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Erebus Offshore Wind: Underwater noise assessment

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Glossary

Term	Definition
Decibel (dB)	A customary scale 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 $10 \log_{10}(\text{actual/reference})$ where (<i>actual/reference</i>) is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is $20 \log_{10}(\text{actual pressure/reference pressure})$. The standard reference for underwater sound is 1 micropascal (μPa). The dB value is followed by a second value identifying the specific reference pressure (e.g., re 1 μPa).
High-order UXO detonation	Full destruction by detonation of an unexploded ordnance device by means of an initial donor charge to trigger the detonation.
Low-order UXO detonation/clearance	Any destruction of an unexploded ordnance device that does not lead to full (high-order) detonation, through destruction or burning of the explosive material.
Peak pressure	The maximum instantaneous sound pressure during a measurement period or noise event.
Peak-to-peak pressure	The magnitude of range of the greatest positive and negative pressures that are associated with a sound wave.
Permanent Threshold Shift (PTS)	A permanent total or partial loss of hearing caused by acoustic 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 is an expression of sound pressure using the decibel (dB) scale; the standard frequency pressures of which are 1 μPa for water and 20 μPa for air.
Temporary Threshold Shift (TTS)	Temporary reduction of hearing acuity because of exposure to sound over time. Exposure to high levels of sound over relatively short time periods could cause the same amount of TTS as exposure to lower levels of sound over longer time periods. The duration of TTS varies depending on the nature of the stimulus.
Unweighted sound level	Sound levels which are “raw” or have not been adjusted in any way, for example to account for the frequency response 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 relative loudness of sounds in air as perceived by the human ear, or the filters used by Southall <i>et al.</i> (2019) for marine mammals.

Acronyms

Acronym	Definition
EIA	Environmental Impact Assessment
FPSO	Floating Production Storage and Offloading vessel
HF	High-Frequency Cetaceans (Marine mammal hearing group from Southall <i>et al.</i> , 2019)
HRA	Habitat Regulations Assessment
INSPIRE	Impulse Noise Sound Propagation and Range Estimator (Subacoustech's noise model for estimating impact piling noise)
LF	Low-Frequency Cetaceans (Marine mammal hearing group from Southall <i>et al.</i> , 2019)
MTD	Marine Technical Directorate Ltd.
NEQ	Net Explosive Quantity (usually given in kg as a TNT equivalent)
NPL	National Physical Laboratory
OWF	Offshore Wind Farm
PCW	Phocid Carnivores in Water (Marine mammal hearing group from Southall <i>et al.</i> , 2019)
PTS	Permanent Threshold Shift
RMS	Root Mean Square
SE	Sound Exposure
SEL	Sound Exposure Level
SEL _{cum}	Cumulative Sound Exposure Level
SEL _{ss}	Single Strike Sound Exposure Level
SPEAR	Simple Propagation Estimator And Ranking model (Subacoustech noise model for low-level underwater noise estimation)
SPL	Sound Pressure Level
SPL _{peak}	Peak Sound Pressure Level
SPL _{peak-to-peak}	Peak-to-peak Sound Pressure Level
SPL _{RMS}	Root Mean Square Sound Pressure Level
TNT	Trinitrotoluene (explosive)
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance
VHF	Very High-Frequency Cetaceans (Marine mammal hearing group from Southall <i>et al.</i> , 2019)

Units

Unit	Definition
dB	Decibel (sound pressure)
Hz	Hertz (frequency)
kHz	Kilohertz (frequency)
kg	Kilogram (mass)
km	Kilometre (distance)
knot	Knot (speed, at sea)
m	Metre (distance)
ms ⁻¹	Metres per second (speed)
Pa ² s	Pascal squared seconds (acoustic energy)
μPa	Micropascal (pressure)

Executive summary

The development of the Erebus Offshore Wind Farm (OWF) project will involve activities that will introduce underwater noise into the local environment. These will include both short-term noise sources active during construction, as well as the operation of the turbines themselves over the lifetime of the project. These noise emissions have the potential to affect sensitive receptors in the Irish Sea, including species of marine mammals and fish.

This report investigates these sources of noise and uses underwater noise modelling software to predict the distribution of noise around the Erebus OWF and estimates ranges of impact at which various thresholds dictated by relevant guidance would be exceeded. This guidance is based primarily on Southall *et al.* (2019) for marine mammal species, and Popper *et al.* (2014) for fishes, and provide noise thresholds within which potential injury and onset of effects on hearing (both permanent, “PTS” and temporary, “TTS”) could occur in relevant species. These are based on both instantaneous and longer duration exposure to the noise.

Noise sources expected during the construction phase include ground preparation activities such as dredging, trenching, cable laying, and rock placement, turbine mooring activities such as the installation of ground embedment anchors, drilling and suction piling, and vessel movements. Impact piling is considered unlikely but has been included to cover the worst-case scenario. Clearance of unexploded ordnance (UXO) may also be required, and the noise this could produce has also been assessed using both high-order and low-order techniques.

Ground preparation, vessels and mooring installation (other than by impact piling) are relatively low-level noise sources and have been assessed using a simple propagation model alongside the impact criteria from Southall *et al.* (2019) and Popper *et al.* (2014). Assuming the most plausible scenario for modelling, that a receptor swims away from the noise source when it is operating, any fish or marine mammal species would need to be within 20 m of the source to receive sufficient exposure for a potential recoverable injury or permanent hearing impairment. A temporary, recoverable hearing impairment could potentially occur up to 990 m from the source to the harbour porpoise, or any other marine mammal species in the Very High Frequency category. All other species categories, including fishes, would need to be within 100 m of any of these sources to acquire a noise exposure sufficient to incur a temporary effect on hearing.

The site specific UXO assessment concluded that the largest, most likely, device that could be found in the area could have charge weights of up to 389 kg NEQ. However for consistency with previous assessments within the area, devices of up to 794 kg NEQ have been included with the modelling presented even though these are unlikely. The clearance of such a device using high-order detonation, assuming no degradation of the UXO over time, could lead to PTS onset impact ranges of a maximum of 15 km for Very High Frequency (VHF) cetaceans and 12 km for the Low Frequency (LF) cetacean marine mammal categories. Using a low order-technique for clearance, if possible, given the circumstances of any UXO identified, would lead to PTS onset impact ranges of up to 990 m (VHF) and 230 m (LF), assuming that a 0.25 kg shaped charge was used to initiate the low-order clearance. This is the most likely limit for the size of the shaped charge required for a low-order clearance.

In the event that impact piling is required, the maximum PTS onset range is 2.7 km for Low Frequency Cetaceans using worst-case piling parameters. All other species would need to be within 280 m at the start of piling for any such effect to occur.

When operational, predictions of the underwater noise present continuously have been made for the turbines proposed, based on extrapolations from measurements of other turbines installed in the UK and US. No significant adverse impacts from noise from operational turbines are expected to any species of fish or marine mammal.

1 Introduction

The Erebus Offshore Wind Farm (OWF) project is a proposed wind farm development off the coast of South Wales in the Celtic Sea. As part of both the Environmental Impact Assessment (EIA) and Habitat Regulations Assessment (HRA) processes, Subacoustech Environmental Ltd. have undertaken underwater noise modelling and analysis in relation to marine fauna and diving birds for the Erebus site.

The primary activities considered for this study are associated with the ground preparation and installation of the floating turbines and their associated infrastructure. The expected or potential noise sources at the Erebus OWF considered in this assessment are:

- Vessel movements;
- Seabed preparation;
- Cable installation;
- Cable protection;
- Installation of drag embedment anchors;
- Suction pile installation;
- Drilling to install foundation piles;
- Operational turbine noise, and
- Potential UXO detonation.

In addition, there is the potential that impact piling may be necessary to install piles to secure the WTG moorings and the expected noise from these activities has also been included.

This report presents a detailed assessment of the potential underwater noise and its effects during construction of the Erebus OWF, and covers the following:

- 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 the possible environmental effects in marine receptors (Section 2);
- Discussion of the approach, input parameters and assumptions for the noise modelling undertaken (Section 3);
- Noise modelling results for the potential noise sources during construction of the wind farm (Section 4); and
- Summary and conclusions (Section 5).

2 Underwater noise metrics

2.1 Underwater noise

2.1.1 Background

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 pressure associated with underwater sound tends to be much higher than in air. As an example, background noise levels in the sea of 130 dB re 1 µPa for UK coastal waters are not uncommon (Nedwell *et al.* 2003 and 2007).

It should be noted that stated underwater noise levels should not be confused with noise levels in air, which use a different scale.

2.1.2 Units of measurement

Sound measurements underwater are usually expressed using the decibel (dB) scale, which is a logarithmic measure of sound. A logarithmic scale is used because, rather than a linear scale, each doubling of sound level will cause a 3 dB increase of “loudness.”

Any quantity expressed in this scale is termed a “level.” If the unit is sound pressure, expressed on the dB scale, it will be termed a “sound pressure level.”

The fundamental definition of the dB scale is given by:

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

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

The dB scale represents a ratio. 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 example, a reference quantity of 20 µPa is used for sound in air since that is the lower threshold of human hearing.

When used with sound pressure, the pressure value is squared. So that variations in the units agree, the sound pressure must be specified as units of Root Mean Square (RMS) pressure squared. This is equivalent to expressing the sound as:

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

For underwater sound, a unit of 1 µPa is typically used as the reference unit (P_{ref}); a Pascal is equal to the pressure exerted by one Newton over one square metre, one micropascal equals one millionth of this.

2.1.2.1 Sound pressure level (SPL)

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 sound. The SPL can therefore be considered a measure of the average unweighted level of sound over the measurement period.

Where SPL is used to characterise transient pressure waves, such as that from impact piling or UXO clearance, it is critical that the period over which the RMS level is calculated is quoted. For instance, in the case of a pile strike lasting a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean averaged over one second. Often, transient sounds such as these are quantified using “peak” SPLs or sound exposure levels (SELs).

Unless otherwise defined, all SPL noise levels in this report are referenced to 1 µPa. It is recognised that ISO 18405 (2017) defines SPL in reference to the unit 1 µPa². As the key publications used in this assessment use the unit 1 µPa, this terminology will also be used in this report. This does not affect any results or values.

2.1.2.2 Peak sound pressure level (SPL_{peak})

Peak SPLs are often used to characterise transient sound from impulsive sources, such as percussive impact piling. SPL_{peak} 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.

A further variation of this is the peak-to-peak SPL ($SPL_{peak-to-peak}$) where the maximum variation of the pressure from positive to negative is considered. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak pressure will be twice the peak level, or 6 dB higher (see section 2.1.2).

2.1.2.3 Sound exposure level (SEL)

When considering the noise from transient sources, the issue of the duration of the pressure wave is often addressed by measuring the total acoustic energy (energy flux density) of the wave. This form of analysis was initially used to explain the apparent discrepancies in the biological effect of short and long-range blast waves on human divers. Currently, the SEL metric has been used to develop criteria for assessing injury ranges for fish and marine mammals from various noise sources (Popper *et al.*, 2014 and Southall *et al.*, 2019).

The SEL sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound and the duration it 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 total duration of the sound in seconds, and t is the time in seconds. The SE is a measurement of acoustic energy and has units of Pascal squared seconds (Pa²s).

To express the SE on a logarithmic scale by means of a dB, it has to be compared with a reference acoustic energy level (p_{ref}^2) and a reference time (T_{ref}). The SEL is then defined by:

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

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 broadband noise and the SEL sums the cumulative broadband noise energy.

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 continuous sound of 10 seconds duration, the SEL will be 10 dB higher than the SPL; for a sound of 100 seconds duration the SEL will be 20 dB higher than the SPL, and so on).

2.2 Analysis of environmental effects

2.2.1 Background

Over the last 20 years it has become increasingly evident that noise from human activities in and around underwater environments can have an impact on the marine species in the area. The extent to which intense underwater sound might cause adverse impacts in species is dependent upon the incident sound level, source 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 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 immediate environmental impact and therefore the clearest observable effects, although interest in chronic noise exposure is increasing.

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.

The following sections discuss the underwater noise criteria used in this study.

2.2.2 Criteria to be used

The main metrics and criteria that have been used in this study to aid assessment of environmental effects come from two key papers covering underwater noise and its effects:

- Southall *et al.* (2019) marine mammal noise exposure criteria; and
- Popper *et al.* (2014) sound exposure guidelines for fishes.

At the time of writing these are used as the most up to date and authoritative criteria for assessing environmental effects for use in impact assessments.

A discussion of the effects of noise on diving birds and how they have been assessed for this study is given in section 2.2.2.3.

2.2.2.1 Marine mammals

The Southall *et al.* (2019) guidance groups marine mammals into categories of similar species and applies filters to the unweighted noise to approximate the hearing sensitivities of the receptor. The hearing groups given in Southall *et al.* (2019) are summarised in Table 2-1 and Figure 2-1. Further groups for sirenians and other marine carnivores in water are also given, but these have not been used for this study as those species are not commonly found in the Celtic Sea.

Hearing group	Generalised hearing range	Example species
Low-frequency cetaceans (LF)	7 Hz to 35 kHz	Baleen whales
High-frequency cetaceans (HF)	150 Hz to 160 kHz	Dolphins, toothed whales, beaked whales, bottlenose whales (including bottlenose dolphin)
Very high-frequency cetaceans (VHF)	275 Hz to 160 kHz	True porpoises (including harbour porpoise)
Phocid carnivores in water (PCW)	50 Hz to 86 kHz	True seals (including harbour seal)

Table 2-1 Marine mammal hearing groups (from Southall *et al.*, 2019).

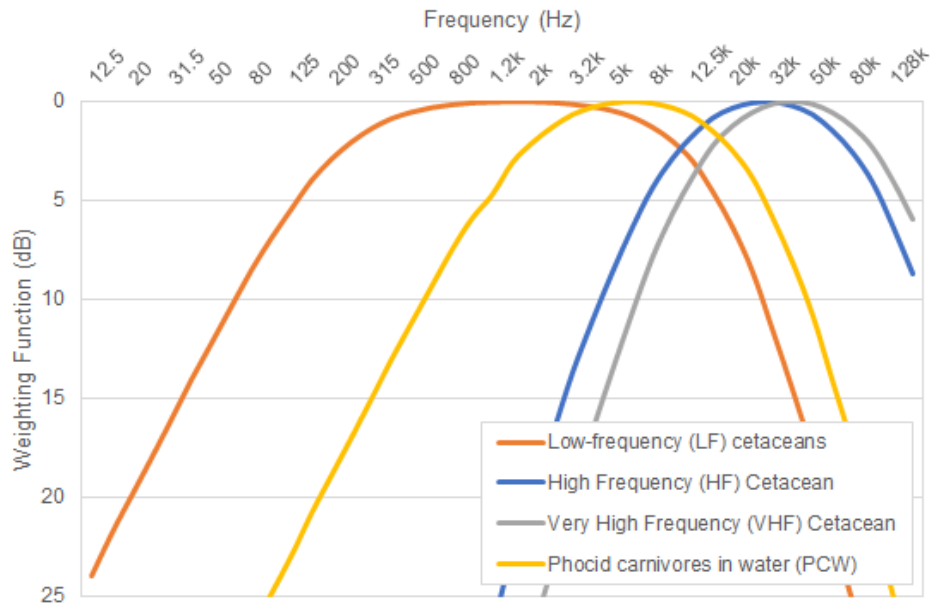


Figure 2-1 Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall *et al.*, 2019).

Southall *et al.* (2019) also gives individual criteria based on whether the noise source is considered impulsive or non-impulsive. Southall *et al.* categorises impulsive noises as having high peak sound pressure, short duration, fast rise-time and broad frequency content at source, and non-impulsive sources as steady-state noise. For the noise sources considered in this study, UXO detonations and impact piling are considered impulsive noise sources and all other sources are considered non-impulsive. A non-impulsive noise does not necessarily have to have a long duration.

Southall *et al.* (2019) presents single pulse, 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. In principle the SEL_{cum} metric is effectively still valid for a single instance of noise, although this is more commonly defined as SEL_{ss} (single pulse/strike). These dual criteria are only used for impulsive noise, with the criteria set giving the greatest calculated range used as the PTS impact range.

Table 2-2 and Table 2-3 present the Southall *et al.* (2019) criteria for the onset of PTS and TTS risk for each of the key marine mammal hearing groups considering impulsive and non-impulsive sources.

Southall <i>et al.</i> (2019)	Unweighted SPL_{peak} (dB re 1 μ Pa)	
	Impulsive	
	PTS	TTS
Low-frequency cetaceans (LF)	219	213
High-frequency cetaceans (HF)	230	224
Very high-frequency cetaceans (VHF)	202	196
Phocid carnivores in water (PCW)	218	212

Table 2-2 Single strike, impulsive, SPL_{peak} criteria for PTS and TTS in marine mammals (Southall *et al.*, 2019).

Southall <i>et al.</i> (2019)	Weighted SEL _{cum} (dB re 1 µPa ² s)			
	Impulsive		Non-impulsive	
	PTS	TTS	PTS	TTS
Low-frequency cetaceans (LF)	183	168	199	179
High-frequency cetaceans (HF)	185	170	198	178
Very high-frequency cetaceans (VHF)	155	140	173	153
Phocid carnivores in water (PCW)	185	170	201	181

Table 2-3 Impulsive and non-impulsive SEL_{cum} criteria for PTS and TTS in marine mammals (Southall *et al.*, 2019).

Where SEL_{cum} are required, both a fleeing animal and a stationary animal model have been assumed for marine mammals. The fleeing animal model assumes that a receptor, when 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 cetaceans (LF) 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 for fleeing, which is a cruising speed for a harbour porpoise (Otani *et al.*, 2000). These are considered worst-case assumptions as marine mammals are expected to be able to swim much faster under stress conditions.

The stationary animal model assumes that a receptor will stay at the same range from a noise source for the entire duration that the source is present, which for low-level sources (i.e., compared to impact piling) such as those being considered herein, can provide useful impact range results. Basing the modelling on a stationary (zero flee speed) receptor is likely to greatly overestimate the potential risk to a receptor, assuming that an individual would remain in the high noise level region of the water column, especially when considering the precautionary nature of the parameters already built into the cumulative exposure calculations. However, given the lack of evidence in the literature to support a fleeing animal model for low-level sources, it is considered to be precautionary to present the stationary model results alongside the fleeing animal model results.

2.2.2.2 Fish

The large number of, and 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 previous studies applied broad criteria based on limited studies of fish that are 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 fish exposure to sound and uses categories for fish that are representative of the species present in UK waters.

The Popper *et al.* (2014) study groups species of fish by whether they possess a swim bladder, and whether it is involved in its hearing; a group for fish eggs and larvae is also included. The guidance also gives specific criteria (as both unweighted SPL_{peak} and unweighted SEL_{cum} values) for a variety of noise sources. A further set of criteria also exists for turtles, which have not been included as part of this study as they are not in sufficient abundance at the site to warrant detailed assessment.

A specific set of criteria for explosions (covering UXO detonation), pile driving (covering impact piling for WTG foundations) and continuous noise sources (covering all other noise sources considered in this study) are available in Popper *et al.* (2014) which have been considered in this study; these are summarised in Table 2-4 to Table 2-6.

Type of animal	Mortality and potential mortal injury
<i>Fish: no swim bladder</i>	229 – 234 dB peak
<i>Fish: swim bladder is not involved in hearing</i>	229 – 234 dB peak
<i>Fish: swim bladder involving in hearing</i>	229 – 234 dB peak
<i>Eggs and larvae</i>	> 13 mm s ⁻¹ peak velocity

Table 2-4 Criteria for potential mortal injury in species of fish from explosions (Popper et al., 2014).

Type of animal	Mortality and potential mortal injury	Impairment	
		Recoverable injury	TTS
<i>Fish: no swim bladder</i>	> 219 dB SEL _{cum} > 213 dB peak	> 216 dB SEL _{cum} > 213 dB peak	>> 186 dB SEL _{cum}
<i>Fish: swim bladder is not involved in hearing</i>	210 dB SEL _{cum} > 207 dB peak	203 dB SEL _{cum} > 207 dB peak	> 186 dB SEL _{cum}
<i>Fish: swim bladder involving in hearing</i>	207 dB SEL _{cum} > 207 dB peak	203 dB SEL _{cum} > 207 dB peak	186 dB SEL _{cum}
<i>Eggs and larvae</i>	210 dB SEL _{cum} > 207 dB peak	See Table 2-8	See Table 2-8

Table 2-5 Criteria for potential mortal injury, recoverable injury and TTS in species of fish from pile driving noise sources (Popper et al., 2014).

Type of animal	Impairment	
	Recoverable injury	TTS
<i>Fish: swim bladder involving in hearing</i>	170 dB RMS for 48 hrs	158 dB RMS For 12 hrs

Table 2-6 Criteria for recoverable injury and TTS in species of fish from continuous noise sources (Popper et al., 2014).

Where insufficient data are available, Popper et al. (2014) also gives qualitative criteria that summarise the effect of the noise as having either a high, moderate or low effect on an individual in either the near-field (tens of metres), intermediate-field (hundreds of metres), or far-field (thousands of metres). These qualitative effects are reproduced in Table 2-7 to Table 2-9.

Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
<i>Fish: no swim bladder</i>	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) Moderate (F) Low
<i>Fish: swim bladder is not involved in hearing</i>	(N) High (I) High (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) High (F) Low
<i>Fish: swim bladder involving in hearing</i>	(N) High (I) High (F) Low	(N) High (I) High (F) Low	N/A	(N) High (I) High (F) Low
<i>Eggs and larvae</i>	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low

Table 2-7 Summary of the qualitative effects on species of fish from explosions (Popper et al., 2014)
(N = Near-field; I = Intermediate-field; F = Far-field).

Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
<i>Fish: no swim bladder</i>	See Table 2-5	See Table 2-5	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
<i>Fish: swim bladder is not involved in hearing</i>	See Table 2-5	See Table 2-5	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
<i>Fish: swim bladder involving in hearing</i>	See Table 2-5	See Table 2-5	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
<i>Eggs and larvae</i>	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

Table 2-8 Summary of the qualitative effects on species of fish from pile driving (Popper *et al.*, 2014)
(N = Near-field; I = Intermediate-field; F = Far-field).

Type of animal	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
<i>Fish: no swim bladder</i>	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
<i>Fish: swim bladder is not involved in hearing</i>	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
<i>Fish: swim bladder involving in hearing</i>	(N) Low (I) Low (F) Low	See Table 2-6	See Table 2-6	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
<i>Eggs and larvae</i>	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

Table 2-9 Summary of the qualitative effects on fish from continuous noise from Popper *et al.* (2014)
(N = Near-field; I = Intermediate-field; F = Far-field).

As only SPL_{peak} and SPL_{RMS} criteria are presented for explosions and continuous noise sources in Popper *et al.* (2014), fleeing animal exposure calculations using SEL_{cum} for fish do not need to be considered.

2.2.2.3 Diving birds

As regular but intermittent users of the sea, diving birds are also potentially at risk of the adverse effects of noise. Although the greatest risk to birds from offshore wind farms is generally understood to be collision risk during the OWF's operational phase (e.g., Bailey *et al.*, 2014), the hearing ability of seabirds below the water is known but relatively little studied (Crowell *et al.*, 2015). Crowell *et al.* (2015) presented the hearing sensitivity of diving bird species including the red-throated loon, the northern gannet and a selection of ducks, which all showed greatest hearing sensitivity between 1,000 and 3,000 Hz using auditory brainstem response (ABR) techniques. Hansen *et al.* (2016) demonstrated a consistent reaction by the great cormorant to underwater sound stimuli.

Although their sensitivity to underwater sound is recognised, any risk of injury from noise to diving birds has not been identified or quantified. The key difference between the risk of noise exposure to diving birds compared with marine mammals is that birds are mainly in the air, and will be aware of the airborne component of a high noise source (e.g., impact piling, if present), which is likely to act as a deterrent, allowing a bird to rapidly flee an area to a significant distance much more quickly than a waterborne individual such as a marine mammal.

Due to the distances and noise levels involved, the risk of any direct impacts in the air (i.e., hearing damage) will be significantly lower than those present in the water. Birds are most sensitive to airborne noise when at roost and to some extent fixed. Offshore, birds will be continuously mobile and rapidly able to avoid any significant noise exposure in the air. As a consequence, any risk of significant impacts to seabirds from airborne noise is considered very unlikely.

In the event that a diving bird is underwater during generation of high noise levels, this will typically be for less than a minute, limiting their exposure. This assumes normal diving behaviour in seabirds present in European waters; it is expected that dives would be aborted in the presence in noise levels high enough to cause damage.

The construction of an offshore wind farm is more likely to cause disturbance to bird life than injury, with the presence of construction-related vessels likely to be disruptive and lead to avoidance behaviour in the immediate vicinity (Fox and Petersen, 2019). It is anticipated that prey species are also less likely to be present in the vicinity of OWF construction for the same reasons. Assessment of these effects is covered in detail by the marine ornithologists working on this project.

Noise levels in the vicinity of operational offshore wind turbines, above and below the water will be continuous and low-level (see section 3.4) and so this would present a very low risk of any injury from noise, and due to the short period of time to which a diving bird would be in the water, and the relatively low area that noise from an operational turbine would spread in the water, any impact to diving birds is expected to be negligible.

3 Modelling methodology

3.1 Introduction

Several approaches have been used to model the noise sources that are likely to be present during construction of the Erebus OWF. For all noise making activities (except UXO and impact piling), the modelling approach is based on directly measured data from Subacoustech Environmental's underwater noise measurement database. To model noise from UXO detonation, an approach based on equations from Soloway and Dahl (2014) is used. Subacoustech's INSPIRE noise model has been used to predicted noise from impact piling, which is discussed in greater detail in section 3.4.

The modelling methodologies used have all been presented and developed via consultations with the relevant statutory bodies. All consultations are summarised below in *Table 3-1*.

Consultee	Response	Applicant Action
NRW and JNCC, Erebus Underwater Noise Assessment Technical Note v1.0 (March 2021)	NRW advisory are content that the SPEAR and INSPIRE models provided are suitable for use for the types of noise sources identified, but further information is required to establish if the specific approach outlined in the Technical Note is appropriate. Information to be provided: - Details of the INSPIRE model and pile measurements - Rationale for modelling locations chosen and the directions noise propagation will be modelled - Clarification on the proposed approach for assessing UXO clearance - The 'preliminary desk-based study of UXO risk'	Meeting arranged to discuss the questions in more detail
Meeting to introduce the proposed approach to subsea noise assessment with NRW/JNCC/The Wildlife Trust in response to questions raised about the Technical Note (May 2021)	More information was required on the UXO worst case scenario modelled within the Greenlink ES. Clarification and confidence gained on both the INSPIRE and SPEAR model.	Greenlink ES modelled a 794 kg explosive. This could possibly be found within the St George's Channel area. The Project does not cross this channel but modelling results have been included for reference. Technical note to be updated as a result of discussions
Revised Technical Note issued to NRW/JNCC/The Wildlife Trusts v2.0 (May 2021)	Joint response from NRW and JNCC; - Welcome the comprehensive response from Subacoustech which has answered all our questions about INSPIRE; With regard to UXO: - NRW encourage the applicant to determine the	JNCC and NRW comments have been noted and have informed this Technical Report and Chapter 13: Marine Mammals.

	most proportionate precautionary approach given the risks associated with the project; - JNCC highlight that all projects carry a risk, and to provide appropriate and proportionate advice, we need to understand the degree of uncertainty when managing risks.	
Issued the draft Underwater Noise and Vibration Technical Report with NRW/JNCC (July 2021)	NRW: - The model used for some noise sources should be specified; - Clarity is needed on the location of the 794kg UXO in relation to the Erebus site boundary; - Additional information is needed to support the piling schedule used in modelling; - Evidence is required to support the position that identified operational noise from HYWIND OWF will not be present as Erebus OWF; - Evidence is required to support the position that spacing between turbines will prohibit any cumulative effects from operational noise	JNCC and NRW comments have been noted and have informed this Technical Report and Chapter 13: Marine Mammals. A meeting was also arranged with JNCC and NRW to further discuss the approach to deflagration.
Meeting with JNCC/NRW to discuss approach to deflagration modelling (August 2021)	Agreed that it is acceptable for the Project to re-run the UWN model looking at smaller charges as a proxy for deflagration and this will form the basis of the impact assessment for marine mammals and fish.	See Section 3.3

Table 3-1 Summary of consultation

The NPL Good Practice Guide 133 for underwater noise measurements (Robinson *et al.*, 2014) indicated that under certain circumstances, a simple modelling approach, such as those considered here for sources other than impact piling, may be considered acceptable. Such an approach has been used for these noise sources, which are variously either quiet compared to impact piling (e.g., drilling and cable laying) or where detailed modelling would imply unjustified accuracy (e.g., where data is limited such as with UXO detonation). The method of modelling that has been presented here is considered sufficient and there would be little benefit in undertaking a more detailed modelling approach. The limitations of this approach are noted, including the lack of frequency or bathymetric dependence, but are acceptable due to the relatively low noise levels produced by the non-impulsive noise sources.

3.2 Noise making activities (except UXO and impact piling)

Approximate subsea noise levels have been predicted for the proposed site activities (other than UXO clearance and impact piling, see the following sections) using a modelling approach based on measured data from Subacoustech Environmental's own underwater noise measurement database, scaled to

relevant parameters for the site and specific noise sources where a proxy has been used due to lack of data available. The calculation of underwater noise transmission loss for the non-impulsive sources is based on an empirical analysis of the noise measurements taken on transects around these sources by Subacoustech Environmental and uses the SPEAR model. The predictions use the following principle fitted to the measured data, where R is the range from the source, N is the transmission loss and α is the absorption loss:

$$\text{Source level (SL)} - N \log R - \alpha R$$

Noise modelling requires knowledge of the source level, which is the theoretical noise level at one metre from the noise source. It is worth noting that the “source level” concept technically does not exist in the context of many shallow water noise sources (Heaney *et al.* 2020). In practice, in underwater noise modelling, it is an ‘apparent source level’ and simply a value that can be used to produce correct noise levels at range (for a specific model), as required in impact assessments.

Predicted source levels and propagation calculations for the construction activities are presented below along with a summary of the number of datasets used in each case. These figures are presented in accordance with typical requests by regulatory authorities, although as noted above they are not necessarily compatible or comparable with any other model or predicted source levels.

It should be noted that the SPEAR modelling approach does not take bathymetry or other environmental conditions into account, and as such can be applied to any location in or around the Erebus site.

- Vessel movement – two groups of vessel noise have been considered, large and medium:
 - Large vessels
Source level: 168 dB re 1 μ Pa @ 1 m
Transmission loss: $12 \log R - 0.0021R$
Based on five datasets of large vessels including container ships, floating production storage and offloading vessels (FPSOs) and other vessels more than 100 m in length. Vessel speed assumed as 10 knots.
 - Medium vessels
Source level: 161 dB re 1 μ Pa @ 1 m
Transmission loss: $12 \log R - 0.0021R$
Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 10 knots.
- Seabed preparation – two types of dredging, backhoe and suction, have been modelled for seabed preparation:
 - Backhoe dredging
Source level: 165 dB re 1 μ Pa @ 1 m
Transmission loss: $19 \log R - 0.0009R$
Based on seven datasets from backhoe dredgers.
 - Suction dredging
Source level: 186 dB re 1 μ Pa @ 1 m
Transmission loss: $19 \log R - 0.0009R$
Based on five datasets from suction and cutter suction dredgers.

- Cable installation – noise from a cable laying vessel and trenching machinery have been considered to cover the noise from cable installation:
 - Cable laying
Source level: 171 dB re 1 μ Pa @ 1 m
Transmission loss: $13 \log R$ (no absorption)
Based on 11 datasets from a pipe laying vessel measuring 300 m in length; this is considered a worst-case noise source for cable laying operations.
 - Trenching
Source level: 172 dB re 1 μ Pa @ 1 m
Transmission loss: $13 \log R - 0.0004R$
Based on three datasets of measurements from trenching vessels more than 100 m in length.
- Cable protection – the noise from and associated with rock placement has been used to model cable protection:
 - Rock placement
Source level: 172 dB re 1 μ Pa @ 1 m
Transmission loss: $12 \log R - 0.0005R$
Based on four datasets from rock placement vessel 'Rollingstone.'
- Installation of drag embedment anchors:
Source level: 171 dB re 1 μ Pa @ 1 m
Transmission loss: $19 \log R - 0.0009R$
Based on two datasets excavator scraping noise, which would have a worst-case equivalence to the noise that could occur. As the anchors should be embedded in deep mud, this is expected to be highly precautionary. Vessel noise is likely to be the greatest noise source during this installation.
- Suction pile installation – limited data is available for the noise levels from suction pile installation. Underwater suction pumps are the primary source of noise:
Source level: 192 dB re 1 μ Pa @ 1 m
Transmission loss: $19 \log R - 0.0009R$
Based on a review by Koschinski and Lüdemann (2019), which states that the noise of suction pumps used at Borkum Riffgrund 2 could not be measured above background levels (137 dB) at a range of 750 m. Therefore, the estimated source level given here is highly precautionary.
- Drilling to install foundation piles:
Source level: 170.1 dB re 1 μ Pa @ 1 m
Transmission loss: $16 \log R - 0.0006R$
Based on seven datasets of offshore rotary drilling using a variety of drill sizes and powers. The modelling assumes a drill similar to a Wirth 818/2500/300, which is able to install piles of up to 2.5 m in diameter.

For SEL_{cum} calculations, the duration the noise is present is also considered, with all sources assumed to be operating for a worst-case 12 hours in any given 24-hour period, apart from vessel noise which is assumed to be present for 24 hours a day.

To account for the weightings required for modelling using the Southall *et al.* (2019) criteria (section 2.2.2.1), reductions in source level have been applied to the various noise sources. Table 3-2 presents details of the reductions in source levels for each of the weightings used for modelling.

Noise source	Reduction in source level from the unweighted level			
	LF	HF	VHF	PCW
Vessel movement	5.5 dB	34.4 dB	38.6 dB	17.4 dB
Dredging	2.5 dB	7.9 dB	9.6 dB	4.2 dB
Cable laying	3.6 dB	22.9 dB	23.9 dB	13.2 dB
Trenching	4.1 dB	23.0 dB	25.0 dB	13.7 dB
Rock placement	1.6 dB	11.9 dB	12.5 dB	8.2 dB
Drag embedment anchors	2.5 dB	7.9 dB	9.6 dB	4.2 dB
Suction pile installation	2.5 dB	7.9 dB	9.6 dB	4.2 dB
Drilling	4.0 dB	25.8 dB	28.4 dB	13.2 dB

Table 3-2 Reductions in source level for the different construction noise sources considered when the Southall *et al.* (2019) weightings are applied.

3.3 UXO detonation

It is possible that UXO devices with a range of charge weights (or quantity of contained explosive) may exist within the boundary of the Erebus OWF site. These need to be cleared before any construction can begin. There are expected to be a variety of explosive types, many of which have been subject to degradation and burying over time. Two otherwise identical explosive devices are likely to produce different blasts in the case where one has spent an extended period on the seabed. A selection of explosive sizes has been considered based on site surveys and with consultation with Statutory Bodies (Table 3-1). In each case, it has been assumed that the maximum explosive charge in each device is present and either detonates with the clearance (high-order) or alternatively a clearance method such as deflagration (low-order) can be used.

3.3.1 Estimation of underwater noise levels

3.3.1.1 High order clearance

The noise produced by the detonation of explosives is affected by several different elements, only one of which can easily be factored into a calculation: the charge weight. In this case the charge weight is based in the equivalent weight of TNT. Many other elements relating to its situation (e.g., its design, composition, age, position, orientation, whether it is covered by sediment) and exactly how they will affect the sound produced by detonation are usually unknown and cannot be directly considered in this type of assessment. This leads to a high degree of uncertainty in the estimation of the source noise level. A worst-case estimation has therefore been used for calculations, assuming the UXO to be detonated is not buried, degraded or subject to any other significant attenuation from its “as new” condition. It assumes that a ‘high-order’ clearance technique is used, using an external ‘donor charge’ initiator to detonate the explosive material in the UXO, producing a blast wave equivalent to full detonation of the device.

The consequence of this is that the noise levels produced, particularly by the larger explosives under consideration, are likely to be over-estimated as some degree of degradation would be expected.

Within the equivalent assessment commissioned by Greenlink Interconnector Limited's and provided in support of their Marine Licence application, a 794 kg TNT equivalent charge weight had the potential of being present in a WWII minefield in St George's Channel. Although this location is circa 4 km from the Project array area, and following consultations with statutory bodies, for completeness/consistency this charge weight has been included within the current assessment. The site specific UXO Threat and

Risk Assessment Report carried out for Erebus (6 Alpha Associates, 2020) concluded that such charge weights are not likely to be encountered and that the maximum realistic worst case charge weight that can be expected to be presented in the Erebus study area is 331 kg (ferrous mass). As such, modelling results for the 794 kg scenario are provided for contextual information only, as discussed with NRW and JNCC during meeting dated 11 August 2021 (referenced in Table 3-1)..

Estimation of the source noise level for each charge weight has been carried out in accordance with the methodology of Soloway and Dahl (2014), which follows Arons (1954) and MTD (1996).

3.3.1.2 Low order clearance or deflagration

Other techniques are being considered to reduce the impact of noise impacts from high order UXO clearance, caused by detonation of the main charge of the UXO. Deflagration is such an alternative technique, intended to result in a 'low order' burn of the explosive material in a UXO, which destroys but does not detonate the internal explosive.

Deflagration is a safer technique for UXO disposal as it is intended to avoid the high pressures associated with an explosion, which would lead to an increased risk of adverse effects to marine life. Where the UXO device cannot be moved, deflagration represents the best-case scenario in respect to environmental effects.

Where the technique proceeds as intended, it is still not without noise impact. The process requires an initial shaped explosive charge, typically less than 250g, to breach the casing and ignite the internal high explosive (HE) material without full detonation. The shaped charge and burn will both produce noise, although it will be significantly less than the high order detonation of the much larger UXO. It may not destroy all of the HE, necessitating further deflagration events or collection of the remnants. The deflagration may produce an unintentional high order event.

For calculation of the scenario of total destruction of the HE material using deflagration, it is anticipated that the initial shaped charge is the greatest source of noise (Cheong *et al.* 2020). The shaped charge is treated as a bulk charge with NEQ determined according to the size of UXO on which it is placed. A prediction of this impact is based on a charge weight of 2 kg, which is larger than that which would reasonably be expected for deflagration or similar techniques (up to 250 grams as noted above) but represents a high-end scenario for deflagration. The worst-case scenario would of course be a high order detonation with maximum pressures from complete detonation of the UXO, and this has also been used in the calculation of impact for comparison.

3.3.2 Estimation of underwater noise propagation

For this assessment, the attenuation of the noise from UXO detonation has been accounted for in calculations using geometric spreading and a sound absorption coefficient, primarily using the methodologies cited in Soloway and Dahl (2014), which establishes a trend based on measured data in open water. These are, for SPL_{peak} :

$$SPL_{peak} = 52.4 \times 10^6 \left(\frac{R}{W^{1/3}} \right)^{-1.13}$$

and for SEL_{ss}

$$SEL = 6.14 \times \log_{10} \left(W^{1/3} \left(\frac{R}{W^{1/3}} \right)^{-2.12} \right) + 219$$

where W is the equivalent charge weight for TNT in kilograms and R is the range from the source.

These equations give a relatively simple calculation which can be used to give an indication of the range of effect. The equation does not consider variable bathymetry or seabed type, and thus calculation

results will be the same regardless of where it is used. An attenuation correction can be added to the Soloway and Dahl (2014) equations for the absorption over long ranges (i.e., of the order of thousands of metres), based on measurements of high intensity noise propagation taken in the North and Irish Seas in similar depths to those present at Erebus. In order to best accommodate the effect on noise transmission over longer ranges, an additional term was included in Subacoustech's calculations for sound absorption in seawater, α , in decibels per meter, without which a substantial overestimate for the noise level at long range would be expected. This figure is based on typical environmental conditions in the North Sea and the dominant frequency of sound seen by Subacoustech from UXO clearance in direct measurements.

Despite this attenuation correction, the resulting noise levels still need to be considered carefully. For example, SPL_{peak} noise levels over larger distances are difficult to predict accurately (von Benda-Beckmann *et al.*, 2015). Soloway and Dahl (2014) only verify results from the equation above for small charges at ranges of less than 1 km, although the results do agree with the measurements presented by von Benda-Beckmann *et al.* (2015). At longer ranges, greater confidence is expected with the SEL calculations.

A further limitation in the Soloway and Dahl (2014) equations that must be considered are that variations in noise levels at different depths are not considered. Where animals are swimming near the surface, the acoustics can cause the noise level, and hence the exposure, to be lower (MTD, 1996). The risk to animals near the surface may therefore be lower than indicated by the impact ranges and therefore the results presented can be considered conservative in respect of the impact on animals swimming near the water surface.

Additionally, an impulsive wave tends to be smoothed (i.e., the pulse becomes longer) over distance (Cudahy and Parvin, 2001, Hastie *et al.* 2019), meaning the injurious potential of a wave at greater range can be even lower than just a reduction in the absolute noise level. Research is ongoing on the use of kurtosis as a metric for assessment of impulsiveness in impact assessments (Muller *et al.* 2020). An assessment in respect of SEL is considered preferential at long range as it considers the overall energy, and the smoothing of the peak is less critical to the consideration of harm to a receptor.

The selection of assessment criteria must also be considered in light of this. As discussed in section 2.2.2.1, the smoothing of the pulse at range means that a pulse may be considered a non-pulse at greater distance. As there is still doubt in the transition point between pulse and non-pulse, and what the degree of benefit may be to a receptor from this characteristic, this study has presented impact ranges for only impulsive criteria. On this basis it should be expected that long-range PTS or TTS impact ranges (i.e., a minimum of 5 km from the pile) are likely to be highly precautionary.

A summary of the unweighted UXO source levels calculated using the equations above are given for high-order detonations in Table 3-3 and low-order clearances in Table 3-4.

Charge weight	25 kg	55 kg	120 kg	240 kg	525 kg	794 kg
SPL _{peak} source level (dB re 1 μ Pa @ 1 m)	284.9	287.4	290.0	292.2	294.8	296.2
SEL _{ss} source level (dB re 1 μ Pa ² s @ 1 m)	227.9	230.1	232.3	234.2	236.4	237.5

Table 3-3 Summary of the unweighted SPL_{peak} and SEL_{ss} source levels used for high-order UXO modelling.

Charge weight	0.1 kg	0.25 kg	0.5 kg	2.0 kg
SPL _{peak} source level (dB re 1 μ Pa @ 1 m)	266.8	269.8	272.1	276.6
SEL _{ss} source level (dB re 1 μ Pa ² s @ 1 m)	212.6	215.2	217.1	220.9

Table 3-4 Summary of the unweighted SPL_{peak} and SEL_{ss} source levels used for low-order UXO modelling.

As with the modelling for the other noise sources, when considering the Southall *et al.* (2019) criteria (section 2.2.2.1), weightings have been applied to the noise levels. Table 3-5 presents details of the reductions in source levels for each of the weightings used for the modelling.

Noise source	Reduction in source level from the unweighted level			
	LF	HF	VHF	PCW
UXO clearance	1.4 dB	28.9 dB	35.0 dB	9.2 dB

Table 3-5 Reductions in source level for UXO detonation when the Southall *et al.* (2019) weightings are applied.

3.4 Impact piling

It is possible that impact piling may be necessary for the installation of the mooring line anchors. The modelling of impact piling has been undertaken using the INSPIRE noise model. The INSPIRE model (currently version 5.1) is a semi-empirical underwater noise propagation model. It is based around a combination of numerical modelling, using a combined geometric and energy flow/hysteresis loss methodology, and actual measured data, and has been validated in Thompson *et al.* (2013). It is designed to calculate the propagation of noise in shallow, mixed water, typical of the conditions around the UK and well suited to the region surrounding the Erebus OWF. The model has been widely used in the consent phase for offshore wind projects around the UK and has been tuned for accuracy using over 80 datasets of underwater noise propagation from monitoring offshore piling activities, including in the Irish Sea.

The INSPIRE model estimates 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 two degrees). For each modelling run a criterion can be specified allowing a contour to be drawn, within which a given effect may occur. These results can then be plotted over digital bathymetry data so that impact ranges can be clearly visualised, as necessary. INSPIRE also produces these contours as GIS shapefiles.

INSPIRE considers a wide array of input parameters, including variations in bathymetry and source frequency content to ensure accurate results are produced specific to the location and nature of the piling operation. It should also be noted that the results presented in this study should be considered conservative as maximum design parameters and worst-case assumptions have been selected for:

- Piling hammer blow energies;
- Soft start, ramp-up profile, and strike rate;
- Total duration of piling; and

- Receptor swim speeds.

3.4.1 Modelling parameters

Modelling has been undertaken at two representative locations, covering the extents of the Erebus OWF, with the north-western (NW) and eastern (E) WTG locations chosen for modelling. These locations are shown in Figure 3-1 and summarised in Table 3-6.

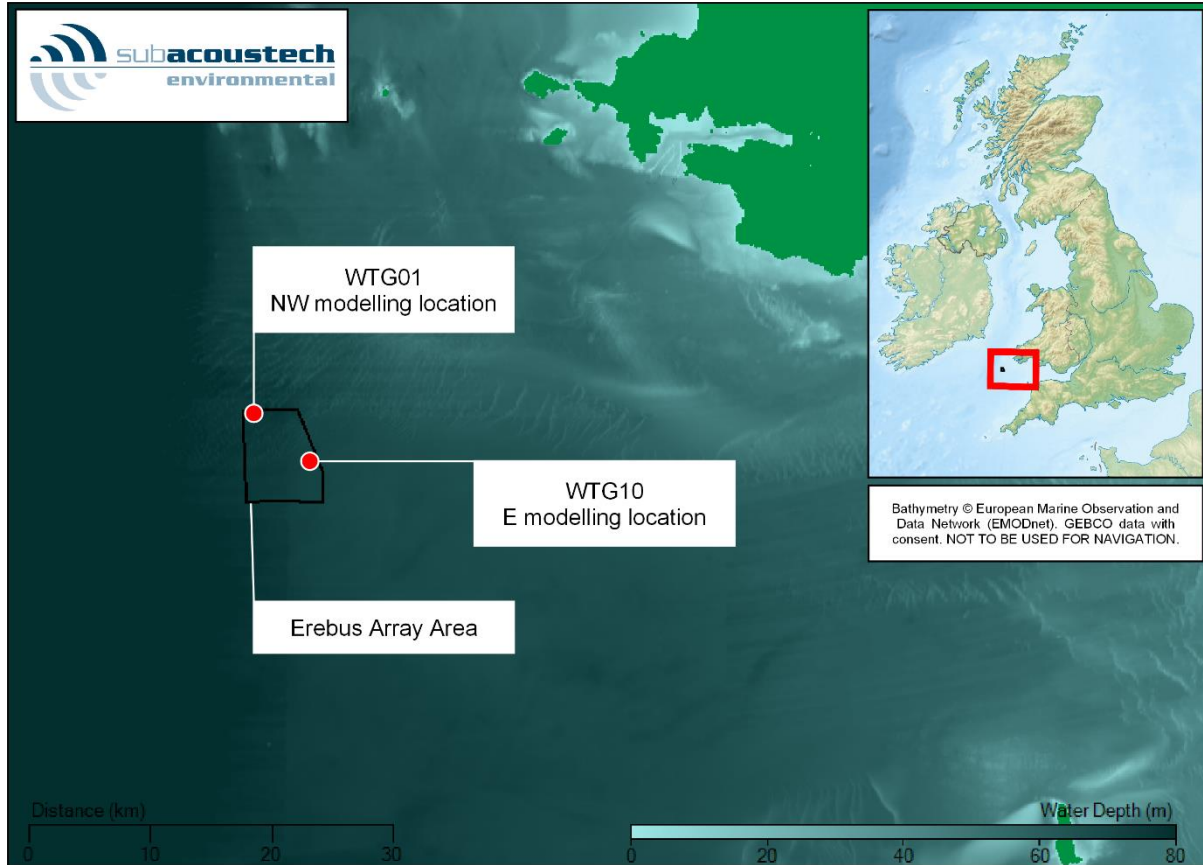


Figure 3-1 Map showing the approximate impact piling locations used for modelling

Modelling locations	WTG01 (NW)	WTG10 (E)
Latitude	51.4546 °N	51.4897 °N
Longitude	5.5682 °W	5.6329 °W
Water depth (mean tide)	70 m	75 m

Table 3-6 Summary of the underwater noise modelling locations at the Erebus OWF.

Two piling scenarios have been modelled including worst-case and most likely impact piling installation scenarios. Whereas the worst-case scenario utilises a layering of the most extreme parameters that could occur with the equipment expected to be used, the most likely scenario takes a realistic selection of parameters likely to occur in practice. For SEL_{cum} , the soft start and ramp-up of blow energies, along with the total duration and strike rate, must also be considered. These vary for the worst-case and most likely scenarios and are summarised in Table 3-7 and Table 3-8. Both are based on the installation of a pile up to 2.5 m in diameter. The main difference between the worst-case and most likely scenarios are that the most likely scenario uses lower blow energies and a lower overall number of strikes.

The parameters that will be used for this project will be within those seen previously on other projects, providing a great deal of confidence in the outputs without the need for extrapolation outside known ranges.

The modelled scenarios contain a total of 2,820 strikes over 114 minutes for each pile for the worst-case scenario and 2,340 strikes over 98 minutes for each pile for the most likely scenario. In both cases a maximum of two piles will be installed in any 24-hour period and only one pile will be driven at any one time (i.e., no concurrent piling).

	80 kJ	160 kJ	320 kJ	480 kJ	640 kJ	800 kJ
Number of strikes	300	150	150	150	150	1,920
Duration	30 mins	5 mins	5 mins	5 mins	5 mins	64 mins
Strikes per minute	10 str/min	30 str/min				

Table 3-7 Summary of the worst-case soft start and ramp-up scenario used for calculating SEL_{cum} for impact piling

	80 kJ	120 kJ	240 kJ	360 kJ	480 kJ	600 kJ
Number of strikes	300	150	150	150	150	1,440
Duration	30 mins	5 mins	5 mins	5 mins	5 mins	48 mins
Strikes per minute	10 str/min	30 str/min				

Table 3-8 Summary of the most likely soft start and ramp-up scenario used for calculating SEL_{cum} for impact piling

For impact piling, the INSPIRE model assumes that the noise source (the hammer striking the pile) acts as a single point, as it will appear at a distance. The source level is estimated based on the pile diameter and the blow energy imparted on the pile by the hammer. This is then adjusted depending on the water depth at the modelling location to allow for the length of the pile in contact with the water, which can affect the amount of noise that is transmitted from the pile into its surroundings. As described in section 3.2, technically a source level does not exist for piling in this situation and so this figure is effectively an 'apparent source level', critical to the operation of the model. The source levels are not necessarily compatible or comparable with any other model or predicted source levels.

The unweighted single strike SPL_{peak} and SEL_{ss} source levels estimated for impact piling are provided in Table 3-9. It should be noted that the differences between the source levels at the two locations are too small to be shown in the table due to the relative uniformity of the water depths at the source locations.

Source levels	Location	Worst-case 2.5 m / 800 kJ	Most Likely 2.5 m / 600 kJ
Unweighted SPL_{peak} (dB re 1 μ Pa @ 1 m)	WTG01 (NW)	236.9	217.4
	WTG10 (E)	236.9	217.4
Unweighted SEL_{ss} (dB re 1 μ Pa ² s @ 1 m)	WTG01 (NW)	235.3	216.0
	WTG10 (E)	235.3	216.0

Table 3-9 Summary of the unweighted SPL_{peak} and SEL_{ss} source levels used for modelling

3.5 Operational noise

The main source of underwater noise from operational WTGs will be mechanically generated vibration from the rotating machinery in the turbines, which is transmitted into the water column through the structure of the turbine tower and foundations (Nedwell *et al.*, 2003, Tougaard *et al.*, 2020). Noise levels generated above the water surface are low enough that no significant airborne sound will pass from the air to the water.

Tougaard *et al.* (2020) published a study investigating underwater noise data from 17 operational WTGs in Europe and at the United States, from 0.2 MW to 6.15 MW nominal power output. The paper identified the nominal power output and wind speed as the two primary driving factors for the underwater noise

generation. Although the datasets were acquired under different conditions, the authors devised a formula based on the published data for the operational wind farms, allowing a broadband noise level to be estimated based on the application of wind speed, turbine size (by nominal power output) and distance from the turbine:

$$L_{eq} = C + \alpha \log_{10} \left(\frac{\text{distance}}{100\text{m}} \right) + \beta \log_{10} \left(\frac{\text{wind speed}}{10 \text{ m/s}} \right) + \gamma \log_{10} \left(\frac{\text{turbine size}}{1 \text{ MW}} \right)$$

With C a fixed constant and the coefficients α , β and γ derived from the empirical data for the 17 datasets.

The turbine sizes proposed at Erebus are much larger than those used for the estimation above, with turbines of up to 18 MW being considered. The Erebus site is also situated in greater water depths than the sites in the Tougaard *et al.* study, so in theory this would suggest that sound would attenuate more slowly in this location than the mainly continental North Sea and coastally located wind farms. However, the turbine foundations and moorings at Erebus are of a different type to those in the Tougaard *et al.* (2020) study and this is likely to make a significant difference to the noise produced at source. Due to the lack of available information for the foundations and moorings at Erebus, using the data from Tougaard *et al.* (2020) gives a worst-case estimate for noise levels.

The noise source for most operational wind turbines is the radiating area of the foundation in the water. For a monopile, this is the surface area of the cylindrical pile in the water column. Other fixed foundations such as jacket or tripod foundations are more complex. The complexities of the acoustics in large structures such as any of these make it difficult to predict their effect on the noise output (Tougaard *et al.*, 2020).

The radiating area source for a floating turbine is limited to the weighted and buoyant section that rests beneath the sea surface; a significantly smaller area than a fixed turbine. With a much smaller radiating area, the noise is expected to be lower, with a reasonable assumption of equivalent sound generation within the turbine and transmission through the turbine tower.

Little empirical data exists for the operational noise data produced by floating wind turbines. Tougaard *et al.* (2020) and a similar study by Stöber and Thomsen (2021) did not include any floating designs. Measurements taken by Jasco Applied Science (Martin *et al.* 2011) of the HYWIND demonstrator west of Stavanger, Norway, showed broadband noise levels of the order of 120 dB SPL_{RMS} over an approximately 10-week period in June-August 2011 at 150 m from the turbine. However much of this was found to be influenced by ambient noise from existing shipping sources and none of the components of the noise relating to turbine operation appeared to exceed 110 dB at the monitoring location. It is worth noting that this is dominated by noise at low frequency (<100 Hz) and they differ negligibly from background noise over the long term at all measured frequencies up to approximately 16 kHz 1/3rd octave band. It is therefore likely that even if the noise measurement at the position near the turbine position was influenced by turbine noise, ambient noise levels will typically reach this level naturally. The turbine was a 2.3 MW design. While some monitoring data for floating projects do exist (Molinero, 2020), comparing potential noise levels to worst-case examples such as those from HYWIND are considered best practice for this study.

Using the Tougaard *et al.* (2020) calculator, an uplift of approximately 13 dB would apply to increase the sound output from a 2.3 MW turbine to an 18 MW turbine. This would suggest an upper limit of 118 dB SPL_{RMS} at 150 m from the largest proposed turbine at Erebus. At 10 m, this would be 145 dB SPL_{RMS}, or 122 dB at 100 m. Based on the criteria from Popper *et al.* (2014) for continuous noise, the TTS threshold of 158 dB SPL_{RMS} would require an individual to be much closer than 10 m for 12 hours continuously, which, for a source near the surface in depths of the order of 80 m would be very low risk. As studies have shown that fish populations have increased in the vicinity of offshore wind farms (Stenberg *et al.* 2015), there appears to be a negligible risk to fish from operational turbines.

To compare this to the relevant marine mammal impact thresholds in Southall *et al.* (2019 and 2007) requires the values to be presented in SEL. For continuous-type noise sources, a sound as a 1-second SPL_{RMS} (as described above) is roughly equivalent to an SEL over 1-second. An SPL_{RMS} for a continuous noise will remain the same over an extended period of time, where, as an exposure metric, SEL will increase with and is thus dependent on the time the exposure to the sound continues.

As an example, at an arbitrary 100 m from the turbine for an hour, a receptor would receive an unweighted 158 dB re 1 μPa^2s SEL. With weighting taken into account, this is still well below potentially injurious or TTS thresholds for any Southall *et al.* 2019 species group, and somewhat quieter than vessels at this range (see section 4.1 for continuous or non-pulsed noise).

Therefore, for noise from operational WTGs, TTS risk is small. Importantly this assumes a stationary animal model with an individual remaining within 100 m from a turbine for much more than a 1-hour period. This is a highly unlikely scenario; when the animal is able to move, the risk of direct harm from the noise is effectively negligible.

Multiple turbines operating simultaneously will each contribute to the underwater noise within the wind farm boundary. It has been shown that a receptor would need to remain very close (much less than 100 m) to a turbine over an extended period to have any risk of impact. At this range the closest turbine, combined with natural ambient noise, will be much louder than any other turbine in the wind farm. To give a numeric example, if the noise level was 122 dB SPL_{RMS} at 100 m from a turbine, and the next nearest turbine was separated by 1000 m (approximate minimum separation, actual separations vary between designs) then the predicted noise level contribution from the next turbine would be 23 dB lower, which combined would contribute less than 0.1 dB to the overall noise level from the closest turbine. At the centre-point between two turbines separated by 1000 m, the theoretical noise level would be under 110 dB, well below any impact threshold. The contribution to a receptor's total noise exposure from any other turbine will therefore be negligible.

3.6 Cable “snapping”

The availability of underwater noise-related data for operational noise from floating wind turbines is limited due to the relatively small number of turbines installed and generating offshore. Of those that have been installed, measurements taken by JASCO (2011) for Statoil presented underwater noise levels sampled at 150 m from the HYWIND 1 installation, off the coast of Norway. Measurements were taken in water depths of 200 m at 91 m off the seabed, approximately mid-depth.

As well as relatively low noise levels from the operational machinery in a variety of conditions (see Operational Noise in section 3.4), the measurements identified what appeared to be a “snapping” noise that were thought to be related to tension release in the mooring system, although this has not been verified. It is understood that the mooring cables are designed to be permanently in tension such that no line should ever go into slack, even in extreme conditions, partly to avoid the risk of entanglement of marine mammals (Statoil, 2015). If the cables are the source of the noise, this will be caused by the specific circumstances at the HYWIND 1 OWF: that is, the depth of water, length of cables in use, current and current fluctuations. The findings at HYWIND 1 were isolated, and it does not necessarily follow that this will occur at the Erebus OWF, but does not rule out the potential for it either. Unless there was further evidence that other floating turbine moorings, or some other noise source associated with the turbines, is shown to create this snap then it may be an anomaly or potentially even an artifact of the monitoring system.

According to Jasco (2011), up to 23 of these snaps were identified per day. Over the two months of monitoring undertaken by Jasco, less than 10 snaps (exceeding 160 dB SPL_{peak} at the measurement position, 150 m from the turbine) were identified on most days.

As the source of noise is unclear, its distance from the monitor cannot be ascertained and thus a prediction of the noise closer to the source is not possible for estimation of PTS in terms of SPL_{peak} .

Subsequent analysis of the HYWIND 1 data by Xodus (2015) for the HYWIND Scotland Pilot Park Project predicted a potential cumulative SEL of up to 157 dB re 1 $\mu\text{Pa}^2\text{s}$ over 24 hours caused by snapping chains from six turbines; the equivalent for ten would be approximately 160 dB SEL re 1 $\mu\text{Pa}^2\text{s}$. This prediction makes a series of worst-case assumptions (e.g., all turbines producing the maximum number of snaps in a day, equivalent noise levels from multiple locations affecting a receptor to the same degree) and this level is below any PTS or injury criteria to marine mammals or fish.

There are no reliable noise thresholds that would be recommended to identify disturbance for rare/intermittent impulses of this type. As any snapping occurs at an average rate of less than one snap per hour, disturbance leading to avoidance behaviour is considered unlikely.

4 Modelling results

The following sections present the modelling outputs for the various noise sources being considered including vessel movement, suction pile installation, seabed preparation and protection, cable installation, drag embedment anchor installation, drilling for the installation of foundation piles (all in section 4.1), UXO detonation (in section 4.2), and impact piling (in section 4.3).

4.1 Noise making activities

Table 4-1 to Table 4-5 summarise the predicted impact ranges for the noise sources covered in section 3.2. It is worth noting that Southall *et al.* (2019) and Popper *et al.* (2014) give different criteria for non-impulsive or continuous noise sources compared to impulsive noise (see section 2.2.2); all sources in this section are considered non-pulse or continuous.

Given the modelled impact ranges, assuming a fleeing animal, it is calculated that any marine mammal would have to be less than 10 m from the continuous noise source at the start of the activity to acquire the necessary exposure to induce PTS as per Southall *et al.* (2019). The exposure calculations assume the fleeing receptor swim speeds detailed in section 2.2.2.1.

It should also be noted that the ranges presented in Table 4-1 and Table 4-2 would only mean that the receptor reaches the 'onset' stage if it were to begin fleeing from that point at the start of piling, which is the minimum exposure that could potentially lead to the start of an effect and may only be marginal. In most hearing groups, the noise levels are low enough that there is negligible risk.

The calculated ranges for stationary marine mammals are larger than those predicted for fleeing animals, with PTS ranges increasing to a maximum of 820 m for VHF cetaceans for noise from suction pile installation. However, as noted in section 2.2.2.1 and 3.2 both the assumptions made for a stationary receptor and the source level estimate for suction pile installation make these calculated ranges precautionary.

For fish, there is a low to negligible risk of any injury or TTS in line with the SPL_{RMS} guidance for continuous noise sources in Popper *et al.* (2014).

The modelling is presented as an unweighted SPL_{RMS} level against range plot in Figure 4-1.

Southall <i>et al.</i> (2019) Weighted SEL _{cum}	PTS (Fleeing)			
	199 dB (LF)	198 dB (HF)	173 dB (VHF)	201 dB (PCW)
Vessel movement (large)	< 10 m	< 10 m	< 10 m	< 10 m
Vessel movement (medium)	< 10 m	< 10 m	< 10 m	< 10 m
Backhoe dredging	< 10 m	< 10 m	< 10 m	< 10 m
Suction dredging	< 10 m	< 10 m	< 10 m	< 10 m
Cable laying	< 10 m	< 10 m	< 10 m	< 10 m
Trenching	< 10 m	< 10 m	< 10 m	< 10 m
Rock placement	< 10 m	< 10 m	< 10 m	< 10 m
Drag embedment anchors	< 10 m	< 10 m	< 10 m	< 10 m
Suction pile installation	< 10 m	< 10 m	< 10 m	< 10 m
Drilling	< 10 m	< 10 m	< 10 m	< 10 m

Table 4-1 Summary of the impact ranges for the different construction noise sources using the non-impulsive PTS criteria from Southall *et al.* (2019) for marine mammals assuming a fleeing receptor

Southall et al. (2019) Weighted SEL _{cum}	TTS (Fleeing)			
	179 dB (LF)	178 dB (HF)	153 dB (VHF)	181 dB (PCW)
Vessel movement (large)	< 10 m	< 10 m	< 10 m	< 10 m
Vessel movement (medium)	< 10 m	< 10 m	< 10 m	< 10 m
Backhoe dredging	< 10 m	< 10 m	< 10 m	< 10 m
Suction dredging	< 10 m	< 10 m	230 m	< 10 m
Cable laying	< 10 m	< 10 m	< 10 m	< 10 m
Trenching	< 10 m	< 10 m	< 10 m	< 10 m
Rock placement	< 10 m	< 10 m	990 m	< 10 m
Drag embedment anchors	< 10 m	< 10 m	< 10 m	< 10 m
Suction pile installation	< 10 m	< 10 m	780 m	< 10 m
Drilling	< 10 m	< 10 m	< 10 m	< 10 m

Table 4-2 Summary of the impact ranges for the different construction noise sources using the non-impulsive TTS criteria from Southall et al. (2019) for marine mammals assuming a fleeing receptor.

Southall et al. (2019) Weighted SEL _{cum}	PTS (Stationary)			
	199 dB (LF)	198 dB (HF)	173 dB (VHF)	201 dB (PCW)
Vessel movement (large)	10 m	< 10 m	< 10 m	< 10 m
Vessel movement (medium)	< 10 m	< 10 m	< 10 m	< 10 m
Backhoe dredging	< 10 m	< 10 m	< 10 m	< 10 m
Suction dredging	40 m	30 m	400 m	30 m
Cable laying	10 m	< 10 m	40 m	< 10 m
Trenching	20 m	< 10 m	40 m	< 10 m
Rock placement	30 m	< 10 m	530 m	< 10 m
Drag embedment anchors	< 10 m	< 10 m	70 m	< 10 m
Suction pile installation	90 m	50 m	820 m	60 m
Drilling	< 10 m	< 10 m	< 10 m	< 10 m

Table 4-3 Summary of the impact ranges for the different construction noise sources using the non-impulsive PTS criteria from Southall et al. (2019) for marine mammals assuming a stationary receptor.

Southall et al. (2019) Weighted SEL _{cum}	TTS (Stationary)			
	179 dB (LF)	178 dB (HF)	153 dB (VHF)	181 dB (PCW)
Vessel movement (large)	480 m	< 10 m	140 m	40 m
Vessel movement (medium)	130 m	< 10 m	30 m	< 10 m
Backhoe dredging	20 m	20 m	30 m	< 10 m
Suction dredging	460 m	280 m	3.3 km	300 m
Cable laying	480 m	20 m	1.3 km	60 m
Trenching	500 m	20 m	1.2 km	< 10 m
Rock placement	1.3 km	230 m	9.9 km	270 m
Drag embedment anchors	60 m	70 m	690 m	20 m
Suction pile installation	930 m	570 m	5.6 km	610 m
Drilling	130 m	< 10 m	160 m	30 m

Table 4-4 Summary of the impact ranges for the different construction noise sources using the non-impulsive TTS criteria from Southall et al. (2019) for marine mammals assuming a stationary receptor.

Popper et al. (2014) Unweighted SPL _{RMS}	Recoverable injury 170 dB (48 hours)	TTS 158 dB (12 hours)
Vessel movement (large)	< 10 m	< 10 m
Vessel movement (medium)	< 10 m	< 10 m
Backhoe dredging	< 10 m	< 10 m
Suction dredging	< 10 m	30 m
Cable laying	< 10 m	10 m
Trenching	< 10 m	10 m
Rock placement	< 10 m	20 m
Drag embedment anchors	< 10 m	< 10 m
Suction pile installation	20 m	60 m
Drilling	< 10 m	< 10 m

Table 4-5 Summary of the impact ranges from Popper et al. (2014) for shipping and continuous noise, covering the different construction noise sources for fish (swim bladder involved in hearing).

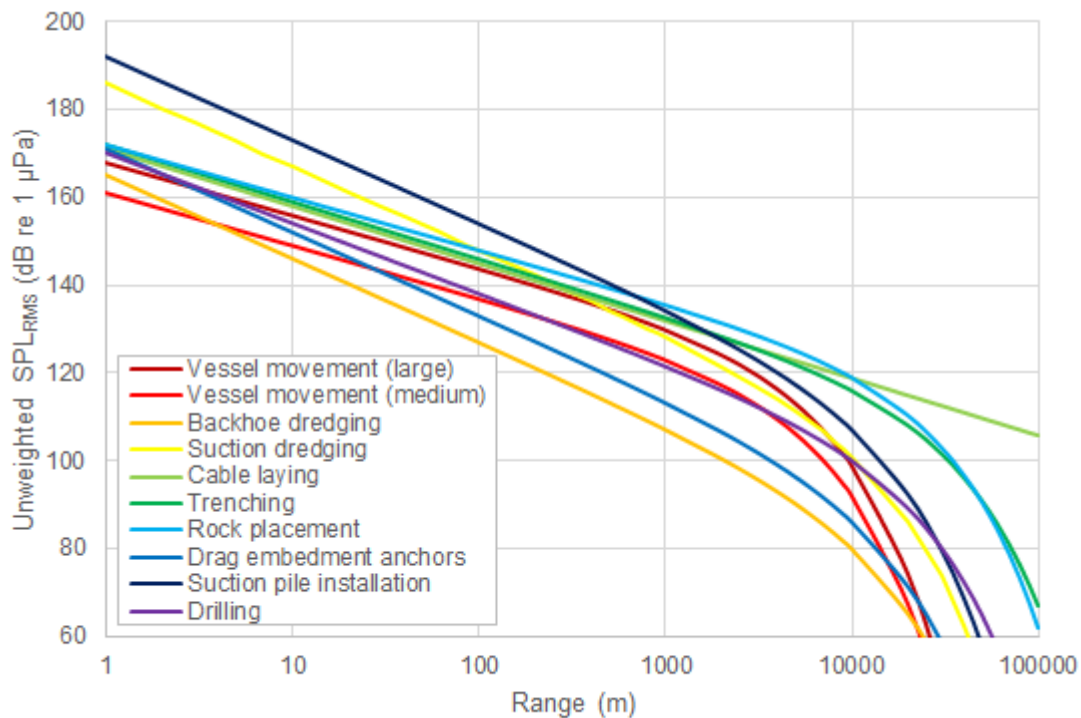


Figure 4-1 Unweighted SPL_{RMS} against range plots for the modelled noise sources.

4.2 UXO detonation

Table 4-6 to Table 4-8 present the impact ranges for both high-order and low-order UXO detonation or clearance, considering various charge weights and impact criteria. It should be noted that Popper *et al.* (2014) gives specific impact criteria for explosions (Table 2-4). A UXO detonation source is defined as a single pulse, and as such the SEL_{cum} criteria from Southall *et al.* (2019) have been given as SEL_{ss} in the tables below, thus, fleeing animal assumptions do not apply.

4.2.1 High-order detonation

The maximum PTS range calculated here for UXO is 15 km for the VHF cetacean category, based on the unweighted SPL_{peak} criteria. For SEL_{ss} criteria, the largest PTS range is calculated for LF cetaceans with a predicted impact of 12 km using the impulsive SEL_{ss} criteria. As explained earlier, this assumes no degradation of the UXO and no smoothing of the pulse over that distance, which is very precautionary. Although an assumption of non-pulse would under-estimate the potential impact (Martin *et al.* 2020) (the equivalent range based on LF cetacean non-pulse criteria is 700 m), it is likely that the long-range smoothing of the pulse peak would reduce its potential harm and the maximum 'impulsive' range for all species is very precautionary and unlikely in practice.

The modelling is presented as unweighted SPL_{peak} and single-pulse unweighted SELs against range in Figure 4-2 and Figure 4-3.

Southall <i>et al.</i> (2019) Unweighted SPL _{peak}		25 kg (NEQ)	55 kg (NEQ)	120 kg (NEQ)	240 kg (NEQ)	525 kg (NEQ)	794 kg (NEQ)
PTS	219 dB (LF)	810 m	1.0 km	1.3 km	1.7 km	2.2 km	2.5 km
	230 dB (HF)	260 m	340 m	450 m	560 m	730 m	840 m
	202 dB (VHF)	4.6 km	6.0 km	7.7 km	9.8 km	13 km	15 km
	218 dB (PCW)	900 m	1.1 km	1.5 km	1.9 km	2.5 km	2.8 km
TTS	213 dB (LF)	1.5 km	1.9 km	2.5 km	3.2 km	4.1 km	4.7 km
	224 dB (HF)	490 m	640 m	830 m	1.0 km	1.3 km	1.5 km
	196 dB (VHF)	8.5 km	11 km	14 km	18 km	23 km	27 km
	212 dB (PCW)	1.6 km	2.1 km	2.8 km	3.5 km	4.6 km	5.2 km

Table 4-6 Summary of the PTS and TTS impact ranges for high-order UXO detonation using the impulsive, unweighted SPL_{peak} noise criteria from Southall *et al.* (2019) for marine mammals.

Southall <i>et al.</i> (2019) Weighted SEL _{ss}		25 kg (NEQ)	55 kg (NEQ)	120 kg (NEQ)	240 kg (NEQ)	525 kg (NEQ)	794 kg (NEQ)
PTS (Impulsive)	183 dB (LF)	2.1 km	3.2 km	4.6 km	6.5 km	9.5 km	12 km
	185 dB (HF)	10 m	20 m	30 m	40 m	50 m	60 m
	155 dB (VHF)	560 m	740 m	950 m	1.1 km	1.4 km	1.6 km
	185 dB (PCW)	380 m	560 m	830 m	1.1 km	1.6 km	2.0 km
TTS (Impulsive)	168 dB (LF)	29 km	41 km	57 km	76 km	103 km	121 km
	170 dB (HF)	150 m	210 m	300 m	390 m	530 m	620 m
	140 dB (VHF)	2.4 km	2.8 km	3.2 km	3.5 km	4.0 km	4.2 km
	170 dB (PCW)	5.2 km	7.4 km	11 km	14 km	20 km	23 km

Table 4-7 Summary of the PTS and TTS impact ranges for high-order UXO detonation using the impulsive, weighted SEL_{ss} noise criteria from Southall *et al.* (2019) for marine mammals.

Popper <i>et al.</i> (2014) Unweighted SPL _{peak}		25 kg (NEQ)	55 kg (NEQ)	120 kg (NEQ)	240 kg (NEQ)	525 kg (NEQ)	794 kg (NEQ)
234 dB (Mortality and potential mortal injury)		170 m	230 m	290 m	370 m	490 m	560 m
229 dB (Mortality and potential mortal injury)		290 m	380 m	490 m	620 m	810 m	930 m

Table 4-8 Summary of the impact ranges for high-order UXO detonation using the unweighted SPL_{peak} explosion noise criteria from Popper *et al.* (2014) for species of fish.

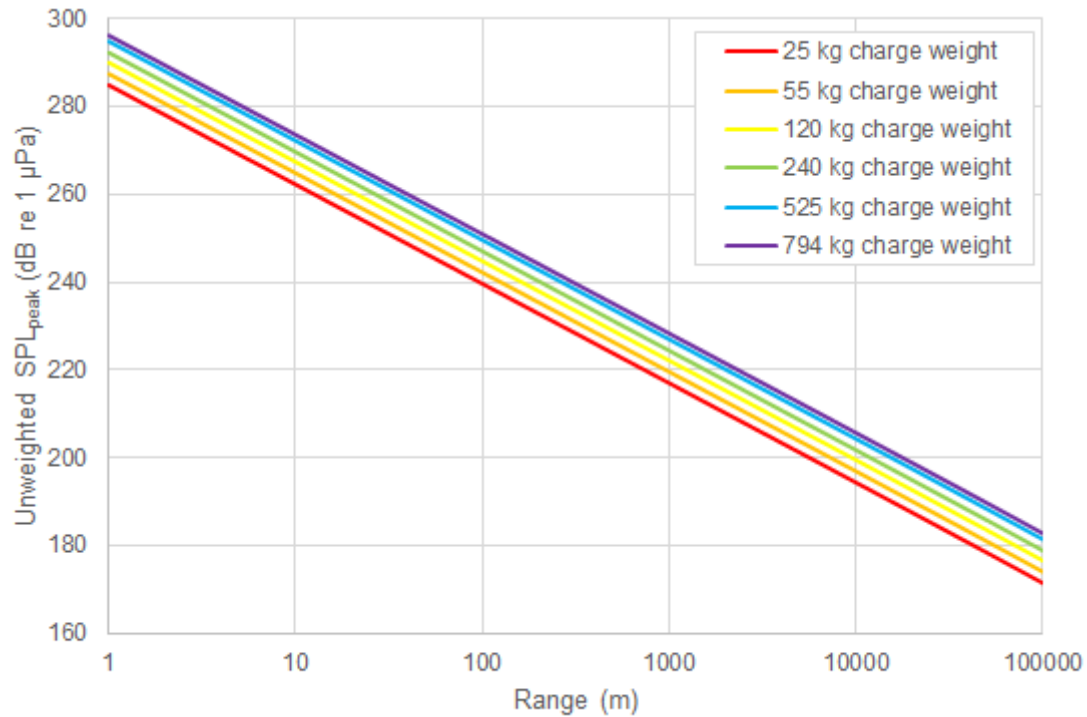


Figure 4-2 Unweighted SPL_{peak} against range plots for the modelled UXO detonation (TNT equivalent) charge weights.

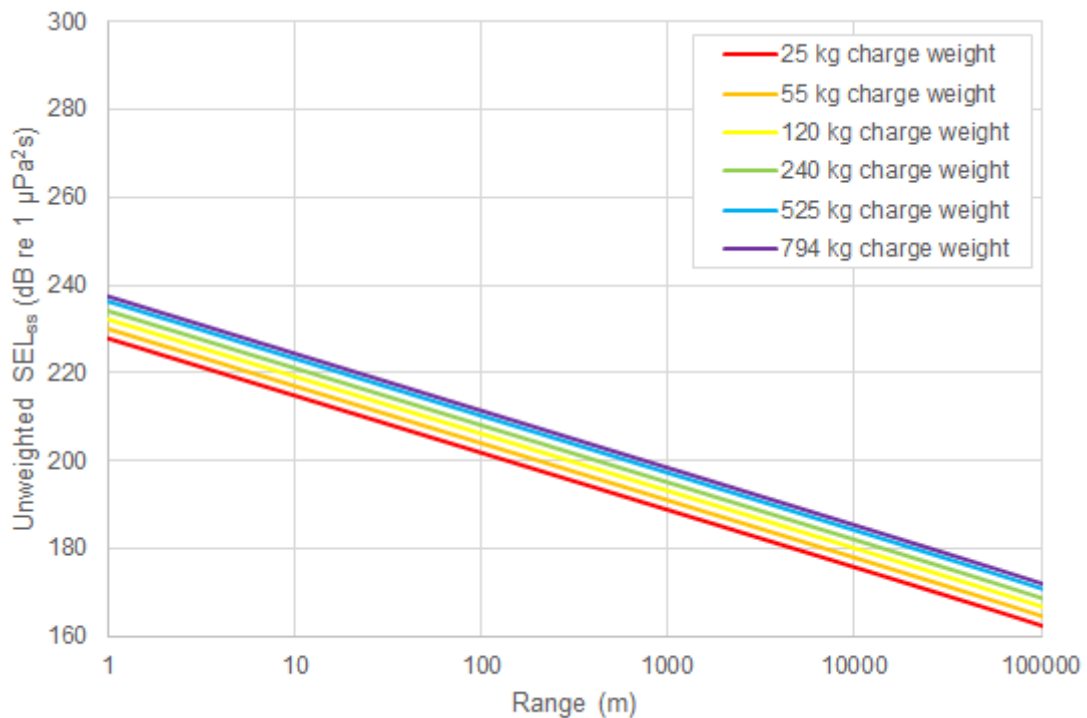


Figure 4-3 Unweighted single-strike SEL_{ss} against range plots for the modelled UXO detonation (TNT equivalent) charge weights.

4.2.2 Low-order clearance

The impact ranges provided below assume a low-order deflagration event for UXO disposal, which involves a much smaller charge than would be necessary for a high-order detonation. Again, a series of charge weights are provided, from 0.1 kg to 2.0 kg, although it is expected that 0.25 kg would represent the most likely maximum size of charge weight used for the initiating device.

The calculated ranges in respect of the Southall *et al.* (2019) criteria are provided in Table 4-9 and Table 4-10, and the results to Popper *et al.* (2014) criteria are given in Table 4-11.

Southall <i>et al.</i> (2019) Unweighted SPL _{peak}		0.1 kg (NEQ)	0.25 kg (NEQ)	0.5 kg (NEQ)	2.0 kg (NEQ)
PTS	219 dB (LF)	130 m	170 m	220 m	350 m
	230 dB (HF)	40 m	60 m	70 m	110 m
	202 dB (VHF)	730 m	990 m	1.2 km	1.9 km
	218 dB (PCW)	140 m	190 m	240 m	390 m
TTS	213 dB (LF)	230 m	320 m	410 m	650 m
	224 dB (HF)	80 m	100 m	130 m	210 m
	196 dB (VHF)	1.3 km	1.8 km	2.3 km	3.6 km
	212 dB (PCW)	260 m	360 m	450 m	720 m

Table 4-9 Summary of the PTS and TTS impact ranges for low-order UXO clearance using the impulsive, unweighted SPL_{peak} noise criteria from Southall *et al.* (2019) for marine mammals.

Southall <i>et al.</i> (2019) Weighted SEL _{ss}		0.1 kg (NEQ)	0.25 kg (NEQ)	0.5 kg (NEQ)	2.0 kg (NEQ)
PTS (Impulsive)	183 dB (LF)	140 m	230 m	320 m	630 m
	185 dB (HF)	<10 m	<10 m	<10 m	<10 m
	155 dB (VHF)	50 m	80 m	110 m	200 m
	185 dB (PCW)	30 m	40 m	60 m	110 m
TTS (Impulsive)	168 dB (LF)	2.0 km	3.2 km	4.5 km	8.8 km
	170 dB (HF)	10 m	20 m	30 m	50 m
	140 dB (VHF)	540 m	750 m	930 m	1.3 km
	170 dB (PCW)	360 m	570 m	800 m	1.5 km

Table 4-10 Summary of the PTS and TTS impact ranges for low-order UXO clearance using the impulsive, weighted SEL_{ss} noise criteria from Southall *et al.* (2019) for marine mammals.

Popper <i>et al.</i> (2014) Unweighted SPL _{peak}	0.1 kg (NEQ)	0.25 kg (NEQ)	0.5 kg (NEQ)	2.0 kg (NEQ)
234 dB (Mortality and potential mortal injury)	30 m	40 m	50 m	80 m
229 dB (Mortality and potential mortal injury)	50 m	70 m	80 m	120 m

Table 4-11 Summary of the impact ranges for low-order UXO clearance using the unweighted SPL_{peak} explosion noise criteria from Popper *et al.* (2014) for species of fish.

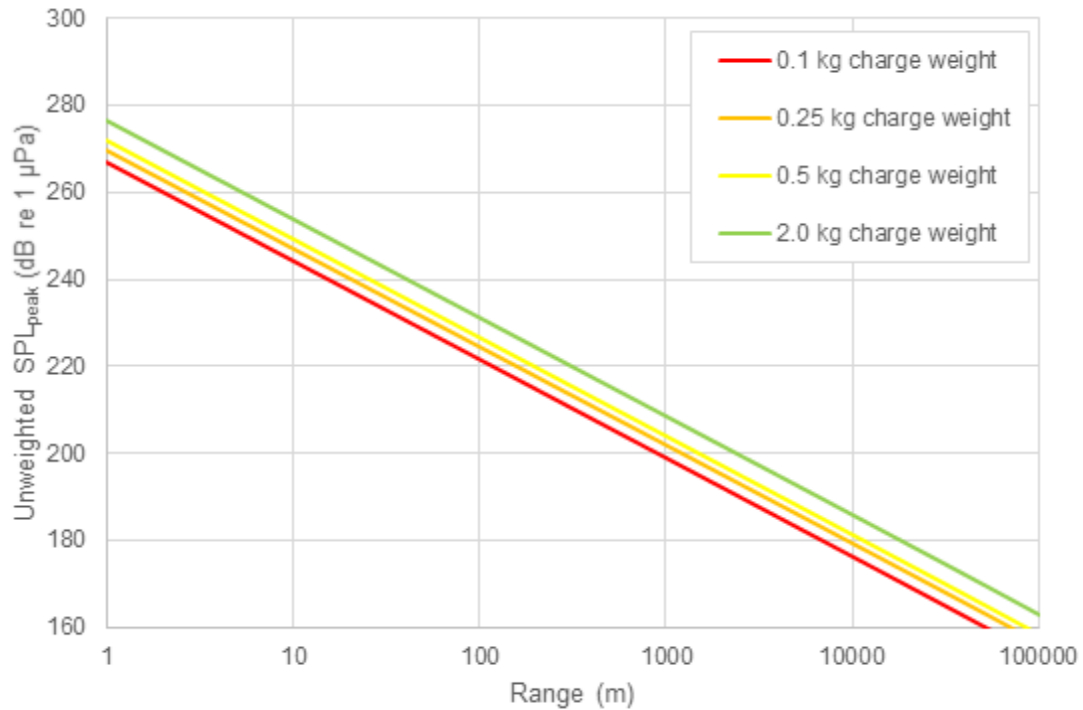


Figure 4-4 Unweighted SPL_{peak} against range plots for the modelled low-order UXO clearance (TNT equivalent) charge weights.

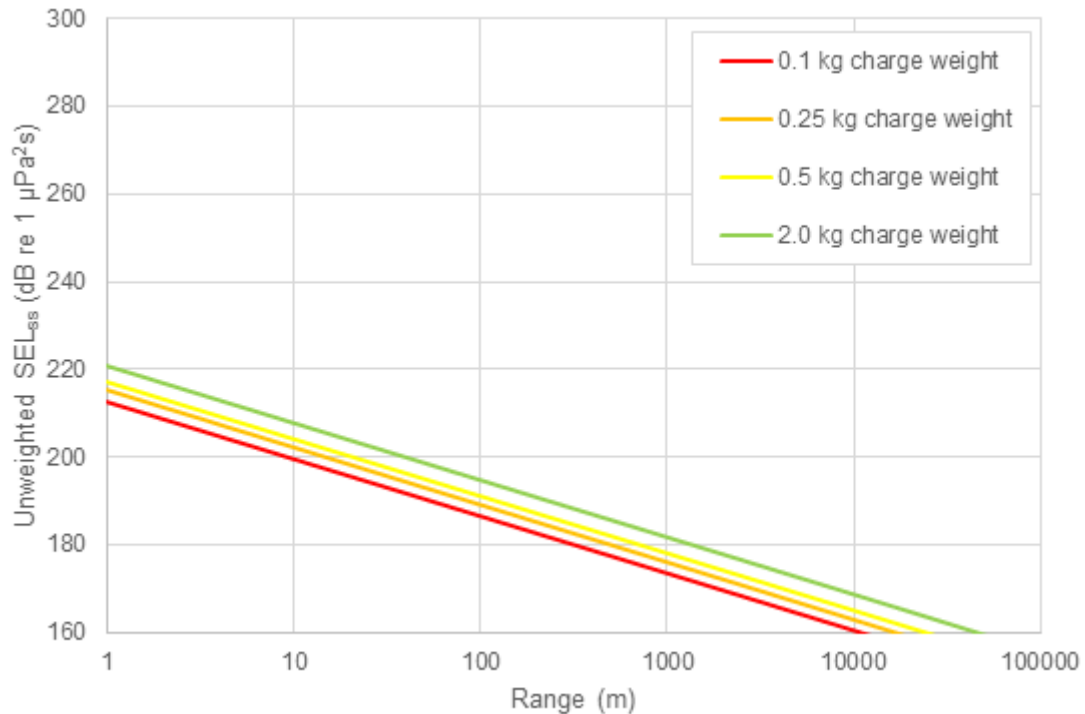


Figure 4-5 Unweighted single-strike SEL_{ss} against range plots for the modelled low-order UXO clearance (TNT equivalent) charge weights.

4.3 Impact piling

The following sections present the modelled impact ranges for the impact piling scenarios detailed in section 3.4.1 and calculated using the INSPIRE model. For the results in this section, predicted ranges smaller than 50 m and areas less than 0.01 km² for single strike criteria, and ranges smaller than 100 m and areas less than 0.1 km² for cumulative criteria, have not been presented. This close to the noise source, the modelling processes are unable to model a sufficient level of accuracy due to the complexity of the acoustic effects near the pile.

The largest ranges are predicted for the worst-case parameters, due to the larger blow energies and greater number of pile strikes. Results were identical for the unweighted SPL_{peak} criteria at the two modelled locations, with the WTG10 (E) location producing the largest SEL_{cum} ranges due to the slightly deeper water at the source.

Figure 4-6 and Figure 4-7 present the modelling impact piling noise levels in 5dB increments for unweighted SPL_{peak} and SEL_{ss} metrics at the two modelling locations. This shows how the bathymetry can change noise propagation, with smaller ranges where the sound travels through shallower water near the coast to the north and north west.

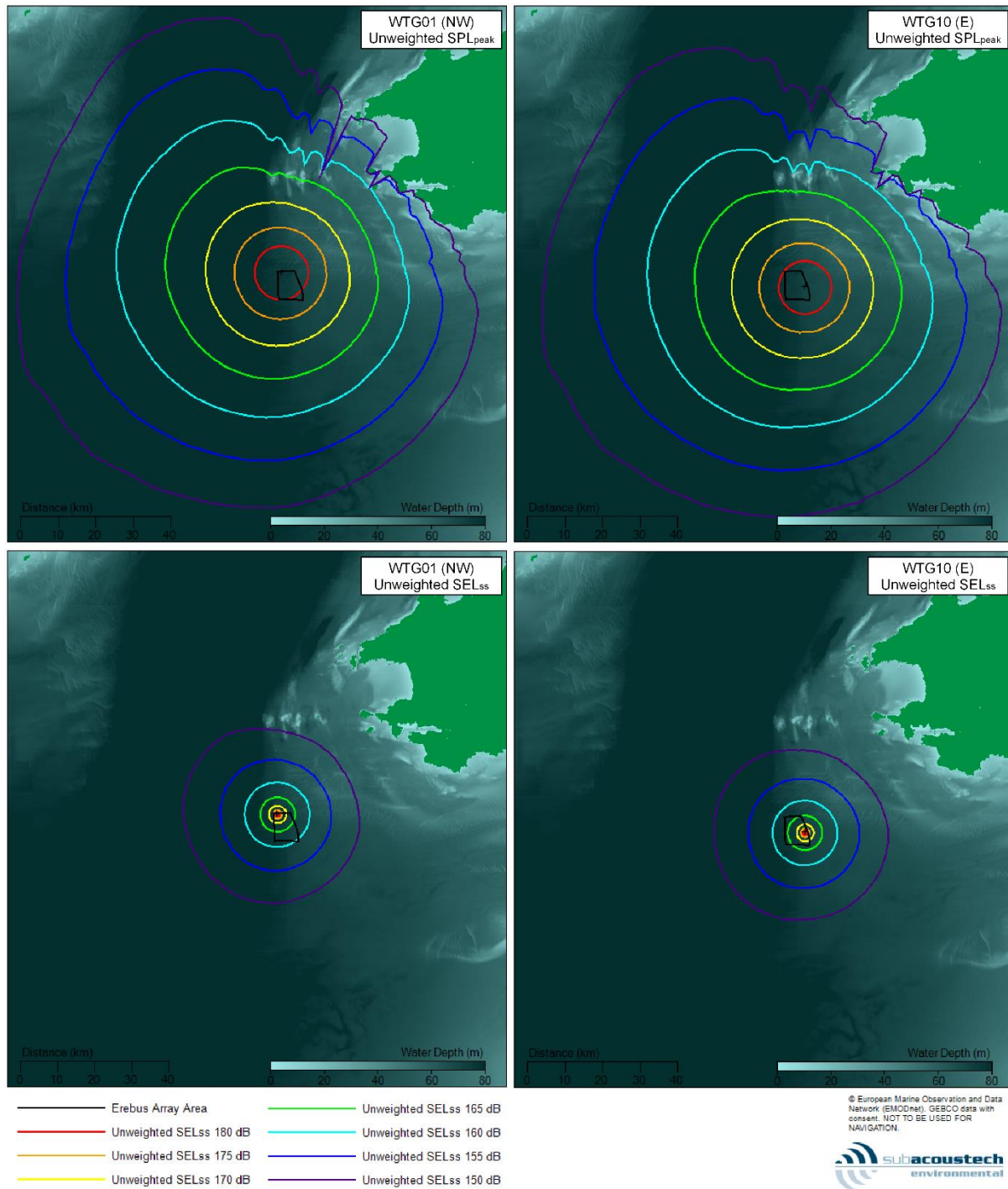


Figure 4-6 Contour plots showing the predicted unweighted SPL_{peak} and SEL_{ss} noise levels from impact piling noise at both locations using the worst-case modelling parameters

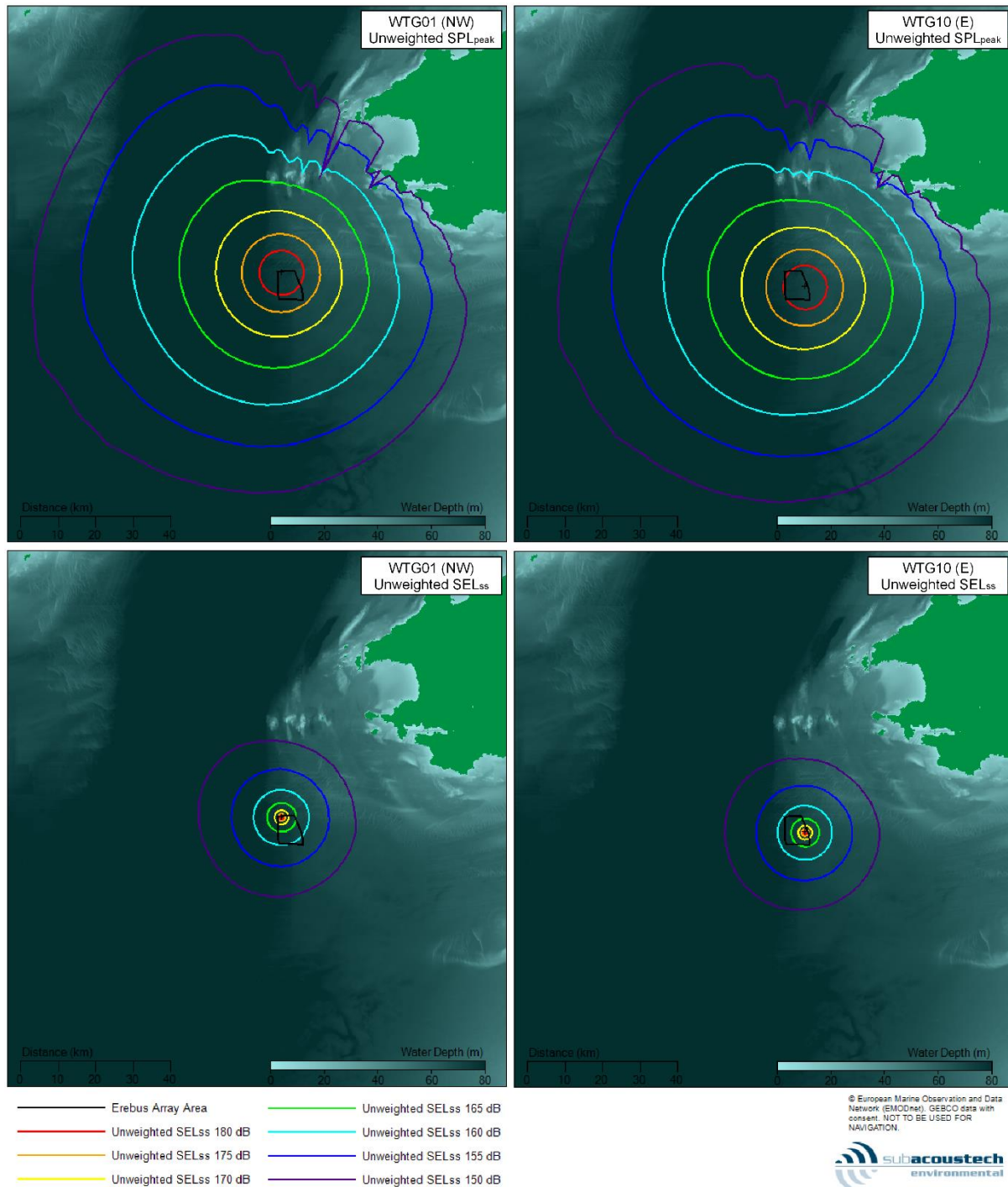


Figure 4-7 Contour plots showing the predicted unweighted SPL_{peak} and SEL_{ss} noise levels from impact piling noise at both locations using the most likely modelling parameters

4.3.1 Worst-case parameters

Table 4-12 to Table 4-16 present the results for the worst-case modelling scenario including the Southall *et al.* (2019) criteria for marine mammals and the Popper *et al.* (2014) criteria for fish, as discussed in section 2.2.2. As an example, impact range contours for the impulsive SEL_{cum} PTS (red contours) and TTS (yellow contours) ranges for LF cetaceans are shown in Figure 4-8; these and the rest of the contours have been provided as GIS shapefiles.

A maximum PTS injury range of 2.7 km for LF cetaceans is predicted using the impulsive SEL_{cum} Southall *et al.* (2019) criteria for marine mammals at the WTG10 (E) location; all other PTS ranges for marine mammals are expected to be less than 100 m. For fish, a maximum fleeing range of 9.9 km (20 km stationary) is predicted for TTS using the Popper *et al.* (2014) criteria at the same location.

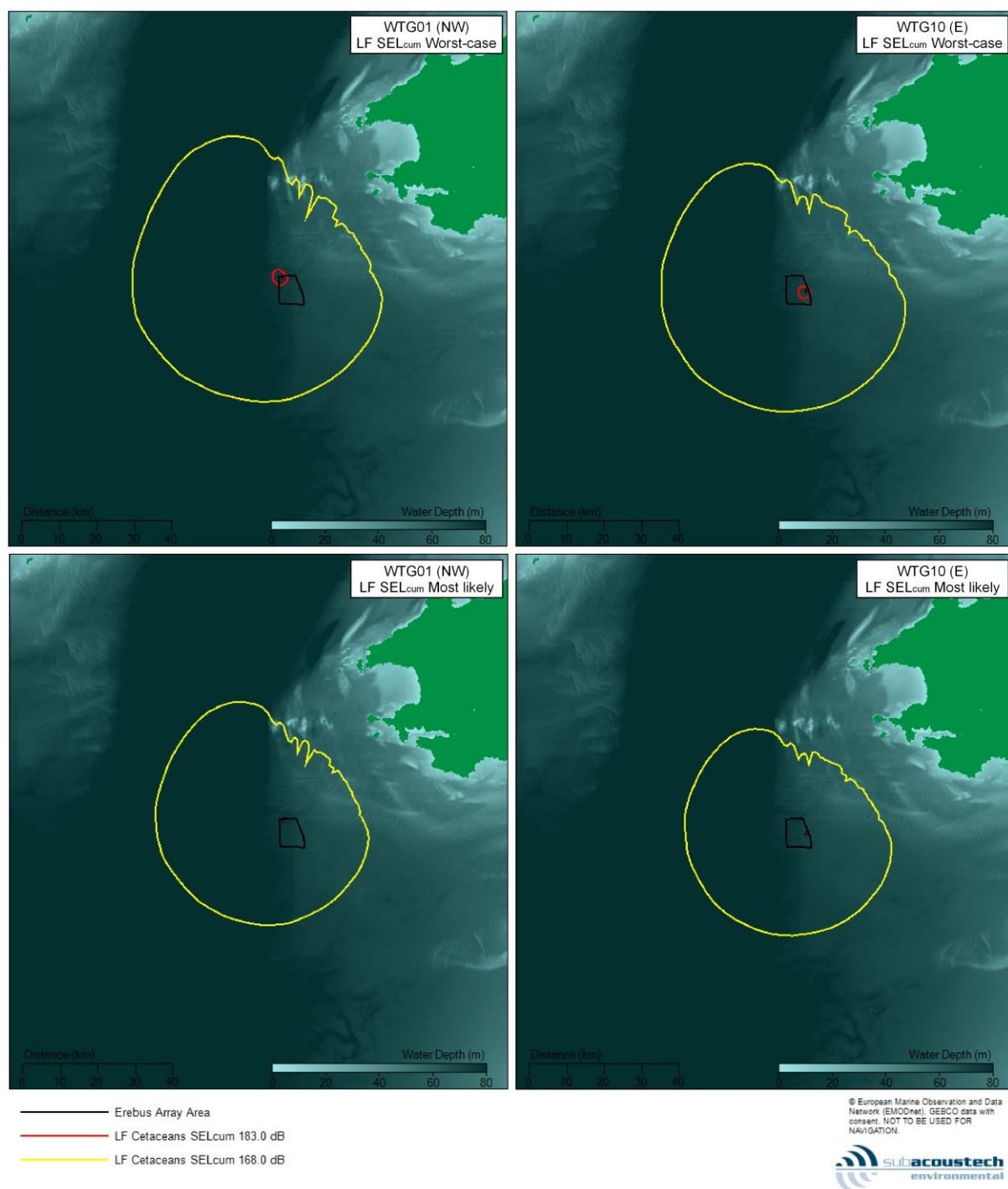


Figure 4-8 Contour plots showing the predicted weighted SEL_{cum} impact ranges for PTS and TTS from impact piling noise at both locations for both the worst-case and most likely modelling parameters assuming a fleeing animal

Southall et al. (2019) Unweighted SPL _{peak}		Worst-case (impulsive criteria)							
		WTG01 (NW)				WTG10 (E)			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	219 dB (LF)	< 0.01 km ²	< 50 m	< 50 m	< 50 m	< 0.01 km ²	< 50 m	< 50 m	< 50 m
	230 dB (HF)	< 0.01 km ²	< 50 m	< 50 m	< 50 m	< 0.01 km ²	< 50 m	< 50 m	< 50 m
	202 dB (VHF)	0.25 km ²	280 m	280 m	280 m	0.25 km ²	280 m	280 m	280 m
	218 dB (PCW)	< 0.01 km ²	< 50 m	< 50 m	< 50 m	< 0.01 km ²	< 50 m	< 50 m	< 50 m
TTS	213 dB (LF)	0.01 km ²	< 50 m	< 50 m	< 50 m	0.01 km ²	50 m	< 50 m	50 m
	224 dB (HF)	< 0.01 km ²	< 50 m	< 50 m	< 50 m	< 0.01 km ²	< 50 m	< 50 m	< 50 m
	196 dB (VHF)	1.7 km ²	730 m	730 m	730 m	1.7 km ²	730 m	730 m	730 m
	212 dB (PCW)	0.01 km ²	60 m	60 m	60 m	0.01 km ²	60 m	60 m	60 m

Table 4-12 Summary of the impact ranges from the worst-case impact piling modelling using the unweighted SPL_{peak} impulsive criteria from Southall et al. (2019) for marine mammals

Southall et al. (2019) Weighted SEL _{cum}		Worst-case (impulsive criteria)							
		WTG01 (NW)				WTG10 (E)			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	183 dB (LF)	8.2 km ²	2.2 km	700 m	1.5 km	12 km ²	2.7 km	900 m	1.9 km
	185 dB (HF)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
	155 dB (VHF)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
	185 dB (PCW)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
TTS	168 dB (LF)	3100 km ²	40 km	19 km	31 km	3400 km ²	41 km	17 km	32 km
	170 dB (HF)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
	140 dB (VHF)	1000 km ²	20 km	15 km	18 km	1100 km ²	22 km	15 km	19 km
	170 dB (PCW)	110 km ²	6.5 km	5.5 km	6.0 km	120 km ²	6.8 km	5.6 km	6.2 km

Table 4-13 Summary of impact ranges from the worst-case impact piling modelling using the weighted SEL_{cum} impulsive criteria from Southall et al. (2019) for marine mammals assuming a fleeing animal

Popper et al. (2014) Unweighted SPL _{peak}		Worst-case (pile driving)							
		WTG01 (NW)				WTG10 (E)			
		Area	Max	Min	Mean	Area	Max	Min	Mean
213 dB		0.01 km ²	< 50 m	< 50 m	< 50 m	0.01 km ²	50 m	< 50 m	50 m
207 dB		0.05 km ²	130 m	130 m	130 m	0.05 km ²	130 m	130 m	130 m

Table 4-14 Summary of impact ranges from the worst-case impact piling modelling using the unweighted SPL_{peak} pile driving criteria from Popper et al. (2014) criteria for species of fish

Popper et al. (2014) Unweighted SEL _{cum}		Worst-case (pile driving; fleeing)							
		WTG01 (NW)				WTG10 (E)			
		Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (fleeing)		< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
216 dB (fleeing)		< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
210 dB (fleeing)		< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
207 dB (fleeing)		< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
203 dB (fleeing)		< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
186 dB (fleeing)		230 km ²	9.3 km	7.6 km	8.5 km	250 km ²	9.9 km	7.8 km	8.9 km

Table 4-15 Summary of impact ranges from the worst-case impact piling modelling using the unweighted SEL_{cum} pile driving criteria from Popper et al. (2014) criteria for species of fish assuming a fleeing animal

Popper et al. (2014) Unweighted SEL _{cum}		Worst-case (pile driving; stationary)							
		WTG01 (NW)				WTG10 (E)			
		Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (stationary)		0.2 km ²	250 m	200 m	230 m	0.2 km ²	250 m	200 m	230 m
216 dB (stationary)		0.4 km ²	400 m	350 m	380 m	0.4 km ²	400 m	350 m	380 m
210 dB (stationary)		2.1 km ²	850 m	800 m	830 m	2.1 km ²	850 m	800 m	830 m
207 dB (stationary)		5.5 km ²	1.4 km	1.3 km	1.3 km	5.5 km ²	1.4 km	1.3 km	1.3 km
203 dB (stationary)		18 km ²	2.4 km	2.4 km	2.4 km	18 km ²	2.5 km	2.4 km	2.4 km
186 dB (stationary)		1000 km ²	19 km	17 km	18 km	1100 km ²	20 km	17 km	19 km

Table 4-16 Summary of impact ranges from the worst-case impact piling modelling using the unweighted SEL_{cum} pile driving criteria from Popper et al. (2014) criteria for species of fish assuming a stationary animal

4.3.2 *Most likely parameters*

Table 4-17 to Table 4-21 present the impact ranges for the most likely parameters as described in section 3.4.1 using the marine mammal and fish criteria detailed in section 2.2.2.

Compared with the worst-case parameters, reductions can be seen in impact ranges for the most likely parameters, with all the predicted SEL_{cum} PTS ranges using the Southall *et al.* (2019) impulsive criteria falling below 100 m. For fish, the maximum range assuming the receptor moves away from the source was 6.5 km for TTS (15 km for a stationary receptor) using the Popper *et al.* (2014) criteria at the WTG10 location.

Southall <i>et al.</i> (2019) Unweighted SPL _{peak}		Most likely (impulsive criteria)							
		WTG01 (NW)				WTG10 (E)			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	219 dB (LF)	< 0.01 km ²	< 50 m	< 50 m	< 50 m	< 0.01 km ²	< 50 m	< 50 m	< 50 m
	230 dB (HF)	< 0.01 km ²	< 50 m	< 50 m	< 50 m	< 0.01 km ²	< 50 m	< 50 m	< 50 m
	202 dB (VHF)	0.15 km ²	220 m	220 m	220 m	0.15 km ²	220 m	220 m	220 m
	218 dB (PCW)	< 0.01 km ²	< 50 m	< 50 m	< 50 m	< 0.01 km ²	< 50 m	< 50 m	< 50 m
TTS	213 dB (LF)	< 0.01 km ²	< 50 m	< 50 m	< 50 m	< 0.01 km ²	< 50 m	< 50 m	< 50 m
	224 dB (HF)	< 0.01 km ²	< 50 m	< 50 m	< 50 m	< 0.01 km ²	< 50 m	< 50 m	< 50 m
	196 dB (VHF)	1.0 km ²	570 m	570 m	570 m	1.0 km ²	570 m	570 m	570 m
	212 dB (PCW)	0.01 km ²	< 50 m	< 50 m	< 50 m	0.01 km ²	< 50 m	< 50 m	< 50 m

Table 4-17 Summary of the impact ranges from the most likely impact piling modelling using the unweighted SPL_{peak} impulsive criteria from Southall *et al.* (2019) for marine mammals

Southall <i>et al.</i> (2019) Weighted SEL _{cum}		Most likely (impulsive criteria)							
		WTG01 (NW)				WTG10 (E)			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	183 dB (LF)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
	185 dB (HF)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
	155 dB (VHF)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
	185 dB (PCW)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
TTS	168 dB (LF)	2200 km ²	33 km	18 km	26 km	2400 km ²	35 km	16 km	27 km
	170 dB (HF)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
	140 dB (VHF)	630 km ²	15 km	13 km	14 km	670 km ²	16 km	13 km	15 km
	170 dB (PCW)	49 km ²	4.2 km	3.7 km	4.0 km	53 km ²	4.4 km	3.8 km	4.1 km

Table 4-18 Summary of impact ranges from the most likely impact piling modelling using the weighted SEL_{cum} impulsive criteria from Southall *et al.* (2019) for marine mammals assuming a fleeing animal

Popper <i>et al.</i> (2014) Unweighted SPL _{peak}		Most likely (pile driving)							
		WTG01 (NW)				WTG10 (E)			
		Area	Max	Min	Mean	Area	Max	Min	Mean
	213 dB	< 0.01 km ²	< 50 m	< 50 m	< 50 m	< 0.01 km ²	< 50 m	< 50 m	< 50 m
	207 dB	0.03 km ²	100 m	100 m	100 m	0.03 km ²	100 m	100 m	100 m

Table 4-19 Summary of impact ranges from the most likely impact piling modelling using the unweighted SPL_{peak} pile driving criteria from Popper *et al.* (2014) criteria for species of fish

Popper <i>et al.</i> (2014) Unweighted SEL _{cum}		Most likely (pile driving; fleeing)							
		WTG01 (NW)				WTG10 (E)			
		Area	Max	Min	Mean	Area	Max	Min	Mean
	219 dB (fleeing)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
	216 dB (fleeing)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
	210 dB (fleeing)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
	207 dB (fleeing)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
	203 dB (fleeing)	< 0.1 km ²	< 100 m	< 100 m	< 100 m	< 0.1 km ²	< 100 m	< 100 m	< 100 m
	186 dB (fleeing)	100 km ²	6.1 km	5.2 km	5.7 km	110 km ²	6.5 km	5.4 km	6.0 km

Table 4-20 Summary of impact ranges from the most likely impact piling modelling using the unweighted SEL_{cum} pile driving criteria from Popper *et al.* (2014) criteria for species of fish assuming a fleeing animal

Popper <i>et al.</i> (2014) Unweighted SEL _{cum}	Most likely (pile driving; stationary)							
	WTG01 (NW)				WTG10 (E)			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (stationary)	0.1 km ²	200 m	150 m	180 m	0.1 km ²	200 m	150 m	180 m
216 dB (stationary)	0.2 km ²	250 m	200 m	230 m	0.2 km ²	250 m	200 m	230 m
210 dB (stationary)	1.0 km ²	600 m	550 m	580 m	1.0 km ²	600 m	550 m	580 m
207 dB (stationary)	2.4 km ²	900 m	850 m	880 m	2.7 km ²	950 m	900 m	930 m
203 dB (stationary)	8.3 km ²	1.7 km	1.6 km	1.6 km	8.3 km ²	1.7 km	1.6 km	1.6 km
186 dB (stationary)	640 km ²	15 km	14 km	14 km	670 km ²	15 km	14 km	15 km

Table 4-21 Summary of impact ranges from the most likely impact piling modelling using the unweighted SEL_{cum} pile driving criteria from Popper et al. (2014) criteria for species of fish assuming a stationary animal

5 Summary and conclusions

As part of both the Environmental Impact Assessment (EIA) and Habitat Regulations Assessment (HRA) processes for the Erebus Offshore Wind Farm, Subacoustech Environmental have undertaken underwater noise modelling and analysis in relation to marine fauna. The primary activities considered are associated with the ground preparation and installation of the turbines and their associated infrastructure.

The noise from the proposed activities (with the exception of impact piling) was considered using a high-level, simple modelling approach, including vessel movements, suction pile installation, seabed preparation and protection, cable installation, drag embedment anchor installation, and drilling for the installation of foundation piles. Additionally, similar approaches were used to assess UXO clearance (Soloway and Dahl, 2014) and operational WTG noise (Tougaard *et al.*, 2020). The predicted noise levels for these construction noise sources show that the risk of any potentially injurious effects to fish or marine mammals from these sources are expected to be negligible when considering a fleeing animal, as opposed to the animal remaining stationary, as the noise emissions from these are close to, or below, the appropriate injury criteria even when very close to the source of the noise. When considering a stationary receptor, PTS impact ranges increase to a maximum of 820 m for VHF cetaceans for noise from suction pile installation. However, it should be noted that assumptions associated with the suction installation methodology make these ranges highly precautionary.

There is also the possibility that impact piling may be used to secure the WTG foundations. Impact ranges have been modelled at two locations assuming 2.5 m diameter piles and worst-case and most likely scenarios based on maximum blow energies of 800 and 600 kJ, respectively. For marine mammals, maximum SEL_{cum} PTS ranges of up to 2.7 km were predicted for LF cetaceans for the worst-case impact piling scenario, with ranges reducing to less than 100 m when considering the most likely piling scenario. For fish, maximum SEL_{cum} TTS ranges of up to 9.9 km were predicted for fleeing receptors, reducing to 6.5 km for the most likely scenario.

Noise from the operational wind turbines has been considered based on recent review papers of wind turbines currently in use in European waters. The noise level predicted for the largest prospective turbines under consideration at the Erebus site are not expected to be high enough to cause PTS or TTS to any species, even assuming that a marine mammal or fish were to remain in proximity to a turbine for over an hour. Due to the relatively low noise output and the spacing between the turbines, noise from multiple turbines operating simultaneously will not produce any significant cumulative effect.

UXO detonation, both high-order and low-order, has also been considered at the Erebus site, and for the expected UXO detonation noise, there is a risk of PTS up to 15 km for the largest UXO considered, a 794 kg device (TNT equivalent charge weight) using the unweighted SPL_{peak} Southall *et al.* (2019) criteria for VHF cetaceans. However, this is likely to be very precautionary as not only is the impact range based on worst-case criteria that do not account for any smoothing of the pulse over long ranges, which reduces the pulse peak and other characteristics of the sound that increase the risk of injury, but also that it is not anticipated that a charge of this size will be found within the Erebus project area. If a low-order clearance technique such as deflagration is used, the most likely ranges of impact, assuming the use of a 250 g charge to initiate the clearance, the maximum PTS range is predicted at 990 m for VHF cetaceans.

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