Morlais Project

Underwater Noise Modelling Report

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Underwater noise modelling of tidal turbines and other associated noise at the Morlais Demonstration Zone

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1 Introduction

Subacoustech Environmental have been instructed by Juno Energy Ltd. on behalf of Royal HaskoningDHV to undertake acoustic propagation modelling for underwater noise from proposed operational tidal turbines, drilling and acoustic deterrent devices (ADDs) at the Morlais Demonstration Zone (MDZ), located off the west coast of Holy Island, north west Wales.

The purpose of the modelling is to estimate the sound pressure levels in the region during construction and operation of a tidal turbine array, focusing on the impact on marine mammals, and whether the noise from operational tidal turbines could act as a deterrent for marine mammals or whether the use of ADDs would be necessary.

1.1 Noise sources

Three main sources of underwater noise have been identified at the MDZ: drilling to secure foundations for the tidal turbines, the operational tidal turbines themselves and ADDs that may be used to keep mammals away from the operating turbines. More information on the assumptions used for modelling can be found in section 3.1.

1.1.1 Drilling

There are various ways that can be used to secure the foundations of the tidal turbine devices, including gravity bases, drilled piles and piles installed using impact or vibration hammer. For the Morlais project, drilling is the most likely installation method. There are various methods and drill powers that can be used depending on the size of foundation being used, as well as the ground type. As this information has not been finalised, a likely worst-case assumption for the drilling has been made based on similar operations and foundation installations. The modelling in this report assumes percussive drilling, where, as well as rotating, the drill head also rapidly impacts the sediment. The assumed percussive drilling uses an approximate power of 300 kW, which can install foundations of up to approximately 3 m in diameter.

1.1.2 Operational tidal turbines

Several options are being considered for the deployment of tidal turbine devices at the MDZ. Two scenarios have been chosen covering either the largest number of turbines or the largest sized turbines. The first option utilises 620 turbines with a rotor diameter of 16.13 m; in this report these will be referred to as the "small tidal turbines." The second option features 120 locations with dual turbines with rotor diameters of 24.6 m, these are referred to as the "large tidal turbines." These two options will show whether more sound is created overall by a greater number of turbines or by a larger rotor diameter.

1.1.3 ADDs

ADDs are being considered for each tidal turbine location, in order to deter marine mammals from the operational rotors. A worst case option, i.e. one of the loudest ADDs that measurements are available for, has been used for modelling; the Lofitech Seal Scarer.

1.2 Survey area

Figure 1-1 shows the MDZ site boundary situated to the west of Holy Island, off Anglesey, north west Wales, as well as the bathymetry for the surrounding area. Water depths within the site vary between 20 and 60 m (mid-tide), with deeper waters of up to 85 m out to the west of the site.

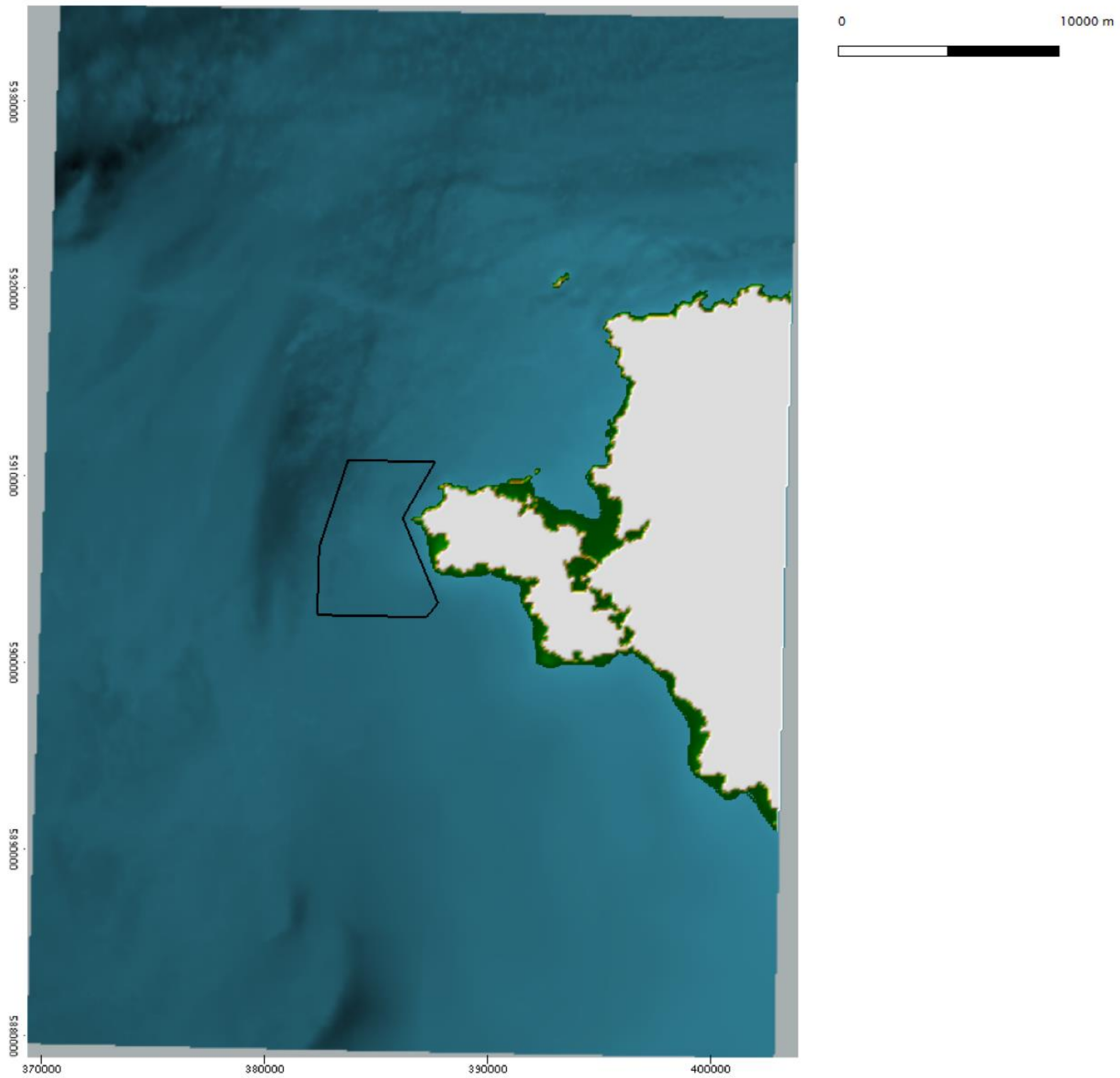

Figure 1-1 Map showing the boundary of the MDZ and the surrounding bathymetry

1.3 Assessment approach

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

- Review of background information on the units for measuring and assessing underwater noise;
- Discussion of the approach, input parameters and assumptions for the noise modelling undertaken;
- Presentation of detailed subsea noise modelling using unweighted metrics and interpretation of the results using suitable noise metrics and criteria; and
- Summary and conclusions

2 Measurement of underwater noise

Sound travels much faster in water (approximately 1,500 ms^{-1}) than in air (340 ms^{-1}). Since water is a relatively incompressible, dense medium, the pressures associated with underwater sound tend to be much higher than in air. As an example, background levels of sea noise of approximately 130 dB re 1 µPa for UK coastal waters are not uncommon (Nedwell *et al*, 2003 and 2007).

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 because rather than equal increments of sound having an equal increase in effect, typically a constant ratio is required for this to be the case, that is, each doubling of sound level will cause a roughly equal increase in “loudness.”

Any quantity expressed in this scale is termed a “level.” If the unit is sound pressure on the dB scale, it will be termed a “Sound Pressure Level” (SPL). 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 and is, therefore, used with a reference unit, which expresses the base from with the ratio is expressed. The reference quantity is conventionally smaller than the smallest value to be expressed on the scale, so that any level quoted is positive. For instance, a reference quantity of 20 µPa is used for sound in air, since this is the threshold of human hearing.

A refinement is that the scale, when used with sound pressure, is applied to the pressure squared rather than the pressure. If this were not the case, when the acoustic power level of a source rose by 10 dB, the SPL would rise by 20 dB. So that variations in the units agree, the sound pressure must be specified in units of root mean square (RMS) pressure squared. This is equivalent to expressing the sound as:

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

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

2.2 Quantities of measurement

Sound may be expressed in many ways depending upon the type of noise, and the parameters of the noise that allow it to be evaluated in terms of a biological effect. These are described below.

2.2.1 Sound Pressure level (SPL)

The 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 Root Mean Square (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 an SPL is used to characterise transient pressure waves, such as that from seismic airguns underwater blasting or impact piling, it is critical that the period over which the RMS level is calculated is quoted. For instance, in the case of a pile strike lasting, say, a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean taken over one second. Often transient sound such as these are quantified using "peak" SPLs.

2.2.2 Peak Sound Pressure Level (SPL_{peak})

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

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

2.2.3 Sound Exposure Level (SEL)

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

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

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

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

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

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

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

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

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

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

Weighted metrics for marine mammals have been proposed by Southall *et al.* (2019), which assign a frequency response to groups of marine mammals, and are discussed in detail in section 3.2.

3 Modelling methodology

To estimate the likely noise levels from the various sources at the MDZ, modelling has been carried out using an approach that is widely used and accepted by the acoustics community, in combination with Subacoustech's own measurement data, publicly available environmental data and information provided by Juno Energy. The approach is described in more detail below.

Modelling has been undertaken at various locations in the MDZ to predict levels of underwater noise from the proposed drilling, operational tidal turbines and ADDs. These are discussed in more detail in section 3.1.

Modelling of underwater noise is complex and can be approached in several different ways. Subacoustech has chosen to use a numerical approach that is based on two different solvers:

- A parabolic equation (PE) method for lower frequencies (12.5 Hz to 200 Hz); and
- A ray tracing method for higher frequencies (250 Hz to 100 kHz).

The PE method is widely used within the underwater acoustics community but has computational limitations at high frequencies. Ray tracing is more computationally efficient at higher frequencies but is not suited to low frequencies (Etter, 1991). This study utilised the dBSea software implementation of these numerical solutions.

These solvers account for a wide array of input parameters, including bathymetry, sediment data, sound speed and source frequency content to ensure as detailed results as possible. These input parameters are described in the following section.

3.1 Input parameters

The modelling takes full account of the environmental parameters within the study area and the characteristics of the noise source. The following parameters have been assumed for modelling.

3.1.1 Bathymetry and modelling locations

The bathymetry data used in the modelling was extracted from the 2018 EMODnet (European Marine Observation and Data Network) mean depth bathymetry dataset, which collates data from over 9,000 bathymetric surveys to a 1/16 arc-minute grid (approximately 115 m square). The extent to the bathymetry used is shown in Figure 1-1.

The chosen locations vary depending on the noise sources being modelled. The modelling locations for the single source investigations are shown in Figure 3-1 (Plot A), with a worst-case location for small tidal turbines in the north west of the MDZ used for percussive drilling and ADD modelling. This position was chosen due to its location near to the deep water to the west of the site, which tends to maximise noise propagation. The modelling location chosen for the single large tidal turbine (the southernmost point in Plot A) is different as there are fewer turbine locations.

Also in Figure 3-1 are the modelling locations used for the multiple location modelling, including 620 individual locations (Plot B) for the small tidal turbines with a minimum spacing of approximately 100 m, and 120 locations (Plot C) for the dual-rotor large tidal turbines, with a minimum spacing of approximately 230 m.

As modelling is undertaken at various depths, ranges and calculations presented in this report have used the worst-case assumption that the receptor is present in the loudest part of the water column at any location.

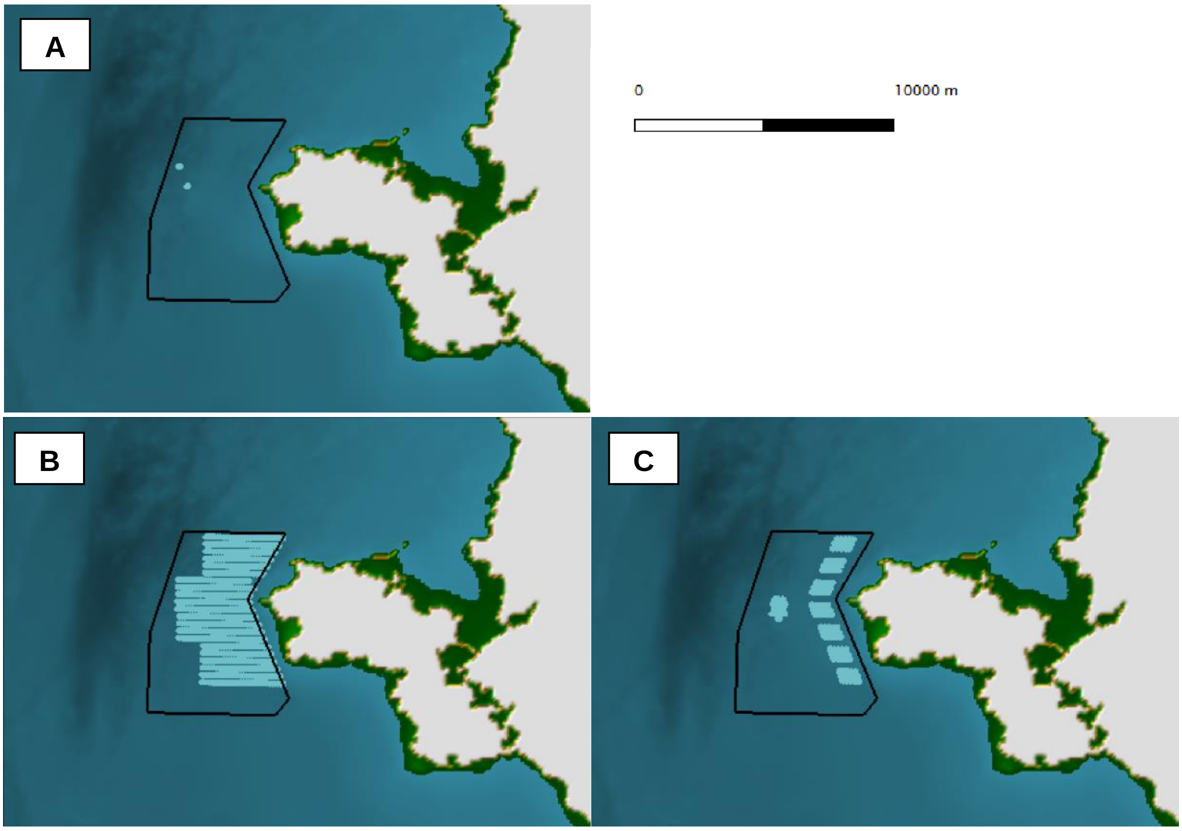

Figure 3-1 Plots showing the locations used for modelling. Plot A shows locations for percussive drilling, single small tidal turbine, and ADDs (northernmost point) and single large tidal turbine (southernmost point). Plot B shows the 620 locations for small tidal turbines. Plot C shows the 120 locations for large tidal turbines.

3.1.2 <u>Sound speed profile</u>

The speed of sound in the water has been calculated using the equation from Mackenzie (1981) and salinity data from Evans *et al.* (2003). The resulting profile is shown in Figure 3-2.

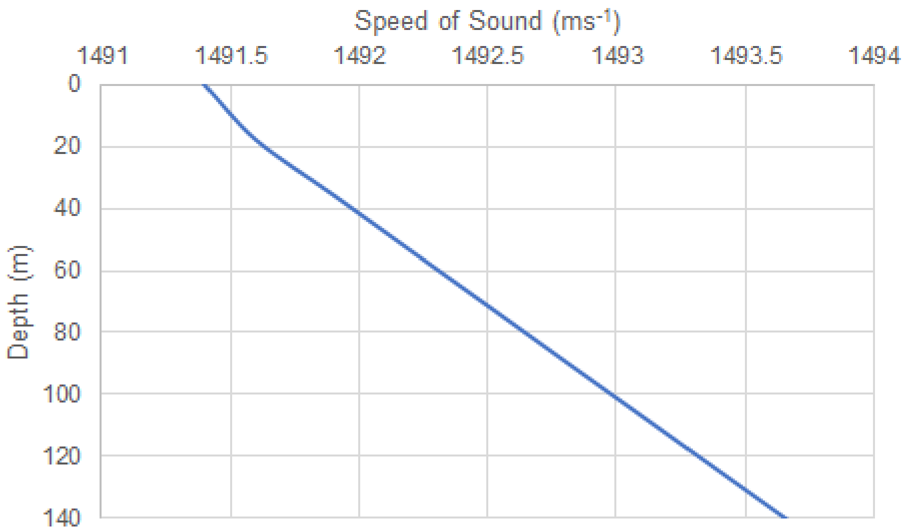

Figure 3-2 Sound speed profile used for modelling

3.1.3 Seabed properties

Using data provided for the seabed at the MDZ, a mixture of sand and gravel has been used for modelling, using geo-acoustic properties based on Jensen *et al.* (2011).

Compressive sound speed profile in substrate (ms^{-1})	Density profile in substrate (kg/m^3)	Attenuation profile in substrate (dB/wavelength)
1688	1850	0.8

Table 3-1 Seabed geo-acoustic properties

3.1.4 Source levels and frequencies

Measured data of percussive drilling has been used from Subacoustech Environmental's noise database and scaled to approximate the type of drilling that could take place at the MDZ. The measurements are of a percussive drilling rig with a power output of 51.5 kW. To install the foundations at the MDZ it is expected that a drill with a power output of 300 kW would be required to install foundation piles of up to 3 m in diameter.

A simple scaling factor has been used to extrapolate the source level of the percussive drilling rig for the MDZ is given below with the two P values representing the two power values in kW.

$$Scaling\ factor\ (dB) = 10 \times \log_{10}\left(\frac{P_1}{P_2}\right)$$

Using this scaling factor an increase of 7.7 dB has been added to the source level of the existing measurement data, resulting in an SPL_{RMS} source level for percussive drilling of **175.9 dB re 1 µPa @ 1 m**. The frequency spectra used as an input for modelling is given in Figure 3-3, with the majority of the energy concentrated in the lower frequency bands.

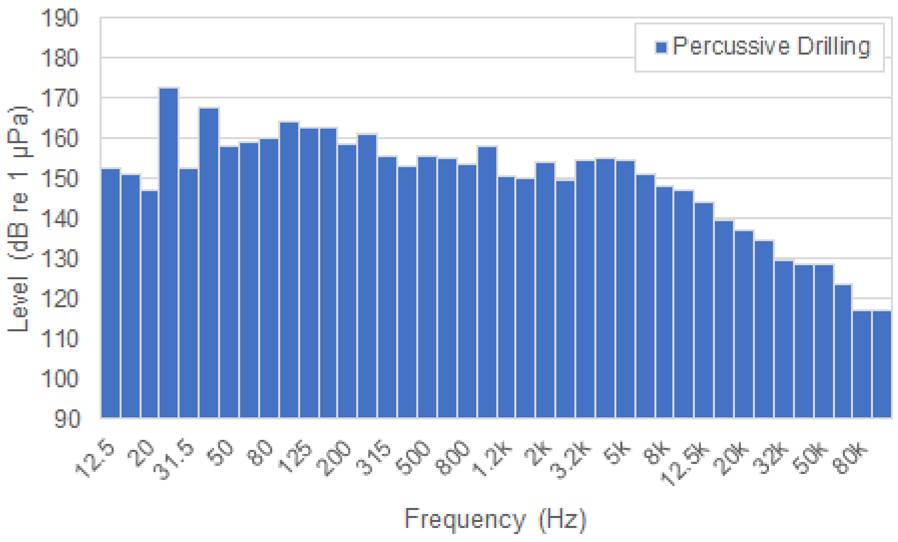

Figure 3-3 Source ⅓ octave band levels used for modelling percussive drilling (SPL_{RMS})

Input parameters for operational tidal turbines has been derived from data from Subacoustech Environmental's measurement database with the source level scaled based on the rotor diameter of the proposed tidal turbine. As mentioned in section 1.1.2, two models of tidal turbine are being modelled, a small turbine with a rotor diameter of 16.13 m and a larger turbine consisting of two rotors, each measuring 24.6 m in diameter.

The scaling factor used here is based on various measurements of different sized turbines, and results in the following source levels for modelling:

- 16.13 m diameter rotor tidal turbine (small) – **155.7 dB re 1 µPa @ 1 m** (SPL_{RMS}), and
- Dual 24.6 m diameter rotor tidal turbine (large) – **161.2 dB re 1 µPa @ 1 m** (SPL_{RMS}).

The operational tidal turbine frequency spectra used as inputs for modelling are given in Figure 3-4, and show a relatively flat response across the ⅓ octave bands.

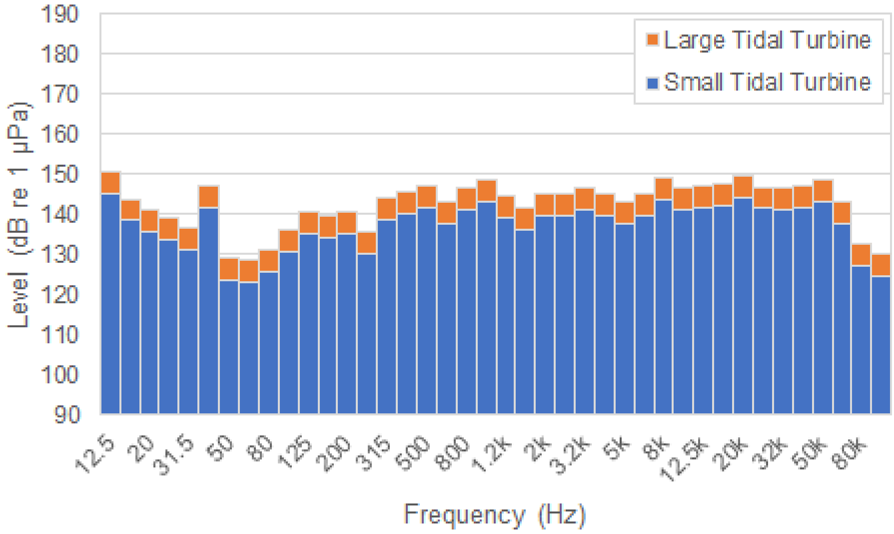

Figure 3-4 Source ⅓ octave band levels used for modelling both sizes of operational tidal turbines (SPL_{RMS})

The Lofitech *Seal Scarer* has been used to model the effect of ADDs at the MDZ as it is one of the loudest ADDs on the market. Modelling used measurements of the device by Subacoustech Environmental (Nedwell *et al*. 2010) and additional information from Brandt *et al*. (2013), which investigated the device's effectiveness on harbour porpoises. A source level of **182.7 dB re 1 µPa @ 1 m** (SPL_{RMS}) has been used, along with the ⅓ octave frequency spectra shown in Figure 3-5. The main output of the Lofitech ADD is high-level pulses at 14.5 kHz, as shown by the spike in Figure 3-5.

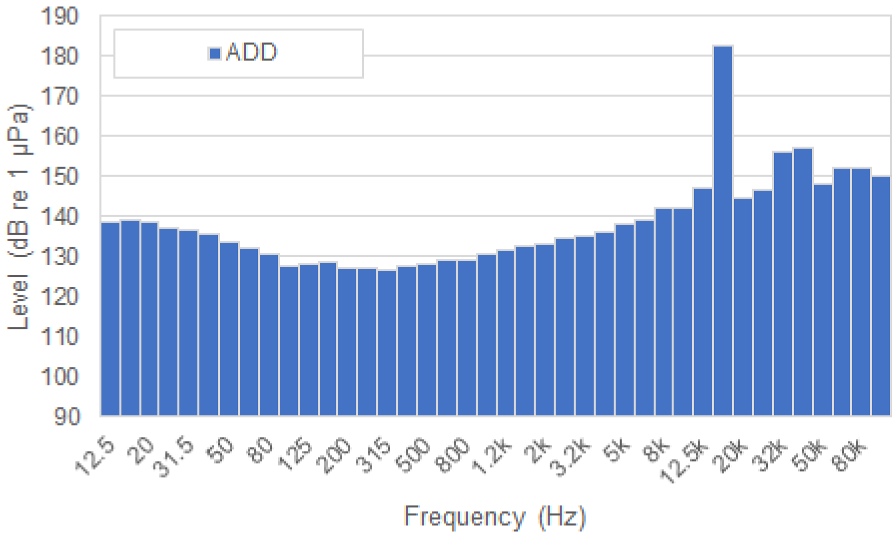

Figure 3-5 Source ⅓ octave band levels used for modelling noise from ADDs (SPL_{RMS})

In all the above scenarios, where cumulative SEL criteria are used, a 24-hour continuous noise has been assumed as a worst case.

3.2 Assessment criteria

Over the past 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 underwater sound might cause an adverse impact in a species is dependent upon the incident sound level, sound frequency, duration of exposure and/or repetition rate of an impulsive sound (see for example Hastings and Popper, 2005). As a result, scientific interest in the hearing abilities of aquatic 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 can be broadly summarised into three categories:

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

The metrics and criteria that have been used in this study to assess environmental effect on marine mammals are from Southall *et al*. (2019). These are discussed in more detail in the following sections.

3.2.1 Marine mammals

Since it was published, Southall *et al.* (2007) has been the source of the most widely used criteria to assess the effects of noise on marine mammals. Southall *et al*. (2019) was co-authored by many of the same academics as the Southall *et al*. (2007) paper and effectively updates it. In the updated guidelines, the frequency weightings have changed along with the impact thresholds. As a result, the criteria have generally become more strict.

The Southall *et al*. (2019) guidance groups marine mammals into functional hearing groups and applies filters to the unweighted noise to approximate the hearing response of the receptor. These hearing groups are summarised in Table 3-2. The auditory weighting functions for each hearing group are provided in Figure 3-6.

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

Table 3-2 Marine mammal hearing groups (from Southall et al. 2019)

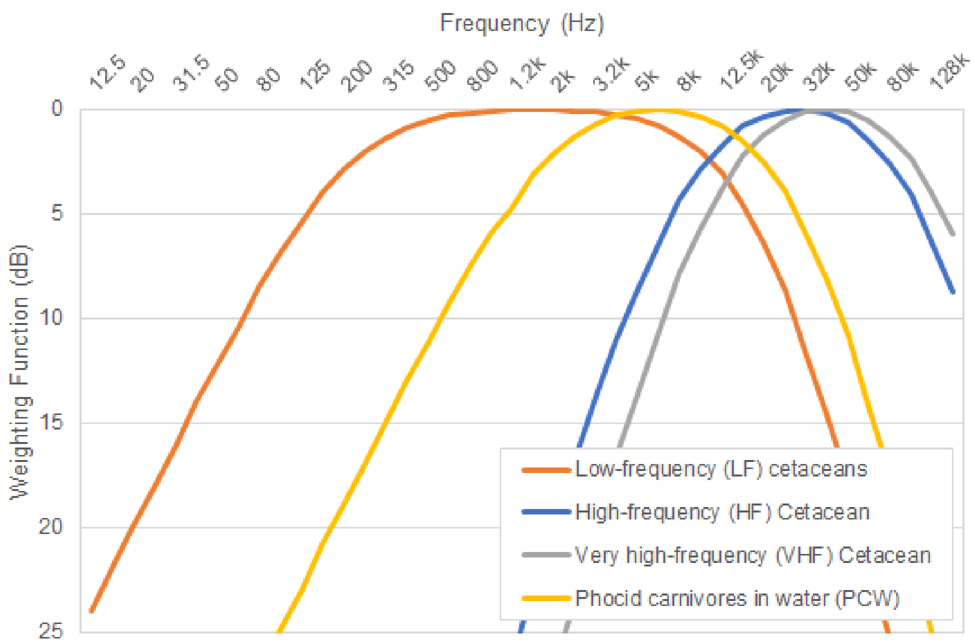

Figure 3-6 Auditory functions for low-frequency (LF) cetaceans, high-frequency (HF) cetaceans, very high-frequency (VHF) cetaceans, phocid carnivores in water (PCW) (from Southall et al. 2019)

Several specific species have been identified as of importance in the areas surrounding the MDZ. These fall into the following Southall *et al.* (2019) hearing groups:

- Harbour porpoise (VHF)
- Bottlenose dolphin, Risso's dolphin and common dolphin (HF)
- Minke whale (LF)
- Grey and harbour seal (PCW)

Southall *et al*. (2019) presents unweighted peak criteria (SPL_{peak}) and cumulative, 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 addition, Southall *et al*. (2019) also gives individual criteria based on whether the noise source is considered impulsive or non-impulsive. Southall *et al*. (2019) 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 (a non-impulsive sound does not necessarily have to have a long duration). The noise sources in this study are all considered non-pulses. Table 3-3 summarises the Southall *et al*. (2019) criteria for onset of risk of PTS and TTS for each of the key marine mammal hearing groups for non-impulsive noise.

Functional group	**PTS criteria** (Weighted SEL_{cum} dB re 1 µPa^{2}s)	**TTS criteria** (Weighted SEL_{cum} dB re 1 µPa^{2}s)
Low Frequency (LF) Cetaceans	199	179
High Frequency (HF) Cetaceans	198	178
Very High Frequency (VHF) Cetaceans	173	153
Phocid Carnivores in Water (PCW)	201	181

Table 3-3 Assessment criteria for marine mammals from Southall et al. (2019) for non-impulsive noise

For the SEL_{cum} criteria a swimming animal model has been used, which assumes that the receptor, when exposed to high noise levels, will swim away from the noise source. A constant swimming speed of 3.25 ms^{-1} has been assumed for the low-frequency cetaceans (LF) (Blix and Folkow, 1995) based on data for minke whale. For other receptors a constant rate of 1.5 ms^{-1} has been assumed, which is a cruising speed for harbour porpoise (Otani *et al*., 2001).

Some recent studies have used criteria from NMFS (2018) to assess effects on marine mammals, however the criteria given are numerically identical to those in Southall *et al*. (2019).I It should also be noted that the criteria in NMFS (2018) apply different names to the marine mammal groupings and weightings. For example, what Southall *et al*. (2019) calls high-frequency cetaceans (HF), NMFS (2018) calls mid-frequency cetaceans (MF) and what Southall et al. (2019) calls very high-frequency cetaceans (VHF), NMFS (2018) refers to as high-frequency cetaceans. As such, care should be taken when comparing results using the Southall *et al*. (2019) and NMFS (2018) criteria, especially as the HF groupings and criteria cover different species depending on which study is being used.

The Southall *et al*. (2019) criteria has been used for this study as it is a peer-reviewed and published paper in a reputable journal, whereas NMFS (2018) is a guidance document from a government agency and as such could be subject to changes at any point.

3.2.2 Weighted source levels

To undertake the modelling with regards to the weighted criteria, the source levels and frequencies were first adjusted using the auditory weighting functions shown in Figure 3-6. This significantly alters the source level for each functional group as shown in Figure 3-7 for the large tidal turbine ⅓ octave frequency spectra. The equivalent source levels used for modelling are summarised in Table 3-4, showing, for example, how the high frequencies (above 10 kHz) are reduced using the LF filter, and the low frequencies (below 1 kHz) are removed for the HF and VHF filters.

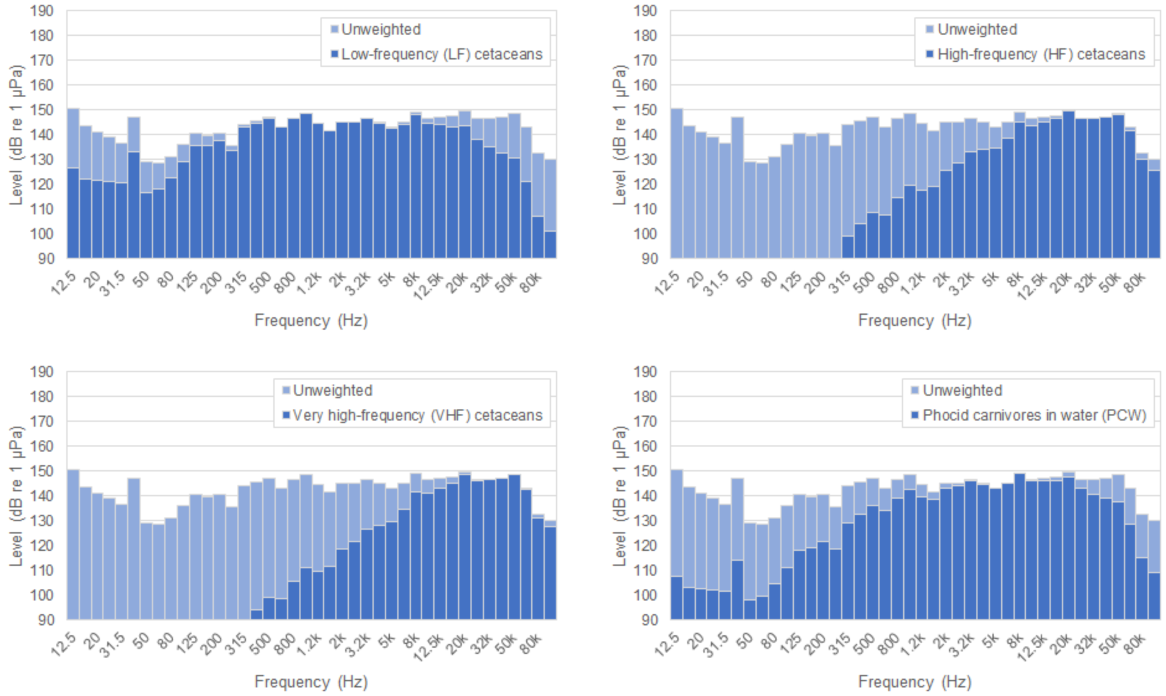

Figure 3-7 Unweighted and Southall et al. (2019) weighted RMS source level ⅓ octave values for the large tidal turbine source

RMS Source Level (dB re 1 µPa @ 1 m)	**Percussive drilling**	**Small tidal turbine**	**Large tidal turbine**	**ADD**
Unweighted	175.9	155.7	161.2	182.7
Low Frequency (LF) Cetaceans	168.6	152.6	158.1	178.2
High Frequency (HF) Cetaceans	153.0	151.1	156.6	181.9
Very High Frequency (VHF) Cetaceans	149.3	150.3	155.8	180.5
Phocid Carnivores in Water (PCW)	162.5	151.7	157.2	181.2

Table 3-4 Summary of the Southall et al. (2019) weighted source levels at 1 metre used for modelling

3.2.3 Disturbance

A key part of this investigation considers disturbance of receptors, but there are very few specific criteria as there is a lot of conflicting information on the subject. Disturbance is a broader and less measurable response, when compared to hearing injury (PTS and TTS). The Southall *et al*. (2019) criteria only covers injury in marine mammals, and as such additional criteria have been used. These are:

- Southall *et al*. (2007) recommends a low-end threshold of **120 dB (SPL_{RMS})** for continuous noise disturbance for marine mammals. The paper presents a large amount of data where various investigations have reported behavioural disturbance with regards to sound, with louder levels causing disturbance, but 120 dB (RMS) being the quietest. It should be noted that 120 dB SPL_{RMS} is approaching the order of background noise in some areas (Nedwell *et al.* 2003, 2007).
- At an unweighted median received level of **142 dB (SPL_{RMS})**, Hastie *et al*. (2018) identified a significant reduction in harbour seal from operational tidal turbine noise. This is the most specific and relevant disturbance threshold available for this type of assessment.

Unweighted RMS levels in 10 dB increments have been presented as part of the modelling results, so that further assessments regarding disturbance can be made.

4 Modelling results

4.1 Drilling

The unweighted SPL_{RMS} noise levels from the modelled percussive drilling operations are presented in Figure 4-1, showing the maximum predicted level in the water column. Cross sections of two transects; 270° into deeper water and 80° towards the Anglesey coast, are presented in Figure 4-2 and Figure 4-3 showing the distribution of noise through the water column. These results are presented and analysed for their effect on species of marine mammals in Table 4-1 to Table 4-3. Where cumulative SELs are considered, a worst-case duration of 24 hours has been assumed.

The results show that injury may only occur at very close ranges to the drilling operations (i.e. less than 10 m), with disturbance potentially occurring out to a maximum range of 6.9 km mainly due to the lower frequencies present in the drilling noise, compared to the other noise sources being considered.

Also of note, in Figure 4-2 and Figure 4-3 the differences in noise levels within the water column can be seen with sound transmitting further through mid-water and attenuating more at the surface and seabed.

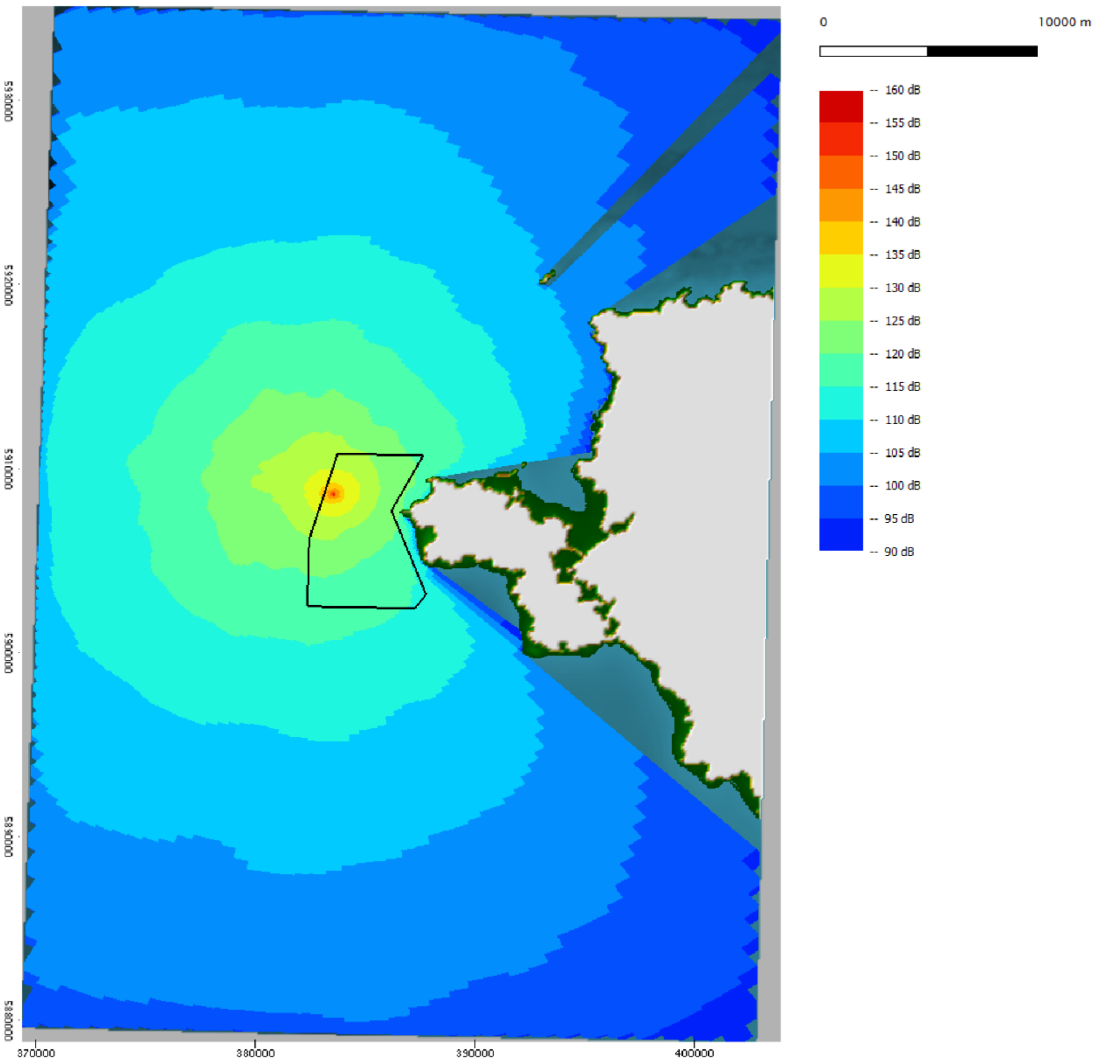

Figure 4-1 Percussive drilling noise plot, single location, unweighted SPL_{RMS}

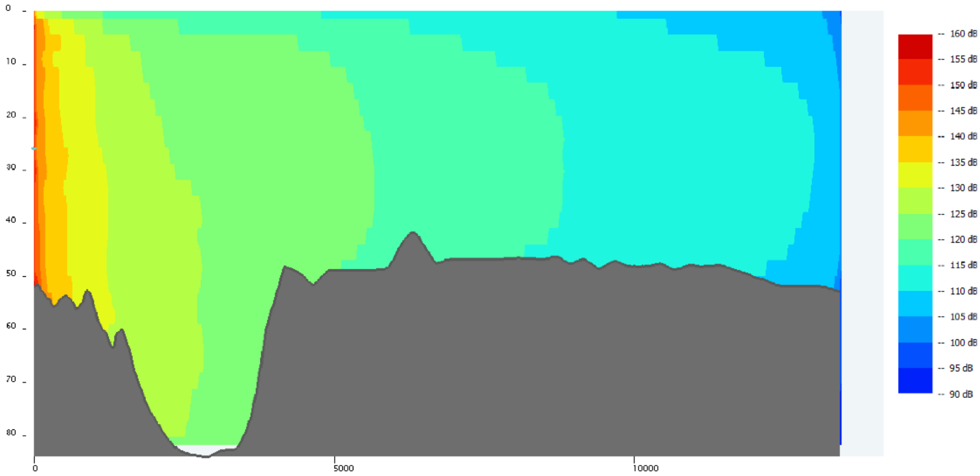

Figure 4-2 Cross section of the deep, 270° transect from percussive drilling, unweighted SPL_{RMS}

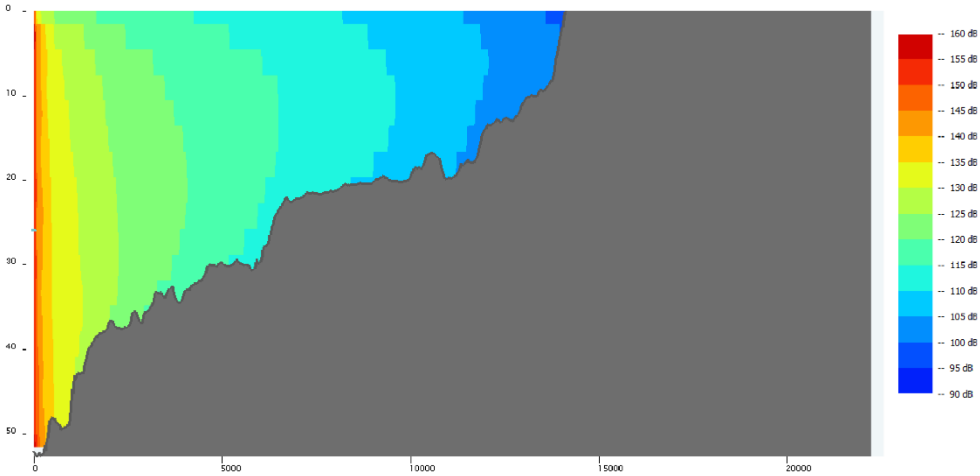

Figure 4-3 Cross section of the shallow, 080° transect from percussive drilling, unweighted SPL_{RMS}

Percussive drilling	**Maximum range**	**Mean range**	**Minimum range**
200 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
190 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
180 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
170 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
160 dB re 1 µPa (RMS)	20 m	20 m	20 m
150 dB re 1 µPa (RMS)	120 m	120 m	120 m
140 dB re 1 µPa (RMS)	390 m	360 m	330 m
130 dB re 1 µPa (RMS)	1.7 km	1.4 km	1.2 km
120 dB re 1 µPa (RMS)	6.9 km	5.0 km	3.2 km *
110 dB re 1 µPa (RMS)	15 km	12 km	3.2 km *
100 dB re 1 µPa (RMS)	30 km	19 km	3.2 km *

Table 4-1 Summary of the modelled unweighted SPL_{RMS} ranges for noise from percussive drilling operations in 10 dB increments (ranges where the coast is met, providing a restricted figure, are designated with an asterisk)

Percussive drilling			**Maximum range**	**Mean range**	**Minimum range**
Low-frequency (LF) cetaceans	PTS	199 dB	< 10 m	< 10 m	< 10 m
	TTS	179 dB	< 10 m	< 10 m	< 10 m
High-frequency (HF) cetaceans	PTS	198 dB	< 10 m	< 10 m	< 10 m
	TTS	178 dB	< 10 m	< 10 m	< 10 m
Very high-frequency (VHF) cetaceans	PTS	173 dB	< 10 m	< 10 m	< 10 m
	TTS	153 dB	< 10 m	< 10 m	< 10 m
Phocid carnivores in water (PCW)	PTS	201 dB	< 10 m	< 10 m	< 10 m
	TTS	181 dB	< 10 m	< 10 m	< 10 m

Table 4-2 Summary of the modelled impact ranges covering the Southall et al. (2019) weighted SEL_{cum} injury criteria for percussive drilling assuming a swimming animal

Percussive drilling	**Maximum range**	**Mean range**	**Minimum range**
142 dB re 1 µPa (RMS)	300 m	280 m	260 m
120 dB re 1 µPa (RMS)	6.9 km	5.0 km	3.2 km *

Table 4-3 Summary of the modelled SPL_{RMS} disturbance impact ranges for percussive drilling using the criteria from Southall et al. (2007) and Hastie et al. (2018)

4.2 Operational tidal turbines

4.2.1 Small turbine layout

Figure 4-4 shows an unweighted SPL_{RMS} noise plot from the small tidal turbine design (16.13 m diameter rotor) at a single location. Table 4-4 to Table 4-6 show that injury is only predicted in marine mammals at a close range, with the Southall *et al*. (2019) TTS criteria being met at 50 m for VHF cetaceans. Disturbance is predicted out to a maximum of 620 m using the 120 dB re 1 µPa (RMS) criteria. Cross sections of the noise are given in Figure 4-5 and Figure 4-6. Modelling of the 620 concurrent tidal turbine locations is presented in section 4.2.3.

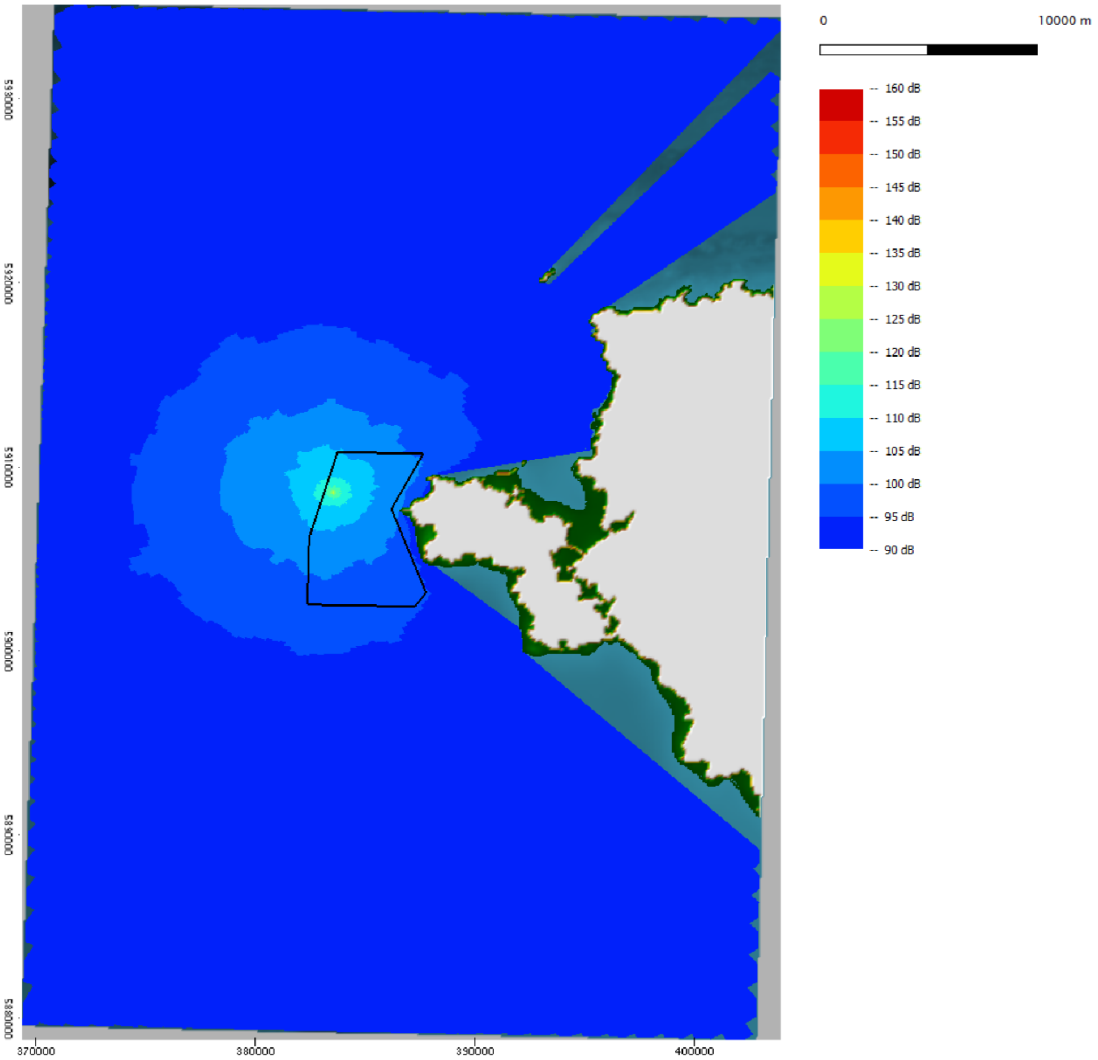

Figure 4-4 Small tidal turbine noise plot (16.13 m diameter rotor), single location, unweighted SPL_{RMS}

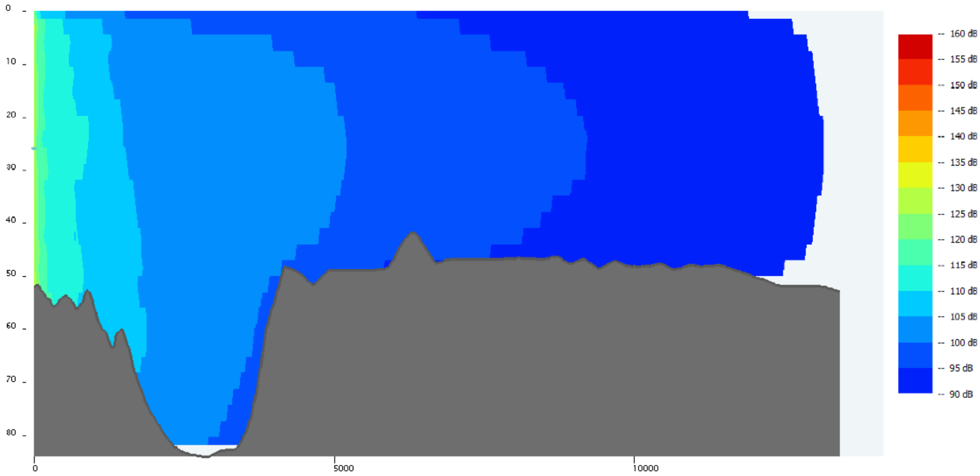

Figure 4-5 Cross section of the deep, 270° transect from the small tidal turbine, unweighted SPL_{RMS}

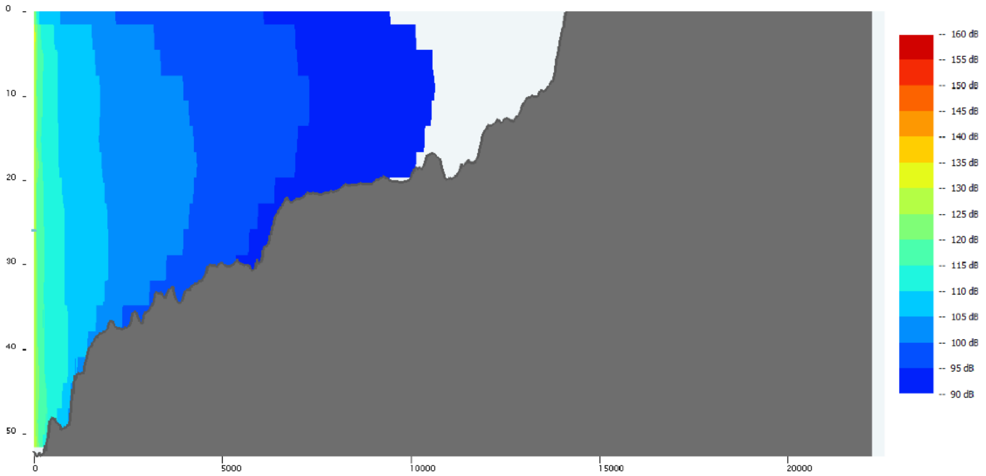

Figure 4-6 Cross section of the shallow, 080° transect from the small tidal turbine, unweighted SPL_{RMS}

Small tidal turbine (single location)	**Maximum range**	**Mean range**	**Minimum range**
200 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
190 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
180 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
170 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
160 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
150 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
140 dB re 1 µPa (RMS)	30 m	30 m	30 m
130 dB re 1 µPa (RMS)	140 m	130 m	120 m
120 dB re 1 µPa (RMS)	620 m	560 m	510 m
110 dB re 1 µPa (RMS)	2.0 km	1.8 km	1.6 km
100 dB re 1 µPa (RMS)	7.5 km	6.1 km	3.2 km *

Table 4-4 Summary of the modelled unweighted SPL_{RMS} ranges for noise from the small operational tidal turbine, at a single location, in 10 dB increments (ranges where the coast is met, providing a restricted figure, are designated with an asterisk)

Small tidal turbine (single location)			**Maximum range**	**Mean range**	**Minimum range**
Low-frequency (LF) cetaceans	PTS	199 dB	< 10 m	< 10 m	< 10 m
	TTS	179 dB	< 10 m	< 10 m	< 10 m
High-frequency (HF) cetaceans	PTS	198 dB	< 10 m	< 10 m	< 10 m
	TTS	178 dB	< 10 m	< 10 m	< 10 m
Very high-frequency (VHF) cetaceans	PTS	173 dB	< 10 m	< 10 m	< 10 m
	TTS	153 dB	50 m	40 m	40 m
Phocid carnivores in water (PCW)	PTS	201 dB	< 10 m	< 10 m	< 10 m
	TTS	181 dB	< 10 m	< 10 m	< 10 m

Table 4-5 Summary of the modelled impact ranges covering the Southall et al. (2019) weighted SEL_{cum} injury criteria for a single small operational tidal turbine assuming a swimming animal

Small tidal turbine (single location)	**Maximum range**	**Mean range**	**Minimum range**
142 dB re 1 µPa (RMS)	20 m	20 m	20 m
120 dB re 1 µPa (RMS)	620 m	560 m	510 m

Table 4-6 Summary of the modelled SPL_{RMS} disturbance impact ranges for a single small operational tidal turbine using the criteria from Southall et al. (2007) and Hastie et al. (2018)

4.2.2 Large turbine layout

The noise levels from the large tidal turbine (with dual 24.6 m diameter rotors) are presented in Figure 4-7 to Figure 4-9 and Table 4-7 to Table 4-9. As expected they are higher than those predicted for the small tidal turbine, due to the higher source level for the larger turbine. Injury is only predicted in marine mammals at a close range, with the Southall *et al*. (2019) TTS criteria resulting in the largest impact range for VHF cetaceans of 230 m. Disturbance is predicted out to 1.3 km using the 120 dB re 1 µPa (RMS) criteria. The noise levels from tidal turbine noise at all 120 locations for the larger turbine model is presented in section 4.2.3.

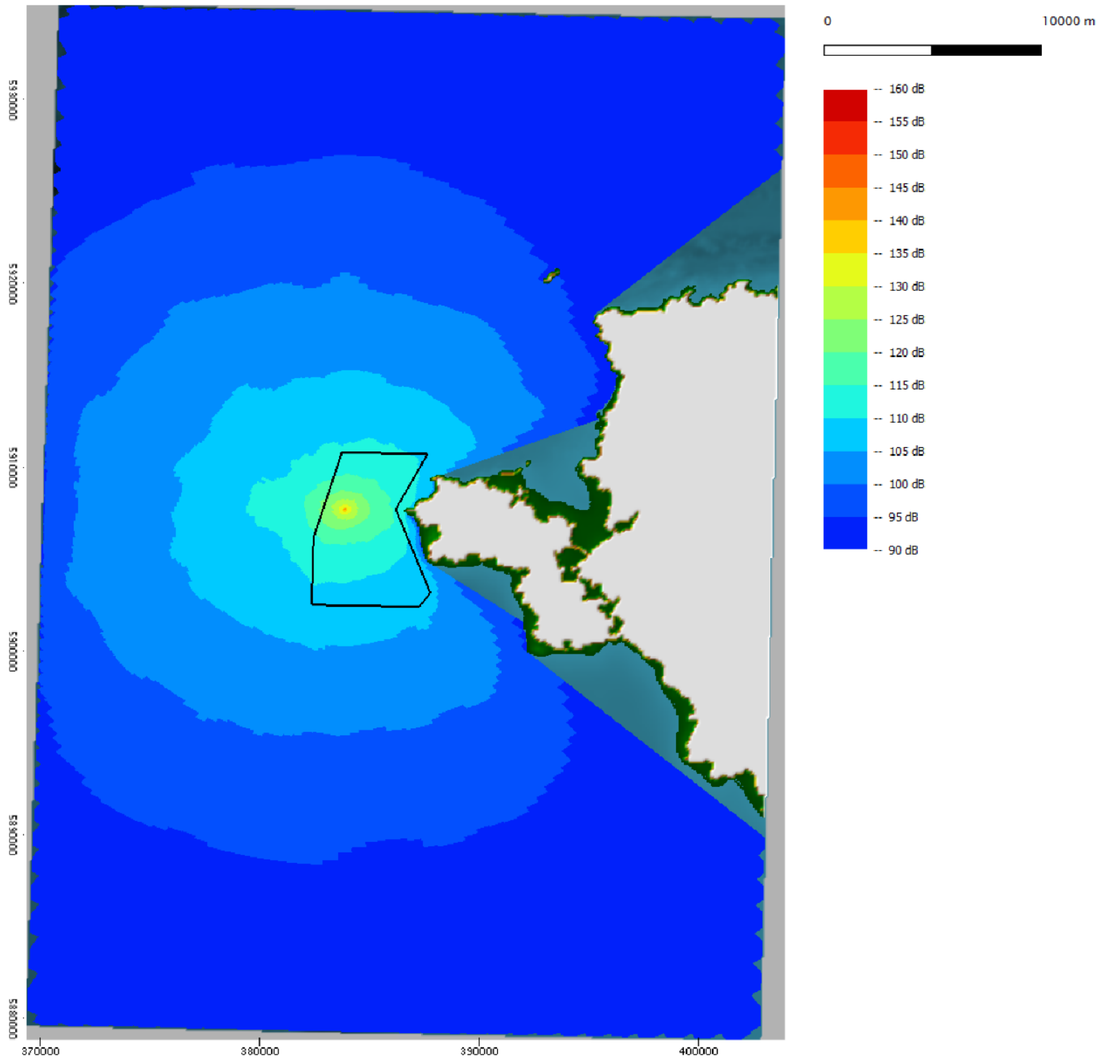

Figure 4-7 Large tidal turbine noise plot (dual 24.6 m diameter rotors), single location, unweighted SPL_{RMS}

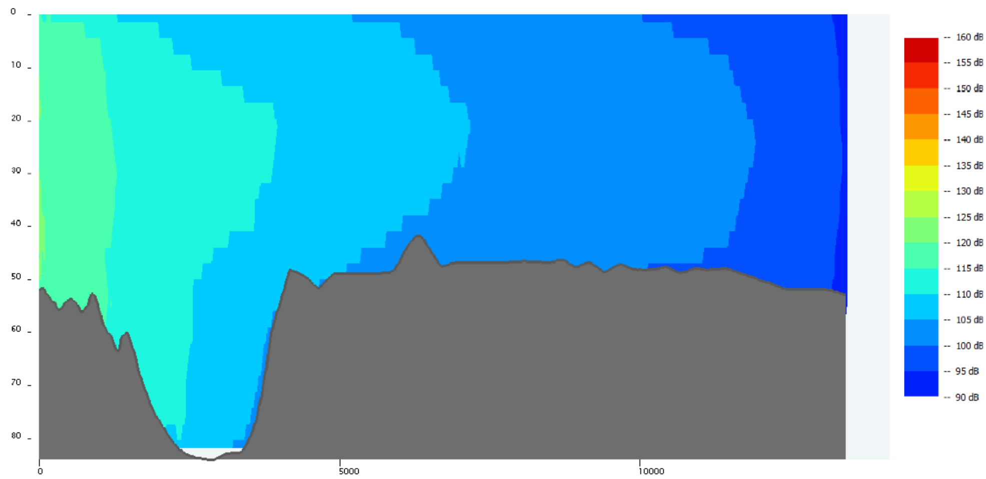

Figure 4-8 Cross section of the deep, 270° transect from the large tidal turbine, unweighted SPL$_{RMS}$

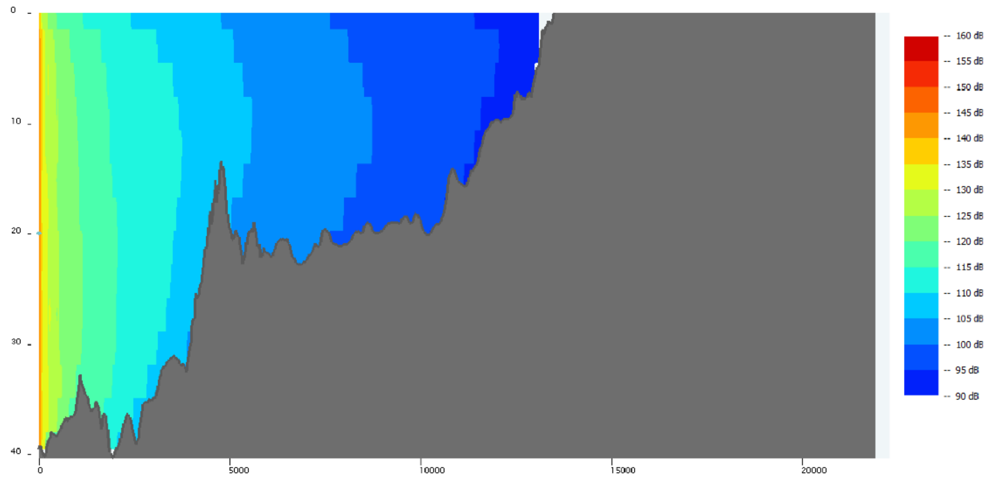

Figure 4-9 Cross section of the deep, 080° transect from the large tidal turbine, unweighted SPL$_{RMS}$

Large tidal turbine (2 rotors) (single location)	Maximum range	Mean range	Minimum range
200 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
190 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
180 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
170 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
160 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
150 dB re 1 µPa (RMS)	20 m	20 m	20 m
140 dB re 1 µPa (RMS)	90 m	90 m	80 m
130 dB re 1 µPa (RMS)	360 m	340 m	310 m
120 dB re 1 µPa (RMS)	1.3 km	1.1 km	1.0 km
110 dB re 1 µPa (RMS)	4.6 km	3.9 km	2.7 km
100 dB re 1 µPa (RMS)	34 km	11 km	2.8 km *

Table 4-7 Summary of the modelled unweighted SPL$_{RMS}$ ranges for noise from the large operational tidal turbine (2 rotors), at a single location, in 10 dB increments (ranges where the coast is met, providing a restricted figure, are designated with an asterisk)

Large tidal turbine (2 rotors) (single location)			**Maximum range**	**Mean range**	**Minimum range**
Low-frequency (LF) cetaceans	PTS	199 dB	< 10 m	< 10 m	< 10 m
	TTS	179 dB	< 10 m	< 10 m	< 10 m
High-frequency (HF) cetaceans	PTS	198 dB	< 10 m	< 10 m	< 10 m
	TTS	178 dB	< 10 m	< 10 m	< 10 m
Very high-frequency (VHF) cetaceans	PTS	173 dB	< 10 m	< 10 m	< 10 m
	TTS	153 dB	230 m	200 m	180 m
Phocid carnivores in water (PCW)	PTS	201 dB	< 10 m	< 10 m	< 10 m
	TTS	181 dB	< 10 m	< 10 m	< 10 m

Table 4-8 Summary of the modelled impact ranges covering the Southall et al. (2019) weighted SEL_{cum} injury criteria for a single large operational tidal turbine (2 rotors) assuming a swimming animal

Large tidal turbine (2 rotors) (single location)	**Maximum range**	**Mean range**	**Minimum range**
142 dB re 1 µPa (RMS)	70 m	60 m	60 m
120 dB re 1 µPa (RMS)	1.3 km	1.1 km	1.0 km

Table 4-9 Summary of the modelled SPL_{RMS} disturbance impact ranges for a single large operational tidal turbine (2 rotors) using the criteria from Southall et al. (2007) and Hastie et al. (2018)

4.2.3 Cumulative impacts

Figure 4-10 and Figure 4-11 present noise plots for operational tidal turbines, considering all the locations presented in Figure 3-1. Both figures use the same spatial and colour scale so can be directly compared.

The results show that overall noise levels are louder overall for the small turbines at 620 locations than they are for large turbines at 120 locations. Although the large turbines are louder individually, the fact that there are 400 fewer locations, and the locations are more spaced out, results in a lower overall level.

It should be noted that tables of impact ranges have not been given for these cumulative impacts due to there being multiple source locations.

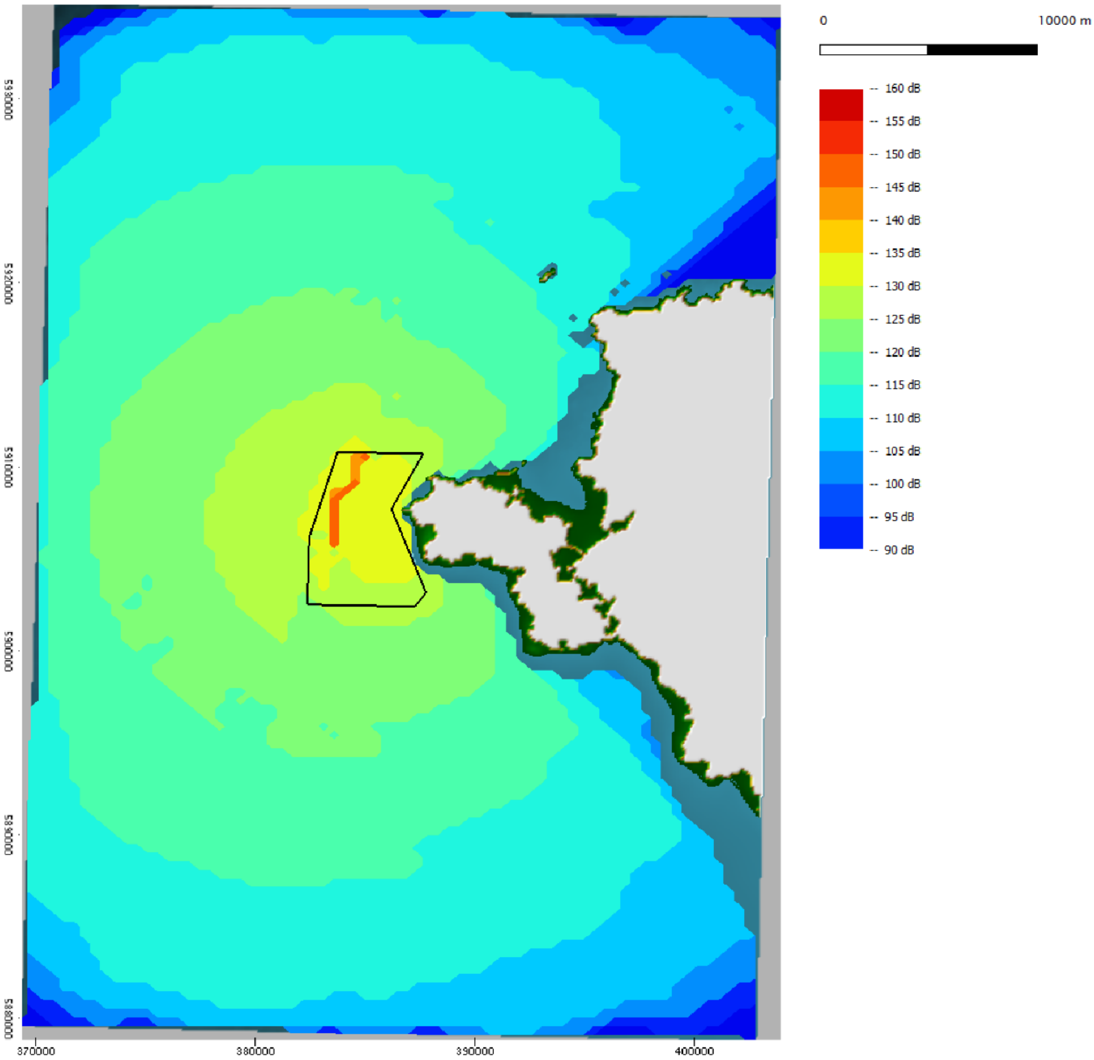

Figure 4-10 Small tidal turbine noise plot (16.13 m diameter rotor), 620 locations, unweighted SPL_{RMS}

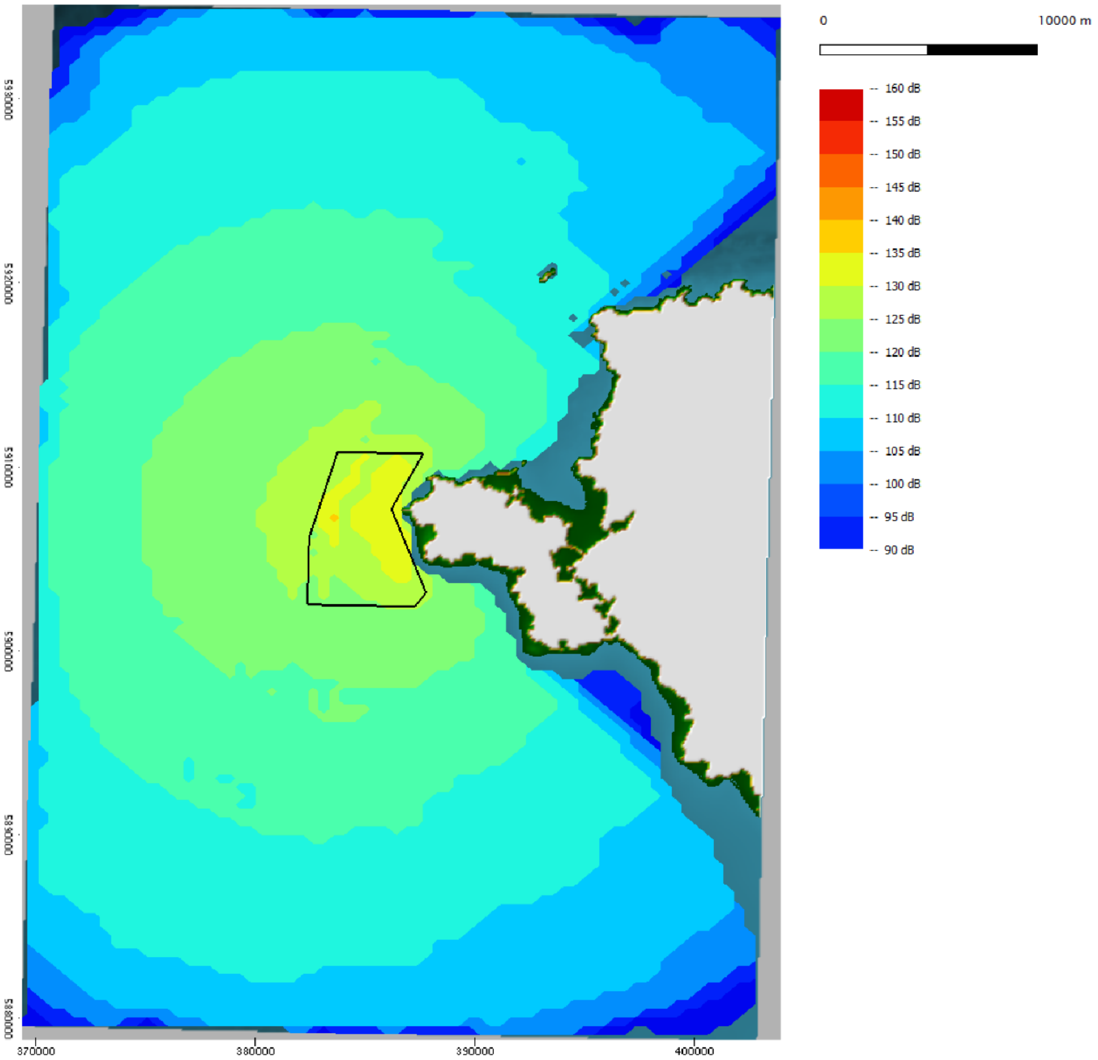

Figure 4-11 Large tidal turbine noise plot (dual 24.6 m diameter rotors), 120 locations, unweighted SPL_{RMS}

4.3 ADDs

Figure 4-12 shows the unweighted SPL_{RMS} noise plot for an ADD, with cross sections in Figure 4-13 and Figure 4-14. The source level and noise at close range is louder than the other sources, however the noise reduces towards background at a faster rate due to much of the noise being high frequency, which attenuates at a faster rate than lower frequency noise.

The results in Table 4-10 to Table 4-12 show that noise from the modelled ADD is louder than the noise from tidal turbine noise (section 4.2), with possible TTS injury using the Southall *et al.* (2019) criteria for VHF cetaceans out to a maximum 5.3 km due to the high-frequency nature of the ADD noise. Disturbance is predicted out to 6.7 km from the operational ADD, although the disturbance range in practice is generally much lower than this (Brandt *et al.* 2013).

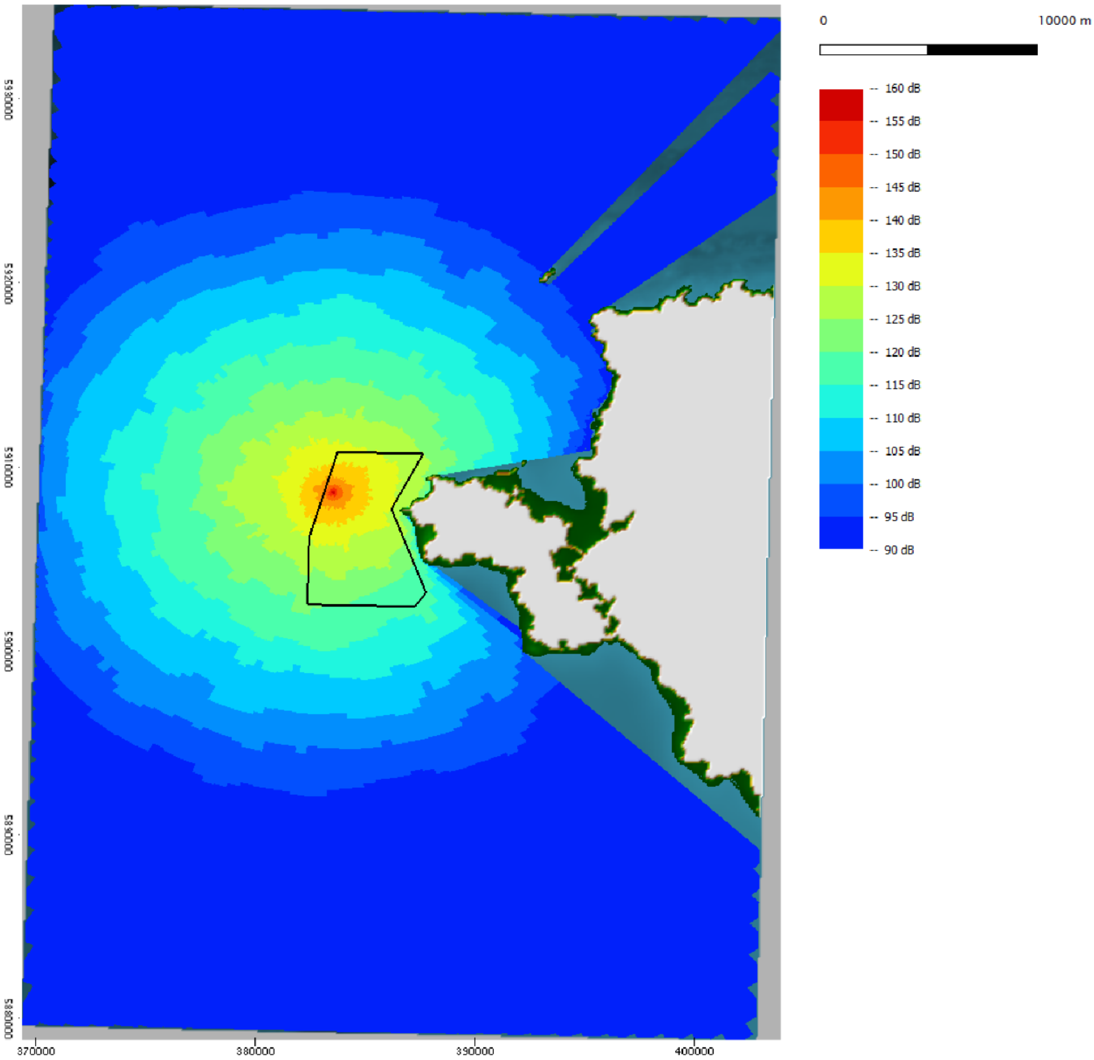

Figure 4-12 ADD noise plot, single location, unweighted SPL_{RMS}

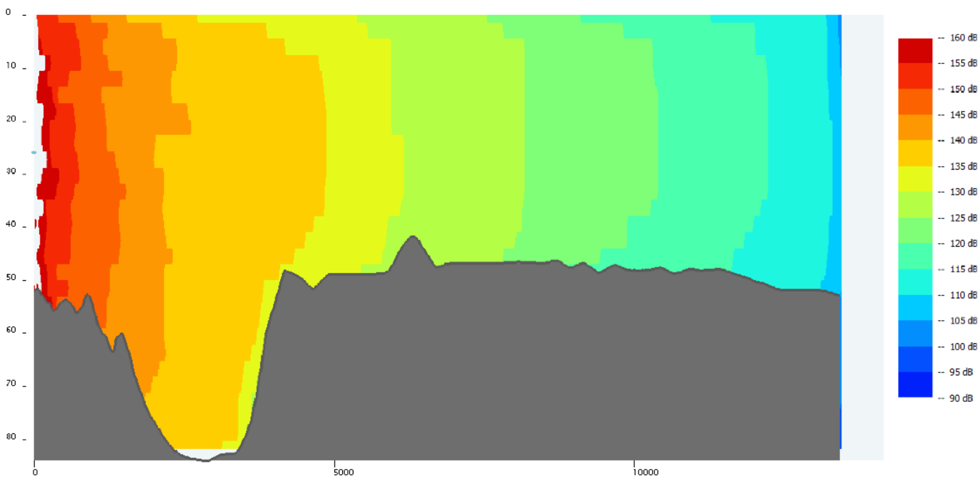

Figure 4-13 Cross section of the deep, 270° transect from ADD noise, unweighted SPL_{RMS}

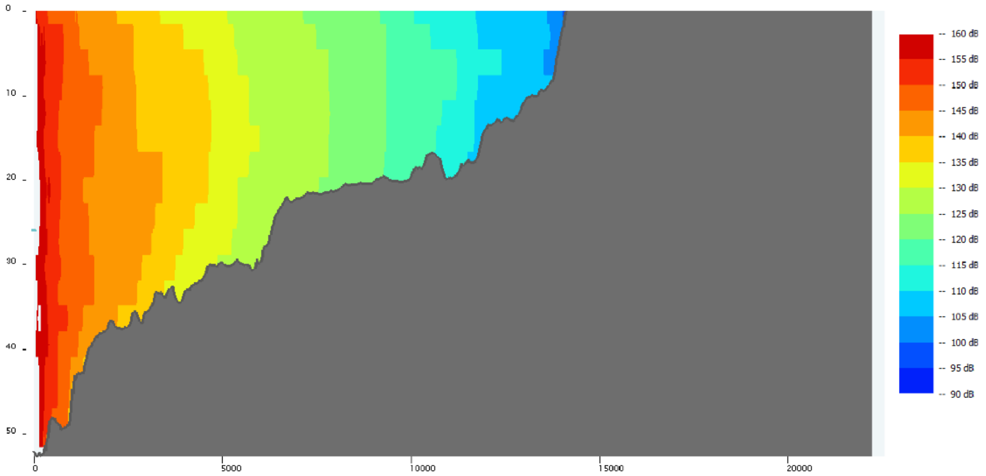

Figure 4-14 Cross section of the deep, 080° transect from ADD noise, unweighted SPL_{RMS}

ADDs	Maximum range	Mean range	Minimum range
200 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
190 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
180 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
170 dB re 1 µPa (RMS)	< 10 m	< 10 m	< 10 m
160 dB re 1 µPa (RMS)	40 m	30 m	30 m
150 dB re 1 µPa (RMS)	270 m	210 m	160 m
140 dB re 1 µPa (RMS)	1.0 km	830 m	680 m
130 dB re 1 µPa (RMS)	3.3 km	2.7 km	2.2 km
120 dB re 1 µPa (RMS)	6.7 km	5.7 km	3.2 km *
110 dB re 1 µPa (RMS)	11 km	9.0 km	3.2 km *
100 dB re 1 µPa (RMS)	15 km	12 km	3.2 km *

Table 4-10 Summary of the modelled unweighted SPL_{RMS} ranges for noise from ADDs in 10 dB increments (ranges where the coast is met, providing a restricted figure, are designated with an asterisk)

ADDs			Maximum range	Mean range	Minimum range
Low-frequency (LF) cetaceans	PTS	199 dB	< 10 m	< 10 m	< 10 m
	TTS	179 dB	10 m	10 m	10 m
High-frequency (HF) cetaceans	PTS	198 dB	< 10 m	< 10 m	< 10 m
	TTS	178 dB	50 m	20 m	20 m
Very high-frequency (VHF) cetaceans	PTS	173 dB	220 m	100 m	70 m
	TTS	153 dB	5.3 km	4.4 km	2.7 km
Phocid carnivores in water (PCW)	PTS	201 dB	< 10 m	< 10 m	< 10 m
	TTS	181 dB	10 m	10 m	10 m

Table 4-11 Summary of the modelled impact ranges covering the Southall et al. (2019) weighted SEL_{cum} injury criteria for ADDs assuming a swimming animal

ADDs	Maximum range	Mean range	Minimum range
142 dB re 1 µPa (RMS)	840 m	640 m	500 m
120 dB re 1 µPa (RMS)	6.7 km	5.7 km	3.2 km *

Table 4-12 Summary of the modelled SPL_{RMS} disturbance impact ranges for ADDs using the criteria from Southall et al. (2007) and Hastie et al. (2018) (ranges where the coast is met are designated with an asterisk)

5 Summary and conclusions

Subacoustech Environmental has undertaken a study of noise propagation for Juno Energy Ltd. on behalf of Royal HaskoningDHV at the Morlais Demonstration Zone for noise from drilling, operational tidal turbines and ADDs.

The level of underwater noise has been estimated using a parabolic equation (PE) method for lower frequencies and a ray tracing solution at higher frequencies. The modelling considers a variety of input parameters including source noise levels, frequency content, duty cycle, seabed properties and the sound speed profile in the water column. Full account is taken of the complex bathymetry in the area.

Worst case assumptions have been used for the modelling including the size, power and type of drilling apparatus, the model of ADD and using the maximum level in the water column. Two tidal turbine models and layouts have been modelled to cover the largest turbines and the greatest number of turbines.

Table 5-1 gives a summary of the maximum Southall *et al*. (2019) injury criteria for TTS in VHF cetaceans and the maximum Hastie *et al*. (2018) disturbance criteria for the different noise sources modelled, showing maximum injury ranges for ADDs and maximum disturbance ranges for drilling and ADDs.

	VHF TTS (Weighted SEL_{cum}) (Southall *et al*. 2019)	**142 dB re 1 µPa (Unweighted SPL_{RMS}) Disturbance (Hastie *et al.* 2018)**
Percussive drilling	< 10 m	300 m
Small tidal turbine	50 m	20 m
Large tidal turbine	230 m	70 m
ADDs	5.3 km	840 m

Table 5-1 Summary of the maximum predicted impact ranges for the modelling noise sources

When considering operational turbines at all possible locations the results showed that overall noise levels are louder for the small turbines at 620 locations than they are for large turbines at 120 locations. Although the large turbines are louder individually, the fact that there are 400 less locations, and the locations are more spaced out, results in a lower overall level.

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