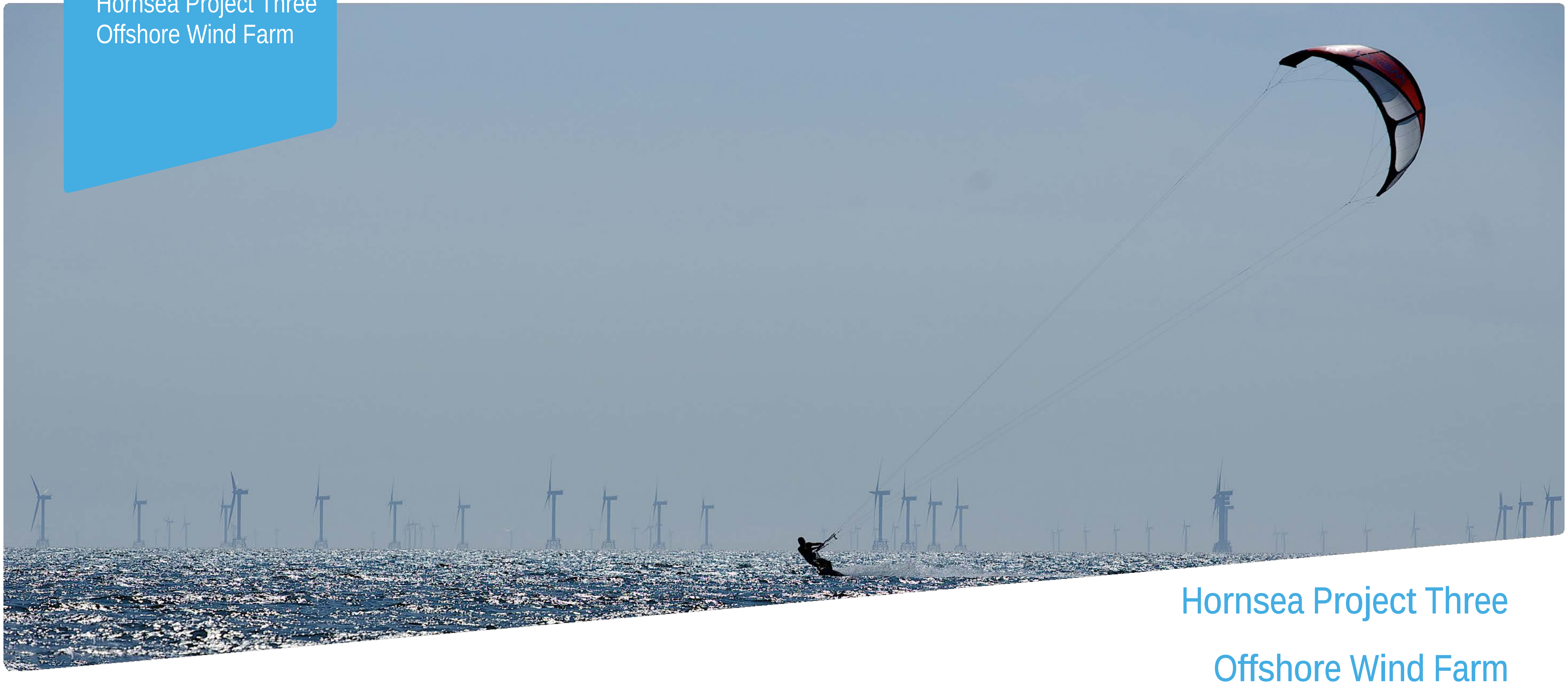
Hornsea Project Three
Offshore Wind Farm



Hornsea Project Three

Offshore Wind Farm

Preliminary Environmental Information Report:
Annex 3.1 – Subsea Noise Technical Report

Date: July 2017

Hornsea 3
Offshore Wind Farm

DONG energy

Environmental Impact Assessment

Preliminary Environmental Information Report

Volume 4

Annex 3.1 – Subsea Noise Technical Report

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Front cover picture: Kite surfer near one of DONG Energy's UK offshore wind farms © DONG Energy Hornsea Project Three (UK) Ltd., 2016.

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Glossary

Term	Definition
Ambient noise	Normal background noise in the environment, which has no distinguishable sources.
Decibel (dB)	A customary scale most commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be 10 $\log_{10}$(actual/reference), where (actual/reference) is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is 20$\log_{10}$ (actual pressure/reference pressure). As noted above, the standard reference for underwater sound pressure is 1 micro-Pascal (μPa). The dB symbol is followed by a second symbol identifying the specific reference value (i.e., re 1 μPa).
Peak pressure	The highest pressure that is associated with a sound wave.
Permanent Threshold Shift (PTS)	A total or partial permanent loss of hearing caused by acoustic or drug trauma. PTS results in irreversible damage to the sensory hair cells of the ear, and thus a permanent reduction of hearing acuity.
Sound Exposure Level (SEL)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics. SEL is sometimes appended with a subscript 'cum' to signify cumulative SELs.
Sound Pressure Level (SPL)	The sound pressure level or SPL is an expression of the sound pressure using the decibel (dB) scale and the standard reference pressures of 1 μPa for water and biological tissues, and 20 μPa for air and other gases.
Temporary Threshold Shift (TTS)	Temporary loss of hearing as a result of exposure to sound over time. Exposure to high levels of sound over relatively short time periods will cause the same amount of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus, but there is generally recovery of full hearing over time.
Unweighted sound level	Sound levels which are 'raw' or have not been adjusted in any way, for example to account for the hearing ability of a species.
Weighted sound level	A sound level which has been adjusted with respect to a 'weighting envelope' in the frequency domain, typically to make an unweighted level relevant to a particular species. Examples of this are the dB(A), where the overall sound level has been adjusted to account for the hearing ability of humans, M-Weightings for marine mammals.

Acronyms

Acronym	Description
BGS	British Geological Survey
HF	High Frequency
HVAC	High Voltage Alternating Current
INSPIRE	Impulse Noise Sound Propagation and Impact Range Estimator
LAT	Lowest Astronomical Tide
LF	Low Frequency
MAREMAP	Marine Environment Mapping Programme
MF	Mid Frequency
NMFS	National Marine Fisheries Service
NPL	National Physical Laboratory
OWF	Offshore Wind Farm
PE	Parabolic Equation
PEIR	Preliminary Environmental Information Report
PTS	Permanent Threshold Shift
PW	Pinnipeds (in water)
RMS	Root Mean Square
SE	Sound Exposure
SEL	Sound Exposure Level
SPL	Sound Pressure Level
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance

Units

Unit	Description
dB	Decibel (sound)
Hz	Hertz (frequency)
kJ	Kilojoule (energy)
km	Kilometre (distance)
MW	Megawatt (power)
m	Metre (distance)
ms^{-1}	Metres per Second (speed)
µPa	Micro Pascal (pressure)
Pa	Pascal (pressure)

1. Introduction

1.1 Overview

1.1.1.1 DONG Energy Power (UK) Ltd. (hereafter referred to as DONG Energy), on behalf of DONG Energy Hornsea Project Three (UK) Ltd., is promoting the development of the Hornsea Project Three Offshore Wind Farm (hereafter referred to as Hornsea Three). The Hornsea Three array area is 696 km^2, at a distance of 121 km from the UK coastline (at Trimingham, Norfolk) and 10.1 km from the median line between UK and Dutch territorial waters, at its closest point (Figure 1.1).

1.1.1.2 This report has been prepared by Subacoustech Environmental Ltd and presents the noise modelling methodology and results at the proposed Hornsea Three during construction, operation and decommissioning of the project.

1.2 Hornsea Three

1.2.1.1 Hornsea Three will contain up to 342 wind turbine generators creating a total combined generating capacity of up 2,400 MW. Turbines ranging from 7 MW (resulting in up to 342 turbines), up to 15 MW (resulting in up to 160 turbines), are being considered, with a maximum monopile foundation diameter of up to 15 m and pin pile diameter of up to 4 m. The parameters included represent the maximum design Scenario and encompass the specifications for substations and platforms.

1.2.1.2 Hornsea Three lies to the east of Hornsea Project One and Hornsea Project Two offshore wind farms. Figure 1.1 below shows the location of the proposed wind farm in relation to nearby offshore wind farm developments and nature conservation designations.

1.3 Subsea noise assessment

1.3.1.1 This report covers underwater noise impacts related to the construction, operation and maintenance, and eventual decommissioning of Hornsea Three. The production of underwater noise during the construction phase has the largest potential impact on marine receptors. The noise from these activities has been considered in terms of subsea noise and seabed vibration.

1.3.1.2 The main modelling has been carried out using a combined parabolic equation (PE) and ray tracing method considering bathymetry, seabed type and frequency content at all depths in the water column, using dBSea subsea supplemented by Subacoustech's INSPIRE noise model.

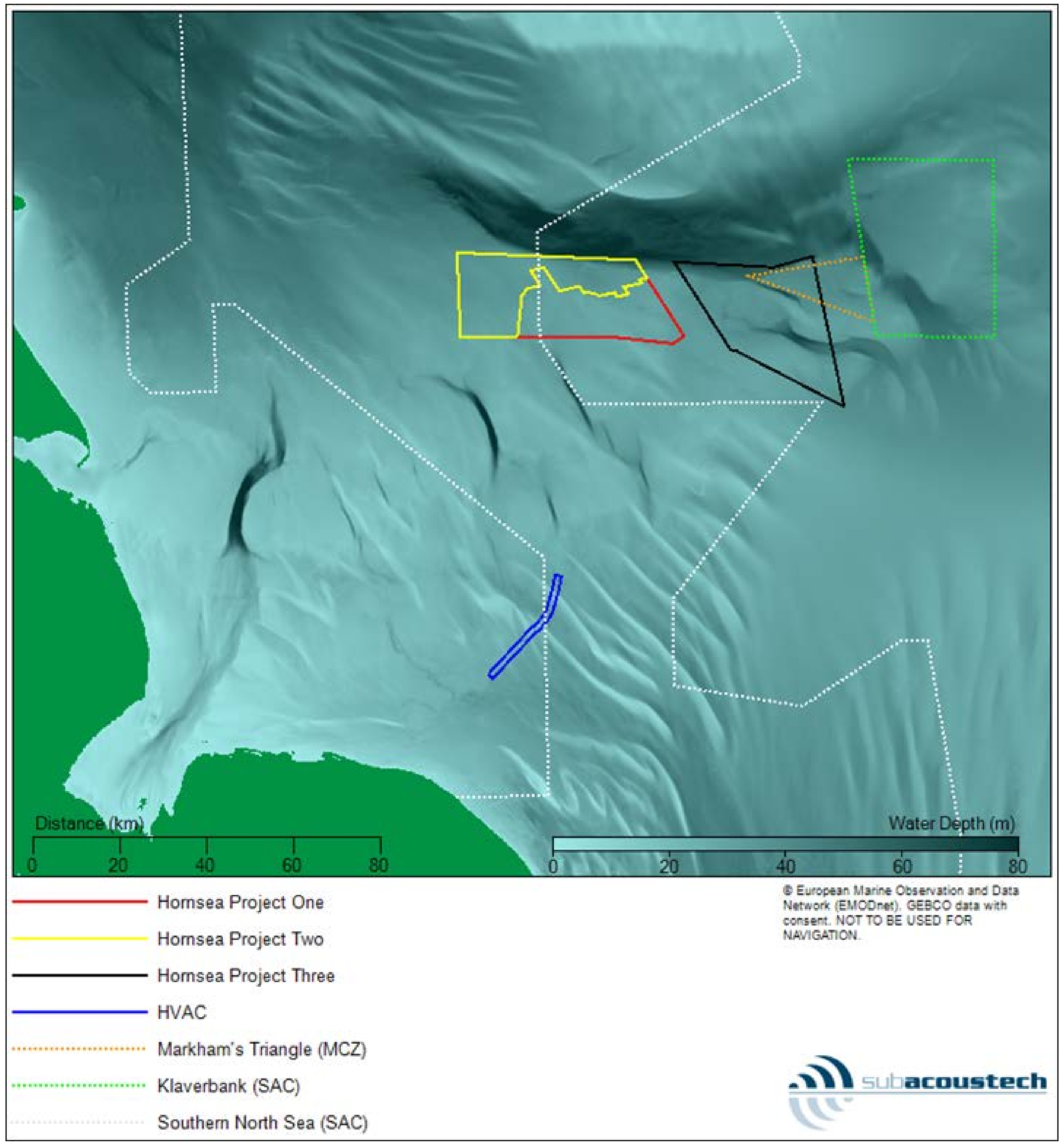

Figure 1.1: Map showing the Hornsea Three boundary along with the offshore HVAC booster station search area, Hornsea Project One, and Hornsea Project Two and designated sites for receptors.

1.4 Assessment Overview

1.4.1.1 This report presents a detailed assessment of the potential underwater noise at Hornsea Three and covers the following:

- Summary of the various activities expected to take place during construction, operation and maintenance, and decommissioning of Hornsea Three (section 2);
- A review of background information on the units for measuring and assessing underwater noise and a review of the underwater noise metrics and criteria used to assess possible environmental effects in marine receptors (section 3);
- A review of available data for baseline underwater noise levels (section 4);
- Discussion of the approach, input parameters and assumptions for the noise modelling undertaken (section 5.1);
- Presentation of detailed subsea noise modelling using unweighted metrics (section 5.2) and interpretation of the subsea noise modelling results with regards to injury and behavioural effects in marine mammals and fish using various noise metrics and criteria (section 5.3);
- A qualitative discussion of seabed vibration (section 5.5);
- Summary of the predicted impacts from operational turbines (section 6) and decommissioning activities (section 7) with regards to noise; and
- Summary and conclusions (section 8).

1.4.1.2 The full noise modelling results are given as part of Appendix A.

2. Potential Sources of Noise

2.1.1.1 Although impact piling is expected to be the primary potential noise source during the life time of Hornsea Three, several other noise sources will also be present; each of these has been considered and its impact assessed in this section.

2.1.1.2 Table 2.1 provides a summary of the various noise producing sources that could be present during construction of Hornsea Three. Where detailed information relating to these activities is not available at this stage, assumptions for parameters have been made based on the Maximum Design Scenario.

Table 2.1: Summary of the possible construction activities at Hornsea Three.

Activity	Description
Dredging	Trailer suction hopper dredger may be required on site for cable installation
Drilling	Necessary in case impact piling refuses
Impact piling	Monopiles installed with a maximum blow energy of up to 5000 kJ over 4 hours[1]
Cable laying	Required during cable installation
Rock placement	Potentially required on site for installation of cable and scour protection
Trenching	Plough trenching may be required during cable installation
Vessel noise	Jack-up barges for piling, substructure and turbine installation

2.1.1.3 The National Physical Laboratory (NPL) Good Practice Guide 133 for underwater noise (Robinson *et al.*, 2014) indicates that under certain circumstances, a simple modelling approach may be considered acceptable. The high level overview of modelling that has been presented is considered sufficient and there would be little benefit in using a more detailed model at this stage. The limitations of this approach include the lack of frequency or bathymetry dependence, therefore these levels are not presented for detailed assessment purposes.

[1] Although the entire pile installation process could last for eight hours, actual hammering will not last for more than four hours.

2.1.1.4 For the purpose of identifying the greatest noise impacts during the construction phase, approximate subsea noise levels have been predicted using a simple modelling approach based on measured data scaled to appropriate parameters. Extrapolated source levels at 1 m range for these activities are presented in Table 2.2. From these results, it is clear that impact piling is the dominant noise source and hence the proposed activity which has the potential to have the greatest effect during construction. This activity has therefore been studied further using detailed noise modelling (section 4).

Table 2.2: Summary of the estimated unweighted source levels for the different construction noise sources considered.

	Estimated unweighted source level	Comments
Dredging	186 dB re 1 µPa @ 1 m (RMS)	Based on five datasets from suction and cutter suction dredgers.
Drilling	179 dB re 1 µPa @ 1 m (RMS)	Based on seven datasets of offshore drilling using a variety of drill sizes and powers.
Impact piling (5000kJ)	244 dB re 1 µPa @ 1 m (Peak)	Based on data from over fifty datasets of offshore piling of various sizes, blow energies and water depths.
Impact piling (2500kJ)	241 dB re 1 µPa @ 1 m (Peak)	As above.
Cable laying	171 dB re 1 µPa @ 1 m (RMS)	Based on eleven datasets from a pipe laying vessel measuring 300 m in length; this is considered a worst case noise source for cable laying operations.
Rock placement	172 dB re 1 µPa @ 1 m (RMS)	Based on four datasets from rock placement vessel 'Rollingstone'.
Trenching	172 dB re 1 µPa @ 1 m (RMS)	Based on three datasets of measurements from trenching vessels in excess of 100 m in length.
Vessel noise (Large)	171 dB re 1 µPa @ 1 m (RMS)	Based on five datasets of large vessels including container ships, FPSOs and other vessels in excess of 100 m in length. Vessel speed assumed as 12 knots.
Vessel noise (Medium)	164 dB re 1 µPa @ 1 m (RMS)	Based on three datasets of moderate sized vessels and other vessels less than 100 m in length. Vessel speed assumed as 12 knots.

2.1.2 Impact piling

2.1.2.1 Impact piling is an installation option within the design envelope for the installation of foundation piles into the seabed. This technique involves a large weight or "ram" being dropped or driven onto the top of the pile, forcing it into the seabed. Usually, double-acting hammers are used in which a downward force on the ram is applied, exerting a larger force than would be the case if it were only dropped under the action of gravity. Impact piling has been established as a source of high level underwater impulsive noise (Würsig *et al.*, 2000; Caltrans, 2001; Nedwell *et al.*, 2003b and 2007; Parvin *et al.*, 2006; and Thomsen *et al.*, 2006).

2.1.2.2 Noise is created in air by the hammer, as a direct result of the impact of the hammer with the pile. Some of this airborne noise is transmitted into the water. Of more significance to underwater noise, is the direct radiation of noise from the surface of the pile into the water as a consequence of the compressional, flexural or other complex structural waves that travel down the pile following the impact of the hammer on its head. Sound or vibrational waves in the submerged section of the pile transmit efficiently into the surrounding water. These waterborne sound waves will radiate outwards, usually providing the greatest contribution to the underwater noise.

2.1.2.3 Where the pile enters the seabed, force is exerted on the substrate not only by the downward motion of the pile, but also by the structural waves travelling down the pile which induce lateral waves in the seabed. The waves can travel outwards through the seabed or by reflection from deeper sediments. As they propagate, sound will tend to "leak" upwards into the water, contributing to the waterborne wave. Since the speed of sound is generally greater in consolidated sediments than in water, these waves usually arrive at a distant receptor first as a precursor to the waterborne wave. Generally, the level of the seismic wave is typically 10 to 20 dB below the waterborne arrival, and hence it is the latter that dominates the noise.

2.2 Operational noise

2.2.1.1 Previous measurements have shown that the levels of noise from operational turbines is likely to be several orders of magnitude less than impact piling noise (Cheesman, 2016). However due to the long term deployment of the turbines, the impacts must still be considered.

2.2.1.2 The generating capacity of turbines at Hornsea Three will be between 7 and 15 MW. Further detail on the noise generated from such turbines is presented in section 6.

2.3 Decommissioning noise

2.3.1.1 When considering decommissioning, the activities to be undertaken are not known at this stage, and very little information has been collected regarding decommissioning of offshore wind farms. In the operational life for Hornsea Three the technology available for decommissioning and removal of an offshore wind farm will likely have advanced greatly.

2.3.1.2 Techniques used for decommissioning in the oil and gas industry have been assumed for this study in order to assess the likely noise levels, and are considered in section 7. These include:

- High-powered water jetting/cutting apparatus; and
- Grinding or drilling techniques.

2.3.1.3 However it should be noted that any of these techniques may be obsolete or superseded by the time Hornsea Three is decommissioned in 25 years after operation (construction phase commences 2023. Allowing 5 years for construction, decommissioning is not likely to commence until 2053).

3. Measurement of Noise

3.1 Underwater noise

3.1.1.1 Sound travels much faster in water (approximately 1,500 ms^{-1}) than in air (340 ms^{-1}). 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, ambient background levels of sea noise, in the presence of natural noise sources and distant shipping, of approximately 130 dB re 1 µPa for UK coastal waters are not uncommon (Nedwell *et al.*, 2003a and 2007). It should be noted that stated underwater noise levels should not be confused with the noise levels in air, which use a different scale.

3.1.2 Units of measurement

3.1.2.1 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".

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

$$Level = 10 \times \log_{10}\left(\frac{Q}{Q_{ref}}\right)$$

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

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

3.1.2.4 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, when the acoustic power level of a source rose by 10 dB the Sound Pressure Level would rise by 20 dB. So that variations in the units agree, the sound pressure must be specified in units of root mean square (RMS) pressure squared. This is equivalent to expressing the sound as:

$$Sound\ Pressure\ Level = 20 \times \log_{10}\left(\frac{P_{RMS}}{P_{ref}}\right)$$

3.1.2.5 For underwater sound, typically a unit of one micropascal (1 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.

3.1.2.6 Where not defined, all noise levels in this report are referenced to 1 µPa.

3.1.3 Sound Pressure Level (SPL)

3.1.3.1 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 sound over the measurement period.

3.1.3.2 Where an SPL is used to characterise transient pressure waves such as that from seismic airguns, underwater blasting or impact piling, it is critical that the time period over which the RMS level is calculated is quoted. For instance, in the case of the underwater sound produced by 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. More often than not, transient sounds such as these are quantified using "peak" SPLs.

3.1.4 Peak Sound Pressure Level (SPL_{peak})

3.1.4.1 Peak SPLs are often used to characterise transients sound pressure waves from impulsive sources, such as percussive impact piling and seismic airgun sources. A peak SPL is calculated using the maximum variation of the pressure from positive to zero within the wave. This represents the maximum change in positive pressure (differential pressure from positive to zero) as the transient pressure wave propagates.

3.1.4.2 A further variation of this is the peak-to-peak SPL where the maximum variation of the pressure from positive to negative within the wave is considered. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak level will be twice the peak level, or 6 dB higher.

3.1.5 Sound Exposure Level (SEL)

3.1.5.1 When assessing the noise from transient sources such as blast waves, impact piling or seismic airgun noise, the issue of the time period of the pressure wave is often addressed by measuring the total acoustic energy (energy flux density) of the wave. This form of analysis was used by Bebb and Wright (1953, 1954a, 1954b and 1955), and later by Rawlins (1987) to explain the apparent discrepancies in the biological effect of short and long range blast waves on human divers. More recently, this form of analysis has been used to develop criteria for assessing the injury range from fish for various noise sources (Popper *et al.*, 2014).

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

$$SE = \int_0^T p^2(t)dt$$

where p is the acoustic pressure in Pascals, T is the duration of the sound in seconds, and t is the time in seconds. The Sound Exposure is a measure of the acoustic energy and, therefore, has units of Pascal squared seconds (Pa^2s).

3.1.5.3 To express the Sound Exposure on a logarithmic scale by means of a dB, it is compared with a reference acoustic energy level (P^2_{ref}) and a reference time (T_{ref}). The SEL is then defined by:

$$SEL = 10 \times \log_{10}\left(\frac{\int_0^T p^2(t)dt}{P^2{}_{ref}T_{ref}}\right)$$

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

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

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

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

3.1.5.6 Weighted metrics for marine mammals have been proposed by the United States National Marine Fisheries Service (NMFS) (2016) and Southall *et al.* (2007). These assign a hearing sensitivity to groups of marine mammals, and are discussed in detail in the following section.

3.2 Analysis of environmental effects

3.2.1 Background

3.2.1.1 It has become increasingly evident that noise from human activities in and around underwater environments may have an impact on the marine species (e.g. OSPAR Commission 2008, Thomsen *et al.*, 2006). The extent to which intense underwater sound might cause an adverse environmental impact in a particular species, is dependent upon the incident sound level, sound frequency, duration of exposure and/or repetition rate of an impulsive sound (see for example Hastings and Popper, 2005). As a result, scientific interest in the hearing abilities of marine animal species has increased. Studies are primarily based on evidence from high level sources of underwater noise such as blasting or impact piling, as these sources are likely to have the greatest environmental impact and therefore the clearest observable effects, although there has been more interest in chronic noise exposure over the last five years.

3.2.1.2 The impacts of underwater sound on marine species can be broadly summarised as follows:

- Physical traumatic injury and fatality;
- Auditory injury (either permanent or temporary); and
- Disturbance.

3.2.1.3 The following sections discuss the agreed criteria for assessing these impacts in species of marine mammal and fish.

3.2.2 Criteria to be used

3.2.2.1 The main metrics and criteria that have been used in this study to assess potential environmental effects, come from two key papers covering underwater noise and its effects: the NMFS guidance (NMFS, 2016) for marine mammals and Sound Exposure Guidelines for Fishes and Sea Turtles by Popper *et al.* (2014). At the time of writing, these present the most up to date and authoritative criteria for assessing environmental effects for use in impact assessments. Reference is also made to Southall *et al.* (2007).

Marine mammals

3.2.2.2 Since it was published, Southall *et al.* (2007) has been the source of the most widely used criteria to assess the effects of noise on marine mammals. NMFS (2016) was co-authored by many of the same authors from the Southall *et al.* (2007) paper, and effectively updates its criteria for assessing the risk of auditory injury. Most of the criteria proposed have become more restrictive.

3.2.2.3 Similarly to Southall *et al.* (2007), the NMFS (2016) guidance groups marine mammals into functional hearing groups and applies filters to the unweighted noise to approximate the hearing sensitivity of the receptor. The hearing groups given in the NMFS (2016) are summarised in Table 3.1 and Figure 3.1. A further group for Otariid Pinnipeds is also given in the guidance for sea lions and fur seals but this has not been used in this study as those species of pinnipeds are not commonly found in the southern North Sea.

Table 3.1: Marine mammal hearing groups (from NMFS, 2016).

Hearing group	Example species	Generalised hearing range
Low Frequency (LF) Cetaceans	Baleen Whales	7 Hz to 35 kHz
Mid Frequency (MF) Cetaceans	Dolphins, toothed whales, beaked whales, bottlenose whales (including bottlenose and beaked dolphin)	150 Hz to 160 kHz
High Frequency (HF) Cetaceans	True Porpoises (including harbour porpoise)	275 Hz to 160 kHz
Phocid Pinnipeds (PW) (underwater)	True Seals (including harbour and grey seal)	50 Hz to 86 kHz

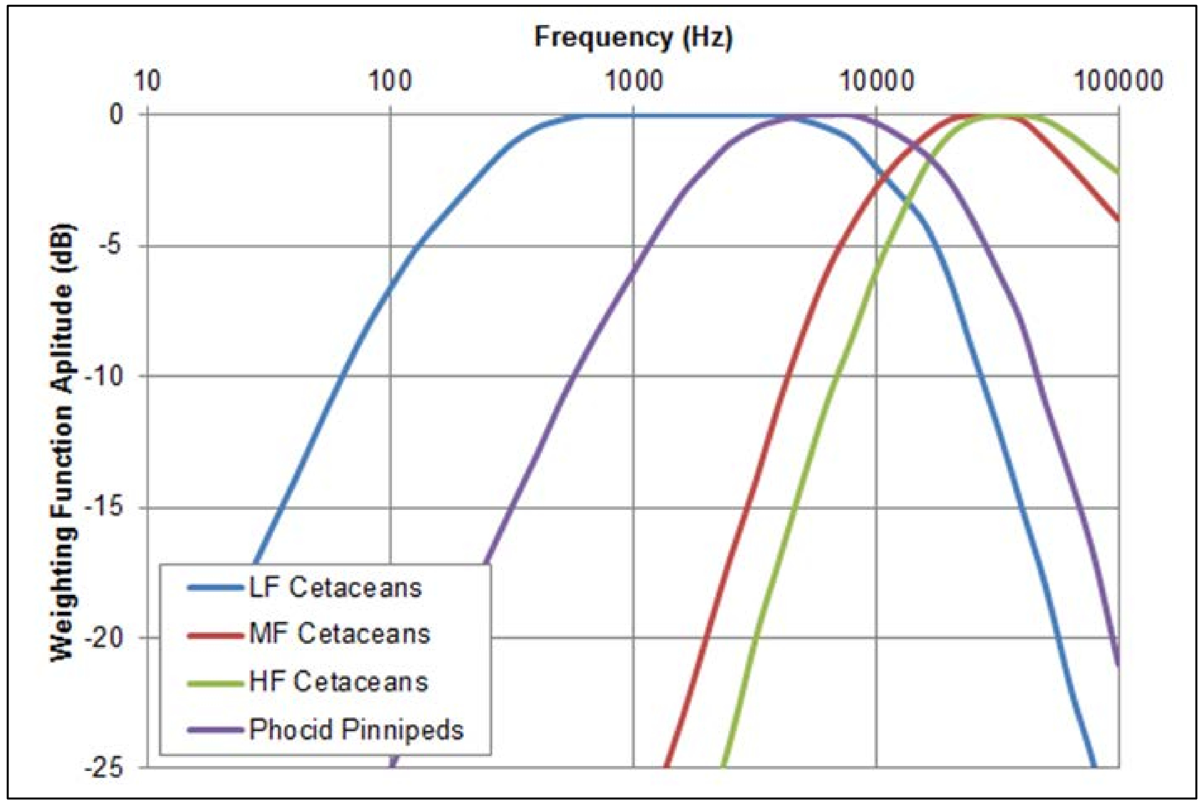

Figure 3.1: Auditory weighting functions for low frequency (LF) cetaceans, mid frequency (MF) cetaceans, high frequency (HF) cetaceans, and phocid pinnipeds (PW) (underwater) (from NMFS, 2016).

3.2.2.4 NMFS (2016) presents single strike, unweighted peak criteria (SPL_{peak}) and cumulative (i.e. more than a single sound impulse), weighted sound exposure criteria (SEL_{cum}) for both permanent threshold shift (PTS) where unrecoverable hearing damage may occur and temporary threshold shift (TTS) where a temporary reduction in hearing sensitivity may occur in individual receptors.

3.2.2.5 Table 3.2 presents the NMFS (2016) criteria for onset of risk of PTS and TTS for each of the key marine mammal hearing groups. Where SEL_{cum} are required, a fleeing animal model has been used, assuming that the animal exposed to high noise levels will swim away from the noise source. For this a constant fleeing speed of 3.25 ms^{-1} has been assumed for the low frequency (LF) cetaceans group (Blix and Folkow, 1995), based on data for minke whale, and for other receptors a constant rate of 1.5 ms^{-1} has been assumed, which is a cruising speed for a harbour porpoise (Otani *et al.*, 2000). These are considered precautionary as marine mammals are expected to be able to swim much faster under stress conditions.

Table 3.2: Criteria for assessment of PTS and TTS to marine mammals.

NMFS (2016)	PTS (Permanent Threshold Shift)		TTS (Temporary Threshold Shift)	
	SPLpeak Unweighted (dB re 1 µPa)	SELcum Weighted (dB re 1 µPa2s)	SPLpeak Unweighted (dB re 1 µPa)	SELcum Weighted (dB re 1 µPa2s)
Low Frequency (LF) Cetaceans)	219	183	213	168
Mid Frequency (MF) Cetaceans	230	185	224	170
High Frequency (HF) Cetaceans	202	155	196	140
Phocid Pinnipeds	218	185	212	170

3.2.2.6 NMFS (2016) does not give guidance for behavioural response (disturbance) in marine mammals and in general there is little reliable evidence for setting general-condition behavioural avoidance criteria. Context and individual behaviour is critical. In lieu of this, the following alternative criteria has been used, derived from (although not explicitly defined in) Southall *et al.* (2007). These are as per the thresholds used in the Hornsea Project Two underwater noise impact assessment. The criteria use unweighted SPL_{peak} and single-pulse SELs and are summarised in Table 3.3. It should be noted that no SPL_{peak} criteria are given for low and mid-frequency cetaceans. Behavioural avoidance criteria for pinnipeds should use the same values as TTS in Table 3.2.

Table 3.3: Criteria for assessment of behavioural reactions by marine mammals.

Southall *et al.* (2007)	Behavioural reactions of area	
	SPL_{peak} Unweighted (dB re 1 µPa)	Single pulse SEL Unweighted (dB re 1 µPa^{2}s)
Low Frequency (LF) Cetaceans	-	142 - 152
Mid Frequency (MF) Cetaceans	-	160 - 170
High Frequency (HF) Cetaceans	168	145
Phocid Pinnipeds	As TTS	As TTS

3.2.2.7 The results tables for LF and MF cetaceans show the upper and lower SEL range limits for behavioural reactions. These correspond with different degrees of reaction; the highest level roughly corresponds to "minor or moderate individual and/or group avoidance of sound source" and the lower level to more general changes in group behaviour, speed or distribution. The lower level does not indicate avoidance behaviour.

3.2.2.8 It is important to note that there is limited research available for assessment of behavioural reactions to noise. The criteria are often based on small scale studies with captive subjects and extrapolated conclusions, are highly context dependent and are intended to be very precautionary.

Fish

3.2.2.9 The vast variation in fish species leads to a greater challenge in production of a generic noise criterion, or range of criteria, for the assessment of noise impacts. Whereas broad criteria were previously applied based on limited studies of fish not present in UK waters (e.g. McCauley *et al.*, 2000), the publication of Popper *et al.* (2014) provides an authoritative summary of the latest research and guidelines for the assessment of fish exposure to sound.

3.2.2.10 The Popper *et al.* (2014) study groups species of fish into whether or not they possess a swim bladder, and whether it is involved in its hearing. The guidance also gives specific criteria (as both SPL_{peak} and SEL_{cum} values) for a variety of noise sources. This assessment has used the criteria given for pile driving noise on fish where their swim bladder is involved in hearing, as these are the most conservative. The modelled criteria are summarised in Table 3.4. Similarly to marine mammals for SEL_{cum} results, a fleeing animal model has been used assuming a receptor flees from the source at a constant rate of 1.5 ms^{-1} based on data from Hirata (1999).

3.2.2.11 Popper *et al.* define behavioural effects as "substantial change in behaviour for the animals exposed to a sound. This may include long-term changes in behaviour and distribution, such as moving from preferred sites for feeding and reproduction, or alteration of migration patterns."

Table 3.4: Criteria for assessment of effects on fish (with swim bladder involved in hearing).

Popper *et al.* (2014)	SPL_{peak} Unweighted (dB re 1 µPa)	SEL_{cum} Weighted (dB re 1 µPa^{2}s)
Recoverable injury	207	203
Masking	Qualitative	Qualitative
Behavioural	Qualitative	Qualitative

3.2.2.12 Masking is the effective reduction of audibility of a sound, impeding for example audible communication, due to increased background noise.

3.2.2.13 The Popper *et al.* (2014) guidelines conclude that there is insufficient data available to apply quantitative thresholds for behavioural effects on fish. Therefore the behavioural effects for fish in this study have been considered qualitatively.

4. Baseline Ambient Noise

4.1.1.1 The baseline noise level in the absence of any specific anthropogenic noise source is generally dependent on a mix of the movement of the water and sediment (especially in shallow water), weather conditions and shipping. There is a component of biological noise from marine mammal and fish vocalisation, as well as an element from invertebrates too.

4.1.1.2 Outside of the naturally occurring ambient noise, man-made noise dominates the background. The North Sea is heavily shipped by fishing, cargo and passenger vessels, which contribute to the ambient noise in the water. The larger vessels are not only louder but the noise tends to have a lower frequency, which travels more readily especially in the deeper open water. Other vessels such as dredgers and small fishing boats, although present, have a lower overall contribution. There are no dredging areas or Active Dredge Zones and Dredging Application Option and Prospecting Areas within the Hornsea Project Three boundary.

4.1.1.3 Other sources of anthropogenic noise include oil and gas platforms and other drilling activity, clearance of unexploded ordnance (UXO) and military exercises. Drilling may contribute some low frequency noise in the Hornsea Three study area, and this may contribute slightly to the overall ambient noise. Clearance of UXO contributes high but infrequent and localised noise. Little information is available on the scope and timing of military exercises but they are not expected to last for an extended period of time, and so would have little contribution to the long-term ambient noise in the area.

4.1.1.4 The Marine Strategy Framework Directive requires European Union members to ascertain baseline noise levels by 2020, and monitoring processes are being put into place for this around Europe. Although the monitoring this will lead to will potentially be limited, it is likely to add considerably to the availability of baseline noise levels for future assessments. Good quality, long-term underwater noise data for the region around Hornsea is not currently available.

4.1.1.5 Typical underwater noise levels show a frequency dependency in relation to different noise sources; the classic curves are given in Wenz (1962) and are reproduced in Figure 4.1 below.

4.1.1.6 Figure 4.1 shows that any unweighted overall (i.e. single-figure non frequency-dependent) noise level is typically dependent on the very low frequency element of the noise. The introduction of a nearby anthropogenic noise source (such as piling or sources involving engines) will tend to increase the noise levels in the 100-1000 Hz region, but to a lesser extent will also extend into higher and lower frequencies.

4.1.1.7 In 2011, around the time of the met mast installation in the former Hornsea zone, snapshot baseline underwater noise levels were sampled as part of the met mast installation noise survey (Nedwell and Cheesman, 2011). Measurements were taken outside of the installation activity and in the absence of any nearby vessel noise on two days. This survey sampled noise levels of 112 to 122 dB re 1 μPa RMS over two days, which were stated as not unusual for the area. The higher figure was due to higher sea state on that day. Unweighted overall noise levels of this type should be used with caution without access to more detail regarding the duration, frequency content and conditions under which the sound was recorded.

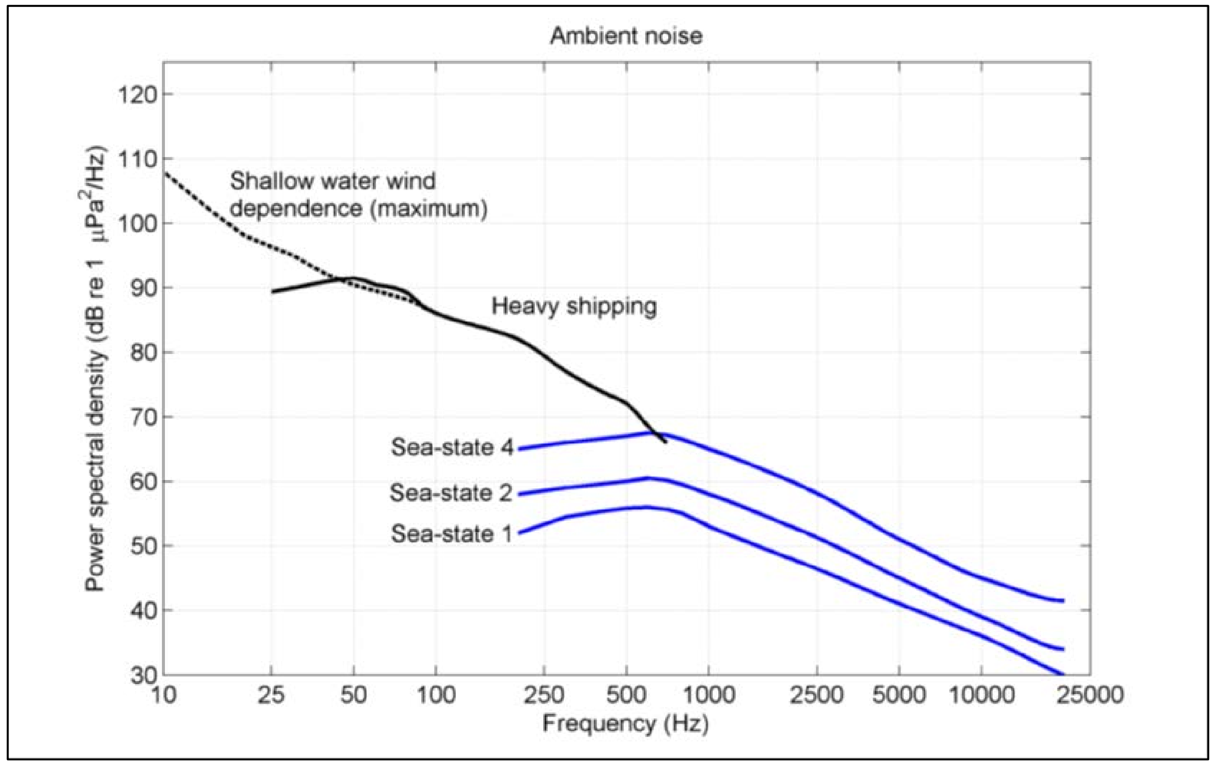

Figure 4.1: Ambient underwater noise as shown in Wenz (1962) showing frequency dependency from different noise sources.

4.1.1.8 There is little documented, additional ambient noise data publicly available for the region. Merchant *et al.* (2014) measured underwater ambient noise in the Moray Firth, acquiring measurements of a similar order to the baseline snapshot levels noted above, which showed significant variation (i.e. a 60 dB spread) in daily average noise levels. Although this is outside of the region and in a much more coastal and heavily shipped location, it demonstrates that the snapshot noted above gives only limited information as the average daily noise levels are so dependent on weather and local activity. However, the snapshot measurements taken do show noise levels that are of the same order as baseline noise levels sampled elsewhere in the North Sea (Nedwell *et al.*, 2005) and so are considered to be realistic.

5. Construction noise assessment

5.1 Modelling methodology

5.1.1.1 In order to estimate the noise levels likely to arise during construction of Hornsea Three, predictive underwater noise modelling has been undertaken. The methods described in this section and utilised within this report, meet the requirements set by the NPL Good Practice Guide 133 for Underwater Noise (Robinson *et al.*, 2004).

5.1.1.2 Modelling has been undertaken at five locations representative of the geographical extents of Hornsea Three, covering the Hornsea Three array site and the accompanying HVAC search area. The locations were chosen to include proximity to nature conservation designations and varying water depths. The chosen locations are shown in Figure 5.1 and summarised in Table 5.1 below.

5.1.1.3 Concurrent piling in two locations within Hornsea Three has also been modelled at the greatest spatial extent. This is described in more detail in section 5.4.

5.1.1.4 The Northwest and Northeast locations give a wide spatial coverage of the Hornsea Three site along the deep water channel to the north. The South location has been chosen to give spatial coverage to the south, showing the greatest potential noise propagation from this region. The two HVAC search area locations give coverage of the HVAC search area in shallower water closer to the coast.

5.1.1.5 Modelling of underwater noise is complex and can be approached in a number of different ways. Subacoustech have chosen to use a numerical approach that is based on two different techniques, which are most appropriate for different frequency ranges, within one modelling package:

- A parabolic equation (PE) method for lower frequencies (12.5 Hz to 250 Hz); and
- Ray tracing method for higher frequencies (315 Hz to 100 kHz).

5.1.1.6 The PE method is widely used within the underwater acoustics community but has computational limitations at high frequencies. Ray tracing is more computationally efficient at higher frequencies and not suited to low frequencies.

Table 5.1: Summary of the modelling locations (WGS84) and the mean annual water depths at each location.

	Northwest	Northeast	South	HVAC North	HVAC South
Latitude	53.9895°N	54.0010°N	53.7106°N	53.3419°N	53.1275°N
Longitude	002.1976°E	002.6812°E	002.7254°E	001.7815°E	001.5636°E
Water depth	59 m	47 m	42 m	33 m	37 m

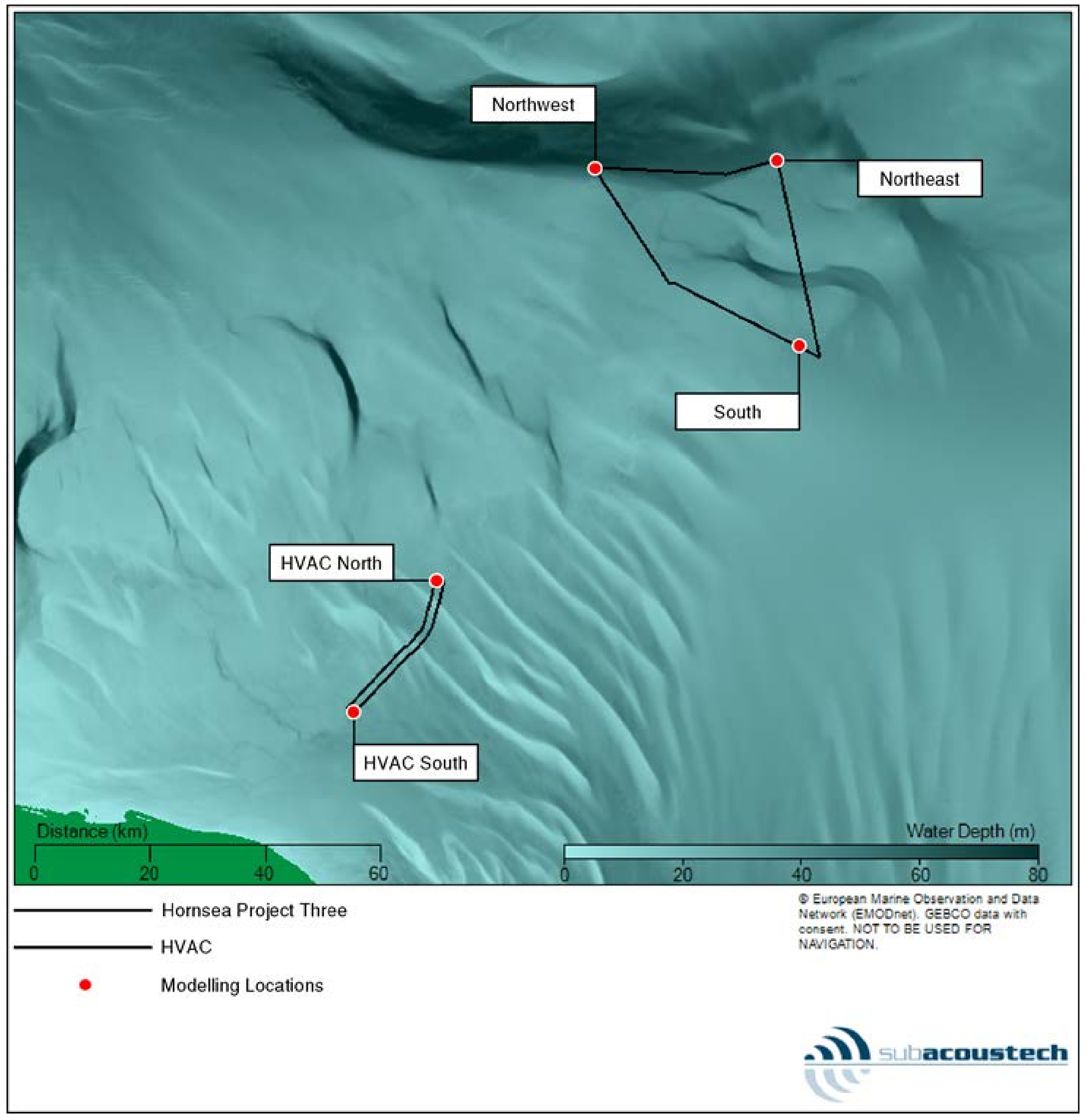

Figure 5.1: Map showing the modelled locations covering the Hornsea Three site and HVAC search area.

5.1.1.7 These techniques take into account a wide array of input parameters, including bathymetry, sediment data, sound speed and source frequency content, to ensure as detailed results as possible. It should also be noted that the results presented from this study should be considered precautionary as the Maximum Design Scenario has been applied for:

- Piling hammer blow energies;
- Soft start ramp-up profile and strike rate;
- Receptor swim speeds;
- Duration of piling; and
- Position of the receptor in the water column.

5.1.1.8 The method for applying precautionary values in each of these categories is explained in detail as follows:

- The soft start ramp-up reaches maximum energy much more quickly than would be expected. Receptors flee at a 'cruising speed', the hammering duration is greater than predicted at Hornsea Three and previous offshore windfarm installation projects and it is assumed that the receptor swims at the location of highest noise level within the water column. When combined, this leads to a layering of conservative parameters which lead to a highly precautionary assessment.

5.1.1.9 Additional modelling of the noise level at a depth of 2 m below the water surface has been undertaken to account for the depth at which harbour porpoise were found to remain for a substantial period of time (Teilman *et al.*, 2013; Westgate *et al.*, 1995). This is presented in volume 2, chapter 4: Marine Mammal.

5.1.1.10 The piling input parameters for the modelling are detailed in the following section.

5.1.2 Input parameters

5.1.2.1 The modelling takes full account of the characteristics of the noise source (see the Source levels section, from paragraph 5.1.2.6) and environmental parameters within the study area (see the Environmental conditions section, from paragraph 5.1.2.11). The following parameters have been assumed for modelling.

Impact piling

5.1.2.2 Two piling source scenarios have been modelled to include monopile and pin pile turbine foundations across the Hornsea Three site and the HVAC search area. These are:

- Monopiles installed using a maximum blow energy of up to 5000 kJ; and
- Pin piles installed using a maximum blow energy of up to 2500 kJ.

5.1.2.3 These parameters represent the maximum energy that the proposed hammer is capable of producing. Under normal circumstances, this energy is not expected to be reached, and if it is will only be used for short periods due to the risk of damage to the pile. Therefore the energies used for prediction of source noise levels (see the Source levels section, from paragraph 5.1.2.6) are highly precautionary.

5.1.2.4 For cumulative SELs, the soft start and ramp up of blow energies along with total duration and strike rate of the piling have also been considered; these are summarised in Table 5.2 below. The ramp up takes place over 30 minutes, starting at 15 percent, gradually increasing in blow energy and strike rate until reaching the maximum energy. The hammering has been assumed to last for 4 hours.

Table 5.2: Summary of the ramp up scenario used for calculating cumulative SELs.

	15%	40%	60%	80%	100%
Monopile blow energy	750 kJ	2000 kJ	3000 kJ	4000 kJ	5000 kJ
Pin Pile blow energy	375 kJ	1000 kJ	1500 kJ	2000 kJ	2500 kJ
Strike Rate	1 strike every 6 seconds	1 strike every 6 seconds	1 strike every 4 seconds	1 strike every 4 seconds	1 strike every 2 seconds
Duration	7.5 minutes	7.5 minutes	7.5 minutes	7.5 minutes	3 hours, 30 minutes

5.1.2.5 As explained above, hammering at maximum energy except very briefly is not expected in practice and the assumption that this will occur for the majority of time is intended to be precautionary. Additionally, piling for four hours is expected to be the upper limit of the period of hammering and the ramp up will typically be over longer than 30 minutes. These both contribute to the precautionary nature of the piling modelling.

Source levels

5.1.2.6 Modelling requires knowledge of the source level, which is the theoretical noise level at 1 m from the noise source. Subacoustech have undertaken numerous measurements of impact piling offshore and have developed a sound level model based primarily on the blow energy and water depth of a piling operation. A base source level and frequency spectrum was derived from measured data of monopile strike pulses. This was modified initially by the 3 dB per doubling or halving of blow energy as found by Robinson *et al.*, 2007 then adjusted to fit the datasets available. Additional adjustments were made to the source level based on the depth of water, as it relates to the radiating surface area of the pile in the water column (Nehls *et al.* 2007).

5.1.2.7 As the model assumes that the noise source acts as a single point, the water depth at the noise source has been used to adjust the source level to allow for the length of pile in contact with the water.

5.1.2.8 The unweighted source levels estimated for this project are provided in Table 5.3.

Table 5.3: Summary of the unweighted peak source levels used for modelling in this study.

	Monopile source level (5000 kJ)	Pin pile source level (2500 kJ)
Northwest	243.6 dB re 1 µPa @ 1 m	241.0 dB re 1 µPa @ 1 m
Northeast	243.6 dB re 1 µPa @ 1 m	241.0 dB re 1 µPa @ 1 m
South	243.6 dB re 1 µPa @ 1 m	241.0 dB re 1 µPa @ 1 m
HVAC North	240.6 dB re 1 µPa @ 1 m	237.8 dB re 1 µPa @ 1 m
HVAC South	242.3 dB re 1 µPa @ 1 m	239.7 dB re 1 µPa @ 1 m

5.1.2.9 The size of the pile being installed is used for estimating the frequency content of the noise; large monopiles contain more low frequency content and the smaller pin piles contain more high frequency content, due to the dimensions and acoustics of the pile. For this modelling, frequency data has been sourced from Subacoustech's noise measurement database and an average taken to obtain representative third octave (i.e. frequency, see Figure 5.2) levels for installing monopiles and pin piles. The frequency spectrum for a pile of 7.0 m in diameter is suitable for the monopile modelling and piles of approximately 4.0 m in diameter have been used for pin pile modelling. Piles of up to 15.0 m in diameter are included in the project envelope, but at this scale the overall noise output from the piling is controlled by the energy with which the pile is struck, adjusted by the length of pile in contact with the water, rather than the size of the pile. Research by Nehls *et al.* 2007 showed that for a given blow energy, pile diameter alone does not necessarily lead to a change in noise output.

5.1.2.10 The noise level spectra used for modelling the Northwest location are illustrated in Figure 5.2 as an example; the shape of each spectrum is the same for all the other locations and blow energies, with the overall source levels adjusted.

Environmental conditions

5.1.2.11 Accurate modelling of underwater noise propagation requires knowledge of the variations in bathymetry surrounding the piling as well as sea and seabed conditions. As modelling has been carried out over a large area with varied substrate and seabed types, assumptions have had to be made regarding this over the whole area. Seabed sediment information from the British Geological Survey (BGS) presented as part of the Marine Environmental Mapping Programme (MAREMAP, 2017) show that the majority of the areas surrounding Hornsea Three are either sand or gravelly sand, as such a 2 m sand layer on top of a gravel layer has been assumed. The geoacoustic properties for the sediment types are taken from Jensen *et al.* (2011).

5.1.2.12 The speed of sound in water at Hornsea Three has been calculated using temperature and salinity data for the southern North Sea using equations by Mackenzie (1981); the levels used in the model vary from 1,487 ms^{-1} at the surface to 1,489 ms^{-1} at depths of 100 m, in the deepest waters in the study area.

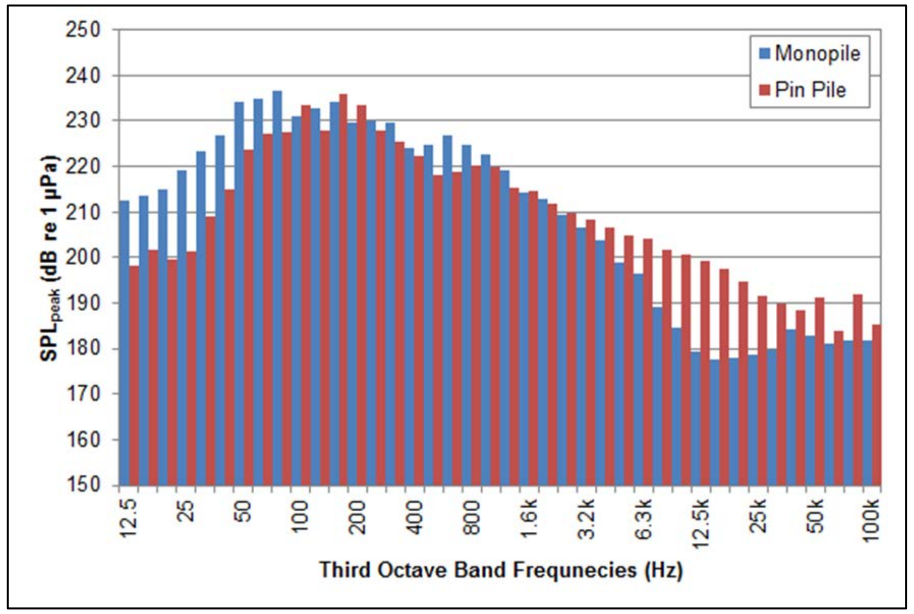

Figure 5.2: Third octave source level frequency spectra for the Northwest location, maximum blow energy.

5.1.2.13 A high tide of 4.0 m above the lowest astronomical tide (LAT) has been used for the modelling, which represents deeper water and greater noise transmission through the water.

5.2 Unweighted subsea noise modelling

5.2.1.1 This section presents the unweighted noise level results from the modelling undertaken for impact piling operations at one location on the Hornsea Three site, selected for proximity to a nature conservation designation, and one on the shallower accompanying HVAC search area, as an example, for a single strike of the hammer. The full, detailed modelling outputs are presented in Appendix A.

5.2.2 Unweighted levels

5.2.2.1 The figures below present unweighted SPL$_{peak}$ noise levels from impact piling operations. The colours shown on the map represent the highest modelled noise level in the water column at that locationbased on the maximum design scenario. The vertical position of the highest noise level is variable. The noise level at 2 m below the sea surface, where harbour porpoises (*Phocoena phocoena*) spend the majority of time (Teilmann *et al.*, 2013) has also been modelled, and is reported in the Marine Mammal chapter. Figure 5.3 and Figure 5.4 show the unweighted SPL$_{peak}$ noise levels for monopiles (installed using a maximum blow energy of 5000 kJ) at the South location, showing the largest predicted impact ranges, and the HVAC North location, the shallowest location modelled. These can be compared against Figure 5.5 and Figure 5.6 which show the same locations, but for installing pin piles using the maximum blow energy of 2500 kJ. The differences in noise levels can be clearly seen when comparing the monopile and pin pile outputs.

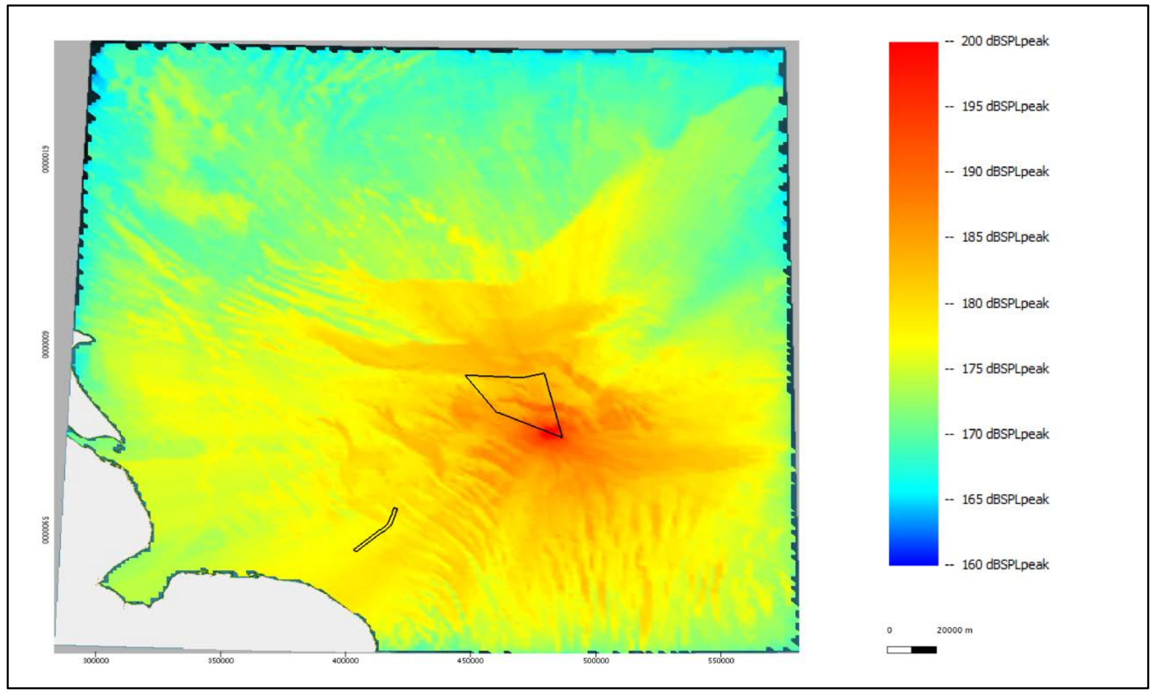

Figure 5.3: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the South location of Hornsea Three for installing a monopile with a maximum blow energy of 5000 kJ.

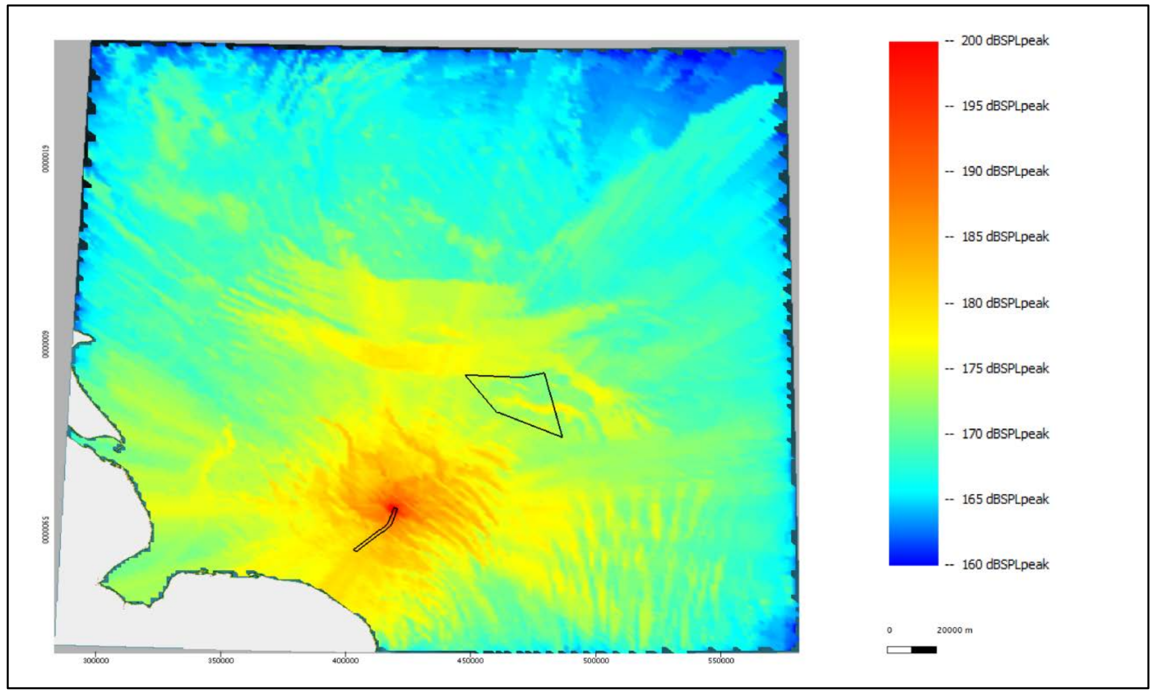

Figure 5.4: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the HVAC North location for installing a monopile with a maximum blow energy of 5000 kJ.

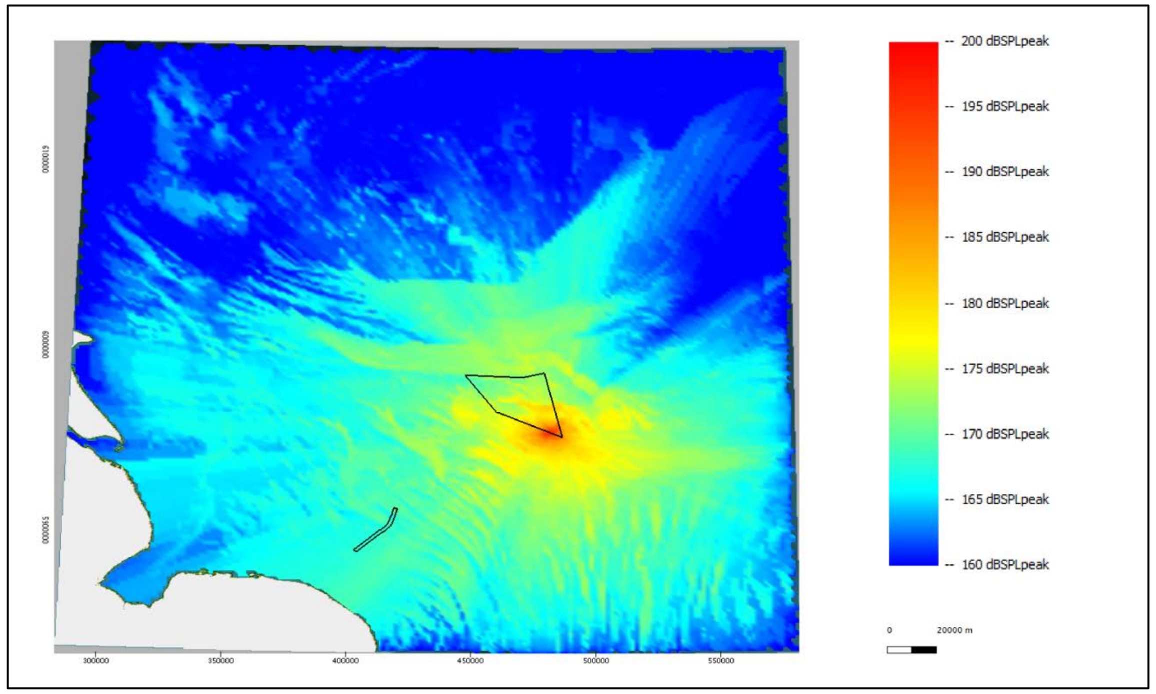

Figure 5.5: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the South location of Hornsea Three for installing a pin pile with a maximum blow energy of 2500 kJ.

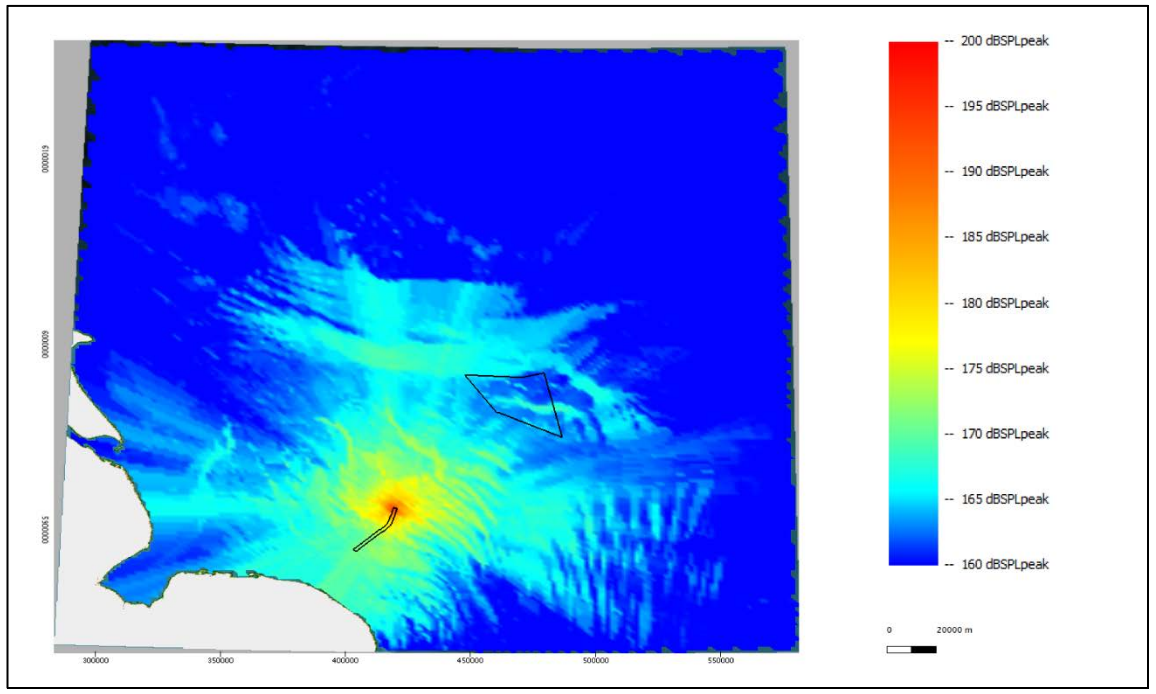

Figure 5.6: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the HVAC North location for installing a pin pile with a maximum blow energy of 2500 kJ.

5.2.2.2 The greatest distribution of increased noise levels, with no weighting applied, occurs in deeper water when driving the monopiles. The pin pile installation is predicted to generate lower noise levels over range irrespective of the installation location or water depth.

5.3 Interpretation of results

5.3.1.1 This section presents the modelling results (section 5.2) in terms of the noise metrics and criteria covered in section 3.2. This discussion will guide the assessment of potential environmental impact on marine species from impact piling and dredging related noise.

5.3.1.2 The full detailed modelling outputs are presented in Appendix A.

5.3.2 Impacts on marine mammals

5.3.2.1 Table 5.4 to Table 5.16 give the maximum and mean impact ranges for species of marine mammal based on the injury criteria found in the NMFS (2016) guidance and the behavioural avoidance criteria from Southall *et al.* (2007), and the criteria used in Hornsea Project Two. For the single strike criteria, ranges for each part of the ramp up (Table 5.2) have been provided. Contour plots of the PTS and TTS ranges are given in Appendix A. Figure 5.7 and Figure 5.8 give the SEL_{cum} values for fleeing animals as a function of cumulative received level and receptor starting range; these figures assume a receptor fleeing in a worst case (for high noise levels) West-northwest direction (290°) through deep water or a South-southwest direction (190°) through shallower water toward the coast away from piling operations at the Northwest location.

5.3.2.2 The results are discussed after the tables.

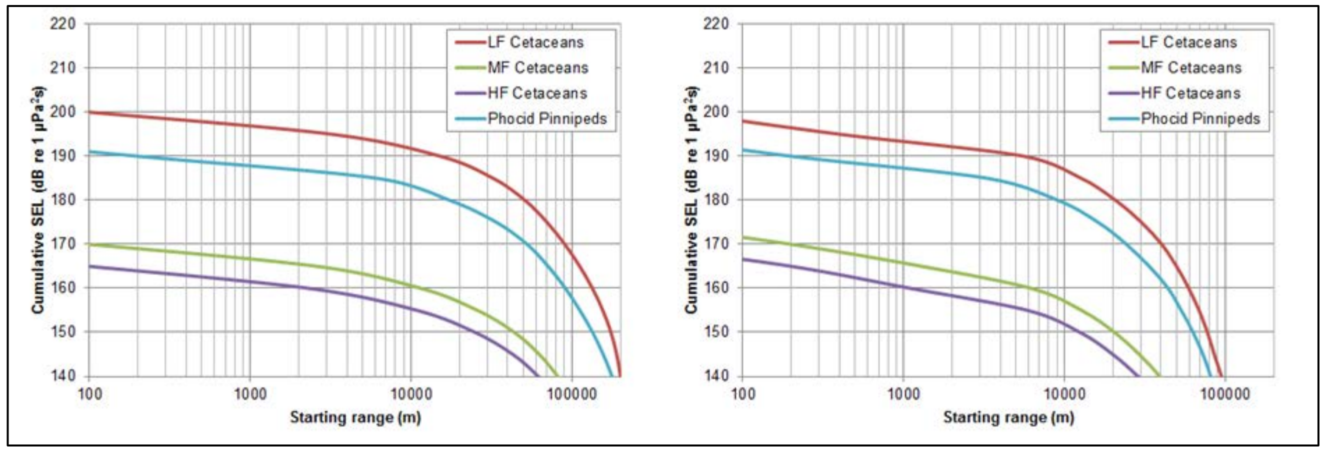

Figure 5.7: Total received cumulative SEL for species of marine mammal (NMFS (2016) criteria for PTS and TTS) when fleeing from impact piling noise at Northwest location for a monopile installed with a maximum hammer energy of 5000 kJ.

(Left plot = West-northwest transect (290°), Right plot = South-southwest transect (190°))

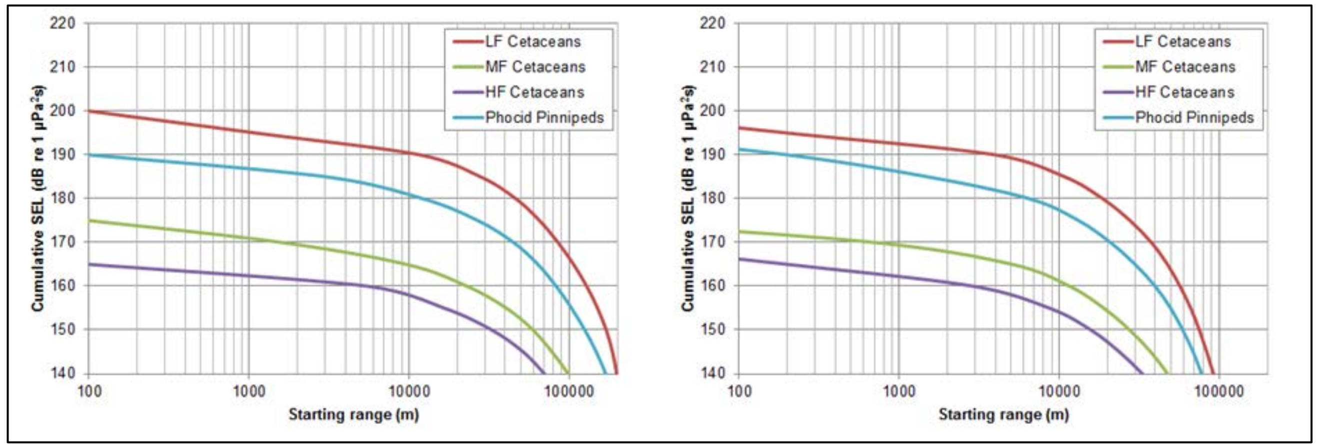

Figure 5.8: Total received cumulative SEL for species of marine mammal (NMFS (2016) criteria for PTS and TTS) when fleeing from impact piling noise at Northwest location for a pin pile installed with a maximum hammer energy of 2500 kJ.

(Left plot = West-northwest transect (290°), Right plot = South-southwest transect (190°))

PTS Results (marine mammals)

Table 5.4: Summary of the maximum and mean ranges out to which PTS is expected to occur in Low Frequency (LF) Cetaceans.

Low Frequency (LF) Cetaceans (PTS)		219 dB re 1 µPa Unweighted SPL_{peak}										183 dB re 1 µPa²s Weighted SEL_{cum} (Fleeing 3.25 ms⁻¹)	
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy			
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	33 m	21 m	100 m	58 m	140 m	81 m	190 m	99 m	210 m	110 m	40 km	23 km
	NE	33 m	22 m	100 m	62 m	140 m	86 m	190 m	110 m	210 m	120 m	37 km	24 km
	S	34 m	23 m	100 m	62 m	150 m	86 m	190 m	110 m	220 m	120 m	23 km	18 km
	HVAC N	13 m	11 m	41 m	30 m	66 m	48 m	76 m	55 m	86 m	61 m	12 km	8.9 km
	HVAC S	24 m	17 m	80 m	49 m	110 m	69 m	170 m	89 m	210 m	100 m	17 km	12 km
Pin Pile (2500kJ)	NW	8 m	7 m	25 m	21 m	38 m	31 m	48 m	40 m	56 m	46 m	35 km	21 km
	NE	9 m	7 m	32 m	22 m	50 m	33 m	64 m	41 m	76 m	47 m	33 km	21 km
	S	9 m	7 m	29 m	22 m	44 m	33 m	57 m	41 m	67 m	48 m	20 km	16 km
	HVAC N	4 m	3 m	14 m	11 m	21 m	17 m	27 m	21 m	34 m	26 m	9.0 km	6.8 km
	HVAC S	7 m	5 m	24 m	17 m	37 m	26 m	48 m	33 m	62 m	41 m	14 km	9.7 km

Table 5.5: Summary of the maximum and mean ranges out to which PTS is expected to occur in Mid Frequency (MF) Cetaceans.

Mid Frequency (MF) Cetaceans (PTS)		230 dB re 1 µPa Unweighted SPL_{peak}										185 dB re 1 µPa²s Weighted SEL_{cum} (Fleeing 1.5 ms⁻¹)[2]	
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy			
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	2 m	2 m	9 m	6 m	13 m	9 m	16 m	11 m	18 m	13 m	< 100 m	< 100 m
	NE	2 m	2 m	9 m	7 m	13 m	9 m	16 m	12 m	18 m	13 m	< 100 m	< 100 m
	S	2 m	2 m	9 m	7 m	13 m	10 m	17 m	12 m	19 m	13 m	< 100 m	< 100 m
	HVAC N	1 m	1 m	4 m	3 m	6 m	5 m	7 m	6 m	8 m	7 m	< 100 m	< 100 m
	HVAC S	2 m	1 m	6 m	5 m	10 m	7 m	13 m	9 m	16 m	11 m	< 100 m	< 100 m
Pin Pile (2500kJ)	NW	1 m	1 m	3 m	3 m	4 m	4 m	6 m	5 m	7 m	6 m	< 100 m	< 100 m
	NE	1 m	1 m	3 m	3 m	5 m	4 m	7 m	5 m	8 m	6 m	< 100 m	< 100 m
	S	1 m	1 m	3 m	3 m	5 m	4 m	6 m	5 m	8 m	6 m	< 100 m	< 100 m
	HVAC N	< 1 m	< 1 m	1 m	1 m	2 m	2 m	3 m	3 m	4 m	3 m	< 100 m	< 100 m
	HVAC S	< 1 m	< 1 m	2 m	2 m	4 m	3 m	5 m	4 m	7 m	5 m	< 100 m	< 100 m

[2] Cumulative SEL modelling is limited to steps of 100 m

Table 5.6: Summary of the maximum and mean ranges out to which PTS is expected to occur in High Frequency (HF) Cetaceans.

High Frequency (HF) Cetaceans (PTS)		202 dB re 1 µPa Unweighted SPL_{peak}										155 dB re 1 µPa²s Weighted SEL_{cum} (Fleeing 1.5 ms^{-1})	
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy			
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	1.4 km	590 m	2.6 km	1.5 km	3.6 km	2.2 km	4.1 km	2.9 km	4.3 km	3.2 km	8.8 km	6.8 km
	NE	1.4 km	660 m	2.6 km	1.6 km	3.5 km	2.4 km	4.5 km	3.0 km	5.1 km	3.3 km	7.9 km	6.6 km
	S	1.5 km	660 m	2.9 km	1.8 km	3.8 km	2.8 km	4.3 km	3.5 km	4.9 km	3.8 km	5.4 km	4.8 km
	HVAC N	470 m	290 m	1.4 km	810 m	1.9 km	1.2 km	2.2 km	1.4 km	2.6 km	1.6 km	1.7 km	1.3 km
	HVAC S	1.1 km	520 m	2.3 km	1.4 km	2.9 km	1.8 km	3.6 km	2.3 km	3.9 km	2.8 km	3.5 km	2.9 km
Pin Pile (2500kJ)	NW	190 m	150 m	590 m	430 m	880 m	630 m	1.1 km	790 m	1.3 km	910 m	17 km	12 km
	NE	280 m	150 m	960 m	460 m	1.4 km	670 m	1.7 km	850 m	1.8 km	970 m	15 km	12 km
	S	230 m	150 m	790 m	470 m	1.1 km	690 m	1.5 km	860 m	1.7 km	1.0 km	10.3 km	9.1 km
	HVAC N	100 m	74 m	340 m	220 m	510 m	320 m	670 m	410 m	820 m	500 m	4.4 km	3.6 km
	HVAC S	200 m	120 m	710 m	380 m	1.0 km	560 m	1.4 km	700 m	1.7 km	870 m	7.2 km	6.0 km

Table 5.7: Summary of the maximum and mean ranges out to which PTS is expected to occur in Phocid Pinnipeds (PW) (underwater).

Phocid Pinnipeds (PW) (PTS)		218 dB re 1 µPa Unweighted SPL_{peak}										185 dB re 1 µPa²s Weighted SEL_{cum} (Fleeing 1.5 ms^{-1})	
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy			
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	42 m	26 m	120 m	70 m	180 m	97 m	240 m	120 m	260 m	130 m	6.1 km	4.8 km
	NE	42 m	27 m	120 m	75 m	180 m	100 m	230 m	130 m	260 m	140 m	5.5 km	4.6 km
	S	42 m	28 m	130 m	76 m	190 m	100 m	240 m	130 m	270 m	140 m	3.6 km	3.2 km
	HVAC N	16 m	13 m	50 m	37 m	81 m	58 m	94 m	66 m	100 m	74 m	700 m	480 m
	HVAC S	31 m	21 m	100 m	60 m	140 m	84 m	210 m	110 m	260 m	130 m	2.1 km	1.7 km
Pin Pile (2500kJ)	NW	10 m	8 m	30 m	25 m	45 m	38 m	58 m	47 m	68 m	55 m	3.0 km	2.3 km
	NE	11 m	9 m	39 m	26 m	61 m	39 m	79 m	49 m	93 m	57 m	2.7 km	2.2 km
	S	10 m	9 m	35 m	27 m	54 m	39 m	69 m	50 m	82 m	58 m	1.6 km	1.4 km
	HVAC N	5 m	4 m	16 m	13 m	25 m	20 m	33 m	25 m	41 m	30 m	< 100 m	< 100 m
	HVAC S	8 m	7 m	29 m	21 m	45 m	31 m	59 m	39 m	75 m	49 m	200 m	160 m

TTS results (marine mammals)

Table 5.8: *Summary of the maximum and mean ranges out to which TTS is expected to occur in Low Frequency (LF) Cetaceans.*

Low Frequency (LF) Cetaceans (TTS)		213 dB re 1 µPa Unweighted SPL_{peak}										168 dB re 1 µPa²s Weighted SEL_{cum} (Fleeing 3.25 ms^{-1})	
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy			
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	120 m	70 m	380 m	180 m	560 m	260 m	720 m	320 m	810 m	360 m	99 km	57 km
	NE	120 m	74 m	380 m	200 m	560 m	280 m	710 m	350 m	810 m	390 m	97 km	58 km
	S	130 m	75 m	390 m	200 m	580 m	280 m	740 m	350 m	840 m	390 m	65 km	52 km
	HVAC N	47 m	35 m	140 m	96 m	230 m	150 m	260 m	170 m	300 m	190 m	41 km	32 km
	HVAC S	94 m	57 m	300 m	160 m	440 m	230 m	690 m	300 m	840 m	360 m	54 km	32 km
Pin Pile (2500kJ)	NW	25 m	21 m	77 m	62 m	110 m	91 m	140 m	110 m	170 m	130 m	94 km	54 km
	NE	31 m	21 m	100 m	64 m	160 m	94 m	210 m	120 m	250 m	140 m	92 km	55 km
	S	28 m	22 m	94 m	65 m	140 m	96 m	180 m	120 m	210 m	140 m	61 km	49 km
	HVAC N	13 m	11 m	43 m	32 m	66 m	48 m	85 m	61 m	100 m	73 m	38 km	29 km
	HVAC S	23 m	17 m	80 m	52 m	120 m	77 m	150 m	96 m	200 m	120 m	50 km	30 km

Table 5.9: Summary of the maximum and mean ranges out to which TTS is expected to occur in Mid Frequency (MF) Cetaceans.

Mid Frequency (MF) Cetaceans (TTS)		224 dB re 1 µPa Unweighted SPL_{peak}										170 dB re 1 µPa²s Weighted SEL_{cum} (Fleeing 1.5 ms^{-1})	
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy			
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	11 m	8 m	34 m	22 m	49 m	30 m	63 m	38 m	71 m	42 m	< 100 m	< 100 m
	NE	11 m	8 m	34 m	23 m	49 m	32 m	63 m	40 m	71 m	44 m	< 100 m	< 100 m
	S	11 m	8 m	34 m	23 m	50 m	32 m	64 m	40 m	73 m	45 m	< 100 m	< 100 m
	HVAC N	4 m	4 m	14 m	11 m	23 m	18 m	27 m	20 m	30 m	23 m	< 100 m	< 100 m
	HVAC S	8 m	6 m	26 m	18 m	38 m	25 m	55 m	33 m	67 m	39 m	< 100 m	< 100 m
Pin Pile (2500kJ)	NW	3 m	3 m	10 m	8 m	15 m	13 m	19 m	16 m	22 m	19 m	1.6 km	1.2 km
	NE	3 m	3 m	12 m	9 m	18 m	13 m	24 m	17 m	28 m	19 m	1.5 km	1.1 km
	S	3 m	3 m	11 m	9 m	17 m	13 m	21 m	17 m	25 m	20 m	700 m	550 m
	HVAC N	1 m	1 m	5 m	4 m	8 m	7 m	10 m	8 m	13 m	11 m	< 100 m	< 100 m
	HVAC S	2 m	2 m	9 m	7 m	13 m	10 m	18 m	13 m	23 m	16 m	< 100 m	< 100 m

Table 5.10: Summary of the maximum and mean ranges out to which TTS is expected to occur in High Frequency (HF) Cetaceans.

High Frequency (HF) Cetaceans (TTS)		196 dB re 1 µPa Unweighted SPL_{peak}										140 dB re 1 µPa²s Weighted SEL_{cum} (Fleeing 1.5 ms⁻¹)	
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy			
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	3.4 km	1.9 km	6.9 km	4.8 km	8.7 km	6.4 km	9.6 km	7.7 km	10.3 km	8.4 km	58 km	36 km
	NE	3.4 km	2.0 km	6.3 km	4.9 km	8.4 km	6.3 km	10 km	7.6 km	10.4 km	8.3 km	56 km	37 km
	S	3.5 km	2.3 km	7.3 km	5.6 km	10 km	7.2 km	12 km	8.8 km	12.8 km	9.6 km	39 km	31 km
	HVAC N	1.6 km	930 m	4.1 km	3.0 km	5.6 km	4.2 km	5.9 km	4.6 km	6.2 km	4.9 km	23 km	19 km
	HVAC S	2.6 km	1.5 km	4.9 km	3.9 km	7.2 km	5.0 km	8.5 km	6.4 km	9.0 km	7.2 km	29 km	21 km
Pin Pile (2500kJ)	NW	590 m	440 m	1.7 km	1.2 km	2.6 km	1.8 km	3.3 km	2.2 km	3.6 km	2.6 km	70 km	44 km
	NE	920 m	450 m	2.1 km	1.3 km	2.8 km	1.8 km	3.5 km	2.3 km	3.7 km	2.7 km	70 km	45 km
	S	760 m	460 m	2.0 km	1.3 km	3.3 km	2.0 km	3.7 km	2.7 km	4.0 km	3.2 km	48 km	38 km
	HVAC N	320 m	210 m	1.0 km	620 m	1.5 km	910 m	1.8 km	1.1 km	2.1 km	1.3 km	28 km	23 km
	HVAC S	670 m	360 m	1.9 km	1.1 km	2.4 km	1.5 km	2.9 km	1.9 km	3.4 km	2.3 km	37 km	25 km

Table 5.11: Summary of the maximum and mean ranges out to which TTS is expected to occur in Phocid Pinnipeds (PW) (underwater).

Phocid Pinnipeds (PW) (TTS)		212 dB re 1 µPa Unweighted SPL_{peak}										170 dB re 1 µPa²s Weighted SEL_{cum} (Fleeing 1.5 ms⁻¹)	
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy			
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	150 m	85 m	480 m	220 m	690 m	310 m	900 m	390 m	1.0 km	430 m	53 km	33 km
	NE	150 m	90 m	480 m	240 m	690 m	340 m	890 m	430 m	1.0 km	480 m	51 km	34 km
	S	160 m	91 m	490 m	240 m	720 m	340 m	920 m	430 m	1.0 km	480 m	34 km	28 km
	HVAC N	58 m	42 m	170 m	110 m	280 m	180 m	330 m	210 m	370 m	230 m	21 km	17 km
	HVAC S	110 m	70 m	380 m	200 m	550 m	280 m	860 m	370 m	1.0 km	440 m	27 km	19 km
Pin Pile (2500kJ)	NW	30 m	26 m	93 m	74 m	130 m	110 m	170 m	130 m	200 m	150 m	45 km	29 km
	NE	38 m	26 m	130 m	77 m	200 m	110 m	260 m	140 m	310 m	160 m	43 km	29 km
	S	34 m	26 m	110 m	78 m	170 m	110 m	220 m	140 m	260 m	170 m	29 km	24 km
	HVAC N	16 m	13 m	52 m	38 m	79 m	57 m	100 m	72 m	120 m	87 m	16 km	13 km
	HVAC S	28 m	20 m	98 m	62 m	150 m	91 m	190 m	110 m	250 m	140 m	22 km	16 km

Behavioural results (marine mammals)

5.3.2.3 As described in the Marine mammals section (from paragraph 3.2.2.2), the results for LF and MF mammals show two sets of ranges. Only the higher noise level (and consequent lower range) denotes any avoidance reaction as defined by Southall *et al.* 2007. The lower 142 dB re 1 µPa²s noise level corresponds to more general changes in behaviour.

Table 5.12: Summary of the maximum and mean ranges out to which a behavioural response is expected to occur in Low Frequency (LF) Cetaceans during the ramp-up procedure (Lower Bound).

Low Frequency (LF) Cetaceans (Behavioural)		152 dB re 1 µPa²s Unweighted SEL (single pulse) (Lower Bound)									
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	35 km	27 km	53 km	58 km	60 km	41 km	64 km	44 km	66 km	45 km
	NE	32 km	27 km	51 km	38 km	58 km	42 km	62 km	44 km	64 km	45 km
	S	25 km	22 km	37 km	32 km	42 km	36 km	45 km	38 km	47 km	39 km
	HVAC N	16 km	15 km	25 km	21 km	29 km	25 km	30 km	26 km	31 km	27 km
	HVAC S	21 km	18 km	30 km	25 km	34 km	27 km	36 km	28 km	38 km	29 km
Pin Pile (2500kJ)	NW	22 km	18 km	41 km	30 km	48 km	34 km	53 km	38 km	57 km	40 km
	NE	20 km	18 km	38 km	31 km	45 km	35 km	51 km	38 km	55 km	40 km
	S	16 km	16 km	29 km	25 km	33 km	29 km	37 km	32 km	40 km	34 km
	HVAC N	10 km	9.8 km	19 km	17 km	23 km	20 km	25 km	21 km	27 km	23 km
	HVAC S	13 km	12 km	23 km	20 km	27 km	23 km	30 km	25 km	32 km	26 km

Table 5.13: Summary of the maximum and mean ranges out to which a behavioural response is expected to occur in Low Frequency (LF) Cetaceans during the ramp-up procedure (Upper Bound).

Low Frequency (LF) Cetaceans (Behavioural)		142 dB re 1 µPa²s Unweighted SEL (single pulse) (Upper Bound)									
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	72 km	48 km	91 km	60 km	98 km	64 km	103 km	66 km	105 km	67 km
	NE	70 km	49 km	91 km	61 km	98 km	65 km	102 km	67 km	104 km	69 km
	S	52 km	43 km	65 km	54 km	70 km	58 km	73 km	61 km	74 km	62 km
	HVAC N	33 km	28 km	43 km	37 km	49 km	40 km	50 km	42 km	52 km	43 km
	HVAC S	41 km	31 km	54 km	38 km	59 km	40 km	61 km	41 km	63 km	42 km
Pin Pile (2500kJ)	NW	55 km	38 km	78 km	52 km	85 km	57 km	91 km	60 km	95 km	62 km
	NE	52 km	39 km	78 km	53 km	85 km	57 km	91 km	61 km	95 km	63 km
	S	38 km	33 km	57 km	47 km	62 km	51 km	65 km	54 km	69 km	57 km
	HVAC N	25 km	22 km	36 km	31 km	40 km	34 km	43 km	37 km	46 km	38 km
	HVAC S	31 km	25 km	45 km	33 km	51 km	36 km	54 km	38 km	57 km	39 km

Table 5.14: Summary of the maximum and mean ranges out to which a behavioural response is expected to occur in Mid Frequency (MF) Cetaceans during the ramp-up procedure (Lower Bound).

Mid Frequency (MF) Cetaceans (Behavioural)		170 dB re 1 µPa²s Unweighted SEL (single pulse) (Lower Bound)									
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	3.3 km	3.2 km	7.0 km	6.7 km	9.0 km	8.5 km	11 km	9.8 km	11 km	10 km
	NE	3.2 km	3.1 km	7.0 km	6.6 km	8.8 km	8.4 km	10 km	9.6 km	11 km	10 km
	S	3.1 km	3.0 km	6.3 km	6.1 km	7.8 km	7.6 km	8.9 km	8.6 km	9.5 km	9.1 km
	HVAC N	1.8 km	1.8 km	3.9 km	3.8 km	5.3 km	5.0 km	5.7 km	5.5 km	6.4 km	6.0 km
	HVAC S	2.5 km	2.4 km	5.0 km	4.9 km	6.3 km	6.1 km	7.2 km	6.9 km	8.0 km	7.6 km
Pin Pile (2500kJ)	NW	1.6 km	1.6 km	4.2 km	4.1 km	5.7 km	5.5 km	7.1 km	6.8 km	8.1 km	7.7 km
	NE	1.6 km	1.6 km	4.2 km	4.0 km	5.6 km	5.4 km	7.0 km	6.6 km	8.0 km	7.6 km
	S	1.6 km	1.6 km	3.9 km	3.8 km	5.2 km	5.1 km	6.3 km	6.1 km	7.1 km	6.9 km
	HVAC N	900 m	850 m	2.3 km	2.3 km	3.2 km	3.1 km	3.9 km	3.7 km	4.5 km	4.3 km
	HVAC S	1.3 km	1.2 km	3.1 km	3.0 km	4.2 km	4.1 km	5.0 km	4.9 km	5.8 km	5.6 km

Table 5.15: Summary of the maximum and mean ranges out to which a behavioural response is expected to occur in Mid Frequency (MF) Cetaceans during the ramp-up procedure (Upper Bound).

Mid Frequency (MF) Cetaceans (Behavioural)		160 dB re 1 µPa²s Unweighted SEL (single pulse) (Upper Bound)									
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	14 km	13 km	26 km	21 km	31 km	25 km	35 km	27 km	36 km	28 km
	NE	13 km	12 km	24 km	21 km	29 km	25 km	32 km	27 km	34 km	28 km
	S	11 km	11 km	19 km	18 km	23 km	20 km	25 km	22 km	26 km	23 km
	HVAC N	7.2 km	6.8 km	13 km	12 km	16 km	14 km	17 km	15 km	18 km	16 km
	HVAC S	9.3 km	8.8 km	16 km	14 km	19 km	17 km	21 km	18 km	22 km	19 km
Pin Pile (2500kJ)	NW	7.5 km	7.2 km	17 km	15 km	22 km	19 km	26 km	21 km	29 km	23 km
	NE	7.4 km	7.0 km	16 km	15 km	21 km	18 km	24 km	21 km	27 km	23 km
	S	6.6 km	6.5 km	14 km	13 km	17 km	16 km	19 km	18 km	21 km	19 km
	HVAC N	4.0 km	3.8 km	8.6 km	8.1 km	11 km	10 km	13 km	12 km	14 km	13 km
	HVAC S	5.2 km	5.1 km	11 km	10 km	14 km	13 km	16 km	14 km	17 km	16 km

Table 5.16: Summary of the maximum and mean ranges out to which a behavioural response is expected to occur in High Frequency (HF) Cetaceans during the ramp-up procedure.

High Frequency (HF) Cetaceans (Behavioural)		145 dB re 1 µPa²s Unweighted SEL (single pulse)									
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	61 km	42 km	79 km	53 km	86 km	57 km	90 km	59 km	92 km	60 km
	NE	58 km	42 km	80 km	54 km	86 km	58 km	90 km	60 km	92 km	61 km
	S	42 km	36 km	58 km	48 km	62 km	52 km	65 km	54 km	66 km	55 km
	HVAC N	28 km	24 km	38 km	32 km	41 km	36 km	42 km	37 km	45 km	38 km
	HVAC S	34 km	27 km	46 km	34 km	51 km	36 km	54 km	37 km	56 km	39 km
Pin Pile (2500kJ)	NW	44 km	32 km	67 km	45 km	74 km	50 km	79 km	53 km	83 km	55 km
	NE	41 km	18 km	65 km	46 km	73 km	51 km	80 km	54 km	83 km	56 km
	S	31 km	27 km	47 km	40 km	54 km	44 km	58 km	48 km	61 km	50 km
	HVAC N	20 km	18 km	31 km	26 km	35 km	30 km	38 km	32 km	39 km	34 km
	HVAC S	25 km	21 km	38 km	29 km	43 km	32 km	46 km	34 km	49 km	35 km

5.3.2.4 It should be noted that Lucke *et al.* (2009) showed a consistent aversive behaviour by a harbour porpoise at sound pressure levels above 168 dB SPL_{peak}[3] re 1 µPa or a SEL of 145 dB re 1 µPa²s, with both levels sampled in the same location. As modelled, this shows a large disparity between HF cetacean ranges which should, nominally, be 'identical'. This is expected to be because Lucke *et al.* (2009) sampled the noise levels at close range in laboratory conditions, whereas the effect on the sound wave as it propagates will be different at long range in open water as the sound wave 'spreads'. This means the modelled SPL_{peak} will be noticeably overestimated and so the range to 145 dB SEL is more appropriate.

5.3.2.5 As per Table 3.3, pinniped potential behavioural effect ranges are the same as for TTS in Table 5.11.

Discussion

5.3.2.6 The ranges of impact vary depending on the functional hearing (species) group and severity of impact. This variation is expressed clearly between the results of the LF, MF and HF cetaceans shown in Table 5.4, Table 5.5 and Table 5.6.

5.3.2.7 In general, the LF cetacean weighting leads to the greatest ranges as the MF and HF cetacean weighting filters out the majority of the piling energy; this is discussed further below. Although the MF and HF weightings are similar (see Figure 3.1), the HF cetacean criterion is much stricter (a lower noise level, i.e. HF cetaceans are deemed more sensitive) and so the ranges before this level is reached in the sea are much higher than for MF cetaceans.

5.3.2.8 The SEL_{cum} results for MF and HF cetaceans using the NMFS criteria (Table 5.6, Table 5.9 and Table 5.10) appear to be paradoxical, as a larger hammer hitting a larger monopile results in lower impact ranges than a smaller hammer hitting a pin pile. This is explained by the difference in sensitivity of the hearing groups and the sound frequencies produced by the different piles.

5.3.2.9 The frequency spectra used as inputs to the model (Figure 5.2) show that the noise from pin piles contain more high frequency components than the noise from monopiles. The overall unweighted noise level is higher for the monopile due to the low frequency components of piling noise (i.e. the majority of the pile strike energy is at low frequency). The MF and HF cetacean filters (Figure 3.1) both remove the low frequency components of the noise, as these marine mammals are much less sensitive at these frequencies. This leaves the high frequency noise, which, in the case of the pin piles, is greater than that for monopiles.

5.3.2.10 In order to illustrate this, Figure 5.9 shows the sound frequency spectra for monopiles and pin piles, adjusted (weighted) to account for the sensitivities of MF and HF cetaceans. These can be compared to the original unweighted frequency spectra in Figure 5.2 (shown as greyed out in Figure 5.9). It can be seen that, overall, higher levels are present in the weighted pin pile spectrum, especially around 6 kHz to 12 kHz.

[3] Value approximately equivalent to 174 dB_{pk-pk} re 1 µPa as reported in Lucke *et al.* (2009).

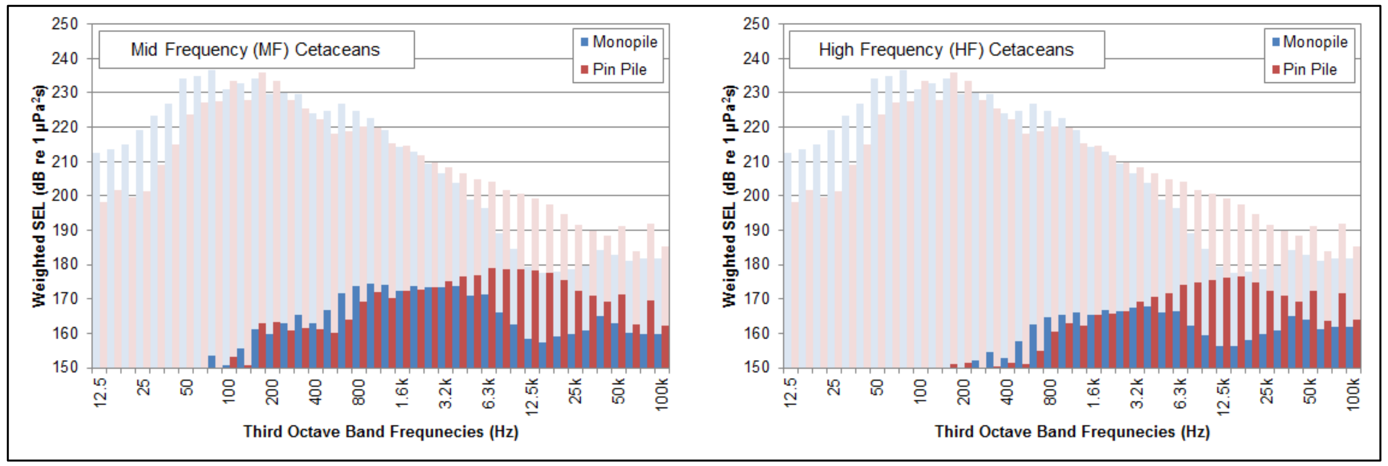

Figure 5.9: Filtered noise inputs for monopiles and pin piles using the MF cetacean and HF cetacean filters from NMFS (2016). The translucent bars show the unweighted third octave levels.

5.3.2.11 In order to not underestimate the potential impacts, each step of the modelling uses the maximum possible value to ensure that the risks are covered, although this leads to an assessment of a situation that is much worse than would happen in practice. As well as assumptions that the maximum hammer energy is used for the majority of the time during the piling process, which continues for four hours (two hours being more typical for installation of offshore windfarm monopiles), the following aspects to the modelling should be considered:

- The maximum noise level vertically in the water column was used in cumulative noise exposure calculations, meaning at all distances from the pile the receptor animal is assumed to be at the loudest position in the water;
- When close to the pile, the noise is highly impulsive, whereas over distance the noise spreads due to the difference in the speed of sound with frequency. This reduction in 'sharpness' is not taken into account in modelling, nor the proposed criteria, and will lead to lower peak levels and a reduced likelihood of reaction by a receptor; and
- Other modelling parameters, such as temperatures in the water, were selected to represent those that would produce greatest ranges.

5.3.2.12 The new NMFS criteria, published in 2016, add to the layers of precautionary parameters in the modelling for marine mammals, particularly for the LF and HF cetaceans. The new LF and HF thresholds have led to substantially greater modelled ranges of impact than have been seen previously, and combined with the use of precautionary parameters mean that a situation where this could occur in practice is extremely unlikely.

5.3.2.13 Taking these considerations into account, it is recommended the ranges modelled to cumulative SEL criteria are treated with caution.

Impacts on fish

5.3.2.14 Table 5.17 gives the maximum and mean impact ranges for species of fish based on the injury criteria found in the Popper *et al.* (2014) guidance. Contour plots of the SEL_{cum} ranges are given in Appendix A. Figure 5.10 and Figure 5.11 give the SEL_{cum} values for fleeing animals as a function of cumulative received level and receptor starting range on single transects. Fish impact thresholds are not weighted.

Table 5.17: Summary of the maximum and mean ranges for recoverable injury in species of fish.

Fish (Recoverable Injury)		207 dB re 1 µPa Unweighted SPL_{peak}										203 dB re 1 µPa²s Unweighted SEL_{cum} (Fleeing 1.5 ms⁻¹)	
		15% blow energy		40% blow energy		60% blow energy		80% blow energy		100% blow energy			
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Monopile (5000kJ)	NW	470 m	220 m	1.4 km	600 m	1.8 km	830 m	2.0 km	1.0 km	2.0 km	1.1 km	5.4 km	4.2 km
	NE	470 m	240 m	1.4 km	660 m	1.8 km	910 m	2.0 km	1.1 km	2.1 km	1.2 km	4.9 km	4.1 km
	S	490 m	240 m	1.5 km	670 m	1.8 km	920 m	2.0 km	1.1 km	2.1 km	1.2 km	3.2 km	2.9 km
	HVAC N	160 m	110 m	500 m	310 m	810 m	490 m	940 m	560 m	1.0 km	620 m	500 m	310 m
	HVAC S	360 m	190 m	1.1 km	540 m	1.6 km	770 m	1.9 km	990 m	2.0 km	1.1 km	1.8 km	1.4 km
Pin Pile (2500kJ)	NW	77 m	63 m	230 m	170 m	340 m	260 m	440 m	330 m	520 m	380 m	2.1 km	1.6 km
	NE	100 m	63 m	350 m	180 m	540 m	270 m	700 m	350 m	830 m	400 m	1.9 km	1.5 km
	S	91 m	64 m	300 m	190 m	450 m	280 m	580 m	350 m	690 m	410 m	1.0 km	840 m
	HVAC N	41 m	31 m	130 m	91 m	200 m	130 m	260 m	170 m	320 m	200 m	< 100 m	< 100 m
	HVAC S	76 m	50 m	260 m	150 m	400 m	220 m	520 m	280 m	670 m	360 m	< 100 m	< 100 m

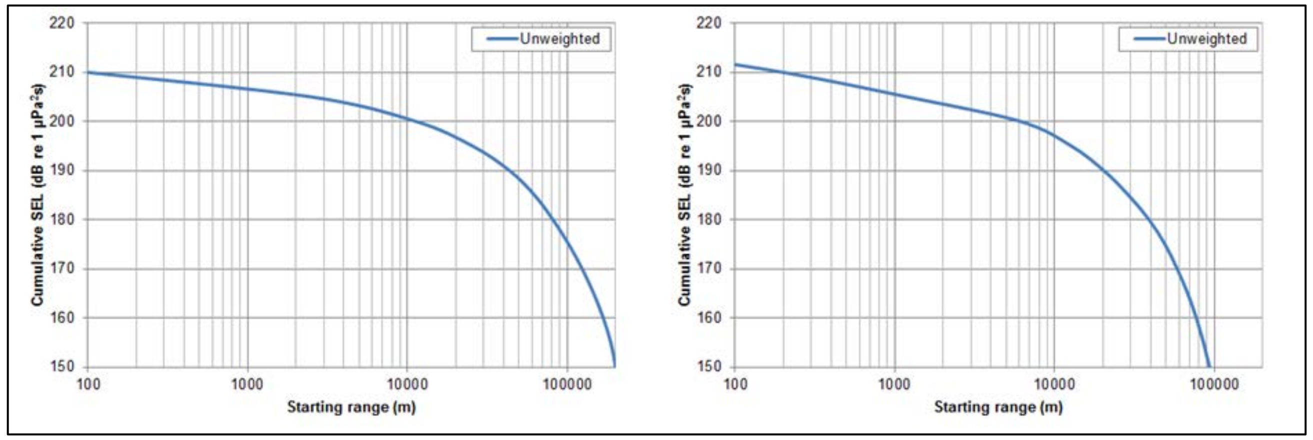

Figure 5.10: Total received cumulative SEL for species of fish (Popper *et al.* (2014) criteria) when fleeing from impact piling noise at Northwest location for a monopile installed with a maximum hammer energy of 5000 kJ.

(Left plot = West-northwest transect (290°), Right plot = South-southwest transect (190°))

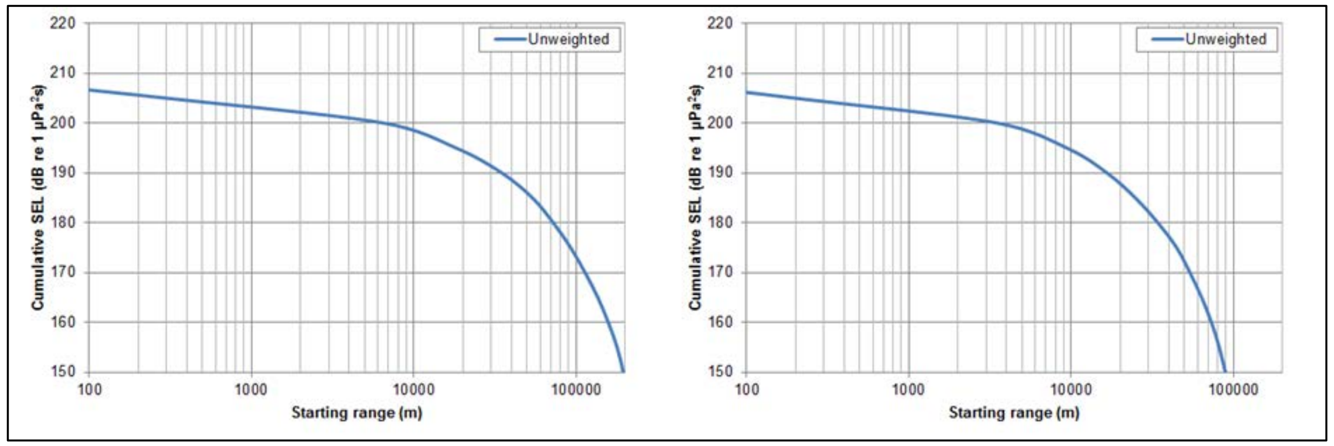

Figure 5.11: Total received cumulative SEL for species of fish (Popper *et al.* (2014) criteria) when fleeing from impact piling noise at Northwest location for a pin pile installed with a maximum hammer energy of 2500 kJ

(Left plot = West-northwest transect (290°), Right plot = South-southwest transect (190°))

5.3.2.15 As stated in section 3.2.2, for effects where insufficient data exist to make recommendations for thresholds Popper *et al.* (2014) gives an indication of the relative risk of the effect. In each case three overarching distances for source are given along with a relative risk rating.

5.3.2.16 The three qualitative distances given are “near”, “intermediate”, and “far”; Popper *et al.* (2014) states that “while it would not be appropriate to ascribe particular distances to effects because of the many variables in making such decisions, “near” might be considered to be in the tens of meters from the source, “intermediate” in the hundreds of meters, and “far” in the thousands of meters.” These ranges are each given a risk rating or either “high”, “moderate”, or “low”. The ratings are again split into noise type (in this case, pile driving) and type of fish.

5.3.2.17 Table 5.18 summarises the qualitative impacts for pile driving given by Popper *et al.* (2014) for fish with swim bladders involved with their hearing, which are most sensitive. Table 5.19 shows the results from the two remaining categories, “no swim bladder” and “swim bladder not involved in hearing”, which are less sensitive to sound.

Table 5.18: Summary of the qualitative impacts on fish with swim bladder involved in hearing (most sensitive).

Effect	Near ranges	Intermediate ranges	Far ranges
Masking	High risk	High risk	Moderate risk
Behavioural	High risk	High risk	Moderate risk

Table 5.19: Summary of the qualitative impacts on other species of fish.

Effect	Near ranges	Intermediate ranges	Far ranges
Masking	Moderate risk	Low risk	Low risk
Behavioural	High risk	Moderate risk	Low risk

5.4 Concurrent piling within Hornsea Three

5.4.1.1 It is possible that two piling vessels could be operational at the same time during construction work at Hornsea Three. In order to show the effect of this, modelling has been carried out at the Northwest and South locations on Hornsea Three (Figure 5.1), which gives the greatest spatial range of noise propagation for two operations on the Hornsea Three wind farm site. This modelling is presented in Figure 5.12 for monopiles and Figure 5.13 for pin piles.

5.4.1.2 It should be noted that this simultaneous piling scenario is based on the maximum design scenario modelling presented in section 5.2 and models two piling vessels reaching their maximum blow energies at the same time.

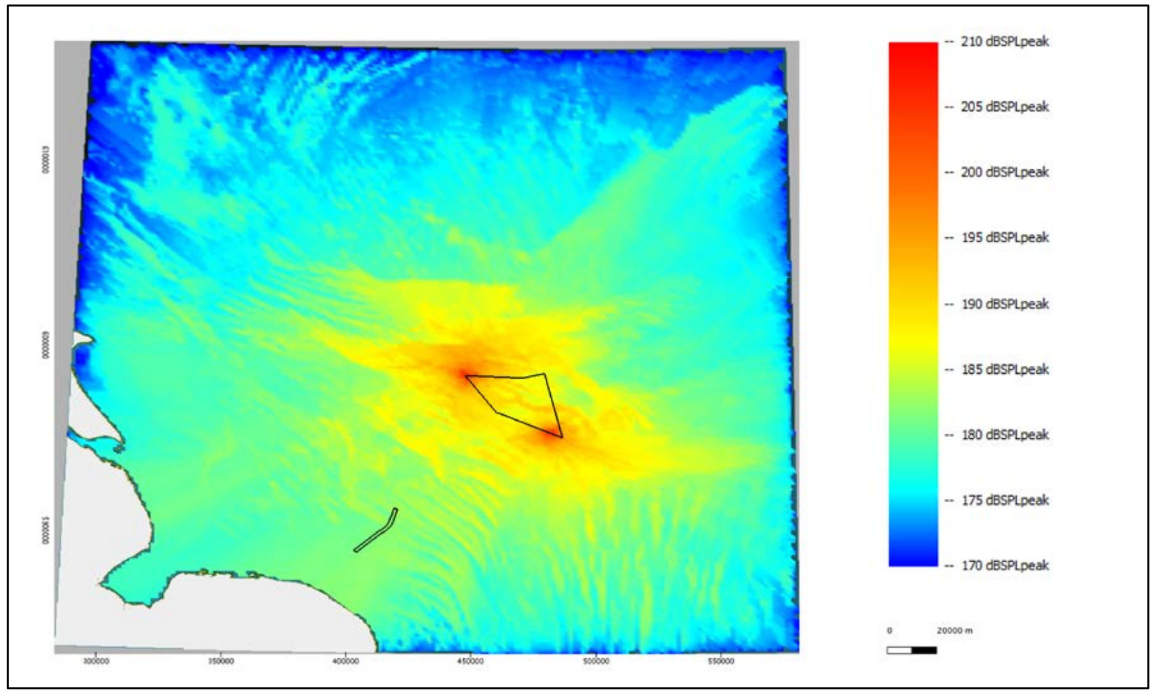

Figure 5.12: Noise level plot showing the modelled unweighted SPL_{peak} noise levels for simultaneous piling at the Northwest and South locations of Hornsea Three for installing monopiles with a maximum blow energy of 5000 kJ.

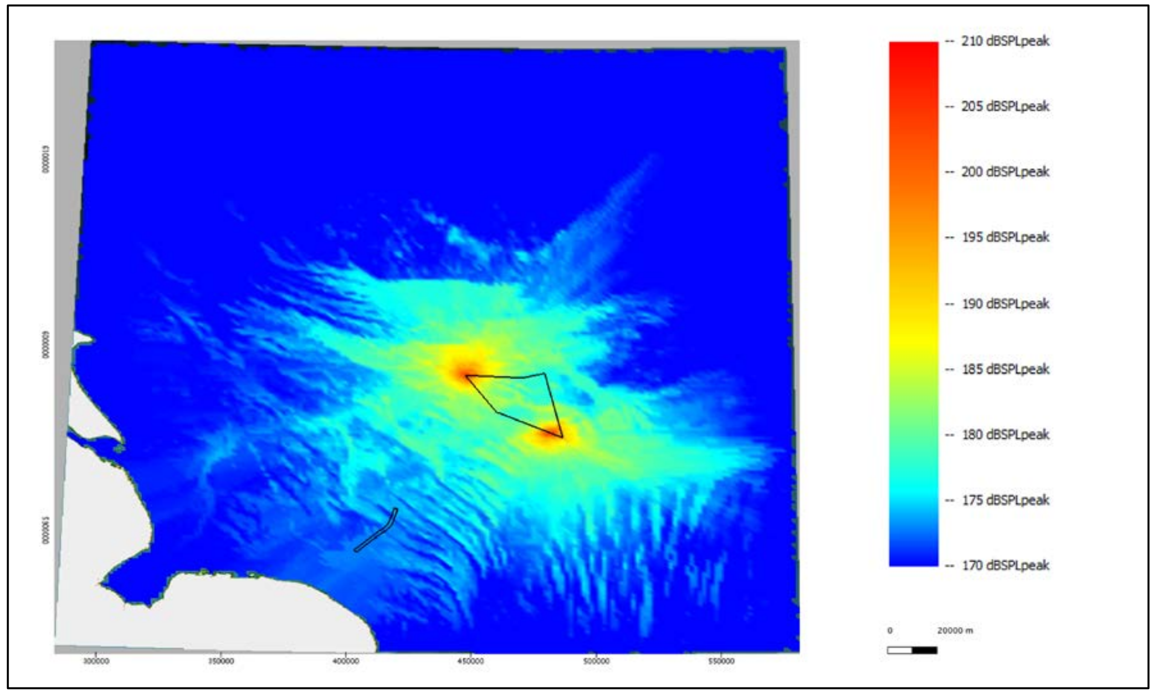

Figure 5.13: Noise level plot showing the modelled unweighted SPL_{peak} noise levels for simultaneous piling at the Northwest and South locations of Hornsea Three for installing pin piles with a maximum blow energy of 2500 kJ.

5.5 Seabed vibration (qualitative)

5.5.1.1 In addition to the waterborne noise produced by piling during the wind farm life cycle, the hammer strike on the piles transmits vibration down the structure and propagates vibration into the seabed sediment, where invertebrates, flat and benthic fish are found. Any introduced energy to the seabed could potentially have an impact on receptors experiencing increased levels.

5.5.1.2 Although Mooney *et al.* (2012) and Samson *et al.* (2016) identified cephalopods' sensitivity to subsea noise in the water column and that it can act as a stressor, any specific sensitivity to seabed vibration could not be determined. There is insufficient data for development of vibration criteria for any species. However, the damping effect of the sediment within the seabed means that vibrations in the seabed would not travel as far as through the water column and so any effect is likely to be over a relatively short range.

5.5.1.3 Roberts and Elliott (2017) conducted a literature review of the impacts of low and high levels of seabed vibration and found evidence of behavioural and physiological sensitivity in benthic species. The overall significance of this however is still unknown, particularly due to the short-term nature of the pile installation period.

5.5.1.4 Any quantitative impact over the life cycle of the wind farm is hard to identify. Although Bergström *et al.* (2014), in a wide review of offshore wind farm impact literature, suggested that OWFs could create a beneficial artificial reef effect, Langhamer *et al.* (2016) found no positive or negative impact on populations of Common Shore Crab (*Carcinus maenas*) at the Lillgrund OWF in Sweden, suggesting the effects of any seabed vibration are minimal. Concerning marine benthic species generally, the OSPAR Commission (2008) could not identify any evidence or trend for organisms associated with the construction of an offshore wind farm in UK waters. A long-term impact specifically associated with seabed vibration during the operational phase therefore appears unlikely.

6. Operational Noise

6.1.1.1 It is believed that the main source of underwater noise from operational turbines will be mechanically generated vibration from the turbines, which is transmitted into the sea through the structure of the support pile and foundations (Nedwell *et al.*, 2003a, Sigray and Andersson, 2011). Noise levels generated above the water surface are low enough that no significant airborne sound will pass from the air to the water.

6.1.1.2 Operational turbine noise has been observed by Lindell, 2003 and Nedwell *et al.* 2007) to be relatively broadband with a tonal component. The exact position and level of the tonal component is expected to be dependent on wind-speed and turbine-make; more generally it has been observed that the sound can be broken into three distinct bands:

- Frequencies up to 10 Hz – spectra are relatively featureless with measurement levels dominated by hydrodynamic pressure changes;
- From 10 Hz to 200 Hz – the spectra tend to be dominated by tonal noise; and
- From 200 Hz to 10 kHz – broadband noise; however the nature of the noise is consistent with noise caused by the wind interacting with the rough sea surface (i.e. independent of the wind turbine).

6.2 Noise modelling

6.2.1.1 The size and model of turbines to be used at Hornsea Three have yet to be finalised, however operational offshore wind farm sites where measurements have been collected are summarised in Table 6.1 below. The turbines to be used at Hornsea Three are almost certainly going to be larger than these, and hence a scaling factor has been assumed in order to estimate impact ranges, explained further below.

6.2.1.2 It has been assumed that the turbines at Hornsea Three will be between 7 and 15 MW in capacity. In order to give a representative spread of impact ranges, three turbine sizes have been modelled; 7 MW, 10 MW and 15 MW.

6.2.1.3 The estimation of the effects of operational noise in these situations has two features that make it harder to assess compared with noise sources such as impact piling. Primarily, the problem is one of level; noise measurements made at many wind farms have demonstrated that the operational noise produced was at such a low level that it was difficult to measure relative to the background noise (Cheesman, 2016). Also, an offshore wind farm should be considered as an extended, distributed noise source, as opposed to a 'point source' as would be appropriate for pile driving, for example. In fact, the measurement techniques used at the sites above have dealt with these issues by considering the operational noise spectra in terms of levels within and on the edge of the wind farm (but relatively close to the wind farm so that some measurements above background could be detected).

Table 6.1: Characteristics of measured operational wind farms used as a basis for modelling.

	Lynn	Inner Dowsing	Gunfleet Sands 1 & 2	Gunfleet Sands 3
Type of turbine used	Siemens SWT-3.6-107	Siemens SWT-3.6-107	Siemens SWT-3.6-107	Siemens SWT-6.0-120
Number of turbines	27	27	48	2
Rotor diameter	107 m	107 m	107 m	120 m
Water depths	6 to 18 m	6 to 14 m	0 to 15 m	5 to 12 m
Representative sediment type	Sandy gravel / Muddy sandy gravel	Sandy gravel / Muddy sandy gravel	Sand / Muddy Sand / Muddy Sandy Gravel	Sand / Muddy Sand / Muddy Sandy Gravel
Turbine separation (representative)	500 m	500 m	890 m	435 m

6.2.1.4 All three of the turbine sizes considered for this modelling are larger than those listed in Table 6.1. Hornsea Three is in greater water depths and as such, estimations of a scaling factor have to be highly conservative.

6.2.1.5 The operational source levels (as SPL_{RMS}) for the three sites are given in Table 6.2 (Cheesman, 2016) with estimated source levels for Hornsea Three given in the bottom three rows. To predict the operational noise emission at Hornsea Three, the noise levels sampled at each of the sites have been taken, and then a linear correction factor has been added to scale up the source levels; as shown in Figure 6.1. A linear fit has been chosen to give a worst case estimate due to the lack of available data for larger turbines, and is likely to significantly overestimate the noise output from the largest turbines relative to the smaller ones where empirical data is available.

Table 6.2: Measured operational noise taken at operational wind farms and the predicted source levels for various sizes of turbine at Hornsea Three.

	Turbine power output	Unweighted source level (RMS)
Lynn	3.6 MW	141 dB re 1 µPa (RMS) @ 1 m
Inner Dowsing	3.6 MW	142 dB re 1 µPa (RMS) @ 1 m
Gunfleet Sands 1 & 2	3.6 MW	145 dB re 1 µPa (RMS) @ 1 m
Gunfleet Sands 3	6.0 MW	146 dB re 1 µPa (RMS) @ 1 m
Hornsea Three (7MW turbine)	7.0 MW	147.4 dB re 1 µPa (RMS) @ 1 m
Hornsea Three (10MW turbine)	10.0 MW	151.6 dB re 1 µPa (RMS) @ 1 m
Hornsea Three (15 MW turbine)	15.0 MW	158.5 dB re 1 µPa (RMS) @ 1 m

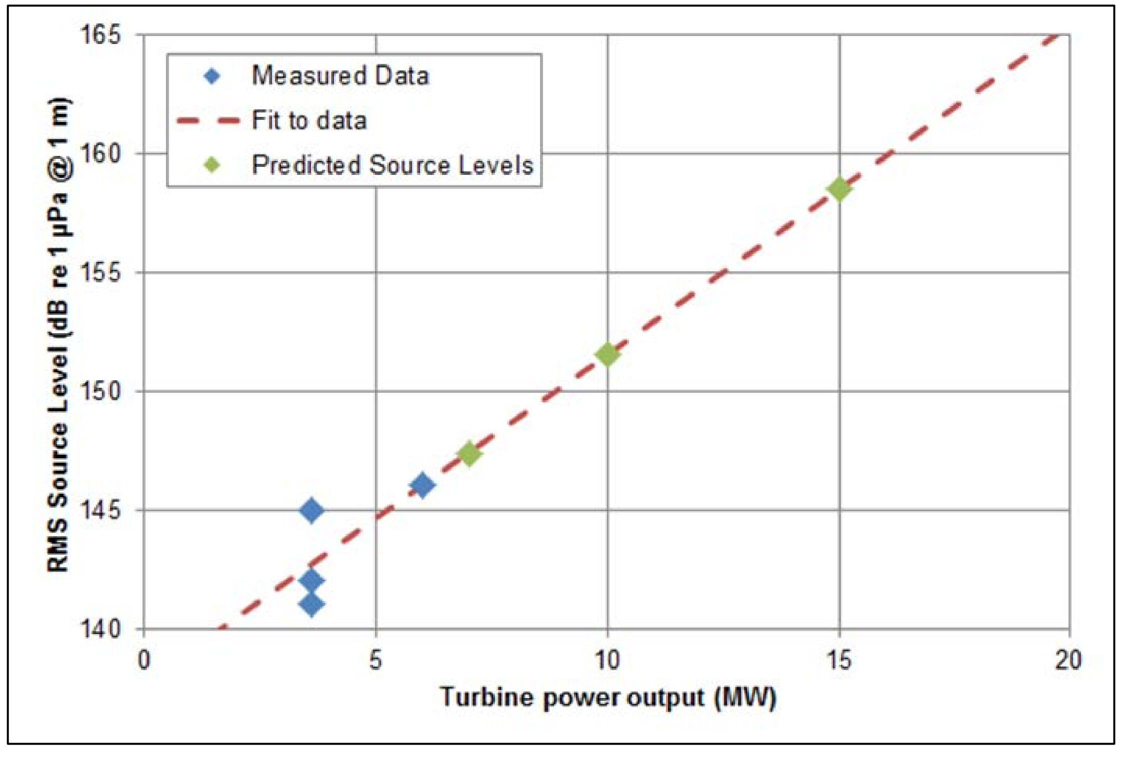

Figure 6.1: Extrapolated source levels from operational turbines plotted with a linear fit to estimate source levels for larger turbines.

6.2.1.6 A typical modelling scenario was run using the same approach as section 5.1 for impact piling, concentrating on the levels of the three turbine sizes at the Northwest location of Hornsea Three (Figure 5.1). These predicted levels were extrapolated as SEL_{cum} values and adjusted for the criteria given in NMFS (2016) and Popper *et al.* (2014); it should be noted that these studies give alternative criteria for non-impulsive and continuous noise, which includes operational turbine noise.

6.2.1.7 Assuming the same fleeing speeds used for the construction noise modelling over a 24 hour period the predicted impact ranges for turbine noise, even that for the largest 15MW turbine, are less than 10 m. This means that underwater noise during the operational phase is expected to have a negligible range of influence on any marine receptors.

7. Decommissioning Noise

7.1.1.1 Decommissioning noise also needs to be considered even in light of the expected 25 years of operational life. With present technologies, the following decommissioning techniques have been considered.

- High-powered water jetting/cutting apparatus; and
- Grinding or drilling techniques.

7.1.1.2 It is also worth noting that by the time Hornsea Three is decommissioned, there are likely to be many more options available for decommissioning.

7.1.1.3 Water jetting and grinding techniques would produce noise at a much lower and less intrusive level than impact piling. Decommissioning is anticipated to take approximately eleven years, about the same duration as expected for construction. Thus, the overall impact is expected to be lower than during the construction phase.

7.1.1.4 Only closer to the time of decommissioning, when local marine life is known and understood, can a realistic and useful assessment of the effects of the noise, and the appropriate mitigation, be carried out. Subsequently, it seems clear that a separate and new impact assessment will be required closer to the time of decommissioning and no further discussion will be made here.

8. Summary and conclusions

8.1.1.1 Subacoustech Environmental has undertaken a study on behalf of DONG Energy Ltd to assess the effect of potential noise from construction, operation and eventual decommissioning of the Hornsea Project Three offshore wind farm site located in the southern North Sea.

8.1.1.2 A study of various underwater noises showed that the greatest effects occur during impact piling. The level of underwater noise from the installation of monopiles and pin piles during construction has been estimated using a parabolic equation (PE) method for lower frequencies, and a ray tracing method for higher frequency noise. The modelling takes into account a wide variety of input parameters including bathymetry, hammer blow energy, frequency content, seabed properties and the speed of sound in water.

8.1.1.3 Five locations covering the wind farm site and the nearby HVAC search area have been modelled to give a wide spatial coverage, and modelling has assumed two piling scenarios; a 5000 kJ maximum hammer energy for installing a monopile and a 2500 kJ maximum hammer energy for installing a pin pile. Ramp up scenarios have been assumed for calculations of cumulative sound exposure level criteria.

8.1.1.4 The modelled results have then been assessed in terms of biologically significant metrics and impact criteria from NFMS (2016) for marine mammals and Popper *et al.* (2014) for fish. These have been used to predict permanent threshold shift (PTS), temporary threshold shift (TTS) and behavioural effects in marine receptors. Noise from two simultaneous piling operations occurring at the Hornsea Three site have been discussed.

8.1.1.5 Underwater noise during the operational phase is expected to have a range of influence of the order of tens of metres. While noise during decommissioning techniques has the potential for considerable effect, a separate and new impact assessment will be required once the techniques are understood.

8.1.1.6 The potential impacts of seabed vibration on benthic receptors have been considered and are investigated further in volume 2, chapter 3: Fish and Shellfish and volume 2, chapter 4: Marine Mammal.

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Appendix A Modelling Figures

A.1.1.1 The following pages present the modelling outputs for all the modelling locations and scenarios.

A.2 Unweighted levels

A.2.1.1 The following figures, produced using combined parabolic equation and ray tracing modelling, present the unweighted SPL_{peak} noise levels with reference to the unweighted results presented in section 5.2 of this report. As stated previously, these figures show the highest modelled noise level in the water column at that point, which is variable, and give a worst case overview of the unweighted noise from impact piling:

- Figure A.1 Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the Northwest location of Hornsea Three for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.2 Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the Northeast location of Hornsea Three for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.3 Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the South location of Hornsea Three for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.4 Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the HVAC North location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.5 Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the HVAC South location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.6 Noise level plot showing the modelled unweighted SPLpeak noise levels at the Northwest location of Hornsea Three for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.7 Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the Northeast location of Hornsea Three for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.8 Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the South location of Hornsea Three for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.9 Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the HVAC North location for installing a pin pile with a maximum blow energy of 2500 kJ; and
- Figure A.10 Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the HVAC South location for installing a pin pile with a maximum blow energy of 2500 kJ.

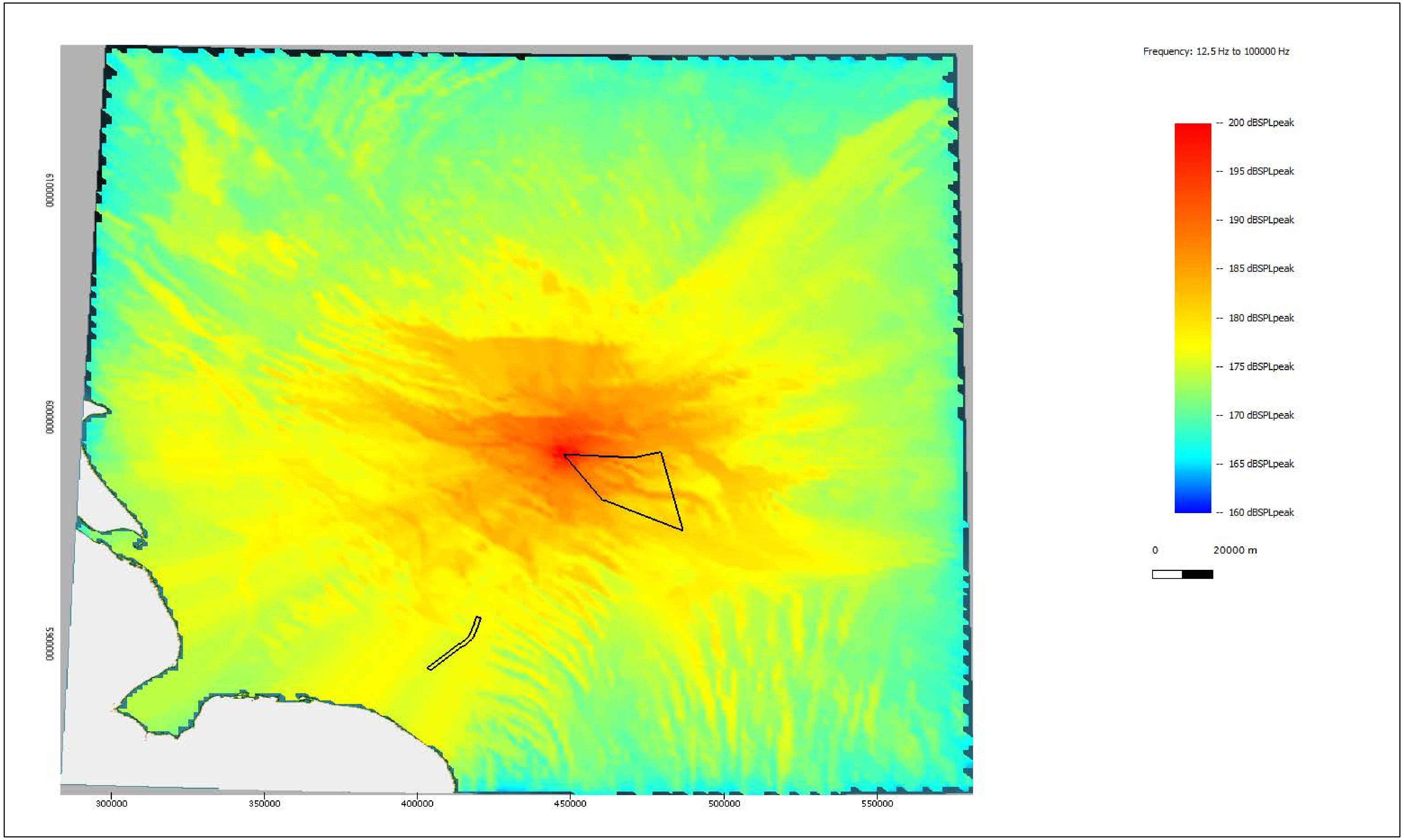

Figure A.1: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the Northwest location of Hornsea Three for installing a monopile with a maximum blow energy of 5000 kJ.

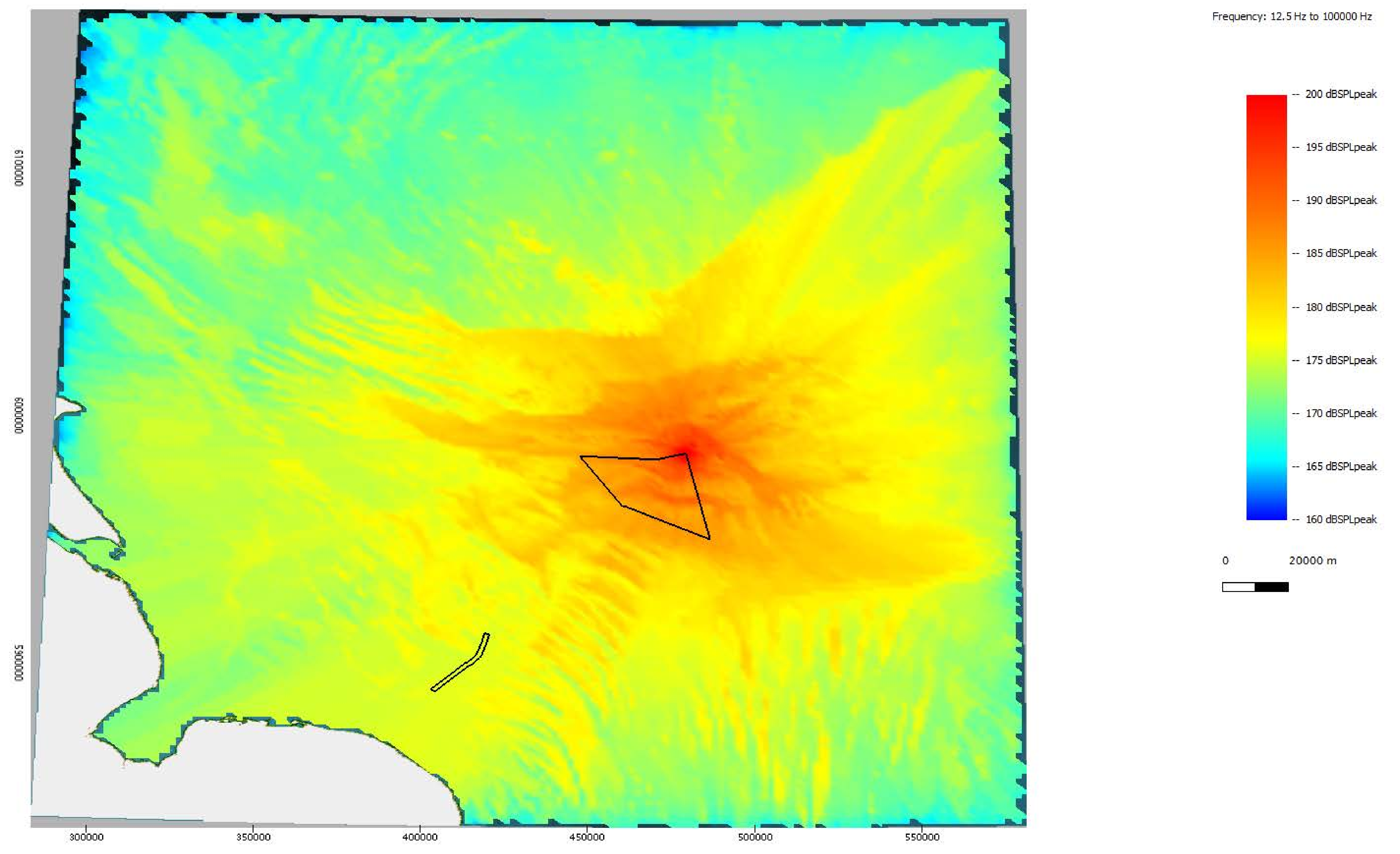

Figure A.2: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the Northeast location of Hornsea Three for installing a monopile with a maximum blow energy of 5000 kJ.

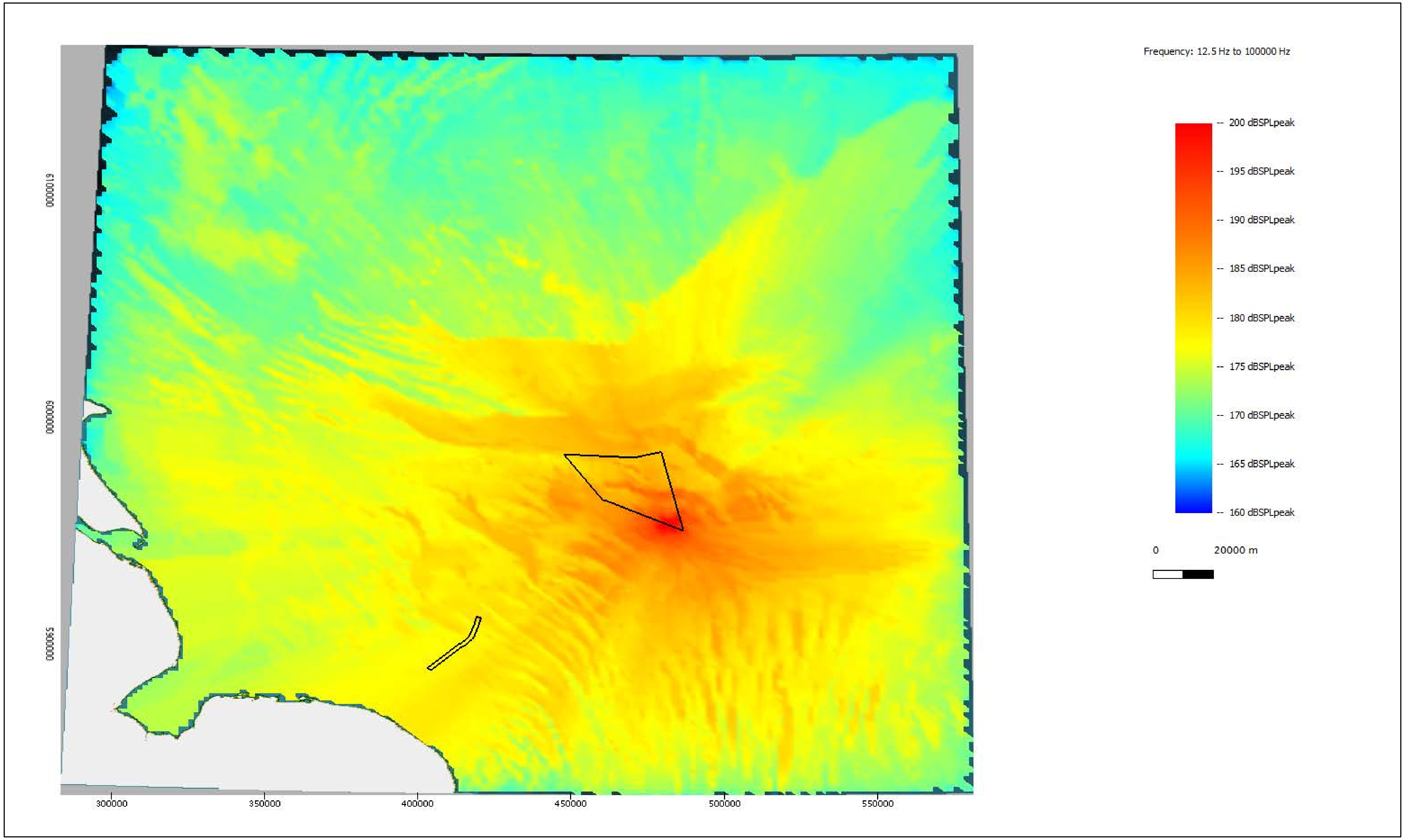

Figure A.3: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the South location of Hornsea Three for installing a monopile with a maximum blow energy of 5000 kJ.

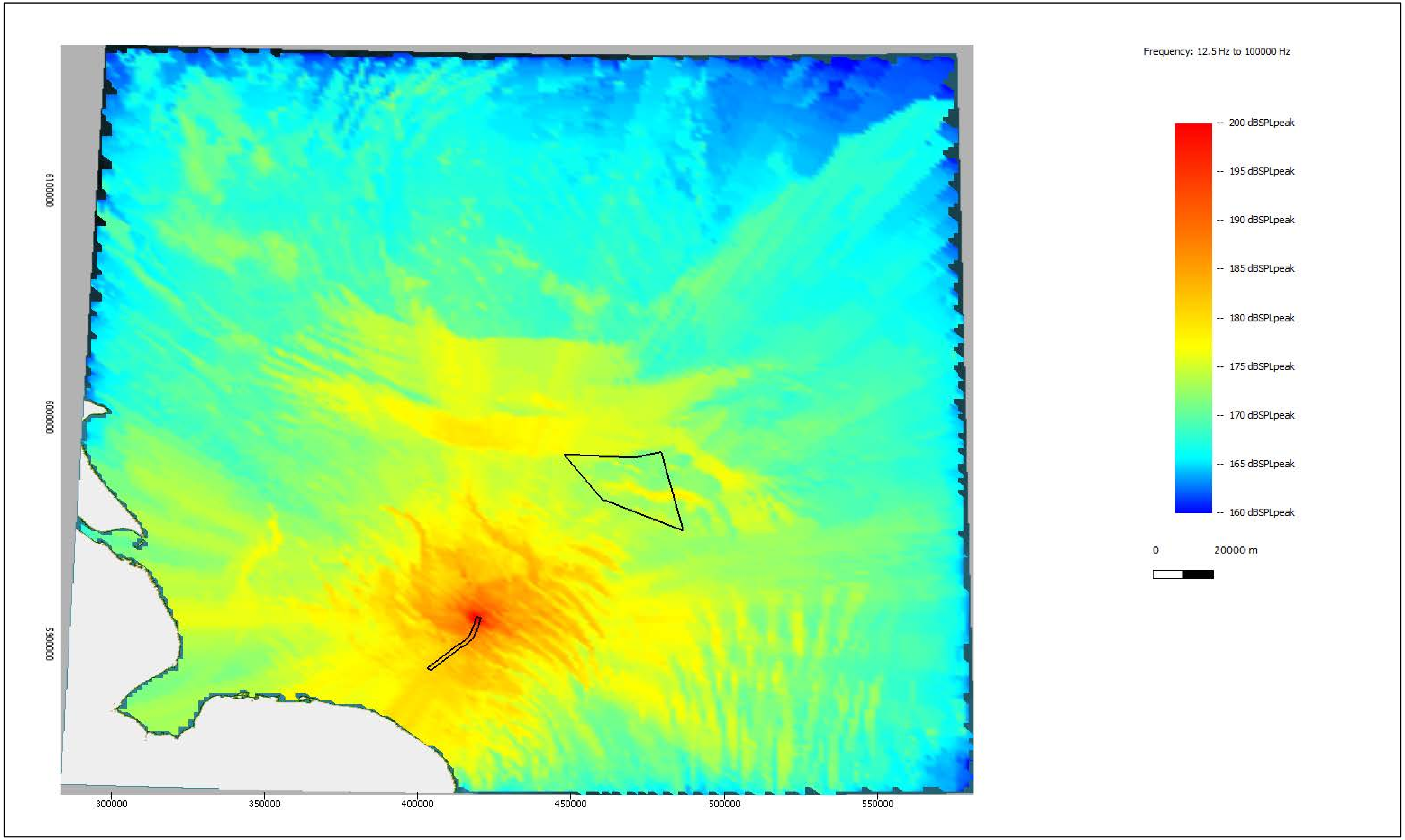

Figure A.4: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the HVAC North location for installing a monopile with a maximum blow energy of 5000 kJ.

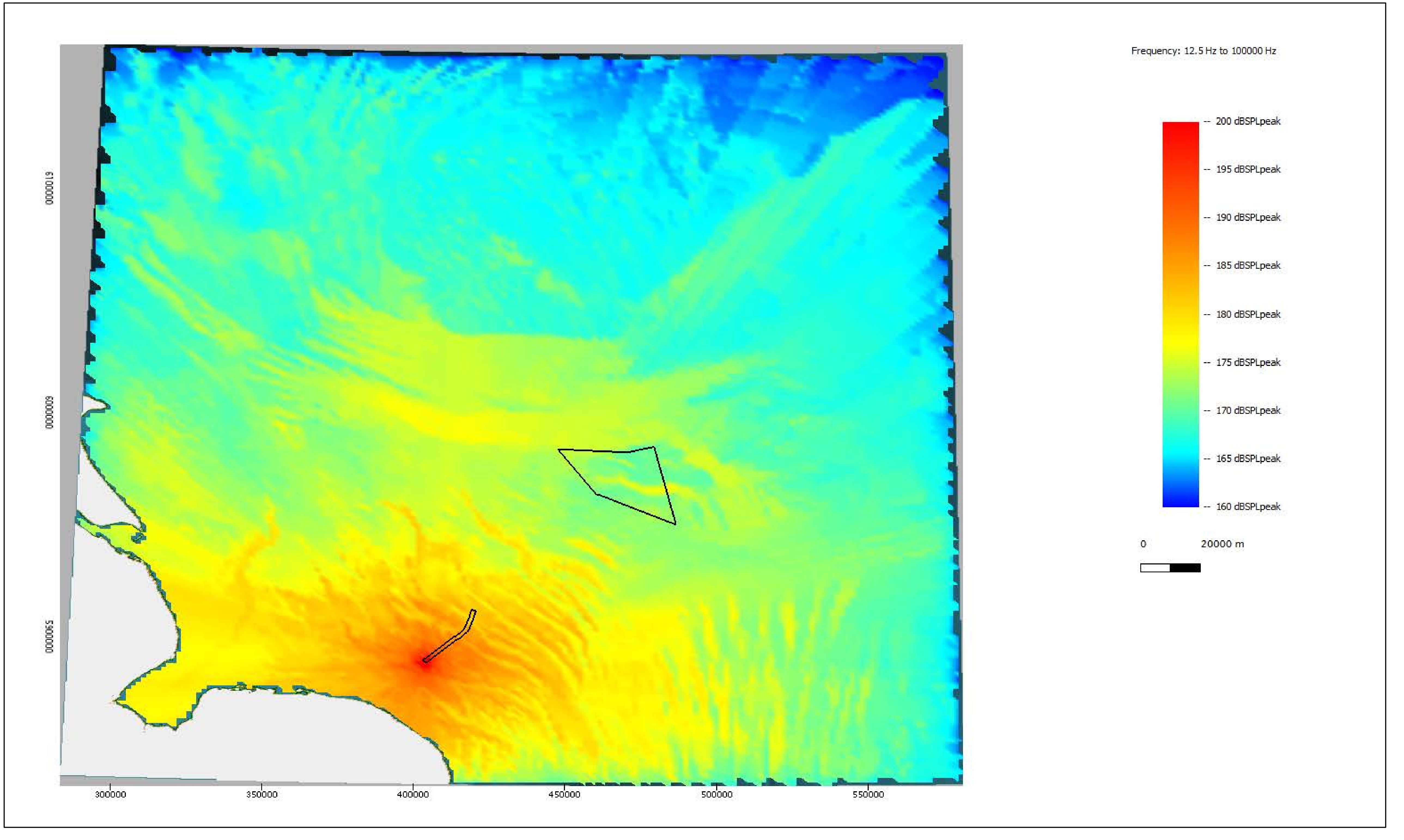

Figure A.5: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the HVAC South location for installing a monopile with a maximum blow energy of 5000 kJ.

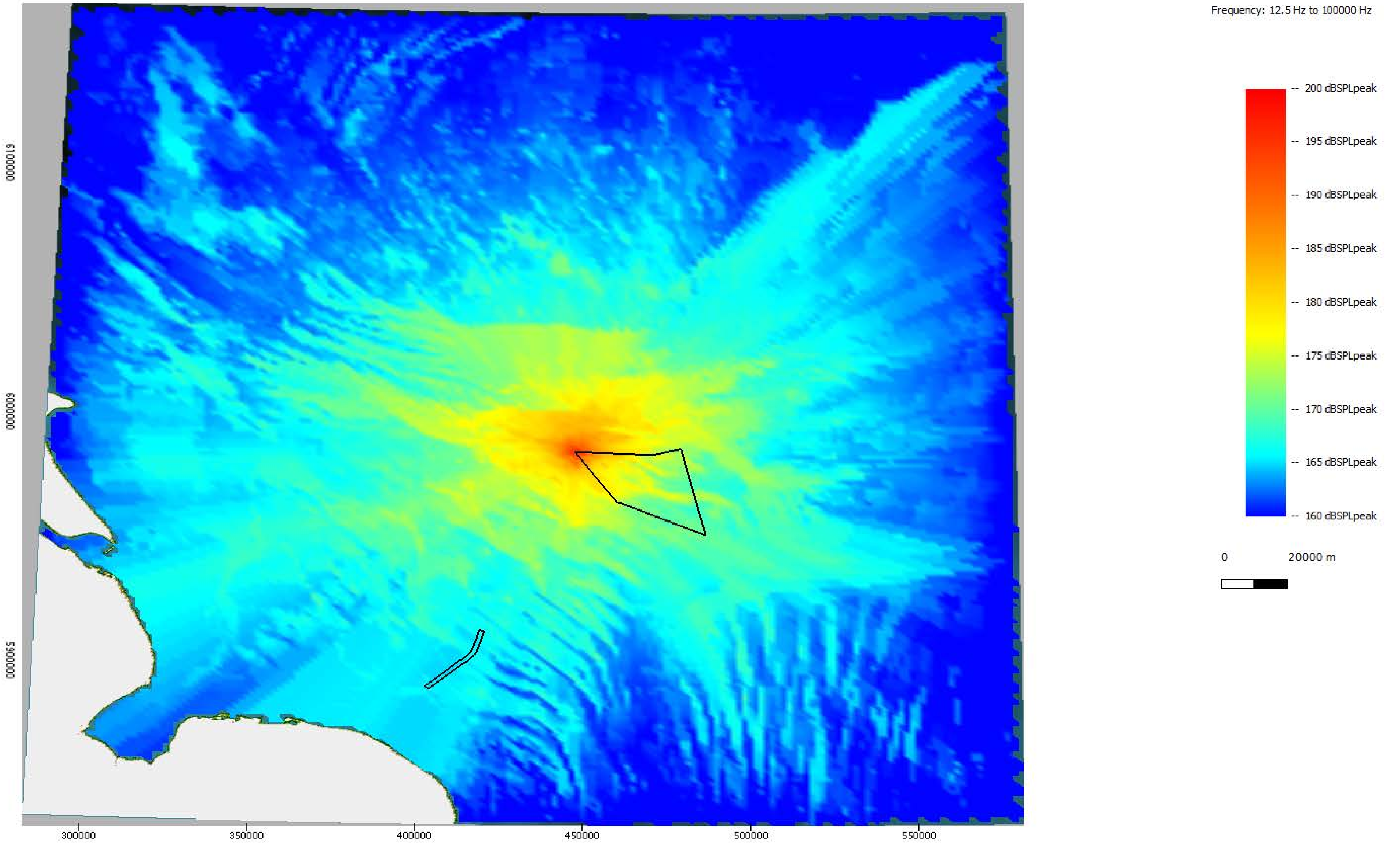

Figure A.6: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the Northwest location of Hornsea Three for installing a pin pile with a maximum blow energy of 2500 kJ.

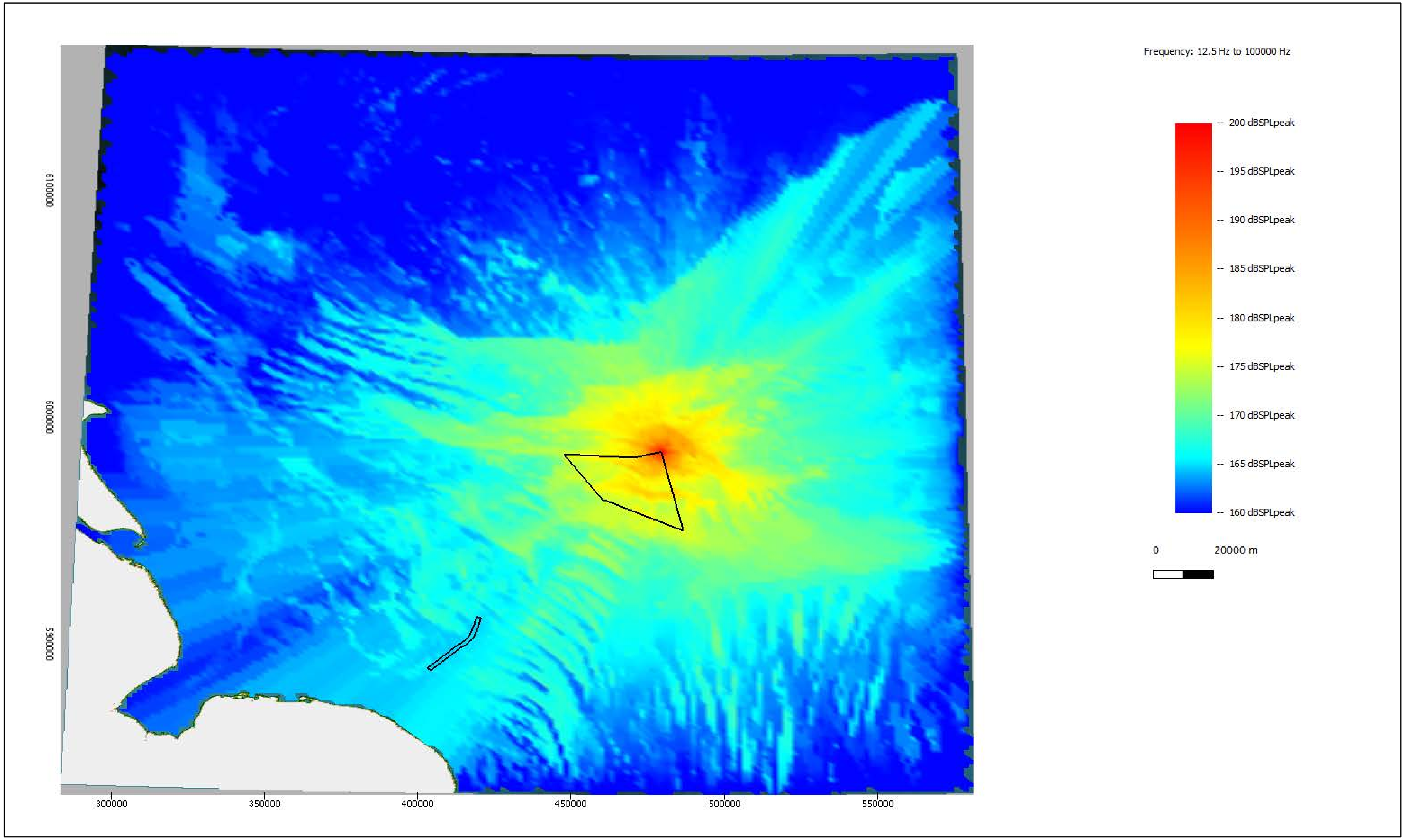

Figure A.7: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the Northeast location of Hornsea Three for installing a pin pile with a maximum blow energy of 2500 kJ.

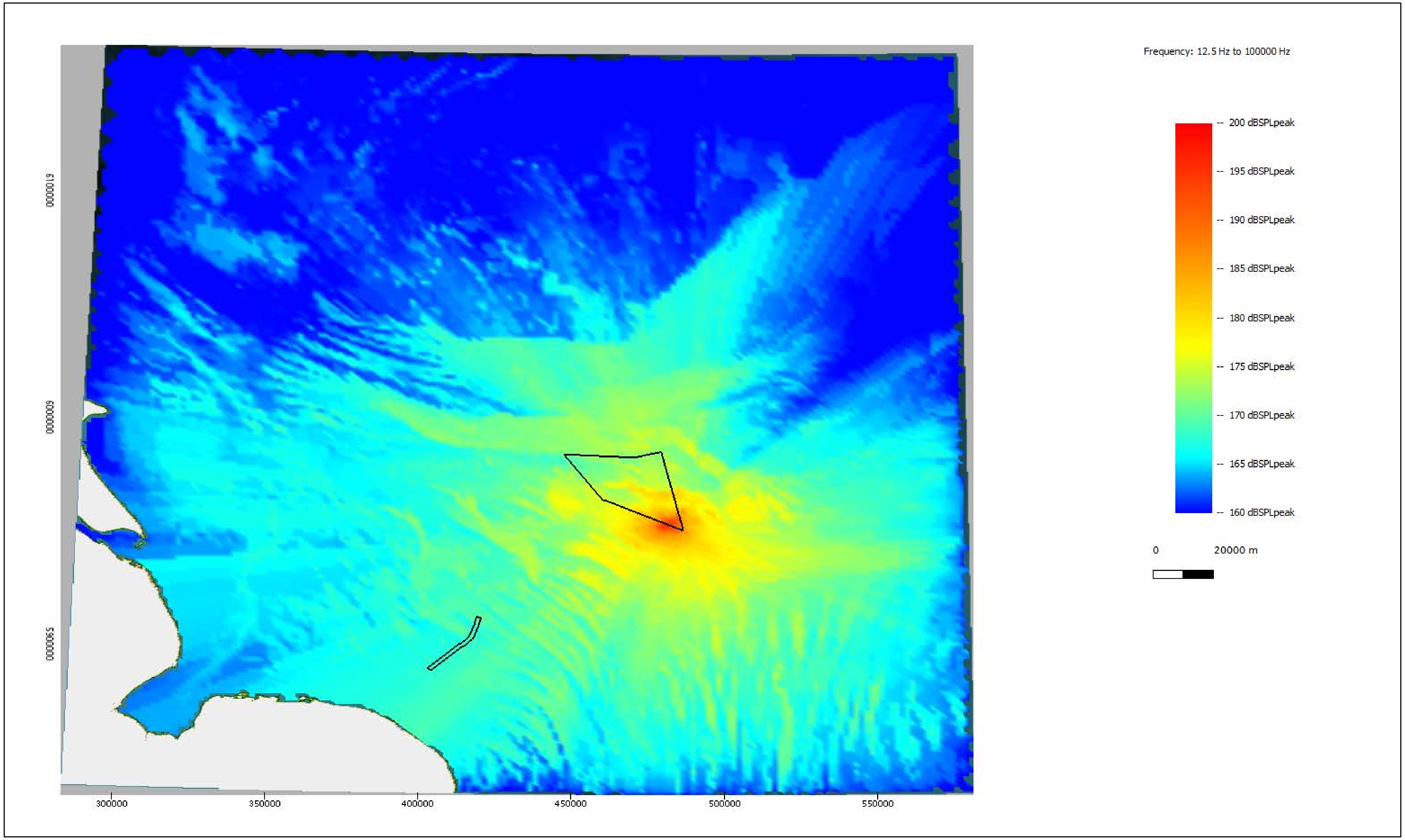

Figure A.8: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the South location of Hornsea Three for installing a pin pile with a maximum blow energy of 2500 kJ.

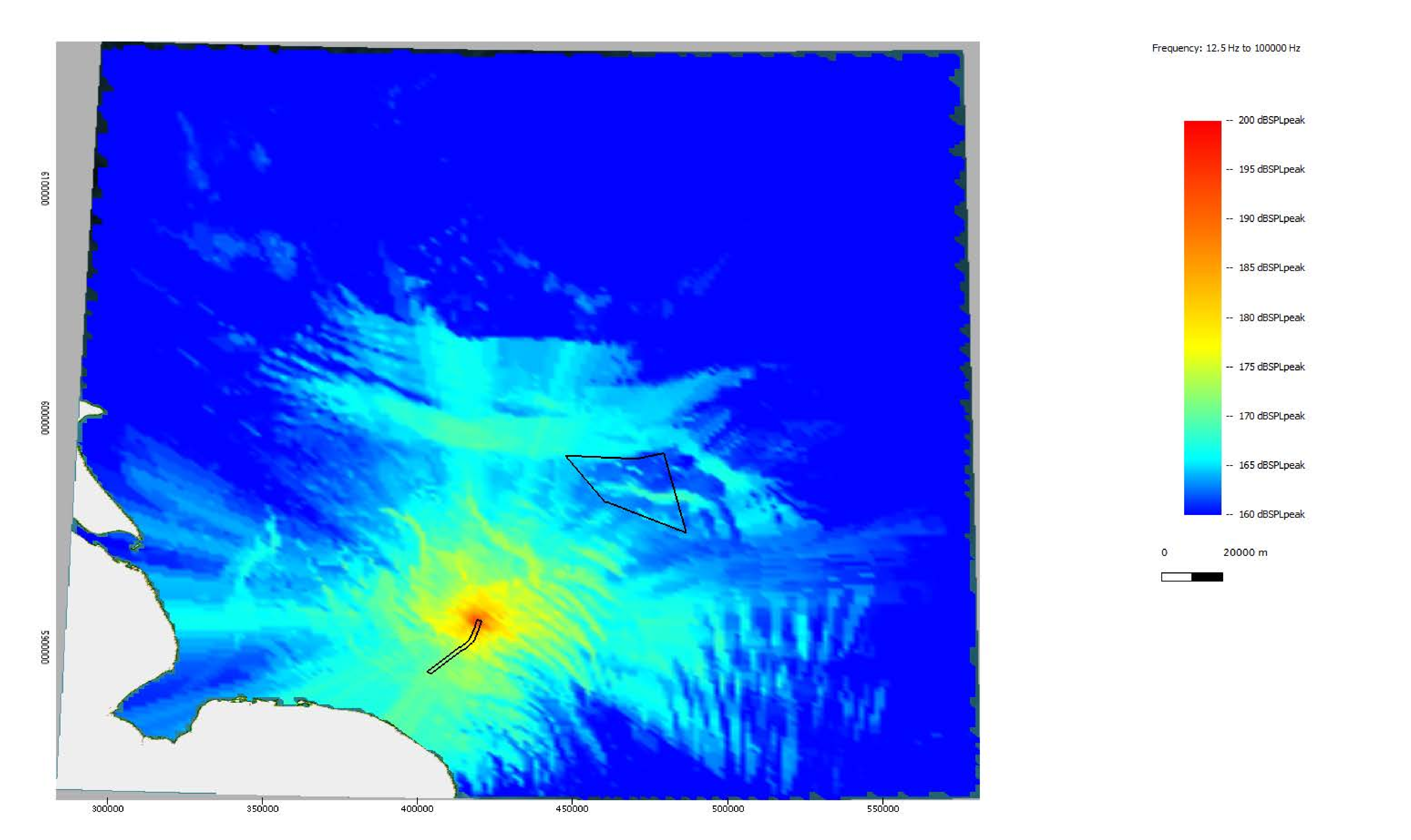

Figure A.9: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the HVAC North location for installing a pin pile with a maximum blow energy of 2500 kJ.

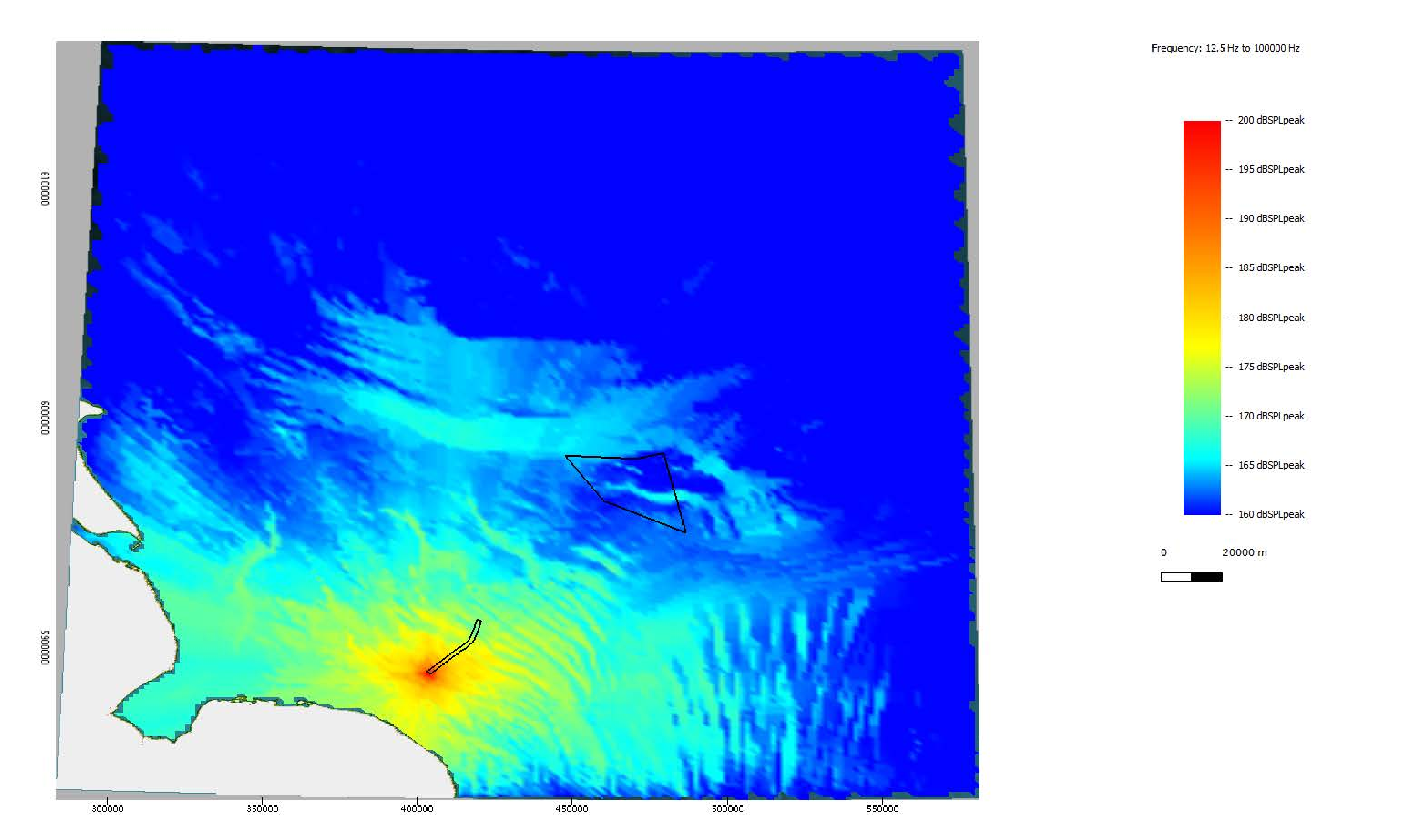

Figure A.10: Noise level plot showing the modelled unweighted SPL_{peak} noise levels at the HVAC South location for installing a pin pile with a maximum blow energy of 2500 kJ.

A.3 Impacts on marine mammals

A.3.1.1 The following figures, produced in INSPIRE, present the predicted impact ranges for marine mammals with reference to the results presented in section 5.3.2 of this report. The figures here differ from those presented in section A.1 as these figures show SEL_{cum} criteria for fleeing animals, which cannot be presented in the same way as SPL_{peak} results. It should be noted that plots for Mid Frequency (MF) Cetaceans have not been included as the results were too small to be shown at the scale of the map.

A.3.1.2 The contours presented on the plots define the range from the pile where, at the start of piling, an animal from the functional hearing group would receive their respective sound exposure criterion:

- Figure A.11 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the Northwest location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.12 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the Northeast location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.13 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the South location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.14 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the HVAC North location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.15 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the HVAC South location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.16 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the Northwest location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.17 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the Northeast location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.18 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the South location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.19 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the HVAC North location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.20 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the HVAC South location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.21 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the Northwest location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.22 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the Northeast location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.23 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the South location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.24 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the HVAC North location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.25 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the HVAC South location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.26 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the Northwest location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.27 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the Northeast location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.28 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the South location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.29 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the HVAC North location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.30 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the HVAC South location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.31 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the Northwest location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.32 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the Northeast location for installing a pin pile with a maximum blow energy of 2500 kJ;

- Figure A.33 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the South location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.34 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the HVAC North location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.35 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the HVAC South location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.36 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the Northwest location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.37 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the Northeast location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.38 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the South location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.39 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the HVAC North location for installing a pin pile with a maximum blow energy of 2500 kJ; and
- Figure A.40 Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the HVAC South location for installing a pin pile with a maximum blow energy of 2500 kJ.

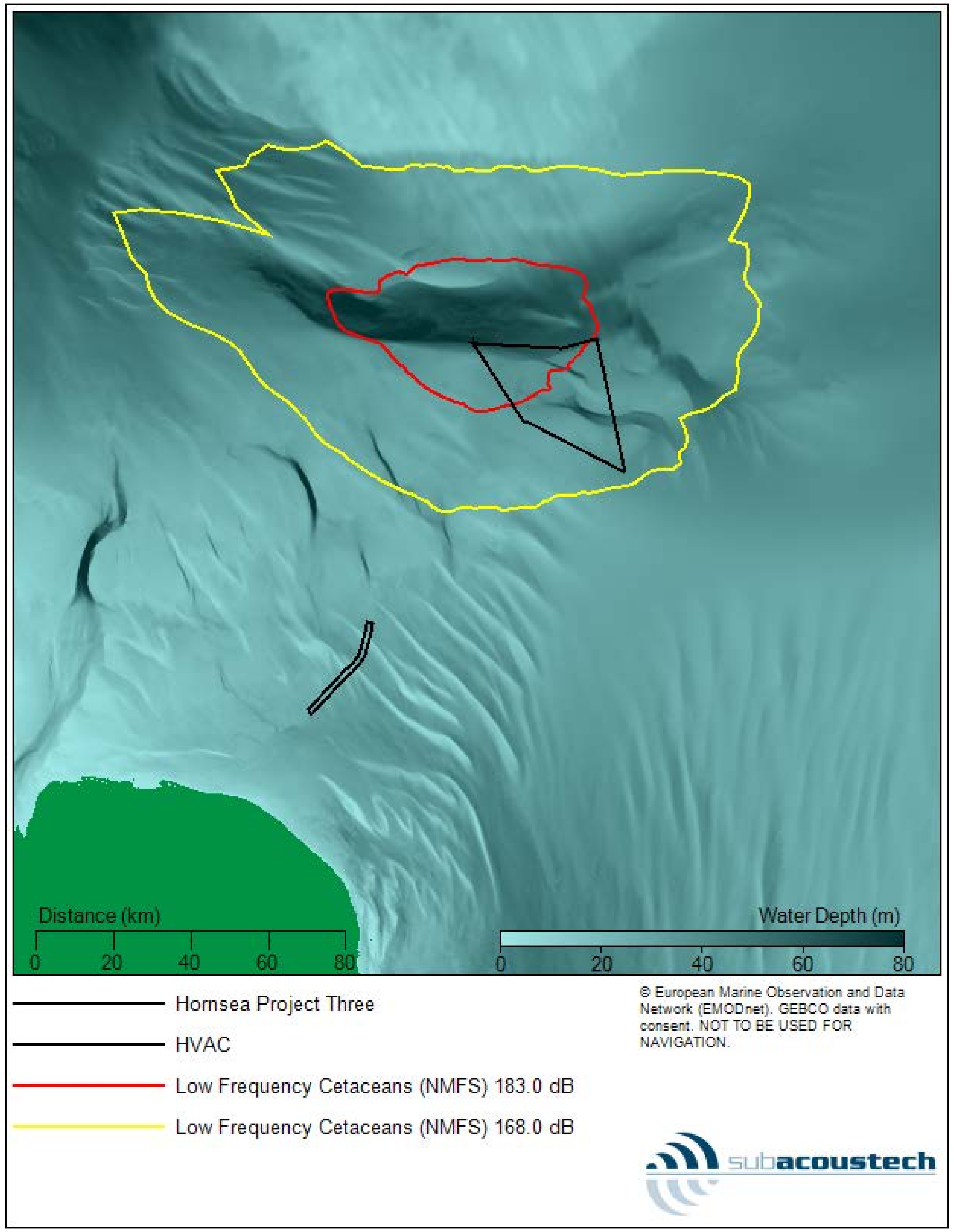

Figure A.11: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the Northwest location for installing a monopile with a maximum blow energy of 5000 kJ.

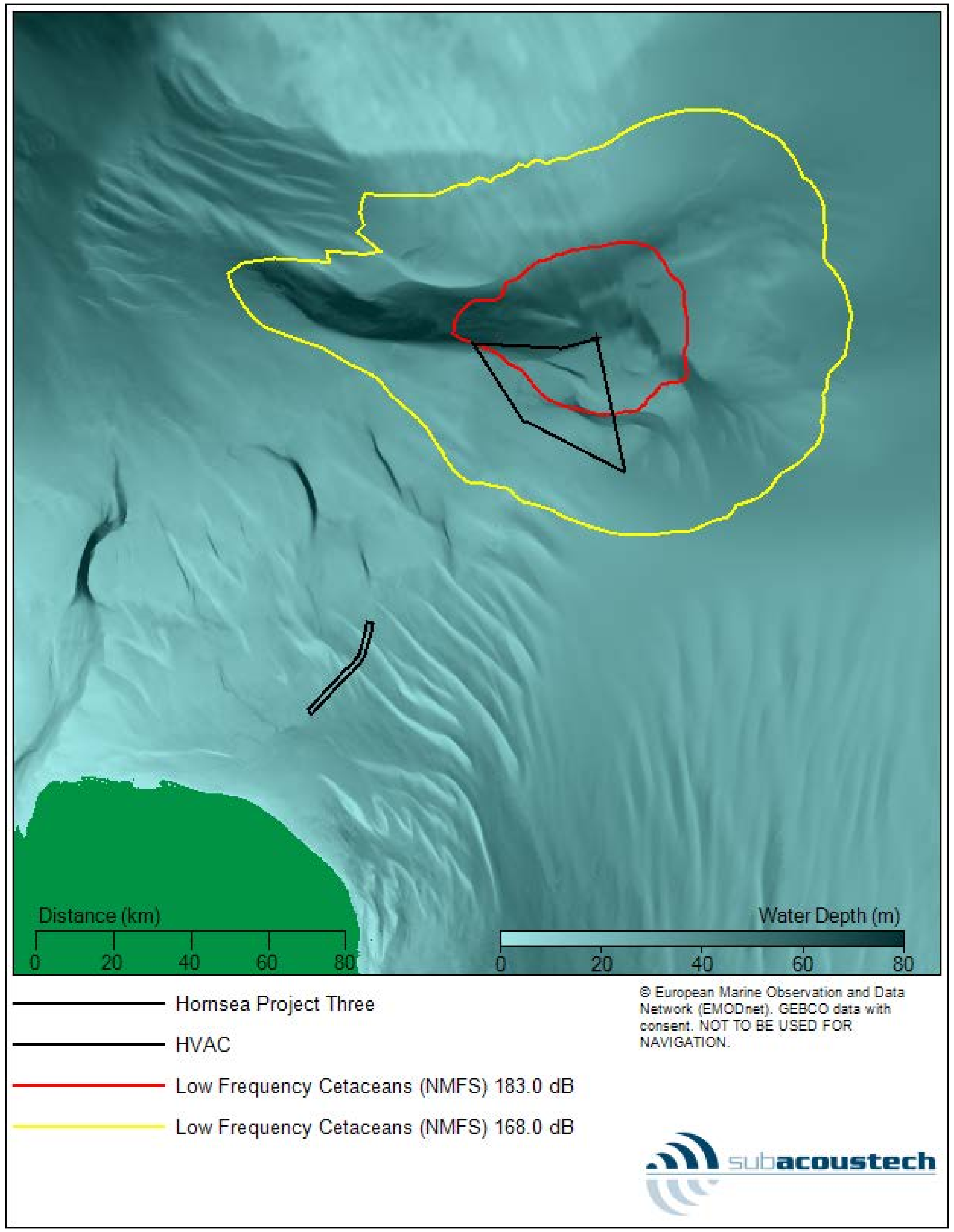

Figure A.12: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the Northeast location for installing a monopile with a maximum blow energy of 5000 kJ.

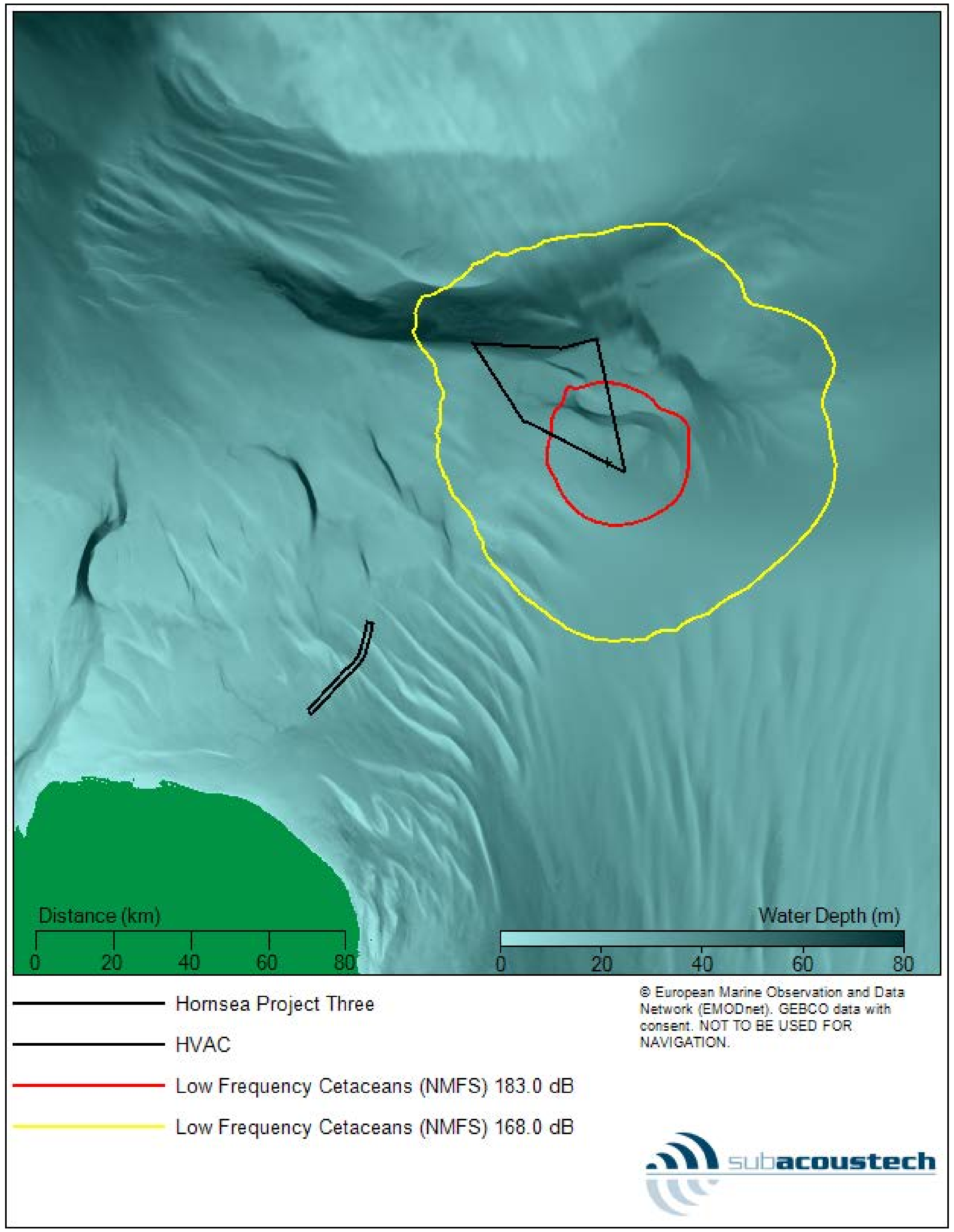

Figure A.13: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the South location for installing a monopile with a maximum blow energy of 5000 kJ.

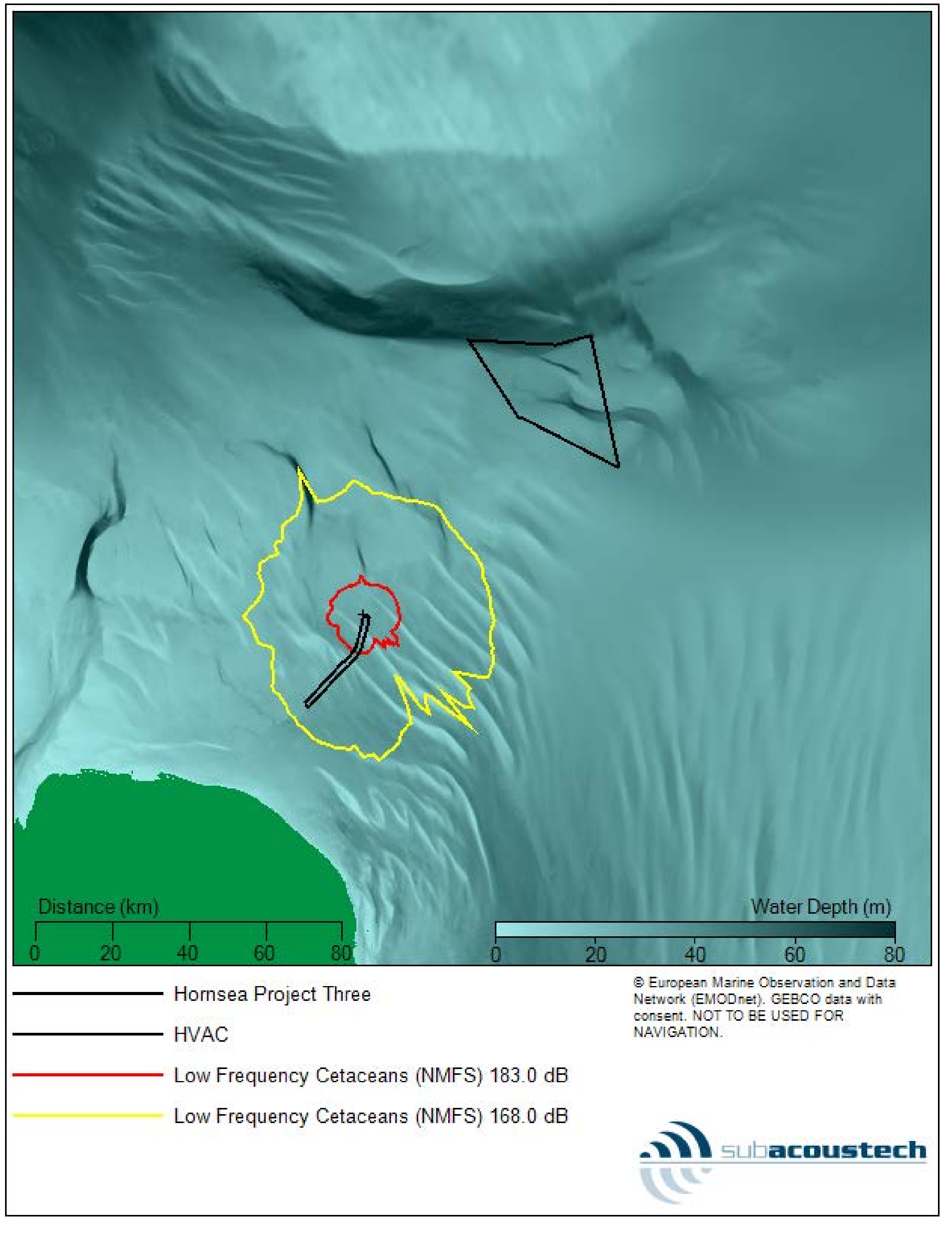

Figure A.14: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the HVAC North location for installing a monopile with a maximum blow energy of 5000 kJ.

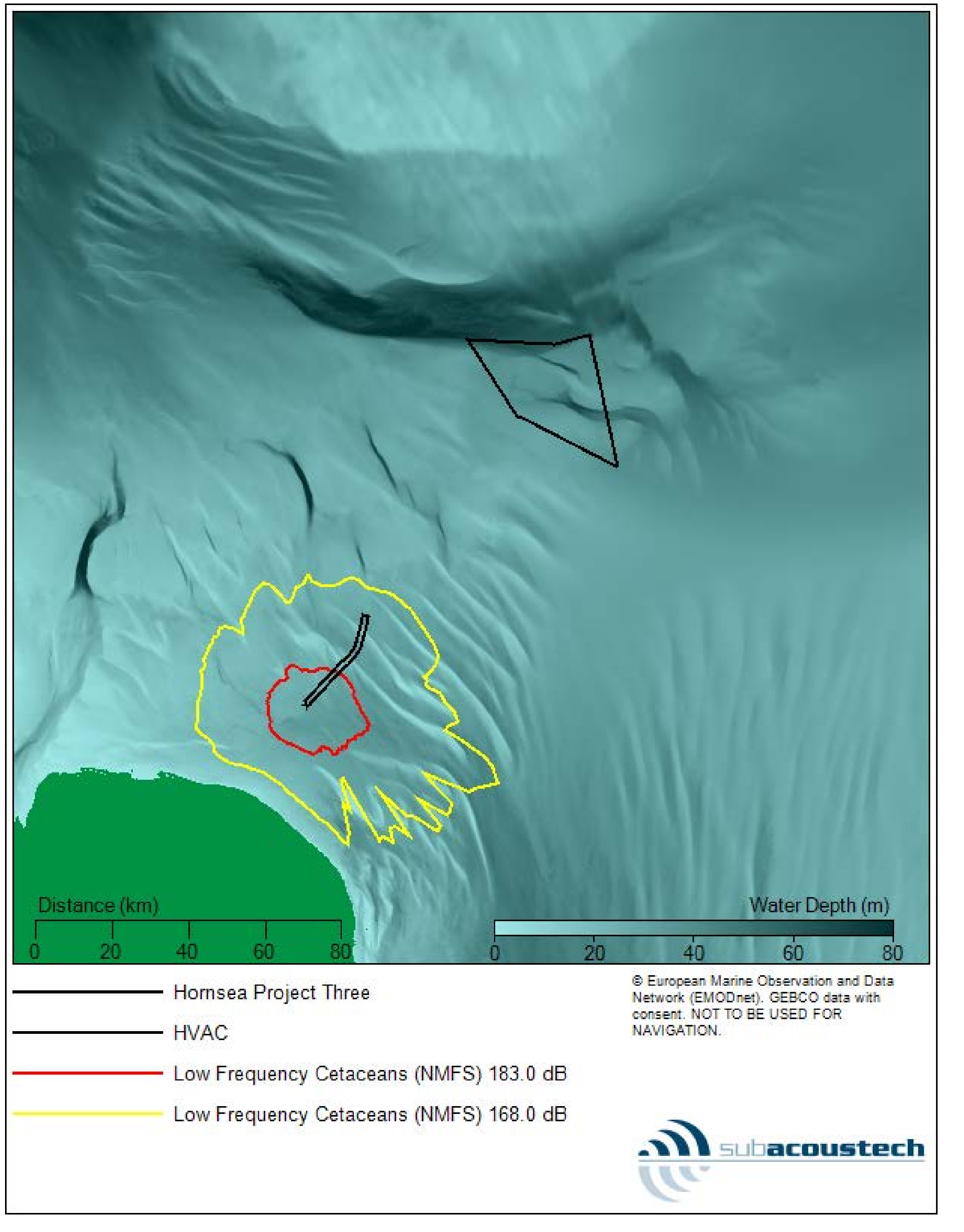

Figure A.15: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the HVAC South location for installing a monopile with a maximum blow energy of 5000 kJ.

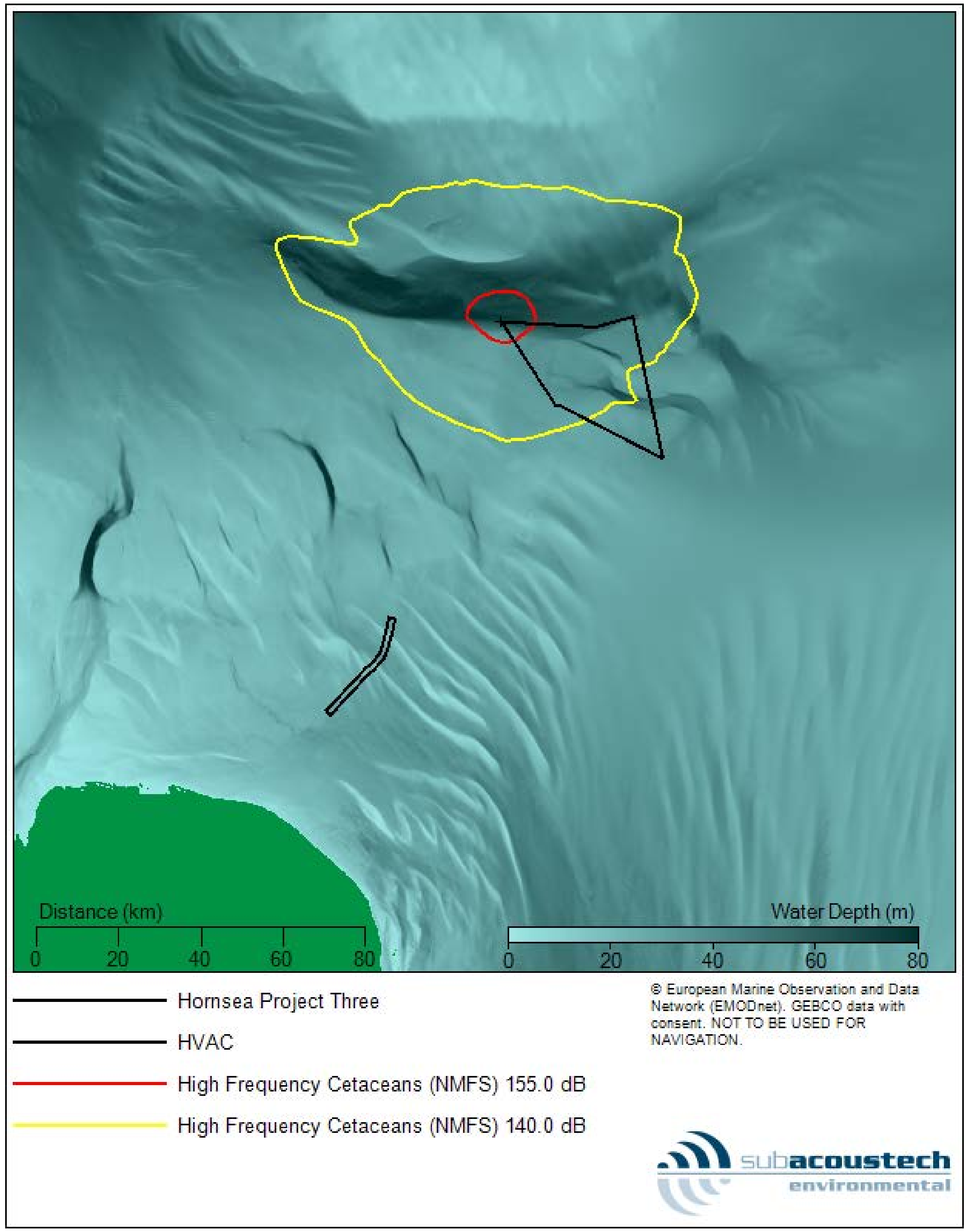

Figure A.16: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the Northwest location for installing a monopile with a maximum blow energy of 5000 kJ.

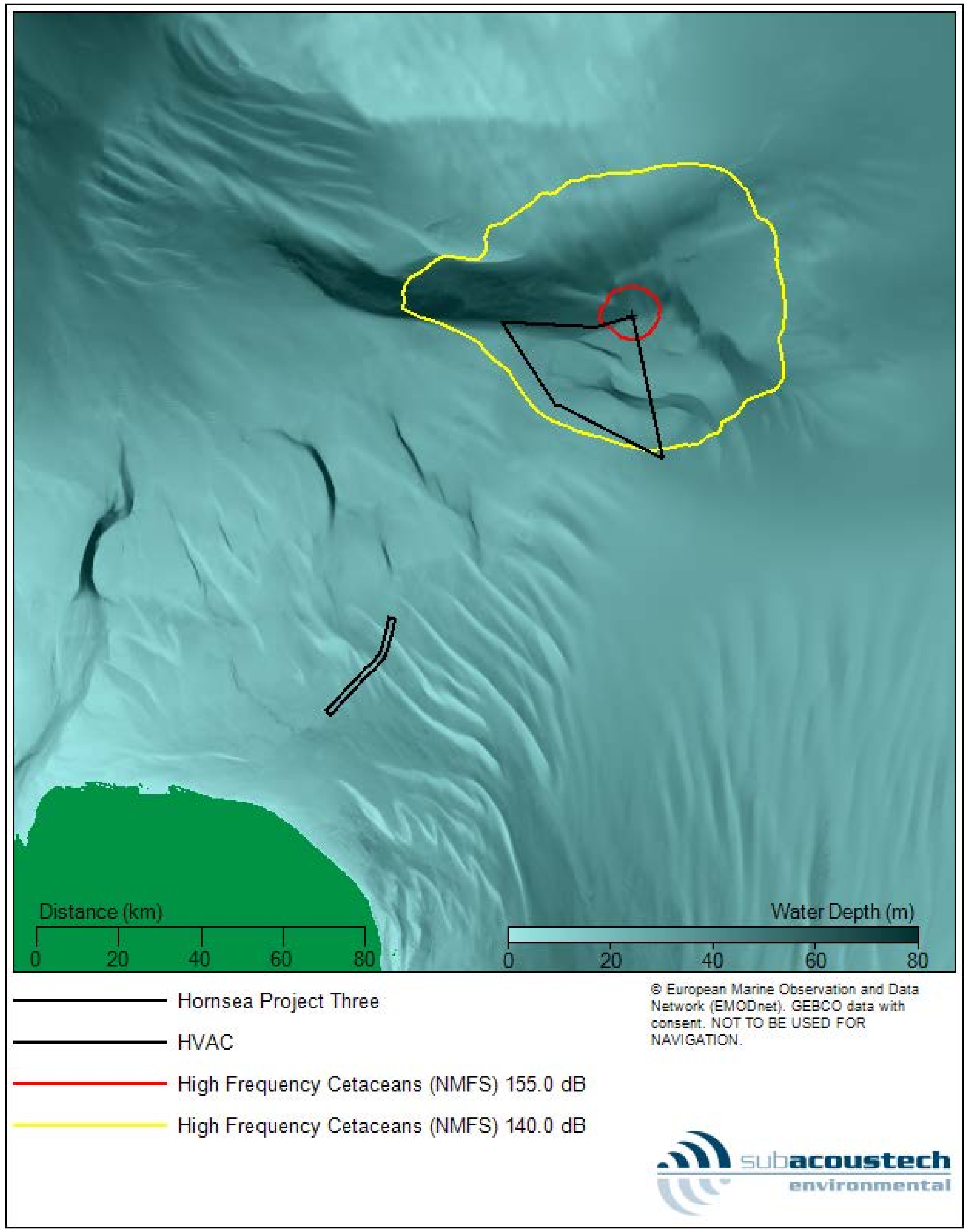

Figure A.17: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the Northeast location for installing a monopile with a maximum blow energy of 5000 kJ.

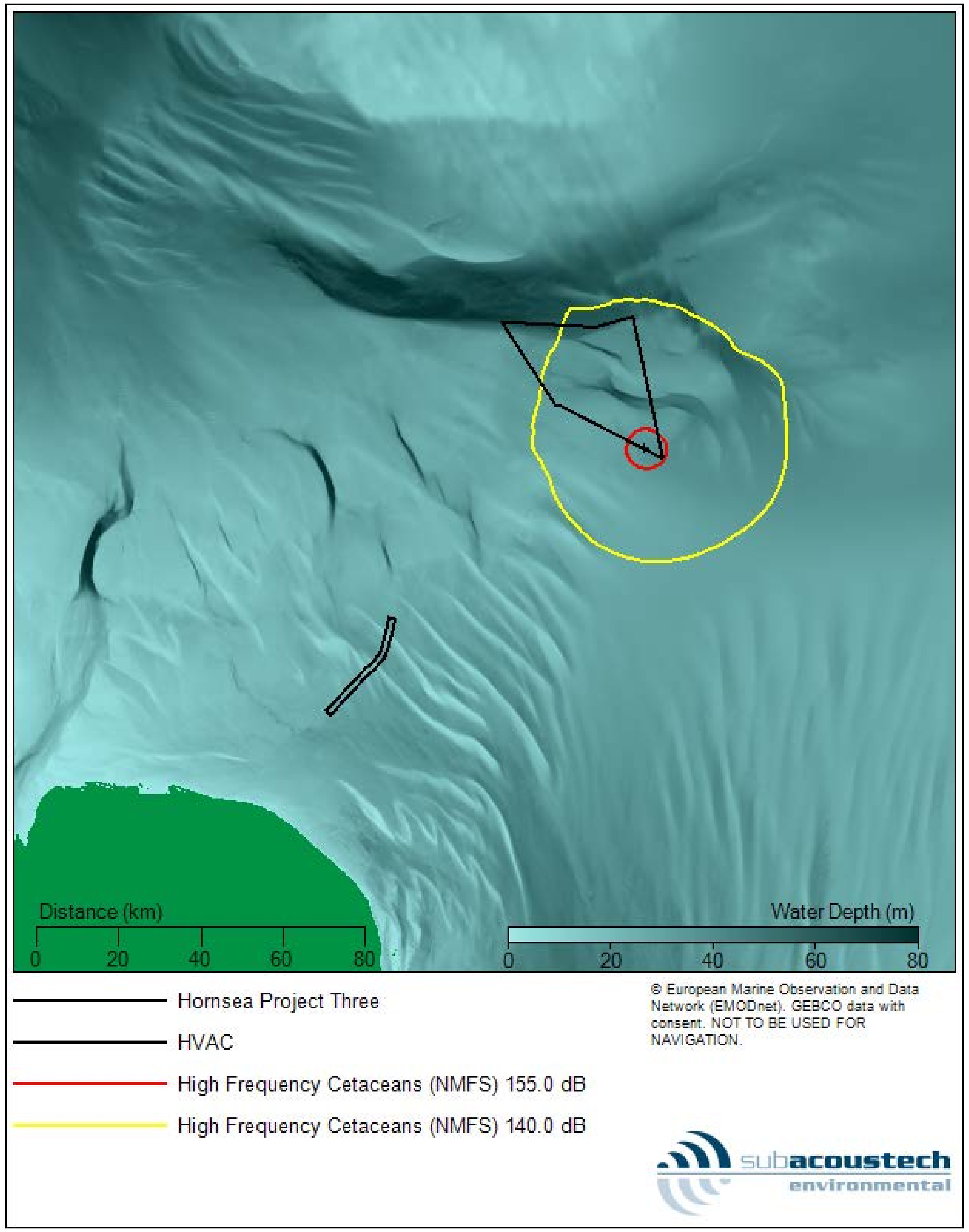

Figure A.18: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the South location for installing a monopile with a maximum blow energy of 5000 kJ.

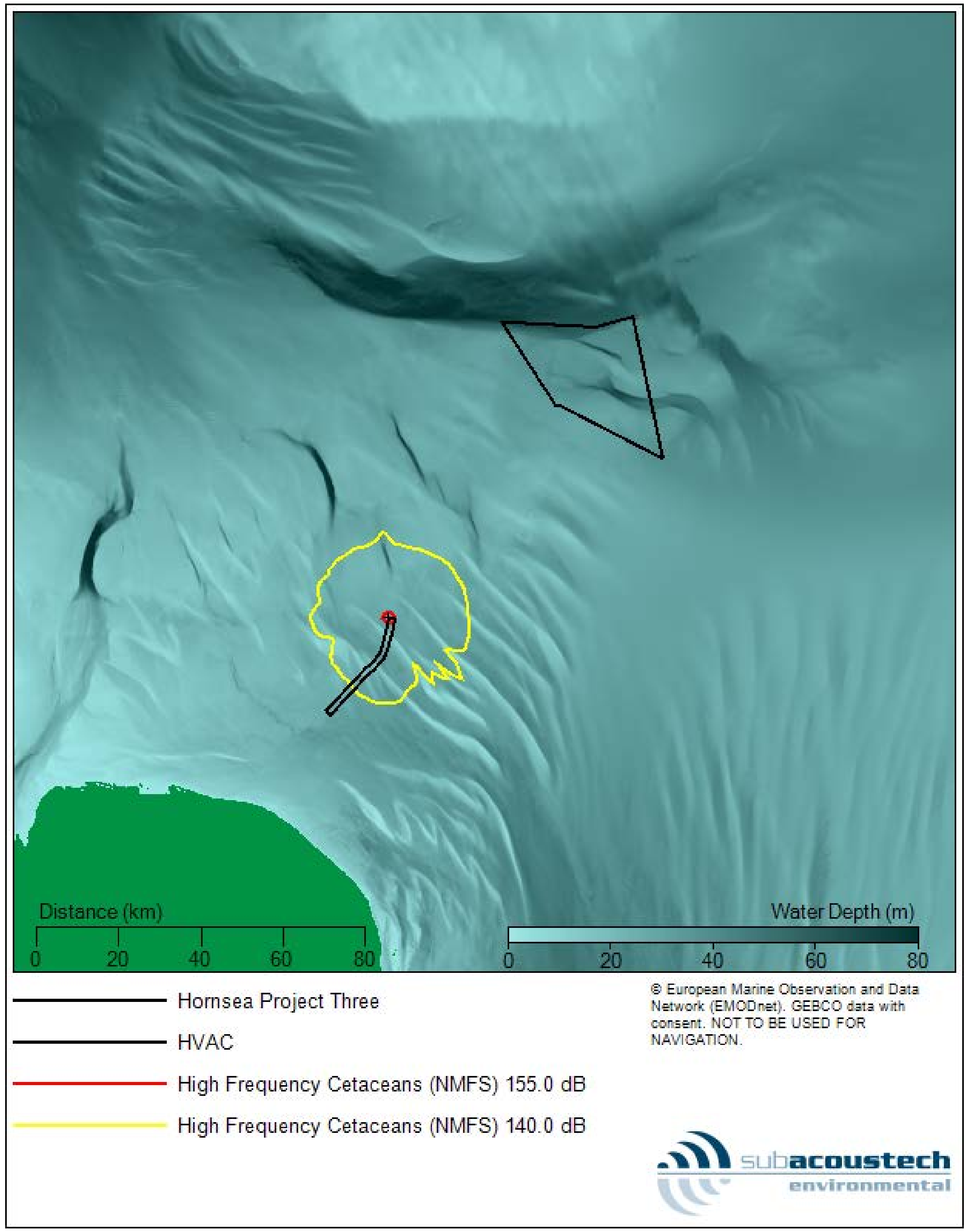

Figure A.19: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the HVAC North location for installing a monopile with a maximum blow energy of 5000 kJ.

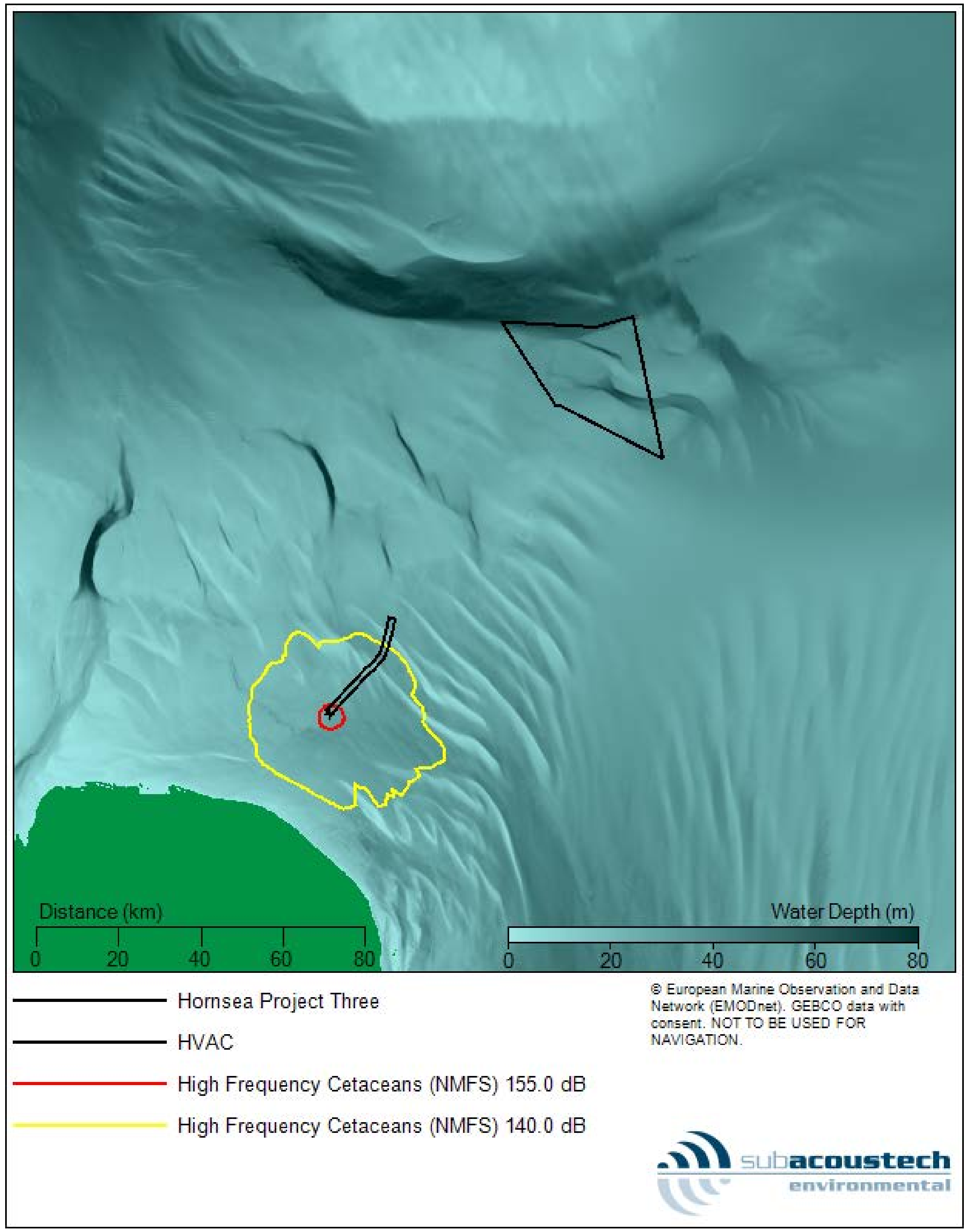

Figure A.20: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the HVAC South location for installing a monopile with a maximum blow energy of 5000 kJ.

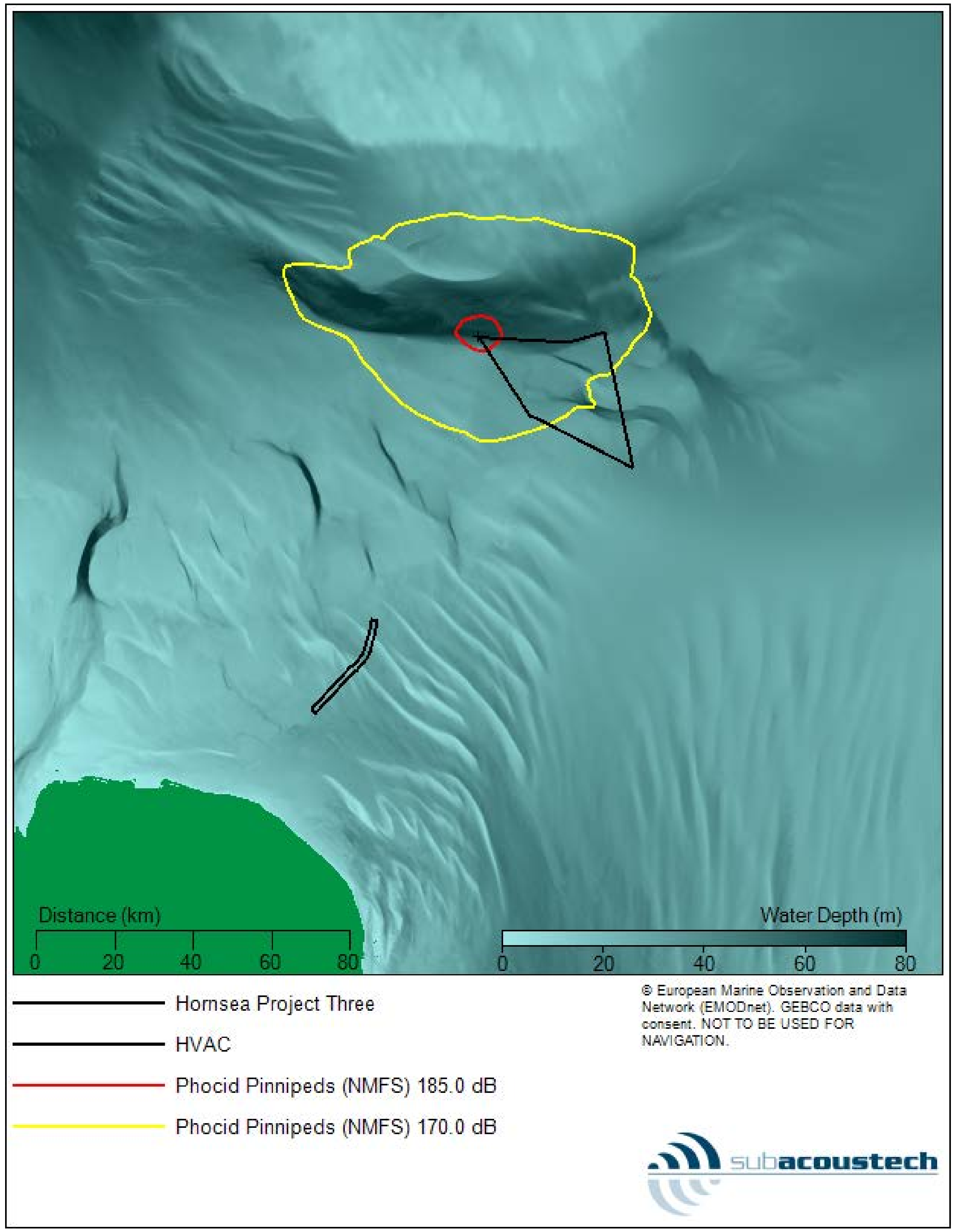

Figure A.21: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the Northwest location for installing a monopile with a maximum blow energy of 5000 kJ.

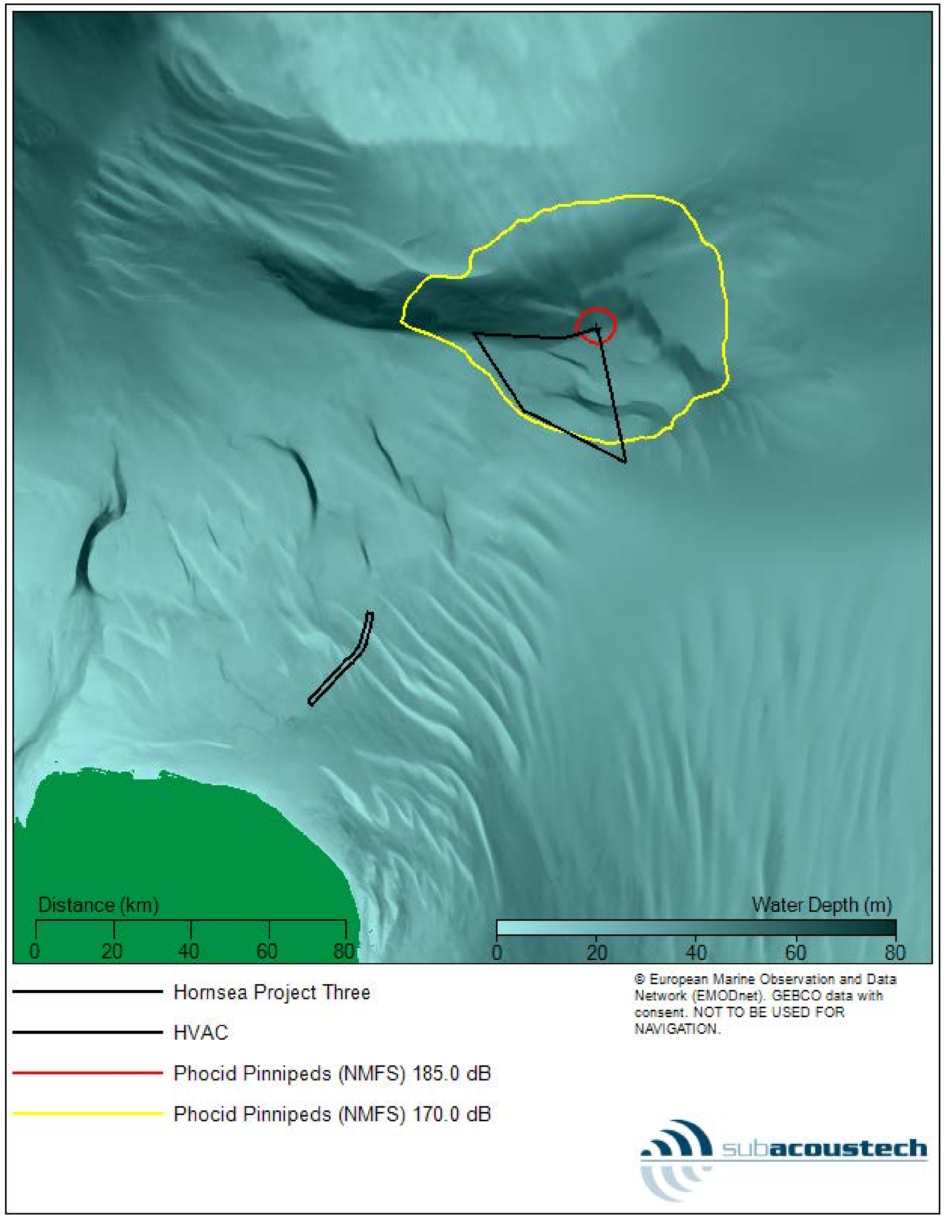

Figure A.22: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the Northeast location for installing a monopile with a maximum blow energy of 5000 kJ.

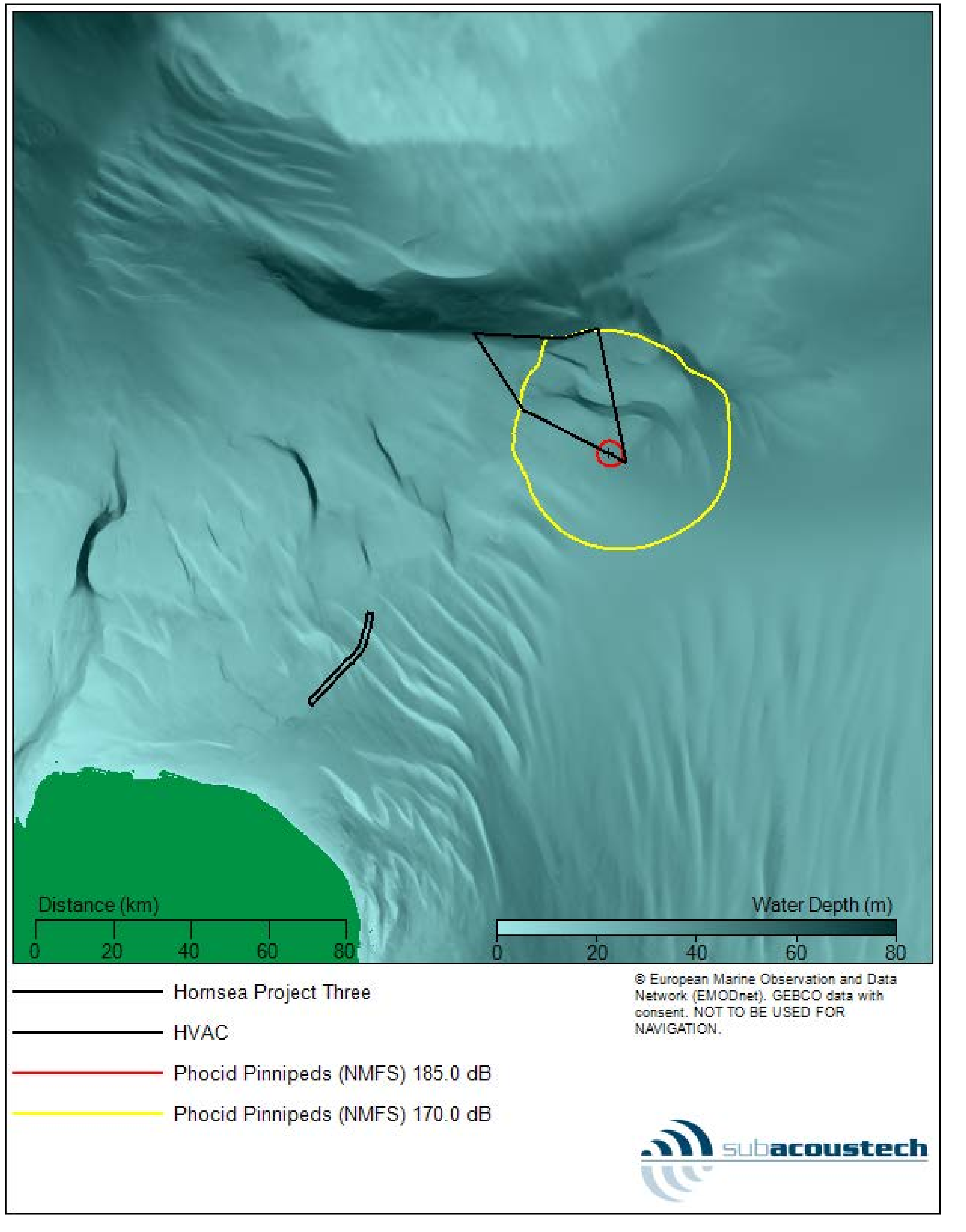

Figure A.23: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the South location for installing a monopile with a maximum blow energy of 5000 kJ

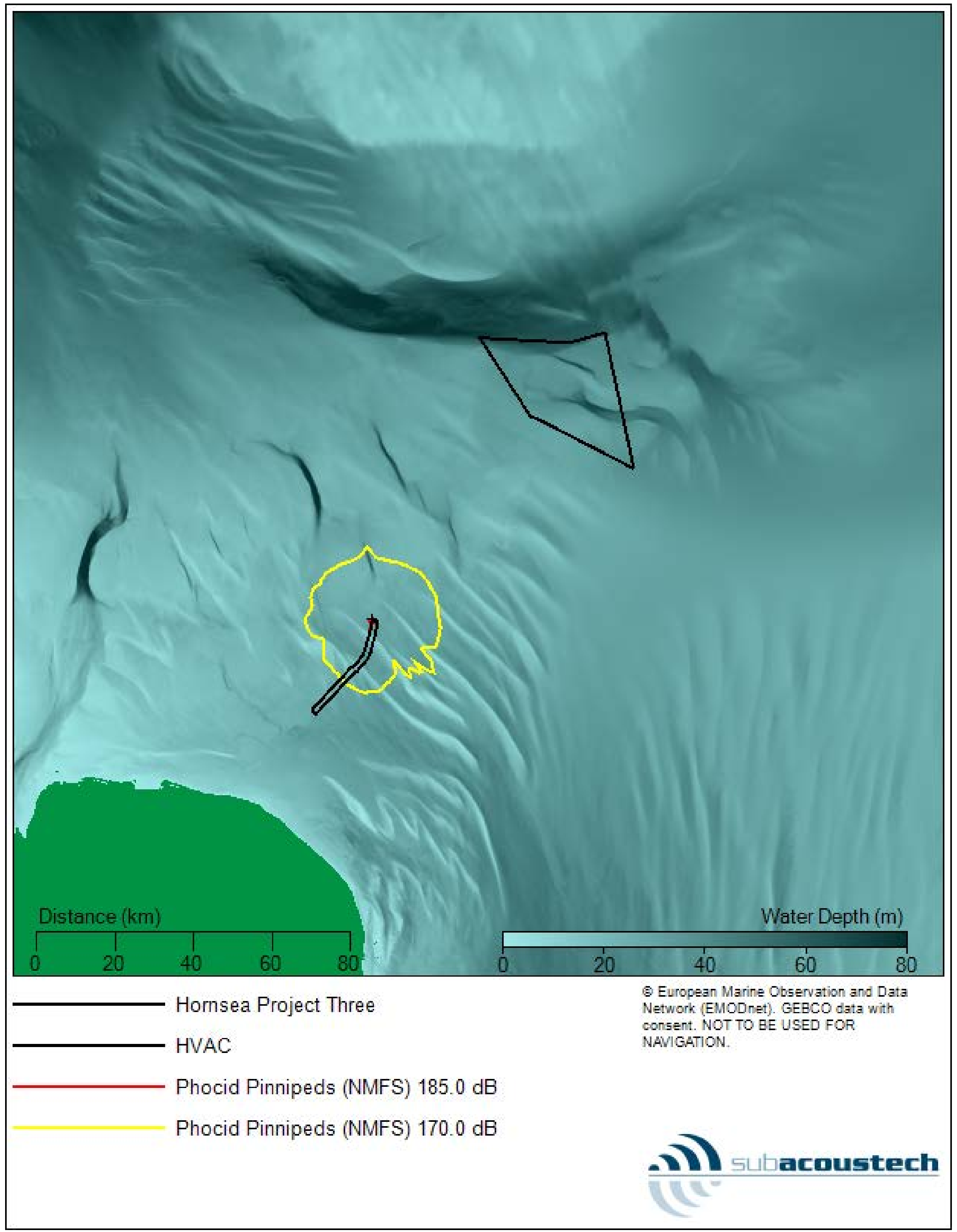

Figure A.24: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the HVAC North location for installing a monopile with a maximum blow energy of 5000 kJ.

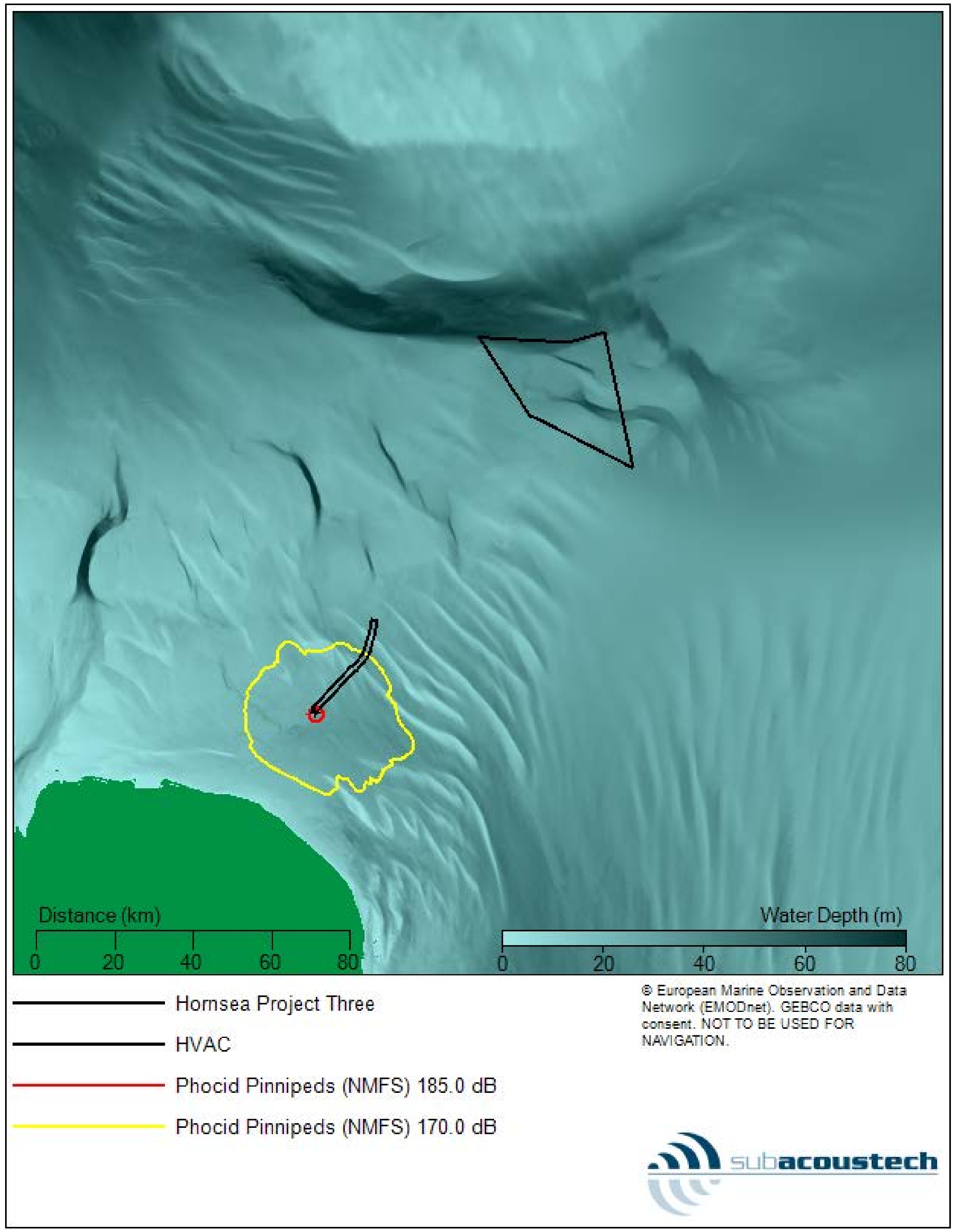

Figure A.25: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the HVAC South location for installing a monopile with a maximum blow energy of 5000 kJ.

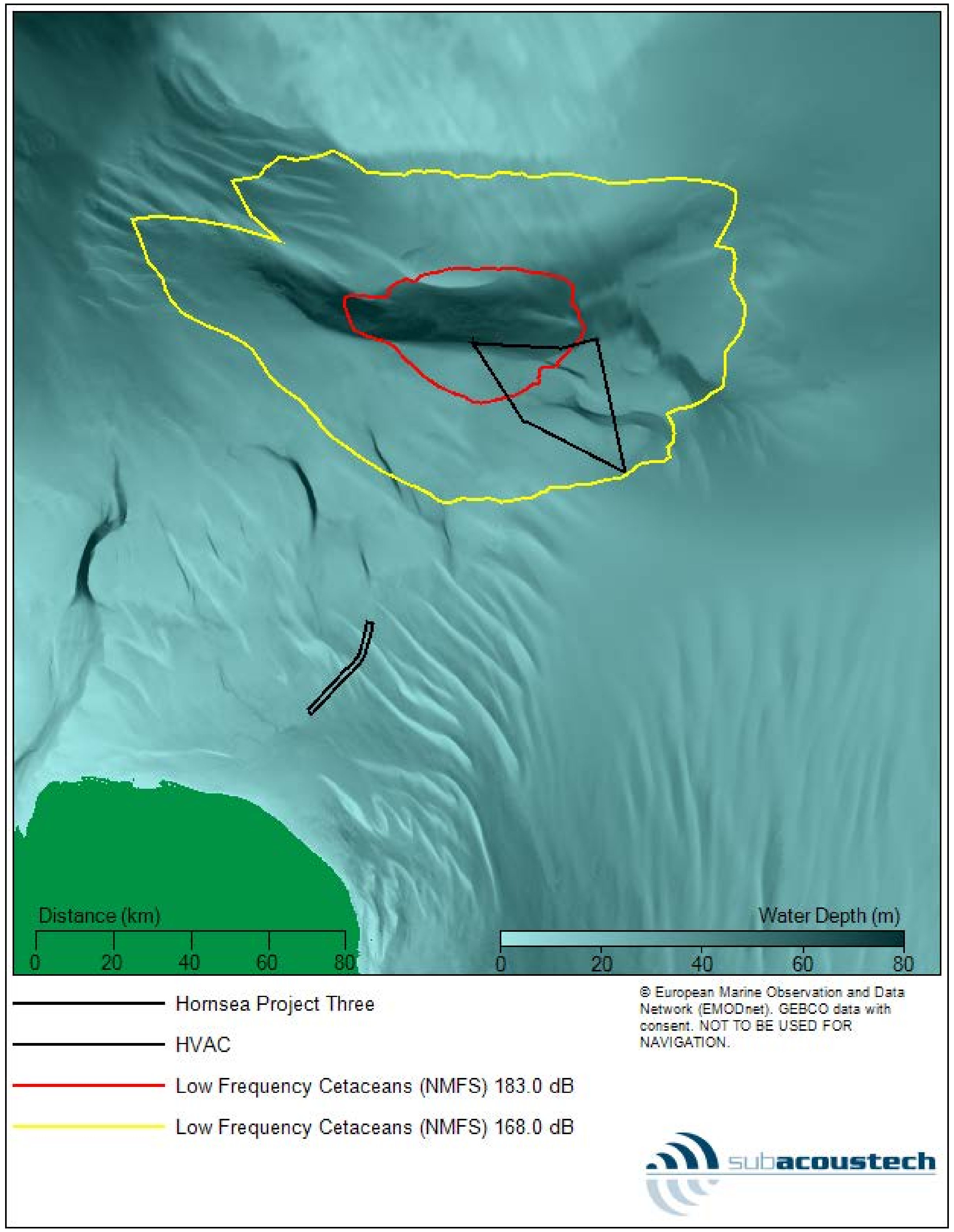

Figure A.26: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the Northwest location for installing a pin pile with a maximum blow energy of 2500 kJ.

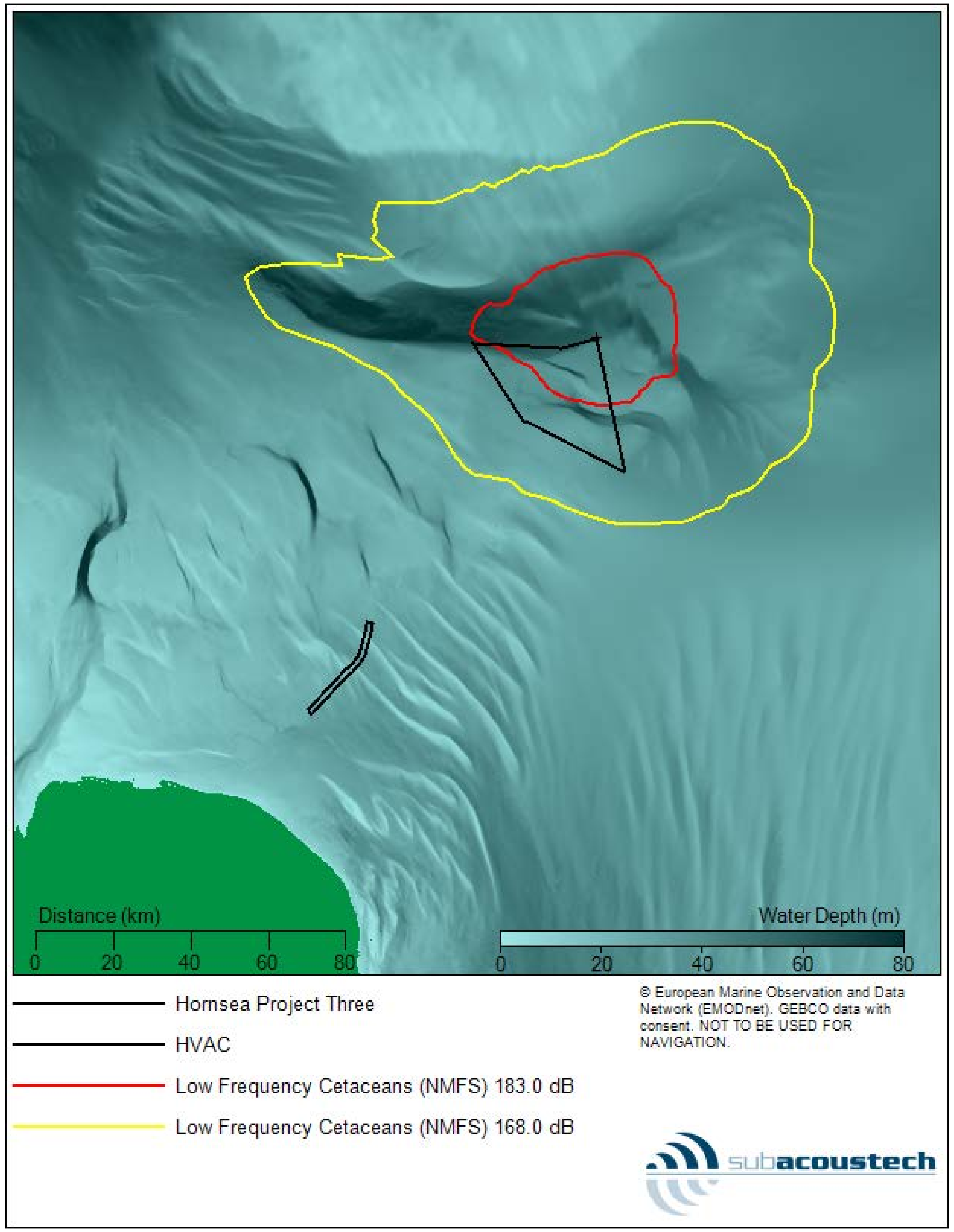

Figure A.27: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the Northeast location for installing a pin pile with a maximum blow energy of 2500 kJ.

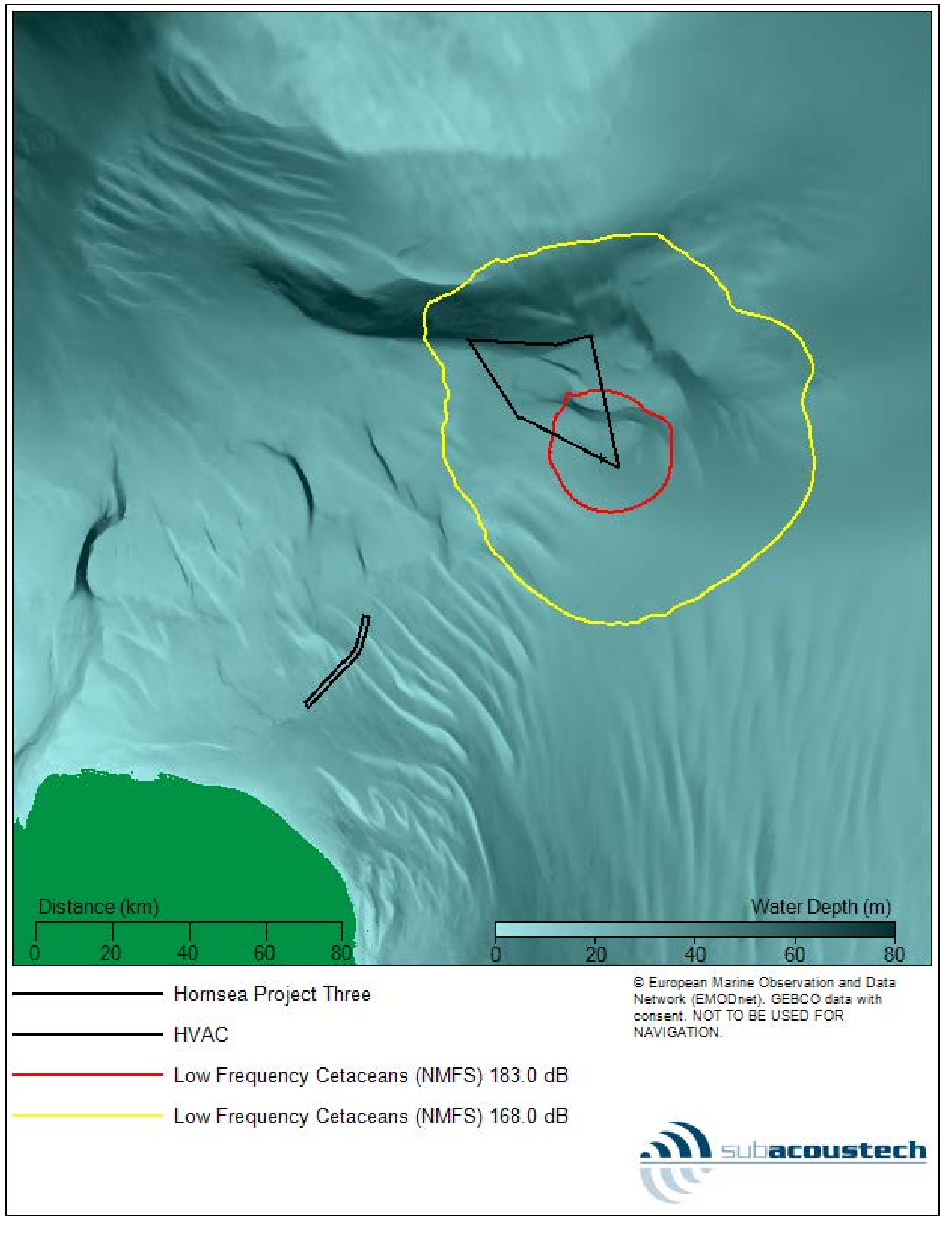

Figure A.28: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the South location for installing a pin pile with a maximum blow energy of 2500 kJ.

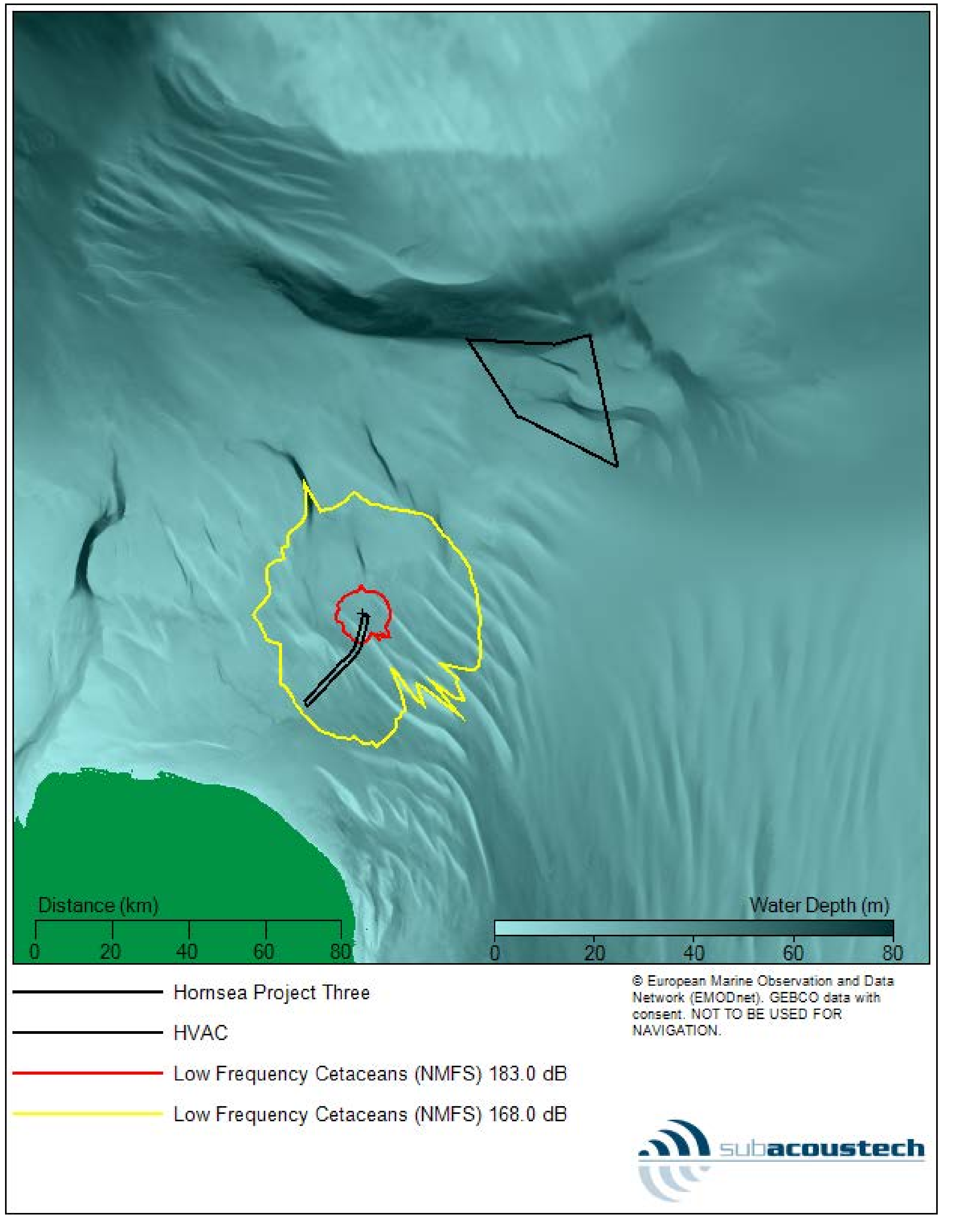

Figure A.29: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the HVAC North location for installing a pin pile with a maximum blow energy of 2500 kJ.

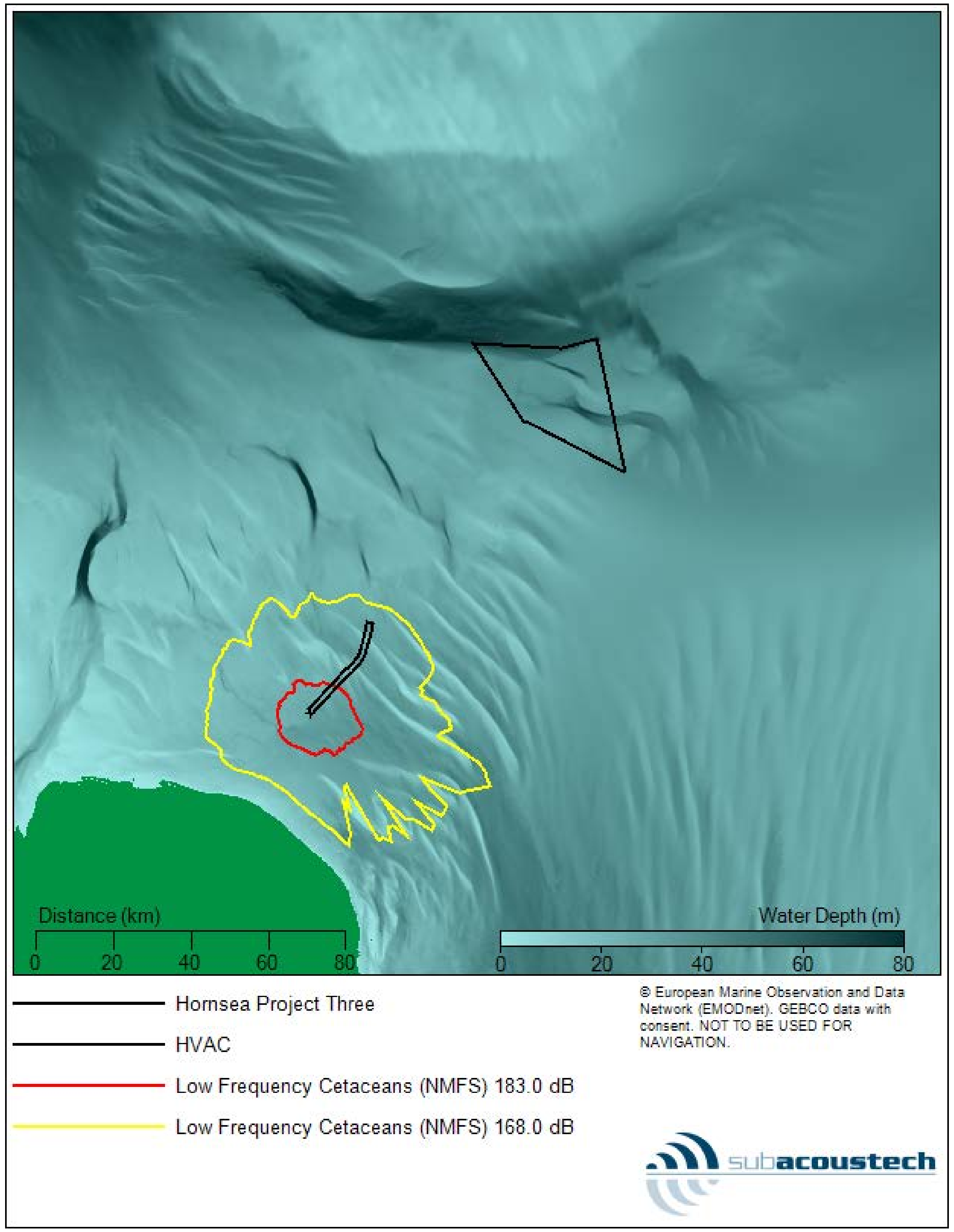

Figure A.30: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the HVAC South location for installing a pin pile with a maximum blow energy of 2500 kJ.

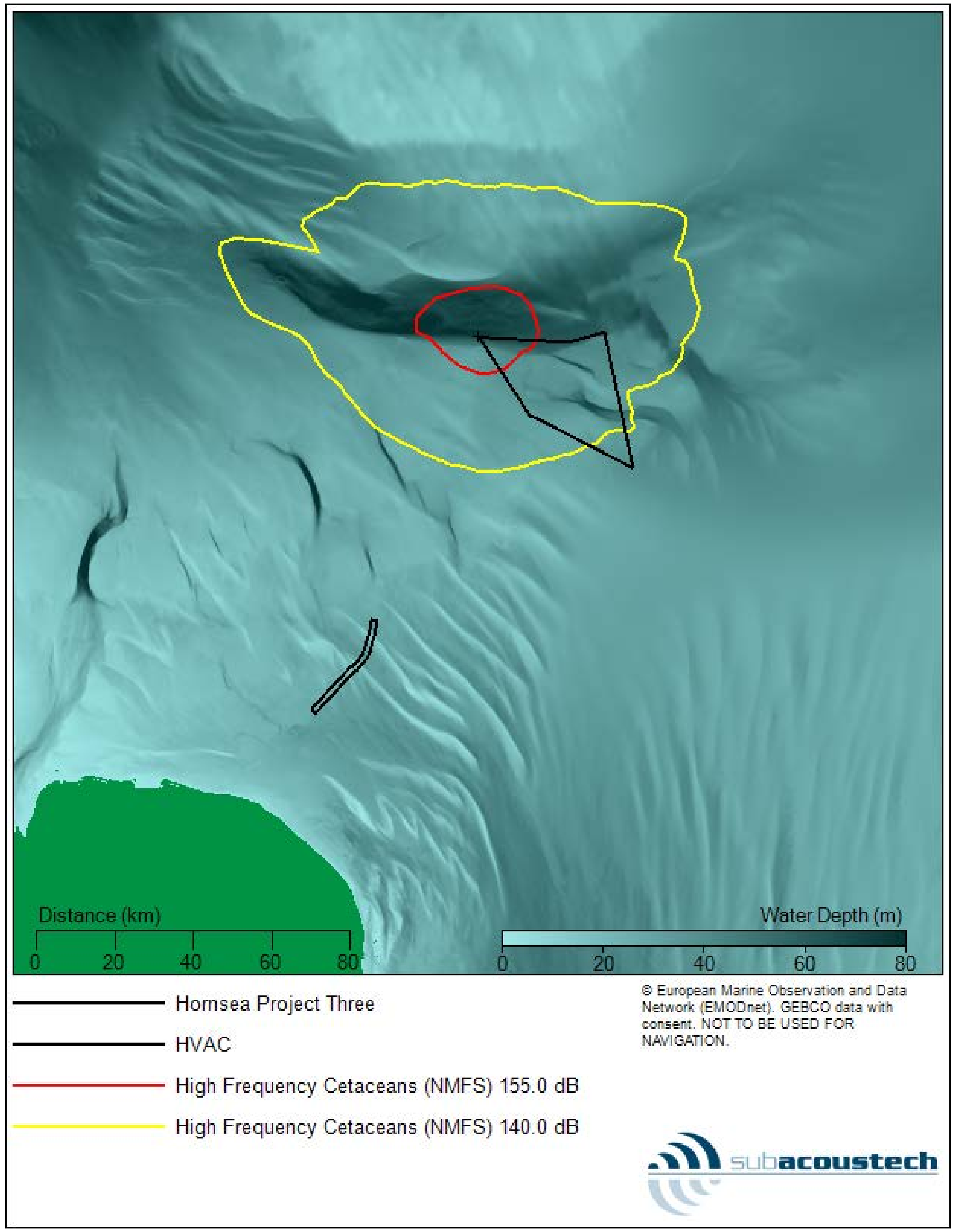

Figure A.31: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the Northwest location for installing a pin pile with a maximum blow energy of 2500 kJ.

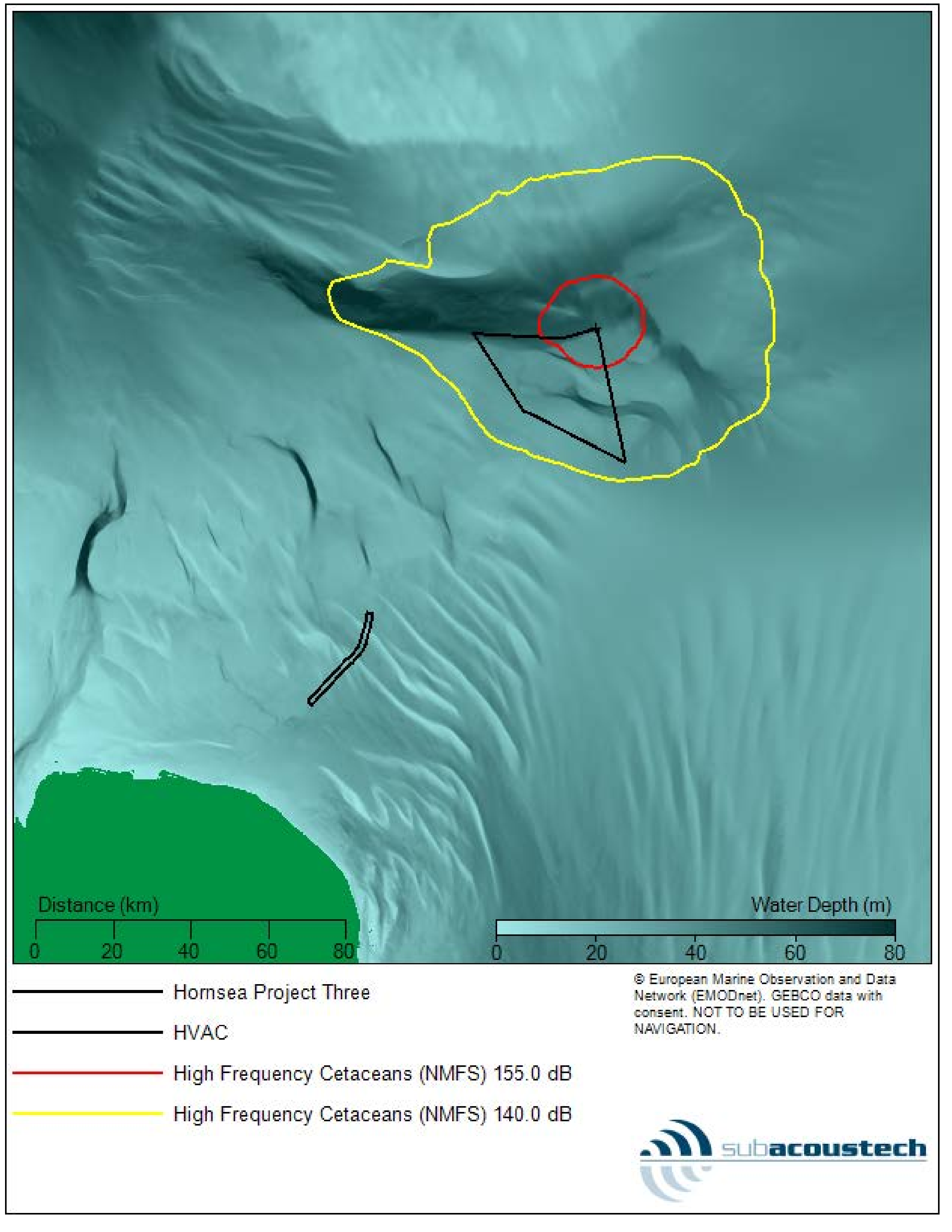

Figure A.32: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the Northeast location for installing a pin pile with a maximum blow energy of 2500 kJ.

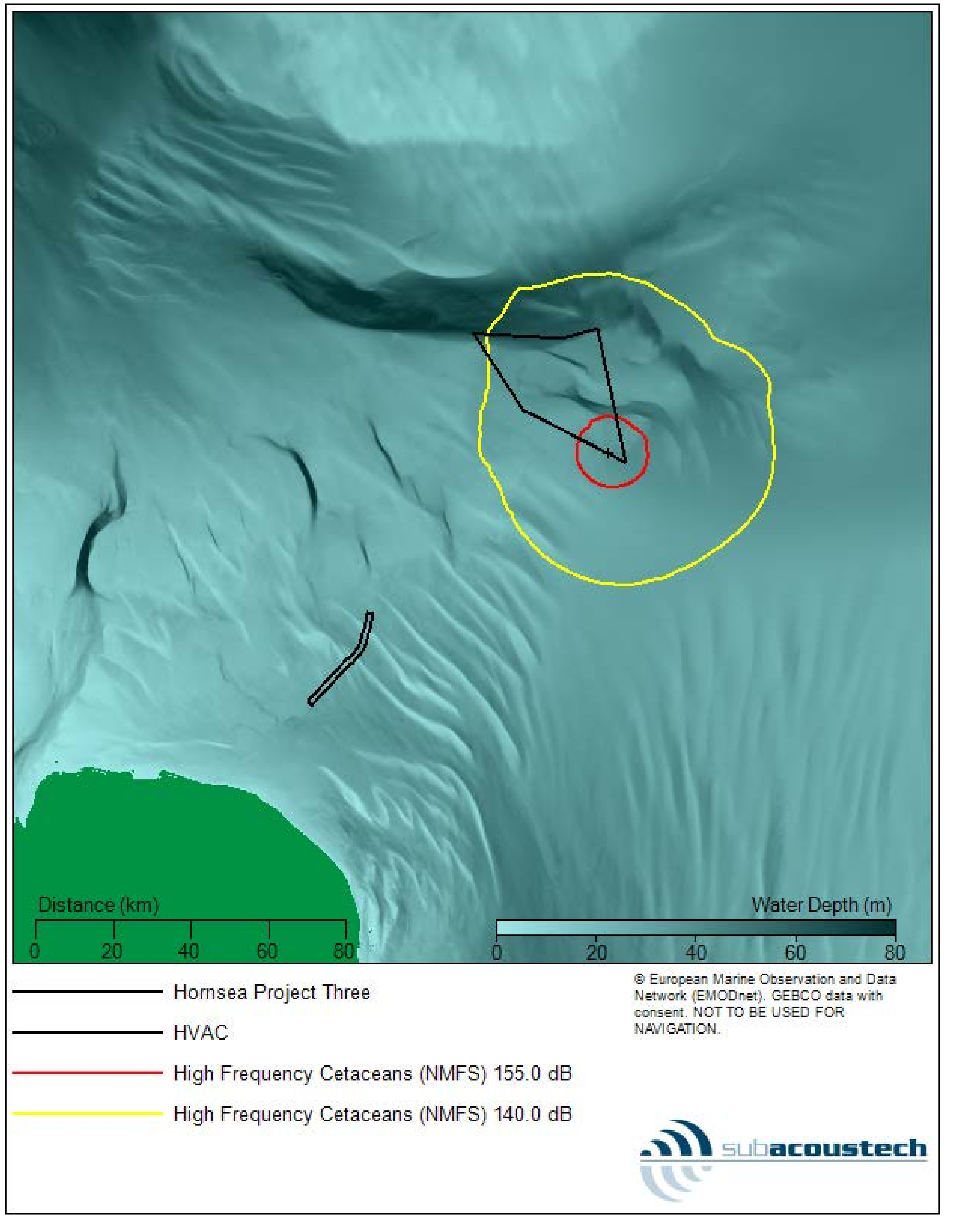

Figure A.33: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the South location for installing a pin pile with a maximum blow energy of 2500 kJ.

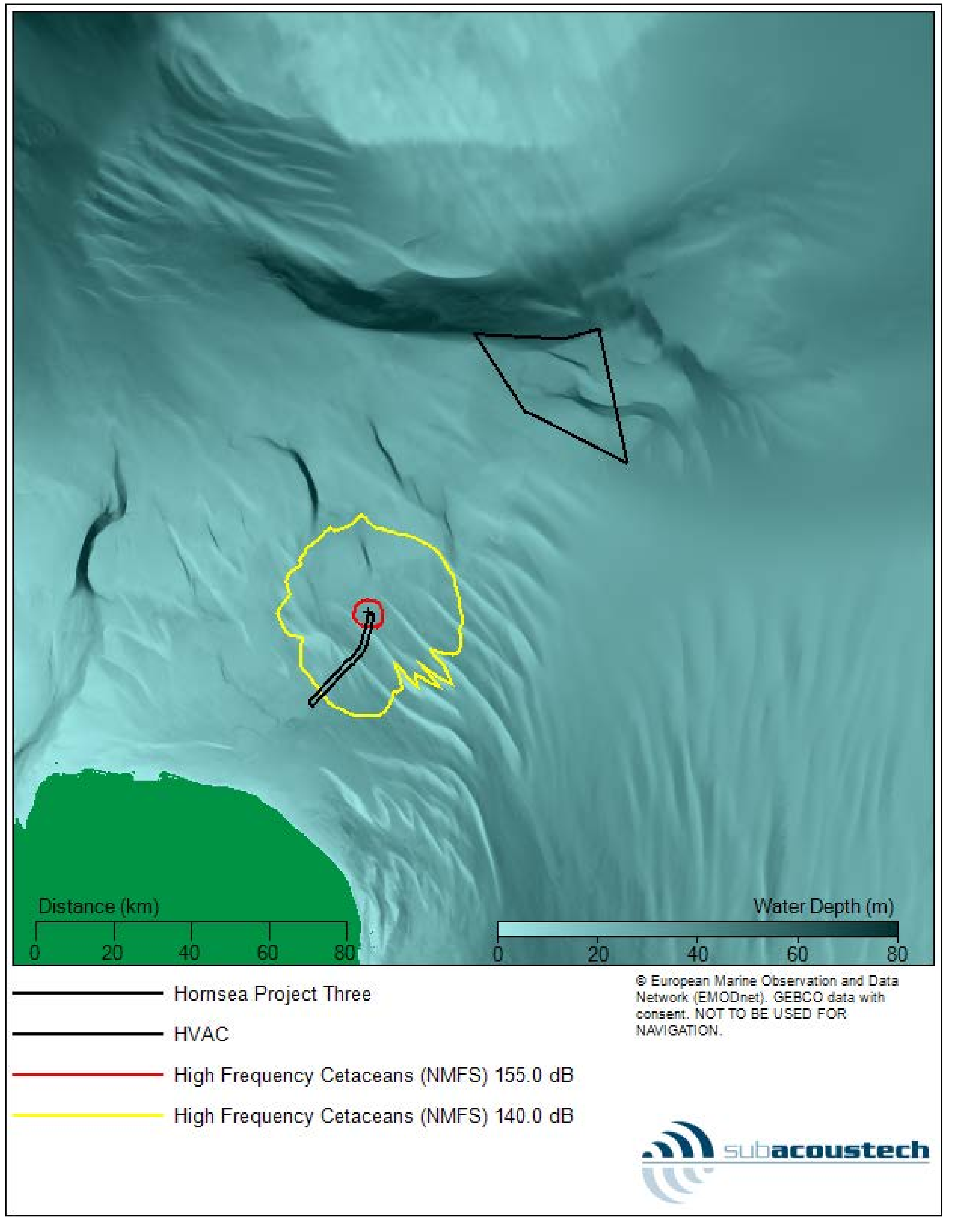

Figure A.34: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the HVAC North location for installing a pin pile with a maximum blow energy of 2500 kJ.

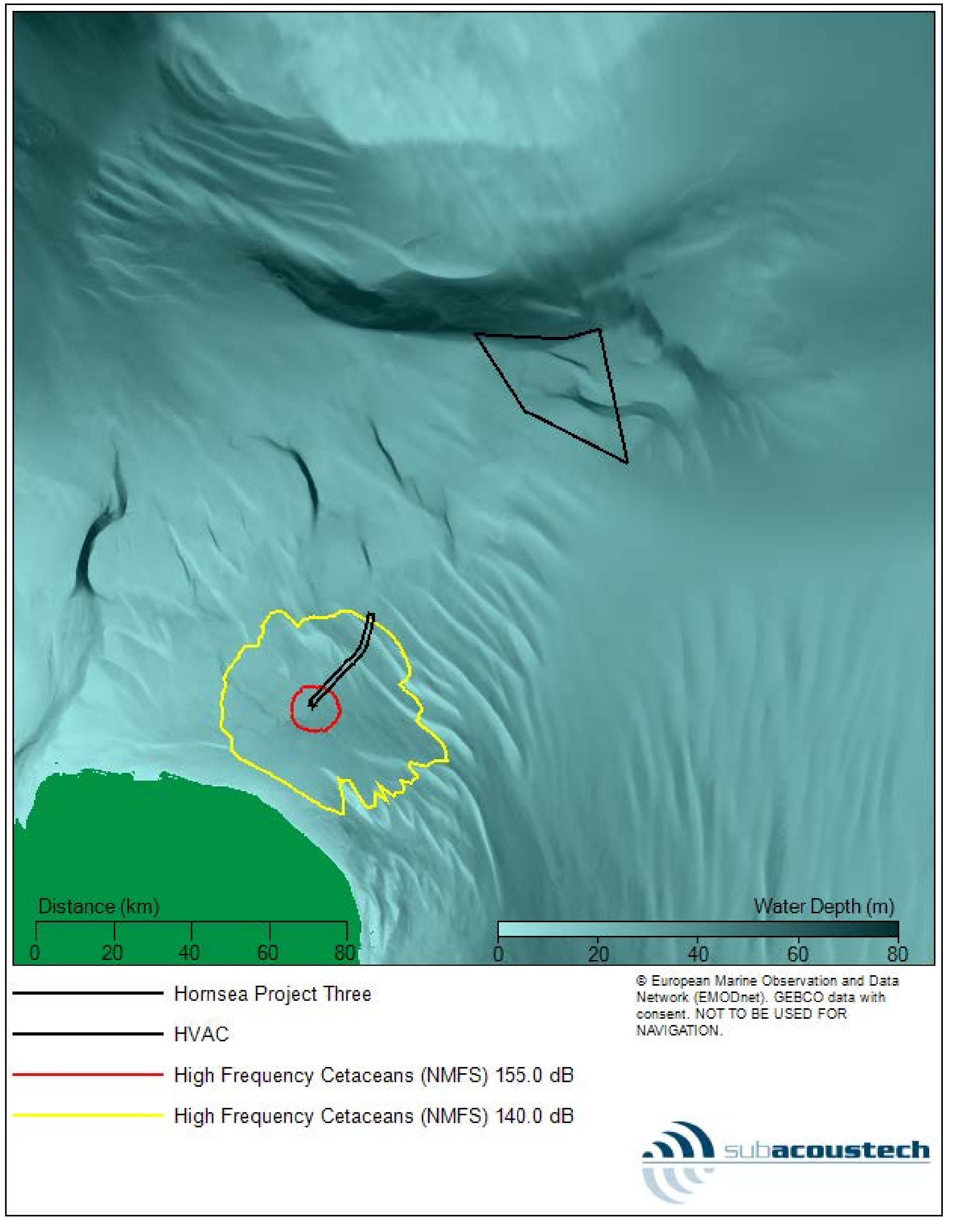

Figure A.35: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the HVAC South location for installing a pin pile with a maximum blow energy of 2500 kJ.

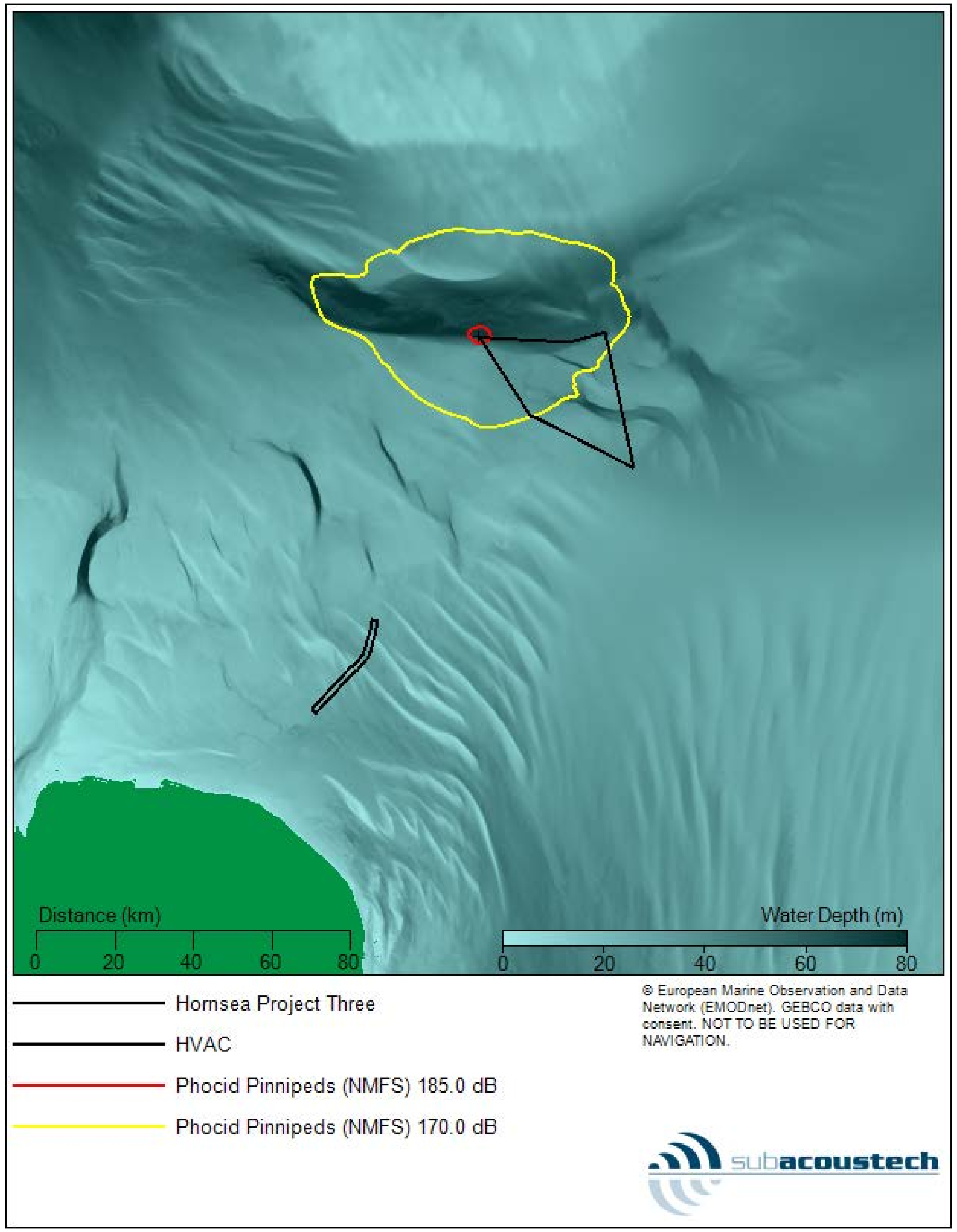

Figure A.36: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the Northwest location for installing a pin pile with a maximum blow energy of 2500 kJ.

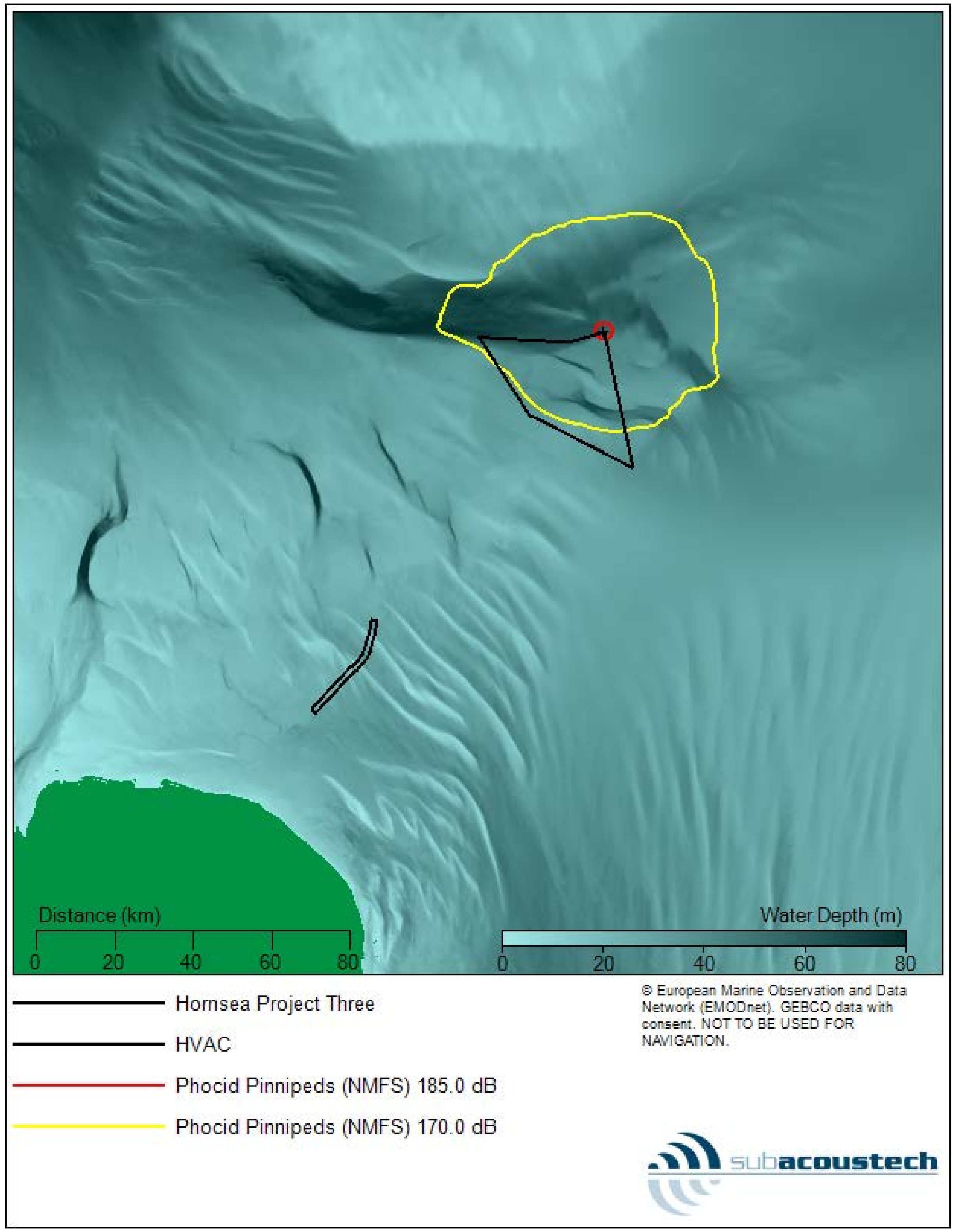

Figure A.37: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the Northeast location for installing a pin pile with a maximum blow energy of 2500 kJ.

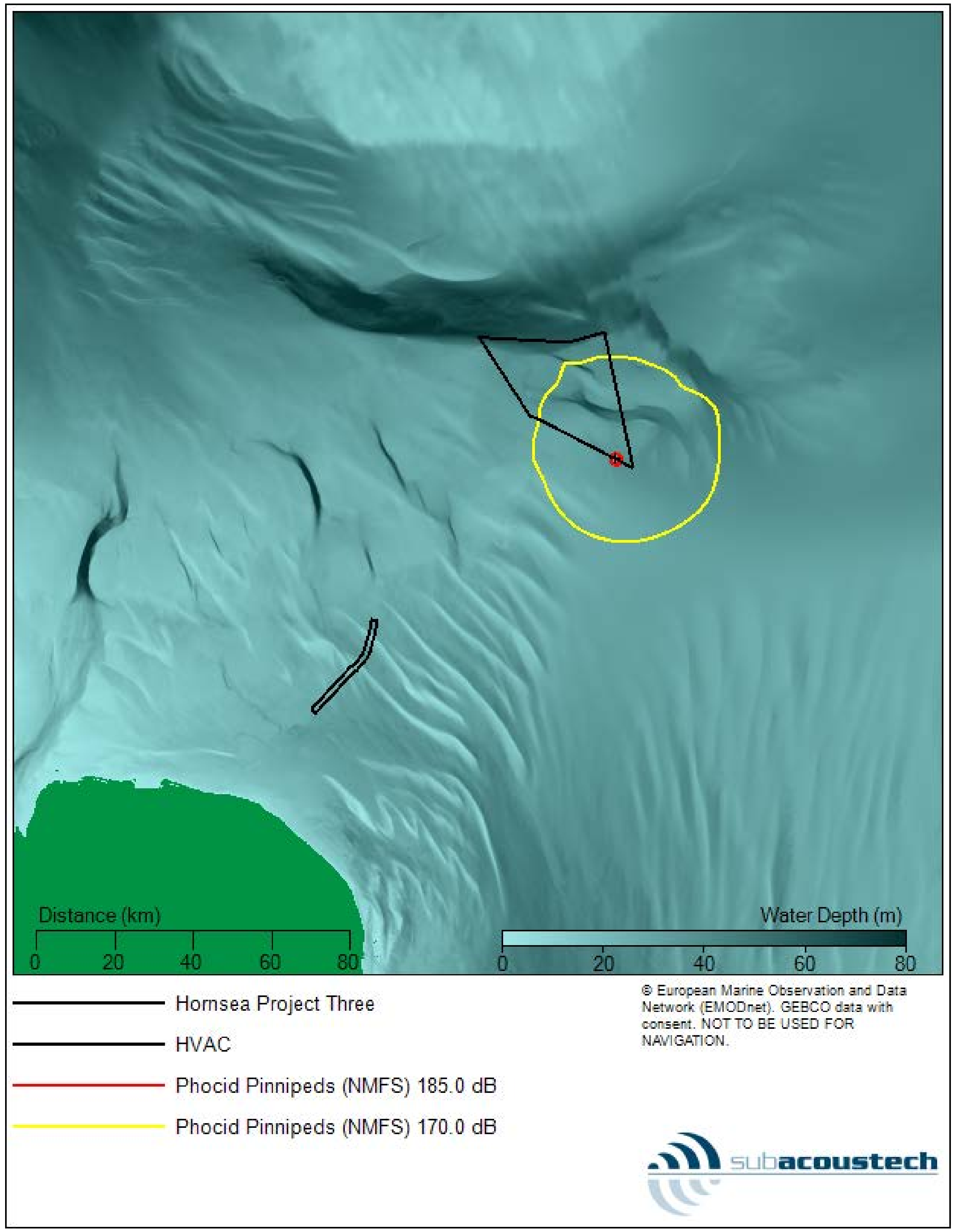

Figure A.38: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the South location for installing a pin pile with a maximum blow energy of 2500 kJ.

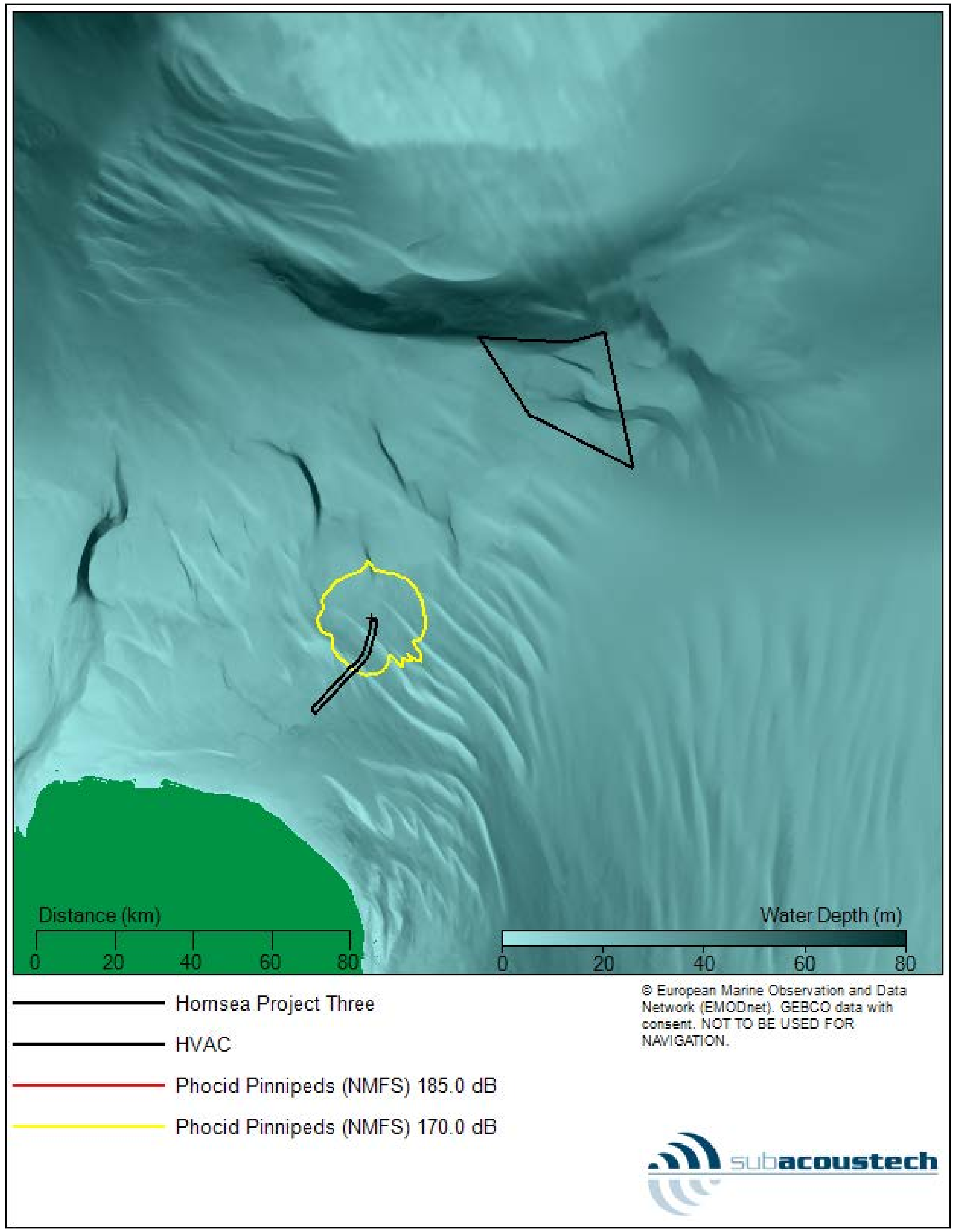

Figure A.39: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the HVAC North location for installing a pin pile with a maximum blow energy of 2500 kJ.

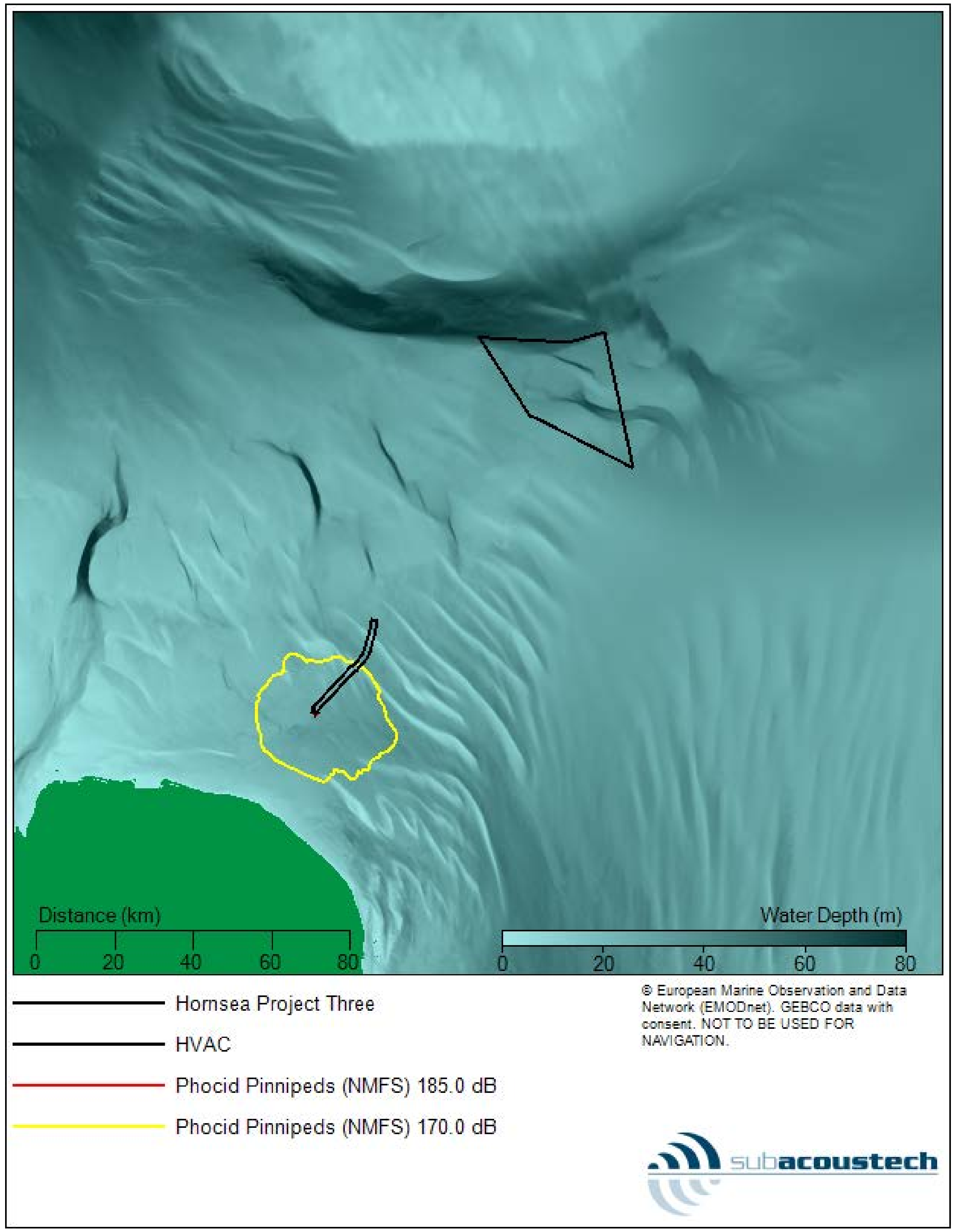

Figure A.40: Contour plot showing the PTS and TTS impact ranges (NMFS, 2016) for fleeing Phocid Pinnipeds (PW) (underwater) at the HVAC South location for installing a pin pile with a maximum blow energy of 2500 kJ.

A.4 Impacts on fish

A.4.1.1 The following figures present the predicted impact ranges for fish with reference to the results presented in section 5.3.2 of this report. Once again, the figures here differ from those presented in section A.2 as these figures show SEL_{cum} criteria for fleeing receptors. Please note that some of the contours are too small to be seen at the scale of the map. The contours define the distance from the pile, at the start of piling, where the fish must be to receive the exposure criterion:

- Figure A.41 Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the Northwest location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.42 Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the Northeast location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.43 Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the South location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.44 Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the HVAC North location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.45 Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the HVAC South location for installing a monopile with a maximum blow energy of 5000 kJ;
- Figure A.46 Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the Northwest location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.47 Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the Northeast location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.48 Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the South location for installing a pin pile with a maximum blow energy of 2500 kJ;
- Figure A.49 Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the HVAC North location for installing a pin pile with a maximum blow energy of 2500 kJ; and
- Figure A.50 Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the HVAC South location for installing a pin pile with a maximum blow energy of 2500 kJ.

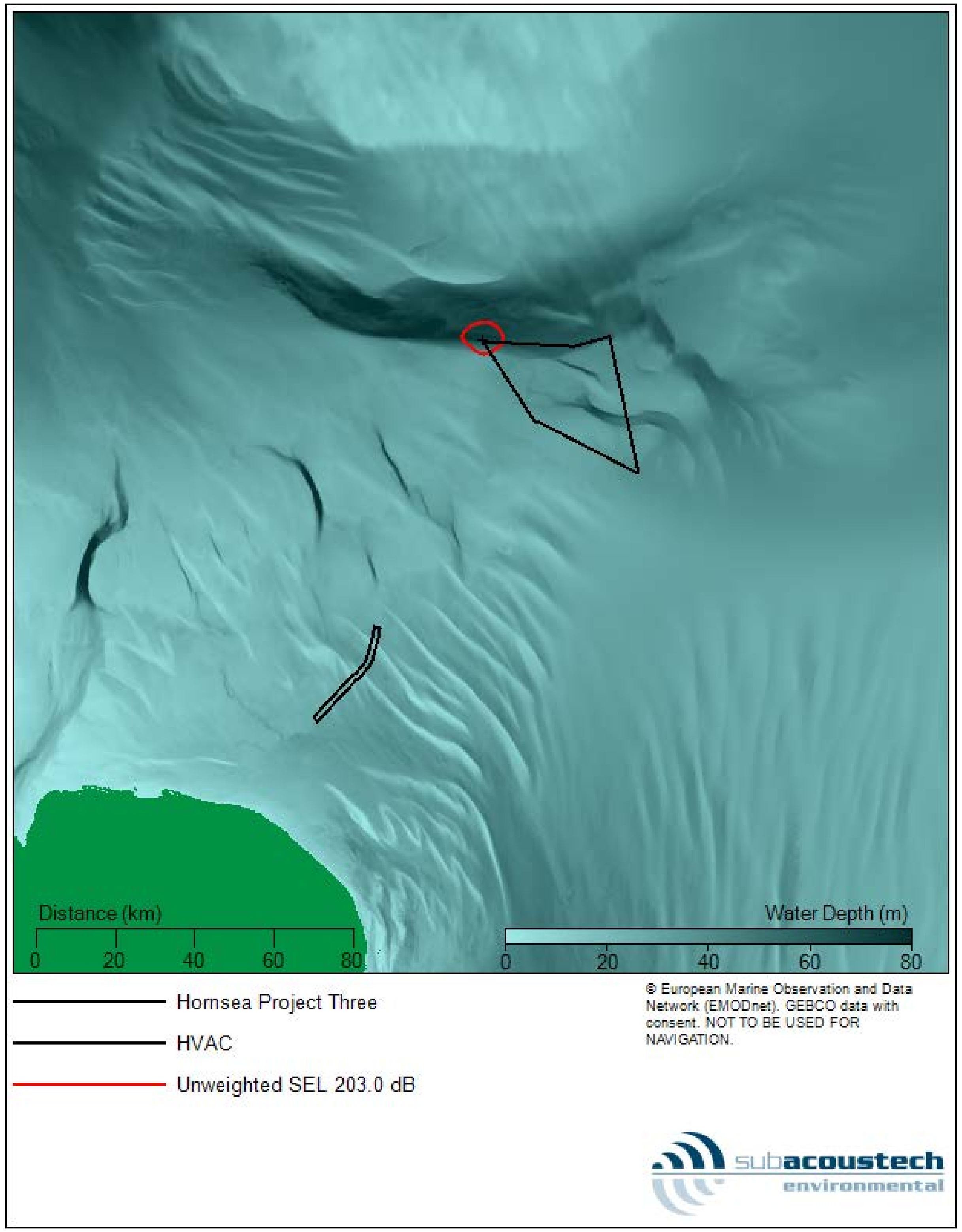

Figure A.41: Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the Northwest location for installing a monopile with a maximum blow energy of 5000 kJ.

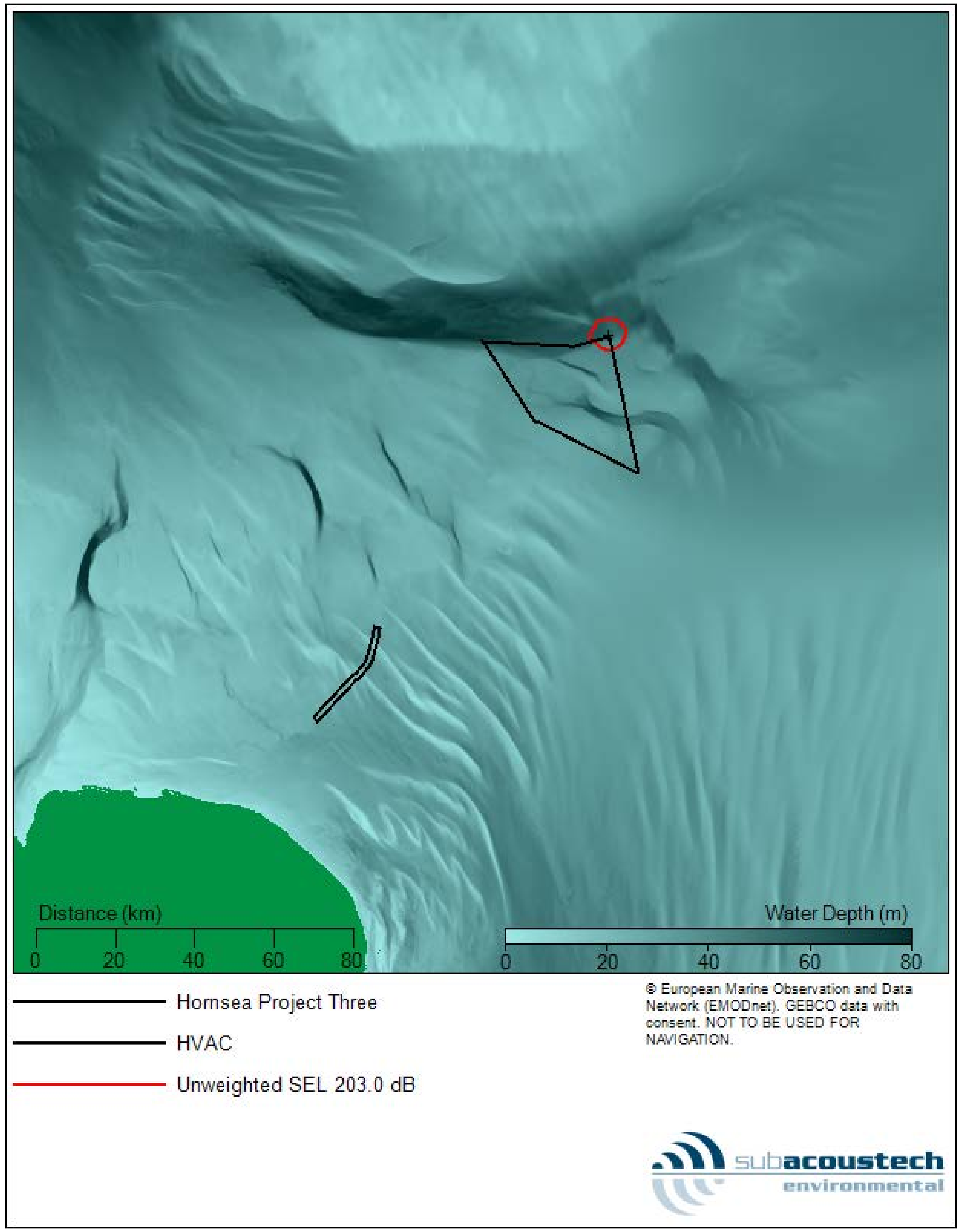

Figure A.42: Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the Northeast location for installing a monopile with a maximum blow energy of 5000 kJ.

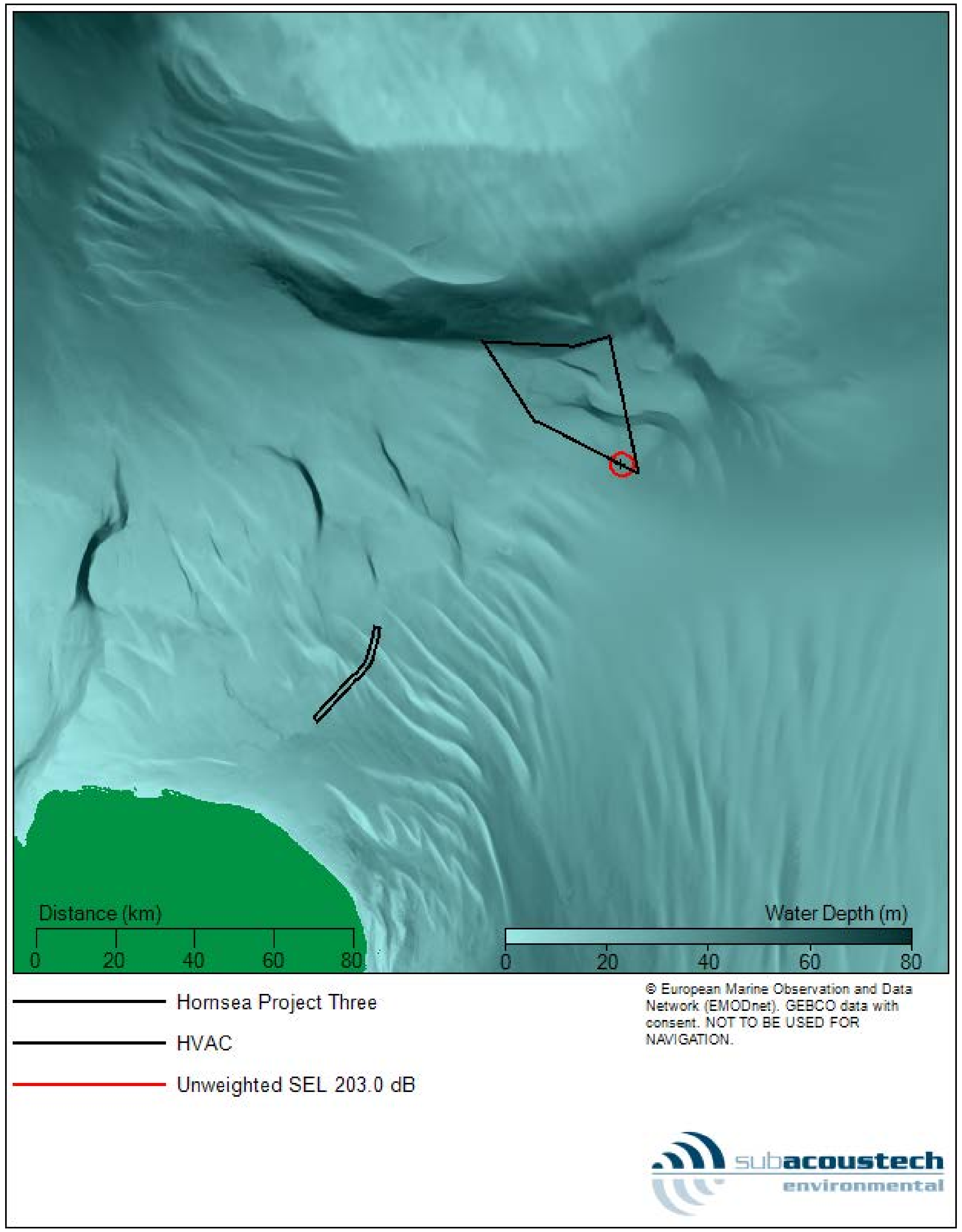

Figure A.43: Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the South location for installing a monopile with a maximum blow energy of 5000 kJ.

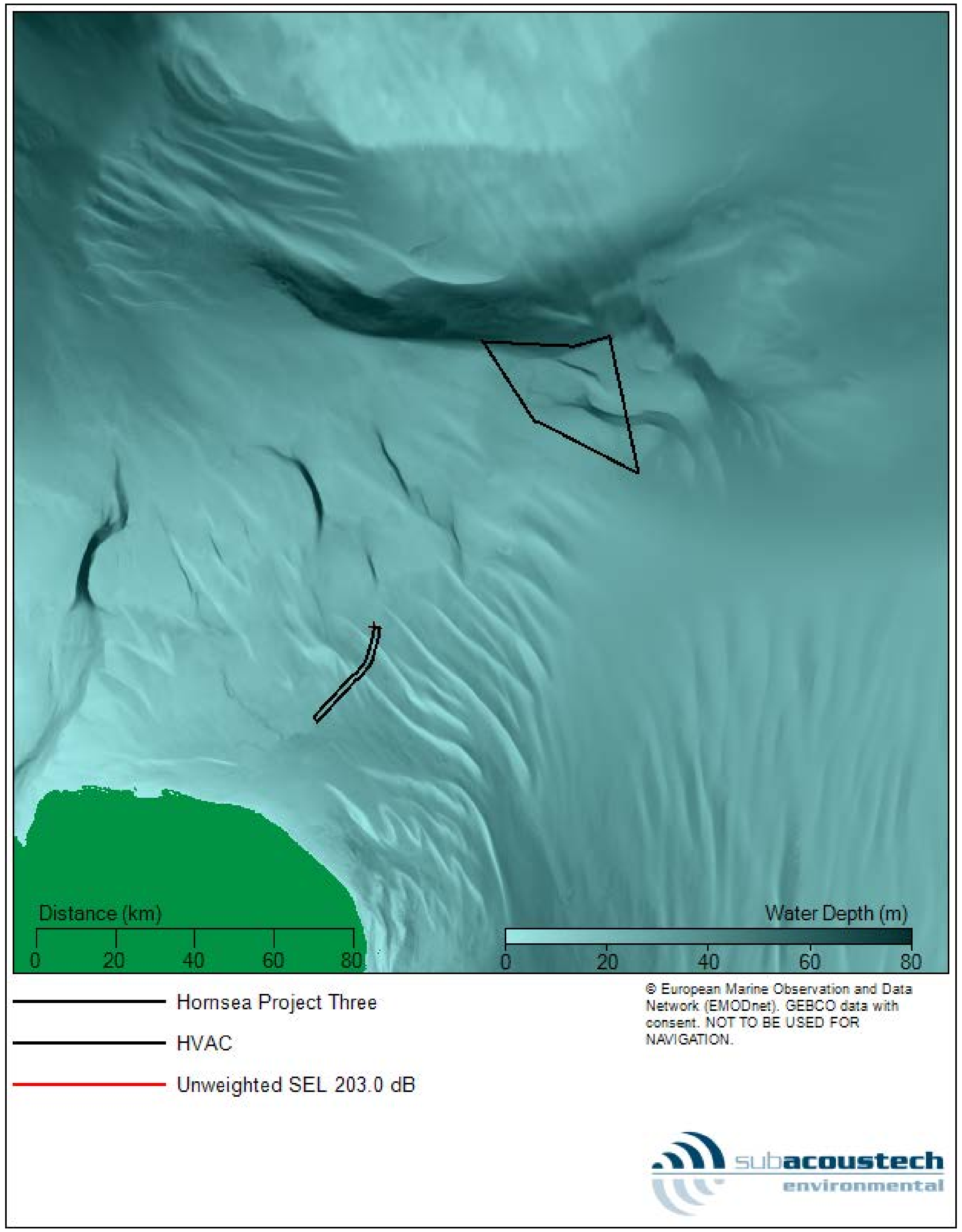

Figure A.44: Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the HVAC North location for installing a monopile with a maximum blow energy of 5000 kJ.

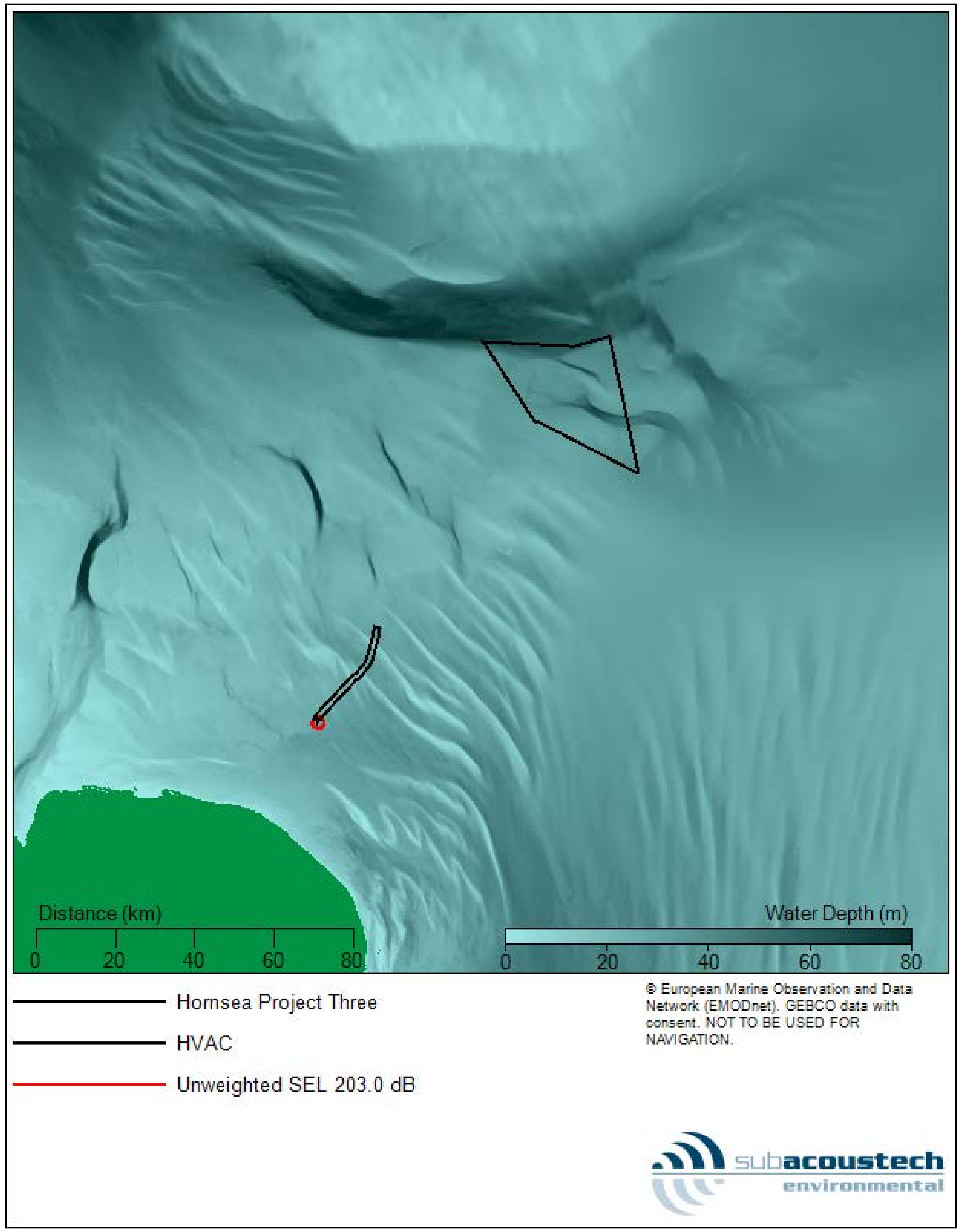

Figure A.45: Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the HVAC South location for installing a monopile with a maximum blow energy of 5000 kJ.

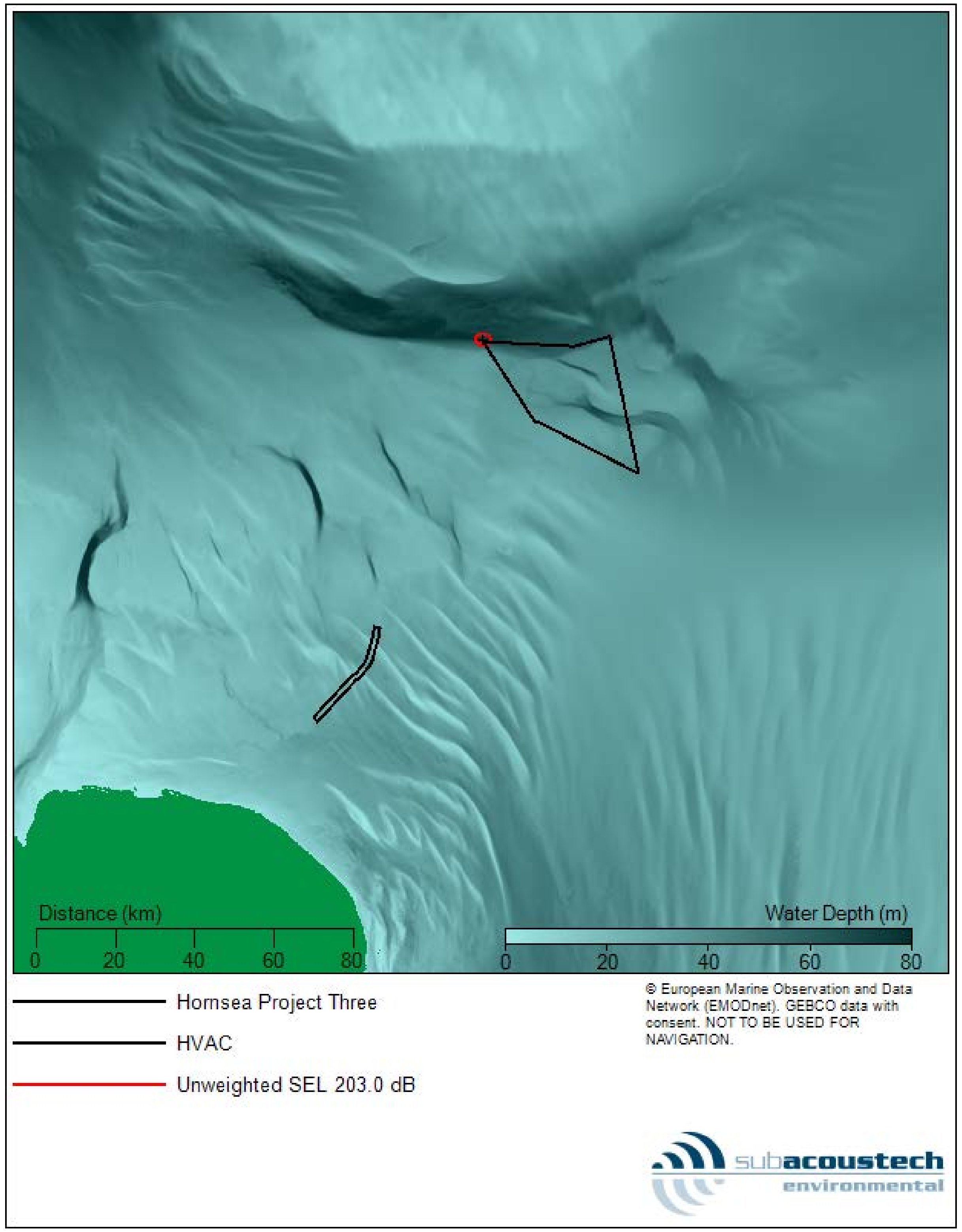

Figure A.46: Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the Northwest location for installing a pin pile with a maximum blow energy of 2500 kJ.

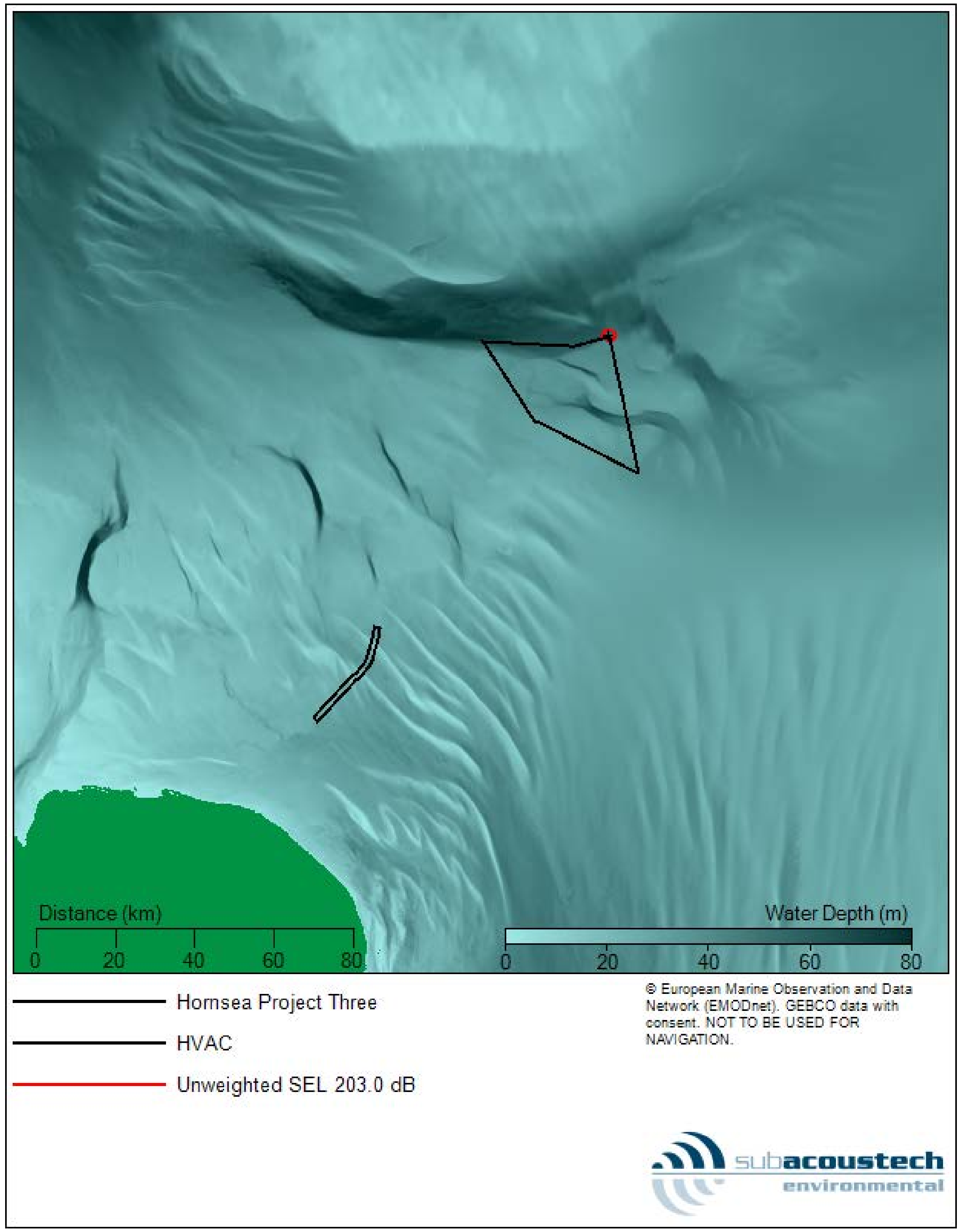

Figure A.47: Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the Northeast location for installing a pin pile with a maximum blow energy of 2500 kJ.

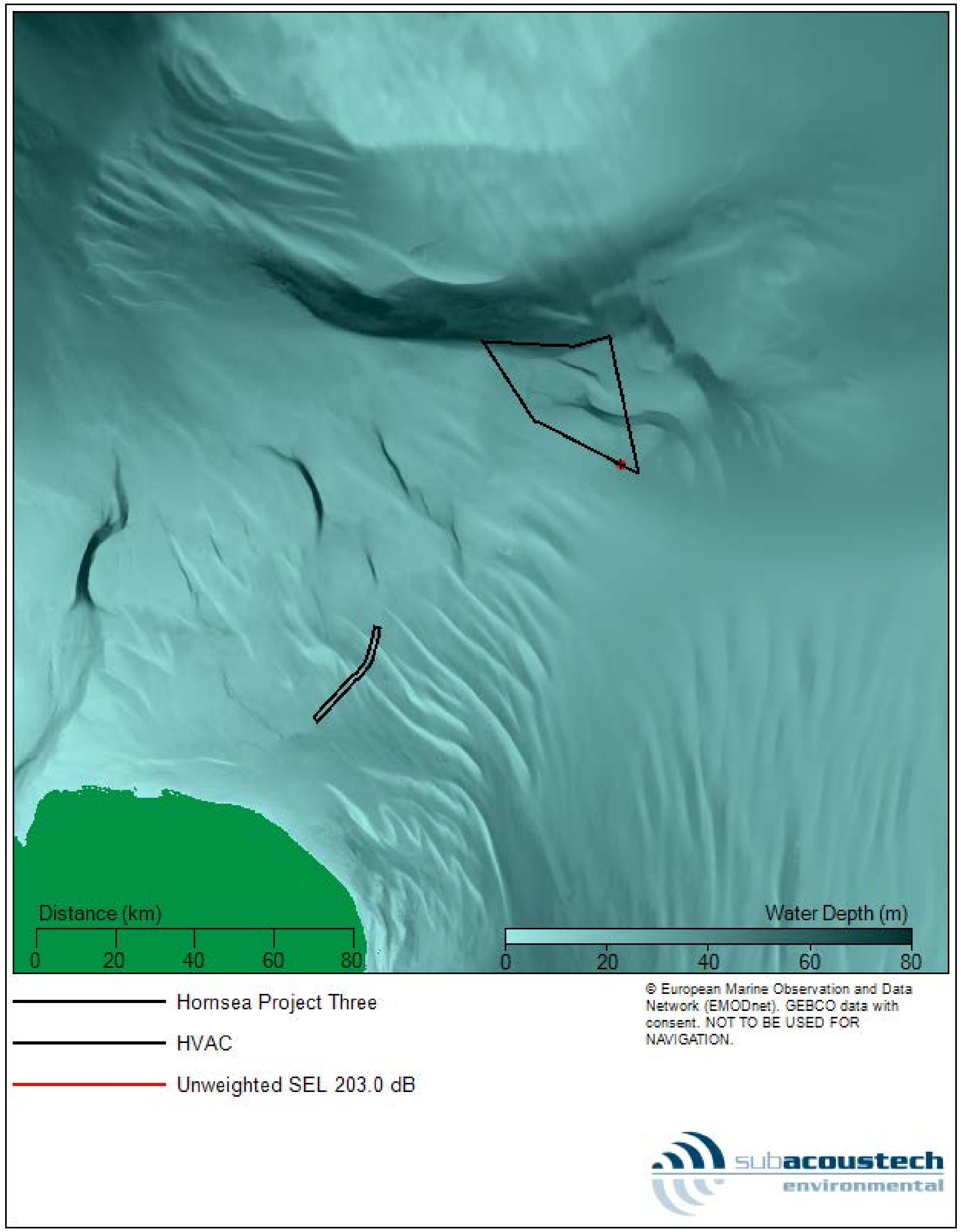

Figure A.48: Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the South location for installing a pin pile with a maximum blow energy of 2500 kJ.

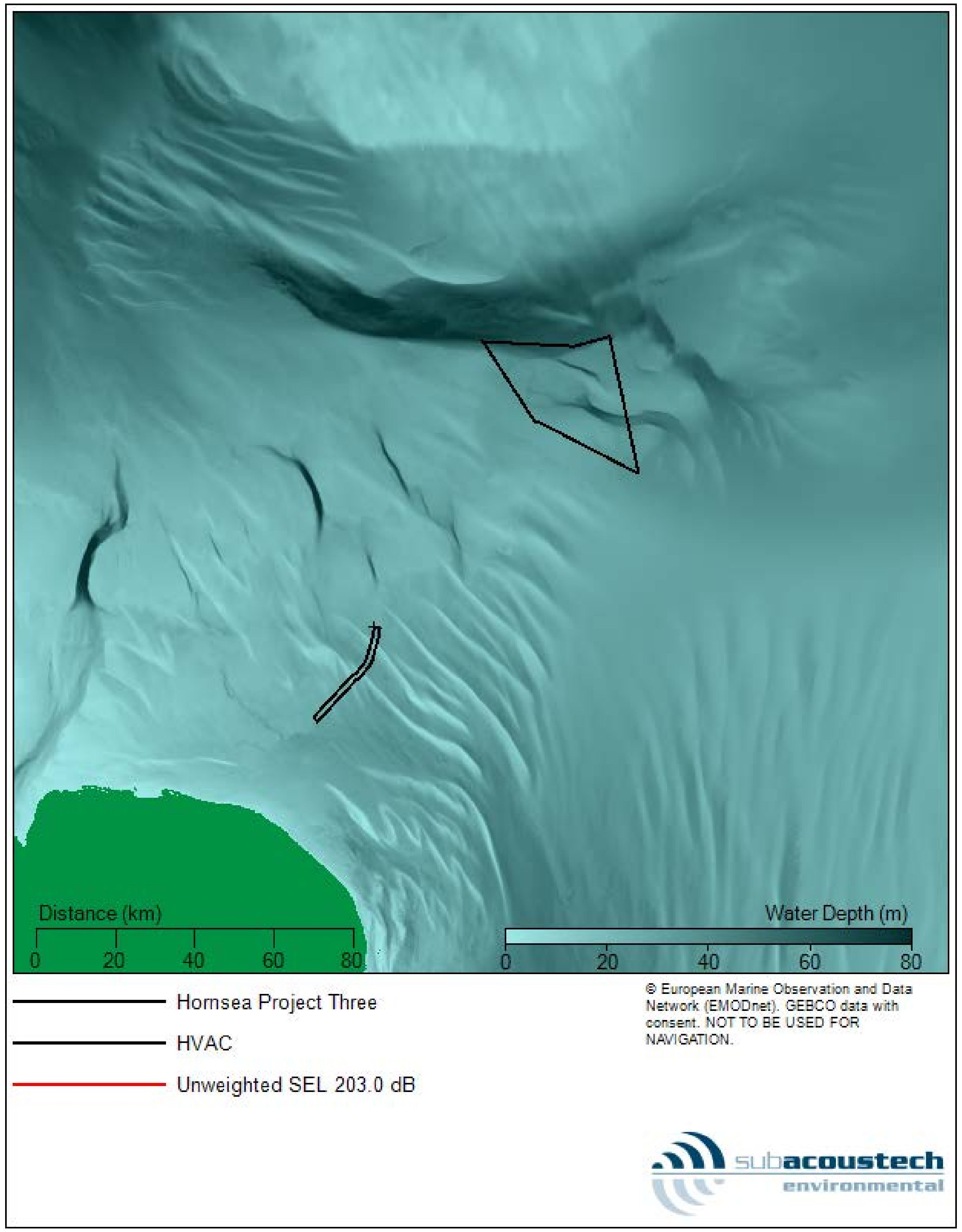

Figure A.49: Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the HVAC North location for installing a pin pile with a maximum blow energy of 2500 kJ.

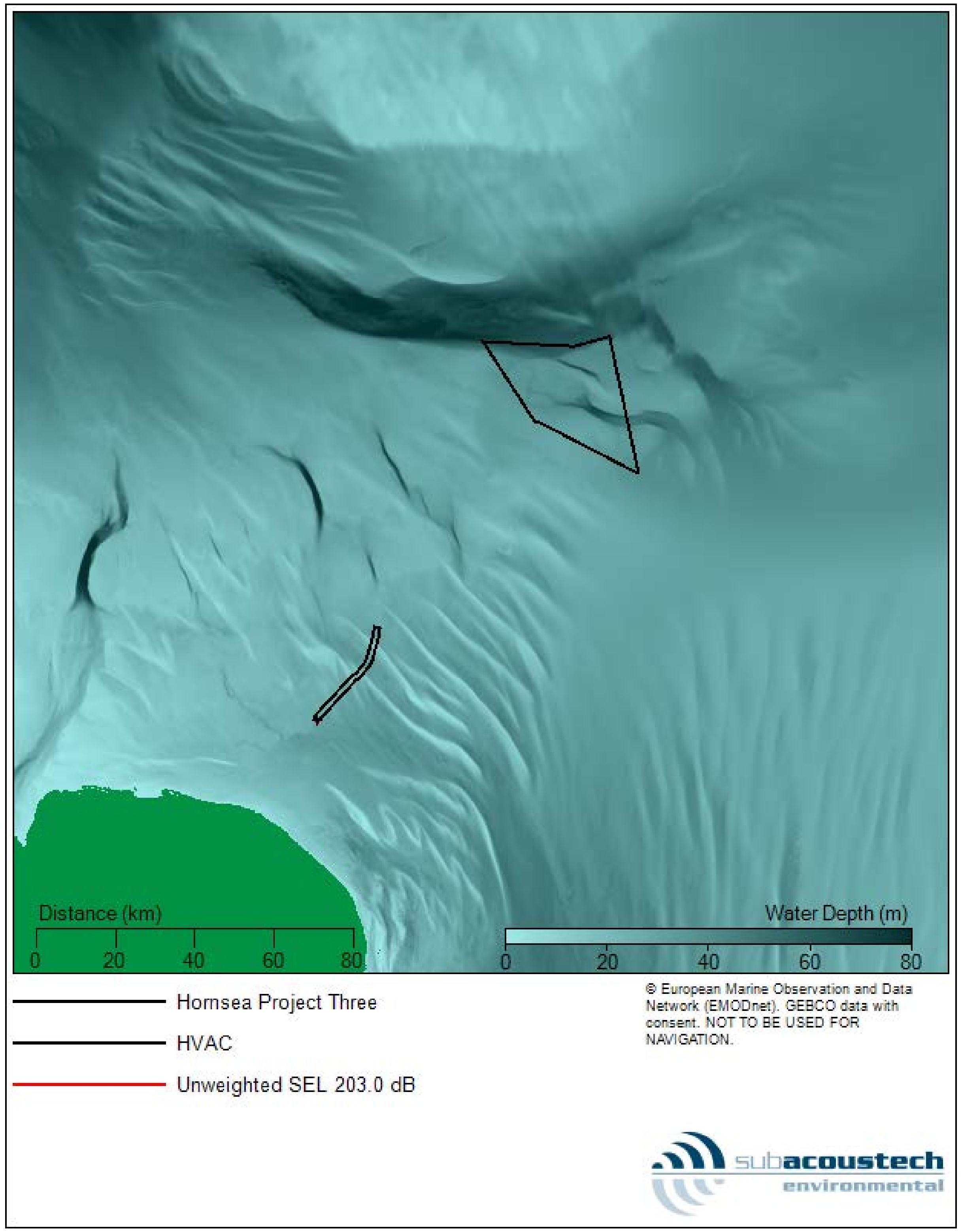

Figure A.50: Contour plot showing the recoverable injury impact ranges (Popper *et al.*, 2014) for fleeing fish at the HVAC South location for installing a pin pile with a maximum blow energy of 2500 kJ.