APPENDIX 11

UNDERWATER NOISE MODELLING AND ASSESSMENT REPORT

Sceirde Rocks Offshore Wind Farm: Underwater Noise Modelling and Assessment

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Executive Summary

Subacoustech Environmental Ltd, on behalf of Xodus Group Limited, has undertaken an underwater noise modelling study for Sceirde Rocks offshore windfarm, located off County Galway on the west coast of Ireland. The installation of 30 gravity base wind turbine generators (WTG) at Sceirde Rocks requires UXO clearance, as well as other construction activities (cable laying, rock placement, trenching, vessels) that will generate underwater noise. The operation of the turbines will also generate underwater noise. The impact of underwater noise from these sources on marine mammal and fish species found in this region has been assessed.

The modelling was undertaken using three separate modelling approaches: one for UXO clearance, one for the construction activities, and a detailed modelling approach using the dBSea software package was used to model the noise generated by the WTGs when operational. Of all noise sources assessed, UXO clearance is predicted to generate the greatest impact ranges for both fish and marine mammals.

Finally, it should be stressed that, due to the nature of the modelling, while the results present specific ranges at which each impact threshold is met, the ranges should be taken as indicative, albeit worst case, in determining where environmental effects may occur in receptors during the proposed operations.

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Terminology

Decibel (dB)	A customary scale commonly used (in various ways) for reporting levels of sound. The dB represents a ratio/comparison of a sound measurement (e.g sound pressure) over a fixed reference level. The dB symbol is followed by a second symbol identifying the specific reference value (e.g., re 1 µPa).
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Peak-to-peak pressure	The sum of the highest positive and negative pressures that 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.
Root Mean Square (RMS)	The square root of the arithmetic average of a set of squared instantaneous values. Used for presentation of an average sound pressure level.
Sound Exposure Level (SEL or $L_{E,p}$)	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 Exposure Level, cumulative (SEL_{cum})	Single value for the collected, combined total of sound exposure over a specified time or multiple instances of a noise source.
Sound Exposure Level, single strike (SEL_{ss})	Calculation of the sound exposure level representative of a single noise impulse, typically a pile strike.
Sound Pressure Level (SPL or L_p)	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.
Sound Pressure Level Peak (SPL_{peak} or $L_{p,pk}$)	The highest (zero-peak) positive or negative sound pressure, in decibels.
Temporary Threshold Shift (TTS)	Temporary reduction of hearing acuity because of exposure to sound over time. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus.
Unweighted sound level	Sound levels which are “raw” or have not been adjusted in any way, for example to account for the hearing ability of a species.
Weighted sound level	A sound level which has been adjusted with respect to a “weighting envelope” in the frequency domain, typically to make an unweighted level relevant to a particular species.

Units

dB	Decibel (sound pressure)
Hz	Hertz (frequency)
kg	Kilogram (mass)
kJ	Kilojoule (energy)
kHz	Kilohertz (frequency)
km	Kilometre (distance)
km^2	Square kilometres (area)
m	Metre (distance)
mm/s	Millimetres per second (particle velocity)
m/s	Metres per second (speed)
MW	Megawatt (power)
Pa	Pascal (pressure)
Pa^2s	Pascal squared seconds (acoustic energy)
µPa	Micropascal (pressure)

Abbreviations

EIA	Environmental Impact Assessment
EMODnet	European Marine Observation and Data Network
GIS	Geographic Information System
HF	High-Frequency Cetaceans
LF	Low-Frequency Cetaceans
NPL	National Physical Laboratory
NMFS	National Marine Fisheries Service
OWF	Offshore Wind Farm
PCW	Phocid Carnivores in Water
PPV	Peak Particle Velocity
PTS	Permanent Threshold Shift
RMS	Root Mean Square
SE	Sound Exposure
SEL ($L_{E,p}$)	Sound Exposure Level
SEL_{cum}	Cumulative Sound Exposure Level
SEL_{ss}	Single Strike Sound Exposure Level
SPL	Sound Pressure Level
SPL_{peak} (L_{pk-pk})	Peak Sound Pressure Level
$SPL_{peak-to-peak}$	Peak-to-peak Sound Pressure Level
SPL_{RMS} ($L_{p,RMS}$)	Root Mean Square Sound Pressure Level
TTS	Temporary Threshold Shift
UXO	Unexploded Ordinance
VHF	Very High-Frequency Cetaceans
WTG	Wind Turbine Generator

1 Introduction

1.1 Project Overview

Subacoustech Environmental Ltd have been requested by Xodus to undertake underwater noise modelling for noise generating activities related to the Sceirde Rocks Offshore Wind Farm (OWF), Ireland.

Sceirde Rocks is a proposed offshore wind farm (OWF) off the coast of County Galway, West Ireland, in the Atlantic Ocean. This development includes the installation of 30 wind turbine generators (WTGs) with a concrete gravity base. Other activities are associated with the construction phase of the project, such as unexploded ordinance (UXO) clearance, rock placement, trenching and cable laying, although not all are guaranteed (such as clearance in the presence of UXO). The noise generated by construction phase activities, as well as noise generated from the WTGs once they are operational, will contribute to a temporary or long-term increase in noise levels in the area. Therefore, the impact of these increased noise levels needs to be considered and assessed in this report, as requested as part of the associated EIAR.

The effect of underwater noise depends on the sensitive receptors in the existing environment. Based on previous assessments undertaken by Subacoustech on similar situations, the effect of underwater noise on marine species, particularly fish and marine mammals, is an important consideration for regulators and consultees. Therefore, the potential impact of underwater noise on migratory and resident fish species, as well as marine mammals, will require assessment.

This report provides the results and findings of an underwater noise modelling assessment for pre-construction and construction phase activities, as well as a detailed underwater modelling assessment for noise generated by the WTGs once they are operational. These models are used to estimate the received sound pressure levels and sound exposure levels in the region, with particular focus on the impact on marine mammals and fish.

1.2 Study Area

The proposed wind farm site is off the coast of County Galway, West Ireland, in Europe’s Atlantic Margin. The proposed locations for each of the 30 WTGs are shown in Figure 1-1 (see next page). The bathymetry around the windfarm site shows shallower waters towards the coast, with significantly deeper water to the south and southwest of the margins of the windfarm site. The deepest water depth for any individual WTG is 58 m.

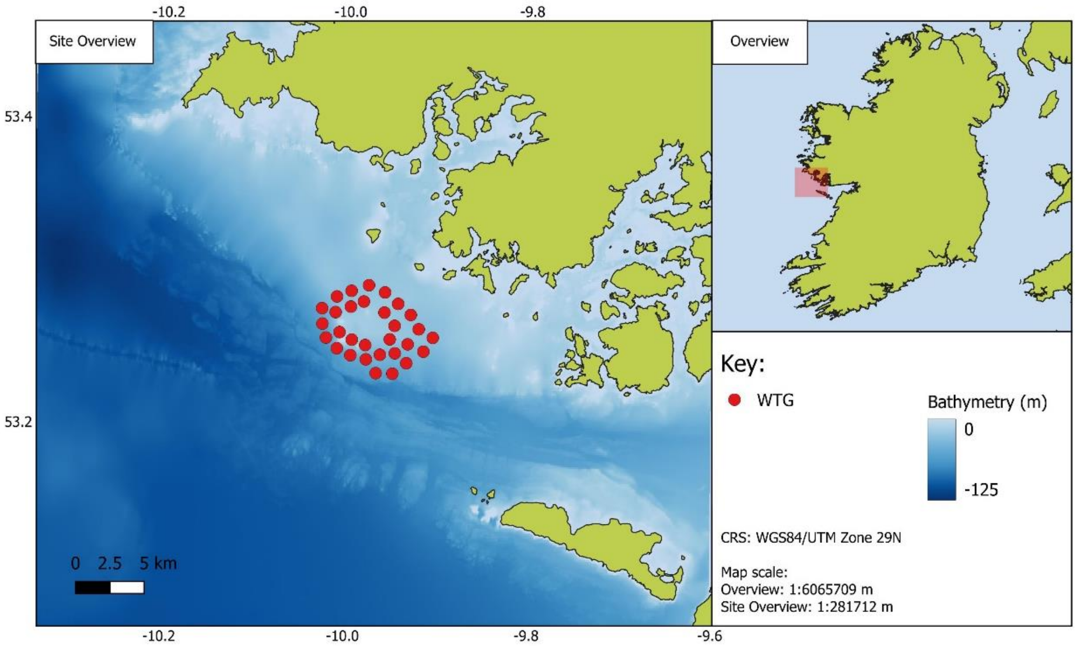

Figure 1-1: The proposed location of the Sceirde Rocks Offshore Wind Farm, including the location of the 30 WTGs. The extent of the "Site Overview" map covers the exact extent of the area which was included in the underwater noise modelling.

1.3 Noise Sources

During the construction phase, the following noise sources are predicted:

- UXO clearance
- Construction noise sources:
    - Rock placement
    - Trenching
    - Vessels (all phases)
    - Cable Laying

And during the operational phase, the following noise sources are predicted:

- 30 operational, concrete gravity base WTGs with a 292 m diameter rotor

Further details on the modelling of these noise sources, including the source level calculations, are described in Section 3.1.1 (UXO clearance), Section 3.2.1 (construction noise sources) and Section 4.1 (operational WTGs).

1.4 Assessment Overview

This report presents an assessment of the potential underwater noise from the construction activities and subsequent operation of WTGs in the Atlantic Ocean off the West Coast of Ireland, and covers the following:

- Review of background information on the units for measuring and assessing underwater noise.
- Discussion of the simple modelling approach used for UXO clearance and construction noise sources, including:

    - Outline of modelling methodology
    - Assumptions for the noise modelling undertaken.
    - Presentation and interpretation of the results.
- Discussion of the detailed modelling approach used for WTG operational noise, including:
    - Assumptions for the noise modelling undertaken, including input parameters.
    - Presentation and interpretation of the results.
- Summary and conclusions.

2 Underwater Noise Concepts

Sound travels much faster in water (approximately 1,500 m/s) than in air (340 m/s). Since water is a relatively incompressible, dense medium, the pressure associated with underwater sound tends to be much higher than in air. Therefore, it should be noted that stated underwater noise levels are different to those stated for airborne noise levels, as a different scale is used between in water and in air measurements. Therefore, noise measured in air is incomparable to noise measured underwater.

2.1 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 as this better reflects how sound is perceived. For example, equal increments of sound levels do not have an equal increase in the perceived sound. Instead, each doubling of sound level will cause a roughly equal increase of loudness. Any quantity expressed in this dB scale is termed a "level." For example, if the unit is sound pressure, it will be termed a "sound pressure level" on the dB scale.

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 typically expressed as units of Root Mean Square (RMS) pressure squared. This is equivalent to expressing the sound as:

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

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.

2.1.1 Sound Pressure Level (SPL, L_p)

The Sound Pressure Level (SPL or L_p) 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 ($L_{p,RMS}$) 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, seismic airgun or underwater blasting, it is critical that the period over which the RMS level is calculated is quoted (e.g., $L_{p,125ms}$) 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 ($L_{p,pk}$) or Sound Exposure Levels (SEL or $L_{E,p}$).

Unless otherwise defined, all SPL noise levels in this report are referenced to 1 µPa.

2.1.2 Peak Sound Pressure Level (SPL_{peak} or $L_{p,pk}$)

The peak SPL, or $L_{p,pk}$, is often used to characterise transient sound from impulsive sources, such as explosions or percussive impact piling. $L_{p,pk}$ 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 ($L_{p,pk\text{-}pk}$) 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.

2.1.3 Sound Exposure Level (SEL or $L_{E,p}$)

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 used by Bebb and Wright (1953, 1954a, 1954b, 1955), and later by Rawlins (1987), to explain the apparent discrepancies in the biological effect of short and long-range blast waves on human divers. More recently, this form of analysis has been used to develop criteria for assessing injury ranges for fish and marine mammals from various noise sources (Popper *et al.,* 2014; Southall *et al.,* 2019; Southall *et al.,* 2007).

The $L_{E,p}$ sums the acoustic energy over a measurement period, and effectively takes account of both the L_p 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 sound in seconds, and t is time in seconds. The SE is a measurement of acoustic energy and has units of Pascal squared seconds (Pa^2s).

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

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

By using a common reference pressure (p_{ref}) of 1 µPa for assessments of underwater noise, the L_E and L_p can be compared using the expression:

$$L_{E,p} = L_p + 10 \times \log_{10} T$$

where the L_p is a measure of the average level of broadband noise and the $L_{E,p}$ sums the cumulative broadband noise energy.

This means that, for continuous sounds of less than (i.e., fractions of) one second, the $L_{E,p}$ will be lower than the L_p. For periods greater than one second, the $L_{E,p}$ will be numerically greater than the L_p (i.e., for a continuous sound of 10 seconds duration, the $L_{E,p}$ will be 10 dB higher than the L_p; for a sound of 100 seconds duration the $L_{E,p}$ will be 20 dB higher than the L_p, and so on).

Where a single impulse noise such as the soundwave from an explosion is considered in isolation, this can be represented by a “single strike” $L_{E,p}$ or SEL_{ss}. A cumulative $L_{E,p}$, or SEL_{cum}, accounts for the exposure from multiple impulses over time, where the number of impulses replaces the T in the equation above, leading to:

$$Cumulative\ L_{E,p} = L_{E,p} + 10 \times \log_{10} X$$

Where $L_{E,p}$ is the sound exposure level of one impulse and X is the total number of impulses or strikes. Unless otherwise defined, all $L_{E,p}$ noise levels in this report are referenced to 1 µPa²s.

2.2 Properties of Sound

2.2.1 Impulsive vs Non-impulsive

Sound can be categorised loosely into two types: impulsive noise and non-impulsive noise. Impulsive noise can be defined as a sound with a high peak sound pressure, short duration, fast rise-time, and a broad frequency content at the source (e.g., seismic airguns, explosives, impact piling). Non-impulsive noise can be defined as steady-state noise, or without the characteristics of impulsive noise, which does not necessarily have a long duration (e.g., vibropiling, drilling).

These differences are important to consider regarding the potential for auditory injury, as impulsive noise is generally more injurious than non-impulsive noise.

Due to the differences between impulsive and non-impulsive noise sources, different metrics are appropriate for describing these different sound sources. For example:

- Impulsive noises: Use peak SPL ($L_{p,pk}$) and cumulative SEL ($L_{E,p}$)
- Non-impulsive noises: cumulative SEL ($L_{E,p}$)

Objective categorisation of noise sources as impulsive or non-impulsive can sometimes be challenging. This is particularly this case if a sound is travelling over long distances. For example, if an impulsive sound propagates through an environment, the energy within the sound wave will also dissipate and becomes less impulsive with distance from the noise source. This is important to consider regarding auditory injury and impact range calculations, as impulsive noise will become less injurious if it becomes less impulsive.

Active research is currently underway to define impulsive and non-impulsive noise (see Martin *et al.,* 2020). Although the situation is complex, Hastie *et al.* (2019) concluded that an impulsive sound can be considered effectively non-impulsive 3.5 km from the source. Using these findings, Southall (2021) suggests that noise should be considered non-impulsive when there is no longer energy content above 10 kHz. However, research remains in progress, with work is ongoing in an attempt to determine numerical values of other pulse characteristics, such as for kurtosis, that can aid categorisation of a pulse as either impulsive or non-impulsive.

2.2.2 Particle Motion

The motion of the particles that make up a medium is an important component of sound. Particle motion is present wherever there is sound, and it describes the back-and-forth movement of particles in water, which in the context of underwater noise, are caused by a sound wave passing through the water column. This back-and forth movement means that, unlike sound pressure at a single point, particle motion always contains directional information (Hawkins and Popper, 2017). Regarding quantifying particle motion, it is usually defined in reference to the velocity of the particle (often a peak particle velocity, PPV), but sometimes the related acceleration or displacement of the particle is used.

It has been identified by several researchers that many fish species, (e.g., Popper and Hawkins, 2019; Nedelec *et al*., 2016; Radford *et al.,* 2012), as well as marine invertebrates (see Sole *et al*., 2023 for review) are sensitive to particle motion as opposed to sound pressure. However, sound pressure metrics are still preferred and more widely used than particle motion due to a lack of supporting data (Popper and Hawkins, 2018). There continue to be calls for additional research on the levels of and effects with respect to particle motion (Hawkins, 2023).

2.3 Analysis of Environmental Effects: Assessment Criteria

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 seismic airguns, impact piling and blasting 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).
- Behavioural changes.

The following sections discuss the underwater noise criteria used in this study with respect to species of marine mammals and fish that may be present around the study area off the west coast of Ireland.

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 exposure criteria.
- Popper *et al*. (2014) sound exposure guidelines for fishes and sea turtles.

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

2.3.1 Marine Mammals

2.3.1.1 Auditory Injury (PTS and TTS) criteria

The Southall *et al*. (2019) paper is the most used and recognised reference for marine mammal hearing thresholds. It is effectively an update of the previous Southall *et al.* (2007) paper and provides identical thresholds to those from the National Marine Fisheries Service (NMFS; 2018) guidance for marine mammals. It should be noted that, despite the identical thresholds, the marine mammal hearing groups are described slightly differently in the Southall *et al.* (2019) paper to the NMFS (2018) guidance. Therefore, care should be taken if comparing results using the Southall *et al*. (2019) to NMFS (2018) criteria.

The Southall *et al*. (2019) guidance categorises marine mammals into groups of similar species and applies filters to the unweighted noise to approximate the hearing sensitivities of the receptor in question. The hearing groups given by Southall *et al*. (2019) are summarised in Table 2-1**Error! Reference source not found.** and their auditory weighting functions are shown in Figure 2-1. Further groups for sirenians and other marine carnivores in water are given, but these have not been included in this study as those species are not commonly found off the west coast of Ireland.

It should be noted that although Southall *et al.* (2019) refers to peak SPL as SPL_{peak}, this notation has since been deprecated (ISO 18405:2017) and will be referred to as $L_{p,pk}$ in the rest of this report.

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

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 seals)

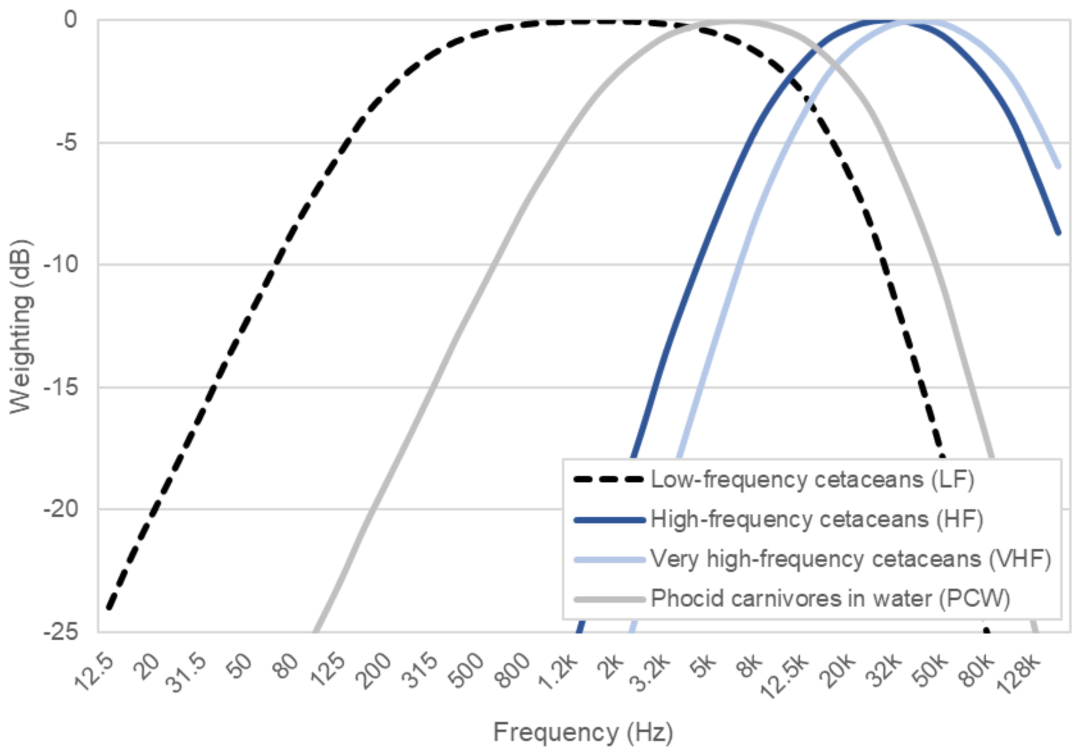

Figure 2-1: Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019)

Southall *et al.* (2019) presents noise impact thresholds for pre-categorised groups of marine mammals (described above), which are dependent on:

- The nature of the sound (impulsive vs non-impulsive)
- The type of auditory injury of concern (PTS vs TTS)

Southall *et al.* (2019) considers the nature of the sound in the context of whether it is considered as impulsive or non-impulsive noise source (see section 2.2.1 for details).

Where cumulative SEL thresholds are required for marine mammals, usually a fleeing animal model is used. This assumes that when a receptor (marine mammal) is exposed to high noise levels, they will swim away from the noise source. However, due to the low noise levels generated by all modelled noise sources, with the exception of UXO, it is not necessarily the case that the animal can be assumed to swim away from the area. Therefore, only impact ranges from stationary receptors have been included in this report. In the case of UXO the effect is the same as the noise is singular and isolated, and no aversive behaviour is assumed.

Within each of the impulsive and non-impulsive noise criterion set out by Southall *et al.* (2019), different impact thresholds are presented depending on the potential of different levels of auditory injury at different noise levels of that sound. Auditory injury has been categorised into two types:

- PTS (permanent threshold shift) onset: the greatest severity, which is an unrecoverable (but incremental) reduction in hearing sensitivity.
- TTS (temporary threshold shift) onset: the least severity, which is a temporary reduction in hearing sensitivity.

It should be noted that the greatest calculated impact ranges are usually associated with TTS. However, the effects from PTS represent the onset of permanent (but only incremental, not total) impairment, and thus PTS is usually quoted as the most important impact threshold.

In summary, when using Southall *et al.* (2019) as an assessment criterion to calculate impact ranges, three variables are considered:

- The marine mammal receptors within the area.
- The nature of the sound (and subsequent appropriate metrics).
- The type of auditory injury of concern.

The noise generated by cable laying, vessel noise, rock dumping and trenching are considered non-impulsive noise sources. However, the noise generated by UXO clearance is considered as impulsive and is likely to propagate beyond 3.5 km (see section 2.2.1). Therefore, for this study, the criteria set out by Southall *et al.* (2019) for PTS and TTS in marine mammals in response to impulsive noise has been considered only for UXO clearance, and non-impulsive noise sources for all noise sources have been considered, which summarised in Table 2-2 and Table 2-3.

Table 2-2: Peak SPL ($L_{p,pk}$) criteria for PTS and TTS in marine mammals (Southall et al., 2019)

Southall *et al.* (2019)	$L_{p,pk}$ (dB re 1 µPa)	
	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 2-3: Cumulative SEL ($L_{E,24h,wtd}$) criteria for PTS and TTS in marine mammals (Southall et al., 2019)

Southall *et al.* (2019)	$L_{E,p,24h,wtd}$ (dB re 1 µPa²s)			
	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

2.3.2 Fish

2.3.2.1 Mortality, injury and behavioural effects

The Popper *et al.* (2014) guidelines are recognised as a suitable reference for underwater noise impacts on marine fauna (aside from marine mammals). While previous studies have applied broad criteria based on limited studies of fish that are not present, or measurement data not intended to be used as criteria, Popper *et al.* (2014) provides a summary of the latest research and guidelines for fish (and other marine fauna) exposure to sound and uses categories for fish that are representative of the species present in Ireland.

Popper *et al.* (2014) considers the source of the sound, and provides separate criteria for explosions, pile driving, seismic airguns, low frequency naval sonar, mid frequency naval sonar, and shipping and other continuous noise. For the purposes of this assessment, the appropriate criteria are in the explosions, and shipping and other continuous noise categories.

If a sound source is not listed, it is common practice to use the criteria which is the best fit to the characteristics of the sound source required in the assessment (e.g frequency, duration etc.).

For each sound source, the marine fauna is categorised into groups of sea turtles, eggs and larvae, and fish. Due to their diversity and quantity, fish are categorised further into three groups depending on their hearing capabilities, which can be indicated by whether they possess a swim bladder or not, and whether the swim bladder is involved in hearing. These three categories are:

- Fish: no swim bladder
- Fish: swim bladder not involved in hearing
- Fish: Swim bladder involved in hearing.

Popper *et al.* (2014) provides separate criteria, depending on the species and the noise source, for various impacts associated with noise exposure. These include:

- Mortality and potential mortal injury
- Impairment
    - Recoverable injury
    - TTS
    - Masking
- Behavioural effects.

Depending on the noise source, quantitative criteria are given in appropriate metrics (SPL_{peak}, SEL_{cum} etc.), which can then be used as thresholds for onsets of listed impacts. Where insufficient data is available, Popper *et al.* (2014) also gives a qualitative description. This summarises the effect of the noise as having either a high, moderate or low relative risk of an effect on an individual in either near (tens of meters), intermediate (hundreds of meters) or far (thousands of meters) from the source.

Most species described by Popper *et al.* (2014) are likely to move away from a sound that is loud enough to cause harm (Dahl *et al*., 2015; Popper *et al*., 2014). However, considering the diversity of species described by Popper *et al.* (2014), whether an animal flees or remains stationary in response to a loud noise will differ between species. It is recognised that there is limited evidence for fish fleeing from high level noise sources in the wild. Those species that are likely to remain stationary are thought more likely to be benthic species or species without a swim bladder, due to their reduced hearing capabilities making these species the least sensitive to noise (e.g., Goertner *et al*., 1994, 1978; Stephenson *et al*., 2010; Halvorsen *et al*., 2012). However, due to the low (or singular, for UXO) noise levels generated by the modelled noise sources, it is not necessarily the case that the animal can be assumed to swim away from the area. Therefore, only impact ranges from stationary receptors have been included in this report.

Due to the various noise sources which need to be considered, two of the criteria from Popper et al. (2014) have been used in this assessment. For the UXO clearance, the criteria set out by Popper et al. (2014) for explosions have been considered, which is summarised in Table 2-4. Since the noise generated by operational WTGs is a continuous noise source, for this study, the criteria set out by Popper et al. (2014) for shipping and continuous noise sources have been considered as a proxy, which is summarised in Table 2-5.

Table 2-4: Recommended guidelines for explosions according to Popper et al. (2014) for speices of fish, sea turtles and eggs and larvae (N = Near-field; I = Intermediate-field; F = Far-field).

Popper *et al*. (2014) criteria for Explosions					
Type of fish	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	229 – 234 dB peak	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	NA	(N) High (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	229 – 234 dB peak	(N) High (I) High (F) Low	(N) High (I) Moderate (F) Low	NA	(N) High (I) High (F) Low
Fish: swim bladder involved in hearing	229 – 234 dB peak	(N) High (I) High (F) Low	(N) High (I) High (F) Low	NA	(N) High (I) High (F) Low
Sea Turtles	229 – 234 dB peak	(N) High (I) High (F) Low	(N) High (I) High (F) Low	NA	(N) High (I) High (F) Low
Eggs and Larvae	> 13 mm/s peak velocity	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	NA	(N) High (I) Low (F) Low

Table 2-5: Recommended guidelines for shipping and continuous sounds according to Popper et al. (2014) for speices of fish, sea turtles and eggs and larvae (N = Near-field; I = Intermediate-field; F = Far-field).

Popper *et al*. (2014) criteria for Shipping and Continuous sounds					
Type of fish	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	(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
Fish: swim bladder not involved in hearing	(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
Fish: swim bladder involved in hearing	(N) Low (I) Low (F) Low	170 dB rms for 48 h	158 dB rms for 12 h	((N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Sea Turtles	(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) High (I) Moderate (F) Low
Eggs and Larvae	(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

It is important to note that despite the emerging evidence that fish are sensitive to particle motion (see section 2.2.2), the Popper *et al.* (2014) guidance defines noise impacts in terms of sound pressure or sound pressure-associated functions (i.e. SEL).

It has been suggested that the criteria set out by Popper *et al.* (2014) could have been derived from unmeasured particle motion, as well as sound pressure. Whilst this may be true, sound pressure remains the preferred metric in the criteria due to a lack of data surrounding particle motion (Popper and Hawkins, 2018), particularly in regarding the ability to predict the consequences of the particle motion of a noise source, and the sensitivity of fish to a specific particle motion value. Therefore, as stated by Popper and Hawkins (2019): "since there is an immediate need for updated criteria and guidelines on potential effects of anthropogenic sound on fishes, we recommend, as do our colleagues in Sweden (Andersson *et al*., 2017), that the criteria proposed by Popper *et al*. (2014) should be used."

2.3.3 Marine Invertebrates

A review by Sole *et al.* (2023) highlights the increasing evidence that some types of anthropogenic noise can negatively impact a variety of marine invertebrate taxa. These impacts include changes in behaviour, physiology and rate of mortality, as well as physical impairment, at the individual, population or ecosystem level. Much of the damage from exposure to noise comes from vibration of the invertebrate body (André *et al.,* 2016) caused by the passage of sound.

Comparatively, the studies described by Sole *et al.* (2023) show a general inconsistency in the way noise impacts have been quantified for marine invertebrates. For example, Hubert *et al.* (2021) notes behavioural changes in blue mussels to 150 and 300 Hz tones, whereas Spiga *et al.* (2016) describes behavioural changes in the same species at SEL_{ss} 153.47 dB re 1 µPa. These inconsistencies make it difficult to generate accurate thresholds for the onset of any impact for species. A notable exception is the cephalopods group, in which several studies, mainly by Sole *et al.* (2019, 2018, 2013a) and André *et al.* (2011) show a consistent threshold for auditory damage on various species of cephalopod at 157 dB re 1 µPa. While further research is needed even on this group to ensure accurate thresholds which are satisfactory to regulators, the current state of research on cephalopods sets a goal for the research required for other marine invertebrate groups, if they are to be used usefully as impact thresholds.

The meta-analysis conducted by Sole *et al.* (2023) also reveals inconsistencies in the responses of taxonomically near species of marine invertebrates to the effect of anthropogenic noise. For example, Fields *et al.* (2019) demonstrates low mortality of zooplankton during seismic airguns, whereas for the same noise source, McCauley *et al.* (2017) showed mass mortality of krill larvae. Clearly, the effect of noise on one species may not necessarily be applicable on another species despite being taxonomically near, which again makes it difficult to generate a generalised impact threshold that can confidently be applied to different taxonomic groups of marine invertebrates.

In its current state, research on the effects of anthropogenic noise on marine invertebrates is emerging, but more slowly than for marine mammals and fish. At this time, this research is in too early a stage to be used to accurately generate impact thresholds which would be satisfactory to regulators. However, it cannot be ignored that convincing evidence of noise impacts to marine invertebrates does exist. The data available could potentially be referenced for some species but with caution, as there are still considerable gaps in the knowledge that would enable reliable conclusions for the impact of noise for most species.

3 Pre-Construction and Construction Noise Sources

Under certain circumstances, a simple modelling approach may be considered acceptable (Robinson *et al.*, 2014). These circumstances include modelling for noise sources which are comparably quiet or where detailed modelling would imply unjustified accuracy due to a lack of relevant data. Therefore, to estimate noise levels generated by activities associated with the pre-construction, construction, and operational phase of the Sceirde Rocks OWF, other than operational noise, Subacoustech have chosen to undertake a simple modelling approach. This approach, as well as the resulting calculated impact ranges, are detailed in the following section.

3.1 UXO clearance

Unexploded ordinance (UXO) may be present within the boundaries of the proposed development. Before construction works for Sceirde Rocks OWF can begin, any UXO devices must be cleared. This does not necessarily require detonation of the device, but may, and so this is considered as the primary and worst-case noise source. The clearance of each device will generate underwater noise, which requires assessment.

3.1.1 UXO clearance: Methodology

The noise levels generated by UXO clearance are affected by several factors, including the UXO charge weight, as well as the devices design, composition, age, position, orientation, whether it is covered by sediment etc. Of all these factors, charge weight is the only variable that can easily be used in acoustic propagation calculations, and thus is the only variable considered in this assessment.

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 the Marine Technical Directorate Ltd (MTD) (1996). These methodologies establish a trend based on measured data in open water. These are:

1. SPL_{peak} ($L_{p,pk}$):

$$L_{p,pk} = 52.4 \times 10^{6} \left(\frac{R}{W^{1/3}}\right)^{-1.13}$$

2. Cumulative SEL ($L_{E,p}$):

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

Where:

W = equivalent charge weight for TNT (kg)
R = range from the source.

The equivalent charge weights considered in the modelling for the UXOs are from 25 kg to 800 kg. In each case, an additional donor charge has been included, although this makes a negligible difference to the overall noise level compared to the main charge. Low-order deflagration has also been modelled, which assumes UXO is destroyed through detonation of a special donor charge of 0.5 kg. This initiates a burnout of the explosive material without detonating the UXO itself. No noise mitigation has been included in this modelling.

The Soloway and Dahl (2014) equation does not include a sound absorption coefficient. Therefore, an attenuation correction has been added to the Soloway and Dahl (2014) equation. This correction is based on high intensity noise propagation taken from previous measurements in the North and Irish Sea, which uses standard frequency-based absorption coefficients for the seawater conditions expected in the region.

A summary of the unweighted UXO clearance source levels ($L_{p,pk}$ and $L_{E,p}$), calculated at 1 m from the device using the equations above, are given in Table 3-1.

Table 3-1: Summary of the unweighted $L_{p,pk}$ and $L_{E,p}$ source levels used for UXO clearance modelling.

Charge Weight (kg)	$L_{p,pk}$ source level (dB re 1 µPa @ 1 m)	$L_{E,p}$ source level (dB re 1 µPa^{2}s @ 1 m)
0.5 (low-order deflagration)	272.1	217.1
25 (+ donor)	284.9	228.0
55 (+ donor)	287.5	230.1
120 (+ donor)	290.0	232.3
240 (+ donor)	292.3	234.2
525 (+ donor)	294.8	236.4
700 (+ donor)	295.8	237.2
800 (+ donor)	296.2	237.5

3.1.2 UXO clearance: Results

The results for the underwater noise calculations for UXO clearance of various charge weights are given in terms of the marine mammal assessment using Southall *et al.* (2019) for both impulsive and non-impulsive noise sources, and in terms of the fish assessment criteria using Popper *et al.* (2014) for explosions.

It should be noted that due to the complexity in noise conditions at close range to the source, estimated impact ranges are limited to a resolution of 50 m from the source. Ranges predicted to be less than this are presented as "< 50 m".

3.1.2.1 Marine Mammals

3.1.2.1.1 $L_{p,pk}$ criteria

Using the Southall *et al.* (2019) the highest $L_{p,pk}$ impact ranges calculated are for VHF cetaceans, where there is the potential for PTS within 14,000 m (14 km) of the UXO, if the UXO charge weight is either 700 kg or 800 kg. These details, including other calculated marine mammal PTS and TTS ranges for various UXO charge weights, are detailed in Table 3-2.

Table 3-2: Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, unweighted $L_{p,pk}$ noise criteria from Southall et al. (2019) for marine mammals.

Charge Weight (kg)	Estimated Impact Range (m)							
	PTS (impulsive)				TTS (impulsive)			
	LF	HF	VHF	PCW	LF	HF	VHF	PCW
0.5 (low order)	220	80	1200	240	410	130	2300	450
25 (+ donor)	820	260	4600	910	1500	490	8500	1600
55 (+ donor)	1000	340	6000	1100	1900	640	11000	2100
120 (+ donor)	1300	450	7800	1500	2500	830	14000	2800
240 (+ donor)	1700	560	9800	1900	3200	1000	18000	3500
525 (+ donor)	2200	730	12000	2500	4100	1300	23000	4600
700 (+ donor)	2400	810	14000	2700	4500	1400	25000	5000
800 (+ donor)	2600	840	14000	2800	4700	1500	26000	5300

3.1.2.1.2 $L_{E,p}$ criteria

The Southall *et al.* (2019) criteria for impulsive and non-impulsive noise have been weighted to account for each marine mammal group hearing sensitivity. It should be noted that since a UXO detonation is defined as a single pulse source, the SEL_{cum} criteria from Southall *et al.* (2019) have been given as SEL_{ss} in the tables below. Fleeing animal assumptions have not been applied.

When the noise source is considered impulsive, the highest PTS impact ranges are predicted for LF cetaceans within 11,000 m (11 km) of UXO devices with an 800 kg charge weight. These details, including other calculated marine mammal PTS and TTS ranges for various UXO charge weights, are detailed in Table 3-3Table 3-2.

Table 3-3: Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, weighted $L_{E,p}$ noise criteria from Southall et al. (2019) for marine mammals.

Charge Weight (kg)	Estimated Impact Range (m)							
	PTS (impulsive)				TTS (impulsive)			
	LF	HF	VHF	PCW	LF	HF	VHF	PCW
0.5 (low order)	320	< 50	110	60	4500	< 50	930	800
25 (+ donor)	2200	< 50	570	390	29000	150	2400	5200
55 (+ donor)	3200	< 50	740	570	41000	210	2800	7500
120 (+ donor)	4700	< 50	950	830	57000	300	3200	10000
240 (+ donor)	6500	< 50	1100	1100	76000	390	3500	14000
525 (+ donor)	9500	60	1400	1500	100000	530	4100	22000
700 (+ donor)	10000	60	1500	1900	110000	590	4100	22000
800 (+ donor)	11000	70	1600	2000	120000	620	4200	23000

When the noise source is considered non-impulsive, the highest PTS impact ranges are predicted for LF cetaceans, that must be within 700 m of UXO devices with an 800 kg charge weight to exceed their PTS threshold. Although this uses the lower non-impulsive thresholds, it should be noted that their relevance will only be at the point where the blast wave becomes non-impulsive, which will be at some distance beyond 3.5 km. This distance is yet to be defined and as such any non-impulsive ranges calculated at less than 3500 m should be disregarded in preference to the impulsive calculation.

Details of the non-impulsive results, including other calculated marine mammal PTS and TTS ranges for various UXO charge weights, are detailed in Table 3-4.

Table 3-4: Summary of the PTS and TTS impact ranges for UXO detonation using the non-impulsive, weighted $L_{E,p}$ noise criteria from Southall et al. (2019) for marine mammals.

Charge Weight (kg)	Estimated Impact Range (m)							
	PTS (impulsive)				TTS (impulsive)			
	LF	HF	VHF	PCW	LF	HF	VHF	PCW
0.5 (low order)	< 50	< 50	< 50	< 50	650	< 50	150	110
25 (+ donor)	130	< 50	< 50	< 50	4400	< 50	730	790
55 (+ donor)	190	< 50	< 50	< 50	6400	60	940	1100
120 (+ donor)	280	< 50	70	50	9400	90	1100	1600
240 (+ donor)	390	< 50	100	70	13000	110	1400	2300
525 (+ donor)	570	< 50	130	100	18000	160	1700	3300
700 (+ donor)	660	< 50	150	110	21000	180	1800	3800
800 (+ donor)	700	< 50	160	120	22000	190	1800	4100

3.1.2.2 Fish

The impact ranges for the UXO clearance were assessed using the Popper *et al.* (2014) criteria for explosions. All fish species considered by Popper *et al.* (2014) have the same thresholds, which are listed only for mortality and potential mortal injury criteria (see Table 2-4). All fish species considered will need to be within 560 - 930 m of a UXO device with a charge weight of 800 kg to exceed their mortality and potential mortal injury threshold. These details, including impact ranges for various UXO charge weights, are presented in Table 3-5.

Table 3-5: Summary of the impact ranges for UXO detonation using the unweighted $L_{p,pk}$ explosion noise criteria from Popper et al. (2014) for species of fish.

Charge Weight (kg)	Estimated Impact Range (m)
	Mortality and potential mortal Injury
0.5 (low order)	< 50 - 80
25 (+ donor)	170 - 290
55 (+ donor)	230 - 380
120 (+ donor)	300 - 490
240 (+ donor)	370 - 620
525 (+ donor)	490 - 810
700 (+ donor)	530 - 890
800 (+ donor)	560 - 930

3.1.3 UXO clearance: Discussion

It should be noted that several limitations exist to the methodology used to calculate impact ranges for UXO clearance. Noise propagation calculations for UXO often results in worst-case estimations, as other factors aside from charge weight, which will negatively contribute to the acoustic propagation, cannot be directly considered in these 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 than predicted by the modelling (MTD, 1996). Therefore, the risk to animals near the surface may be lower than indicated by the impact ranges and thus the results presented can again be considered as a worst-case estimation in respect of the impact at different depths.

A further consideration is equation does not consider the effect of absorption over long ranges on predicted noise levels. Due to the nature of sound propagation, peak SPL noise levels over larger distances are difficult to predict accurately (von Benda-Beckmann *et al*., 2015). It should also be noted that Soloway and Dahl (2014) only verify results from the equation at ranges of less than 1 km. At longer distances, greater confidence is expected with impact ranges predicted using the SEL metric than with the peak SPL. While the addition of an attenuation correction is likely to improve the accuracy of peak SPL estimates at long ranges, this correction is theoretical, and its accuracy has not been verified in the field. It is thought that the attenuation correction is likely to result in over-estimated impact ranges, and therefore the distances calculated will represent a worst-case scenario.

Therefore, the results assume no degradation of the UXO and no smoothing of the pulse over that distance, which is very precautionary. Although an assumption of non-pulse could under-estimate the potential impact (Martin *et al*., 2020), 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.

3.2 Construction Noise Sources

Before each WTG can be installed, other activities must take place within the boundary of the proposed development to prepare the area and install essential infrastructure. Several of these activities will generate underwater noise which requires assessment. This has been done using a simple modelling approach, which is described in the following sections.

The noise generating activities associated with the pre-construction and construction phases of the Sceirde Rocks OWF that have been considered in simple modelling are detailed in Table 3-6.

Table 3-6: Summary of the possible noise making activities at Sceirde Rocks OWF, aside from noise generated directly from the WTGs.

Activity	Description
Cable laying	Noise from the Cable Laying Vessel and any other associated noise during the offshore cable installation.
Rock placement	Potentially required on site for installation of offshore cables (Cable Crossings and Cable Protection) and Scour Protection around foundation structures.
Trenching	Plough trenching may be required during Offshore Cable installation.
Vessel activities	Jack-up barges for WTG installation. Other large and medium sized vessels to carry out other construction tasks and anchor handling. Other small vessels for crew transport and maintenance on site.

3.2.1 Construction Noise Sources: Methodology

For each noise source described in Table 3-6, approximate underwater noise levels have been predicted based on measurement data from Subacoustech’s own underwater noise measurement database. These noise levels were then scaled to relevant noise source parameters (e.g. noise duration). Using these scaled noise levels, the transmission loss of the underwater noise was then calculated. This was based on an empirical calculation of noise measurements along line transects from the noise source, taken previously by Subacoustech. The predictions use the following principle fitted to the measured data:

$$Recieved\ level = Source\ level\ (SL) - N\log_{10} R - \alpha R$$

where R is the range from the source, N is the transmission loss, and α is the absorption loss.

Predicted source levels and propagation calculations for the considered activities are presented in Table 3-7 along with a summary of the number of datasets used in each case. It should be noted that all values of N and α are empirically derived and will be linked to the size and shape of the machinery and the noise source on it, the transect on which the measurements are taken and the local environment at the time.

It should be noted that unlike the detailed modelling, this simple modelling approach does not consider bathymetry of the area or other environmental conditions to calculate acoustic propagation loss.

Table 3-7: Summary of the estimated unweighted source levels and transmission losses for the different considered noise sources related to construction.

Noise Source	Estimated Unweighted Source Level dB re 1 µPa @ 1 m (RMS)	Transmission loss parameters		Comment
		N	α	
Cable laying	171	13	0	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.
Rock placement	172	12	0.0005	Based on four datasets from rock placement vessel '*Rollingstone*.'
Trenching	172	13	0.0004	Based on three datasets of measurements from trenching vessels more than 100 m in length.
Vessel noise (large)	168	12	0.0021	Based on five datasets of large vessels including container ships, FPSOs and other vessels more than 100 m in length. Vessel speed assumed as 10 knots.
Vessel noise (medium)	161	12	0.0021	Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 10 knots.

To calculate impact ranges for marine mammal groups presented by Southall *et al.* (2019), the weightings for each hearing group must be accounted for in each noise source calculation. Reductions to the source level given in Table 3-7 for each activity has been applied, and Figure 3-1 shows the resulting noise measurements used. Details of the reductions in sources levels for each of the weightings used for modelling are given in Table 3-8.

Table 3-8: Reductions in source level for the different noise sources considered when the Southall et al. (2019) weightings are applied.

Noise Source	Reduction in source level from unweighted level (dB)			
	LF	HF	VHF	PCW
Cable Laying	3.6	22.9	23.9	13.2
Rock Placement	1.6	11.9	12.5	8.2
Trenching	4.1	23.0	25.0	13.7
Vessel Noise	5.5	34.4	38.6	17.4

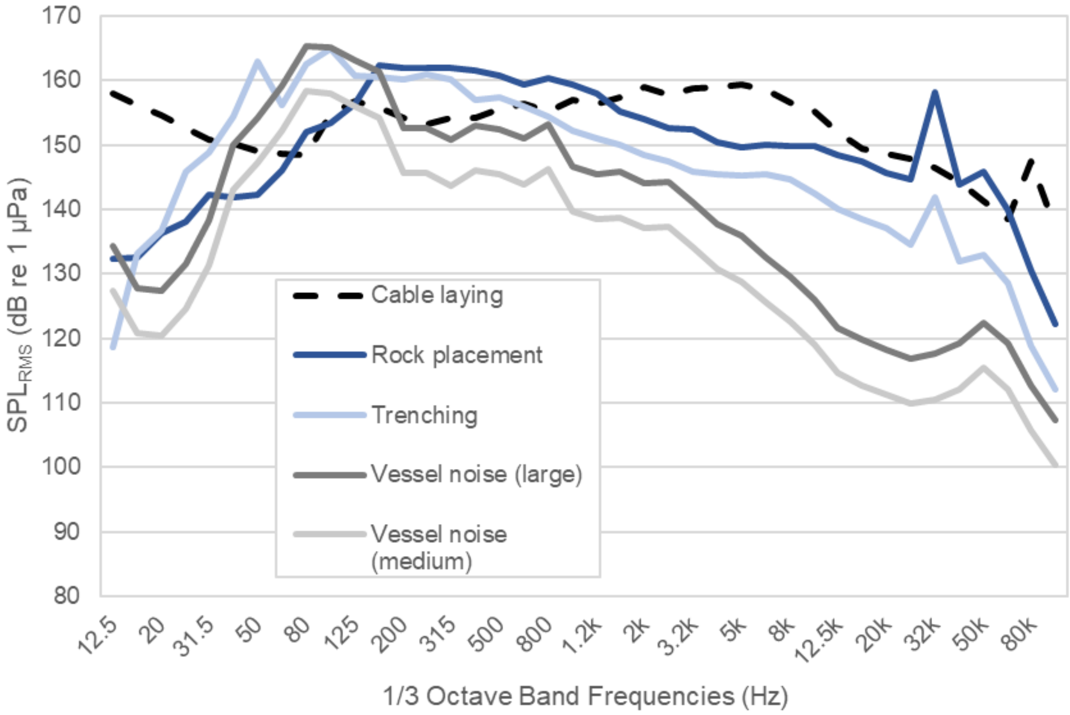

Figure 3-1: Summary of the 1/3rd octave frequency bands to which the Southall et al. (2019) weightings were applied in the simple modelling.

For $L_{E,p}$ calculations, the duration the noise is present also needs to be considered, with all sources assumed to operate constantly for 24-hours per day, to give a worst-case assessment of the noise.

Due to the low noise levels generated by the modelled activities, it is not necessarily the case that the animal can be assumed to swim away from the area. Therefore, modelling has been undertaken assuming a stationary receptor, as a worst-case scenario.

3.2.2 Construction Noise Sources: Results

The results for the underwater noise calculations for peripheral noise sources are given in terms of the marine mammal assessment using Southall *et al.* (2019) for non-impulsive noise sources, and in terms of the fish assessment criteria using Popper *et al.* (2014) for shipping and other continuous noise sources.

It should be noted that due to the complexity in noise conditions at close range to the source, estimated impact ranges are limited to a resolution of 10 m from the source. Ranges predicted to be less than this are presented as “< 10 m”.

3.2.2.1 Marine Mammals

Due to the low source levels associated with each considered activity, and the nature of the noise sources being continuous, the Southall *et al.* (2019) criteria for non-impulsive noise have been used. These criteria have been adjusted to account for the different marine mammal groups’ hearing sensitivity. Across all marine mammal groups considered, rock placement produces the highest impact ranges of all activities. The highest predicted impact ranges for rock placement are for VHF cetaceans, that must remain within 900 m of the activity for 24-hours to exceed their PTS criteria.

These details, including the estimated TTS and PTS ranges for each marine mammal group for each activity, are presented in Table 3-9.

Table 3-9: Summary of the impact ranges for the different noise sources related to construction using the non-impulsive criteria from Southall et al. (2019) for marine mammals assuming a stationary animal, using the $L_{E,p,24h,wtd}$ metric.

Activity	Estimated Impact Range (m)							
	PTS (non-impulsive)				TTS (non-impulsive)			
	LF	HF	VHF	PCW	LF	HF	VHF	PCW
Cable Laying	30	<10	70	<10	810	40	2300	<10
Trenching	30	<10	70	<10	2100	40	1900	<10
Rock Placement	60	10	900	20	830	410	13000	20
Vessel Noise (Large)	20	<10	<10	<10	480	<10	140	<10
Vessel Noise (Medium)	<10	<10	<10	<10	130	<10	40	<10

3.2.2.2 Fish

The Popper *et al.* (2014) criteria for shipping and other continuous noises only sets out criteria for fish with a swim bladder involved in hearing. This group be within <10 m of the noise sources to exceed their recoverable injury threshold for all activities. These details, included calculated TTS ranges, are provided in Table 3-10.

Table 3-10: Summary of the impact ranges for the different noise sources related to construction using the continuous noise criteria from Popper et al. (2014) for fish (swim bladder involved in hearing), assuming a stationary receptor, using the $L_{E,p,24h,\ wtd}$ metric.

Activity	Estimated Impact Range (m)	
	Recoverable Injury	TTS
Cable Laying	<10	20
Trenching	<10	20
Rock Placement	<10	20
Vessel Noise (Large)	<10	<10
Vessel Noise (Medium)	<10	<10

3.2.3 Construction Noise Sources: Discussion

While this modelling approach is considered accurate and appropriate for these noise sources, it should be noted that bathymetry or any other environmental conditions, have not been taken into account. While this means that this approach can therefore be applied to any location at or surrounding the planned location for Sceirde Rocks OWF, caution should be applied if using the results to estimate noise levels at a specific location, as the results may vary. However, in this case the ranges calculated are low enough that variations would not be expected to lead to a meaningful change in impact range or significance.

Furthermore, it should be noted that the ranges for a stationary animal are theoretical only and are expected to be over-conservative as the assumption is for the animal to remain stationary for 24-hours in respect to the noise source, which is unlikely.

4 Operational WTGs

To estimate the noise levels generated by the operational WTGs, Subacoustech have chosen to utilise the dBSea underwater noise model, which uses a numerical approach that is based on two different solvers:

- A parabolic equation (PE) method for lower frequencies (12.5 Hz to 250 Hz)
    - Widely used within the underwater acoustics community but has computational limitations at high frequencies.
- A ray tracing method for higher frequencies (315 Hz to 100 kHz).
    - More computationally efficient at higher frequencies but is not suited to low frequencies (Etter, 1991).

These solvers account for a wide array of environmental parameters within the study area, including bathymetry, sediment data and sound speed, as well as the characteristics of the noise source, such as source frequency content, to ensure as detailed results as possible. These are input parameters, and they are described in the following sections.

4.1 Underwater Noise Modelling: Methodology

4.1.1 Input Parameters

4.1.1.1 Modelling Locations

Underwater noise modelling consisted of simultaneous operation of 30 WTGs at all locations. Locations of individual turbines are shown in Appendix A (Table A-1). All sources were modelled at mid-water depth, with the exact depth dependent on the depth at which the WTG was located.

4.1.1.2 Bathymetry

The bathymetry data used in the modelling was obtained from The European Marine Observation and Data Network (EMODnet, 2018). This data has a resolution of 30 arc-seconds (approximately 500 m^2).

4.1.1.3 Seabed Properties

Characteristics of the seabed were based on local data for the Sceirde Rocks OWF region, supplied by Marine Scotland[1]. The seabed in the area is assumed to be comprised of a 1 m sediment layer of sand, which is above a bedrock layer of granite. Geo-acoustic properties for the seabed were based on available data from Jensen *et al*. (1994, 2011), which are provided in Table 4-1.

Table 4-1: Seabed geo-acoustic properties of the survey area.

Material	Compressive sound speed profile in substrate (m/s)	Density profile in substrate (kg/m^3)	Attenuation profile in substrate (dB/wavelength)
Sand	1650	1900	0.8
Granite	5250	2650	0.1

[1] https://mapapps2.bgs.ac.uk/geoindex_offshore/home.html

4.1.1.4 Sound Speed Properties

The speed of sound in the water has been calculated for the average annual temperature and salinity using the Mackenzie (1981) equation, with data supplied by Marine Scotland[2] for specific areas in the Atlantic Ocean. The resulting profile is shown in Figure 4-1.

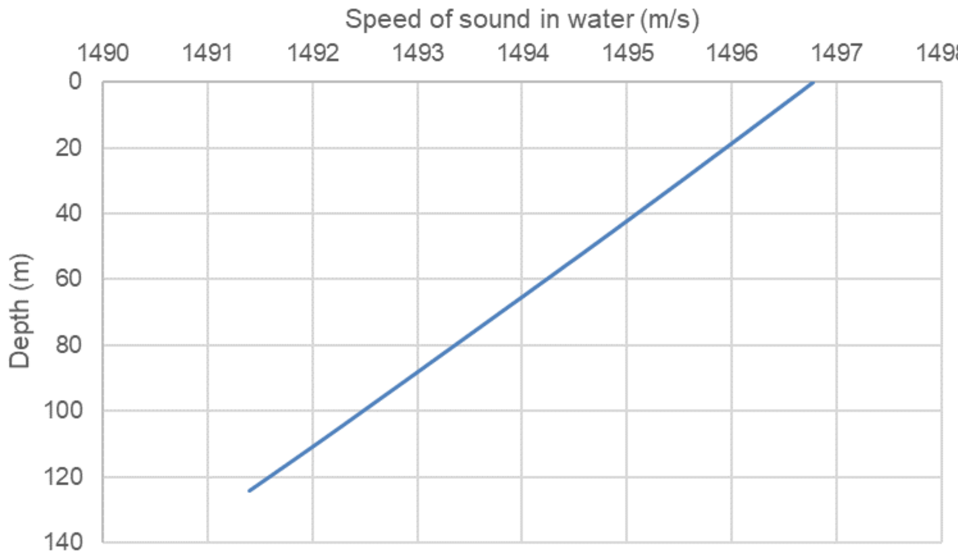

Figure 4-1: Sound speed profile used for detailed modelling.

4.1.1.5 Noise Source

Installation of the WTG is not considered significant due to the foundation type being gravity base, and thus requiring no piling. The main source of underwater noise associated with the WTGs is predicted to be when they are operational. Noise will be mechanically generated vibration from the rotating machinery in the WTGs, which is transmitted into the sea through the structure of the WTG 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.

To carry out detailed noise modelling, a source spectrum and estimated source levels for SPL_{RMS} ($L_{p,RMS}$) from the operational WTGs must be used. A source spectrum was obtained from previous measurements of operational noise from concrete gravity base WTGs, with a power output of 0.5 MW in wind speeds of 13 m/s, taken by Degn (2000). Using this source spectrum, source levels were calculated to be 130.3 dB re 1 µPa, as shown in Table 4-2. This would be scaled up to the anticipated size of the wind turbines at Sceirde Rocks.

Tougaard *et al.* (2020) identified that power output and wind speed are the two primary driving factors for underwater noise generation in operational WTGs. Since this source spectrum was based on WTGs with a power output of 0.5 MW, the source spectrum was then upscaled to match the WTG modelled with the estimated power output (based on the diameter of the WTG rotor of 292 m). This was calculated using the formula from Tougaard *et al.* (2020):

[2] https://marinescotland.atkinsgeospatial.com/nmpi/

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

where C is a fixed constant and the coefficients α, β, and γ are derived from the empirical data.

Tougaard *et al.* (2020) predicts that the noise level from 18 MW WTGs will be 22.8 dB higher than WTFs with an output of 0.5 MW. Therefore, the source level used for modelling is 153.1 dB re 1 µPa, which is presented in Table 4-2. It should be noted that a wind speed of 13 m/s was assumed for upscaling using the Tougaard *et al*. (2020) formula, to remain consistent with the conditions in which the measured data was taken by Degn (2000).

Table 4-2: Summary of the estimated $L_{p,RMS}$ for operational WTGs with a power output of 0.5 MW (used to derive the source spectrum) and the power output estimated for modelling.

Source	Source level @ 1 m
	$L_{p,RMS}$ (dB re 1 µPa)
Operational WTG (0.5 MW)	130.3
Operational WTG (18 MW)	153.1

The resulting upscaled source spectrum used in modelling is shown in Figure 4-2.

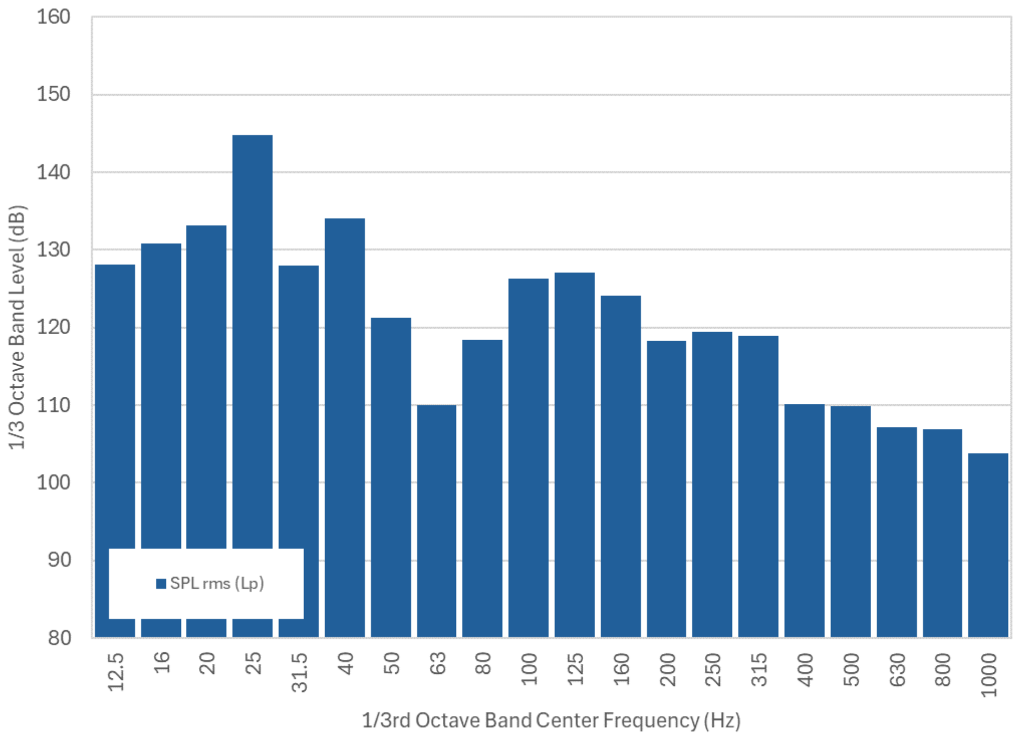

Figure 4-2: Source spectrum containing 1/3rd octave band levels used to model the survey vessel.

For cumulative SEL ($L_{E,p}$) calculations, the total duration of operation must also be considered. Since the WTGs are designed to be operational for 24-hours per day, it has been assumed in the modelling that the WTGs will be generating noise for the entirety of this period, as a worst-case scenario. Impact ranges have been calculated from one WTG location with the deepest water depth (WTG 7), whilst assuming that all WTGs are operating simultaneously at any one time.

As previously, it cannot be assumed that the receptor animal would swim away from the turbine, so for cumulative SEL calculations the modelling assumed a stationary receptor, as a worst-case scenario. Impact ranges have been calculated from one WTG (WTG 7) and assume that all WTGs are operating simultaneously at any one time.

4.2 Underwater Noise Modelling: Results

The results for the dBSea underwater noise modelling are given in terms of the marine mammal assessment criteria using Southall *et al*. (2019) for non-impulsive noise, and in terms of the fish assessment criteria using Popper *et al.* (2014) for shipping and other continuous noise sources.

All impact ranges were calculated based on the maximum level in the water column. It should be noted that due to the complexity in noise conditions at close range to the source, estimated impact ranges are limited to a resolution of 10 m from the source. Ranges predicted to be less than this are presented as “<10 m”.

4.2.1 Marine Mammals

4.2.1.1 Cumulative SEL ($L_{E,24h,wtd}$)

The Southall *et al.* (2019) criteria for non-impulsive noise have been adjusted to account for the different marine mammal groups’ hearing sensitivity. Whilst all WTGs are operating simultaneously, if all receptors are assumed to remain stationary for 24-hours, all the marine mammal species assessed would need to remain within <10 m of each operational WTG for their PTS criteria to be exceeded. These details, including TTS impact ranges, are provided in Table 4-3.

Table 4-3: Predicted impact ranges associated with the noise generated by operational WTGs for marine mammals using the Southall et al. (2019) $L_{E,24h,wtd}$ criteria for non-impulsive noise sources assuming a stationary receptor.

Southall *et al*. (2019)		Estimated Impact Range (m)		
		Max	Mean	Min
LF Cetaceans	*PTS*	<10	<10	<10
	TTS	10	10	10
HF Cetaceans	*PTS*	<10	<10	<10
	TTS	<10	<10	<10
VHF Cetaceans	*PTS*	<10	<10	<10
	TTS	<10	<10	<10
PCW Pinnipeds	PTS	<10	<10	<10
	TTS	<10	<10	<10

Visual representation of the noise level contours calculated for the operational WTGs are shown Figure 4-3 (page 27).

4.2.2 Fish

4.2.2.1 Sound Pressure Level ($L_{p,RMS}$)

The impact ranges for the operational WTGs were assessed using the Popper *et al.* (2014) criteria for shipping and other continuous noise sources. It should be noted that this criterion only provides thresholds for fish with a swim bladder involved in hearing. It is predicted that if all WTGs are operating simultaneously at any one time, fish with a swim bladder involved in hearing will need remain stationary within <10 m of each operational WTG for 24-hours to exceed their mortality/potential mortal injury threshold. These details, including impact ranges for recoverable injury, are presented Table 4-4.

Table 4-4: Predicted impact ranges associated with the noise generated by operational WTGs for fish and sea turtles using the Popper et al. (2014) criteria for shipping and other continuous noise sources, assuming a stationary receptor.

Popper *et al.* (2014)		Estimated Impact Range (m)		
		Max	Mean	Min
Fish: swim bladder involved in hearing	*Recoverable injury*	< 10	< 10	< 10
	TTS	< 10	< 10	< 10

Visual representation of the noise level contours calculated for the operational WTGs are shown Figure 4-3 (next page).

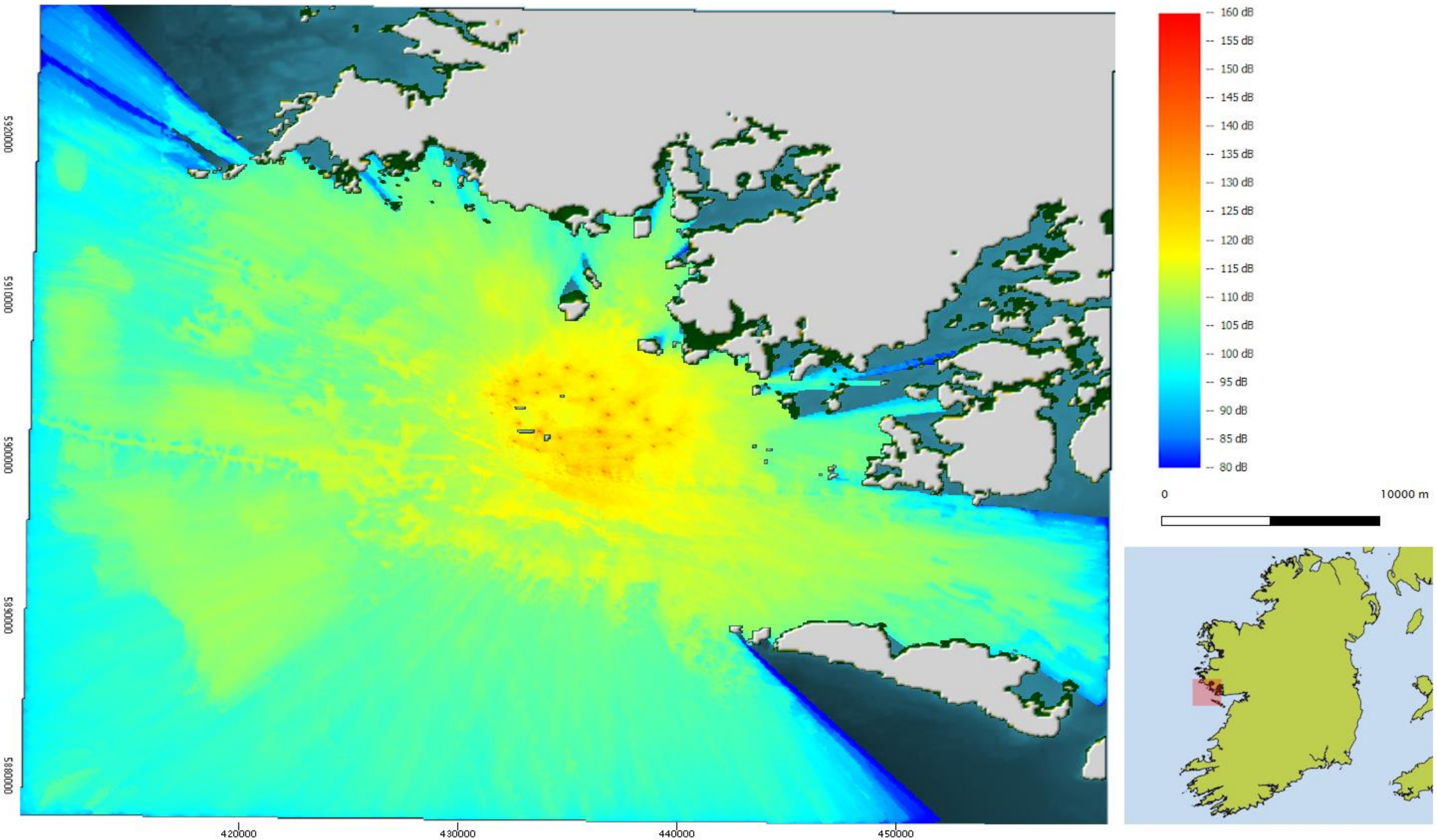

Figure 4-3: An overview of the $L_{p,RMS}$ noise levels during the operation of 30 WTGs at the planned site for Sceirde Rocks OWF.

5 Summary and Conclusions

Subacoustech Environmental, on behalf of Xodus, has undertaken an underwater noise modelling study in anticipation for Sceirde Rocks OWF off the west coast of Ireland in the Atlantic Ocean. These works propose the installation of 30 concrete gravity base wind turbine generators (WTGs). The preparation process will involve UXO clearance, as well as cable laying, trenching, rock placement and the presence of construction vessels will generate noise that has been assessed. These, along with noise from the operational WTGs, have also been assessed in the context of marine mammal and fish.

Various modelling approaches have been undertaken to assess the different noise sources. A modelling approach using equations set out by Soloway and Dahl (2014) has been used for UXO clearance, and for cable laying, trenching, rock placement and the presence of construction vessels, using an empirical approach based on previous measurements taken by Subacoustech. A detailed modelling approach has been used to predict noise levels generated by the operational WTGs. This approach uses a combined parabolic equation and ray tracing modelling methodology, which considers a wide array of input parameters including the sound frequency content, seabed properties, bathymetry, and the sound speed profile in the water column. Results from each modelling approach are summarised below:

- UXO clearance
    - For marine mammals, using criteria from Southall *et al.* (2019), the maximum PTS impact ranges for the $L_{p,pk}$ metric are predicted for VHF cetaceans, which must be within 14,000 m (14 km) of a 700-800 kg charge weight UXO detonation to exceed this criterion. When considering the $L_{E,p}$ metric, the maximum PTS impact ranges are predicted for the LF cetacean group when the noise is considered impulsive. This group must be within 11,000 m (11 km) of an 800 kg charge weight UXO detonation to exceed their PTS criteria.
    - For fish, using the criteria for explosions set by Popper *et al.* (2014), the largest predicted impact range for mortality/potential mortal injury is predicted for all species of fish considered, if they are within 560 - 930 m of the 800 kg UXO detonation.
- Construction Noise Sources
    - For marine mammals, using criteria from Southall *et al.* (2019), rock placement was predicted to result in the highest impact ranges. The highest PTS impact range, at 900 m of the rock placement activity, was predicted for VHF cetaceans, although the receptor would need to remain within this distance and incur continuous exposure for 24 hours to exceed this criterion.
    - For fish, using the criteria for shipping and other continuous noise set by Popper *et al*. (2014), the most sensitive species group, fish with a swim bladder involved in hearing, would need to remain within < 10 m of all activities considered to exceed the recoverable injury threshold.
- Operational WTGs
    - For marine mammals, using criteria from Southall *et al.* (2019), all marine mammal species considered must remain within < 10 m of each operational WTG for their PTS criteria to be exceeded. This is assuming they remain stationary for an entire 24-hour period.
    - For fish, using the criteria for shipping and other continuous noise set by Popper *et al.* (2014), fish with a swim bladder involved in hearing, which are the only group with associated impact range thresholds for this noise source, must remain within < 10 m of the operational WTGs for

24-hours to exceed their recoverable injury threshold. A negligible risk is assumed for all other species.

Of all noise sources considered across the whole assessment period, UXO clearance is predicted to result in the highest impact ranges for both marine mammals and fish.

Finally, it should be stressed that, by its nature, mathematical modelling will produce results that indicate a precise range at which a criterion will be reached, but this does not reflect the inherent uncertainty in the process. The results give a specific numerical value to a process with a vast number of variables and parameters, including many that change constantly under real world conditions. Most modelling parameters, such as the source noise level, the duration of operation and the location, are selected to be precautionary to avoid the risk of underestimating an impact. While the results present specific ranges at which each impact threshold is met based on the modelling results, the ranges should be taken as indicative, albeit worst case, in determining where environmental effects may occur in receptors during the proposed operations.

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Appendix A Locations of WTGs

Table A-1: Locations of each WTG modelled

WTG ID	Latitude (Easting)	Longitude (Northing)	Depth (m)
1	434951	5905283	23
2	433679.3057	5904880.992	26
3	433625.6286	5903730.578	21
4	432512.8791	5903326.164	25
5	431545.9237	5902487.873	55
6	432793.4025	5901869.869	18
7	431802.6152	5901471.998	58
8	432596.2335	5900691.459	44
9	433687.5311	5901319.384	19
10	434668.3325	5900921.564	27
11	434715	5899881	42
12	435741	5900217	35
13	436815.3032	5902325.303	21
14	436649.8645	5898836.34	52
15	436831.3778	5900318.83	36
16	436461.539	5901339.38	23

WTG ID	Latitude (Easting)	Longitude (Northing)	Depth (m)
17	437765.4321	5900974.976	29
18	438577.3615	5902070.323	26
19	437998.4303	5903119.348	24
20	433581.5182	5900182.008	45
21	437076.9221	5903925.699	21
22	434573.4559	5904099.231	20
23	436122.7488	5904760.877	21
24	436075.8614	5903289.497	19
25	431522.2782	5903613.745	46
26	437664	5899600	43
27	435432.7938	5898874.307	48
28	432615.4637	5904468.774	24
29	438914.7432	5900440.782	34
30	439602.6522	5901446.808	27

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