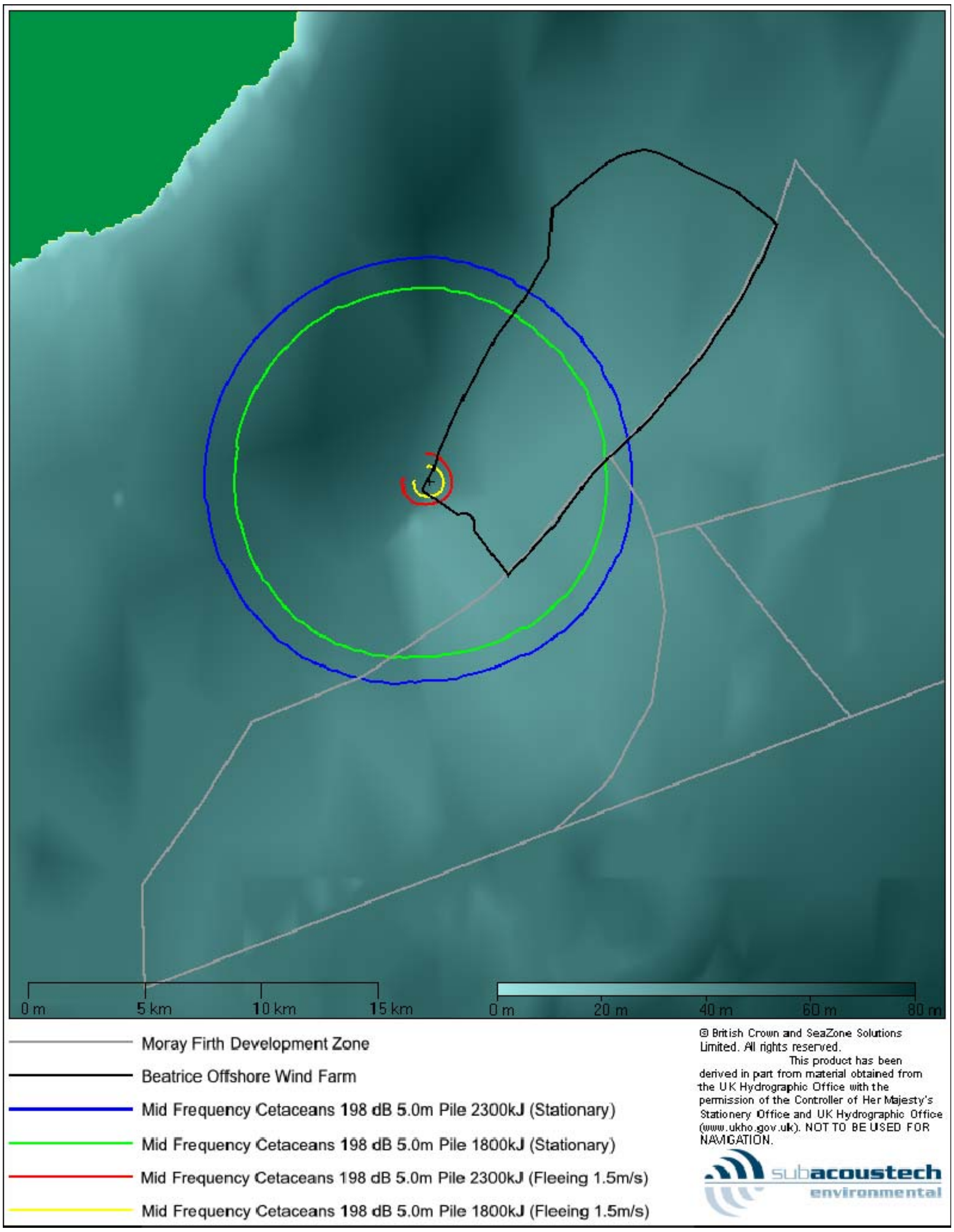
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	2300
Species	Pinniped in water

Figure 10.49b 186 dB(Mpw) contour for a stationary pinniped in water, and locus of starting distances from which a fleeing pinniped in water would just reach 186 dB(Mmf) at the cessation of the driving of the pile. 2.4 m diameter pile being driven at location B. Results for two piling energies



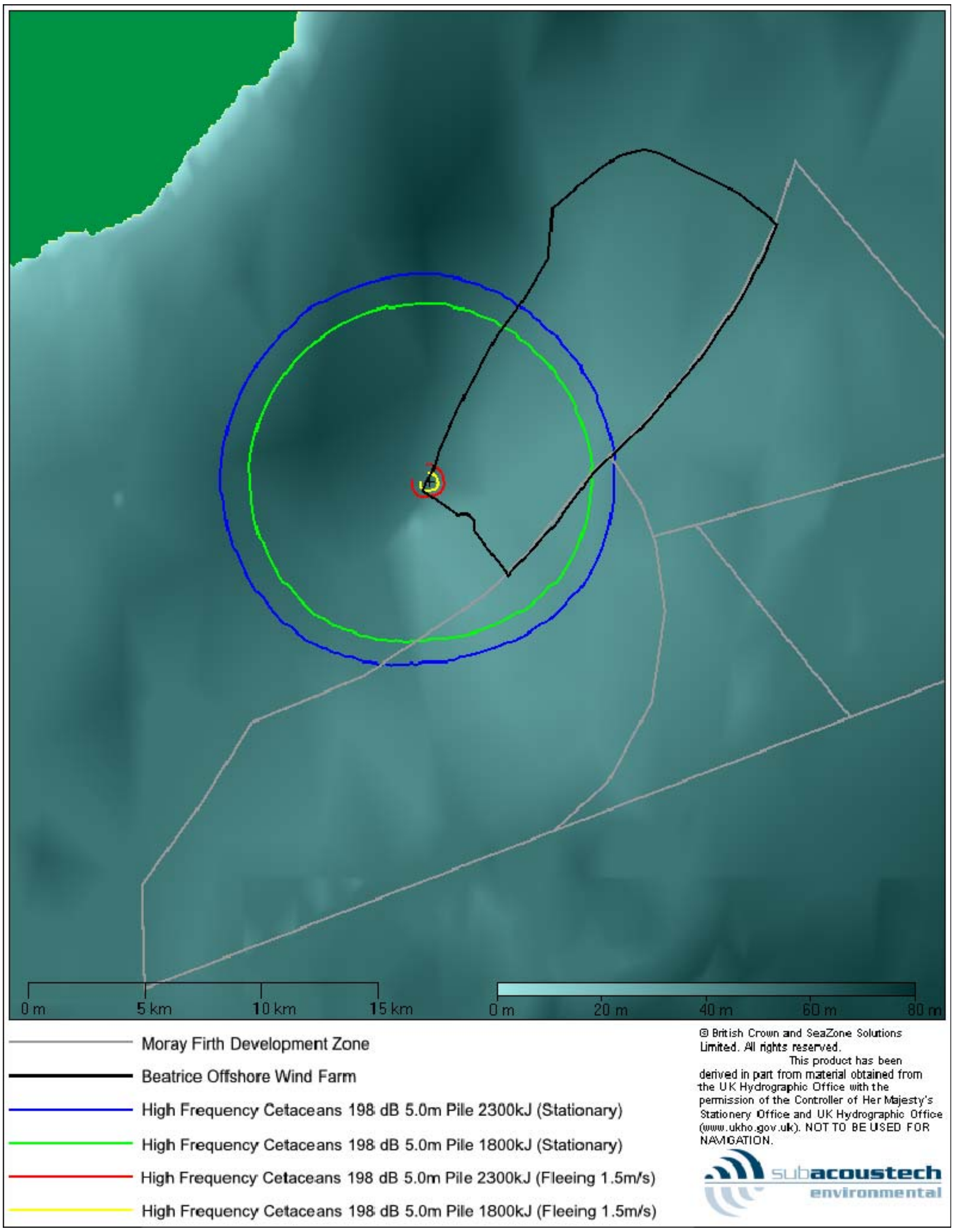
Pile diameter (m)	2.4
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	Pinniped in water

Figure 10.50 198 dB(Mmf) contour for a stationary mid-frequency cetacean, and locus of starting distances from which a fleeing mid-frequency cetacean would just reach 198 dB(Mmf) at the cessation of the driving of the pile. 5 m diameter pile being driven at location B. Results for two piling energies



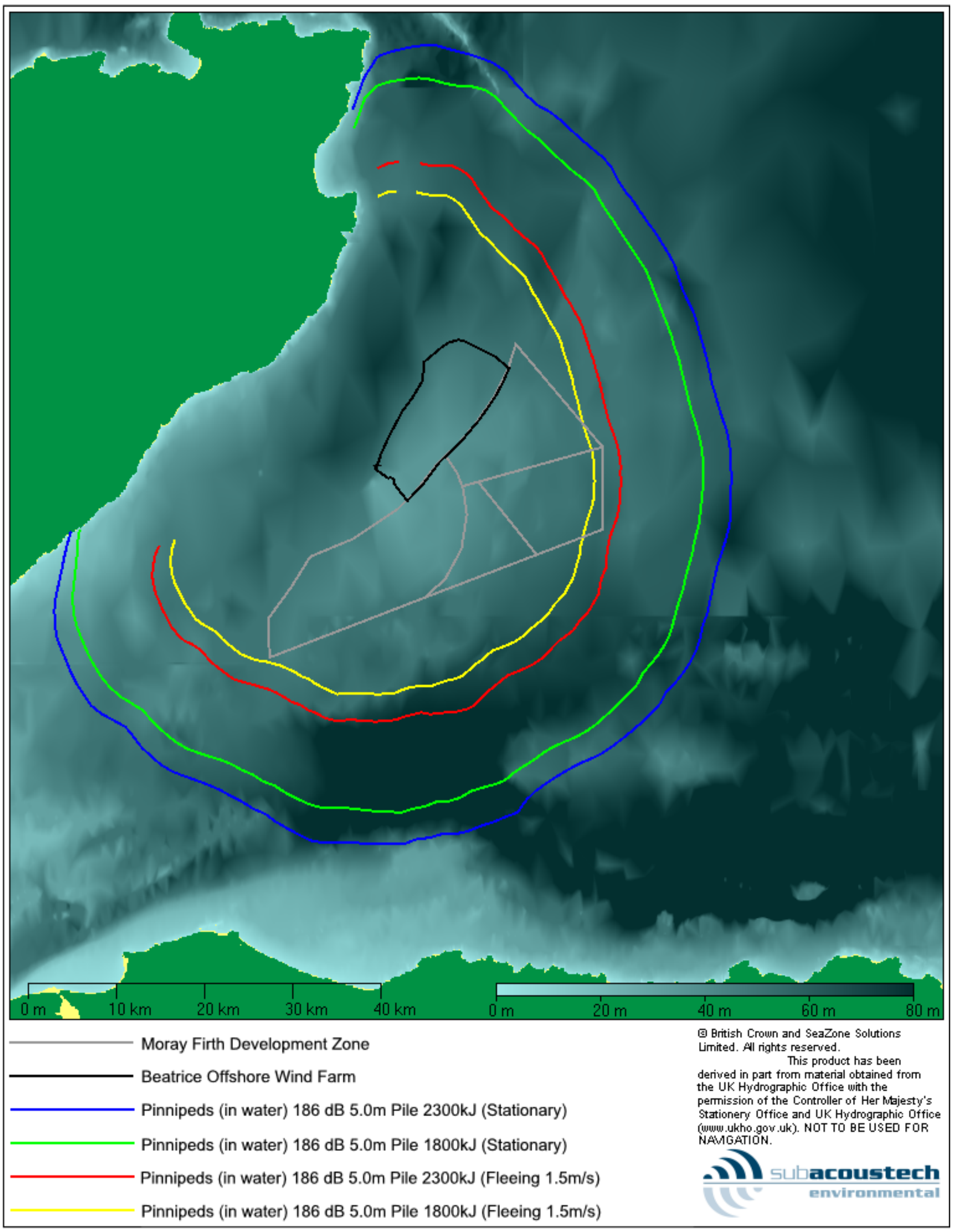
Pile diameter (m)	5
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	Mid-frequency cetacean

Figure 10.51 198 dB(Mhf) contour for a stationary high-frequency cetacean, and locus of starting distances from which a fleeing high-frequency cetacean would just reach 198 dB(Mmf) at the cessation of the driving of the pile. 5 m diameter pile being driven at location B. Results for two piling energies



Pile diameter (m)	5
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	High-frequency cetacean

Figure 10.52 186 dB(Mpw) contour for a stationary pinniped in water, and locus of starting distances from which a fleeing pinniped in water would just reach 186 dB(Mmf) at the cessation of the driving of the pile. 5 m diameter pile being driven at location B. Results for two piling energies



Pile diameter (m)	5
Pile location (see map, Figure 10.13)	B
Pile driving energy (kJ)	1800 and 2300
Species	Pinniped in water

10.8 MITIGATION

A key element in developing a strategy for piling that has a minimised environmental impact has been the use of the INSPIRE model to understand the potential environmental effect of various piling regimes and select an optimal construction process. In addition, the model has allowed the effect of mitigation, including soft and slow start, and the use of pin piles and monopoles, to be investigated. This has allowed the engineering to be further optimised. In principle it is possible to further reduce the noise generated by impact piling at source. However, while other forms of piling, such as vibropiling, drill driving and hydraulic piling, may generate much lower noise levels, and have been considered, these approaches are only suitable for much smaller piles than are required for offshore wind farms, take considerably longer than impact piling, and generally require impact piling as a final measure to drive the pile to depth. Various technologies are being developed which may be used to attenuate noise transmission from impact piling, such as cladding and bubble barriers, but currently these are either of limited efficacy or are unproven technologies.

10.9 MONITORING AND ENHANCEMENTS

10.9.1 In general, the INSPIRE model that has been used to estimate the noise from the piling has been shown to be accurate when tested against actual measurements of impact piling noise. However, it is considered good practice to test the model against actual results and hence in the early stage of the installation of the piles it is recommended that the noise from four piles be measured and compared with the model.

10.10 SUMMARY

10.10.1 The impact of introduced noise as a result of impact piling during construction of the Beatrice Offshore Wind Farm has been calculated using the proprietary INSPIRE noise modelling software.

10.10.2 The range of noise emissions with reference to the different species has been calculated in respect of dB_{ht}(*Species*) and M-weighted dB SEL to assess the potential impact of the piling on marine species. This is both in terms of injury (M-weighted dB SEL) and behavioural response (dB_{ht}).

10.10.3 These calculated levels have been used to inform the fish and marine mammal assessment.

10.11 *CUMULATIVE IMPACTS*

Introduction

10.11.1 The cumulative effects of noise may be taken to reflect the total exposure to noise that an animal has in the course of its daily existence. Consequently, this may include not only the noise from an impact piling operation, but also the way in which the additional noise dose created by the piling accumulates with noise from existing sources that the animal is exposed to, such as the noise from other piling operations, seismic exploration, vessel traffic and so on.

Scope of Assessment

10.11.2 There is little information concerning the detail of activities in coastal waters that may contribute to an animal's exposure to noise. Hence, it is difficult to define the noise field through which an animal transits during a day, and hence difficult or impossible to estimate the total exposure to noise of an animal during the activity that brings it into in the vicinity of the piling operation. However, it will be noted from the SPEAR analysis that impact piling, where it occurs, tends to be the dominant noise source. The contributions to noise exposure offered by all other noise sources are significantly lower in importance. During the development of Round 3 sites a considerable number of piling operations may be conducted around the coastal waters of the UK, and hence a key element of cumulative noise exposure is considered to be the case where animals may encounter two or more piling operations simultaneously. Consequently, the scenario where an animal encounters two or more simultaneous piling operations has provided the main thrust of the investigation into the cumulative effects of noise.

10.11.3 The way in which the effects of noise accumulate depends on the effect of noise that is considered. In the worst case, impact piling operations could commence simultaneously at two sites within a few kilometres of each other. Where the animal is much closer to one operation than the other it is likely that the noise dose would be dominated by the closest piling operation, and the animal would perceive a high level of noise, likely to cause it to attempt to flee from the noise in much the same way as if the other piling operation were not happening. However, an animal trapped between the two operations would have fewer options as to how to flee from the noise, and might be expected to flee at a roughly constant distance from both. During this period the animal may therefore receive exposure to noise from both operations.

10.11.4 It is possible to estimate the effects of the noise in this multi-source case in a similar way to that of a single piling operation. Each of the piling operations, where conducted individually, will have a zone within which the animal will receive a noise dose sufficient to create a risk of hearing damage as it flees from the noise. Where auditory damage is considered, using for instance the SEL criterion of Southall *et al*, and the piling operations are conducted simultaneously, the animal will receive a noise dose from both piling operations, and the zone in which the animal will receive a noise dose sufficient to create a risk of hearing damage will be larger than the sum of the individual zones for the operations conducted individually. While this in principle creates a greater risk for the animal, it should be remembered that since the duration of the exposure of the animal to noise would be less when the operations are conducted simultaneously, the reduced time may serve to mitigate the somewhat greater area in which animals may be exposed to risk of hearing damage.

10.11.5 The situation is somewhat different when the behavioural effects of the noise are considered. Two piling operations occurring simultaneously, at roughly similar distances, create noise impulses that are of similar level to each of the piling operations alone. It may be shown that even for piling strikes that occur at the same moment the level is similar to that of each of the impulses alone. The pulses of noise differ in shape and hence do not interfere constructively. As a consequence of this the zone in which behavioural avoidance is estimated to occur around two simultaneous piling operations is simply the union of the two zones for each piling operation conducted simultaneously. Where the zones intersect the area in which a behavioural response is expected is actually smaller than the sum of the two zones for individual piling operations.

Development Considered in the Assessment

10.11.6 The SPEAR analysis considered the likely potential impacts of a number of different sources on the marine species under consideration. In all cases in the analysis, the noise from impact piling was by far the dominant source with all other potential sources having a relatively insignificant noise impact, with reference to their noise output and the hearing capability of each species. Consequently, only noise from impact piling will be considered in the cumulative assessment.

10.11.7 There are two main sources of impact piling noise that will be considered in the cumulative assessment: multiple piling operations within the Beatrice Offshore Wind Farm and multiple piling accounting for potentially simultaneous operations at other nearby wind farm developments.

Predicted Impacts

10.11.8 As noted earlier, this section presents the results for the multiple pile cases.

10.11.9 The sketch map given earlier shows the locations of the piles for which calculations have been made. The multiple, simultaneous piling cases included some combinations of piles A to E, but additionally considered combinations of piles M1 to M6 (filled circles). A summary of these cases is given in Tables 10.13 to 10.15.

Table 10.13 ***Summary of conditions modelled for two piles being driven simultaneously. All piles were 2.4 m diameter.***

Piles driven	Driving energy (kJ)	Species	Results shown	Figure
A and B	1800	Plaice	90 dBht and 75 dBht contours	Figure 10.53
A and B	1800	Salmon		Figure 10.54
A and B	1800	Bottlenose dolphin		Figure 10.55
A and B	1800	Harbour porpoise		Figure 10.56
A and B	1800	Harbour seal		Figure 10.57
A and B	1800	Stationary mid-frequency cetacean	198 dB(M_{mf}) contours	Figure 10.58
A and B	1800	Fleeing mid-frequency cetacean	Locus of starting distances for fleeing animal	Figure 10.59
A and B	1800	Stationary high-frequency cetacean	198 dB(M_{hf}) contours	Figure 10.60
A and B	1800	Fleeing high-frequency cetacean	Locus of starting distances for fleeing animal	Figure 10.61
A and B	1800	Stationary pinniped in water	186 dB(M_{pw}) contours	Figure 10.62
A and B	1800	Fleeing pinniped in water	Locus of starting distances for fleeing animal (186dB(M_{pw}) criteria)	Figure 10.63
A and B	2300	Plaice	90 dBht and 75 dBht contours	Figure 10.64
A and B	2300	Salmon		Figure 10.65
A and B	2300	Bottlenose dolphin		Figure 10.66
A and B	2300	Harbour porpoise		Figure 10.67
A and B	2300	Harbour seal		Figure 10.68
A and B	2300	Stationary mid-frequency cetacean	198 dB(M_{mf}) contours	Figure 10.69
A and B	2300	Fleeing mid-frequency cetacean	Locus of starting distances for fleeing animal	Figure 10.70
A and B	2300	Stationary high-frequency cetacean	198 dB(M_{hf}) contours	Figure 10.71
A and B	2300	Fleeing high-frequency cetacean	Locus of starting distances for fleeing animal	Figure 10.72
A and B	2300	Stationary pinniped in water	198 dB(M_{pw}) contours	Figure 10.73a
A and B	2300	Stationary pinniped in water	186 dB(M_{pw}) contours	Figure 10.73b
A and B	2300	Fleeing pinniped in water	Locus of starting distances for fleeing animal (198dB(M_{pw}) criteria)	Figure 10.74a
A and B	2300	Fleeing pinniped in water	Locus of starting distances for fleeing animal (186dB(M_{pw}) criteria)	Figure 10.74b
A and E	1800	Cod	90 dBht and 75 dBht contours	Figure 10.75
A and E	2300	Cod		Figure 10.76
C and D	1800	Herring	90 dBht and 75 dBht contours	Figure 10.77
C and D	2300	Herring		Figure 10.78

Table 10.14 Summary of conditions modelled for two piles at the BOWL site, being driven simultaneously with piles M1, M2 and M3.Piles at the BOWL site were driven with 2300 kJ of energy, while piles M1, M2 and M3 were driven with 2700 kJ of energy

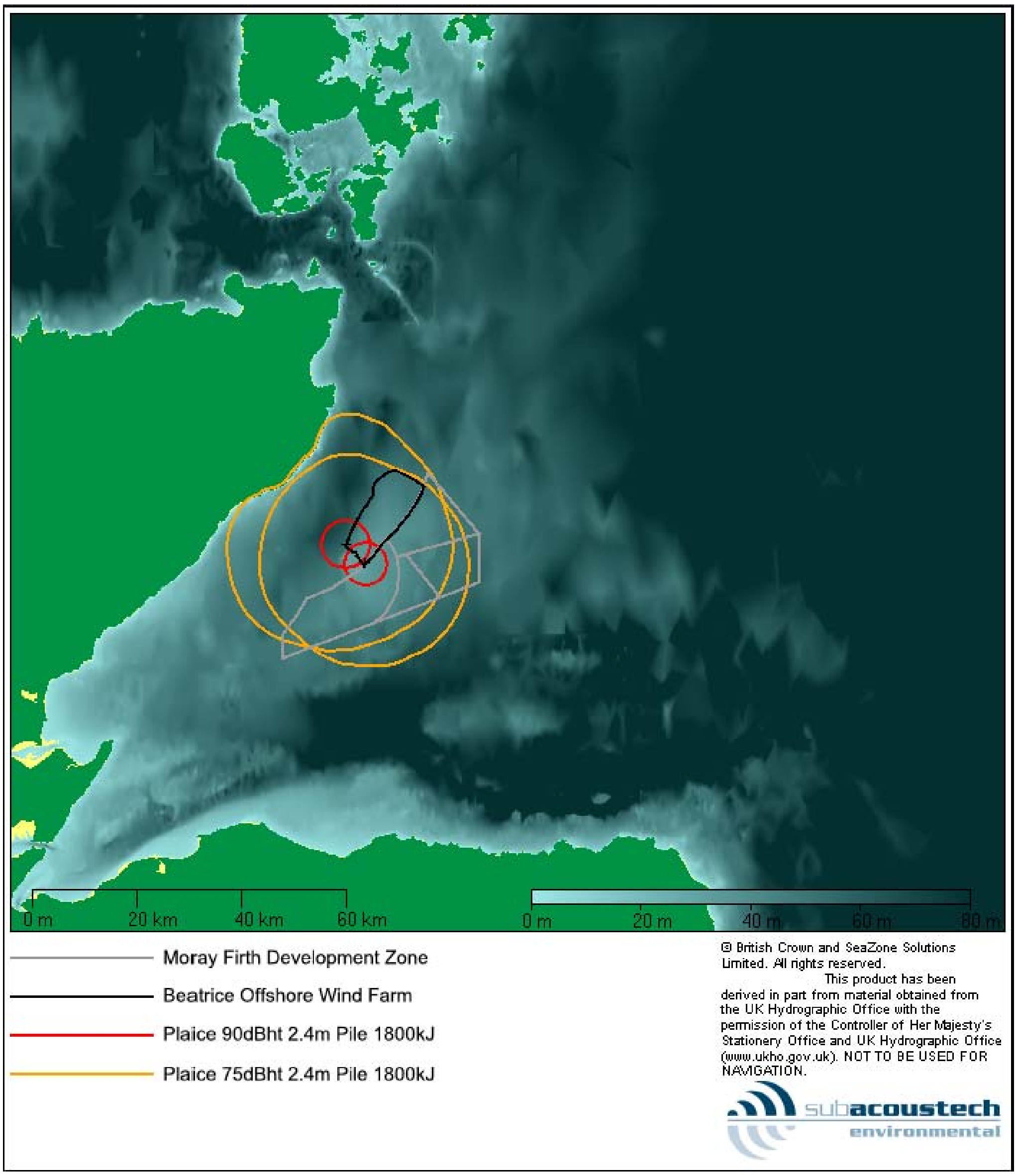
Piles driven	Species	Results shown	Figure
A, B, M1, M2 and M3	Plaice	90 dBht and 75 dBht contours	Figure 10.79
A, B, M1, M2 and M3	Salmon		Figure 10.80
A, B, M1, M2 and M3	Bottlenose dolphin		Figure 10.81
A, B, M1, M2 and M3	Harbour porpoise		Figure 10.82
A, B, M1, M2 and M3	Harbour seal		Figure 10.83
A, B, M1, M2 and M3	Mid-frequency stationary cetacean	198 dB(M_{mf}) contours	Figure 10.84
A, B, M1, M2 and M3	Mid-frequency fleeing cetacean	Locus of starting distances for fleeing animal	Figure 10.85
A, B, M1, M2 and M3	High-frequency stationary cetacean	198 dB(M_{hf}) contours	Figure 10.86
A, B, M1, M2 and M3	High-frequency fleeing cetacean	Locus of starting distances for fleeing animal	Figure 10.87
A, B, M1, M2 and M3	Stationary pinniped in water	198 dB(M_{pw}) contours	Figure 10.88a
A, B, M1, M2 and M3	Stationary pinniped in water	186 dB(M_{pw}) contours	Figure 10.88b
A, B, M1, M2 and M3	Fleeing pinniped in water	Locus of starting distances for fleeing animal (198dB(M_{pw}) criteria)	Figure 10.89a
A, B, M1, M2 and M3	Fleeing pinniped in water	Locus of starting distances for fleeing animal (186dB(M_{pw}) criteria)	Figure 10.89
A, E, M1, M2 and M3	Cod	90 dBht and 75 dBht contours	Figure 10.90
C, D, M1, M2 and M3	Herring		Figure 10.91

Table 10.15 ***Summary of conditions modelled for two piles at the BOWL site, being driven simultaneously with six piles at the MORL site. Piles at the BOWL site were 2.4 m diameter, and piles at the MORL site were 3 m diameter. Piles at the BOWL site were driven with 2300 kJ of energy, while piles at the MORL site were driven with 1800 kJ of energy***

Piles driven	Species	Results shown	Figure
A, E, M1, M2 and M3	Cod	90 dBht and 75 dBht contours	Figure 10.92
C, D, M1, M2 and M3	Herring		Figure 10.93
A, B, M1, M2 and M3	Plaice		Figure 10.94
A, B, M1, M2 and M3	Salmon		Figure 10.95
A, B, M1, M2 and M3	Bottlenose dolphin		Figure 10.96
A, B, M1, M2 and M3	Harbour porpoise		Figure 10.97
A, B, M1, M2 and M3	Harbour seal		Figure 10.98
A, B, M1, M2 and M3	Mid-frequency stationary cetacean	198 dB(M_{mf}) contours	Figure 10.99
A, B, M1, M2 and M3	Mid-frequency fleeing cetacean	Locus of starting distances for fleeing animal	Figure 10.100
A, B, M1, M2 and M3	High-frequency stationary cetacean	198 dB(M_{hf}) contours	Figure 10.101
A, B, M1, M2 and M3	High-frequency fleeing cetacean	Locus of starting distances for fleeing animal	Figure 10.102
A, B, M1, M2 and M3	Stationary pinniped in water	198 dB(M_{pw}) contours	Figure 10.103
A, B, M1, M2 and M3	Fleeing pinniped in water	Locus of starting distances for fleeing animal (198dB(M_{pw}) criteria)	Figure 10.103

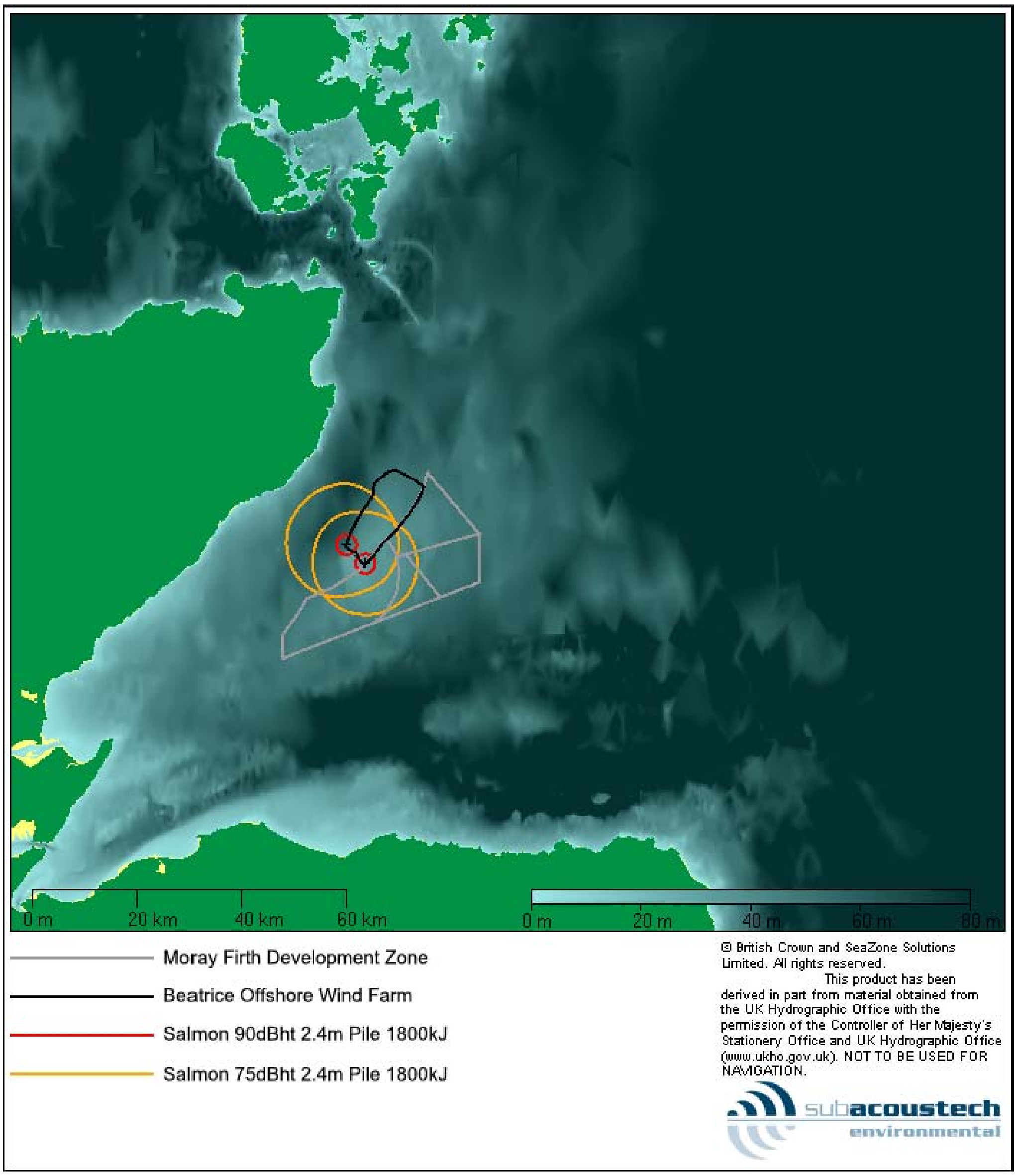
Results for two 2.4 m diameter piles being driven simultaneously

Figure 10.53 90 dBht and 75 dBht contours for the plaice. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 1800 kJ



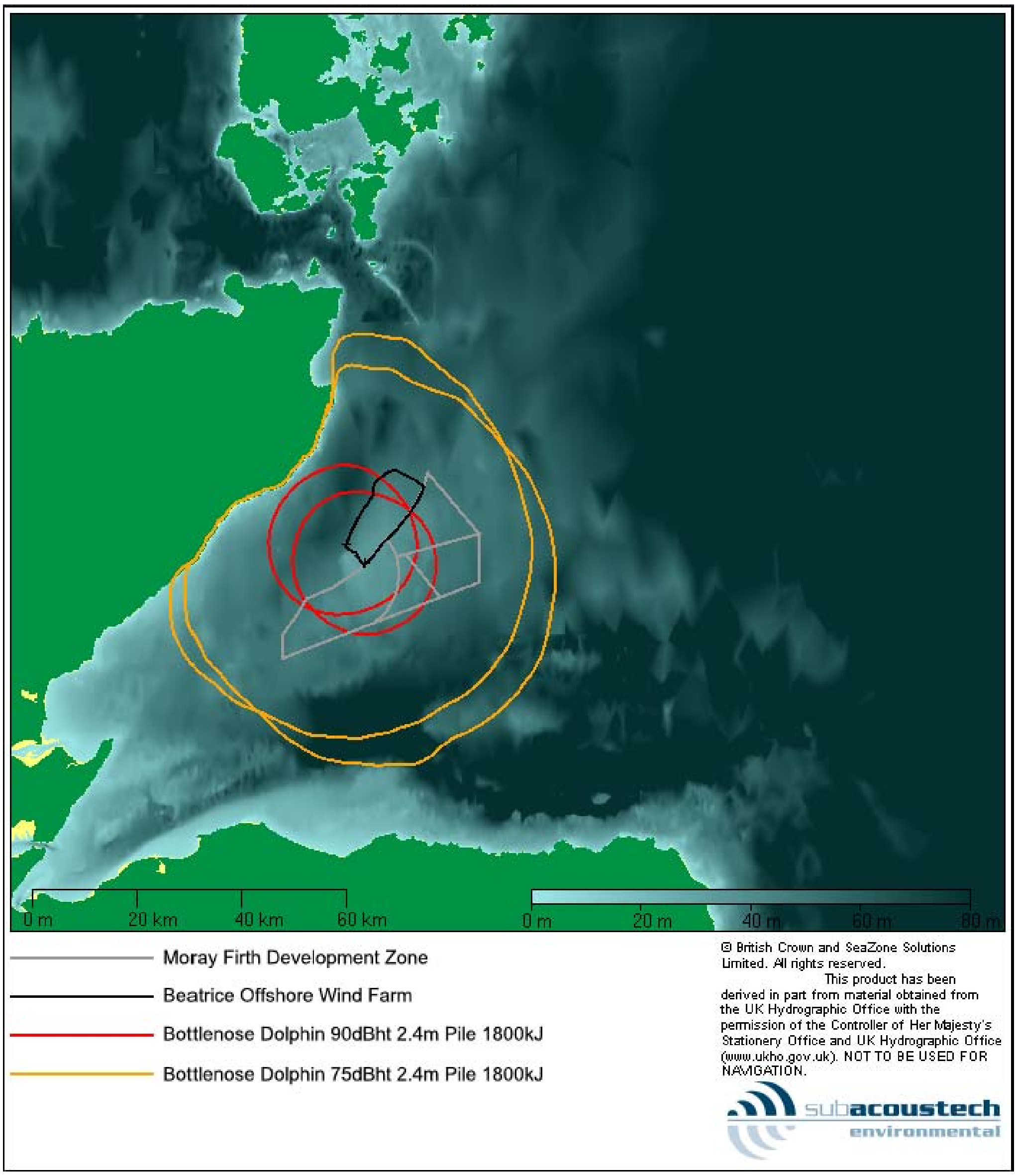
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	1800
Species	Plaice

Figure 10.54 90 dBht and 75 dBht contours for the salmon. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 1800 kJ



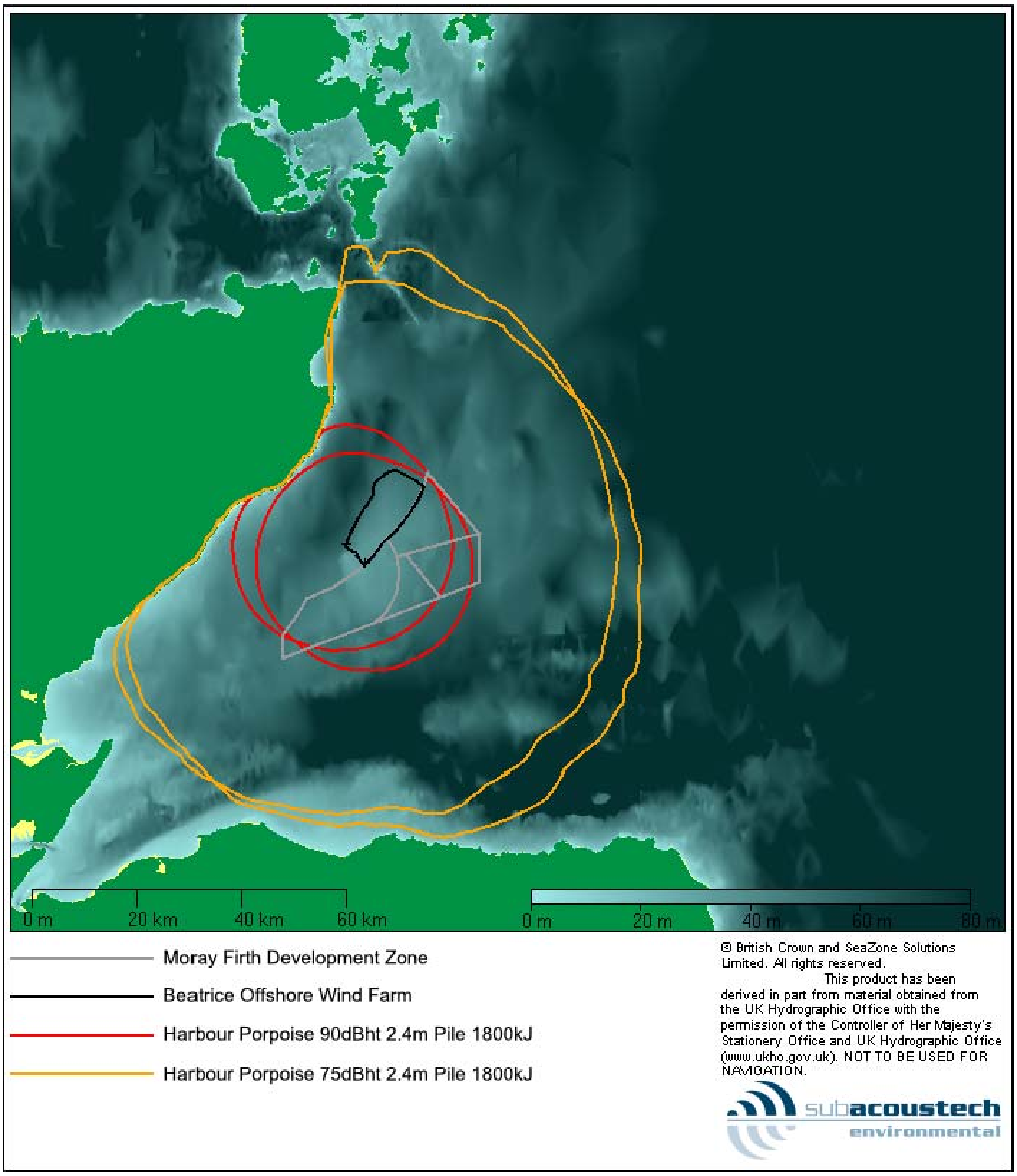
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	1800
Species	Salmon

Figure 10.55 90 dBht and 75 dBht contours for the bottlenose dolphin. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 1800 kJ



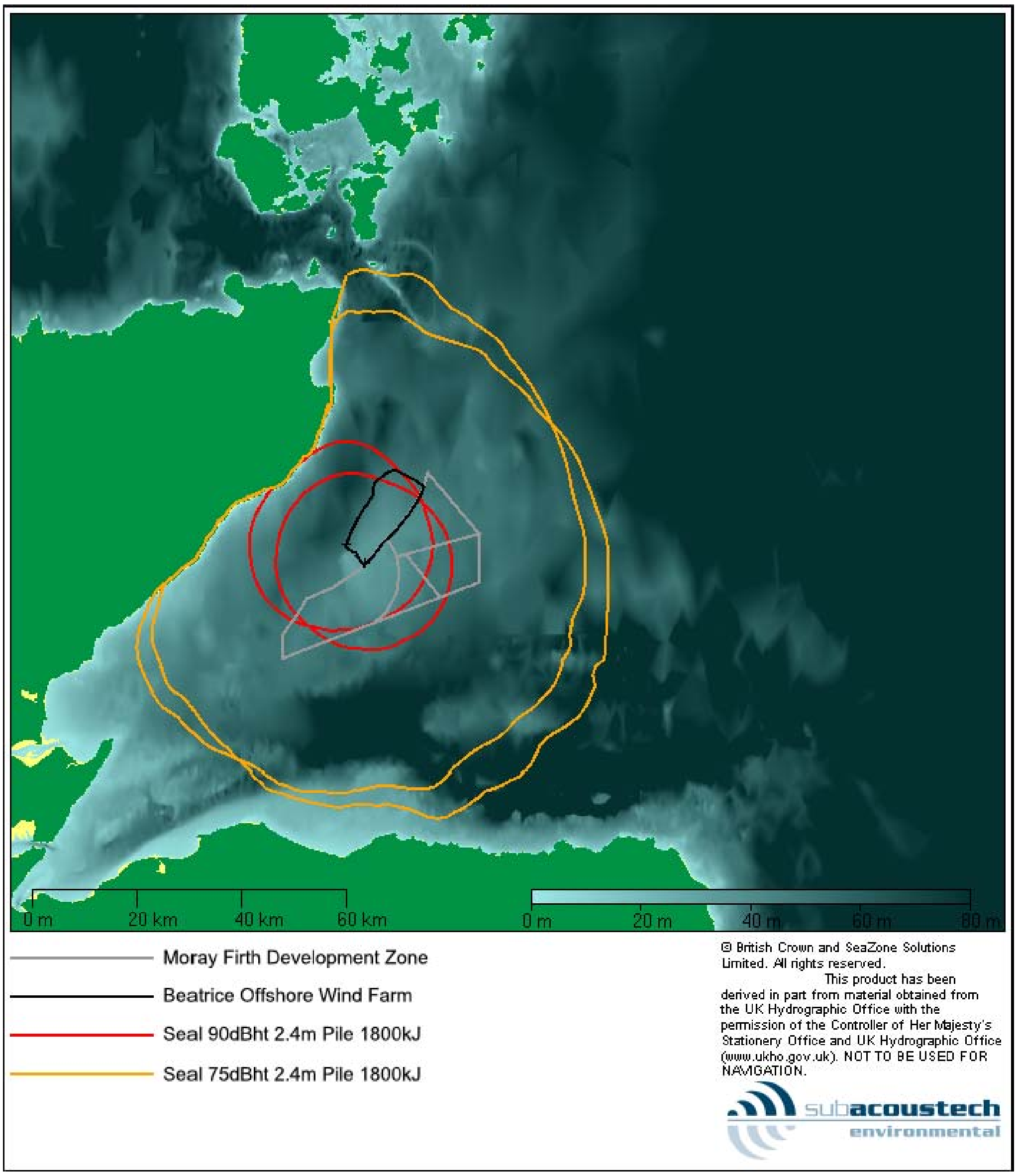
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	1800
Species	Bottlenose dolphin

Figure 10.56 90 dBht and 75 dBht contours for the harbour porpoise. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 1800 kJ



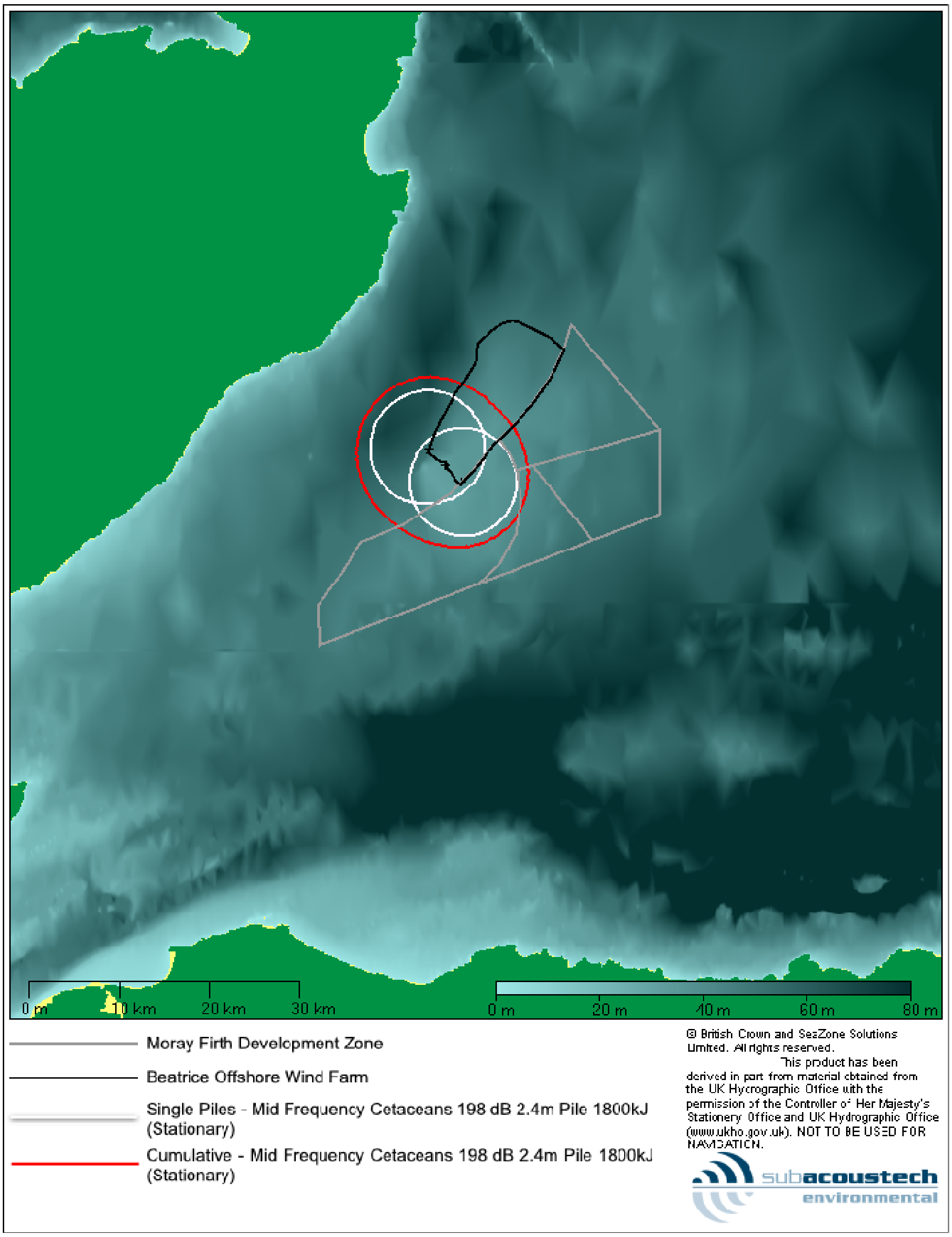
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	1800
Species	Harbour porpoise

Figure 10.57 90 dBht and 75 dBht contours for the harbour seal. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 1800 kJ



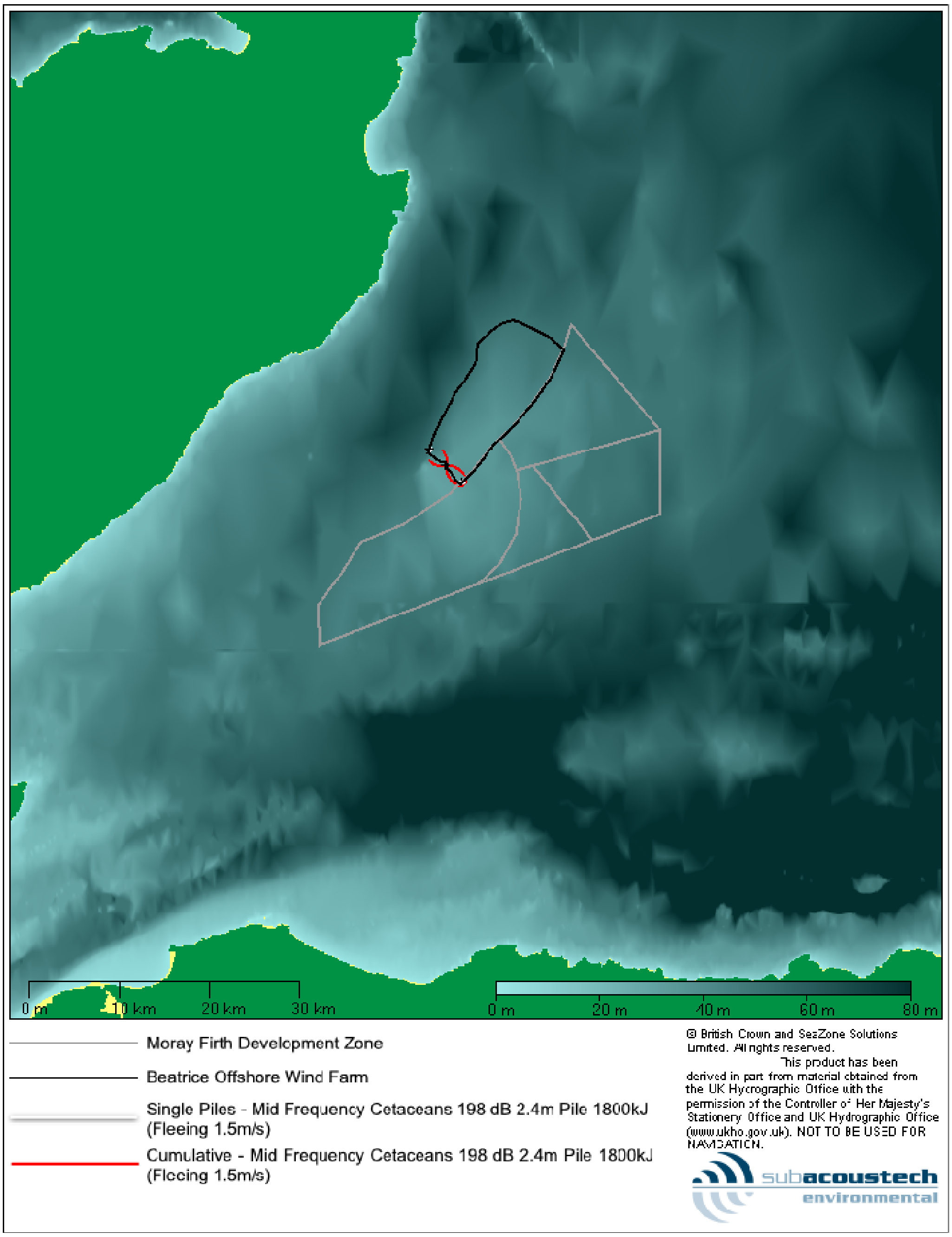
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	1800
Species	Harbour seal

Figure 10.58 198 dB(Mmf) contours for a stationary mid-frequency cetacean. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 1800 kJ



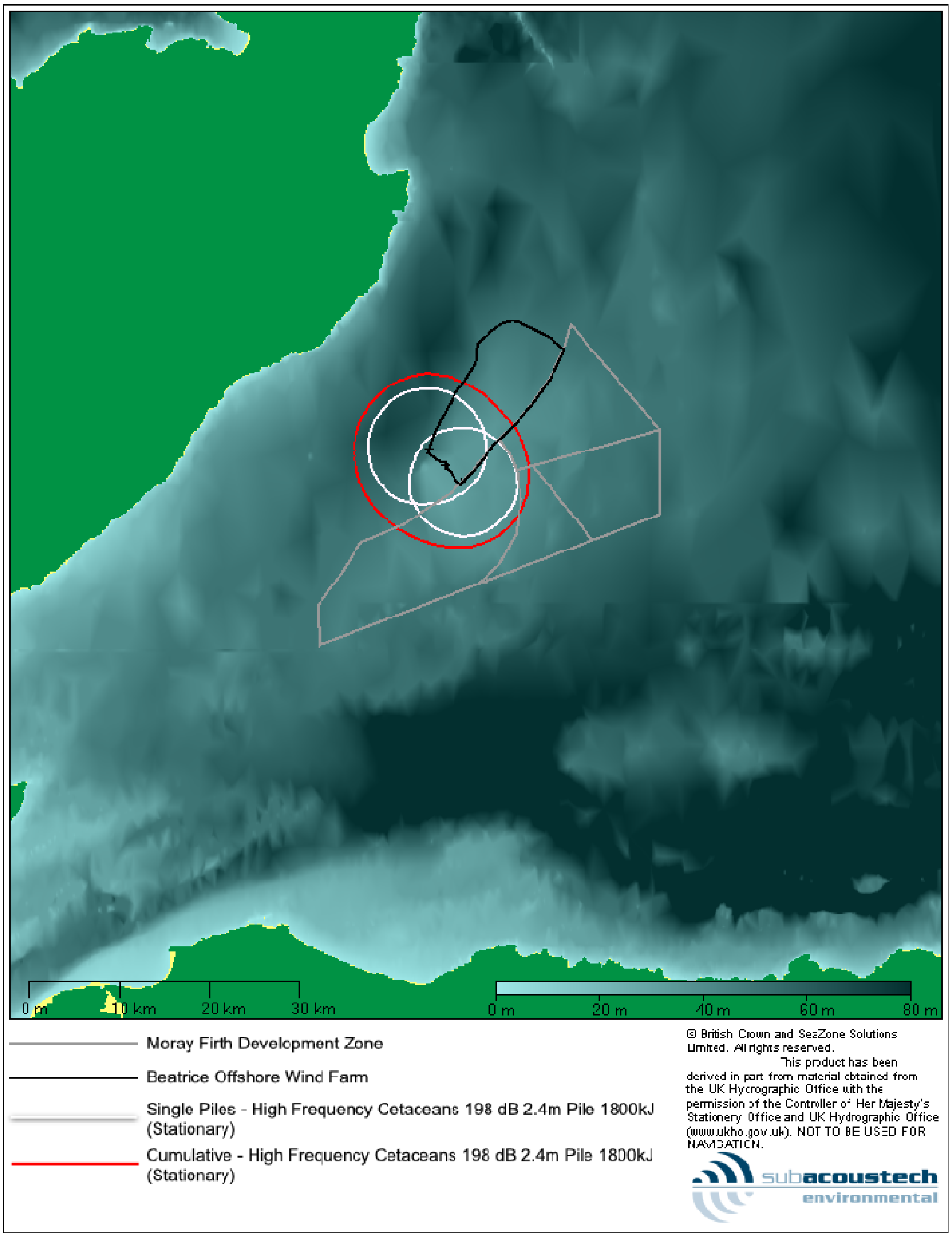
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	1800
Species	Mid-frequency cetacean

Figure 10.59 Locus of starting distances from which a fleeing mid-frequency cetacean would just reach 198 dB(Mmf) at the cessation of the driving of the piles. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 1800 kJ



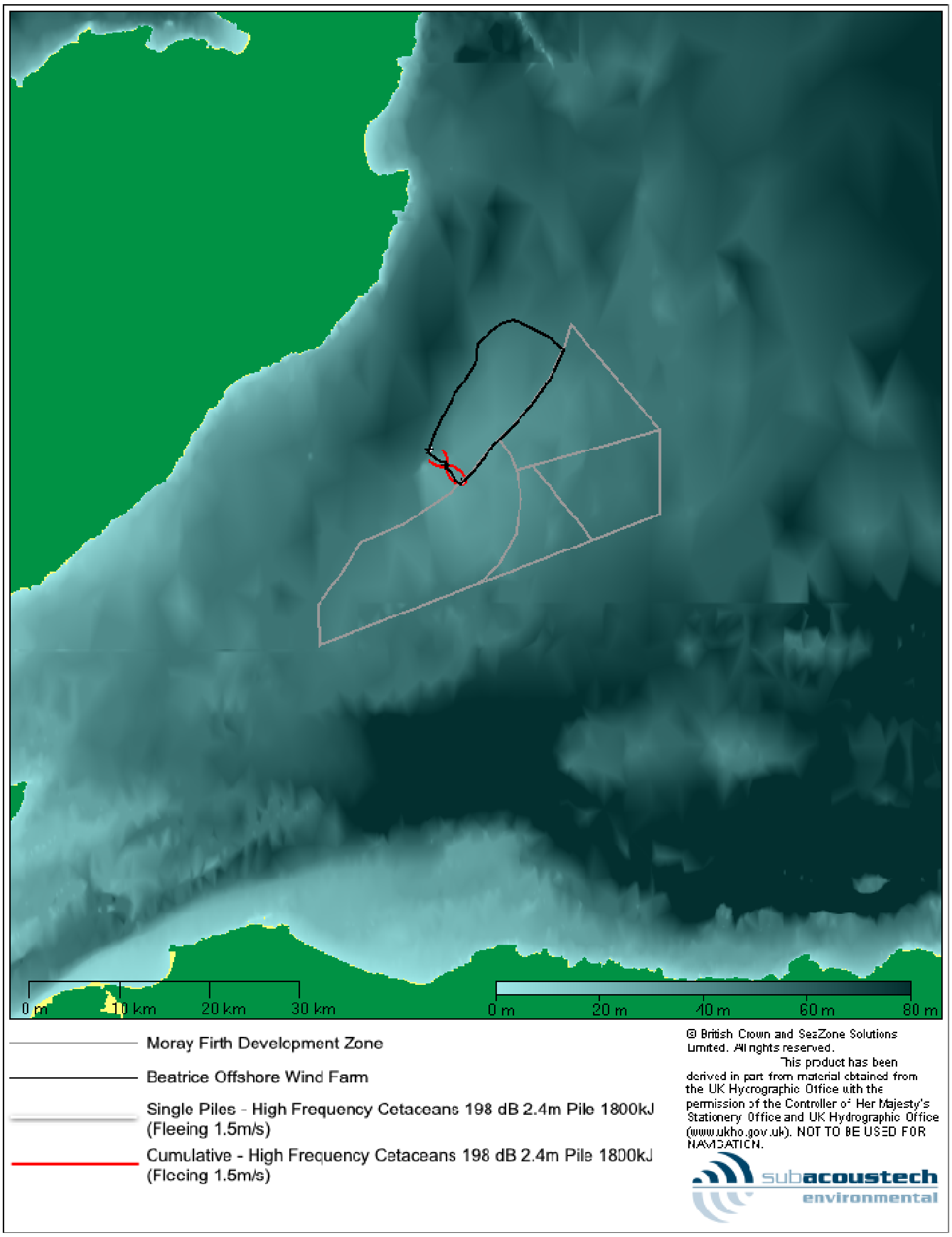
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	1800
Species	Mid-frequency cetacean

Figure 10.60 198 dB(Mhf) contours for a stationary high-frequency cetacean. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 1800 kJ



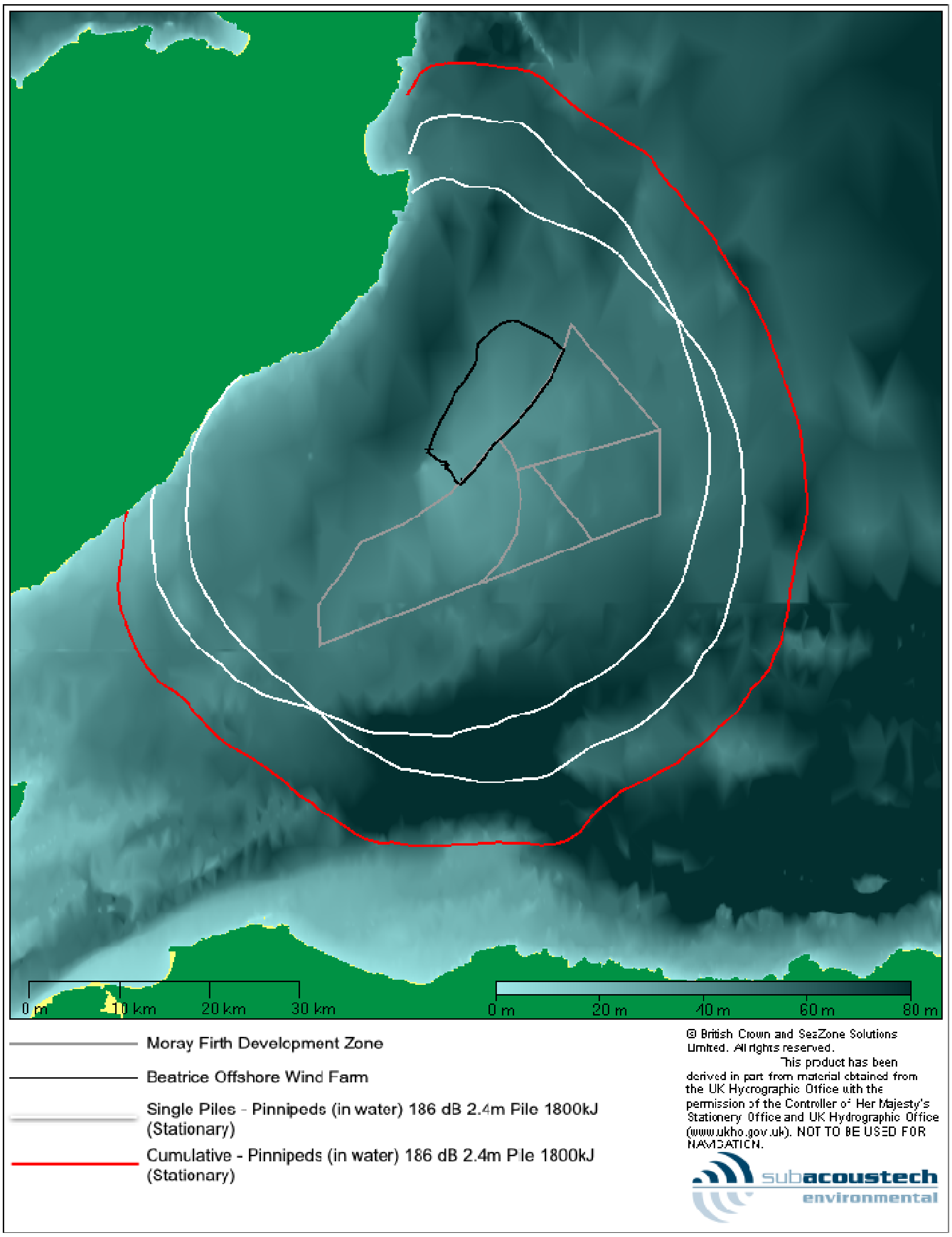
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	1800
Species	High-frequency cetacean

Figure 10.61 Locus of starting distances from which a fleeing high-frequency cetacean would just reach 198 dB(Mhf) at the cessation of the driving of the piles. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 1800 kJ



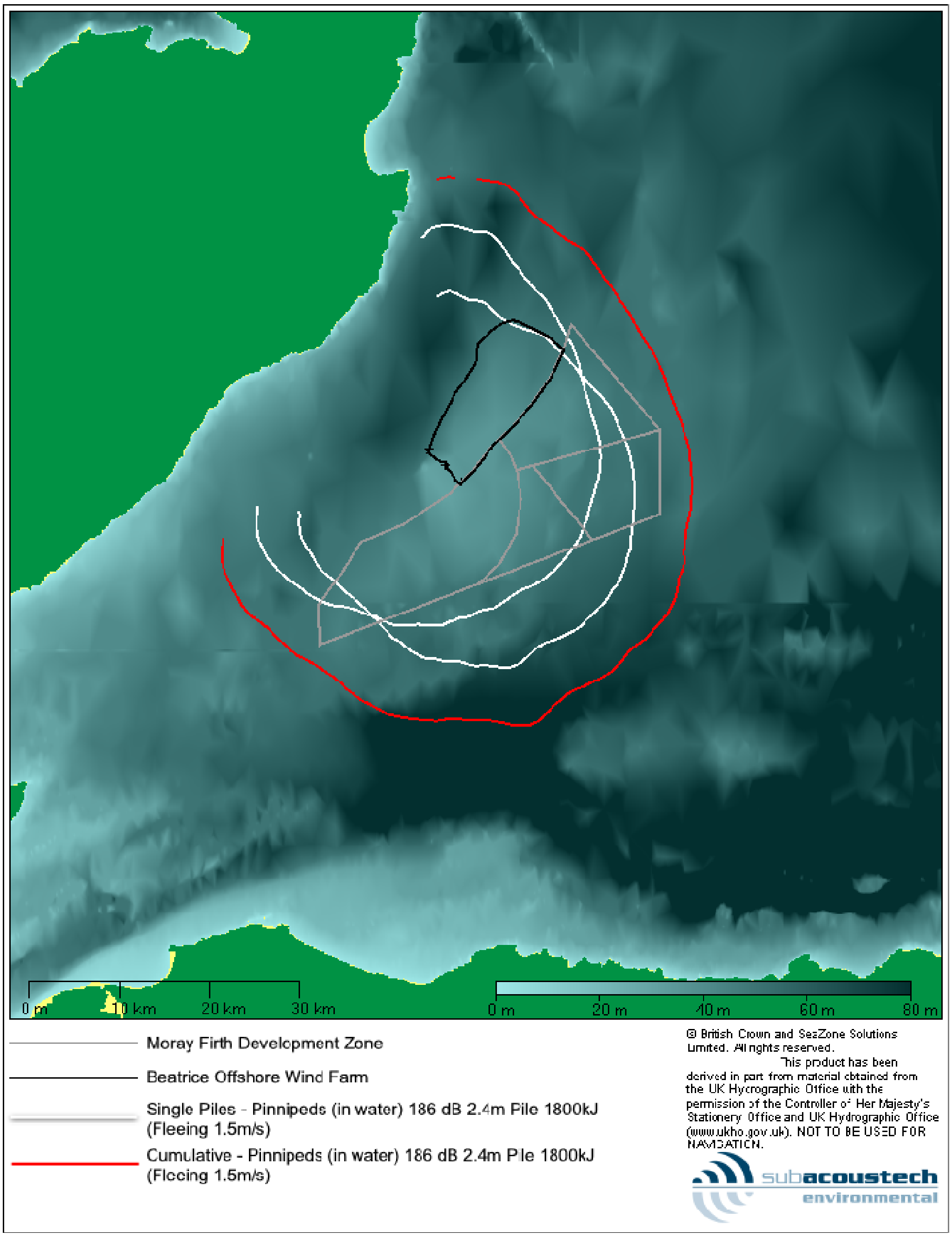
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	1800
Species	High-frequency cetacean

Figure 10.62 186 dB(Mpw) contours for a stationary pinniped in water. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 1800 kJ



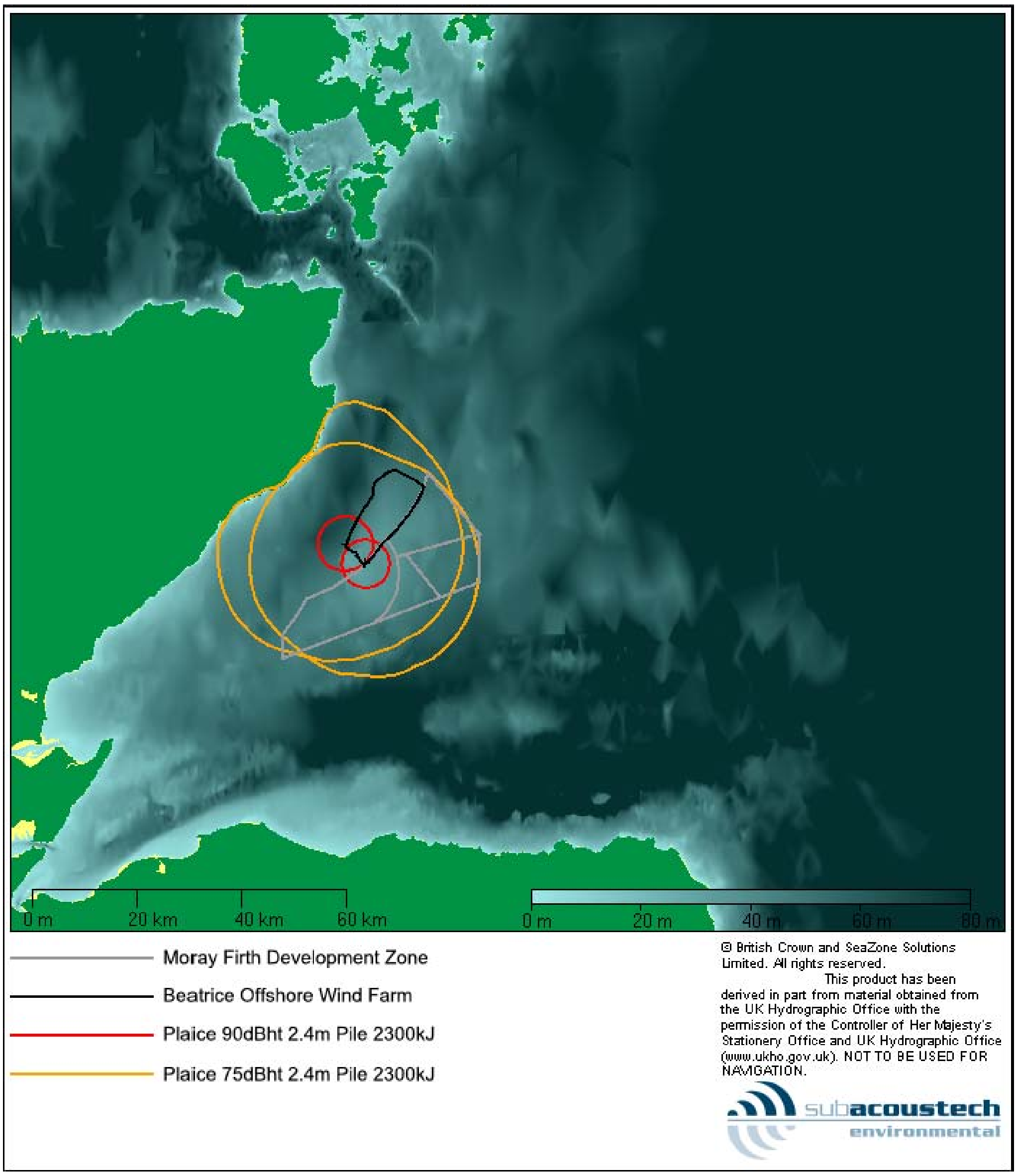
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	1800
Species	Pinniped in water

Figure 10.63 Locus of starting distances from which a fleeing pinniped in water would just reach 186 dB(Mpw) at the cessation of the driving of the piles. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 1800 kJ



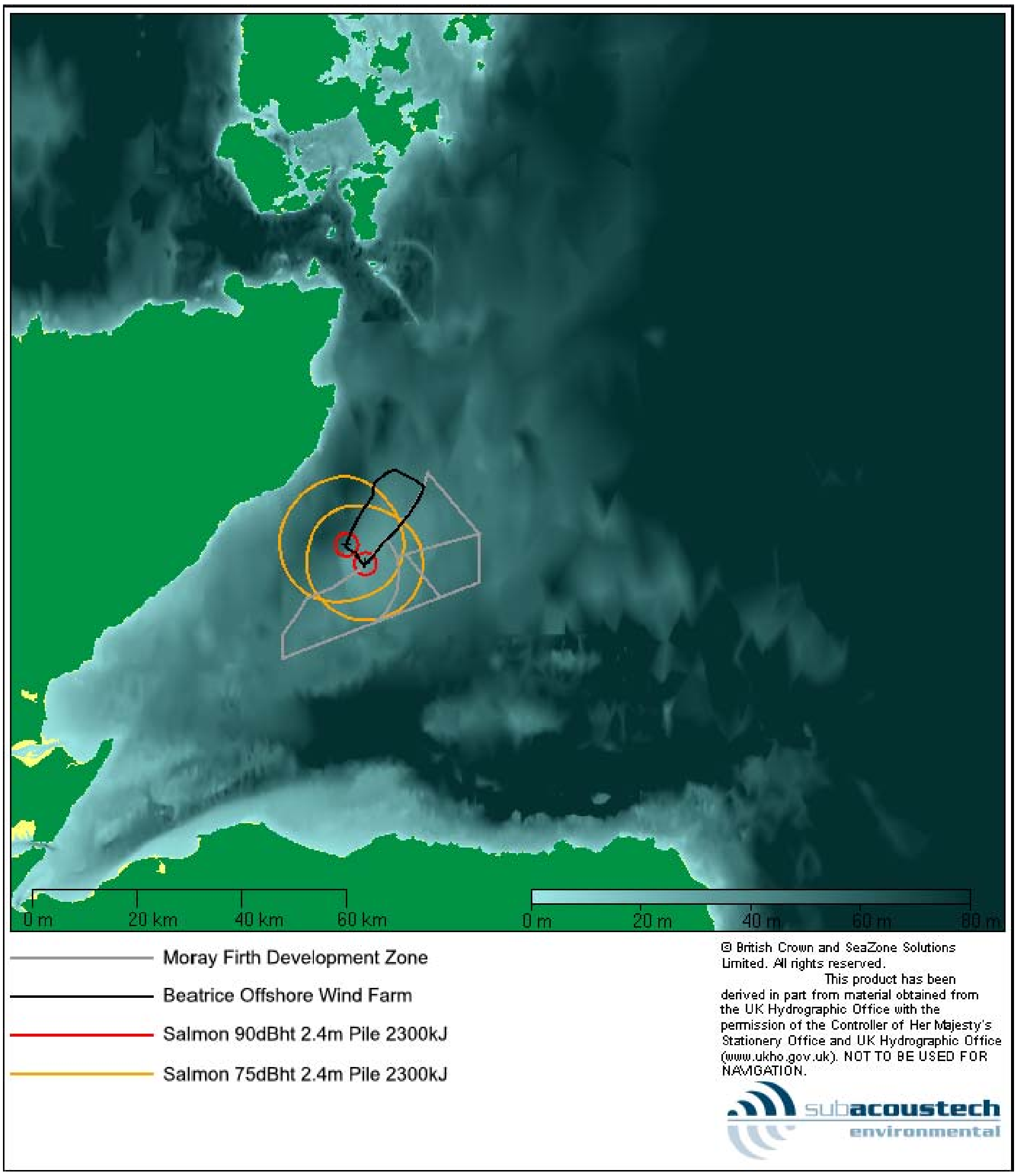
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	1800
Species	Pinniped in water

Figure 10.64 90 dBht and 75 dBht contours for the plaice. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 2300 kJ



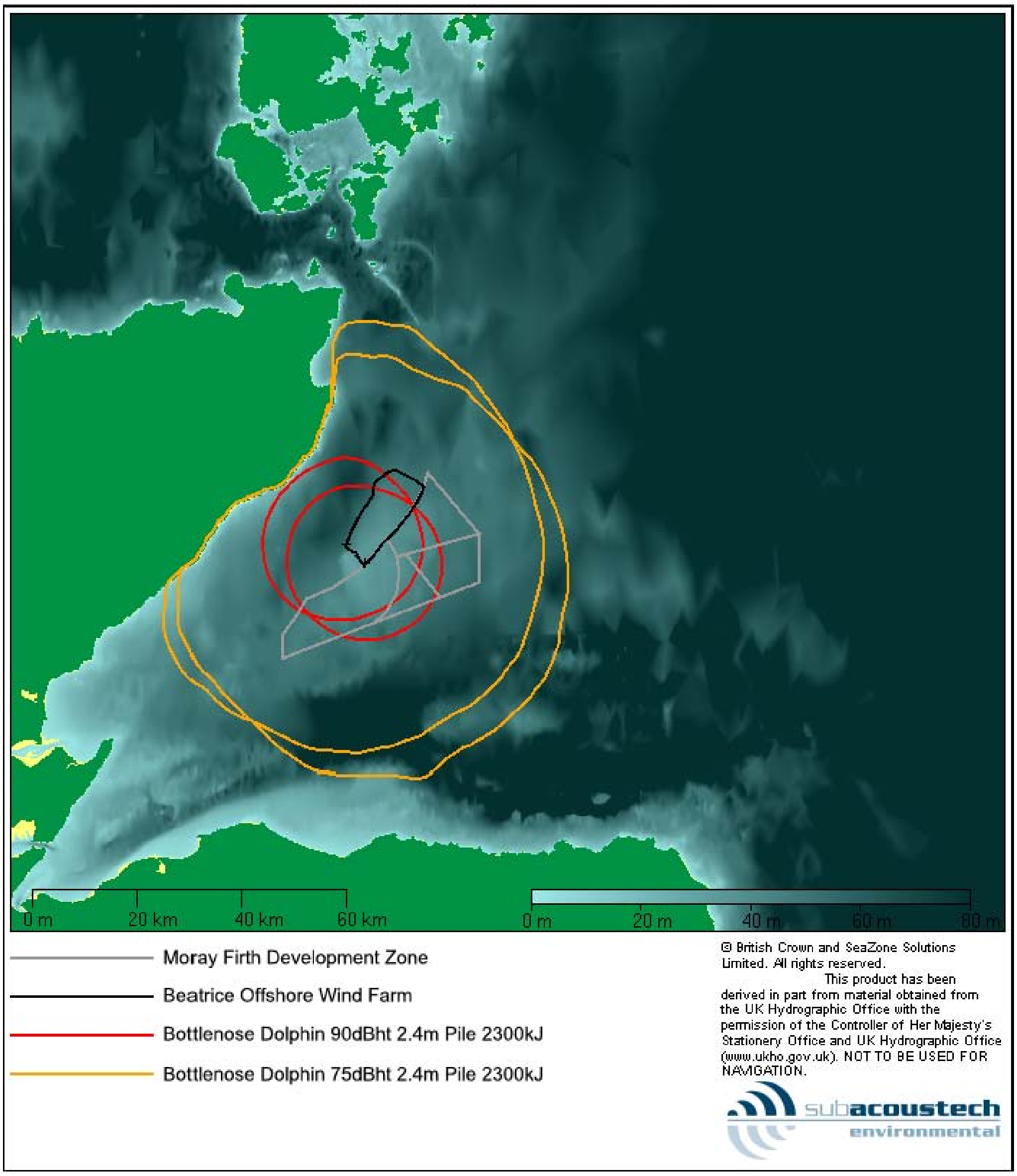
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	2300
Species	Plaice

Figure 10.65 90 dBht and 75 dBht contours for the salmon. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 2300 kJ



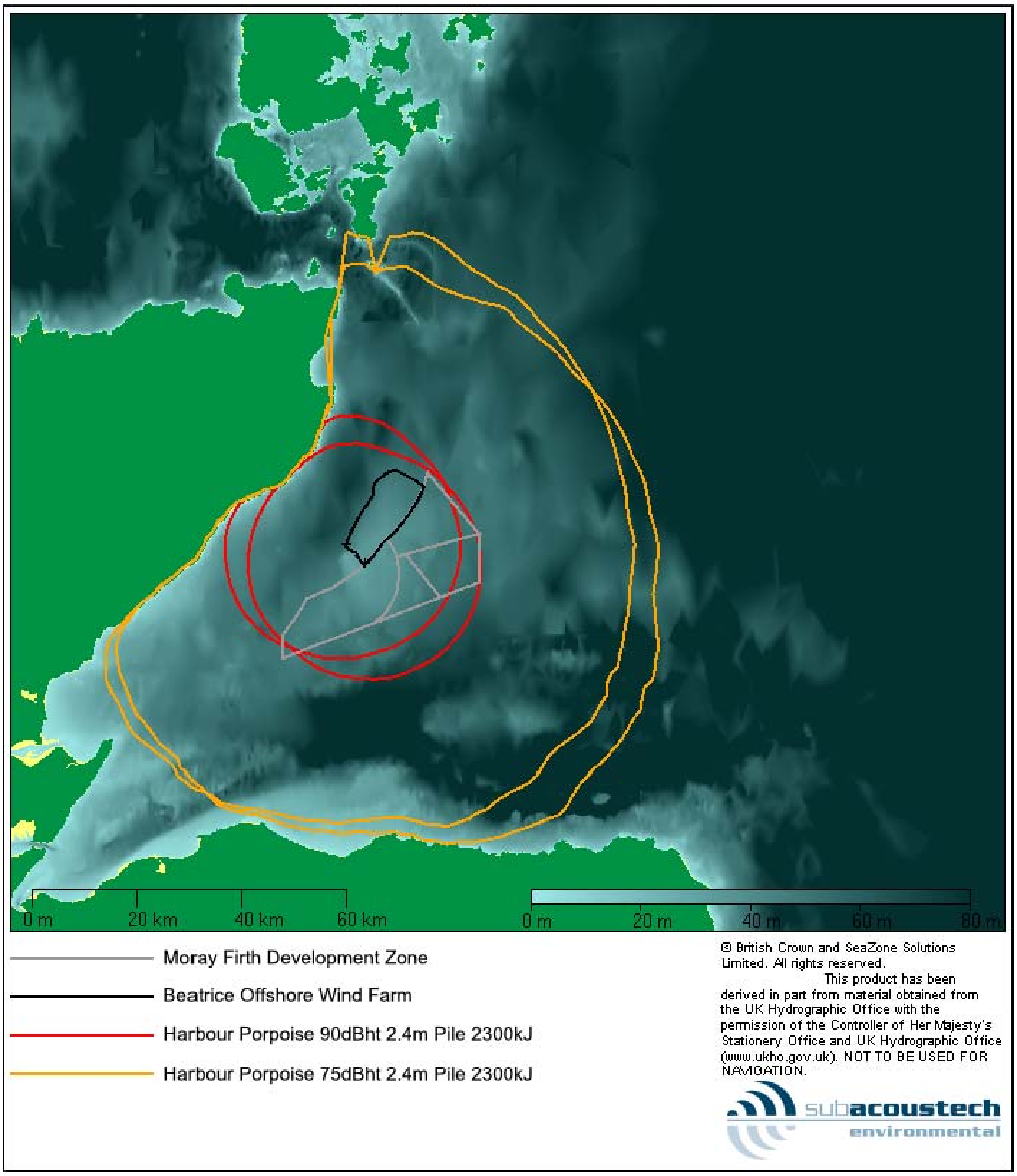
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	2300
Species	Salmon

Figure 10.66 90 dBht and 75 dBht contours for the bottlenose dolphin. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 2300 kJ



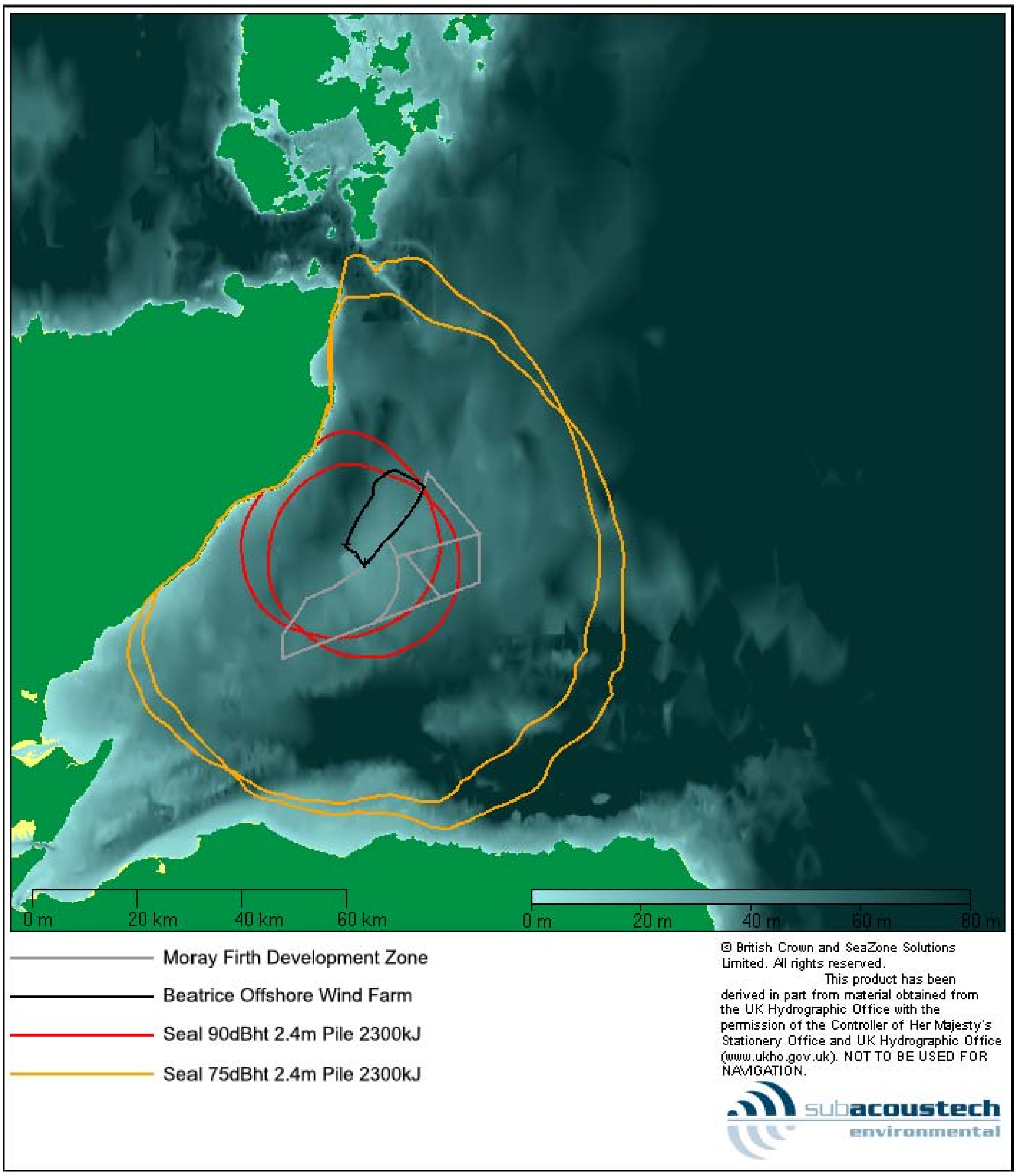
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	2300
Species	Bottlenose dolphin

Figure 10.67 90 dBht and 75 dBht contours for the harbour porpoise. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 2300 kJ



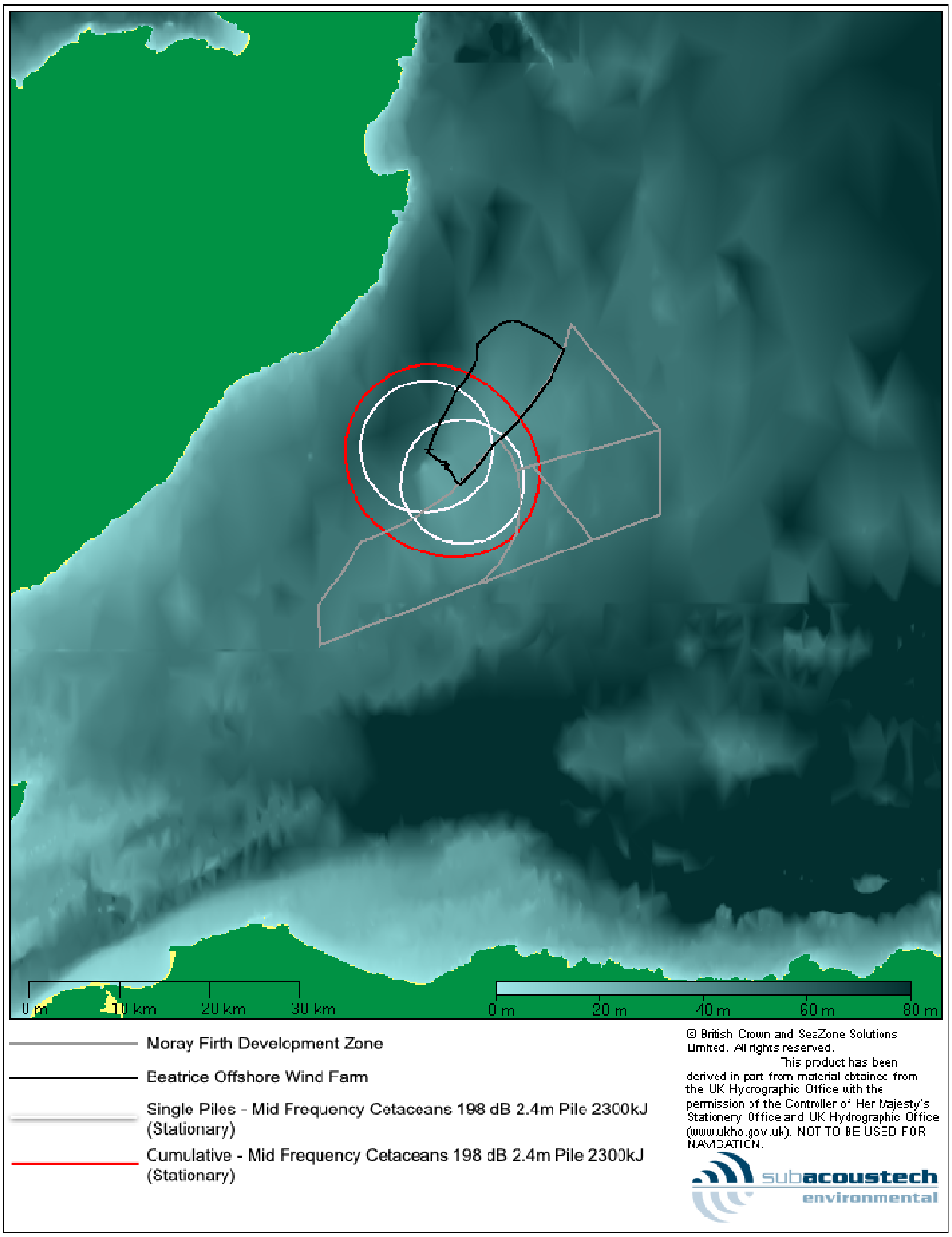
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	2300
Species	Harbour porpoise

Figure 10.68 90 dBht and 75 dBht contours for the harbour seal. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 2300 kJ



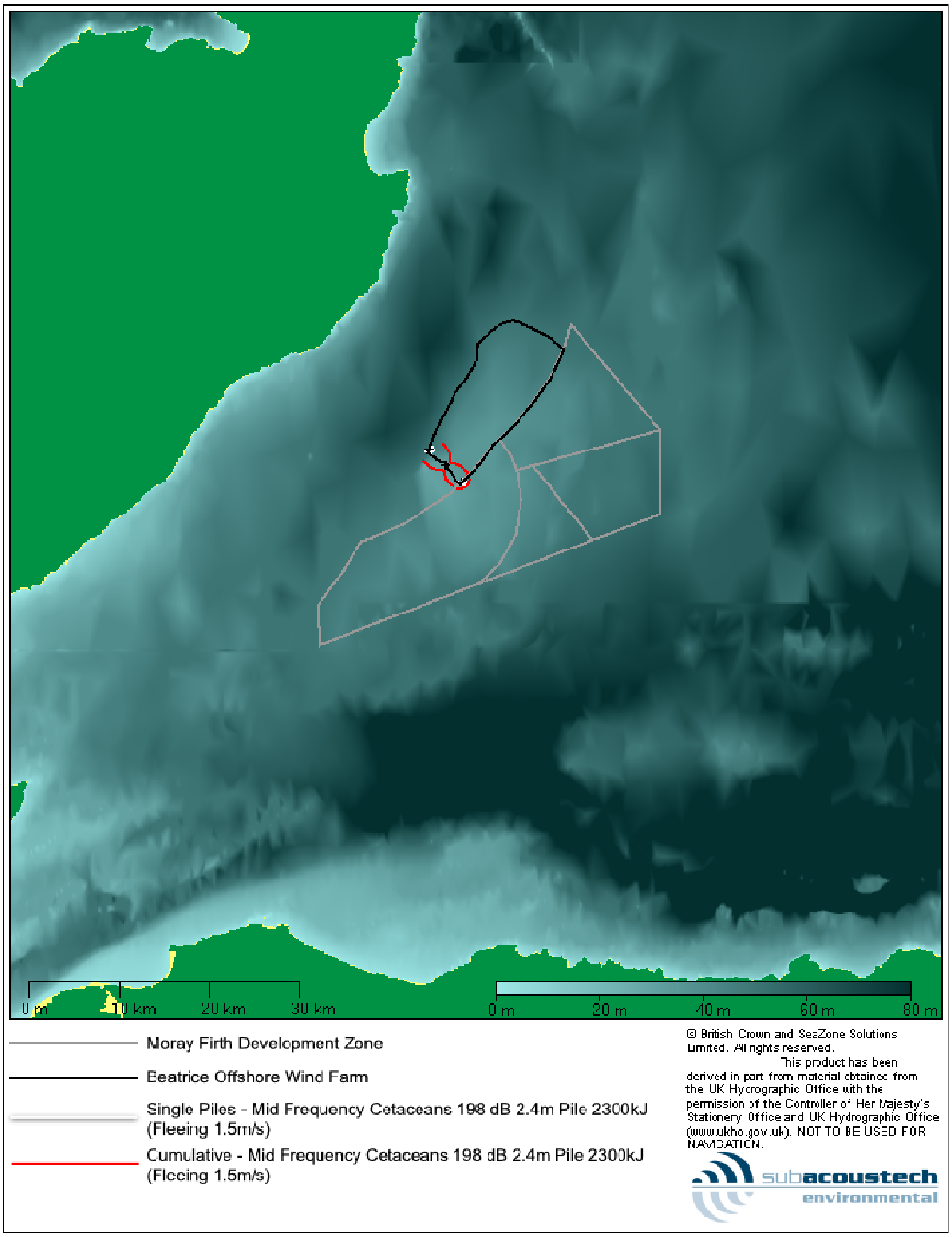
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	2300
Species	Harbour seal

Figure 10.69 198 dB(Mmf) contours for a stationary mid-frequency cetacean. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 2300 kJ



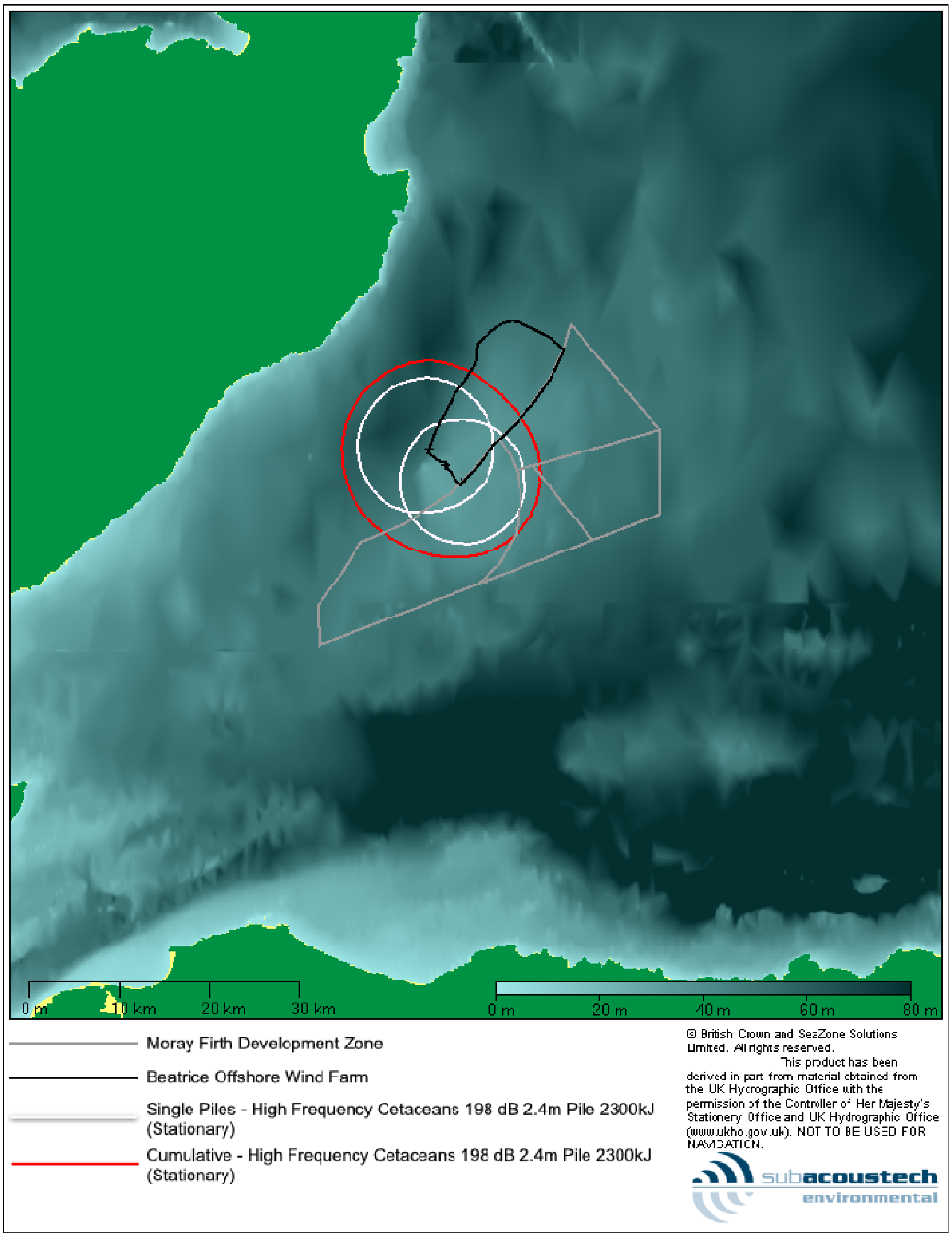
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	2300
Species	Mid-frequency cetacean

Figure 10.70 Locus of starting distances from which a fleeing mid-frequency cetacean would just reach 198 dB(Mmf) at the cessation of the driving of the piles. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 2300 kJ



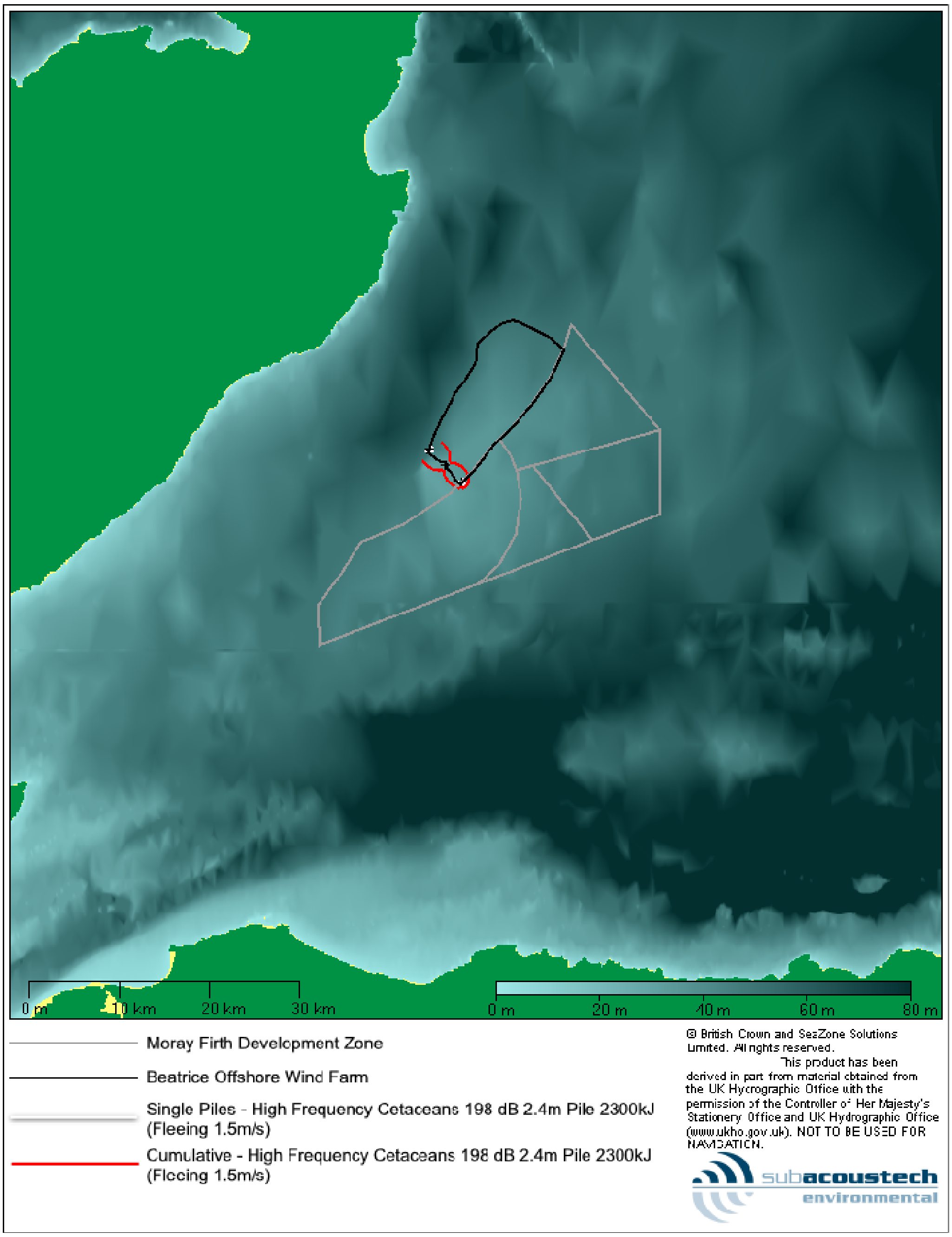
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	2300
Species	Mid-frequency cetacean

Figure 10.71 *198 dB(Mhf) contours for a stationary high-frequency cetacean. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 2300 kJ*



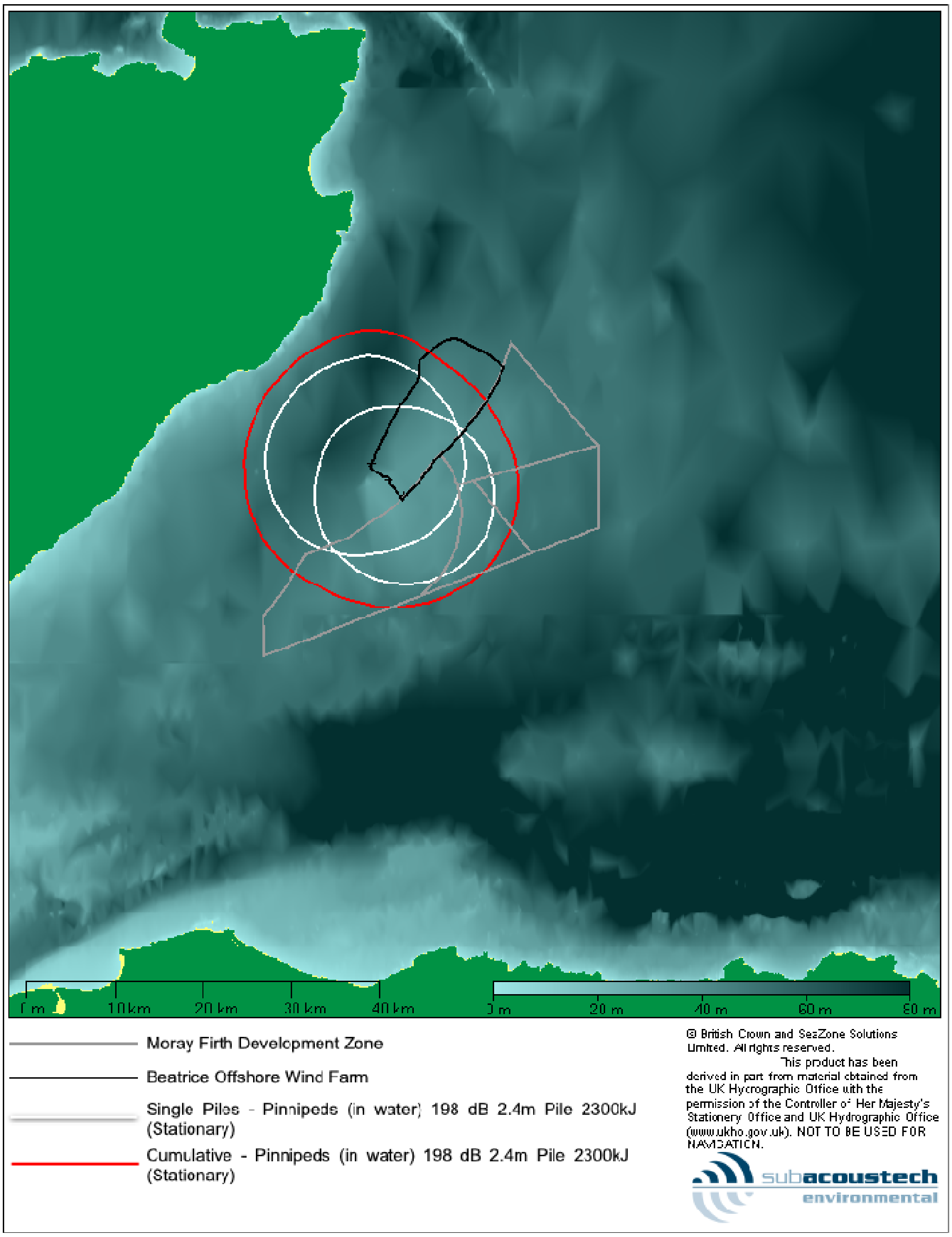
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	2300
Species	High-frequency cetacean

Figure 10.72 Locus of starting distances from which a fleeing high-frequency cetacean would just reach 198 dB(Mhf) at the cessation of the driving of the piles. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 2300 kJ



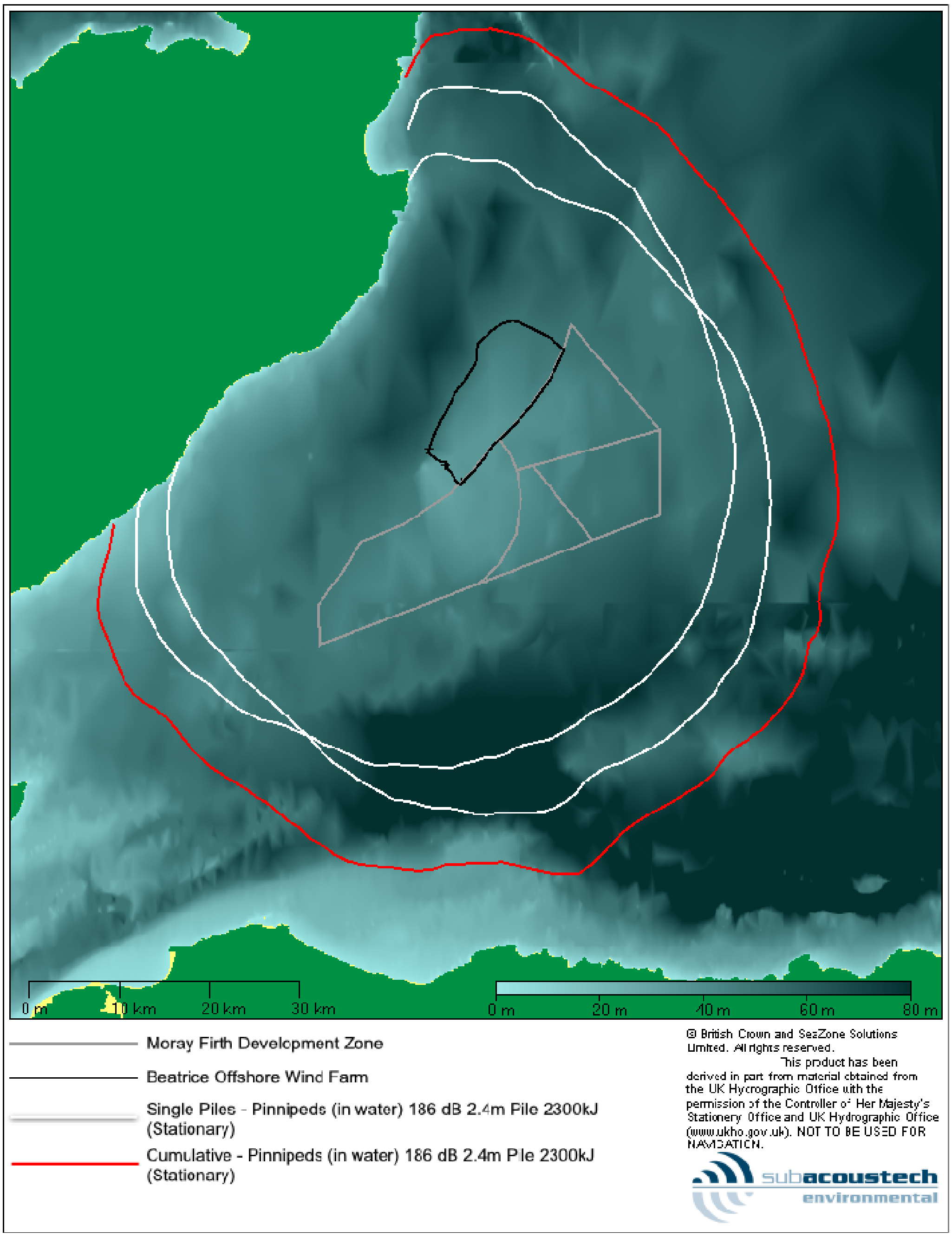
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	2300
Species	High-frequency cetacean

Figure 10.73a 198 dB(Mpw) contours for a stationary pinniped in water. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 2300 kJ



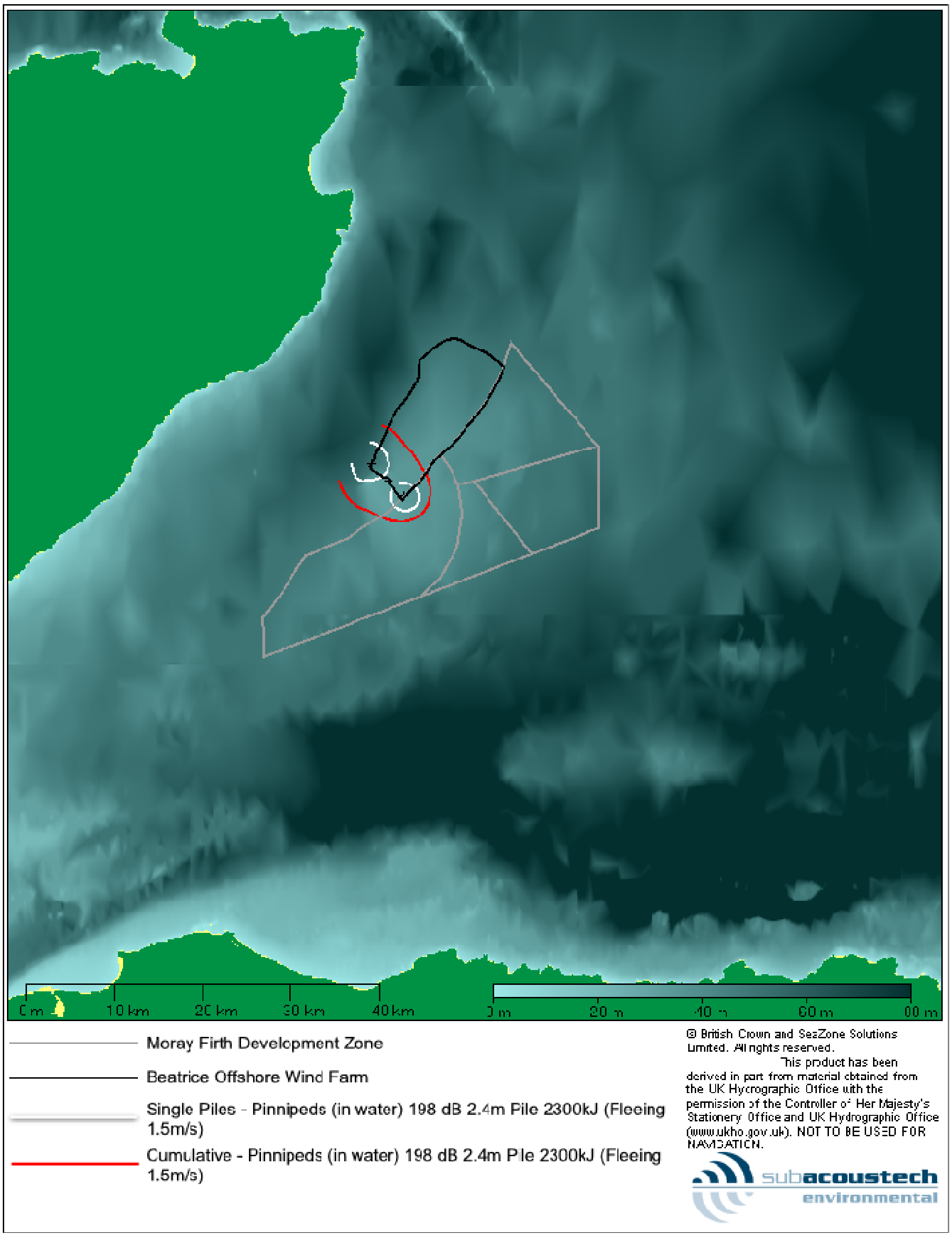
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	2300
Species	Pinniped in water

Figure 10.73b 186 dB(Mpw) contours for a stationary pinniped in water. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 2300 kJ



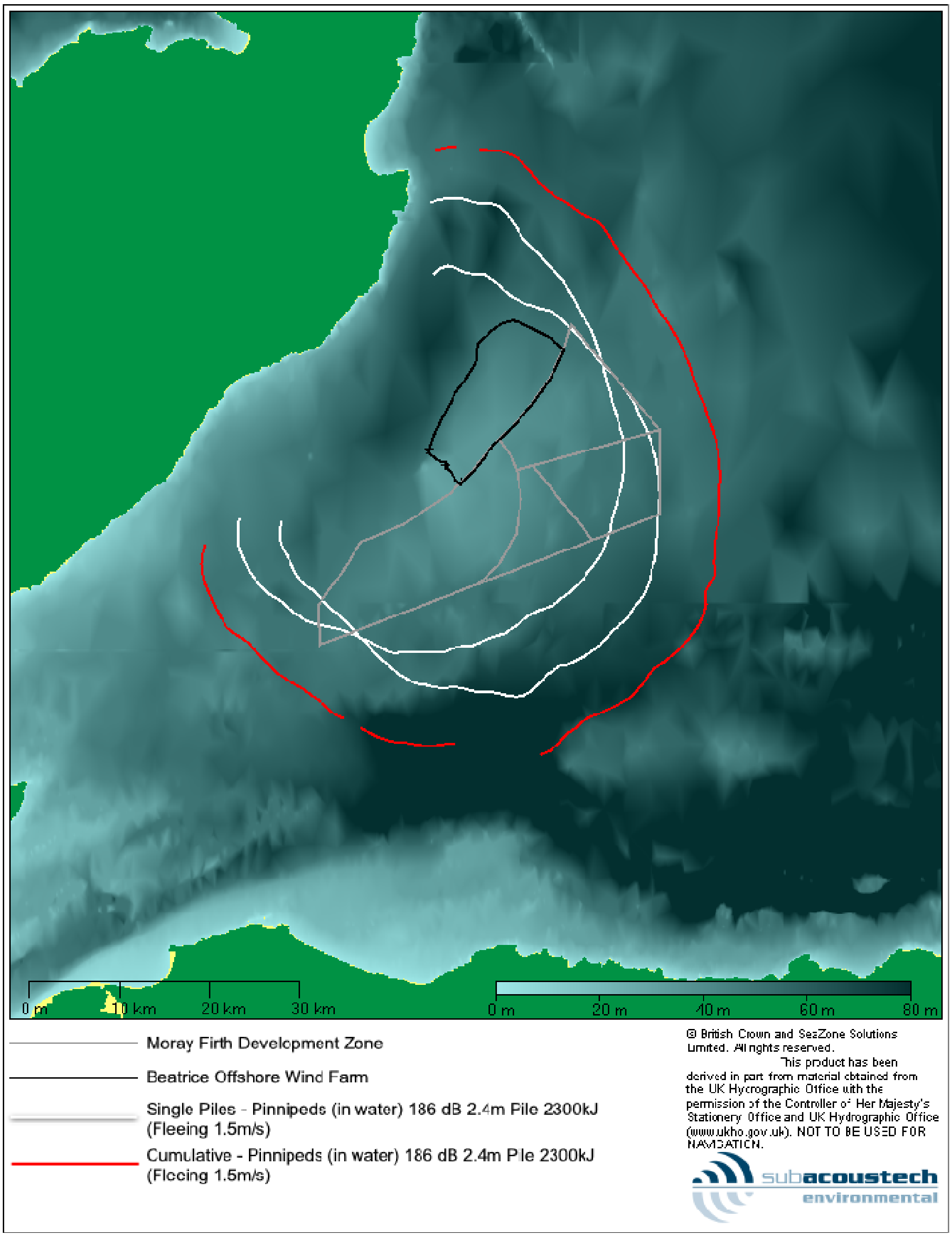
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	2300
Species	Pinniped in water

Figure 10.74a Locus of starting distances from which a fleeing pinniped in water would just reach 198 dB(Mpw) at the cessation of the driving of the piles. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 2300 kJ



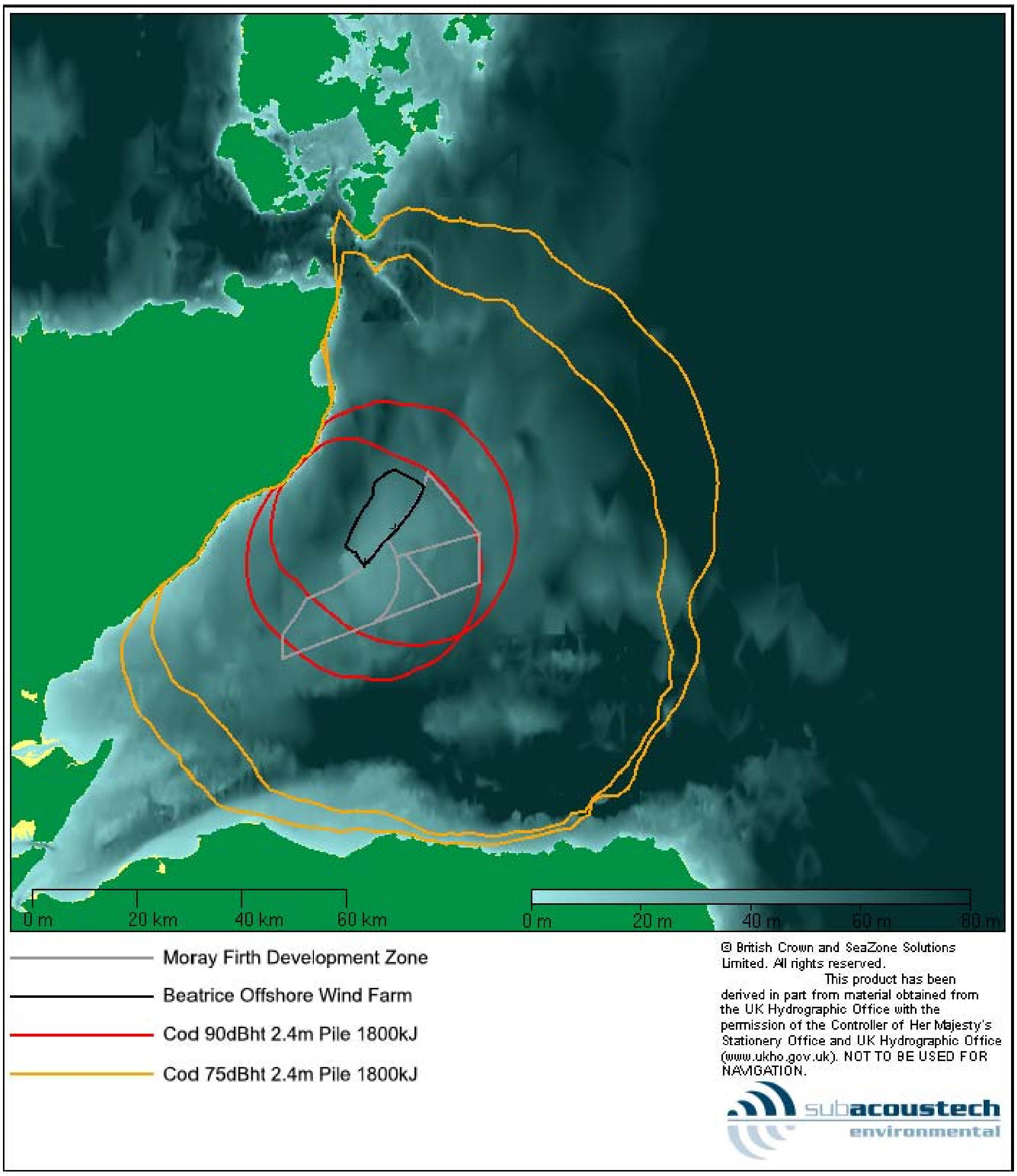
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	2300
Species	Piniped in water

Figure 10.74b Locus of starting distances from which a fleeing pinniped in water would just reach 186 dB(Mpw) at the cessation of the driving of the piles. Two 2.4 m diameter piles being driven simultaneously at locations A and B. Piling energy 2300 kJ



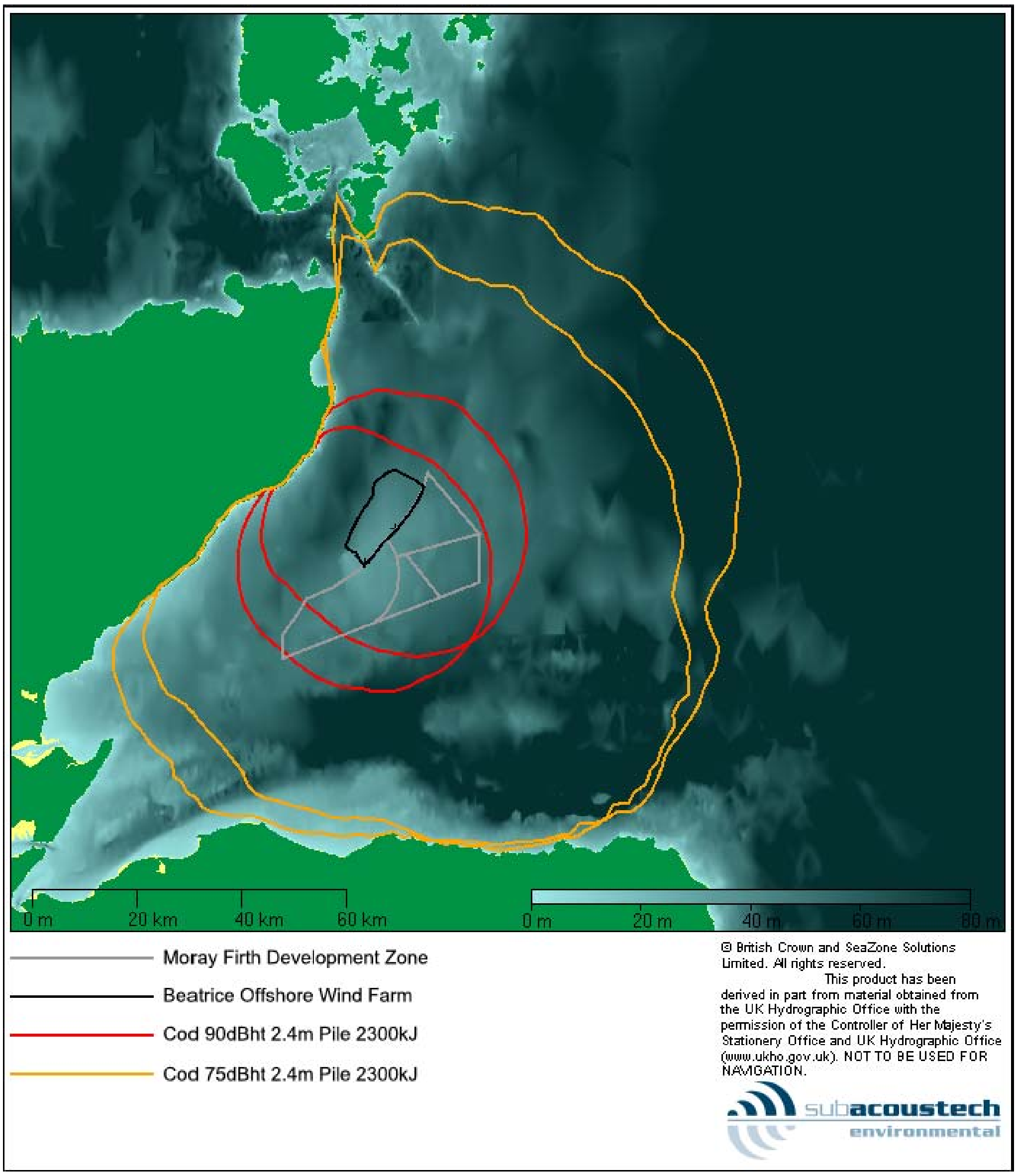
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and B
Pile driving energy (kJ)	2300
Species	Piniped in water

Figure 10.75 90 dBht and 75 dBht contours for the cod. Two 2.4 m diameter piles being driven simultaneously at locations A and E. Piling energy 1800 kJ



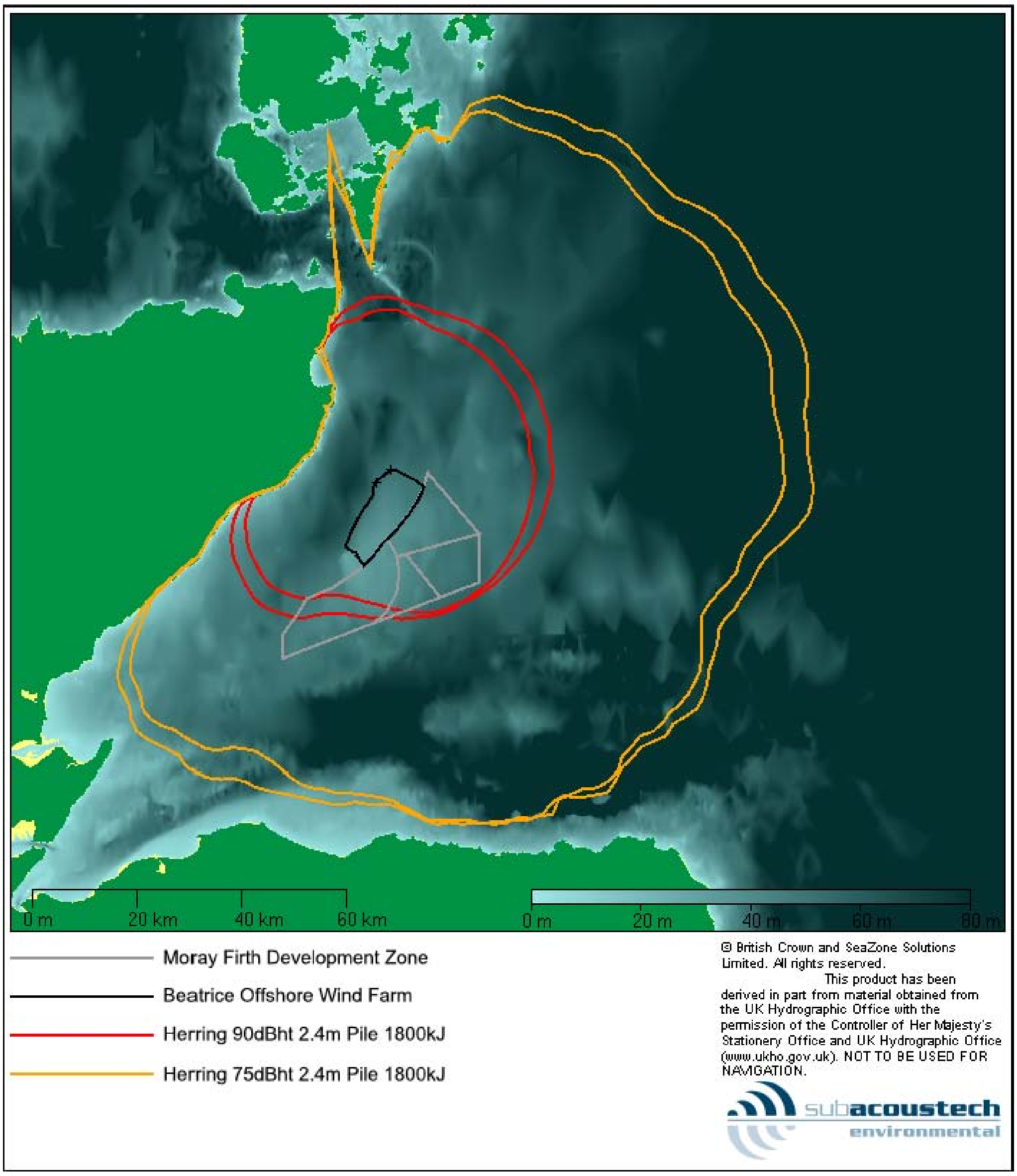
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and E
Pile driving energy (kJ)	1800
Species	Cod

Figure 10.76 90 dBht and 75 dBht contours for the cod. Two 2.4 m diameter piles being driven simultaneously at locations A and E. Piling energy 2300 kJ



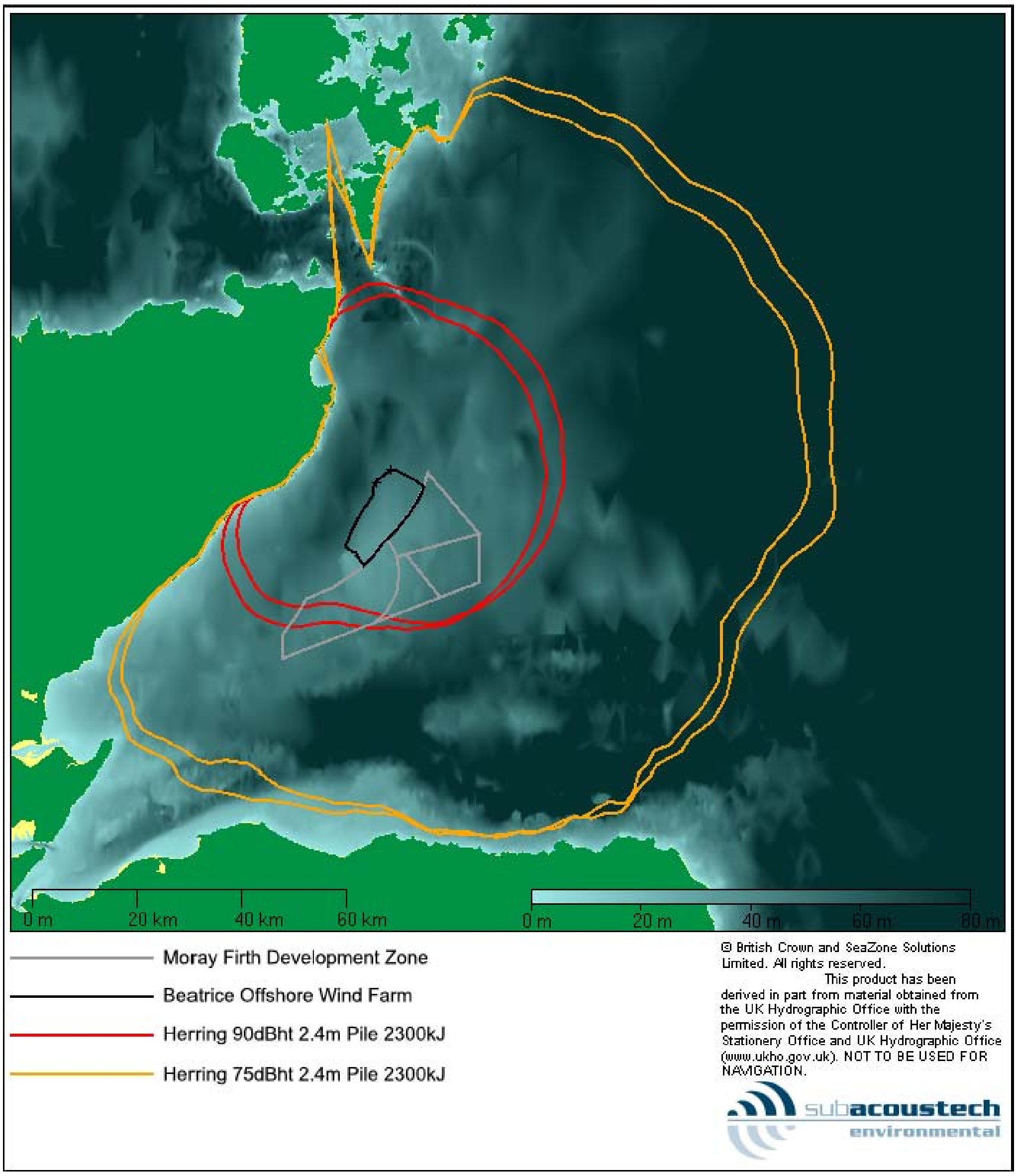
Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	A and E
Pile driving energy (kJ)	2300
Species	Cod

Figure 10.77 90 dBht and 75 dBht contours for the herring. Two 2.4 m diameter piles being driven simultaneously at locations C and D. Piling energy 1800 kJ



Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	C and D
Pile driving energy (kJ)	1800
Species	Herring

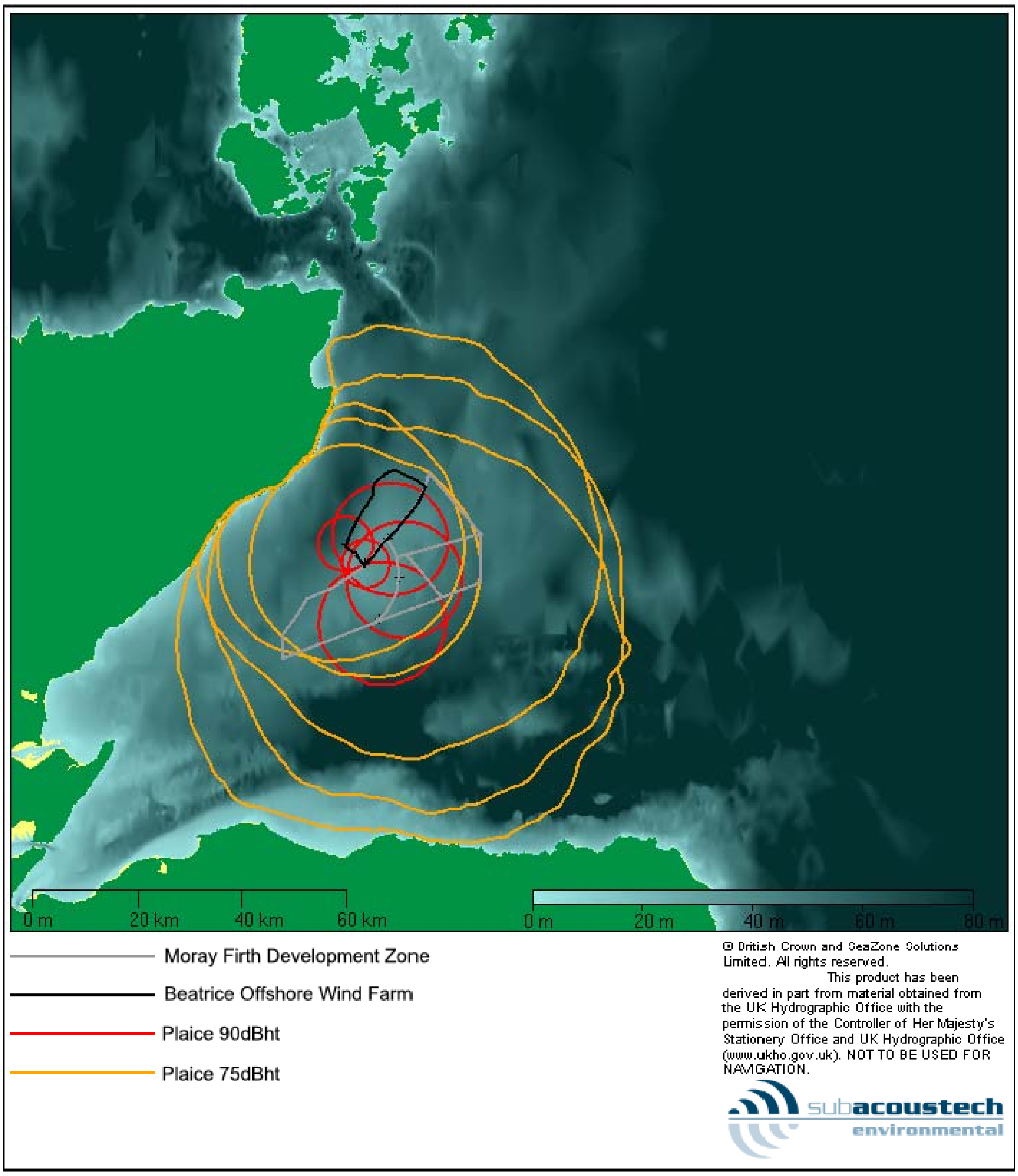
Figure 10.78 90 dBht and 75 dBht contours for the herring. Two 2.4 m diameter piles being driven simultaneously at locations C and D. Piling energy 2300 kJ



Pile diameter (m)	2 X 2.4
Pile locations (see map, Figure 10.13)	C and D
Pile driving energy (kJ)	2300
Species	Herring

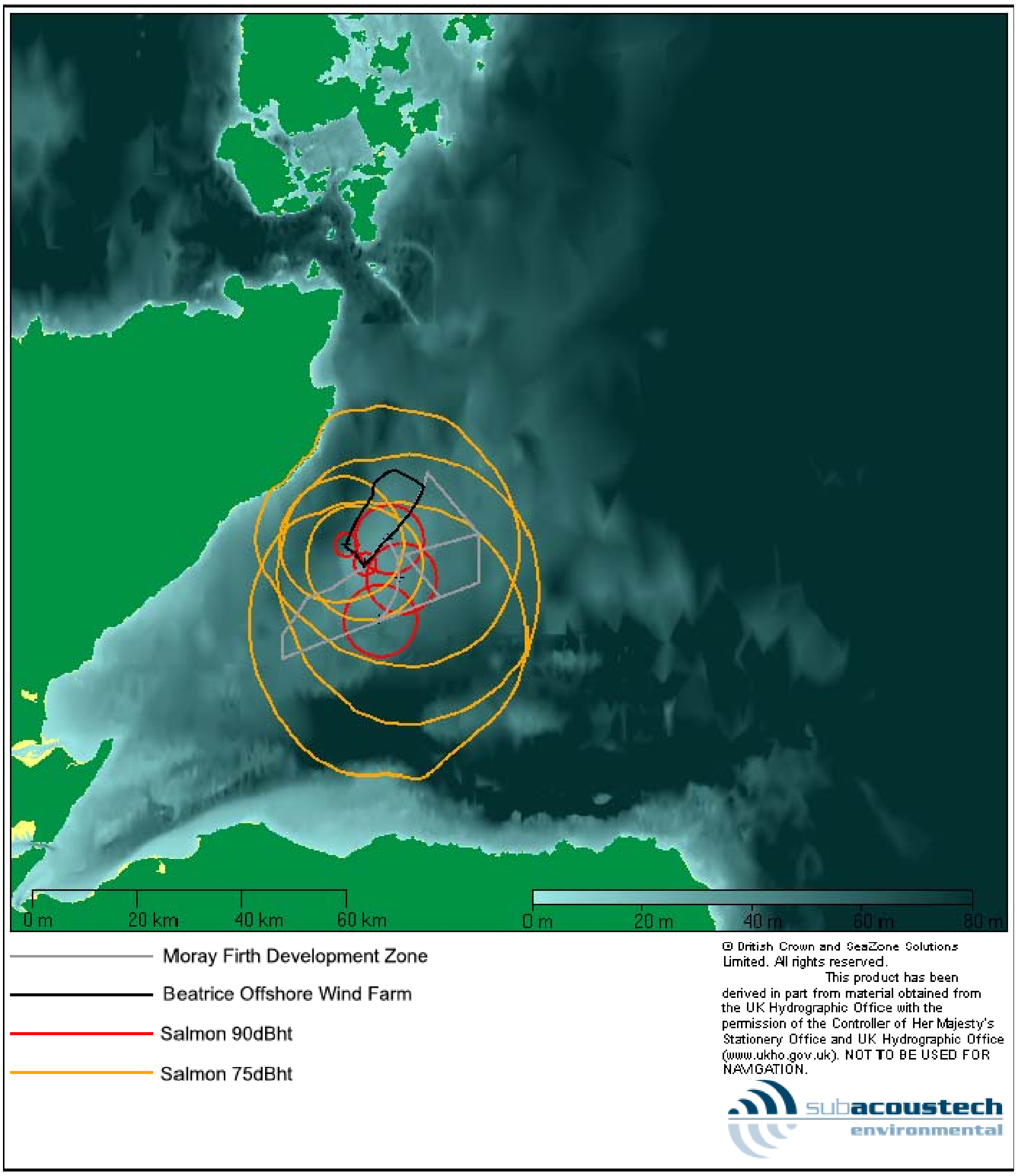
Results for two 2.4 m diameter piles and three 10 m diameter piles being driven simultaneously

Figure 10.79 90 dBht and 75 dBht contours for the plaice. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



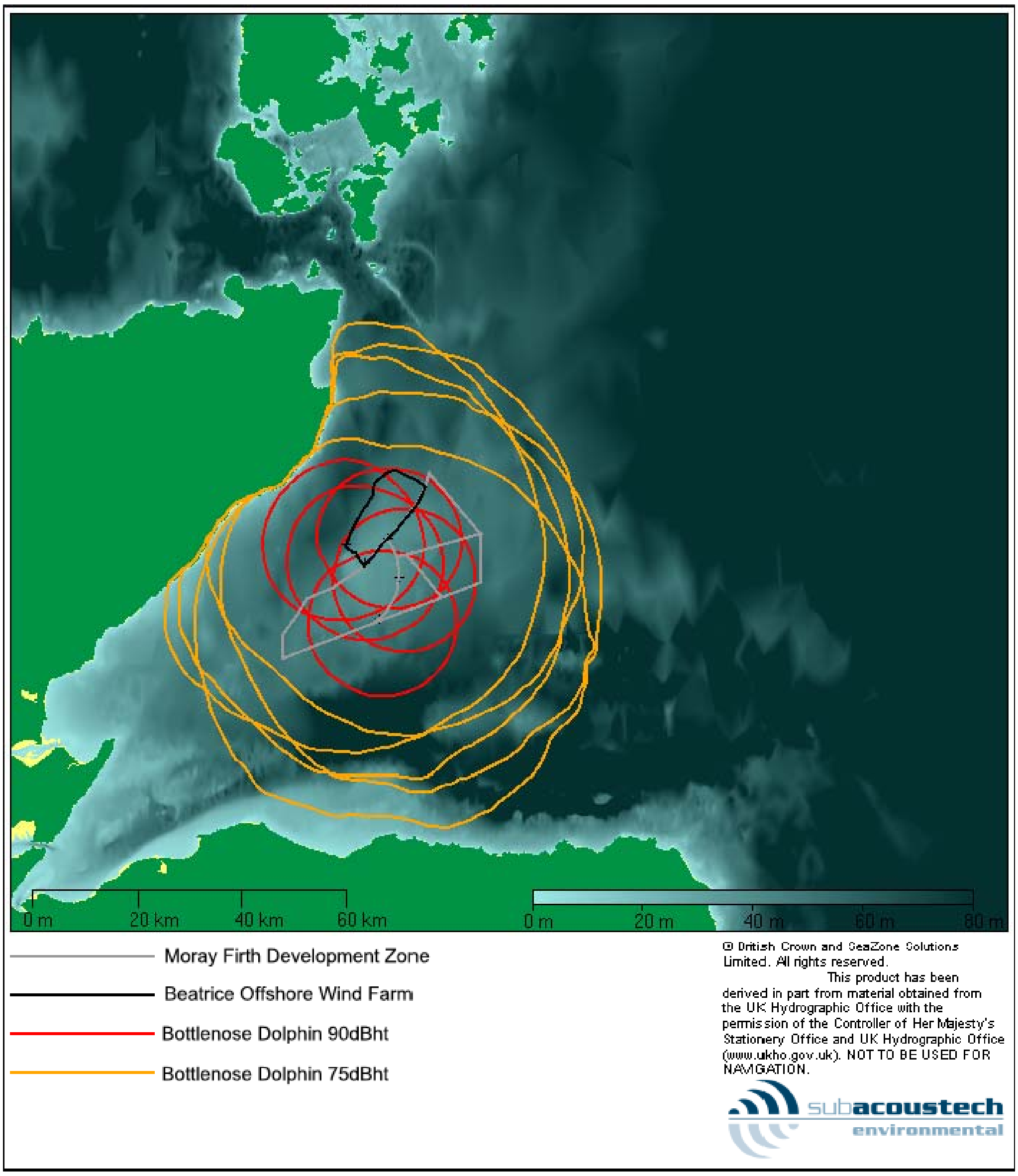
Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and B; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. –2300; 10 m dia. – 2700
Species	Plaice

Figure 10.80 90 dBht and 75 dBht contours for the salmon. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



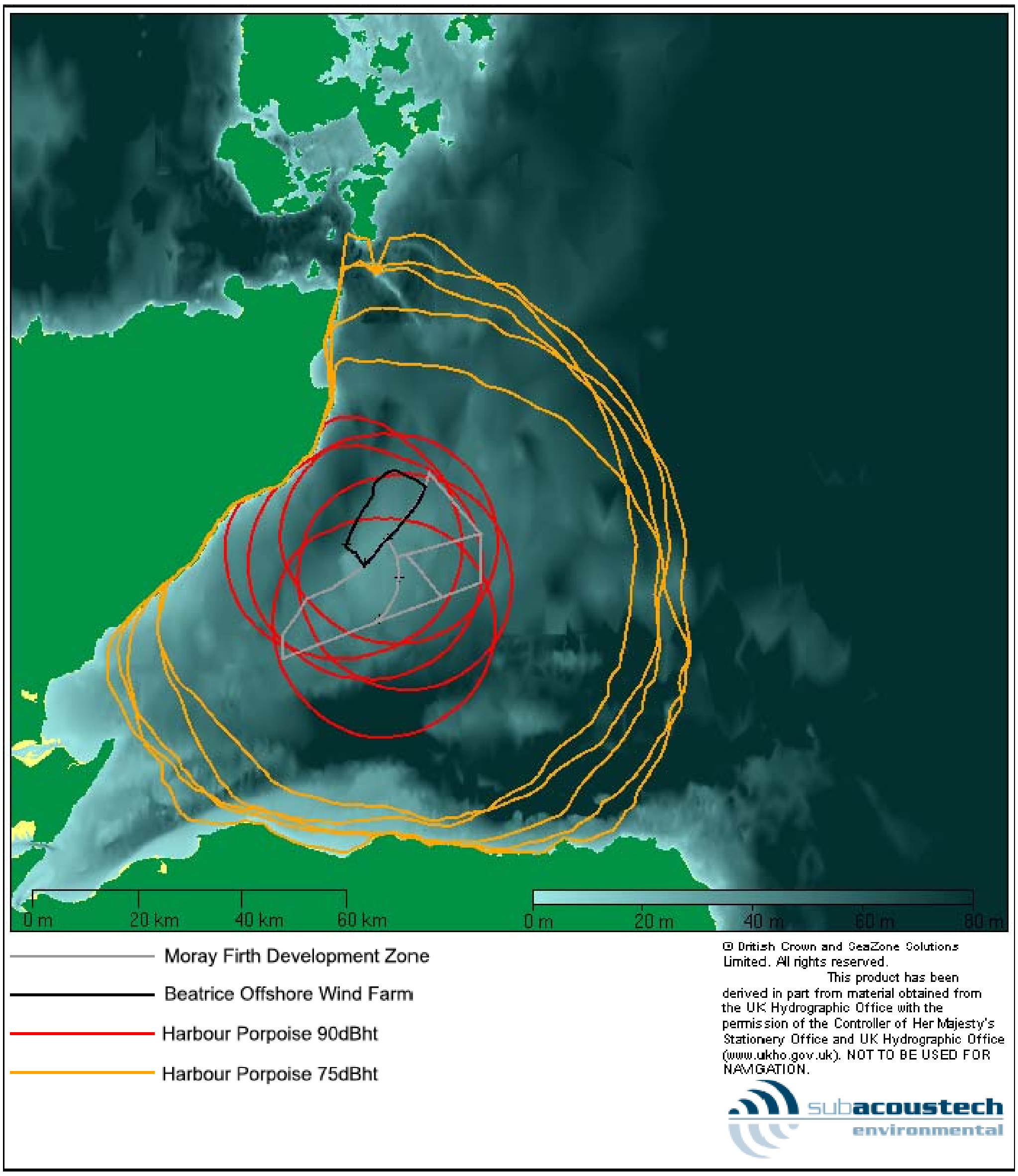
Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and B; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. –2300; 10 m dia. – 2700
Species	Salmon

Figure 10.81 90 dBht and 75 dBht contours for the bottlenose dolphin. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



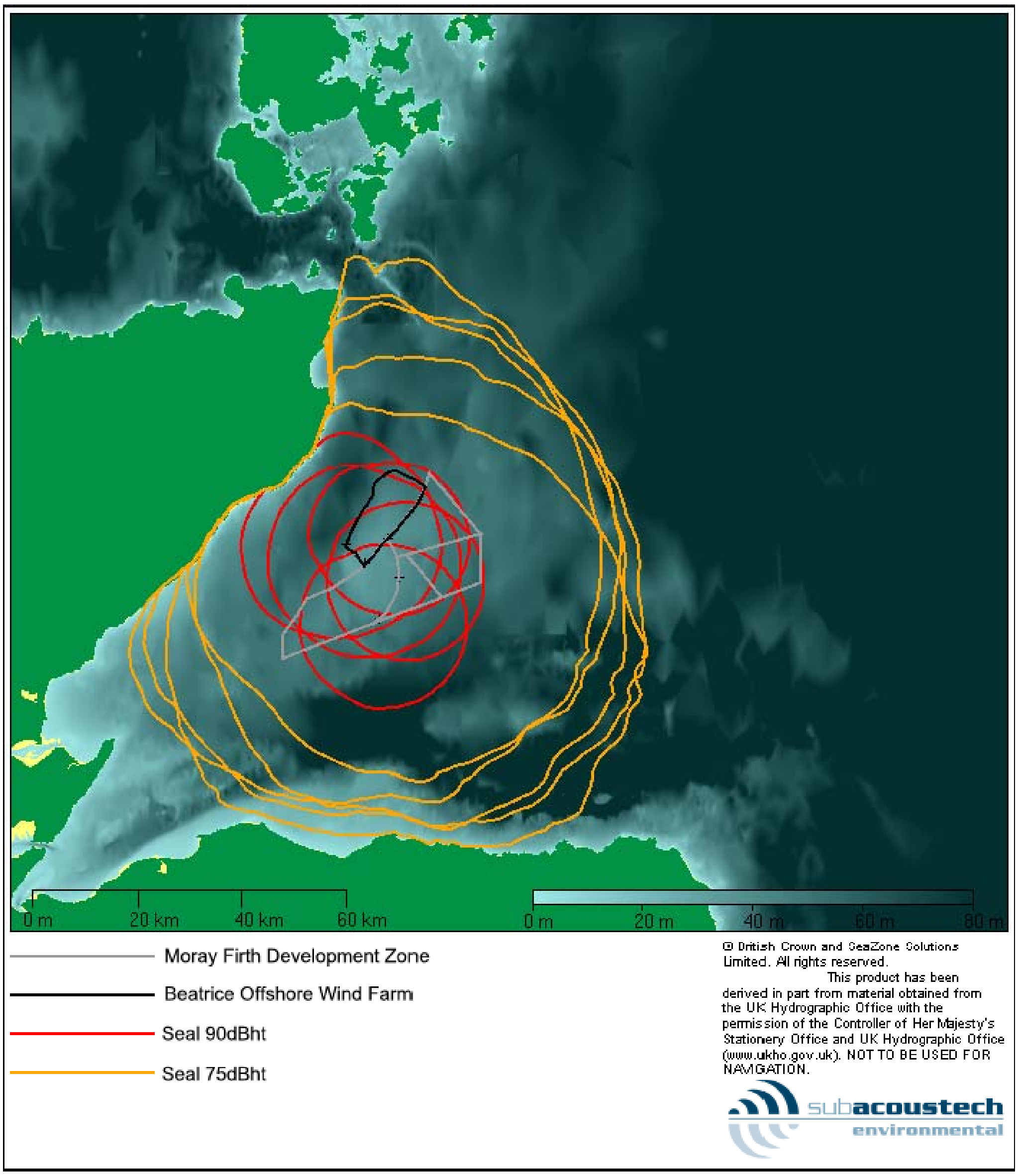
Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and B; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. –2300; 10 m dia. – 2700
Species	Bottlenose dophin

Figure 10.82 90 dBht and 75 dBht contours for the harbour porpoise. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



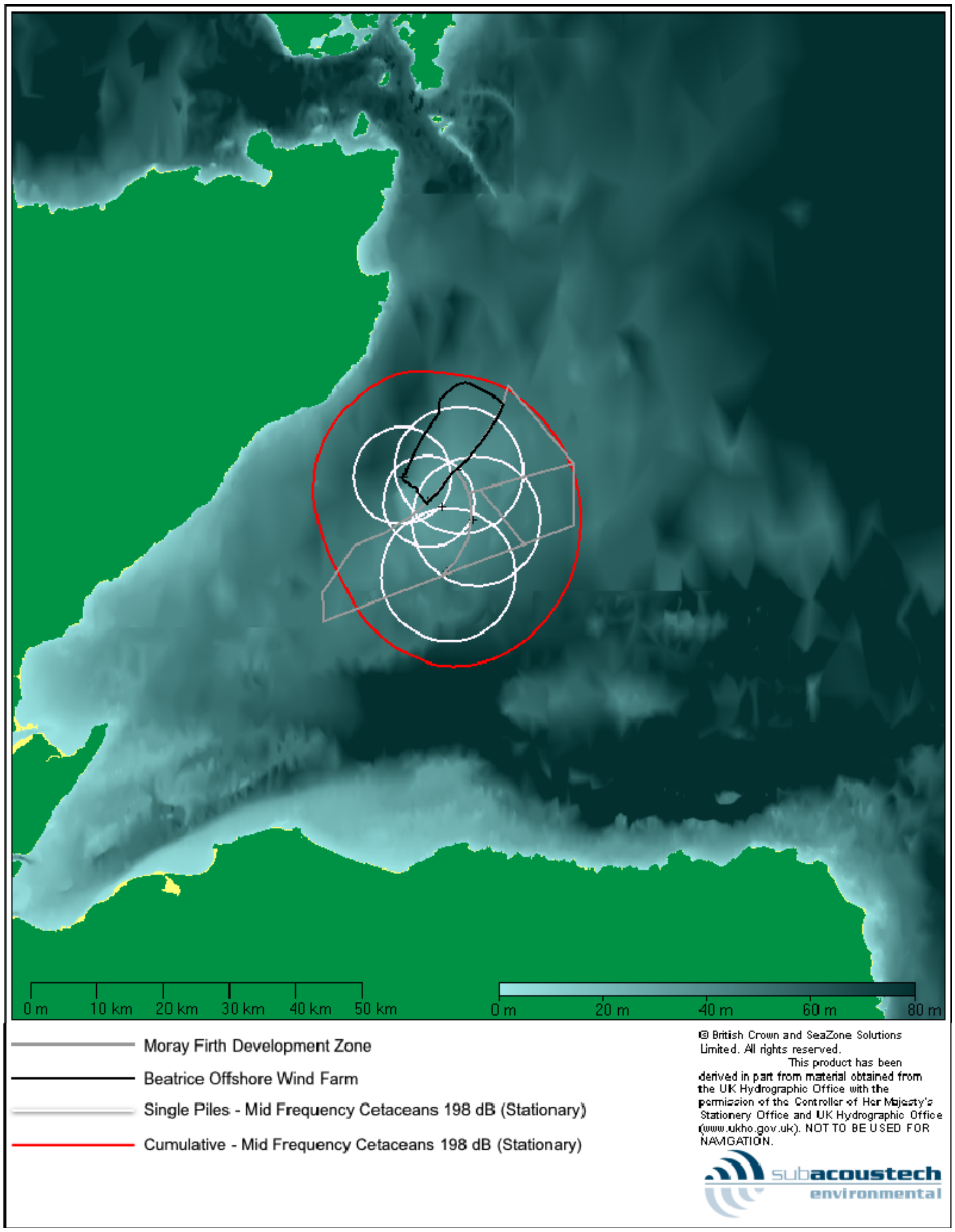
Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and B; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. – 2300; 10 m dia. – 2700
Species	Harbour porpoise

Figure 10.83 90 dBht and 75 dBht contours for the harbour seal. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



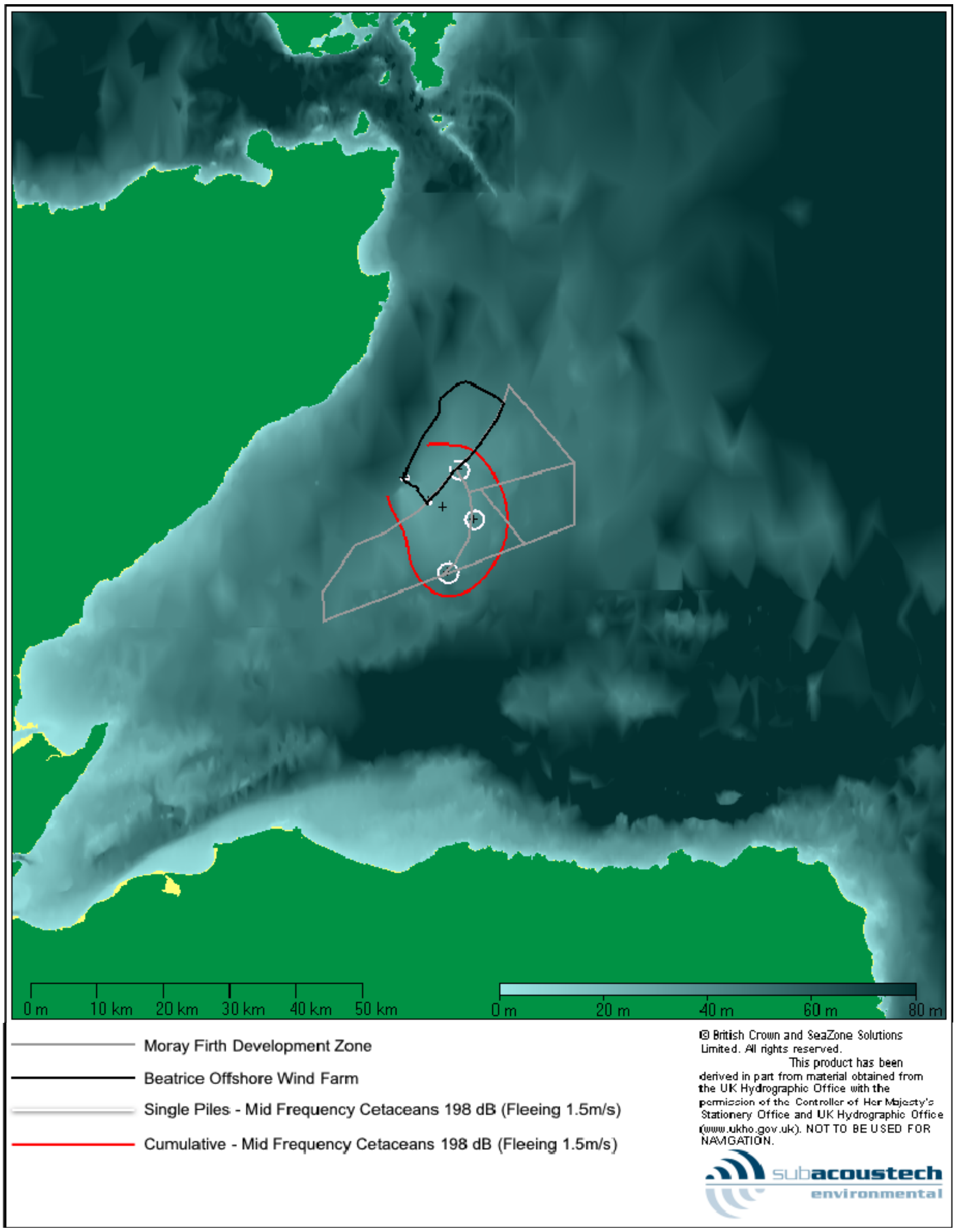
Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and B; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. –2300; 10 m dia. – 2700
Species	Harbour seal

Figure 10.84 198 dB(Mmf) contours for a stationary mid-frequency cetacean. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



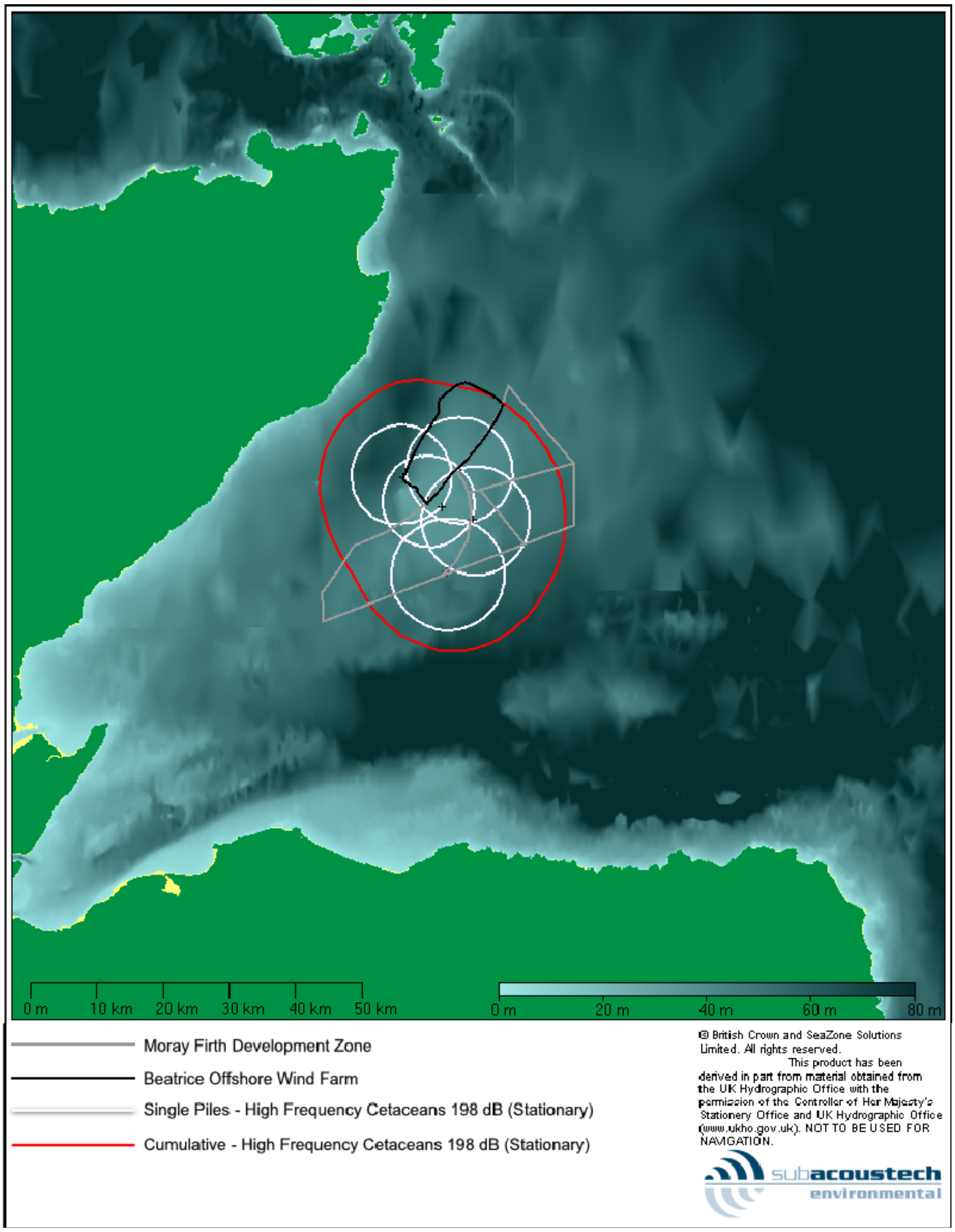
Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and B; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. –2300; 10 m dia. – 2700
Species	Mid-frequency stationary cetacean

Figure 10.85 Locus of starting distances from which a fleeing mid-frequency cetacean would just reach 198 dB(Mmf) at the cessation of the driving of the piles. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



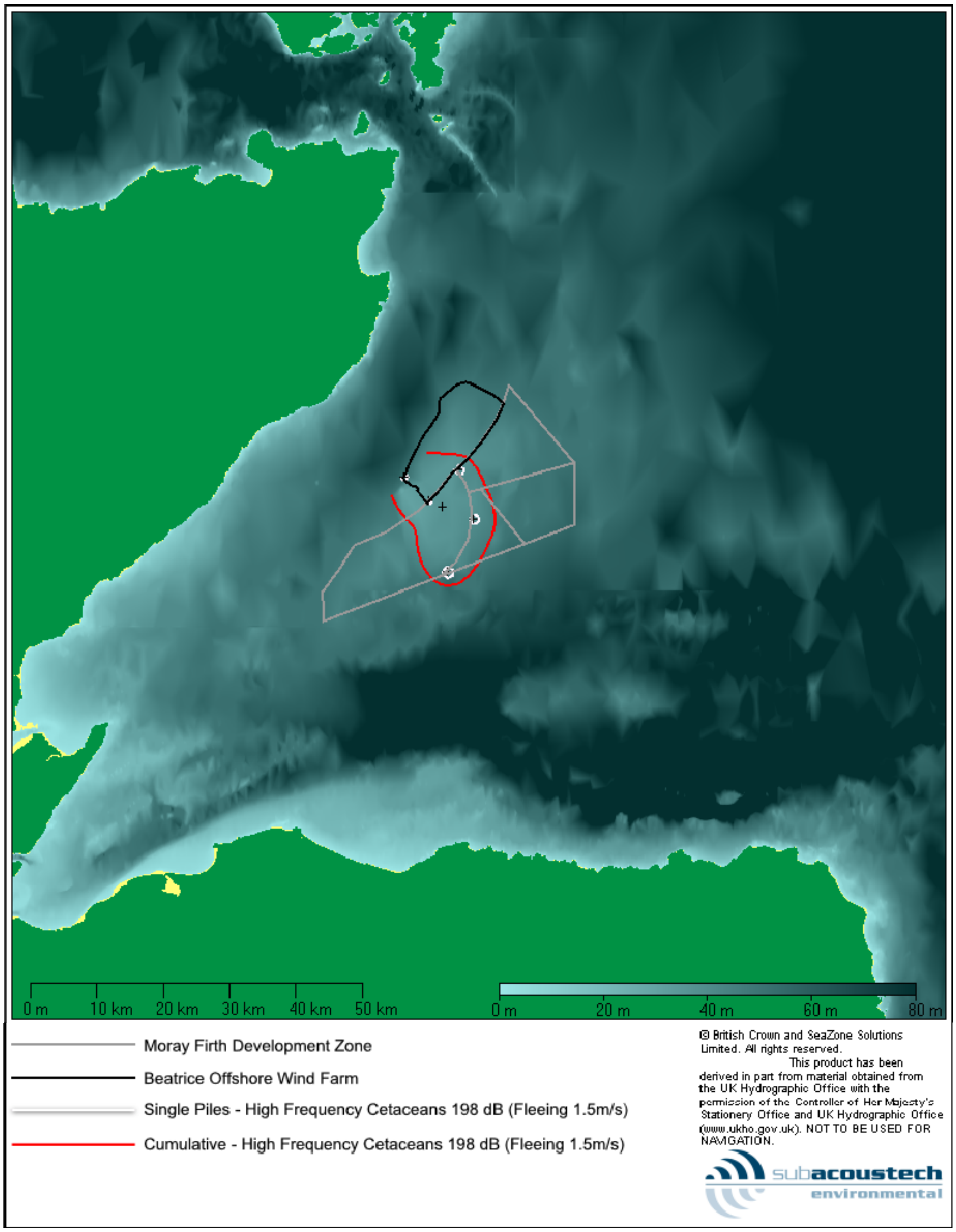
Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and B; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. – 2300; 10 m dia. – 2700
Species	Mid-frequency fleeing cetacean

Figure 10.86 198 dB(Mhf) contours for a stationary high-frequency cetacean. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



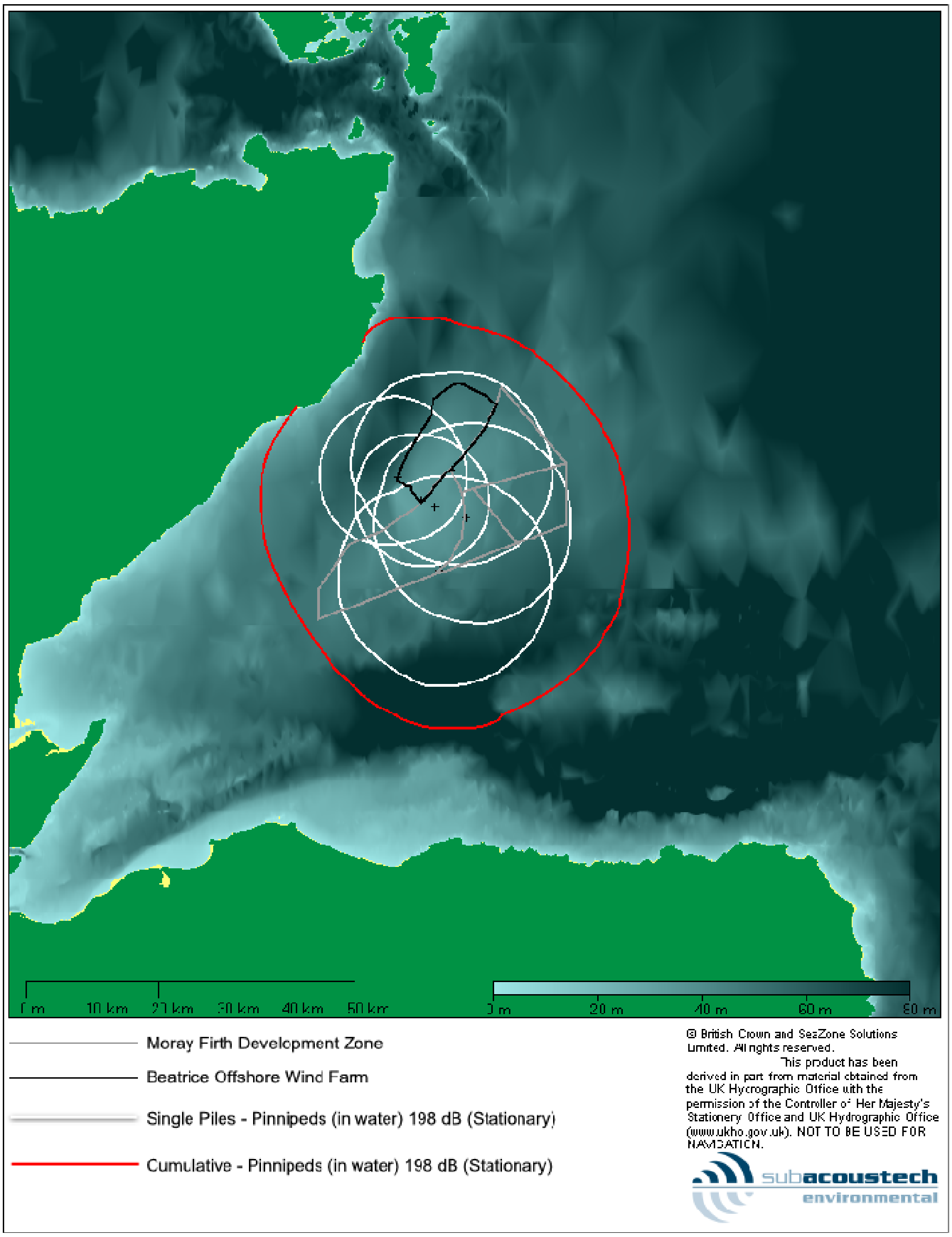
Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and B; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. –2300; 10 m dia. – 2700
Species	High-frequency stationary cetacean

Figure 10.87 Locus of starting distances from which a fleeing high-frequency cetacean would just reach 198 dB(Mhf) at the cessation of the driving of the piles. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



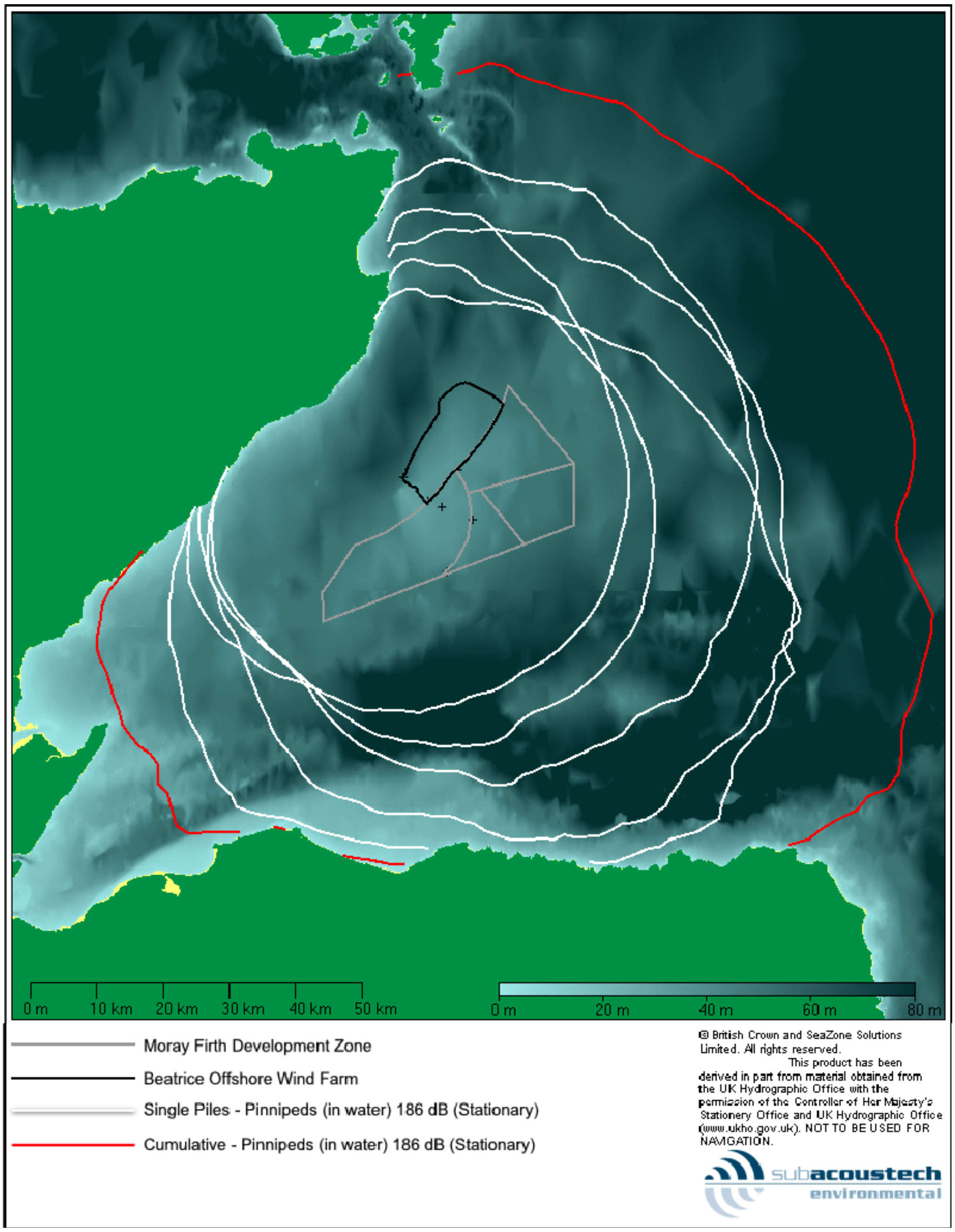
Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and B; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. –2300; 10 m dia. – 2700
Species	High-frequency fleeing cetacean

Figure 10.88a 198 dB(Mpw) contours for a stationary pinniped in water. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



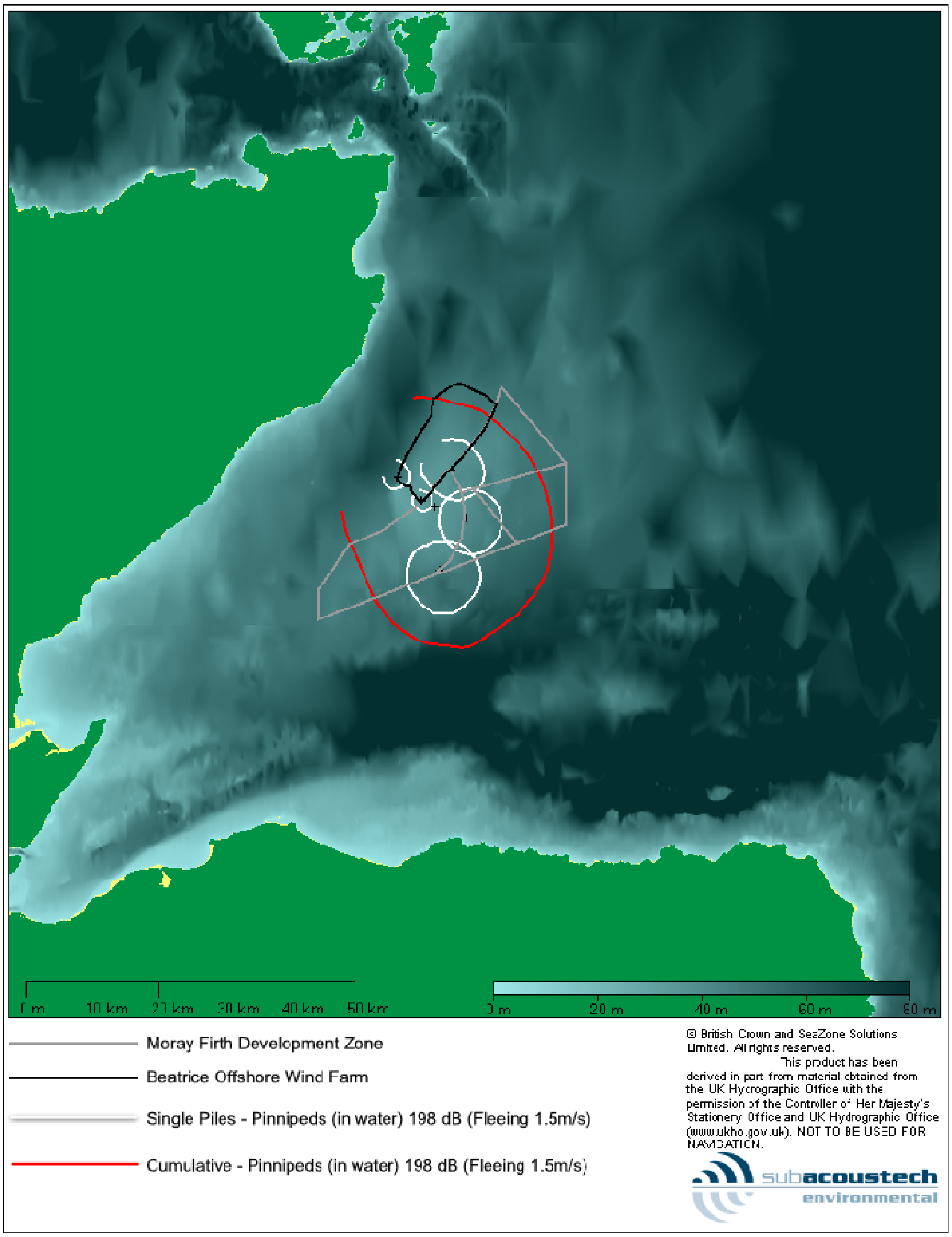
Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and B; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. – 2300; 10 m dia. – 2700
Species	Stationary pinniped in water

Figure 10.88b 186 dB(Mpw) contours for a stationary pinniped in water. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



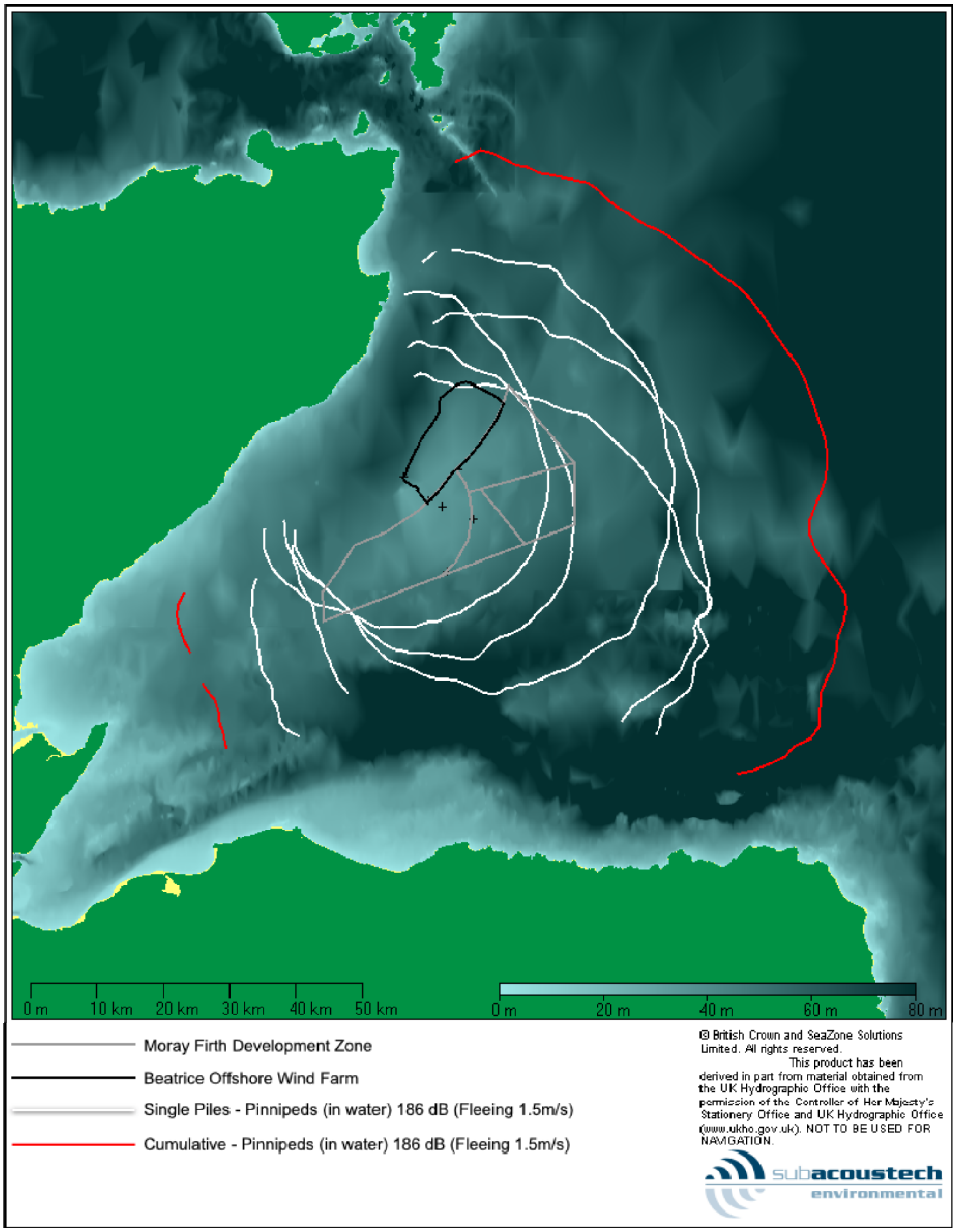
Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and B; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. –2300; 10 m dia. – 2700
Species	Stationary pinniped in water

Figure 10.89a Locus of starting distances from which a fleeing pinniped in water would just reach 198 dB(Mpw) at the cessation of the driving of the piles. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



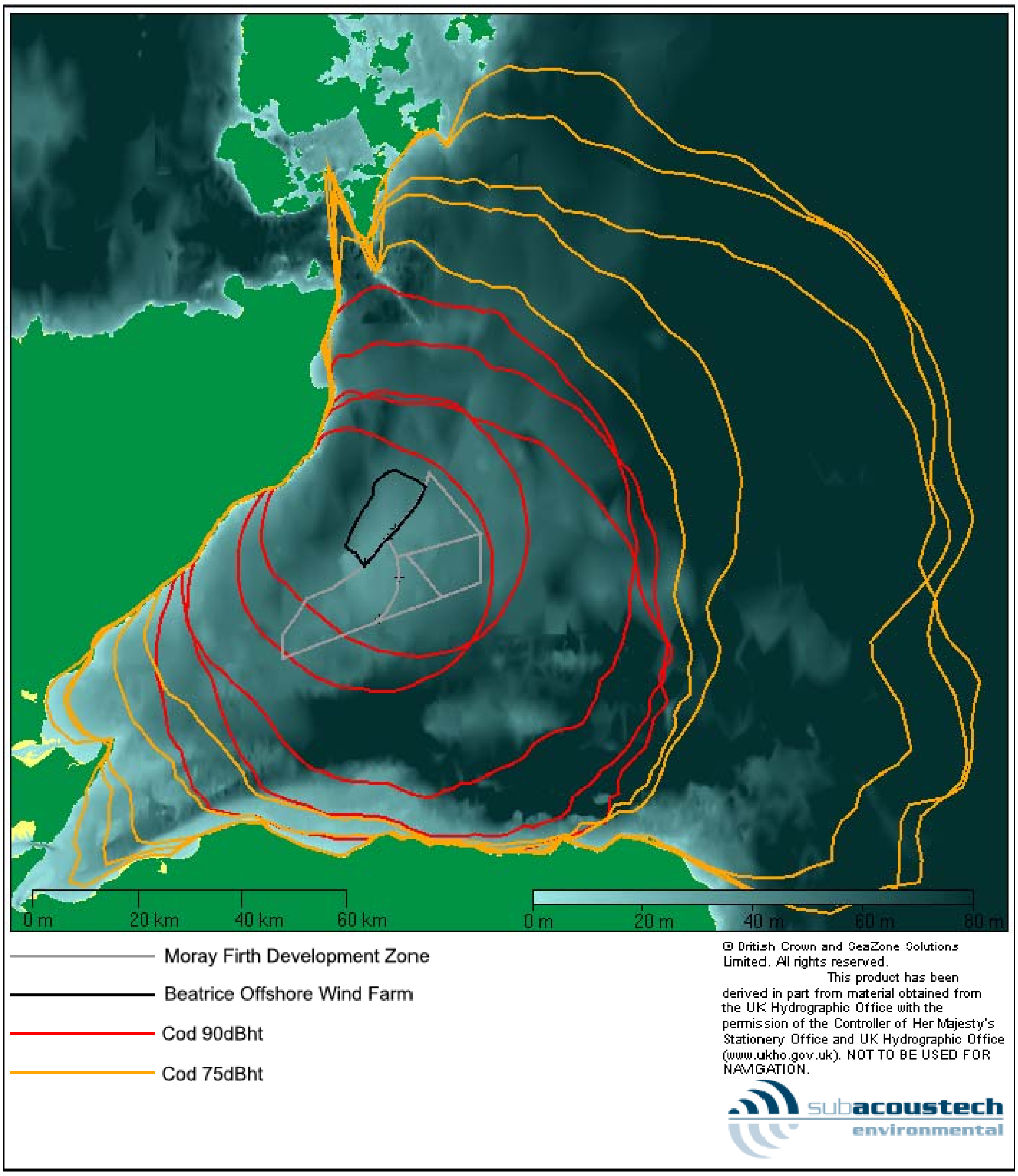
Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and B; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. – 2300; 10 m dia. – 2700
Species	Fleeing pinniped in water

Figure 10.89b Locus of starting distances from which a fleeing pinniped in water would just reach 186 dB(Mpw) at the cessation of the driving of the piles. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



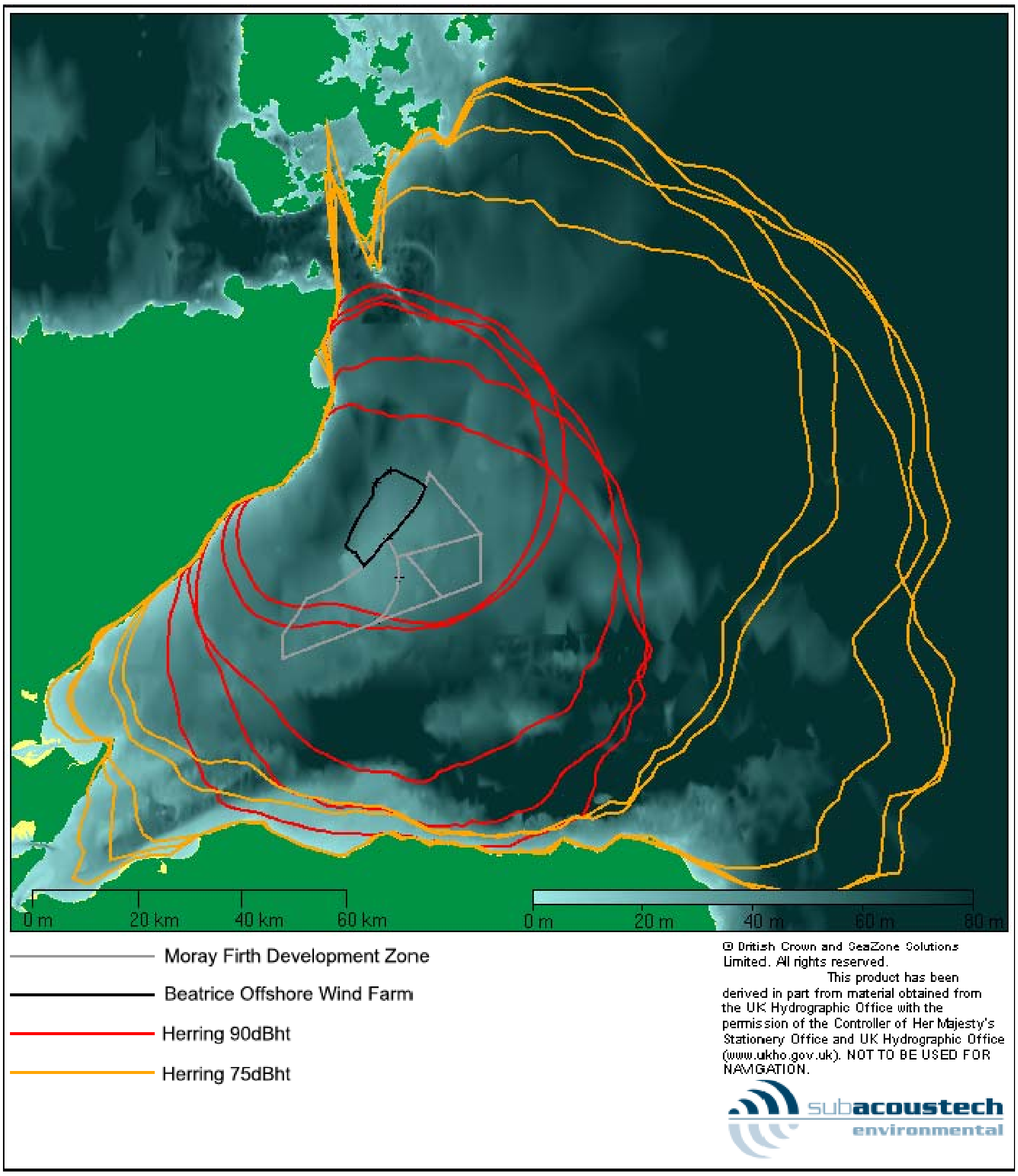
Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and B; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. –2300; 10 m dia. – 2700
Species	Fleeing pinniped in water

Figure 10.90 90 dBht and 75 dBht contours for the cod. Piles at locations A and E (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – A and E; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. –2300; 10 m dia. – 2700
Species	Cod

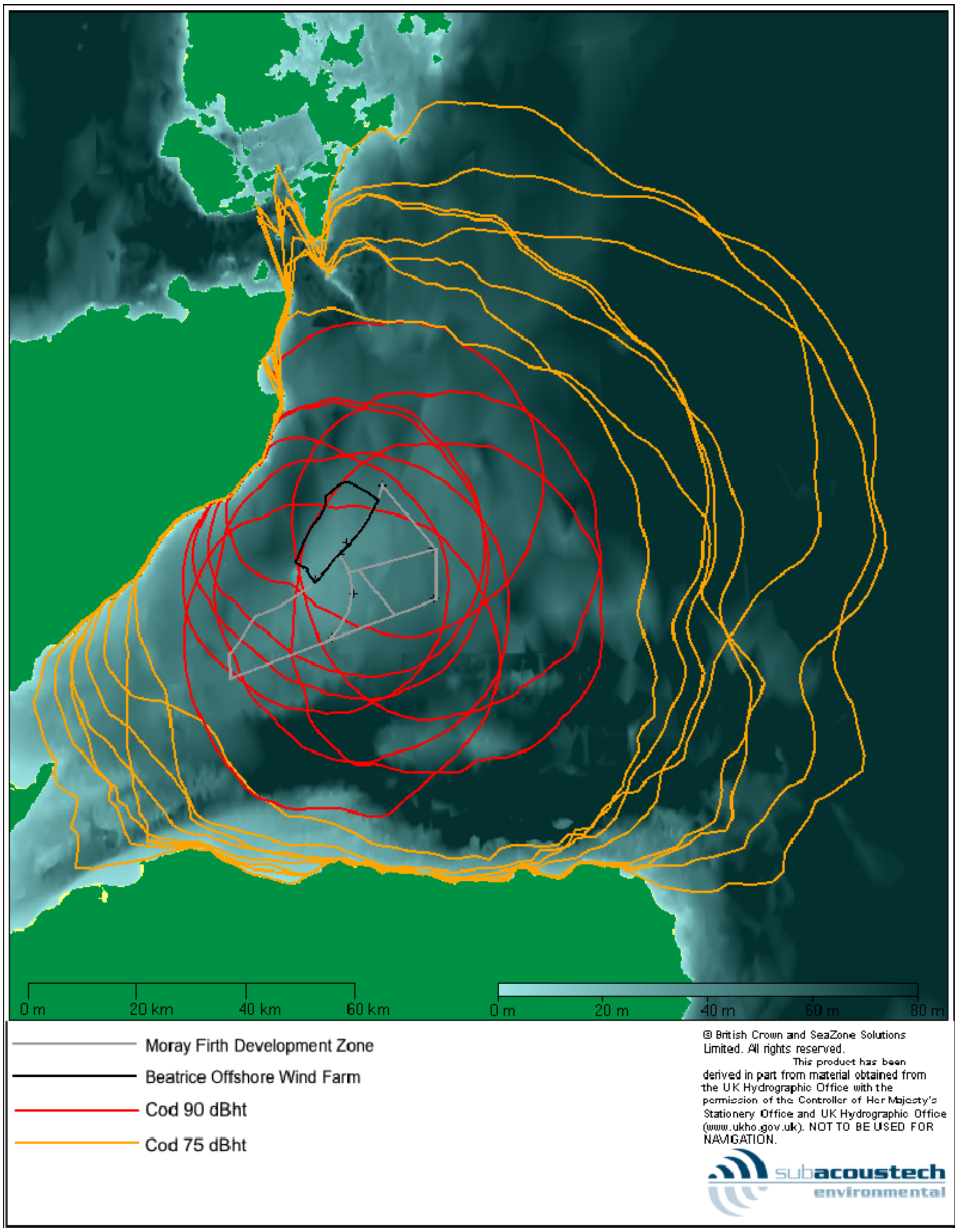
Figure 10.91 90 dBht and 75 dBht contours for the herring. Piles at locations C and D (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2 and M3 (10 m diameter, 2700 kJ driving energy)



Pile diameters (m)	2 X 2.4; 3 X 10
Pile locations (see map, Figure 10.13)	2.4 m dia. – C and D; 10 m dia. – M1, M2, M3
Pile driving energy (kJ)	2.4 m dia. –2300; 10 m dia. – 2700
Species	Herring

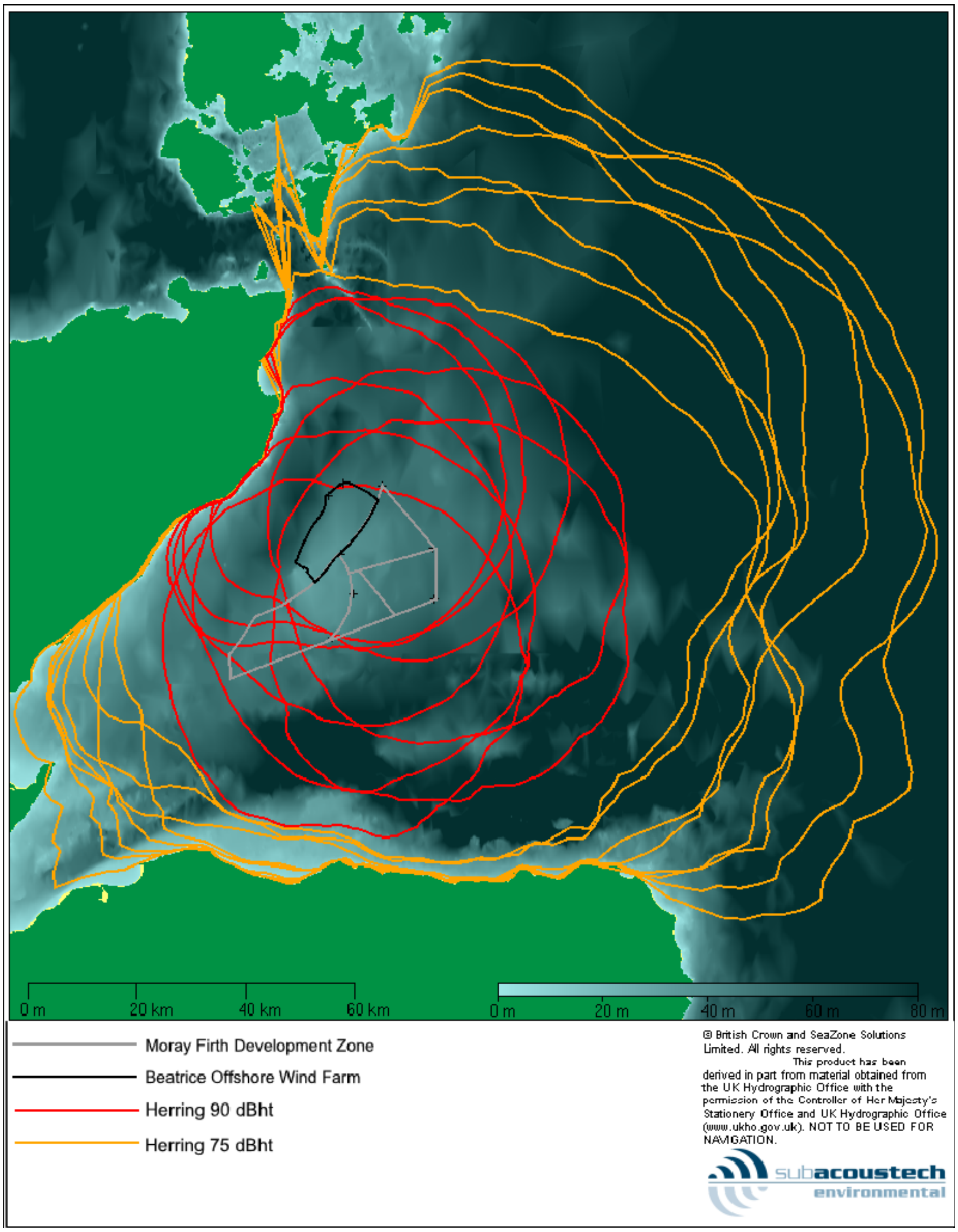
Results for three 10 m diameter piles being driven simultaneously

Figure 10.92 90 dBht and 75 dBht contours for the cod. Piles at locations A and E (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2, M3, M4, M5 and M6 (3 m diameter, 1800 kJ driving energy)



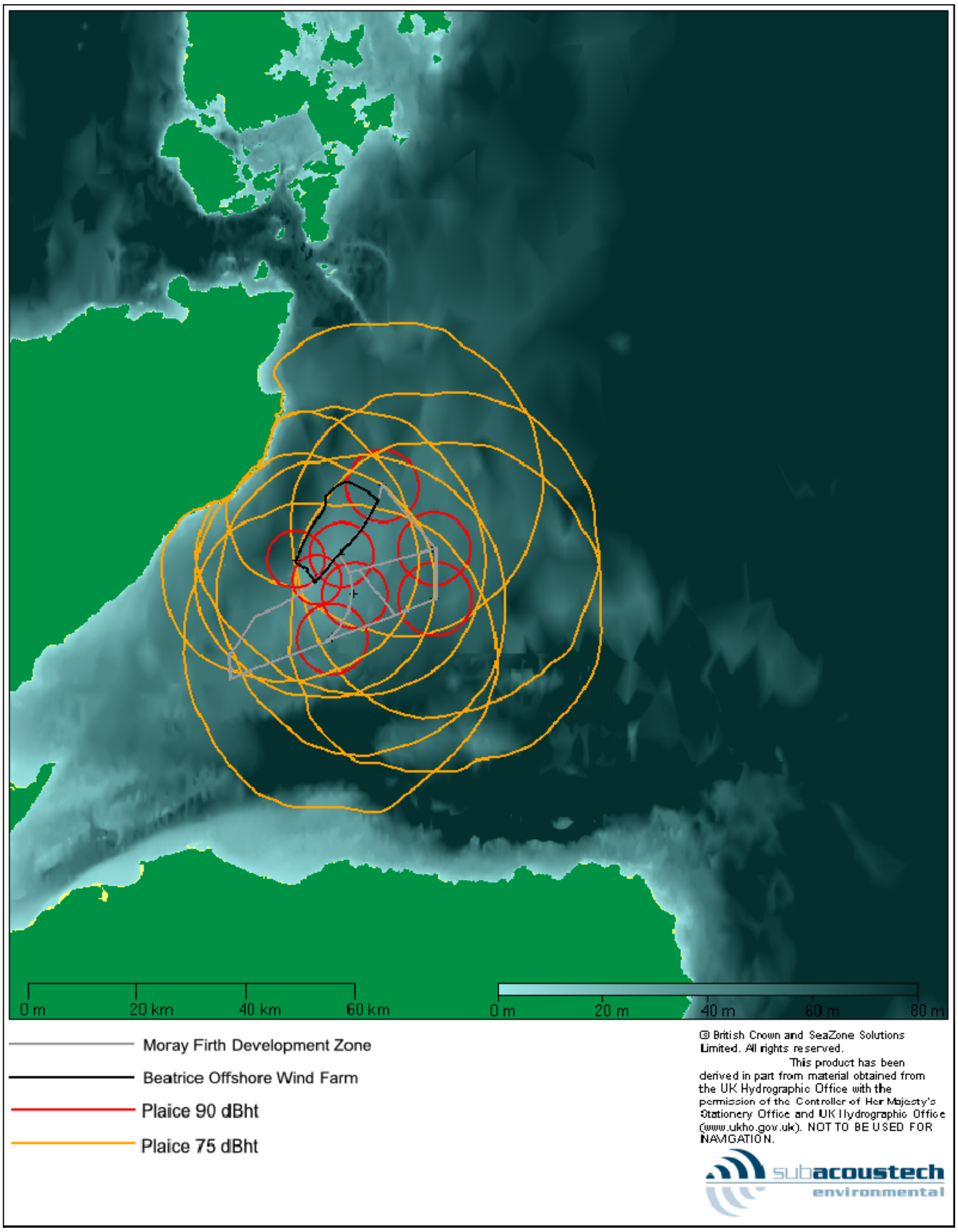
Pile diameter (m)	2 X 2.4; 6 X 3
Pile location (see map, Figure 10.13)	2.4 m dia. – A and E; 3 m dia. – M1, M2, M3, M4, M5, M6
Pile driving energy (kJ)	2.4 m dia. –2300; 3 m dia. – 1800
Species	Cod

Figure 10.93 90 dBht and 75 dBht contours for the herring. Piles at locations C and D (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2, M3, M4, M5 and M6 (3 m diameter, 1800 kJ driving energy)



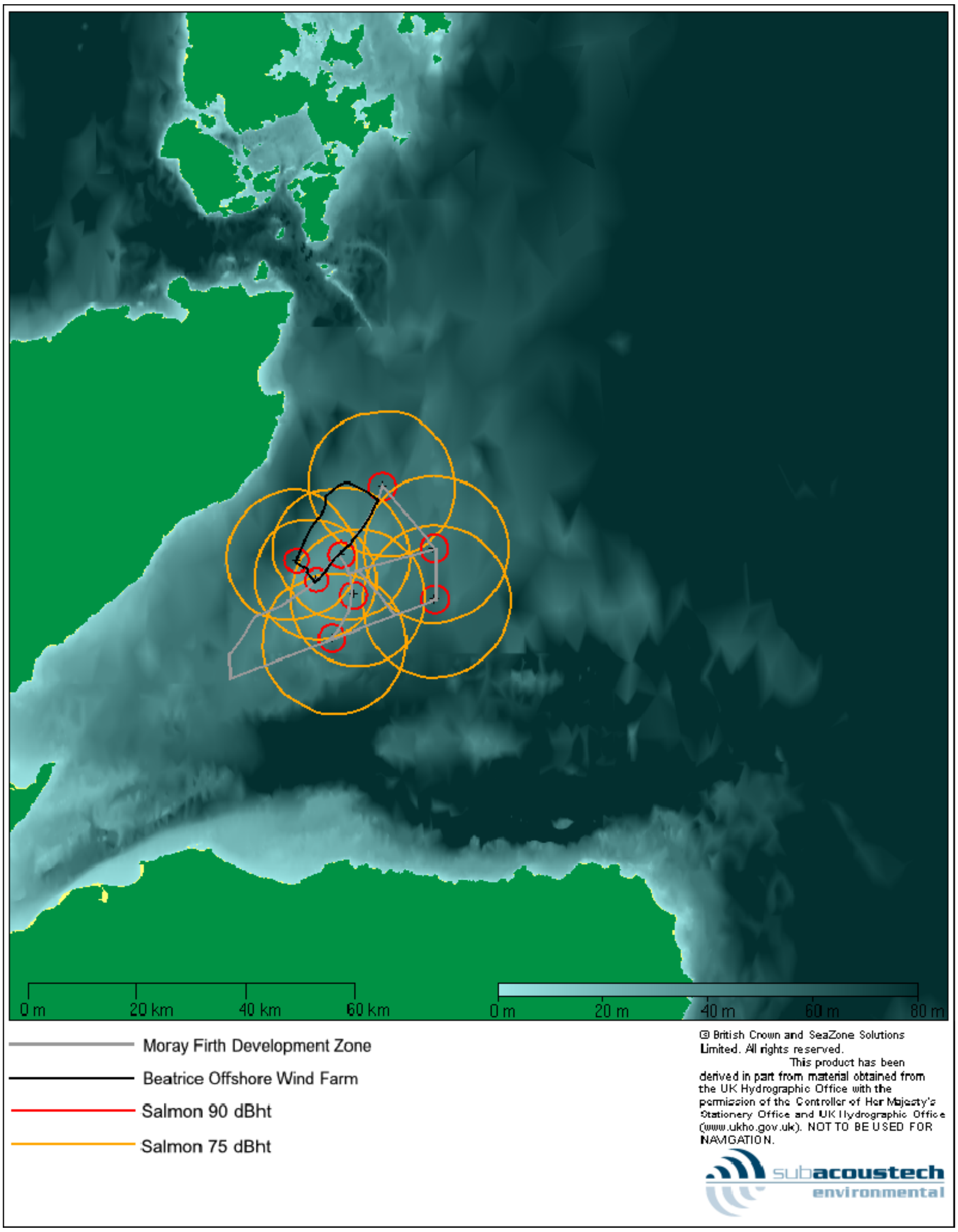
Pile diameter (m)	2 X 2.4; 6 X 3
Pile location (see map, Figure 10.13)	2.4 m dia. – C and D; 3 m dia. – M1, M2, M3, M4, M5, M6
Pile driving energy (kJ)	2.4 m dia. –2300; 3 m dia. – 1800
Species	Herring

Figure 10.94   90 dBht and 75 dBht contours for the plaice. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2, M3, M4, M5 and M6 (3 m diameter, 1800 kJ driving energy)



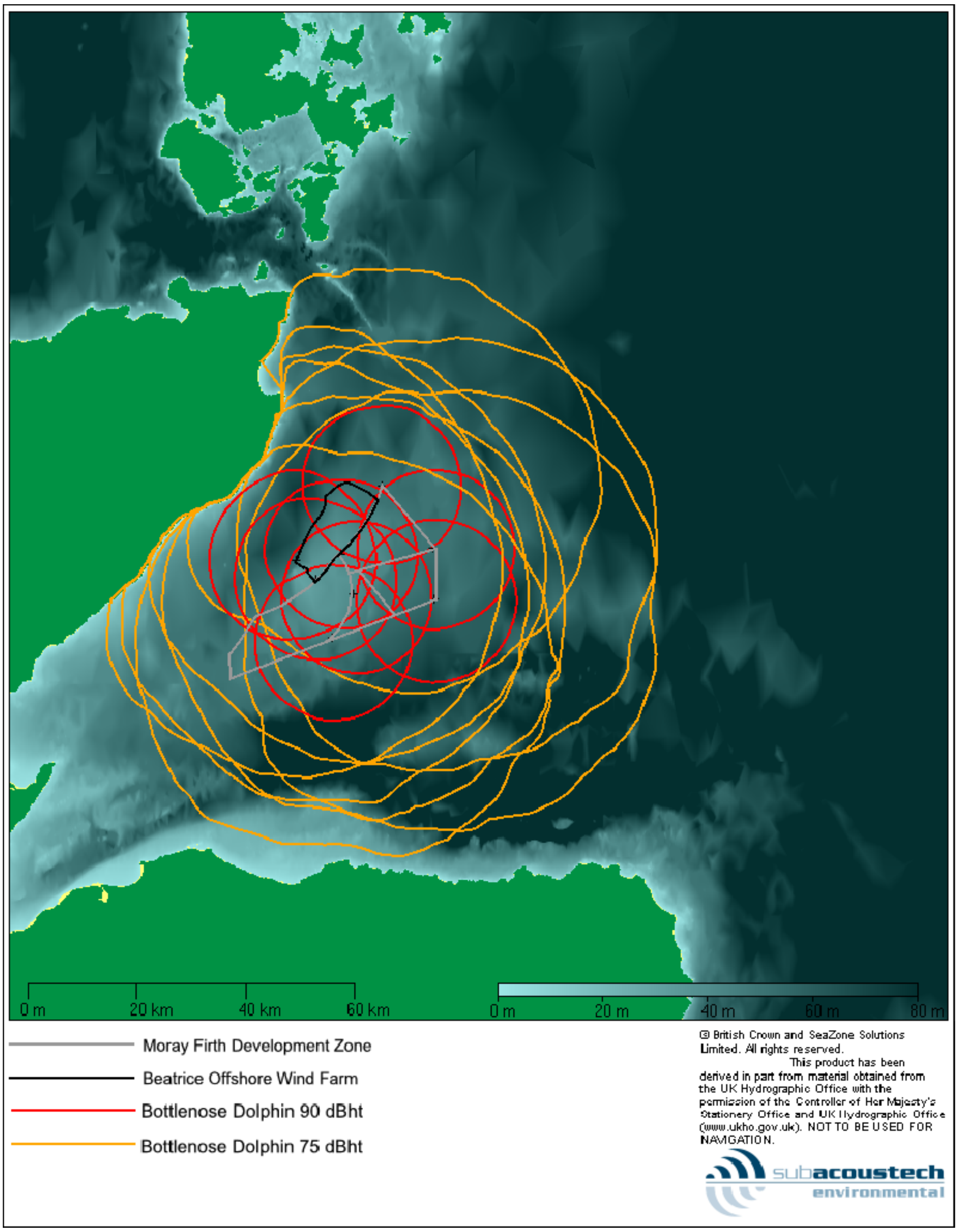
Pile diameter (m)	2 X 2.4; 6 X 3
Pile location (see map, Figure 10.13)	2.4 m dia. – A and B; 3 m dia. – M1, M2, M3, M4, M5, M6
Pile driving energy (kJ)	2.4 m dia. –2300; 3 m dia. – 1800
Species	Plaice

Figure 10.95 90 dBht and 75 dBht contours for the salmon. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2, M3, M4, M5 and M6 (3 m diameter, 1800 kJ driving energy)



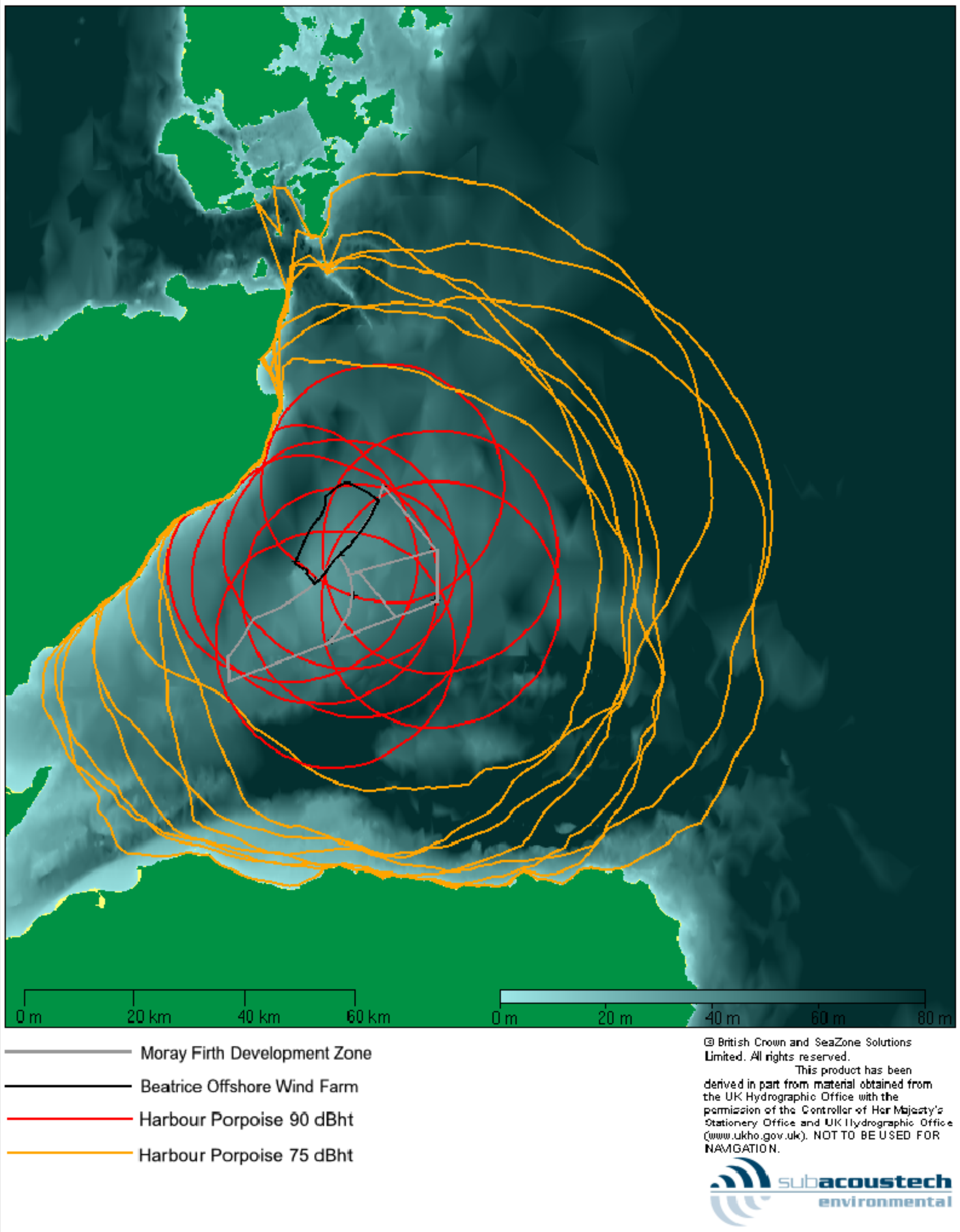
Pile diameter (m)	2 X 2.4; 6 X 3
Pile location (see map, Figure 10.13)	2.4 m dia. – A and B; 3 m dia. – M1, M2, M3, M4, M5, M6
Pile driving energy (kJ)	2.4 m dia. –2300; 3 m dia. – 1800
Species	Salmon

Figure 10.96 90 dBht and 75 dBht contours for the bottlenose dolphin. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2, M3, M4, M5 and M6 (3 m diameter, 1800 kJ driving energy)



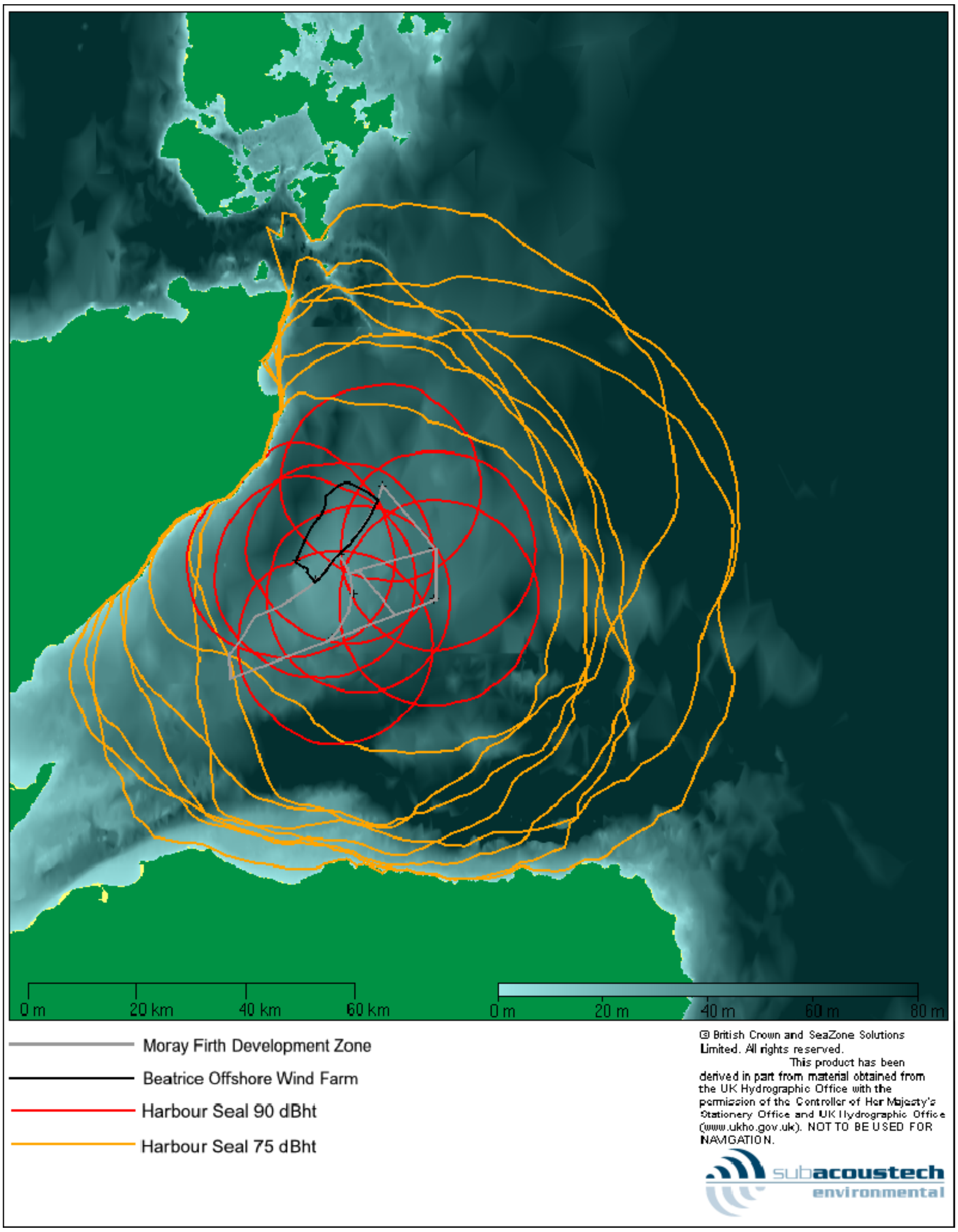
Pile diameter (m)	2 X 2.4; 6 X 3
Pile location (see map, Figure 10.13)	2.4 m dia. – A and B; 3 m dia. – M1, M2, M3, M4, M5, M6
Pile driving energy (kJ)	2.4 m dia. – 2300; 3 m dia. – 1800
Species	Bottlenose dolphin

Figure 10.97 90 dBht and 75 dBht contours for the harbour porpoise. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2, M3, M4, M5 and M6 (3 m diameter, 1800 kJ driving energy)



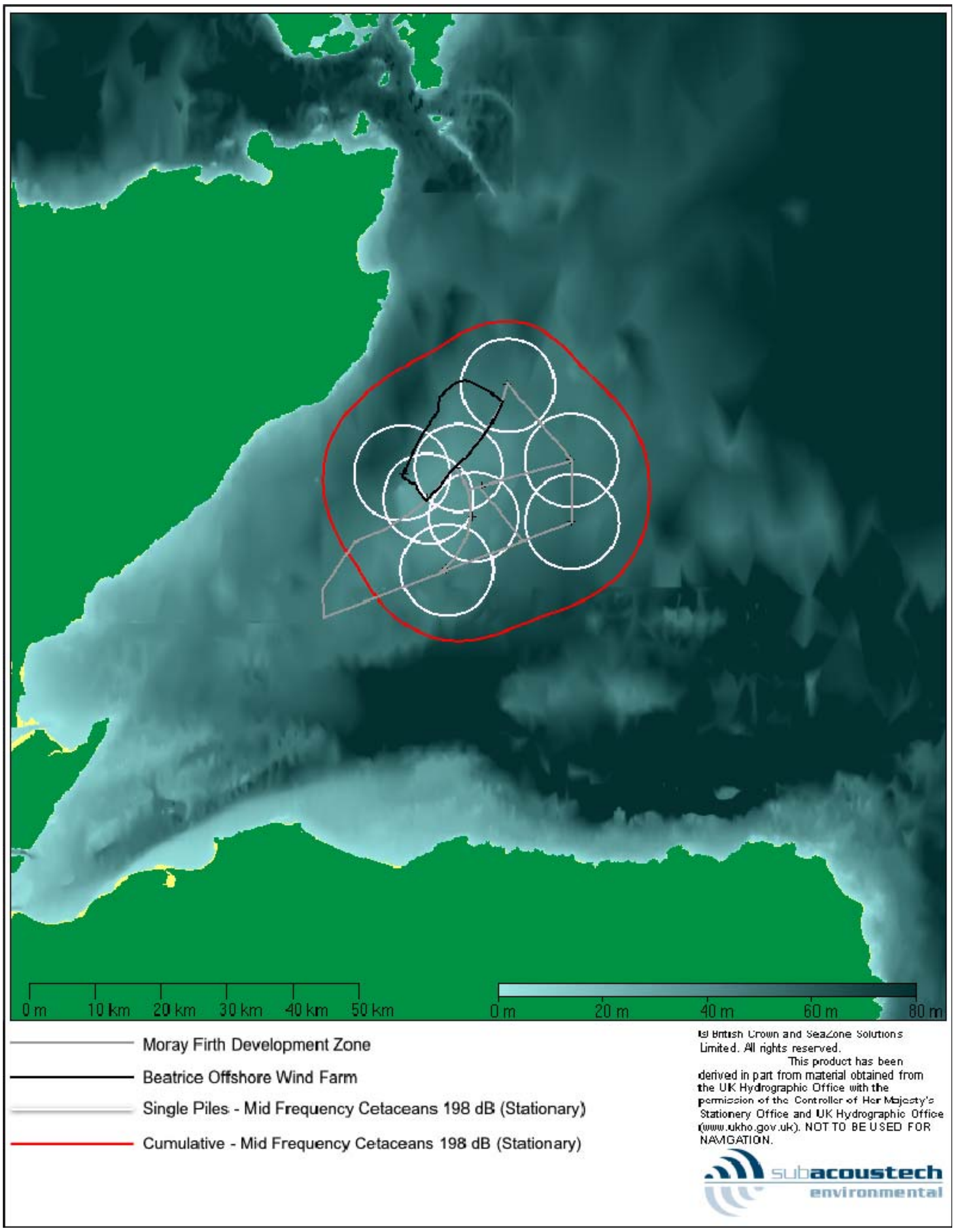
Pile diameter (m)	2 X 2.4; 6 X 3
Pile location (see map, Figure 10.13)	2.4 m dia. – A and B; 3 m dia. – M1, M2, M3, M4, M5, M6
Pile driving energy (kJ)	2.4 m dia. –2300; 3 m dia. – 1800
Species	Harbour porpoise

Figure 10.98 90 dBht and 75 dBht contours for the harbour seal. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2, M3, M4, M5 and M6 (3 m diameter, 1800 kJ driving energy)



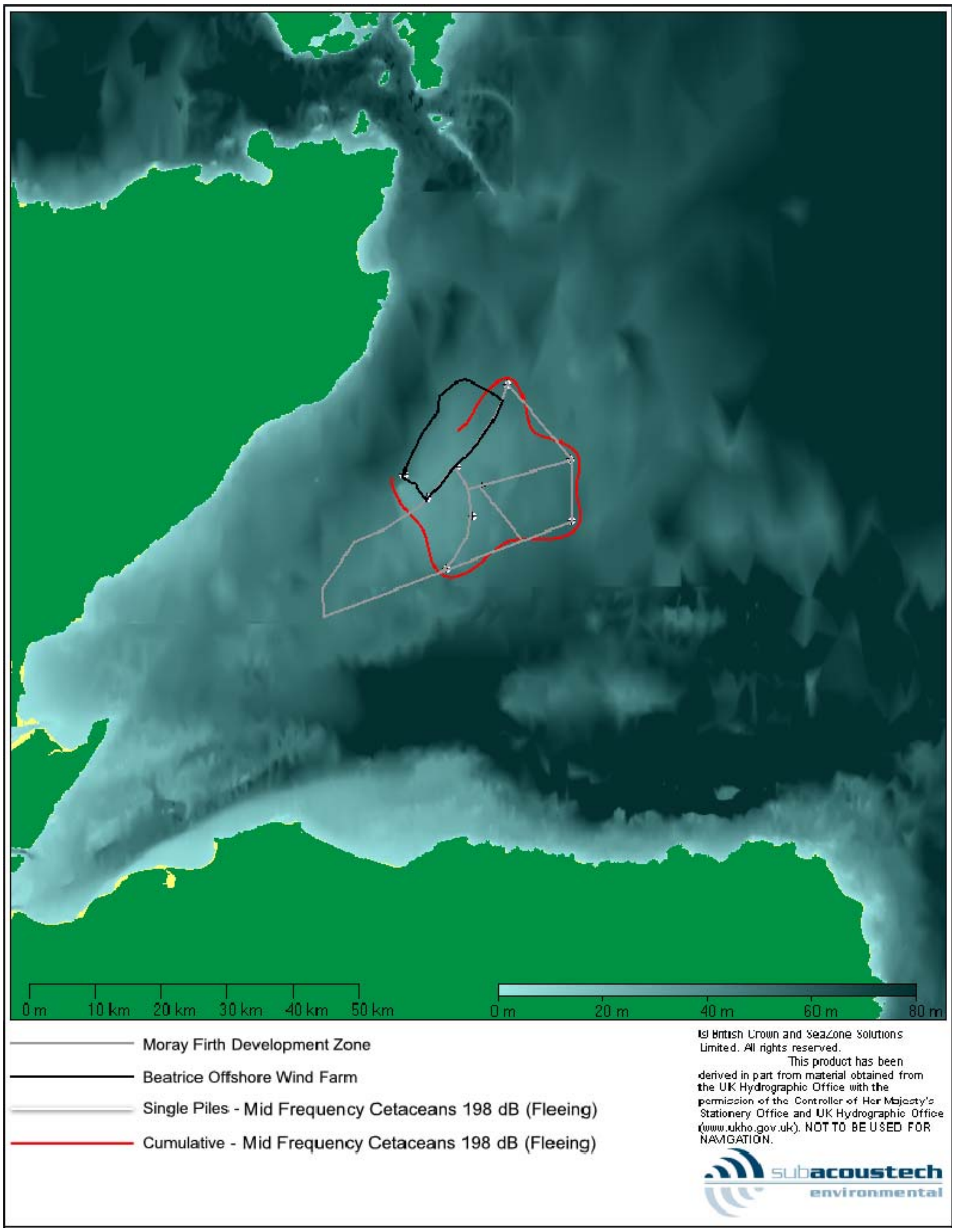
Pile diameter (m)	2 X 2.4; 6 X 3
Pile location (see map, Figure 10.13)	2.4 m dia. – A and B; 3 m dia. – M1, M2, M3, M4, M5, M6
Pile driving energy (kJ)	2.4 m dia. –2300; 3 m dia. – 1800
Species	Harbour seal

Figure 10.99 198 dB(Mmf) contours for a stationary mid-frequency cetacean. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2, M3, M4, M5 and M6 (3 m diameter, 1800 kJ driving energy)



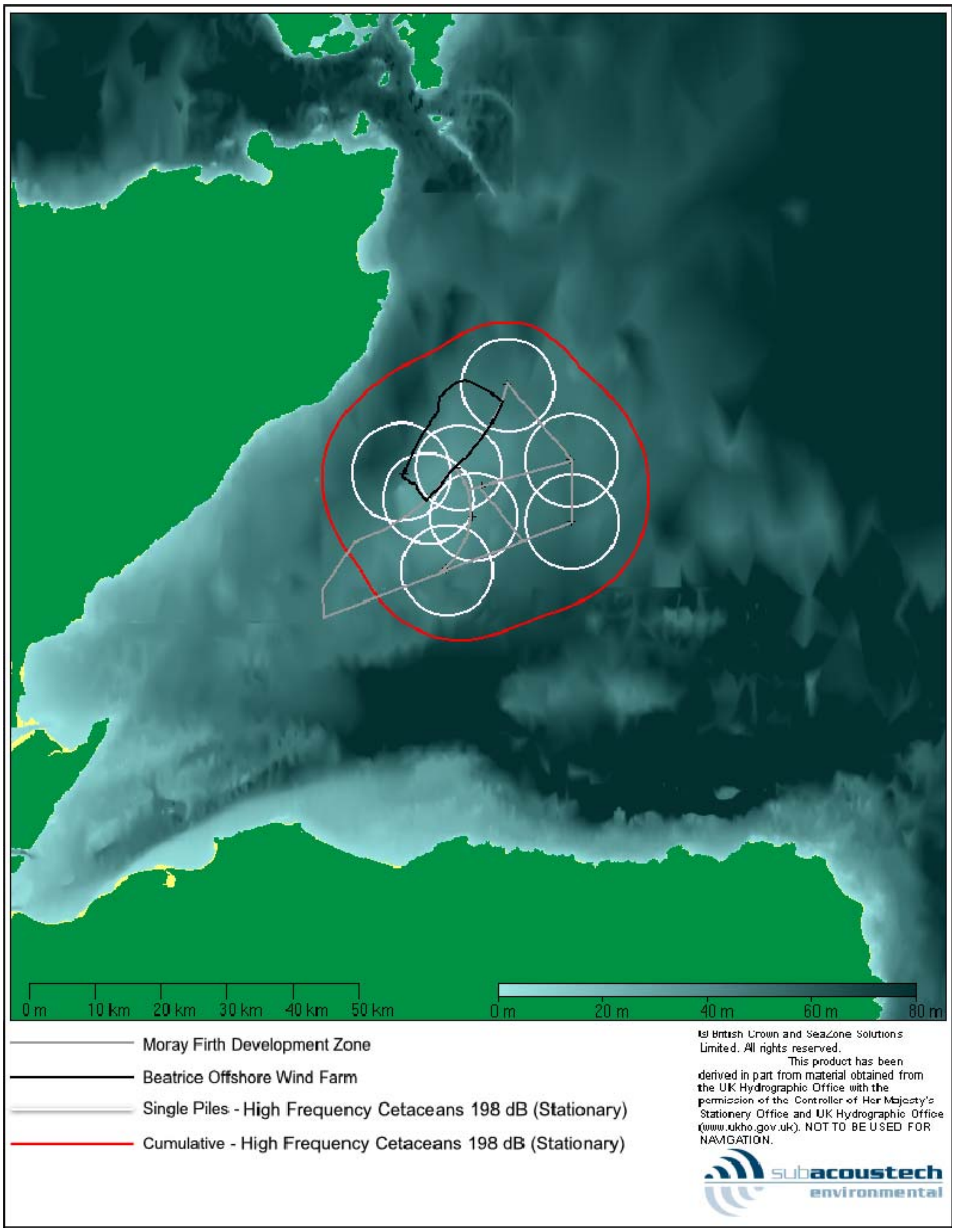
Pile diameter (m)	2 X 2.4; 6 X 3
Pile location (see map, Figure 10.13)	2.4 m dia. – A and B; 3 m dia. – M1, M2, M3, M4, M5, M6
Pile driving energy (kJ)	2.4 m dia. –2300; 3 m dia. – 1800
Species	Stationary mid-frequency cetacean

Figure 10.100 Locus of starting distances from which a fleeing mid-frequency cetacean would just reach 198 dB(Mmf) at the cessation of the driving of the piles. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2, M3, M4, M5 and M6 (3 m diameter, 1800 kJ driving energy)



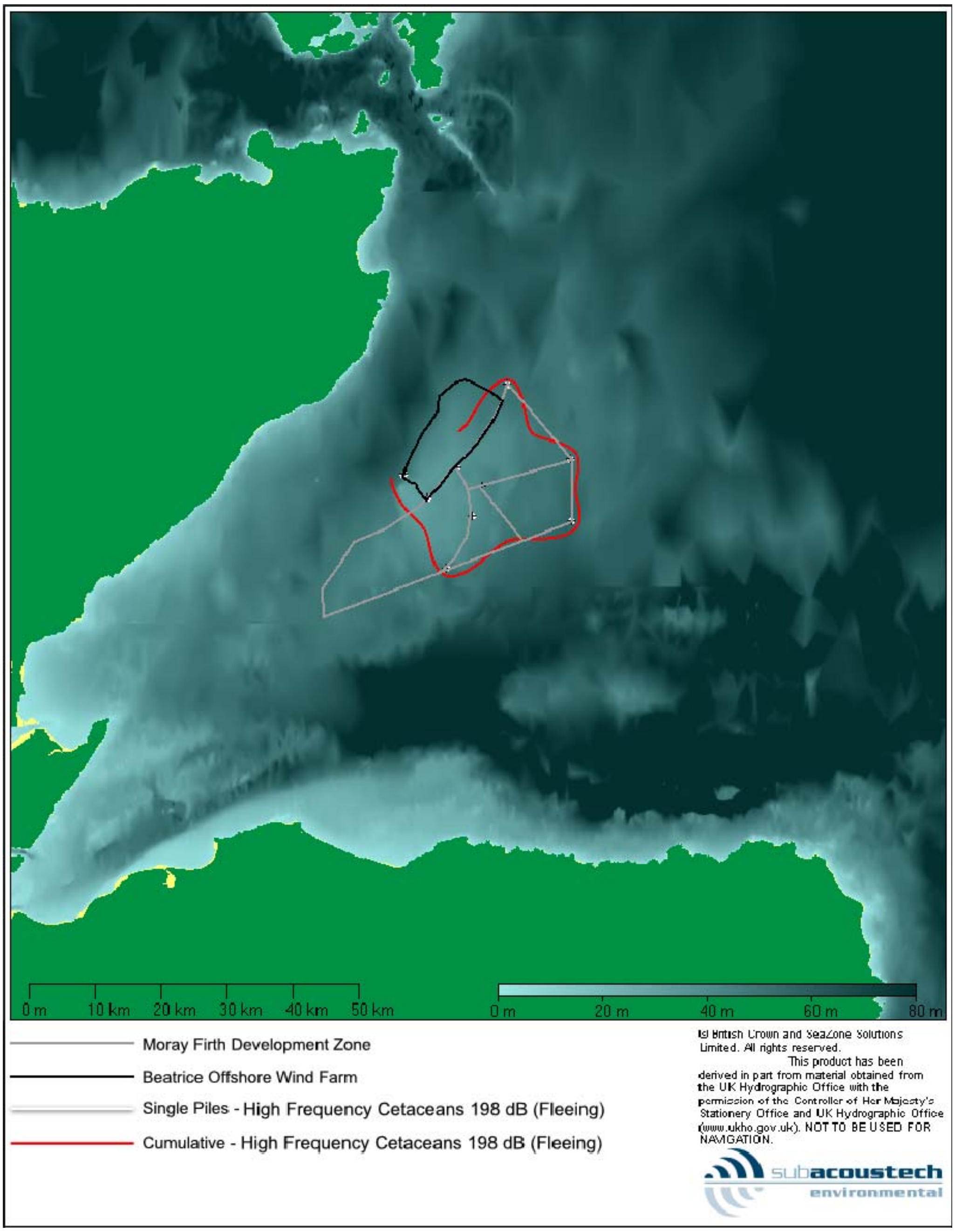
Pile diameter (m)	2 X 2.4; 6 X 3
Pile location (see map, Figure 10.13)	2.4 m dia. – A and B; 3 m dia. – M1, M2, M3, M4, M5, M6
Pile driving energy (kJ)	2.4 m dia. –2300; 3 m dia. – 1800
Species	Fleeing mid-frequency cetacean

Figure 10.101 198 dB(Mhf) contours for a stationary high-frequency cetacean. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2, M3, M4, M5 and M6 (3 m diameter, 1800 kJ driving energy)



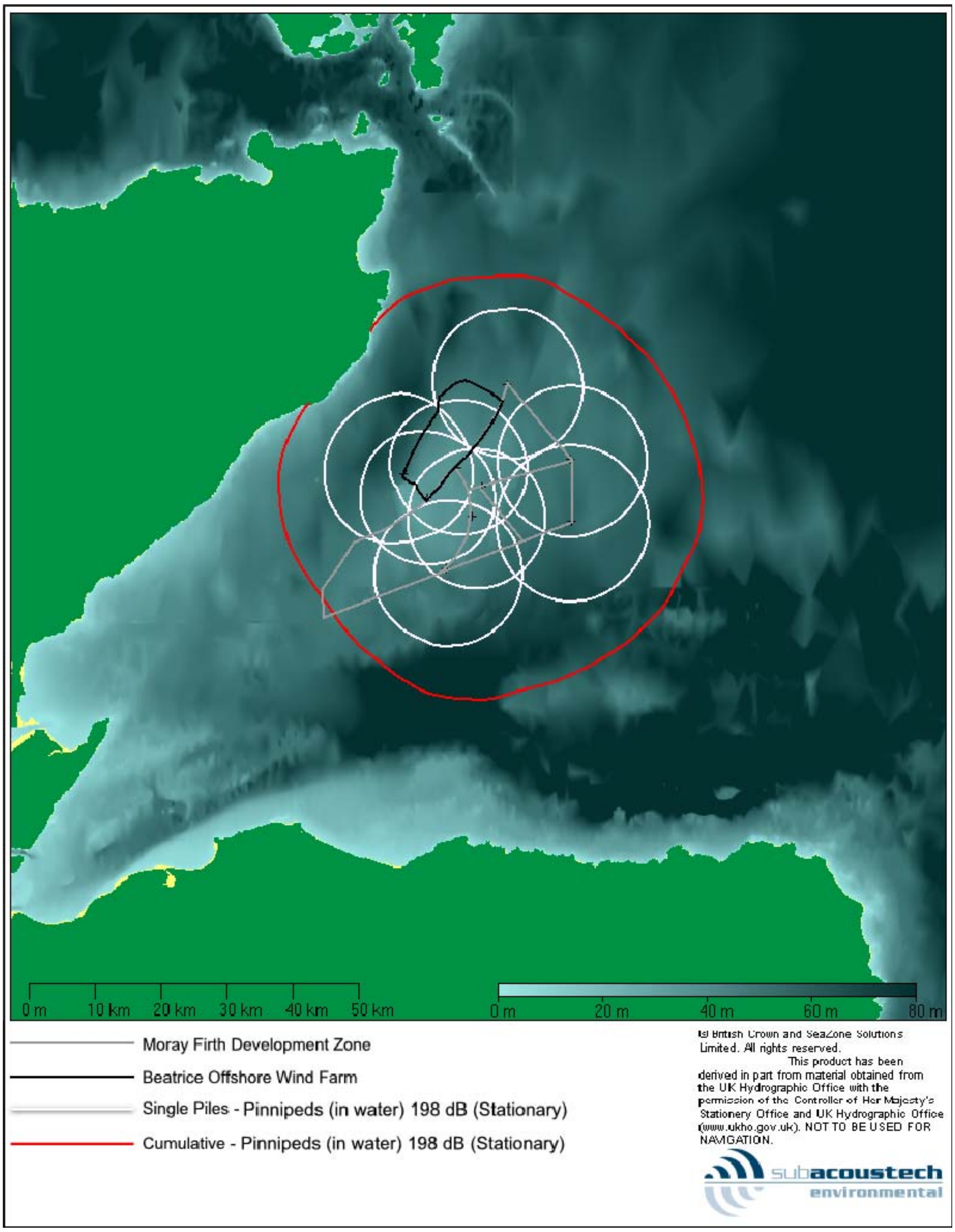
Pile diameter (m)	2 X 2.4; 6 X 3
Pile location (see map, Figure 10.13)	2.4 m dia. – A and B; 3 m dia. – M1, M2, M3, M4, M5, M6
Pile driving energy (kJ)	2.4 m dia. –2300; 3 m dia. – 1800
Species	Stationary high-frequency cetacean

Figure 10.102 Locus of starting distances from which a fleeing mid-frequency cetacean would just reach 198 dB(Mmf) at the cessation of the driving of the piles. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2, M3, M4, M5 and M6 (3 m diameter, 1800 kJ driving energy)



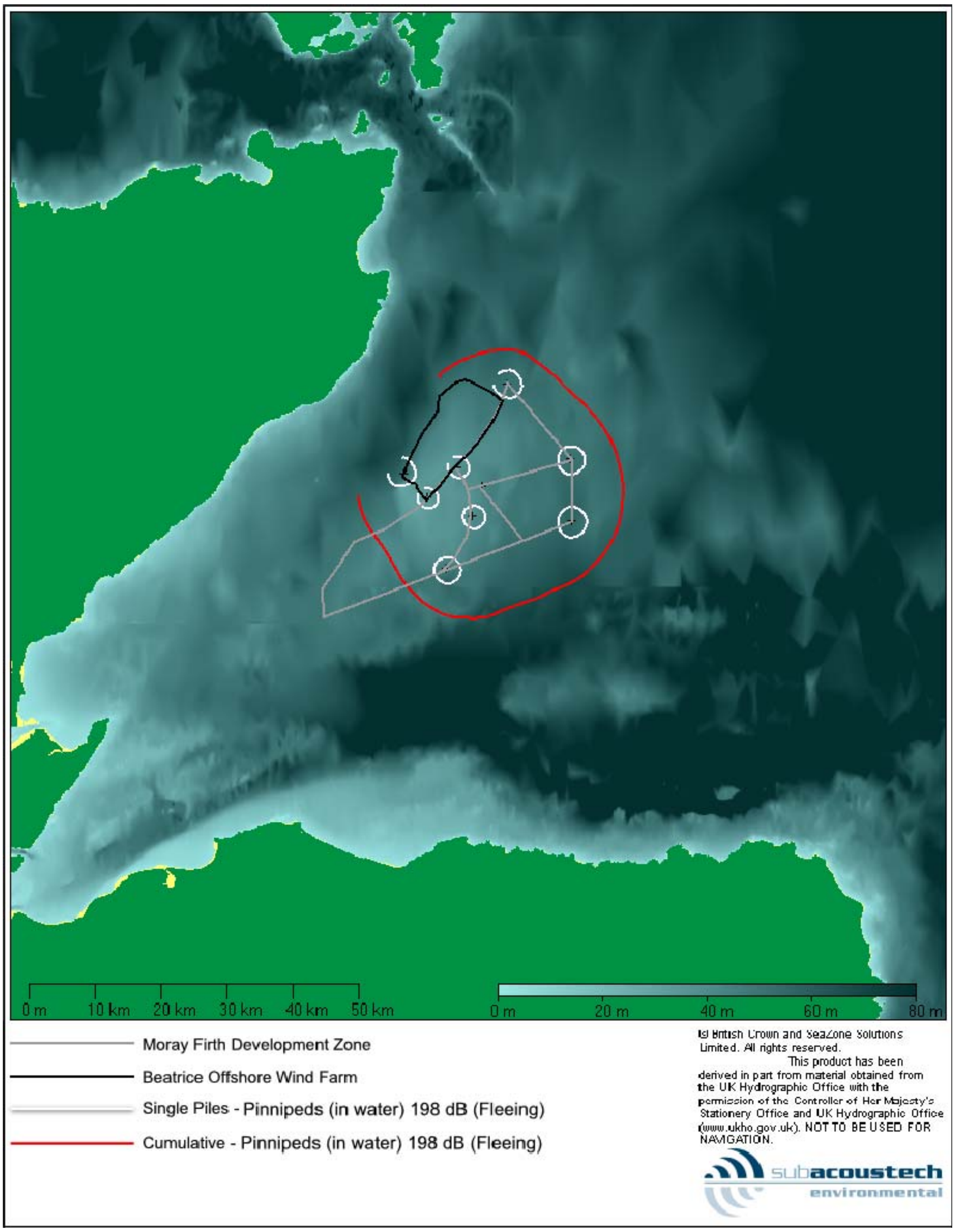
Pile diameter (m)	2 X 2.4; 6 X 3
Pile location (see map, Figure 10.13)	2.4 m dia. – A and B; 3 m dia. – M1, M2, M3, M4, M5, M6
Pile driving energy (kJ)	2.4 m dia. –2300; 3 m dia. – 1800
Species	Fleeing high-frequency cetacean

Figure 10.103 198 dB(Mpw) contours for a stationary pinniped in water. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2, M3, M4, M5 and M6 (3 m diameter, 1800 kJ driving energy)



Pile diameter (m)	2 X 2.4; 6 X 3
Pile location (see map, Figure 10.13)	2.4 m dia. – A and B; 3 m dia. – M1, M2, M3, M4, M5, M6
Pile driving energy (kJ)	2.4 m dia. –2300; 3 m dia. – 1800
Species	Stationary pinniped in water

Figure 10.104 Locus of starting distances from which a fleeing pinniped in water would just reach 198 dB(Mpw) at the cessation of the driving of the piles. Piles at locations A and B (2.4 m diameter, 2300 kJ driving energy) being driven simultaneously with piles at locations M1, M2, M3, M4, M5 and M6 (3 m diameter, 1800 kJ driving energy)



Pile diameter (m)	2 X 2.4; 6 X 3
Pile location (see map, Figure 10.13)	2.4 m dia. – A and B; 3 m dia. – M1, M2, M3, M4, M5, M6
Pile driving energy (kJ)	2.4 m dia. – 2300; 3 m dia. – 1800
Species	Fleeing pinniped in water

10.12 SUMMARY

10.12.1 The impact of introduced noise as a result of impact piling in multiple locations during construction of the Beatrice Offshore Wind Farm has been calculated using the proprietary INSPIRE noise modelling software.

10.12.2 The range of noise emissions with reference to the different species has been calculated in respect of dB_{ht}(*Species*) and M-weighted dB SEL to assess the potential impact of the piling on marine species. This is both in terms of injury and behavioural response. These calculated levels have been used to inform the fish and marine mammal assessment, and detailed biological interpretation of the data can be found in the Wind Farm Fish and Shellfish Ecology section and the Wind Farm Marine Mammals section of the Offshore Environmental Statment for the Beatrice Offshore Windfarm Project.

10.12.3 General comments with respect to cumulative noise exposure can be made. The area of sea affected by noise from simultaneous piling generally is not much greater than if the piling was undertaken at separate times. Indeed, the total area is often less due to the overlap of the insonified areas. In this respect, the overall sound exposure during piling simultaneously at multiple locations is sometimes lower than if the piling was undertaken at separate times.