Arklow Bank Wind Park 2

Environmental Impact Assessment Report

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Arklow Bank Wind Park 2:
Underwater noise assessment

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Statement of Authority

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Continuous post-graduate consultancy experience since 2001 in design and impact assessment of both underwater and traditional airborne noise situations. Responsible for project management and QA in addition to technical consultancy and reporting. Acts as an expert witness for planning enquiries with respect to underwater noise and its effects on marine life. Experienced in a wide range of acoustic disciplines in addition to underwater noise modelling and monitoring; other disciplines include road, rail and construction noise impacts, industrial noise mapping and control, planning and architectural acoustics, vibration and noise nuisance. Delivered presentations on underwater noise impacts at national and international conferences and has been invited to speak on underwater noise at the Royal Society.

Richard Barham, BSc (Hons) AMIOA - Underwater Noise Modelling Specialist

15 years' years' experience in the development and execution of underwater noise models. Oversees development of the Impulse Noise Sound Propagation and Range Estimator (INSPIRE) underwater noise model and INSPIRE light model; a cut down version of INSPIRE which can be used in meetings and workshops. Experienced with the RAMSGeo and dBSea acoustic models. Involved with noise measurements and data analysis of various sources of underwater noise including impact piling, drilling vessel noise and diving equipment. Highly skilled in technical report writing and graphic representation of data.

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Acronyms

Acronym	Definition
ABWP2	Arklow Bank Wind Park 2
ADD	Acoustic Deterrent Device
BGS	British Geological Survey
EIA	Environmental Impact Assessment
EIAR	Environmental Impact Assessment Report
EMODnet	European Marine Observation and Data Network
FPSO	Floating Production Storage and Offloading
GIS	Geographic Information System
HF	High-Frequency Cetaceans (Marine mammal hearing group from Southall *et al.*, 2019)
INSPIRE	Impulse Noise Sound Propagation and Range Estimator (Subacoustech Environmental's noise model for estimating impact piling noise)
LF	Low-Frequency Cetaceans (Marine mammal hearing group from Southall *et al.*, 2019)
MTD	Marine Technology Directorate
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPL	National Physical Laboratory
OSP	Offshore Platform

Acronym	Definition
PCW	Phocid Carnivores in Water (Marine mammal hearing group from Southall *et al.*, 2019)
PPV	Peak Particle Velocity
PTS	Permanent Threshold Shift
RMS	Root Mean Square
SE	Sound Exposure
SEL	Sound Exposure Level
SEL$_{cum}$	Cumulative Sound Exposure Level
SEL$_{ss}$	Single Strike Sound Exposure Level
SPL	Sound Pressure Level
SPL$_{peak}$	Peak Sound Pressure Level
SPL$_{peak-to-peak}$	Peak-to-peak Sound Pressure Level
SPL$_{RMS}$	Root Mean Square Sound Pressure Level
TNT	Trinitrotoluene (explosive)
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance
VHF	Very High-Frequency Cetaceans (Marine mammal hearing group from Southall *et al.*, 2019)
WTG	Wind Turbine Generator

Technical Glossary

Term	Definition
Decibel (dB)	A customary scale commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be $10\log_{10}(actual/reference)$ where $(actual/reference)$ is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is $20\log_{10}(actual\ pressure/reference\ pressure)$. The standard reference for underwater sound is 1 micro pascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (e.g., re 1 µPa).
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Peak-to-peak pressure	The sum of the highest positive and negative pressures that are associated with a sound wave.
Permanent Threshold Shift (PTS)	A permanent total or partial loss of hearing caused by acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the air, and thus a permanent reduction of hearing acuity.
Root Mean Square (RMS)	The square root of the arithmetic average of a set of squared instantaneous values. Used for presentation of an average sound pressure level.
Sound Exposure Level (SEL)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Exposure Level, cumulative (SEL$_{cum}$)	Single value for the collected, combined total of sound exposure over a specified time or multiple instances of a noise source.
Sound Exposure Level, single strike (SEL$_{ss}$)	Calculation of the sound exposure level representative of a single noise impulse, typically a pile strike.

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Term	Definition
Sound Pressure Level (SPL)	The sound pressure level is an expression of sound pressure using the decibel (dB) scale; the standard frequency pressures of which are 1 µPa for water and 20 µPa for air.
Sound Pressure Level Peak (SPL$_{peak}$)	The highest (zero-peak) positive or negative sound pressure, in decibels.
Temporary Threshold Shift (TTS)	Temporary reduction of hearing acuity because of exposure to sound over time. Exposure to high levels of sound over relatively short time periods could cause the same level of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus.
Unweighted sound level	Sound levels which are "raw" or have not been adjusted in any way, for example to account for the hearing ability of a species.
Weighted sound level	A sound level which has been adjusted with respect to a "weighting envelope" in the frequency domain, typically to make an unweighted level relevant to a particular species. Examples of this are the dB(A), where the overall sound level has been adjusted to account for the hearing ability of humans in air, or the filters used by Southall *et al*. (2019) for marine mammals.

Units

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

1   Introduction

Arklow Bank Wind Park 2 (ABWP2) is a proposed offshore windfarm in the southern Irish Sea. As part of the Environmental Impact Assessment Report (EIAR) process, Subacoustech Environmental Ltd. has undertaken detailed modelling and analysis in relation to the effect of underwater noise on marine mammals and fish.

The Array Area for ABWP2 covers an area of 63.4 km^2 and is situated 6 to 15 km from the Wicklow coast. The proposed development has a proposed capacity of 800 Megawatt (MW), utilising either 47 or 56 wind turbine generators (WTGs). The location of ABWP2 is shown in Figure 1-1.
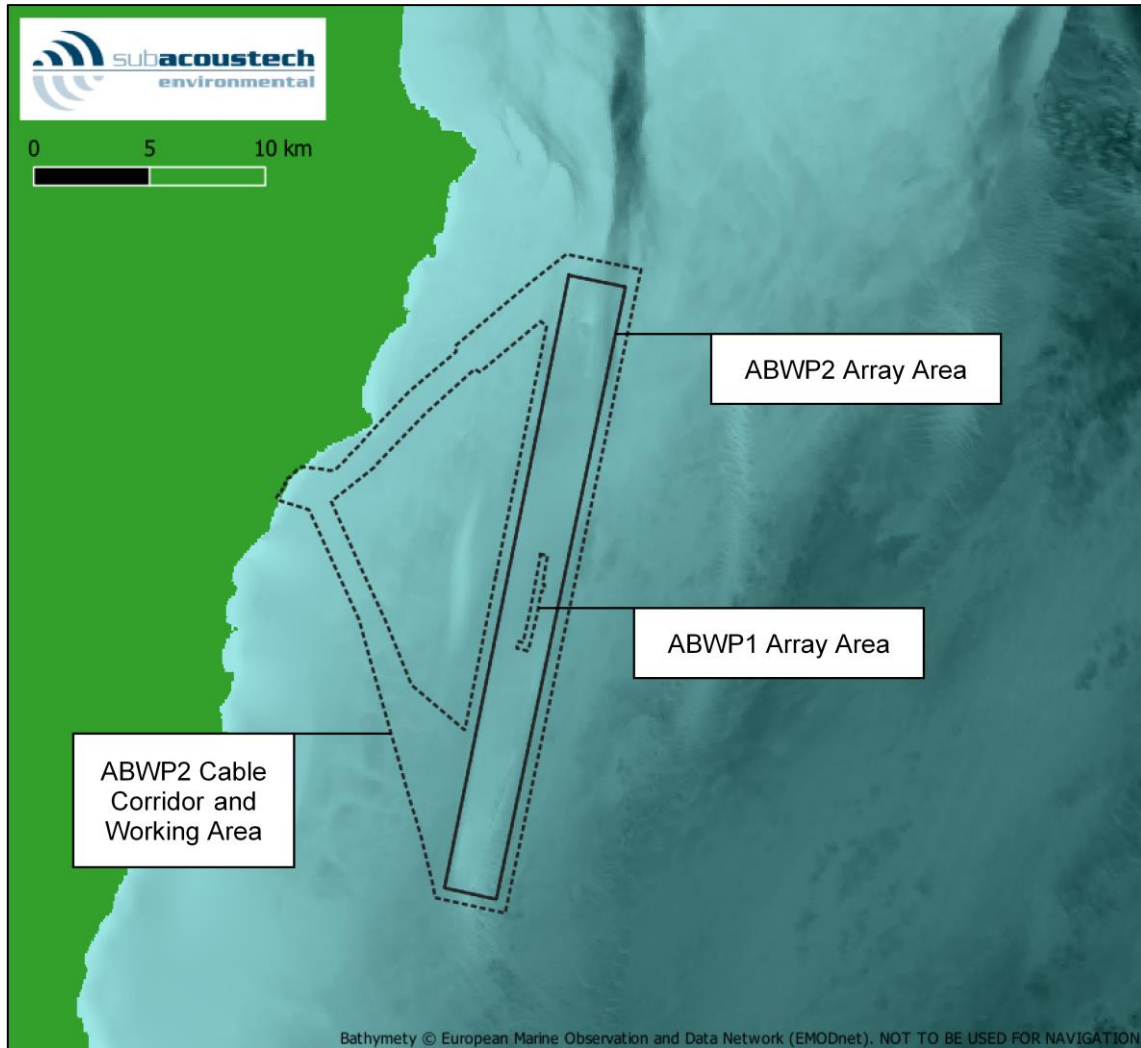
Figure 1-1 Overview map showing the ABWP2 Boundary, Cable Corridor and Working Area, and the surrounding bathymetry and coastline

This report presents a detailed assessment of the potential underwater noise during construction and operation of ABWP2, 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 and assumptions for the detailed 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)

- Noise modelling of other noise sources expected around the construction and operation of ABWP2 including cable laying, dredging, drilling, rock placement, vessel movements, operational WTG noise, and unexploded ordnance (UXO) clearance (section 5); and

- Summary and conclusions (section 6)

Further modelling results are presented in Appendix A.

2 Background to underwater noise

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.

Underwater noise levels should not be confused with noise levels in air, which use a different scale.

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 because, rather than equal increments of sound having an equal increase in effect, typically each doubling of sound level will cause a roughly equal increase of "loudness."

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

The fundamental definition of the dB scale is given by:

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

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

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

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

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

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

2.1.2 *Sound Pressure Level (SPL)*

The Sound Pressure Level (SPL) 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 can therefore be considered a measure of the average unweighted level of sound over the measurement period.

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

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

2.1.3 _Peak Sound Pressure Level (SPL$_{peak}$)_

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

A further variation of this is the peak-to-peak SPL (SPL$_{peak-to-peak}$) where the maximum variation of the pressure from positive to negative is considered. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak pressure will be twice the peak level, or 6 dB higher (see section 2.1.1).

2.1.4 _Sound Exposure Level (SEL)_

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

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

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

where p is the acoustic pressure in Pascals, T is the total duration of 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^{2}s).

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

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

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

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

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

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

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

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

Where SEL is the sound exposure level of one impulse and X is the total number of impulses or strikes.

Unless otherwise defined, all SEL noise levels in this report are referenced to 1 µPa²s.

2.2 Analysis of environmental effects

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 blasting or impact piling, as these sources are likely to have the greatest immediate environmental impact and therefore the clearest observable effects, although interest in chronic noise exposure is increasing.

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

- Physical traumatic injury and fatality;

- Auditory injury (either permanent or temporary); and

- Disturbance.

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 ABWP2.

The main metrics and criteria that have been used in this study to aid assessment of environmental effects come from three 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 relevant and authoritative criteria for assessing environmental effects for use in impact assessments.

2.2.1 *Marine mammals*

The Southall *et al*. (2019) paper provides identical thresholds to those from the National Marine Fisheries Service (NMFS) (2018) guidance for marine mammals (although it names marine mammal categories slightly differently). It updates and supersedes the methodology from the previous Southall *et al*. (2007) guidance.

The Southall *et al*. (2019) guidance groups marine mammals into categories 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 Irish Sea.

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

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

Hearing group	Generalised hearing range	Example species
Phocid carnivores in water (PCW)	50 Hz to 86 kHz	True seals (including harbour seals)
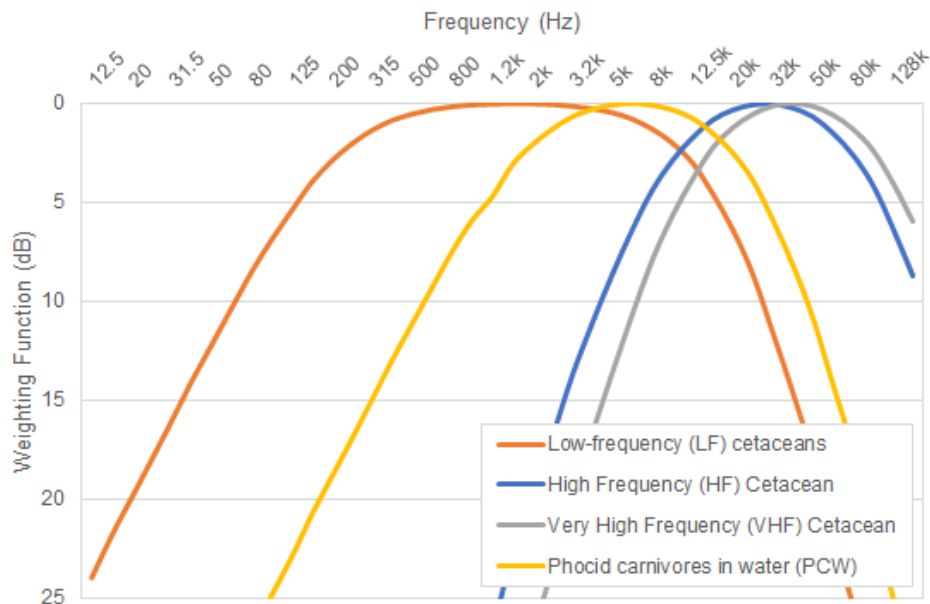
Figure 2-1 Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019)

Southall *et al*. (2019) also gives individual criteria based on whether the noise source is considered impulsive or non-impulsive. Southall *et al*. (2019) categorises impulsive noises as having high peak sound pressure, short duration, fast rise-time and broad frequency content at source, and non-impulsive sources as steady-state noise. Explosives, impact piling and seismic airguns are considered impulsive noise sources and sonars, vibro-piling, drilling and other low-level continuous noises are considered non-impulsive. A non-impulsive noise does not necessarily have to have a long duration.

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

As sound pulses propagate through the environment and dissipate, they also lose their most injurious characteristics (e.g., rapid pulse rise time and high peak sound pressure) and become more like a "non-pulse" at greater distances; Southall *et al*. (2019) briefly discusses this. Active research is currently underway into the identification of the distance at which the pulse can be considered effectively non-impulsive, and Hastie *et al*. (2019) have analysed a series of impulsive data to investigate it. Although the situation is complex, the paper reported that most of the signals crossed their threshold for rapid rise time and high peak sound pressure characteristics associated with impulsive noise at around 3.5 km from the source. Southall (2021) discusses this further and suggests that the impulsive characteristics can correspond with significant energy content of the pulse above 10 kHz. This will naturally change depending on the noise source and the environment over which it travels. To provide as much detail as possible, both impulsive and non-impulsive criteria from Southall *et al*. (2019) have been included in this study.

Although the use of impact ranges derived using the impulsive criteria are recommended for all but the clearly non-impulsive sources (such as drilling), it should be recognised that where calculated ranges are beyond 3.5 km, they would be expected to become increasingly less impulsive and harmful, and the impact range is therefore likely to be somewhere between the modelled impulsive and non-impulsive impact range. Where the impulsive impact range is significantly greater than 3.5 km, the non-impulsive range should be considered.

Table 2-2 and Table 2-3 present the unweighted SPL$_{peak}$ and weighted SEL$_{cum}$ criteria for marine mammals from Southall *et al*. (2019) covering both impulsive and non-impulsive noise.

Table 2-2 Single strike SPL$_{peak}$ criteria for PTS and TTS in marine mammals (Southall et al., 2019)

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

Table 2-3 Impulsive and non-impulsive SEL$_{cum}$ criteria for PTS and TTS in marine mammals (Southall et al., 2019)

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

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

Limited data is available for behavioural disturbance on species of marine mammal. To take this into account, the National Oceanic and Atmospheric Administration (NOAA) (2005) Level B (behavioural disturbance) harassment criterion for impulsive noise on marine mammals has been included to cover disturbance effects. This criterion is 160 dB unweighted Root Mean Square Sound Pressure Level (SPL$_{RMS}$).

2.2.2 _Fish_

The large number of, and variation in, fish species leads to a greater challenge in production of a generic noise criterion, or range of criteria, for the assessment of noise impacts. Whereas previous studies applied broad criteria based on limited studies of fish that are not present in UK waters (e.g., McCauley _et al_., 2000) or measurement data not intended to be used as criteria (Hawkins _et al_., 2014), the publication of Popper _et al_. (2014) provides an authoritative summary of the latest research and guidelines for fish exposure to sound and uses categories for fish that are representative of the species present in UK and Irish waters.

The Popper _et al_. (2014) study groups species of fish by whether they possess a swim bladder, and whether it is involved in its hearing; groups for sea turtles and fish eggs and larvae are also included. The guidance also gives specific criteria (as both unweighted SPL_{peak} and unweighted SEL_{cum} values) for a variety of noise sources. (It is recognised that these are related to sound pressure, whereas more recent documents (e.g., Popper and Hawkins, 2019) clearly state that many fish species are most sensitive to particle motion. This is discussed in section 2.2.3.)

For this study, criteria for impact piling, continuous noise sources, and explosions have been considered; these are summarised in Table 2-4 to Table 2-6.

Table 2-4 Criteria for mortality and potential mortal injury, recoverable injury, and TTS in species of fish from impact piling noise (Popper et al., 2014)

Type of animal	Mortality and potential mortal injury	Impairment	
		Recoverable injury	TTS
Fish: no swim bladder	> 219 dB SEL_{cum} > 213 dB SPL_{peak}	> 216 dB SEL_{cum} > 213 dB SPL_{peak}	>> 186 dB SEL_{cum}
Fish: swim bladder is not involved in hearing	210 dB SEL_{cum} > 207 dB SPL_{peak}	203 dB SEL_{cum} > 207 dB SPL_{peak}	> 186 dB SEL_{cum}
Fish: swim bladder involved in hearing	207 dB SEL_{cum} > 207 dB SPL_{peak}	203 dB SEL_{cum} > 207 dB SPL_{peak}	186 dB SEL_{cum}
Sea turtles	> 210 dB SEL_{cum} > 207 dB SPL_{peak}	See Table 2-7	
Eggs and larvae	> 210 dB SEL_{cum} > 207 dB SPL_{peak}		

Table 2-5 Criteria for recoverable injury and TTS in species of fish from continuous noise sources (Popper et al., 2014)

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

Table 2-6 Criteria for potential mortal injury in species of fish from explosions (Popper et al., 2014)

Type of animal	Mortality and potential mortal injury
Fish: no swim bladder	229 – 234 dB SPL_{peak}
Fish: swim bladder is not involved in hearing	229 – 234 dB SPL_{peak}
Fish: swim bladder involved in hearing	229 – 234 dB SPL_{peak}
Sea turtles	229 – 234 dB SPL_{peak}
Eggs and larvae	> 13 mm/s peak velocity

Where insufficient data are available, Popper _et al_. (2014) also gives qualitative criteria that summarise the effect of the noise as having either a high, moderate, or low effect on an individual in either the near-

field (tens of metres), intermediate-field (hundreds of metres), or far-field (thousands of metres). These qualitative effects are reproduced in Table 2-7 to Table 2-9.

Table 2-7 Summary of the qualitative effects on species of fish from impact piling noise (Popper et al., 2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
Fish: no swim bladder	See Table 2-4		(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing			(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing			(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
Sea turtles	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) High (I) Moderate (F) Low
Eggs and larvae	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

Table 2-8 Summary of the qualitative effects on fish from continuous noise from Popper et al. (2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	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 is not involved in hearing	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder involved in hearing	(N) Low (I) Low (F) Low	See Table 2-5		(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

Table 2-9 Summary of the qualitative effects on species of fish from explosions (Popper et al., 2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
Fish: no swim bladder	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) Moderate (F) Low

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Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
Fish: swim bladder is not involved in hearing	(N) High (I) High (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) High (F) Low
Fish: swim bladder involved in hearing	(N) High (I) High (F) Low	(N) High (I) High (F) Low	N/A	(N) High (I) High (F) Low
Sea turtles	(N) High (I) High (F) Low	(N) High (I) High (F) Low	N/A	(N) High (I) High (F) Low
Eggs and larvae	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low

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

Although it is feasible that some species will not flee, those that are likely to remain are thought more likely to be benthic species or species without a swim bladder; these are the least sensitive species. For example, from Popper *et al*. (2014): "There is evidence (e.g., Goertner *et al*., 1994; Stephenson *et al*., 2010; Halvorsen *et al*., 2012) that little or no damage occurs to fish without a swim bladder except at very short ranges from an in-water explosive event. Goertner (1978) showed that the range from an explosive event over which damage may occur to a non-swim bladder fish is in the order of 100 times less than that for swim bladder fish."

Stationary animal modelling has been included in this study, acknowledging the limited evidence for fish fleeing behaviour as a result of noise exposure, and other modelling for similar Environmental Impact Assessment (EIA) projects. However, basing the modelling on a stationary (zero flee speed) receptor is likely to greatly overestimate the potential risk to fish species, assuming that an individual would remain in the high noise level region of the water column for the whole duration of piling, especially when considering the precautionary nature of the parameters already built into the cumulative exposure calculations.

2.2.3 *Invertebrates*

A review by Solé *et al.* (2023) highlights that although the data on sound perception in invertebrates is scarce (see also ABPmer, 2023), there is 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 passing 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 SEL$_{ss}$ 153.5 dB re 1 µPa^{2}s. These inconsistencies make it

difficult to generate accurate thresholds for the onset of any impact for species. Gastropod species[1] showed effects ranging from changes in movement to cell damage and larva mortality, although numerical noise data at which these could occur is frequently not available. A notable exception is the cephalopods group, which, in several studies, mainly by Solé *et al*. (2019, 2018, 2013) and André *et al*. (2011) show a consistent threshold for auditory damage on various species of cephalopod at 157 dB re 1 μPa^2s (SEL_{ss}). 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. However, it cannot be ignored that convincing evidence of noise impacts to marine invertebrates does exist. The data available could potentially be referenced for some species but with caution, as there are still considerable gaps in the knowledge that would enable reliable conclusions for the impact of noise for most species.

2.2.4 *Particle motion*

The criteria defined in the above section define the noise impacts on fishes in terms of sound pressure or sound pressure-associated functions (i.e., SEL). It has been identified by researchers (e.g., Popper and Hawkins, 2019; Nedelec *et al*., 2016; Radford *et al.,* 2012) that many species of fish, as well as invertebrates, actually detect particle motion rather than acoustic pressure. Particle motion describes the back-and-forth movement of a tiny theoretical 'element' of water, substrate or other media as a sound wave passes, rather than the pressure caused by the action of the force created by this movement. Particle motion 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. Note that species in the "Fish: swim bladder involved in hearing" category, the species most sensitive to noise, are sensitive to sound pressure.

Popper and Hawkins (2018) state that in derivation of the sound pressure-based criteria in Popper *et al.* (2014) it may be the unmeasured particle motion detected by the fish, to which the fish were responding: there is a relationship between particle motion and sound pressure in a medium. This relationship is very difficult to define where the sound field is complex, such as close to the noise source or where there are multiple reflections of the sound wave in shallow water. Even these terms "shallow" and "close" do not have simple definitions.

The primary reason for the continuing use of sound pressure as the criteria, despite particle motion appearing to be the physical measure to which so many fish react or sense, is a lack of data (Popper and Hawkins, 2018) both in respect of predictions of the particle motion level as a consequence of a noise source such as piling, and a lack of knowledge of the sensitivity of a fish, or a wider category of fish, to a particle motion value. There continue to be calls for additional research on the levels of and

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[1] It is understood the gastropod species whelk (family *Buccinum*) is of particular concern in the region of Arklow Bank. No specific data is available for this species.

effects with respect to levels of particle motion. Until sufficient data are available to enable revised thresholds based on the particle motion metric, Popper and Hawkins, 2019 states that "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."

2.2.5 *Seabed vibration*

Vibration is commonly mentioned in association with noise and would typically be thought of as the movement of a solid surface (or substrate), which either radiates sound into an adjacent fluid medium (e.g. the vibration of the surface of a foundation pile transmitting sound into water) and propagates further, or affects a receptor directly connected to it.

High intensity sources that directly affect the seabed, such as impact piling, will also generate vibration and be transmitted through the substrate. This has the potential to affect benthic and demersal species (Roberts and Elliott, 2017; Popper and Hawkins, 2019). While the presence of vibration during piling is expected, an assessment of this has the same limitations as those for particle motion in fish, as little is known of the quantitative influence of the vibration source, or of the sensitivity of relevant species to it.

3   Modelling methodology

To estimate the underwater noise levels likely to arise during the construction and operation of ABWP2, 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).

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). As such, the noise related to impact piling activities is the primary focus of this study.

The modelling of impact piling has been undertaken using the INSPIRE underwater noise model, developed by Subacoustech Environmental. The INSPIRE model (currently version 5.2) 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 (i.e., less than 100 m), mixed water; typical of the conditions around Ireland and the UK, and well suited for use in the Irish Sea. The model has been tuned for accuracy using over 80 datasets of underwater noise propagation from monitoring around offshore piling activities.

The model provides estimates of unweighted SPL_{peak}, SEL_{ss} and SEL_{cum} noise levels, as well as various 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 Geographic Information System (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 impact piling that may be present during the construction and operation of ABWP2; these are discussed in section 5.

3.1   Modelling confidence

INSPIRE is semi-empirical, as such, a validation process is inherently built into the development process. Whenever a new set of good, reliable, impact piling measurement data is gathered through offshore surveys it is compared against the outputted levels from INSPIRE and, if necessary, the model can be adjusted. Currently over 80 separate impact piling noise datasets primarily from piling in the Irish Sea and North Sea have been used as part of the development for the latest version of INSPIRE, and in each case, an average fit is used.

In addition, 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).

The current version of INSPIRE (version 5.2) 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 conditions.

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. 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 SEL_{cum}. With this in mind, the current version of INSPIRE attempts to calculate closer to the average fit of the measured noise levels at all ranges.

Figure 3-1 presents 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 v5.2, matching the pile size, blow energy and position of the measured data. These show the fit to the data, with the INSPIRE data points sitting, more or less, in the middle of the measured noise levels at each range. 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, where the influence on the SEL_{cum} will be minimal.
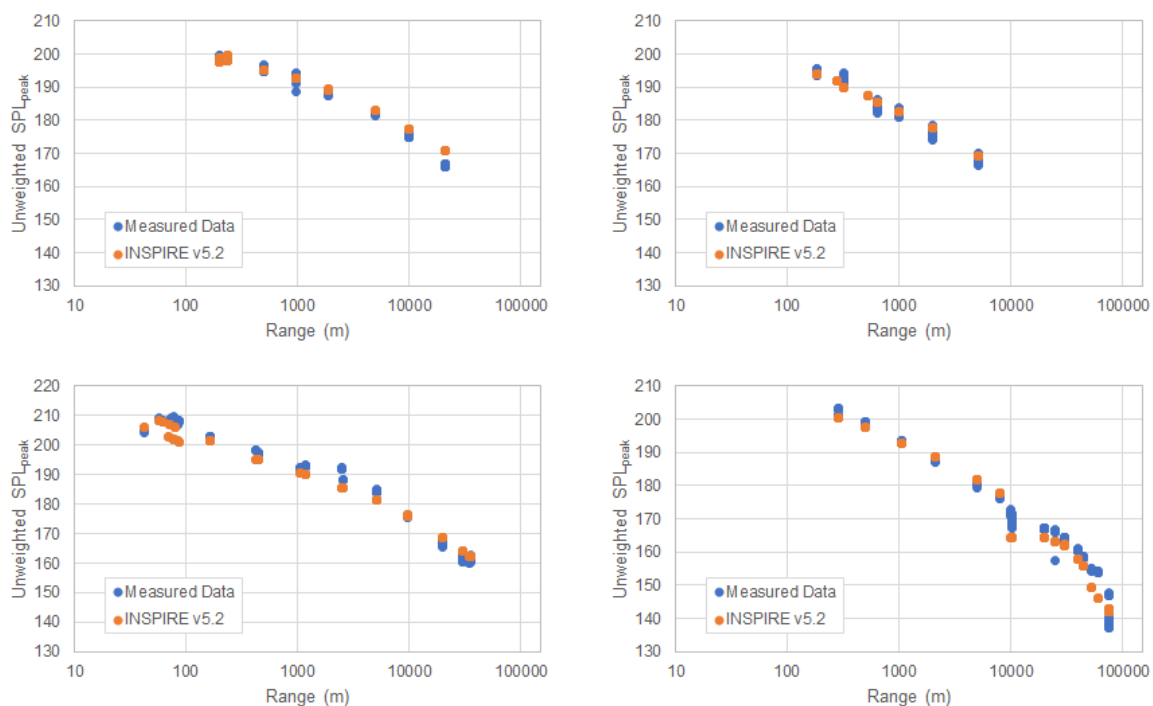
Figure 3-1 Comparison between example measured impact piling data (blue points) and modelled data using INSPIRE version 5.2 (orange points)[2].

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[2] Top Left: 6.0 m pile, off the Suffolk coast, North Sea, 2009; Top Right: 1.8 m pile, West of Barrow-in-Furness, Irish Sea, 2010; Bottom Left: 5.3 m pile, off the North Welsh coast, 2012; Bottom Right: 6.0 m pile, off the coast of Cumbria, 2010.

3.2 Modelling parameters

3.2.1 Modelling locations

Modelling for WTG and Offshore Platform (OSP) foundation impact piling has been undertaken at a total of five representative locations covering the extents of the ABWP2 site. The locations were chosen to give the greatest geographical spread to maximise the potential impact ranges to the north and the south of the site. These locations are summarised in Table 3-1 and illustrated in Figure 3-2.

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

Modelling locations	Latitude	Longitude	Water depth
North West (NW) WTG	52.91636 N	005.93213 W	18.7 m
Centre (C) WTG	52.79306 N	005.93687 W	35.6 m
South West (SW) WTG	52.68177 N	005.99187 W	30.3 m
North OSP	52.90933 N	005.92903 W	24.4 m
South OSP	52.68553 N	005.98133 W	26.3 m
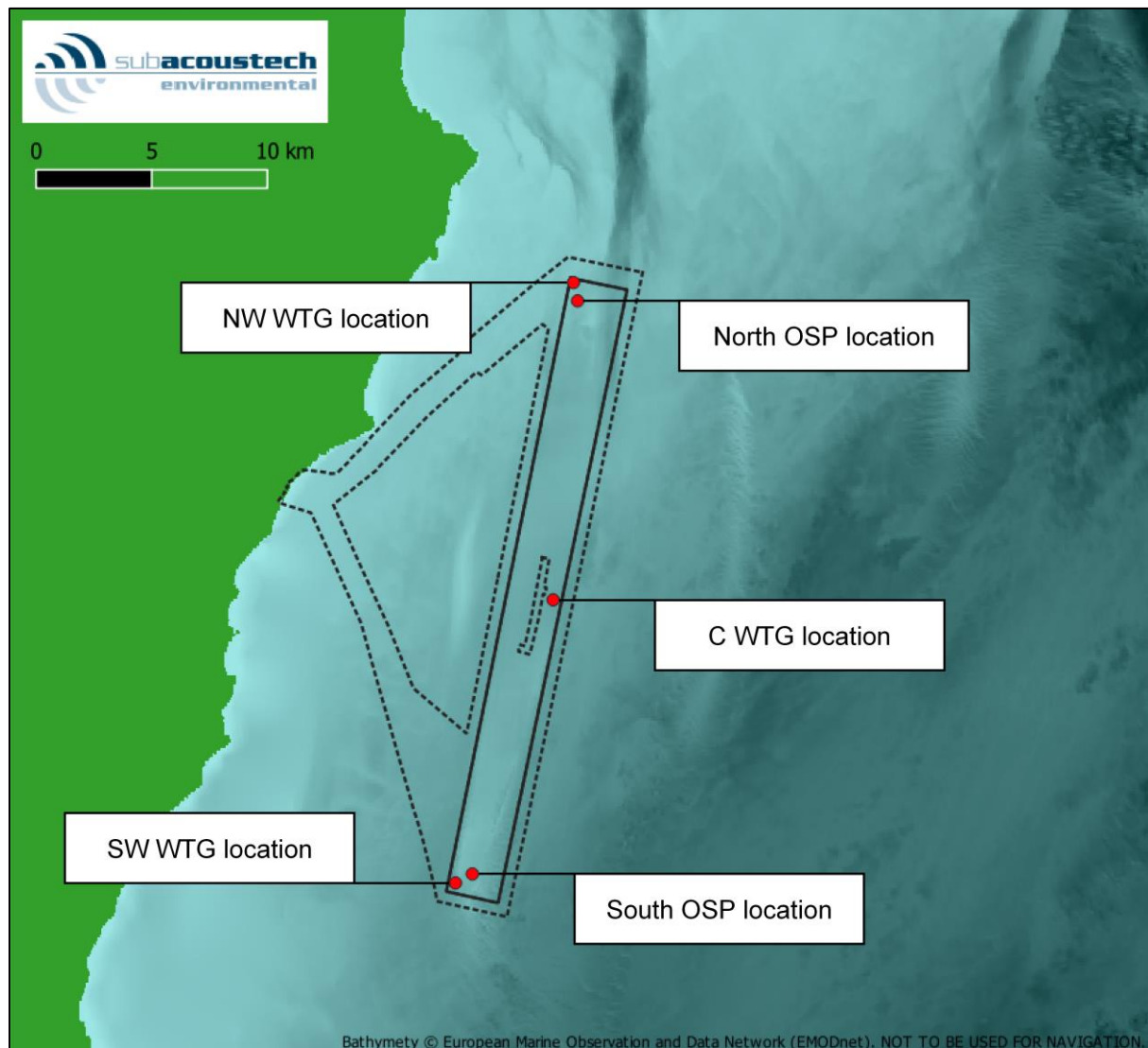
Figure 3-2 Positions of the modelling locations at ABWP2

3.2.2   *WTG and OSP foundation and impact piling parameters*

For each location, two foundation scenarios have been considered to cover the foundation options for this study, including large (11 m diameter for WTG and 14 m diameter for OSP) monopiles and smaller (7 m diameter) monopiles. Maximum hammer energies have been identified in engineering estimates relevant to each piling location. These are proposed for different locations within the site. In summary these are:

- 11 m and 7 m monopile foundations at the NW and C WTG locations, installed with a maximum blow energy of 4,000 kJ;

- 11 m and 7 m monopile foundations at the SW WTG location, installed with a maximum blow energy of 6,600 kJ;

- 14 m and 7 m monopile foundations at the North OSP location, installed with a maximum blow energy of 4,000 kJ; and

- 14 m and 7 m monopile foundations at the South OSP location, installed with a maximum blow energy of 6,600 kJ.

For SEL_{cum} criteria, the soft start and ramp up of blow energies along with the total duration of piling and strike rate must also be considered. The soft start and ramp up have been designed to reduce the cumulative effect on marine fauna, especially by minimising the blow energy and strike rate at the start of the piling event. The scenarios used for modelling are summarised in Table 3-2 to Table 3-5.

Table 3-2 Summary of the soft start and ramp up scenario used for both the 11 m and 7 m monopile foundation modelling at the NW and C WTG locations

	825 kJ		1,550 kJ	2,275 kJ	3,000 kJ	3,300 kJ	3,600 kJ	4,000 kJ
Number of strikes	6	600	400	400	400	450	450	3,300
Duration	10 min	20 min	13 min 20 sec	13 min 20 sec	13 min 20 sec	15 min	15 min	110 min
Strike rate	0.6 bl/min	30 blows/minute						
6,006 strikes, 3 hours 30 minutes duration								

Table 3-3 Summary of the soft start and ramp up scenario used for the 11 m and 7 m monopile foundation modelling at the SW WTG location

	825 kJ		1,550 kJ	2,275 kJ	3,000 kJ	4,000 kJ	4,450 kJ	6,600 kJ
Number of strikes	6	600	400	400	400	2,750	450	4,000
Duration	10 min	20 min	13 min 20 sec	13 min 20 sec	13 min 20 sec	91 min 40 sec	15 min	133 min 20 s
Strike rate	0.6 bl/min	30 blows/minute						
9,006 strikes, 5 hours 10 minutes duration								

Table 3-4 Summary of the soft start and ramp up scenario used for both the 14 m and 7 m monopile foundation modelling at the North OSP location

	825 kJ		1,550 kJ	2,275 kJ	3,000 kJ	3,300 kJ	3,600 kJ	4,000 kJ
Number of strikes	6	600	400	400	400	450	450	3,300
Duration	10 min	20 min	13 min 20 sec	13 min 20 sec	13 min 20 sec	15 min	15 min	110 min
Strike rate	0.6 bl/min	30 blows/minute						
6,006 strikes, 3 hours 30 minutes duration								

Table 3-5 Summary of the soft start and ramp up scenario used for both the 14 m and 7 m monopile foundation modelling at the South OSP location

	825 kJ		1,550 kJ	2,275 kJ	3,000 kJ	4,000 kJ	4,450 kJ	6,600 kJ
Number of strikes	6	600	400	400	400	2,750	450	4,000
Duration	10 min	20 min	13 min 20 sec	13 min 20 sec	13 min 20 sec	91 min 40 sec	15 min	133 min 20 s
Strike rate	0.6 bl/min	30 blows/minute						
9,006 strikes, 5 hours 10 minutes duration								

3.2.3   Source levels

Noise modelling requires knowledge of the source level, which is the theoretical noise level at one metre from the noise source. The INSPIRE model assumes that the noise source – that is, the hammer striking the pile – acts as an effective single point, as it will appear at long distance. The source level 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 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.

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). 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 sound propagation model), as required in impact assessments.

The unweighted, single strike SPL_{peak} and SEL_{ss} source levels estimated for this study are provided in Table 3-6, based on the maximum blow energy. These figures are in line with what has been previously requested by regulatory authorities in England, Scotland and Wales and have been presented as it is not yet known what requirements are expected by Irish regulatory authorities. As indicated above they are not necessarily compatible or comparable with any other model or predicted source level. In each case, the differences in source level for each location are minimal.

Table 3-6 Summary of the unweighted source levels used for modelling, maximum blow energy

Source levels	Location	Large monopile foundation 11 m / 4,000 kJ (NW and C WTG) 11 m / 6,600 kJ (SW WTG) 14 m / 4,000 kJ (North OSP) 14 m / 6,600 kJ (South OSP)	Smaller monopile foundation 7 m / 4,000 kJ (NW, C WTG and North OSP) 7 m / 6,600 kJ (SW WTG and South OSP)
Unweighted SPL$_{peak}$	NW WTG	242.4 dB re 1 µPa @ 1 m	242.2 dB re 1 µPa @ 1 m
	C WTG	242.4 dB re 1 µPa @ 1 m	242.4 dB re 1 µPa @ 1 m
	SW WTG	243.1 dB re 1 µPa @ 1 m	243.1 dB re 1 µPa @ 1 m
	North OSP	242.4 dB re 1 µPa @ 1 m	242.4 dB re 1 µPa @ 1 m
	South OSP	243.1 dB re 1 µPa @ 1 m	243.0 dB re 1 µPa @ 1 m
Unweighted SEL$_{ss}$	NW WTG	223.5 dB re 1 µPa^{2}s @ 1 m	223.1 dB re 1 µPa^{2}s @ 1 m
	C WTG	223.5 dB re 1 µPa^{2}s @ 1 m	223.4 dB re 1 µPa^{2}s @ 1 m
	SW WTG	224.3 dB re 1 µPa^{2}s @ 1 m	224.3 dB re 1 µPa^{2}s @ 1 m
	North OSP	223.5 dB re 1 µPa^{2}s @ 1 m	223.4 dB re 1 µPa^{2}s @ 1 m
	South OSP	224.3 dB re 1 µPa^{2}s @ 1 m	224.3 dB re 1 µPa^{2}s @ 1 m

3.2.4 *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, as well as the sediment type surrounding the site. Data from the British Geological Survey (BGS) show that the seabed in and around ABWP2 is generally made up of variations of gravel, sand, and muddy sand, which are typical of the seabed conditions at which many of the measurements of piling included in the INSPIRE model have been sampled (McBreen *et al.*, 2011).

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

3.3 Cumulative SELs and fleeing receptors

Expanding on the information in section 2.2 regarding SEL$_{cum}$ criteria and the fleeing animal model used for modelling, it is important to understand the meaning of the results presented in the following sections.

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

To help explain this, it is helpful to examine how the multiple pulse SEL$_{cum}$ ranges are calculated. As explained in section 2.1.4, the SEL$_{cum}$ is a measure of the total received noise over a whole operation: in the cases of the Southall *et al*. (2019) and Popper *et al*. (2014) criteria, this covers noise in a 24-hour period unless otherwise specified.

When considering a stationary receptor (i.e., one that stays at the same position throughout piling), calculating the SEL$_{cum}$ is straightforward: all the noise levels produced and received at a single point along a transect are aggregated to calculate the SEL$_{cum}$. If this calculated level is greater than the threshold being modelled, the model steps from the noise source and the noise levels from that new location are aggregated to calculate a new SEL$_{cum}$. 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 starting point close to the source is chosen and the received noise level for each noise event (e.g., pile strike) while the receptor is fleeing is noted. For example, if a noise event

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 SEL_{cum} value over the entire operation. The faster an animal is fleeing the greater distance travelled between noise events. 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 in Figure 3-3 and Figure 3-4 show the difference in the received SEL from a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 m/s, using the 11 m monopile foundation scenario at the SE WTG location.

The received SEL_{ss} from the stationary receptor, as illustrated in Figure 3-3, 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 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 minutes of the piling scenario, during the slow start where the blow energy is 660 kJ, at a rate of 1.5 m/s, the fleeing receptor will have moved 0.9 km away. After the full piling installation of more than five hours, the receptor will be almost 28 km from the pile.

Figure 3-4 shows the effect these different received levels have when calculating the SEL_{cum}. It clearly shows the difference in cumulative effect of the 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 218.3 dB re 1 $\mu Pa^2 s$. If the receptor were to remain stationary throughout the piling operation it would receive a cumulative level of 262.7 dB re 1 $\mu Pa^2 s$, whereas when fleeing at 1.5 m/s over the same scenario would result in a cumulative received level of just 218.5 dB re 1 $\mu Pa^2 s$ for the receptor.
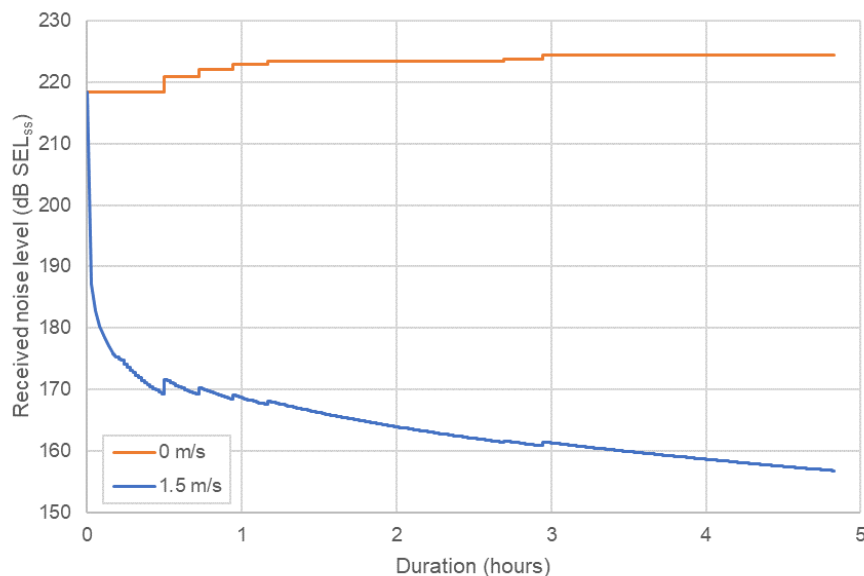
Figure 3-3 Received single-strike noise levels (SEL$_{ss}$) for receptors using the 11 m monopile foundation installation parameters at the SE location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source
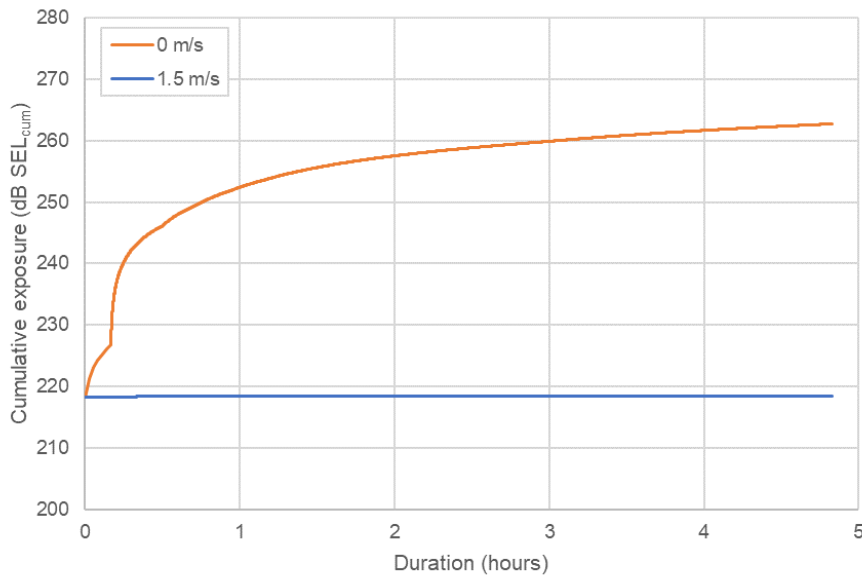
Figure 3-4 Cumulative received noise levels (SEL_cum) for receptors using the 11 m monopile foundation installation parameters at the SE location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source

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 criteria, and if the receptor were to start fleeing from a range further than the modelled value it would receive a noise exposure below the criteria. This is illustrated in Figure 3-5.
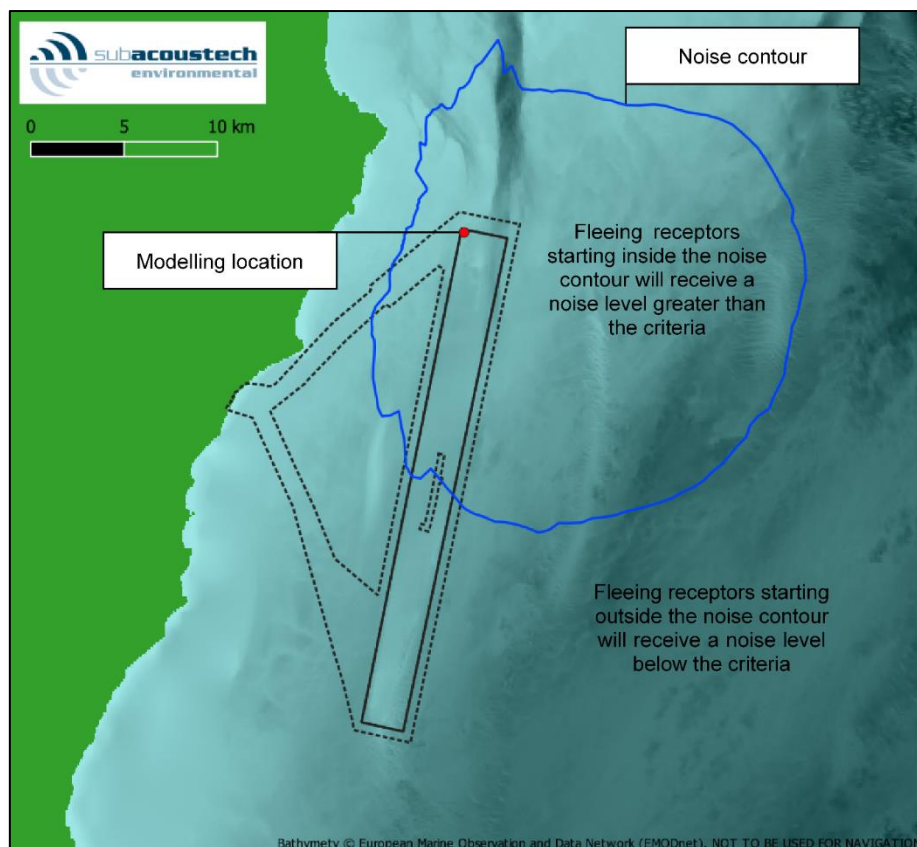
Figure 3-5 Plot showing a fleeing animal SEL_cum criteria contour and the areas where the cumulative noise exposure will exceed the impact criteria

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 modelling approach does not include this, however the effects 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 cumulative SEL impact range from INSPIRE was calculated to be below 1.8 km, it can safely be assumed that the ADD will be effective in eliminating the risk of injury on the receptor. The noise from an ADD is of a much lower level than impact piling, and as such the overall effect on the SEL_{cum} exposure on a receptor would be minimal.

3.3.1 *The effects of input parameters on SELs and fleeing receptors*

As discussed in section 3.2.2, parameters such as bathymetry, hammer blow energies, piling ramp up, strike rate and duration all have an effect on predicted noise levels. When considering SEL_{cum} and a fleeing animal model, some of these parameters can have a greater influence than others.

Parameters like hammer blow energy can have a clear effect on impact ranges, with higher energies resulting in higher 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 low blow energies to higher ones requires careful consideration for fleeing animals, as the levels while the receptors are relatively close 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 on the SEL_{cum}. The faster the strike rate, the shorter the distance the receptor can flee between each pile strike, which leads to greater exposure.

4 Modelling results

This section presents the modelled impact ranges for impact piling noise following the parameters detailed in section 3.2, covering the Southall *et al*. (2019) marine mammal criteria (section 2.2.1) and the Popper *et al*. (2014) fish criteria (section 2.2.2). To aid navigation, Table 4-1 contains a list of the impact range tables included in this section. The biggest modelled ranges are predicted for the larger monopile scenarios at the SW and South OSP locations due to the combination of larger blow energies used and the proximity to deep water out to the south and east of the site.

For marine mammals, the maximum PTS injury ranges are predicted for LF cetaceans using the SEL_{cum} criteria, with ranges of up to 19 km. For VHF cetaceans, PTS ranges are predicted up to 10 km for the same scenario.

For fish, the largest recoverable injury ranges (203 dB SEL_{cum} threshold) are predicted to be 7.9 km assuming a stationary receptor; if a fleeing animal is assumed, these ranges reduce to less than 100 m. Maximum TTS ranges (186 dB SEL_{cum} threshold) are predicted up to 50 km for a stationary animal, reducing to 36 km for a fleeing animal.

The modelling results for the Southall *et al*. (2019) non-impulsive criteria are presented in Appendix A.

For the results presented 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. 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 pile. These ranges are given as "less than" this limit (e.g., "<100 m").

Table 4-1 Summary of the impact piling modelling results tables presented in this section

Table (page)	Parameters (section)		Criteria	
Table 4-3 (p24)	NW WTG location (4.2)	11 m monopile, 4,000 kJ (4.2.1)	Southall *et al*. (2019)	Unweighted SPL_{peak} (Impulsive)
Table 4-4 (p24)				Weighted SEL_{cum} (Impulsive)
Table 4-5 (p24)			NOAA (2005)	Unweighted SPL_{RMS} (Level B)
Table 4-6 (p24)			Popper *et al*. (2014)	Unweighted SPL_{peak} (Pile driving)
Table 4-7 (p24)				Unweighted SEL_{cum} (Pile driving)
Table 4-8 (p25)		7 m monopile, 4,000 kJ (4.2.2)	Southall *et al*. (2019)	Unweighted SPL_{peak} (Impulsive)
Table 4-9 (p25)				Weighted SEL_{cum} (Impulsive)
Table 4-10 (p25)			NOAA (2005)	Unweighted SPL_{RMS} (Level B)
Table 4-11 (p25)			Popper *et al*. (2014)	Unweighted SPL_{peak} (Pile driving)
Table 4-12 (p26)				Unweighted SEL_{cum} (Pile driving)
Table 4-13 (p26)	C WTG location (4.3)	11 m monopile, 4,000 kJ (4.3.1)	Southall *et al*. (2019)	Unweighted SPL_{peak} (Impulsive)
Table 4-14 (p26)				Weighted SEL_{cum} (Impulsive)
Table 4-15 (p26)			NOAA (2005)	Unweighted SPL_{RMS} (Level B)
Table 4-16 (p27)			Popper *et al*. (2014)	Unweighted SPL_{peak} (Pile driving)
Table 4-17 (p27)				Unweighted SEL_{cum} (Pile driving)
Table 4-18 (p27)		7 m monopile, 4,000 kJ (4.3.2)	Southall *et al*. (2019)	Unweighted SPL_{peak} (Impulsive)
Table 4-19 (p27)				Weighted SEL_{cum} (Impulsive)
Table 4-20 (p28)			NOAA (2005)	Unweighted SPL_{RMS} (Level B)
Table 4-21 (p28)			Popper *et al*. (2014)	Unweighted SPL_{peak} (Pile driving)
Table 4-22 (p28)				Unweighted SEL_{cum} (Pile driving)
Table 4-23 (p28)	SW WTG location (4.4)	11 m monopile, 6,600 kJ (4.4.1)	Southall *et al*. (2019)	Unweighted SPL_{peak} (Impulsive)
Table 4-24 (p29)				Weighted SEL_{cum} (Impulsive)
Table 4-25 (p29)			NOAA (2005)	Unweighted SPL_{RMS} (Level B)
Table 4-26 (p29)			Popper *et al*. (2014)	Unweighted SPL_{peak} (Pile driving)
Table 4-27 (p29)				Unweighted SEL_{cum} (Pile driving)
Table 4-28 (p29)		7 m monopile,	Southall *et al*. (2019)	Unweighted SPL_{peak} (Impulsive)
Table 4-29 (p30)				Weighted SEL_{cum} (Impulsive)
Table 4-30 (p30)			NOAA (2005)	Unweighted SPL_{RMS} (Level B)

Table (page)	Parameters (section)		Criteria
Table 4-31 (p30)	6,600 kJ (4.4.2)	Popper *et al.* (2014)	Unweighted SPL_{peak} (Pile driving)
Table 4-32 (p30)			Unweighted SEL_{cum} (Pile driving)
Table 4-33 (p31)	14 m monopile, 4,000 kJ (4.5.1)	Southall *et al.* (2019)	Unweighted SPL_{peak} (Impulsive)
Table 4-34 (p31)			Weighted SEL_{cum} (Impulsive)
Table 4-35 (p31)		NOAA (2005)	Unweighted SPL_{RMS} (Level B)
Table 4-36 (p31)		Popper *et al.* (2014)	Unweighted SPL_{peak} (Pile driving)
Table 4-37 (p31)			Unweighted SEL_{cum} (Pile driving)
Table 4-38 (p32)	7 m monopile, 4,000 kJ (4.5.2)	Southall *et al.* (2019)	Unweighted SPL_{peak} (Impulsive)
Table 4-39 (p32)			Weighted SEL_{cum} (Impulsive)
Table 4-40 (p32)		NOAA (2005)	Unweighted SPL_{RMS} (Level B)
Table 4-41 (p32)		Popper *et al.* (2014)	Unweighted SPL_{peak} (Pile driving)
Table 4-42 (p33)			Unweighted SEL_{cum} (Pile driving)
Table 4-43 (p33)	14 m monopile, 6,600 kJ (4.6.1)	Southall *et al.* (2019)	Unweighted SPL_{peak} (Impulsive)
Table 4-44 (p33)			Weighted SEL_{cum} (Impulsive)
Table 4-45 (p33)		NOAA (2005)	Unweighted SPL_{RMS} (Level B)
Table 4-46 (p34)		Popper *et al.* (2014)	Unweighted SPL_{peak} (Pile driving)
Table 4-47 (p34)			Unweighted SEL_{cum} (Pile driving)
Table 4-48 (p34)	7 m monopile, 6,600 kJ (4.6.2)	Southall *et al.* (2019)	Unweighted SPL_{peak} (Impulsive)
Table 4-49 (p34)			Weighted SEL_{cum} (Impulsive)
Table 4-50 (p35)		NOAA (2005)	Unweighted SPL_{RMS} (Level B)
Table 4-51 (p35)		Popper *et al.* (2014)	Unweighted SPL_{peak} (Pile driving)
Table 4-52 (p35)			Unweighted SEL_{cum} (Pile driving)

Note: "North OSP location (4.5)" spans Table 4-33 to Table 4-42. "South OSP location (4.6)" spans Table 4-43 to Table 4-52.

4.1 Predicted noise levels at 750 m from the noise source

In addition to the source levels given in section 3.2.3, it is useful to look at the potential noise levels at a range of 750 m from the noise source, which although not a requirement in the Irish sector, is a common consideration for underwater noise studies at offshore windfarms. It has the added advantage of being comparable with other modelling or on-site measurements. A summary of the modelled unweighted levels at a range of 750 m are given in Table 4-2 considering the transect with the greatest noise transmission at each location while piling at the maximum hammer energy. These show the variation between the different locations, but that there is only a minimal difference between the different monopile diameters.

Table 4-2 Summary of the maximum predicted unweighted SPL_{peak} and SEL_{ss} noise levels at a range of 750 m from the noise source when considering maximum hammer blow energy

Predicted level at 750 m range	Location	Large monopile foundation 11 m / 4,000 kJ (NW and C WTG) 11 m / 6,600 kJ (SW WTG) 14 m / 4,000 kJ (North OSP) 14 m / 6,600 kJ (South OSP)	Smaller monopile foundation 7 m / 4,000 kJ (NW, C WTG and North OSP) 7 m / 6,600 kJ (SW WTG and South OSP)
Unweighted SPL_{peak}	NW WTG	200.3 dB re 1 µPa	200.3 dB re 1 µPa
	C WTG	202.4 dB re 1 µPa	202.4 dB re 1 µPa
	SW WTG	203.1 dB re 1 µPa	203.0 dB re 1 µPa
	North OSP	201.1 dB re 1 µPa	201.1 dB re 1 µPa
	South OSP	202.3 dB re 1 µPa	202.3 dB re 1 µPa
Unweighted SEL_{ss}	NW WTG	181.5 dB re 1 µPa	181.5 dB re 1 µPa
	C WTG	183.5 dB re 1 µPa	183.5 dB re 1 µPa
	SW WTG	184.3 dB re 1 µPa	184.2 dB re 1 µPa
	North OSP	182.3 dB re 1 µPa	182.2 dB re 1 µPa
	South OSP	183.7 dB re 1 µPa	183.6 dB re 1 µPa

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4.2 NW WTG location

4.2.1 11 m monopile foundation

Table 4-3 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 11 m monopile foundation modelling at the NW WTG location

Southall *et al.* (2019) Unweighted SPL_{peak}		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.73 km²	500 m	480 m	480 m
	PCW (218 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.03 km²	90 m	90 m	90 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	4.3 km²	1.2 km	1.1 km	1.2 km
	PCW (212 dB)	0.04 km²	110 m	110 m	110 m

Table 4-4 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 11 m monopile foundation modelling at the NW WTG location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	58 km²	7.6 km	200 m	3.4 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	31 km²	4.6 km	1.1 km	2.9 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	4,500 km²	63 km	3.5 km	30 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	2,000 km²	42 km	4.4 km	22 km
	PCW (170 dB)	380 km²	18 km	2.8 km	9.8 km

Table 4-5 Summary of the unweighted SPL_{RMS} impact ranges for marine mammals using the NOAA (2005) impulsive criteria for the 11 m monopile foundation modelling at the NW WTG location

NOAA (2005) Unweighted SPL_{RMS}		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	980 km²	26 km	5.9 km	16 km

Table 4-6 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the 11 m monopile foundation modelling at the NW WTG location

Popper *et al.* (2014) Unweighted SPL_{peak}	Area	Maximum range	Minimum range	Mean range
213 dB	0.03 km²	90 m	90 m	90 m
207 dB	0.16 km²	230 m	230 m	230 m

Table 4-7 Summary of the unweighted SEL_{cum} impact ranges for marine mammals using the Popper et al. (2014) pile driving criteria for the 11 m monopile foundation modelling at the NW WTG location assuming both fleeing and stationary animals

Popper *et al.* (2014) Unweighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	440 km²	19 km	2.8 km	10 km

Popper *et al.* (2014) Unweighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
Stationary (0 m/s)	219 dB	0.6 km²	500 m	400 m	440 m
	216 dB	1.3 km²	700 m	600 m	700 m
	210 dB	6.8 km²	1.6 km	1.4 km	1.5 km
	207 dB	15 km²	2.4 km	2.0 km	2.2 km
	203 dB	42 km²	4.1 km	3.2 km	3.6 km
	186 dB	1,200 km²	29 km	5.8 km	18 km

4.2.2   7 m monopile foundation

Table 4-8 Summary of the unweighted SPL$_{peak}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 7 m monopile foundation modelling at the NW WTG location

Southall *et al.* (2019) Unweighted SPL$_{peak}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.7 km²	490 m	470 m	480 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.03 km²	90 m	90 m	90 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	4.2 km²	1.2 km	1.1 km	1.2 km
	PCW (212 dB)	0.03 km²	110 m	110 m	110 m

Table 4-9 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 7 m monopile foundation modelling at the NW WTG location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	56 km²	7.5 km	200 m	3.4 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	31 km²	4.6 km	1.1 km	2.9 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	4,500 km²	63 km	3.5 km	30 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	2,000 km²	42 km	4.4 km	22 km
	PCW (170 dB)	380 km²	18 km	2.8 km	9.7 km

Table 4-10 Summary of the unweighted SPL$_{RMS}$ impact ranges for marine mammals using the NOAA (2005) impulsive criteria for the 7 m monopile foundation modelling at the NW WTG location

NOAA (2005) Unweighted SPL$_{RMS}$		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	970 km²	25 km	5.9 km	16 km

Table 4-11 Summary of the unweighted SPL$_{peak}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the 7 m monopile foundation modelling at the NW location

Popper *et al.* (2014) Unweighted SPL$_{peak}$	Area	Maximum range	Minimum range	Mean range
213 dB	0.03 km²	90 m	90 m	90 m
207 dB	0.16 km²	230 m	220 m	230 m

Table 4-12 Summary of the unweighted SEL$_{cum}$ impact ranges for marine mammals using the Popper et al. (2014) pile driving criteria for the 7 m monopile foundation modelling at the NW WTG location assuming both fleeing and stationary animals

Popper *et al.* (2014) Unweighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	420 km^2	19 km	2.7 km	10 km
Stationary (0 m/s)	219 dB	0.6 km^2	500 m	400 m	400 m
	216 dB	1.3 km^2	700 m	600 m	600 m
	210 dB	6.5 km^2	1.5 km	1.4 km	1.4 km
	207 dB	15 km^2	2.4 km	2.0 km	2.2 km
	203 dB	41 km^2	4.0 km	3.2 km	3.6 km
	186 dB	1,200 km^2	28 km	5.8 km	18 km

4.3   C WTG location

4.3.1   11 m monopile foundation

Table 4-13 Summary of the unweighted SPL$_{peak}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 11 m monopile foundation modelling at the C WTG location

Southall *et al.* (2019) Unweighted SPL$_{peak}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.5 km^2	700 m	690 m	690 m
	PCW (218 dB)	0.01 km^2	50 m	50 m	50 m
TTS	LF (213 dB)	0.04 km^2	120 m	120 m	120 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	9.5 km^2	1.8 km	1.7 km	1.7 km
	PCW (212 dB)	0.06 km^2	140 m	140 m	140 m

Table 4-14 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 11 m monopile foundation modelling at the C WTG location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	400 km^2	17 km	3.2 km	10 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	150 km^2	9.1 km	3.7 km	6.6 km
	PCW (185 dB)	0.3 km^2	500 m	< 100 m	300 m
TTS	LF (168 dB)	8,500 km^2	86 km	8.3 km	43 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	4,500 km^2	56 km	8.9 km	33 km
	PCW (170 dB)	1,500 km^2	32 km	7.2 km	20 km

Table 4-15 Summary of the unweighted SPL$_{RMS}$ impact ranges for marine mammals using the NOAA (2005) impulsive criteria for the 11 m monopile foundation modelling at the C WTG location

NOAA (2005) Unweighted SPL$_{RMS}$		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	2,300 km^2	37 km	11 km	25 km

Table 4-16 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the 11 m monopile foundation modelling at the C WTG location

Popper *et al.* (2014) Unweighted SPL_{peak}	Area	Maximum range	Minimum range	Mean range
213 dB	0.04 km²	120 m	120 m	120 m
207 dB	0.3 km²	310 m	310 m	310 m

Table 4-17 Summary of the unweighted SEL_{cum} impact ranges for marine mammals using the Popper et al. (2014) pile driving criteria for the 11 m monopile foundation modelling at the C WTG location assuming both fleeing and stationary animals

Popper *et al.* (2014) Unweighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	1,400 km²	31 km	6.9 km	19 km
Stationary (0 m/s)	219 dB	1.1 km²	600 m	600 m	600 m
	216 dB	2.5 km²	900 m	900 m	900 m
	210 dB	14 km²	2.2 km	2.1 km	2.1 km
	207 dB	33 km²	3.4 km	3.2 km	3.3 km
	203 dB	96 km²	5.9 km	5.2 km	5.6 km
	186 dB	2,800 km²	41 km	11 km	27 km

4.3.2 *7 m monopile foundation*

Table 4-18 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 7 m monopile foundation modelling at the C WTG location

Southall *et al.* (2019) Unweighted SPL_{peak}		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.5 km²	690 m	680 m	690 m
	PCW (218 dB)	0.01 km²	50 m	50 m	50 m
TTS	LF (213 dB)	0.04 km²	120 m	120 m	120 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	9.4 km²	1.8 km	1.7 km	1.7 km
	PCW (212 dB)	0.06 km²	140 m	140 m	140 m

Table 4-19 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 7 m monopile foundation modelling at the C WTG location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	400 km²	17 km	3.2 km	9.9 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	150 km²	9.1 km	3.7 km	6.6 km
	PCW (185 dB)	0.3 km²	400 m	< 100 m	300 m
TTS	LF (168 dB)	8,500 km²	86 km	8.2 km	43 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	4,500 km²	56 km	8.9 km	33 km
	PCW (170 dB)	1,500 km²	32 km	7.2 km	20 km

Table 4-20 Summary of the unweighted SPL$_{RMS}$ impact ranges for marine mammals using the NOAA (2005) impulsive criteria for the 7 m monopile foundation modelling at the C WTG location

NOAA (2005) Unweighted SPL$_{RMS}$		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	2,300 km^2	37 km	11 km	25 km

Table 4-21 Summary of the unweighted SPL$_{peak}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the 7 m monopile foundation modelling at the C WTG location

Popper *et al.* (2014) Unweighted SPL$_{peak}$	Area	Maximum range	Minimum range	Mean range
213 dB	0.04 km^2	120 m	120 m	120 m
207 dB	0.3 km^2	310 m	310 m	310 m

Table 4-22 Summary of the unweighted SEL$_{cum}$ impact ranges for marine mammals using the Popper et al. (2014) pile driving criteria for the 7 m monopile foundation modelling at the C WTG location assuming both fleeing and stationary animals

Popper *et al.* (2014) Unweighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	1,400 km^2	31 km	6.9 km	19 km
Stationary (0 m/s)	219 dB	1.1 km^2	600 m	600 m	600 m
	216 dB	2.5 km^2	900 m	900 m	900 m
	210 dB	14 km^2	2.2 km	2.1 km	2.1 km
	207 dB	33 km^2	3.3 km	3.2 km	3.2 km
	203 dB	95 km^2	5.8 km	5.1 km	5.5 km
	186 dB	2,700 km^2	41 km	11 km	27 km

4.4 SW WTG location

4.4.1 *11 m monopile foundation*

Table 4-23 Summary of the unweighted SPL$_{peak}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 11 m monopile foundation modelling at the SW WTG location

Southall *et al.* (2019) Unweighted SPL$_{peak}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	0.01 km^2	50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.6 km^2	750 m	690 m	720 m
	PCW (218 dB)	0.01 km^2	60 m	60 m	60 m
TTS	LF (213 dB)	0.05 km^2	130 m	130 m	130 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	10 km^2	1.9 km	1.7 km	1.8 km
	PCW (212 dB)	0.07 km^2	150 m	150 m	150 m

Table 4-24 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 11 m monopile foundation modelling at the SW WTG location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	470 km^2	19 km	3.7 km	11 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	180 km^2	10 km	4.1 km	7.3 km
	PCW (185 dB)	0.2 km^2	400 m	< 100 m	200 m
TTS	LF (168 dB)	9,200 km^2	98 km	9.0 km	45 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	5,500 km^2	63 km	9.6 km	3.6 km
	PCW (170 dB)	1,800 km^2	35 km	7.9 km	22 km

Table 4-25 Summary of the unweighted SPL$_{RMS}$ impact ranges for marine mammals using the NOAA (2005) impulsive criteria for the 11 m monopile foundation modelling at the SW WTG location

NOAA (2005) Unweighted SPL$_{RMS}$		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	2,600 km^2	39 km	11 km	27 km

Table 4-26 Summary of the unweighted SPL$_{peak}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the 11 m monopile foundation modelling at the SW WTG location

Popper *et al.* (2014) Unweighted SPL$_{peak}$	Area	Maximum range	Minimum range	Mean range
213 dB	0.05 km^2	130 m	130 m	130 m
207 dB	0.34 km^2	340 m	320 m	330 m

Table 4-27 Summary of the unweighted SEL$_{cum}$ impact ranges for marine mammals using the Popper et al. (2014) pile driving criteria for the 11 m monopile foundation modelling at the SW WTG location assuming both fleeing and stationary animals

Popper *et al.* (2014) Unweighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	1,900 km^2	36 km	7.6 km	22 km
Stationary (0m/s)	219 dB	2.0 km^2	800 m	700 m	800 m
	216 dB	4.7 km^2	1.3 km	1.1 km	1.2 km
	210 dB	26 km^2	3.1 km	2.6 km	2.9 km
	207 dB	61 km^2	4.7 km	3.8 km	4.4 km
	203 dB	170 km^2	7.9 km	6.3 km	7.4 km
	186 dB	4,000 km^2	50 km	12 km	33 km

4.4.2 *7 m monopile foundation*

Table 4-28 Summary of the unweighted SPL$_{peak}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 7 m monopile foundation modelling at the SW WTG location

Southall *et al.* (2019) Unweighted SPL$_{peak}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.6 km^2	740 m	680 m	720 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m

Southall *et al.* (2019) Unweighted SPL$_{peak}$		Area	Maximum range	Minimum range	Mean range
TTS	LF (213 dB)	0.05 km^2	130 m	120 m	130 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	10 km^2	1.9 km	1.7 km	1.8 km
	PCW (212 dB)	0.07 km^2	150 m	150 m	150 m

Table 4-29 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 7 m monopile foundation modelling at the SW WTG location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	460 km^2	18 km	3.6 km	11 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	180 km^2	10 km	4.1 km	7.3 km
	PCW (185 dB)	0.1 km^2	380 m	< 100 m	150 m
TTS	LF (168 dB)	9,200 km^2	98 km	9.0 km	45 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	5,500 km^2	63 km	9.6 km	36 km
	PCW (170 dB)	1,800 km^2	35 km	7.9 km	21 km

Table 4-30 Summary of the unweighted SPL$_{RMS}$ impact ranges for marine mammals using the NOAA (2005) impulsive criteria for the 7 m monopile foundation modelling at the SW WTG location

NOAA (2005) Unweighted SPL$_{RMS}$	Area	Maximum range	Minimum range	Mean range
Level B 160 dB	2,600 km^2	39 km	11 km	27 km

Table 4-31 Summary of the unweighted SPL$_{peak}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the 7 m monopile foundation modelling at the SW WTG location

Popper *et al.* (2014) Unweighted SPL$_{peak}$	Area	Maximum range	Minimum range	Mean range
213 dB	0.05 km^2	130 m	120 m	130 m
207 dB	0.33 km^2	330 m	320 m	330 m

Table 4-32 Summary of the unweighted SEL$_{cum}$ impact ranges for marine mammals using the Popper et al. (2014) pile driving criteria for the 7 m monopile foundation modelling at the SW WTG location assuming both fleeing and stationary animals

Popper *et al.* (2014) Unweighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	1,800 km^2	35 km	7.5 km	22 km
Stationary (0 m/s)	219 dB	1.7 km^2	780 m	700 m	740 m
	216 dB	4.3 km^2	1.2 km	1.1 km	1.2 km
	210 dB	25 km^2	3.0 km	2.5 km	2.8 km
	207 dB	59 km^2	4.6 km	3.8 km	4.3 km
	203 dB	170 km^2	7.8 km	6.2 km	7.4 km
	186 dB	3,900 km^2	50 km	11 km	32 km

4.5 North OSP location

4.5.1 14 m diameter pile foundation

Table 4-33 Summary of the unweighted SPL$_{peak}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 14 m monopile foundation modelling at the North OSP location

Southall et al. (2019) Unweighted SPL$_{peak}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.0 km^2	580 m	570 m	570 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.03 km^2	110 m	100 m	110 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	5.9 km^2	1.4 km	1.3 km	1.4 km
	PCW (212 dB)	0.05 km^2	120 m	120 m	120 m

Table 4-34 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 14 m monopile foundation modelling at the North OSP location assuming a fleeing animal

Southall et al. (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	100 km^2	9.5 km	700 m	4.8 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	49 km^2	5.4 km	1.5 km	3.7 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	5,400 km^2	67 km	4.0 km	33 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	2,500 km^2	45 km	4.8 km	24 km
	PCW (170 dB)	570 km^2	21 km	3.4 km	12 km

Table 4-35 Summary of the unweighted SPL$_{RMS}$ impact ranges for marine mammals using the NOAA (2005) impulsive criteria for the 14 m monopile foundation modelling at the North OSP location

NOAA (2005) Unweighted SPL$_{RMS}$		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	1,200 km^2	28 km	6.3 km	18 km

Table 4-36 Summary of the unweighted SPL$_{peak}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the 14 m monopile foundation modelling at the North OSP location

Popper et al. (2014) Unweighted SPL$_{peak}$	Area	Maximum range	Minimum range	Mean range
213 dB	0.03 km^2	110 m	100 m	110 m
207 dB	0.22 km^2	270 m	270 m	270 m

Table 4-37 Summary of the unweighted SEL$_{cum}$ impact ranges for marine mammals using the Popper et al. (2014) pile driving criteria for the 14 m monopile foundation modelling at the North OSP location assuming both fleeing and stationary animals

Popper et al. (2014) Unweighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m

Popper *et al.* (2014) Unweighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
	186 dB	600 km²	22 km	3.3 km	12 km
Stationary (0 m/s)	219 dB	0.8 km²	500 m	500 m	500 m
	216 dB	1.8 km²	800 m	700 m	800 m
	210 dB	9.3 km²	1.8 km	1.6 km	1.7 km
	207 dB	20 km²	2.8 km	2.4 km	2.6 km
	203 dB	56 km²	4.7 km	3.7 km	4.2 km
	186 dB	1,500 km²	31 km	6.3 km	20 km

4.5.2   *7 m diameter pile foundation*

Table 4-38 Summary of the unweighted SPL$_{peak}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 7 m monopile foundation modelling at the North OSP location

Southall *et al.* (2019) Unweighted SPL$_{peak}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.0 km²	570 m	560 m	570 m
	PCW (218 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.03 km²	110 m	100 m	100 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	5.8 km²	1.4 km	1.3 km	1.4 km
	PCW (212 dB)	0.05 km²	120 m	120 m	120 m

Table 4-39 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 7 m monopile foundation modelling at the North OSP location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	100 km²	9.4 km	700 m	4.7 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	49 km²	5.4 km	1.5 km	3.7 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	5,300 km²	67 km	4.0 km	33 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	2,500 km²	45 km	4.8 km	24 km
	PCW (170 dB)	570 km²	21 km	3.4 km	12 km

Table 4-40 Summary of the unweighted SPL$_{RMS}$ impact ranges for marine mammals using the NOAA (2005) impulsive criteria for the 7 m monopile foundation modelling at the North OSP location

NOAA (2005) Unweighted SPL$_{RMS}$	Area	Maximum range	Minimum range	Mean range
Level B 160 dB	1,200 km²	28 km	6.3 km	18 km

Table 4-41 Summary of the unweighted SPL$_{peak}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the 7 m monopile foundation modelling at the North OSP location

Popper *et al.* (2014) Unweighted SPL$_{peak}$	Area	Maximum range	Minimum range	Mean range
213 dB	0.03 km²	110 m	100 m	100 m
207 dB	0.22 km²	270 m	260 m	260 m

Table 4-42 Summary of the unweighted SEL$_{cum}$ impact ranges for marine mammals using the Popper et al. (2014) pile driving criteria for the 7 m monopile foundation modelling at the North OSP location assuming both fleeing and stationary animals

Popper *et al.* (2014) Unweighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	590 km^2	21 km	3.3 km	12 km
Stationary (0 m/s)	219 dB	0.8 km^2	500 m	500 m	500 m
	216 dB	1.7 km^2	800 m	700 m	700 m
	210 dB	8.9 km^2	1.8 km	1.6 km	1.7 km
	207 dB	20 km^2	2.7 km^2	2.4 km	2.5 km
	203 dB	54 km^2	4.6 km	3.7 km	4.2 km
	186 dB	1,500 km^2	31 km	6.3 km	20 km

4.6 South OSP location

4.6.1 *14 m diameter pile foundation*

Table 4-43 Summary of the unweighted SPL$_{peak}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 14 m monopile foundation modelling at the South OSP location

Southall *et al.* (2019) Unweighted SPL$_{peak}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.4 km^2	680 m	660 m	670 m
	PCW (218 dB)	0.01 km^2	60 m	60 m	60 m
TTS	LF (213 dB)	0.05 km^2	120 m	120 m	120 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	8.9 km^2	1.7 km	1.6 km	1.7 km
	PCW (212 dB)	0.06 km^2	140 m	140 m	140 m

Table 4-44 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 14 m monopile foundation modelling at the South OSP location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	450 km^2	18 km	3.4 km	10 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	170 km^2	10 km	4.0 km	7.1 km
	PCW (185 dB)	< 0.1 km^2	200 m	< 100 m	100 m
TTS	LF (168 dB)	9,100 km^2	95 km	9.3 km	45 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	5,500 km^2	62 km	9.9 km	36 km
	PCW (170 dB)	1,700 km^2	34 km	7.9 km	21 km

Table 4-45 Summary of the unweighted SPL$_{RMS}$ impact ranges for marine mammals using the NOAA (2005) impulsive criteria for the 14 m monopile foundation modelling at the South OSP location

NOAA (2005) Unweighted SPL$_{RMS}$		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	2,600 km^2	39 km	12 km	27 km

Table 4-46 Summary of the unweighted SPL$_{peak}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the 14 m monopile foundation modelling at the South OSP location

Popper *et al.* (2014) Unweighted SPL$_{peak}$	Area	Maximum range	Minimum range	Mean range
213 dB	0.05 km^2	120 m	120 m	120 m
207 dB	0.3 km^2	310 m	310 m	310 m

Table 4-47 Summary of the unweighted SEL$_{cum}$ impact ranges for marine mammals using the Popper et al. (2014) pile driving criteria for the 14 m monopile foundation modelling at the South OSP location assuming both fleeing and stationary animals

Popper *et al.* (2014) Unweighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	1,800 km^2	35 km	7.6 km	22 km
Stationary (0 m/s)	219 dB	1.7 km^2	800 m	700 m	700 m
	216 dB	4.0 km^2	1.2 km	1.1 km	1.1 km
	210 dB	23 km^2	2.8 km	2.6 km	2.7 km
	207 dB	54 km^2	4.4 km	3.8 km	4.2 km
	203 dB	160 km^2	7.7 km	6.3 km	7.1 km
	186 dB	4,000 km^2	50 km	12 km	33 km

4.6.2   7 m diameter pile foundation

Table 4-48 Summary of the unweighted SPL$_{peak}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 7 m monopile foundation modelling at the South OSP location

Southall *et al.* (2019) Unweighted SPL$_{peak}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.4 km^2	670 m	660 m	670 m
	PCW (218 dB)	0.01 km^2	60 m	60 m	60 m
TTS	LF (213 dB)	0.04 km^2	120 m	120 m	120 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	8.8 km^2	1.7 km	1.6 km	1.7 km
	PCW (212 dB)	0.06 km^2	140 m	140 m	140 m

Table 4-49 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the 7 m monopile foundation modelling at the South OSP location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	440 km^2	18 km	3.4 km	10 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	170 km^2	10 km	4.0 km	7.1 km
	PCW (185 dB)	< 0.1 km^2	200 m	< 100 m	100 m
TTS	LF (168 dB)	9,000 km^2	94 km	9.3 km	45 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	5,500 km^2	62 km	9.9 km	36 km

Southall et al. (2019) Weighted SEL$_{cum}$	Area	Maximum range	Minimum range	Mean range
PCW (170 dB)	1,700 km^2	34 km	7.9 km	21 km

Table 4-50 Summary of the unweighted SPL$_{RMS}$ impact ranges for marine mammals using the NOAA (2005) impulsive criteria for the 7 m monopile foundation modelling at the South OSP location

NOAA (2005) Unweighted SPL$_{RMS}$	Area	Maximum range	Minimum range	Mean range
Level B	160 dB	2,600 km^2	38 km	12 km	27 km

Table 4-51 Summary of the unweighted SPL$_{peak}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the 7 m monopile foundation modelling at the South OSP location

Popper et al. (2014) Unweighted SPL$_{peak}$	Area	Maximum range	Minimum range	Mean range
213 dB	0.04 km^2	120 m	120 m	120 m
207 dB	0.29 km^2	310 m	310 m	310 m

Table 4-52 Summary of the unweighted SEL$_{cum}$ impact ranges for marine mammals using the Popper et al. (2014) pile driving criteria for the 7 m monopile foundation modelling at the South OSP location assuming both fleeing and stationary animals

Popper et al. (2014) Unweighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	1,800 km^2	35 km	7.6 km	21 km
Stationary (0 m/s)	219 dB	1.6 km^2	800 m	700 m	700 m
	216 dB	3.9 km^2	1.2 km	1.1 km	1.1 km
	210 dB	23 km^2	2.8 km	2.5 km	2.7 km
	207 dB	53 km^2	4.3 km	3.8 km	4.1 km
	203 dB	160 km^2	7.6 km	6.2 km	7.0 km
	186 dB	3,900 km^2	49 km	12 km	33 km

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 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 and operation of ABWP2.

Table 5-1 Summary of the possible noise making activities at ABWP2 other than impact piling

Activity	Description
Cable laying	Noise from the Cable Laying Vessel and any other associated noise during the offshore cable installation.
Dredging	Dredging may be required on site for seabed preparation work for certain foundation options (e.g., gravity bases), as well as for the Export Cable, Array Cables and Interconnector Cable Installation. Suction dredging has been assumed as a worst case due to the louder processes involved compared to other considered methods such as backhoe dredging.
Drilling	There is the potential for WTG Foundations to be installed using drilling depending on seabed type or if a pile refuses during impact piling operations.
Rock placement	Potentially required on site for installation of offshore cables (Cable Crossings and Cable Protection) and Scour Protection around foundation structures.
Trenching	Plough trenching may be required during Offshore Cable installation.
Trenchless techniques	Trenchless techniques will also be considered as part of construction, which do not involve breaking the surface of the seabed, rather using an under-seabed directional drilling technique. Little directly measured noise data is available for this and its prediction is extremely complex. As there is no significant noisy activity in the water column itself for trenchless techniques, except briefly at the exit point, drilling (above) will be assumed as the wort case scenario.
Vessel activities	Jack-up barges for piling substructure and WTG installation. Other large and medium sized vessels to carry out other construction tasks and anchor handling. Other small vessels for crew transport and maintenance on site.
Operational WTG	Noise transmitted through the water from operational WTGs.
UXO clearance	There is a possibility, albeit highly unlikely, that Unexploded Ordnance (UXO) may exist within the boundaries of APWP2, which would need to be cleared before construction can begin.

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 acceptable. Such an approach has been used for these noise sources, which are variously either quiet compared to impact piling (e.g., Cable laying and dredging), or where detailed modelling would imply unjustified accuracy (e.g., where data is limited such as with UXO detonation). As such, the high-level overview of modelling that has been presented here is considered sufficient. The limitations of this approach are noted, including the lack of frequency or bathymetric dependence.

Most of these activities are considered in section 5.1, with operational WTG noise and UXO clearance assessed in sections 5.2 and 5.3 respectively.

5.1   Noise making activities

For the purposes of identifying the greatest noise levels, 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 site and to the specific noise sources to be used. The calculation of underwater noise transmission loss

for the non-impulsive sources is based on an 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, and α is the absorption loss:

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

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 SEL$_{cum}$ criteria use the same assumptions as presented in section 2.2, and ranges smaller than 50 m (single strike) 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, ABWP2.

Table 5-2 Summary of the estimated unweighted source levels and transmission losses for the different considered noise sources related to construction

Source	Estimated unweighted source level	Transmission loss parameters	Comments
Cable laying	171 dB re 1 µPa @ 1 m (RMS)	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.
Dredging (Backhoe)	165 dB re 1 µPa @ 1 m (RMS)	N: 19, α: 0.0009	Based on three datasets from backhoe dredgers.
Dredging (Suction)	186 dB re 1 µPa @ 1 m (RMS)	N: 19, α: 0.0009	Based on five datasets from suction and cutter suction dredgers.
Drilling (including trenchless techniques)	169 dB re 1 µPa @ 1 m (RMS)	N: 16, α: 0.0006	Based on six datasets from various drilling operations covering ground investigations and pile installation. A 200kW drill has been assumed for modelling.
Rock placement	172 dB re 1 µPa @ 1 m (RMS)	N: 12, α: 0.0005	Based on four datasets from rock placement vessel '*Rollingstone.*'
Trenching	172 dB re 1 µPa @ 1 m (RMS)	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 (RMS)	N: 12, α: 0.0021	Based on five datasets of large vessels including container ships, Floating Production Storage and Offloading (FPSOs) 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 (RMS)	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 and the noise source on it, the transect on which the measurements are taken and the local environment at the time.

For SEL$_{cum}$ calculations, 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 considered both fleeing and stationary animals have been included for all SEL$_{cum}$ criteria.

To account for the weightings required for modelling using the Southall *et al*. (2019) criteria (see section 2.2.1), reductions in source level have been applied to the various noise sources: Figure 5-1 shows the representative noise measurements used for this, which have been adjusted for the source levels given in Table 5-2. Details of the reductions in sources levels for each of the weightings used for modelling are given in Table 5-3.
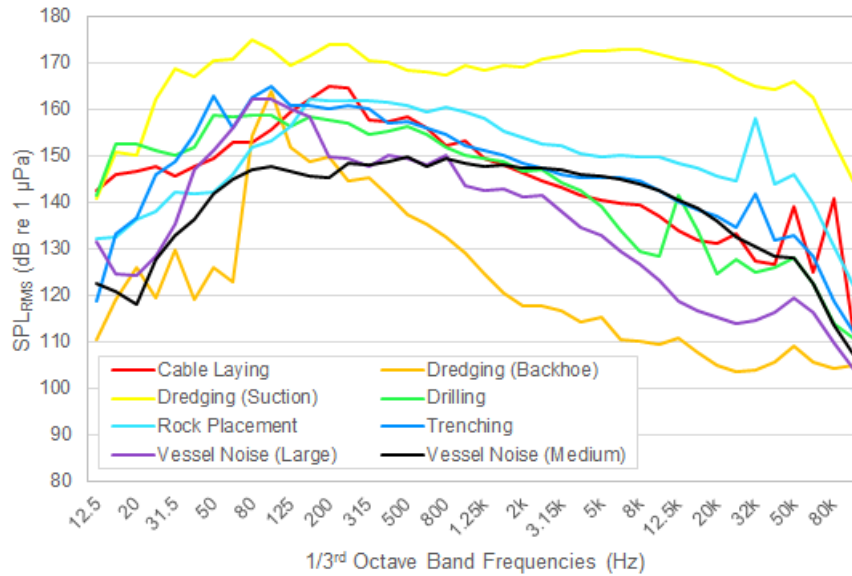
Figure 5-1 Summary of the 1/3rd octave frequency bands to which the Southall et al. (2019) weightings were applied in the simple modelling

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 source level from the unweighted level (Southall *et al.*, 2019)			
	LF	HF	VHF	PCW
Cable laying	3.6 dB	22.9 dB	23.9 dB	13.2 dB
Dredging (backhoe and suction)	2.5 dB	7.9 dB	9.6 dB	4.2 dB
Drilling	4.0 dB	25.8 dB	48.7 dB	13.2 dB
Rock placement	1.6 dB	11.9 dB	12.5 dB	8.2 dB
Trenching	4.1 dB	23.0 dB	25.0 dB	13.7 dB
Vessel noise	5.5 dB	34.4 dB	38.6 dB	17.4 dB

Table 5-4 to Table 5-6 summarise the predicted impact ranges for these noise sources. All the sources in this section are considered non-impulsive or continuous. As with the previous results, ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented.

Given the modelled impact ranges, any marine mammal would have to be closer than 100 m from the continuous noise source at the start of the activity to acquire the necessary exposure to induce PTS as per Southall *et al*. (2019). The exposure calculation assumes the same receptor swim speeds as the impact piling modelling in section 4. As explained in section 3.3, this would only mean that the receptor reaches the 'onset' stage at these ranges, 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 there is a minimal risk.

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

Table 5-4 Summary of the impact ranges for the different noise sources related to construction using the non-impulsive criteria from Southall et al. (2019) for marine mammals assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$	PTS (non-impulsive)				TTS (non-impulsive)			
	LF 199 dB	HF 198 dB	VHF 173 dB	PCW 201 dB	LF 179 dB	HF 178 dB	VHF 153 dB	PCW 181 dB
Cable laying	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	110 m	< 100 m
Dredging (Backhoe)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Dredging (Suction)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	230 m	< 100 m
Drilling	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Rock placement	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	990 m	< 100 m
Trenching	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Vessel noise (large)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Vessel noise (medium)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-5 Summary of the impact ranges for the different noise sources related to construction using the non-impulsive criteria from Southall et al. (2019) for marine mammals assuming a stationary animal

Southall *et al.* (2019) Weighted SEL$_{cum}$	PTS (non-impulsive)				TTS (non-impulsive)			
	LF 199 dB	HF 198 dB	VHF 173 dB	PCW 201 dB	LF 179 dB	HF 178 dB	VHF 153 dB	PCW 181 dB
Cable laying	< 100 m	< 100 m	< 100 m	< 100 m	810 m	< 100 m	2.3 km	110 m
Dredging (Backhoe)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Dredging (Suction)	< 100 m	< 100 m	570 m	< 100 m	640 m	390 m	4.3 km	420 m
Drilling	< 100 m	< 100 m	< 100 m	< 100 m	160 m	< 100 m	200 m	< 100 m
Rock placement	< 100 m	< 100 m	900 m	< 100 m	2.1 km	410 m	13 km	460 m
Trenching	< 100 m	< 100 m	< 100 m	< 100 m	830 m	< 100 m	1.9 km	120 m
Vessel noise (large)	< 100 m	< 100 m	< 100 m	< 100 m	480 m	< 100 m	140 m	< 100 m
Vessel noise (medium)	< 100 m	< 100 m	< 100 m	< 100 m	130 m	< 100 m	< 100 m	< 100 m

Ranges for a stationary animal are theoretical only and are expected to be over-conservative as the assumption is for the animal to remain stationary in respect to the noise source, when the source itself is moving in most cases.

Table 5-6 Summary of the impact ranges for the different noise sources related to construction using the continuous noise criteria from Popper et al. (2014) for fish (swim bladder involved in hearing)

Popper *et al*. (2014) Unweighted SPL$_{RMS}$	Recoverable injury 170 dB (48 hours)	TTS 158 dB (12 hours)
Cable laying	< 50 m	< 50 m
Dredging (Backhoe)	< 50 m	< 50 m
Dredging (Suction)	< 50 m	< 50 m
Drilling	< 50 m	< 50 m
Rock placement	< 50 m	< 50 m
Trenching	< 50 m	< 50 m
Vessel noise (large)	< 50 m	< 50 m
Vessel noise (medium)	< 50 m	< 50 m

5.2   Operational WTG noise

The main source of underwater noise from operational WTGs will be mechanically generated vibration from the rotating machinery in the WTGs, which is transmitted into the sea through the structure of the WTG tower and foundations (Nedwell *et al*., 2003; Tougaard *et al*, 2020). Noise levels generated above the water surface are low enough that no significant airborne sound will pass from the air to the water.

Tougaard *et al*. (2020) published a study investigating underwater noise data from 17 operational WTGs in Europe and the United States, from 0.2 MW to 6.15 MW nominal power output. The paper identified the nominal power output and wind speed as the two primary driving factors for underwater noise generation. Although the datasets were acquired under different conditions, the authors devised a formula based on the published data for the operational windfarms, allowing a broadband noise level to be estimated based on the application of wind speed, turbine size (by nominal power output) and distance from the turbine:

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

where C is a fixed constant and the coefficients α, β, and γ are derived from the empirical data for the 17 datasets.

WTG power outputs have been assumed based on turbine size, with rotor diameters of between 236 and 250 m considered for this study.

As the maximum turbine sizes considered at ABWP2 are much larger than those used for the estimation above, caution must be used when considering the results presented in this section; no empirical data is available for large wind turbines close to the specifications proposed here. Figure 5-2 presents a level against range plot for the two turbine sizes using the Tougaard *et al*. (2020) calculation, assuming an average 6 m/s wind speed at hub height. Although wind speeds (and thus operational noise levels) may be greater than this, meaning this will not represent the typical condition. It is also worth noting that the background noise level will also naturally increase, due primarily to rougher seas, somewhat offsetting any additional impact this may have.
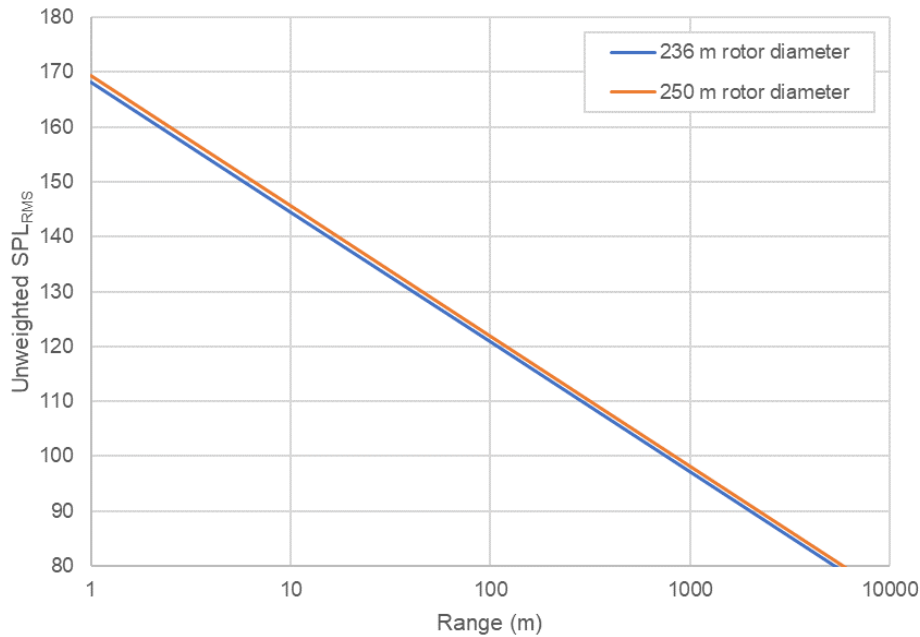
Figure 5-2 Predicted unweighted SPL$_{RMS}$ from operational WTGs with rotor diameters of between 236 and 250 m using the calculation from Tougaard et al. (2020)

Using this data, a summary of the predicted impact ranges has been produced, shown in Table 5-7 to Table 5-9. All SEL$_{cum}$ criteria use the same assumptions as presented in section 2.2, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. Operational WTG noise is considered a non-impulsive, or continuous, source.

For SEL$_{cum}$ calculations, it has been assumed that the operational WTG noise is present 24 hours a day, and similarly to the noise sources in section 5.1, both fleeing and stationary animals have been included for all SEL$_{cum}$ criteria due to the low noise levels considered.

Table 5-7 Summary of the operational WTG noise impact ranges using the non-impulsive noise criteria from Southall et al. (2019) for marine mammals assuming a fleeing receptor

Southall *et al.* (2019) Weighted SEL$_{cum}$	PTS (non-impulsive)				TTS (non-impulsive)			
	LF 199 dB	HF 198 dB	VHF 173 dB	PCW 201 dB	LF 179 dB	HF 178 dB	VHF 153 dB	PCW 181 dB
236 m rotor diameter	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
250 m rotor diameter	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-8 Summary of the operational WTG noise impact ranges using the non-impulsive noise criteria from Southall et al. (2019) for marine mammals assuming a stationary receptor

Southall *et al.* (2019) Weighted SEL$_{cum}$	PTS (non-impulsive)				TTS (non-impulsive)			
	LF 199 dB	HF 198 dB	VHF 173 dB	PCW 201 dB	LF 179 dB	HF 178 dB	VHF 153 dB	PCW 181 dB
236 m rotor diameter	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
250 m rotor diameter	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-9 Summary of the operational WTG noise impact ranges using the continuous noise criteria from Popper et al. (2014) for fish (swim bladder involved in hearing)

Popper *et al.* (2014) Unweighted SPL$_{RMS}$	Recoverable injury 170 dB (48 hours)	TTS 158 dB (12 hours)
236 m rotor diameter	< 50 m	< 50 m
250 m rotor diameter	< 50 m	< 50 m

The results show that, for operational WTGs, injury risk is minimal. Increasing the wind speed does not lead to significant increases in the impact ranges.

Stöber and Thomsen (2021) produced a similar study of an operational wind turbine dataset to Tougaard *et al.* (2020) and it raises the potential for behavioural disturbance caused by larger wind turbines. While prospective turbine sizes are increasing, Stöber and Thomsen conclude that these might only have limited impacts related to behavioural response on marine mammals and fish, although there is considerable uncertainty in criteria available to assess these. However, based on the highly precautionary NOAA Level B behavioural threshold for continuous noise sources (120 dB SPL$_{RMS}$, see NOAA, 2005) that the study utilises, it is estimated that the WTGs may only reach that threshold at around 120 m away. As the distance between turbines at ABWP2 is expected to be considerably greater than this distance (the minimum separation distance is 944 m), this would indicate that any array effect from the turbines is not expected.

5.3 UXO clearance

It is possible, although highly unlikely, that UXO devices with a range of charge weights (or quantity of contained explosive) are present within the boundaries of the proposed development. 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. 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 detonates with the clearance.

5.3.1 *Estimation of underwater noise levels*

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 Trinitrotoluene (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.

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 degradation would be expected.

The maximum equivalent charge weight for the potential UXO devices that could be present within the proposed development has been estimated as 800 kg. This has been modelled alongside a range of smaller devices, at charge weights of 25, 55, 120, 240, 525 and 700 kg. In each case, an additional donor weight of 0.5 kg has been included to initiate detonation. Low-order deflagration has also been assessed, which assumes that the donor or shaped charge (charge weight of 0.5 kg) detonates fully to

initiate a burnout of the explosive but without the follow-up detonation of the UXO. No mitigation has been considered for this modelling.

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).

5.3.2   *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 SPL_{peak}:

$$SPL_{peak} = 52.4 \times 10^6 \left(\frac{R}{W^{1/3}} \right)^{-1.13}$$

and for SEL_{ss}

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

where W is the equivalent charge weight for TNT in kilograms 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, SPL_{peak} 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 SEL calculations.

A further limitation in the Soloway and Dahl (2014) equations that must be considered are that variations in noise levels at different depths are not considered. Where animals are swimming near the surface, the acoustics can cause the noise level, and hence the exposure, to be lower (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 with 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).

A summary of the unweighted UXO clearance source levels, calculated using the equations above, are given in Table 5-10.

Table 5-10 Summary of the unweighted SPLpeak and SELss source levels used for UXO clearance modelling

Charge weight	SPLpeak source level (dB re 1 µPa @ 1 m)	SELss source level (dB re 1 µPa²s @ 1 m)
0.5 kg	272.1	217.1
25 kg + donor	284.9	228.0
55 kg + donor	287.5	230.1
120 kg + donor	290.0	232.3
240 kg + donor	292.3	234.2
525 kg + donor	294.8	236.4
700 kg + donor	295.8	237.2
800 kg + donor	296.2	237.5

5.3.3 Impact ranges

Table 5-11 to Table 5-14 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 2-6). A UXO detonation source is defined as a single pulse, and as such the SELcum criteria from Southall *et al*. (2019) have been given as SELss in the tables below. Thus, 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 5-11 to Table 5-14 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 5-11 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, unweighted SPLpeak noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al.* (2019) Unweighted SPLpeak	PTS (impulsive)				TTS (impulsive)			
	LF 219 dB	HF 230 dB	VHF 202 dB	PCW 218 dB	LF 213 dB	HF 224 dB	VHF 196 dB	PCW 212 dB
0.5 kg	220 m	70 m	1.2 km	240 m	410 m	130 m	2.3 km	450 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
700 kg + donor	2.4 km	810 m	14 km	2.7 km	4.5 km	1.4 km	25 km	5.0 km
800 kg + donor	2.6 km	840 m	14 km	2.8 km	4.7 km	1.5 km	26 km	5.3 km

Table 5-12 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, weighted SELss noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al.* (2019) Weighted SELss	PTS (impulsive)				TTS (impulsive)			
	LF 183 dB	HF 185 dB	VHF 155 dB	PCW 185 dB	LF 168 dB	HF 170 dB	VHF 140 dB	PCW 170 dB
0.5 kg	320 m	< 50 m	110 m	60 m	4.5 km	< 50 m	930 m	800 m
25 kg + donor	2.2 km	< 50 m	570 m	390 m	29 km	150 m	2.4 km	5.2 km
55 kg + donor	3.2 km	< 50 m	740 m	570 m	41 km	210 m	2.8 km	7.5 km
120 kg + donor	4.7 km	< 50 m	950 m	830 m	57 km	300 m	3.2 km	10 km
240 kg + donor	6.5 km	< 50 m	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
700 kg + donor	10 km	60 m	1.5 km	1.9 km	110 km	590 m	4.1 km	22 km
800 kg + donor	11 km	60 m	1.6 km	2.0 km	120 km	620 m	4.2 km	23 km

Table 5-13 Summary of the PTS and TTS impact ranges for UXO detonation using the non-impulsive, weighted SELss noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al.* (2019) Weighted SELss	PTS (non-impulsive)				TTS (non-impulsive)			
	LF 199 dB	HF 198 dB	VHF 173 dB	PCW 201 dB	LF 179 dB	HF 178 dB	VHF 153 dB	PCW 181 dB
0.5 kg	< 50 m	< 50 m	< 50 m	< 50 m	650 m	< 50 m	150 m	110 m
25 kg + donor	130 m	< 50 m	< 50 m	< 50 m	4.4 km	< 50 m	730 m	790 m
55 kg + donor	190 m	< 50 m	< 50 m	< 50 m	6.4 km	60 m	940 m	1.1 km
120 kg + donor	280 m	< 50 m	70 m	< 50 m	9.4 km	80 m	1.1 km	1.6 km
240 kg + donor	390 m	< 50 m	100 m	70 m	13 km	110 m	1.4 km	2.3 km
525 kg + donor	570 m	< 50 m	130 m	100 m	18 km	160 m	1.7 km	3.3 km
700 kg + donor	660 m	< 50 m	150 m	110 m	21 km	180 m	1.8 km	3.8 km
800 kg + donor	700 m	< 50 m	160 m	120 m	22 km	190 m	1.8 km	4.1 km

Table 5-14 Summary of the impact ranges for UXO detonation using the unweighted SPLpeak explosion noise criteria from Popper et al. (2014) for species of fish

Popper *et al.* (2014) Unweighted SPLRMS	Mortality and potential mortal injury	
	234 dB	229 dB
0.5 kg	< 50 m	80 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
700 kg + donor	530 m	890 m
800 kg + donor	560 m	930 m

5.3.4   Summary

The maximum PTS range calculated for UXO is 14 km for the VHF cetacean category, when considering the unweighted SPLpeak criteria. For SELss criteria, the largest PTS range is calculated for LF cetaceans with a predicted impact 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 that distance, which is very precautionary. Although an assumption of non-pulse could under-estimate the potential impact (Martin *et al*., 2020) (the equivalent range based on LF cetacean non-pulse criteria is 700 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.

6 Summary and conclusions

Subacoustech Environmental have undertaken a study on behalf of GoBe Consultants to assess the potential underwater noise and its effects during construction and operation of the proposed ABWP2, located in the southern Irish Sea.

The level of underwater noise from the installation of turbine foundations during construction has been estimated using INSPIRE, a 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.

Five representative modelling locations (three for the WTGs and two for OSPs) were chosen to give spatial variation as well as account for changes in water depth around the Array Area and OSPs. At each location, two sizes of monopile have been considered covering the various foundation options.

The loudest levels of noise and greatest impact ranges have been predicted for the larger monopile foundation scenarios at the SW WTG location and the South OSP locations due to the proximity to deep water areas to the south and east of the site.

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 aid biological assessments.

For marine mammals, maximum PTS ranges were predicted for LF cetaceans, with ranges of up to 19 km predicted for the larger piles at the south of the site. For fish, the largest recoverable injury ranges (203 dB SEL_{cum}) were predicted to be less than 100 m for a fleeing receptor, increasing to a maximum of 7.9 km for a stationary receptor.

Noise sources other than piling were considered using a high-level, simple modelling approach, including Cable laying, dredging, drilling, rock placement, vessel movements, and operational WTG noise. The predicted noise levels for the other construction noise sources and during WTG operation 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.

UXO clearance has also been considered at the proposed development, and for the expected UXO clearance noise, there is a risk of PTS up to 14 km for the largest UXO device considered, 800 kg, using the unweighted SPL_{peak} criteria for VHF cetaceans. This is likely to be 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 analysis of the impacts of underwater noise on marine mammals and fish in their respective reports.

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Appendix A Additional modelling results

Following from the Southall *et al*. (2019) modelled impact piling ranges presented in section 4 of the main report, the modelling results for the non-impulsive criteria from impact piling noise at ABWP2, as discussed in section 2.2.1, are presented below.

Table A 1 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the 11 m monopile foundation modelling at the NW WTG location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	330 km^2	18 km	1.4 km	8.4 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	72 km^2	7.1 km	1.6 km	4.4 km
	PCW (181 dB)	0.7 km^2	800 m	< 100 m	400 m

Table A 2 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the 7 m monopile foundation modelling at the NW WTG location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	330 km^2	18 km	1.4 km	8.4 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	72 km^2	7.1 km	1.6 km	4.4 km
	PCW (181 dB)	0.7 km^2	800 m	< 100 m	400 m

Table A 3 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the 11 m monopile foundation modelling at the C WTG location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	1,300 km^2	32 km	5.1 km	18 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	280 km^2	13 km	4.7 km	9.0 km
	PCW (181 dB)	28 km^2	3.9 km	1.7 km	2.9 km

Table A 4 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the 7 m monopile foundation modelling at the C WTG location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

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Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	1,300 km²	32 km	5.1 km	18 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	280 km²	13 km	4.7 km	9.0 km
	PCW (181 dB)	28 km²	3.9 km	1.7 km	2.9 km

Table A 5 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the 11 m monopile foundation modelling at the SW WTG location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	1,600 km²	34 km	5.7 km	19 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	360 km²	15 km	5.2 km	10 km
	PCW (181 dB)	29 km²	4.0 km	1.7 km	2.9 km

Table A 6 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the 7 m monopile foundation modelling at the SW WTG location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	1,500 km²	34 km	5.6 km	19 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	350 km²	15 km	5.2 km	10 km
	PCW (181 dB)	28 km²	4.0 km	1.7 km	2.9 km

Table A 7 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the 14 m monopile foundation modelling at the North OSP location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	490 km²	21 km	2.0 km	10 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	100 km²	8.2 km	2.1 km	5.4 km
	PCW (181 dB)	3.4 km²	1.4 km	200 m	920 m

Table A 8 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the 7 m monopile foundation modelling at the North OSP location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	480 km^2	21 km	1.9 km	10 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	100 km^2	8.2 km	2.1 km	5.4 km
	PCW (181 dB)	3.3 km^2	1.4 km	200 m	900 m

Table A 9 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the 14 m monopile foundation modelling at the South OSP location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	1,500 km^2	33 km	5.6 km	19 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	340 km^2	14 km	5.1 km	9.9 km
	PCW (181 dB)	23 km^2	3.8 km	1.5 km	2.6 km

Table A 10 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the 7 m monopile foundation modelling at the South OSP location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	1,500 km^2	33 km	5.6 km	18 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	340 km^2	14 km	5.1 km	9.9 km
	PCW (181 dB)	23 km^2	3.7 km	1.5 km	2.6 km

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