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Modelling of underwater noise from activities related to the construction of the Neptun Deep project in the Black Sea

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List of contents

Glossary

Term	Definition
Decibel (dB)	A customary scale commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be $10\log_{10}(actual/reference)$ where $(actual/reference)$ is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is $20\log_{10}(actual\ pressure/reference\ pressure)$. The standard reference for underwater sound is 1 micro pascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (e.g., re 1 µPa).
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Peak-to-peak pressure	The sum of the highest positive and negative pressures that are associated with a sound wave.
Permanent Threshold Shift (PTS)	A permanent total or partial loss of hearing caused by acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the air, 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)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Exposure Level, cumulative (SEL_{cum})	Single value for the collected, combined total of sound exposure over a specified time or multiple instances of a noise source.
Sound Exposure Level, single strike (SEL_{ss})	Calculation of the sound exposure level representative of a single noise impulse, typically a pile strike.
Sound Pressure Level (SPL)	The sound pressure level is an expression of sound pressure using the decibel (dB) scale; the standard frequency pressures of which are 1 µPa for water and 20 µPa for air.
Sound Pressure Level Peak (SPL_{peak})	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. Exposure to high levels of sound over relatively short time periods could cause the same level of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus.
Unweighted sound level	Sound levels which are "raw" or have not been adjusted in any way, for example to account for the hearing ability of a species.
Weighted sound level	A sound level which has been adjusted with respect to a "weighting envelope" in the frequency domain, typically to make an unweighted level relevant to a particular species. Examples of this are the dB(A), where the overall sound level has been adjusted to account for the hearing ability of humans in air, or the filters used by Southall *et al*. (2019) for marine mammals.

1 Introduction

Subacoustech Environmental have been requested by io consulting to carry out underwater noise modelling for various noise sources related to the construction of the Neptun Deep project in the Black Sea, off the east coast of Romania.

The project is expected to utilise dredging, drilling, impact piling, micro tunnelling, trenching and related vessel noise.

1.1 Site description

The Neptun Deep site covers a large area of the Black Sea to the east of Romania. The water depths in the Project Area extend to approximately 1.7 km deep, with shallower waters towards the coast and water depths in excess of 2 km further out to the southeast of the site into the centre of the Black Sea.

The Project Area, as well as the three modelling locations used for this study, are presented in Figure 1-1.

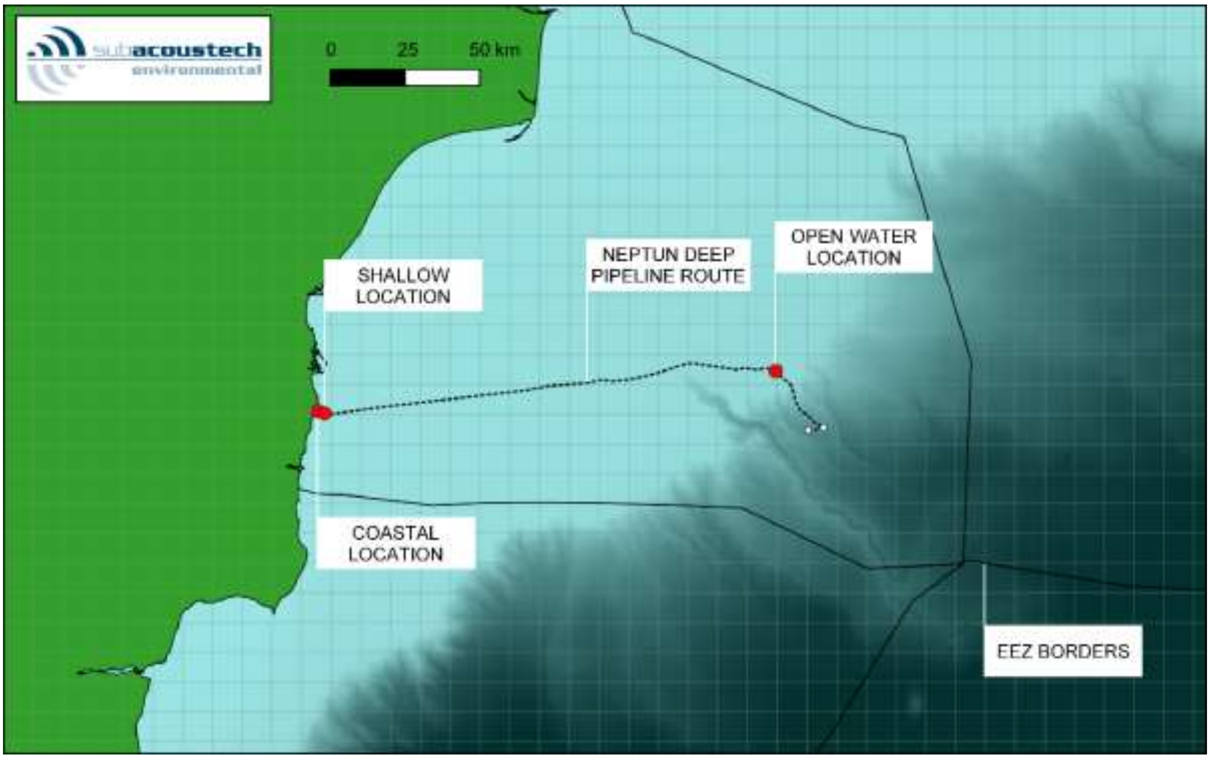

Figure 1-1 Map showing the locations used for modelling in the Black Sea along with the boundary of the Neptun Deep site

The modelling locations have been selected to be the deepest locations where each of the construction activities may occur. Deeper water tends to lead to the greatest underwater noise propagation and the largest impact ranges. The exact locations chosen at the Shallow Location and Coastal Location represent the deepest location for the activities there, including backhoe dredging and cutter suction dredging in the Shallow location and Micro-tunnelling in the Coastal location. The Open Water location included drilling, impact piling, trenching, and vessel noise. More detail on the modelling methodology is given in Section 4.1.

2 Background to underwater noise metrics

Sound travels much faster in water (approximately 1,500 ms^{-1}) than in air (340 ms^{-1}). Since water is a relatively incompressible, dense medium, the pressure associated with underwater sound tends to be much higher than in air.

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

2.1 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 each doubling of sound level will cause a roughly equal increase of "loudness."

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

The fundamental definition of the dB scale is given by:

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

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

The dB scale represents a ratio. It is therefore used with a reference unit, which expresses the base from which the ratio is expressed. The reference quantity is conventionally smaller than the smallest value to be expressed on the scale so that any level quoted is positive. For example, a reference quantity of 20 µPa is used for sound in air since that is the lower threshold of human hearing.

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

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

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

2.2 Sound Pressure Level (SPL)

The Sound Pressure Level (SPL) is normally used to characterise noise and vibration of a continuous nature, such as drilling, boring, continuous wave sonar, or background sea and river noise levels. To calculate the SPL, the variation in sound pressure is measured over a specific period to determine the RMS level of the time-varying sound. The SPL can therefore be considered a measure of the average unweighted level of sound over the measurement period.

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

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

2.3 Peak Sound Pressure Level (SPL_{peak})

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

A further variation of this is the peak-to-peak SPL ($SPL_{peak\text{-}to\text{-}peak}$) where the maximum variation of the pressure from positive to negative is considered. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak pressure will be twice the peak level, or 6 dB higher (see section 2.1).

2.4 Sound Exposure Level (SEL)

When considering the noise from transient sources, the issue of the duration of the pressure wave is often addressed by measuring the total acoustic energy (energy flux density) of the wave. This form of analysis was used by Bebb and Wright (1953, 1954a, 1954b, 1955), and later by Rawlins (1987), to explain the apparent discrepancies in the biological effect of short and long-range blast waves on human divers. More recently, this form of analysis has been used to develop criteria for assessing injury ranges for fish and marine mammals from various noise sources (Popper *et al*., 2014; Southall *et al*., 2019).

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

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

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

To express the SE on a logarithmic scale by means of a dB, it must be 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 broadband noise and the SEL sums the cumulative broadband noise energy.

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

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

$$SEL_{cum} = SEL + 10 \times \log_{10} X$$

Where SEL is the sound exposure level of one impulse and X is the total number of impulses or strikes. Unless otherwise defined, all SEL noise levels in this report are referenced to 1 μPa^{2}s.

3 Noise sources

The following construction activities and noise sources are expected as part of the installation of the Neptun Deep pipeline:

- Dredging;
- Drilling;
- Impact piling;
- Micro tunnelling;
- Trenching; and
- Vessel noise.

Detailed source noise levels (i.e., the effective noise level at 1 m from the source used in the modelling) for these activities and noise sources are given in Section 4.1.2.

3.1 Dredging

Two types of dredgers have been considered for this modelling: backhoe dredging, where material is removed from the seabed using a bucket on a mechanical excavator arm, and cutter suction dredging, where a cutter head breaks up hard soil or rock into fragments on the seabed before a suction pipe pumps it to the surface. For the Neptun Deep project, the proposed dredging will cover over 3 km for the installation of the gas production pipeline, dredging to depths of between 20 and 40 m.

No specific dredging vessels or equipment could be identified at this stage so generic noise measurements from Subacoustech Environmental's noise database have been used, with backhoe dredging noise measured from the *Zenne* dredger in Northwest Ireland, and cutter suction dredging from the *Taurus II* rock cutter in the Persian Gulf.

3.2 Drilling

Drilling will be present at the Neptun Deep site as part of the completion of offshore production wells. No specific drilling rig was specified so measurements of a 400 kW *Seacore / Wirth B5* drill taken in Northeast Ireland have been used as a source for this modelling.

3.3 Impact piling

Skirt piles measuring 2.44 m in diameter are to be installed to a depth of between 92 and 102 m at the site. The piling method has not been confirmed but impact piling has been assumed as a worst case.

The impact piling approach chosen for modelling is two-stage: a MENCK 800S hammer is used to partially install a set of four piles, then the hammer is changed to the larger MENCK 3200iS hammer to fully install those piles. Due to the piling durations and hammer changeover time, it is not expected that the two hammers will be utilised in the same 24-hour period.

The soft start and ramp up processes for the two piling hammers are summarised in Table 3-1 to Table 3-4, as supplied by io consulting. For each pile, four piling scenarios have been considered, an upper bound and a best estimate as well as the installation of a single pile, and four piles installed sequentially.

Table 3-1 Impact piling parameters for the upper bound scenario using the MENCK 800S hammer

MENCK 800S (Upper bound)	**164 kJ**	**410 kJ**	**492 kJ**	**574 kJ**	**656 kJ**	**820 kJ**
Number of strikes	100	483	3,281	2,887	3,483	4,063
Duration	10 mins	16 mins	82 mins	72 mins	87 mins	90 mins
Strike rate	10 bl/min	~30 bl/min	~40 bl/min			~45 bl/min
Single pile: 14,297 strikes, 5.95 hours duration 4 piles: 57,188 strikes, 23.8 hours duration						

Table 3-2 Impact piling parameters for the best estimate scenario using the MENCK 800S hammer

MENCK 800S (Best estimate)	**164 kJ**	**410 kJ**	**492 kJ**	**574 kJ**	**656 kJ**	**820 kJ**
Number of strikes	100	260	2,398	1,702	1,827	1,893
Duration	10 mins	9 mins	60 mins	43 mins	46 mins	42 mins
Strike rate	10 bl/min	~29 bl/min	~40 bl/min			~45 bl/min
Single pile: 8,180 strikes, 3.5 hours duration 4 piles: 32,720 strikes, 14 hours duration						

Table 3-3 Impact piling parameters for the upper bound scenario using the MENCK 3200iS hammer

MENCK 3200iS (Upper bound)	**640 kJ**	**1,600 kJ**	**2,401 kJ**	**3,201 kJ**
Number of strikes	100	3,606	3,205	5,206
Duration	10 mins	120 mins	80 mins	116 mins
Strike rate	10 bl/min	~30 bl/min	~40 bl/min	~45 bl/min
Single pile: 12,117 strikes, 5.43 hours duration 4 piles: 48,468 strikes, 21.73 hours duration				

Table 3-4 Impact piling parameters for the best estimate scenario using the MENCK 3200iS hammer

MENCK 3200iS (Best estimate)	**640 kJ**	**1,600 kJ**	**2,401 kJ**	**3,201 kJ**
Number of strikes	100	1,383	1,190	1,432
Duration	10 mins	46 mins	30 mins	32 mins
Strike rate	10 bl/min	~30 bl/min	~40 bl/min	~45 bl/min
Single pile: 4,105 strikes, 1.97 hours duration 4 piles: 16,420 strikes, 7.87 hours duration				

3.4 Micro tunnelling

A Tunnel Boring Machine (TBM) is proposed for micro tunnelling beneath the Romanian coastline. This method has been chosen as this particular area is a protected site. The proposed TBM will create a borehole 2.5 m in diameter.

Borehole drilling measurements from the Moray Firth in Scotland with a similar drilling diameter have been used as a proxy for the micro tunnelling noise in this modelling.

3.5 Trenching

Trenching equipment, whereby a device on the seabed digs a trench, lays pipe or cables and subsequently backfills the trench, is included in the noise modelling. For the Neptun Deep project this will be used for umbilicals and flowlines. The SMD and Fugro TSM Q1400 Trenching System has been identified as a potential trenching option for this project. Measurements of a similar trenching system, an RT1 Rock Trencher, taken in Northwest Ireland has been used a source for this modelling.

3.6 Vessel noise

All the noise sources identified above have related vessel noise, for example, tugs and hopper barges for dredging, crew boats, ROV survey vessels and the piling barge for impact piling. A Fishing and Shipping Study Report produced for the Neptun Deep Project (ROND-EW-YRRPT-20-0002) also details the potential vessels that may be present during construction. Data is not available for these individual vessels so as a worst case, measurements from the *Vega Stockholm*, a large container vessel, have been used to encompass all the potential vessels at the Neptun Deep Site.

4 Assessment approach

This section presents a summary of the modelling approach used to assess the expected underwater noise levels from the proposed construction activities and noise sources for the Neptun Deep pipeline, as well as the criteria used to assess the noise impact on the relevant marine species.

The modelling approach presented herein conforms to the recommendations found in the National Physical Laboratory (NPL) Good Practice Guide 133 for Underwater Noise (Robinson *et al*., 2014).

4.1 Modelling methodology

To estimate the likely underwater noise levels from the various construction activities, noise propagation modelling has been carried out using an approach that is widely used and accepted by the acoustics community, in combination with publicly available environmental data, information provided by the client, and data from Subacoustech Environmental's measurement library. The approach is described in more detail below.

Modelling has been undertaken at three locations, representing the worst-cases for each activity listed in Section 2. The locations, shown in Figure 1-1, are summarised in Table 4-1.

Table 4-1 Summary of the underwater noise modelling location coordinates, and associated water depths (mean sea level)

	Open water location	Shallow location	Coastal location
Noise sources	Drilling, Impact piling, Trenching, and Vessel noise	Backhoe dredging, and Cutter suction dredging	Micro tunnelling
Decimal degrees	44.04778° N, 030.5875° E	43.96389° N, 028.6925° E	43.97111° N, 028.66389° E
Eastings and Northings	306733.2, 4880010 (UTM 36N)	154428.3, 4876892 (UTM 36N)	152175.0, 4877815 (UTM 36N)
Water depth	124 m	24 m	10 m

Modelling of underwater noise is complex and can be approached in several different ways. In this case, Subacoustech Environmental have chosen to use a numerical modelling approach that is based on both a parabolic equation (PE) method for low frequencies and a ray tracing method for high frequencies (Etter, 1991). This study implements these numerical solutions using the dBSea software (v2.3).

This model uses a wide array of input parameters including bathymetry, sediment data, sound speed and source frequency to ensure the results are as detailed and accurate as possible. These parameters are described in detail in Sections 4.1.1 and 4.1.2.

It should be noted that the modelling presented in this study assumes stationary noise sources. As some of these activities, such as trenching and dredging, move over time, these results should be considered conservative due to the lower total exposure to noise of any one area.

By its nature, mathematical modelling will produce results which indicate a precise range at which a criterion (Section 4.2) will be reached, but this does not reflect the inherent uncertainties in the process. The results give a specific numeric value to a problem with a vast number of variables and parameters, including many that change constantly in real world conditions. Most modelling parameters, such as the source noise level, the duration of operation and its location, are selected to be precautionary, to avoid the risk of underestimating the impact. The results given in Section 5 present specific ranges at which each impact threshold is met, to determine where environmental effects may occur in receptors during the noisy activities. Due to the natural fluctuations noted above, the ranges should be taken as indicative, albeit they are intended to be worst case.

4.1.1 Modelling inputs

The bathymetry data used in the modelling was obtained from the European Marine Observation and Data Network (EMODnet), which has a grid resolution of approximately 115 m. This data is normalised to mean sea level and no attempt has been made to account for tidal range.

The speed of sound in the water has been calculated from temperature and salinity data supplied by the client for the area. The calculation from Mackenzie (1981) was used to ascertain speed of sound with depth for the modelling locations.

Based on information supplied by the client the characteristics of the seabed around the modelling locations assume a mix of circalittoral sand and mud. The parameters used for modelling are presented in Table 4-2. The geoacoustic properties used in modelling were based on available data for sand and mud from Jensen *et al*. (2011).

Table 4-2 Seabed geoacoustic properties used for modelling

Seabed type	Compressive sound speed in substrate	Density profile in substrate	Attenuation profile in substrate
Circalittoral sand / mud	1,675 ms^{-1}	1,700 kg/m^3	0.9 dB/wavelength

4.1.2 Source noise levels and frequency content

Source noise levels for the equipment being modelled have been derived using data available from manufacturers, data provided by the client and from empirical measurements of similar equipment from Subacoustech Environmental’s noise measurement database. The references for these are given in Section 2. A summary of the peak sound pressure level (SPL_{peak}) and sound exposure level (SEL) source levels are given in Table 4-3.

The equipment has been given equivalent source noise levels appropriate to the frequency range used for modelling (12.5 Hz to 100 kHz); frequencies above this range have not been used as the potential effects from them will be relatively low due to the noise sources not generating significant noise at frequencies above this and the relative insensitivity of receptor species. An SPL_{peak} source level is only given from impact piling as this is the only noise considered impulsive. All of the other sources are designated as continuous or non-pulsed noise and are represented by SEL. All the SELs presented are normalised to 1 second. The 1/3rd-octave band spectra for these sources are presented in Figure 4-1.

Table 4-3 Summary of the unweighted SPL_{peak} and SEL source levels used for the noise sources in this study

Noise source		SPL_{peak} source level	SEL source level
Backhoe dredging		N/A	176.0 dB re 1 µPa²s @ 1 m (1 second)
Cutter suction dredging		N/A	177.0 dB re 1 µPa²s @ 1 m (1 second)
Drilling		N/A	171.8 dB re 1 µPa²s @ 1 m (1 second)
Impact piling	MENCK 800S, full energy (820 kJ)	237.1 dB re 1 µPa @ 1 m	217.7 dB re 1 µPa²s @ 1 m (single strike)
	MENCK 800S, soft start (164 kJ)	255.2 dB re 1 µPa @ 1 m	207.4 dB re 1 µPa²s @ 1 m (single strike)
	MENCK 3200iS, full energy (3,201 kJ)	241.7 dB re 1 µPa @ 1 m	222.4 dB re 1 µPa²s @ 1 m (single strike)
	MENCK 3200iS, soft start (640 kJ)	235.8 dB re 1 µPa @ 1 m	216.5 dB re 1 µPa²s @ 1 m (single strike)
Micro tunnelling		N/A	177.0 dB re 1 µPa²s @ 1 m (1 second)
Trenching		N/A	197.0 dB re 1 µPa²s @ 1 m (1 second)
Vessel noise		N/A	198.3 dB re 1 µPa²s @ 1 m (1 second)

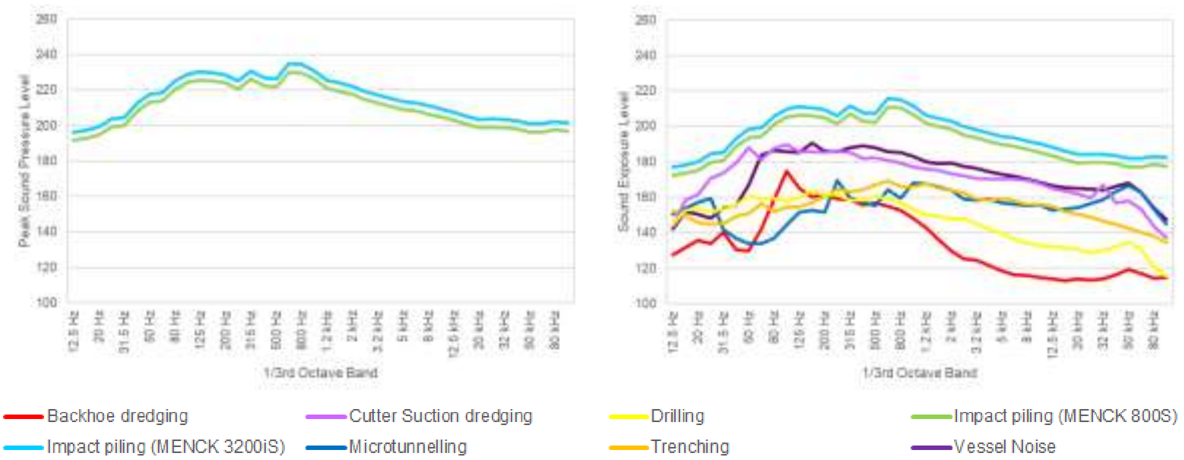

Figure 4-1 Unweighted source 1/3rd-octave band levels (SPL_{peak} and 1 s SEL) for all the modelled sources (impact piling full energy levels shown)

Different source depths have been used for the equipment considered, with dredging, drilling, micro tunnelling and trenching modelled to occur 1 m above the seabed, vessel noise at the surface, and impact piling at mid-water as a worst-case due to the noise being a line source rather than a point source.

Except for impact piling, where cumulative exposure is calculated, a worst-case assumption of constant operation over 24-hours has been used.

4.2 Assessment of underwater noise

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. As a result, scientific interest in the hearing abilities of aquatic animal species, which may be affected by noise, has increased. Studies are primarily based on evidence from high level sources of underwater noise such as blasting, seismic airguns or impact piling, as these sources are likely to have the greatest environmental impact. The extent to which intense underwater sound might cause an adverse environmental impact in a species is dependent upon the incident sound level, sound frequency, duration of exposure and/or the repetition rate of the sound wave (e.g., Hastings and Popper, 2005).

Adverse impacts of underwater sound can be broadly summarised into three categories:

- Physical traumatic injury and fatality;
- Auditory injury, either permanent threshold shift (PTS) or temporary threshold shift (TTS); and
- Disturbance.

The following sections discuss the underwater noise criteria used in this study with respect to species of marine mammals and fish.

4.2.1 Criteria to be used

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

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

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

4.2.2 Marine mammals (Southall et al. 2019)

The Southall *et al*. (2019) paper is effectively an update of the previous widely referenced Southall *et al.* (2007) paper and provides identical thresholds to those from the National Marine Fisheries Service (NMFS) (2018) guidance for marine mammals.

The Southall *et al*. (2019) guidance groups marine mammals into groups of similar species and applies filters to the unweighted noise to approximate the hearing sensitivities of the receptor in question. The hearing groups given in Southall *et al*. (2019) are summarised in Table 4-4 and Figure 4-2.

Table 4-4 Marine mammal hearing groups (from Southall et al., 2019)

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

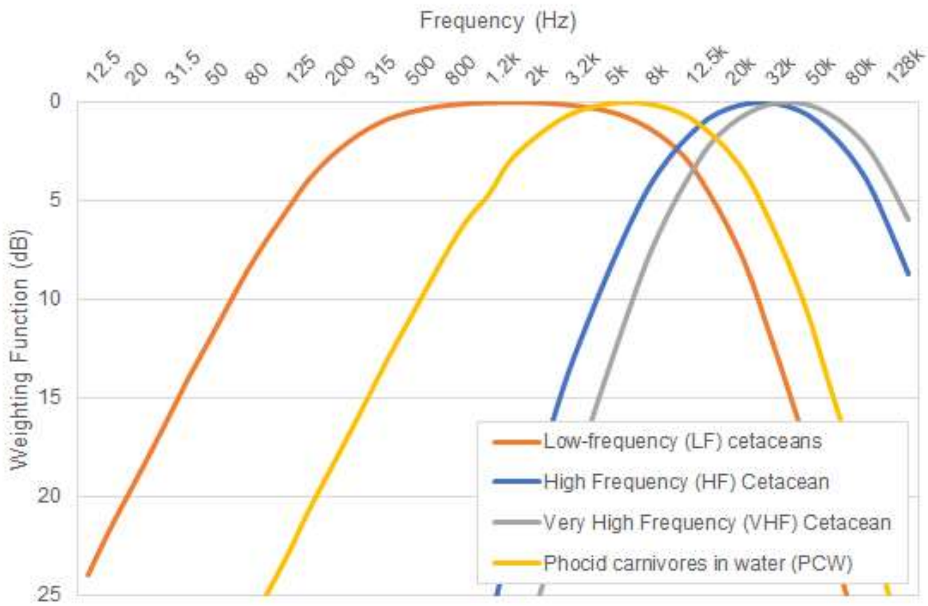

Figure 4-2 Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019)

Southall *et al*. (2019) also gives individual criteria based on whether the noise source is considered impulsive or non-impulsive. How these sounds can be categorised is advised in NMFS (2018):

- Impulsive sounds are typically transient, brief (less than 1 second), broadband and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI, 1986; ANSI, 2005, NIOSH, 1998). This category includes sources such as seismic airgun surveys, impact piling and underwater explosions.
- Non-impulsive sounds can be broadband, narrowband, or tonal, brief or prolonged, continuous or intermittent and typically do not have a high peak sound pressure with a rapid rise/decay time that impulsive sounds do (ANSI, 1995; NIOSH, 1998). This category includes sound sources such as continuous running machinery, sonar, and vessels.

For the sources considered, only impact piling is considered impulsive, all others are considered non-impulsive.

Southall *et al*. (2019) presents single strike, unweighted peak criteria (SPL_{peak}) and cumulative weighted sound exposure criteria (SEL_{cum}, i.e., can include the accumulated exposure of multiple pulses) for both permanent threshold shift (PTS), where unrecoverable (but incremental) hearing damage may occur, and temporary threshold shift (TTS), where a temporary reduction in hearing sensitivity may occur in individual receptors. These dual criteria (SPL_{peak} and SEL_{cum}) are only used for impulsive noise: the criteria set giving the greatest calculated range is used as the PTS impact range.

As sound pulses propagate through the environment and dissipate, they also lose their most injurious characteristics (e.g., rapid pulse rise time and high peak sound pressure) and become more like a "non-pulse" at greater distances; Southall *et al*. (2019) briefly discusses this. Active research is currently underway into the identification of the distance at which the pulse can be considered effectively non-impulsive, and Hastie *et al*. (2019) have analysed a series of impulsive data to investigate it. Although the situation is complex, the paper reported that most of the signals crossed their threshold for rapid rise time and high peak sound pressure characteristics associated with impulsive noise at around 3.5 km from the source. However, research by Martin *et al*. (2020) casts doubt on these findings, showing that noise in this category should be considered impulsive as long as it is above effective quiet, or a noise sufficiently low enough that it does not contribute significantly to any auditory impairment or injury. To provide as much detail as possible, where necessary, both impulsive and non-impulsive criteria from Southall *et al.* (2019) have been included in this study.

Table 4-5 and Table 4-6 present the criteria from Southall *et al*. (2019) for the onset of PTS and TTS risk for each of the key marine mammal hearing groups, considering both impulsive and non-impulsive sources.

Table 4-5 Single strike SPL_{peak} criteria for PTS and TTS in marine mammals (Southall et al., 2019)

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

Table 4-6 Impulsive and non-impulsive SEL_{cum} criteria for PTS and TTS in marine mammals (Southall et al., 2019)

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

Where SEL_{cum} exposure thresholds are required, a fleeing animal model has been used for marine mammals. This assumes that a receptor, when exposed to high noise levels, will swim away from the noise source. A constant fleeing speed of 3.25 ms^{-1} has been assumed for the low-frequency cetaceans (LF) group (Blix and Folkow, 1995), based on data for minke whale, and for other receptors, a constant rate of 1.5 ms^{-1} has been assumed for fleeing, which is a cruising speed for a harbour porpoise (Otani *et al*., 2000). These are considered worst case assumptions as marine mammals are expected to be able to swim much faster under stress conditions (Kastelein *et al.* 2018), especially at the start of any noisy process when the receptor will be closest.

It is worth noting that, comparing Southall *et al.* (2019) to NMFS (2018), the guidance applies different names to otherwise identical marine mammal groups and weightings, which are otherwise numerically identical. 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 (HF). 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.

4.2.3 Fish (Popper et al. 2014)

The large number of, and variation in, fish species leads to a greater challenge in production of a generic noise criterion, or range of criteria, for the assessment of noise impacts. The publication of Popper *et al*. (2014) provides an authoritative summary of the latest research and guidelines for fish exposure to sound.

The Popper *et al*. (2014) study groups species of fish by whether they possess a swim bladder, and whether it is involved in its hearing; groups for sea turtles and for fish eggs and larvae are also included. The guidance also gives specific criteria (as both unweighted SPL_{peak} and unweighted SEL_{cum} values) for a variety of noise source types (e.g., piling, seismic airguns, etc.).

The most appropriate criteria sets for the sources considered for this study are the impact piling criteria and the continuous noise sources criteria; these criteria are detailed in Table 4-7 and Table 4-8.

Table 4-7 Criteria for mortality and potential mortal injury, recoverable injury and TTS in species of fish from impact piling noise (Popper et al., 2014)

Type of animal	Mortality / potential mortal injury	Impairment	
		Recoverable injury	TTS
Fish: no swim bladder	> 219 dB SEL_{cum} > 213 dB peak	> 216 dB SEL_{cum} 213 dB peak	>> 186 dB SEL_{cum}
Fish: swim bladder is not involved in hearing	210 dB SEL_{cum} > 207 dB peak	203 dB SEL_{cum} > 207 dB peak	> 186 dB SEL_{cum}
Fish: swim bladder involved in hearing	207 dB SEL_{cum} > 207 dB peak	203 dB SEL_{cum} > 207 dB peak	186 dB SEL_{cum}
Sea turtles	210 dB SEL_{cum} > 207 dB peak	See Table 4-9	See Table 4-9
Eggs and larvae	210 dB SEL_{cum} > 207 dB peak	See Table 4-9	See Table 4-9

Table 4-8 Criteria for recoverable injury and TTS in species of fish and sea turtles from continuous noise sources (Popper et al., 2014)

Type of animal	Impairment	
	Recoverable injury	TTS
Fish: swim bladder involving in hearing	170 dB SPL_{RMS} for 48 hours	158 dB SPL_{RMS} for 12 hours

Where insufficient data are available, Popper *et al*. (2014) also give qualitative criteria that summarise the effect of the noise as having either a high, moderate or low effect on an individual in either the near-field (of the order of tens of metres), intermediate-field (hundreds of metres), or far-field (thousands of metres). These qualitative effects are reproduced in Table 4-9 and Table 4-10.

Table 4-9 Summary of the qualitative effects on species of fish from impact piling noise (Popper et al., 2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
Fish: no swim bladder	See Table 4-7	See Table 4-7	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing	See Table 4-7	See Table 4-7	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing	See Table 4-7	See Table 4-7	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
Sea turtles	(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	(N) Moderate (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

Table 4-10 Summary of the qualitative effects on species of fish and sea turtles from continuous noise sources (Popper et al., 2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	Mortality / 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 is 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	See Table 4-8	See Table 4-8	(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

Both fleeing animal and stationary animal models have been used to cover the SEL_{cum} criteria for fish. It is recognised that there is limited evidence for fish fleeing from high level noise sources in the wild, and it would reasonably be expected that the reaction would differ between species. Most species are likely to move away from a sound that is loud enough to cause harm (Dahl *et al.*, 2015; Popper *et al.*, 2014), some may seek protection in the sediment and others may dive deeper in the water column. For those species that flee, the speed chosen for this study of 1.5 ms^{-1} is relatively slow in relation to data from Hirata (1999) and thus is considered somewhat conservative.

Although it is feasible that some species will not flee, those that are likely to remain are thought more likely to be benthic species or species without a swim bladder; these are the least sensitive species.

For example, from Popper *et al*. (2014): "There is evidence (e.g., Goertner *et al*., 1994; Stephenson *et al*., 2010; Halvorsen *et al*., 2012) that little or no damage occurs to fish without a swim bladder except at very short ranges from an in-water explosive event. Goertner (1978) showed that the range from an explosive event over which damage may occur to a non-swim bladder fish is in the order of 100 times less than that for swim bladder fish."

Stationary animal modelling has been included in this study, based on research from Hawkins *et al*. (2014) and other modelling for similar EIA projects. However, basing the modelling on a stationary (zero flee speed) receptor is likely to greatly overestimate the potential risk to fish species, assuming that an individual would remain in the high noise level region of the water column, especially when considering the precautionary nature of the parameters already built into the cumulative exposure calculations.

5 Modelling results

This section presents the modelling results in terms of the biologically significant noise metrics and impact criteria detailed in Section 4.2. These results will help guide the assessment of environmental impact in marine species from the various operations proposed at the Neptun Deep site. In each case the loudest predicted level modelled at any depth in the water column has been used as a worst-case assumption. A discussion of the potential mitigation measures is given in section 5.7.

The loudest source, in terms of biological impact, is predicted to be impact piling. This is due to the impulsive nature of the noise coupled with the source level, which is much higher than those predicted for the other noise sources (Table 4-3).

For presentation of the impact range tables, predicted impact ranges smaller than 50 m for single strike criteria, and impact ranges smaller than 100 m for cumulative criteria, have not been presented in detail as within this range from the noise source, the modelling processes are unable to predict to a sufficient level of accuracy due to acoustic effects near the noise-producing equipment. These ranges are presented as < 50 m and < 100 m respectively.

All noise level plots are presented at the same scales for ease of comparison, and as such some of the levels from quieter sources are very small in the figures. All the contours given in this report have also been provided as GIS shapefiles.

5.1 Dredging

The modelled 1 s SEL noise from dredging noise at the shallow modelling location is presented in Figure 5-1 and Figure 5-2. The noise levels for the backhoe dredger are slightly louder at longer range than for the cutter suction dredging due to the lower frequency components of the noise, shown in Figure 4-1, which are transmitted further through the water even though the cutter suction dredger has a louder broadband source level (Table 4-3). However, the low level of noise from dredging results in negligible impact ranges, as shown in Table 5-1 to Table 5-6.

5.1.1 Backhoe dredging

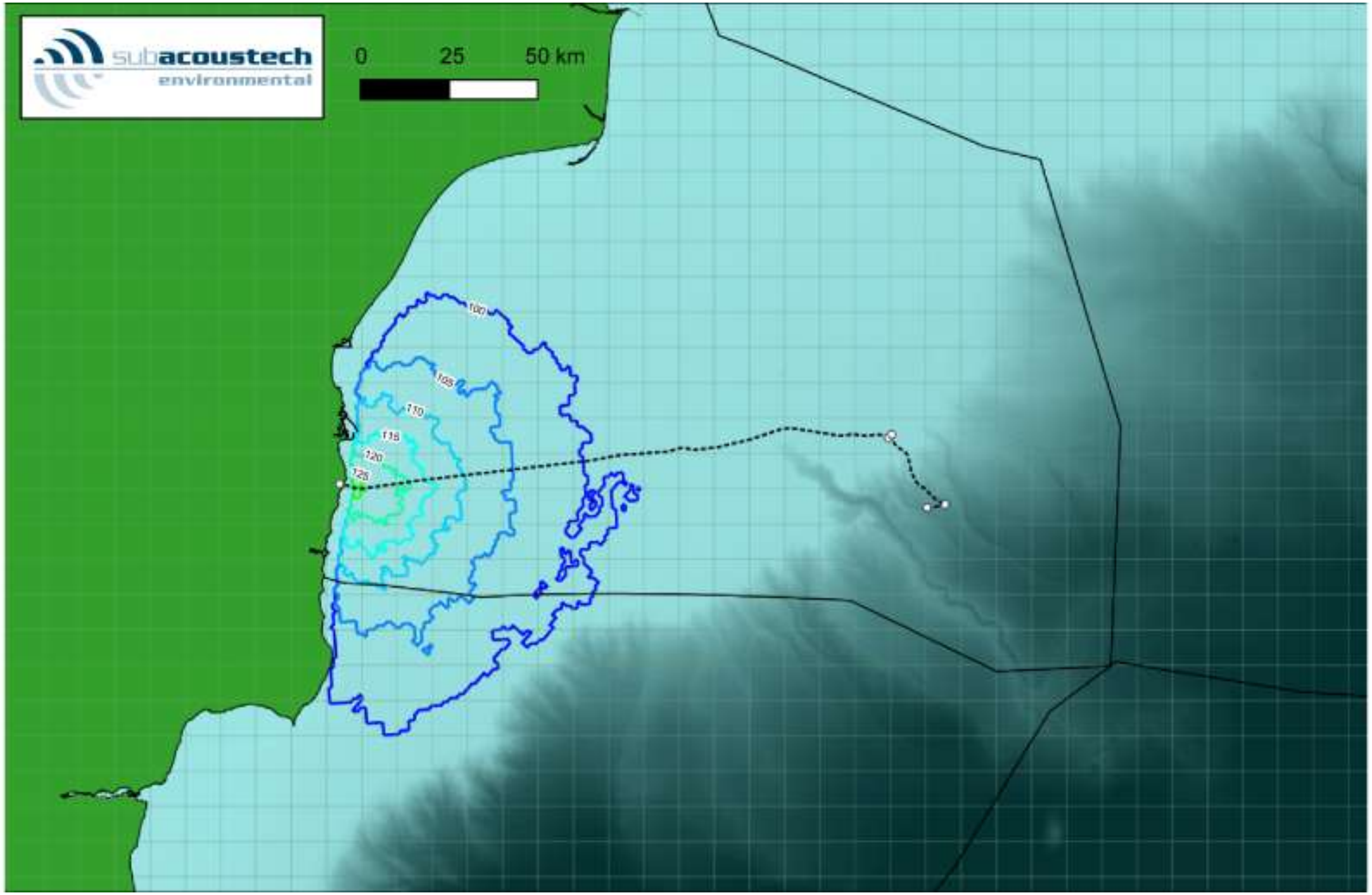

Figure 5-1 Noise plot showing the predicted unweighted noise levels (1 s SEL only) from backhoe dredging at the shallow modelling location, 100-125 dB contours

Table 5-1 Summary of the modelled Southall et al. (2019) cumulative PTS impact ranges for marine mammals from backhoe dredging noise

Southall *et al*. (2019) **Backhoe dredging**		Weighted SEL_{cum} (fleeing) Non-impulsive			
		LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)
PTS	Maximum	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-2 Summary of the modelled Southall et al. (2019) cumulative TTS impact ranges for marine mammals from backhoe dredging noise

Southall *et al*. (2019) **Backhoe dredging**		Weighted SEL_{cum} (fleeing) Non-impulsive			
		LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
TTS	Maximum	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-3 Summary of the modelled Popper et al. (2019) impact ranges for fish from backhoe dredging noise

Popper *et al*. (2014) **Backhoe dredging**	Unweighted SPL_{RMS} Continuous sound	
	170 dB	158 dB
Maximum	< 50 m	< 50 m
Minimum	< 50 m	< 50 m
Mean	< 50 m	< 50 m

5.1.2 Cutter suction dredging

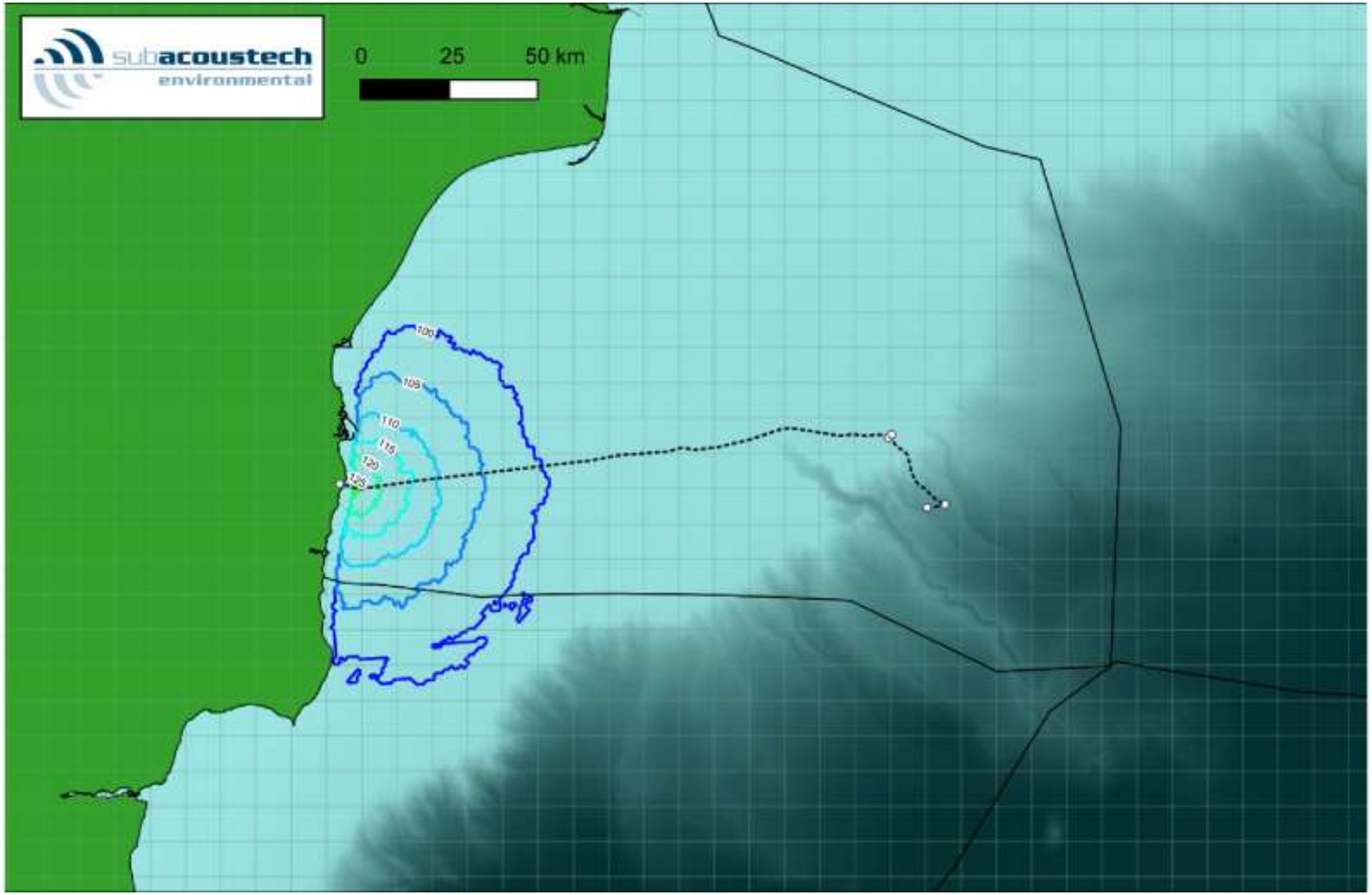

Figure 5-2 Noise plot showing the predicted unweighted noise levels (1 s SEL only) from cutter suction dredging at the shallow modelling location, 100-125 dB contours

Table 5-4 Summary of the modelled Southall et al. (2019) cumulative PTS impact ranges for marine mammals from cutter suction dredging noise

Southall *et al*. (2019) **Cutter suction dredging**		Weighted SEL_{cum} (fleeing) Non-impulsive LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)
PTS	Maximum	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-5 Summary of the modelled Southall et al. (2019) cumulative TTS impact ranges for marine mammals from cutter suction dredging noise

Southall *et al*. (2019) **Cutter suction dredging**		Weighted SEL_{cum} (fleeing) Non-impulsive LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
TTS	Maximum	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-6 Summary of the modelled Popper et al. (2019) impact ranges for fish from cutter suction dredging noise

Popper *et al*. (2014) **Cutter suction dredging**	Unweighted SPL_{RMS} Continuous sound 170 dB	158 dB
Maximum	< 50 m	< 50 m
Minimum	< 50 m	< 50 m
Mean	< 50 m	< 50 m

5.2 Drilling

The noise from drilling operations at the open water modelling location is presented in Figure 5-3, with the modelled impact ranges for marine mammals and fish summarised in Table 5-7 to Table 5-9. The low level of the drilling noise results in negligible impact ranges even when considering a worst-case 24-hour continuous operation.

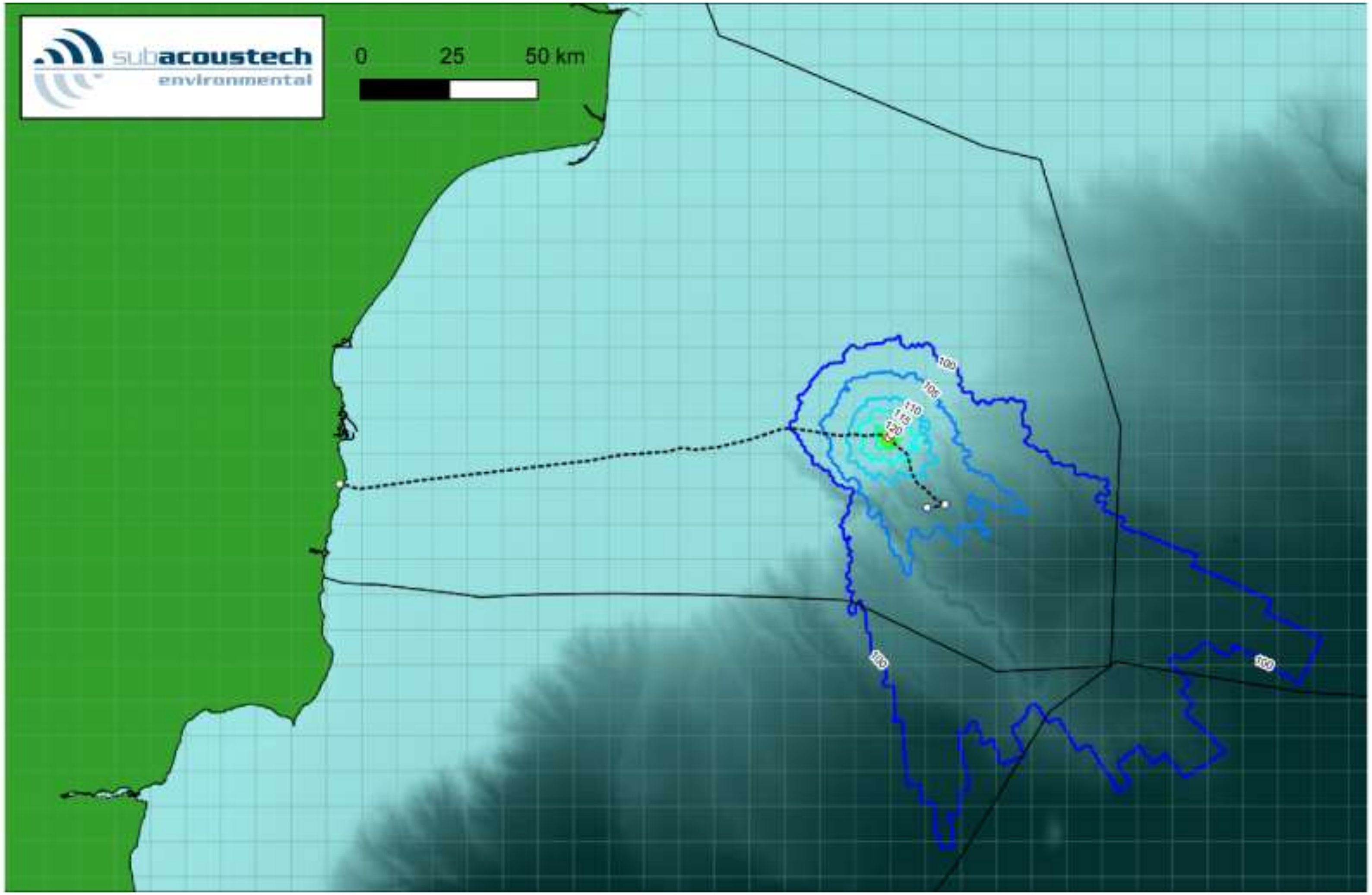

Figure 5-3 Noise plot showing the predicted unweighted noise levels (1 s SEL only) from drilling at the open water modelling location, 100-125 dB contours

Table 5-7 Summary of the modelled Southall et al. (2019) cumulative PTS impact ranges for marine mammals from drilling noise

Southall *et al*. (2019) **Drilling**		**Weighted SEL_{cum} (fleeing)**			
		Non-impulsive			
		LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)
PTS	Maximum	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-8 Summary of the modelled Southall et al. (2019) cumulative TTS impact ranges for marine mammals from drilling noise

Southall *et al*. (2019) **Drilling**		**Weighted SEL_{cum} (fleeing)**			
		Non-impulsive			
		LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
TTS	Maximum	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-9 Summary of the modelled Popper et al. (2019) impact ranges for fish from drilling noise

Popper *et al*. (2014) **Drilling**	**Unweighted SPL_{RMS}**	
	Continuous sound	
	170 dB	158 dB
Maximum	< 50 m	< 50 m
Minimum	< 50 m	< 50 m
Mean	< 50 m	< 50 m

5.3 Impact piling

Figure 5-4 to Figure 5-11 present the unweighted SPL_{peak} and single strike SEL noise levels for the modelled impact piling noise scenarios at the open water modelling location, assuming the parameters detailed in Section 3.3, covering noise levels from both full hammer energy and soft start. Due to the combination of a high source noise level and the impulsive nature of the noise, the predicted noise from impact piling travels much further than the other sources considered in this study. It is also possible that the piling could be carried out using other techniques, for example vibro piling, in which case noise levels will be greatly reduced.

The modelled impact ranges are presented in Table 5-10 to Table 5-12 for single strike SPL_{peak} criteria, and in Table 5-13 to Table 5-28**Error! Reference source not found.** for SEL_{cum} criteria, covering the upper bound, best estimate, single pile and four sequential pile scenarios; further figures (Figure 5-12 to Figure 5-27) show the SEL_{cum} criteria as noise contours.

The largest impact ranges using the Southall *et al*. (2019) criteria for marine mammals are predicted for the LF and VHF cetacean groups, with maximum PTS ranges of 33 km and 15 km respectively when considering a single pile installation for the larger MENCK 3200iS hammer and the upper bound scenario. These ranges increase to 57 km for LF cetaceans, and remaining at 15 km for VHF cetaceans when considering four sequential pile installations; the increase for four sequential piles is less noticeable for VHF cetaceans due to the drop off in level for higher frequencies to which this species group is most sensitive, meaning that the additional sound energy is less of an issue when the receptor has fled to a distance after the first pile installation.

It is worth noting that the maximum TTS ranges for LF cetacean when considering the impulsive criteria are predicted to be greater than 100 km, and a more specific range has not been included due to the uncertainties in the model at these long ranges and when considering the depths present in the Black Sea. At these ranges any noise from the impact piling will no longer be considered impulsive and will have lost much of the characteristics that make impulsive sound hazardous, so the non-impulsive criteria will be more appropriate.

For fish, the largest recoverable injury ranges (203 dB threshold) using the Popper *et al*. (2014) criteria are predicted for the larger MENCK 2300iS hammer using the upper bound scenario out to 7.2 km for a stationary receptor, and this decreases to 180 m when a fleeing receptor is considered. When four piles are installed sequentially the maximum recoverable injury impact range increases to 16 km for a stationary animal.

5.3.1 Single strike criteria

This subsection describes impact ranges specifically associated with instantaneous noise thresholds and covers the noise levels from the full energy piling as well as the soft start (i.e., the first strike). Cumulative (SEL_{cum}) thresholds are considered in the following subsections.

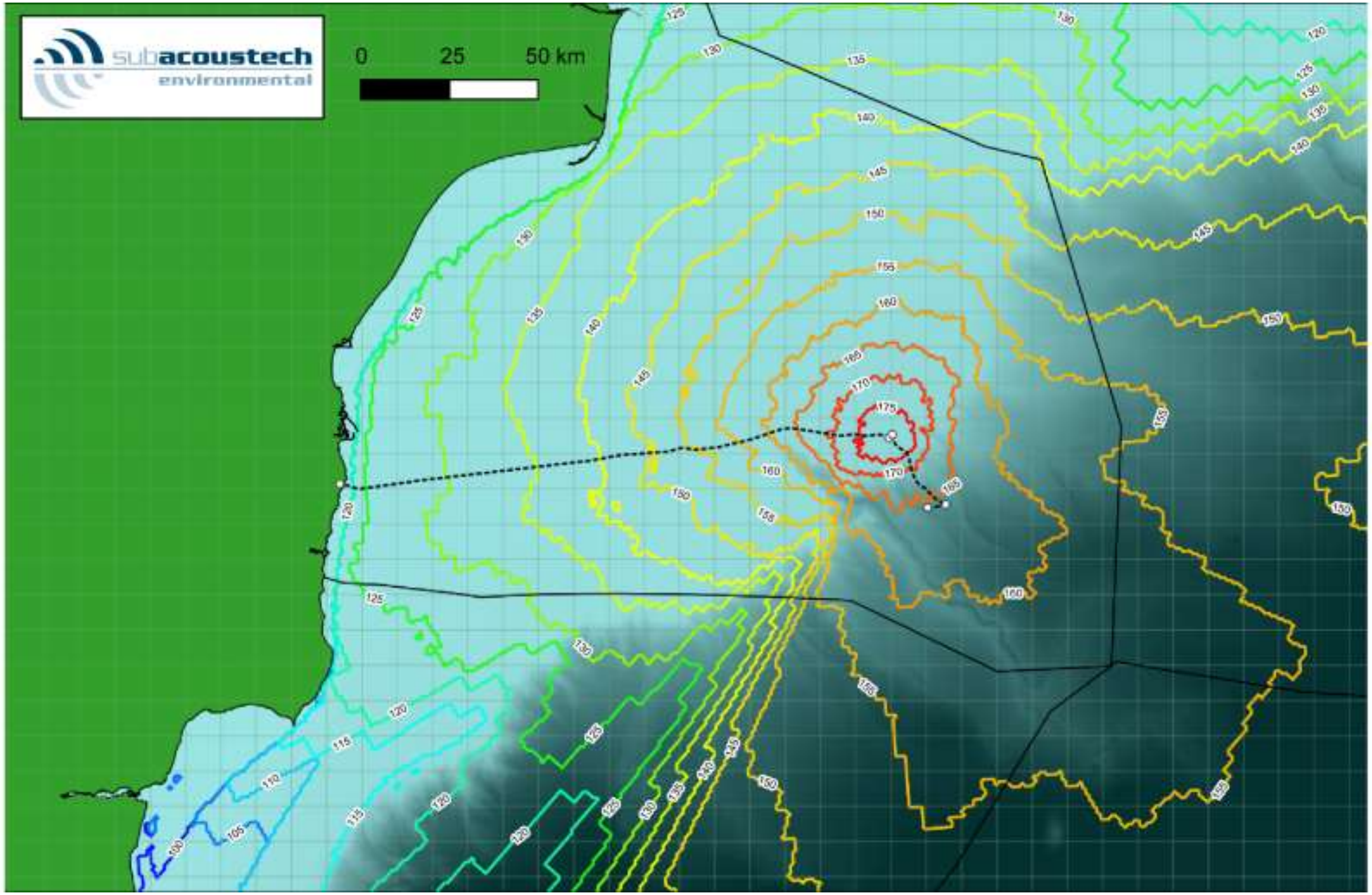

Figure 5-4 Noise plot showing the predicted unweighted, SPL_{peak} noise levels from impact piling at the open water modelling location using the MENCK 800S hammer at full energy, contours from 100 dB (dark blue) to 175 dB (red)

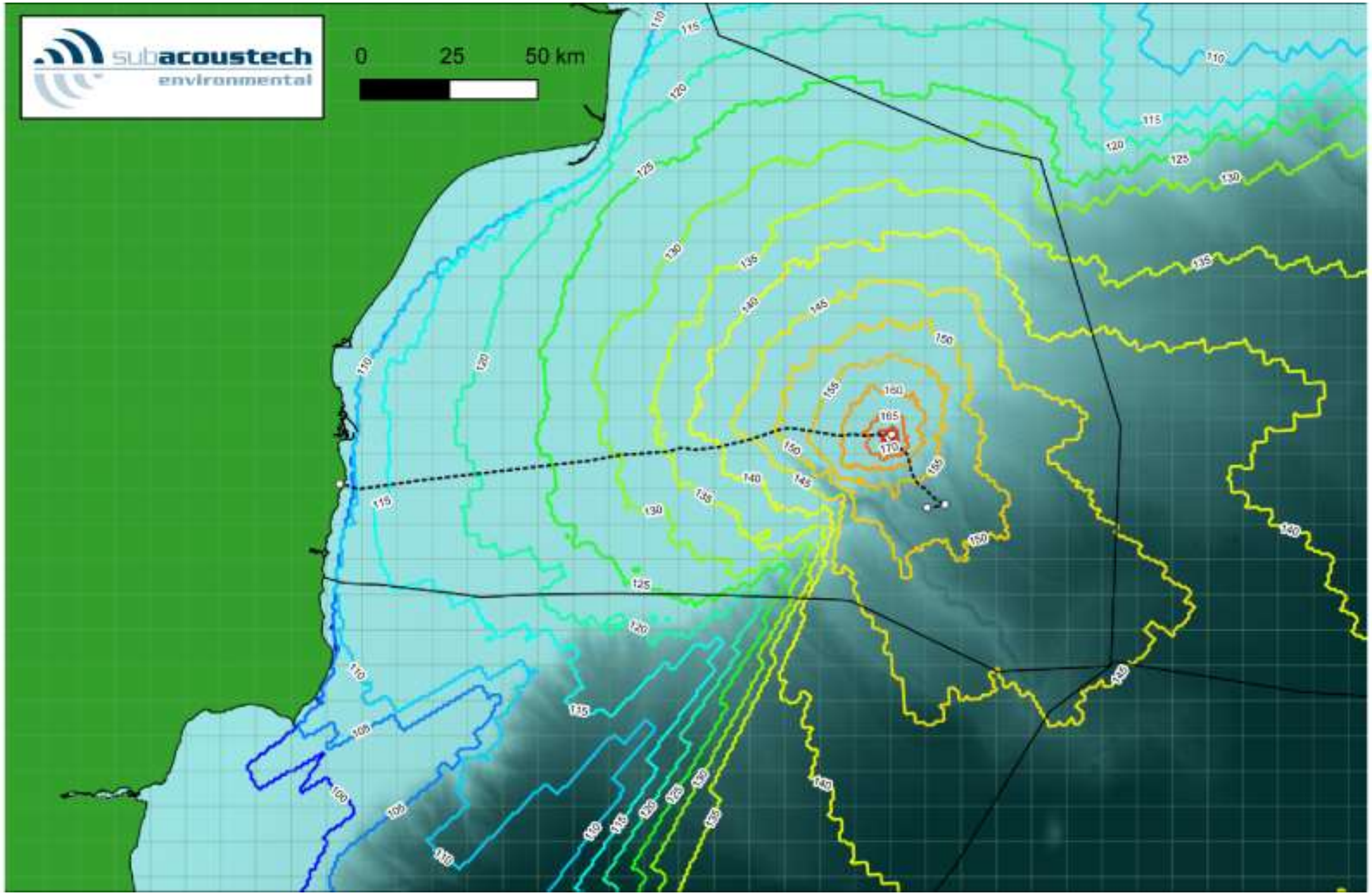

Figure 5-5 Noise plot showing the predicted unweighted, SPL_{peak} noise levels from impact piling at the open water modelling location using the MENCK 800S hammer during the soft start period, contours from 100 dB (dark blue) to 175 dB (red)

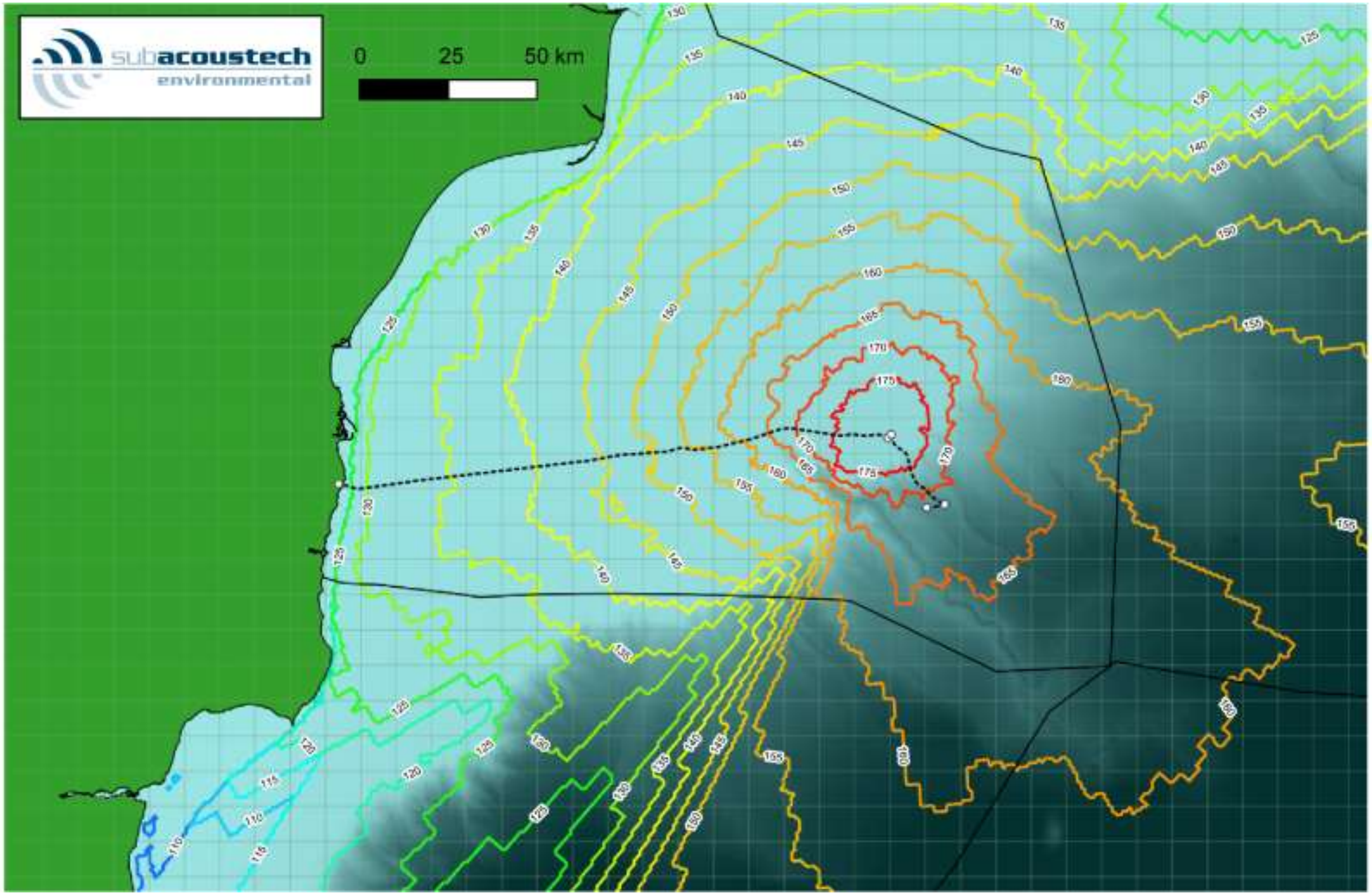

Figure 5-6 Noise plot showing the predicted unweighted, SPL_{peak} noise levels from impact piling at the open water modelling location using the MENCK 3200iS hammer at full energy, contours from 100 dB (dark blue) to 175 dB (red)

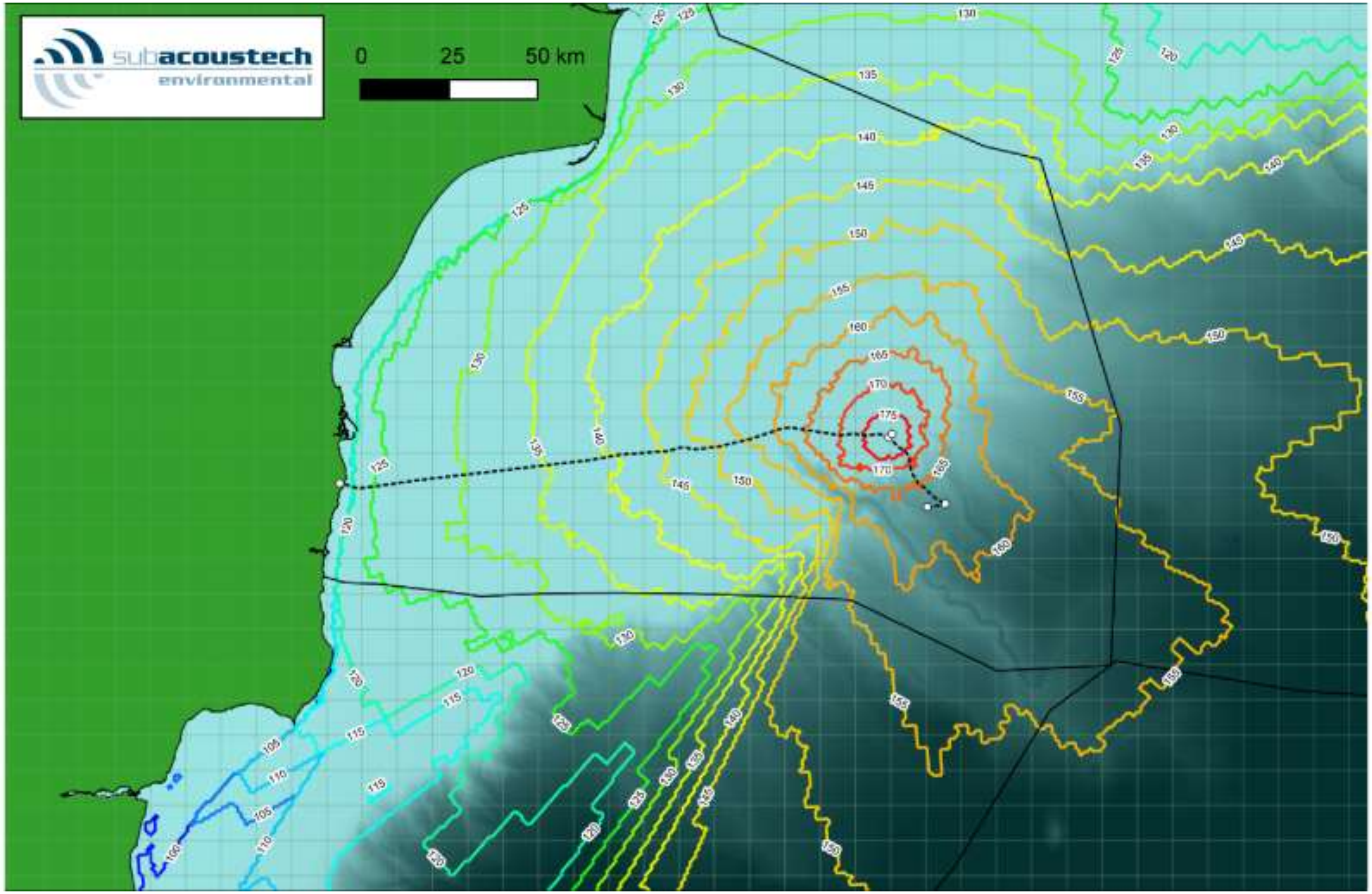

Figure 5-7 Noise plot showing the predicted unweighted, SPL$_{peak}$ noise levels from impact piling at the open water modelling location using the MENCK 3200iS hammer during the soft start period, contours from 100 dB (dark blue) to 175 dB (red)

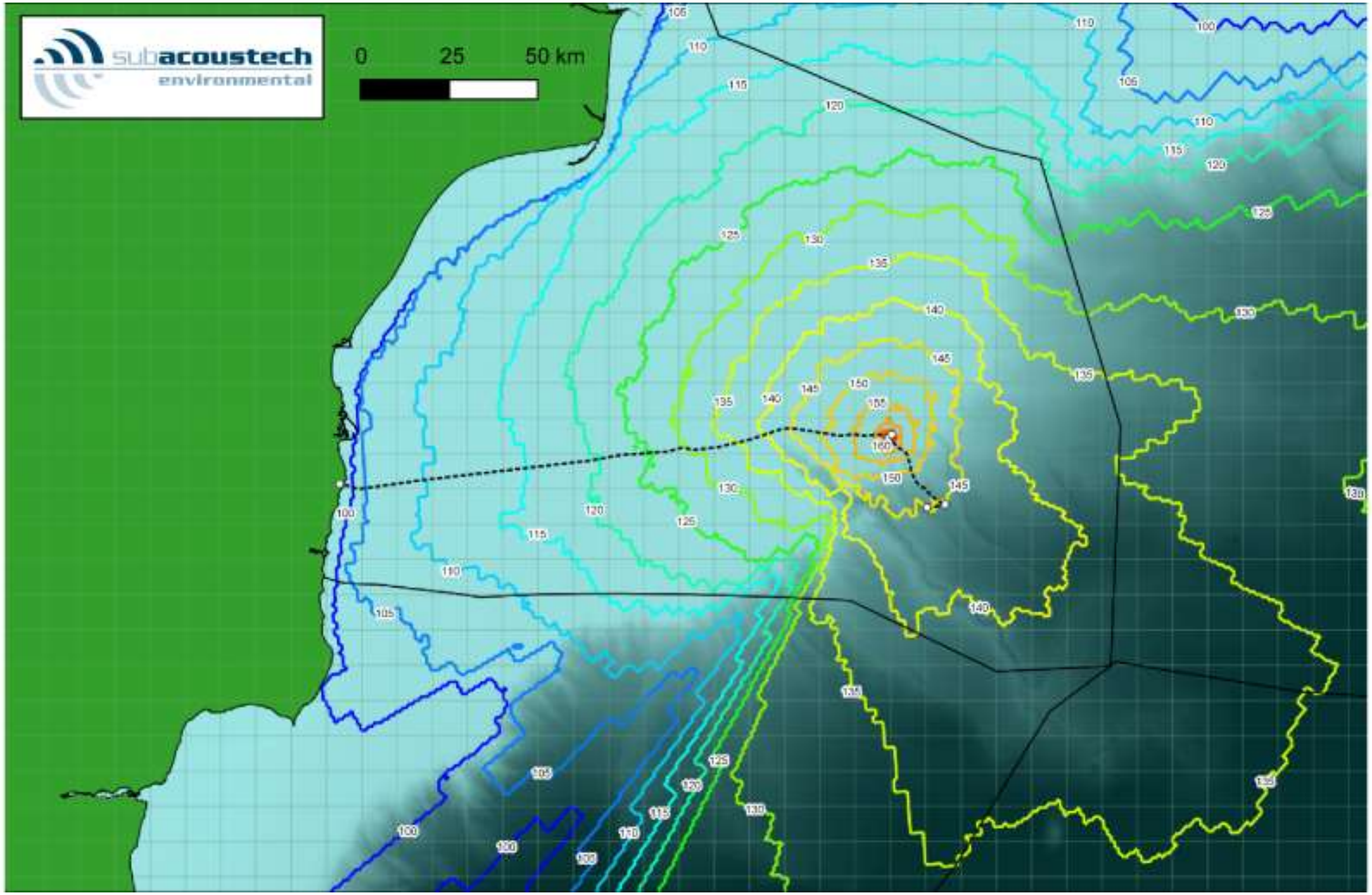

Figure 5-8 Noise plot showing the predicted unweighted, single strike SEL noise levels from impact piling at the open water modelling location using the MENCK 800S hammer at full energy, contours from 100 dB (dark blue) to 175 dB (red)

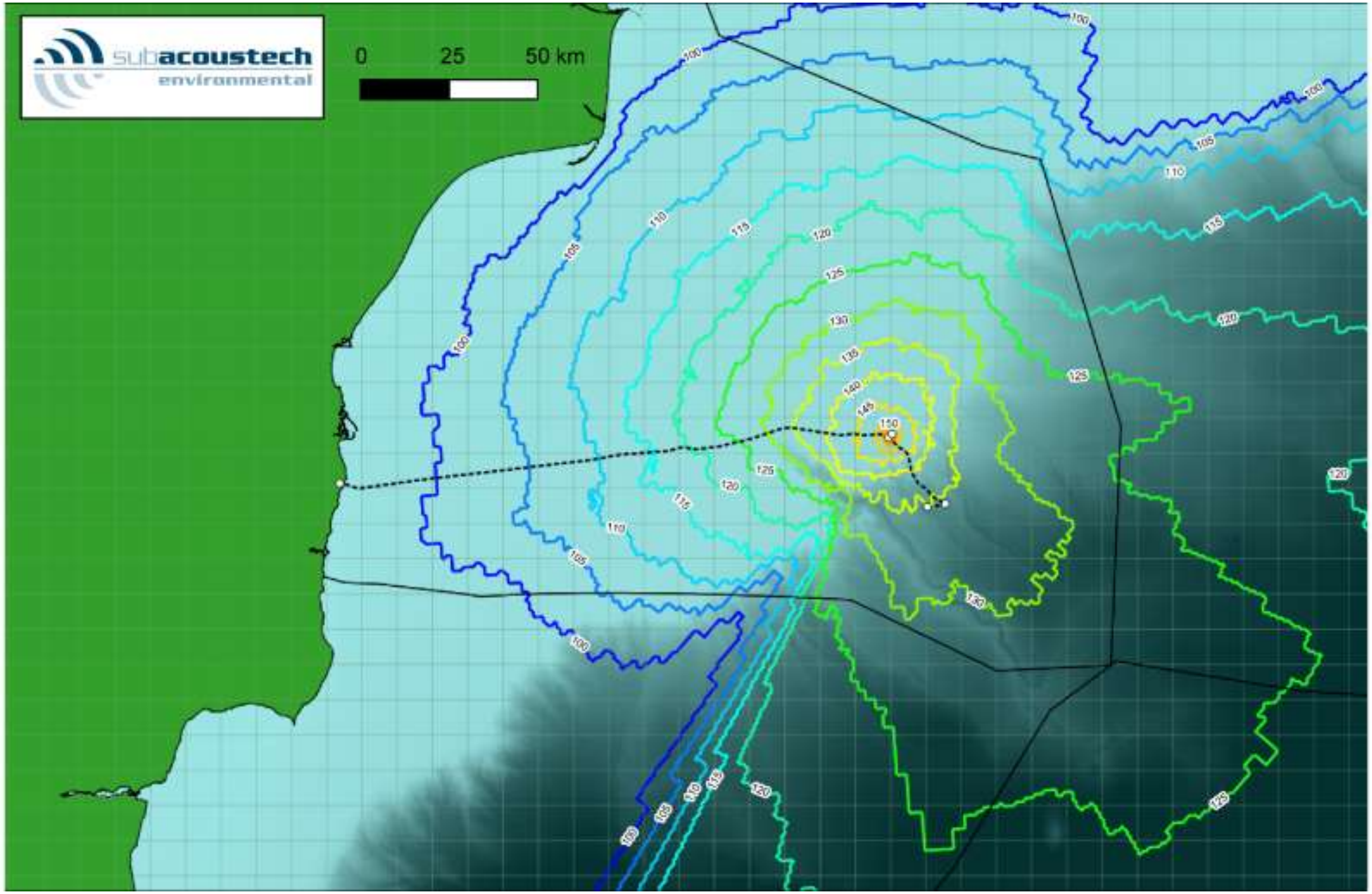

Figure 5-9 Noise plot showing the predicted unweighted, single strike SEL noise levels from impact piling at the open water modelling location using the MENCK 800S hammer during the soft start period, contours from 100 dB (dark blue) to 150 dB (orange)

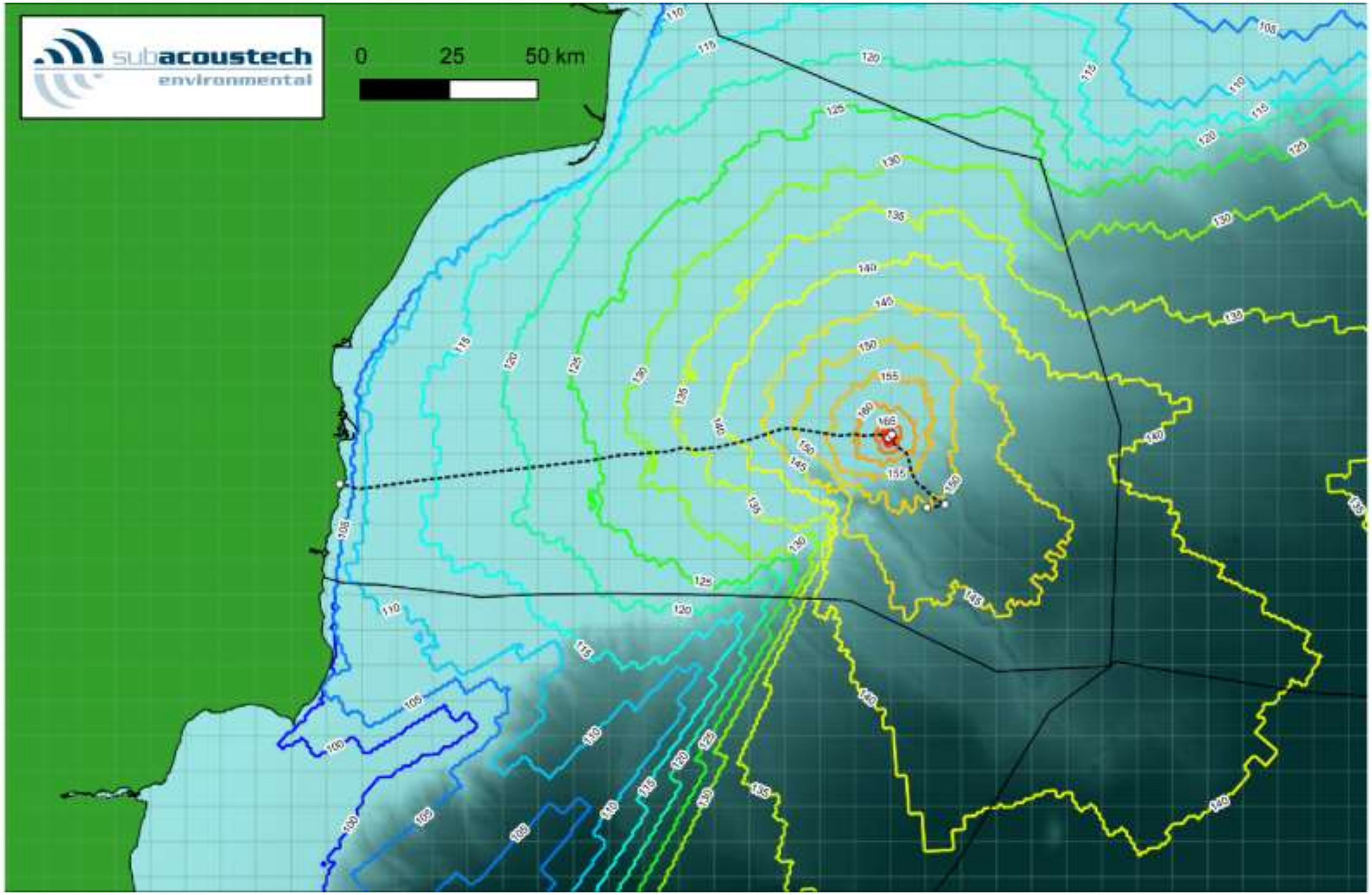

Figure 5-10 Noise plot showing the predicted unweighted, single strike SEL noise levels from impact piling at the open water modelling location using the MENCK 3200iS hammer at full energy, contours from 100 dB (dark blue) to 175 dB (red)

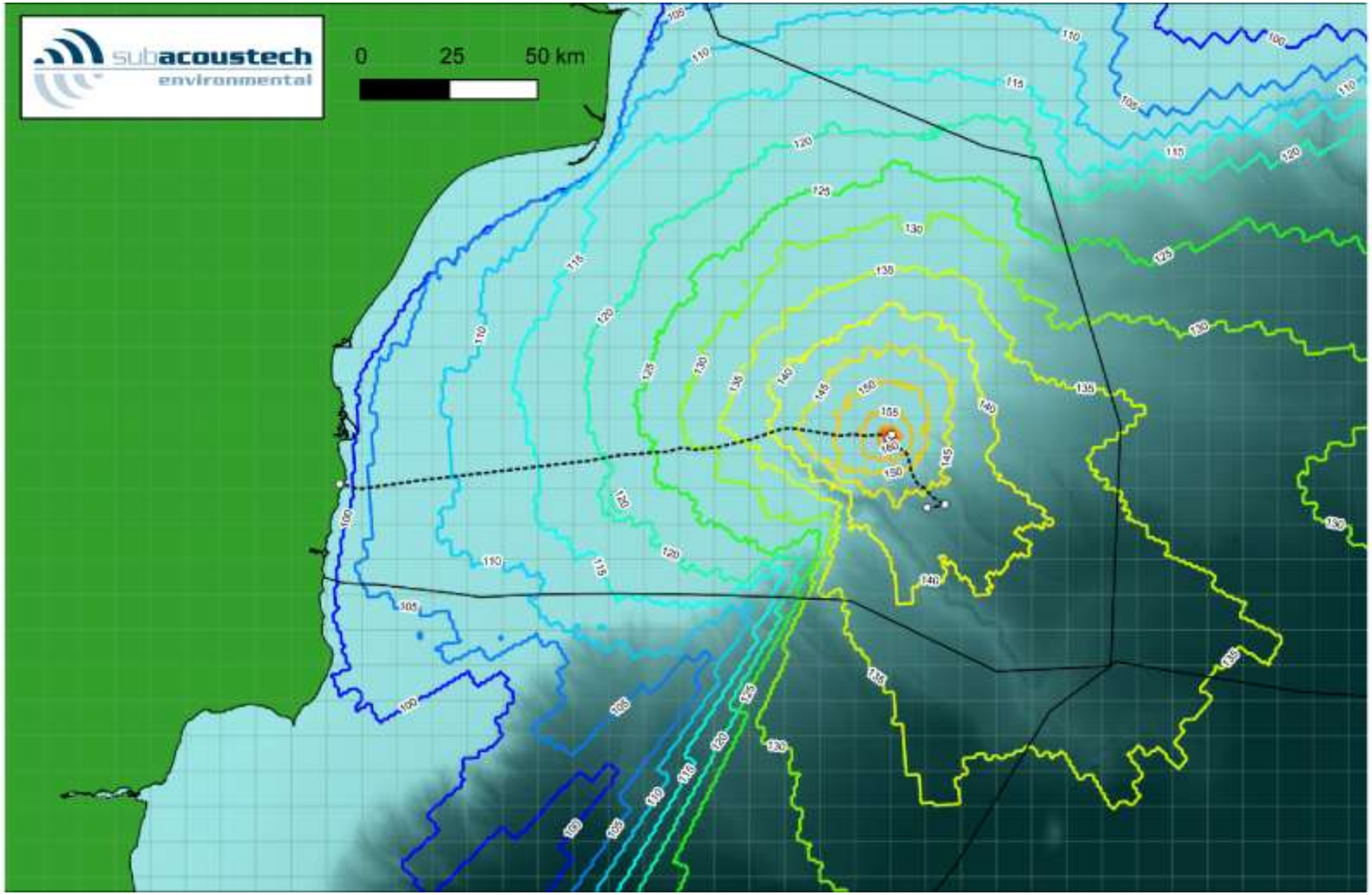

Figure 5-11 Noise plot showing the predicted unweighted, single strike SEL noise levels from impact piling at the open water modelling location using the MENCK 3200iS hammer during the soft start period, contours from 100 dB (dark blue) to 175 dB (red)

Table 5-10 Summary of the modelled Southall et al. (2019) single-strike PTS impact ranges for marine mammals from impact piling noise using the MENCK 800S and 3200iS piling hammers

Southall *et al*. (2019) **Impact piling** PTS		Unweighted SPL_{peak}							
		Full energy				**Soft start**			
		LF (219 dB)	HF (230 dB)	VHF (202 dB)	PCW (218 dB)	LF (219 dB)	HF (230 dB)	VHF (202 dB)	PCW (218 dB)
MENCK 800S	Maximum	< 50 m	< 50 m	260 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
	Minimum	< 50 m	< 50 m	220 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
	Mean	< 50 m	< 50 m	230 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
MENCK 3200iS	Maximum	< 50 m	< 50 m	540 m	< 50 m	< 50 m	< 50 m	210 m	< 50 m
	Minimum	< 50 m	< 50 m	450 m	< 50 m	< 50 m	< 50 m	180 m	< 50 m
	Mean	< 50 m	< 50 m	490 m	< 50 m	< 50 m	< 50 m	190 m	< 50 m

Table 5-11 Summary of the modelled Southall et al. (2019) single-strike TTS impact ranges for marine mammals from impact piling noise using the MENCK 800S and 3200iS piling hammers

Southall *et al*. (2019) **Impact piling** TTS		Unweighted SPL_{peak}							
		Full energy				**Soft start**			
		LF (213 dB)	HF (224 dB)	VHF (196 dB)	PCW (212 dB)	LF (213 dB)	HF (224 dB)	VHF (196 dB)	PCW (212 dB)
MENCK 800S	Maximum	50 m	< 50 m	670 m	50 m	< 50 m	< 50 m	100 m	< 50 m
	Minimum	< 50 m	< 50 m	550 m	< 50 m	< 50 m	< 50 m	90 m	< 50 m
	Mean	< 50 m	< 50 m	600 m	50 m	< 50 m	< 50 m	100 m	< 50 m
MENCK 3200iS	Maximum	90 m	< 50 m	1.2 km	110 m	< 50 m	< 50 m	540 m	< 50 m
	Minimum	80 m	< 50 m	1.0 km	100 m	< 50 m	< 50 m	460 m	< 50 m
	Mean	90 m	< 50 m	1.1 km	100 m	< 50 m	< 50 m	500 m	< 50 m

Table 5-12 Summary of the modelled Popper et al. (2014) single-strike impact ranges for fish from impact piling noise using the MENCK 800S and 3200iS piling hammers

Popper *et al*. (2014) **Impact piling**		Unweighted SPL_{RMS}			
		Full energy		**Soft start**	
		213 dB	207 dB	213 dB	207 dB
MENCK 800S	Maximum	50 m	110 m	< 50 m	< 50 m
	Minimum	< 50 m	100 m	< 50 m	< 50 m
	Mean	< 50 m	100 m	< 50 m	< 50 m
MENCK 3200iS	Maximum	90 m	240 m	< 50 m	100 m
	Minimum	80 m	210 m	< 50 m	80 m
	Mean	90 m	220 m	< 50 m	90 m

5.3.2 Cumulative criteria

5.3.2.1 MENCK 800S hammer, upper bound scenario

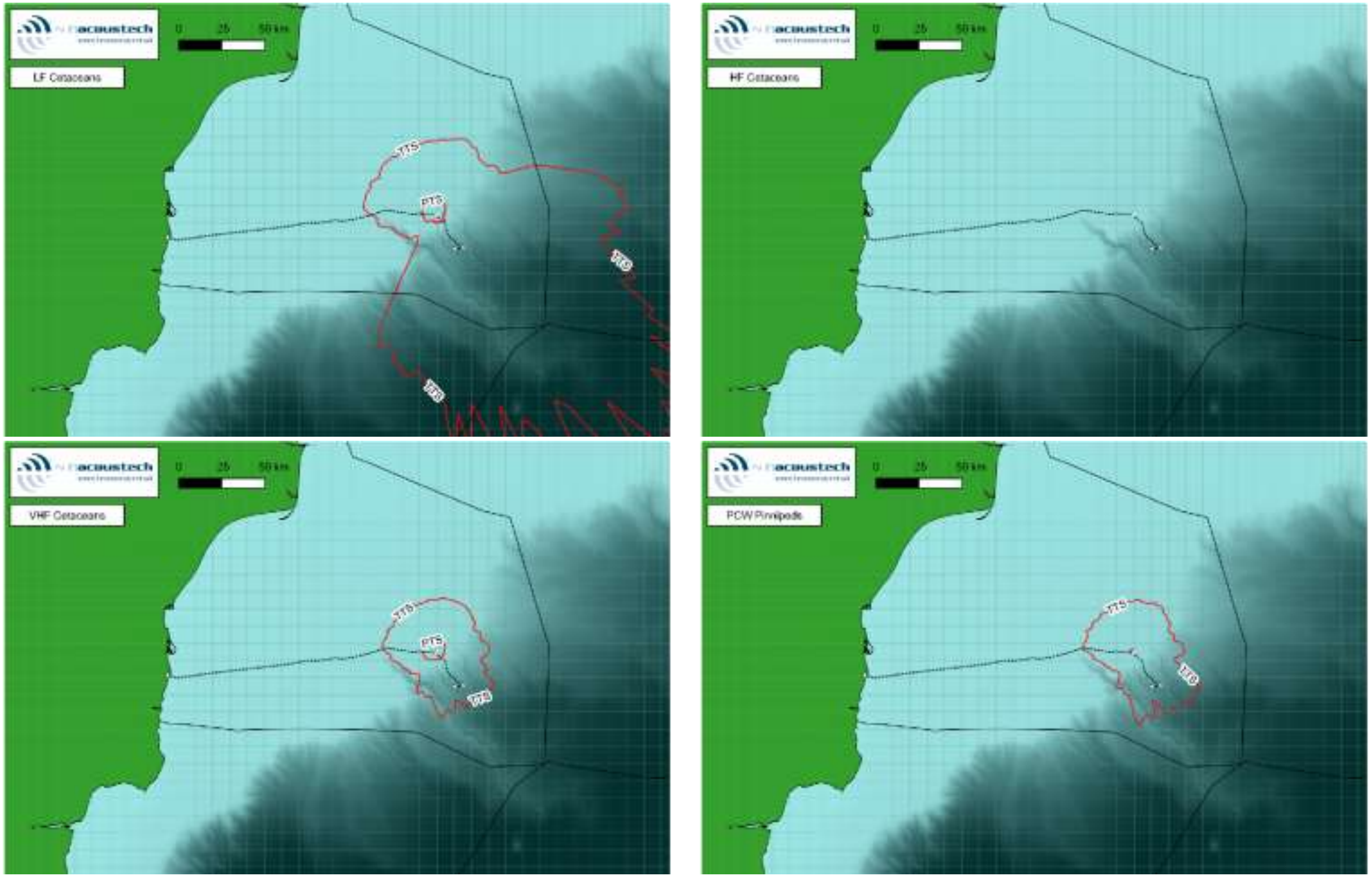

Figure 5-12 Noise plots showing the predicted weighted impulsive SEL_{cum} zones of impact (Southall et al., 2019) from impact piling at the open water modelling location for the MENCK 800S hammer upper bound scenario for a single pile installation, contours are PTS (inner) and TTS (outer)

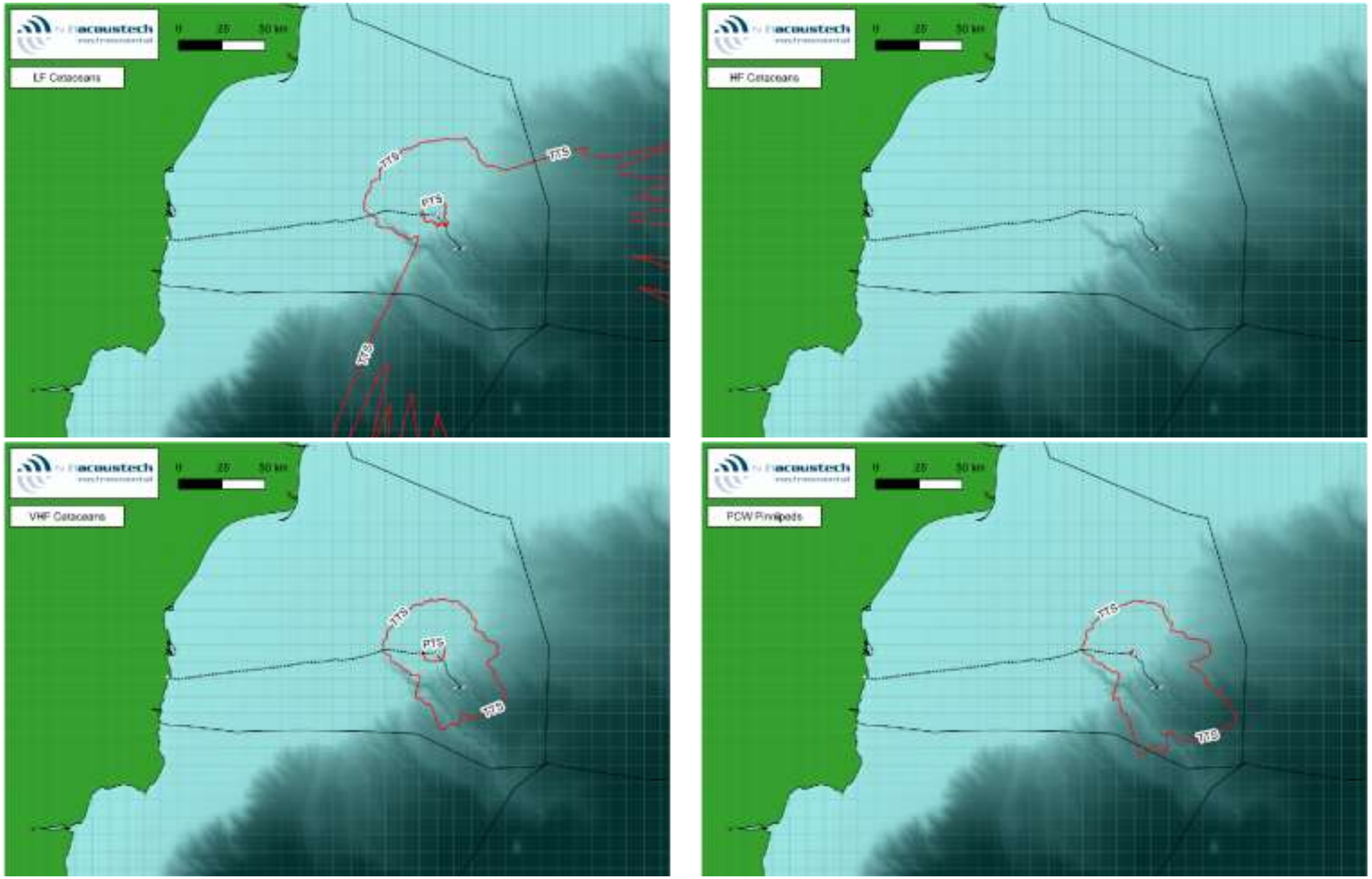

Figure 5-13 Noise plots showing the predicted weighted impulsive SEL_{cum} zones of impact (Southall et al., 2019) from impact piling at the open water modelling location for the MENCK 800S hammer upper bound scenario for four sequentially installed piles, contours are PTS (inner) and TTS (outer)

Table 5-13 Summary of the modelled Southall et al. (2019) cumulative PTS impact ranges for marine mammals from impact piling noise for the MENCK 800S hammer upper bound scenario

Southall *et al*. (2019) **Impact piling** (MENCK 800S Upper bound)		**Weighted SEL$_{cum}$ (fleeing)**							
		Impulsive				**Non-impulsive**			
		LF (183 dB)	HF (185 dB)	VHF (155 dB)	PCW (185 dB)	LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)
Single pile	Maximum	9.2 km	< 100 m	7.7 km	2.2 km	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	3.4 km	< 100 m	3.8 km	340 m	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	6.5 km	< 100 m	5.9 km	1.1 km	< 100 m	< 100 m	< 100 m	< 100 m
4 piles	Maximum	9.2 km	< 100 m	7.8 km	2.3 km	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	3.4 km	< 100 m	3.9 km	410 m	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	6.9 km	< 100 m	5.9 km	1.2 km	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-14 Summary of the modelled Southall et al. (2019) cumulative TTS impact ranges for marine mammals from impact piling noise for the MENCK 800S hammer upper bound scenario

Southall *et al*. (2019) **Impact piling** (MENCK 800S Upper bound)		**Weighted SEL$_{cum}$ (fleeing)**							
		Impulsive				**Non-impulsive**			
		LF (168 dB)	HF (170 dB)	VHF (140 dB)	PCW (170 dB)	LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
Single pile	Maximum	>100 km	< 100 m	39 km	46 km	28 km	< 100 m	11 km	7.8 km
	Minimum	16 km	< 100 m	16 km	14 km	7.3 km	< 100 m	5.2 km	2.7 km
	Mean	71 km	< 100 m	29 km	28 km	16 km	< 100 m	7.9 km	5.3 km
4 piles	Maximum	>100 km	< 100 m	48 km	71 km	46 km	< 100 m	11 km	8.0 km
	Minimum	16 km	< 100 m	16 km	14 km	7.3 km	< 100 m	5.3 km	3.1 km
	Mean	82 km	< 100 m	32 km	35 km	18 km	< 100 m	8.0 km	5.5 km

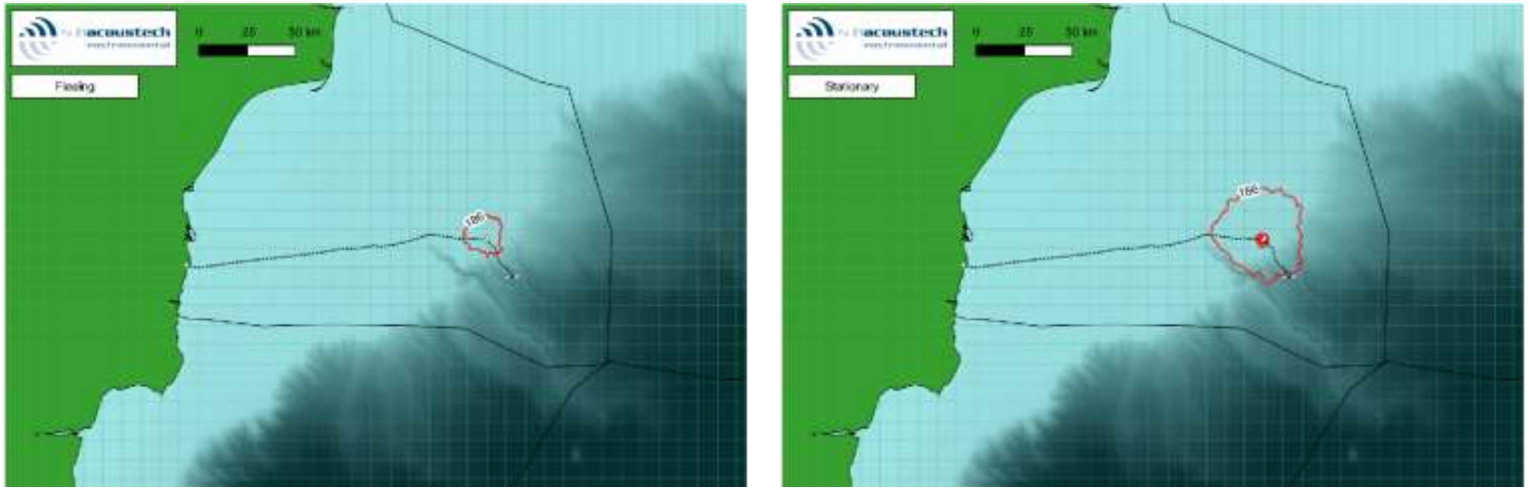

Figure 5-14 Noise plots showing the predicted unweighted SEL_{cum} zones fish of impact (Popper et al., 2014) from impact piling at the open water modelling location for the MENCK 800S hammer upper bound scenario for a single pile installation, contours are TTS (outer), ≥ 203 dB (inner)

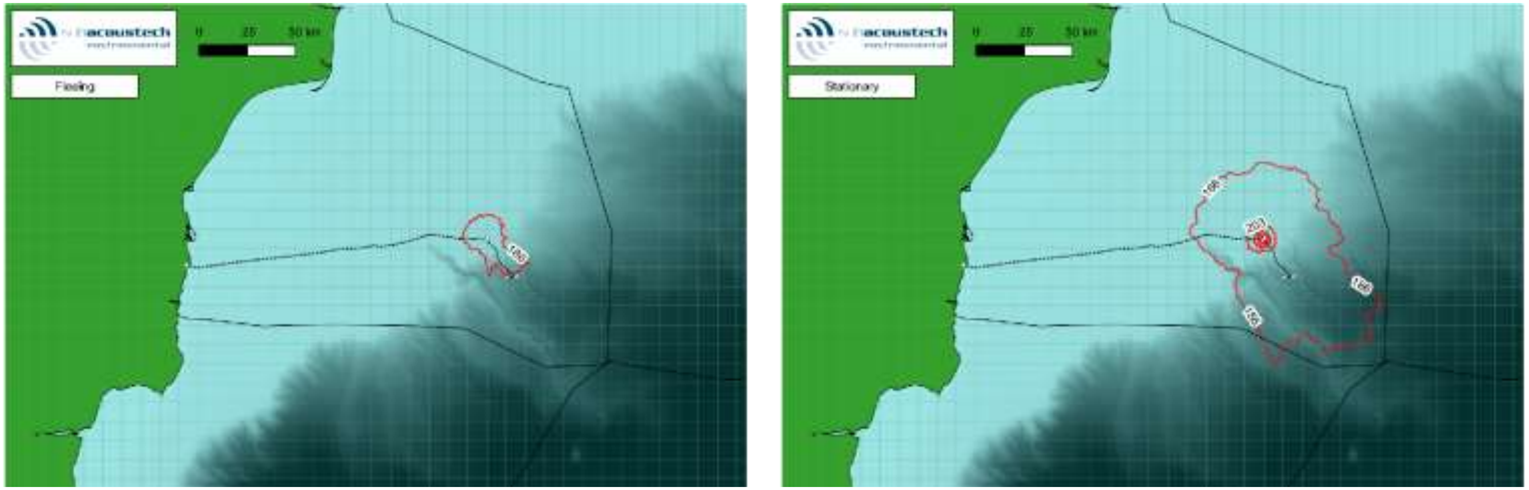

Figure 5-15 Noise plots showing the predicted unweighted SEL_{cum} zones fish of impact (Popper et al., 2014) from impact piling at the open water modelling location for the MENCK 800S hammer upper bound scenario for four sequentially installed piles, contours are TTS (outer), ≥ 203 dB (inner)

Table 5-15 Summary of the modelled Popper et al. (2014) cumulative impact ranges for fish from impact piling noise for fleeing receptors for the MENCK 800S hammer upper bound scenario

Popper *et al*. (2014) **Impact piling** (MENCK 800S Upper bound)		Unweighted SEL_{cum} (fleeing)					
		219 dB	216 dB	210 dB	207 dB	203 dB	186 dB
Single pile	Maximum	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	13 km
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	6.1 km
	Mean	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	9.6 km
4 piles	Maximum	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	26 km
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	6.1 km
	Mean	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	12 km

Table 5-16 Summary of the modelled Popper et al. (2014) cumulative impact ranges for fish from impact piling noise for stationary receptors for the MENCK 800S hammer upper bound scenario

Popper *et al*. (2014) **Impact piling** (MENCK 800S Upper bound)		Unweighted SEL_{cum} (stationary)					
		219 dB	216 dB	210 dB	207 dB	203 dB	186 dB
Single pile	Maximum	490m	780 m	1.8 km	2.8 km	4.0 km	28 km
	Minimum	410 m	650 m	1.4 km	1.8 km	2.7 km	17 km
	Mean	440 m	710 m	1.5 km	2.1 km	3.3 km	23 km
4 piles	Maximum	1.2 km	1.8 km	3.7 km	5.0 km	9.2 km	76 km
	Minimum	990 m	1.4 km	2.5 km	3.7 km	5.8 km	20 km
	Mean	1.1 km	1.5 km	2.9 km	4.2 km	7.1 km	41 km

5.3.2.2 MENCK 800S hammer, best estimate scenario

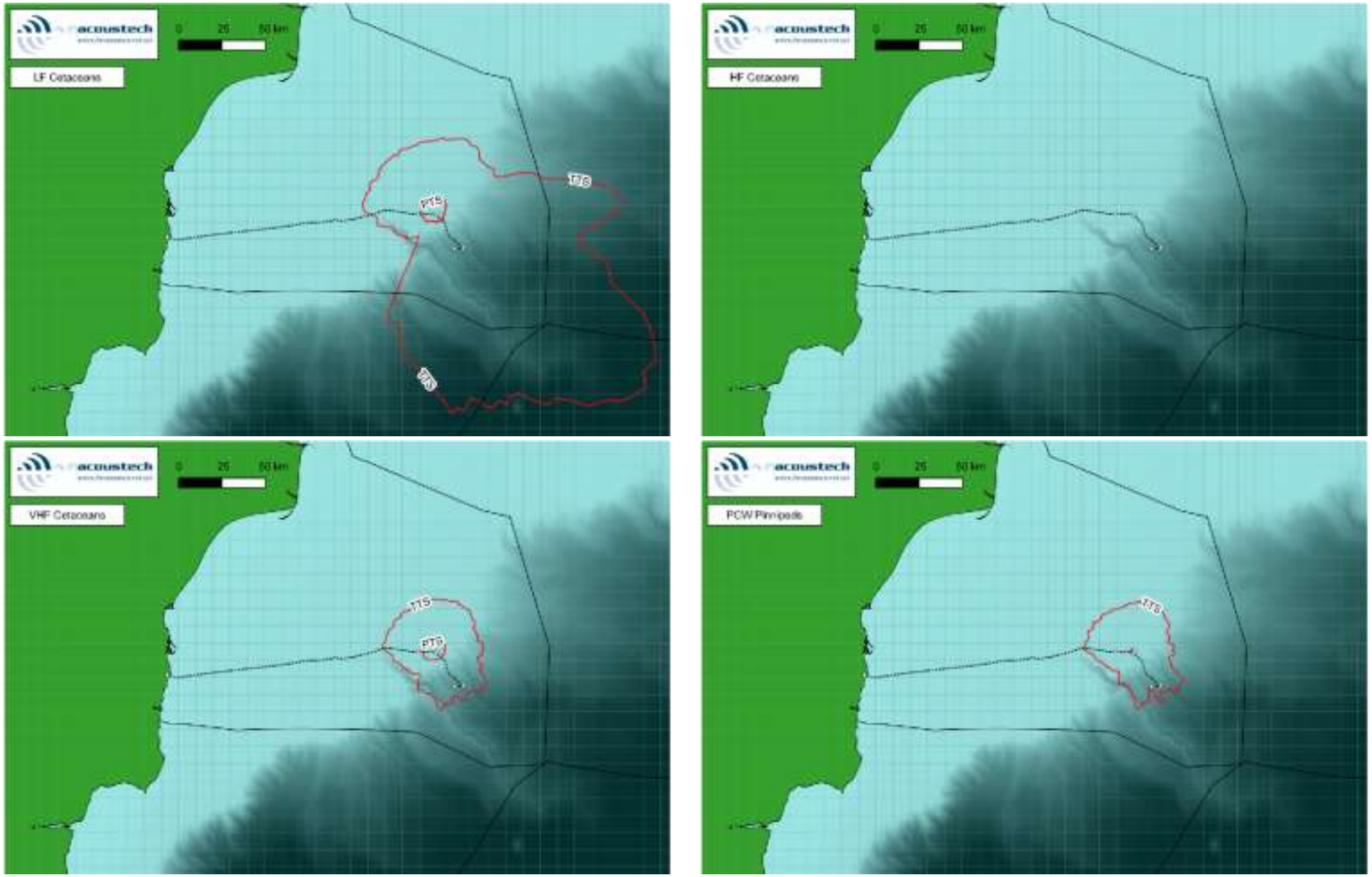

Figure 5-16 Noise plots showing the predicted weighted impulsive SEL_{cum} zones of impact (Southall et al., 2019) from impact piling at the open water modelling location for the MENCK 800S hammer best estimate scenario for a single pile installation, contours are PTS (inner) and TTS (outer)

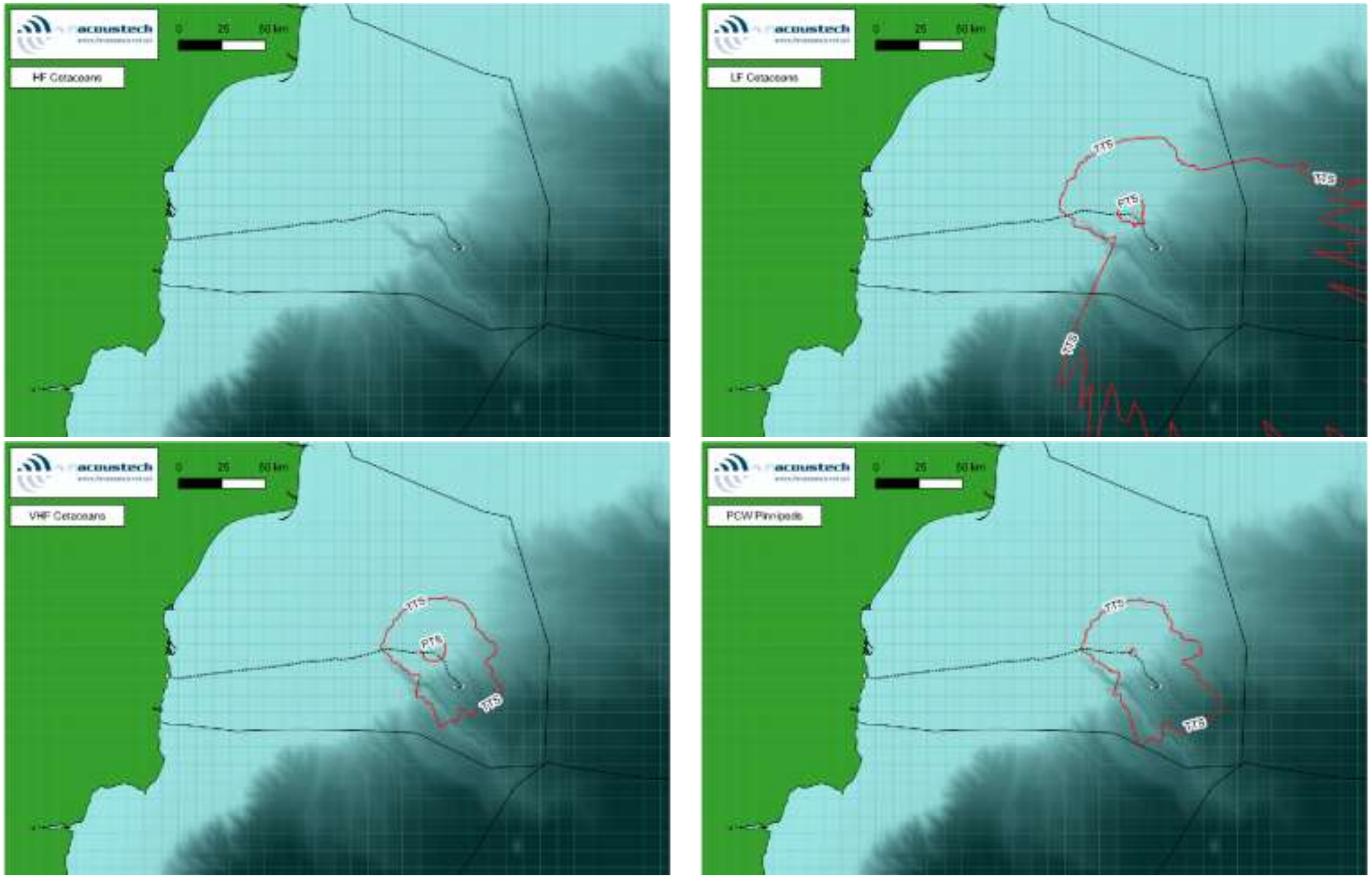

Figure 5-17 Noise plots showing the predicted weighted impulsive SEL_{cum} zones of impact (Southall et al., 2019) from impact piling at the open water modelling location for the MENCK 800S hammer best estimate scenario for four sequentially installed piles, contours are PTS (inner) and TTS (outer)

Table 5-17 Summary of the modelled Southall et al. (2019) cumulative PTS impact ranges for marine mammals from impact piling noise for the MENCK 800S hammer best estimate scenario

Southall *et al*. (2019) **Impact piling** (MENCK 800S Best estimate)		**Weighted SEL_{cum} (fleeing)**							
		Impulsive				**Non-impulsive**			
		LF (183 dB)	HF (185 dB)	VHF (155 dB)	PCW (185 dB)	LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)
Single pile	Maximum	9.7 km	< 100 m	7.9 km	2.3 km	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	3.6 km	< 100 m	3.9 km	400 m	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	6.7 km	< 100 m	6.0 km	1.2 km	< 100 m	< 100 m	< 100 m	< 100 m
4 piles	Maximum	9.9 km	< 100 m	8.2 km	2.6 km	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	3.8 km	< 100 m	4.1 km	520 m	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	7.2 km	< 100 m	6.2 km	1.4 km	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-18 Summary of the modelled Southall et al. (2019) cumulative TTS impact ranges for marine mammals from impact piling noise for the MENCK 800S hammer best estimate scenario

Southall *et al*. (2019) **Impact piling** (MENCK 800S Best estimate)		**Weighted SEL_{cum} (fleeing)**							
		Impulsive				**Non-impulsive**			
		LF (168 dB)	HF (170 dB)	VHF (140 dB)	PCW (170 dB)	LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
Single pile	Maximum	>100 km	< 100 m	34 km	34 km	21 km	< 100 m	11 km	7.7 km
	Minimum	16 km	< 100 m	16 km	14 km	7.7 km	< 100 m	5.2 km	2.6 km
	Mean	65 km	< 100 m	28 km	25 km	14 km	< 100 m	8.0 km	5.2 km
4 piles	Maximum	>100 km	< 100 m	45 km	61 km	37 km	< 100 m	11 km	8.4 km
	Minimum	16 km	< 100 m	16 km	14 km	7.7 km	< 100 m	5.5 km	3.2 km
	Mean	78 km	< 100 m	31 km	32 km	18 km	< 100 m	8.4 km	5.8 km

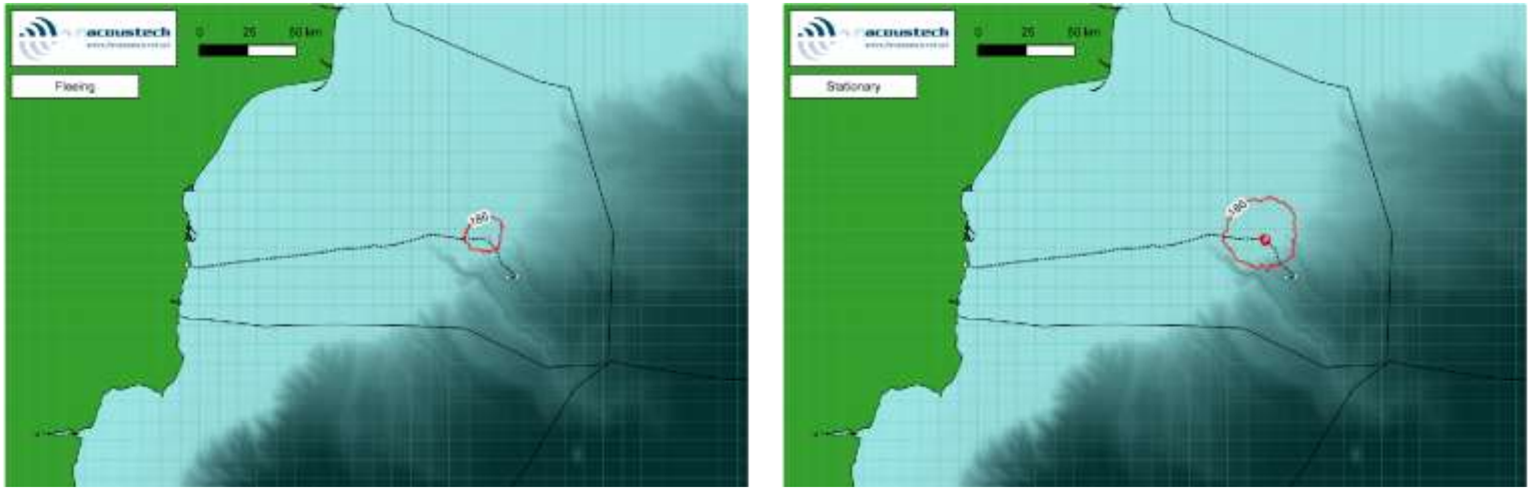

Figure 5-18 Noise plots showing the predicted unweighted SEL_{cum} zones of fish impact (Popper et al., 2014) from impact piling at the open water modelling location for the MENCK 800S hammer best estimate scenario for a single pile installation, contours are TTS (outer), ≥ 203 dB (inner)

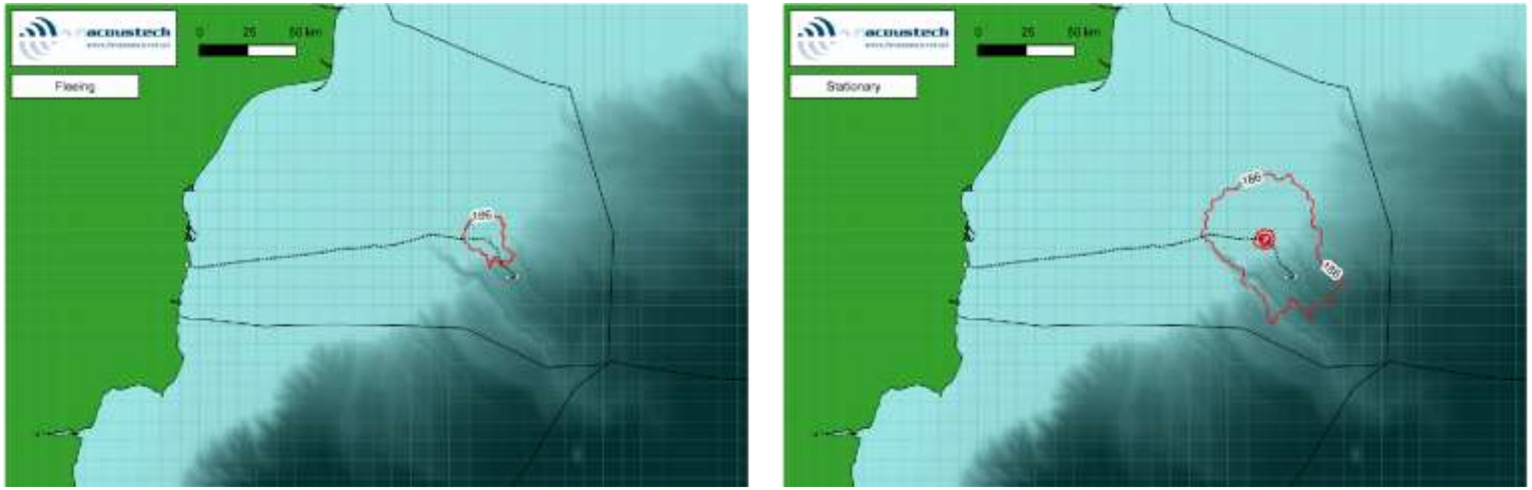

Figure 5-19 Noise plots showing the predicted unweighted SEL_{cum} zones of fish impact (Popper et al., 2014) from impact piling at the open water modelling location for the MENCK 800S hammer best estimate scenario for four sequentially installed piles, contours are TTS (outer) and ≥ 203 dB (inner)

Table 5-19 Summary of the modelled Popper et al. (2014) cumulative impact ranges for fish from impact piling noise for fleeing receptors for the MENCK 800S hammer best estimate scenario

Popper *et al*. (2014) **Impact piling** (MENCK 800S Best estimate)		**Unweighted SEL_{cum} (fleeing)**					
		219 dB	216 dB	210 dB	207 dB	203 dB	186 dB
Single pile	Maximum	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	12 km
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	5.8 km
	Mean	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	9.1 km
4 piles	Maximum	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	17 km
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	6.4 km
	Mean	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	11 km

Table 5-20 Summary of the modelled Popper et al. (2014) cumulative impact ranges for fish from impact piling noise for stationary receptors for the MENCK 800S hammer best estimate scenario

Popper *et al*. (2014) **Impact piling** (MENCK 800S Best estimate)		**Unweighted SEL_{cum} (stationary)**					
		219 dB	216 dB	210 dB	207 dB	203 dB	186 dB
Single pile	Maximum	320 m	520 m	1.2 km	1.9 km	3.1 km	23 km
	Minimum	280 m	440 m	1.1 km	1.4 km	2.2 km	13 km
	Mean	300 m	470 m	1.2 km	1.6 km	2.5 km	18 km
4 piles	Maximum	830 m	1.3 km	2.9 km	3.9 km	6.1 km	48 km
	Minimum	690 m	1.1 km	1.9 km	2.6 km	4.4 km	19 km
	Mean	760 m	1.2 km	2.2 km	3.0 km	5.1 km	32 km

5.3.2.3 MENCK 3200iS hammer, upper bound scenario

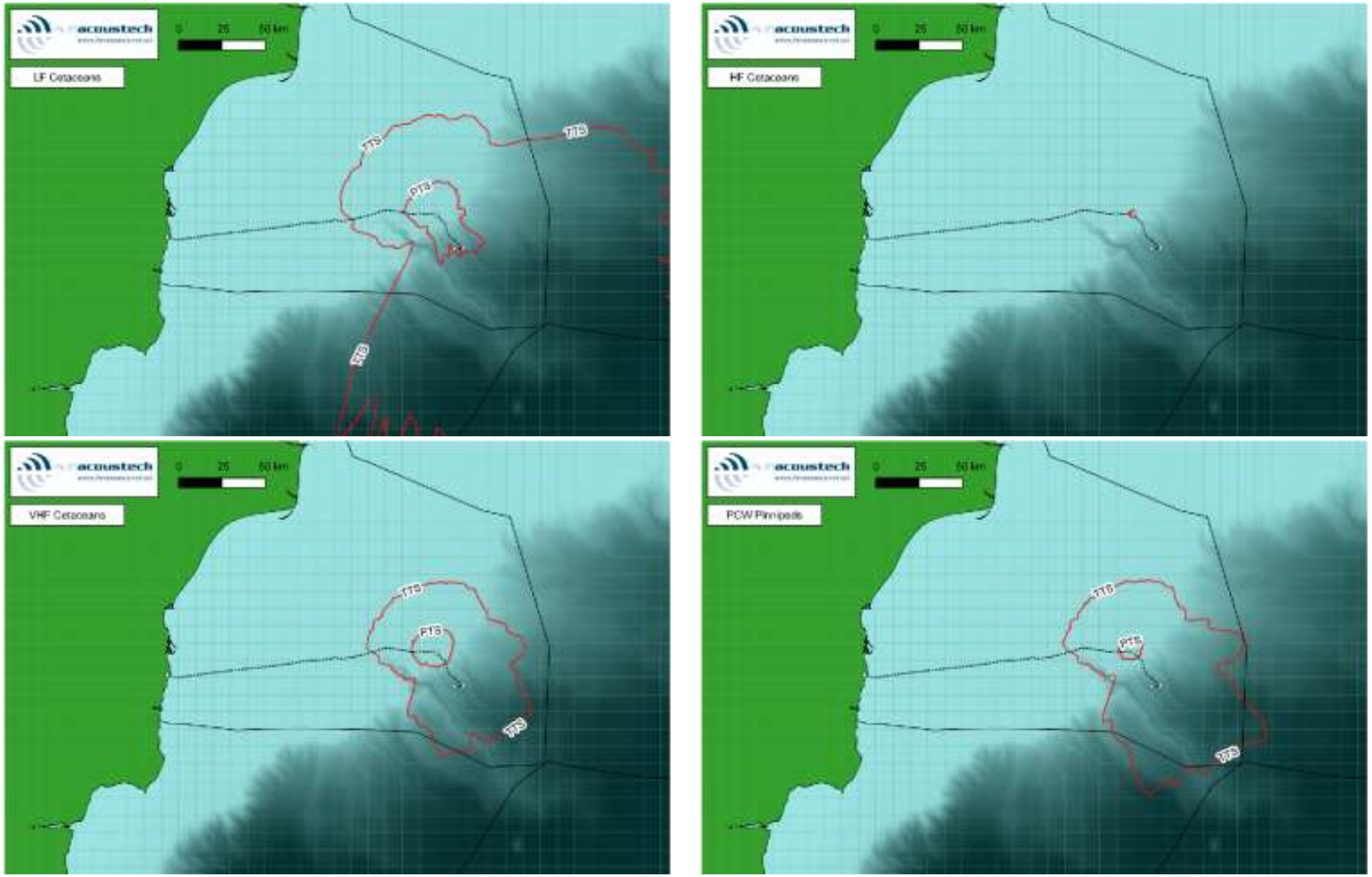

Figure 5-20 Noise plots showing the predicted weighted impulsive SEL_{cum} zones of impact (Southall et al., 2019) from impact piling at the open water modelling location for the MENCK 3200iS hammer upper bound scenario for a single pile installation, contours are PTS (inner) and TTS (outer)

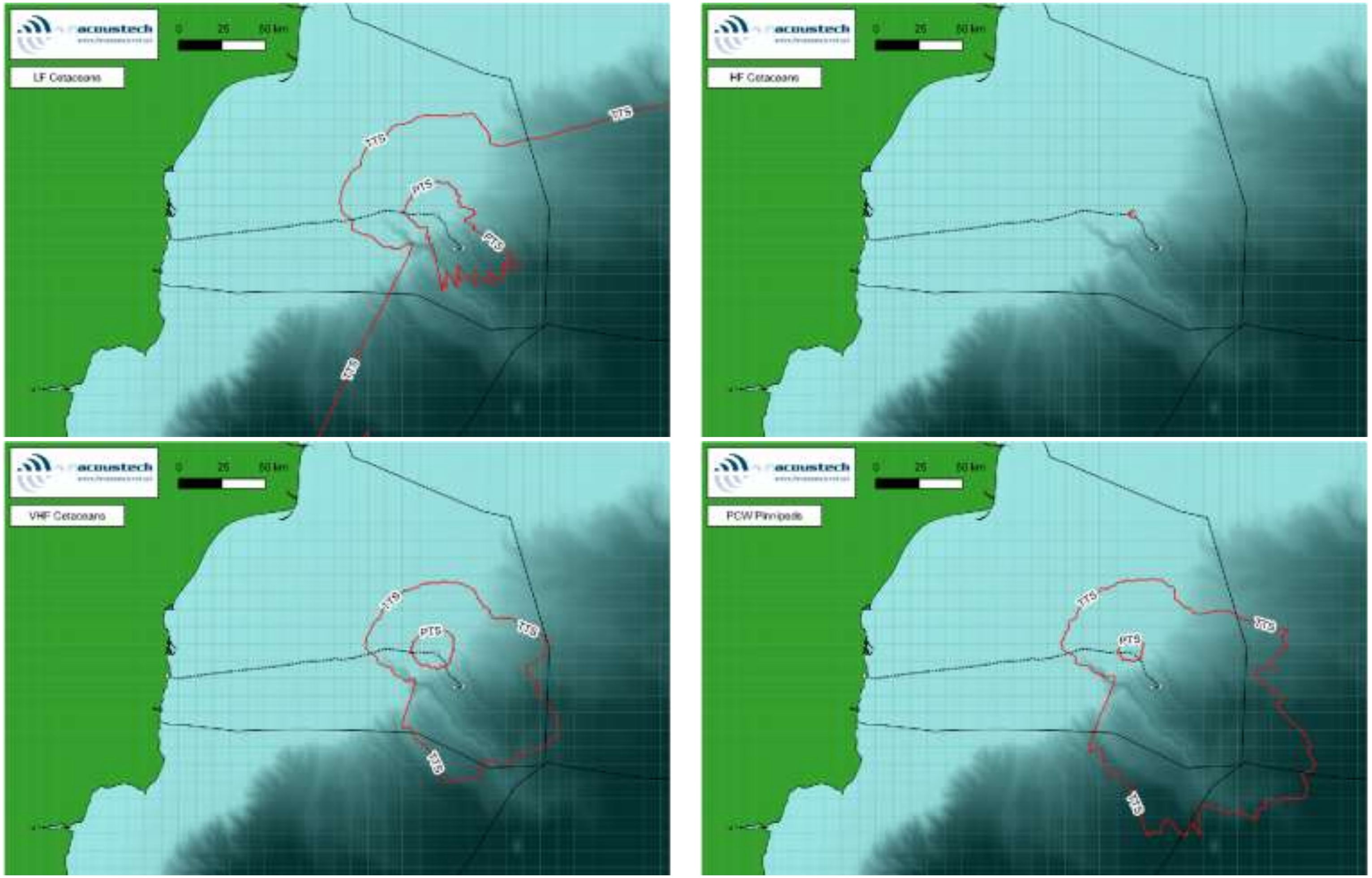

Figure 5-21 Noise plots showing the predicted weighted impulsive SEL_{cum} zones of impact (Southall et al., 2019) from impact piling at the open water modelling location for the MENCK 3200iS hammer upper bound scenario for four sequentially installed piles, contours are PTS (inner) and TTS (outer)

Table 5-21 Summary of the modelled Southall et al. (2019) cumulative PTS impact ranges for marine mammals from impact piling noise for the MENCK 3200iS hammer upper bound scenario

Southall *et al*. (2019) **Impact piling** (MENCK 3200iS Upper bound)		**Weighted SEL$_{cum}$ (fleeing)**							
		Impulsive				**Non-impulsive**			
		LF (183 dB)	HF (185 dB)	VHF (155 dB)	PCW (185 dB)	LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)
Single pile	Maximum	33 km	< 100 m	15 km	9.1 km	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	8.6 km	< 100 m	7.5 km	3.4 km	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	18 km	< 100 m	11 km	6.3 km	< 100 m	< 100 m	< 100 m	< 100 m
4 piles	Maximum	57 km	< 100 m	15 km	9.4 km	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	8.6 km	< 100 m	7.9 km	3.9 km	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	22 km	< 100 m	12 km	6.7 km	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-22 Summary of the modelled Southall et al. (2019) cumulative TTS impact ranges for marine mammals from impact piling noise for the MENCK 3200iS hammer upper bound scenario

Southall *et al*. (2019) **Impact piling** (MENCK 3200iS Upper bound)		**Weighted SEL$_{cum}$ (fleeing)**							
		Impulsive				**Non-impulsive**			
		LF (168 dB)	HF (170 dB)	VHF (140 dB)	PCW (170 dB)	LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
Single pile	Maximum	>100 km	2.5 km	66 km	92 km	81 km	< 100 m	17 km	17 km
	Minimum	21 km	1.1 km	19 km	17 km	12 km	< 100 m	9.6 km	7.6 km
	Mean	92 km	1.8 km	42 km	48 km	35 km	< 100 m	14 km	13 km
4 piles	Maximum	>100 km	2.6 km	85 km	>100 km	>100 km	< 100 m	18 km	18 km
	Minimum	21 km	1.2 km	19 km	17 km	13 km	< 100 m	9.9 km	7.8 km
	Mean	97 km	1.8 km	48 km	59 km	47 km	< 100 m	14 km	14 km

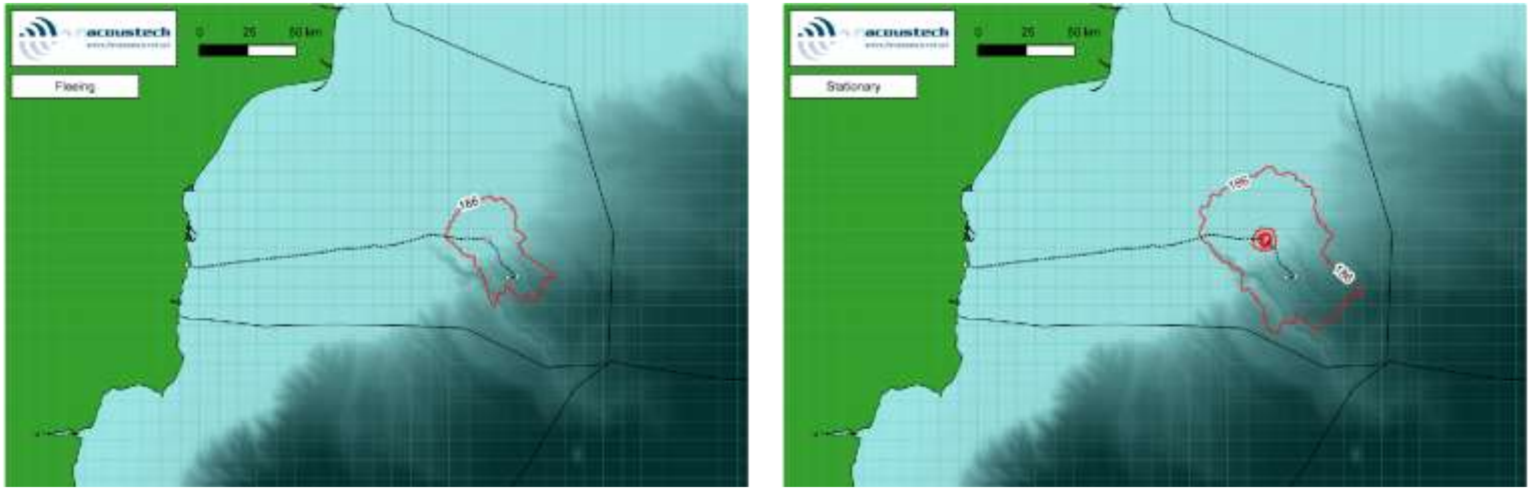

Figure 5-22 Noise plots showing the predicted unweighted SEL_{cum} zones of fish impact (Popper et al., 2014) from impact piling at the open water modelling location for the MENCK 3200iS hammer upper bound scenario for a single pile installation, contours are TTS (outer), ≥ 203 dB (inner)

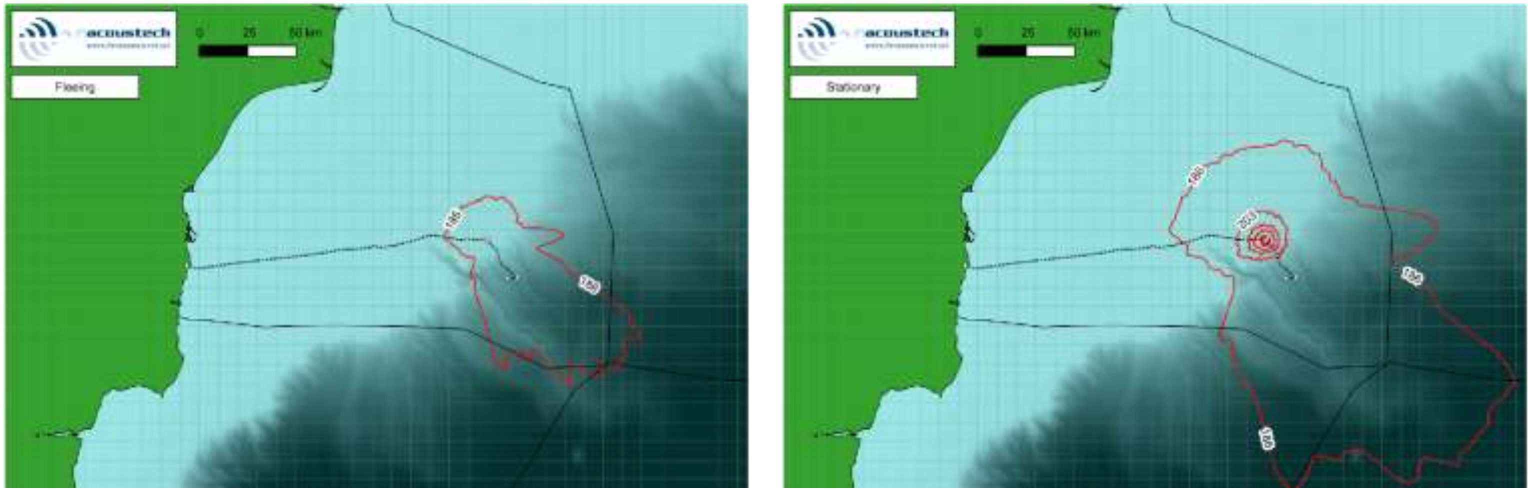

Figure 5-23 Noise plots showing the predicted unweighted SEL_{cum} zones of fish impact (Popper et al., 2014) from impact piling at the open water modelling location for the MENCK 3200iS hammer upper bound scenario for four sequentially installed piles, contours are TTS (outer), ≥ 203 dB (inner)

Table 5-23 Summary of the modelled Popper et al. (2014) cumulative impact ranges for fish from impact piling noise for fleeing receptors for the MENCK 3200iS hammer upper bound scenario

Popper *et al*. (2014) **Impact piling** (MENCK 3200iS Upper bound)		**Unweighted SEL_{cum} (fleeing)**					
		219 dB	216 dB	210 dB	207 dB	203 dB	186 dB
Single pile	Maximum	< 100 m	< 100 m	< 100 m	< 100 m	180 m	41 km
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	11 km
	Mean	< 100 m	< 100 m	< 100 m	< 100 m	120 m	21 km
4 piles	Maximum	< 100 m	< 100 m	< 100 m	< 100 m	180 m	96 km
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m	100 m	11 km
	Mean	< 100 m	< 100 m	< 100 m	< 100 m	130 m	32 km

Table 5-24 Summary of the modelled Popper et al. (2014) cumulative impact ranges for fish from impact piling noise for stationary receptors for the MENCK 3200iS hammer upper bound scenario

Popper *et al*. (2014) **Impact piling** (MENCK 3200iS Upper bound)		**Unweighted SEL_{cum} (stationary)**					
		219 dB	216 dB	210 dB	207 dB	203 dB	186 dB
Single pile	Maximum	960 m	1.4 km	3.1 km	4.2 km	7.2 km	58 km
	Minimum	820 m	1.2 km	2.2 km	2.8 km	4.9 km	20 km
	Mean	890 m	1.3 km	2.5 km	3.5 km	5.9 km	35 km
4 piles	Maximum	2.0 km	3.1 km	6.3 km	9.6 km	16 km	>100 km
	Minimum	1.6 km	2.2 km	4.5 km	6.0 km	9.1 km	25 km
	Mean	1.8 km	2.5 km	5.1 km	7.6 km	13 km	67 km

5.3.2.4 MENCK 3200iS hammer, best estimate scenario

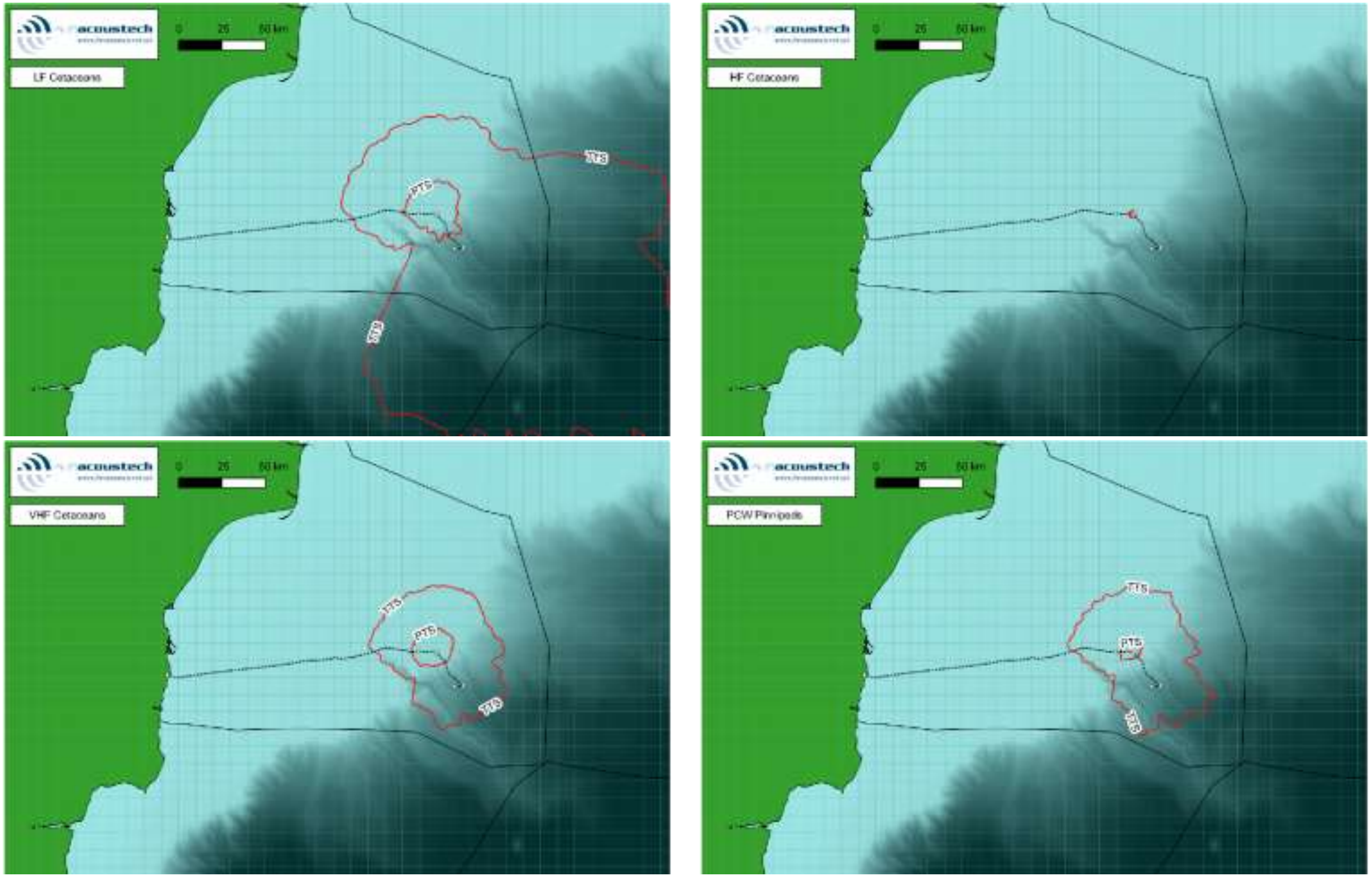

Figure 5-24 Noise plots showing the predicted weighted impulsive SEL_{cum} zones of impact (Southall et al., 2019) from impact piling at the open water modelling location for the MENCK 3200iS hammer best estimate scenario for a single pile installation, contours are TTS (outer), PTS (inner)

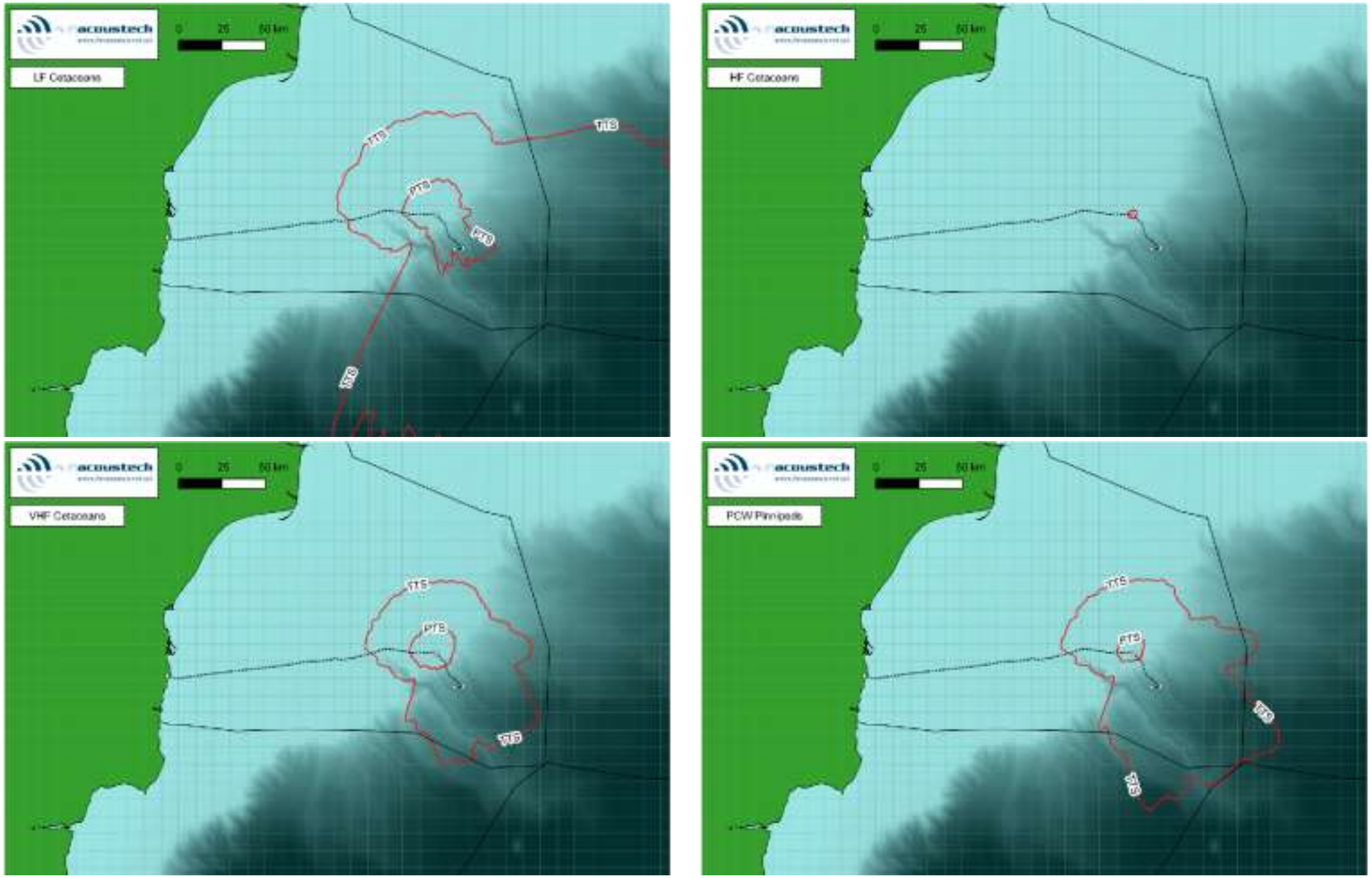

Figure 5-25 Noise plots showing the predicted weighted impulsive SEL$_{cum}$ zones of impact (Southall et al., 2019) from impact piling at the open water modelling location for the MENCK 3200iS hammer best estimate scenario for four sequentially installed piles, contours are TTS (outer), PTS (inner)

Table 5-25 Summary of the modelled Southall et al. (2019) cumulative PTS impact ranges for marine mammals from impact piling noise for the MENCK 3200iS hammer best estimate scenario

Southall *et al*. (2019) **Impact piling** (MENCK 3200iS Best estimate)		**Weighted SEL_{cum} (fleeing)**							
		Impulsive				**Non-impulsive**			
		LF (183 dB)	HF (185 dB)	VHF (155 dB)	PCW (185 dB)	LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)
Single pile	Maximum	20 km	< 100 m	14 km	8.3 km	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	8.8 km	< 100 m	7.1 km	3.0 km	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	15 km	< 100 m	11 km	5.7 km	< 100 m	< 100 m	< 100 m	< 100 m
4 piles	Maximum	40 km	< 100 m	15 km	11 km	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	8.8 km	< 100 m	8.1 km	3.9 km	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	20 km	< 100 m	12 km	7.2 km	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-26 Summary of the modelled Southall et al. (2019) cumulative TTS impact ranges for marine mammals from impact piling noise for the MENCK 3200iS hammer best estimate scenario

Southall *et al*. (2019) **Impact piling** (MENCK 3200iS Best estimate)		**Weighted SEL_{cum} (fleeing)**							
		Impulsive				**Non-impulsive**			
		LF (168 dB)	HF (170 dB)	VHF (140 dB)	PCW (170 dB)	LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
Single pile	Maximum	>100 km	2.4 km	47 km	55 km	46 km	< 100 m	17 km	15 km
	Minimum	21 km	1.2 km	19 km	17 km	13 km	< 100 m	8.9 km	6.0 km
	Mean	85 km	1.8 km	36 km	36 km	26 km	< 100 m	13 km	11 km
4 piles	Maximum	>100 km	3.1 km	71 km	100 km	92 km	< 100 m	19 km	19 km
	Minimum	22 km	1.4 km	19 km	17 km	13 km	< 100 m	11 km	8.3 km
	Mean	94 km	2.2 km	45 km	51 km	38 km	< 100 m	15 km	14 km

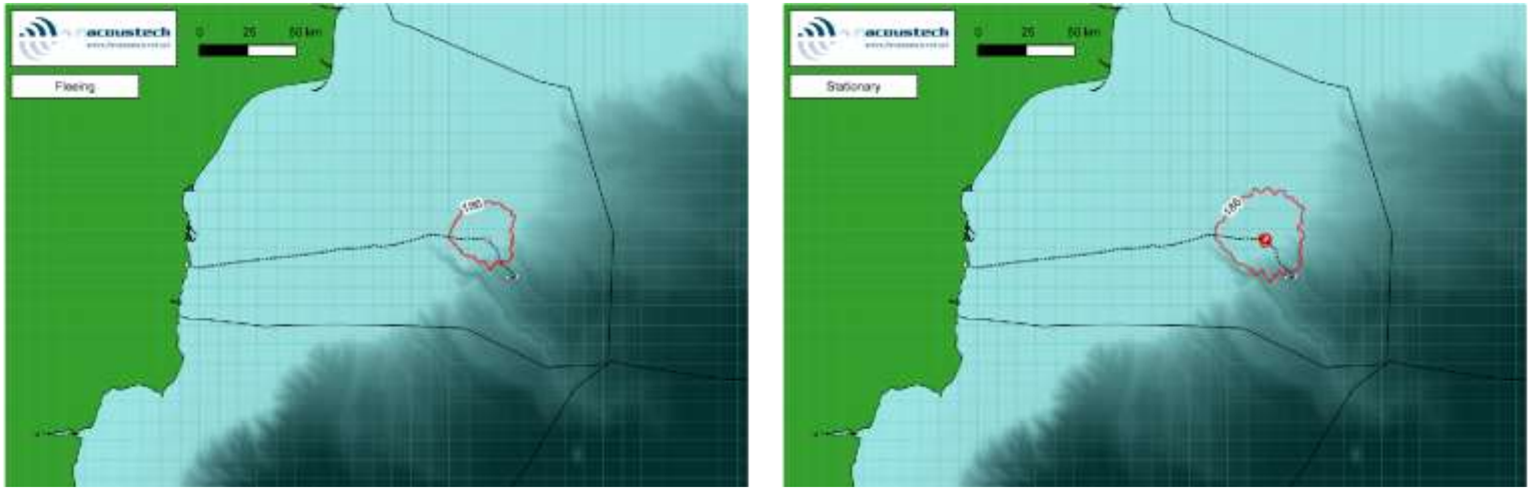

Figure 5-26 Noise plots showing the predicted unweighted SEL_{cum} zones of fish impact (Popper et al., 2014) from impact piling at the open water modelling location for the MENCK 3200iS hammer best estimate scenario for a single pile installation, contours are TTS (outer), ≥ 203 dB (inner)

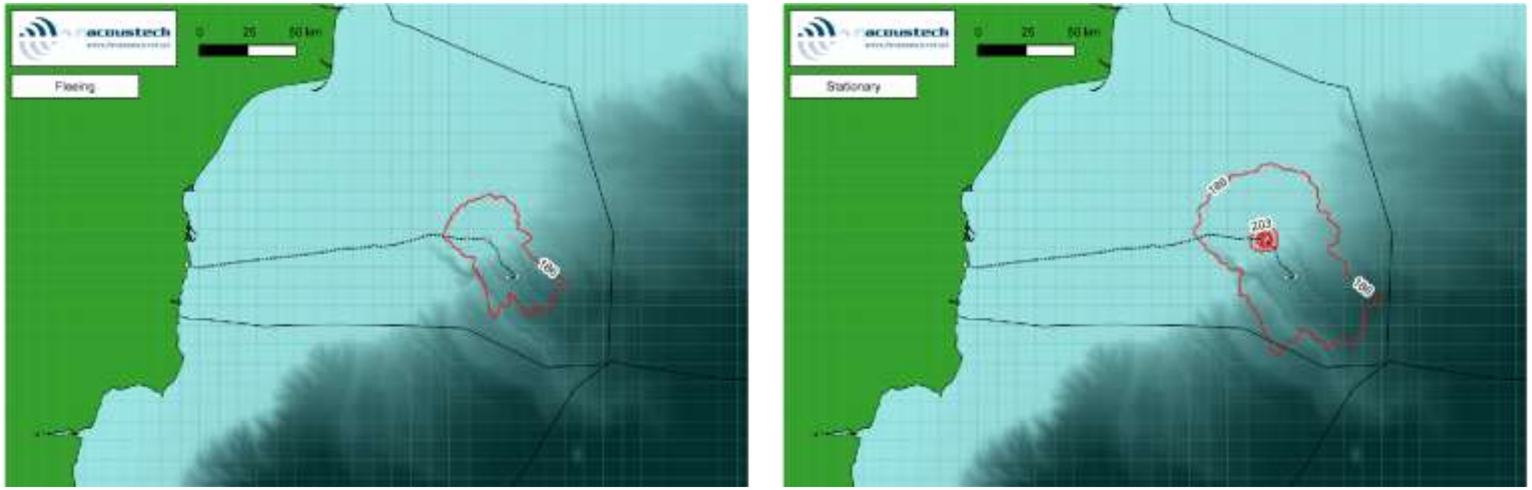

Figure 5-27 Noise plots showing the predicted unweighted SEL_{cum} zones of fish impact (Popper et al., 2014) from impact piling at the open water modelling location for the MENCK 3200iS hammer best estimate scenario for four sequentially installed piles, contours are TTS (outer), ≥ 203 dB (inner)

Table 5-27 Summary of the modelled Popper et al. (2014) cumulative impact ranges for fish from impact piling noise for fleeing receptors for the MENCK 3200iS hammer best estimate scenario

Popper *et al*. (2014) **Impact piling** (MENCK 3200iS Best estimate)		**Unweighted SEL_{cum} (fleeing)**					
		219 dB	216 dB	210 dB	207 dB	203 dB	186 dB
Single pile	Maximum	< 100 m	< 100 m	< 100 m	< 100 m	180 m	20 km
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	11 km
	Mean	< 100 m	< 100 m	< 100 m	< 100 m	120 m	16 km
4 piles	Maximum	< 100 m	< 100 m	< 100 m	< 100 m	210 m	49 km
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m	100 m	11 km
	Mean	< 100 m	< 100 m	< 100 m	< 100 m	140 m	24 km

Table 5-28 Summary of the modelled Popper et al. (2014) cumulative impact ranges for fish from impact piling noise for stationary receptors for the MENCK 3200iS hammer best estimate scenario

Popper *et al*. (2014) **Impact piling** (MENCK 3200iS Best estimate)		**Unweighted SEL_{cum} (stationary)**					
		219 dB	216 dB	210 dB	207 dB	203 dB	186 dB
Single pile	Maximum	460 m	740 m	1.7 km	2.6 km	3.9 km	27 km
	Minimum	390 m	620 m	1.3 km	1.8 km	2.6 km	16 km
	Mean	420 m	670 m	1.5 km	2.0 km	3.1 km	22 km
4 piles	Maximum	1.1 km	1.7 km	3.6 km	4.6 km	8.3 km	71 km
	Minimum	960 m	1.3 km	2.4 km	3.6 km	5.6 km	20 km
	Mean	1.1 km	1.5 km	2.8 km	4.0 km	6.8 km	40 km

5.4 Micro tunnelling

Figure 5-28 presents the predicted unweighted 1 s SEL noise levels from micro tunnelling operations at the coastal modelling location. The modelled impact ranges for marine mammals and fish are given in Table 5-29 to Table 5-31. Due to the low level of the noise, coupled with the shallow water at this location, the predicted impact ranges are small, with TTS injury ranges for VHF cetaceans predicted out to a maximum of 920 m. Impact ranges from all other species groups are much lower.

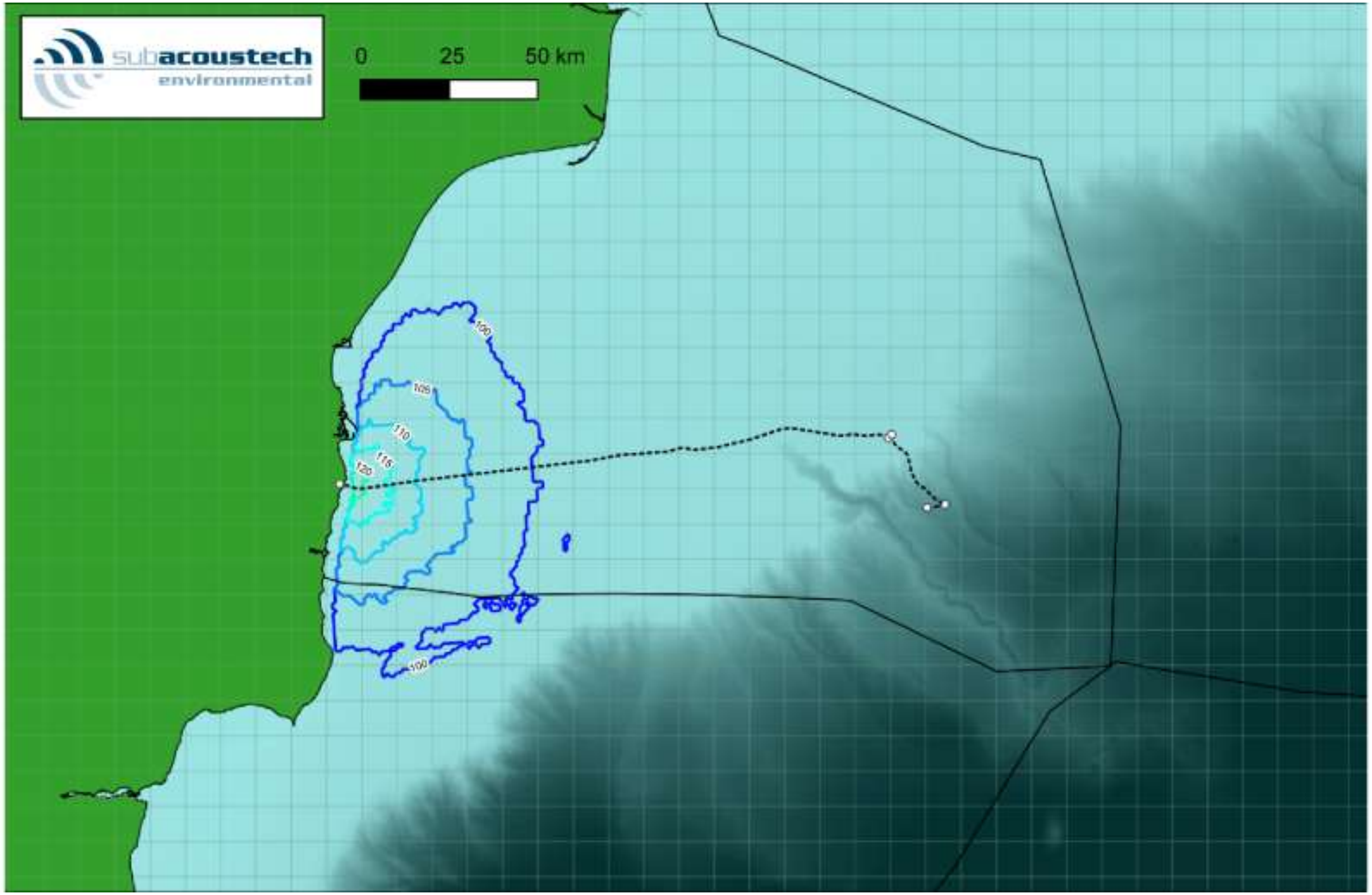

Figure 5-28 Noise plot showing the predicted unweighted noise levels (1 s SEL only) from micro tunnelling at the coastal modelling location, contours from 100 dB (dark blue) to 125 dB (light green)

Table 5-29 Summary of the modelled Southall et al. (2019) cumulative PTS impact ranges for marine mammals from micro tunnelling noise

Southall *et al*. (2019) **Micro tunnelling**		**Weighted SEL_{cum} (fleeing)** **Non-impulsive** LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)
PTS	Maximum	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-30 Summary of the modelled Southall et al. (2019) cumulative TTS impact ranges for marine mammals from micro tunnelling noise

Southall *et al*. (2019) **Micro tunnelling**		**Weighted SEL_{cum} (fleeing)** **Non-impulsive** LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
TTS	Maximum	< 100 m	< 100 m	920 m	< 100 m
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	< 100 m	< 100 m	120 m	< 100 m

Table 5-31 Summary of the modelled Popper et al. (2019) impact ranges for fish from micro tunnelling noise

Popper *et al*. (2014) **Micro tunnelling**	**Unweighted SPL_{RMS}** **Continuous sound** 170 dB	158 dB
Maximum	< 50 m	< 50 m
Minimum	< 50 m	< 50 m
Mean	< 50 m	< 50 m

5.5 Trenching

Figure 5-29 shows the predicted unweighted 1 s SEL noise levels from trenching operations at the open water modelling location; the modelled impact ranges are presented in Table 5-32 to Table 5-34. Due to the low frequency components (< 50 Hz) of the trenching noise (as shown in Figure 4-1) the sound travels out to greater distances than some of the other sources, and as such the maximum marine mammal TTS impact ranges using the Southall *et al*. (2019) criteria are predicted out to 5.2 km for LF cetaceans and 680 m for VHF cetaceans. Using the Popper *et al.* (2014) criteria for fish, TTS ranges of up to 2.0 km from the trenching are predicted for fish with a swim bladder involved in hearing, if the noise is present for a duration of 12 hours.

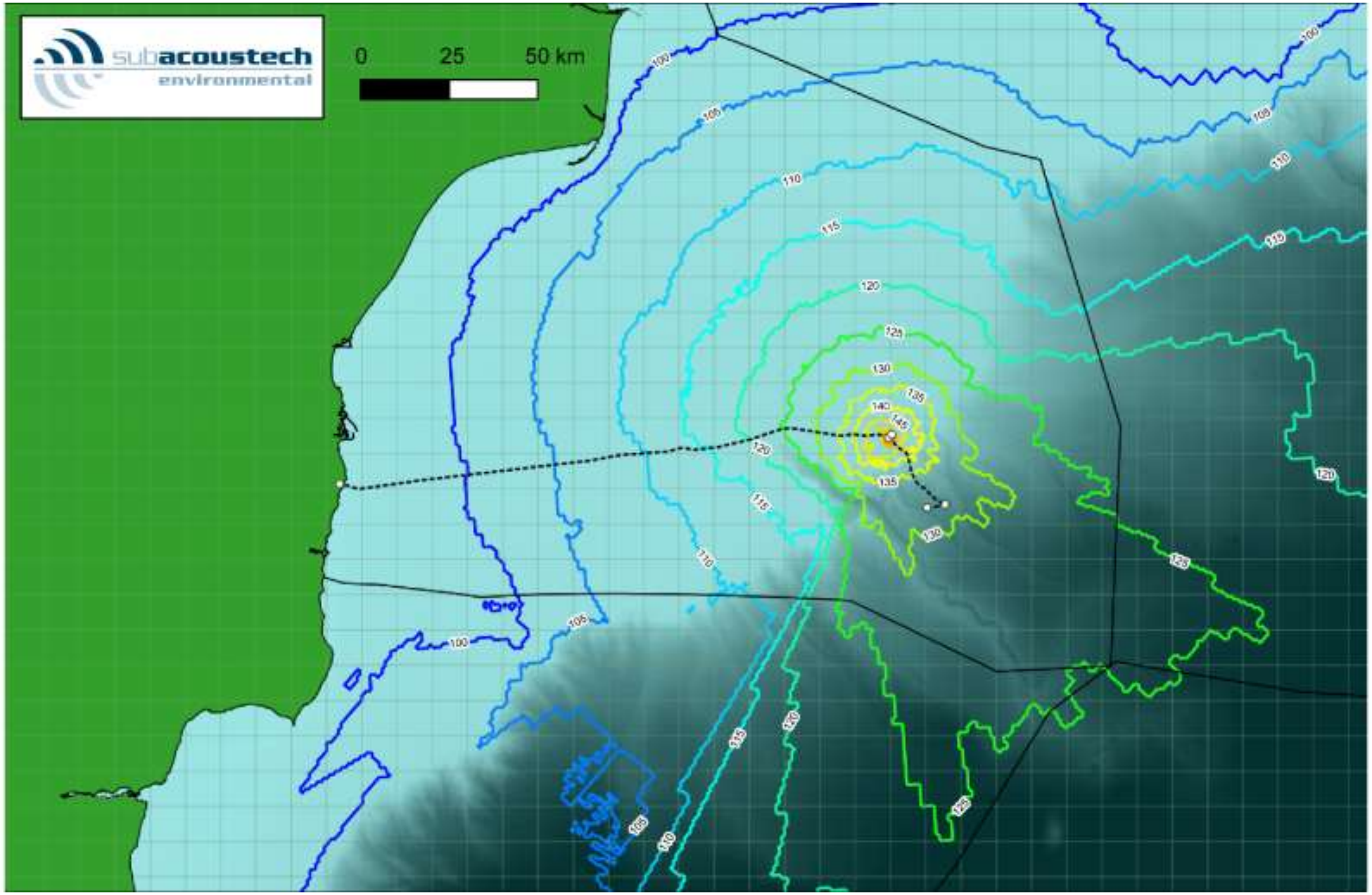

Figure 5-29 Noise plot showing the predicted unweighted noise levels (1 s SEL only) from trenching at the open water modelling location, contours from 100 dB (dark blue) to 150 dB (orange)

Table 5-32 Summary of the modelled Southall et al. (2019) cumulative PTS impact ranges for marine mammals from trenching noise

Southall *et al*. (2019) **Trenching**		Weighted SEL_{cum} (fleeing)			
		Non-impulsive			
		LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)
PTS	Maximum	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-33 Summary of the modelled Southall et al. (2019) cumulative TTS impact ranges for marine mammals from trenching noise

Southall *et al*. (2019) **Trenching**		Weighted SEL_{cum} (fleeing)			
		Non-impulsive			
		LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
TTS	Maximum	5.2 km	< 100 m	680 m	< 100 m
	Minimum	2.9 km	< 100 m	170 m	< 100 m
	Mean	4.1 km	< 100 m	350 m	< 100 m

Table 5-34 Summary of the modelled Popper et al. (2019) impact ranges for fish from trenching noise

Popper *et al*. (2014) **Trenching**	Unweighted SPL_{RMS}	
	Continuous sound	
	170 dB	158 dB
Maximum	250 m	2.0 km
Minimum	180 m	1.2 km
Mean	200 m	1.4 km

5.6 Vessel noise

The predicted noise levels from vessel noise at the open water location are presented in Figure 5-30, with the corresponding impact ranges given in Table 5-35 to Table 5-37. The maximum TTS impact ranges for marine mammals are predicted out to 660 m for LF cetaceans and 700 m for VHF cetaceans. For fish with a swim bladder involved in hearing, TTS ranges of up to 630 m from vessels are also predicted if the noise is present for a duration of 12 hours.

It is worth reiterating that the vessel used for this modelling, a large container ship, is a worst-case assumption for the vessels at the Neptun Deep site, and most impact ranges presented here will be smaller for smaller vessels.

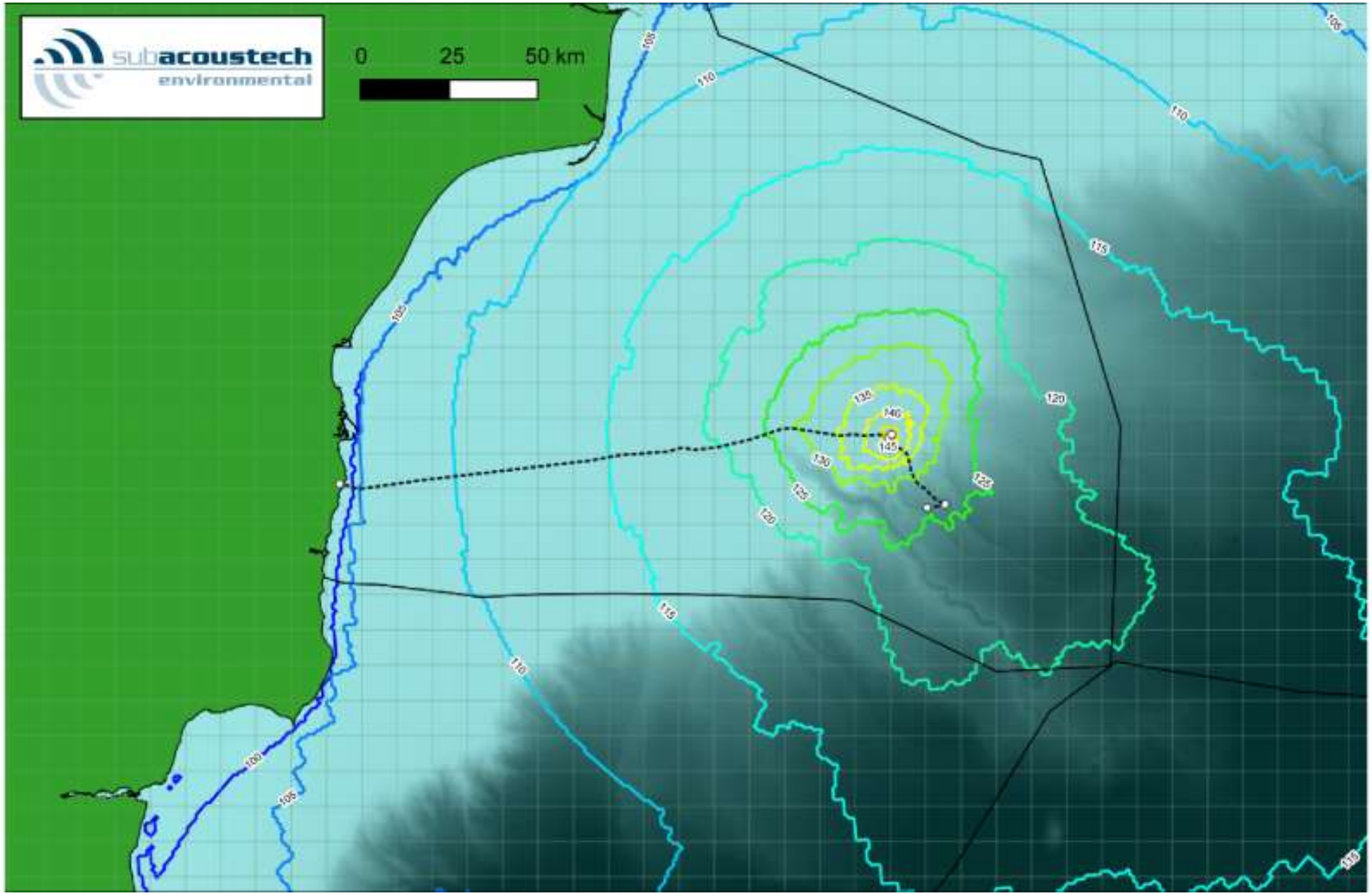

Figure 5-30 Noise plot showing the predicted unweighted noise levels (1 s SEL only) from vessel noise at the open water modelling location, contours from 100 dB (dark blue) to 150 dB (orange)

Table 5-35 Summary of the modelled Southall et al. (2019) cumulative PTS impact ranges for marine mammals from vessel noise

Southall *et al*. (2019) **Vessel noise**		Weighted SEL_{cum} (fleeing) Non-impulsive			
		LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)
PTS	Maximum	< 100 m	< 100 m	< 100 m	< 100 m
	Minimum	< 100 m	< 100 m	< 100 m	< 100 m
	Mean	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-36 Summary of the modelled Southall et al. (2019) cumulative TTS impact ranges for marine mammals from vessel noise

Southall *et al*. (2019) **Vessel noise**		Weighted SEL_{cum} (fleeing) Non-impulsive			
		LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
TTS	Maximum	660 m	< 100 m	700 m	< 100 m
	Minimum	370 m	< 100 m	410 m	< 100 m
	Mean	470 m	< 100 m	540 m	< 100 m

Table 5-37 Summary of the modelled Popper et al. (2019) impact ranges for fish from vessel noise

Popper *et al*. (2014) **Vessel noise**	Unweighted SPL_{RMS} Continuous sound	
	170 dB	158 dB
Maximum	90 m	630 m
Minimum	80 m	490 m
Mean	80 m	550 m

5.7 Mitigation measures

During the activities noted in the sections above, various mitigation measures may be considered although not all will be suitable. Marine Mammal Observers (MMOs, sometimes known as Protected Species Observers, PSOs) will be situated in the vicinity of the piling to identify the presence of any marine mammal and warn the construction contractor prior to commencement of noisy activities. This will limit any immediate risk to marine mammals.

Other mitigation measures may be suitable for the situation, subject to Best Practical Mean principles. Bubble curtains are increasing in use for high noise sources including piling but have effectiveness limitations in environments such as this. In this situation, the deep water will make these devices ineffective, as limits of the order of 50 m water depth may apply (subject to specific designs and performance). Strong currents also severely limit the effectiveness of these techniques, as a result of the dispersion of the bubbles. It may be suitable for some of the shallower piling locations.

Other manufacturer-specific techniques may be suitable. Menck produces a Noise Reduction Unit (MNRU) which restricts noise transmission in the surrounding water, although it is not known whether this can be applied to the hammer available for this project.

Any potential noise reduction technique will have to undergo project and location-specific analysis for its suitability and efficacy.

6 Summary and conclusions

Subacoustech Environmental has undertaken a study on behalf of io consulting to assess the impact of underwater noise during various activities related to the construction of the Neptun Deep project in the Black Sea, off the east coast of Romania. The expected noise sources include dredging, drilling, impact piling, micro tunnelling, trenching and vessel noise.

The level of underwater noise around the operation of the equipment has been estimated using a combined parabolic equation and ray tracing noise propagation modelling methodology. The modelling also considers a wide array of input parameters including source noise 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 Neptun Deep site.

The modelling was undertaken at three locations of the project area depending on the noise source, as certain activities will only occur in particular areas of the site. Although many of the noise sources will be constantly moving, the use of stationary locations provides a precautionary assessment.

The maximum PTS impact ranges for marine mammals are predicted for the LF cetacean and VHF cetacean hearing groups from Southall *et al*. (2019) with ranges from the loudest source, impact piling, resulting in SEL_{cum} ranges of up to 57 km (LF cetaceans) and 15 km (VHF cetaceans) for four sequentially installed piles assuming the larger piling hammer and the upper bound installation scenario. This assumes that the noise still retains impulsive characteristics after this long distance; in fact, noise becomes more non-impulsive over distance and impact ranges in practice are expected to be much lower.

For fish, maximum recoverable injury ranges of 16 km are predicted for impact piling using the criteria from Popper *et al*. (2014) assuming a stationary receptor. It should be noted that the impact piling parameters used for this study are precautionary, and that other methods such as vibro piling would lead to lower impact ranges.

Noise mitigation techniques may be suitable for the Neptun Deep project. MMOs will be deployed in the vicinity of the noisy activity to monitor for the presence of protected species. Other direct noise mitigation may be available but will need to go through specific project-related assessment as to their performance and efficacy under Best Practicable Means.

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

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