Bellrock Offshore Wind Farm

Wind Farm Development Area

Environmental Impact Assessment Report - Volume IV

Appendix 9.2: Underwater Noise Assessment

Date: April 2026

Document Number: RHDV_BEL_CST_REP_0004_020

Revision Number: 1

Classification: Public

Bellrock Offshore Wind Farm: Wind Farm Development Area Underwater Noise Assessment

RB

19 September 2025

Subacoustech Environmental Report No. P355R0103

Submitted to: Haskoning

Website: www. haskoning.com

Submitted by: Subacoustech

Website: www.subacoustech.com

Document No.	*Date*	*Written*	*Approved*	*Distribution*
P355R0101	*12/03/2025*	*RB*	*TM*	*Haskoning*
P355R0102	*14/08/2025*	*RB*	*TM*	*Haskoning*
P355R0103	*19/09/2025*	*RB*	*TM*	*Haskoning*

This report is a controlled document. The report documentation page lists the version number, record of changes, referencing information, abstract and other documentation details.

Executive summary

Subacoustech Environmental Limited has been appointed by Haskoning on behalf of Bellrock Offshore Wind Farm Limited, to undertake an assessment of potential underwater noise and its effects during the construction, operation and maintenance, and decommissioning of Wind Farm Infrastructure and (to inform the cumulative effects assessment) Offshore Transmission Infrastructure located within the Bellrock Wind Farm Development Area (WFDA). The Bellrock WFDA is located in the North Sea off the east coast of Scotland.

Modelling of underwater noise generated by impact piling was undertaken for floating substructures (associated with wind turbine generators) and fixed substructures (associated with offshore substations (OfSS) at three representative locations within the WFDA:

- Northwest corner (NW corner), the closest point of the WFDA to the Scottish coast, covering noise transmission to the north and west toward the coast;
- Southwest corner (SW corner), covering noise transmission to the south and west toward the Scottish coast; and
- Eastern boundary midpoint (E boundary midpoint), covering some of the deepest water along the WFDA boundary and transmission into deeper water to the east.

The loudest noise levels and the greatest impact ranges are predicted from piling of the OfSSs' fixed bottom substructure (FBSS) located on the WFDA's E boundary midpoint modelling location, due to their higher blow energies compared to that required to anchor floating offshore units (FOU)[1], and deeper water at that location.

The modelling results were analysed in terms of relevant noise metrics and criteria to assess the effects of impact piling noise on marine mammals and fish, which have been used to aid biological assessments. For marine mammals, the largest permanent threshold shift (PTS) ranges from impact piling, were predicted for animals in the low frequency (LF) cetacean hearing category, with maximum ranges out to 28 km. For fish, the largest recoverable injury ranges were predicted to be 12 km for a stationary receptor, reducing to a minimal range when considering a moving receptor.

For the FOU driven piles, the largest PTS ranges from impact piling, were predicted for marine mammals at the E boundary midpoint with maximum ranges out to 25 km for the LF cetacean hearing category and for fish. The largest recoverable injury ranges were predicted to be 8.6 km for a stationary receptor, reducing to a minimal range when considering a moving receptor.

Additionally, the impacts of concurrently installed piles at multiple separate locations were considered, which resulted in expanded cumulative impact areas when compared against the results for the individual installations.

Noise sources other than impact piling, including cable laying, drilling, rock placement, trenching, vessel noise and operational WTG and mooring line noise, were all predicted to be much lower than those predicted for impact piling noise.

Noise from unexploded ordnance (UXO) clearance showed there is a risk of PTS up to 990 m using the unweighted $L_{p,pk}$ criteria for very high-frequency (VHF) cetaceans, with use of a low order UXO clearance technique. If a high-order detonation does occur, the maximum PTS range is up to 14 km from detonation of the largest UXO device considered (750 kg + donor charge), using the same VHF criteria. However, this is likely to be highly precautionary as the impact range is based on a worst-case criterion and calculation methodology that does not account for any smoothing of the pulse over long ranges, which would reduce the pulse peak and other characteristics of the sound that cause injury.

[1] A floating offshore unit is the combined wind turbine generator and floating substructure.

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

The outputs of this modelling have been used to inform analysis of the impacts of underwater noise on marine mammals and fish in their respective reports.

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Glossary of Terminology

Bellrock Offshore Wind Farm (or the Bellrock Project)	An offshore wind farm capable of exporting up to 1.8 GW of renewable energy to the National Electricity Transmission System. The Wind Farm Development Area is located 120 km east of Stonehaven, and will connect to the National Electricity Transmission System at the proposed SSEN Transmission Hurlie substation, west of Stonehaven in Aberdeenshire. The Bellrock Offshore Wind Farm comprises of the following Development Areas: • Wind Farm Development Area; • Offshore Transmission Development Area; and • Onshore Transmission Development Area.
Charge weight	Quantity of contained explosive within unexploded ordnance (sometimes referred to as the Net Explosive Quantity based upon the equivalent Trinitrotoluene (TNT) mass).
Decibel (dB)	A customary scale commonly used (in various ways) for reporting levels of sound. The dB represents a ratio/comparison of a sound measurement (e.g., sound pressure) over a fixed reference level. The dB symbol is followed by a reference value (e.g., re 1 µPa).
Floating offshore unit	The combined wind turbine generator and floating substructure.
FOU driven pile	A driven pile(s) securing the mooring lines of each floating offshore unit to the seabed.
OfSS driven pile	A driven pile(s) securing the fixed bottom substructure of each of to the seabed.
Offshore Transmission Development Area	The boundary within which the Offshore Transmission Infrastructure will be constructed, operated and maintained, and decommissioned (and includes the whole of the Wind Farm Development Area).
Offshore substation	An offshore platform which houses electrical equipment such as transformers, switchgear, and protection and control systems, enabling the wind farm's renewable electricity to be received via inter-array cables and exported via the offshore export cables.
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)	Noise threshold that represents the onset level of a permanent impairment hearing caused by acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the ear, and thus a permanent reduction of hearing acuity.

Root Mean Square (RMS)	The square root of the arithmetic average of a set of squared instantaneous values. Used for presentation of an average sound pressure level.
Sound Exposure Level (SEL or $L_{E,p}$)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Exposure Level, cumulative (SEL_{cum} or $L_{E,p,t}$)	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} 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 µPa for water and 20 µPa for air.
Sound Pressure Level Peak (SPL_{peak} or $L_{p,pk}$)	The highest (zero-peak) positive or negative sound pressure, in decibels.
Temporary Threshold Shift (TTS)	Onset threshold level for a temporary reduction of hearing acuity caused by exposure to sound over time.
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.
Wind Farm Development Area	The boundary within which the Wind Farm Infrastructure will be constructed, operated and maintained, and decommissioned.
Wind Farm Infrastructure	Infrastructure located within the Wind Farm Development Area including wind turbine generators; floating substructures, station keeping systems and associated scour protection; inter-array cables and associated cable protection; and subsea cable hubs; and ancillary infrastructure including buoys (including activities associated with the Wind Farm Infrastructure construction, operation and maintenance, and decommissioning).

Glossary of Abbreviations

ADD	Acoustic Deterrent Device
BGS	British Geological Survey
DDD	Drill-drive-drill
EIA	Environmental impact assessment
EMODnet	European Marine Observation and Data Network
FBSS	Fixed bottom substructure
FOU	Floating Offshore Unit
FSS	Floating substructure
GIS	Geographic information systems
HE	High explosive
HF	High-frequency
INSPIRE	Impulsive Noise Sound Propagation and Impact Range Estimator
ISO	International Organisation for Standardisation
LF	Low-frequency
MTD	Marine Technical Directorate
NEQ	Net explosive quantity
NMFS	National Marine Fisheries Service
NPL	National Physical Laboratory
OfSS	Offshore substation
OfTDA	Offshore Transmission Infrastructure
PCW	Phocid carnivores in water
PPV	Peak particle velocity
PTS	Permanent threshold shift
RMS	Root mean square
SE	Sound exposure
SEL ($L_{E,p}$)	Sound exposure level
SEL_{cum} ($L_{E,p,t}$)	Cumulative sound exposure level
SEL_{ss} ($L_{E,p,ss}$)	Single strike sound exposure level
SPL	Sound pressure level
SPL_{peak} ($L_{p,pk}$)	Peak sound pressure level
SPL_{RMS} (L_p)	Root mean square sound pressure level
TNT	Trinitrotoluene (explosive)

TTS	Temporary threshold shift
UXO	Unexploded ordnance
VHF	Very high-frequency
WFDA	Wind Farm Development Area
WTG	Wind turbine generator

Units

dB	Decibel (sound pressure)
GW	Gigawatt (power)
Hz	Hertz (frequency)
kHz	Kilohertz (frequency)
kJ	Kilojoule (energy)
km	Kilometre (distance)
km^2	Square kilometres (area)
kW	Kilowatt (power)
m	Metre (distance)
m/s	Metres per second (speed)
MW	Megawatt (power)
Pa	Pascal (pressure)
Pa^2s	Pascal squared seconds (acoustic energy)
µPa	Micropascal (pressure)

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1 Introduction

Bellrock Offshore Wind Farm (Bellrock) is a proposed floating offshore wind farm in the North Sea, Scotland. As part of the environmental impact assessment (EIA) process for the Bellrock Wind Farm Development Area (WFDA), Subacoustech Environmental Limited has undertaken detailed modelling and analysis in relation to the effect of underwater noise on marine mammals and fish during the construction, operation and maintenance, and decommissioning of the Wind Farm Infrastructure located within the Bellrock WFDA.

In addition, to support the WFDA cumulative effects assessment, detailed modelling and analysis has also been undertaken in relation to the effect of underwater noise on marine mammals and fish during the construction, operation and maintenance, and decommissioning of the offshore substations[2] (OfSS) which are also located within the Bellrock WFDA.

The Bellrock WFDA covers an area of 280 km^2 and is situated 120 km east of Stonehaven (and 116 km southeast of Peterhead). The location of the Bellrock WFDA is shown in Figure 1-1.

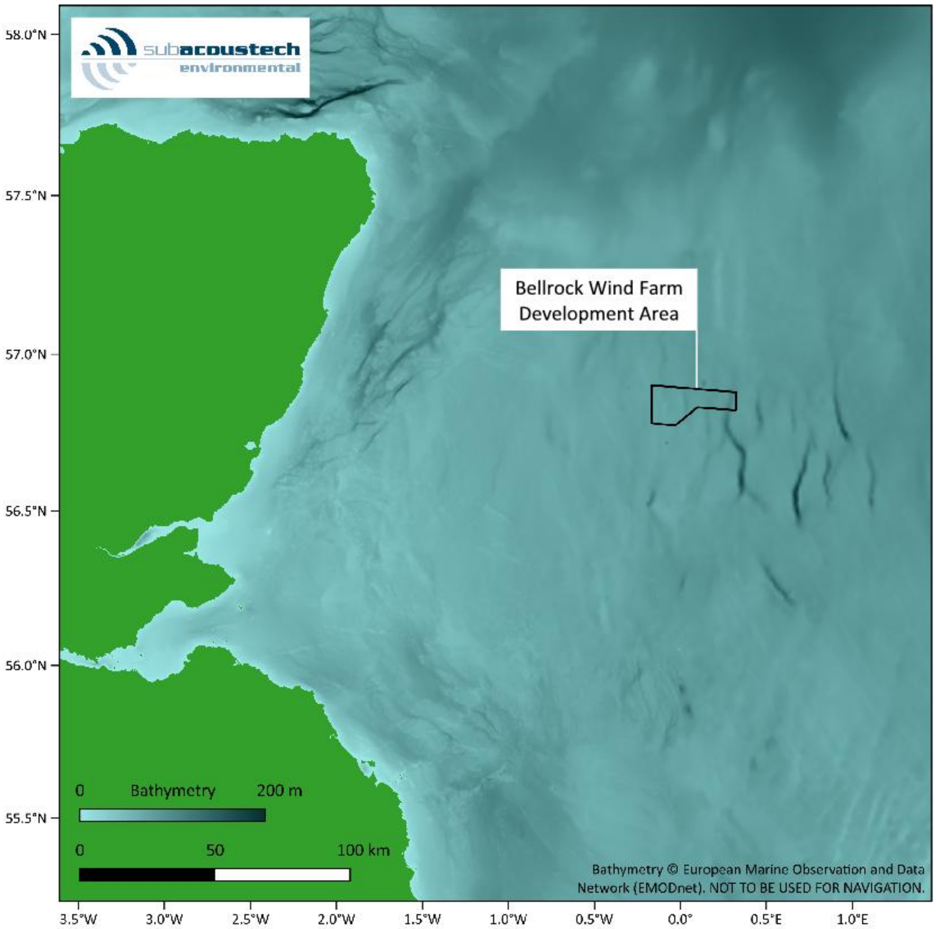

Figure 1-1: Overview map showing the Bellrock WFDA, its location in the North Sea and the surrounding bathymetry.

[2] The OfSSs form part of the Offshore Transmission Infrastructure located within the Bellrock Offshore Transmission Development Area (OfTDA). The OfSS are located within part the of the OfTDA which overlaps with the WFDA.

This report presents a detailed assessment of the potential underwater noise during the construction, operation and maintenance, and decommissioning of the Wind Farm Infrastructure and Offshore Transmission Infrastructure (OfTDA) located within the WFDA, and includes the following:

- Background information covering the units for measuring and assessing underwater noise, and a review of the underwater noise metrics and criteria used to assess the possible environmental effects in marine receptors (section 2);
- Discussion of the approach, input parameters, and assumptions for the detailed impact piling modelling undertaken (section 3);
- Presentation and interpretation of the detailed subsea noise modelling for impact piling with regards to its effect on marine mammals and fish (section 4);
- Modelling of other noise sources expected around the construction, operation and maintenance, and decommissioning of the Wind Farm Infrastructure and Offshore Transmission Infrastructure located within the Bellrock WFDA, including cable laying, drilling (for drill-drive-drill (DDD)), rock placement, trenching, vessel noise, operational wind turbine generator (WTG) noise and mooring line noise, and unexploded ordnance (UXO) clearance (section 5); and
- Summary and conclusions (section 6).

Further modelling results covering non-impulsive thresholds (see section 2.2.1) are presented in Appendix A.

2 Background to underwater noise metrics

2.1 Underwater noise

Sound travels much faster in water (approximately 1,500 m/s) than in air (340 m/s). Since water is a relatively incompressible, dense medium, the pressure associated with underwater sound tends to be much higher than in air. It should be noted that presentation of underwater noise levels is different to airborne noise levels, as a different scale is used between in water and in air measurements. Therefore, noise measurements in air are not directly comparable to noise measurements underwater.

2.1.1 Units of measurement

Sound measurements underwater are usually expressed using the Decibel (dB) scale, which is a logarithmic measure of sound. A logarithmic scale is used, as this better reflects how sound is perceived. For example, equal increments of sound levels do not have an equal increase in the perceived sound. Instead, each doubling of sound level will cause a roughly equal increase of loudness. Any quantity expressed in this dB scale is termed a "level." For example, if the unit is sound pressure, it will be termed a "sound pressure level" on the dB scale.

The fundamental definition of the dB scale is given by:

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

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

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

When used with sound pressure, the pressure value is 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:

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

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

2.1.2 Sound pressure level (L_p or SPL)

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

Where SPL is used to characterise transient pressure waves, such as that from impact piling, seismic airgun or underwater blasting, it is critical that the period over which the RMS level is calculated is quoted e.g., $L_{p,125ms}$. For instance, in the case of a pile strike lasting a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean averaged over one second. Often, transient sounds such as these are quantified using "peak" SPLs ($L_{p,pk}$) or Sound Exposure Levels (SELs, L_E).

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

2.1.3 Peak sound pressure level ($L_{p,pk}$ or SPL_{peak})

The peak SPL, or $L_{p,pk}$, is often used to characterise transient sound from impulsive sources, such as percussive impact piling. $L_{p,pk}$ is calculated using the maximum variation of the pressure from positive to zero within the wave. This represents the maximum change in positive pressure (differential pressure from positive to zero) as the transient pressure wave propagates.

2.1.4 Sound exposure level ($L_{E,p,t}$ or 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 ($L_{E,p}$) sums the acoustic energy over a measurement period (t), 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 Pa, T is the total duration of sound in seconds, and t is time in seconds. The SE is a measurement of acoustic energy and has units of Pascal squared seconds (Pa^2s).

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

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

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

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

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

This means that, for continuous sounds of less than (i.e., fractions of) one second, the $L_{E,p,1s}$ will be lower than the L_p. For periods greater than one second, the $L_{E,p}$ will be numerically greater than the L_p (i.e., for a continuous sound of 10 seconds duration, the $L_{E,p,10s}$ will be 10 dB higher than the L_p; for a sound of 100 seconds duration the $L_{E,p,100s}$ will be 20 dB higher than the L_p, 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" $L_{E,p}$ or SEL_{ss}. A cumulative $L_{E,p,t}$, or SEL_{cum}, accounts for the exposure from multiple impulses or pile strikes over time, where the number of impulses replaces the T in the equation above, leading to:

$$L_{E.p.t} = L_E + 10 \times \log_{10} X$$

where L_E is the sound exposure level of one impulse and X is the total number of impulses or strikes. Unless otherwise defined, all L_E noise levels in this report are references to 1 µPa²s.

2.2 Properties of sound

2.2.1 Impulsive and non-impulsive noise

Sound can be categorised loosely into two types: impulsive noise and non-impulsive noise. Non-impulsive noise can be defined as a steady-state noise which does not necessarily have a long duration (e.g., vibropiling, drilling). Impulsive noise can be defined as a sound with a high peak sound pressure, short duration, fast rise-time and a broad frequency content at the source (e.g., seismic airguns, explosives, impact piling).

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

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

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

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

Active research is currently underway to define the range-dependant transition from impulsive and non-impulsive noise (see Martin *et al.*, 2020). Although the situation is complex, Hastie *et al.* (2019) concluded that an impulsive sound can be considered effectively non-impulsive 3.5 km from the source on some metrics.

However, the recent study by Matei *et al.* (2024) concludes that there is still insufficient evidence to clearly define a transition point suitable for an assessment such as this, although it is reasonable to presume there is a fully impulsive region close to the source, a fully non-impulsive region at a greater distance, and a transition region in between. The paper makes it clear that there is a substantial reduction in impulsiveness within the first 5 km. Due to the uncertainty, no presumption of a change in impulsiveness has been made in this report, although the sound should be considered not fully impulsive where PTS ranges are calculated above 5 km. Results in respect of both impulsive and non-impulsive criteria (see section 2.3.1) have been presented for piling noise sources.

2.2.2 Particle motion

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

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

2.3 Analysis of environmental effects: Assessment criteria

Over the last 20 years it has become increasingly evident that noise from human activities in and around underwater environments can have an impact on the marine species in the area. The extent to which intense underwater sound might cause adverse impacts in species is dependent upon the incident sound level, source frequency, duration of exposure, and/or repetition rate of an impulsive sound (see, for example, Hastings and Popper, 2005). As a result, scientific interest in the hearing abilities of aquatic species has increased. Studies are primarily based on evidence from high level sources of underwater noise such as seismic airguns, impact piling and blasting as these sources are likely to have the greatest immediate environmental impact and therefore the clearest observable effects, although interest in chronic noise exposure is increasing.

The impacts of underwater sound on marine species can be broadly summarised as follows:

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

The following sections discuss the underwater noise criteria used in this study with respect to species of marine mammals and fish that may be present around the Bellrock WFDA.

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

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

At the time of writing these include the most up-to-date and authoritative criteria for assessing environmental effects for use in impact assessments. Although it is noted that other papers have been published recently with new guidance (e.g. NMFS, 2024), these have not yet been accepted by the Scottish regulators.

2.3.1 Marine mammals

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

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

It should be noted that despite Southall *et al*. (2019) referring to peak SPL as SPL_{peak} and cumulative SEL as SEL_{cum}, this notation has since been deprecated (ISO 18405:2017) and will be referred to as $L_{p,pk}$ and $L_{E,p,t}$ respectively in the rest of this report.

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

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

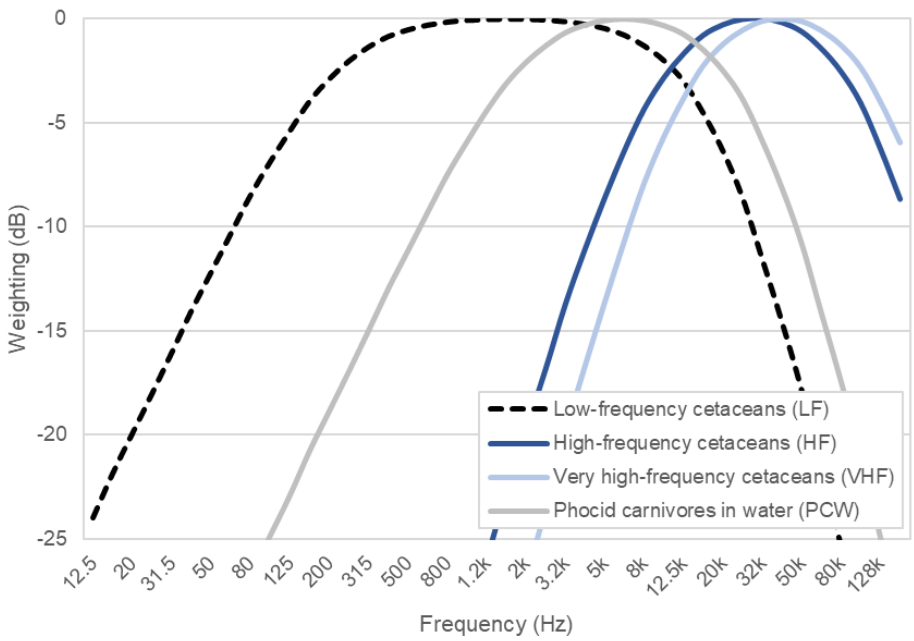

Figure 2-1: Auditory weighting functions for LF cetaceans, HF cetaceans, VHF cetaceans , and PCW (from Southall et al., 2019).

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

Although the use of impact ranges derived using the impulsive criteria are recommended for all but clearly defined non-impulsive sources, it should be recognised that where calculated ranges are beyond 5 km (see section 2.2.1), the sound is expected to be beyond the fully impulsive region and the real impact range is likely to be somewhere between the impulsive and non-impulsive impact criteria. Therefore, if the modelled impact range of an impulsive noise has been predicted to be greater than 5 km, the non-impulsive impact range should also be considered. Both impulsive and non-impulsive criteria have been presented in this study.

Table 2-2 and Table 2-3 present the impulsive and non-impulsive criteria set out by Southall *et al*. (2019) for Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS) in marine mammals used in this study.

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

Southall *et al.* (2019)	$L_{p,pk}$ (dB re 1 µPa)	
	Impulsive	
	PTS	TTS
LF cetaceans	219	213
HF cetaceans	230	224
VHF cetaceans	202	196
PCW	218	212

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

Southall *et al.* (2019)	$L_{E,p,24h,wtd}$ (dB re 1 µPa²s)			
	Impulsive		Non-impulsive	
	PTS	TTS	PTS	TTS
LF cetaceans	183	168	199	179
HF cetaceans	185	170	198	178
VHF cetaceans	155	140	173	153
PCW	185	170	201	181

Where $L_{E,p,t}$ thresholds are required for marine mammals, a fleeing animal model has been used. This assumes that a receptor, when exposed to high noise levels, will swim away from the noise source. For this study, the following flee speeds have been used for marine mammals:

- 2.1 m/s for LF cetaceans (Scottish Natural Heritage; SNH, 2016);
- 1.52 m/s for HF cetaceans (Bailey and Thompson, 2006);
- 1.4 m/s for VHF cetaceans (SNH, 2016); and
- 1.8 m/s for PCW (SNH, 2016).

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.

The fleeing animal model and the assumptions related to it are discussed in more detail in section 3.3.

2.3.2 Fish

The Popper *et al*. (2014) guidelines are recognised as a suitable reference for underwater noise impacts on marine fauna (aside from marine mammals) in UK waters. Popper *et al*. (2014) provides a summary of the latest research and guidelines for fish (and other marine fauna) exposure to sound and uses categories for fish that are representative of the species present around Bellrock.

The Popper *et al*. (2014) guidelines present criteria dependent on the type of noise source, species of marine fauna and their hearing capabilities, and impact type. Noise sources considered in the guidance include explosions, pile driving, seismic airguns, sonar, and shipping and continuous noise. For this study, criteria for pile driving, explosions, and shipping and continuous noise have been used.

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

Popper *et al*. (2014) provides separate criteria, depending on the species and the noise source, for various impacts associated with noise exposure. These are mortality and potential mortal injury, impairment (split into recoverable injury, TTS, and masking), and behavioural effects.

Depending on the noise source, quantitative criteria are given in appropriate metrics ($L_{p,pk}$, $L_{E,p,24h}$, etc.), which can then be used as thresholds for the onsets of listed impacts. Where insufficient data is available, Popper *et al.* (2014) also gives a description of relative risk. This summarises the effect of the noise as having either a high, moderate or low relative risk of an effect on an individual in either near (tens of meters), intermediate (hundreds of meters) or far (thousands of meters) from the source.

Where $L_{E,p,t}$ thresholds are required for fish, both a stationary and a fleeing animal model has been used. This is due to the diversity of species considered under this criterion, and as a result, both models encompass the diversity of responses to noise.

Most species described by Popper *et al.* (2014) are likely to move away from a sound that is loud enough to cause harm (Dahl *et al*., 2015; Popper *et al*., 2014). For those species that flee, a speed of 1.5 m/s (based on Hirata, 1999) is considered a conservative speed at which to base a fleeing animal model. However, considering the diversity of species described by Popper *et al*. (2014), whether an animal flees or remains stationary in response to a loud noise will differ between species. It is recognised that there is limited evidence for fish fleeing from high level noise sources in the wild. Those species that are likely to remain stationary are thought more likely to be benthic species or species without a swim bladder, due to their reduced hearing capabilities making these species the least sensitive to noise (e.g., Goertner *et al*., 1994; Goertner *et al*., 1978; Stephenson *et al*., 2010; Halvorsen *et al*., 2012). Hubert *et al*. (2024) noted that pelagic fish did not clearly flee on exposure to sound, albeit at sound pressure levels far lower than piling noise, and did not rule out the possibility that a flee response could occur at higher levels. Despite this, including only a stationary animal model as a worst-case scenario is likely to greatly overestimate the potential risk to fish species. A combined approach is recommended, which considers impact ranges from both fleeing and stationary receptors. Impact ranges from both stationary and fleeing receptors are therefore included in this report.

The thresholds and relative risk descriptions from the Popper *et al*. (2014) criteria used in this study are reproduced in Table 2-4 to Table 2-6, covering pile driving, explosions, and shipping and continuous noise sources. Similar to the Southall *et al*. (2019) criteria in section 2.3.1, the Popper *et al*. (2014) criteria use the deprecated SPL_{peak}, SPL_{RMS} and SEL_{cum} notation, and this report will use respectively the $L_{p,pk}$, L_p, and $L_{E,p,t}$ notation from ISO 18405:2017 from hereon.

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					
Receptor	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	> 219 dB $L_{E,p,24h}$ > 213 dB $L_{p,pk}$	> 216 dB $L_{E,p,24h}$ > 213 dB $L_{p,pk}$	>> 186 dB $L_{E,p,24h}$	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	210 dB $L_{E,p,24h}$ > 207 dB $L_{p,pk}$	203 dB $L_{E,p,24h}$ > 207 dB $L_{p,pk}$	> 186 dB $L_{E,p,24h}$	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing	207 dB $L_{E,p,24h}$ > 207 dB $L_{p,pk}$	203 dB $L_{E,p,24h}$ > 207 dB $L_{p,pk}$	186 dB $L_{E,p,24h}$	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
Sea turtles	> 210 dB $L_{E,p,24h}$ > 207 dB $L_{p,pk}$	(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 dB $L_{E,p,24h}$ > 207 dB $L_{p,pk}$	(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 explosions 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 explosions					
Receptor	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	229 – 234 dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	229 – 234 dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) Low (F) Low
Fish: swim bladder involved in hearing	229 – 234 dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low
Sea turtles	229 – 234 dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low
Eggs and larvae	> 13 mm/s peak velocity	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low

Table 2-6: 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					
Receptor	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder involved in hearing	(N) Low (I) Low (F) Low	170 dB $L_{p,48h}$	158 dB $L_{p,12h}$	(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

It is important to note that despite the emerging evidence that fish are sensitive to particle motion (see section 2.2.1), the Popper *et al*. (2014) guidance defines noise impacts in terms of sound pressure or sound pressure-associated functions (i.e., $L_{E,p,t}$).

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

2.3.3 Marine invertebrates

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

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

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

In its current state, research on the effects of anthropogenic noise on marine invertebrates is emerging, but more slowly than for marine mammals and fish. At this time, this research is in too early a stage to be used to accurately generate impact thresholds which would be satisfactory to regulators. The data available could potentially be referenced for some species but with caution, as there are still considerable gaps in the knowledge that would enable reliable conclusions for the impact of noise for most species.

3 Modelling methodology

To estimate the underwater noise levels likely to arise during the construction, operation and maintenance, and decommissioning of the infrastructure in the Bellrock WFDA, predictive noise modelling has been undertaken. The methods described in this section, and used within this report, meet the requirements set by the National Physical Laboratory (NPL) Good Practice Guide 133 for underwater noise measurement (Robinson *et al*., 2014) and are as agreed with NatureScot in their response to the Bellrock WFDA Scoping Report (NatureScot, 2024).

Of those considered, the noise source most important to consider is impact piling due to the noise level and duration it will be present (Bailey *et al*., 2014), and as such, the noise related to impact piling activity is the primary focus of this study.

The modelling of impact piling has been undertaken using the INSPIRE underwater noise model, which has been widely used for wind farm assessments around the UK. The INSPIRE model (currently version 5.3) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling, a combined geometric and energy flow/hysteresis loss method, and actual measured data. It is designed to calculate the propagation of noise in shallow, mixed water, typical of the conditions within and around the Bellrock WFDA and well suited for use in the North Sea.

The model provides estimates of unweighted $L_{p,pk}$, $L_{E,p,ss}$ and $L_{E,p,t}$ noise levels, as well as other weighted noise metrics. Calculations are made along 180 equally spaced radial transects (one every two degrees). For each modelling run a criterion level can be specified allowing a contour to be drawn, within which a given effect may occur. These results can then be plotted over digital bathymetry data so that impact ranges can be clearly visualised as necessary. INSPIRE also produces these contours as GIS shapefiles.

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

- Piling hammer blow energies;
- Soft start, hammer energy ramp-up, and strike rate;
- Total duration of piling, and
- Receptor swim speeds.

Simpler modelling approaches have been used for noise sources other than piling that may be present during the construction, operation and maintenance, and decommissioning of the infrastructure in the Bellrock WFDA, these are covered in section 5.

3.1 Modelling confidence

The INSPIRE model is semi-empirical and as such a validation process is inherently built into it's development process. Whenever a new set of good, reliable, impact piling measurement data is gathered through offshore surveys, either by Subacoustech or a third party, it is compared against the outputted levels from INSPIRE and, if necessary, the model can be adjusted. Currently over 100 separate impact piling noise datasets primarily from the North and Irish Seas have been used as part of the development for the latest version of INSPIRE, and in each case, an average, or slightly conservative, fit to the data is used. This means that for a given parameter set, some measured data points will be louder than the predicted level. Making the model over-predict for all parameters ultimately would lead to an over-precautionary and unrealistic model.

INSPIRE is also validated by comparing the noise levels outputted from the model with measurements and modelling undertaken by third parties, for example Thompson *et al*. (2013) and Thomson *et al.* (in prep.). The largest pile diameter included in this validation was 9.5 metres, and the highest blow energy was 3,000 kJ.

INSPIRE is designed to predict trends in the effect of increasing parameters beyond empirical data, and uses the data combined with standard acoustic theory to predict the effect of greater blow energies, larger piles and deeper water on the noise levels produced and propagated in the water.

The version of INSPIRE used for the Bellrock WFDA (v5.3) is the product of reanalysing all the impact piling noise in Subacoustech Environmental's measurement database and any other data available and cross-referencing it with blow energy data from piling logs. This gives a database of single strike noise levels referenced to a specific blow energy at a specific range and environmental conditions, primarily water depth.

Previous iterations of the INSPIRE model have endeavoured to give a worst-case estimate of underwater noise levels produced by various permutations of impact piling parameters. There is always some natural variability with underwater noise measurements, even when considering measurements of pile strikes under the same conditions (i.e., at the same blow energy, taken at the same range). For example, there can be variations in noise level of up to five or even 10 dB, as seen in Bailey *et al*. (2010) and the data shown in Figure 3-1 and Figure 3-2. When modelling using the upper bounds of this range, in combination with other worst-case parameter selections, conservatism can be compounded to create excessively overcautious predictions, especially when calculating $L_{E,p,t}$. With this in mind, the current version of INSPIRE calculates closer to the average fit of the measured noise levels at all ranges, which maintains an additional degree of precaution in the estimation.

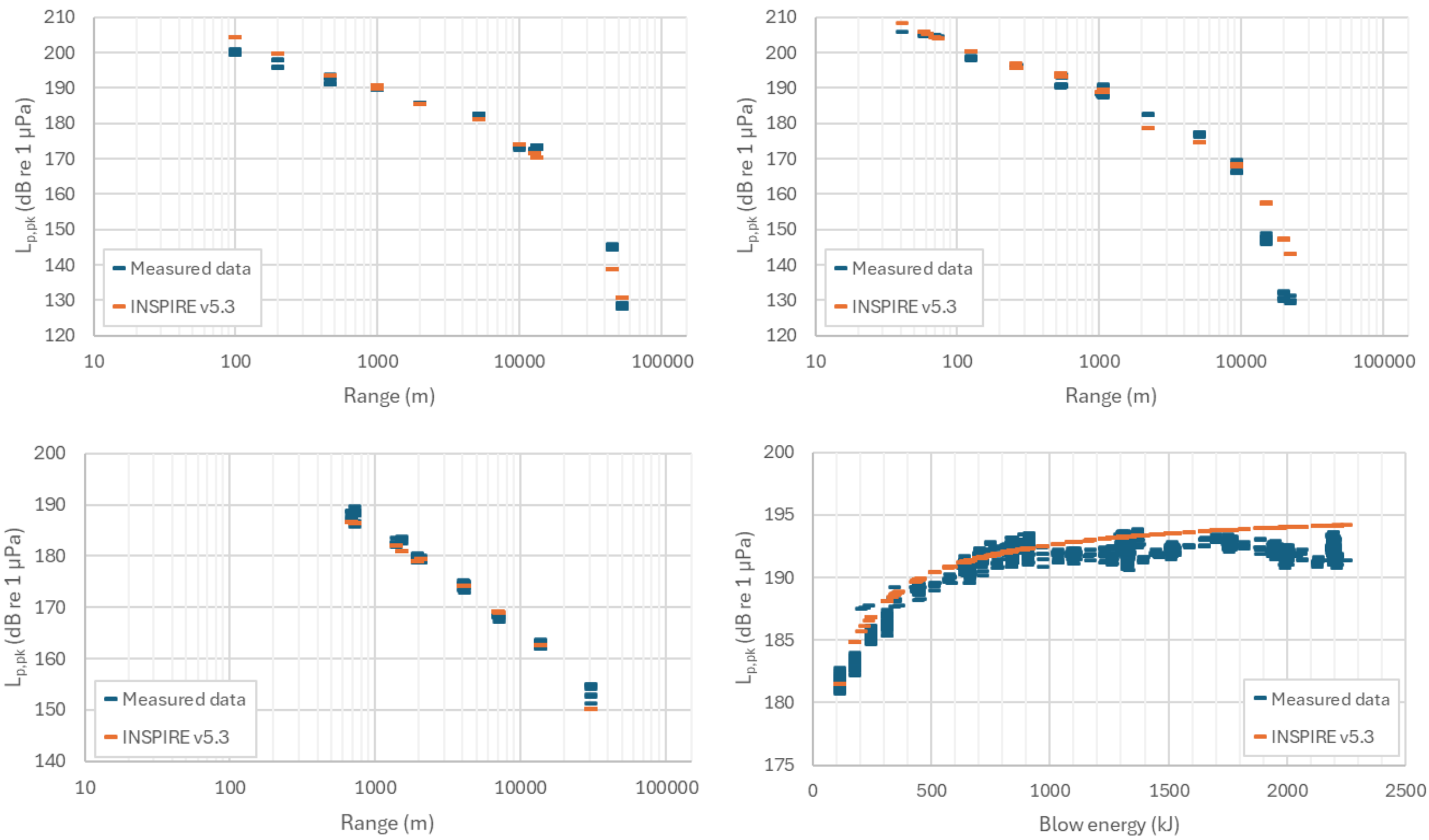

Figure 3-1: Comparison between example measured $L_{p,pk}$ impact piling data (blue) and modelled data using INSPIRE version 5.3 (orange)[3].

[3] Top Left: 6.0 m pile, 890 kJ max hammer energy, Irish Sea, 2010; Top Right: 5.2 m pile, 1,700 kJ max hammer energy, Lincolnshire Coast, 2011; Bottom Left: 1.8 m pile, 300 kJ max hammer energy, North Sea, 2011; Bottom Right: 8.9 m pile, 1.5 km range, 2,250 kJ max hammer energy, North Sea, 2024.

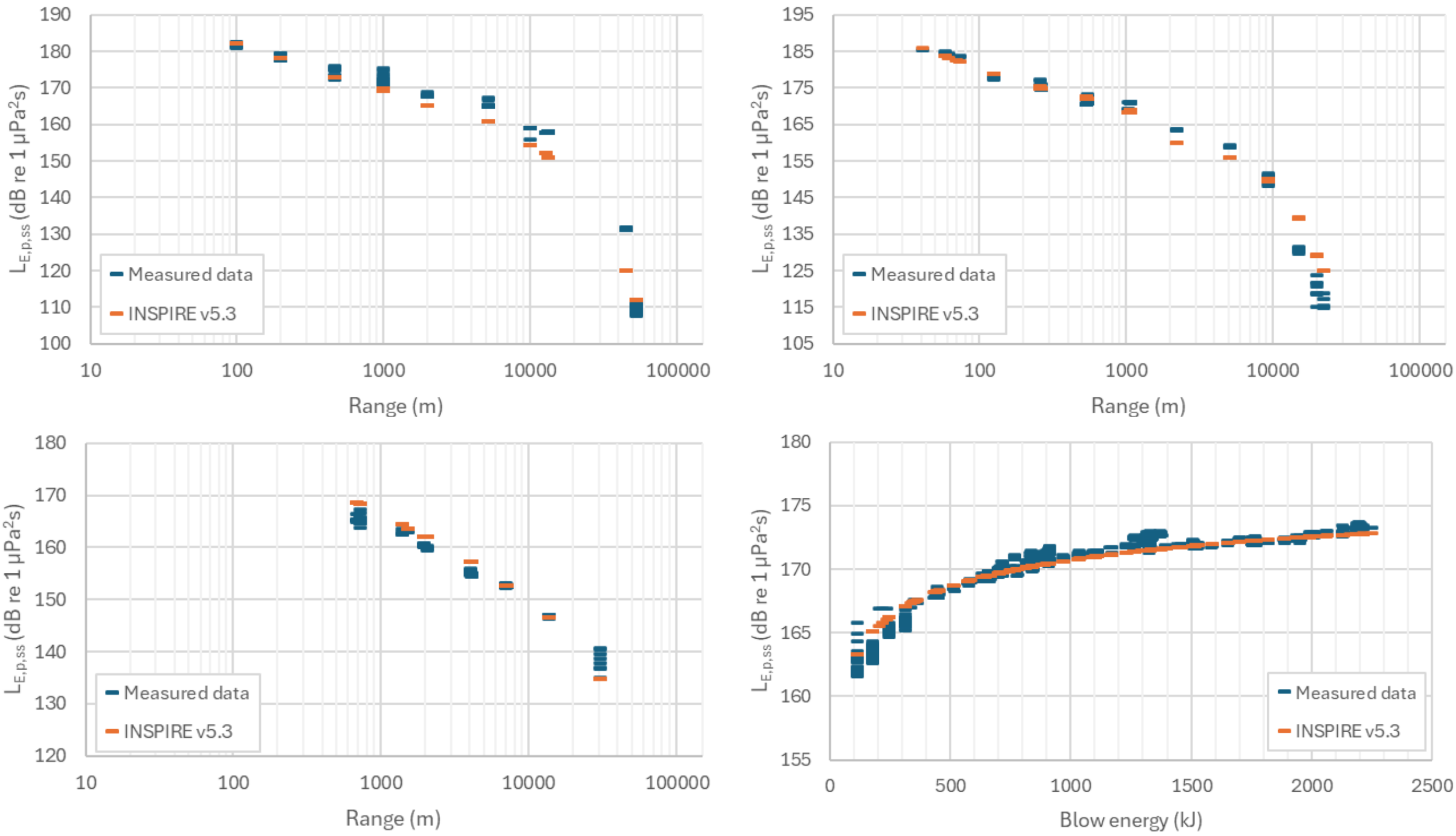

Figure 3-2: Comparison between example measured $L_{E,p,ss}$ impact piling data (blue) and modelled data using INSPIRE version 5.3 (orange)[3].

Figure 3-1 and Figure 3-2 present a small selection of the measured impact piling noise data plotted against outputs from INSPIRE. The plots show data points from measured data (in blue) plotted alongside modelled data (in orange) using INSPIRE v5.3, matching the pile size, blow energy and position of the measured data. These show the fit to the data, with the INSPIRE data points placed, more or less, in the middle of the measured noise levels at each range (as also shown in Figure 3-3 and Figure 3-4). When combined with the worst-case assumptions in parameter selection, modelled results will remain precautionary. The greatest deviations from the model tend to be at the greatest distances (>10 km), where INSPIRE appears over-precautionary in many cases, but due to the lower relative levels the influence on the overall $L_{E,p,t}$ exposure will be small.

Statistical analysis of the fits between measured data and modelled data has been carried out to show the confidence present in INSPIRE modelling using v5.3. Figure 3-3 and Figure 3-4 show the distribution of the predicted against measured data for a slightly conservative fit with unweighted $L_{p,pk}$ ($R^2 = 0.79$) and unweighted $L_{E,p,ss}$ ($R^2 = 0.82$).

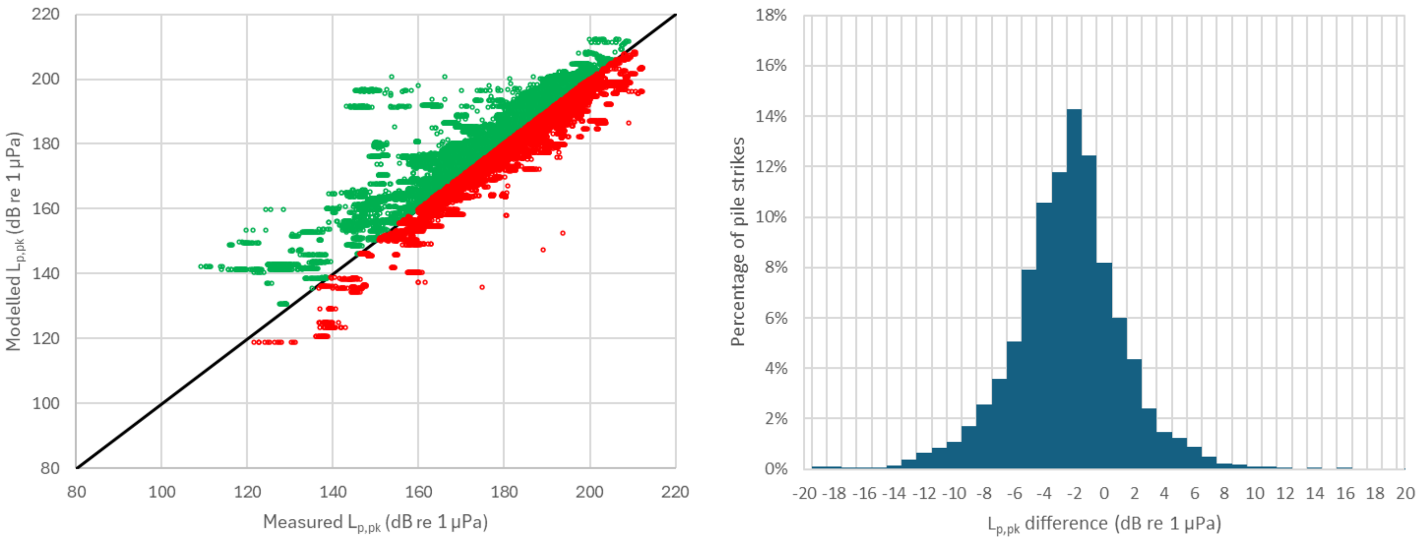

Figure 3-3: Distribution of measured impact piling data against modelled levels using INSPIRE v5.3 for unweighted $L_{p,pk}$ (R^2 = 0.79)

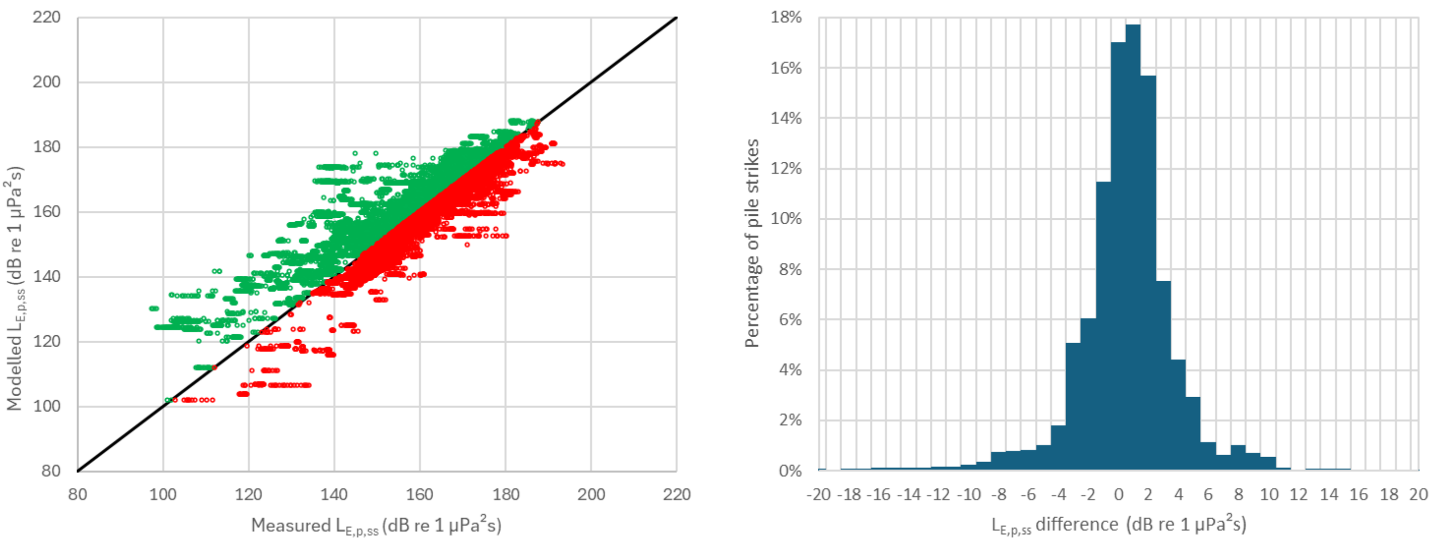

Figure 3-4: Distribution of measured impact piling data against modelled levels using INSPIRE v5.3 for unweighted $L_{E,p,ss}$ (R^2 = 0.82)

Additional validation has been undertaken using data presented by von Pein *et al.* (2022), which studied trends in noise level with changes in piling parameters using data primarily acquired in the North Sea and Baltic Sea. The data showed a strong correlation with blow energy, and a lower correlation with pile diameter, which Subacoustech agrees with, although the calculated correlation based on that data appears to overestimate its trend. Figure 3-5 and Figure 3-6 are adapted from von Pein *et al.* (2022), replicating their results and overlaying with measured data from Subacoustech (selecting samples taken at the reference distance) and results at equivalent datapoints using INSPIRE v5.3.

This shows a very good agreement with Subacoustech's data (relating to blow energy). It should be noted that the upper and lower bounds for a correlation of noise level with pile diameter, based on the von Pein *et al.*

(2022) data alone, could easily be close to horizontal; there is also no control for blow energy, which is not constant. With the inclusion of Subacoustech's data, there is little correlation at greater pile diameters, and it can be seen that the variations at a single pile diameter are largely controlled by changes in blow energy.

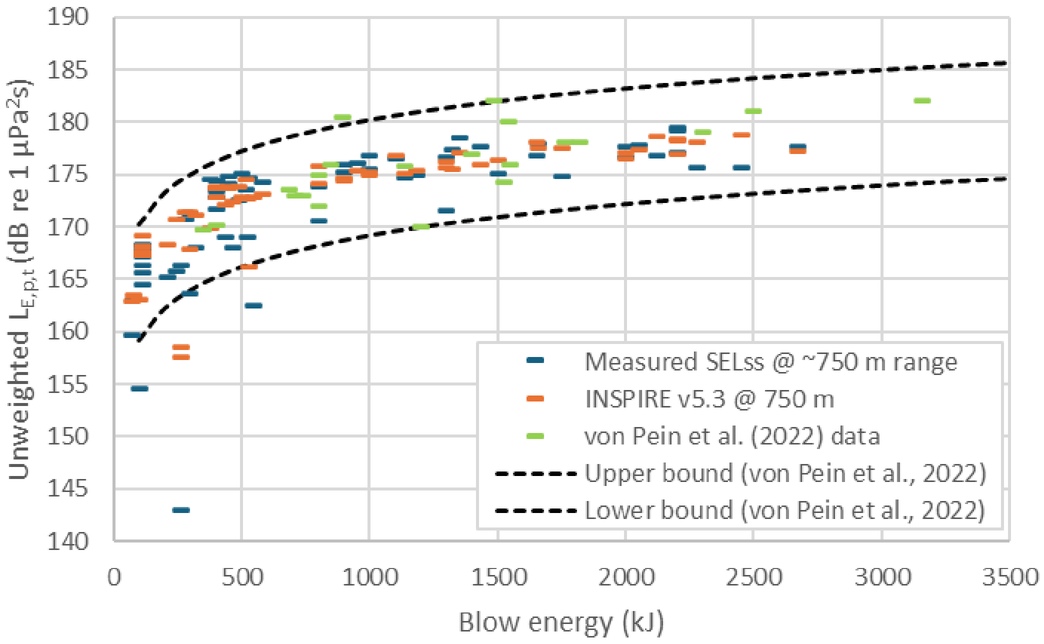

Figure 3-5: Data relating blow energy to noise level ($L_{E,p,ss}$) adapted from von Pein (2022) (green) overlaid with Subacoustech measured data (blue) and INSPIRE v5.3 predictions (orange). Upper and Lower bounds from von Pein (2022).

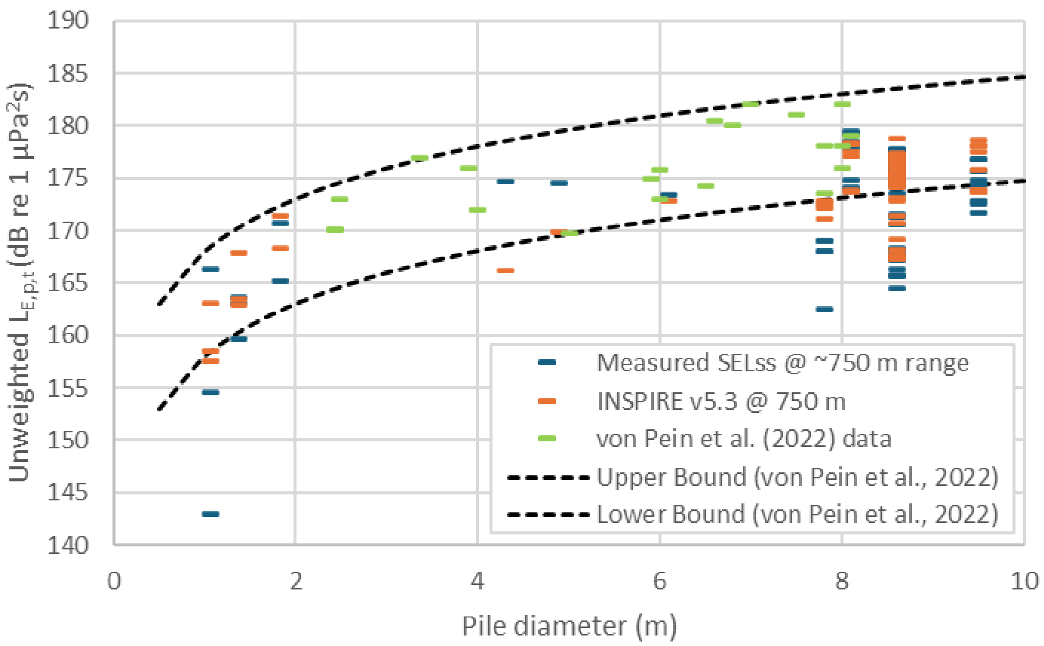

Figure 3-6: Data relating pile diameter to noise level ($L_{E,p,ss}$) adapted from von Pein (2022) (green) overlaid with Subacoustech measured data (blue) and INSPIRE v5.3 predictions (orange). Upper and Lower bounds from von Pein (2022).

3.2 Modelling parameters

3.2.1 Modelling locations

Modelling for impact piling has been undertaken at three representative locations covering the extents of the Bellrock WFDA, giving a spread of various water depths, distances to shore and bathymetry stretching into deeper water to the east of the array. These locations are summarised in Table 3-1 and illustrated in Figure 3-7.

Table 3-1: Summary of the underwater noise modelling locations used for this study.

Modelling locations	Latitude	Longitude	Water depth (Below LAT)
NW corner	56.9012° N	000.1650° W	71.4 m
SW corner	56.7802° N	000.1632° W	73.0 m
E boundary midpoint	56.8527° N	000.3245° E	82.5 m

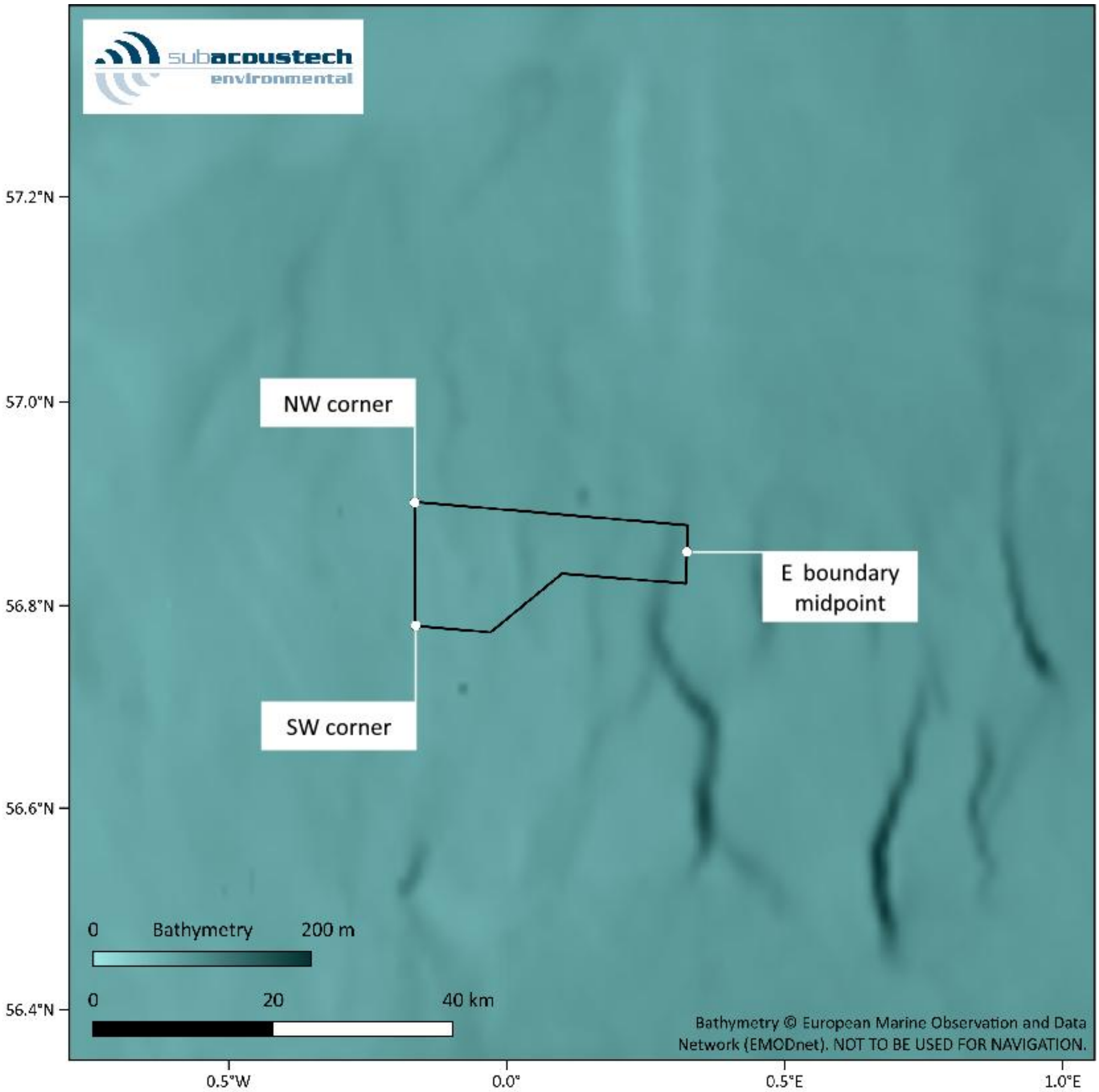

Figure 3-7: Approximate positions of the modelling locations at the Bellrock WFDA.

3.2.2 Impact piling parameters

Two substructure designs have been considered for this study:

- Wind Farm Infrastructure: Driven piles securing the mooring lines of each floating offshore unit (FOU) (combined floating substructure and WTG) to the seabed (the FOU driven pile), comprising 6.0 m diameter piles with a maximum blow energy of 3,000 kJ; and
- Offshore Transmission Infrastructure: Driven piles securing the FBSS of each OfSS to the seabed (the OfSS driven pile), comprising 4.0 m diameter piles with a maximum blow energy of 5,500 kJ.

For $L_{E,p,t}$ criteria, the soft start and ramp-up of blow energies along with the total duration of piling and strike rate must be considered. These are summarised in Table 3-2 and

Table 3-3.

Table 3-2: Summary of the soft start and ramp-up scenario used for the FOU driven pile modelling.

Percentage of hammer energy used	9% (277 kJ)	15% (443 kJ)	37% (1,112 kJ)	56% (1,670 kJ)	88% (2,649 kJ)	100% (3,000 kJ)
No. of strikes	95	42	577	307	3,746	150
Duration	15 minutes 50 seconds	4 minutes 10 seconds	19 minutes 14 seconds	10 minutes 14 seconds	124 minutes 52 seconds	5 minutes
Strike rate (bl/min)	6	10	30	30	30	30
4,917 strikes over 2 hours, 59 minutes, 20 seconds per pile 14,751 strikes over 8 hours, 58 minutes for three sequential piles 49 m length pile / 5 m pile stick-up once installed						

Table 3-3: Summary of the soft start and ramp-up scenario used for the OfSS driven pile modelling.

Percentage of hammer energy used	5% (257 kJ)	9% (480 kJ)	25% (1,348 kJ)	59% (3,253 kJ)	94% (5,156 kJ)	100% (5,500 kJ)
No. of strikes	63	58	624	282	4,930	150
Duration	10 minutes 30 seconds	9 minutes 30 seconds	20 minutes 48 seconds	9 minutes 24 seconds	164 minutes 20 seconds	5 minutes
Strike rate (bl/min)	6	6	30	30	30	30
6,107 strikes over 3 hours ,39 minutes, 32 seconds per pile 18,321 strikes over 10 hours, 58 minutes, 36 seconds for three sequential piles 85 m length pile / 5 m pile stick-up once installed						

It is expected that up to three FOU driven piles can be installed sequentially from the same piling vessel in a 24-hour period. Where multiple sequential piles are modelled, no break has been assumed between each one, as a worst-case scenario.

Considering cumulative effects, there is also the possibility that two piling vessels (one installing a FOU driven pile and one installing a OfSS driven pile) could be operational simultaneously within the Bellrock WFDA. This has been modelled with each using the parameters given here, and results are presented in section 4.2.

Due to the deep water and the length of piles used, piling will take place subsea, with the piling hammer submerged. The following pile lengths and subsequent pile stick-up lengths (i.e. the residual length of pile remaining in the water column on completion of driving) have been assumed for this modelling:

- FOU driven piles: 49 m maximum length pile, 5 m pile stick-up once installed; and
- OfSS driven piles: 85 m maximum length pile, 5 m pile stick-up once installed.

The above has been included in the modelling to account for the change in radiating area as the pile is installed.

3.2.3 Apparent source levels

Noise modelling requires knowledge of a source level, which is the theoretical noise level at one metre from the noise source. It is worth noting that the 'source level' technically does not exist in the context of many shallow water (< 100 m) noise sources (Heaney *et al*., 2020). The actual noise level one metre from the pile will be highly complex and vary up and down the water column by the pile, which is a long, extended noise source, rather than being one simple noise level. In practice, for underwater noise modelling such as this, it is effectively an 'apparent source level' that is used, essentially a value that can be used to produce correct noise levels at range (for a specific model), as required in impact assessments.

The INSPIRE model requires an apparent source level, which is estimated based on the pile diameter and the blow energy imparted on the pile by the hammer. This is adjusted depending on the water depth at the modelling location to allow for the length of the pile (and effective surface area) in contact with the water, which can affect the amount of noise that is transmitted from the pile into its surroundings. The unweighted, single strike $L_{p,pk}$ and $L_{E,p,ss}$ apparent source levels estimated for this study are provided in Table 3-4. These figures are presented in accordance with requests commonly made by regulatory authorities, although as indicated above, they are not necessarily compatible with any other model or predicted apparent source level. Due to the subsea piling taking place, only the length of the pile and not the depth of the water is a factor, and so the apparent source levels for the anchors and OfSS FBSS at each location are the same.

Table 3-4: Summary of the maximum unweighted source levels used for modelling.

Source levels	Modelling location	$L_{p,pk}$ @ 1 m	$L_{E,p,ss}$ @ 1 m
FOU driven piles (6.0 m diameter pile / 3,000 kJ maximum energy)	NW corner	245.5 dB re 1 µPa @ 1 m	217.2 dB re 1 µPa^{2}s @ 1 m
	SW corner	245.5 dB re 1 µPa @ 1 m	217.2 dB re 1 µPa^{2}s @ 1 m
	E boundary midpoint	245.5 dB re 1 µPa @ 1 m	217.2 dB re 1 µPa^{2}s @ 1 m
OfSS driven pile (4.0 m diameter pile / 5,500 kJ maximum energy)	NW corner	245.8 dB re 1 µPa @ 1 m	218.6dB re 1 µPa^{2}s @ 1 m
	SW corner	245.8 dB re 1 µPa @ 1 m	218.6 dB re 1 µPa^{2}s @ 1 m
	E boundary midpoint	245.8 dB re 1 µPa @ 1 m	218.6 dB re 1 µPa^{2}s @ 1 m

3.2.4 Predicted noise levels at 750 m from the noise source

In addition to the apparent source levels given in the previous section, it is useful to look at the potential noise levels at a range of 750 m from the noise source, which is a common feature of underwater noise studies where the primary consideration is impact piling. This has the added advantage of being comparable with other modelling or measurements (as a valid measurement can be taken), where the source level (or apparent source level) may not. A summary of the modelled unweighted levels at a range of 750 m are given in Table 3-5, considering the transect with the greatest noise transmission at each location while piling at the maximum hammer blow energy.

Table 3-5: Summary of the maximum predicted $L_{p,pk}$ and $L_{E,p,ss}$ (single strike) noise levels at a range of 750 m from the noise source when considering the maximum hammer blow energy.

Predicted levels at 750 m range	Modelling location	$L_{p,pk}$ @ 750 m	$L_{E,p,ss}$ @ 750 m
FOU driven piles (6.0 m diameter pile / 3,000 kJ maximum energy)	NW corner	202.5 dB re 1 µPa	180.0 dB re 1 µPa²s
	SW corner	202.5 dB re 1 µPa	180.0 dB re 1 µPa²s
	E boundary midpoint	202.6 dB re 1 µPa	180.1 dB re 1 µPa²s
OfSS driven pile (4.0 m diameter pile / 5,500 kJ maximum energy)	NW corner	202.8 dB re 1 µPa	181.4 dB re 1 µPa²s
	SW corner	202.8 dB re 1 µPa	181.4 dB re 1 µPa²s
	E boundary midpoint	203.0 dB re 1 µPa	181.5 dB re 1 µPa²s

3.2.5 Predicted noise levels against range

Figure 3-8 has been presented in order to show the noise transmission, which can be used as a basis to compare and validate the levels against any future noise monitoring. This plot presents the predicted unweighted $L_{p,pk}$ and $L_{E,p,ss}$ noise levels from the E boundary midpoint modelling location during the maximum blow energy of the OfSS driven pile scenario (4.0 m diameter pile, 5,500 kJ blow energy), against range, over the longest calculated transect; due north. It should not be assumed necessarily comparable to any other transect or blow energy, although it is expected to present a worst-case scenario.

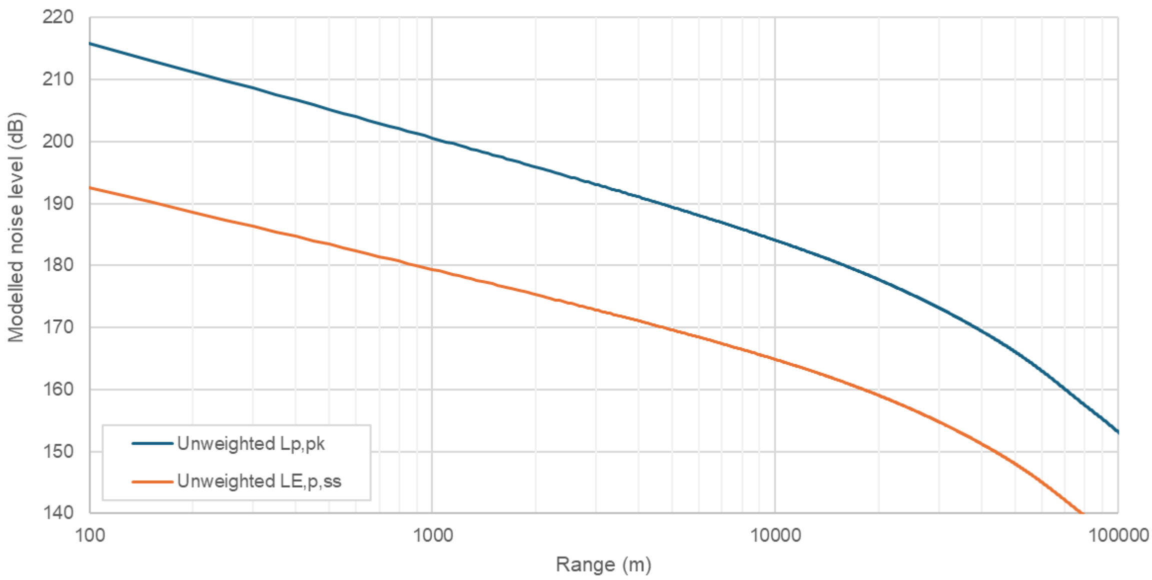

Figure 3-8: Modelled unweighted $L_{p,pk}$ and $L_{E,p,ss}$ noise levels with range for the maximum OfSS pile blow energy from the E boundary midpoint, due north.

3.2.6 Environmental conditions

With the inclusion of measured noise propagation data for similar offshore piling operations in UK waters, the INSPIRE model intrinsically accounts for various environmental conditions. This includes the differences that can occur with the temperature and salinity of the water throughout the day or year, as well as the sediment type in and around the site. Data from the British Geological Survey (BGS) show that the seabed in and around the Bellrock WFDA is generally made up of sand over a sandstone bedrock.

Digital bathymetry from the European Marine Observation and Data Network (EMODnet) has been used for this modelling. Mean tidal depth has been assumed throughout.

3.3 $L_{E,p,t}$ and fleeing receptors

Expanding on the information in section 2.3 regarding $L_{E,p,t}$ and the fleeing animal assumptions used for modelling, it is important to understand the meaning of the results presented in the following sections.

When an $L_{E,p,t}$ impact range is presented for a fleeing animal, this range can be considered a starting position (at the commencement of piling) for the fleeing receptor. For example, if a receptor began to flee in a straight line from the noise source, starting at the position (distance from a pile) denoted by a modelled PTS contour, the receptor would receive exactly the noise exposure as per the PTS onset criterion under consideration.

When considering a stationary receptor (i.e., one that stays at the same position throughout piling, with no flee response), calculating the $L_{E,p,t}$ is straightforward: all the noise levels produced and received at a single point along a transect are aggregated to calculate the $L_{E,p,t}$. If this calculated level is greater than the threshold being modelled, the model steps away from the noise source and the noise levels from that new location are aggregated to calculate a new $L_{E,p,t}$. This continues outward until the threshold is met.

For a fleeing animal, the receptor's distance from the noise source while moving away also needs to be considered. To model this, a nominal starting point close to the source is chosen and the received noise level for each noise event (e.g., pile strike) is noted; the receptor moves away from the source at a defined speed throughout the piling event. For example, if a noise (i.e., a pulse from a pile strike) occurs every six seconds, and an animal is fleeing at a rate of 1.5 m/s, it is 9 m further from the source after each noise pulse, resulting in a slightly reduced noise level each time. These values are then aggregated into an $L_{E,p,t}$ value over the entire operation. The faster an animal is fleeing, the greater the distance travelled between noise pulses. The impact range outputted by the model for this situation is the distance the receptor must be at the start of the operation to exactly meet the exposure threshold.

As an example, the graphs Figure 3-9 and Figure 3-10 show the difference in the received $L_{E,p,t}$ from a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 m/s, using the OfSS driven pile scenario (being the greater hammer energy compared to the FOU driven piles) at the E boundary midpoint modelling location for a single pile installation.

The received single strike $L_{E,p,ss}$ from the stationary receptor, as illustrated in Figure 3-9, shows the noise level gradually increasing as the blow energy increases throughout the piling operation. These step changes are also visible for the fleeing receptor, but as the receptor is further from the noise source by the time the levels increase, the total received exposure reduces, resulting in progressively lower received noise levels. As an example, for the first 10.5 minutes of piling, where the blow energy for the monopile is 257 kJ (5% of maximum energy), fleeing at a rate of 1.5 m/s, a receptor has the potential to move 945 m from the noise source. After the full installation of 3 hours, 40 minutes, the receptor has the potential to be almost 20 km from the noise source.

Figure 3-10 shows the effect that these different received levels have when calculating the $L_{E.p,t}$, clearly showing the difference in the cumulative levels between a receptor remaining still, as opposed to fleeing. To use an extreme example, starting at a range of 1 m, the first strike results in a received level of 210.3 dB re 1 $\mu Pa^2 s$. If the receptor were to remain stationary throughout the piling operation, it would receive a cumulative noise exposure of 255.9 dB re 1 $\mu Pa^2 s$, whereas when fleeing at 1.5 m/s over the same scenario, a cumulative received exposure of just 212.4 dB re 1 $\mu Pa^2 s$ would be received.

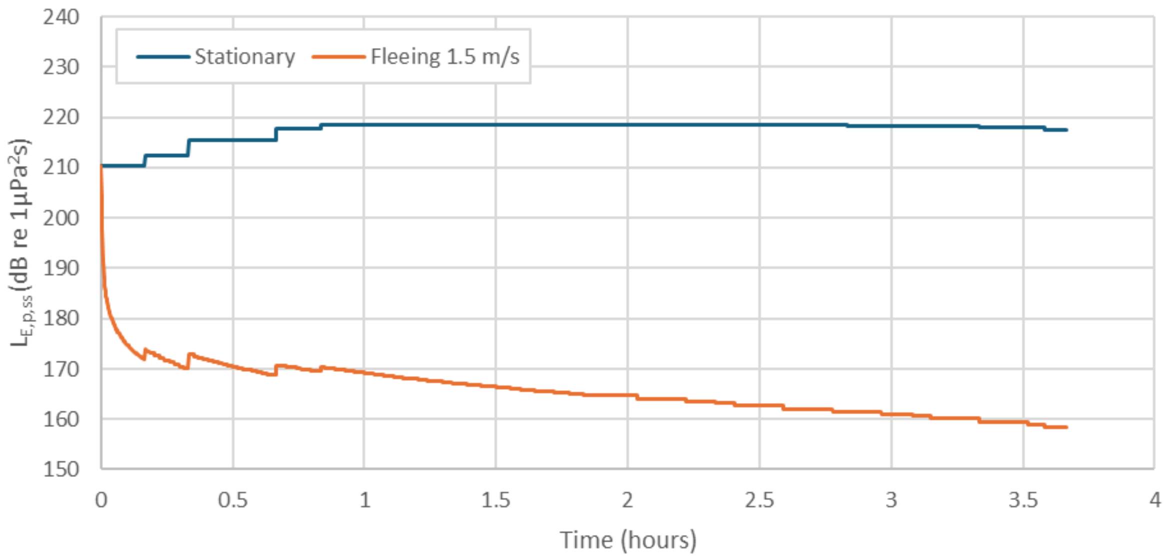

Figure 3-9 Received single strike noise levels ($L_{E,p,ss}$) for receptors during the OfSS driven pile installation at the E boundary midpoint location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source.

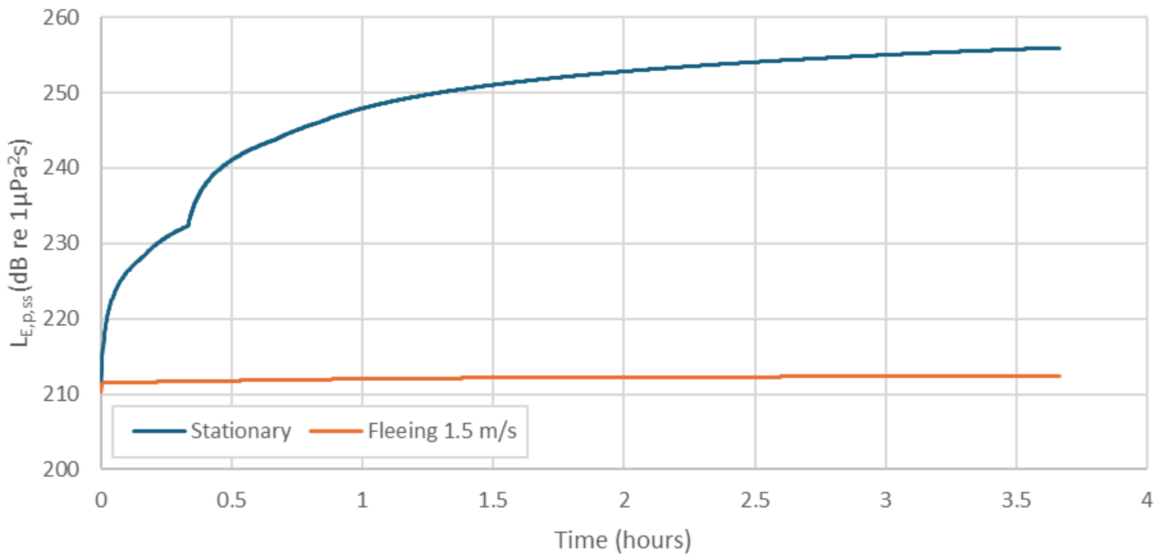

Figure 3-10 Cumulative received noise level ($L_{E,p,t}$) for receptors during the OfSS driven pile installation at the E boundary midpoint location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source.

To summarise, if the receptor were to start fleeing in a straight line from the noise source starting at a range closer than the modelled value, it would receive a noise exposure in excess of the criterion, and if the receptor were to start fleeing from a range further than the modelled value, it would receive a noise exposure below the criterion. This is illustrated in Figure 3-11.

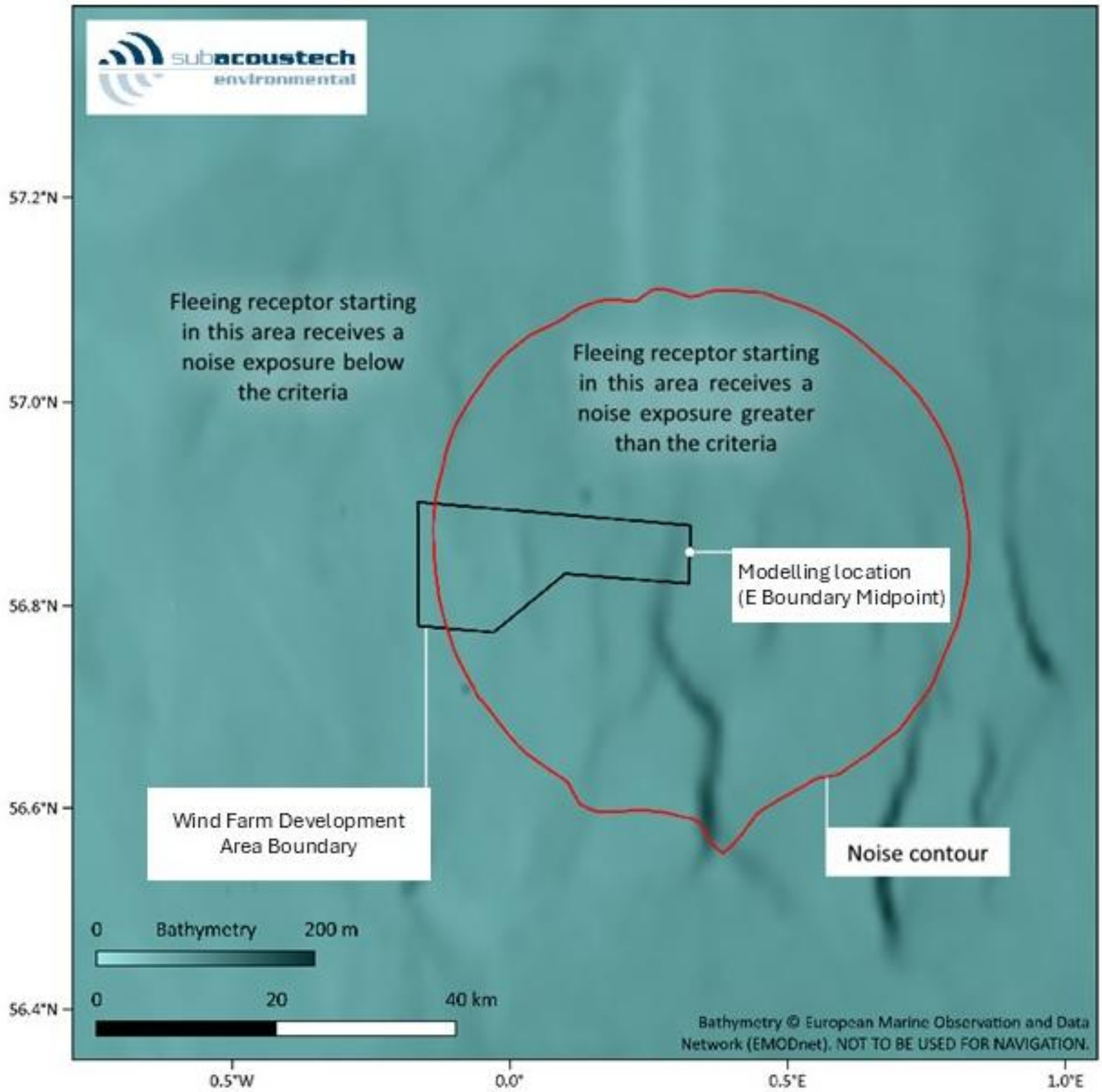

Figure 3-11 Example plot showing a fleeing animal $L_{E,p,t}$ criteria contour and the areas where the cumulative noise exposure will exceed an impact criteria.

Some modelling approaches include the effects of Acoustic Deterrent Devices (ADDs) that cause receptors to flee from the immediate area around the pile before activity commences. Subacoustech Environmental's approach does not include this, however the efficacy of using an ADD can still be inferred from the results. For example, if a receptor were to flee for 20 minutes from an ADD at a rate of 1.5 m/s, it would travel 1.8 km before piling begins. If a calculated cumulative $L_{E,p,t}$ impact range was below 1.8 km, it can be assumed that the ADD will be effective in eliminating the risk of exceedance of the threshold. The noise from an ADD is of a much lower level than impact piling, and as such its overall effect on the total $L_{E,p,t}$ exposure would be minimal.

3.3.1 The effects of input parameters on $L_{E,p,t}$ and fleeing receptors

As discussed in section 3.1, parameters such as bathymetry, hammer blow energies, piling ramp-up, strike rate and duration all have an effect on predicted noise levels. When considering $L_{E,p,t}$ and a fleeing animal model, some of these parameters can have a greater influence on the predicted noise levels than others.

Parameters like hammer blow energy can have a clear effect on the impact ranges, with higher energies resulting in high apparent source noise levels and therefore larger impact ranges. When considering cumulative noise levels, these higher levels are compounded, sometimes thousands of times, due to the number of pile strikes. With this in mind, the ramp-up from lower to higher blow energies requires careful consideration for fleeing receptors, as levels while the receptor is closer to the noise source will have a greater effect on the overall cumulative exposure level.

Linked to the effect of the ramp-up is the strike rate, as the more pile strikes that occur while the receptor is close to the noise source, the greater the exposure and the greater effect it will have to the $L_{E,p,t}$. The faster the strike rate, the shorter the distance the receptor can flee between each pile strike, which leads to a greater exposure overall.

In general, the greatest contribution to the receptors' exposure is found when it is close to the noise source. If high blow energies or a fast strike rate are implemented at or close to the start of piling activities, it will tend to make impact ranges worse.

Another factor that can cause big differences in calculated impact ranges is the bathymetry, as deeper water results in a slower attenuation of noise (i.e. levels remain higher over greater distances). However, it is not feasible to limit piling activity in or near to deep water at the Bellrock WFDA.

4 Modelling results

This section presents the modelled impact ranges from impact piling noise at the Bellrock WFDA following the parameters detailed in section 3.2, covering the Southall *et al*. (2019) marine mammal criteria (section 2.3.1), and the Popper *et al*. (2014) fish criteria (section 2.3.2). To aid navigation, Table 4-1 gives a list of the modelling tables included in section 4.1. The largest modelled ranges in this assessment are predicted for the OfSS driven pile scenario at the E boundary midpoint location due to the higher blow energies used (compared to the FOU driven piles) and the deeper water at and surrounding this location. Modelling covering simultaneous piling at multiple locations is covered in section 4.2. The modelling results for the Southall *et al*. (2019) non-impulsive criteria are presented in Appendix A.

Throughout this report, any predicted ranges smaller than 50 m and areas less than 0.01 km^2 for single strike criteria, and ranges smaller than 100 m and areas less than 0.1 km^2 for cumulative criteria, have not been presented and are given as "N/A". At ranges this close to the noise source, the modelling processes are unable to model to a sufficient level of accuracy due to complex acoustic effects present near the source.

Table 4-1 Summary of the single location impact piling modelling results presented in section 4.1.

Table	Parameters		Criteria		
Table 4-2	FOU driven piles (4.1.1)	NW corner (4.1.1.1)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4-3	FOU driven piles (4.1.1)	NW corner (4.1.1.1)	Southall *et al.* (2019)	Weighted $L_{E,p,t}$	Single pile
Table 4-4	FOU driven piles (4.1.1)	NW corner (4.1.1.1)	Southall *et al.* (2019)	Weighted $L_{E,p,t}$	Three sequential piles
Table 4-5	FOU driven piles (4.1.1)	NW corner (4.1.1.1)	Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4-6	FOU driven piles (4.1.1)	NW corner (4.1.1.1)	Popper *et al.* (2014)	Unweighted $L_{E,p,t}$	Single pile
Table 4-7	FOU driven piles (4.1.1)	NW corner (4.1.1.1)	Popper *et al.* (2014)	Unweighted $L_{E,p,t}$	Three sequential piles
Table 4-8	FOU driven piles (4.1.1)	SW corner (4.1.1.2)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4-9	FOU driven piles (4.1.1)	SW corner (4.1.1.2)	Southall *et al.* (2019)	Weighted $L_{E,p,t}$	Single pile
Table 4-10	FOU driven piles (4.1.1)	SW corner (4.1.1.2)	Southall *et al.* (2019)	Weighted $L_{E,p,t}$	Three sequential piles
Table 4-11	FOU driven piles (4.1.1)	SW corner (4.1.1.2)	Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4-12	FOU driven piles (4.1.1)	SW corner (4.1.1.2)	Popper *et al.* (2014)	Unweighted $L_{E,p,t}$	Single pile
Table 4-13	FOU driven piles (4.1.1)	SW corner (4.1.1.2)	Popper *et al.* (2014)	Unweighted $L_{E,p,t}$	Three sequential piles
Table 4-14	FOU driven piles (4.1.1)	E boundary midpoint (4.1.1.3)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4-15	FOU driven piles (4.1.1)	E boundary midpoint (4.1.1.3)	Southall *et al.* (2019)	Weighted $L_{E,p,t}$	Single pile
Table 4-16	FOU driven piles (4.1.1)	E boundary midpoint (4.1.1.3)	Southall *et al.* (2019)	Weighted $L_{E,p,t}$	Three sequential piles
Table 4-17	FOU driven piles (4.1.1)	E boundary midpoint (4.1.1.3)	Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4-18	FOU driven piles (4.1.1)	E boundary midpoint (4.1.1.3)	Popper *et al.* (2014)	Unweighted $L_{E,p,t}$	Single pile
Table 4-19	FOU driven piles (4.1.1)	E boundary midpoint (4.1.1.3)	Popper *et al.* (2014)	Unweighted $L_{E,p,t}$	Three sequential piles
Table 4-20	OfSS driven piles (4.1.2)	NW corner (4.1.2.1)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4-21	OfSS driven piles (4.1.2)	NW corner (4.1.2.1)	Southall *et al.* (2019)	Weighted $L_{E,p,t}$	Single pile
Table 4-22	OfSS driven piles (4.1.2)	NW corner (4.1.2.1)	Southall *et al.* (2019)	Weighted $L_{E,p,t}$	Three sequential piles
Table 4-23	OfSS driven piles (4.1.2)	NW corner (4.1.2.1)	Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4-24	OfSS driven piles (4.1.2)	NW corner (4.1.2.1)	Popper *et al.* (2014)	Unweighted $L_{E,p,t}$	Single pile
Table 4-25	OfSS driven piles (4.1.2)	NW corner (4.1.2.1)	Popper *et al.* (2014)	Unweighted $L_{E,p,t}$	Three sequential piles
Table 4-26	OfSS driven piles (4.1.2)	SW corner (4.1.2.2)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4-27	OfSS driven piles (4.1.2)	SW corner (4.1.2.2)	Southall *et al.* (2019)	Weighted $L_{E,p,t}$	Single pile
Table 4-28	OfSS driven piles (4.1.2)	SW corner (4.1.2.2)	Southall *et al.* (2019)	Weighted $L_{E,p,t}$	Three sequential piles
Table 4-29	OfSS driven piles (4.1.2)	SW corner (4.1.2.2)	Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4-30	OfSS driven piles (4.1.2)	SW corner (4.1.2.2)	Popper *et al.* (2014)	Unweighted $L_{E,p,t}$	Single pile
Table 4-31	OfSS driven piles (4.1.2)	SW corner (4.1.2.2)	Popper *et al.* (2014)	Unweighted $L_{E,p,t}$	Three sequential piles

Table	Parameters	Criteria		
Table 4-32	E boundary midpoint (4.1.2.3)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4-33			Weighted $L_{E,p,t}$	Single pile
Table 4-34				Three sequential piles
Table 4-35		Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4-36			Unweighted $L_{E,p,t}$	Single pile
Table 4-37				Three sequential piles

4.1 Single location modelling

Table 4-2 to

Table 4-37 present the modelling results for the single location impact piling scenarios, covering the FOU driven pile and OfSS driven pile scenarios. For these scenarios, the largest marine mammal impact ranges are predicted for the OfSS driven pile scenario, with maximum marine mammal PTS ranges predicted for LF cetaceans out to 28 km for three sequentially installed piles at the E boundary midpoint modelling location. For fish, the largest recoverable injury ranges (203 dB $L_{E,p,24h}$) are predicted out to 12 km when considering a stationary receptor, reducing to a minimal range when a fleeing receptor is assumed.

4.1.1 FOU driven piles

4.1.1.1 NW corner

Table 4-2: Summary of the unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum blow energy used during FOU driven pile modelling at the NW corner modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		FOU driven piles			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	0.01 km²	60 m	60 m	60 m
	HF (230 dB)	N/A	N/A	N/A	N/A
	VHF (202 dB)	1.8 km²	760 m	760 m	760 m
	PCW (218 dB)	0.01 km²	70 m	70 m	70 m

Table 4-3: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the FOU driven pile modelling for a single pile at the NW corner modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		FOU driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	1,000 km²	19 km	17 km	18 km
	HF (185 dB)	N/A	N/A	N/A	N/A
	VHF (155 dB)	32 km²	3.3 km	3.2 km	3.2 km
	PCW (185 dB)	N/A	N/A	N/A	N/A

Table 4-4: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the FOU driven pile modelling for three sequentially installed piles at the NW corner modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		FOU driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	1,200 km^2	21 km	19 km	20 km
	HF (185 dB)	N/A	N/A	N/A	N/A
	VHF (155 dB)	47 km^2	4.1 km	3.8 km	3.9 km
	PCW (185 dB)	N/A	N/A	N/A	N/A

Table 4-5: Summary of the unweighted $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum blow energy used during FOU driven pile modelling at the NW corner modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		FOU driven pile			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.07 km^2	150 m	140 m	150 m
	207 dB	0.40 km^2	360 m	360 m	360 m

Table 4-6: Summary of the unweighted $L_{E,p,t}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the FOU driven pile modelling for a single pile at the NW corner modelling location, assuming both fleeing and stationary animals.

Popper *et al.* (2014) Unweighted $L_{E,p,t}$		FOU driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A	N/A
	203 dB	N/A	N/A	N/A	N/A
	186 dB	1,600 km^2	24 km	22 km	23 km
Stationary (0 m/s)	219 dB	0.26 km^2	300 m	280 m	290 m
	216 dB	0.74 km^2	500 m	480 m	490 m
	210 dB	5.2 km^2	1.3 km	1.3 km	1.3 km
	207 dB	14 km^2	2.1 km	2.1 km	2.1 km
	203 dB	49 km^2	4.0 km	4.0 km	4.0 km
	186 dB	3,100 km^2	32 km	30 km	31 km

Table 4-7: Summary of the unweighted $L_{E,p,t}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the FOU driven pile modelling for three sequentially installed piles at the NW corner modelling location, assuming both fleeing and stationary animals.

Popper *et al.* (2014) Unweighted $L_{E,p,t}$		FOU driven pile (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A	N/A
	203 dB	N/A	N/A	N/A	N/A
	186 dB	2,200 km^2	28 km	25 km	27 km
Stationary (0 m/s)	219 dB	1.3 km^2	650 m	630 m	640 m
	216 dB	3.5 km^2	1.1 km	1.1 km	1.1 km
	210 dB	25 km^2	2.8 km	2.8 km	2.8 km
	207 dB	63 km^2	4.5 km	4.5 km	4.5 km
	203 dB	200 km^2	8.1 km	7.9 km	8.0 km
	186 dB	6,300 km^2	47 km	43 km	45 km

4.1.1.2 SW corner

Table 4-8: Summary of the unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum blow energy used during FOU driven pile modelling at the SW corner modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		FOU driven piles			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	0.01 km²	60 m	60 m	60 m
	HF (230 dB)	N/A	N/A	N/A	N/A
	VHF (202 dB)	1.0 km²	760 m	750 m	760 m
	PCW (218 dB)	0.01 km²	70 m	70 m	70 m

Table 4-9: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the FOU driven pile modelling for a single pile at the SW corner modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		FOU driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	990 km²	18 km	17 km	18 km
	HF (185 dB)	N/A	N/A	N/A	N/A
	VHF (155 dB)	32 km²	3.3 km	3.1 km	3.2 km
	PCW (185 dB)	N/A	N/A	N/A	N/A

Table 4-10: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the FOU driven pile modelling for three sequentially installed piles at the SW corner modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		FOU driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	1,200 km²	21 km	19 km	20 km
	HF (185 dB)	N/A	N/A	N/A	N/A
	VHF (155 dB)	46 km²	3.9 km	3.8 km	3.9 km
	PCW (185 dB)	N/A	N/A	N/A	N/A

Table 4-11: Summary of the unweighted $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum blow energy used during FOU driven pile modelling at the SW corner modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		FOU driven piles			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.07 km²	150 m	140 m	150 m
	207 dB	0.40 km²	360 m	360 m	360 m

Table 4-12: Summary of the unweighted $L_{E,p,t}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the FOU driven pile modelling for a single pile at the SW corner modelling location, assuming both fleeing and stationary animals.

Popper *et al.* (2014) Unweighted $L_{E,p,t}$		FOU driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A	N/A
	203 dB	N/A	N/A	N/A	N/A
	186 dB	1,600 km^2	23 km	22 km	22 km
Stationary (0 m/s)	219 dB	0.26 km^2	300 m	280 m	290 m
	216 dB	0.74 km^2	500 m	480 m	490 m
	210 dB	5.2 km^2	1.3 km	1.3 km	1.3 km
	207 dB	14 km^2	2.1 km	2.1 km	2.1 km
	203 dB	49 km^2	4.0 km	4.0 km	4.0 km
	186 dB	3,000 km^2	32 km	30 km	31 km

Table 4-13: Summary of the unweighted $L_{E,p,t}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the FOU driven pile modelling for three sequentially installed piles at the SW corner modelling location, assuming both fleeing and stationary animals.

Popper *et al.* (2014) Unweighted $L_{E,p,t}$		FOU driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A	N/A
	203 dB	N/A	N/A	N/A	N/A
	186 dB	2,200 km^2	28 km	25 km	26 km
Stationary (0 m/s)	219 dB	1.3 km^2	650 m	630 m	640 m
	216 dB	3.4 km^2	1.1 km	1.0 km	1.1 km
	210 dB	24 km^2	2.8 km	2.8 km	2.8 km
	207 dB	62 km^2	4.5 km	4.4 km	4.5 km
	203 dB	200 km^2	8.1 km	7.9 km	8.0 km
	186 dB	6,300 km^2	46 km	43 km	45 km

4.1.1.3 E boundary midpoint

Table 4-14: Summary of the unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum blow energy used during FOU driven pile modelling at the E boundary midpoint modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		FOU driven piles			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	0.01 km^2	60 m	60 m	60 m
	HF (230 dB)	N/A	N/A	N/A	N/A
	VHF (202 dB)	1.9 km^2	770 m	770 m	770 m
	PCW (218 dB)	0.01 km^2	70 m	70 m	70 m

Table 4-15: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the FOU driven pile modelling for a single pile at the E boundary midpoint modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		FOU driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	1,200 km^2	22 km	19 km	19 km
	HF (185 dB)	N/A	N/A	N/A	N/A
	VHF (155 dB)	37 km^2	3.7 km	3.4 km	3.5 km
	PCW (185 dB)	N/A	N/A	N/A	N/A

Table 4-16: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the FOU driven pile modelling for three sequentially installed piles at the E boundary midpoint modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		FOU driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	1,500 km^2	25 km	20 km	22 km
	HF (185 dB)	N/A	N/A	N/A	N/A
	VHF (155 dB)	37 km^2	3.7 km	3.4 km	3.5 km
	PCW (185 dB)	N/A	N/A	N/A	N/A

Table 4-17: Summary of the unweighted $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum blow energy used during FOU driven pile modelling at the E boundary midpoint modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		FOU driven piles			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.07 km^2	150 m	150 m	150 m
	207 dB	0.41 km^2	360 m	360 m	360 m

Table 4-18: Summary of the unweighted $L_{E,p,t}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the FOU driven pile modelling for a single pile at the E boundary midpoint modelling location, assuming both fleeing and stationary animals.

Popper *et al.* (2014) Unweighted $L_{E,p,t}$		FOU driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A	N/A
	203 dB	N/A	N/A	N/A	N/A
	186 dB	1,800 km^2	28 km	23 km	24 km
Stationary (0 m/s)	219 dB	0.26 km^2	300 m	280 m	290 m
	216 dB	0.74 km^2	500 m	480 m	490 m
	210 dB	5.4 km^2	1.3 km	1.3 km	1.3 km
	207 dB	14 km^2	2.2 km	2.1 km	2.1 km
	203 dB	52 km^2	4.2 km	4.1 km	4.1 km
	186 dB	3,400 km^2	36 km	32 km	33 km

Table 4-19: Summary of the unweighted $L_{E,p,t}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the FOU driven pile modelling for three sequentially installed piles at the E boundary midpoint modelling location, assuming both fleeing and stationary animals.

Popper *et al*. (2014) Unweighted $L_{E,p,t}$		FOU driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A	N/A
	203 dB	N/A	N/A	N/A	N/A
	186 dB	2,600 km^2	33 km	27 km	29 km
Stationary (0 m/s)	219 dB	1.3 km^2	650 m	630 m	640 m
	216 dB	3.5 km^2	1.1 km	1.1 km	1.1 km
	210 dB	26 km^2	2.9 km	2.9 km	2.9 km
	207 dB	66 km^2	4.7 km	4.6 km	4.6 km
	203 dB	210 km^2	8.6 km	8.1 km	8.3 km
	186 dB	7,000 km^2	52 km	45 km	47 km

4.1.2 OfSS driven piles

4.1.2.1 NW corner

Table 4-20: Summary of the unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum blow energy used during OfSS driven pile modelling at the NW corner modelling location.

Southall *et al*. (2019) Unweighted $L_{p,pk}$		OfSS driven piles			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	0.01 km^2	60 m	60 m	60 m
	HF (230 dB)	N/A	N/A	N/A	N/A
	VHF (202 dB)	2.0 km^2	800 m	790 m	800 m
	PCW (218 dB)	0.02 km^2	70 m	70 m	70 m

Table 4-21: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the OfSS driven pile modelling for a single pile at the NW corner modelling location.

Southall *et al*. (2019) Weighted $L_{E,p,t}$		OfSS driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	1,400 km^2	22 km	20 km	21 km
	HF (185 dB)	N/A	N/A	N/A	N/A
	VHF (155 dB)	55 km^2	4.4 km	4.1 km	4.2 km
	PCW (185 dB)	N/A	N/A	N/A	N/A

Table 4-22: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the OfSS driven pile modelling for three sequentially installed piles at the NW corner modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		OfSS driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	1,600 km^2	24 km	21 km	22 km
	HF (185 dB)	N/A	N/A	N/A	N/A
	VHF (155 dB)	73 km^2	5.1 km	4.7 km	4.8 km
	PCW (185 dB)	N/A	N/A	N/A	N/A

Table 4-23: Summary of the unweighted $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum blow energy used during OfSS driven pile modelling at the NW corner modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		OfSS driven piles			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.07 km^2	150 m	150 m	150 m
	207 dB	0.44 km^2	380 m	380 m	380 m

Table 4-24: Summary of the unweighted $L_{E,p,t}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the OfSS driven pile modelling for a single pile at the NW corner modelling location, assuming both fleeing and stationary animals.

Popper *et al.* (2014) Unweighted $L_{E,p,t}$		OfSS driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A	N/A
	203 dB	N/A	N/A	N/A	N/A
	186 dB	2,400 km^2	29 km	26 km	27 km
Stationary (0 m/s)	219 dB	0.53 km^2	430 m	400 m	410 m
	216 dB	1.5 km^2	700 m	680 m	690 m
	210 dB	11 km^2	1.9 km	1.9 km	1.9 km
	207 dB	29 km^2	3.1 km	3.0 km	3.0 km
	203 dB	98 km^2	5.7 km	5.6 km	5.6 km
	186 dB	4,400 km^2	39 km	36 km	37 km

Table 4-25: Summary of the unweighted $L_{E,p,t}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the OfSS driven pile modelling for three sequentially installed piles at the NW corner modelling location, assuming both fleeing and stationary animals.

Popper *et al.* (2014) Unweighted $L_{E,p,t}$		OfSS driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A	N/A

Popper *et al.* (2014) Unweighted $L_{E,p,t}$		OfSS driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
	203 dB	N/A	N/A	N/A	N/A
	186 dB	3,000 km^2	33 km	29 km	31 km
Stationary (0 m/s)	219 dB	2.8 km^2	950 m	930 m	940 m
	216 dB	7.4 km^2	1.6 km	1.5 km	1.5 km
	210 dB	50 km^2	4.0 km	4.0 km	4.0 km
	207 dB	120 km^2	6.3 km	6.2 km	6.3 km
	203 dB	360 km^2	11 km	11 km	11 km
	186 dB	8,500 km^2	55 km	49 km	52 km

4.1.2.2 SW corner

Table 4-26: Summary of the unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum blow energy used during OfSS driven pile modelling at the SW corner modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		OfSS driven piles			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	0.01 km^2	60 m	60 m	60 m
	HF (230 dB)	N/A	N/A	N/A	N/A
	VHF (202 dB)	2.0 km^2	790 m	790 m	790 m
	PCW (218 dB)	0.02 km^2	70 m	70 m	70 m

Table 4-27: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the OfSS driven pile modelling for a single pile at the SW corner modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		OfSS driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	1,300 km^2	22 km	20 km	21 km
	HF (185 dB)	N/A	N/A	N/A	N/A
	VHF (155 dB)	54 km^2	4.3 km	4.1 km	4.2 km
	PCW (185 dB)	N/A	N/A	N/A	N/A

Table 4-28: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the OfSS driven pile modelling for three sequentially installed piles at the SW corner modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		OfSS driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	1,500 km^2	23 km	21 km	22 km
	HF (185 dB)	N/A	N/A	N/A	N/A
	VHF (155 dB)	72 km^2	4.9 km	4.7 km	4.8 km
	PCW (185 dB)	N/A	N/A	N/A	N/A

Table 4-29: Summary of the unweighted $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum blow energy used during OfSS driven pile modelling at the SW corner modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		OfSS driven piles			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.07 km²	150 m	150 m	150 m
	207 dB	0.44 km²	380 m	370 m	380 m

Table 4-30: Summary of the unweighted $L_{E,p,t}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the OfSS driven pile modelling for a single pile at the SW corner modelling location, assuming both fleeing and stationary animals.

Popper *et al.* (2014) Unweighted $L_{E,p,t}$		OfSS driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A	N/A
	203 dB	N/A	N/A	N/A	N/A
	186 dB	2,300 km²	28 km	26 km	27 km
Stationary (0 m/s)	219 dB	0.53 km²	430 m	400 m	410 m
	216 dB	1.5 km²	700 m	680 m	690 m
	210 dB	11 km²	1.9 km	1.9 km	1.9 km
	207 dB	29 km²	3.1 km	3.0 km	3.0 km
	203 dB	97 km²	5.6 km	5.5 km	5.6 km
	186 dB	4,300 km²	39 km	36 km	37 km

Table 4-31: Summary of the unweighted $L_{E,p,t}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the OfSS driven pile modelling for three sequentially installed piles at the SW corner modelling location, assuming both fleeing and stationary animals.

Popper *et al.* (2014) Unweighted $L_{E,p,t}$		OfSS driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A	N/A
	203 dB	N/A	N/A	N/A	N/A
	186 dB	2,900 km²	33 km	29 km	31 km
Stationary (0 m/s)	219 dB	2.8 km²	950 m	930 m	940 m
	216 dB	7.3 km²	1.6 km	1.5 km	1.5 km
	210 dB	50 km²	4.0 km	4.0 km	4.0 km
	207 dB	120 km²	6.3 km	6.2 km	6.2 km
	203 dB	360 km²	11 km	11 km	11 km
	186 dB	8,400 km²	54 km	49 km	52 km

4.1.2.3 E boundary midpoint

Table 4-32: Summary of the unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum blow energy used during OfSS driven pile modelling at the E boundary midpoint modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		OfSS driven piles			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	0.01 km²	60 m	60 m	60 m
	HF (230 dB)	N/A	N/A	N/A	N/A
	VHF (202 dB)	2.1 km²	810 m	810 m	810 m
	PCW (218 dB)	0.02 km²	70 m	70 m	70 m

Table 4-33: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the OfSS driven pile modelling for a single pile at the E boundary midpoint modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		OfSS driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	1,600 km²	26 km	21 km	22 km
	HF (185 dB)	N/A	N/A	N/A	N/A
	VHF (155 dB)	64 km²	4.8 km	4.4 km	4.5 km
	PCW (185 dB)	N/A	N/A	N/A	N/A

Table 4-34: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the OfSS driven pile modelling for three sequentially installed piles at the E boundary midpoint modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		OfSS driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	1,800 km²	28 km	23 km	24 km
	HF (185 dB)	N/A	N/A	N/A	N/A
	VHF (155 dB)	87 km²	5.7 km	5.1 km	5.3 km
	PCW (185 dB)	N/A	N/A	N/A	N/A

Table 4-35: Summary of the unweighted $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum blow energy used during OfSS driven pile modelling at the E boundary midpoint modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		OfSS driven piles			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.07 km²	150 m	150 m	150 m
	207 dB	0.45 km²	380 m	380 m	380 m

Table 4-36: Summary of the unweighted $L_{E,p,t}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the OfSS driven pile modelling for a single pile at the E boundary midpoint modelling location, assuming both fleeing and stationary animals.

Popper *et al.* (2014) Unweighted $L_{E,p,t}$		OfSS driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A	N/A
	203 dB	N/A	N/A	N/A	N/A
	186 dB	2,700 km^2	33 km	28 km	29 km
Stationary (0 m/s)	219 dB	0.50 km^2	430 m	400 m	410 m
	216 dB	1.5 km^2	700 m	680 m	690 m
	210 dB	11 km^2	1.9 km	1.9 km	1.9 km
	207 dB	30 km^2	3.2 km	3.1 km	3.1 km
	203 dB	100 km^2	5.9 km	5.7 km	5.8 km
	186 dB	4,900 km^2	44 km	38 km	39 km

Table 4-37: Summary of the unweighted $L_{E,p,t}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the OfSS driven pile modelling for three sequentially installed piles at the E boundary midpoint modelling location, assuming both fleeing and stationary animals.

Popper *et al.* (2014) Unweighted $L_{E,p,t}$		OfSS driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A	N/A
	203 dB	N/A	N/A	N/A	N/A
	186 dB	3,500 km^2	38 km	31 km	33 km
Stationary (0 m/s)	219 dB	2.8 km^2	950 m	930 m	940 m
	216 dB	7.5 km^2	1.6 km	1.5 km	1.6 km
	210 dB	53 km^2	4.2 km	4.1 km	4.1 km
	207 dB	130 km^2	6.6 km	6.4 km	6.5 km
	203 dB	400 km^2	12 km	11 km	11 km
	186 dB	9,500 km^2	60 km	52 km	55 km

4.2 Multiple location modelling

Modelling has been carried out to investigate the potential impacts of multiple piling vessels installing piles simultaneously at separated locations. Three scenarios have been selected to represent the potential worst-case piling parameters in a 24-hour period, covering combinations of simultaneous piling of anchor and OfSS driven piles. The piling parameters used are as per the worst-case anchor and OfSS scenarios in section 3.2.2, each for three piles installed in a 24-hour period. The three scenarios considered are summarised below:

- FOU driven piles at the NW corner and the E boundary midpoint (2 concurrent locations);
- FOU driven piles at the NW corner and OfSS driven piles at the E boundary midpoint (2 concurrent locations (to support the Bellrock WFDA cumulative effects assessment); and

- FOU driven piles at the NW corner and the SW corner, and OfSS driven piles at the E boundary midpoint (3 concurrent locations) (to support the Bellrock WFDA cumulative effects assessment.

When considering $L_{E,p,t}$ modelling, piling from multiple sources can increase impact ranges significantly as, in this case, it introduces noise from up to three times the number of pile strikes to the water over a geographically separated space. Unlike the sequential piling investigated in section 4.1, fleeing receptors can be closer to a source for a higher number of the pile strikes, taking into account the other piling locations, which results in higher cumulative noise exposures and impact areas.

The modelled scenarios for this study were chosen to provide the greatest geographical spread of noise sources that would lead to the greatest impact range contours. In a modelling scenario where piles are installed close to each other, there would be an expansion of the single location contour in all directions, but by less overall than the spread seen in the modelling results.

Figure 4-1 shows the TTS contour for fish from Popper *et al*. (2014) (186 dB $L_{E,p,24h}$) for a fleeing receptor as an example. The red contours show the impact from each of the two locations modelled individually (as presented in section Figure 4-1), and the blue contour shows the increase in the predicted impacts when the same two sources are active simultaneously, resulting in a contour encircling all the red contours.

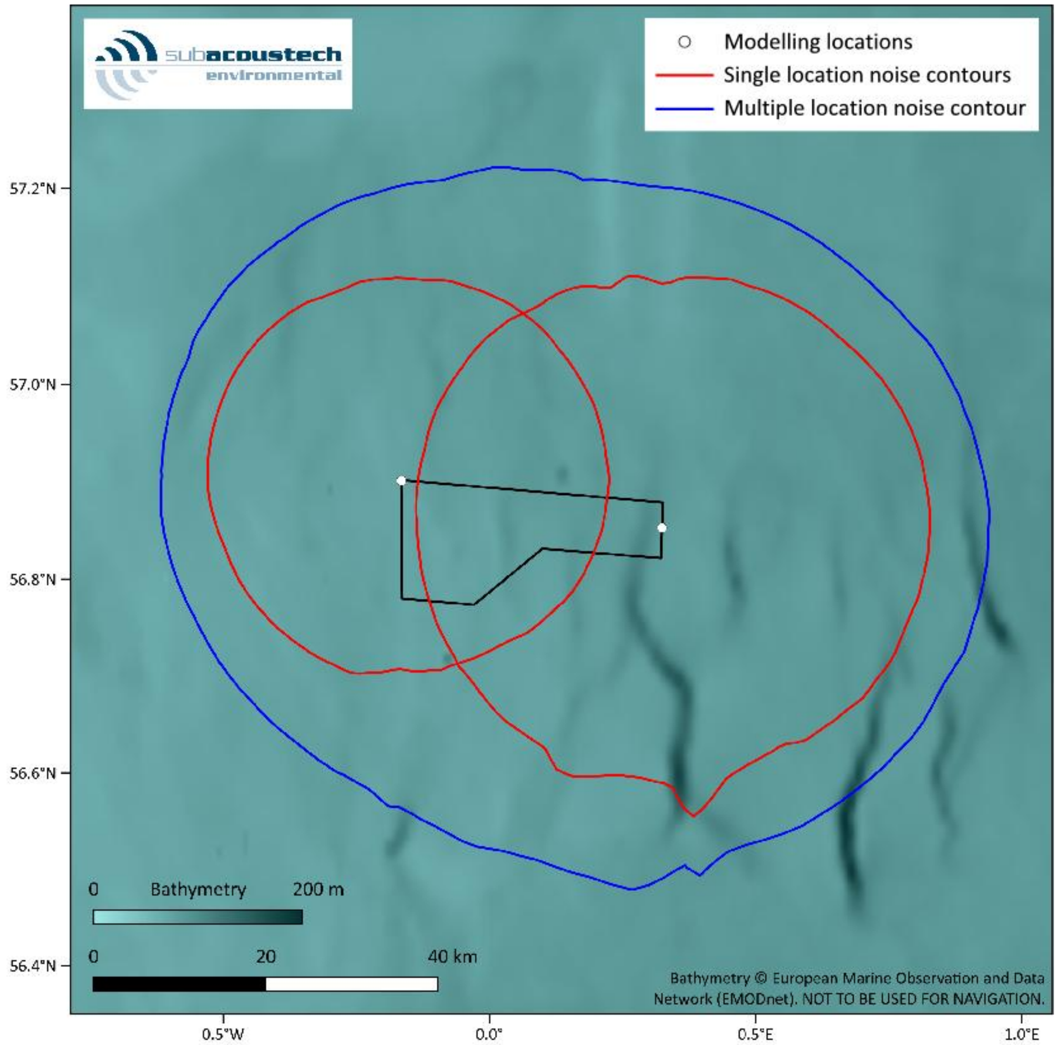

Figure 4-1 Example contour plot showing the interaction between two noise sources occurring simultaneously (TTS in fish, 186 dB $L_{E,p,24h}$, fleeing animal).

For the results in the following section only impact areas rather than linear ranges are provided as results; impact ranges have not been presented due to there being multiple starting points for receptors (a linear impact range, such as those discussed in section 3.3, requires a single start point, which is not possible with multiple pile locations). Fields denoted with “N/A” show where there is no in-combination effect when piling occurs at the two locations simultaneously. This is generally where the ranges are small enough that the distant sites do not produce an influencing additional exposure, such as with the typically small HF cetacean-weighted impact ranges.

Specific circumstances would lead to the combined range being less than the separated ranges combined: this is commonly where the modelling locations are close, or individual ranges are very large and overlap. In other cases, the combined ranges may be greater than the two separated ranges in summation: this is often where the individual ranges are large but there is little overlap between them when not in combination.

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4.2.1 FOU driven piles at the NW corner and the E boundary midpoint

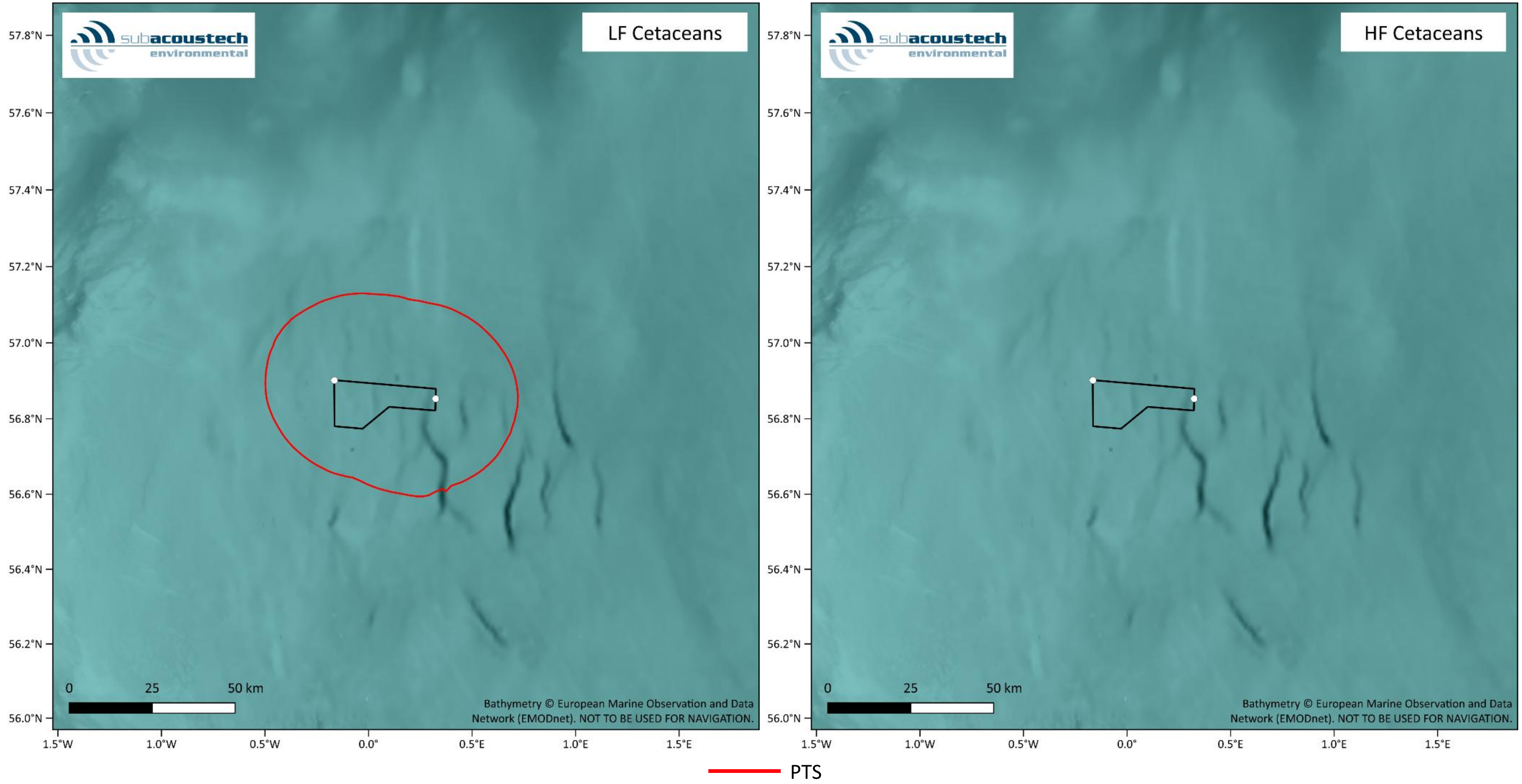

Figure 4-2 Contour plots showing the in-combination impacts of concurrent installation of FOU driven piles at the NW corner and the E boundary midpoint modelling locations for LF and HF cetaceans using the impulsive Southall et al. (2019) criteria assuming fleeing animals.

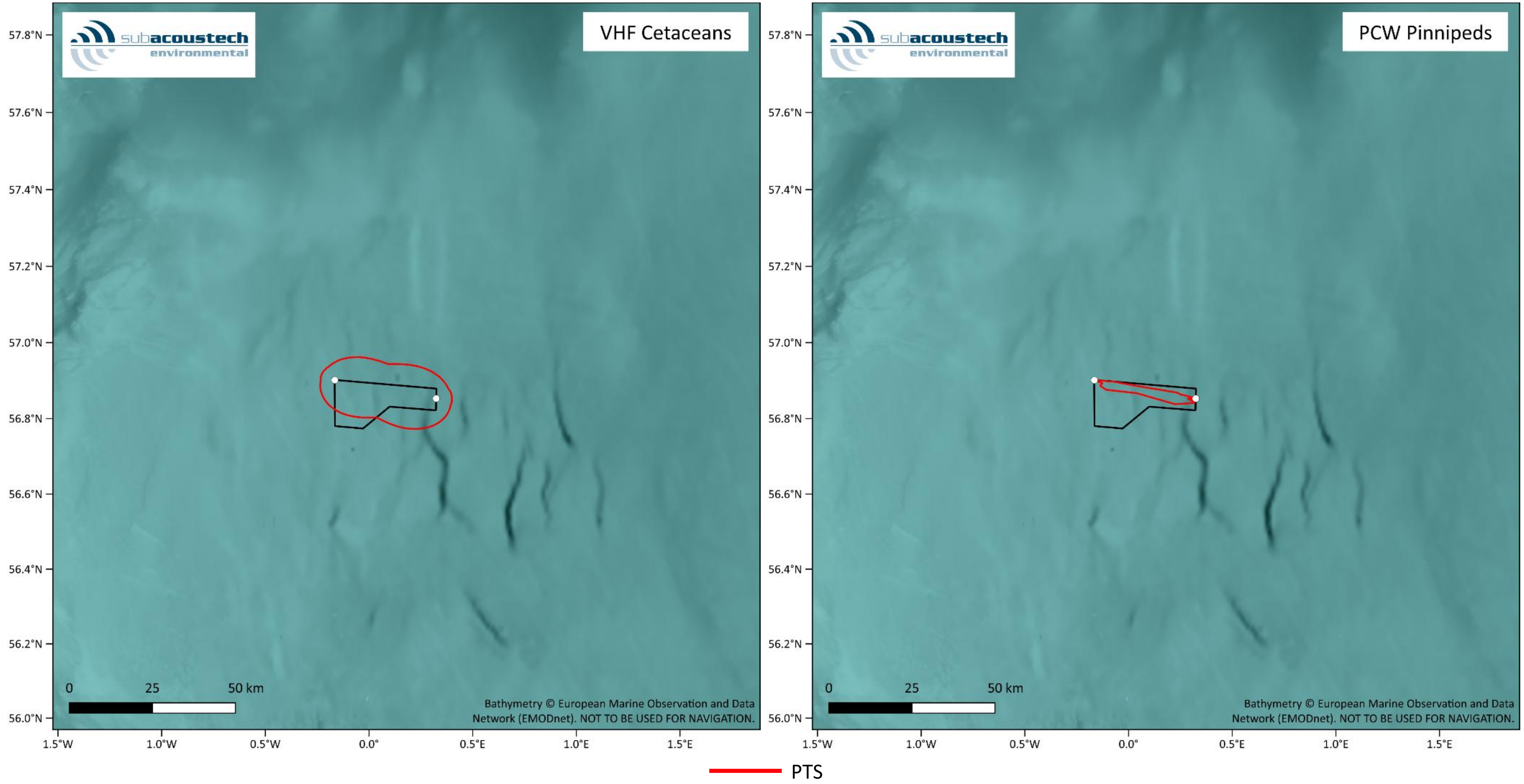

Figure 4-3 Contour plots showing the in-combination impacts of concurrent installation of FOU driven piles at the NW corner and the E boundary midpoint modelling locations for VHF cetaceans and PCW using the impulsive Southall et al. (2019) criteria assuming fleeing animals.

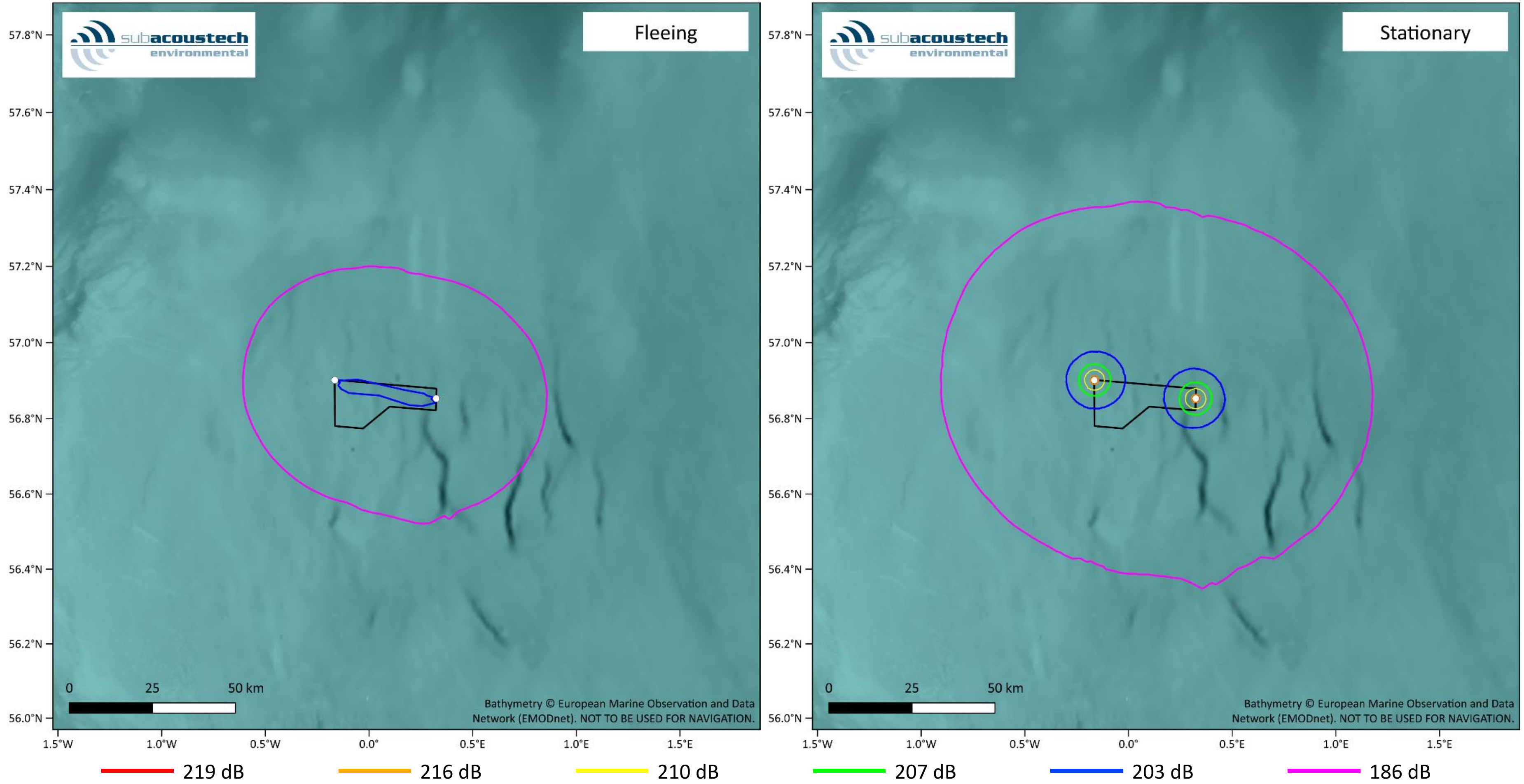

Figure 4-4 Contour plots showing the in-combination impacts of concurrent installation of FOU driven piles at the NW corner and the E boundary midpoint modelling locations for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals.

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Table 4-38: Summary of the impact areas for the installation of piles using the FOU driven pile parameters at the NW corner and the E boundary midpoint for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal.

FOU driven piles (Southall *et al.*, 2019) Weighted $L_{E,p,t}$		NW corner (FOU)	E boundary midpoint (FOU)	In-combination area
PTS (Impulsive)	LF (183 dB)	1,200 km^2	1,500 km^2	3,400 km^2
	HF (185 dB)	N/A	N/A	N/A
	VHF (155 dB)	47 km^2	37 km^2	600 km^2
	PCW (185 dB)	N/A	N/A	70 km^2

Table 4-39: Summary of the impact areas for the installation of piles using the FOU driven pile parameters at the NW corner and the E boundary midpoint for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals.

FOU driven piles (Popper *et al.*, 2014) Unweighted $L_{E,p,t}$		NW corner (FOU)	E boundary midpoint (FOU)	In-combination area
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A
	203 dB	N/A	N/A	100 km^2
	186 dB	2,200 km^2	1,800 km^2	5,200 km^2
Stationary (0 m/s)	219 dB	1.3 km^2	0.26 km^2	3.5 km^2
	216 dB	3.5 km^2	0.74 km^2	8.4 km^2
	210 dB	25 km^2	5.4 km^2	55 km^2
	207 dB	63 km^2	14 km^2	140 km^2
	203 dB	200 km^2	52 km^2	470 km^2
	186 dB	6,300 km^2	3,400 km^2	11,000 km^2

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4.2.2 FOU driven piles at the NW corner and OfSS driven piles at the E boundary midpoint

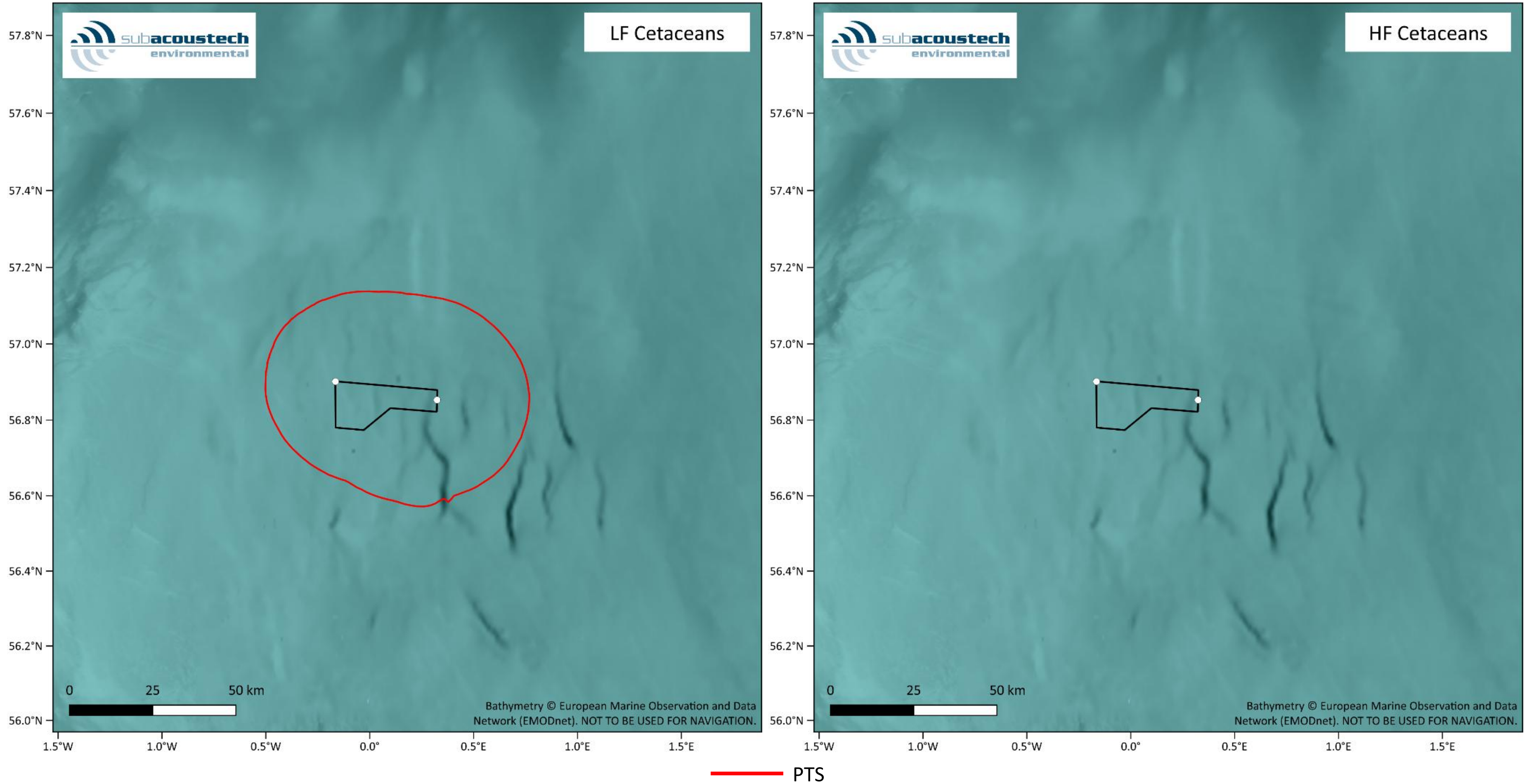

Figure 4-5 Contour plots showing the in-combination impacts of concurrent installation of FOU driven piles at the NW corner and OfSS driven piles at the E boundary midpoint modelling locations for LF and HF cetaceans using the impulsive Southall et al. (2019) criteria assuming fleeing animals.

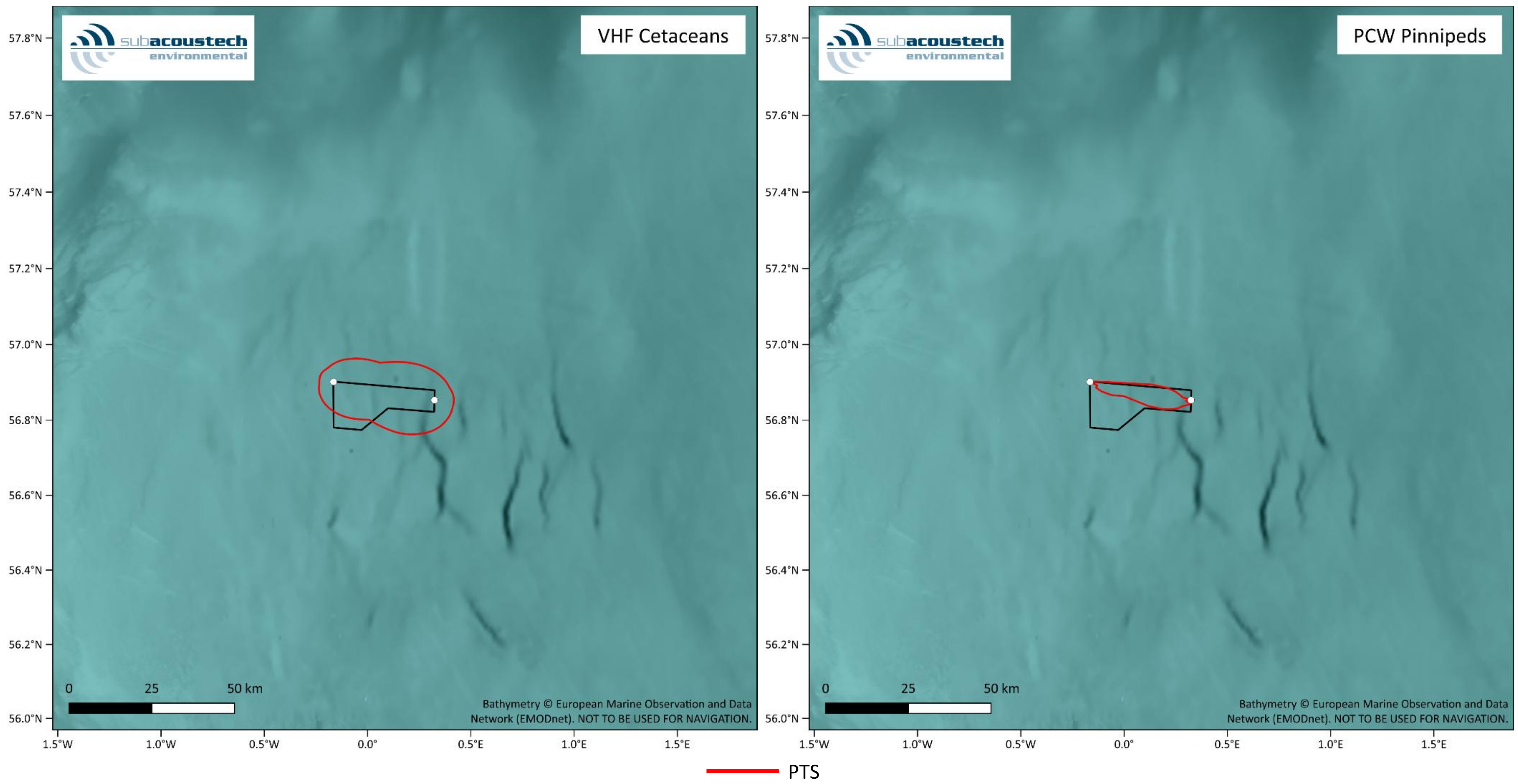

Figure 4-6 Contour plots showing the in-combination impacts of concurrent installation of FOU driven piles at the NW corner and OfSS driven piles at the E boundary midpoint modelling locations for VHF cetaceans and PCW using the impulsive Southall et al. (2019) criteria assuming fleeing animals.

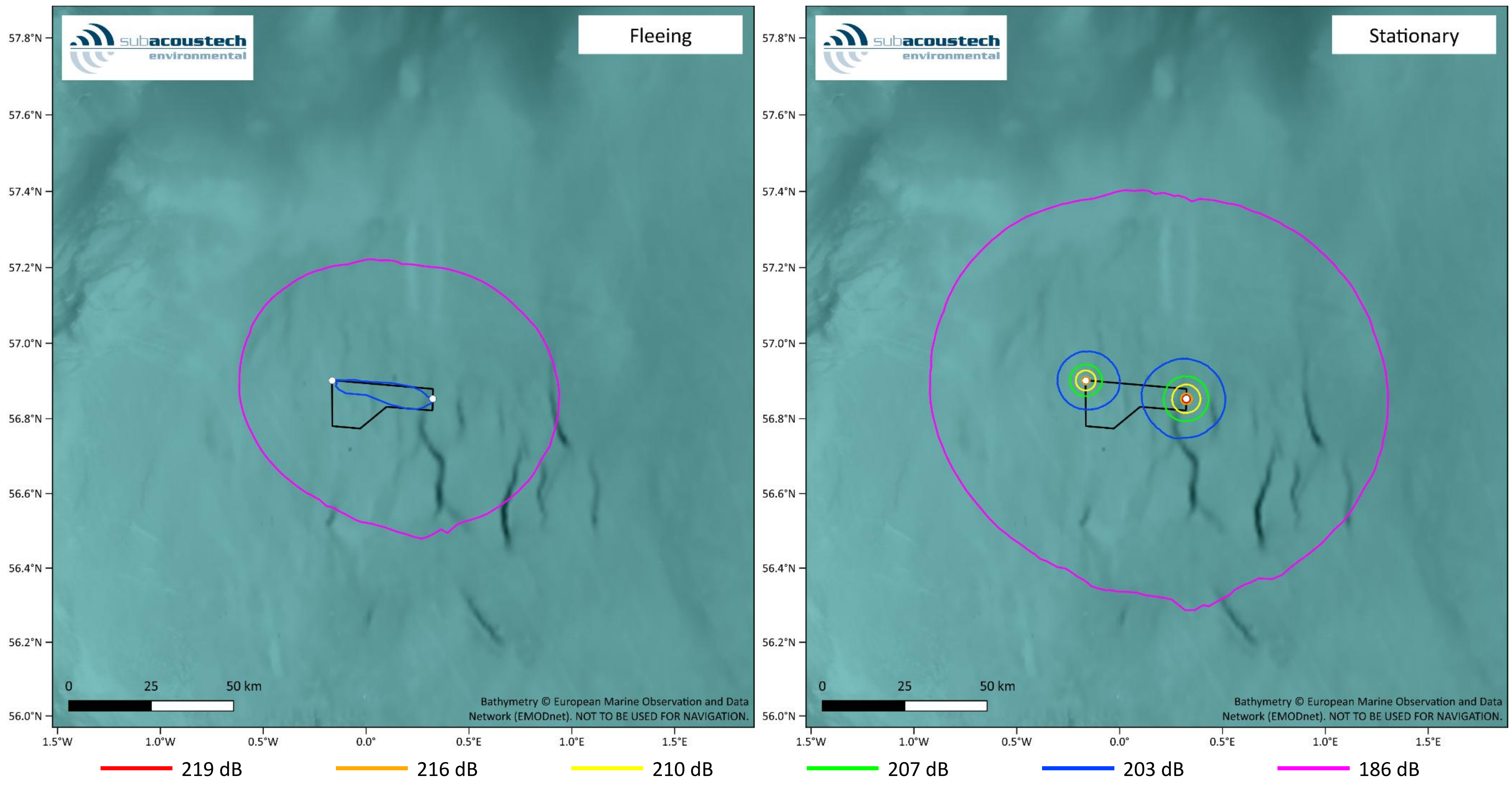

Figure 4-7 Contour plots showing the in-combination impacts of concurrent installation of FOU driven piles at the NW corner and OfSS driven piles at the E boundary midpoint modelling locations for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals.

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Table 4-40: Summary of the impact areas for the installation of piles using the FOU driven pile parameters at the NW corner and OfSS driven pile parameters at the E boundary midpoint for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal.

FOU / OfSS driven piles (Southall *et al.*, 2019) Weighted $L_{E,p,t}$		NW corner (FOU)	E boundary midpoint (OfSS FBSS)	In-combination area
PTS (Impulsive)	LF (183 dB)	1,200 km²	1,800 km²	3,800 km²
	HF (185 dB)	N/A	N/A	N/A
	VHF (155 dB)	47 km²	87 km²	670 km²
	PCW (185 dB)	N/A	N/A	130 km²

Table 4-41: Summary of the impact areas for the installation of piles using the FOU driven pile parameters at the NW corner and OfSS driven pile parameters at the E boundary midpoint for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals.

FOU / OfSS driven piles (Popper *et al.*, 2014) Unweighted $L_{E,p,t}$		NW corner (FOU)	E boundary midpoint (OfSS FBSS)	In-combination area
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A
	203 dB	N/A	N/A	140 km²
	186 dB	2,200 km²	3,500 km²	5,900 km²
Stationary (0 m/s)	219 dB	1.3 km²	2.8 km²	5.3 km²
	216 dB	3.5 km²	7.5 km²	13 km²
	210 dB	25 km²	53 km²	83 km²
	207 dB	63 km²	130 km²	210 km²
	203 dB	200 km²	400 km²	700 km²
	186 dB	6,300 km²	9,500 km²	13,000 km²

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4.2.3 FOU driven piles at the NW corner and the SW corner, and OfSS driven piles at the E boundary midpoint

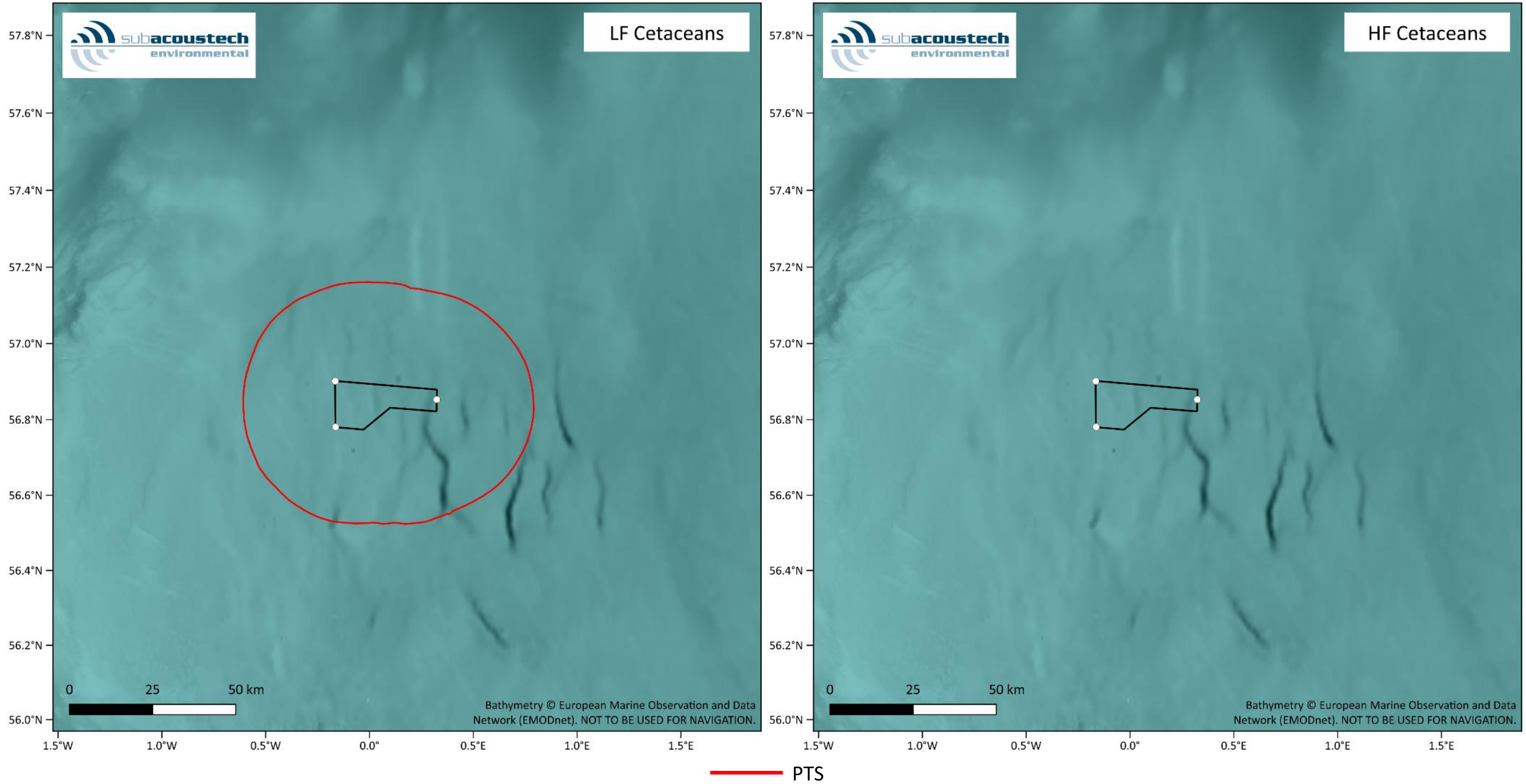

Figure 4-8 Contour plots showing the in-combination impacts of concurrent installation of FOU driven piles at the NW corner and SW corner, and OfSS driven piles at the E boundary midpoint modelling locations for LF and HF cetaceans using the impulsive Southall et al. (2019) criteria assuming fleeing animals.

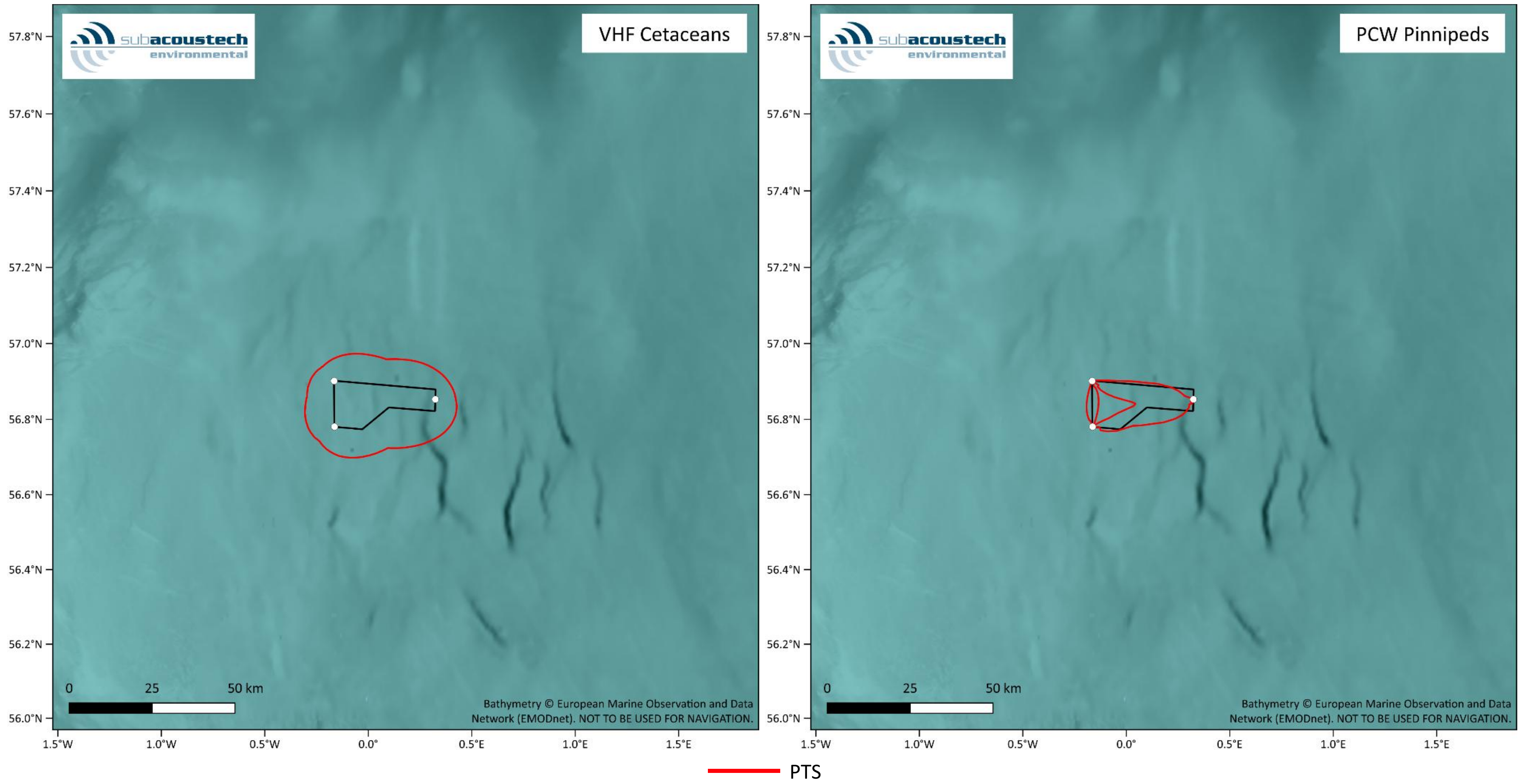

Figure 4-9 Contour plots showing the in-combination impacts of concurrent installation of FOU driven piles at the NW corner and SW corner, and OfSS driven piles at the E boundary midpoint modelling locations for VHF cetaceans and PCW using the impulsive Southall et al. (2019) criteria assuming fleeing animals.

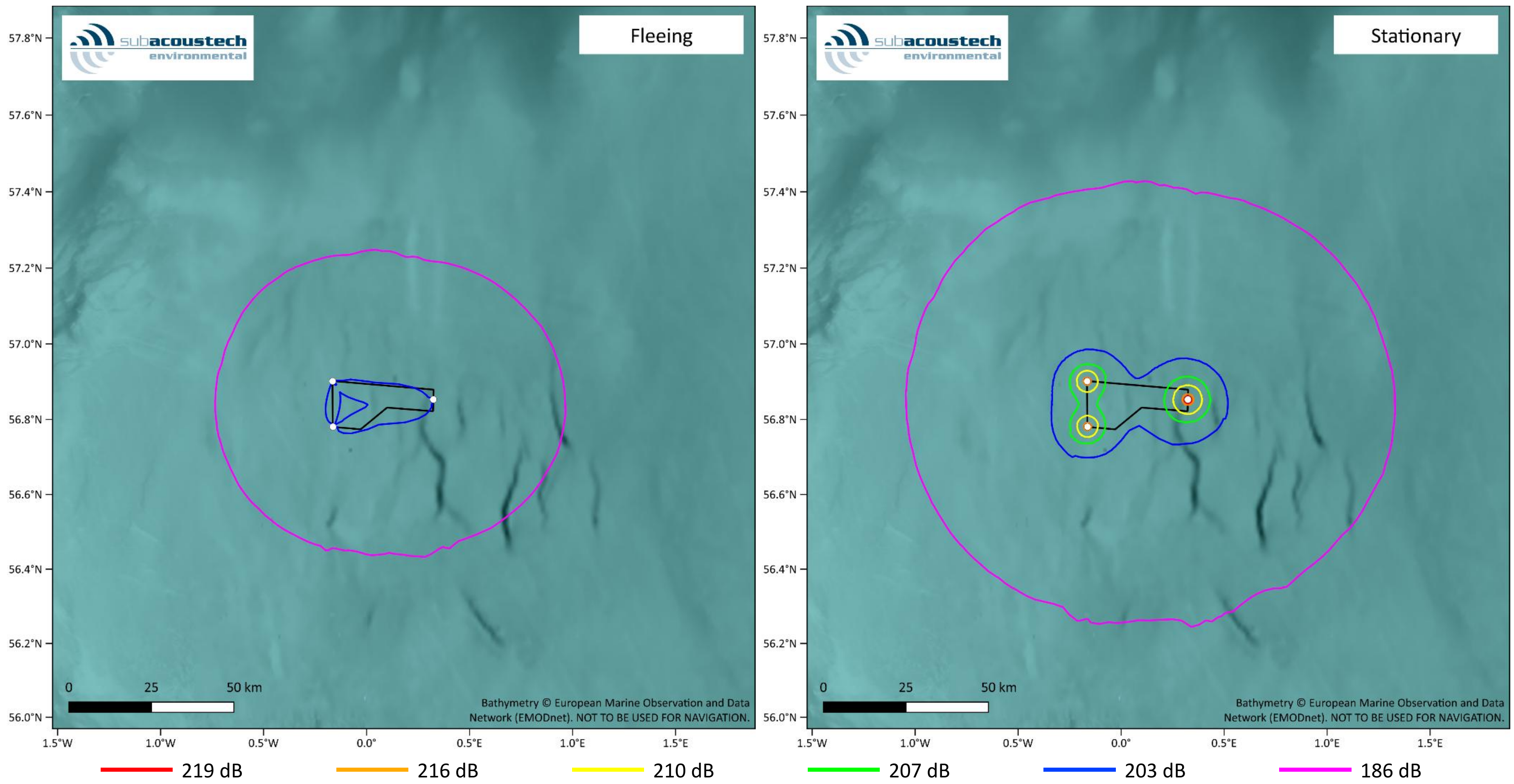

Figure 4-10 Contour plots showing the in-combination impacts of concurrent installation of FOU driven piles at the NW corner and SW corner, and OfSS driven piles at the E boundary midpoint modelling locations for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals.

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Table 4-42: Summary of the impact areas for the installation of piles using the FOU driven pile parameters at the NW corner and SW corner, and OfSS driven pile parameters at the E boundary midpoint for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal.

FOU / OfSS driven piles (Southall *et al.*, 2019) Weighted $L_{E,p,t}$		NW corner (FOU)	SW corner (FOU)	E boundary midpoint (OfSS FBSS)	In-combination area
PTS (Impulsive)	LF (183 dB)	1,200 km^2	990 km^2	1,800 km^2	4,900 km^2
	HF (185 dB)	N/A	N/A	N/A	N/A
	VHF (155 dB)	47 km^2	32 km^2	87 km^2	1,100 km^2
	PCW (185 dB)	N/A	N/A	N/A	300 km^2

Table 4-43: Summary of the impact areas for the installation of piles using the FOU driven pile parameters at the NW corner and SW corner, and OfSS driven pile parameters at the E boundary midpoint for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals.

FOU / OfSS driven piles (Popper *et al.*, 2014) Unweighted $L_{E,p,t}$		NW corner (FOU)	SW corner (FOU)	E boundary midpoint (OfSS FBSS)	In-combination area
Fleeing (1.5 m/s)	219 dB	N/A	N/A	N/A	N/A
	216 dB	N/A	N/A	N/A	N/A
	210 dB	N/A	N/A	N/A	N/A
	207 dB	N/A	N/A	N/A	N/A
	203 dB	N/A	N/A	N/A	330
	186 dB	2,200 km^2	1,600 km^2	3,500 km^2	7,400 km^2
Stationary (0 m/s)	219 dB	1.3 km^2	0.26 km^2	2.8 km^2	7.1 km^2
	216 dB	3.5 km^2	0.74 km^2	7.5 km^2	17 km^2
	210 dB	25 km^2	5.2 km^2	53 km^2	120 km^2
	207 dB	63 km^2	14 km^2	130 km^2	340 km^2
	203 dB	200 km^2	49 km^2	400 km^2	1,200 km^2
	186 dB	6,300 km^2	3,000 km^2	9,500 km^2	15,000 km^2

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5 Other noise sources

Although impact piling is expected to be the greatest overall noise source during offshore construction and development (Bailey *et al.*, 2014), several other anthropogenic underwater noise sources may be present. Each of these has been considered, and relevant biological noise criteria presented, in this section.

Table 5-1 provides a summary of the various noise producing sources, aside from impact piling, that are expected to be present during the construction, operation and maintenance, and decommissioning of the Bellrock Wind Farm Infrastructure.

Table 5-1: Summary of the possible noise making activities within the Bellrock WFDA other than impact piling.

Activity	Description
Cable laying	Noise from the cable laying vessel and other associated noise during the inter-array cable installation (Wind Farm Infrastructure) and interconnector and offshore export cable installation (Offshore Transmission Infrastructure).
Drilling (for Drive-Drill-Drive)	In the event of a pile refusal (i.e. the pile becoming stuck due to challenging or unforeseen conditions) drilling may be used in a drive-drill-drive (DDD) process to progress the pile before being driven again until the final penetration depth is reached.
Rock placement	May be required for installation of inter-array cables (Wind Farm Infrastructure) and interconnector and offshore export cables (Offshore Transmission Infrastructure) (at cable crossings or for cable protection); and scour protection around FBSSs or FSS anchors.
Trenching	Plough and other trenching techniques may be required during installation of inter-array cables (Wind Farm Infrastructure) and interconnector and offshore export cables (Offshore Transmission Infrastructure).
Vessel noise	Vessels for piled anchor and FBSS installation. Other large and medium sized vessels to carry out other construction tasks including anchor handling. Jack up vessels and other small vessels for crew transport and operations and maintenance of the Wind Farm Infrastructure and Offshore Transmission Infrastructure located within the Bellrock WFDA.
Operational WTGs	Noise transmitted through the water from operational WTGs.
Mooring lines	Noise associated with the strain and friction in the mooring system.
UXO clearance	There is a possibility that unexploded ordnance (UXO) may exist within the Bellrock WFDA, which would need to be cleared before construction can begin.

Cable laying, drilling, rock placement, trenching and vessel noise are covered in section 5.1, with operational WTG noise, mooring line noise and UXO clearance assessed in sections 5.2 and 5.3 respectively.

The NPL Good Practice Guide 133 for underwater noise measurements (Robinson *et al.*, 2014) indicates that under certain circumstances, a simple modelling approach may be considered appropriate. Such an approach has been used for these noise sources, which are variously either quiet compared to impact piling (e.g. drilling), or where detailed modelling would imply unjustified accuracy (e.g. for small explosive charges such as those used in low-order detonations). The high-level overview of modelling that has been presented here is considered sufficient and there would be little benefit in using a more detailed modelling approach at this stage due to their relatively low impacts. The limitations of this approach are noted, including the lack of frequency and bathymetric dependence.

5.1 Noise making activities

For the purposes of identifying the greatest effects from noise, approximate subsea noise levels have been predicted using a simple modelling approach based on measurement data from Subacoustech Environmental's own underwater noise measurement database scaled to relevant parameters for the Bellrock WFDA and to the specific noise sources to be used. The calculation of underwater noise transmission loss for these non-impulsive sources is based on empirical analysis of the noise measurements taken along transects around these sources by Subacoustech Environmental. The predictions use the following principle fitted to the measured data, where R is the range from the source, N is the transmission loss coefficient, and α is the absorption loss coefficient:

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

Predicted source levels and propagation calculations for the construction activities are presented in Table 5-2 along with a summary of the number of datasets used in each case. As previously, all criteria use the same assumptions as presented in section 2.3, and ranges smaller than 50 m (single pulse) and 100 m (cumulative) have not been presented. It should be reiterated that this modelling approach does not take bathymetry or any other environmental conditions into account, and as such can be applied to any location at, or surrounding, Bellrock.

Table 5-2: Summary of the estimated unweighted source levels and transmission losses for the different considered noise sources.

Source	Estimated L_p source level	Transmission loss parameters	Comments
Cable laying	171 dB re 1 µPa @ 1 m	N: 13, α: 0 (no absorption)	Based on 11 datasets from a pipe laying vessel measuring 300 m in length; this is considered a worst-case noise source for cable laying operations.
Drilling	169 dB re 1 µPa @ 1 m	N: 16, α: 0.0006	Based on six datasets from various drilling operations covering ground investigations and pile installation. A drill with a 200 kW power output has been assumed for modelling.
Rock placement	166 dB re 1 µP @ 1 m	N: 9, α: 0.0025	Based on four datasets from rock placement vessel *Rollingstone*.
Trenching	172 dB re 1 µPa @ 1 m	N: 13, α: 0.0004	Based on three datasets of measurements from trenching vessels more than 100 m in length.
Vessel noise (large)	168 dB re 1 µPa @ 1 m	N: 12, α: 0.0021	Based on five datasets of large vessels including container ships, floating production storage and offloading vessels and other vessels more than 100 m in length. Vessel speed assumed as 10 knots.
Vessel noise (medium)	161 dB re 1 µPa @ 1 m	N: 12, α: 0.0021	Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 10 knots.

All values of N and α are empirically derived and will be linked to the size and shape of the machinery, the transect on which the measurements were taken and the local environment at the time.

For $L_{E,p,t}$ calculations in this section, the duration the noise is present also needs to be considered, with all sources assumed to operate constantly for 24 hours to give a worst-case assessment of the noise. Due to the low noise level of the sources, both fleeing and stationary animals have been included for all $L_{E,p,t}$ criteria.

To account for the weightings required for modelling using the Southall *et al*. (2019) criteria (see section 2.3.1), reductions have been applied to the source levels of the various noise sources. Figure 5-1 shows the representative noise measurements used to calculate these reductions, which have been adjusted based on the source levels given in Table 5-2. Details of the reductions in source level for each of the marine mammal weightings are given in Table 5-3.

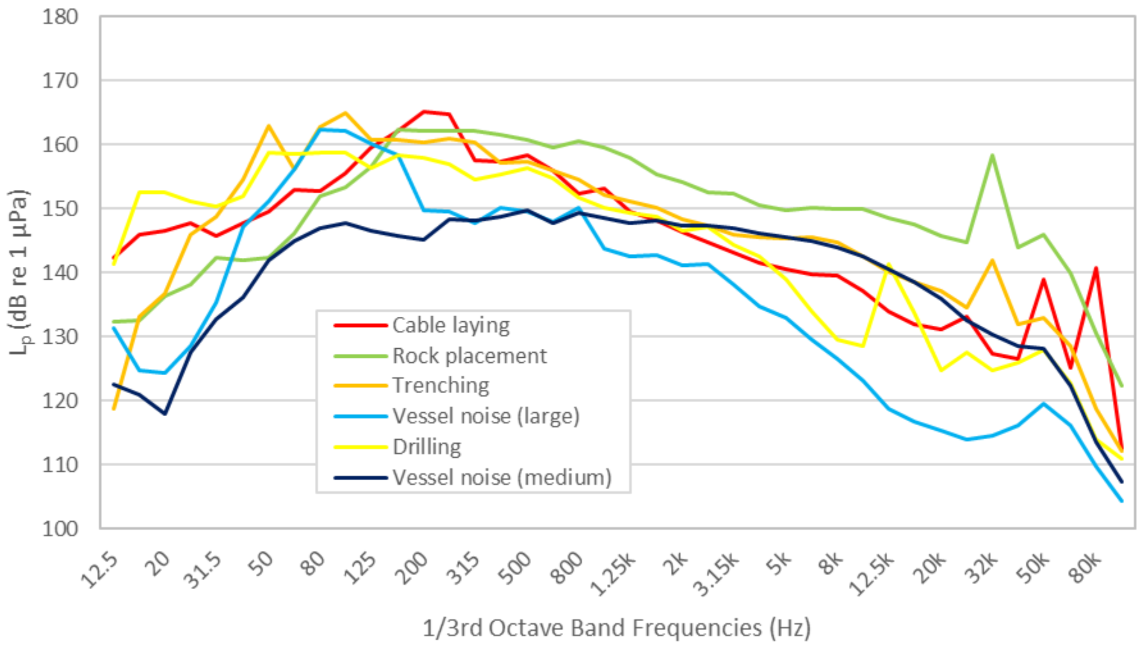

Figure 5-1: Summary of the 1/3rd octave frequency bands to which Southall et al. (2019) weightings have been applied.

Table 5-3: Reductions in source level for the different construction noise sources considered when the Southall et al. (2019) weightings are applied.

Source	Reduction in L_p source level from the unweighted level (Southall *et al.*, 2019)			
	LF	HF	VHF	PCW
Cable laying	3.6 dB re 1 µPa	22.9 dB re 1 µPa	23.9 dB re 1 µPa	13.2 dB re 1 µPa
Drilling	4.0 dB re 1 µPa	25.8 dB re 1 µPa	48.7 dB re 1 µPa	13.2 dB re 1 µPa
Rock placement	1.6 dB re 1 µPa	11.9 dB re 1 µPa	12.5 dB re 1 µPa	8.2 dB re 1 µPa
Trenching	4.1 dB re 1 µPa	23.0 dB re 1 µPa	25.0 dB re 1 µPa	13.7 dB re 1 µPa
Vessel noise	5.5 dB re 1 µPa	34.4 dB re 1 µPa	38.6 dB re 1 µPa	17.4 dB re 1 µPa

The modelled impact ranges for these sources are presented in Table 5-4 to Table 5-6. Given the low modelled impact ranges, almost all marine mammals would have to be at very close range at the start of the activity to acquire the necessary exposure to induce PTS as per Southall *et al*. (2019), with the possible exception of cable laying and rock placement for stationary receptors. The exposure calculations assume the same receptor fleeing speeds as the impact piling modelling in section 4. These ranges only represent a range where the receptor reaches the 'onset' stage, which is the minimum exposure that could potentially lead to the start of an effect and may only be marginal. In most hearing groups the noise levels are low enough that this only represents a minimal risk.

For fish, there is a minimal risk of any injury or TTS with reference to the L_p guidance for continuous noise sources in Popper *et al*. (2014).

All sources presented here produce much quieter levels than the results presented for impact piling in section 4.

Table 5-4: Summary of the impact ranges for the different noise sources related to the construction of Wind Farm Infrastructure and Offshore Transmission Infrastructure located within the Bellrock WFDA using the non-impulsive criteria from Southall et al. (2019) for marine mammals assuming a fleeing receptor.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$ (Fleeing)	PTS (Non-impulsive)			
	LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)
Cable laying	N/A	N/A	N/A	N/A
Drilling	N/A	N/A	N/A	N/A
Rock placement	N/A	N/A	N/A	N/A
Trenching	N/A	N/A	N/A	N/A
Vessel noise (large)	N/A	N/A	N/A	N/A
Vessel noise (medium)	N/A	N/A	N/A	N/A

Table 5-5: Summary of the impact ranges for the different noise sources related to the construction of Wind Farm Infrastructure and Offshore Transmission Infrastructure located within the Bellrock WFDA using the non-impulsive criteria from Southall et al. (2019) for marine mammals assuming a stationary receptor.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$ (Stationary)	PTS (Non-impulsive)			
	LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)
Cable laying	N/A	N/A	N/A	N/A
Drilling	N/A	N/A	N/A	N/A
Rock placement	N/A	N/A	1.1 km	N/A
Trenching	N/A	N/A	N/A	N/A
Vessel noise (large)	N/A	N/A	N/A	N/A
Vessel noise (medium)	N/A	N/A	N/A	N/A

It should be noted that ranges for stationary animals are theoretical only and are expected to be over-conservative as the assumption is for the receptor to remain stationary in relation to the noise source for the entire assessment period (24 hours), when in a number of these instances, the noise source moves.

Table 5-6: Summary of the impact ranges for the different noise sources related to the construction of Wind Farm Infrastructure and Offshore Transmission Infrastructure located within the Bellrock WFDA using the continuous noise criteria from Popper et al. (2014) for fish (swim bladder involved in hearing).

Popper *et al.* (2014) L_p	Recoverable injury 170 dB re 1 µPa (48 hours)	TTS 158 dB re 1 µPa (12 hours)
Cable laying	N/A	N/A
Drilling	N/A	N/A
Rock placement	N/A	N/A
Trenching	N/A	N/A
Vessel noise (large)	N/A	N/A
Vessel noise (medium)	N/A	N/A

5.2 Operational WTG noise

The noise source for most operational WTGs is the radiating area of its FSS in the water. For a fixed bottom monopile substructures, this is the surface area of the cylindrical pile in the water column. The complexities of the acoustics in large structures such as these make it difficult to predict their effect on the noise output (Tougaard *et al*., 2020). The radiating area source for a floating WTG is limited to the weighted and buoyant section of the FSS that rests beneath the sea surface, a significantly smaller area than for a fixed WTG substructure. With a much smaller submerged radiating area, the noise is expected to be equal to or lower than fixed bottom turbines, with a reasonable assumption of equivalent sound generation within the WTG and transmission through the tower (Risch *et al*., 2023).

Little empirical data exists for the operational noise produced by floating WTGs. For example, Bellmann *et al.* (2023), Tougaard *et al*. (2020) and the study by Stöber and Thomsen (2021) did not consider any floating designs. Measurements taken by Jasco Applied Science (Martin *et al*., 2011) of the Hywind demonstrator, west of Stavanger, Norway, showed broadband noise levels of the order of 120 dB re 1 µPa (L_p) over an approximate 10-week period in June to August 2011, at a range of 150 m from the WTG. However, much of this was found to be influenced by ambient noise from existing shipping sources and none of the components of noise relating to WTG operation appeared to exceed 110 dB re 1 µPa (L_p) at the monitoring location. It is worth noting that this is dominated by noise at low frequency (< 100 Hz), which is below the auditory sensitivity for most marine mammals, and they differ minimally from background noise over the long term at all measured frequencies up to 16 kHz (1/3rd octave band). It is therefore likely that even if the noise measurement at the position near the WTG was influenced by operational WTG noise, ambient noise levels will typically reach this level naturally; the WTG in this study was 2.3 MW (82.4 m rotor diameter). While some other monitoring data for floating wind farm projects do exist (Molinero, 2020; Risch *et al*., 2023), comparing potential noise levels to worst-case examples such as those from Hywind are considered best practice for this study as they are the largest available.

Using the Tougaard *et al*. (2020) calculator for FBSSs, uplifts of between 11 dB and 15 dB would need to be applied to the data from a 2.3 MW floating WTG to the sizes proposed for the Bellrock WFDA. This would suggest levels of between 131 and 135 dB re 1 µPa (L_p) at 150 m for the WTGs.

Using this extrapolated level and the Popper *et al*. (2014) criteria for continuous noise, the TTS threshold of 158 dB (L_p) would require an individual to be closer than 20 m for 12 hours continuously. For a source near the surface in water depths of the order of 80 to 100 m, this would be very low risk. As studies have shown that fish populations have increased in the vicinity of OWFs (Stenberg *et al*., 2015), there appears to be minimal risk to fish from operational WTGs from the standpoint of underwater noise or any other potential stressor.

To compare this to the relevant marine mammal impact thresholds in Southall *et al*. (2019), at a range of 100 m from the floating WTG for an hour, a receptor would receive an unweighted 174 dB ($L_{E,p,1h}$) considering the larger WTG size. With weighting considered, this is still well below potentially injurious or TTS thresholds for any of the non-impulsive Southall *et al*. (2019) criteria. Therefore, for noise from operational floating WTGs, TTS risk is small. Importantly this also assumes a stationary animal model with an individual remaining within 100 m from a WTG for much more than a 1-hour period. This is a highly unlikely scenario. When the animal is able to move, as will be the case in practice, the risk of direct harm from the noise is minimal.

5.2.1 Mooring line noise

As well as relatively low noise levels from the operational machinery in a variety of conditions (see the previous section), measurements taken by Jasco (2011) for Statoil at Hywind Demonstrator in Norway identified what appeared to be a “snapping” noise. A subsequent more detailed study at Hywind Scotland (Burns *et al.*, 2022) showed a lower level of somewhat different (and less impulsive) noises, but transients identified were associated with strain and friction in the mooring system (steel cables, chains or wired ropes), and they became increasingly frequent with increasing wave height. It is understood that the Hywind Demonstrator mooring lines are designed to be permanently in tension such that no line should ever go into slack, even in extreme conditions, partly to avoid the risk of entanglement of marine mammals (Statoil, 2015), although they may be subject to periodic tension releases (Risch *et al.*, 2023). As the mooring lines appear to be the source of the noise, this may be caused by the specific circumstances at the Hywind Demonstrator or Scotland projects: that is, the specific type of mooring, depth of water, length of mooring lines in use, current and current fluctuations. More recent studies at Hywind Tampen (Welch *et al.,* 2025) showed very few transient noises, far less than those at Hywind Scotland. The findings at the earlier Hywind projects were therefore isolated, and it does not necessarily follow that this will occur at Bellrock, but it cannot exclude the potential for it either.

As the source of noise is unclear and Burns *et al.* (2022) showed it to be somewhat variable, its distance from the monitor cannot be ascertained and thus a prediction of the noise closer to the source is not possible for estimation of PTS in terms of $L_{p,pk}$. Analysis of the Hywind data by Xodus (2015) for the Hywind Scotland Project predicted a potential $L_{E,p,24h}$ of up to 157 dB re 1 µPa^{2}s at 150 m caused by snapping mooring line chains from six WTGs; the equivalent for ten (for example) would, in theory, be approximately 160 dB re 1 µPa^{2}s. This prediction makes a series of worst-case assumptions (e.g., all WTGs producing the maximum number of 'snaps' in a day, equivalent noise levels from multiple locations affecting a receptor to the same degree) and this level is below any PTS or injury criteria to marine mammals or fish. Also as noted, the subsequent study by Burns *et al.* did not identify the snapping noise so this is likely to be moot.

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

5.3 UXO clearance

It is possible that UXO devices with a range of charge weights (or quantity of contained explosive) are present within the Bellrock WFDA. These would need to be cleared before any construction can begin. When modelling potential noise from UXO clearance, a variety of explosive types need to be considered, with the potential that many have been subject to degradation and burying over time. Two otherwise identical explosive devices are likely to produce different blasts in the case where one has spent an extended period on the seabed or sits in a different topographical situation. A selection of explosive sizes has been considered based on what might be present, and in each case, it has been assumed that the maximum explosive charge in each device is present and either detonates with the clearance (high-order) or a clearance method such as deflagration (low-order) can be used. The low order technique will be the default method adopted where possible and safe to do so, with high order clearance occurring as a contingency method were necessary (UK Government *et al.,* 2025; Marine Directorate, 2025)[4]. It is also noted that low order clearance may be initiated but fail (typically due to the condition of the UXO), resulting in higher noise levels which are assumed to be similar to that experienced during high order clearance.

An initial assessment indicates that there is potential for UXO to be present in the Bellrock WFDA:

- 53.3 cm G7e Torpedo (Net Explosive Quality (NEQ) = 364 kg);
- 50 cm G7 Torpedo (NEQ = 254 kg); and
- 8.8 cm Naval Projectile (NEQ = 1.42 kg).

[4] Approach also agreed with NatureScot via email to the Applicant on 2 May 2025.

5.3.1 Estimation of underwater noise level

5.3.1.1 High-order clearance

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

The consequence of this is that the noise levels produced, particularly by the larger explosives under consideration, are likely to be over-estimated as some degree of attenuation (i.e. from topography, burying, degradation, orientation) would be expected.

As mentioned above, low order technique will be the default technique used where possible and safe to do so, with high order clearance occurring as a contingency method were necessary (see the section 5.3.1.2).

The maximum equivalent charge weight for the potential UXO devices considered in this report is 750 kg following the Natural England Offshore Wind Marine Environmental Assessments: Best Practice Advice for Evidence and Data Standards (Parker *et al*., 2025). This is a larger charge weight than desk based review suggest present within the Bellrock WFDA. This has been modelled alongside a range of smaller devices, at charge weights of 25, 55, 120, 240, 525, and 698 kg, which have been chosen to give a reasonable spread of potential devices that have been identified at other sites in the North Sea. In each case, an additional donor weight of 0.5 kg has been included to initiate detonation.

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

5.3.1.2 Low-order clearance

The low order clearance technique (i.e., deflagration) will be adopted where possible and safe to do so, thereby reducing the consequences of noise caused by detonation of the main charge of the UXO. Deflagration is intended to result in a 'low order' burn of the explosive material in a UXO, which destroys, but does not detonate, the internal explosive.

Where the technique proceeds as intended, it is still not without noise impact. The process requires an initial shaped explosive donor charge, typically less than 250 g, to breach the casing and ignite the internal high explosive (HE) material without full detonation. The shaped charge and burn will both produce noise, although it will be significantly less than the high order detonation. It may not destroy all of the HE, in which case further deflagration events or collection of the remnants would be required. It is noted that where low order clearance is initiated but fails (typically due to the condition of the UXO), the deflagration may produce an unintentional high-order event.

For calculation of the scenario of total destruction of the HE material using deflagration, it is anticipated that the initial shaped charge is the greatest source of noise (Cheong *et al.*, 2020). The shaped charge is treated as a bulk charge with NEQ determined according to the size of UXO on which it is placed. A prediction of this impact is based on a charge weight of 250 g. The worst-case scenario would of course be a high order detonation with maximum pressures from complete detonation of the UXO, and this has been calculated separately for comparison.

5.3.2 Estimation of underwater noise propagation

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

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

and for $L_{E,p}$:

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

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

These equations give a relatively simple calculation which can be used to give an indication of the range of effect. The equation does not consider variable bathymetry or seabed type, and thus calculation results will be the same regardless of where it is used. An attenuation correction can be added to the Soloway and Dahl (2014) equations for the absorption over long ranges (i.e., of the order of thousands of metres), based on measurements of high intensity noise propagation taken in the North Sea and Irish Sea. This uses standard frequency-based absorption coefficients for the seawater conditions expected in the region.

Despite this attenuation correction, the resulting noise levels still need to be considered carefully. For example, $L_{p,pk}$ noise levels over larger distances are difficult to predict accurately (von Benda-Beckmann *et al*., 2015). Soloway and Dahl (2014) only verify results from the equation above for small charges at ranges of less than 1 km, although the results are similar to the measurements presented by von Benda-Beckmann *et al*. (2015). At longer ranges, greater confidence is expected with the $L_{E,p}$ calculations. It should be noted that that Ocean Winds (2024) indicates that, based on measurements of noise from deflagration in the Moray Firth, these calculations are likely to produce a higher, and therefore precautionary, prediction of noise levels than are seen in practice.

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

Additionally, an impulsive wave tends to be smoothed (i.e., the pulse becomes longer) over distance (Cudahy and Parvin, 2001), meaning the injurious potential of a wave at greater range can be even lower than just a reduction in the absolute noise level. An assessment in respect of SEL is considered preferential at long range as it considers the overall energy, and the degree of smoothing of the peak with increasing distance is less critical.

The selection of assessment criteria must also be considered in light of this. As discussed in section 2.2.1, the smoothing of the pulse at range means that a pulse may be considered non-impulsive at distance, suggesting that, at greater ranges, it may be more appropriate to use the non-impulsive criteria. This consideration may begin at 3.5 km (Hastie *et al*., 2019) to 5 km (Matei *et al*., 2023), although as blast noise is inherently more impulsive than piling, the transition from full impulsivity may occur further from the UXO source location.

A summary of the unweighted UXO clearance source levels, calculated using the equations above, are given in Table 5-7.

Table 5-7: Summary of the $L_{p,pk}$ and $L_{E,p}$ source levels used for UXO clearance modelling.

Charge weight	$L_{p,pk}$ source level	$L_{E,p}$ source level
Low order (0.25 kg)	269.8 dB re 1 µPa @ 1 m	215.2 dB re 1 µPa²s @ 1 m
25 kg (+ donor)	284.9 dB re 1 µPa @ 1 m	228.0 dB re 1 µPa²s @ 1 m
55 kg (+ donor)	287.5 dB re 1 µPa @ 1 m	230.1 dB re 1 µPa²s @ 1 m
120 kg (+ donor)	290.0 dB re 1 µPa @ 1 m	232.3 dB re 1 µPa²s @ 1 m
240 kg (+ donor)	292.3 dB re 1 µPa @ 1 m	234.2 dB re 1 µPa²s @ 1 m
525 kg (+ donor)	294.8 dB re 1 µPa @ 1 m	236.4 dB re 1 µPa²s @ 1 m
698 kg (+ donor)	295.7 dB re 1 µPa @ 1 m	237.1 dB re 1 µPa²s @ 1 m
750 kg (+ donor)	296.0 dB re 1 µPa @ 1 m	237.3 dB re 1 µPa²s @ 1 m

5.3.3 Impact ranges

Table 5-8 to Table 5-11 present the impact ranges for UXO detonation, considering various charge weights and impact criteria. It should be noted that Popper *et al*. (2014) gives specific impact criteria for explosions (Table 2-5). A UXO detonation source is defined as a single pulse, as such the $L_{E,p}$ criteria from Southall *et al*. (2019) have been given as single pulse values in the following tables and fleeing animal assumptions do not apply. As with the previous sections, ranges smaller than 50 m have not been presented.

Although the impact ranges in Table 5-8 to Table 5-11 are large, the duration the noise is present must also be considered. For the detonation of a UXO, each explosion is a single noise event, compared to the multiple pulse nature and longer durations of impact piling.

Table 5-8: Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive $L_{p,pk}$ noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al*. (2019) $L_{p,pk}$	PTS (impulsive)				TTS (impulsive)			
	LF 219dB	HF 230dB	VHF 202dB	PCW 218dB	LF 213dB	HF 224dB	VHF 196dB	PCW 212dB
Low order (0.25 kg)	**170 m**	**60 m**	**990 m**	**190 m**	**320 m**	**100 m**	**1.8 km**	**360 m**
25 kg (+ donor)	820 m	260 m	4.6 km	910 m	1.5 km	490 m	8.5 km	1.6 km
55 kg (+ donor)	1.0 km	340 m	6.0 km	1.1 km	1.9 km	640 m	11 km	2.1 km
120 kg (+ donor)	1.3 km	450 m	7.8 km	1.5 km	2.5 km	830 m	14 km	2.8 km
240 kg (+ donor)	1.7 km	560 m	9.8 km	1.9 km	3.2 km	1.0 km	18 km	3.5 km
525 kg (+ donor)	2.2 km	730 m	12 km	2.5 km	4.1 km	1.3 km	23 km	4.6 km
698 kg (+ donor)	2.4 km	810 m	13 km	2.7 km	4.5 km	1.4 km	25 km	5.0 km
750 kg (+ donor)	2.5 km	830 m	14 km	2.8 km	4.6 km	1.5 km	26 km	5.1 km

Table 5-9: Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive $L_{E,p}$ (single pulse) noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al*. (2019) $L_{E,p}$ (single pulse)	PTS (impulsive)				TTS (impulsive)			
	LF 183dB	HF 185dB	VHF 155dB	PCW 185dB	LF 168dB	HF 170dB	VHF 140dB	PCW 170dB
Low order (0.25 kg)	**230 m**	**N/A**	**80 m**	**N/A**	**3.2 km**	**N/A**	**750 m**	**570 m**
25 kg (+ donor)	2.2 km	N/A	570 m	390 m	29 km	150 m	2.4 km	5.2 km
55 kg (+ donor)	3.2 km	N/A	740 m	570 m	41 km	210 m	2.8 km	7.5 km
120 kg (+ donor)	4.7 km	N/A	950 m	830 m	57 km	300 m	3.2 km	10 km
240 kg (+ donor)	6.5 km	N/A	1.1 km	1.1 km	76 km	390 m	3.5 km	14 km
525 kg (+ donor)	9.5 km	50 m	1.4 km	1.6 km	100 km	530 m	4.0 km	19 km

Southall *et al.* (2019) $L_{E,p}$ (single pulse)	PTS (impulsive)				TTS (impulsive)			
	LF 183dB	HF 185dB	VHF 155dB	PCW 185dB	LF 168dB	HF 170dB	VHF 140dB	PCW 170dB
698 kg (+ donor)	10 km	60 m	1.5 km	1.9 km	110 km	590 m	4.1 km	22 km
750 kg (+ donor)	11 km	60 m	1.5 km	2.0 km	110 km	600 m	4.2 km	22 km

Table 5-10: Summary of the PTS and TTS impact ranges for UXO detonation using the non-impulsive $L_{E,p}$ (single pulse) noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al.* (2019) $L_{E,p}$ (single pulse)	PTS (non-impulsive)				TTS (non-impulsive)			
	LF 199dB	HF 198dB	VHF 173dB	PCW 201dB	LF 179dB	HF 178dB	VHF 153dB	PCW 181dB
Low order (0.25 kg)	**N/A**	**N/A**	**N/A**	**N/A**	**460 m**	**N/A**	**110 m**	**80 m**
25 kg (+ donor)	130 m	N/A	N/A	N/A	4.4 km	N/A	730 m	790 m
55 kg (+ donor)	190 m	N/A	N/A	N/A	6.4 km	60 m	940 m	1.1 km
120 kg (+ donor)	280 m	N/A	70 m	N/A	9.4 km	80 m	1.1 km	1.6 km
240 kg (+ donor)	390 m	N/A	100 m	70 m	13 km	110 m	1.4 km	2.3 km
525 kg (+ donor)	570 m	N/A	130 m	100 m	18 km	160 m	1.7 km	3.3 km
698 kg (+ donor)	660 m	N/A	150 m	110 m	21 km	180 m	1.8 km	3.8 km
750 kg (+ donor)	680 m	N/A	160 m	120 m	22 km	190 m	1.8 km	4.0 km

Table 5-11: Summary of the impact ranges for UXO detonation using the explosions $L_{p,pk}$ noise criteria from Popper et al. (2014) for species of fish.

Popper *et al.* (2014) $L_{p,pk}$	Mortality and potential mortal injury	
	234dB	229dB
Low order (0.25 kg)	**N/A**	**60 m**
25 kg (+ donor)	170 m	290 m
55 kg (+ donor)	230 m	380 m
120 kg (+ donor)	300 m	490 m
240 kg (+ donor)	370 m	620 m
525 kg (+ donor)	490 m	810 m
698 kg (+ donor)	530 m	890 m
750 kg (+ donor)	550 m	910 m

5.3.4 UXO summary

The maximum PTS ranges calculated for the largest high-order UXO clearance is 14 km for the VHF cetacean category when considering the $L_{p,pk}$ criteria. For $L_{E,p}$ criteria, the largest PTS range is calculated for LF cetaceans with a predicted impact range of 11 km using the impulsive noise criteria. As explained earlier, this assumes no degradation of the UXO and no smoothing of the pulse over distance, which is very precautionary. Although an assumption of non-pulse could underestimate the potential impact (Martin *et al.*, 2020) (the equivalent range based on LF cetacean non-pulse criteria is 680 m), it is likely that the long-range smoothing of the pulse peak would reduce its potential harm and the maximum 'impulsive' range for all species is very precautionary.

A low order clearance would produce a maximum impact range of 990 m for VHF cetaceans, with all other species groups lower than this. A low order methodology is expected to be used for UXO clearance, with high order being a last resort.

6 Summary and conclusions

Subacoustech Environmental has been appointed by Haskoning on behalf of Bellrock Offshore Wind Farm Limited to undertake a study to assess the potential underwater noise and its effects during the construction, operation and maintenance, and decommissioning of the Wind Farm Infrastructure and Offshore Transmission Infrastructure located within the Bellrock WFDA. The Bellrock WFDA is located in the North Sea off the east coast of Scotland.

The level of underwater noise from the installation of anchors and OfSS FBSSs during construction using impact piling has been estimated using the INSPIRE semi-empirical underwater noise model. The modelling considers a wide variety of input parameters including bathymetry, hammer blow energy, strike rate, and receptor fleeing speed.

Three modelling locations were chosen to give spatial variation across the Bellrock WFDA as well as accounting for changes in water depth:

- NW corner, the closest point of the WFDA to the Scottish coast, covering noise transmission to the north and west toward the coast;
- SW corner, covering noise transmission to the south and west toward the Scottish coast; and
- E boundary midpoint, covering some of the deepest water of the WFDA boundary, and transmission into deeper water to the east.

Two design scenarios were considered across each of the modelling locations for impact piling:

- Wind Farm Infrastructure: Driven piles securing the mooring lines of each floating offshore unit (FOU) (combined floating substructure and WTG) to the seabed (the FOU driven pile), comprising 6.0 m diameter piles with a maximum blow energy of 3,000 kJ; and
- Offshore Transmission Infrastructure: Driven piles securing the FBSS of each OfSS to the seabed (the OfSS driven pile), comprising 4.0 m diameter piles with a maximum blow energy of 5,500 kJ.

The modelling results were analysed in terms of relevant noise metrics and criteria to assess the effects of the impact piling on marine mammals (Southall *et al*., 2019) and fish (Popper *et al*., 2014), which have been used to inform biological assessments.

For marine mammals, maximum PTS ranges were predicted for LF cetaceans, with ranges of up to 28 km predicted based on the OfSS driven pile scenario, due to the larger blow energies used. For fish, the largest recoverable injury ranges (203 dB $L_{E,p,24h}$) were predicted to be 12 km for a stationary receptor, reducing to a minimal range for a fleeing receptor.

For the FOU driven piles, the largest PTS ranges from impact piling, were predicted for marine mammals at the E boundary midpoint with maximum ranges out to 25 km for the LF cetacean hearing category and for fish. The largest recoverable injury ranges were predicted to be 8.6 km for a stationary receptor, reducing to a minimal range when considering a moving receptor. Additionally, the impacts of concurrently installed piles at multiple separate locations were considered:

- FOU driven piles at the NW corner and the E boundary midpoint (2 concurrent locations);
- FOU driven piles at the NW corner and OfSS driven piles at the E boundary midpoint (2 concurrent locations; and

- FOU driven piles at the NW corner and the SW corner, and OfSS driven piles at the E boundary midpoint (3 concurrent locations).

Each of these scenarios resulted in expanded cumulative impact areas when compared against the results for the individual installations.

Noise sources other than piling have been considered using a high-level, simple modelling approach, including cable laying, drilling, rock placement, trenching, vessel noise, operational WTG noise and mooring line noise. The predicted noise levels for these construction noises are well below those predicted for impact piling noise. The risk of any potentially injurious effects to fish or marine mammals from these sources are expected to be minimal as the noise emissions from these are close to, or below, the appropriate injury criteria, even when very close to the source of the noise.

Potential noise from UXO clearance has also been considered across the Bellrock WFDA. There is a risk of PTS up to 990 m for VHF cetacean, with use of low order UXO clearance technique (be adopted where possible and safe to do so). In the event that a high order detonation does occur, the maximum PTS range is up to 14 km from the largest UXO device considered (750 kg + donor charge), using the unweighted $L_{p,pk}$ criteria for VHF cetaceans. However, this is likely to be highly precautionary as the impact range is based on a worst-case criterion and calculation methodology that does not account for any smoothing of the pulse over long ranges, which would reduce the pulse peak and other characteristics of the sound that cause injury.

The outputs of this modelling have been used to inform assessments of the impacts of underwater noise on marine mammals and fish at the Bellrock WFDA.

References

Andersson M H, Andersson S, Ahlsén J, Andersson B L, Hammar J, Persson L K G, Pihl J, Sigray P, Wilkström A (2017). *A framework for regulating underwater noise during pile driving*. A technical Vindval report, ISBN 978-91-620-6775-5, Swedish Environmental Protection Agency, Stockholm, Sweden

André M, Solé M, Lenoir M, Durfort M, Quero C, Mas A, Lombarte A, van der Schaar M, Lopez-Bejar M, Morell M, Zaugg S, Houegnigan L (2011). *Low-frequency sounds induce acoustic trauma in cephalopods*. Front. Ecol. Environ. 9 (9).

André M, Kaifu K, Solé M, van der Schaar M, Akamatsu T (2016). *Contribution to the understanding of particle motion perception in marine invertebrates* In: *The Effects of Noise on Aquatic Life II. Advances in Experimental Medicine and Biology*. Eds A. N. Popper and A. Hawkins (New York: Springer). P. 47–55.

Arons A B (1954). *Underwater explosion shock wave parameters at large distances from the charge.* J. Acoust. Soc. Am. 26, 343-346.

Bailey H, Thompson P (2006). *Quantitive analysis of bottlenose dolphin movement patterns and their relationship with foraging.* Journal of Animal Ecology 75: 456-465.

Bailey H, Senior B, Simmons D, Rusin J, Picken G, Thompson P M (2010). *Assessing underwater noise levels during pile-driving at an offshore wind farm and its potential effects on marine mammals.* Marine Pollution Bulletin 60 (2010), pp 888-897.

Bailey H, Brookes K L, Thompson P M (2014). *Assessing environmental impacts of offshore wind farms: lessons learned and recommendations for the future.* Aquatic Biosystems 2014, 10:8.

Bebb A H, Wright H C (1953). *Injury to animals from underwater explosions.* Medical Research Council, Royal Navy Physiological Report 53/732, Underwater Blast Report 31, January 1953.

Bebb A H, Wright H C (1954a). *Lethal conditions from underwater explosion blast.* RNP Report 51/654, RNPL 3/51, National Archies Reference ADM 298/109, March 1954.

Bebb A H, Wright H C (1954b). *Protection from underwater explosion blast: III. Animal experiments and physical measurements.* RNP Report 57/792, RNPL 2/54m March 1954.

Bebb A H, Wright H C (1955). *Underwater explosion blast data from the Royal Navy Physiological Labs 1950/1955.* Medical Research Council, April 1955.

Bellmann M A, Müller T, Scheiblich K, Betke K (2023). *Experience report on operational noise - Cross-project evaluation and assessment of underwater noise measurements from the operational phase of offshore wind farms*, itap report no. 3926.Burns R D J, Martin S B, Wood M A, Wilson C C, Lumsden C E, Pace F (2022). *Hywind Scotland Floating Offshore Wind Farm: Sound Source Characterisation of Operational Floating Turbines*. Document 02521, Version 3.0 FINAL. Technical report by Jasco Applied Sciences for Equinor Energy AS.

Cheong S-H, Wang L., Lepper P, Robinson S (2020). *Characterization of Acoustic Fields Generated by UXO Removal, Phase 2*. NPL Report AC 19, National Physical Laboratory.

Cudahy E, Parvin S (2001). *The effects of underwater blast on divers.* Naval Submarine Medical Research Laboratory Report #1218.

Dahl P H, de Jong C A, Popper A N (2015). *The underwater sound field from impact pile driving and its potential effects on marine life.* Acoustics Today, Spring 2015, Volume 11, Issue 2.

Fields D M, Handegard N O, Dalen J, Eichner C, Malde K, Karlsen Ø, Skiftesvik A, Durif C, Browman H (2019). *Airgun blasts used in marine seismic surveys have limited effects on mortality, and no sublethal effects on behaviour or gene expression, in the copepod Calanus finmarchicus*. ICES J. Mar. Sci. 76 (7), 2033–2044.

Goertner J F (1978). *Dynamical model for explosion injury to fish.* Naval Surface Weapons Center, White Oak Lab, Silver Spring, MD. Report No. NSWC/WOL.TR-76-155.

Goertner J F, Wiley M L, Young G A, McDonald W W (1994). *Effects of underwater explosions on fish without swim bladders.* Naval Surface Warfare Center. Report No. NSWC/TR-76-155.

Halvorsen M B, Casper B C, Matthew D, Carlson T J, Popper A N (2012). *Effects of exposure to pile driving sounds on the lake sturgeon, Nila tilapia, and hogchoker.* Proc. Roy. Soc. B 279: 4705-4714.

Hastie G, Merchant N D, Götz T, Russell D J F, Thompson P, Janik V M (2019). *Effects of impulsive noise on marine mammals: Investigating range-dependent risk.* DOI: 10.1002/ eap.1906.

Hastings M C, Popper A N (2005). *Effects of sound on fish.* Report to the California Department of Transport, under Contract No. 43A01392005, January 2005.

Hawkins A D, Popper A N (2017). *A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates.* ICES J. Mar. Sci. 74 (3), 635-651 doi: 10.1093/icesjms.fsw205.

Heaney K D, Ainslie M A, Halvorsen M B, Seger K D, Müller, R A J, Nijhof M J J, Lippert T (2020). *A Parametric Analysis and Sensitivity Study of the Acoustic Propagation for Renewable Energy Sources*. Sterling (VA): U.S. Department of the Interior, Bureau of Ocean Energy Management. Prepared by CSA Ocean Sciences Inc. OCS Study BOEM 2020-011, 165 p.

Hirata K (1999). *Swimming speeds of some common fish.* National Maritime Research Institute (Japan). Data sourced from Iwai T, Hisada M (1998). *Fishes – Illustrated book of Gakken* (in Japanese). Accessed on 14th December 2022 at https://www.nmri.go.jp/archives/eng/khirata/fish/general/speed/speede.htm khirata/fish/general/speed/speede.htm

Hubert J, van Bemmelen J J, Slabbekoorn H (2021). *No negative effects of boat sound playbacks on olfactory-mediated food finding behaviour of shore crabs in a T-maze*. Environ. Pollut. 270, 116184.

Hubert J, Demuynck J M, Remmelzwaal M R, Muñiz C, Debusschere E, Berges B, Slabbekoorn H (2024). *An experimental sound exposure study at sea: No spatial deterrence of free-ranging pelagic fish*. J. Acoust. Soc. Am. 155, 1151–1161 (2024).

International Organisation for Standardisation (2017). *Underwater acoustics – Terminology (ISO standard no. 18405:2017) https://www.iso.org/standard/62406.html*

Jasco (2011). *Hywind Acoustic Measurement Report*. Jasco Report No. 00229.

Kastelein R A, van de Voorde S, Jennings N (2018). *Swimming speed of a harbor porpoise (Phoco74hocoenaoena) during playbacks of offshore pile driving sounds.* Aquatic Mammals. 2018, 44(1), 92-99, DOI 10.1578/AM.44.1.2018.92.

Marine Directorate (2025). Marine licensing – unexploded ordnance clearance: application guidance. Available at: https://www.gov.scot/publications/marine-licensing-unexploded-ordnance-clearance-guidance/pages/marine-licensing-requirements/

Marine Technical Directorate (MTD) (1996). *Guidelines for the safe use of explosives underwater.* MTD Publication 96/101. ISBN 1 870553 23 3.

Martin B, MacDonnell J, Vallarta J, Lumsden E, Burns R (2011). *Hywind acoustic measurement report: Ambient levels and Hywind signature*. Technical report for Statoil by Jasco Applied Sciences.

Martin S B, Lucke K, Barclay D R (2020). *Techniques for distinguishing between impulsive and non-impulsive sound in the context of regulating sound exposure for marine mammals.* The Journal of the Acoustical Society of America 147, 2159.

Matei M, Chudzińska M, Remmers P, Bellman M, Darias-O'Hara A K, Verfuss U, Wood J, Hardy N, Wilder F, Booth C (2024). *Range dependent nature of impulsive noise (RaDIN)*. Report on behalf of the Carbon Trust and Offshore Renewables Joint Industry Programme (ORJIP) for Offshore Wind.

McCauley R D, Day R D, Swadling K M, Fitzgibbon Q P, Watson R A, Semmens J M (2017). *Widely used marine seismic survey air gun operations negatively impact zooplankton*. Nat. Ecol. Evol. 1 (7), 1–8.

NatureScot (2024). Scoping representation on the Bellrock WFDA Scoping Report. Available at: https://marine.gov.scot/?q=node/25450

Molinero (2020). *Windfloat Environmental Data – Noise.* Principle Power Report No. PPI-WFBGW-GN-HSE-25012.

National Marine Fisheries Service (NMFS) (2018). *Revisions to: Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing (version 2.0): Underwater thresholds for onset of permanent and temporary threshold shifts.* U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OPR-59.

National Marine Fisheries Service (NMFS) (2024). *2024 update to: Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing (version 3.0): Underwater and in-air criteria for onset of auditory injury and temporary threshold shifts.* U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OPR-71.

Nedelec S L, Campbell J, Radford A N, Simpson S D, Merchant N D (2016). *Particle motion: The missing link in underwater acoustic ecology.* Methods Ecol. Evol. 7, 836 – 842.

Ocean Winds (2024). *Low order deflagration of unexploded ordnance reduces underwater noise impacts from offshore wind farm construction*. Report for Ocean Winds, in collaboration with EODEX.

Parker J, Fawcett A, Banks A, Rowson T, Allen S, Rowell H, Harwood A, Ludgate C, Humphrey O, Axelsson M, Baker A, Copley V, Robertson A, Hodgkiss R, Berridge R, Farmer R (2025). *Offshore Wind Marine Environmental Assessments: Best Practice Advice for Evidence and Data Standards. Phase III: Expectations for data analysis and presentation at examination for offshore wind applications*. Natural England. Version 2. 140 pp

Popper A N, Hawkins A D, Fay R R, Mann D A, Bartol S, Carlson T J, Coombs S, Ellison W T, Gentry R L, Halvorsen M B, Løkkeborg S, Rogers P H, Southall B L, Zeddies D G, Tavolga W N (2014). *Sound exposure guidelines for Fishes and Sea Turtles.* Springer Briefs in Oceanography, DOI 10.1007/978-3-319-06659-2.

Popper A N, Hawkins A D (2018). *The importance of particle motion to fishes and invertebrates.* J. Acoust. Soc. Am. 143, 470 – 486.

Popper A N, Hawkins A D (2019). *An overview in fish bioacoustics and the impacts of anthropogenic sounds on fishes.* Journal of Fish Biology, 1-22. DOI: 10.111/jfp.13948.

Radford C A, Montgomery J C, Caiger P, Higgs D M (2012). *Pressure and particle motion detection thresholds in fish: a re-examination of salient auditory cues in teleosts.* Journal of Experimental Biology, 215, 3429 – 3435.

Rawlins J S P (1987). *Problems in predicting safe ranges from underwater explosions.* Journal of Naval Science, Volume 13, No. 4, pp 235-246.

Risch D, Favill G, Marmo B, van Geen N, Benjamins S, Thompson P, Wittch A, Wilson B (2023). *Characterisation of underwater operational noise of two types of floating offshore wind turbines.* Technical report for Supergen Offshore Renewable Energy by SAMS, Xi Engineering Consultants, University of Aberdeen.

Robinson S P, Lepper P A, Hazelwood R A (2014). *Good practice guide for underwater noise measurement.* National Measurement Office, Marine Scotland, The Crown Estate. NPL Good Practice Guide No. 133, ISSNL 1368-6550.

Scottish Natural Heritage (SNH) (2016). *Assessing collision risk between underwater turbines and marine wildlife.* SNH guidance note.

Solé, Lenoir M, Durfort M, López-Bejar M, Lombarte A, André M (2013). *Ultrastructural damage of Loligo vulgaris and Illex coindetii statocysts after low frequency sound exposure*. PloS One 8 (10), 1–12.

Solé M, Lenoir M, Fortuño J-M, van der Schaar M, André M (2018). *A critical period of susceptibility to sound in the sensory cells of cephalopod hatchlings*. Biol. Open 7 (10), bio033860.

Solé M, Monge M, André M, Quero C (2019). *A proteomic analysis of the statocyst endolymph in common cuttlefish (Sepia officinalis): An assessment of acoustic trauma after exposure to sound*. Sci. Rep. 9 (1), 9340.

Solé M, Kaifu K, Mooney T A, Nedelec, S L, Olivier F, Radford A N, Vazzana M, Wale M A, Semmens J M, Simpson S D, Buscaino G, Hawkins A, Aguilar de Soto N, Akamatsu T, Chauvaud L, Day R D, Fitzgibbon Q, McCauley R D, André M (2023) *Marine invertebrates and noise*. Frontiers in Marine Science, 10.

Soloway A G, Dahl P H (2014). *Peak sound pressure and sound exposure level from underwater explosions in shallow water.* The Journal of the Acoustical Society of America, 136(3), EL219 – EL223. http://dx.doi.org/10.1121/1.4892668.

Southall B L, Finneran J J, Reichmuth C, Nachtigall P E, Ketten D R, Bowles A E, Ellison W T, Nowacek D P, Tyack P L (2019). *Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects.* Aquatic Mammals 2019, 45 (20, 125-232) DOI 10.1578/AM.45.2.2019.125.

Spiga I, Caldwell G S, Bruintjes R (2016). *Influence of pile driving on the clearance rate of the blue mussel, Mytilus edulis (L.)*. Proc. Meetings Acoustics 27 (1).

Statoil (2015). *Hywind Scotland Pilot Park – Environmental Statement.* April 2015. Document Number: A-100142-S35-EIAS-001-01.

Stenberg C, Støttrup J G, van Deurs M, Berg C W, Dinesen G E, Mosegaard H, Grome T M, Leonard S B (2015). *Long-term effects of an offshore wind farm in the North Sea on fish communities.* Mar Ecol Prog Ser. Vol. 528: 257-265, 2015 doi: 10.3354/meps11261.

Stephenson J R, Gingerich A J, Brown R S, Pflugrath B D, Deng Z, Carlson T J, Langeslay M J, Ahmann M L, Johnson R L, Seaburg A G (2010). *Assessing barotrauma in neutrally and negatively buoyant juvenile salmonids exposed to simulated hydro-turbine passage using a mobile aquatic barotrauma laboratory.* Fisheries Research Volume 106, Issue 3, pp 271-278, December 2010.

Stöber U, Thomsen F (2021). *How could operational underwater sound from future offshore wind turbines impact marine life?* The Journal of the Acoustical Society of America, 149, 1791-1795. https://doi.org/10.1121/10.0003760.

Thompson P M, Hastie G D, Nedwell J, Barham R, Brookes K L, Cordes L S, Bailey H, McLean N (2013). *Framework for assessing impacts of pile-driving noise from offshore wind farm construction on a harbour seal population*. Environmental Impact Assessment Review 43 (2013) 73-85.

Thompson P M, Benhemma-Le Gall A, Mason T, Stephenson S (2025, in prep.). *Measurements of noise levels and porpoise disturbance during pile-driving at Moray West Offshore Windfarm; comparison with model predictions used in regulatory assessments.* Submission to Effects of Noise on Aquatic Life conference, Prague, 2025.

Tougaard J, Hermannsen L, Madsen P T (2020), *How loud is the underwater noise from operating offshore wind turbines?* J. Acoust. Soc. Am. 148 (5). doi.org/10.1121/10.0002453.

UK Government, Defra, BEIS, MMO, JNCC, Natural England, The Scottish Government, Natural Resource Wales, Offshore Petroleum Regulator for Environment and Decommissioning, Department of Agriculture, Environment and Rural Affairs (Northern Ireland), DESNZ (2025). *Marine environment: unexploded ordnance clearance Joint Position Statement [online]*. Published 21 January 2025. Available at: https://www.gov.uk/government/publications/marine-environment-unexploded-ordnance-clearance-joint-position-statement.

von Benda-Beckmann, A M, Aarts G, Sertlek H Ö, Lucke K, Verboom W C, Kastelein R A, Ketten D R, van Bemmelen R, Lamm F-P A, Kirkwood R J, Ainslie M A (2015). *Assessing the impact of underwater clearance of unexploded ordnance on harbour porpoises (Phocoena phocoena) in the southern North Sea.* Aquatic Mammals 2015, 41(4), pp 503-523, DOI 10.1578/ AM.41.4.2015.503.

von Pein J, Lippert T, Lippert S, von Estorff O (2022). *Scaling laws for unmitigated pile driving: Dependence of underwater noise on strike energy, pile diameter, ram weight, and water depth.* Applied Acoustics 198 (2022) 108986.

Welch S J, Burns R D J, Lumsden C E, Wood M A, Kowarski K A, Martin S B, Christie C P, Richardson A L, Maxner E E, Wilson C C, Gaudet B J, Callaghan E. (2025). *Hywind Tampen Floating Offshore Wind Farm: Sound Source Characterisation of Operational Floating Turbines*. Document 03642, Version 1.0. Technical report by JASCO Applied Sciences for Equinor Energy AS.

Xodus (2015). *Technical note on underwater noise.* A-100142-S20-TECH-001.

Appendix A Additional modelling results

Following the impulsive Southall *et al*. (2019) modelled impact piling ranges presented in section 4, the modelling results for the non-impulsive criteria are presented below. The predicted ranges here fall well below the impulsive criteria presented in the main report.

A.1 Single location modelling

A.1.1 FOU driven piles

Table A 1: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the FOU driven pile modelling for a single pile at the NW corner modelling location.

Southall *et al*. (2019) Weighted $L_{E,p,t}$		FOU driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	N/A	N/A
	HF (198 dB)	N/A	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A	N/A

Table A 2: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the FOU driven pile modelling for three sequentially installed piles at the NW corner modelling location.

Southall *et al*. (2019) Weighted $L_{E,p,t}$		FOU driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	N/A	N/A
	HF (198 dB)	N/A	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A	N/A

Table A 3: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the FOU driven pile modelling for a single pile at the SW corner modelling location.

Southall *et al*. (2019) Weighted $L_{E,p,t}$		FOU driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	N/A	N/A
	HF (198 dB)	N/A	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A	N/A

Table A 4: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the FOU driven pile modelling for three sequentially installed piles at the SW corner modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		FOU driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	N/A	N/A
	HF (198 dB)	N/A	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A	N/A

Table A 5: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the FOU driven pile modelling for a single pile at the E boundary midpoint modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		FOU driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	N/A	N/A
	HF (198 dB)	N/A	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A	N/A

Table A 6: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the FOU driven pile modelling for three sequentially installed piles at the E boundary midpoint modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		FOU driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	N/A	N/A
	HF (198 dB)	N/A	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A	N/A

A.1.2 OfSS driven piles

Table A 7: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the OfSS driven pile modelling for a single pile at the NW corner modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		OfSS driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	N/A	N/A
	HF (198 dB)	N/A	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A	N/A

Table A 8: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the OfSS driven pile modelling for three sequentially installed piles at the NW corner modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		OfSS driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	N/A	N/A
	HF (198 dB)	N/A	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A	N/A

Table A 9: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the OfSS driven pile modelling for a single pile at the SW corner modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		OfSS driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	N/A	N/A
	HF (198 dB)	N/A	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A	N/A

Table A 10: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the OfSS driven pile modelling for three sequentially installed piles at the SW corner modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		OfSS driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	N/A	N/A
	HF (198 dB)	N/A	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A	N/A

Table A 11: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the OfSS driven pile modelling for a single pile at the E boundary midpoint modelling location.

Southall *et al.* (2019) Weighted $L_{E,p,t}$		OfSS driven piles (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	N/A	N/A
	HF (198 dB)	N/A	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A	N/A

Table A 12: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the OfSS driven pile modelling for three sequentially installed piles at the E boundary midpoint modelling location.

Southall *et al*. (2019) Weighted $L_{E,p,t}$		OfSS driven piles (three sequentially installed piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	N/A	N/A
	HF (198 dB)	N/A	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A	N/A

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A.2 Multiple location modelling, all scenarios

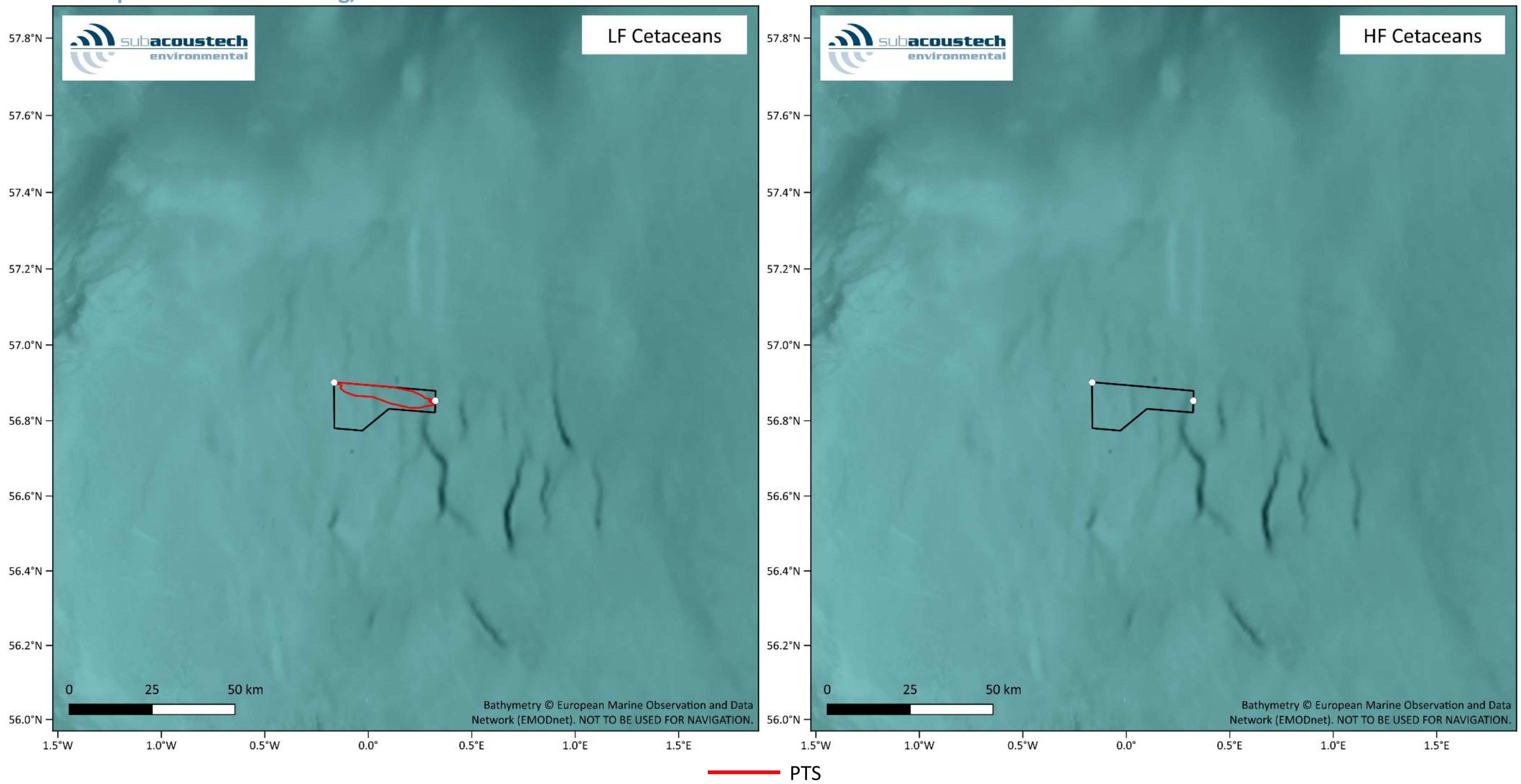

Figure A 1: Contour plots showing the in-combination impacts of simultaneous installation of FOU driven piles at the NW corner and the E boundary midpoint modelling locations for LF and HF cetaceans using the non-impulsive Southall et al. (2019) criteria assuming fleeing animals.

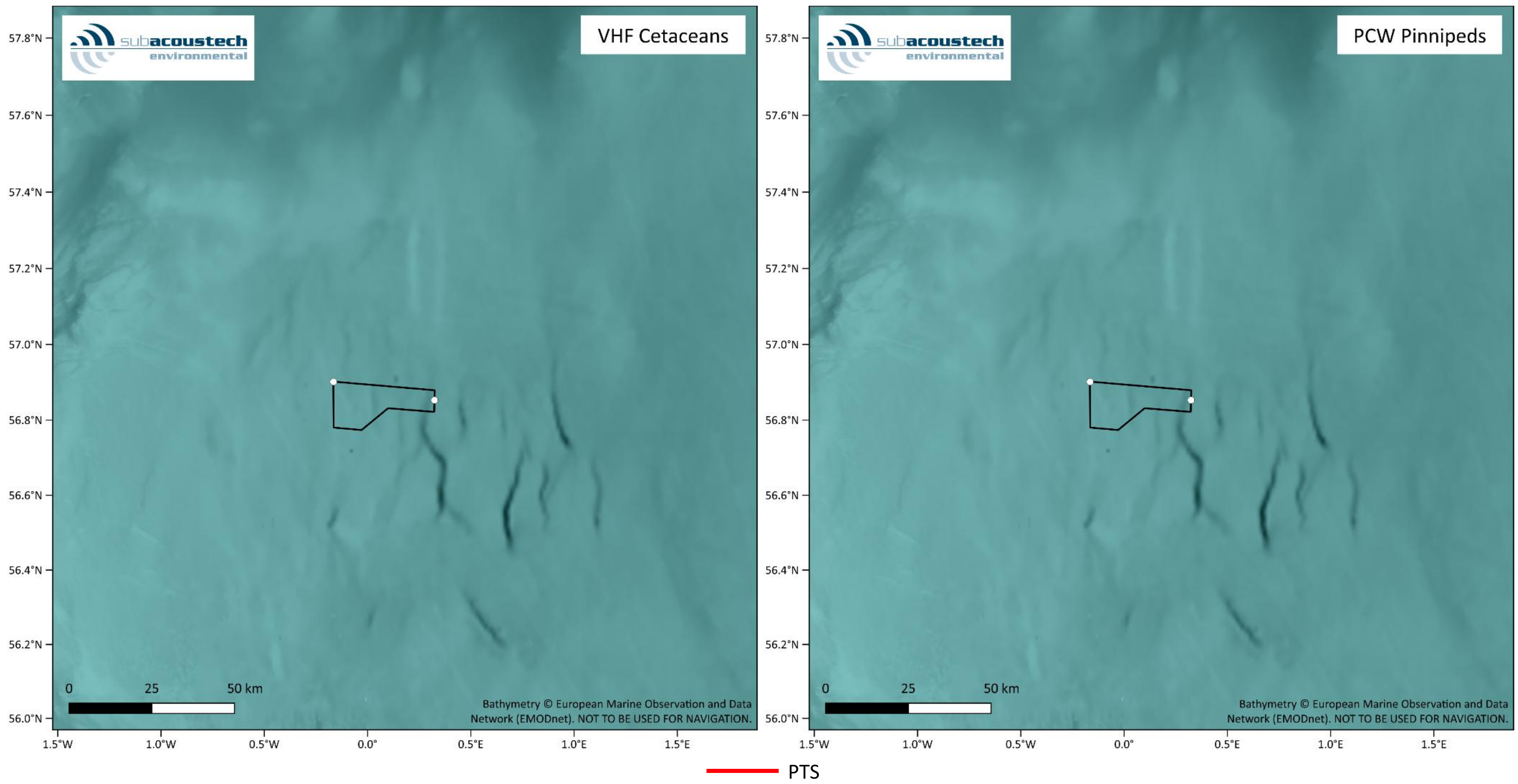

Figure A 2: Contour plots showing the in-combination impacts of simultaneous installation of FOU driven piles at the NW corner and the E boundary midpoint modelling locations for VHF cetaceans and PCW using the non-impulsive Southall et al. (2019) criteria assuming fleeing animals.

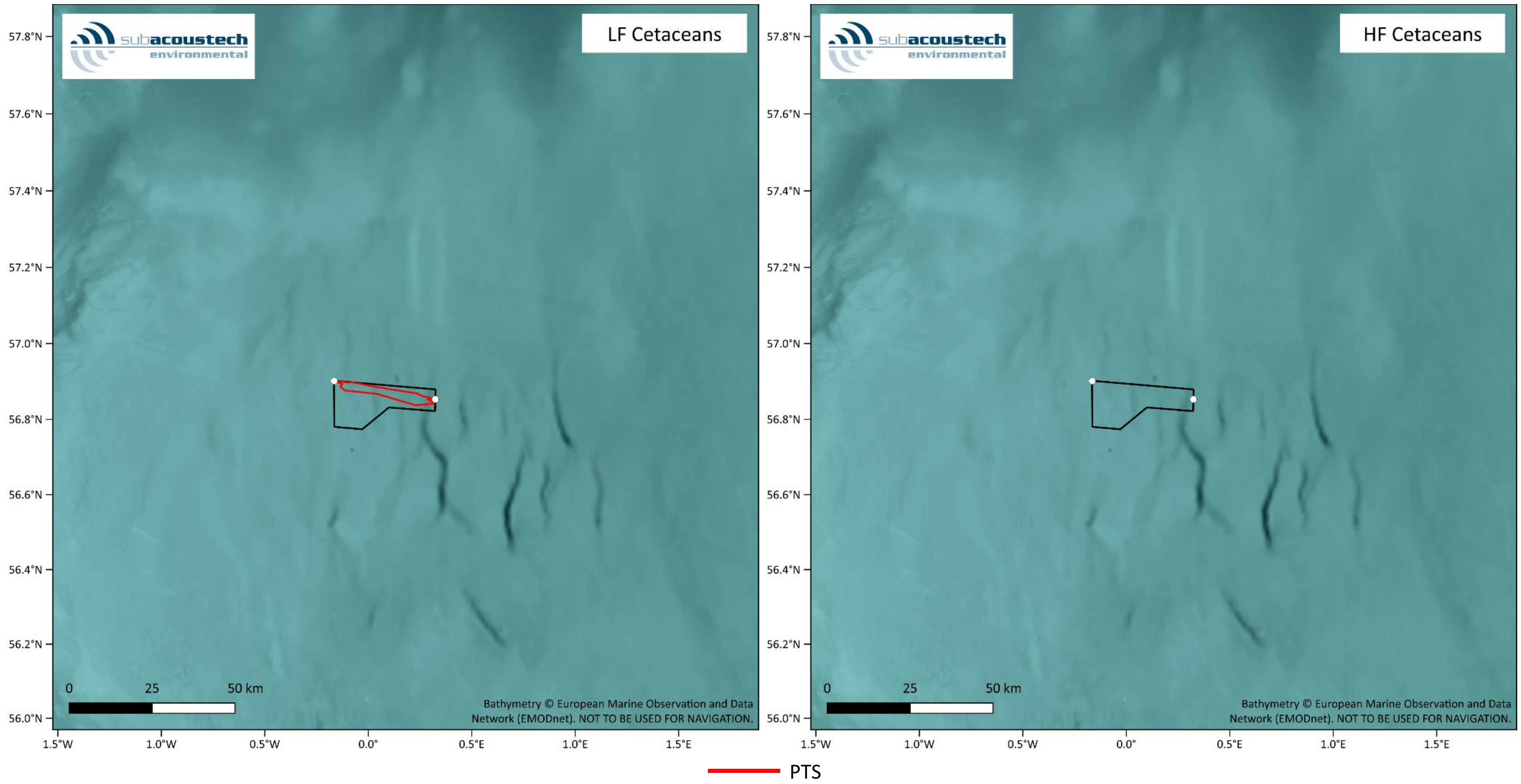

Figure A 3: Contour plots showing the in-combination impacts of simultaneous installation of FOU driven piles at the NW corner and OfSS driven piles at the E boundary midpoint modelling locations for LF and HF cetaceans using the non-impulsive Southall et al. (2019) criteria assuming fleeing animals.

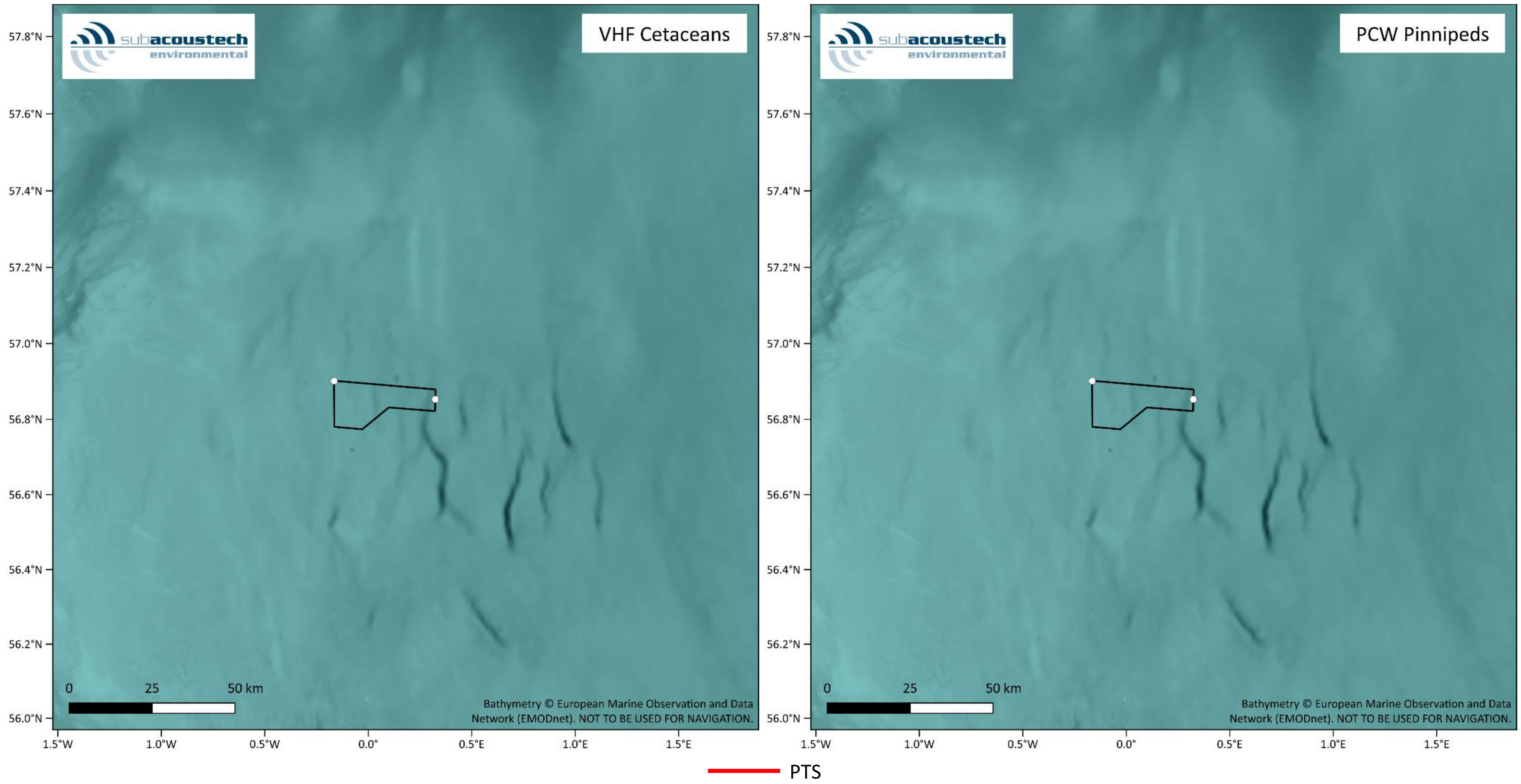

Figure A 4: Contour plots showing the in-combination impacts of simultaneous installation of FOU driven piles at the NW corner and OfSS driven piles at the E boundary midpoint modelling locations for VHF cetaceans and PCW using the non-impulsive Southall et al. (2019) criteria assuming fleeing animals.

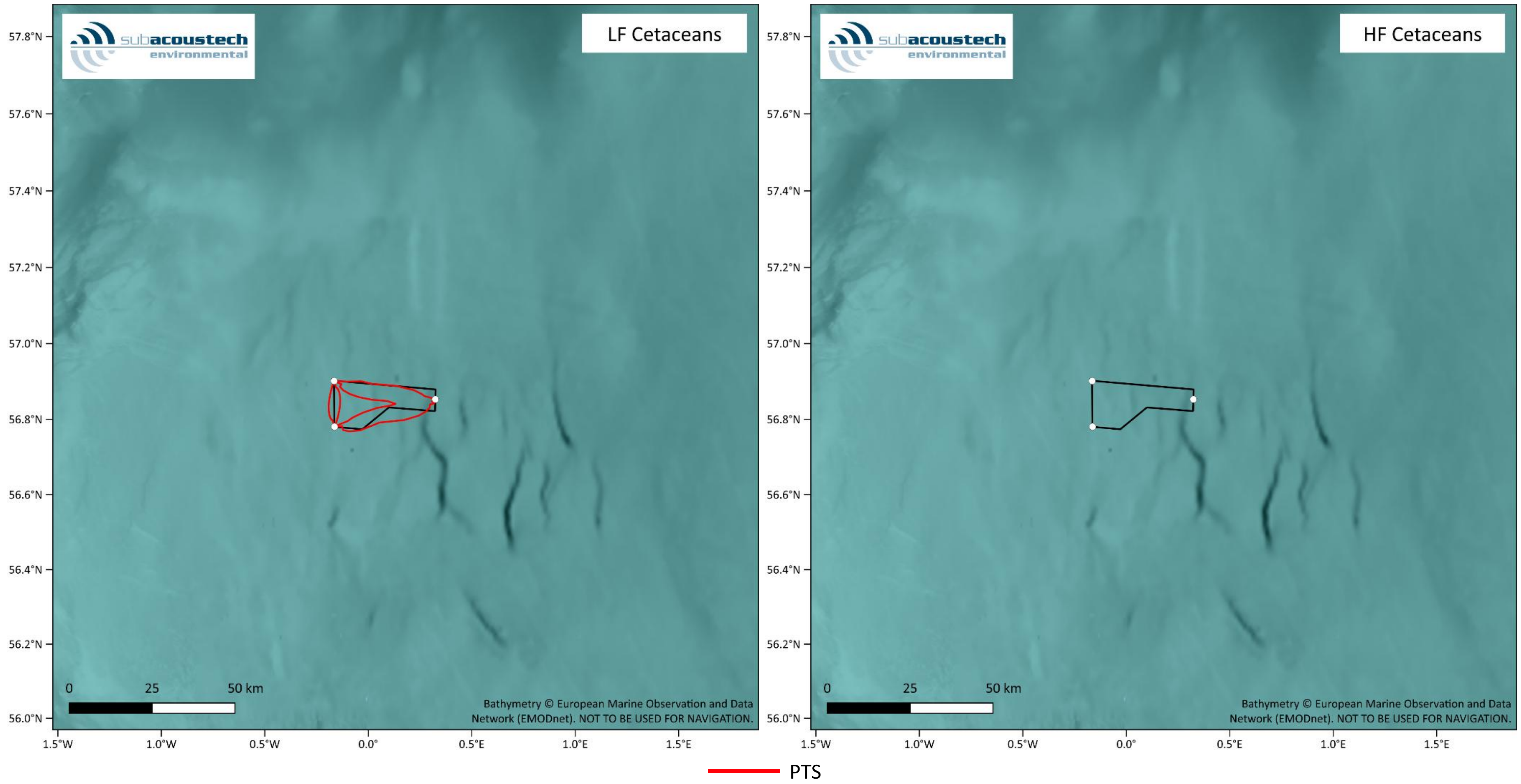

Figure A 5: Contour plots showing the in-combination impacts of simultaneous installation of FOU driven piles at the NW corner and SW corner, and OfSS driven piles at the E boundary midpoint modelling locations for LF and HF cetaceans using the non-impulsive Southall et al. (2019) criteria assuming fleeing animals.

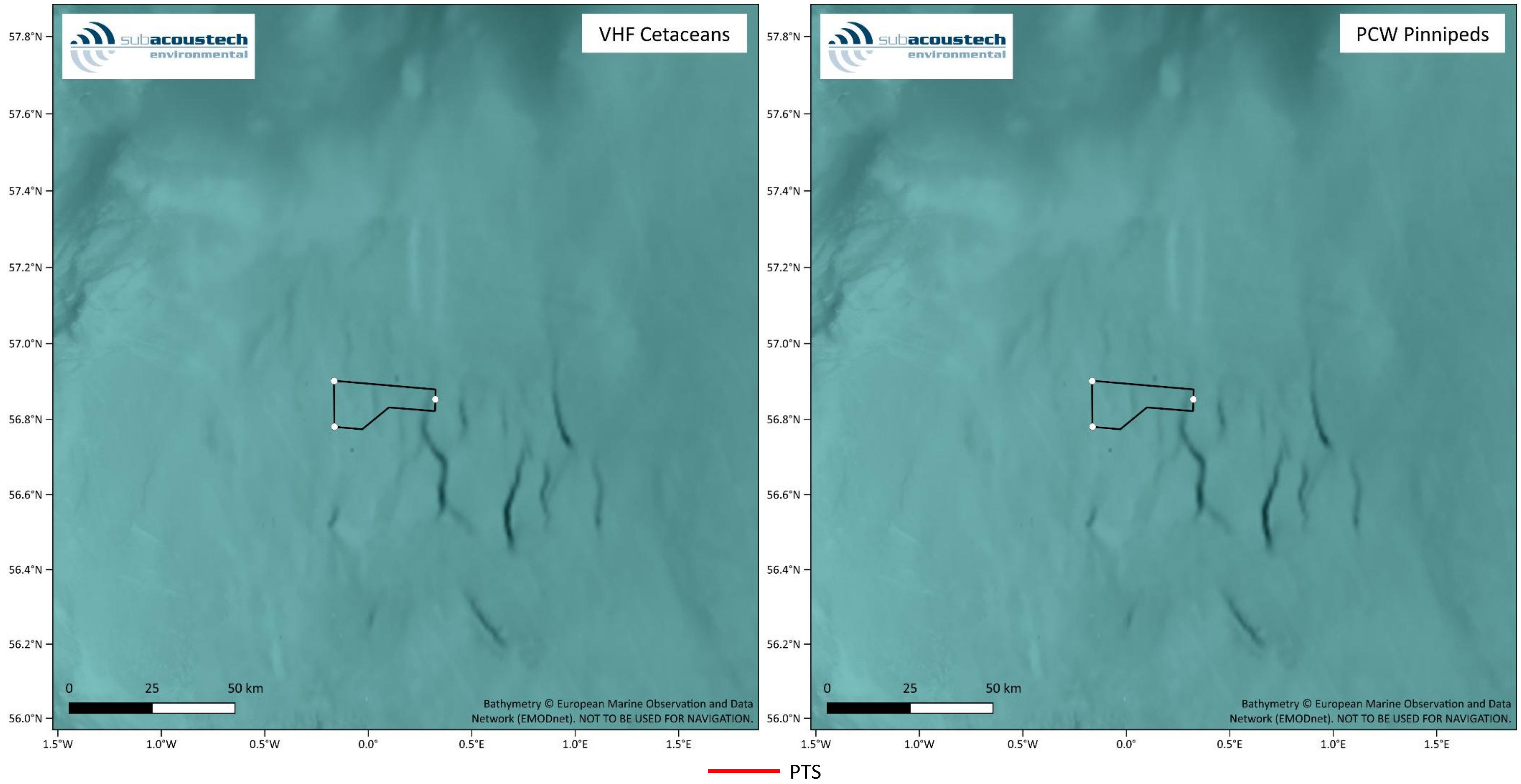

Figure A 6: Contour plots showing the in-combination impacts of simultaneous installation of FOU driven piles at the NW corner and SW corner, and OfSS driven piles at the E boundary midpoint modelling locations for VHF cetaceans and PCW using the non-impulsive Southall et al. (2019) criteria assuming fleeing animals.

Table A 13: Summary of the impact areas for the installation of piles using the FOU driven pile parameters at the NW corner and the E boundary midpoint for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal.

FOU driven piles (Southall *et al.*, 2019) Weighted $L_{E,p,t}$		NW corner (FOU)	E boundary midpoint (FOU)	In-combination area
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	69 km^2
	HF (198 dB)	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A

Table A 14: Summary of the impact areas for the installation of piles using the FOU driven piles parameters at the NW corner and OfSS driven pile parameters at the E boundary midpoint for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal.

FOU / OfSS driven piles (Southall *et al.*, 2019) Weighted $L_{E,p,t}$		NW corner (FOU)	E boundary midpoint (OfSS FBSS)	In-combination area
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	100 km^2
	HF (198 dB)	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A

Table A 15: Summary of the impact areas for the installation of piles using the FOU driven pile parameters at the NW corner and SW corner, and OfSS driven pile parameters at the E boundary midpoint for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal.

FOU / OfSS driven piles (Southall *et al.*, 2019) Weighted $L_{E,p,t}$		NW corner (FOU)	SW corner (FOU)	E boundary midpoint (OfSS FBSS)	In-combination area
PTS (Non-impulsive)	LF (199 dB)	N/A	N/A	N/A	250 km^2
	HF (198 dB)	N/A	N/A	N/A	N/A
	VHF (173 dB)	N/A	N/A	N/A	N/A
	PCW (201 dB)	N/A	N/A	N/A	N/A

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Document No.	Draft	Date	Details of change
P335R0100	01	19/02/2025	Initial writing and internal review.
P335R0101	01	12/03/2025	First issue to client.
P335R0102	-	14/08/2025	Inclusion of additional concurrent piling scenarios.
P335R0103	-	19/09/2025	Minor amendments following comments.

Originator's current report number	P355R0103
Originator's name and location	RB; Subacoustech Environmental Ltd.
Contract number and period covered	P355; September 2024 – September 2025.
Sponsor's name and location	HF, Haskoning
Report classification and caveats in use	UNRESTRICTED – *May be published or distributed publicly where approved by the project sponsor*
Date written	February – September 2025.
Pagination	Cover + ix + 90
References	70
Report title	
Translation/Conference details (if translation, give foreign title/if part of a conference, give conference particulars)	
Title classification	UNRESTRICTED
Author(s)	RB
Descriptors/keywords	
Abstract	
Abstract classification	UNRESTRICTED