



Construction Works at the Port of Dundee: Underwater Noise Modelling Assessment

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Executive Summary

An assessment of the likely effect on marine mammals and fish of underwater noise from planned construction works at the Port of Dundee has been undertaken by Subacoustech Environmental Ltd. The assessment covers the noise generated from impact piling, vibropiling and backhoe dredging. Detailed numerical modelling of the survey was used to generate noise contours, which were then used to predict the likely ranges to the relevant noise exposure criteria for marine mammals and fish.

The results have been interpreted using the guidelines provided in Southall *et al.* (2019) for marine mammals, and Popper *et al.* (2014) for fish. These interpretations are based on worst-case parameters with no implemented mitigation measures. Marine mammals, including harbour seals and grey seals, are unlikely to be at risk of permanent auditory injury at any distance from impact piling, vibropiling or dredging activities. Fish, such as Salmon, Trout, Herring, Cod, Sprat and Shad are predicted to be at risk of mortality if they are at 10 m of impact piling. Fish such as Herring, Cod, Sprat and Shad at risk of recoverable injury if they are within less than 10 m from the vibropiling. All fish species considered in this assessment are unlikely to be at risk of any negative impacts during backhoe dredging.

Note that the modelling calculations and predicted impact ranges will produce results that should be considered indicative of the onset of effects on receptors during the works and should not be considered as absolute ranges.

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Terminology

Decibel (dB)	A scale commonly used 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 μ Pa).
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 $L_{E,p}$)	A widely use measure of the overall acoustic energy It is the time-integrated, sound-pressure-squared expressed in dB re 1 μ Pa ² s. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Exposure Level, cumulative (SEL _{cum} or $L_{E,p,dur}$)	Single value for the collected, combined total of sound exposure over a specified time or multiple instances of a noise event.
Sound Exposure Level, single strike (SEL _{ss} or $L_{E,p,ss}$)	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 μ Pa for water and 20 μ Pa 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 represent a sound as a level relevant to a particular species group.

Units

dB	Decibel (sound pressure)
Hz	Hertz (frequency)
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)
Pa	Pascal (pressure)
Pa ² s	Pascal squared seconds (acoustic energy)
μPa	Micropascal (pressure)

Acronyms

BGS	British Geological Survey
EMODnet	European Marine Observation and Data Network
GIS	Geographic Information System
HF	High-Frequency Cetaceans
LF	Low-Frequency Cetaceans
LS	Lady Shoal
NNR	National Nature Reserve
NPL	National Physical Laboratory
PCW	Phocid Carnivores in Water
PoD	Port of Dundee
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_{p-pk})	Peak Sound Pressure Level
SPL _{peak-to-peak}	Peak-to-peak Sound Pressure Level
SPL _{RMS} (L_p)	Root Mean Square Sound Pressure Level
TTS	Temporary Threshold Shift
VHF	Very High-Frequency Cetaceans

1 Introduction

1.1 Project Overview

Subacoustech Environmental have been requested by Royal Haskoning DHV to undertake an underwater noise modelling assessment for the planned construction works at the Prince Charles Wharf in the Port of Dundee, Scotland, UK.

The construction works are part of plans to upgrade the existing berth for vessels with a deeper draft. Therefore, the installation of 48 main piles, plus infill sheets, is required via the use of vibratory (vibro) piling, then impact piling. Backhoe dredging is also planned in an area near the pile installation site and at a section near the mouth of the River Tay. An underwater noise assessment is required to consider the potential impact from the noise generated from the works on all marine mammals and fish in the region. Concern is for harbour seals and grey seals that regularly haul out at Tentsmuir National Nature Reserve (NNR), which is near the works.

This report provides the results of a detailed modelling assessment for piling and dredging activities associated with the works. The modelling has been used to predict the received sound pressure levels and sound exposure levels generated during these noise-generating activities in the region.

1.2 Study Area

Piling works are planned at Prince Charles Wharf in the Port of Dundee (PoD), along the River Tay in Scotland. Two dredging sites are associated with the project: one near the construction site at PoD and another at Lady Shoal (LS), near the river's mouth. Figure 1-1 shows the construction location within the UK, the dredging areas, and the nearby Tentsmuir NNR. Bathymetry indicates shallow waters in the River Tay with a central deeper channel and increasing depths toward the North Sea.

1.3 Noise Sources

Underwater noise sources that could impact marine fauna, and have therefore been included in the assessment include:

- Impact piling
 - Vibropiling
 - Backhoe dredging

Details of the input parameters used for the modelling of each of these sources in the assessment are presented in Section 3.1.

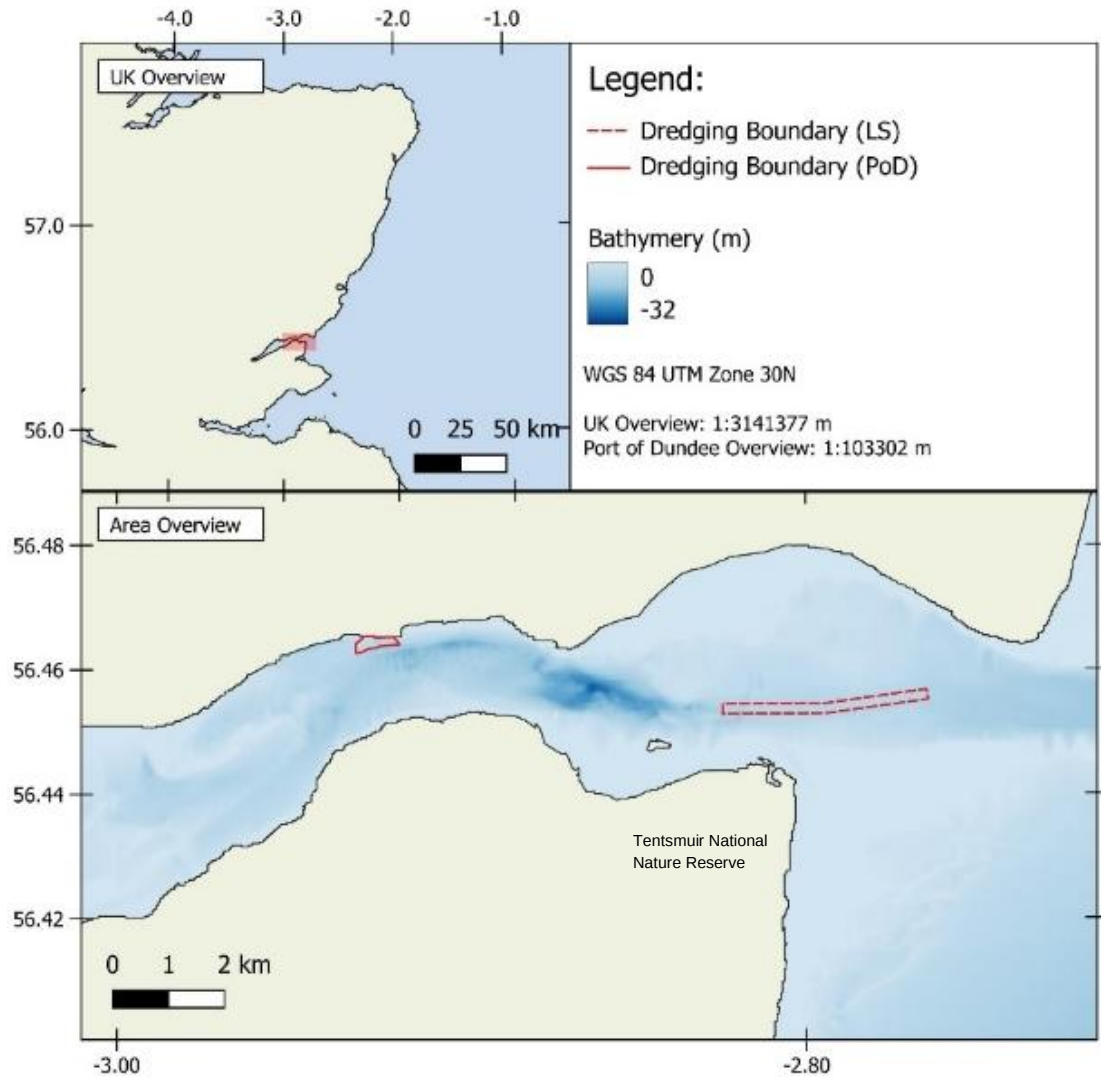


Figure 1-1: Assessment area showing the extent of the dredging sites and the proximity to the Tentsmuir NNR.

1.4 Document Overview

This report presents a detailed assessment of the potential underwater noise from the construction works at the Port of Dundee, and covers the following:

- Section 2: Review of background information on the units for measuring and assessing underwater noise
- Section 3: Discussion of the modelling approach, input parameters and assumptions for the noise modelling undertaken
- Section 4: Presentation of detailed noise modelling and interpretation of the results using suitable noise metrics and criteria
- Section 5: Summary and conclusions

2 Underwater Noise Concepts

Sound travels much faster in water (approximately $1,500 \text{ ms}^{-1}$) than in air (343 ms^{-1}) as water is relatively incompressible and has a higher density than air. This affects the way in which sound measurements are expressed between the two mediums, which means that underwater sound levels are not directly comparable to airborne sound levels. This is noted for context; this report does not contain or include any reference to airborne sound levels.

2.1 Units of Measurement

Sound measurements are usually expressed using the decibel (dB) scale, which is a logarithmic measure of sound. The dB scale represents a ratio, and therefore, it is used with a reference unit, which is the base from which the ratio is expressed. The fundamental definition of the dB scale is given in Equation 1:

(1)

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

where P is pressure, measured in Pascals (Pa), and P_{ref} is the reference pressure, also measured in Pa. For underwater noise, a reference pressure of $1 \mu\text{Pa}$ ($1 \times 10^{-6} \text{ Pa}$) is used as defined in ISO 18405:2017. Noise can be quantified using various metrics depending on the nature of the sound, as discussed below.

2.1.1 Sound Pressure Level

Sound Pressure Level (SPL or L_p) is a measure of the pressure variation caused by sound waves, expressed in decibels (dB), as seen in Equation 1. Variations of SPL are used depending on the noise source being measured. Unless otherwise defined, all SPL noise levels in this report are referenced to $1 \mu\text{Pa}$.

2.1.1.1 Level of the Mean Squared Sound Pressure

For continuous, non-impulsive noise sources such as drilling or vibropiling, an unweighted sound pressure level, averaged over a measurement period, known as a root mean squared (RMS) sound pressure level (SPL_{RMS} or $L_{p,\text{RMS}}$), can be used to represent the noise levels. The RMS period must be specified (e.g. $L_{p,\text{RMS}(125\text{ms})}$), as the mean level can vary significantly depending on the measurement duration.

2.1.1.2 Level of the Peak Sound Pressure

Transient, impulsive pressure waves, such as generated from impact piling are usually expressed using level of the peak sound pressure (SPL_{peak} or $L_{p,\text{pk}}$). This is calculated using the maximum pressure variation from positive to zero, representing the peak change in pressure as the transient wave propagates. A further variation of this is the peak-to-peak sound pressure level ($\text{SPL}_{\text{peak-peak}}$ or $L_{p,\text{pk-pk}}$) which considers the maximum pressure variation from positive to negative. For a symmetrically distributed wave, the peak-to-peak pressure is twice the peak level, or 6 dB higher.

2.1.2 Sound Exposure Level

Sound Exposure Level (SEL) is a measure of Sound Exposure (SE), which represents the total acoustic energy of a sound event in decibels (dB), accounting for both the sound's intensity and duration. SEL provides a way to quantify the total energy in a sound, making it useful for assessing the impact of both continuous and transient sounds. Variations of SEL are used depending on the noise source being measured. For context, SEL can be compared SPL using Equation 2:

(2)

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

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. For continuous sounds shorter than one second, the SEL is lower than the SPL. For durations longer than one second, the SEL exceeds the SPL (e.g., a 10-second sound results in a 10 dB higher SEL and a 100-second sound gives a 20 dB higher SEL). Unless otherwise defined, all $L_{E,p}$ noise levels in this report are referenced to $1 \mu\text{Pa}^2\text{s}$.

2.1.2.1 Single Strike Sound Exposure Level

Single strike Sound Exposure Level (SEL_{ss} or $L_{E,p,ss}$) refers to the total acoustic energy from a single, loud, short duration noise event (such as a blast or impact) measured over a specified duration. This can be expressed using Equation 3:

(3)

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

where p is the acoustic pressure in Pascals, T is the total duration of sound in seconds, and t is time in seconds.

2.1.2.2 Cumulative Sound Exposure Level

A cumulative Sound Exposure Level (SEL_{cum} or $L_{E,cum}$) accounts for the exposure from multiple impulses or pile strikes over time, where the number of impulses replaces the T in the Equation 3, leading to Equation 4:

(4)

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

Where $L_{E,p,ss}$ is the SEL_{ss} and X is the total number of impulses or strikes.

2.2 Properties of Sound

2.2.1 Impulsive vs Non-impulsive

Sound can be categorised loosely into two types: impulsive and non-impulsive. These can be defined as:

- Non-impulsive: a steady-state sound. It does not necessarily have to have a long duration.
 - Examples: vibropiling, dredging
- Impulsive: a sound with a high peak sound pressure, short duration, fast rise-time and broad frequency content at the source.
 - Examples: seismic airguns, explosives, impact piling

The category of sound is important for assessing auditory injury, as impulsive sound is typically more harmful than non-impulsive sound. Different metrics are used to describe each type of sound source:

- Impulsive: Use SPL_{peak} ($L_{p,pk}$) or SEL_{cum} ($L_{E,p,ss}$ or $L_{E,cum}$)
- Non-impulsive: Use SPL_{rms} ($L_{p,rms}$) or SEL_{cum} ($L_{E,cum}$)

Categorising sound as impulsive or non-impulsive can be challenging, especially over long distances. As impulsive sounds travel, their energy dissipates, making them less impulsive and therefore potentially less injurious. Ongoing research, such as Martin *et al.* (2020), aims to define these categories. Hastie *et al.* (2019) found that impulsive sound can be considered non-impulsive 3.5 km from the source, while Southall (2021) suggests noise should be non-impulsive if energy above 10 kHz is absent. Research is ongoing to refine pulse characteristics, like kurtosis, for better categorisation.

2.2.2 Particle Motion

Particle motion, a key component of sound, describes the back-and-forth movement of particles in a medium, such as water, caused by sound waves. Unlike sound pressure, particle motion contains directional information (Hawkins and Popper, 2017). It is typically quantified by peak particle velocity (PPV), though acceleration or displacement can also be used. Research shows many fish species and marine invertebrates are sensitive to particle motion (e.g., Popper and Hawkins, 2019; Nedelec *et al.*, 2016, Radford *et al.*, 2012, Sole *et al.*, 2023), but sound pressure metrics are still more commonly used due to limited data (Popper and Hawkins, 2018). Calls for further research on particle motion levels and effects continue.

2.3 Analysis of Environmental Effects: Assessment Criteria

Human-generated underwater noise can significantly affect marine species. The severity of these effects depends on factors like sound level, frequency, exposure duration, and repetition rate (Hastings and Popper, 2005). As a result, research on aquatic species' hearing abilities has grown, with studies focused on high-level noise sources such as seismic airguns, impact piling, and blasting, which have the most immediate environmental effects, though interest in chronic noise exposure is rising.

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 responses.

The following sections outline the underwater noise criteria used in this study for marine mammals and fish species in the area.

2.3.1 Marine Mammals

2.3.1.1 Southall *et al.* (2019): Auditory Injury (PTS and TTS) criteria

Southall *et al.* (2019) is the most widely used reference for marine mammal hearing thresholds. The Southall *et al.* (2019) guidance categorises marine mammals into groups based on similar species and applies filters to the unweighted noise levels to approximate their hearing sensitivities. These groups are summarised in Table 2.1, with auditory weighting functions in Figure 2.1. Additional groups for sirenians and other marine carnivores are provided but not included in this study, as these species are not common in the area.

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

Hearing group	Auditory Weighting Function	Generalised hearing range	Species group	Example species
Low-frequency Cetaceans	LF	7 Hz to 35 kHz	Baleen whales	Sei Whale, Fin Whale, Minke Whale, Humpback Whale
High-frequency Cetaceans	HF	150 Hz to 160 kHz	Toothed whales, including dolphins and beaked whales	Bottlenose Dolphin, White-beaked Dolphin, Risso's Dolphin, Common Dolphin, Orca, Sperm Whale, Pilot Whale, Northern Bottlenose Whale
Very high-frequency Cetaceans	VHF	275 Hz to 160 kHz	True porpoise	Harbour porpoise
Phocid carnivores in water	PCW	50 Hz to 86 kHz	True seals	Harbour seal, Grey Seal

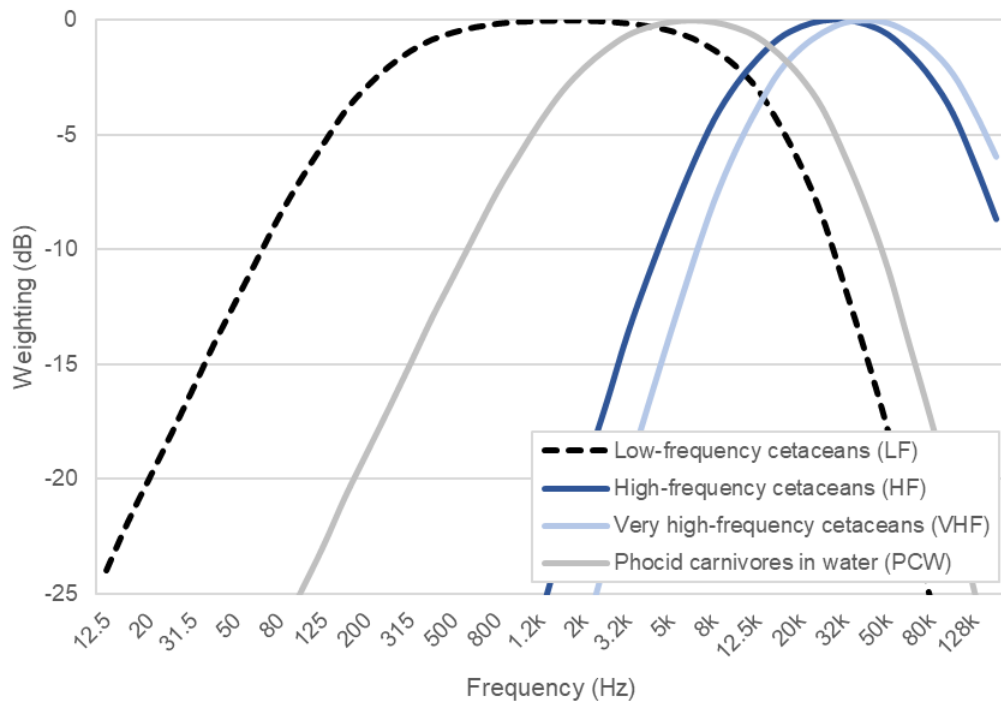


Figure 2-1: Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall *et al.*, 2019)

Southall *et al.* (2019) presents noise impact thresholds for marine mammal groups based on:

- The sound type (impulsive vs non-impulsive)
- The severity of auditory injury

Impact ranges based on impulsive criteria are recommended for most sources, except clearly non-impulsive ones. However, if the predicted range exceeds 3.5 km (see Section 1.2.1), the true impact range is likely to lie between the impulsive and non-impulsive ranges. Thus, both criteria are considered unless the sound source is explicitly non-impulsive.

For SEL_{cum} thresholds in marine mammals, a fleeing animal model is used, assuming the animal swims away from the sound source. These are worst-case assumptions, as marine mammals can swim faster under stress (Kastelein *et al.*, 2018), particularly at the start of a noisy event when they are closest to the source. The following flee speeds are applied for each marine mammal group:

- 2.1 ms^{-1} for LF cetaceans (Scottish Natural Heritage; SNH, 2016)
- 1.52 ms^{-1} for HF cetaceans (Bailey and Thompson, 2006)
- 1.4 ms^{-1} for VHF cetaceans (SNH, 2016)
- 1.8 ms^{-1} for PCW pinnipeds (SNH, 2016)

Southall *et al.* (2019) presents different impact thresholds for impulsive and non-impulsive sound criteria, based on varying levels of auditory injury at different sound levels. Auditory injury is categorised into two types:

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

TTS typically results in the largest impact range, but PTS represents the most significant and permanent impairment, making it the key impact threshold.

Impact piling is an impulsive noise source, however, vibropiling and dredging are a non-impulsive noise source. Therefore, this study considered the both the impulsive and non-impulsive criteria for marine mammal PTS and TTS thresholds from Southall *et al.* (2019), which is 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 <i>et al.</i> (2019)	$L_{p,pk}$ (dB re 1 μ Pa)	
	Impulsive	
	PTS	TTS
Low-frequency cetaceans (LF)	219	213
High-frequency cetaceans (HF)	230	224
Very high-frequency cetaceans (VHF)	202	196
Phocid carnivores in water (PCW)	218	212

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

Southall <i>et al.</i> (2019)	$L_{E,24h,wtd}$ (dB re 1 μ Pa ² s)			
	Impulsive		Non-impulsive	
	PTS	TTS	PTS	TTS
Low-frequency cetaceans (LF)	183	168	199	179
High-frequency cetaceans (HF)	185	170	198	178
Very high-frequency cetaceans (VHF)	155	140	173	153
Phocid carnivores in water (PCW)	185	170	201	181

2.3.2 Fish

2.3.2.1 Popper *et al.* (2014): Mortality, injury and behavioural effects

The Popper *et al.* (2014) guidelines are a reliable reference for underwater noise impacts on marine fauna, excluding marine mammals.

Popper *et al.* (2014) provides specific criteria for common anthropogenic underwater sound sources. If a source is not listed, it is common practice to use the criteria which is the best fit to the source required in the assessment. Across all sources, marine faunae are categorised into sea turtles, eggs and larvae, and fish. Fish are further divided into three groups based on their hearing capabilities, determined by the presence and role of a swim bladder:

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

Popper *et al.* (2014) then provides impact thresholds for each marine fauna category related to sound exposure, including:

- Mortality and potential mortal injury: immediate or delayed death.
- Impairment, such as:
 - Recoverable injury: injuries unlikely to result in mortality.
 - Temporary Threshold Shift (TTS): short or long-term changes in hearing sensitivity that may or may not reduce fitness.
 - Masking: Reduction in sound detectability due to the simultaneous presence of another sound.
- Behavioural effects: substantial change in behaviour for the animals exposed to a sound (long or short term).

Despite emerging evidence of fish sensitivity to particle motion (see Section 1.2.2), the Popper *et al.* (2014) guidelines provide a numerical criterion as thresholds for impact onsets in terms of sound pressure related functions (e.g., SPL_{peak} , SPL_{rms} , SEL_{ss} , SEL_{cum}). For fish, both stationary and fleeing animal models are used for SEL_{cum} thresholds to account for species diversity and varying responses to noise. Most species in Popper *et al.* (2014) are likely to flee from harmful sounds (Dahl *et al.*, 2015), and these flee speeds are likely to vary widely across species. Therefore, a conservative fleeing speed of 1.5 ms^{-1} (Hirata, 1999) is used in fleeing animal models. However, some species in Popper *et al.* (2014) have lower sensitivity to sound, such as benthic or swim bladderless species, and may remain stationary even when exposed to high intensity sounds (e.g., Goertner *et al.*, 1994, 1978; Stephenson *et al.*, 2010; Halvorsen *et al.*, 2012). Therefore, to avoid overestimating risk, a combined approach, which presents both fleeing and stationary models, is used in this report.

When data is insufficient to provide a numerical criterion, Popper *et al.* (2014) provides a relative risk, which describes the risk of an effect on a receptor occurring in either the near-field (tens of meters), intermediate-field (hundreds of meters) or far-field (thousands of meters) from the sound source, as high, moderate or low.

To assess the impact ranges for impact piling, this study used the criteria from Popper *et al.* (2014) for pile driving, which is summarised in Table 2-4. Since vibropiling and dredging are continuous noise sources, this study uses the criteria from Popper *et al.* (2014) for shipping and continuous noise sources as a proxy to assess vibropiling and dredging, which is summarised in Table 2-5.

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

Popper et al. (2014) criteria for Pile Driving					
Type of fish	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	>219 $L_{E,p}$ >213 $L_{p,pk}$	>216 $L_{E,p}$ >213 $L_{p,pk}$	>>186 $L_{E,p}$	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	210 $L_{E,p}$ >207 $L_{p,pk}$	203 $L_{E,p}$ >207 $L_{p,pk}$	>186 $L_{E,p}$	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing	207 $L_{E,p}$ >207 $L_{p,pk}$	203 $L_{E,p}$ >207 $L_{p,pk}$	186 $L_{E,p}$	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
Sea Turtles	210 $L_{E,p}$ >207 $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) High (I) Moderate (F) Low
Eggs and Larvae	>210 $L_{E,p}$ >207 $L_{p,pk}$	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

Table 2-5: Recommended guidelines for shipping and continuous sounds according to Popper et al. (2014) for species 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 $L_{p,48h}$	158 $L_{p,12h}$	((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

2.3.3 Marine Invertebrates

A review by Sole *et al.* (2023) highlights growing evidence that certain anthropogenic noises harm marine invertebrates, affecting behaviour, physiology, mortality rates, and causing physical impairment at individual, population, or ecosystem levels. Much of this damage results from vibrations of the invertebrate's body caused by sound (André *et al.*, 2016).

Studies reviewed by Sole *et al.* (2023) show inconsistency in quantifying noise impacts on marine invertebrates. For example, Hubert *et al.* (2021) reports behavioural changes in blue mussels at 150-300 Hz tones, while Spiga *et al.* (2016) notes a behavioural change at $L_{E,p,ss}$ 153.47 dB re 1 μ Pa. These inconsistencies make it challenging to develop accurate thresholds. A notable exception is cephalopods, where studies (e.g., Sole *et al.*, 2019, 2018, 2013a; André *et al.*, 2011) show consistent auditory damage at 157 dB re 1 μ Pa, providing a benchmark for other groups. However, further research is needed for more accurate thresholds.

Furthermore, Sole *et al.* (2023) highlights inconsistencies in the responses of taxonomically similar marine invertebrates to anthropogenic noise. For instance, Fields *et al.* (2019) reports low mortality in zooplankton exposed to seismic airguns, while McCauley *et al.* (2017) observes mass mortality in krill larvae from the same source. This suggests that noise impacts vary by species, complicating the development of generalised impact thresholds for marine invertebrates.

For now, research on the effects of anthropogenic noise on marine invertebrates is emerging, but at a slower pace than for marine mammals and fish. Currently, the data is insufficient to establish reliable impact thresholds for regulatory use. However, convincing evidence of noise impacts exists, and while some species' data may be referenced, caution is needed due to significant knowledge gaps.

3 Underwater Noise Modelling: Methodology

Modelling of underwater noise is complex and can be approached in several different ways. Measurements are only possible at limited locations, so modelling has been undertaken to provide a more comprehensive set of results. To estimate the noise levels generated by impact piling, vibropiling and dredging, Subacoustech have chosen to utilise the dBSea noise modelling software, which uses various numerical solvers to calculate underwater noise. This assessment uses 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 input 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. The input parameters used in this study are described in the following sections.

3.1 Input Parameters

3.1.1 Modelling Location

A single representative modelling location was selected for each activity. One modelling location was selected for both piling activities (impact piling and vibropiling). Two modelling locations were selected for dredging: one at each dredging site (Port of Dundee and Lady Shoal). Within the extent of each dredging site, a location was selected that represented the worst-case scenario with the most extensive line of sight for acoustic propagation. For piling, the depth of the source was modelled at mid-water depth, whereas for dredging, the depth of the source was modelled at the maximum depth of the modelling location, at the seabed. Details of the noise source locations used are presented in Table 3-1, and Figure 3-1.

Table 3-1: Details of the modelling locations. Eastings/Northings are in WGS84, UTM Zone 30N.

Modelling location	Easting (m)	Northing (m)	Depth of Source (m)	Depth at source location (m)
Piling Site	504604.5	6257790.7	6	11
Dredging (Port of Dundee)	504279.7	6257575.4	12	12
Dredging (Lady Shoal)	514513.2	6256764.3	13	13

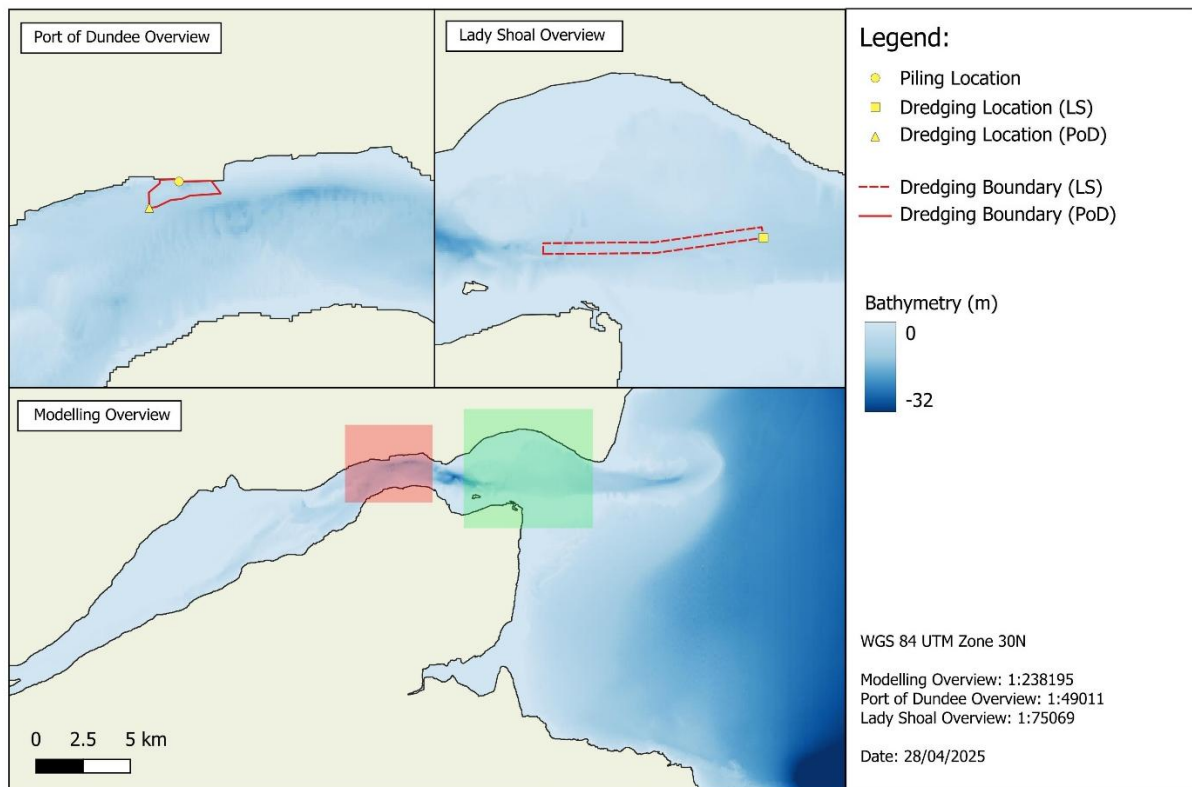


Figure 3-1: Overview of the modelling locations selected for each activity.

3.1.2 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 1/16th arcminutes (approximately 115 × 115 m). The bathymetry used for modelling covers an area of 25 km × 25 km surrounding the survey area.

3.1.3 Seabed Properties

Seabed characteristics were based on local data from the Marine Scotland NMPI tool. At the Port of Dundee, the seabed was assumed to consist of 20 m of gravelly sand, and at Lady Shoal, 20 m of gravel, both overlying sandstone bedrock. Geo-acoustic properties were taken from Jensen *et al.* (1994, 2011) as listed in Table 3-2.

Table 3-2: Seabed geo-acoustic properties of the area.

Material	Compressive sound speed profile in substrate (m/s)	Density profile in substrate (kg/m ³)	Attenuation profile in substrate (dB/wavelength)
Gravelly Sand	1,725	1,950	0.7
Gravel	1800	2000	0.6
Sandstone	3,000	2,500	0.1

3.1.4 Sound Speed Profile

The speed of sound in the water has been calculated for the average annual temperature and salinity using the Mackenzie (1981) equation, with data from the Marine Scotland for the modelling location. The resulting profile is shown in Figure 3-2.

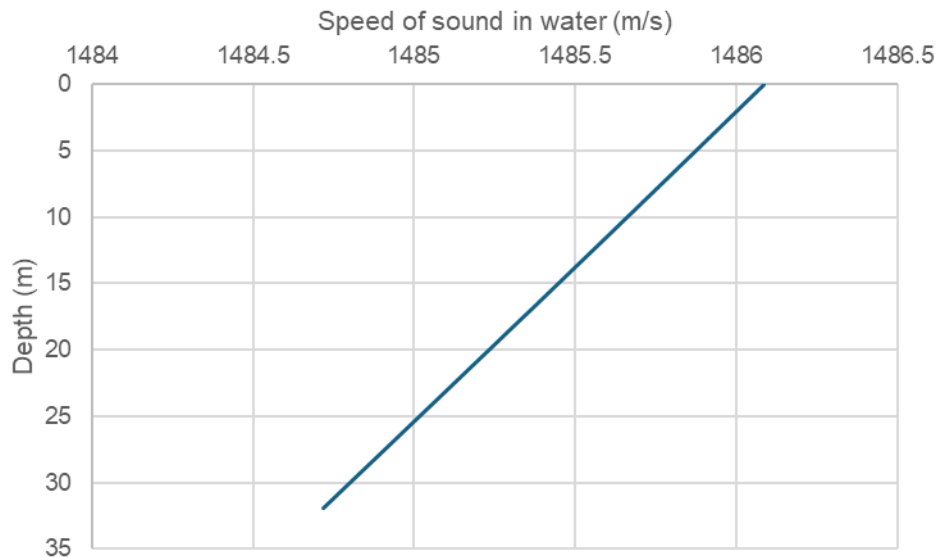


Figure 3-2: Sound speed profile used for detailed modelling of the area.

3.1.5 Noise Source

At the time of writing, the following information has been provided:

- Impact piling:
 - Hammer: CX85
 - Number of blows: 42 blows per minute (total of 1646 blows)
 - Piling time per pile: 40 minutes
 - Maximum Energy: 83 kNm
- Vibropiling:
 - Hammer: ICE 816C Vibratory Hammer

It is currently understood that the installation of each pile will consist of 2 minutes of vibropiling, followed by impact piling (approximately 40 minutes duration) to drive the pile to its final depth. Currently, no detailed information has been provided regarding the dredger used for backhoe dredging.

Using the information provided, source levels for impact piling and vibropiling have been estimated based on previous measurements taken for equipment of similar specification. Since no information on the pile diameter was available, it was assumed that 700 mm piles will be used, and the source level was scaled to reflect this. Since details on the dredging equipment were unavailable at the time of writing, source levels were estimated using data from “Magnor,” the largest backhoe dredger, as a worst-case noise source. The source levels used in modelling for each activity are presented in Table 3-3.

Table 3-3: Summary of the calculated $L_{p,pk}$, $L_{E,p,1s}$ and $L_{p,rms}$ source levels for the impact piling, vibropiling and dredging.

Equipment	Estimated source level @ 1 m		
	$L_{p,pk}$ (dB re 1 μ Pa)	$L_{E,p,1s}$ (dB re 1 μ Pa ² s)	$L_{p,rms}$ (dB re 1 μ Pa)
Impact Piling	200.7	170	-
Vibropiling	-	-	176.4
Dredging	-	-	152.3

A relevant source spectrum for each activity were obtained using Subacoustech's library of measurements, using data measured at Portsmouth Harbour for impact piling and vibropiling (Midforth and East, 2019) of piles with a 1067 mm diameter, using a hammer blow energy of 260 kNm, and data measured in Southampton Docks of "Magnor", currently the world's largest backhoe dredger, for dredging (Midforth and Morgan, 2024). Both sets of measured data were taken in enclosed bodies of water with a mix of coarse and soft sediment types, which is similar to the environmental conditions in the Port of Dundee. From this measured data, the 1/3rd octave levels were then adjusted to achieve the required source levels for each source type (values stated in Table 3-3). The 1/3rd octave source spectrums used for modelling is shown in Figure 3-3 for impact piling, Figure 3-4 for vibropiling and Figure 3-5 for dredging.

For cumulative noise exposure calculations, estimates were based on 4 hours of continuous activity for impact and vibropiling, and 8 hours for dredging, as a realistic worst-case scenario

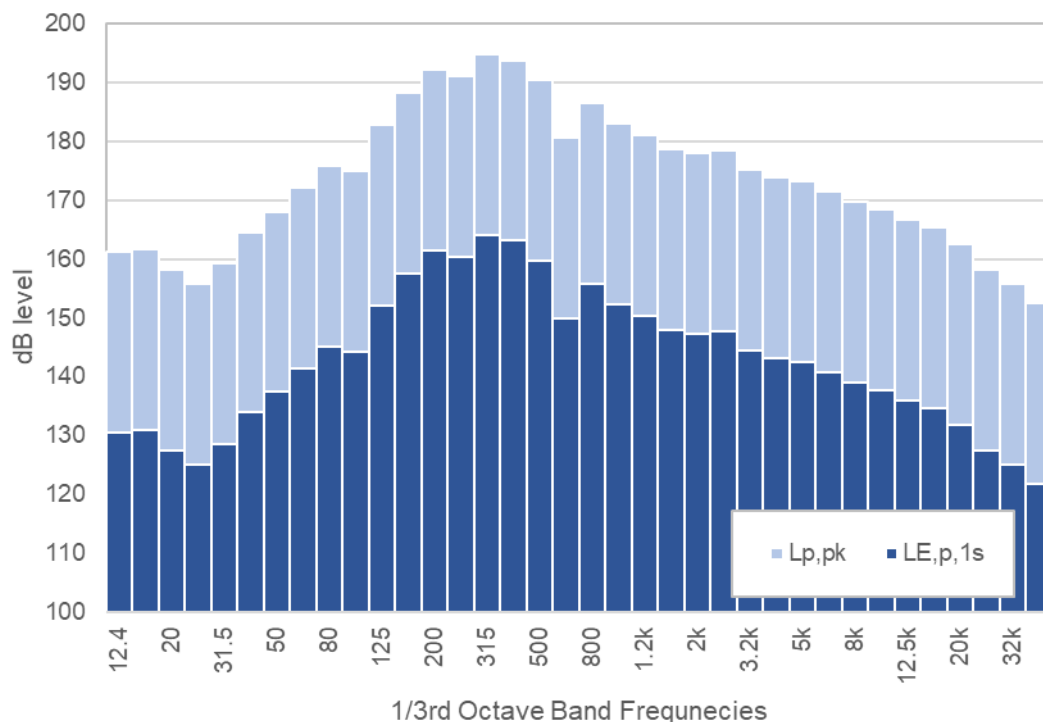


Figure 3-3: The $L_{p,pk}$ and $L_{E,p,1s}$ source spectrums containing 1/3rd octave band levels used to model impact piling.

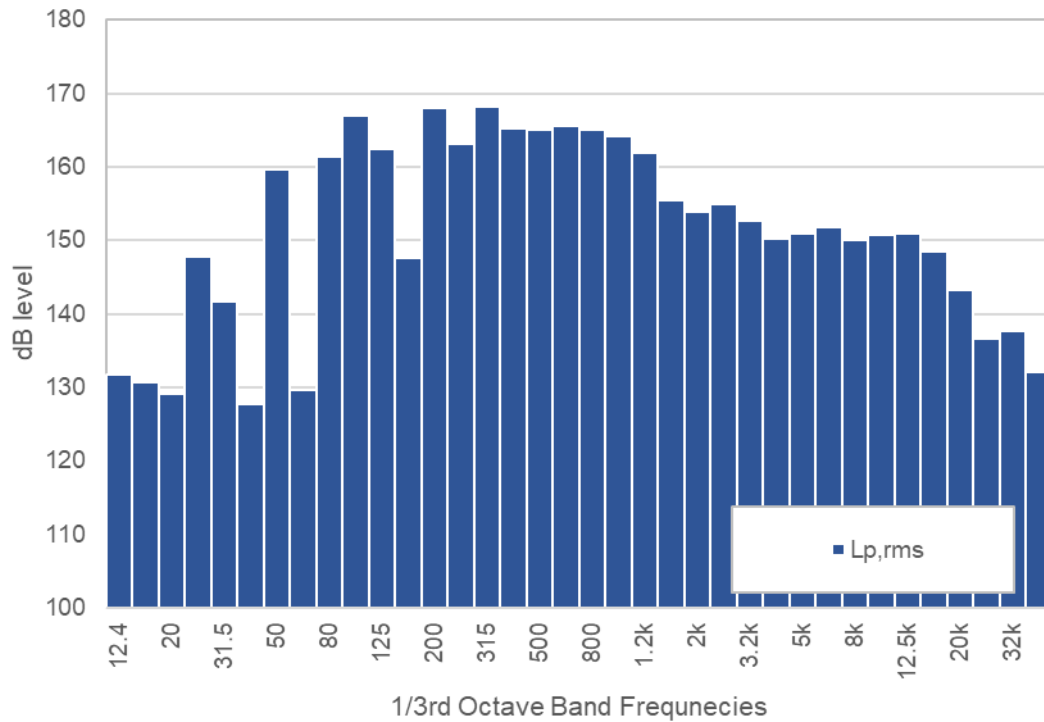


Figure 3-4: The $L_{p,rms}$ source spectrum containing 1/3rd octave band levels used to model the vibropiling.

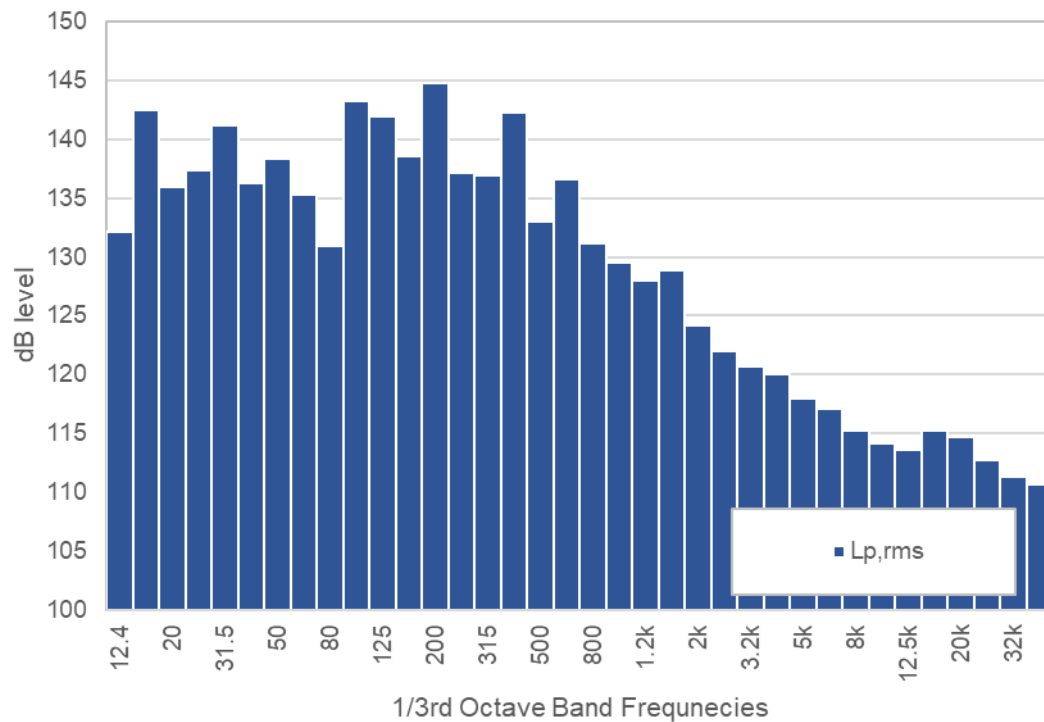


Figure 3-5: The $L_{p,rms}$ source spectrum containing 1/3rd octave band levels used to model dredging.

4 Underwater Noise Modelling: Results

The distribution of noise from all noise generating activities are presented as noise contour plots in the following section. Please note the scale difference of the plots between each activity. These noise contours are then interpreted using the relevant criteria from Southall *et al.* (2019) for marine mammals, and Popper *et al.* (2014) for fish.

For cumulative $L_{E,p,t}$ metrics at the Port of Dundee (impact piling, vibropiling, and dredging), where land constrains sound propagation, impact ranges have been calculated along two sets of transects; Southeast (SE) is several transects between bearings 90° - 116° and the Southwest (SW) is several transects between bearings 204° - 248°. These bearings were selected as they represent transects which are not constrained by landmass near to the noise source and so are plausible directions for a fleeing animal.

Any impact range noted as *NE* indicates that no exceedance is expected for the given criteria based on the results of the modelling.

4.1 Impact Piling

4.1.1 Predicted Noise Levels

The distribution of noise from the impact piling at the Port of Dundee is presented as noise contour plots in Figure 4-1 and Figure 4-2. These plots show the maximum predicted noise level in the water column.

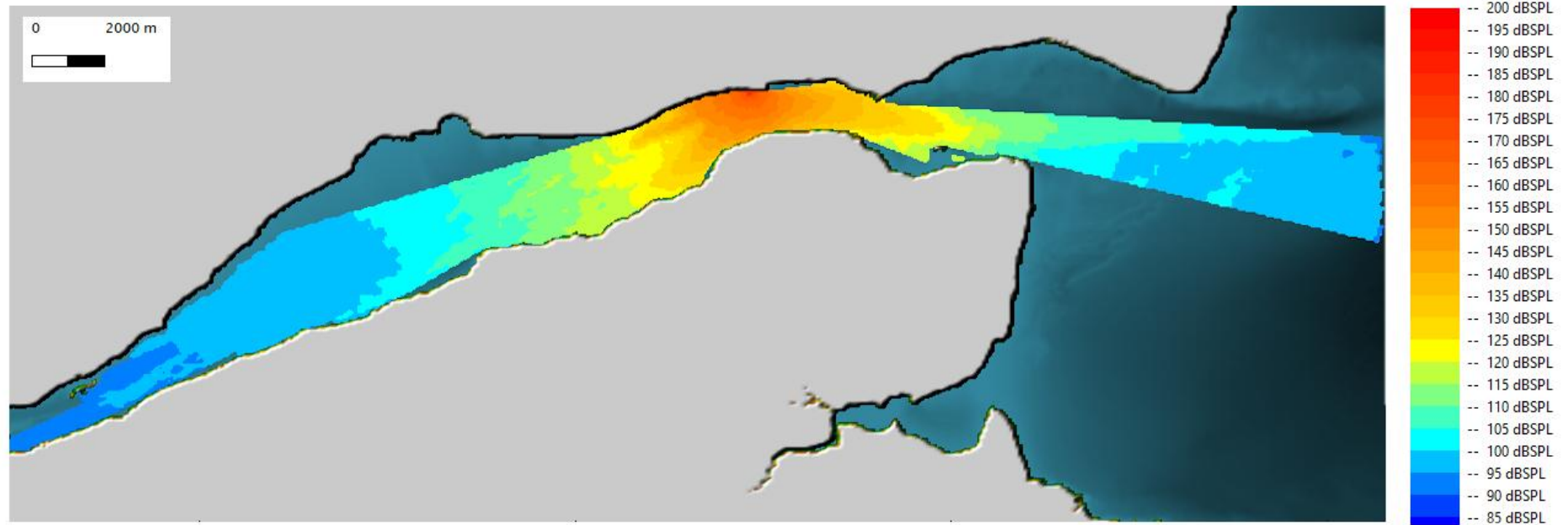


Figure 4-1: $L_{p,pk}$ noise level contours predicted for impact piling at the Port of Dundee.

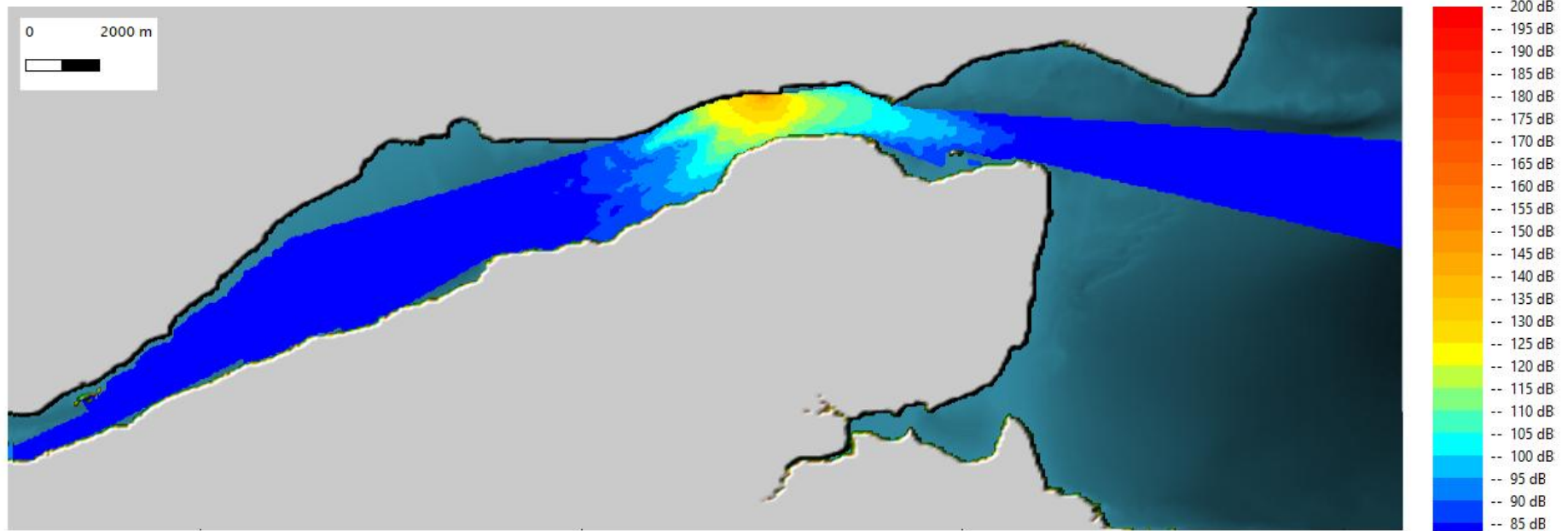


Figure 4-2: $L_{E,p}$ noise level contours predicted for impact piling at the Port of Dundee.

4.1.2 Interpretation

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, as such, ranges smaller than this have been presented as “< 10 m”.

4.1.2.1 Assessment: Marine Mammals

The noise level results from Section 4.1 were assessed against the Southall *et al.* (2019) guidelines and weightings to predict the likely range at which the thresholds for impulsive and non-impulsive sounds would be exceeded by marine mammals.

Using the $L_{p,pk}$ criteria applied to the predicted noise contours, it is unlikely that animals will exceed the PTS threshold for all marine mammal species at any range from the impact piling activities. These details, along with TTS impact ranges predicted across all groups, are presented in Table 4-1.

Table 4-1: Estimated impact ranges for impact piling activities using the Southall *et al.* (2019) $L_{p,pk}$ marine mammal criteria for impulsive noise sources.

Southall <i>et al.</i> (2019) criteria $L_{p,pk}$ (Impulsive)		Estimated impact range (m)		
		Maximum	Mean	Minimum
LF Cetaceans	PTS	NE	NE	NE
	TTS	NE	NE	NE
HF Cetaceans	PTS	NE	NE	NE
	TTS	NE	NE	NE
VHF Cetaceans	PTS	NE	NE	NE
	TTS	10	10	10
PCW Pinnipeds	PTS	NE	NE	NE
	TTS	NE	NE	NE

NE = No predicted exceedance

When comparing the predicted $L_{E,p,24h,wtd}$ against both impulsive and non-impulsive criteria from Southall *et al.* (2019) for marine mammals, it is unlikely that it will exceed the PTS threshold for all marine mammal species at any range from the impact piling activities. This is based on a cumulative SEL calculated over 4 hours of impact piling and the animals fleeing at a constant speed. These details, along with TTS impact ranges predicted across all groups, are presented in Table 4-2 for the impulsive criteria and Table 4-3 for the non-impulsive criteria.

Table 4-2: Estimated impact ranges for the impact piling activities using the Southall et al. (2019) $L_{E,p,wtd}$ marine mammal criteria for impulsive noise sources assuming a fleeing animal.

Southall et al. (2019) criteria $L_{E,p,wtd}$ (Impulsive)		Maximum Estimated Impact Range (m)	
		SE	SW
LF Cetaceans	PTS	NE	NE
	TTS	10	10
HF Cetaceans	PTS	NE	NE
	TTS	NE	NE
VHF Cetaceans	PTS	< 10	< 10
	TTS	80	80
PCW Pinnipeds	PTS	NE	NE
	TTS	NE	NE

NE = No predicted exceedance

Table 4-3: Estimated impact ranges for the impact piling activities using the Southall et al. (2019) $L_{E,p,wtd}$ marine mammal criteria for non-impulsive noise sources assuming a fleeing animal.

Southall et al. (2019) criteria $L_{E,p,wtd}$ (Non-impulsive)		Maximum Estimated Impact Range (m)	
		SE	SW
LF Cetaceans	PTS	NE	NE
	TTS	NE	NE
HF Cetaceans	PTS	NE	NE
	TTS	NE	NE
VHF Cetaceans	PTS	NE	NE
	TTS	10	10
PCW Pinnipeds	PTS	NE	NE
	TTS	NE	NE

NE = No predicted exceedance

4.1.2.2 Assessment: Fish

The noise level results from Section 4.1 were assessed against the Popper *et al.* (2014) guidelines to predict the likely range at which the thresholds for pile driving would be exceeded by fish.

Based on the results for $L_{p,pk}$ metric, it is unlikely that any criteria for fish species will be exceeded at any range from the impact piling activities.

Using the $L_{E,p}$ metric, if the fish are to flee from the source at a constant speed, it is unlikely that the thresholds for all fish species will be exceeded at any range from the impact piling activities. However, if they are assumed to remain stationary for the entire 4 hour piling period, animals within 10 m of the impact piling activities will exceed the mortality and potential mortal injury threshold, and the recoverable injury threshold for fish with a swim bladder (involved and no involved in hearing). These details, along with other fish species are provided in Table 4-4 for stationary fish.

Table 4-4: Estimated impact ranges for the impact piling activities the Popper *et al* (2014) $L_{E,p,24h}$ fish criteria for pile driving assuming a stationary animal.

Popper <i>et al.</i> (2014) criteria $L_{E,p,24h}$ (Pile Driving)		Maximum Estimated Stationary Impact Range (m)	
		SE	SW
Fish: no swim bladder	Mortal and potential mortal injury	NE	NE
	Recoverable injury	NE	NE
	TTS	80	80
Fish: swim bladder not involved in hearing	Mortal and potential mortal injury	10	10
	Recoverable injury	10	10
	TTS	80	80
Fish: swim bladder involved in hearing	Mortal and potential mortal injury	10	10
	Recoverable injury	10	10
	TTS	80	80

NE = No predicted exceedance

4.2 Vibropiling

4.2.1 Predicted Noise Levels

The distribution of noise from the vibropiling at the Port of Dundee is presented as noise contour plots in Figure 4-3. This shows the maximum predicted noise level in the water column.

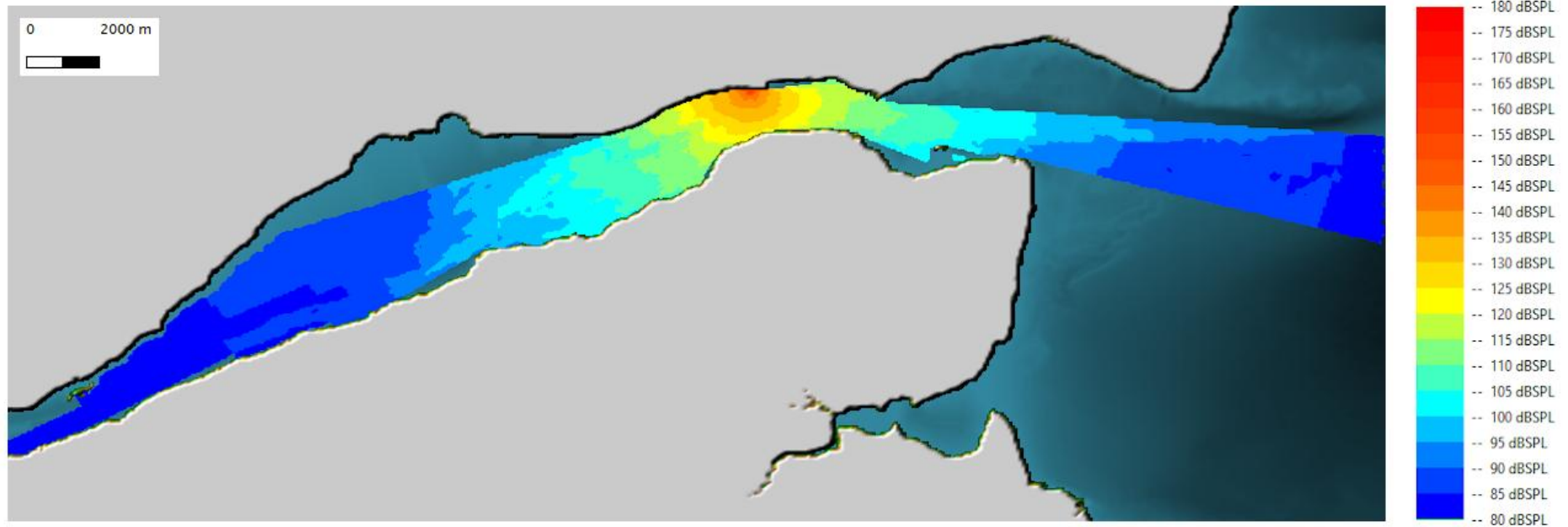


Figure 4-3: $L_{p,RMS}$ noise level contours predicted for vibropiling at the Port of Dundee.

4.2.2 Interpretation

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, as such, ranges smaller than this have been presented as “< 10 m”.

4.2.2.1 Assessment: Marine Mammals

The noise level results from Section 4.2 were assessed against the Southall *et al.* (2019) guidelines and weightings to predict the likely range at which the thresholds for non-impulsive sounds would be exceeded by marine mammals.

When the $L_{E,p,24h,wtd}$ criteria for non-impulsive noise is applied to the predicted noise contours, it is unlikely that animals will exceed the PTS threshold for all marine mammal species at any range from the vibropiling activities. This assumes that impact piling is occurring continuously for 4 hours, and that the animals flee away from the noise source at a constant speed. These details, along with TTS impact ranges predicted across all groups, are presented in Table 4-5.

Table 4-5: Estimated impact ranges for the vibropiling activities using the Southall *et al.* (2019) $L_{E,p,wtd}$ marine mammal criteria for non-impulsive noise sources assuming a fleeing animal.

Southall <i>et al.</i> (2019) criteria $L_{E,p,wtd}$ (Non-impulsive)		Maximum Estimated impact range (m)	
		SE	SW
LF Cetaceans	PTS	NE	NE
	TTS	< 10	< 10
HF Cetaceans	PTS	NE	NE
	TTS	NE	NE
VHF Cetaceans	PTS	NE	NE
	TTS	20	30
PCW Pinnipeds	PTS	NE	NE
	TTS	NE	NE

NE = No predicted exceedance

4.2.2.2 Assessment: Fish

The noise level results from Section 4.2 were assessed against the Popper *et al.* (2014) guidelines to predict the likely range at which the thresholds for shipping and continuous sounds would be exceeded by fish.

Based on the results for the $L_{p,rms}$ metric, animals within < 10 m of the vibropiling activities may exceed the recoverable injury threshold for fish with a swim bladder involved in hearing. These details, along with TTS impact ranges are provided in Table 4-6.

Table 4-6: Estimated impact ranges for the vibropiling activities using the Popper *et al.* (2014) $L_{p,rms}$ fish criteria for shipping and continuous sounds.

Popper <i>et al.</i> (2014) criteria $L_{p,rms}$ (Continuous sounds)		Estimated impact range (m)		
		Maximum	Mean	Minimum
Fish: swim bladder involved in hearing	Recoverable injury	< 10	< 10	< 10
	TTS	50	30	30

4.3 Dredging

4.3.1 Predicted Noise Levels

The distribution of noise from the dredging activities at the Port of Dundee and Lady Shoal is presented as noise contour plots in Figure 4-4 and Figure 4-5. These plots show the maximum predicted noise level in the water column.

4.3.2 Interpretation

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, as such, ranges smaller than this have been presented as “< 10 m”.

4.3.2.1 Assessment: Marine Mammals

The noise level results from Section 4.3 were assessed against the Southall *et al.* (2019) guidelines and weightings to predict the likely range at which the thresholds for non-impulsive sounds would be exceeded by marine mammals.

When the $L_{E,p,24h,wtd}$ criteria for non-impulsive noise is applied to the predicted noise contours, it is unlikely that animals will exceed the PTS threshold for all marine mammal species at any range from the dredging activities at both PoD and LS. This assumes that the dredging is taking place continuously for 8 hours, and that the animals flee away from the noise source at a constant speed.

4.3.2.2 Assessment: Fish

The noise level results from Section 4.3 were assessed against the Popper *et al.* (2014) guidelines to predict the likely range at which the thresholds for shipping and continuous sounds would be exceeded by fish.

Based on the results for the $L_{p,rms}$ metric, it is unlikely that animals will exceed the any threshold for all fish species at any range from the dredging activities at both PoD and LS.

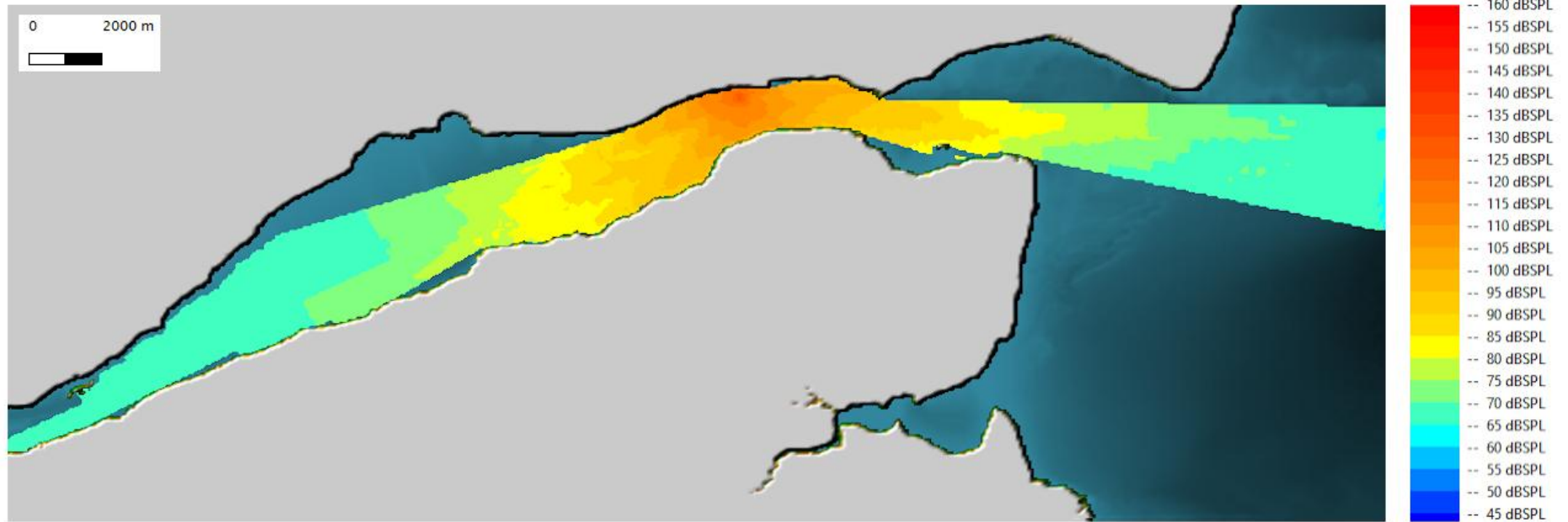


Figure 4-4: $L_{p,RMS}$ noise level contours predicted for dredging at the Port of Dundee.

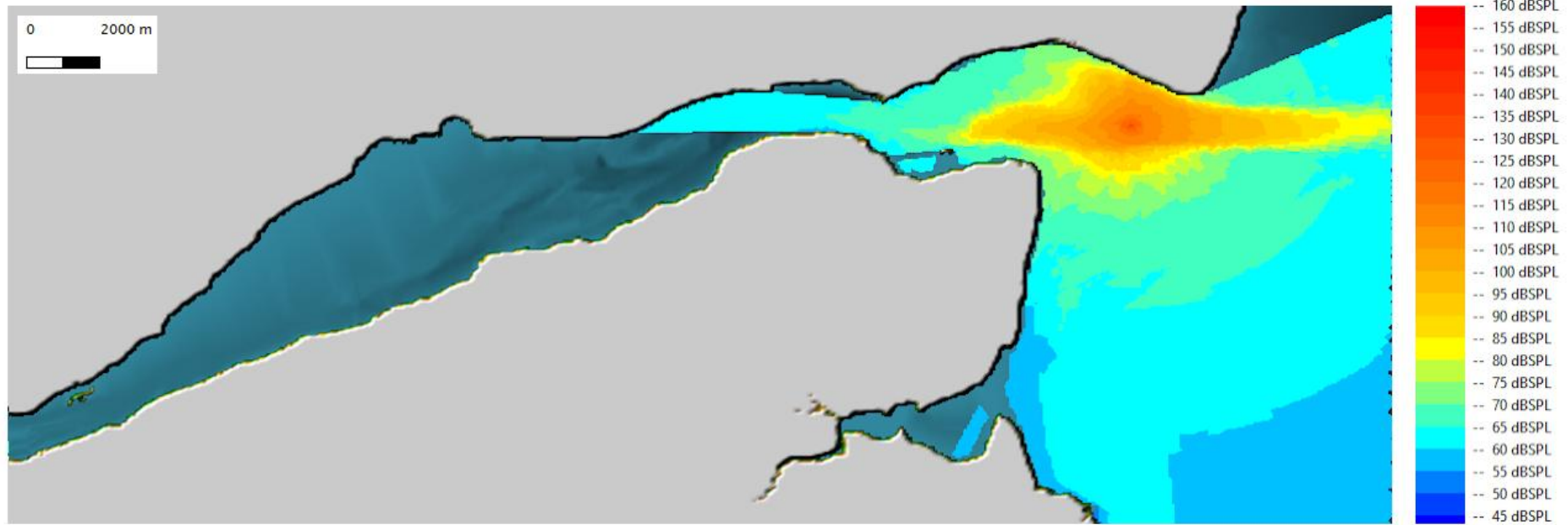


Figure 4-5: $L_{p,RMS}$ noise level contours predicted for dredging at Lady Shoal.

5 Conclusion

Subacoustech Environmental has undertaken an underwater noise modelling study in anticipation of planned construction works at Prince Charles Wharf in the Port of Dundee, along the River Tay, Scotland. The works are proposed to include the use of impact piling and vibropiling for pile installation, and backhoe dredging at both the construction site and Lady Shoal, which is located towards the mouth of the River Tay.

The level of underwater noise generated by the works was estimated using a combined parabolic equation and ray tracing modelling approach. The modelling considers a wide array of input parameters including the equipment source level, sound frequency content, seabed properties and the sound speed profile in the water column. Full account is also taken of the bathymetry in the areas surrounding the survey site.

The modelled noise levels were then interpreted in accordance with the guidelines outlined in Southall *et al.* (2019) for marine mammals in relation to impulsive and non-impulsive noise sources, and Popper *et al.* (2014) for fish in relation to pile driving and continuous sounds.

Using the Southall *et al.* (2019) guidance for marine mammals, all marine mammals, including PCW, are unlikely to exceed any of the criteria for PTS across both the $L_{p,pk}$ and $L_{E,p,t}$ metrics. For TTS the greatest risk of exceedance was found to be for VHF cetaceans within 80 m of impact piling and 30 m of vibropiling.

For fish, using the Popper *et al.* (2014) guidance:

- Fish with a swim bladder both involved and not involved in hearing are predicted to be at risk of mortality only if they are within 10 m of impact piling. A risk of TTS exceedance was found for all fish species remaining within 80 m of impact piling for the full duration.
- Fish with a swim bladder involved in hearing are predicted to be at risk of recoverable injury if they are within 10 m from the vibropiling. There is a risk of TTS for fish remaining within 50 m for the full duration of vibropiling.
- All fish are unlikely to be at risk of any negative noise impacts during backhoe dredging

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 physical processes, including many that change constantly under real world conditions. 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 in determining where environmental effects may occur in receptors during the proposed operations.

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