LIRIC INTERCONNECTOR

MARINE GEOPHYSICAL & GEOTECHNICAL SURVEY
SUBSEA NOISE TECHNICAL REPORT

IE000798
Subsea Noise Technical
Report
A03
06 February 2024

rpsgroup.com

Document status

Version	Purpose of document	Authored by	Reviewed by	Approved by	Review date
A01	Draft	[Redacted]			18/12/2023
A02	Addressing Client Comments	[Redacted]			22/01/2024
A03	Final for Issue	[Redacted]			06/02/2024

Approval for issue

The report has been prepared for the exclusive use of our client and unless otherwise agreed in writing by RPS Group Limited no other party may use, make use of or rely on the contents of this report.

The report has been compiled using the resources agreed with the client and in accordance with the scope of work agreed with the client. No liability is accepted by RPS Group Limited for any use of this report, other than the purpose for which it was prepared.

RPS Group Limited accepts no responsibility for any documents or information supplied to RPS Group Limited by others and no legal liability arising from the use by others of opinions or data contained in this report. It is expressly stated that no independent verification of any documents or information supplied by others has been made.

RPS Group Limited has used reasonable skill, care and diligence in compiling this report and no warranty is provided as to the report's accuracy.

Prepared by**:**	Prepared for**:**
RPS	**TI LirIC Limited**

Contents

Glossary iv
Acronyms v
Units v

1. INTRODUCTION 1

2. ASSESSMENT CRITERIA 2
2.1. General 2
2.2. Injury to Marine mammals 2
2.3. Disturbance to Marine Mammals 5
2.4. Injury and Disturbance to Fish and Sea Turtles 6

3. METHOD, ENVIRONMENT & SITE 8
3.1. Sites 8
3.2. Survey Method 9
3.3. Source Locations 10
3.4. Water Properties 10
3.5. Sediment Properties 11

4. SOURCE NOISE LEVELS 12
4.1. Source models 12
4.1.1. Vessel 13
4.1.2. Side Scan Sonar (SSS) 13
4.1.3. Multibeam Echosounder (MBES) 13
4.1.4. Parametric Sub-bottom Profiler (P-SBP) 13
4.1.5. Boomer Sub-bottom Profiler (B-SBP) 14
4.1.6. Sparker Sub-bottom Profiler (S-SBP) 14
4.1.7. Altimeter 14
4.1.8. Ultra short baseline (USBL) 14
4.1.9. Geotechnical sources (Equipment for physical samples) 14
4.1.10. Trenching noise 14
4.2. Combined Source 15

5. SOUND PROPAGATION MODELLING METHODOLOGY 20
5.1. Semi-empirical models 20
5.2. Analytical models 21
5.3. Exposure Calculations (dB L_E) 21

6. RESULTS AND ASSESSMENT 23
6.1. Geophysical 23
6.2. Geotechnical 24

7. SUMMARY AND CONCLUSIONS 25
7.1. Geophysical Survey 25
7.2. Geotechnical Survey (including trenching) 25
7.3. Mitigation 25
7.3.1. Zone of Absence – Marine Mammal Observer 25
7.3.2. Soft-start 25
7.3.3. Equipment limitations 25
7.4. Conclusion 25

8. REFERENCES 27

APPENDIX A – ACOUSTIC CONCEPTS AND TERMINOLOGY 29

Tables

Table 2-1: PTS and TTS onset acoustic thresholds (Southall *et al., 2019*; Tables 6 and 7) 5
Table 2-2: Comparison of Hearing Group Names between NMFS (2018) and Southall *et al.* (2019) 5
Table 2-3: Disturbance Criteria for Marine Mammals Used in this Study based on Level B harassment of NMFS (National Marine Fisheries Service, 2005)....6
Table 3-1: Modelled source locations for the two sites 10
Table 3-2: Sediment properties 11
Table 4-1: Summary of Noise Sources and Activities Included in the Subsea Noise Assessment 15
Table 5-1: Swim speed examples from literature 22
Table 6-1: Geophysical – Shallow-mud, summary of minimal starting ranges for fleeing animals. 24
Table 6-2: Geophysical – Shallow-mud, summary of minimal starting ranges for fleeing animals. 24

Figures

Figure 2-1: Hearing weighting functions for pinnipeds, cetaceans and sirenians (NMFS, 2018; Southall et al. 2019) 4
Figure 3-1: The Development area (red line). Blues and greens are Silt and Mud (black dashed), Light yellows and light greens are Sand (blue dashed) and dark yellow is coarser sediment (red dashed). (Background maps: EMODnet Sediment & OpenStreetMap)....9
Figure 4-1: Maximal noise level per band for a “quiet” vessel. Broadband level 186 dB SPL. 13
Figure 4-2: Example of a beam pattern on an Innomar 200-Medium. Primary frequencies left, the non-overlapping lobes outside the main lobe, means that the beam pattern for the secondary frequencies (right plot) is very narrow. 14
Figure 4-3: Scenario 1, Shallow-Mud: Overview of sound sources as SPL at 1m. Combined source (black solid line) represents source during survey in shallow silty or muddy areas. 17
Figure 4-4: Scenario 2, Shallow-Sand: Overview of sound sources as SPL at 1m. Combined source (black solid line) represents source during survey in shallow areas with sandy sediment. 17
Figure 4-5: Scenario 3, Deep-Coarse: Overview of sound sources as SPL at 1m. Combined source (black solid line) represents source during survey in deep gravelly areas. 18
Figure 4-6: Geophysical: Overview of sound sources as SPL at 1m. Combined source (black solid line)....18
Figure 4-7: Trenching band levels. 19
Figure 4-8: Sparker impulse for a 2200J. 19
Figure 5-1: Comparison of two semi-empirical models over a sandy bottom at 30m depth. Transmission loss in dB versus range and frequency. 20
Figure A-1: Graphical representation of acoustic wave descriptors. 30
Figure A-2: Comparison between hearing thresholds of different marine animals and humans. 32
Figure A-3: Schematic of the effect of sediment on highly focussed sources. Sediments range from fine silt (top panel), sand (middle panel), and gravel (lower panel). The density of “rays” indicate difference in effective propagation angle from the source, with acoustically harder sediments (gravel) having better reflection at steeper angles leading to more “rays” being effectively propagated (no significant bottom attenuation) in the waveguide. Beam shape indicated in left chart, with the black line showing the same received level. 34
Figure A-4: Lower cut-off frequency as a function of depth for a range of seabed types. 34
Figure A-5: Soundspeed profile as a function of salinity, temperature and pressure. 35
Figure A-6: Effect of wind (at 10m height) on upper portion of soundspeed profile. 35
Figure A-7: Absorption loss coefficient (dB/km) for various salinities and temperature. 36

Glossary

Term	Meaning
Decibel (dB)	A customary scale most commonly used (in various ways) for reporting levels of sound. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be $10 \cdot \log_{10}$(actual/reference), where (actual/reference) is a power ratio. The standard reference for underwater sound pressure is 1 micro-Pascal (μPa), and 20 micro-Pascals is the standard for airborne sound. The dB symbol is followed by a second symbol identifying the specific reference value (i.e. re 1 μPa).
Grazing angle	A glancing angle of incidence (the angle between a ray incident on a surface and the line perpendicular to the surface).
TI LirIC Limited	TI LirIC Limited (the Applicant) is a subsidiary of Transmission Investment Group.
Permanent Threshold Shift (PTS)	A total or partial permanent loss of hearing caused by some kind of acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the ear, and thus a permanent reduction of hearing acuity.
Temporary Threshold Shift (TTS)	Temporary loss of hearing as a result of exposure to sound over time. Exposure to high levels of sound over relatively short time periods will cause the same amount 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, but there is generally recovery of full hearing over time.
Sound Exposure Level (L_E)	The cumulative sound energy in an event, formally: “ten times the base-ten logarithm of the integral of the squared pressures divided by the reference pressure squared”. Equal to the often seen “SEL” or “dB SEL” quantity. Defined in: ISO 18405:2017, 3.2.1.5
Sound Pressure level (SPL)	The average sound energy over a specified period of time, formally: “ten times the base-ten logarithm of the arithmetic mean of the squared pressures divided by the squared reference pressure”. Equal to the deprecated “RMS level”, “dB_{rms}” and to Leq if the period is equal to the whole duration of an event. Defined in ISO 18405:2017, 3.2.1.1
Peak Level, Peak Pressure Level (L_P)	The maximal sound pressure level of an event, formally: “ten times the base-ten logarithm of the maximal squared pressure divided by the reference pressure squared” or “twenty time the base-ten logarithm of the peak sound pressure divided by the reference pressure, where the peak sound pressure is the maximal deviation from ambient pressure”. Defined in ISO 18405:2017, 3.2.2.1

Acronyms

Term	Meaning
ADD	Acoustic Deterrent Device
LF	Low Frequency (Cetaceans)
HF	High Frequency (Cetaceans)
VHF	Very High Frequency (Cetaceans)
MF	*Mid Frequency (Cetaceans) – DEPRECATED only for reference to NOAA/NMFS 2018 groups*
NMFS	National Marine Fisheries Service
OW/OCW	Otariid pinnipeds/Other Carnivores in water (refers to the same weighting and animal groups)
PTS	Permanent Threshold Shift
PW/PCW	Phocid pinnipeds
RMS	Root Mean Square
L_E	Sound Exposure Level, [dB]
SPL	Sound Pressure Level, [dB]
L_P	Peak Pressure Level, [dB]
TTS	Temporary Threshold Shift
PTS	Permanent Threshold Shift

Units

Unit	Description
dB	Decibel (Sound)
Hz	Hertz (Frequency)
kHz	Kilohertz (Frequency)
kJ	Kilojoule (Energy)
km	Kilometre (Distance)
km^2	Kilometre squared (Area)
m	Metre
ms	Millisecond (10^{-3} seconds) (Time)
ms^{-1} or m/s	Metres per second (Velocity)
µPa	Micro Pascal
Pa	Pascal (Pressure)
psu	Practical Salinity Units (parts per thousand of equivalent salt in seawater)
kg/m^3	Specific density (of water, sediment or air)
Z	Acoustic impedance [$kg/(m^2 \cdot s)$ or $(Pa \cdot s)/m^3$]

Units will generally be enclosed in square brackets e.g.: “[m/s]”

1. INTRODUCTION

1.1 TI LirIC Limited (the Applicant), a wholly owned subsidiary in the Transmission Investment Group, is developing a proposed 700 megawatt (MW) High Voltage Direct Current (HVDC) electricity interconnector project to connect the Irish Integrated Single Electricity Market (I-SEM) to the Great Britain (GB) wholesale electricity market through a link between Northern Ireland (NI) and Scotland (the LirIC Project, herein referred to as the Development), which is scheduled to be fully operational around the end of this decade.

1.2 This Subsea Noise Technical Report presents the results of a desktop study considering the potential short term effects of underwater noise on the marine environment from the marine surveys (geophysical and geotechnical) for the Development.

1.3 For the purposes of this Subsea Noise Technical Report the study area for the Offshore Cable Corridor covers ca. 4,100 square kilometres (km^2), in an approximately 30-40 kilometres (km) wide strip extending from the north-east coast of County Antrim, NI across the Irish sea, along the west coast of Ayrshire and the south-east coast of the Isle of Arran in Scotland. The Offshore Cable Corridor covers steep and deep underwater terrain in the Irish sea with depths up to 250 metres (m) and flatter underwater terrain in the Firth of Clyde, with typical depths of 40-80m. The sediment varies from fine mud and silt in the Firth of Clyde to coarse sand and gravel in Irish Sea.

1.4 Sound is readily transmitted into the underwater environment and there is potential for the sound emissions from anthropogenic sources to adversely affect marine mammals and fish. Near a noise source with high noise levels, permanent or temporary hearing damage may occur to marine species, while at a very close range gross physical trauma is possible. At long ranges (several kms) the introduction of any additional noise could, for the duration of the activity, potentially cause behavioural changes, changes to the ability of species to communicate and to determine the presence of predators, food, underwater features, and obstructions.

1.5 This report provides an overview of the potential effects due to underwater noise from the Development on the surrounding marine environment based on the Southall et al. 2019 and Popper et al. 2014 framework for assessing impact from noise on marine mammals and fishes, focussing mainly on effects related to hearing impact.

1.6 Consequently, the primary purpose of the underwater noise assessment is to predict the likely range of onset for potential physiological and behavioural effects due to increased anthropogenic noise as a result of the Development.

2. ASSESSMENT CRITERIA

2.1. General

2.1 To determine the potential spatial range of injury and disturbance, assessment criteria have been developed based on a review of available evidence including national and international guidance and scientific literature. The following Sections summarise the relevant assessment criteria and describe the evidence base used to derive them.

2.2 Underwater noise has the potential to affect marine life in different ways depending on its noise level and characteristics. Assessment criteria generally separate sound into two distinct types, as follows:

- **Impulsive sounds** which are typically transient, momentary (less than one second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI 1986; NIOSH 1998; ANSI 2005). This category includes sound sources such as seismic surveys, impact piling and underwater explosions. Additionally included here are sounds under 1 second in duration with a weighted kurtosis over 40 (see note below*).
- **Non-impulsive** (and continuous) sounds which can be broadband, narrowband or tonal, momentary, brief or prolonged, continuous or intermittent and typically do not have a high peak sound pressure with rapid rise/decay time that impulsive sounds do (ANSI 1995; NIOSH 1998). This category includes sound sources such as continuous vibro-piling, running machinery, some sonar equipment and vessels.

*Note that the European Guidance: “Monitoring Guidance for Underwater Noise in European Seas, Part II: Monitoring Guidance Specifications” (MSFD Technical Subgroup on Underwater Noise, 2014) includes sonar as impulsive sources (see Section 2.2). However, the guidance suggests that “all loud sounds of duration less than 10 seconds should be included” as impulsive. This contradicts research on impact from impulsive sounds suggesting that a limit for “impulsiveness” can be set at a kurtosis[1] of 40 (Martin et al. 2020). This latter criterion has been used for classification of impulsive versus non-impulsive for sonars and similar sources. The justification for departing from the MSFD criterion is that the Southall 2019 framework limits are based on the narrower definition of impulsive as given above under “Impulsive sounds”.

2.3 The acoustic assessment criteria for marine mammals and fish in this report has followed the latest international guidance (based on the best available scientific information), that are widely accepted for assessments in the UK, Europe and worldwide (Southall et al.; Popper et al. 2014).

2.2. Injury to Marine mammals

2.4 Underwater noise has the potential to affect marine life in different ways depending on its noise level and characteristics. Richardson et al. (1995) defined four zones of noise influence which vary with distance from the source and level, to which we have added the “zone of temporary hearing loss”. These are:

- **The zone of audibility**: this is defined as the area within which the animal can detect the sound. Audibility itself does not implicitly mean that the sound will affect the marine mammal.

---

[1] Statistical measure of the asymmetry of a probability distribution.

- **The zone of masking**: this is defined as the area within which noise can interfere with the detection of other sounds such as communication or echolocation clicks. This zone is very hard to estimate due to a paucity of data relating to how marine mammals detect sound in relation to masking levels (for example, humans can hear tones well below the numeric value of the overall noise level).

- **The zone of responsiveness**: this is defined as the area within which the animal responds either behaviourally or physiologically. The zone of responsiveness is usually smaller than the zone of audibility because, as stated previously, audibility does not necessarily evoke a reaction. For most species there is very little data on response, but for species like harbour porpoise there exists several studies showing a relationship between received level and probability of response (Graham IM 2019; Sarnoci nska J 2020; BOOTH 2017; Benhemma-Le Gall A 2021).

- **The zone of temporary hearing loss**: The area where the sound level is high enough to cause the auditory system to lose sensitivity temporarily, causing loss of “acoustic” habitat, the volume of water that can be sensed by hearing by the animal.

- **The zone of injury / permanent hearing loss**: this is the area where the sound level is high enough to cause tissue damage in the ear. This is usually classified as permanent threshold shift (PTS). At even closer ranges, and for very high intensity sound sources (e.g. underwater explosions), physical trauma or acute mortal injuries are possible.

2.5 For this study, it is the zones of injury (PTS) that are of primary interest, along with estimates of behavioural impact ranges. To determine the potential spatial range of injury and behavioural change, a review has been undertaken of available evidence, including international guidance and scientific literature. The following Sections summarise the relevant thresholds for onset of effects and describe the evidence base used to derive them.

2.6 The zone of injury in this study is classified as the distance over which a marine mammal can suffer PTS leading to non-reversible auditory injury. Injury thresholds are based on a dual criteria approach using both un-weighted L_P (maximal instantaneous SPL) and marine mammal hearing weighted L_E. The hearing weighting function is designed to represent the sensitivity for each group within which acoustic exposures can have auditory effects. The categories include:

- **Low Frequency (LF) cetaceans**: Marine mammal species such as baleen whales (e.g. minke whale *Balaenoptera acutorostrata*).

- **High Frequency (HF) cetaceans**: Marine mammal species such as dolphins, toothed whales, beaked whales and bottlenose whales (e.g. bottlenose dolphin *Tursiops truncates* and white-beaked dolphin *Lagenorhynchus albirostris*).

- **Very High Frequency (VHF) cetaceans**: Marine mammal species such as true porpoises, river dolphins and pygmy/dwarf sperm whales and some oceanic dolphins, generally with auditory centre frequencies above 100 Kilohertz (kHz) (e.g. harbour porpoise *Phocoena phocoena*).

- **Phocid Carnivores in Water (PCW)**: True seals, earless seals (e.g. harbour seal *Phoca vitulina* and grey seal *Halichoreus grypus*); hearing in air is considered separately in the group PCA.

- **Other Marine Carnivores in Water (OCW)**: Including otariid pinnipeds (e.g. sea lions and fur seals), sea otters and polar bears; air hearing considered separately in the group Other Marine Carnivores in Air (OCA).

- **Sirenians (SI)**: Manatees and dugongs. This group is only represented in the NOAA guidelines.

2.7 These weightings have therefore been used in this study and are shown in Figure 2-1. It should be noted that not all the above categories of marine mammal will be present in the Offshore Cable Corridor, but criteria are presented in this report for completeness.

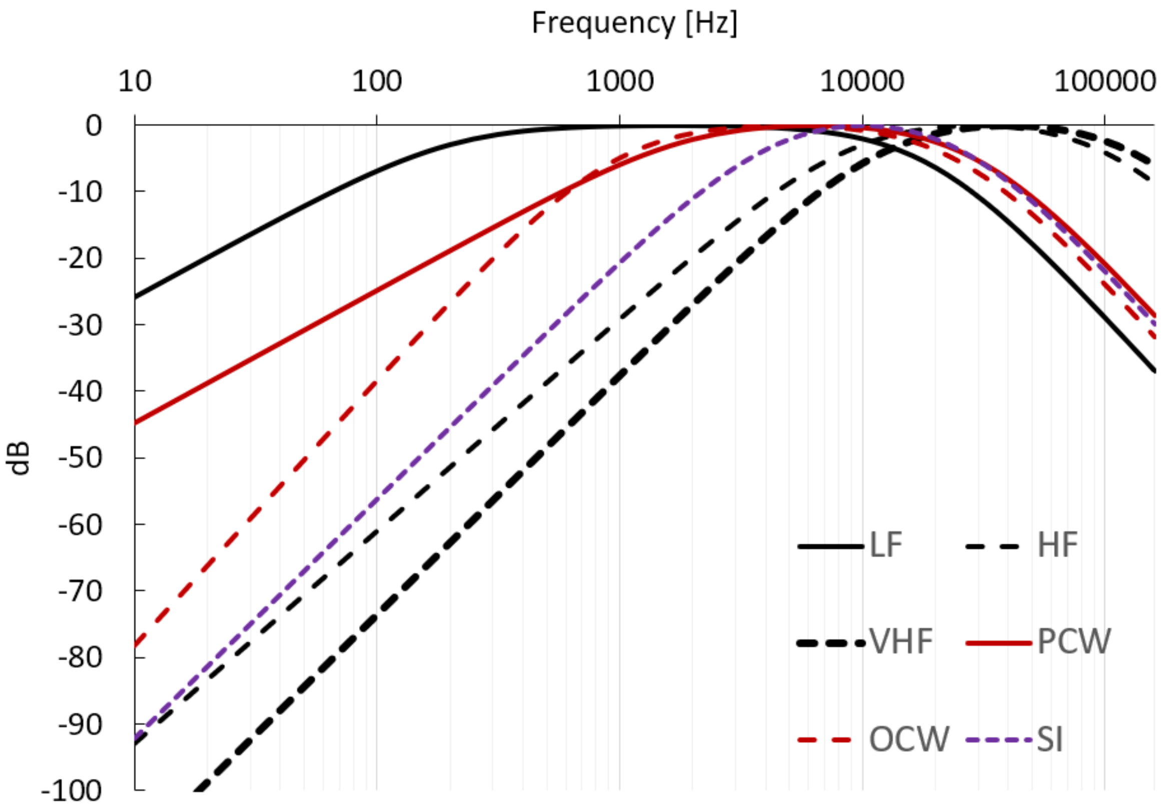

Figure 2-1: Hearing weighting functions for pinnipeds, cetaceans and sirenians (NMFS, 2018; Southall et al. 2019)

2.8 Both the criteria for impulsive and non-impulsive sound are relevant for this study given the nature of the sound sources used during the Development. The relevant PTS and TTS criteria proposed by Southall et al. (2019) are summarised in Table 2-1.

Table 2-1: PTS and TTS onset acoustic thresholds (Southall *et al., 2019*; Tables 6 and 7)

Hearing Group	Parameter	Impulsive (Decibel [dB])		Non-impulsive (Decibel [dB])	
		PTS	TTS	PTS	TTS
Low frequency (LF) cetaceans	L_P, (unweighted)	219	213	-	-
	L_E, (LF weighted)	183	168	199	179
High frequency (HF) cetaceans	L_P, (unweighted)	230	224	-	-
	L_E, (MF weighted)	185	170	198	178
Very high frequency (VHF) cetaceans	L_P, (unweighted)	202	196	-	-
	L_E, (HF weighted)	155	140	173	153
Phocid carnivores in water (PCW)	L_P, (unweighted)	218	212	-	-
	L_E, (PW weighted)	185	170	201	181
Other marine carnivores in water (OCW)	L_P, (unweighted)	232	226	-	-
	L_E, (OW weighted)	203	188	219	199
Sirenians (SI) (NOAA only)	L_P, (unweighted)	226	220	-	-
	L_E, (OW weighted)	190	175	206	186

2.9 These updated marine mammal injury criteria were published in March 2019 (Southall et al.). The paper utilised the same hearing weighting curves and thresholds as presented in the preceding regulations document NMFS (2018) with the main difference being the naming of the hearing groups and introduction of additional thresholds for animals not covered by NMFS (2018). A comparison between the two naming conventions is shown in Table 2-2.

2.10 The naming convention used in this report is based upon those set out in Southall et al. (2019). Consequently, this assessment utilises criteria which are applicable to both NMFS (2018) and Southall et al. (2019).

Table 2-2: Comparison of Hearing Group Names between NMFS (2018) and Southall *et al.* (2019)

NMFS (2018) hearing group name	Southall *et al.* (2019) hearing group name
Low-frequency cetaceans (LF)	LF
Mid-frequency cetaceans (MF)	HF
High-frequency cetaceans (HF)	VHF
Phocid pinnipeds in water (PW)	PCW
Otariid pinnipeds in water (OW)	OCW
Sirenians (SI)	Not included

2.3. Disturbance to Marine Mammals

2.11 Disturbance thresholds for marine mammals are summarised in Table 2-3. Note that the non-impulsive threshold can often be lower than ambient noise for coastal waters with some human activity, meaning that ranges determined using this limit will tend to be higher than actual ranges. Also, as the levels are unweighted the ranges will be dominated by low-frequency noise, which for most hearing groups is outside their hearing range.

Table 2-3: Disturbance Criteria for Marine Mammals Used in this Study based on Level B harassment of NMFS (National Marine Fisheries Service, 2005)

Effect	Non-Impulsive Threshold	Impulsive Threshold
Disturbance (all marine mammals)	120 dB SPL	160 dB $L_{E\ \text{single impulse}}$ or 1-second L_E

2.4. Injury and Disturbance to Fish and Sea Turtles

2.12 The injury criteria used in this noise assessment are given in Table 2-4 and Table 2-5 for impulsive noises and continuous noise respectively. L_P and L_E criteria presented in the tables are unweighted. Physiological effects relating to injury criteria are described below (Popper, et al., 2014):

- **Mortality and potential mortal injury**: either immediate mortality or tissue and/or physiological damage that is sufficiently severe (e.g. a barotrauma) that death occurs sometime later due to decreased fitness. Mortality has a direct effect on animal populations, especially if it affects individuals close to maturity.

- **Recoverable injury ("PTS" in tables and figures)**: Tissue damage and other physical damage or physiological effects, that are recoverable, but which may place animals at lower levels of fitness, may render them more open to predation, impaired feeding and growth, or lack of breeding success, until recovery takes place.

2.13 The PTS term is used here to describe this, more serious impact, even though it is not strictly permanent for fish. This is to better reflect the fact that this level of impact is perceived as serious and detrimental to fish.

- **Temporary Threshold Shift (TTS)**: Short term changes (minutes to few hours) in hearing sensitivity may, or may not, reduce fitness and survival. Impairment of hearing may affect the ability of animals to capture prey and avoid predators, and cause deterioration in communication between individuals, affecting growth, survival, and reproductive success. After termination of a sound that causes TTS, normal hearing ability returns over a period that is variable, depending on many factors, including the intensity and duration of sound exposure.

2.14 Popper et al. 2014 does not set out specific TTS limits for L_P and for disturbance limits for impulsive noise for fishes. Therefore publications: "Washington State Department of Transport Biological Assessment Preparation for Transport Projects Advanced Training Manual" (WSDOT 2011) and "Canadian Department of Fisheries and Ocean Effects of Seismic energy on Fish: A Literature review" (Worcester 2006) on effects of seismic noise on fish are used to determine limits for these:

1. The criteria presented in the Washington State Department of Transport Biological Assessment Preparation for Transport Projects Advanced Training Manual (WSDOT 2011). The manual suggests an un-weighted sound pressure level of 150dB SPL (assumed to be duration of 95% of energy) as the criterion for onset of behavioural effects, based on work by Hastings (2002). Sound pressure levels in excess of 150dB SPL are expected to cause temporary behavioural changes, such as elicitation of a startle response, disruption of feeding, or avoidance of an area. The document notes that levels exceeding this threshold are not expected to cause direct permanent injury but may indirectly affect the individual fish (such as by impairing predator detection). It is important to note that this threshold is for onset of potential effects, and not necessarily an 'adverse effect' threshold. The threshold is implemented here as either single impulse L_E or 1 second L_E, whichever is greater.

2. The report from the Canadian Department of Fisheries and Ocean “Effects of Seismic energy on Fish: A Literature review on fish” (Worcester 2006) found large differences in response between experiments. Onset of behavioural response varied from 107-246dB L_P, the 10th percentile level for behavioural response was 158dB L_P, given the large variations in the data, we have rounded this to 160dB L_P as the behavioural limit for fishes for impulsive noise.

Table 2-4: Criteria for onset of injury to fish and sea turtles due to impulsive noise

Type of animal	Unit	Mortality and potential mortal injury [dB]	Recoverable injury (PTS) [dB]	TTS [dB]	Behavioural [dB]
Fish: no swim bladder (particle motion detection)	L_E	219[1]	216[1]	186[1]	150[3]
	L_P	213[1]	213[1]	193[2]	189[2]
Fish: where swim bladder is not involved in hearing (particle motion detection)	L_E	210[1]	203[1]	186[1]	150[3]
	L_P	207[1]	207[1]	193[2]	189[2]
Fish: where swim bladder is involved in hearing (primarily pressure detection)	L_E	207[1]	203[1]	186	150[3]
	L_P	207[1]	207[1]	193[2]	189[2]
Sea turtles	L_E	210[1]	(*Near*) High (*Intermediate*) Low (*Far*) Low	-	-
	L_P	207[1]		-	-
Eggs and larvae	L_E	210[1]	(*Near*) Moderate (*Intermediate*) Low (*Far*) Low	-	-
	L_P	207[1]		-	-

[1] (Popper et al. 2014)

[2] (Worcester 2006)

[3] (WSDOT 2011)

2.15 Where Popper et al. 2014 present limits as “>” 207 or “>>” 186, we have ignored the “greater than” and used the threshold level as given.

2.16 Relevant limits for fishes relating to PTS, TTS, and behaviour are given in Table 2-5. Note that for the behaviour limit we have used the impulsive limit as basis for the continuous noise limit, in absence of better evidence.

Table 2-5: Criteria for fish due to non-impulsive noise from Popper et al. 2014.

Type of animal	Unit	Mortality and potential mortal injury	Recoverable injury (PTS) [dB]	TTS [dB]	Behavioural [dB]
All fishes	L_E	-	222	210	150 [SPL]*

*This is based on the impulsive criteria.

3. METHOD, ENVIRONMENT & SITE

3.1 The following Section is based on the information given in the documents:

- “Project Description”, dated July 2023, revision 0.3 Draft.
- “LirIC Interconnector Project, Landfall and Marine Survey, Scope of Work” P1770-DC-H187-R0.
- “LirIC Interconnector Project, Landfall and Marine Survey, Technical Specification” P1770-DC-H188-R0.
- Written communication with the client, or client’s representatives.

3.1. Sites

3.2 For the noise impact assessment and modelling, it is useful to sub-divide the area based on factors relevant to sound propagation (Figure 3-1), i.e., sediment types and depth.

3.3 There are three main scenario types for the propagation modelling:

1. “Shallow-Mud”:
   This scenario is dominated by fine muddy/silty sediments and depths <80m.
2. “Shallow-Sand”:
   This scenario is dominated by sandy sediments and depths of 50-100m.
3. “Deep-Coarse”:
   This scenario is dominated coarse sediments and depths >100m.

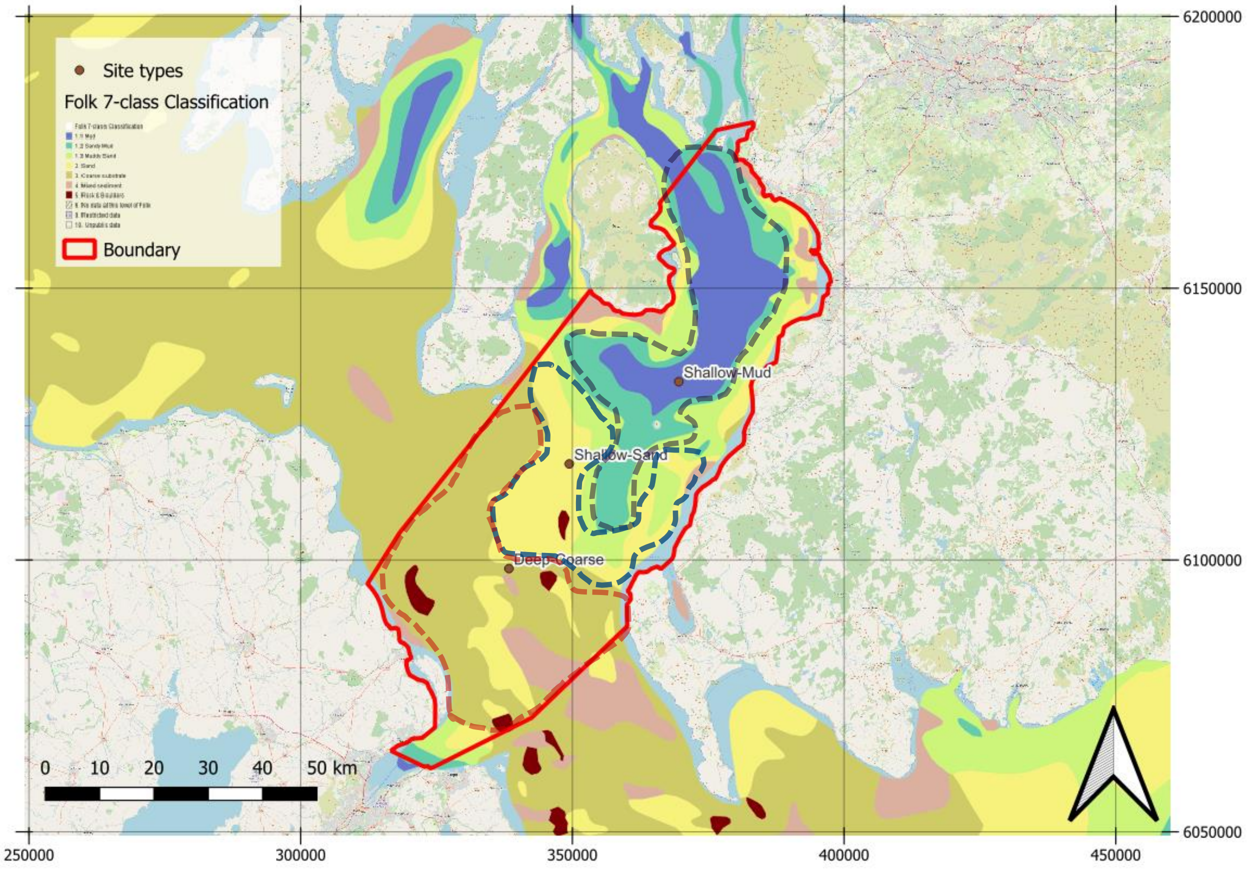

Figure 3-1: The Development area (red line). Blues and greens are Silt and Mud (black dashed), Light yellows and light greens are Sand (blue dashed) and dark yellow is coarser sediment (red dashed). (Background maps: EMODnet Sediment2 & OpenStreetMap).

3.2. Survey Method

3.4 Two surveys are to be carried out with separate noise footprints, namely a geophysical survey (acoustically based depth and sediment survey) and a geotechnical survey (sediment point survey based on physical samples).

3.5 All survey equipment will be similar for all areas (see Table 4-1), with some small differences for very shallow locations where the multibeam echosounder will not be modelled due to its frequency range being outside the hearing range of the animals present.

3.6 Details on the expected equipment to be used (or representative equipment) can be found in Section 4.

---

[2] WMS server: https://drive.emodnet-geology.eu/geoserver/gtk/wms

3.3. Source Locations

3.7 Modelling was based on selected locations within the three scenarios. The locations were chosen to ensure a conservative assessment that covers the variation in the site see Table 3-1.

Table 3-1: Modelled source locations for the two sites

Site	Description	Source easting (UTM 30N)	Source Northing (UTM 30N)
“Shallow-Mud”	Ca. 50m depth Muddy/silty sediment	369524	6132759
“Shallow-Sand”	Ca. 60m depth Sandy sediment	349354	6117621
“Deep-Coarse”	Ca. 130m depth Coarse sediment	338254	6098363

3.4. Water Properties

3.8 Water properties were determined from historical data for the area. Where a range of values are expected, the value leading to less transmission loss was chosen for a more conservative assessment. This thus covers seasonal variation.

- Temperature: 13 degrees – maximal temperature given by Met Eireann for the north Irish Sea[3].
- Salinity: 35 Practical Salinity Units (psu).
- Soundspeed profile: Assumed uniform given high mixing as a result of tidal flows. A uniform soundspeed profile is conservative compared to the likely downward refracting soundspeed profiles seen during summer months, causing increased loss to the sediment (higher temperature in the surface leads to higher soundspeeds).

---

[3] https://www.met.ie/climate/average-monthly-sea-temperature-at-malin-head/

3.5. Sediment Properties

3.9 Sediment properties are taken from EMODnet[4] “Folk 7-class Classification”, nautical charts[5] and British Geological Survey (British Geological Survey 2023). A sediment model (Ainslie 2010) was used to derive the acoustic properties of the sediments from the grain size.

Table 3-2: Sediment properties

Site	Sediment type (Folk 7)	ISO 14688-1:2017	Density (Specific Density [kg/m³])	Soundspeed (metres per second [m/s])	Grain size (Millimetres [mm]) (nominal)
Shallow-Mud	Mud	Fine Silt	1478	1516	0.006
Shallow-Sand	Muddy Sand	Fine Sand	1884	1689	0.1
Deep-Coarse	Sandy Gravel	Fine Gravel	2746	2111	5

---

[4] https://emodnet.ec.europa.eu/ sediment model “Folk 7-class” classification.

[5] https://fishing-app.gpsnauticalcharts.com/i-boating-fishing-web-app/fishing-marine-charts-navigation.html

4. SOURCE NOISE LEVELS

4.1 Underwater noise sources are usually quantified in dB scale with values generally referenced to 1µPa pressure amplitude as if measured at a hypothetical distance of 1m from the source (called the Source Level). In practice, it is not usually possible to measure at 1m from a source, but the metric allows comparison and reporting of different source levels on a like-for-like basis. In reality, for a large sound source this imagined point at 1m from the acoustic centre does not exist. Furthermore, the energy is distributed across the source and does not all emanate from an imagined acoustic centre point. Therefore, the stated sound pressure level at 1m does not occur for large sources. In the acoustic near field (i.e. close to the source), the sound pressure level will be significantly lower than the value predicted by the back-calculated source level (SL).

4.1. Source models

4.2 The noise sources and activities investigated during this assessment are summarised in Table 4-1. Source locations are given in Table 3-1.

4.3 Source levels for the active equipment were added to produce a “combined” source that represents the survey vessel’s sound signature while actively surveying during the survey (see Figure 4-3). This combined source has all levels given as SPL, meaning impulsive source have been converted from single impulse L_E to SPL given the impulse repetition rate as given by the local depths.

4.4 Some equipment types are included more than once, this is to provide coverage as the final equipment configuration is not yet known.

4.5 Note that source levels vary depending on the location of the survey due to two factors:

1. The ping rate, and therefore the SPL and L_E of the source, varies with the local depth.

2. Due to differences in sediment, the angle at which the sediment will tend to reflect sound back into the water column efficiently, changes. As we use this “critical angle” to derive practical source levels for highly directional sources, this will change with sediment type.

4.6 Sonars and echosounder generally use tone pulses of either constant frequency or as a frequency sweep, these pulses are typically windowed to limit “spectral leakage[6]”. We assume use of a Von Hann window (sometimes “Hanning”) which gives effective attenuation of frequencies outside the intended centre frequency. This means that while a sonar with centre frequency of 200kHz is well above the hearing range of any mammal, there will be energy at 100kHz ca. 50dB lower than the source level at 200kHz and we cannot simply ignore it solely based on its centre or nominal frequency.

4.7 Highly directional sources with narrow beams (sonars and echosounders) will tend to only ensonify a narrow cone of water at any given time. As the beams sweep though the water to get full sediment coverage, we have converted these sources to a monopoint (omnidirectional) source with the same acoustic energy as the original. This makes calculations simpler and means that we account for the probabilistic nature of the beam not ensonifying the total water column.

---

[6] Acoustic phenomenon where a sharp change in pressure produced sound in a wide frequency range (similar to an ideal impulse).

4.1.1. Vessel

4.8 The vessel is specified as “large” and “quiet”, these are taken to mean a vessel of up to 80m at water line, conforming to “Quiet” or “Research” noise notations from large Vessel Classification companies (such as DNV, BV, ABS or LR[7]). Maximal broadband level of 186dB SPL with maximal per band levels given in Figure 4-1.

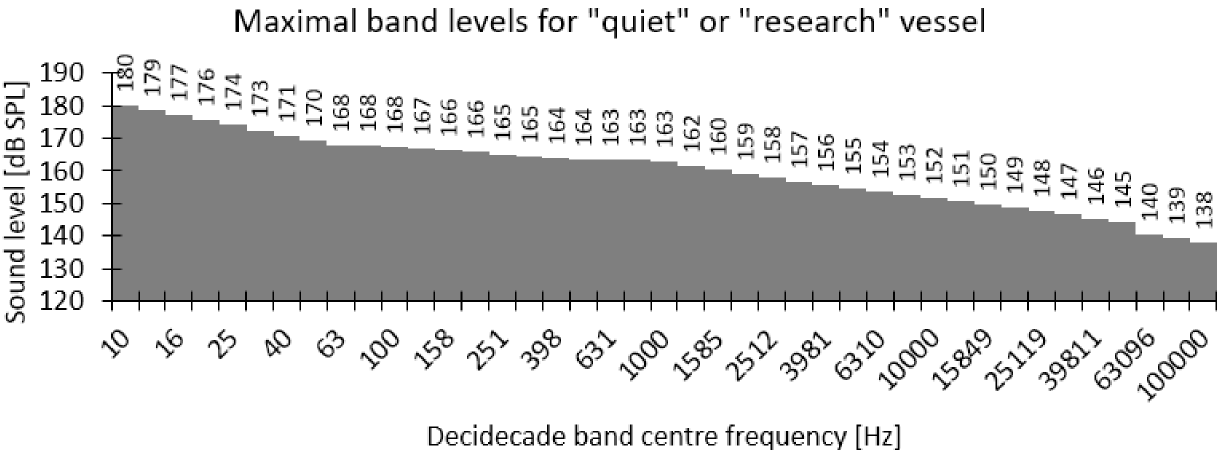

Figure 4-1: Maximal noise level per band for a “quiet” vessel. Broadband level 186 dB SPL.

4.1.2. Side Scan Sonar (SSS)

4.9 The side scan sonar (SSS) is based on the “Edgetech FS-4200” (Full Spectrum), in frequency modulated mode and pulse repetition rates (ping rates) based on the expect two-way travel time for a towed unit 15m above the sediment.

4.10 This SS can operate in 1 of 3 modes: 100/400kHz, 300/600kHz or 300/900kHz. To allow for flexibility in deployment we have included all modes in our assessment.

4.1.3. Multibeam Echosounder (MBES)

4.11 The multibeam echosounder (MBES) source is based on the “Teledyne Reson Seabat T51-R (350-430kHz)”, in dual head configuration and the “Kongsberg EM2040-04 MKII”, also with two transducers.

4.1.4. Parametric Sub-bottom Profiler (P-SBP)

4.12 The Innomar 200-Medium is a parametric sub-bottom profiler, meaning it uses two higher frequencies (“primary frequencies”) to generate an interference pattern at lower frequencies (“secondary frequencies”). This means that the secondary beam can be made extraordinarily narrow, leading to a much smaller noise impact (Figure 4-2). We account for these differences in beam pattern by including the sediment reflection loss at high incidence angles (see APPENDIX A, Figure A-3) to reduce the effective source level accordingly.

---

[7] “Det Norske Veritas Holding”, “Bureau Veritas”, “American Bureau of Shipping”, “Lloyd’s Register”.

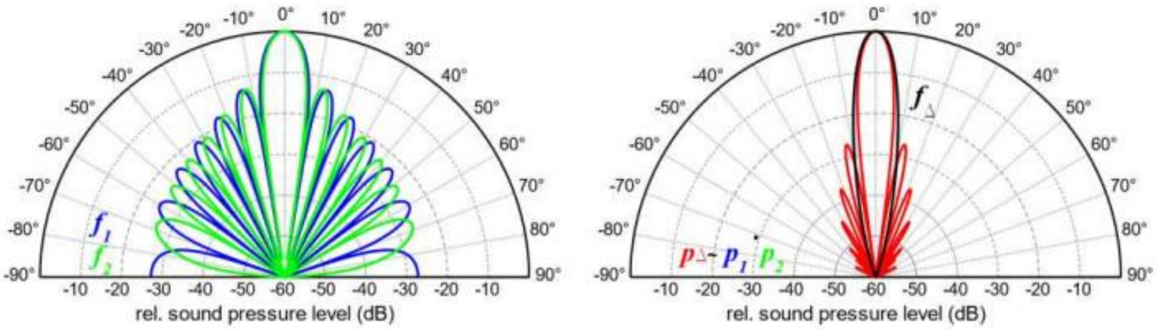

Figure 4-2: Example of a beam pattern on an Innomar 200-Medium. Primary frequencies left, the non-overlapping lobes outside the main lobe, means that the beam pattern for the secondary frequencies (right plot) is very narrow.

4.1.5. Boomer Sub-bottom Profiler (B-SBP)

4.13 The second suggested SBP in shallow water (<15m) is an “Applied Acoustics Surface Towed Boomer”. We have based this source on an aggregate review of nine similar sources to this, as no suitable data for the exact model was found. The boomer model is based on a generic boomer with a single pulse energy of 320 Joules.

4.1.6. Sparker Sub-bottom Profiler (S-SBP)

4.14 The suggested SBP in deeper water (>15m) is a “Dura Spark”, given lack of source level information this source has also been based on previously recorded data from similar equipment (ten different sparkers of varying energy) see Figure 4-8.

4.1.7. Altimeter

4.15 To obtain accurate altitude measurements for deployed equipment, a separate altimeter can be used on-board the deployed equipment. For this survey the altimeter will have a nominal output frequency at 500kHz, which means that even with considerable spectral leakage there will be insignificant energy at frequencies relevant to the assessment.

4.1.8. Ultra short baseline (USBL)

4.16 The USBL source is based on the “Sonardyne Ranger” and “Sonardyne Mini Ranger 2”.

4.1.9. Geotechnical sources (Equipment for physical samples)

4.17 The sample-taking (coring/drilling) and cone penetration testing (CPT) is represented by the maximal per band SPL from vibrocoring and drilling as given by a large review of available data (Center for Marine Acoustics, 2023).

4.1.10. Trenching noise

4.18 Trenching noise is included in the assessment as a surrogate for noise generated by grab sampling. While there are very few recordings available from trenching operations, two that were found for similar conditions both have lower source levels across all bands than the

"Geotechnical" source levels, and thus this activity deemed to be covered by this source and will not be considered further.

4.2. Combined Source

4.19 Individual source types and levels as well as the five different combined sources are given below:

- Table 4-1: Source characteristics and source model details.
- Figure 4-3: Combined source for geophysical survey, Scenario 1, "Shallow-Mud".
- Figure 4-4: Combined source for geophysical survey, Scenario 2, "Shallow-Sand".
- Figure 4-5: Combined source for geophysical survey, Scenario 3, "Deep-Coarse".
- Figure 4-6: Combined source for geotechnical survey.
- Figure 4-7 : Combined source for trenching.

Table 4-1: Summary of Noise Sources and Activities Included in the Subsea Noise Assessment

Equipment	Source level [SPL] (as used in model)	Primary decidecade bands (-20 dB width)	Source model details	Impulsive/non-impulsive
Survey vessel (based on "quiet" vessel)	186dB SPL	10-1,600 Hertz (Hz)	Maximal allowable to qualify as "quiet" or "research" with large vessel classification companies (details in Section 4.1.1)	Non-impulsive
Side scan sonar (Edgetech FS4200 or equivalent)	203dB SPL	100,000Hz & 900,000Hz	Based on all frequency modes available to the FS4200, covering 100kHz to 900kHz	Impulsive
Multibeam echosounder (Reson Seabat T51R & Kongsberg EM 2040-4 MKII or equivalent)	205-213dB SPL (ping rate dependent, spherical level)	200,000 – 800,000Hz	Model based on frequency modulated tone bursts, but representative for constant frequency tone bursts, von Hann window, ping rate determined by local depth.	Impulsive
Parametric sub-bottom profiler (Innomar 2000-Medium)	Primary: 208-210dB SPL Secondary: 148-154dB SPL	4,000 – 15,000Hz & 85,000 – 115,000Hz	Manufacturer Model based on frequency modulated tone bursts, but representative for constant frequency tone bursts, von Hann window, ping rate determined by local depth.	Impulsive

Equipment	Source level [SPL] (as used in model)	Primary decidecade bands (-20 dB width)	Source model details	Impulsive/non-impulsive
			Source level used for modelling adjusted for beam pattern and local sediment properties.	
Boomer type sub-bottom profiler	169-177dB SPL	125 – 16,000Hz	Model based on similar sources. Ping rate determined by local depth. Source level used for modelling adjusted for beam pattern and local sediment properties.	Impulsive
Sparker type sub-bottom profiler	182-190dB SPL	400 – 6300Hz	Model based on similar sources. Ping rate determined by local depth. Source level used for modelling adjusted for beam pattern and local sediment properties.	Impulsive
Ultra Short Baseline (USBL) positioning system	180dB SPL	19,000 – 34,000Hz	Manufacturer. 3 x 8 millisecond (ms) pulses per second.	Impulsive
Geotechnical, Vibro-coring, drilling, cone penetration testing	195dB SPL	10 – 4,000Hz	Based on review of available data.	Non-impulsive
Trenching	172dB SPL	10 – 4,000Hz	Based on back-calculated recordings from trenching in gravel.	Non-impulsive

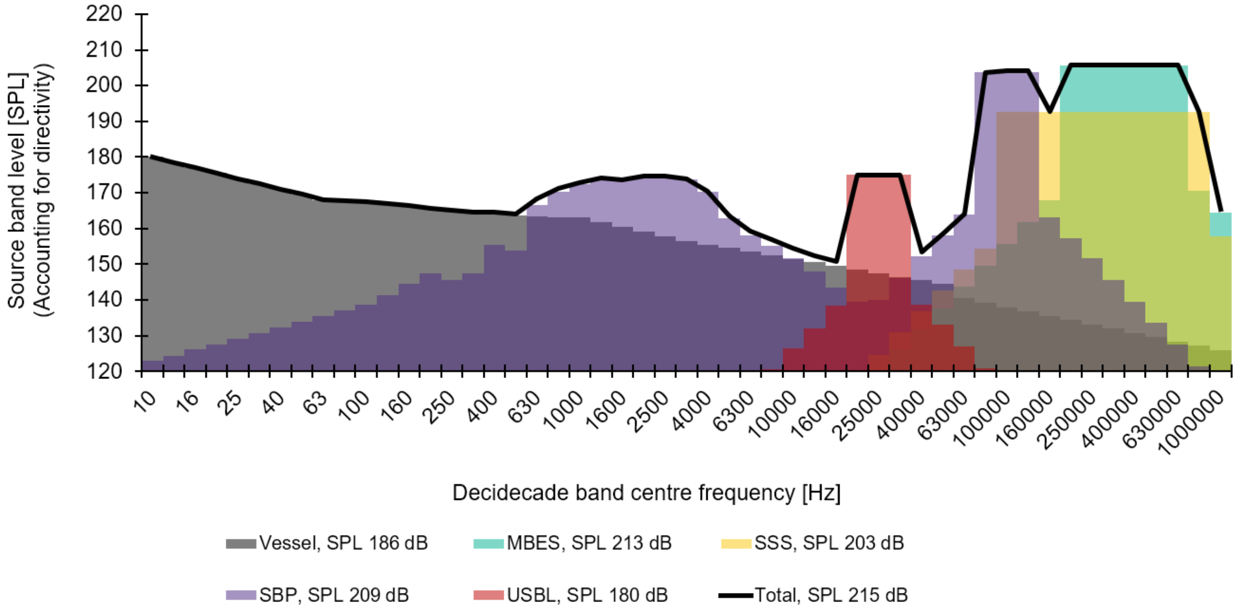

Figure 4-3: Scenario 1, Shallow-Mud: Overview of sound sources as SPL at 1m. Combined source (black solid line) represents source during survey in shallow silty or muddy areas.

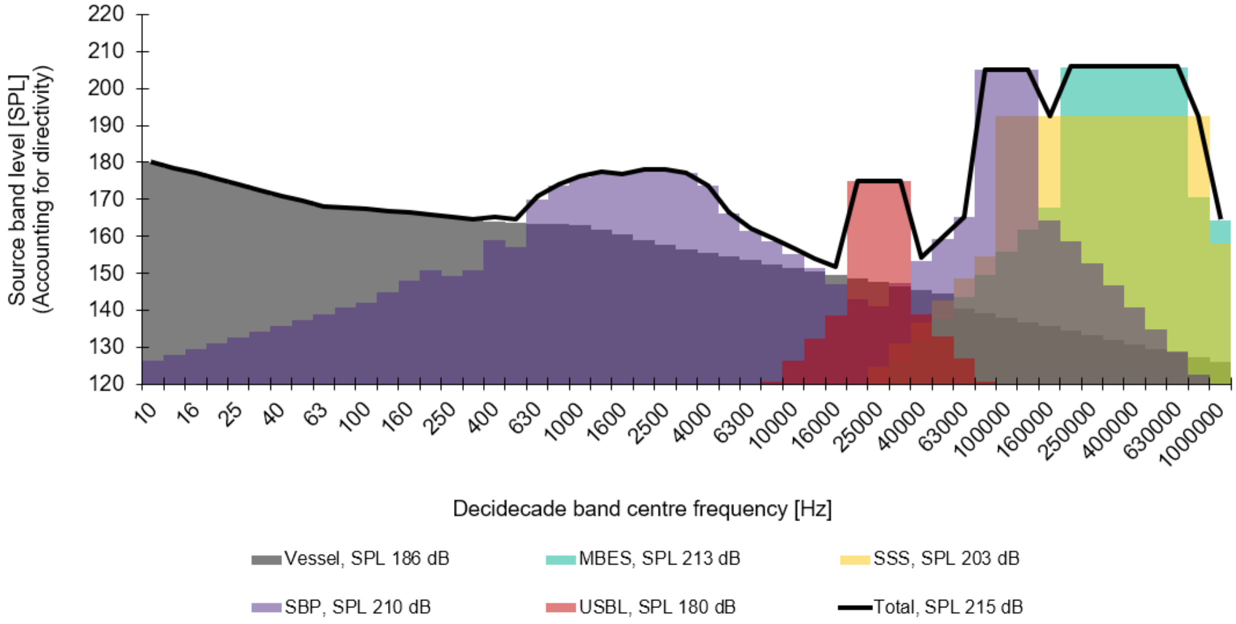

Figure 4-4: Scenario 2, Shallow-Sand: Overview of sound sources as SPL at 1m. Combined source (black solid line) represents source during survey in shallow areas with sandy sediment.

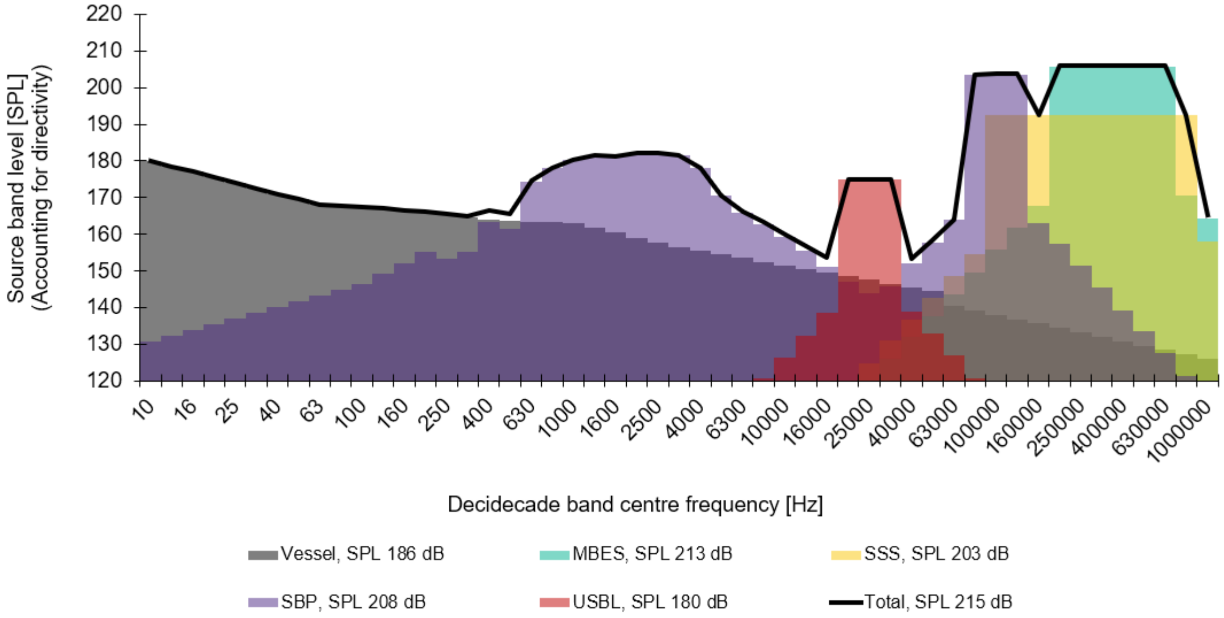

Figure 4-5: Scenario 3, Deep-Coarse: Overview of sound sources as SPL at 1m. Combined source (black solid line) represents source during survey in deep gravelly areas.

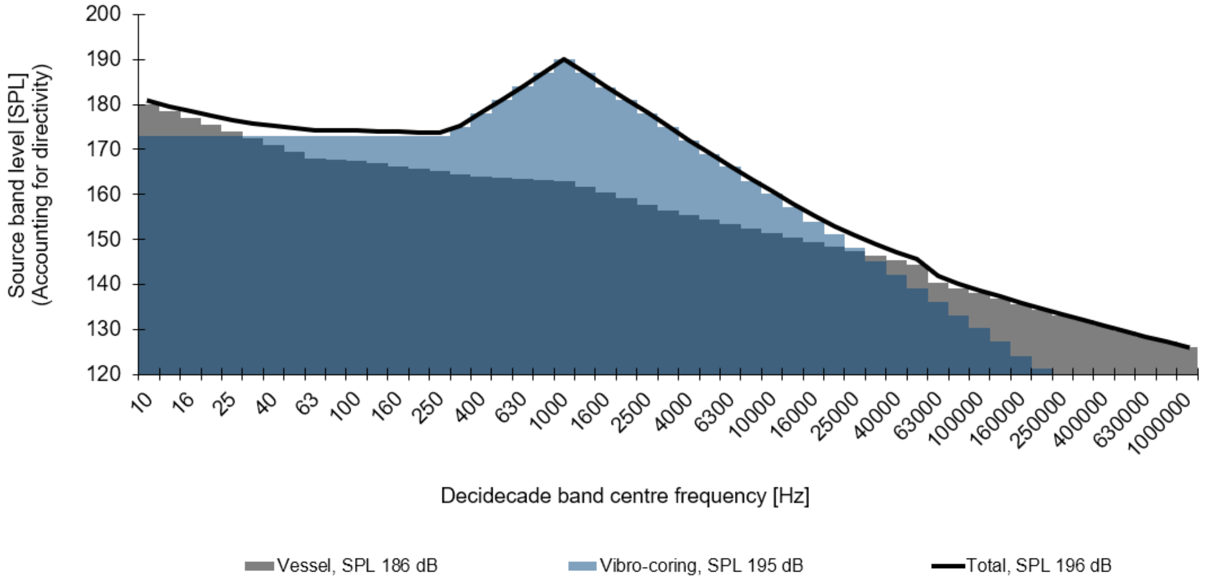

Figure 4-6: Geophysical: Overview of sound sources as SPL at 1m. Combined source (black solid line).

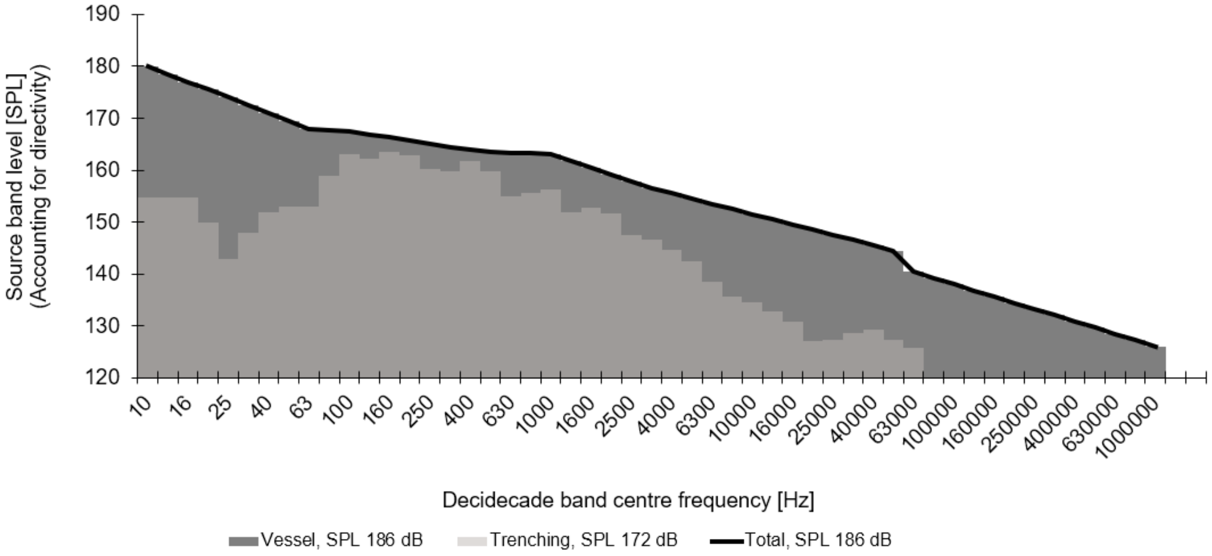

Figure 4-7: Trenching band levels.

4.20 All modelling assumed sources are omnidirectional, this is a conservative estimate as all sources bar the vessel and drilling/coring are highly directional in nature and angled towards the sediment, giving rise to increased transmission losses when compared to an omnidirectional source.

4.21 The vessel is assumed to move at 2 knots during the surveying, this is a conservative measure to increase the survey time as the vessel will likely move at 4-5 knots (limited by the temporal resolution of the survey equipment).

4.22 The maximal impulsive noise generated by any of the considered sources (after accounting vertical directivity) is the sparker type SBP with a peak pressure level of 227dB LP.

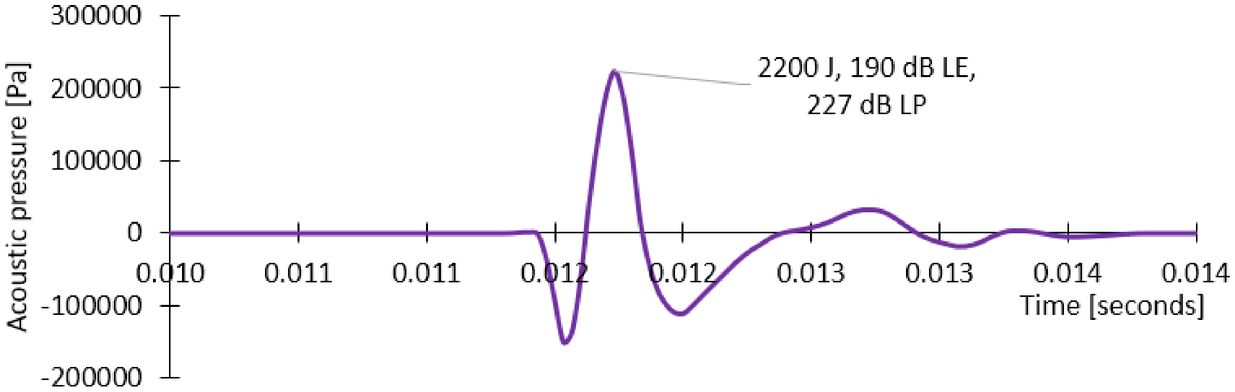

Figure 4-8: Sparker impulse for a 2200J.

5. SOUND PROPAGATION MODELLING METHODOLOGY

5.1 There are several methods available for modelling the propagation of sound between a source and receiver ranging from very simple models which simply assume spreading according to a 10·$\log_{10}$(range) or 20·$\log_{10}$(range) relationship to full acoustic models (e.g. ray tracing, normal mode, parabolic equation, wavenumber integration and energy flux models). In addition, semi-empirical models are available which lie somewhere in between these two extremes in terms of complexity (e.g. (Rogers 1981; Weston 1971)).

5.1. Semi-empirical models

5.2 For simpler scenarios where the sediment is relatively uniform and mostly flat or where greater detail in modelling is not warranted, due to uncertainty in model input or where the source level is relatively low compared to the receiver sensitivity, the speed of these simpler models is preferred over the higher accuracy of numerical models and are routinely used for these types of assessments. For this assessment we have used the “Rogers” model (Rogers 1981). This produces very similar output to the also regularly applied “Weston” model (Weston 1971), but Rogers produces a smoother transition between spherical/cylindrical spreading, mode-stripping and single mode regions of the loss and would normally be preferred unless comparing to earlier work done using the Weston model. Both these models are compared to measurements in the papers describing them and are both capable of accurate modelling in acoustically simpler scenarios[8]. We have presented a comparison between Rogers and Weston’s model here for a 30m deep scenario to show the similarities in the transmission losses they predict. We prefer the Rogers model as it is more conservative for lower frequencies, as it does not have “sharp” steps between different propagation regions.

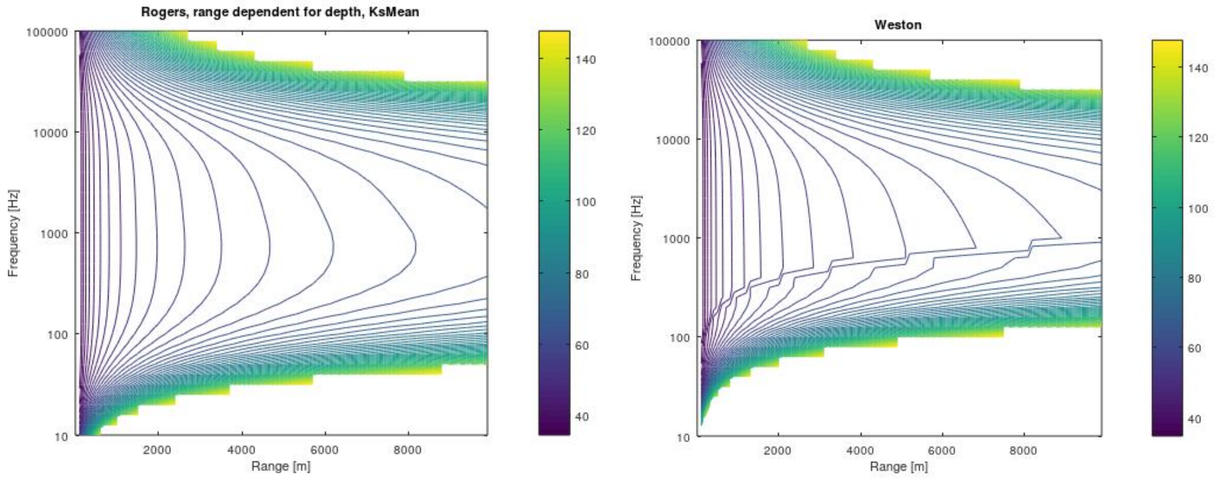

Figure 5-1: Comparison of two semi-empirical models over a sandy bottom at 30m depth. Transmission loss in dB versus range and frequency.

---

[8] Simpler meaning shallow in relation to the wavelengths and with no significant sound speed gradient in the water column.

5.3 These semi-empirical models will tend to underestimate the transmission losses (leading to estimated greater than actual impact) due primarily to the omission of surface roughness, wind effects and shear waves in the sediment.

5.2. Analytical models

5.4 For the impulsive sources we have used the dBSea software’s ray tracing solver dBSeaRay as this accounts for the full waveform propagation of the impulsive. This means including surface and bottom reflections as well as time-of-arrival in the calculations, as these are important to include to correctly estimate the effects of constructive and destructive interference. dBSea solvers are validated against a range of opensource solvers for so-called “standard scenarios” that have agreed solutions[9].

5.3. Exposure Calculations (dB L_E)

5.5 To compare modelled levels with the two impact assessment frameworks (Southall et al. 2019 & Popper et al. 2014) it’s necessary to calculate received levels as exposure levels, L_E, weighted for marine mammals, and unweighted for fishes. For ease of implementation sources have generally been converted to an SPL source level, meaning converting to L_E from SPL or from a number of events is relatively easy:

5.6 To convert from L_E to SPL the following relation can be used:

$$L_E = \mathrm{SPL} + 10 \cdot Log_{10}(t_2 - t_1) \tag{1}$$

5.7 Or where it’s inappropriate to convert to SPL by relating to the number of events as:

$$L_{E,n\ events} = L_{E,single\ event} + 10 \cdot Log_{10}(n) \tag{2}$$

5.8 As a marine mammal swims away from the sound source, the noise it experiences will become progressively more attenuated; the cumulative, fleeing L_E is derived by logarithmically adding the L_E to which the mammal is exposed as it travels away from the source. This calculation was used to estimate the approximate minimum start distance for a marine mammal in order for it to be exposed to sufficient sound energy to result in the onset of potential injury or if a set exclusion zone is sufficient for an activity (e.g. will an exclusion zone of 500m be sufficient to prevent exceeding a limit). It should be noted that the sound exposure calculations are based on the simplistic assumption that the animal will continue to swim away at a fairly constant relative speed. The real-world situation is more complex, and the animal is likely to move in a more complex manner.

5.9 Reported swim speeds are summarised in Table 5-1 along with the source papers for the assumptions. For this assessment, we used a swim speed of 1.5m/s for marine mammals and basking sharks, and 0.5m/s for fishes other than basking shark.

---

[9] https://www.dbsea.co.uk/validation/

Table 5-1: Swim speed examples from literature

Species	Hearing Group	Swim Speed (m/s)	Source Reference
Harbour porpoise	VHF	1.5	Otani *et al.* 2000
Harbour seal	PCW	1.8	Thompson 2015
Grey seal	PCW	1.8	Thompson 2015
Minke whale	LF	2.3	Boisseau *et al.* 2021
Bottlenose dolphin	HF	1.52	Bailey and Thompson 2010
White-beaked dolphin	HF	1.52	Bailey and Thompson 2010
Basking shark	Group 1 fish	1.0	Sims 2000
All other fish groups	All fish groups	0.5	Popper *et al.* 2014

6. RESULTS AND ASSESSMENT

6.1 Tables of various risk measures are presented in this Section. An additional risk range for the estimated 90th percentile value is given. This value is based on the calculated 90th percentile given mean and standard deviation of the results from the site modelled.

6.2 Main assumptions for the validity of the results:

- Final equipment configuration is not louder than the presented equipment (Table 4-1).
- Increasing the locations sampled would lead to a spread in results resembling a normal distribution, allowing statistical methods to be employed for upper bound estimates (90th percentile estimates).

6.3 Four types of results are presented to inform this assessment:

1. **"Minimal starting range for a fleeing animal":**
   The minimal range a fleeing animal needs to start fleeing from to avoid being exposed to noise exceeding its TTS/PTS limit. All these are for animals moving in a straight line away from the source at a constant speed of 1.5m/s and 0.5m/s for marine mammals and fishes respectively.
2. **"90th percentile starting range for a fleeing animal":**
   This range is based on the estimated true 90th percentile rage using the mean and standard deviation from the three sites to estimate true 90th percentile.
3. **"Peak level risk range":**
   The range of acute risk of impact from peak pressure levels associated with the peak pressure level from the impulsive sources.
4. **"Behavioural response range":**
   The range at which the behavioural limit for the marine mammals (160dB SPL for impulsive, 120dB SPL for non-impulsive) or the fishes (150dB SPL) is exceeded. Note that the behavioural limits are unweighted and will therefore be dominated by the low frequency part of the emitted noise, with all hearing groups bar LF, probably unable to hear the noise to this range, or be impacted in any way by its presence.

6.1. Geophysical

6.4 Note that the risk range used for the assessment is the 90th percentile range, a statistical approximation based on the results from the modelled scenarios. This to account for the uncertainty when only modelling a subset of possible scenarios. This represents a more conservative estimate than simply choosing the largest risk range.

6.5 Starting ranges to avoid PTS for fleeing animals of the VHF group extend to approximately 940m, with the remaining groups having ranges below 110m. Behavioural response ranges are 260m and 460m for marine mammals and fishes respectively.

Table 6-1: Geophysical – Shallow-mud, summary of minimal starting ranges for fleeing animals.

Site/Condition	LF (TTS / PTS) [m]	HF (TTS / PTS) [m]	VHF (TTS / PTS) [m]	PCW (TTS / PTS) [m]	OCW (TTS / PTS) [m]	Fish (TTS / PTS) [m]
Shallow-Mud	83 / 2	279 / 54	2193 / 704	65 / <10	<10	162 / 18
Shallow-Sand	389 / <10	344 / 83	2563 / 804	140 / <10	<10	207 / 27
Deep-Coarse	356 / <10	390 / 104	2880 / 909	153 / <10	<10	246 / 36
90th percentile	490 / **<10**	410 / **110**	2990 / **940**	180 / **<10**	**<10**	260 / **40**
Peak level range (max from all sites)	<10	<10	50 / 30	<10	<10	150 / 25
Behavioural response range			260			460

6.2. Geotechnical

6.6 *Note that the risk range used for the assessment is the 90th percentile range, a statistical approximation based on the results from the modelled scenarios. This to account for the uncertainty when only modelling a subset of possible scenarios. This represents a more conservative estimate than simply choosing the largest risk range.*

6.7 Starting ranges to avoid PTS for fleeing animals extend to <10m. Behavioural response ranges are 23km and 500m for marine mammals and fishes respectively. Note that the large behavioural response range for marine mammals is here based on the 120dB SPL (unweighted) limit. As this source has most energy at lower frequencies, it’s unlikely that any group except for the LF group can hear the source to this distance.

Table 6-2: Geophysical – Shallow-mud, summary of minimal starting ranges for fleeing animals.

Site/Condition	LF (TTS / PTS) [m]	HF (TTS / PTS) [m]	VHF (TTS / PTS) [m]	PCW (TTS / PTS) [m]	OCW (TTS / PTS) [m]	Fish (TTS / PTS) [m]
Shallow-Mud	87 / <10	<10	27 / <10	<10	<10	<10
Shallow-Sand	164 / <10	<10	51 / <10	<10	<10	<10
Deep-Coarse	452 / <10	<10	135 / <10	<10	<10	<10
90th percentile	480 / <10	<10	140 / <10	<10	<10	<10
Behavioural response range			23km			500

7. SUMMARY AND CONCLUSIONS

7.1. Geophysical Survey

7.1 For cumulative noise, the main hearing group driving mitigation range is the VHF group, with risk ranges for PTS to approximately 940m. The HF hearing group have risk ranges for PTS to below 110m, remaining hearing groups are <50m.

7.2 The deeper scenarios with an acoustically harder sediment (sand and gravel rather than silt) have lower propagation loss than the shallower scenarios, meaning that for the shallower scenarios risk ranges are shorter (700-800m for VHF rather than 940m).

7.3 For peak pressure levels the largest risk range is for the fishes group, with a PTS risk range of ca. 150m.

7.2. Geotechnical Survey (including trenching)

7.4 All PTS risk ranges are below 10m, with TTS risk ranges <500m.

7.3. Mitigation

7.3.1. Zone of Absence – Marine Mammal Observer

7.5 The modelling did not assume absence of marine mammals within a 500m range prior to survey start but given the modelled risk ranges for the VHF group extend to 940m we recommend extending a pre-survey search to a 1,000m radius for harbour porpoise, and to 100m for other marine mammals.

7.6 This means a 30-minute search by a certified Marine Mammal Observer (MMO) to establish likely absence of marine mammals within 1,000m of the vessel for harbour porpoise prior to commencing the survey is required to mitigate likely hearing injury.

7.3.2. Soft-start

7.7 An alternative option to a 1,000m exclusion zone prior to survey start, is a 30-minute soft-start, where acoustic output is reduced by at least 10 dB (either by reducing power to 10 % or reducing ping-rate to a tenth) hence a 30-minute search by a certified MMO to establish likely absence of marine mammals within just 500 m (as opposed to ca. 1,000 m) will suffice to mitigate risk of inducing PTS.

7.3.3. Equipment limitations

7.8 Final equipment configuration is not louder than the presented equipment (Table 4-1).

7.4. Conclusion

7.9 Under the assumptions laid out for the survey method, the sources used, and the mitigation applied, the noise arising from the surveys is unlikely to cause permanent injury to marine mammals and fishes.

7.10 While there is little risk of exceedance of the injury limits, we note that the survey uses high-powered sound sources that, while not likely to cause auditory harm, are likely to exceed the behavioural response limits as well as temporary hearing impact limits to ca. 3km for harbour porpoises. Note here that the assessment is based on the worst-case estimates for noise sources (most conservative), with the realised impacts likely to be smaller.

8. REFERENCES

Ainslie Michael A. Principles of Sonar Performance Modeling [Book]. - Heidelberg : Springer, 2010.

Benhemma-Le Gall A Graham IM, Merchant ND and Thompson PM Broad-Scale Responses of Harbor Porpoises to Pile-Driving and Vessel Activities During Offshore Windfarm Construction [Journal]. - [s.l.] : Frontiers in Marine Science, 2021. - 664724 : Vol. 8.

BOOTH C.G., HARWOOD, J., PLUNKETT, R, MENDES, S, & WALKER, R. Using the Interim PCoD framework to assess the potential impacts of offshore wind developments in Eastern English Waters on harbour porpoises in the North Sea [Report]. - [s.l.] : Natural England, 2017.

British Geological Survey Geology Viewer [Online] // British Geological Survey. - 11 05 2023. - 11 05 2023. - https://geologyviewer.bgs.ac.uk.

Center for Marine Acoustics Sound source list: a description of sounds commonly produced during ocean exploration and industrial activity. [Report]. - Sterling (VA) : U.S. Department of the Interior, Bureau of Ocean Energy Management, 2023.

Frisk George V. Noiseonomics: The relationship between ambient noise levels in the sea and global economic trends [Journal]. - [s.l.] : nature, 2012. - 437 : Vol. 2.

Graham IM Merchant ND, Farcas A, Barton TR, Cheney B, Bono S, Thompson PM. Harbour porpoise responses to pile-driving diminish over time [Journal]. - [s.l.] : Royal Society Open Science, 2019. - 190335 : Vol. 6.

Heitmeyer Stephen C. Wales and Richard M. An ensemble source spectra model for merchant ship-radiated noise [Journal]. - Washington : Naval Research Laboratory, 2001.

Jakob Tougaard Line Hermannsen, Peter T. madsen How loud is the underwater noise from operating offshore wind turbines? [Report]. - [s.l.] : The Journal of the Acoustical Society of America, 2020.

Jensen Finn B. [et al.] Computational Ocean Acoustics [Book]. - [s.l.] : Springer, 2011.

JNCC JNCC guidelines for minimising the risk of injury to marine mammals from geophysical surveys [Report]. - [s.l.] : Joint Nature Conservation Committee, 2017.

JNCC Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise [Report]. - [s.l.] : Joint Nature Conservation Committee, 2010.

National Marine Fisheries Service Scoping report for NMFS EIS for the National Acoustic Guidelines on Marine Mammals [Report]. - [s.l.] : National Marine Fisheries Service, 2005.

Popper A. N. [et al.] Sound Exposure Guidelines for Fishes and Sea Turtles [Report]. - [s.l.] : Springer, 2014.

Rogers P. H. Onboard Prediction of Propagation Loss in Shallow Water [Report]. - Washington DC : Naval Research Laboratory, 1981.

Rogers P. H. Onboard Prediction of Propagation Loss in Shallow Water [Report]. - Washington DC : Naval Research Laboratory, 1981.

Sarnoci´nska J Teilmann J, Balle JD, van Beest FM, Delefosse M and Tougaard J Harbor Porpoise (Phocoena phocoena) Reaction to a 3D Seismic Airgun Survey in the North Sea [Journal]. - [s.l.] : Frontiers in Marine Science, 2020. - 824 : Vol. 6.

Simard Yvan, RoyCédric Nathalie and Giard Gervaise Samuel Analysis and modeling of 255 source levels of merchant ships from an acoustic observatory along St. Lawrence Seaway [Journal]. - [s.l.] : journal of the Acoustical Society of America, 2016. - 2002 : Vol. 140.

Southall Brandon L. [et al.] Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects [Journal]. - [s.l.] : Aquatic Mammals. - 2 : Vol. 45.

Weston D. E. Intensity-Range Relations in Oceanographic Acoustics [Report]. - Teddington : Admiralty Research Laboratory, 1971.

Wittekind Dietrich Kurt A Simple Model for the Underwater Noise Source Level of Ships [Journal]. - Schwentinental : DW-ShipConsult GmbH, 2014.

Worcester T. Effects of Seismic Energy on Fish; A Literature Review [Report]. - Dartmouth, Canada : Department of Fisheries and Oceans, Bedford Institute of Oceanography, 2006.

Appendix A – Acoustic Concepts and Terminology

A.1. Sound travels through water as vibrations of the fluid particles in a series of pressure waves. The waves comprise a series of alternating compressions (positive pressure variations) and rarefactions (negative pressure fluctuations). Because sound consists of variations in pressure, the unit for measuring sound is usually referenced to a unit of pressure, the Pascal (Pa). The unit usually used to describe sound is the decibel (dB) and, in the case of underwater sound, the reference unit is taken as 1µPa, one micro-pascal, whereas airborne sound is usually referenced to a pressure of 20µPa. To convert from a sound pressure level referenced to 20µPa to one referenced to µPa, a factor of 20 log (20/1) i.e. 26dB has to be added to the former quantity. Thus, a sound pressure of 60dB re 20µPa is the same as 86dB re 1µPa, although care also needs to be taken when converting from in air noise to in water noise levels due to the different sound speeds and densities of the two mediums resulting in a conversion factor of approximately 62dB for comparing intensities (watt/m^2), see Table A-1 , below.

Table A-1: Comparing sound quantities between air and water

	Constant intensity		Constant pressure	
Properties	**Air**	**Water**	**Air**	**Water**
Soundspeed (C) [m/s]	340	1500	340	1500
Density (ρ) [kg/m^3]	1.293	1026	1.293	1026
Acoustic impedance ($Z=C\cdot\rho$) [kg/(m$^2\cdot$s) or (Pa$\cdot$s)/m^3]	440	1539000	440	1539000
Sound intensity ($I=p^2/Z$) [Watt/m^2]	1	1	22.7469	0.0065
Sound pressure ($p=(I*Z)^{½}$) [Pascal, Pa]	21	1241	100	100
Particle velocity (I/p) [m/s]	0.04769	0.00081	0.22747	0.00006
dB re 1 micropascal squared (µPa^2)	146.4	**181.9**	160.0	**160.0**
dB re 20 µPa^2	**120.4**	155.9	**134.0**	134.0
Difference dB re 1µPa^2 & dB re 20µPa^2	**61.5**		**26.0**	

A.2. All underwater sound pressure levels in this report are described in dB re 1µPa^2. In water, the sound source strength is defined by its sound pressure level in dB re 1µPa^2, referenced back to a representative distance of 1m from an assumed (infinitesimally small) point source. This allows calculation of sound levels in the far-field. For large, distributed sources, the actual sound pressure level in the near-field will be lower than predicted.

A.3. There are several descriptors used to characterise a sound wave. The difference between the lowest pressure deviation (rarefaction) and the highest pressure deviation (compression) from ambient is the peak to peak (or pk-pk) sound pressure (L_{P-P} for the level in dB), Note that L_{P-P} can be hard to measure consistently, as the maximal duration between the lowest and highest pressure deviation is not standardised. The difference between the highest deviation (either positive or negative) and the ambient pressure is called the peak pressure (L_P for the level in dB). Lastly, the average sound pressure is used as a description of the average amplitude of the variations in pressure over a specific time window (SPL for the level in dB). SPL is equal to the L_{eq} when the time window for the SPL is equal to the time window for the total duration of an event. The cumulative sound energy from pressure is the integrated squared pressure over a given period (L_E for the level in dB). L_E is the current ISO standard name for what was previously named “SEL”. These descriptions are shown graphically in Figure A-1 and reflect the units as given in ISO 18405:2017, “Underwater Acoustics – Terminology”.

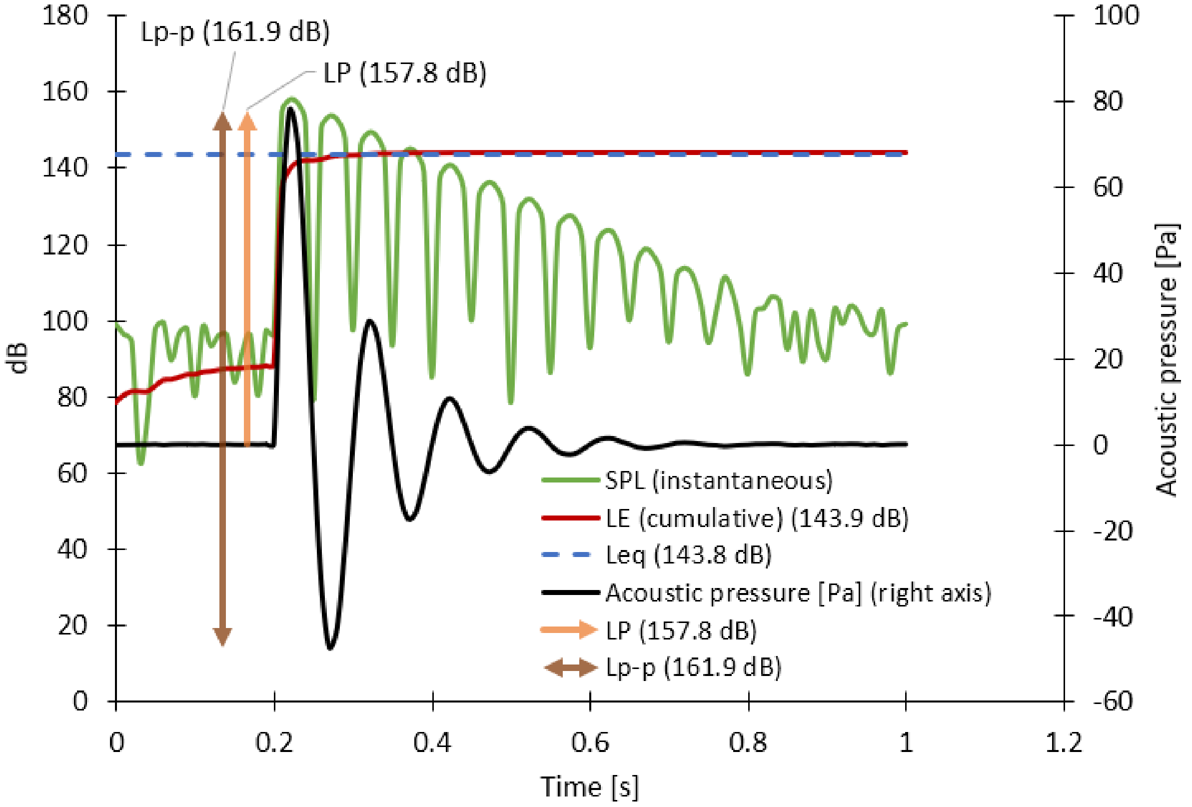

Figure A-1: Graphical representation of acoustic wave descriptors.

A.4. The sound pressure level (SPL[10]) is defined as follows (ISO 18405:2017, 3.2.1.1):

$$SPL = 10 \cdot Log_{10}\left(\frac{\overline{p^2}}{1 \cdot 10^{-12} Pa}\right) \quad (1)$$

A.5. Here $\overline{p^2}$ is the arithmetic mean of the squared pressure values. Note that L_P is simply the instantaneous SPL (ISO 18405:2017, 3.2.2.1).

A.6. The peak sound pressure level, L_P, is the instantaneous decibel level of the maximal deviation from ambient pressure and is defined in (ISO 18405:2017, 3.2.2.1) and can be calculated as:

$$L_P = 10 \cdot Log_{10}\left(\frac{max(p^2)}{1 \cdot 10^{-12} Pa}\right)$$

A.7. Another useful measure of sound used in underwater acoustics is the Exposure Level, or L_E. This descriptor is used as a measure of the total sound energy of a single event or a number of events (e.g. over the course of a day). This allows the total acoustic energy contained in events lasting a different amount of time to be compared on a like for like basis. Historically, use was

---

[10] Equivalent to the commonly seen “RMS-level”.

primarily made of SPL and L_P metrics for assessing the potential effects of sound on marine life. However, the L_E is increasingly being used as it allows exposure duration and the effect of exposure to multiple events over e.g. a 24-hour period to be taken into account. The L_E is defined as follows (ISO 18405:2017, 3.2.1.5):

$$L_E = 10 \cdot Log_{10}\left(\frac{\int_{t_1}^{t_2} p(t)^2 dt}{1 \cdot 10^{-12} Pa}\right) \qquad (2)$$

A.8. To convert from L_E to SPL the following relation can be used:

$$L_E = \text{SPL} + 10 \cdot Log_{10}(t_2 - t_1) \qquad (3)$$

A.9. Converting from a single event to multiple events for L_E:

$$L_{E,n\ events} = L_{E,single\ event} + 10 \cdot Log_{10}(n) \qquad (4)$$

A.10. The frequency, or pitch, of the sound is the rate at which these oscillations occur and is measured in cycles per second, or Hertz (Hz). When sound is measured in a way which approximates to how a human would perceive it using an A-weighting filter on a sound level meter, the resulting level is described in values of dB(A). However, the hearing faculties of marine mammals and fish are not the same as humans, with marine mammals hearing over a wider range of frequencies, fish over a typically smaller range of frequencies and both with different sensitivities. It is therefore important to understand how an animal’s hearing varies over the entire frequency range to assess the effects of sound on marine life. Consequently, use can be made of frequency weighting scales to determine the level of the sound in comparison with the auditory response of the animal concerned. A comparison between the typical hearing response curves for fish, humans and marine mammals is shown in Figure A-2. Note that hearing thresholds are sometimes shown as audiograms with sound level on the y axis rather than sensitivity, resulting in the graph shape being the inverse of the graph shown. It is also worth noting that some fish are sensitive to particle velocity rather than pressure, although paucity of data relating to particle velocity levels for anthropogenic noise sources means that it is often not possible to quantify this effect.

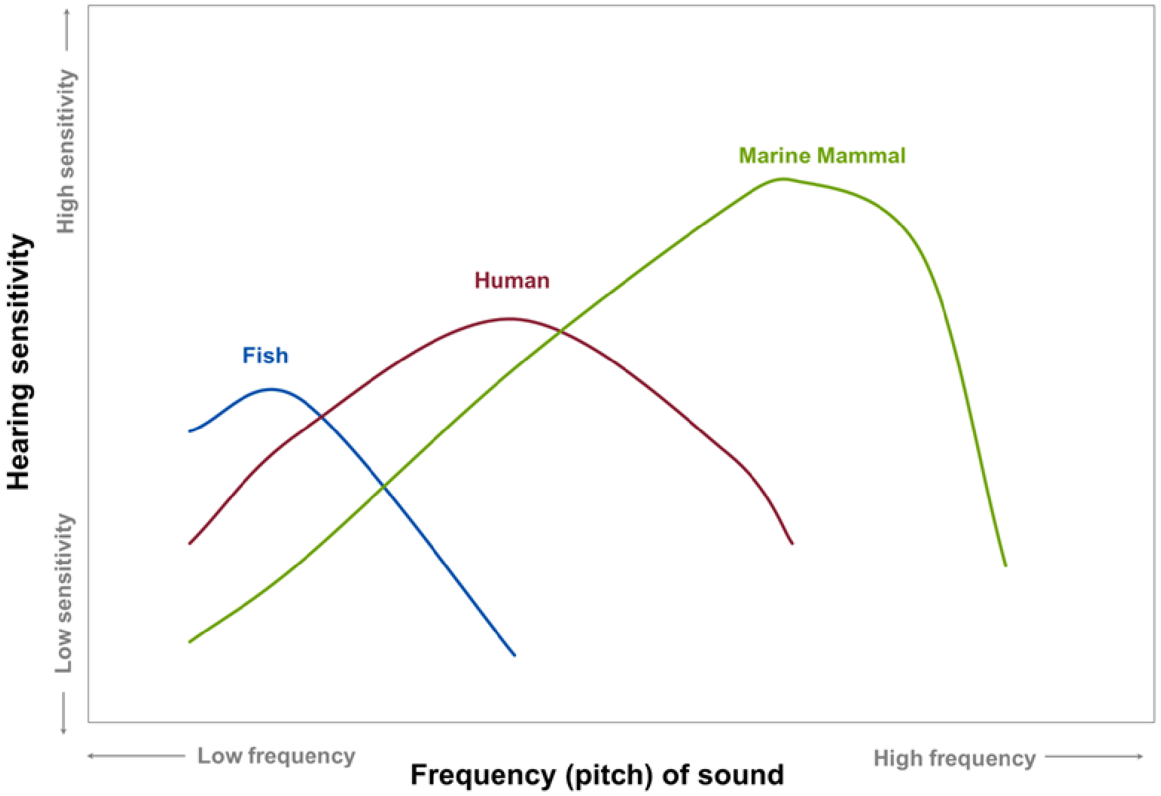

Figure A-2: **Comparison between hearing thresholds of different marine animals and humans.**

Review of Sound Propagation Concepts

A.11. Increasing the distance from the noise source usually results in the level of noise getting lower, due primarily to the spreading of the sound energy with distance, analogous to the way in which the ripples in a pond spread after a stone has been thrown in.

A.12. The way that the noise spreads will depend upon several factors such as water column depth, pressure, temperature gradients, salinity, as well as water surface and seabed conditions. Thus, even for a given locality, there are temporal variations to the way that sound will propagate. However, in simple terms, the sound energy may spread out in a spherical pattern (close to the source, with no boundaries) or a cylindrical pattern (much further from the source, bounded by the surface and the sediment), although other factors mean that decay in sound energy may be somewhere between these two simplistic cases.

A.13. In acoustically shallow waters[11] in particular, the propagation mechanism is coloured by multiple interactions with the seabed and the water surface (Lurton 2002; Etter 2013; Urick 1983; Brekhovskikh and Lysanov 2003, Kinsler et al. 1999). Whereas in deeper waters, the sound will propagate further without encountering the surface or bottom of the sea, in shallower waters the sound is reflected many times by the surface and sediment.

---

[11] Acoustically, shallow water conditions exist whenever the propagation is characterised by multiple reflections with both the sea surface and seabed (Etter 2013). Consequently, the depth at which water can be classified as acoustically deep or shallow depends upon numerous factors including the sound speed gradient, water depth, sediment type, frequency of the sound and distance between the source and receiver.

A.14. At the sea surface, the majority of sound is reflected back into the water due to the difference in acoustic impedance (i.e. sound speed and density) between air and water. However, scattering of sound at the surface of the sea is an important factor with respect to the propagation of sound from a source. In an ideal case (i.e. for a perfectly smooth sea surface), the majority of sound wave energy will be reflected back into the sea. However, for rough waters, much of the sound energy is scattered (Eckart 1953; Fortuin 1970; Marsh, Schulkin and Kneale 1961; Urick and Hoover 1956). Scattering can also occur due to bubbles near the surface such as those generated by wind or fish or due to suspended solids in the water such as particulates and marine life. Scattering is more pronounced for higher frequencies than for low frequencies and is dependent on the sea state (i.e. wave height). However, the various factors affecting this mechanism are complex. Generally, the scattering effect at a particular frequency depends on the physical size of the roughness in relation to the wavelength of the frequency of interest.

A.15. As surface scattering results in differences in reflected sound, its effect will be more important at longer ranges from the source sound and in acoustically shallow water (i.e. where there are multiple reflections between the source and receiver). The degree of scattering will depend upon the water surface smoothness/wind speed, water depth, frequency of the sound, temperature gradient, grazing angle and range from source. Depending upon variations in the aforementioned factors, significant scattering could occur at sea state 3 or more for higher frequencies (e.g. 15kHz or more). It should be noted that variations in propagation due to scattering will vary temporally (primarily due to different sea-states/wind speeds at different times) and that more sheltered areas (which are more likely to experience calmer waters) could experience surface scattering to a lesser extent, and less frequently, than less sheltered areas which are likely to encounter rougher waters. However, over shorter ranges (e.g. within 10-20 times the water depth) the sound will experience fewer reflections and so the effect of scattering should not be significant. Consequently, over the likely distances over which injury will occur, this effect is unlikely to significantly affect the injury ranges presented in this report, and not including this effect will overestimate the impact.

A.16. When sound waves encounter the seabed, the amount of sound reflected will depend on the geoacoustic properties of the seabed (e.g. grain size, porosity, density, sound speed, absorption coefficient and roughness) as well as the grazing angle (see Figure A-3) and frequency of the sound (Cole 1965; Hamilton 1970; Mackenzie 1960; McKinney and Anderson 1964; Etter 2013; Lurto 2002; Urick 1983). Thus, seabeds comprising primarily of mud or other acoustically soft sediment will reflect less sound than acoustically harder seabeds such as rock or sand. This effect also depends on the profile of the seabed (e.g. the depth of the sediment layers and how the geoacoustic properties vary with depth below the sea floor). The sediment interaction is less pronounced at higher frequencies (a few kHz and above) where interaction is primarily with the top few cm of the sediment (related to the wavelength). A scattering effect (similar to that which occurs at the surface) also occurs at the seabed (Essen 1994; Greaves and Stephen 2003; McKinney and Anderson 1964; Kuo 1992), particularly on rough substrates (e.g. pebbles).

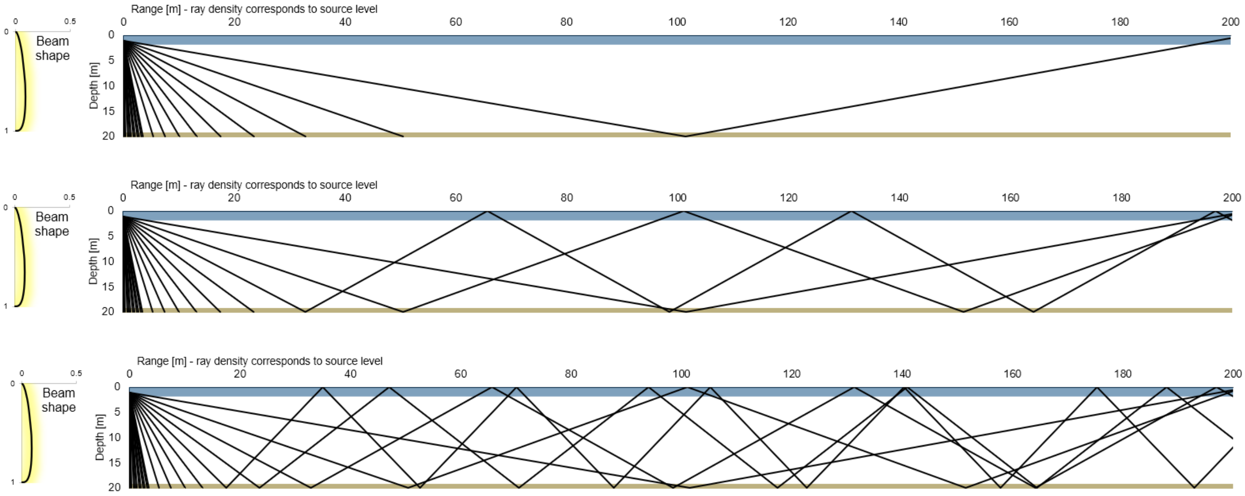

Figure A-3: Schematic of the effect of sediment on highly focussed sources. Sediments range from fine silt (top panel), sand (middle panel), and gravel (lower panel). The density of "rays" indicate difference in effective propagation angle from the source, with acoustically harder sediments (gravel) having better reflection at steeper angles leading to more "rays" being effectively propagated (no significant bottom attenuation) in the waveguide. Beam shape indicated in left chart, with the black line showing the same received level.

A.17. Another phenomenon is the waveguide effect which means that shallow water columns do not allow the propagation of low frequency sound (Urick 1983; Etter 2013). The cut-off frequency of the lowest mode in a channel can be calculated based on the water depth and knowledge of the sediment geoacoustic properties. Any sound below this frequency will not propagate far due to energy losses through multiple reflections. The cut-off frequency as a function of water depth is shown in Figure A-4 for a range of seabed types. Thus, for a water depth of 10m (i.e. shallow waters typical of coastal areas and estuaries) the cut-off frequency would be approximately 70Hz for sand, 115Hz for silt, 155Hz for clay and 10Hz for bedrock.

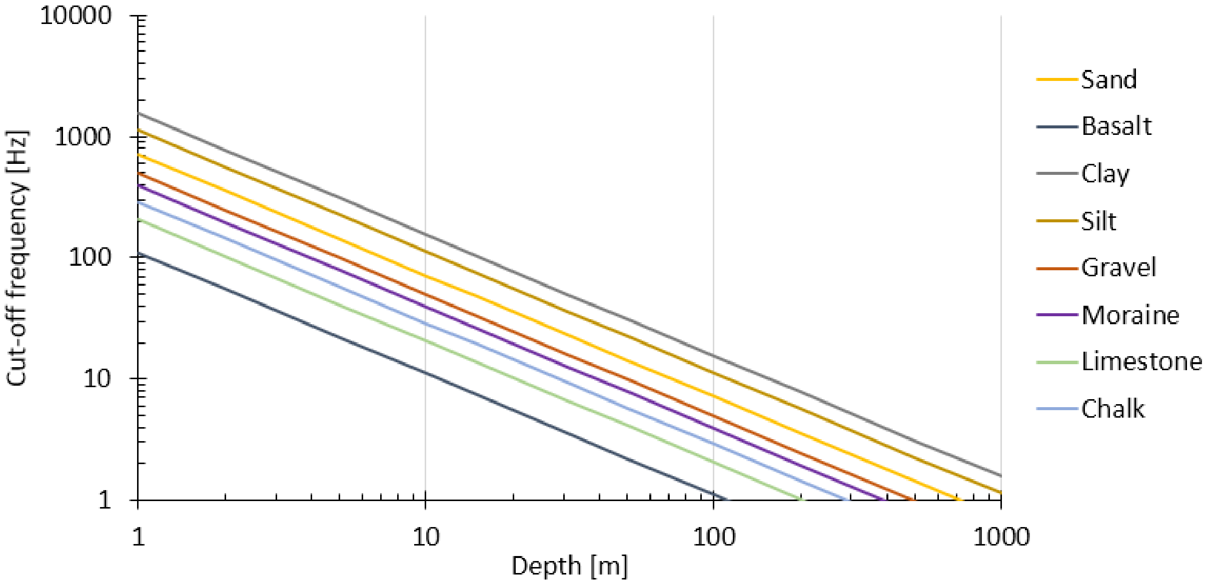

Figure A-4: Lower cut-off frequency as a function of depth for a range of seabed types.

A.18. Changes in the water temperature and the hydrostatic pressure with depth mean that the speed of sound varies throughout the water column. This can lead to significant variations in sound propagation and can also lead to sound channels, particularly for high-frequency sound. Sound can propagate in a duct-like manner within these channels, effectively focussing the sound, and conversely, they can also lead to shadow zones. The frequency at which this occurs depends on the characteristics of the sound channel but, for example, a 25m thick layer would not act as a duct for frequencies below 1.5kHz. The temperature gradient can vary throughout the year and thus there will be potential variation in sound propagation depending on the season.

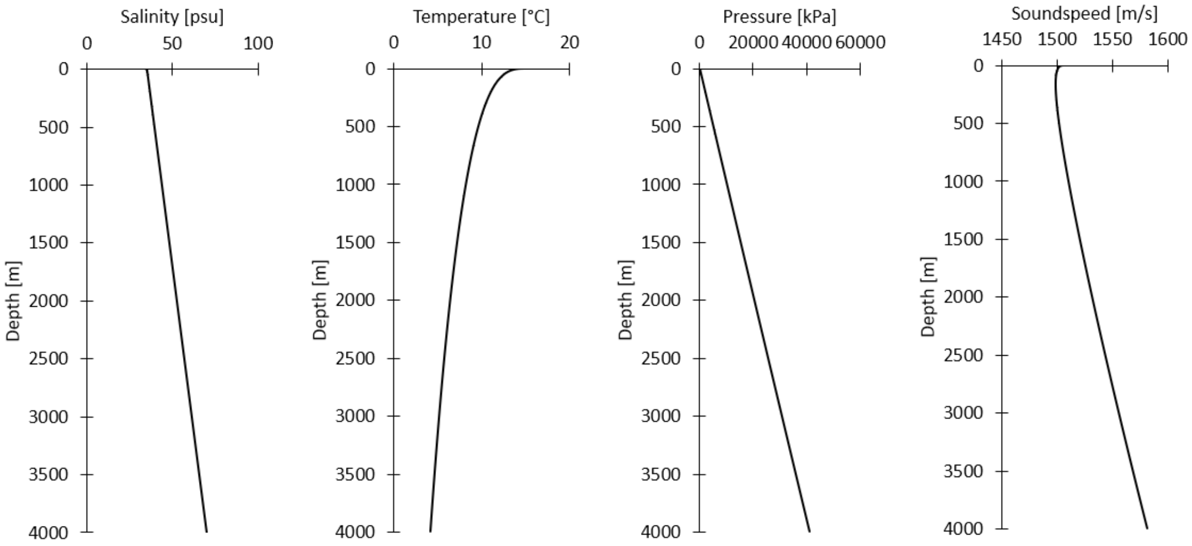

Figure A-5: Soundspeed profile as a function of salinity, temperature and pressure.

A.19. Wind can make a significant difference to the soundspeed in the uppermost layers as the introductions of bubbles decreases the soundspeed and refracts (bends) the sound towards the surface, where the increased roughness and bubbles from the wind will cause increased transmission loss.

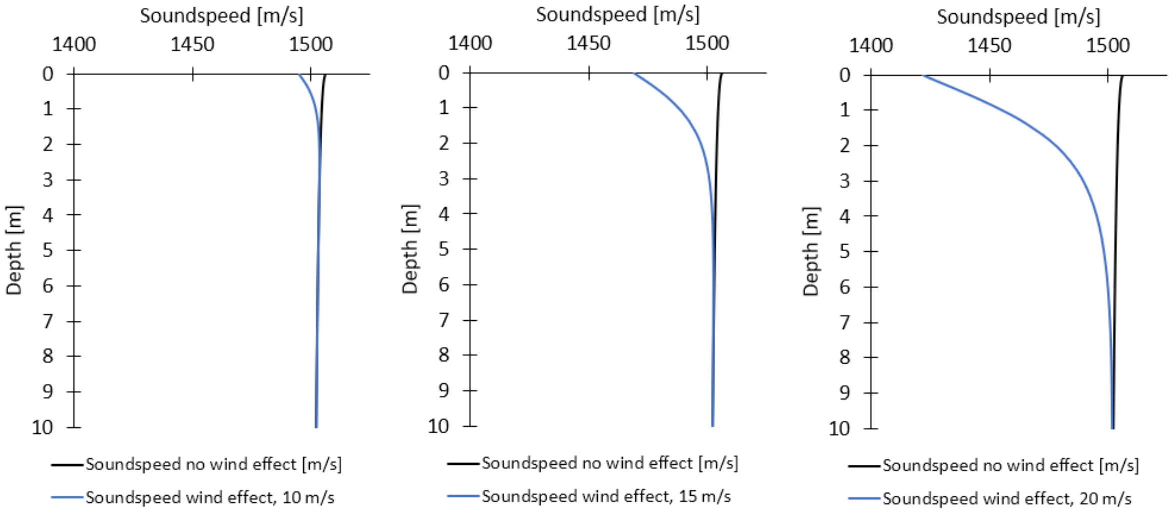

Figure A-6: Effect of wind (at 10m height) on upper portion of soundspeed profile.

A.20. Sound energy can also be absorbed due to interactions at the molecular level converting the acoustic energy into heat. This is another frequency dependent effect with higher frequencies experiencing much higher losses than lower frequencies. This is shown in Figure A-7 where the variation of the absorption (sometimes called volume attenuation) is shown for various salinities and temperatures. As the effect is proportional to the wavelength, colder water, with slower soundspeed/period and being slightly more viscous, will have more absorption. Higher salinity slightly decreases absorption at low frequencies (mostly due to increase in soundspeed and wavelength/period), but much higher absorption at higher frequencies where interaction with pressure sensitive molecules of magnesium sulphite and boric acid increase the conversion acoustic energy to heat.

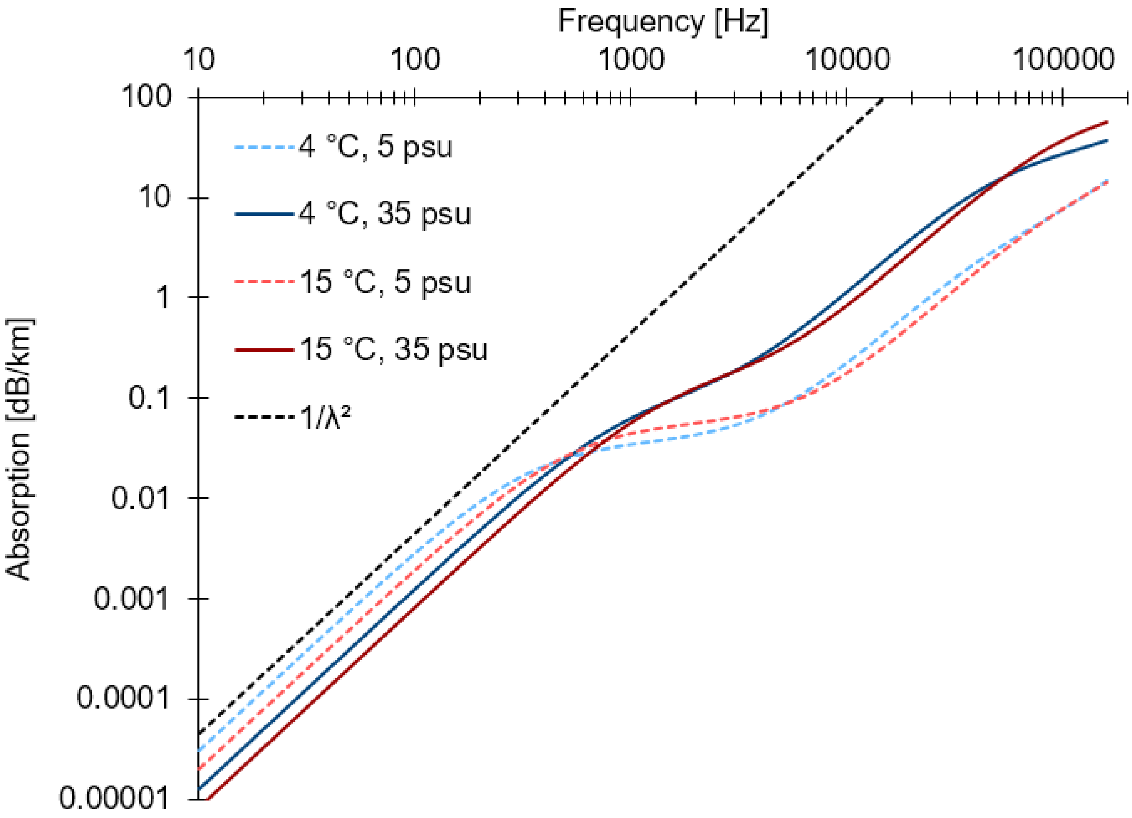

Figure A-7: Absorption loss coefficient (dB/km) for various salinities and temperature.