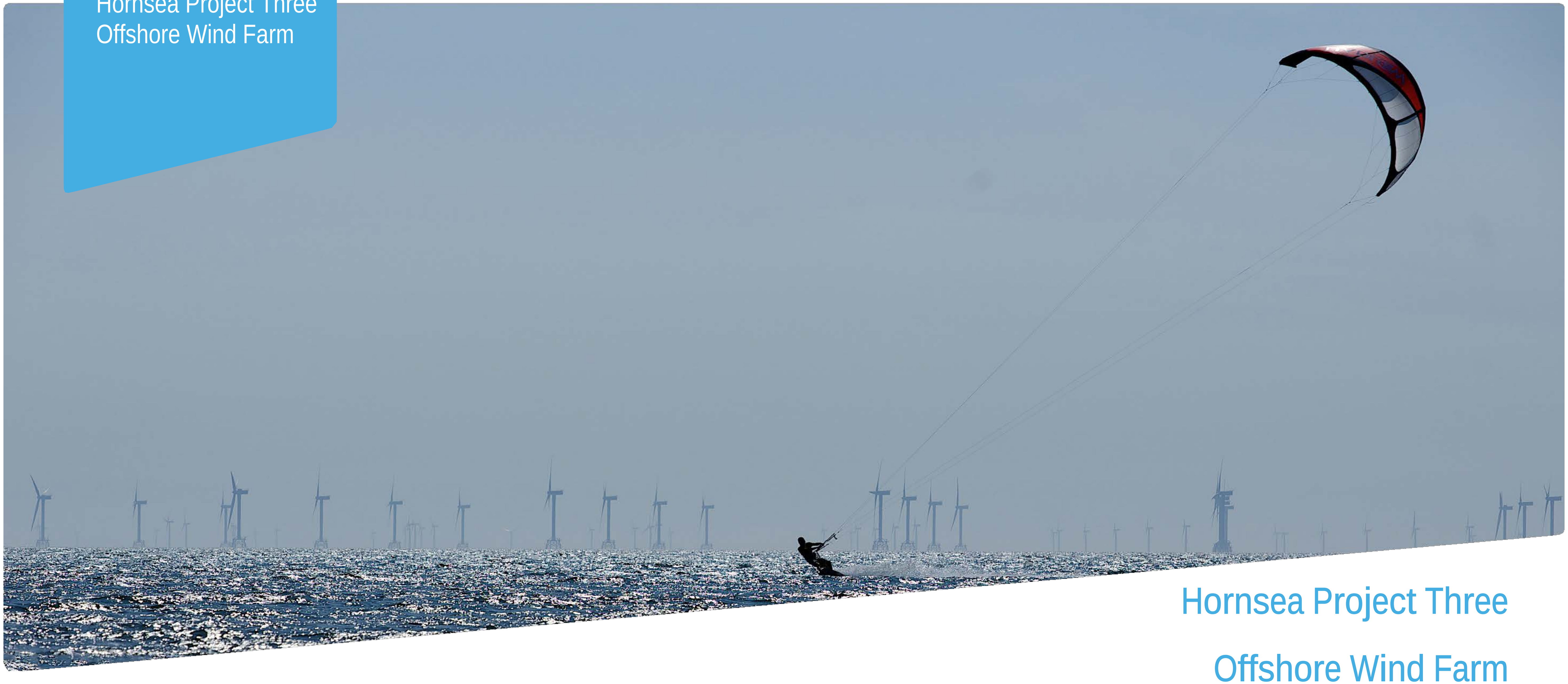
Hornsea Project Three
Offshore Wind Farm



Hornsea Project Three

Offshore Wind Farm

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Hornsea 3
Offshore Wind Farm

Ørsted

Environmental Impact Assessment

Environmental Statement

Volume 4

Annex 3.1 – Subsea Noise Technical Report

Report Number: A6.4.3.1

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This report is also downloadable from the Hornsea Project Three offshore wind farm website at:

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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 log10(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 20log10 (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 above or below ambient that is associated with a sound wave.
Peak-to-peak pressure	The sum of the highest positive and negative pressures that is associated with a sound wave.
Permanent Threshold Shift (PTS)	A total or partial permanent loss of hearing caused by some kind of 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.
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.
Threshold	The threshold generally represents the lowest signal level an animal will detect in some statistically predetermined percent of presentations of a signal. Most often, the threshold is the level at which an animal will indicate detection 50% of the time. Auditory thresholds are the lowest sound levels detected by an animal at the 50% level.
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, or dB_{ht}(*Species*) for fish and marine mammals.

Acronyms

Unit	Description
BGS	British Geological Survey
Cefas	Centre for Environment, Fisheries and Aquaculture Science
cSEL	Cumulative sound exposure level
EMODnet	European Marine Observation and Data Network
GE	General Electric
GEBCO	General Bathymetric Chart of the Oceans
HF	High Frequency
HVAC	High Voltage Alternating Current
INSPIRE	Impulse Noise Sound Propagation and Impact Range Estimator
JNCC	Joint Nature Conservation Committee
LAT	Lowest Astronomical Tide
LF	Low Frequency
MAREMAP	Marine Environmental Mapping Program
MF	Mid Frequency
MMO	Marine Mammal Observer
NMFS	National Marine Fisheries Service
NPL	National Physical Laboratory
OSPAR	Oslo/Paris Convention (for the Protection of the Marine Environment of the North-East Atlantic)
PAM	Passive Acoustic Monitoring
PTS	Permanent Threshold Shift
PW	Pinnipeds (in water)
RMS	Root Mean Square
SE	Sound Exposure
SEL	Sound Exposure Level
SEL_{ss}	Single strike sound exposure level
SEL_{cum}	Cumulative sound exposure level
SPL	Sound Pressure Level
SPL_{peak}	Peak sound pressure level
SPL_{RMS}	Root mean squared sound pressure level

Unit	Description
T-POD	Timing Porpoise Detectors
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance

Units

Unit	Description
dB	Decibel (sound)
Hz	Hertz (frequency)
kHz	Kilohertz (frequency)
kJ	Kilojoule (energy)
km	Kilometre (distance)
km^2	Kilometres squared (area)
m	Metre (distance)
ms^{-1}	Metres per second (speed)
MW	Megawatt (power)
µPa	Micro pascal (pressure)
Pa	Pascal (pressure)

1. Introduction

1.1 Overview

1.1.1.1 This report has been prepared by Subacoustech Environmental Ltd and presents the noise modelling results at the proposed Hornsea Project Three offshore wind farm (hereafter referred to as Hornsea Three).

1.2 Hornsea Three

1.2.1.1 Hornsea Three is a proposed offshore wind farm development in the southern North Sea, located approximately 121 km northeast of the Norfolk coast at Trimingham and 160 km east of the Yorkshire coast, covering an area of approximately 696 km^2. Once complete, the site will contain up to 300 turbines.

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

1.3 Noise assessment

1.3.1.1 This report covers underwater noise impacts related to the construction, operation, and eventual decommissioning of Hornsea Three. The noise from these activities has been considered in terms of subsea noise. The assessment focuses on the pile driving activities during construction as this has the greatest potential to create subsea noise.

1.3.1.2 The modelling undertaken to calculate the noise levels in the water during the pile driving activities has been carried out using Subacoustech's INSPIRE subsea noise propagation and prediction software, which considers bathymetry, frequency content and speed of sound in water when calculating noise levels.

1.4 Assessment overview

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

- Summary of the various activities expected to take place during construction, operation 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 impacts on marine mammals and fish using various noise metrics and criteria (section 5.3);
- 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).

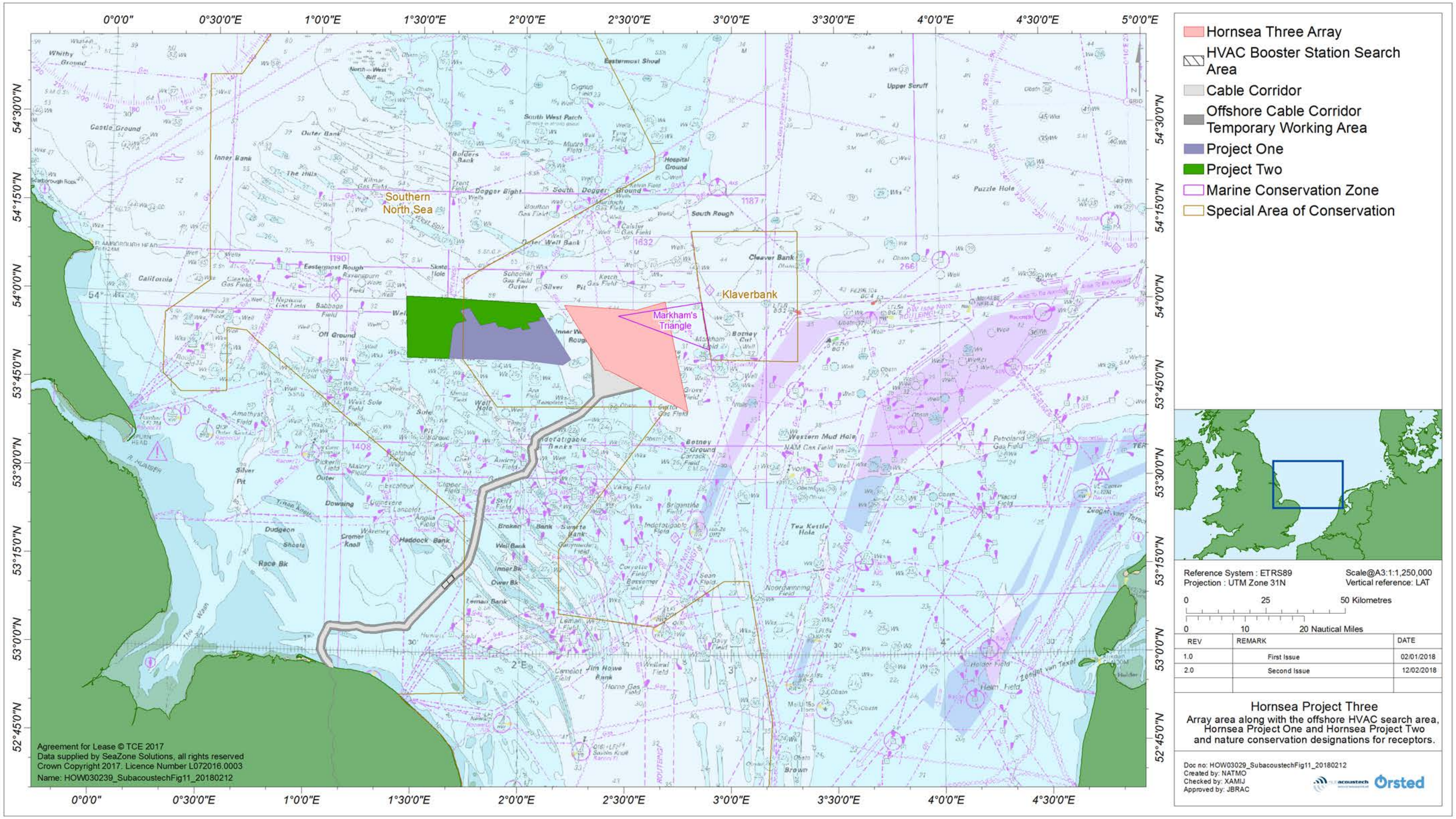

Figure 1.1: Map showing the Hornsea Three array area along with the offshore HVAC search area, Hornsea Project One and Hornsea Project Two, and nature conservation designations for receptors.

2. Potential Sources of Noise

2.1 Construction noise

2.1.1.1 Although impact piling is expected to be the primary and worst case noise source during the Hornsea Three development, several other noise sources will also be present. Initially, each of these has been considered and its impact assessed at high-level 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 the cable installation.
Drilling	Necessary in case impact piling refuses.
Impact piling	Monopiles installed with a maximum blow energy of 5,000 kJ over 4 hours. Pin piles installed with a maximum blow energy of 2,500 kJ over 4 hours.
Cable laying	Required during the cable installation (see below).
Rock placement	Potentially required on site for installation of cable and scour protection.
Trenching	Plough trenching may be required during the cable installation.
Vessel noise	Jack-up barges for piling, substructure and turbine installation. Other large and medium sized vessels on site to carry out other construction tasks, dive support and anchor handling. Other small vessels for crew transport and survey work on site.

2.1.1.3 A simple approach has been used for the high-level overview of modelling in this section. The NPL Good Practice Guide 133 for underwater noise (Robinson *et al.*, 2014) indicates that under certain circumstances, such as a high-level overview like this, a simple modelling approach may be considered acceptable. In this section the overview order of magnitude of the impact of the noise sources is considered and so this approach is considered sufficient. A more detailed model has been used in later sections for noise sources that have the potential for greater impacts..

2.1.1.4 The limitations of this simple modelling approach are noted, including the lack of frequency or bathymetry dependence, and as such these levels are only presented as a guideline to indicative noise levels for rank-ordering purposes and identifying the noise sources that could potentially lead to significant impacts, rather than as a detailed assessment at this stage.

2.1.1.5 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 Subacoustech's measurement database scaled to appropriate parameters. Extrapolated source levels at 1 m range for these activities are presented in Table 2.2.

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

Construction activity	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 more than 100 m in length.
Vessel noise (Large)	171 dB re 1 µPa @ 1 m (RMS)	Based on datasets from five different large vessels including container ships, FPSOs and other vessels more than 100 m in length. Vessel speed assumed as 12 knots.
Vessel noise (Medium)	164 dB re 1 µPa @ 1 m (RMS)	Based on datasets from three different moderate sized vessels, covering vessels less than 100 m in length. Vessel speed assumed as 12 knots.

2.1.1.6 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 the construction phase of Hornsea Three. This activity has therefore been studied in more detail using the INSPIRE model (section 5). Noise levels from all other activities would be expected to reduce to below disturbance criteria (see section 3.2.2) of the order of 100 m or less.

2.2 Impact piling

2.2.1.1 Impact piling is an option within the design envelope for 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. Percussive 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).

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

2.2.1.3 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.

2.3 Operational noise

2.3.1.1 Previous measurements of operational noise undertaken by Subacoustech Environmental 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.

2.4 Decommissioning noise

2.4.1.1 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. 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.

2.4.1.2 It should be noted that any of these techniques may be obsolete or superseded by the time Hornsea Three is decommissioned.

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, background levels of sea noise 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, for instance, 6 dB really means "twice as much as…". It is, therefore, used with a reference unit, which expresses the base from which the ratio is expressed. The reference quantity is conventionally smaller than the smallest value to be expressed on the scale, so that any level quoted is positive. For instance, a reference quantity of 20 µPa is 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 (Pa) is equal to the pressure exerted by one Newton over one square metre; 1 µPa 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 (SPL) 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 period to determine the RMS level of the time varying und. The SPL can therefore 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 period over which the RMS level is calculated is quoted. For instance, in the case of 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. Often, 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 (SPL_{peak}) are often used to characterise sound transients 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 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 NMFS (2016) and Southall *et al.* (2007). These assign a frequency response 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 effect on marine species (e.g. OSPAR Commission 2008, Thomsen *et al.*, 2006). The extent to which intense underwater sound might cause an adverse environmental effect 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 aquatic 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 recently.

3.2.1.2 The effects 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 discussed 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 National Marine Fisheries Service 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.

3.2.2.3 Similarly to Southall *et al.* (2007), the NMFS (2016) guidance groups marine mammals into hearing groups and applies filters to the unweighted noise to approximate the hearing sensitivity of the receptor for some of the criteria. The hearing groups given in 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 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 Seal)	50 Hz to 86 kHz

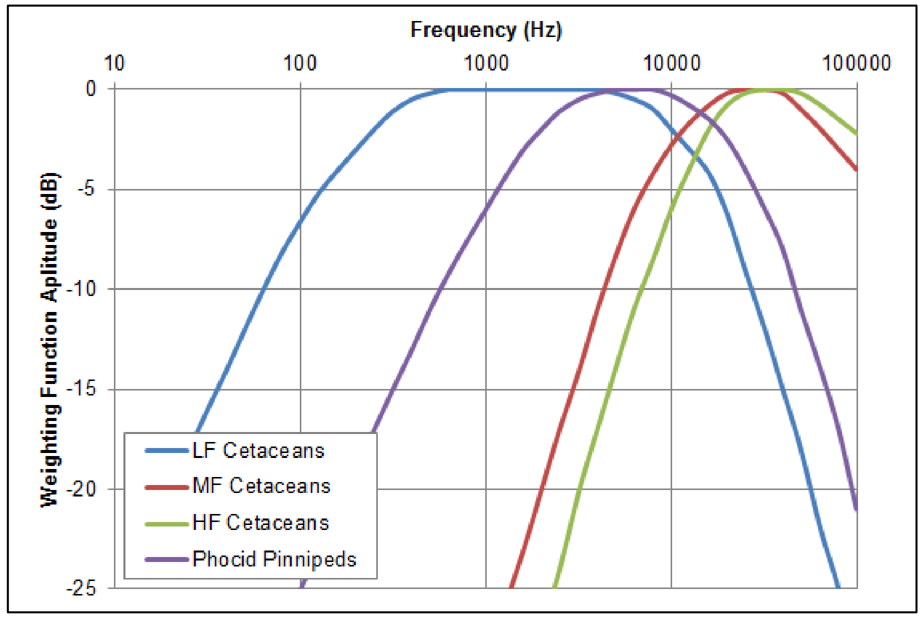

Figure 3.1: Auditory weighting functions for low frequency (LF) cetaceans, mid frequency (MF) cetaceans, high frequency (HF) cetaceans and phocid pinnipeds (PW) (underwater) (from NMFS, 2016).

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, which assumes 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 marine mammal 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)	
	SPL_{peak} Unweighted	SEL_{cum} Weighted	SPL_{peak} Unweighted	SEL_{cum} Weighted
Low Frequency (LF) Cetaceans	219 dB re 1 µPa	183 dB re 1 µPa²s	213 dB re 1 µPa	168 dB re 1 µPa²s
Mid Frequency (MF) Cetaceans	230 dB re 1 µPa	185 dB re 1 µPa²s	224 dB re 1 µPa	170 dB re 1 µPa²s
High Frequency (HF) Cetaceans	202 dB re 1 µPa	155 dB re 1 µPa²s	196 dB re 1 µPa	140 dB re 1 µPa²s
Phocid Pinnipeds (PW)	218 dB re 1 µPa	185 dB re 1 µPa²s	212 dB re 1 µPa	170 dB re 1 µPa²s

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. Marine mammal behavioural responses have been calculated using a dose-response curve, which is described fully in volume 2, chapter 4: Marine Mammals.

Fish

3.2.2.7 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.

3.2.2.8 The Popper *et al.* (2014) study groups species of fish into whether 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 3.3. 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).

3.2.2.9 Popper *et al.* (2014) 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 3.3: Criteria for assessment of effects on fish (with swim bladder involved in hearing).

Popper *et al.* (2014)	**SPL_{peak} Unweighted**	**SEL_{cum} Weighted**
Recoverable injury	207 dB re 1 µPa	203 dB re 1 μPa^2s
TTS	-	186 dB re 1 μPa^2s
Masking	Qualitative	Qualitative
Behavioural	Qualitative	Qualitative

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

3.2.2.11 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 distant 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 natural occurring ambient noise, man-made noise dominates the background. The North Sea is heavily used 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 Three boundary. As noted in section 2.1, where dredging does occur, its potential noise output is so low that any contribution to the overall noise in the context of other developments would be negligible.

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 within and in the vicinity of the Hornsea Three array 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 time, and so would have little contribution to the long-term ambient noise in the area.

4.1.1.4 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.

4.1.1.5 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 to 1,000 Hz region, although often extends into higher and lower frequencies.

4.1.1.6 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 would 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 the Hornsea projects are not currently available.

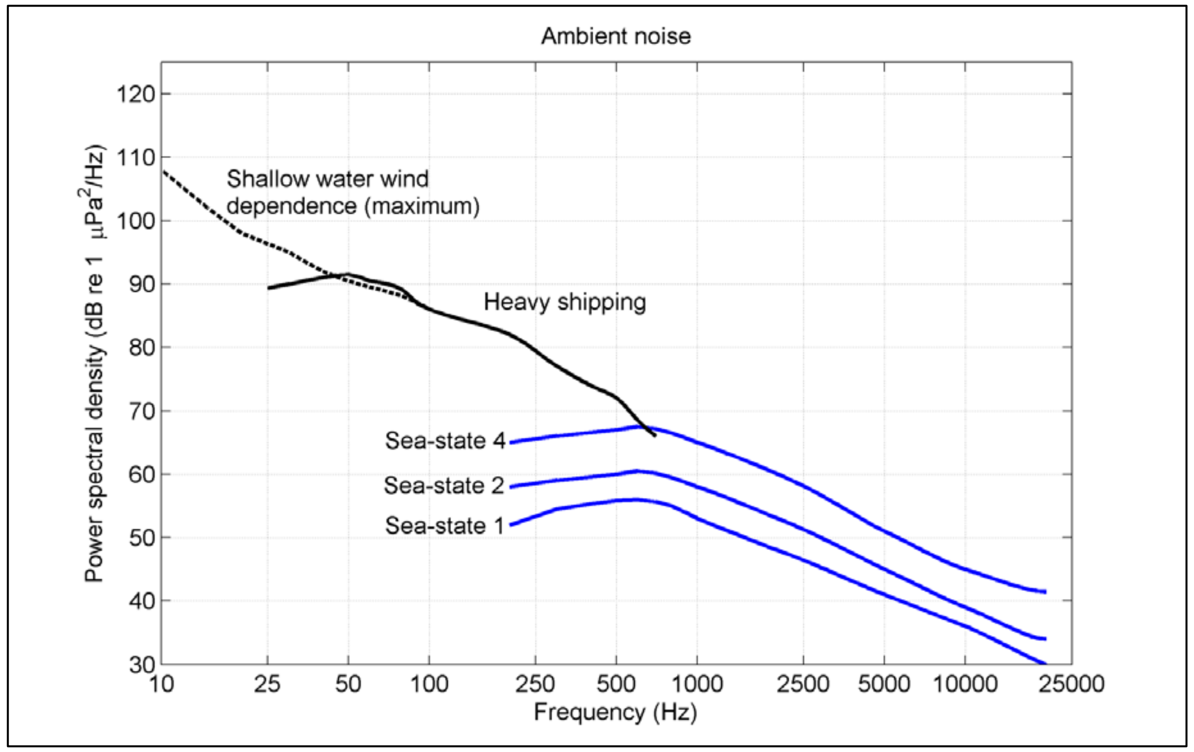

Figure 4.1: Ambient underwater noise as shown in Wenz (1962) showing frequency dependency from different noise sources.

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. Short-term "snapshot" and unweighted overall noise levels of this type should be used with caution due to significant variability in the noise levels that will be present day-to-day.

4.1.1.8 There is little documented, additional ambient noise data publicly available for the region and previous offshore wind farm assessments have relied on this broad approach to estimate the baseline noise conditions. Other studies in the southern North Sea have been reported (Merchant *et al*. 2016) and also describe similar RMS noise levels, although again they use coastal locations and so may have limited applicability to the Hornsea array area. 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 a much more coastal 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.

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 the 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 National Physical Laboratory (NPL) Good Practice Guide 133 for Underwater Noise (Robinson *et al.*, 2004).

5.1.1.2 Modelling has been undertaken at five representative locations covering the Hornsea Three site and the accompanying offshore HVAC booster station search area, 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.

5.1.1.3 The Northwest (hereafter referred to as NW) and Northeast (hereafter referred to as NE) locations give a wide spatial coverage of the Hornsea Three array area along the deep-water channel to the north. The South (hereafter referred to as S) location has been chosen to give spatial coverage to the south, showing the greatest potential noise propagation from this region. The two HVAC locations, HVAC North (hereafter referred to as HVAC N) and HVAC South (hereafter referred to as HVAC S), give coverage of the offshore HVAC booster station search area in shallower water closer to the coast.

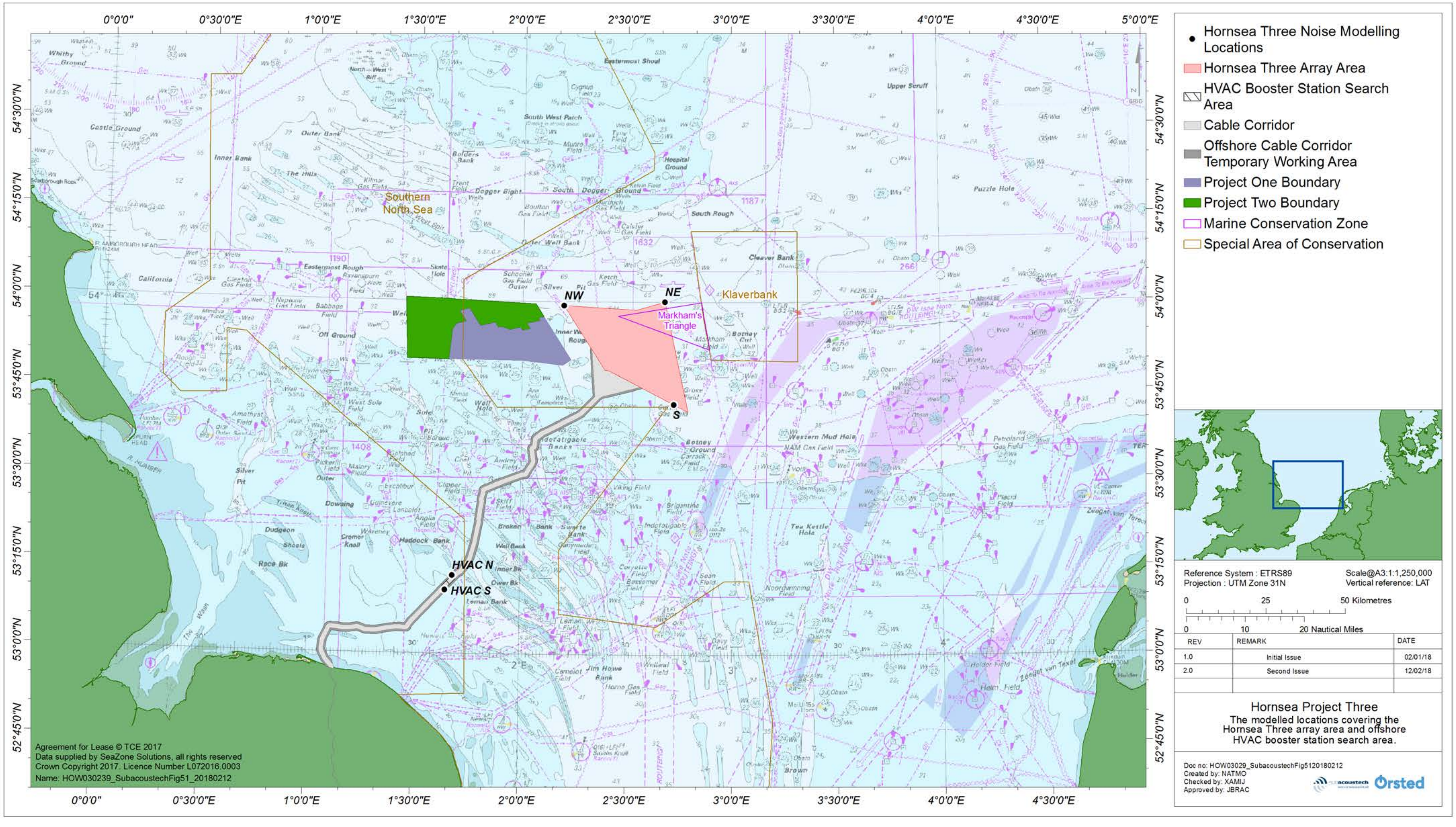

Figure 5.1: Map showing the modelled locations covering the Hornsea Three array area and offshore HVAC booster station search area.

Table 5.1: Summary of the modelling locations and the water depths at each location.

	NW	NE	S	HVAC N	HVAC S
Latitude	53.9895°N	54.0010°N	53.7106°N	53.2223°N	53.1808°N
Longitude	002.1976°E	002.6812°E	002.7254°E	001.6814°E	001.6470°E
Water depth	59 m	47 m	42 m	22 m	31 m

5.1.2 INSPIRE

5.1.2.1 The modelling has been undertaken using the INSPIRE noise model. The INSPIRE model (currently version 3.5) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling and actual measured data. It is designed to calculate the propagation of noise is shallow, mixed, coastal water; typical of the coastal conditions around the UK, and very well-suited to the Hornsea Three array area.

5.1.2.2 The model provides estimates of unweighted SPL_{peak}, SEL_{ss}, and SEL_{cum} noise levels as well as various other weighted noise metrics. Calculations are made along 180 equally spaced radial transects (one every 2°). For each modelling run a criterion level can be specified allowing a contour to be drawn, within which a given effect may occur. These results are then plotted over digital bathymetry data so that impact ranges can be clearly visualised and assessed as necessary.

5.1.2.3 INSPIRE considers a wide array of input parameters, including variations in bathymetry, 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;
- Duration of piling; and
- Receptor swim speeds.

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

5.1.3 Input parameters

5.1.3.1 The modelling takes full account of the characteristics of the noise source (see the source level section from paragraph 5.1.3.5) environmental parameters within the areas surrounding the Hornsea Three array and HVAC booster station. The following parameters have been assumed for modelling.

Impact piling

5.1.3.2 Six piling source scenarios have been modelled to include monopile and pin pile turbine foundations across the Hornsea Three site and the offshore HVAC booster station search area. These are:

- Monopiles installed using maximum blow energies of 5,000 kJ (the maximum blow energy that could be used based on the specifications of the piling hammer considered, the "Maximum Design Scenario"); 3,500 kJ (the maximum blow energy likely to be reached during piling events, based on engineering predictions, "Most Likely"); and 2,000 kJ (an "Average", typical energy representative of the whole project – this value has only been used for single strike criteria); and
- Pin piles installed using maximum blow energies of 2,500 kJ, 1,750 kJ, and 1,250 kJ, descriptions as above.

5.1.3.3 For cumulative SELs (using the sound exposure calculated over the whole pile installation), the soft start and ramp up of blow energies through a piling event along with total duration and strike rate of the piling have also been considered; these are summarised in Table 5.2 and Table 5.3 below. The ramp up takes place over 30 minutes, starting at 15%, gradually increasing in blow energy and strike rate until reaching the maximum energy. The piling operation has been assumed to last for four hours for the Maximum Design Scenario blow energy scenario and two hours for the Most Likely maximum blow energy scenario.

Table 5.2: Summary of the ramp up used for calculating cumulative SELs for the Maximum Design Scenario blow energy.

% of max hammer blow energy	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	One strike every six seconds	One strike every six seconds	One strike every four seconds	One strike every four seconds	One strike every two seconds
Duration	7.5 minutes	7.5 minutes	7.5 minutes	7.5 minutes	3.5 hours

Table 5.3: Summary of the ramp up used for calculating cumulative SELs for the Most Likely maximum blow energy scenario.

% of max hammer blow energy	15%	31%	44%	57%	70%
Monopile blow energy	750 kJ	1560 kJ	2210 kJ	2850 kJ	3500 kJ
Pin pile blow energy	375 kJ	780 kJ	1100 kJ	1430 kJ	1750 kJ
Strike Rate	One strike every six seconds	One strike every six seconds	One strike every four seconds	One strike every four seconds	One strike every two seconds
Duration	7.5 minutes	7.5 minutes	7.5 minutes	7.5 minutes	1.5 hours

5.1.3.4 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

5.1.3.5 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, which have been shown to be the primary factors determining the subsea noise levels produced.

5.1.3.6 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.

5.1.3.7 The unweighted SPL_{peak} source levels estimated for this project are provided in Table 5.4.

Table 5.4: Summary of the unweighted SPL_{peak} source levels used for modelling in this study.

SPL_{peak} Source levels (dB re. 1 µPa @ 1m)	Monopile (5,000 kJ)	Monopile (3,500 kJ)	Monopile (2,000 kJ)	Pin pile (2,500 kJ)	Pin pile (1,750 kJ)	Pin pile (1,250 kJ)
NW	243.6	242.3	240.0	241.0	239.4	237.7
NE	243.6	242.3	240.0	241.0	239.4	237.7
S	243.6	242.3	240.0	241.0	239.4	237.7
HVAC N	235.6	234.0	231.4	232.5	230.7	228.8
HVAC S	239.9	238.5	236.0	237.0	235.3	233.6

5.1.3.8 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.

5.1.3.9 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. The study states that "*when the pile diameter increases, the radiating surface increases, but as long as the pile driver energy is not raised, the amplitude decreases, since the available exciting force now has to excite a larger number of surface elements. Hence a larger diameter alone does not necessarily lead to an increase of noise*." However, a larger pile creates more friction in the sediment, which necessitates a greater blow energy to drive it further. It is this increase in blow energy which causes an increase in the noise output.

5.1.3.10 The third octave levels used for modelling the NW 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.

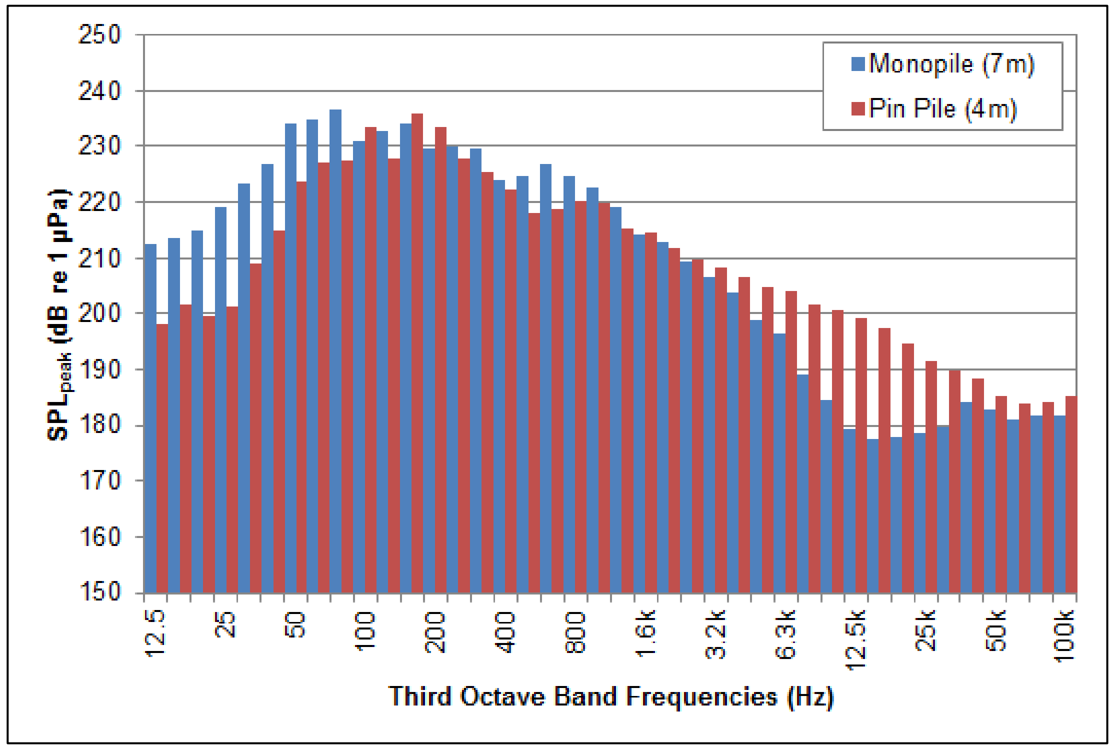

Figure 5.2: Third octave source level frequency spectra for the NW location, maximum blow energy.

Environmental conditions

5.1.3.11 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).

5.1.3.12 For the purposes of modelling, a higher than average tide of 4.0 m above the lowest astronomical tide (LAT) has been used. A consistent, mixed water, temperature profile has been assumed through the water column.

5.2 Underwater 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 array area, selected for proximity to a nature conservation designation, and one on the accompanying offshore HVAC booster station search area, as an example, for a single strike of the hammer.

5.2.1.2 Figure 5.3 to Figure 5.10 present a selection of the unweighted SEL_{ss} modelling outputs as contour plots to help show the difference between the modelling scenarios undertaken. Figure 5.3 to Figure 5.7 showing the results for monopiles using the maximum 5,000 kJ blow energy, and illustrating the differences in propagation for the different modelling locations, with the deeper water to the north of the site resulting in larger ranges at the NW and NE locations. Figure 5.8 can be compared with Figure 5.3 to show the difference in predicted ranges between the monopile and pin pile scenarios. Finally, Figure 5.3, Figure 5.9 and Figure 5.10 show the difference for the three piling blow energy scenarios considered (5,000 kJ, 3,500 kJ, and 2,000 kJ for monopiles), with impact ranges increasing for the increase in blow energies.

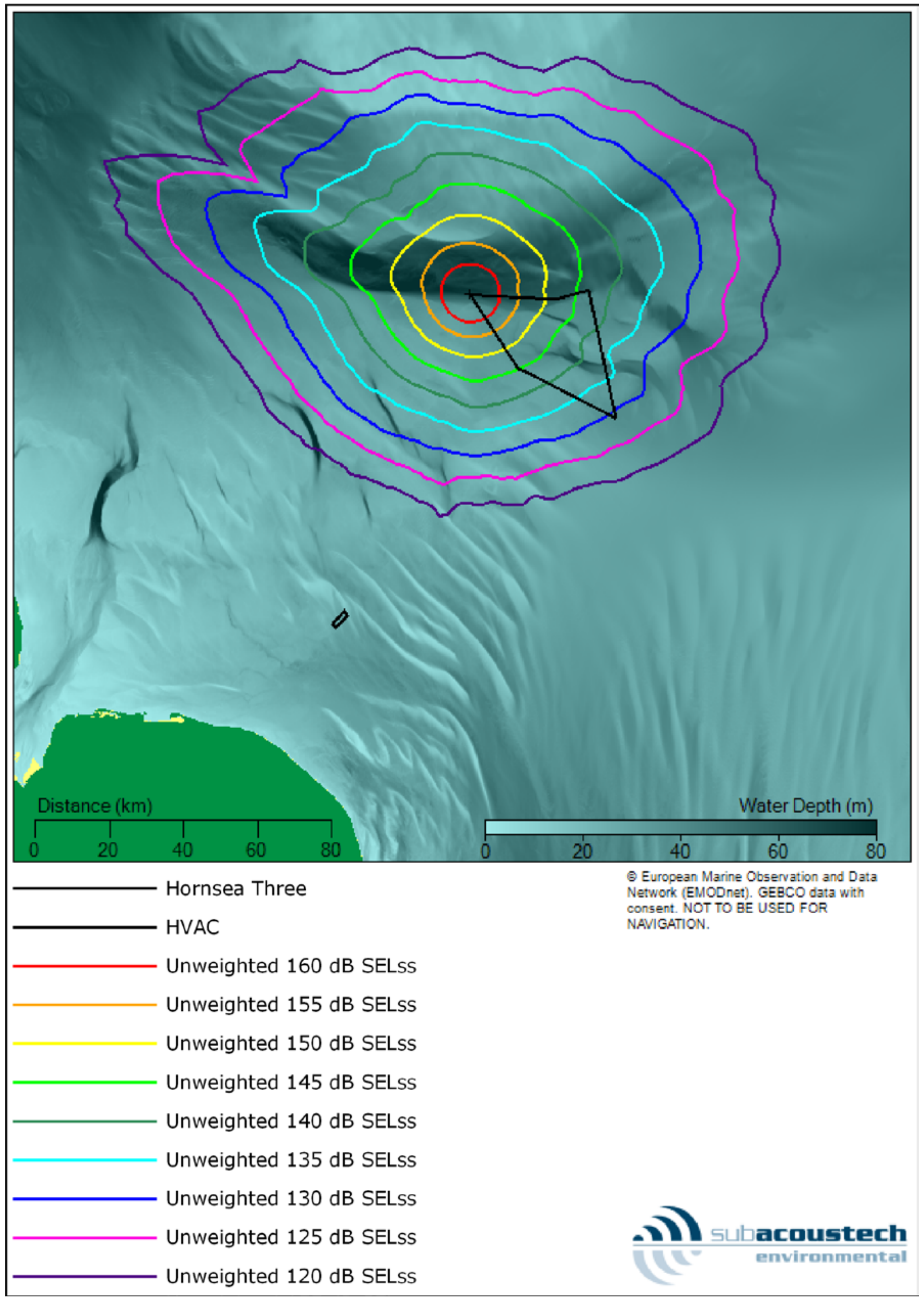

Figure 5.3: Contour plot showing the modelled unweighted SEL_{ss} noise levels at the NW location for installing a monopile with a maximum blow energy of 5000 kJ.

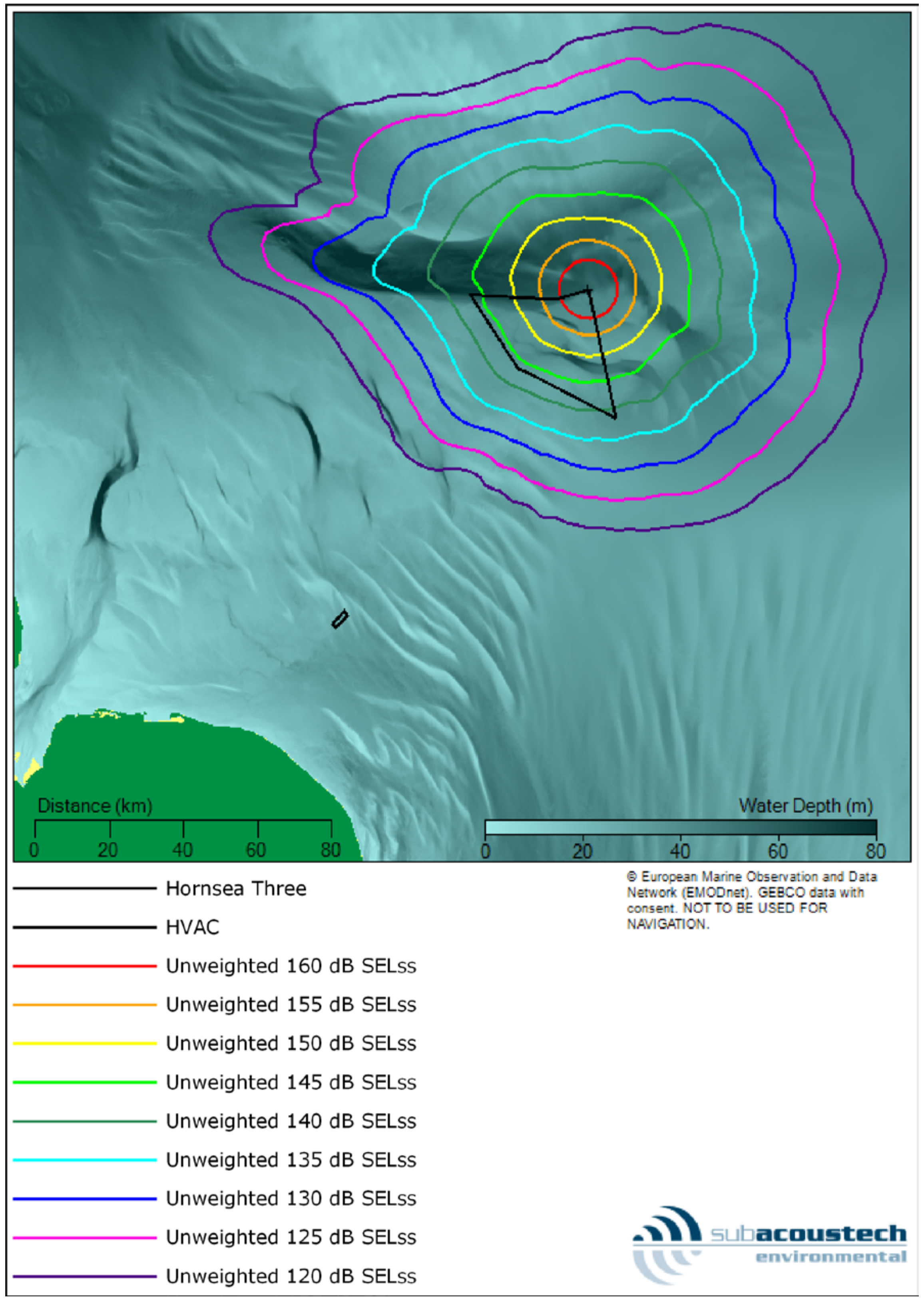

Figure 5.4: Contour plot showing the modelled unweighted SEL_{ss} noise levels at the NE location for installing a monopile with a maximum blow energy of 5000 kJ.

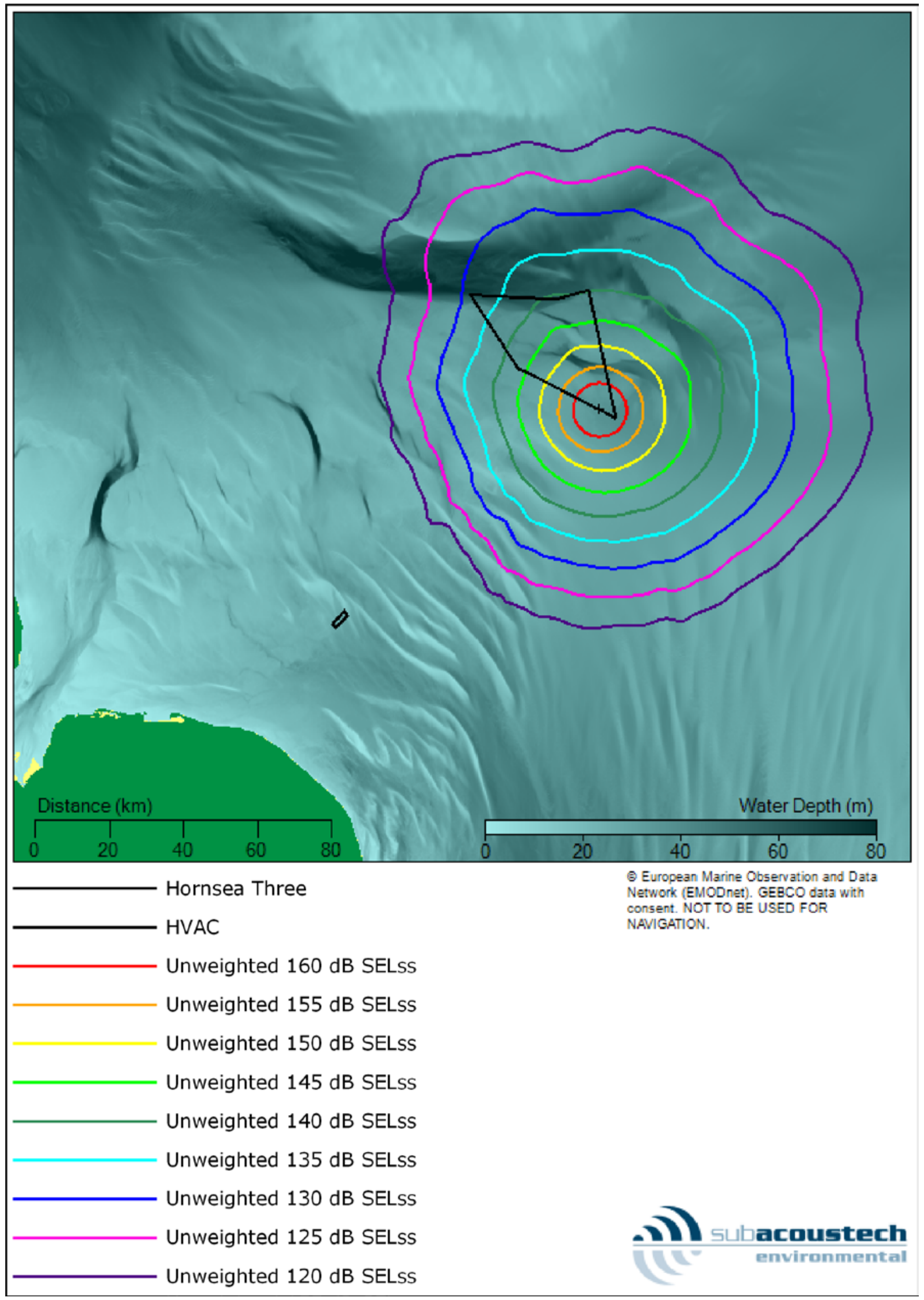

Figure 5.5: Contour plot showing the modelled unweighted SEL_{ss} noise levels at the S location for installing a monopile with a maximum blow energy of 5000 kJ.

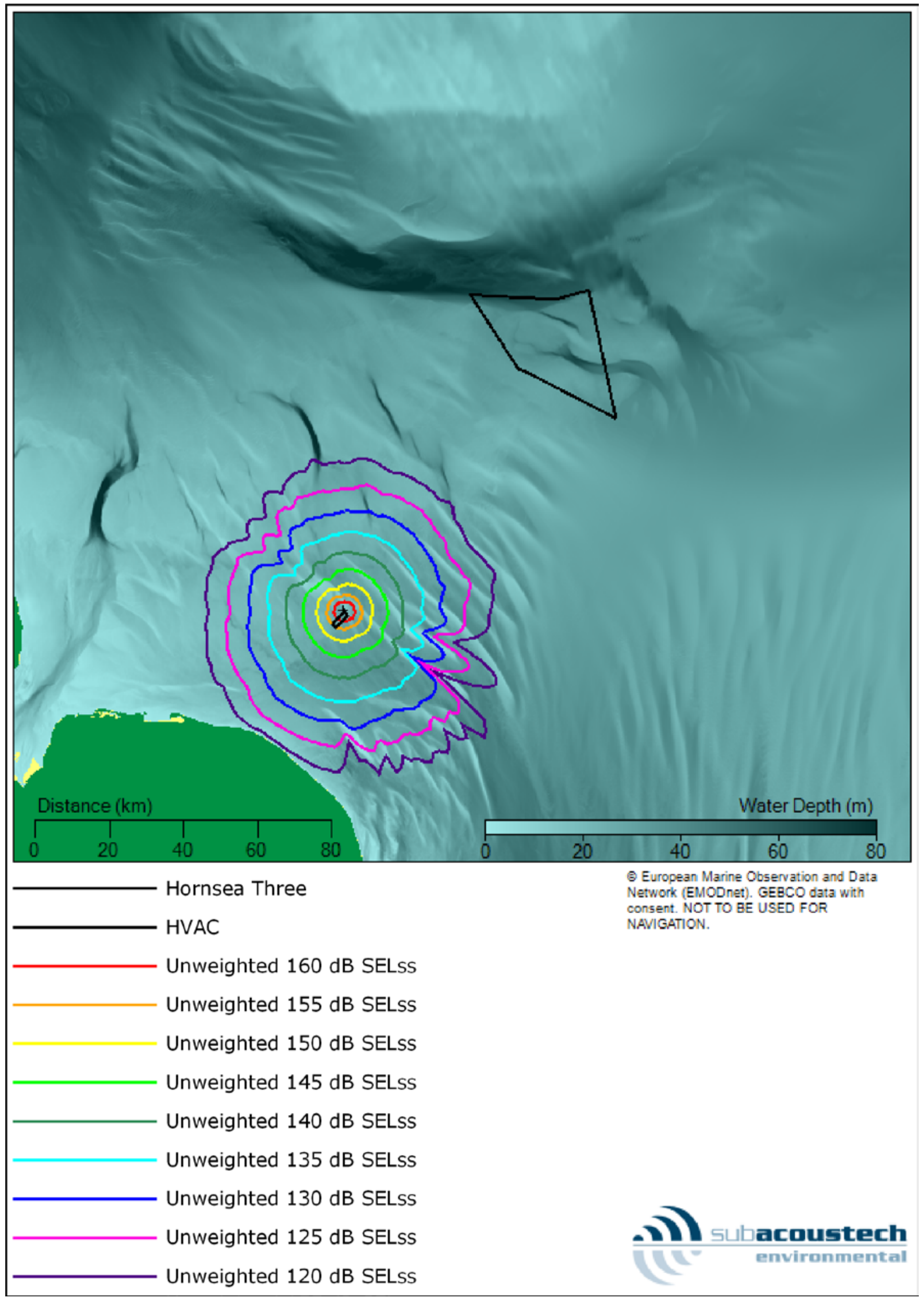

Figure 5.6: Contour plot showing the modelled unweighted SEL_{ss} noise levels at the HVAC N location for installing a monopile with a maximum blow energy of 5000 kJ.

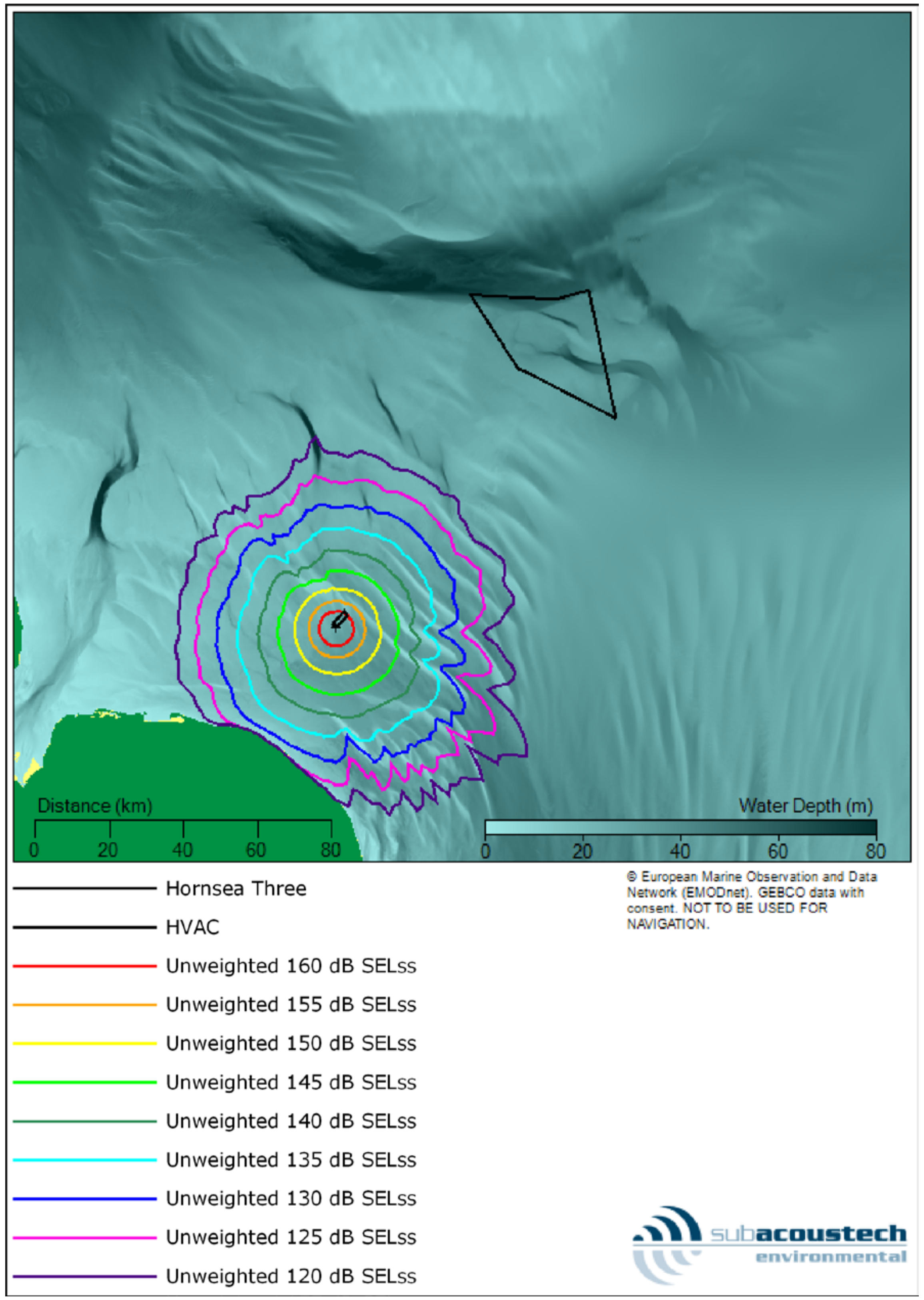

Figure 5.7: Contour plot showing the modelled unweighted SEL_{ss} noise levels at the HVAC S location for installing a monopile with a maximum blow energy of 5000 kJ.

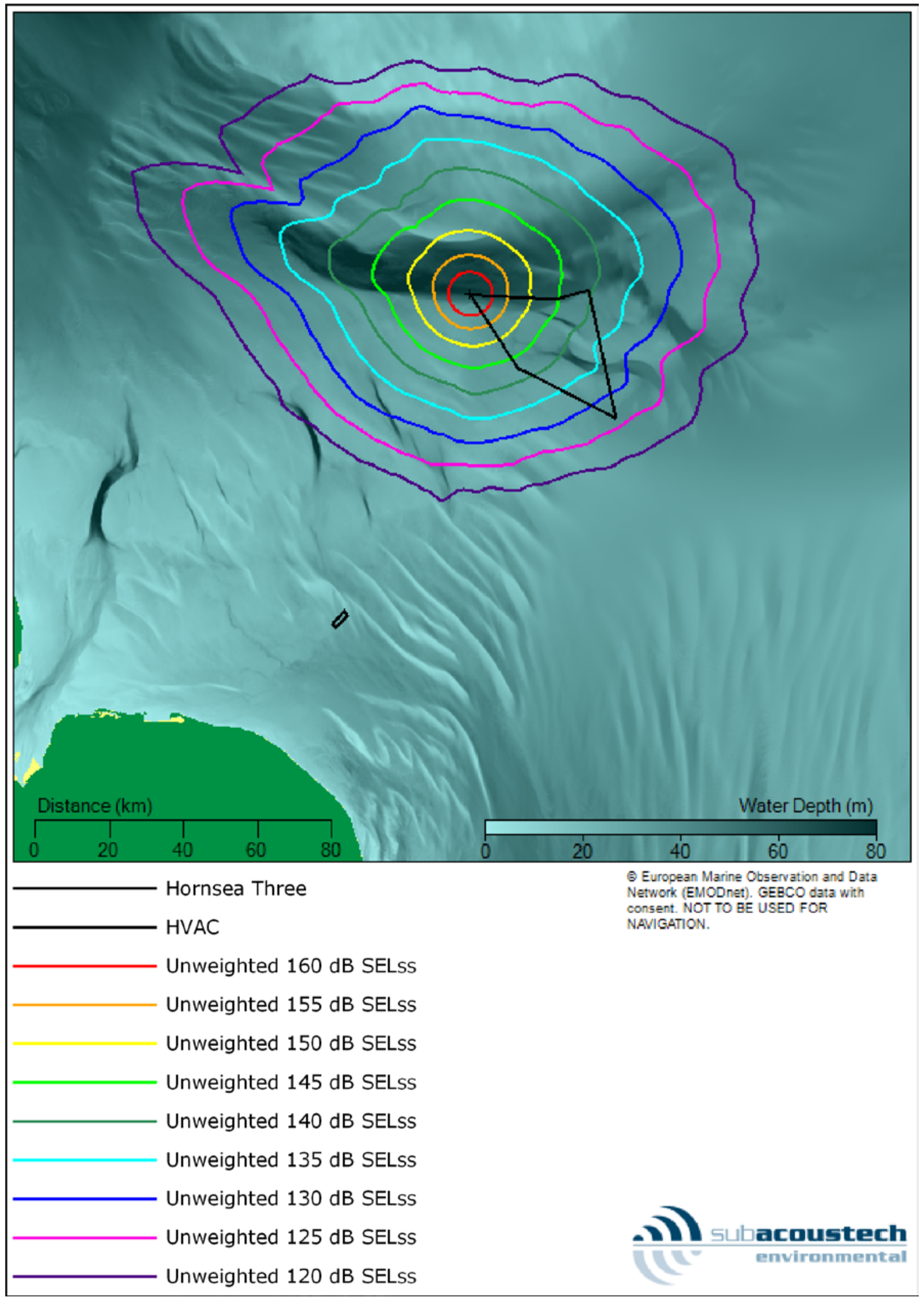

Figure 5.8: Contour plot showing the modelled unweighted SEL_{ss} noise levels at the NW location for installing a pin pile with a maximum blow energy of 2500 kJ.

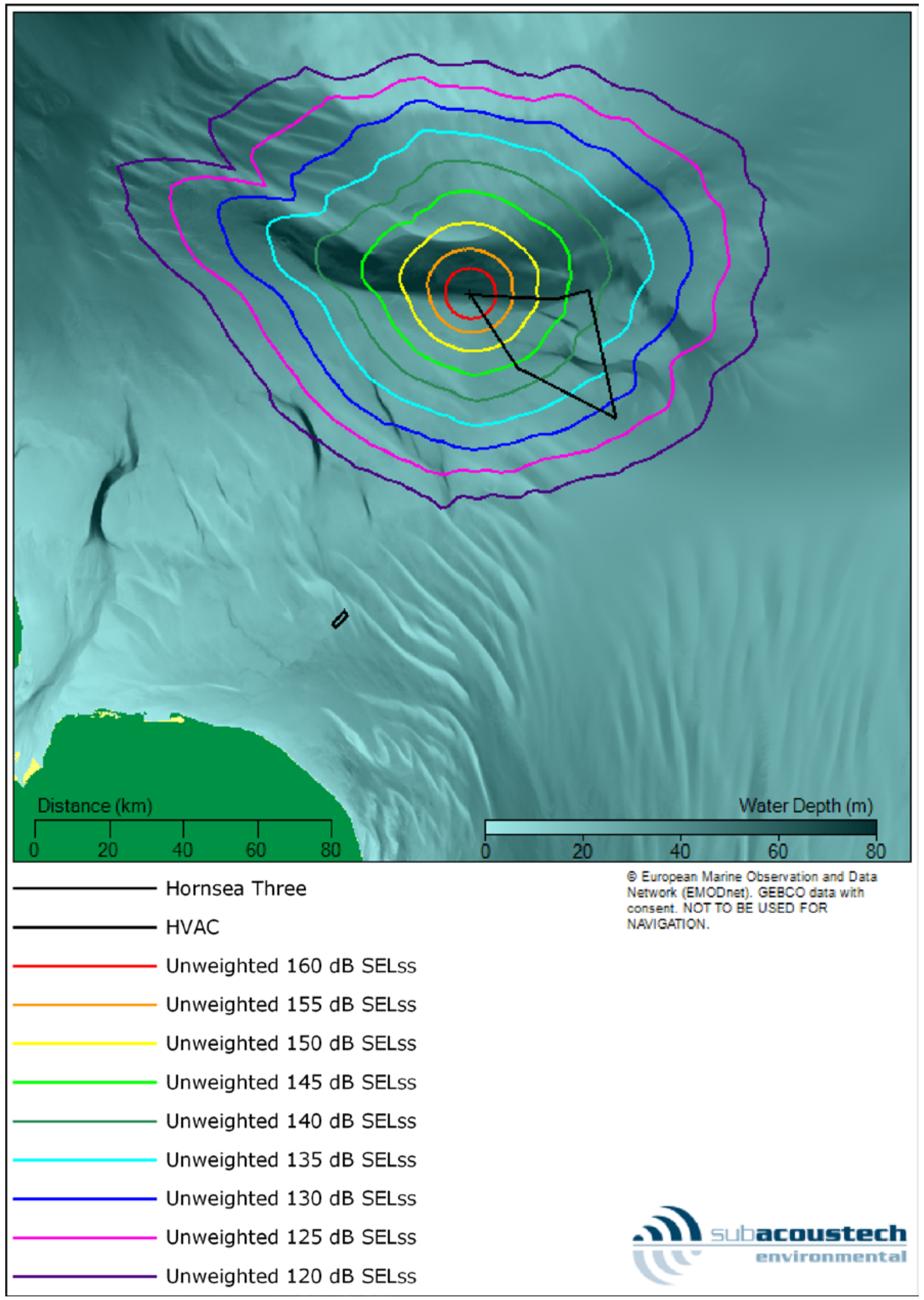

Figure 5.9: Contour plot showing the modelled unweighted SEL_{ss} noise levels at the NW location for installing a monopile with a maximum blow energy of 3500 kJ.

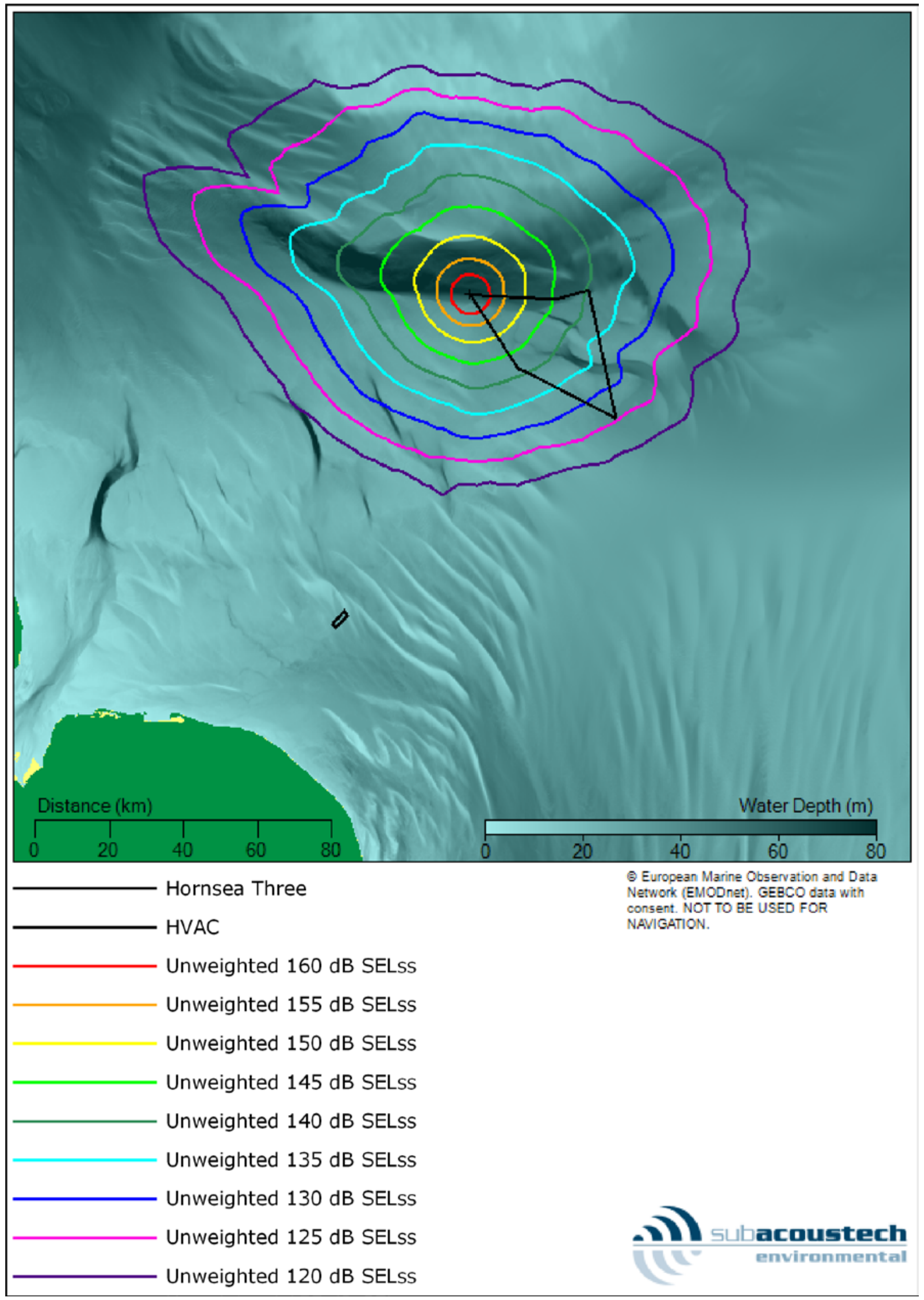

Figure 5.10: Contour plot showing the modelled unweighted SEL_{ss} noise levels at the NW location for installing a monopile with a maximum blow energy of 2000 kJ.

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 described in section 3.2. This discussion will guide the assessment of potential environmental impact to marine species from impact piling and dredging related noise.

5.3.2 Impacts on marine mammals

5.3.2.1 Table 5.5 to Table 5.12 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 criteria used in Hornsea Project Two. For the SEL_{cum} results, several criteria give impact ranges of less than 100 m, which is due to the resolution of the cumulative noise fleeing animal modelling. Behavioural effects (assessed on the basis of unweighted SEL model outputs) are assessed in volume 2, chapter 4: Marine Mammals.

5.3.2.2 Figure 5.11 to Figure 5.17 present a selection of the SEL_{cum} results as contour plots to show the differences between the different critiera and parameters used for modelling. Figure 5.11 to Figure 5.13 show the results for monopiles using the Maximum Design Scenario with a maximum blow energy of 5,000 kJ, with each figure presenting the results for each of the NMFS (2016) marine mammal weightings. The results for MF cetaceans are not shown due to the small size of the predicted ranges (see Table 5.6 and Table 5.10). Figure 5.14 to Figure 5.16 show a similar set of results but for the pin pile Maximum Design Scenario with a maximum blow energy of 2,500 kJ.

5.3.2.3 Figure 5.17 can be compared with Figure 5.15 to show differences between using the maximum blow energy ramp up scenario and the Average blow energy ramp up scenario for pin piles when considered the HF cetaceans critiera, showing a reduction in ranges for the average maximum ramp up scernario.

5.3.2.4 The results are discussed after the tables and figures.

PTS results (marine mammals)

Table 5.5: 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)	
		Max range	Mean range	Max range	Mean range
Monopile (5,000kJ)	NW	36 m	36 m	1.5 km	900 m
	NE	36 m	36 m	1.3 km	900 m
	S	36 m	36 m	500 m	400 m
	HVAC N	12 m	12 m	< 100 m	< 100 m
	HVAC S	22 m	22 m	< 100 m	< 100 m
Monopile (3,500kJ)	NW	30 m	30 m	500 m	370 m
	NE	30 m	30 m	400 m	360 m
	S	30 m	30 m	300 m	250 m
	HVAC N	10 m	10 m	< 100 m	< 100 m
	HVAC S	18 m	18 m	< 100 m	< 100 m
Monopile (2,000kJ)	NW	22 m	22 m	-	-
	NE	22 m	22 m	-	-
	S	22 m	22 m	-	-
	HVAC N	7 m	7 m	-	-
	HVAC S	13 m	13 m	-	-
Pin Pile (2,500kJ)	NW	25 m	25 m	300 m	200 m
	NE	25 m	25 m	200 m	200 m
	S	25 m	25 m	< 100 m	< 100 m
	HVAC N	8 m	8 m	< 100 m	< 100 m
	HVAC S	15 m	15 m	< 100 m	< 100 m
Pin Pile (1,750kJ)	NW	20 m	20 m	< 100 m	< 100 m
	NE	20 m	20 m	< 100 m	< 100 m
	S	20 m	20 m	< 100 m	< 100 m
	HVAC N	7 m	7 m	< 100 m	< 100 m
	HVAC S	12 m	12 m	< 100 m	< 100 m
Pin Pile (1,250kJ)	NW	16 m	16 m	-	-
	NE	16 m	16 m	-	-
	S	16 m	16 m	-	-
	HVAC N	6 m	6 m	-	-
	HVAC S	10 m	10 m	-	-

Table 5.6: 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)	
		Max range	Mean range	Max range	Mean range
Monopile (5,000kJ)	NW	9 m	9 m	< 100 m	< 100 m
	NE	9 m	9 m	< 100 m	< 100 m
	S	9 m	9 m	< 100 m	< 100 m
	HVAC N	4 m	4 m	< 100 m	< 100 m
	HVAC S	6 m	6 m	< 100 m	< 100 m
Monopile (3,500kJ)	NW	7 m	7 m	< 100 m	< 100 m
	NE	7 m	7 m	< 100 m	< 100 m
	S	7 m	7 m	< 100 m	< 100 m
	HVAC N	3 m	3 m	< 100 m	< 100 m
	HVAC S	5 m	5 m	< 100 m	< 100 m
Monopile (2,000kJ)	NW	6 m	6 m	-	-
	NE	6 m	6 m	-	-
	S	6 m	6 m	-	-
	HVAC N	3 m	3 m	-	-
	HVAC S	4 m	4 m	-	-

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})	
		Max range	Mean range	Max range	Mean range
Pin Pile (2,500kJ)	NW	6 m	6 m	< 100 m	< 100 m
	NE	6 m	6 m	< 100 m	< 100 m
	S	6 m	6 m	< 100 m	< 100 m
	HVAC N	3 m	3 m	< 100 m	< 100 m
	HVAC S	4 m	4 m	< 100 m	< 100 m
Pin Pile (1,750kJ)	NW	5 m	5 m	< 100 m	< 100 m
	NE	5 m	5 m	< 100 m	< 100 m
	S	5 m	5 m	< 100 m	< 100 m
	HVAC N	3 m	3 m	< 100 m	< 100 m
	HVAC S	4 m	4 m	< 100 m	< 100 m
Pin Pile (1,250kJ)	NW	5 m	5 m	-	-
	NE	5 m	5 m	-	-
	S	5 m	5 m	-	-
	HVAC N	< 1 m	< 1 m	-	-
	HVAC S	3 m	3 m	-	-

Table 5.7: 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})	
		Max range	Mean range	Max range	Mean range
Monopile (5,000kJ)	NW	400 m	400 m	< 100 m	< 100 m
	NE	400 m	390 m	< 100 m	< 100 m
	S	390 m	390 m	< 100 m	< 100 m
	HVAC N	120 m	120 m	< 100 m	< 100 m
	HVAC S	230 m	230 m	< 100 m	< 100 m

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})	
		Max range	Mean range	Max range	Mean range
Monopile (3,500kJ)	NW	330 m	330 m	< 100 m	< 100 m
	NE	330 m	330 m	< 100 m	< 100 m
	S	330 m	330 m	< 100 m	< 100 m
	HVAC N	98 m	98 m	< 100 m	< 100 m
	HVAC S	190 m	190 m	< 100 m	< 100 m
Monopile (2,000kJ)	NW	240 m	240 m	-	-
	NE	240 m	240 m	-	-
	S	240 m	240 m	-	-
	HVAC N	68 m	68 m	-	-
	HVAC S	130 m	130 m	-	-
Pin Pile (2,500kJ)	NW	270 m	270 m	1.2 km	900 m
	NE	270 m	270 m	1.1 km	900 m
	S	270 m	270 m	700 m	570 m
	HVAC N	79 m	79 m	< 100 m	< 100 m
	HVAC S	150 m	150 m	< 100 m	< 100 m
Pin Pile (1,750kJ)	NW	220 m	220 m	200 m	170 m
	NE	220 m	220 m	200 m	190 m
	S	220 m	220 m	< 100 m	< 100 m
	HVAC N	62 m	61 m	< 100 m	< 100 m
	HVAC S	120 m	120 m	< 100 m	< 100 m
Pin Pile (1,250kJ)	NW	170 m	170 m	-	-
	NE	170 m	170 m	-	-
	S	170 m	170 m	-	-
	HVAC N	48 m	48 m	-	-
	HVAC S	94 m	94 m	-	-

Table 5.8: 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})	
		Max range	Mean range	Max range	Mean range
Monopile (5,000kJ)	NW	41 m	41 m	< 100 m	< 100 m
	NE	41 m	41 m	< 100 m	< 100 m
	S	41 m	41 m	< 100 m	< 100 m
	HVAC N	14 m	14 m	< 100 m	< 100 m
	HVAC S	25 m	25 m	< 100 m	< 100 m
Monopile (3,500kJ)	NW	34 m	34 m	< 100 m	< 100 m
	NE	34 m	34 m	< 100 m	< 100 m
	S	34 m	34 m	< 100 m	< 100 m
	HVAC N	11 m	11 m	< 100 m	< 100 m
	HVAC S	20 m	20 m	< 100 m	< 100 m
Monopile (2,000kJ)	NW	25 m	25 m	-	-
	NE	25 m	25 m	-	-
	S	25 m	25 m	-	-
	HVAC N	8 m	8 m	-	-
	HVAC S	15 m	15 m	-	-
Pin Pile (2,500kJ)	NW	29 m	29 m	< 100 m	< 100 m
	NE	29 m	29 m	< 100 m	< 100 m
	S	29 m	29 m	< 100 m	< 100 m
	HVAC N	5 m	5 m	< 100 m	< 100 m
	HVAC S	8 m	8 m	< 100 m	< 100 m
Pin Pile (1,750kJ)	NW	23 m	23 m	< 100 m	< 100 m
	NE	23 m	23 m	< 100 m	< 100 m
	S	23 m	23 m	< 100 m	< 100 m
	HVAC N	8 m	8 m	< 100 m	< 100 m
	HVAC S	14 m	14 m	< 100 m	< 100 m
Pin Pile (1,250kJ)	NW	19 m	19 m	-	-
	NE	19 m	19 m	-	-
	S	19 m	19 m	-	-
	HVAC N	7 m	7 m	-	-
	HVAC S	11 m	11 m	-	-

TTS results (marine mammals)

Table 5.9: 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})	
		Max range	Mean range	Max range	Mean range
Monopile (5,000kJ)	NW	83 m	83 m	32 km	21 km
	NE	83 m	83 m	29 km	21 km
	S	83 m	83 m	20 km	17 km
	HVAC N	27 m	27 m	5.2 km	3.8 km
	HVAC S	49 m	49 m	11 km	8.8 km
Monopile (3,500kJ)	NW	69 m	69 m	26 km	18 km
	NE	69 m	69 m	24 km	18 km
	S	69 m	69 m	17 km	14 km
	HVAC N	22 m	22 m	600 m	540 m
	HVAC S	40 m	40 m	9.4 km	7.3 km
Monopile (2,000kJ)	NW	50 m	50 m	-	-
	NE	50 m	50 m	-	-
	S	50 m	50 m	-	-
	HVAC N	15 m	15 m	-	-
	HVAC S	29 m	29 m	-	-

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})	
		Max range	Mean range	Max range	Mean range
Pin Pile (2,500kJ)	NW	58 m	58 m	28 km	18 km
	NE	58 m	58 m	26 km	19 km
	S	57 m	57 m	18 km	15 km
	HVAC N	18 m	18 m	3.1 km	2.2 km
	HVAC S	33 m	33 m	9.1 km	7.0 km
Pin Pile (1,750kJ)	NW	46 m	46 m	22 km	15 km
	NE	46 m	46 m	20 km	15 km
	S	46 m	46 m	14 km	12 km
	HVAC N	14 m	14 m	1.6 km	1.1 km
	HVAC S	26 m	26 m	6.7 km	5.3 km
Pin Pile (1,250kJ)	NW	36 m	36 m	-	-
	NE	36 m	36 m	-	-
	S	36 m	36 m	-	-
	HVAC N	11 m	11 m	-	-
	HVAC S	21 m	21 m	-	-

Table 5.10: 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})	
		Max range	Mean range	Max range	Mean range
Monopile (5,000kJ)	NW	18 m	18 m	< 100 m	< 100 m
	NE	18 m	18 m	< 100 m	< 100 m
	S	18 m	18 m	< 100 m	< 100 m
	HVAC N	7 m	7 m	< 100 m	< 100 m
	HVAC S	11 m	11 m	< 100 m	< 100 m
Monopile (3,500kJ)	NW	15 m	15 m	< 100 m	< 100 m
	NE	15 m	15 m	< 100 m	< 100 m
	S	15 m	15 m	< 100 m	< 100 m
	HVAC N	6 m	6 m	< 100 m	< 100 m
	HVAC S	10 m	10 m	< 100 m	< 100 m
Monopile (2,000kJ)	NW	11 m	11 m	-	-
	NE	11 m	11 m	-	-
	S	11 m	11 m	-	-
	HVAC N	4 m	4 m	-	-
	HVAC S	7 m	7 m	-	-
Pin Pile (2,500kJ)	NW	13 m	13 m	< 100 m	< 100 m
	NE	13 m	13 m	< 100 m	< 100 m
	S	13 m	13 m	< 100 m	< 100 m
	HVAC N	5 m	5 m	< 100 m	< 100 m
	HVAC S	8 m	8 m	< 100 m	< 100 m
Pin Pile (1,750kJ)	NW	11 m	11 m	< 100 m	< 100 m
	NE	11 m	11 m	< 100 m	< 100 m
	S	11 m	11 m	< 100 m	< 100 m
	HVAC N	4 m	4 m	< 100 m	< 100 m
	HVAC S	7 m	7 m	< 100 m	< 100 m
Pin Pile (1,250kJ)	NW	9 m	9 m	-	-
	NE	9 m	9 m	-	-
	S	9 m	9 m	-	-
	HVAC N	3 m	3 m	-	-
	HVAC S	5 m	5 m	-	-

Table 5.11: 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)	
		Max range	Mean range	Max range	Mean range
Monopile (5,000kJ)	NW	920 m	920 m	12 km	9.8 km
	NE	920 m	920 m	11 km	9.9 km
	S	900 m	900 m	8.6 km	7.7 km
	HVAC N	280 m	280 m	700 m	500 m
	HVAC S	530 m	530 m	4.0 km	3.4 km
Monopile (3,500kJ)	NW	770 m	770 m	8.2 km	6.9 km
	NE	770 m	760 m	7.8 km	7.0 km
	S	750 m	750 m	6.0 km	5.7 km
	HVAC N	230 m	230 m	200 m	150 m
	HVAC S	440 m	440 m	2.5 km	2.1 km
Monopile (2,000kJ)	NW	550 m	550 m	-	-
	NE	550 m	550 m	-	-
	S	550 m	550 m	-	-
	HVAC N	160 m	160 m	-	-
	HVAC S	310 m	310 m	-	-
Pin Pile (2,500kJ)	NW	640 m	640 m	25 km	19 km
	NE	640 m	640 m	23 km	19 km
	S	630 m	630 m	17 km	15 km
	HVAC N	180 m	180 m	4.3 km	3.6 km
	HVAC S	360 m	360 m	9.8 km	8.2 km
Pin Pile (1,750kJ)	NW	510 m	510 m	17 km	14 km
	NE	510 m	510 m	16 km	14 km
	S	500 m	500 m	13 km	12 km
	HVAC N	140 m	140 m	2.5 km	2.1 km
	HVAC S	280 m	280 m	7.0 km	6.0 km

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)	
		Max range	Mean range	Max range	Mean range
Pin Pile (1,250kJ)	NW	400 m	400 m	-	-
	NE	400 m	400 m	-	-
	S	400 m	400 m	-	-
	HVAC N	110 m	110 m	-	-
	HVAC S	220 m	220 m	-	-

Table 5.12: 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)	
		Max range	Mean range	Max range	Mean range
Monopile (5,000kJ)	NW	96 m	96 m	8.4 km	6.9 km
	NE	96 m	96 m	8.0 km	7.0 km
	S	95 m	95 m	5.9 km	5.4 km
	HVAC N	31 m	31 m	< 100 m	< 100 m
	HVAC S	56 m	56 m	2.2 km	1.8 km
Monopile (3,500kJ)	NW	80 m	80 m	5.5 km	4.6 km
	NE	80 m	80 m	5.1 km	4.6 km
	S	79 m	79 m	4.0 km	3.7 km
	HVAC N	25 m	25 m	< 100 m	< 100 m
	HVAC S	46 m	46 m	1.1 km	940 m
Monopile (2,000kJ)	NW	58 m	58 m	-	-
	NE	58 m	58 m	-	-
	S	57 m	57 m	-	-
	HVAC N	17 m	17 m	-	-
	HVAC S	33 m	33 m	-	-

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})	
		Max range	Mean range	Max range	Mean range
Pin Pile (2,500kJ)	NW	66 m	66 m	5.4 km	4.4 km
	NE	66 m	66 m	5.0 km	4.4 km
	S	66 m	66 m	3.6 km	3.3 km
	HVAC N	20 m	20 m	< 100 m	< 100 m
	HVAC S	38 m	38 m	700 m	500 m
Pin Pile (1,750kJ)	NW	53 m	53 m	2.8 km	2.3 km
	NE	53 m	53 m	2.6 km	2.4 km
	S	53 m	53 m	2.0 km	1.8 km
	HVAC N	16 m	16 m	< 100 m	< 100 m
	HVAC S	30 m	30 m	< 100 m	< 100 m
Pin Pile (1,250kJ)	NW	42 m	42 m	-	-
	NE	42 m	42 m	-	-
	S	42 m	42 m	-	-
	HVAC N	16 m	16 m	-	-
	HVAC S	30 m	30 m	-	-

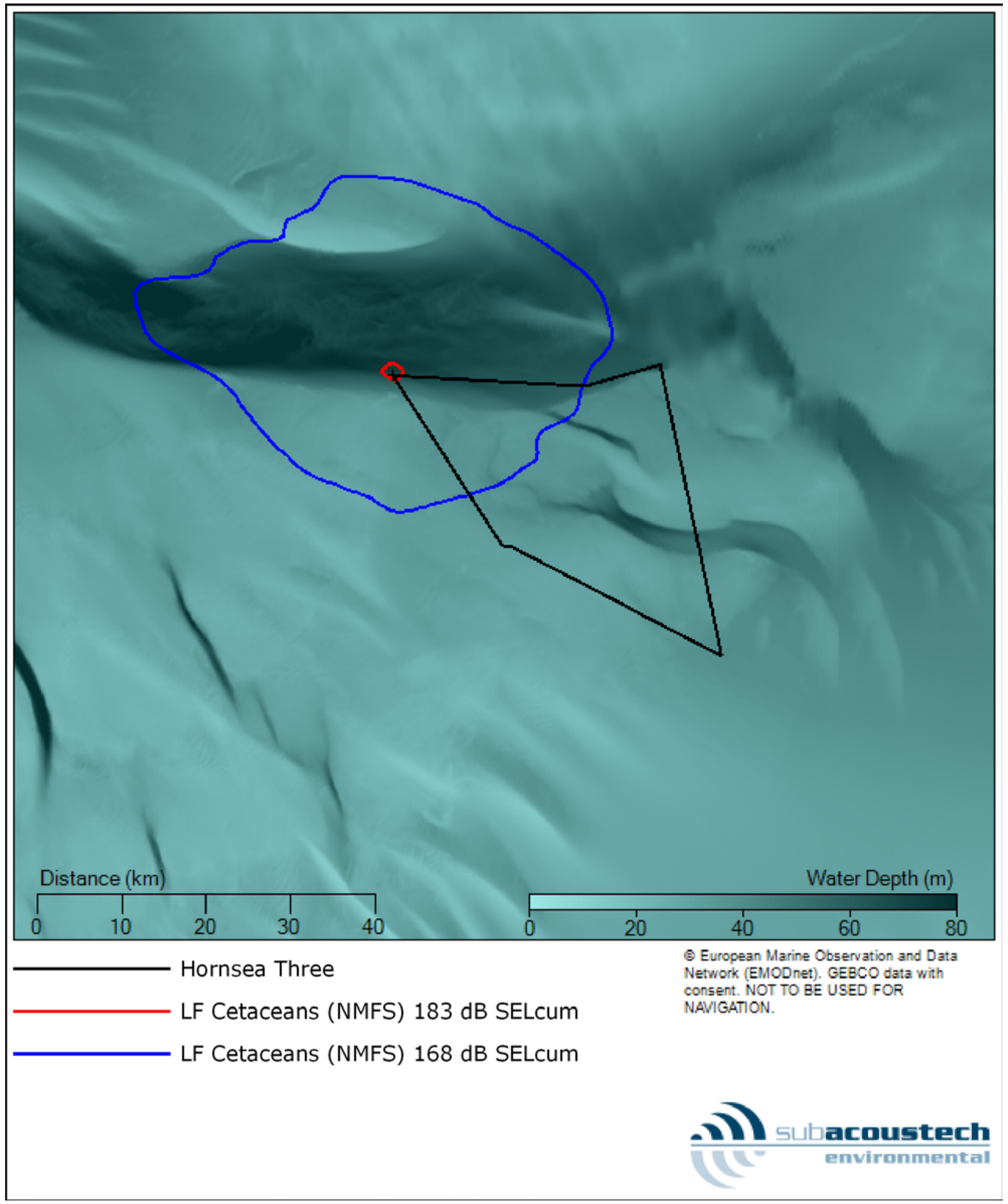

Figure 5.11: Contour plot showing the modelled PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the NW location for installing a monopile with a maximum blow energy of 5000 kJ.

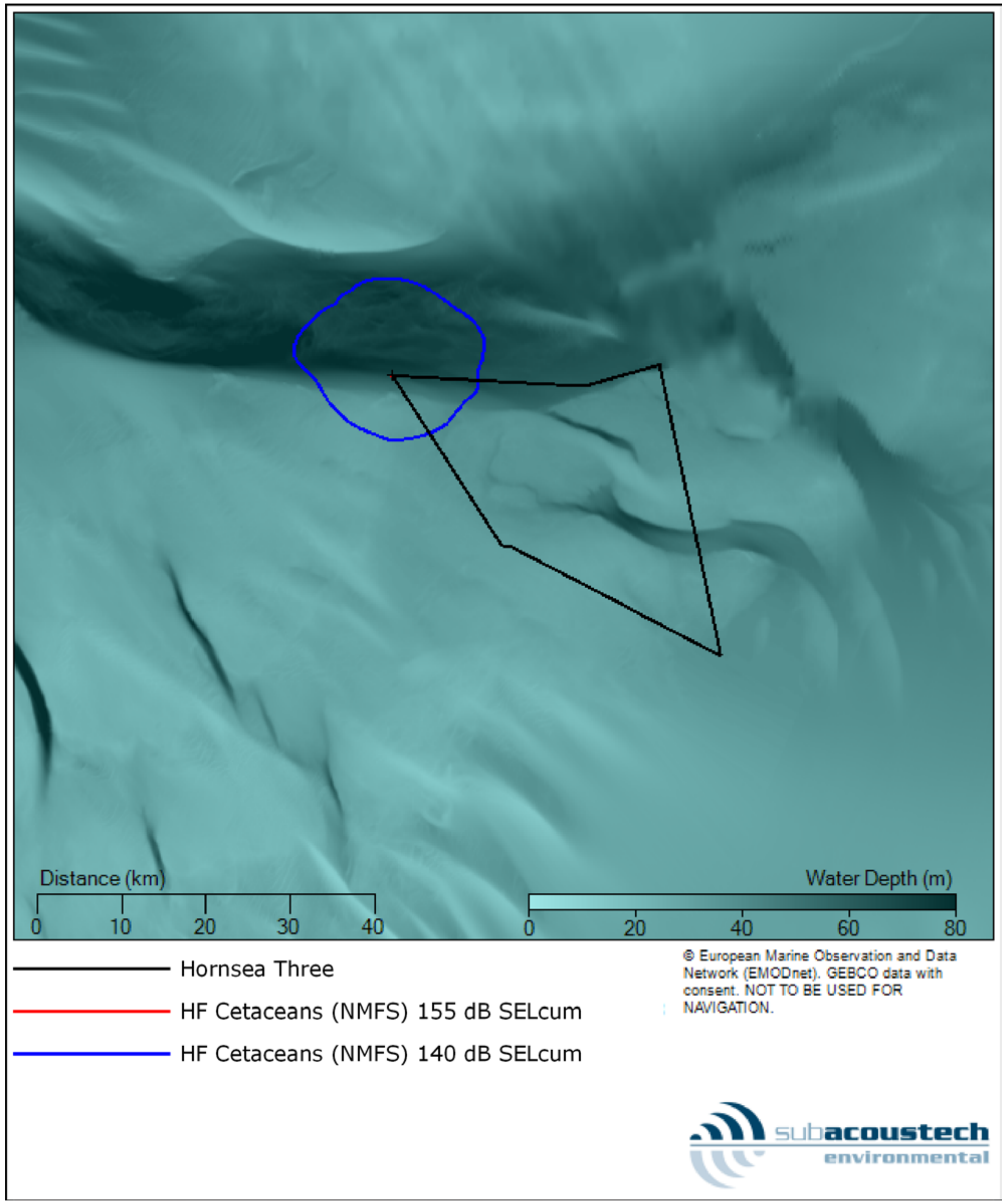

Figure 5.12: Contour plot showing the modelled PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the NW location for installing a monopile with a maximum blow energy of 5000 kJ. Note the 155 dB contour is too small to be visible at this scale.

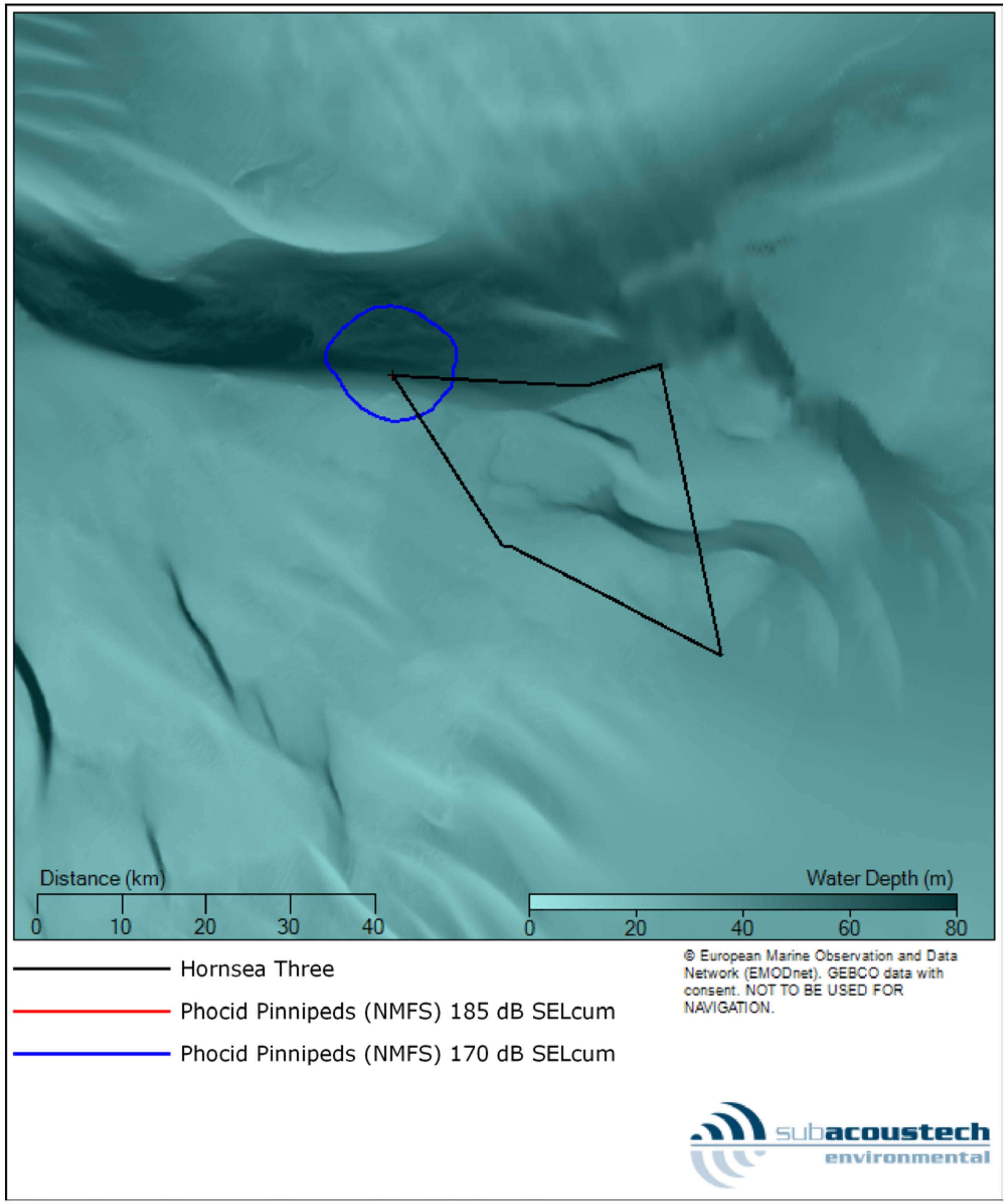

Figure 5.13: Contour plot showing the modelled PTS and TTS impact ranges (NMFS, 2016) for fleeing phocid pinnipeds (PW) at the NW location for installing a monopile with a maximum blow energy of 5000 kJ. Note the 185 dB contour is too small to be visible at this scale.

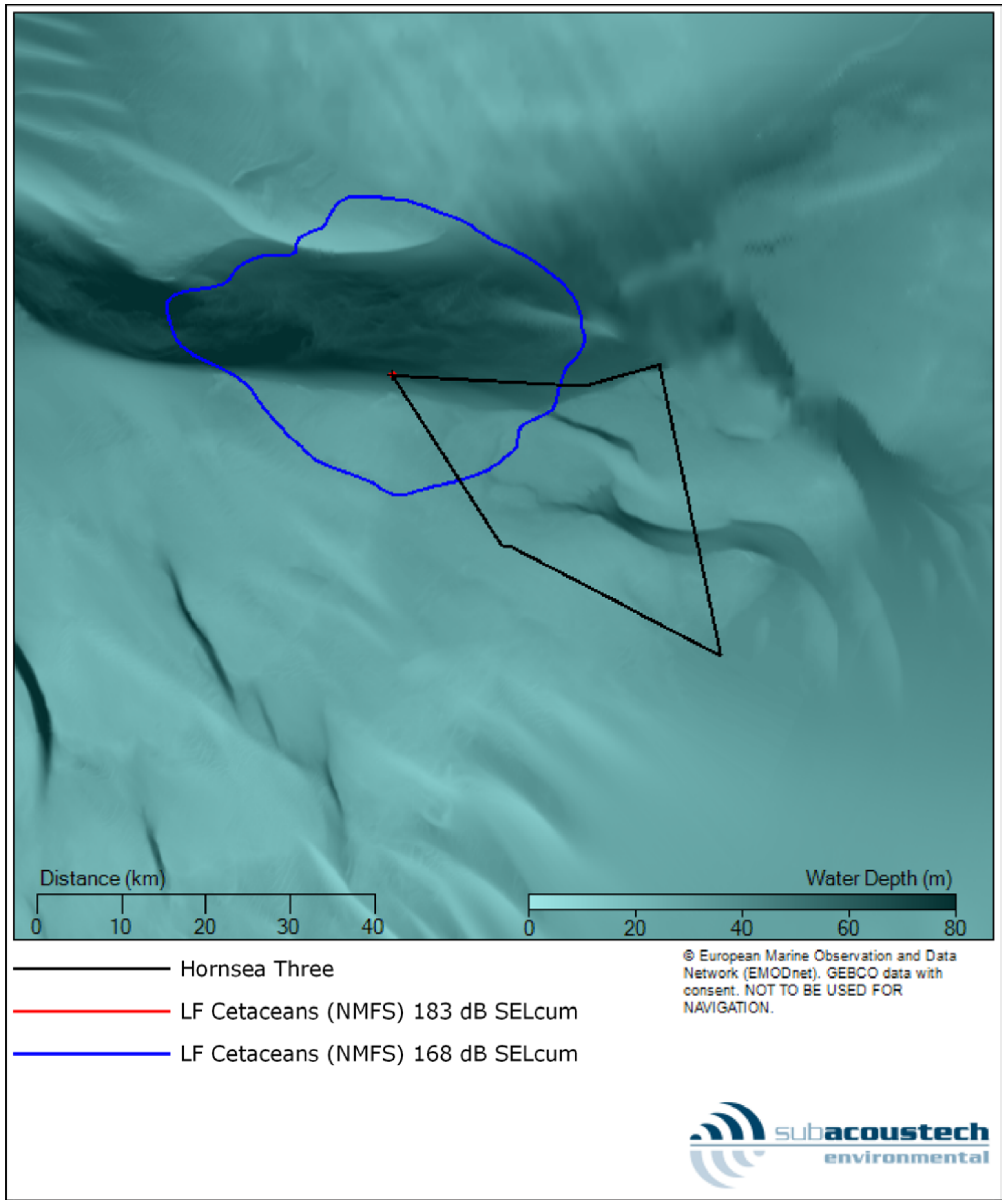

Figure 5.14: Contour plot showing the modelled PTS and TTS impact ranges (NMFS, 2016) for fleeing low frequency (LF) cetaceans at the NW location for installing a pin pile with a maximum blow energy of 2500 kJ.

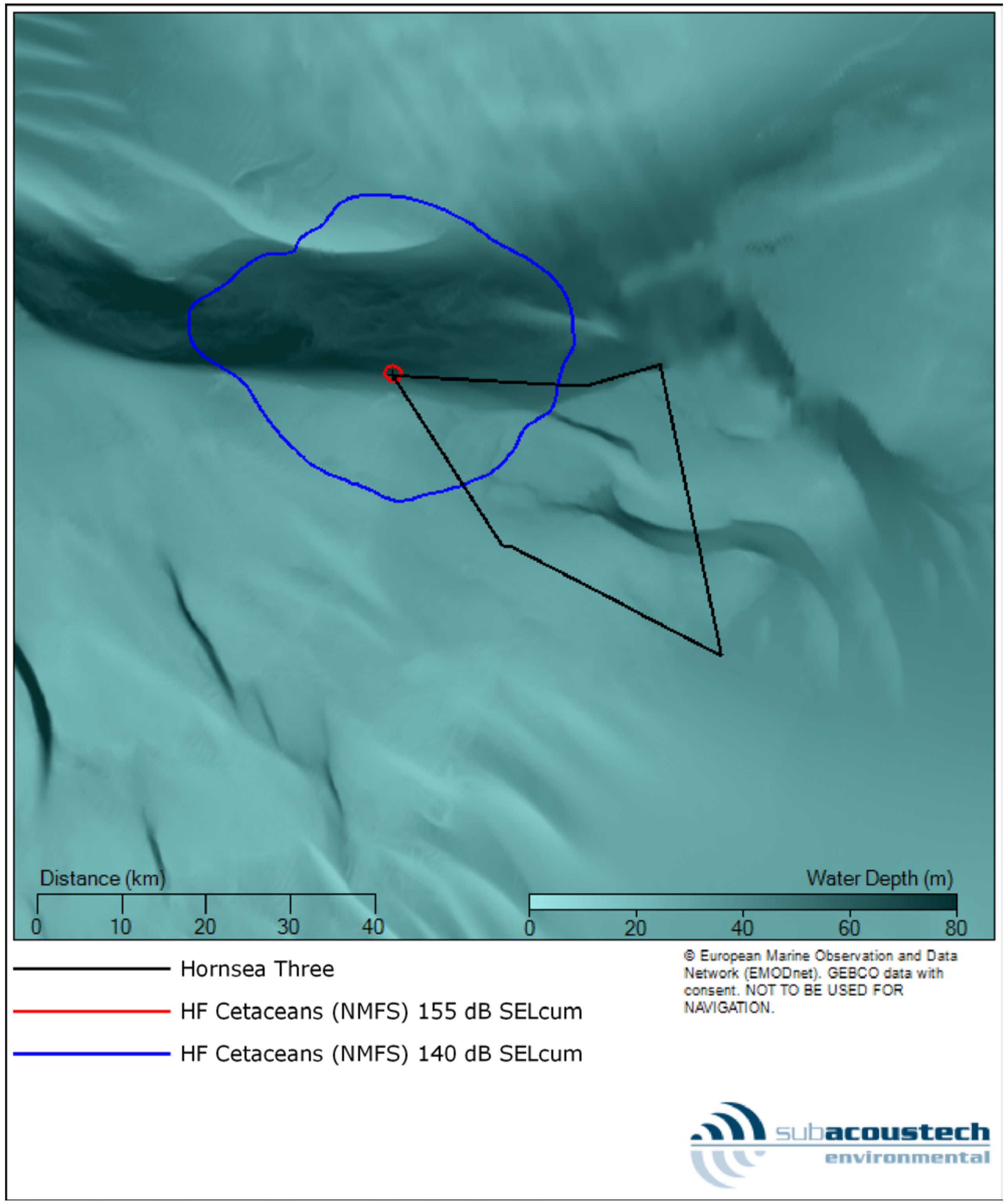

Figure 5.15: Contour plot showing the modelled PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the NW location for installing a pin pile with a maximum blow energy of 2500 kJ.

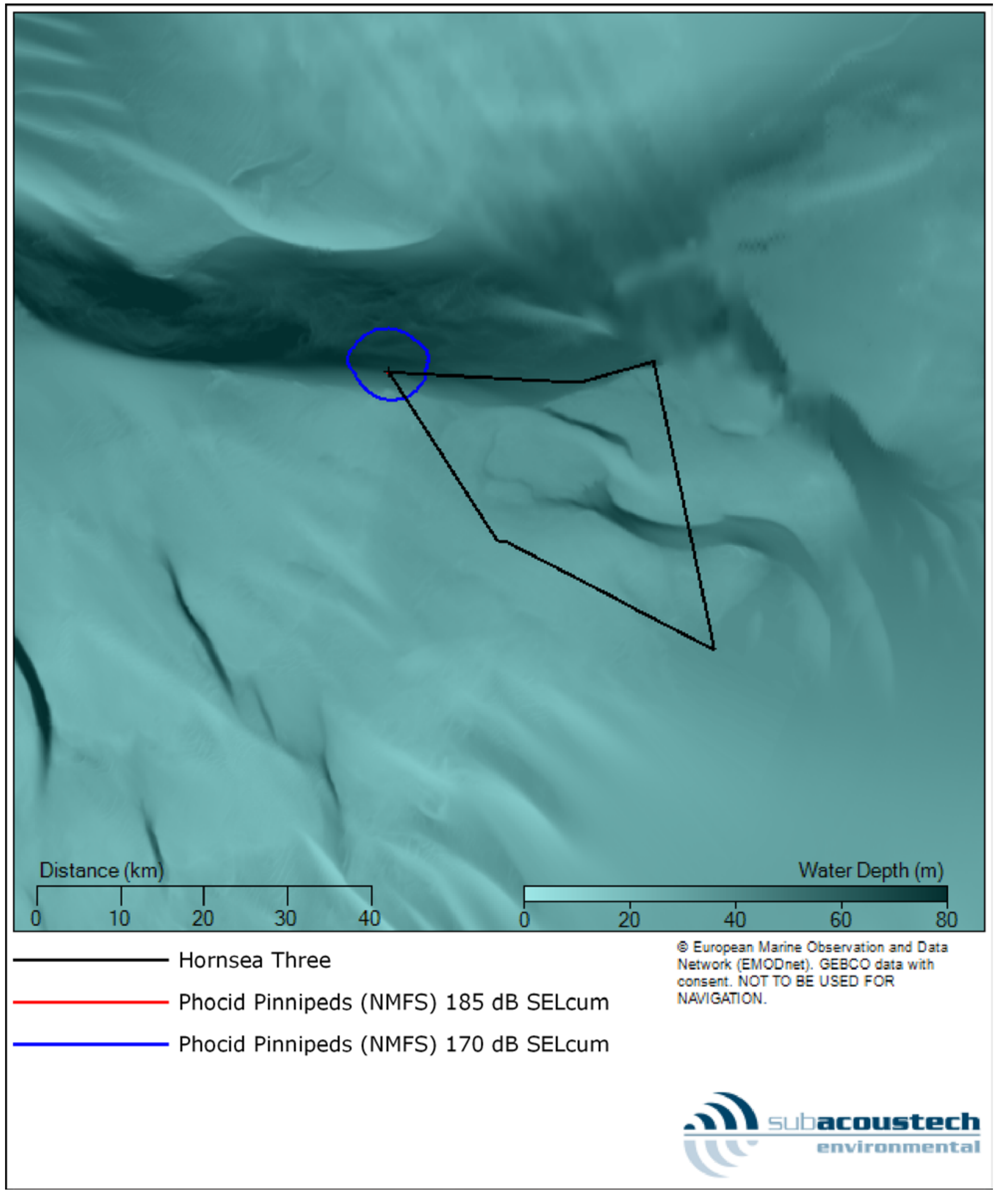

Figure 5.16: Contour plot showing the modelled PTS and TTS impact ranges (NMFS, 2016) for fleeing phocid pinnipeds (PW) at the NW location for installing a pin pile with a maximum blow energy of 2500 kJ. Note the 185 dB contour is too small to be visible at this scale.

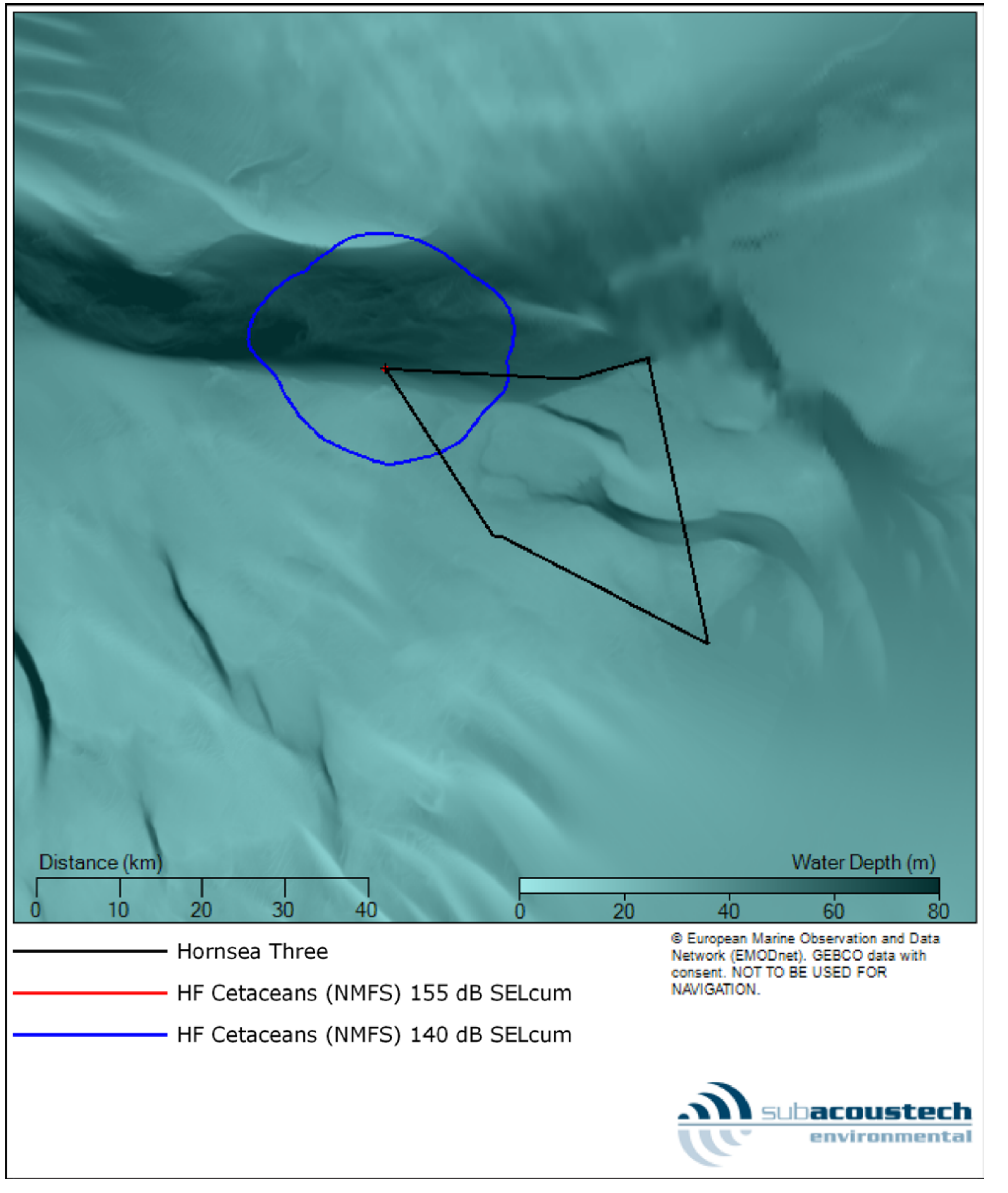

Figure 5.17: Contour plot showing the modelled PTS and TTS impact ranges (NMFS, 2016) for fleeing high frequency (HF) cetaceans at the NW location for installing a pin pile with a Most Likely maximum blow energy of 1750 kJ.

Discussion

5.3.2.5 The ranges of impact vary depending on the hearing (species) group. This variation is expressed clearly between the results of the LF, MF and HF cetaceans shown in Table 5.5, Table 5.6 and Table 5.7.

5.3.2.6 In general, the LF cetacean weighting produces the greatest ranges (for PTS and TTS using the SEL_{cum} criteria) as the MF and HF cetacean weighting filters out much 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 threshold, i.e. HF cetaceans are deemed more sensitive) and so the ranges before this level is reached in the sea are much greater than for MF cetaceans.

5.3.2.7 The SEL_{cum} results for MF and HF cetaceans using the NMFS criteria (Table 5.6, Table 5.7, Table 5.10 and Table 5.11) 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.

5.3.2.8 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. much of the pile strike sound 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 low frequencies. This leaves the high frequency noise, which, in the case of the pin piles, is greater than that for monopiles.

5.3.2.9 In order to illustrate this, Figure 5.18 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 5.18). Overall, higher levels are present in the weighted pin pile spectrum, especially around 6 kHz to 12 kHz.

5.3.2.10 The new LF and HF thresholds have led to substantially greater modelled ranges of impact than have been seen previously, and alongside the use of precautionary parameters such as high blow energies, long piling times and slow flee speeds mean that this combination of situations occuring in practice is extremely unlikely.

5.3.2.11 It is also expected that the characteristics of impulsive sound that make them more injurious start to dissipate over increased distance (NMFS 2016, Urick 1983) reducing the actual risk in a real setting. Taking these considerations into account, it is recommended the ranges modelled against cumulative SEL criteria and the modelled ranges over which an effect may occur are likely to be lower in practice.

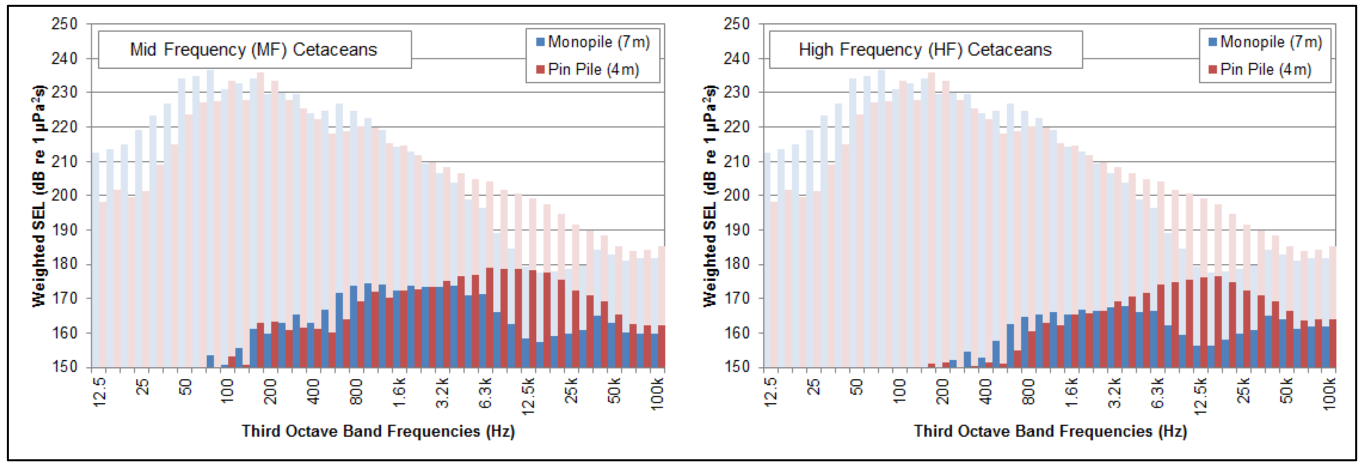

Figure 5.18: Filtered noise inputs for monopiles and pin piles using the MF cetacean and HF cetacean filters from NMFS (2016). The greyed bars show the unweighted third octave levels.

5.3.3 Impacts on fish

5.3.3.1 Table 5.13 and Table 5.14 give the maximum and mean impact ranges for species of fish based on the injury criteria found in the Popper *et al.* (2014) guidance. Figure 5.19 to Figure 5.21 present a selection of SEL_{cum} contour plots using the Popper *et al*. (2014) criteria, showing the TTS ranges for the maximum monopile (Figure 5.19) and pin pile (Figure 5.20) design scenarios; Figure 5.20 and Figure 5.21 can be compared to show differences between the maximum and Most Likely ramp up scenarios. Figure 5.22 to Figure 5.25 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 from Popper *et al.* (2015) are not weighted.

Table 5.13: 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)	
		Max range	Mean range	Max range	Mean range
Monopile (5,000kJ)	NW	190 m	190 m	< 100 m	< 100 m
	NE	190 m	190 m	< 100 m	< 100 m
	S	190 m	190 m	< 100 m	< 100 m
	HVAC N	61 m	61 m	< 100 m	< 100 m
	HVAC S	110 m	110 m	< 100 m	< 100 m

Fish (Recoverable injury)		207 dB re 1 µPa Unweighted SPL_{peak}		203 dB re 1 µPa²s Unweighted SEL_{cum} (Fleeing 1.5 ms^{-1})	
		Max range	Mean range	Max range	Mean range
Monopile (3,500kJ)	NW	160 m	160 m	< 100 m	< 100 m
	NE	160 m	160 m	< 100 m	< 100 m
	S	160 m	160 m	< 100 m	< 100 m
	HVAC N	49 m	49 m	< 100 m	< 100 m
	HVAC S	93 m	93 m	< 100 m	< 100 m
Monopile (2,000kJ)	NW	120 m	120 m	-	-
	NE	120 m	120 m	-	-
	S	120 m	120 m	-	-
	HVAC N	34 m	34 m	-	-
	HVAC S	66 m	66 m	-	-
Pin Pile (2,500kJ)	NW	130 m	130 m	< 100 m	< 100 m
	NE	130 m	130 m	< 100 m	< 100 m
	S	130 m	130 m	< 100 m	< 100 m
	HVAC N	40 m	40 m	< 100 m	< 100 m
	HVAC S	76 m	76 m	< 100 m	< 100 m
Pin Pile (1,750kJ)	NW	110 m	110 m	< 100 m	< 100 m
	NE	110 m	110 m	< 100 m	< 100 m
	S	110 m	110 m	< 100 m	< 100 m
	HVAC N	31 m	31 m	< 100 m	< 100 m
	HVAC S	60 m	60 m	< 100 m	< 100 m
Pin Pile (1,250kJ)	NW	84 m	84 m	-	-
	NE	84 m	84 m	-	-
	S	84 m	84 m	-	-
	HVAC N	24 m	24 m	-	-
	HVAC S	47 m	47 m	-	-

Table 5.14: Summary of the maximum and mean range for TTS in species of fish.

Fish (TTS)		186 dB re 1 µPa²s Unweighted SEL_{cum} (Fleeing 1.5 ms^{-1})	
		Max range	Mean range
Monopile (5,000kJ)	NW	11 km	8.7 km
	NE	10 km	8.8 km
	S	7.6 km	6.9 km
	HVAC N	400 mm	260 m
	HVAC S	3.3 km	2.8 km
Monopile (3,500kJ)	NW	7.2 km	6.1 km
	NE	6.8 km	6.1 km
	S	5.2 km	4.9 km
	HVAC N	< 100 m	< 100 m
	HVAC S	2.0 km	1.7 km
Monopile (2,000kJ)	NW	-	-
	NE	-	-
	S	-	-
	HVAC N	-	-
	HVAC S	-	-
Pin Pile (2,500kJ)	NW	6.9 km	5.6 km
	NE	6.5 km	5.7 km
	S	4.7 km	4.4 km
	HVAC N	< 100 m	< 100 m
	HVAC S	1.3 km	1.1 km
Pin Pile (1,750kJ)	NW	3.9 km	3.3 km
	NE	3.7 km	3.3 km
	S	2.8 km	2.6 km
	HVAC N	< 100 m	< 100 m
	HVAC S	400 m	280 m
Pin Pile (1,250kJ)	NW	-	-
	NE	-	-
	S	-	-
	HVAC N	-	-
	HVAC S	-	-

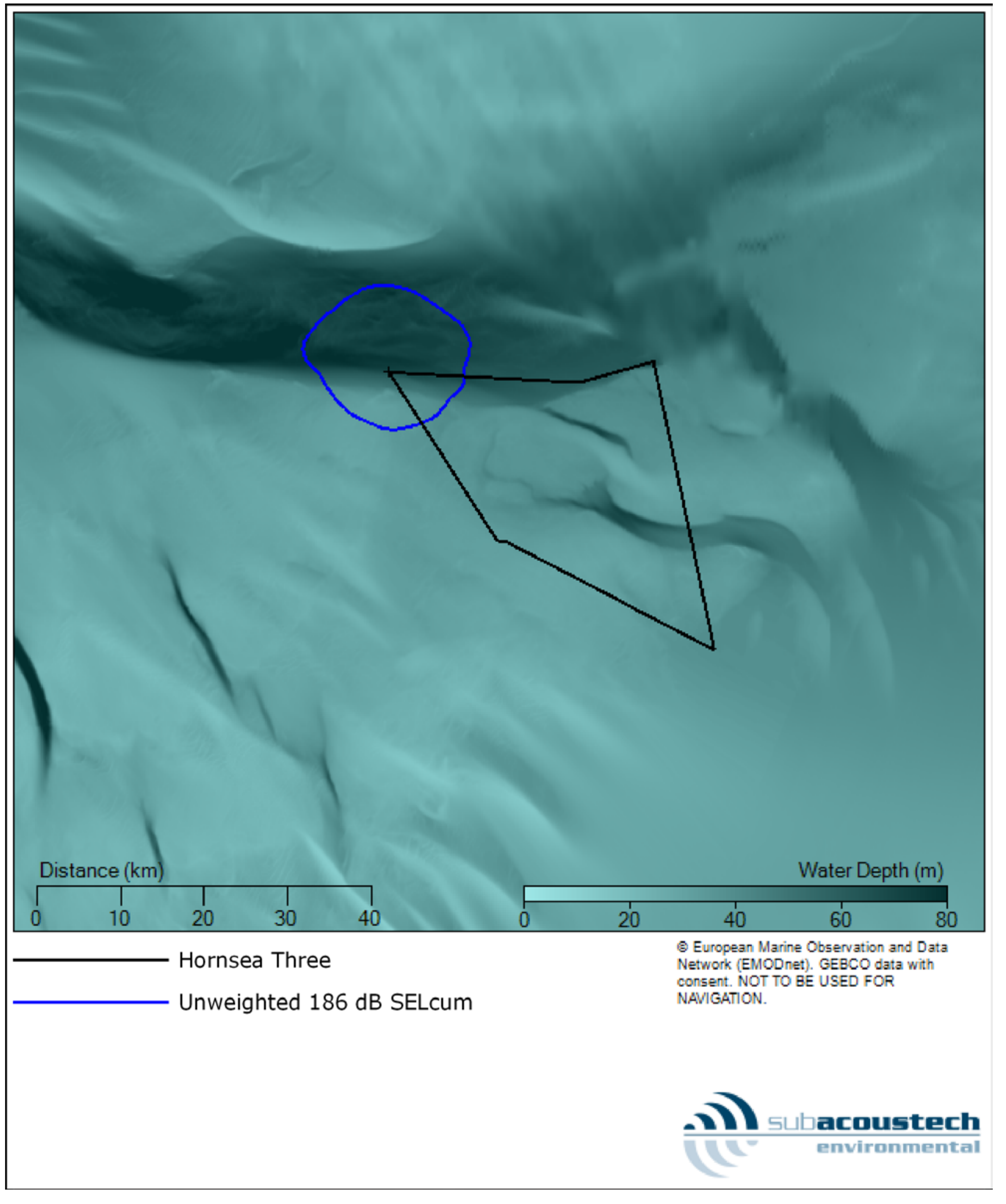

Figure 5.19: Contour plot showing the unweighted SEL_{cum} TTS impact ranges (Popper et al. 2014) for fleeing fish at the NW location for installing a monopile with a maximum blow energy of 5000 kJ.

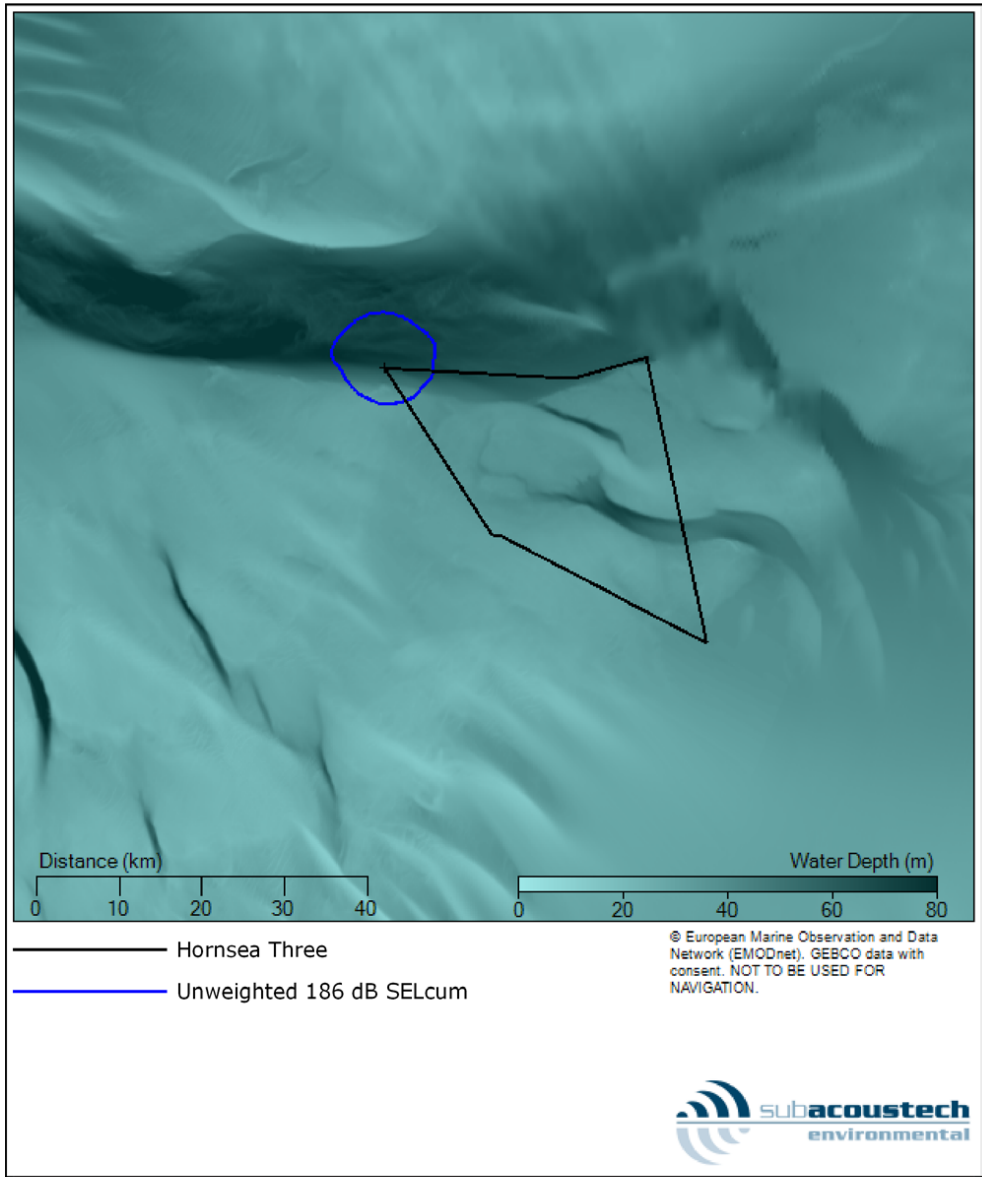

Figure 5.20: Contour plot showing the unweighted SEL_{cum} TTS impact ranges (Popper et al. 2014) for fleeing fish at the NW location for installing a pin pile with a maximum blow energy of 2500 kJ.

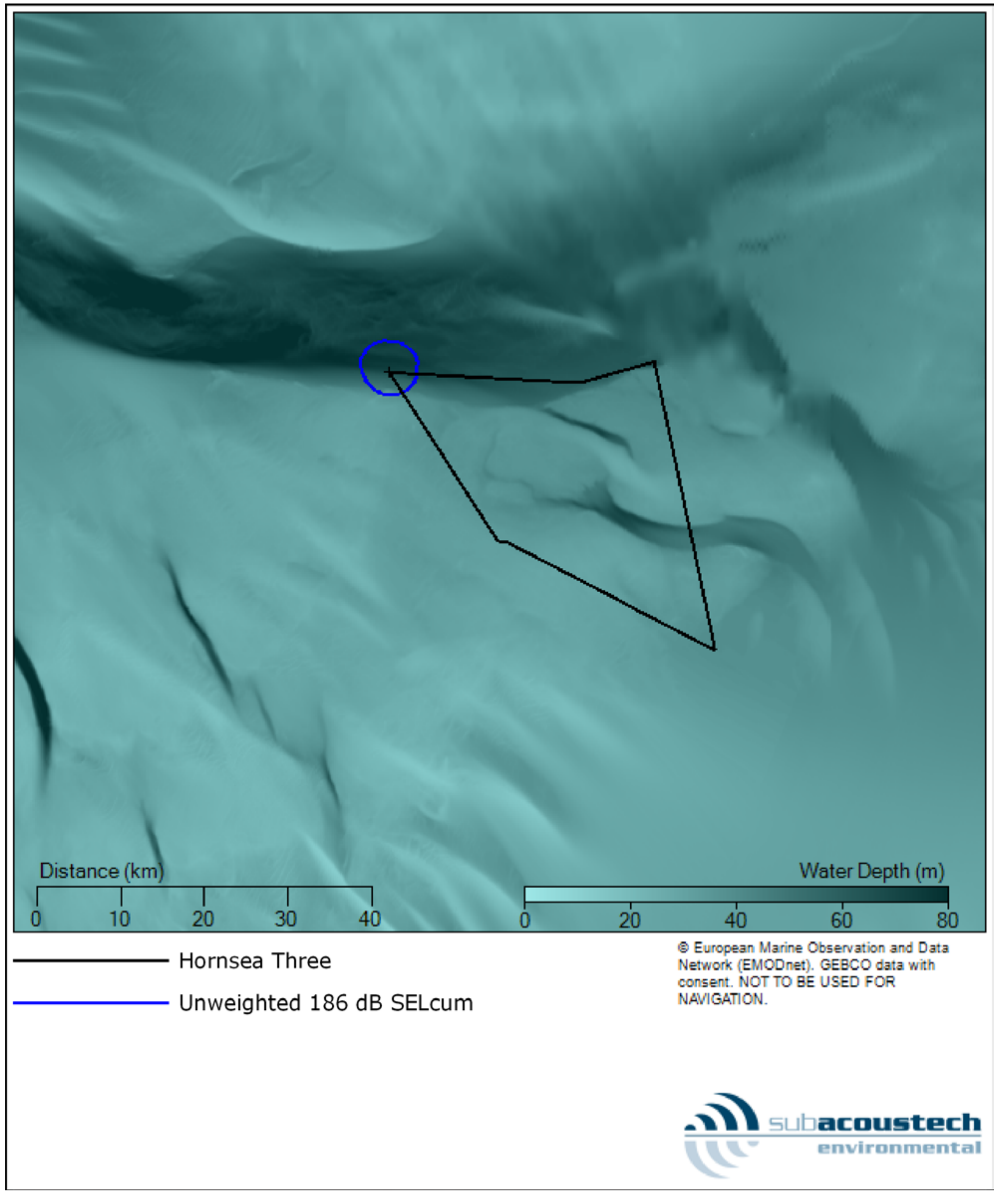

Figure 5.21: Contour plot showing the unweighted SEL_{cum} TTS impact ranges (Popper et al. 2014) for fleeing fish at the NW location for installing a pin pile with a maximum blow energy of 1750 kJ.

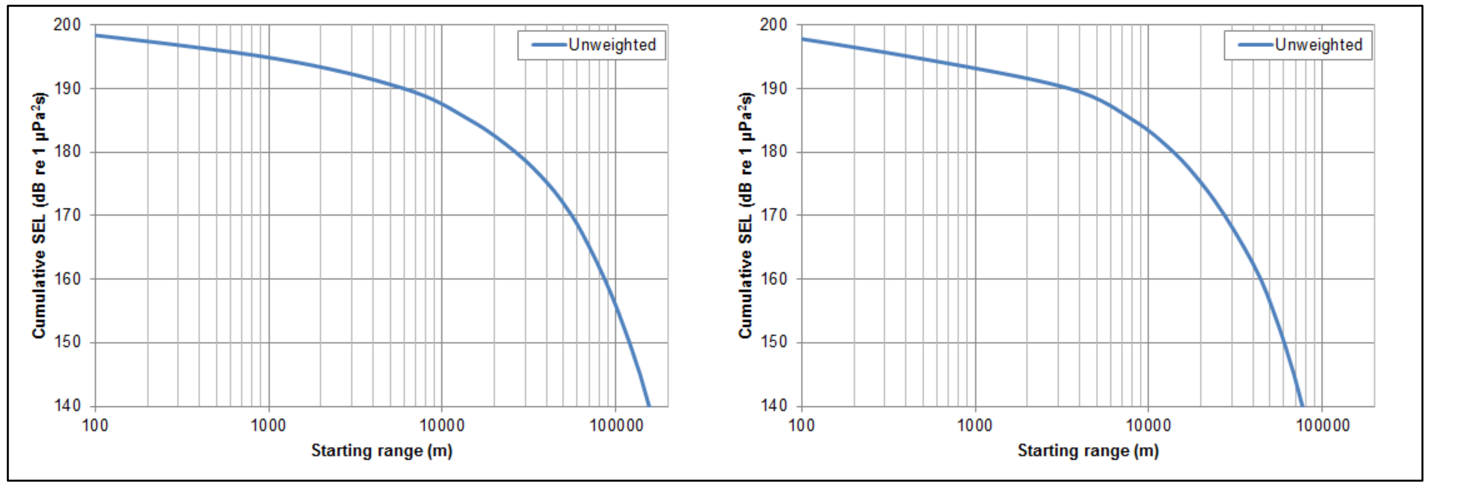

Figure 5.22: Total received cumulative SEL for species of fish (Popper *et al.* (2014) unweighted criteria) when fleeing from impact piling noise at NW location for a monopile installed with a maximum hammer energy of 5,000 kJ (Left plot = WNW transect (290°), Right plot = SSW transect (190°)).

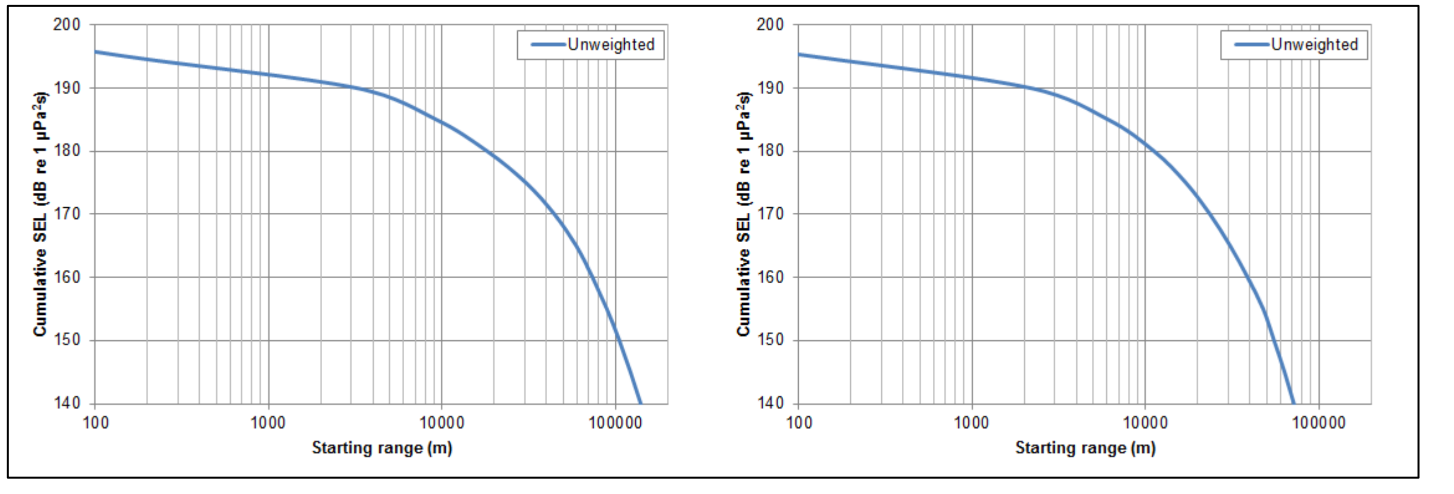

Figure 5.23: Total received cumulative SEL for species of fish (Popper *et al.* (2014) unweighted criteria) when fleeing from impact piling noise at NW location for a monopile installed with a maximum hammer energy of 3500 kJ (Left plot = WNW transect (290°), Right plot = SSW transect (190°)).

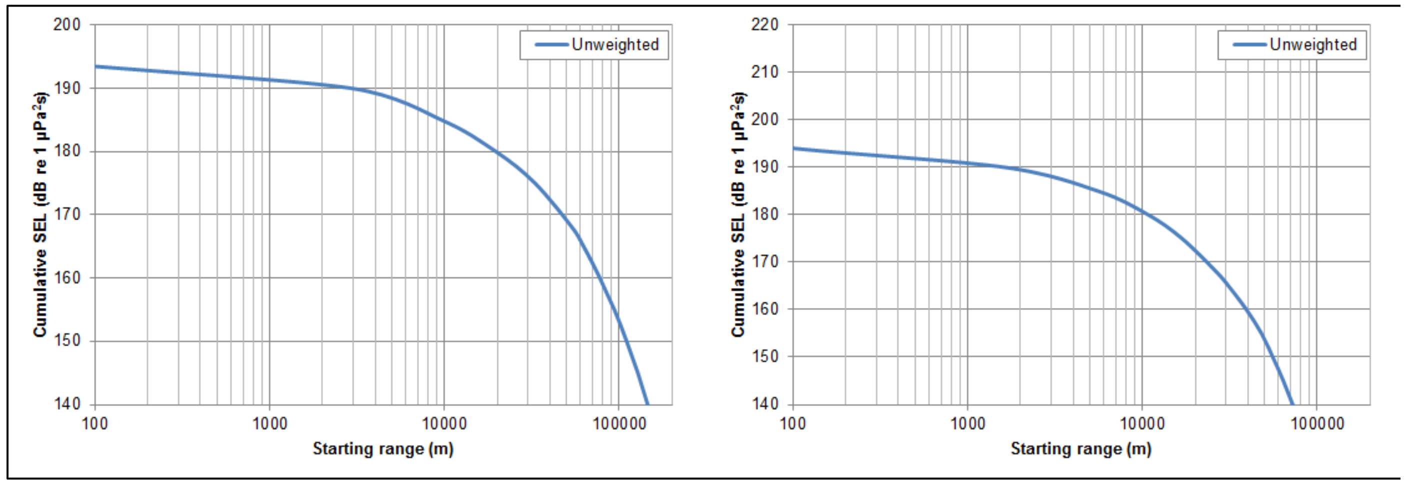

Figure 5.24: Total received cumulative SEL for species of fish (Popper et al. (2014) unweighted criteria) when fleeing from impact piling noise at NW location for a pin pile installed with a maximum hammer energy of 2,500 kJ (Left plot = WNW transect (290°), Right plot = SSW transect (190°)).

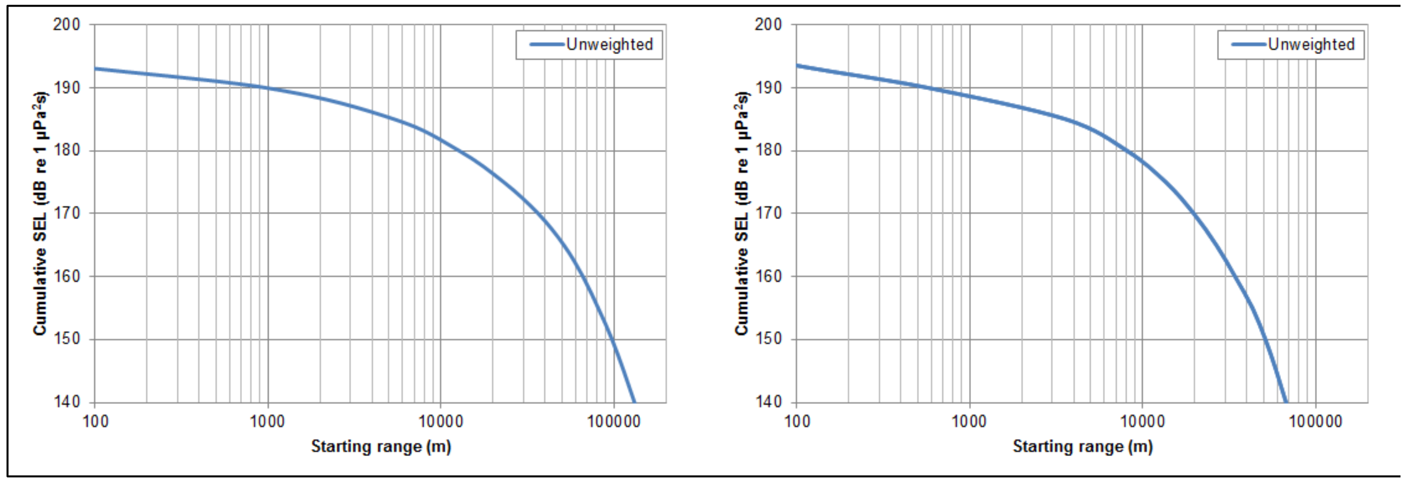

Figure 5.25: Total received cumulative SEL for species of fish (Popper *et al*. (2014) unweighted criteria) when fleeing from impact piling noise at NW location for a pin pile installed with a maximum hammer energy of 1,750 kJ (Left plot = WNW transect (290°), Right plot = SSW transect (190°)).

5.3.3.2 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 each effect are given along with a relative risk rating.

5.3.3.3 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 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.

5.3.3.4 Table 5.15 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 5.16 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 5.15: 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 5.16: 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

6. Operational Noise

6.1 Overview

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). Noise levels generated above the water surface are low enough that no significant airborne sound will pass from the air to the water.

6.2 Literature review

6.2.1.1 Lindell (2003) reported on underwater sound measurements taken between November 2002 and February 2003 near Utgrunden wind farm located on the Utgrunden reef off the southeast Swedish coast. The wind farm is comprised of seven 1.5 MW GE Wind Energy turbines, arranged along a line, in water between 4 and 10 metres deep. Three hydrophones were located on the sea bed along a radial line emanating from the turbine in the middle of the array; the ranges from the turbine were 83, 160 and 463 m. Using sound pressure values taken from Figures 12 and 15 in the report, it is found that, apart from the tonal components, the sound reduces to background level within about 300 m of the turbine. The highest tonal component, at about 180 kHz, reduces to background level at about 450 m. The report concluded that the underwater sound was dominated by a few frequencies between 30 Hz and 800 Hz, relating to gearbox meshing. Also, noise from passing ships dominated the field for frequencies around 63 Hz.

6.2.1.2 The same research documented the variation of noise produced with wind speed. They show that the exact position of tonal components increased with wind speed, consistent with the belief that this aspect of the noise is driven by mechanical aspects of the turbine. Furthermore, they show that although the broadband noise contribution rises with increasing speed this is a relatively small effect for variations of speed between 8 and 13 ms^{-1}.

6.2.1.3 A review of the effects of underwater sounds from wind farms and their effects on marine mammals (Madsen *et al*., 2006) concluded that for operational wind farms the effects were small, especially in comparison to other anthropogenic sources such as shipping noise.

6.2.1.4 Teilmann *et al.* (2006a) reported on monitoring of harbour porpoise around the Horns Rev and Nysted wind farms located off the coast of Denmark, in the North Sea and the south western Baltic Sea respectively. Horns Rev has eighty 2 MW turbines, and Nysted has seventy-two 2.3 MW turbines. T-PODs, which sense for and record porpoise clicks, were deployed on the sea bed around the two sites to take measurements before, during and after the construction of the two wind farms. Their conclusions were that there was no reduction of porpoise activity at Horns Rev in its operational phase, while there was some reduction at Nysted when it was in operation, but that it was recovering to pre-construction levels after about two years.

6.2.1.5 A similar study by Teilmann *et al.* (2006b) reported on monitoring of harbour seals and grey seals at the Horns Rev and Nysted wind farms; this study used visual monitoring and satellite tracking of tagged animals. Their conclusion was that 'no general change in behaviour at sea or on land could be linked to the wind farms'. More recently, a case study at the Egmond aan Zee OWF (Scheidat *et al.*, 2011) investigated the effects on harbour porpoise of the wind farm under normal operational conditions. The harbour porpoise population was found to significantly increase within the wind farm boundary, much larger than any variation in control areas. No effects were found by Brasseur *et al.* (2012) for seal populations in the same location.

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

6.2.1.7 A further study by the Marine Management Organisation (MMO, 2014) states that operational wind farm noise is generally of a low level and has been demonstrated to be broadly comparable with ambient noise within a few hundred metres of the foundation.

6.2.1.8 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).

6.3 Noise modelling

6.3.1.1 The size and model of turbines to be used at Hornsea Three have yet to be finalised, however operational wind farm sites where measurements have been collected are summarised in Table 6.1. 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, and is explained further below.

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

6.3.1.2 The turbine output to be used at Hornsea Three has not yet been defined. In order to give a representative spread of impact ranges, three large turbine sizes (based on their rotor diameter) have been modelled, which represent the scale of turbine that could be expected in Hornsea Project Three.

6.3.1.3 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, a wider 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 at a single location, for example. 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 in, so that some measurements above background could be detected).

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

6.3.1.5 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 level sampled at each of the sites have been taken, and then a linear correction factor has been added to scale up the source levels (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.

	Unweighted source level (RMS)
Lynn	141 dB re 1 µPa (RMS) @ 1 m
Inner Dowsing	142 dB re 1 µPa (RMS) @ 1 m
Gunfleet Sands 1 & 2	145 dB re 1 µPa (RMS) @ 1 m
Gunfleet Sands 3	146 dB re 1 µPa (RMS) @ 1 m
Hornsea Three (125 m rotor diameter)	147.4 dB re 1 µPa (RMS) @ 1 m
Hornsea Three (140 m rotor diameter)	151.6 dB re 1 µPa (RMS) @ 1 m
Hornsea Three (170 m rotor diameter)	158.5 dB re 1 µPa (RMS) @ 1 m

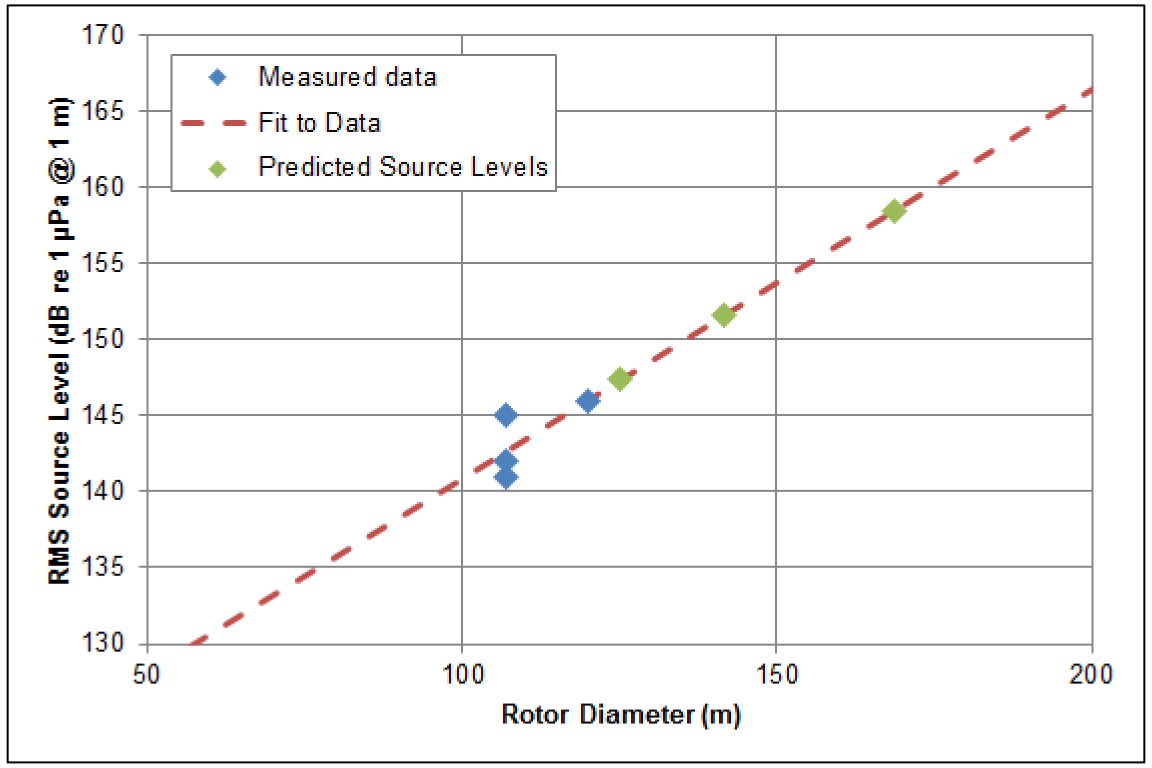

Figure 6.1: Extrapolated source levels from operational turbines plotted with a linear fit to estimate source levels for larger turbines.

6.3.1.6 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 NW 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. Operational noise is considered continuous noise.

6.3.1.7 Assuming the same fleeing speeds used for the construction noise modelling over a 24-hour period the predicted impact ranges for injury from turbine noise, even for the largest 170 m rotor-diameter 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.

6.3.1.8 In respect of disturbance, assuming a source level of up to 158.5 dB re 1 µPa SPL RMS, the noise would be expected to fall to ambient noise levels of the order of 110-120 dB re 1 µPa SPL RMS within a few hundred metres. Therefore no impact would be expected beyond this point, and due to the continuous nature of the noise, there is a low risk of disturbance within this range in general. In respect of MF and HF cetaceans, the risk is even lower as oprational noise is predominately low frequency, which is outside of the hearing range of these species groups.

7. Decommissioning Noise

7.1.1.1 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 Orsted to assess the effect of potential noise from construction, operation and eventual decommissioning of Hornsea Three.

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 the INSPIRE subsea noise modelling software which considers a wide variety of input parameters including bathymetry, hammer blow energy, frequency content, 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 six piling scenarios; 5,000 kJ, 3,500 kJ, and 2,000 kJ maximum hammer energies for installing monopiles and 2,500 kJ, 1,750 kJ, and 1,250 kJ maximum hammer energy for installing pin piles. Ramp up scenarios have been assumed for calculations to 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 potential behavioural effects in marine receptors.

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 Mammals.

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