Peterhead Smith Quay Extension
Noise Modelling

Noise generation and propagation modelling for construction activities during the extension of Peterhead Smith quay

Report

03 March 2025

Prepared for NIRAS Consulting Ltd

The expert in **WATER ENVIRONMENTS**

Peterhead Smith Quay Extension Noise Modelling

Noise generation and propagation modelling for construction activities during the extension of Peterhead Smith quay

Report

Prepared for:	NIRAS Consulting Ltd
Represented by	[Redacted]

Contact person:	[Redacted] , +49 30 67999862
Project Manager:	[Redacted]
Quality Supervisor:	[Redacted]
Author:	[Redacted]
Project No.:	11832119
Approved by:	[Redacted]
Approval date:	05.03.2025
Revision:	Final 1.0
Classification:	**Confidential:** This document is only accessible to the project team members and sharing it outside the project team is subject to the client’s prior approval.
File name:	11832119_Peterhead_Report_v2.docx

DHI A/S • Agern Allé 5 • • DK-2970 Hørsholm • Denmark
Telephone: +45 4516 9200 • dhi@dhigroup.com • www.dhigroup.com • Company Reg. No.: 36466871

Contents

Nomenclature...... 7

1 Executive Summary 9

2 Introduction...... 10

3 Methodology 11

3.1 General approach...... 11
3.2 Underwater noise modelling...... 12
3.2.1 Propagation modelling...... 12
3.2.2 Source definition - pile driving 14
3.2.3 Source definition - rock breaking...... 16
3.2.4 Source definition - dredging 17
3.2.5 Source definition - blasting 18
3.3 Calculation of Biological Impact 19
3.3.1 Threshold values used for pile driving and rock breaking noise 20
3.3.2 Threshold values used for continuous noise...... 21
3.3.3 Threshold values used for explosive noise from blasting 23
3.3.4 Effective quiet – mammals 23

4 Acoustics Results 25

4.1 Pile driving 25
4.2 Rock breaking...... 30
4.3 Dredging 36
4.4 Blasting 41

5 Summary and Conclusions 48

6 References 49

Figures

Figure 3.1 Potential effects of noise at different distances from a sound source 12
Figure 3.2 Map of the source location within the project area 13
Figure 3.3 Map of directions of sound propagation modelling at project location...... 13
Figure 3.4 Map of the Peterhead harbour basin showing the breakwaters and noise source location used in this study (red star) 14
Figure 3.5 Source level for pile driving in 1/3 octave bands, weighted levels and ambient noise level 15
Figure 3.6 Source level for DTH drilling used as proxy for rock breaking in 1/3 octave bands, weighted levels and ambient noise level...... 17
Figure 3.7 Source level for backhoe dredging in 1/3 octave bands, weighted levels and ambient noise level...... 18
Figure 3.8 Source level for blasting in 1/3 octave bands, weighted levels and ambient noise level 19
Figure 4.1 SPL levels and impact ranges for LF cetaceans predicted during piling works at the Peterhead harbour 25
Figure 4.2 LF-weighted SEL levels and impact ranges for LF cetaceans predicted during piling works at the Peterhead harbour...... 26
Figure 4.3 SPL levels and impact ranges for HF cetaceans predicted during piling works at the Peterhead harbour 27
Figure 4.4 HF-weighted SEL levels and impact ranges for HF cetaceans predicted during piling works at the Peterhead harbour...... 27

Figure 4.5 VHF-weighted SPL_{125rms} levels and impact ranges for VHF cetaceans predicted during piling works at the Peterhead harbour 28
Figure 4.6 VHF-weighted SEL levels and impact ranges for VHF cetaceans predicted during piling works at the Peterhead harbour 29
Figure 4.7 SEL levels and impact ranges for fish predicted during piling works at the Peterhead harbour 30
Figure 4.8 SPL levels and impact ranges for LF cetaceans predicted during rock breaking works at the Peterhead harbour 31
Figure 4.9 LF-weighted SEL levels and impact ranges for LF cetaceans predicted during rock breaking works at the Peterhead harbour 31
Figure 4.10 SPL levels and impact ranges for HF cetaceans predicted during rock breaking works at the Peterhead harbour 32
Figure 4.11 HF-weighted SEL levels and impact ranges for HF cetaceans predicted during rock breaking at the Peterhead harbour 33
Figure 4.12 VHF-weighted SPL_{125rms} levels and impact ranges for VHF cetaceans predicted during rock breaking at the Peterhead harbour 34
Figure 4.13 VHF-weighted SEL levels and impact ranges for VHF cetaceans predicted during rock breaking at the Peterhead harbour 34
Figure 4.14 SEL levels and impact ranges predicted for fish with a swim bladder during rock breaking at the Peterhead harbour 35
Figure 4.15 Unweighted SPL levels and impact ranges predicted for LF cetaceans during dredging at the Peterhead harbour 36
Figure 4.16 LF-weighted SEL levels and impact ranges predicted for LF cetaceans during dredging at the Peterhead harbour 37
Figure 4.17 Unweighted SPL levels and impact ranges predicted for HF cetaceans during dredging at the Peterhead harbour 38
Figure 4.18 HF-weighted SEL levels and impact ranges predicted for HF cetaceans during dredging at the Peterhead harbour 38
Figure 4.19 Unweighted SPL levels and impact ranges predicted for VHF cetaceans during dredging at the Peterhead harbour 39
Figure 4.20 VHF-weighted SEL levels and impact ranges predicted for VHF cetaceans during dredging at the Peterhead harbour 40
Figure 4.21 Unweighted SPL levels and impact ranges predicted for fish with a swim bladder during dredging at the Peterhead harbour 41
Figure 4.22 LF-weighted SEL levels and impact ranges predicted for LF cetaceans during blasting at the Peterhead harbour 42
Figure 4.23 SPL_{peak} levels and impact ranges predicted for LF cetaceans during blasting at the Peterhead harbour 42
Figure 4.24 HF-weighted SEL levels and impact ranges predicted for HF cetaceans during blasting at the Peterhead harbour 43
Figure 4.25 SPL_{peak} levels and impact ranges predicted for HF cetaceans during blasting at the Peterhead harbour 44
Figure 4.26 VHF-weighted SEL levels and impact ranges predicted for VHF cetaceans during blasting at the Peterhead harbour 45
Figure 4.27 SPL_{peak} levels and impact ranges predicted for VHF cetaceans during blasting at the Peterhead harbour 45
Figure 4.28 SEL levels and impact ranges predicted for fish during blasting at the Peterhead harbour 46
Figure 4.29 SPL_{peak} levels and impact ranges predicted for fish during blasting at the Peterhead harbour 47

Tables

Table 3.1 Applied sound source location in UTM zone 30 N and WGS 84 12
Table 3.2 Pile driving parameters and resulting broadband source level.................................... 15
Table 3.3 Rock breaking parameters and resulting broadband source levels 16
Table 3.4 Overview of the noise exposure criteria used for calculating impacts of piling and rock breaking noise on cetaceans 20
Table 3.5 Overview of the noise exposure criteria used for calculating impacts of piling and rock breaking noise on fish with a swim bladder 21
Table 3.6 Overview of the noise exposure criteria used for calculating impacts of continuous noise on cetaceans 21
Table 3.7 Overview of the noise exposure criteria used for calculating impacts of continuous on fish 22
Table 3.8 Overview of the noise exposure criteria for calculating impacts of explosive sounds on cetaceans (NMFS 2024b) 23
Table 3.9 Noise exposure criteria for calculating impacts of explosive sounds on fish (NMFS 2024c, FHWG 2008, Popper et al. 2014) 23
Table 4.1 Impact ranges and areas predicted for LF cetaceans during piling works at the Peterhead harbour 26
Table 4.2 Impact ranges and areas predicted for HF cetaceans during piling works at the Peterhead harbour 28
Table 4.3 Impact ranges and areas predicted for VHF cetaceans during piling works at the Peterhead harbour 29
Table 4.4 Impact ranges and areas predicted for Fish with a swim bladder during piling works at the Peterhead harbour 30
Table 4.5 Impact ranges and areas predicted for LF cetaceans during rock breaking works at the Peterhead harbour 32
Table 4.6 Impact ranges and areas predicted for HF cetaceans during rock breaking works at the Peterhead harbour 33
Table 4.7 Impact ranges and areas predicted for VHF cetaceans during rock breaking works at the Peterhead harbour 35
Table 4.8 Impact ranges and areas predicted for fish with a swim bladder during rock breaking works at the Peterhead harbour.. 35
Table 4.9 Impact ranges and areas predicted for LF cetaceans during dredging works at the Peterhead harbour 37
Table 4.10 Impact ranges and areas predicted for HF cetaceans during dredging works at the Peterhead harbour 39
Table 4.11 Impact ranges and areas predicted for VHF cetaceans during dredging works at the Peterhead harbour 40
Table 4.12 Impact ranges and areas predicted for fish with swim bladder during dredging works at the Peterhead harbour 41
Table 4.13 Impact ranges and areas predicted for LF cetaceans during blasting at the Peterhead harbour 43
Table 4.14 Impact ranges and areas predicted for HF cetaceans during blasting at the Peterhead harbour 44
Table 4.15 Impact ranges and areas predicted for VHF cetaceans during blasting at the Peterhead harbour 46
Table 4.16 Impact ranges and areas predicted for fish during blasting at the Peterhead harbour 47

Appendices

Appendix A **Noise modelling**

Appendix A.1 Noise propagation modelling
Appendix A.1.1 Underwater acoustic simulator
Appendix A.1.2 Sound speed profile
Appendix A.1.3 Geo-acoustic profile
Appendix A.1.4 Insertion loss due to breakwater structures

Appendix B **Acoustical Terminology**

Appendix B.1 Sound levels of impulsive noise
Appendix B.2 Sound levels of continuous noise
Appendix B.3 Weighting
Appendix B.4 Impact ranges and areas

Nomenclature

Term	Definition
Effect	Changes caused by sound exposure that are a departure from a prior state, condition, or situation, which is called the ‘baseline’ condition
Impact	Effects that reflect a change whose direction, magnitude, and/or duration might be sufficient to have consequences for the fitness of individuals or populations of individuals
Noise	Sound that is not a useful signal or cue, i.e., it has no adaptive value or biological meaning for the receiver, and may either be neutral or may have adverse effects
Sound	The acoustic energy radiated from a vibrating object, with no reference to its function or potential effect

Abbreviation	Definition
AUD INJ	Damage to the inner ear that can result in destruction of tissue, such as the loss of cochlear neuron synapses or auditory neuropathy Auditory injury includes but is not limited to permanent threshold shift (PTS).
CSD	Cutterhead Suction Dredge, a common type of dredge
dB	Decibel – a logarithmic measure of sound intensity/pressure. Decibel value for acoustic pressure is 10 log10 (P^2/P_o^2) where P = actual pressure and P_o = reference pressure
DTH	Down-the-hole, a pile driving / drilling technique
Hz	Hertz – a unit of frequency, where 1 Hz = 1 cycle per second, 1 kHz is 1000 cycles per second
HF	High Frequency
HF-weighted SEL	Sound exposure level with the high frequency weighting function in accordance with the susceptibility of hearing damage of bottlenose dolphin caused by noise (NMFS 2024 applied)
LF	Low Frequency
LF-weighted SEL	Sound exposure level with the low frequency weighting function in accordance with the susceptibility of hearing damage of minke whale caused by noise (NMFS 2024 applied)
NOAA	National Oceanic and Atmospheric Administration
RAM	Range-dependent Acoustic Model
RL	Received Level
SEL	Sound Exposure Level: often used in marine environmental noise impact assessment and is the measure of the total sound energy normalised to 1 second
SEL_{cum}	Cumulative noise exposure level; summing up the noise exposure levels of many subsequent events.

Abbreviation	Definition
SL	Sound source level – sound pressure at a standard reference distance of 1 m; in dB units re 1 µPa at 1 m
SPL	Sound pressure level [dB re 1µPa] – sound pressure expressed in decibels [dB] relative to a reference pressure P_{ref}=1µPa
SPL_{peak}	Peak sound pressure level (signal amplitude maximum value)
SRC	Source
TL	Transmission Loss
TTS	Temporary Threshold Shift - a temporary threshold shift as a result of exposure to sound; the threshold will return to the pre-exposure state after some time
UAS	Underwater Acoustic Simulator
VHF	Very High Frequency
VHF-weighted SEL	Sound exposure level with the very high frequency weighting function in accordance with the susceptibility of hearing damage of harbour porpoise caused by noise (NMFS 2024 applied)
µPa	Micro pascal – a unit of pressure

1 Executive Summary

This study analysed the generation, propagation and potential impact of noise on marine fauna resulting from construction activities during the proposed development of the Peterhead Smith Quay, the UK (Figure 3.2). This study was prepared for NIRAS Consulting Ltd. by DHI A/S.

The works considered for the implementation of the project (piling, rock breaking, dredging and blasting) were assessed in terms of their noise emissions and potential impact on marine animals in the vicinity of the project area. For this purpose, the sound sources strengths and characteristics were defined, numerical propagation models were created, and the biological impacts were calculated using internationally recognized criteria.

The noise caused by pile driving and rock breaking has been categorised as impulsive and noise caused by dredging as continuous. The blasting considered for the execution of the project is a non-explosive method. It is generally considered to be less invasive than conventional blasting but sounds generated by it are still highly transient, shock-like pulses, so the same principles apply to the risk assessment as for conventional blasting.

The sound propagation in the water column was calculated using the DHI Underwater Acoustic Simulator which uses a parabolic equation for numerical sound modelling. Based on the categorization of the sounds originating from different activities, the corresponding impact criteria were applied to assess the potential impact on animals.

The marine fauna considered in the noise impact assessment were cetaceans and fish. According to the latest guidelines (NMFS 2024), cetaceans are categorised into the following hearing groups: Low-frequency cetaceans (i.e. minke whale; LF-cetaceans), high-frequency cetaceans (i.e. bottlenose dolphin; HF-cetaceans) and very high-frequency cetaceans (i.e. harbour porpoise; VHF-cetaceans). Fish are generally divided into taxa with more sensitive hearing adaptations (i.e. swim bladder involved in hearing) and those without auditory enhancements. For Atlantic salmon, a species that is known to have a relatively low sensitivity to sound, criteria from taxa that are more sensitive to acoustic stimuli were applied as a precautionary measure. The assessed effects of noise exposure on cetaceans were auditory injury, temporary threshold shift, behavioural response and adverse behavioural reaction (fleeing). For fish, the following effects were considered: Temporary threshold shift, recoverable injury, behavioural reaction and - as effects of blasting noise - physical injury and mortality.

The results of the noise modelling show that the sounds generated by the construction activities will propagate in a south-easterly direction. Due to the natural barriers, the sound emissions are expected to have a high directional effect and will be further attenuated by the harbour's breakwaters. Therefore, the potential impact on marine fauna is spatially limited.

Considering all the animal groups included in the study, the maximum impact range from pile driving was found to be 3.24 km for TTS of LF-cetaceans and 4.54 km for the behavioural response of VHF-cetaceans. These results indicate that LF-cetaceans occurring in the waters adjacent to the Peterhead harbour may be at risk of hearing impairment during pile driving. However, the exposure would have to occur over a longer period of time (one complete pile installation) to have such an effect, which is not very likely. The behavioural response of LF and HF cetaceans was restricted to the harbour basin.

In the case of fish, the most pronounced effect was the behavioural response to pile driving noise, which reached a maximum range of almost 3 km.

In summary, the sound modelling study does not indicate any major impacts of serious effects on marine fauna. The noise generated during the proposed works, is not expected to significantly affect cetacean and fish species living outside the Peterhead harbour. It is therefore concluded that the animals most likely to be affected by construction noise are fish species that live in the harbour and are highly sensitive to noise.

2 Introduction

This report prepared for NIRAS Consulting Ltd. provides the results of the numerical underwater noise modelling for piling, dredging and blasting (optional) undertaken during the extension of Peterhead Smith Quay.

The Peterhead harbour is utilized by various sectors, including pelagic fishing, subsea operations, oil and gas decommissioning, ship repair facilities, and renewable energy. The Peterhead Port Authority (PPA) has proposed an extension of the existing Smith Quay, which will involve underwater construction activities that emit sounds into the aquatic environment. The emission of underwater anthropogenic sound can adversely impact aquatic animals (Duarte et al., 2021; Thomsen et al., 2021). Consequently, noise modelling is required to verify whether the emitted sound levels during construction will negatively impact marine fauna and to identify the potential need for mitigation measures.

This report presents the results of numerical underwater noise modelling for piling, dredging, and optional blasting activities undertaken during the extension of Peterhead Smith Quay. The analysis predicts possible impacts on cetaceans and fish. For cetaceans, three hearing groups were included in the calculations to provide representative information for different whale species occurring in the study area. Analyses were conducted for low-frequency cetaceans (e.g., minke whale), high-frequency cetaceans (e.g., bottlenose dolphins), and very high-frequency cetaceans (e.g., harbour porpoise). In the calculations performed for fish, Atlantic salmon was the main species of interest due to its recognized spawning and migration activity in the waters adjacent to Peterhead harbour.

The methods and results of the study are summarized in this report. Detailed information can be found in the appendices.

3 Methodology

3.1 General approach

DHI's approach to the estimation of underwater noise impact ranges and areas comprises three steps:

- Sound source definition (sound exposure level and frequency spectrum);
- Numerical propagation modelling;
- Calculation of biological effects using internationally accepted criteria.

The **sound source definition** for the construction activities was based on publicly available measurement data, empirical models or a combination thereof.

The **numerical propagation modelling** was performed using a parabolic equation model and the in-house MIKE by DHI Underwater Acoustic Simulator (DHI 2023). The model focuses on noise propagation in the far field. UAS uses the RAM code based on the sound propagation model developed by Collins (Collins 1993). The detailed description of the underwater acoustic model, including the scientific bases and the assumptions of the model, is included in the technical documentation for UAS in MIKE (DHI 2023). To approximate the 3-dimensional sound field, a number of 2-dimensional vertical transects are modelled resulting in what is commonly referred to as Nx2D volume approximation.

The sound source properties were fed into the propagation model to calculate the sound propagation in angular directions from the source location at 72 transects in 2D. Specific 1/3 octave bands with centre frequencies from 20 Hz to 4 kHz were modelled. For higher frequencies, the propagation losses at 4 kHz were applied in combination with a correction for the increasing volume attenuation with increasing frequency (Francois and Garrison, 1982a, 1982b). Based on the numerical model, maps were derived presenting the sound exposure level as a function of bearing angle and distance from the sound source.

Since the marine mammals covered in this study use the entire water column, the maximum sound levels in the water column were used as a basis for the calculation of impact ranges.

The **calculation of biological effects** was performed using the framework presented by Thomsen *et al.* 2021. Accordingly, there are several overlapping zones of noise effects which dimensions mainly depend on the relative distance of the animal to the location of the sound source (Figure 3.1). In this study, the focus is on **behavioural response** and **hearing impairment** (TTS, Auditory Injury and recoverable injury in fish with a swim bladder) since these are the effects that need to be considered due to existing regulations. Impacts in the form of TTS, AUD INJ, recoverable injury and behavioural change are considered in the applied guidelines for the analysis of noise impacts on marine organisms.

The most relevant parameters of the impact analysis are those related to TTS, AUD INJ and recoverable injury. This is due to the fact that the investment should be implemented in such a way that the generated underwater noise causes no hearing damage to marine organisms resulting from the underwater noise. Hence, environmental decisions are influenced mainly by the results related to hearing damage. Behavioural changes, however, are also a very important element related to noise impacts, as they can be related to effects on organisms at the population level. Therefore, their importance must be noticed.

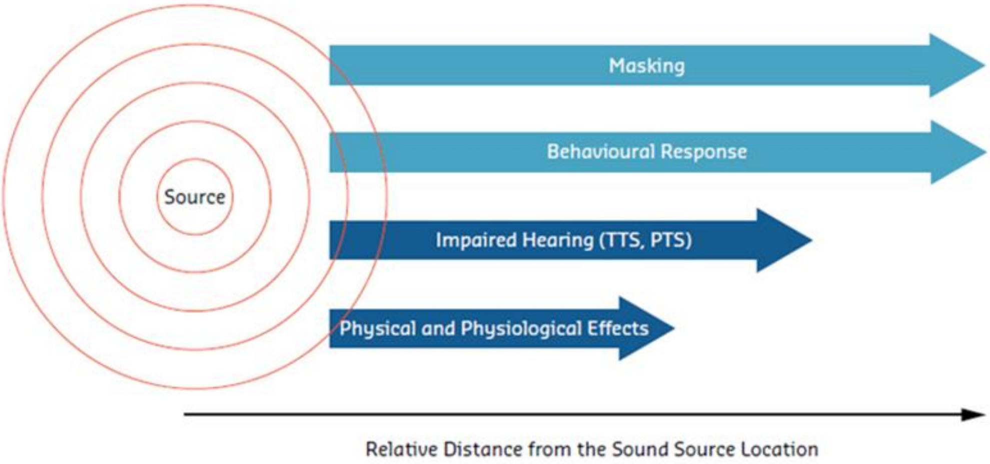

Figure 3.1 **Potential effects of noise at different distances from a sound source** (from Thomsen *et al*. 2021)

3.2 Underwater noise modelling

The underwater noise modelling consists of two sub models. These include the source model and the propagation model.

3.2.1 Propagation modelling

Peterhead harbour is located at the North Sea on the east coast of Scotland.

DHI selected the location of the sound source in Peterhead harbour to represent the worst-case scenario, given that a single position had to be chosen. The location was chosen close to the end of the projected quay extension where the least sound attenuation by the harbour's breakwaters is expected (source location shown in Figure 3.2 and Table 3.1).

The bathymetry in the project area was obtained from the bathymetry dataset of the European Marine Observation and Data Network (European Comission 2025) which was augmented by high-resolution data of the harbour basin[1] supplied by the UK Hydrographic Office (UK Hydrographic Office 2025).

Table 3.1 **Applied sound source location in UTM zone 30 N and WGS 84**

Easting (m)	Northing (m)	Longitude [°]	Latitude [°]	Source depth (m)
573030	6373899	1.78141 W	57.50181 N	5

Based on previous studies and literature data (Thomsen *et al*. 2006), it was determined that the area subjected to modelling should comprise a radius of a maximum of 150 km from the source of sound in all directions. Therefore, 72 transects of 150 km or less were determined, depending on the coastline barrier (Figure 3.3).

The acoustic modelling was performed at a location indicated with a red star in the project area in Figure 3.2.

---

[1] Contains United Kingdom Hydrographic Office data © Crown copyright and database right.

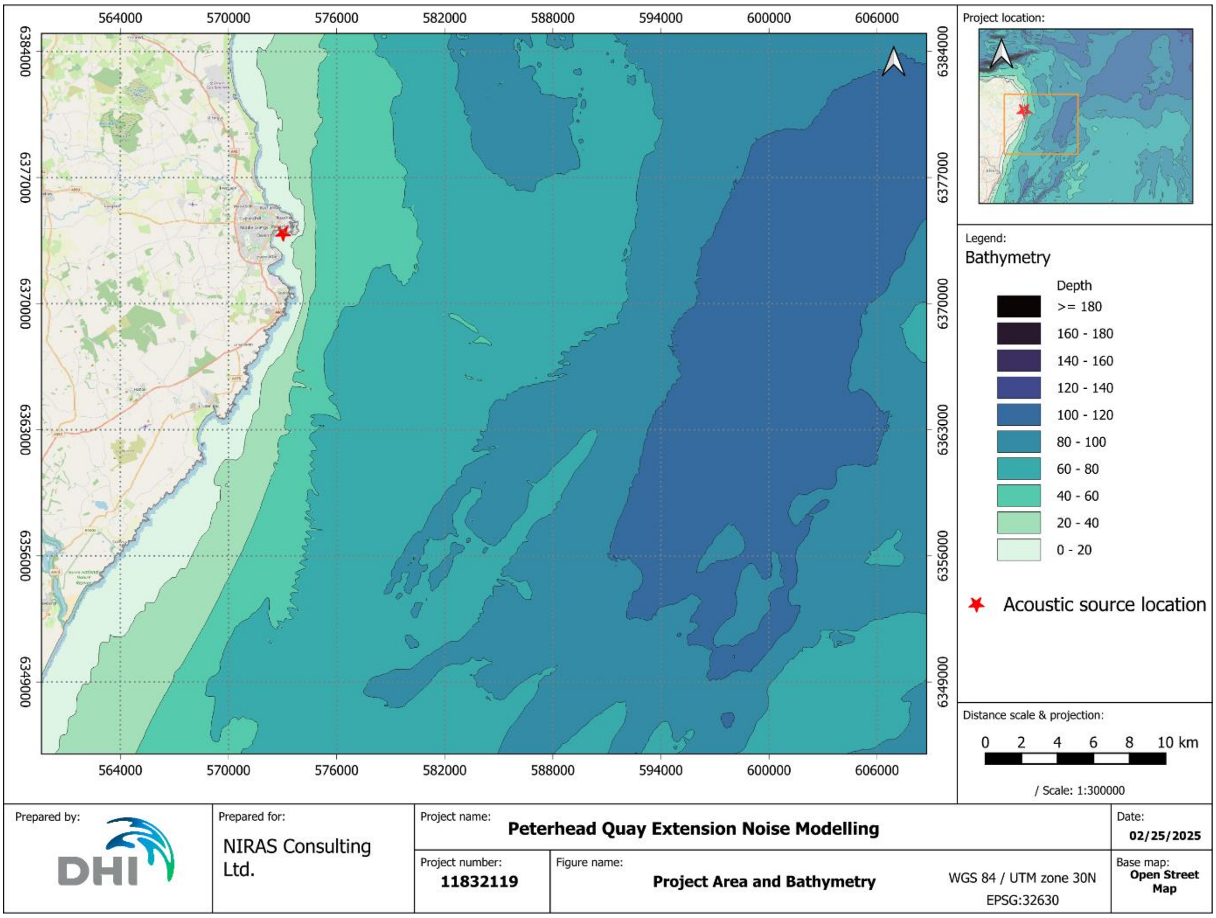

Figure 3.2 Map of the source location within the project area

The transect locations on top of the bathymetry are shown in Figure 3.3.

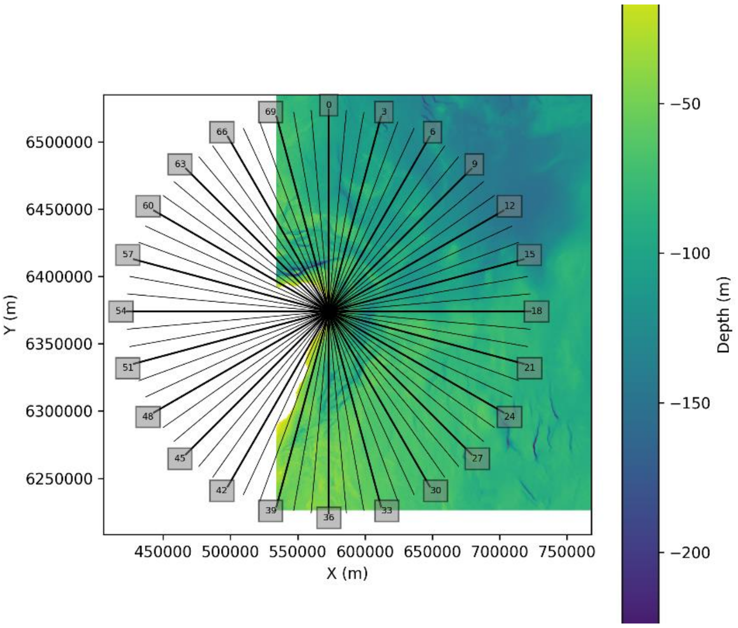

Figure 3.3 Map of directions of sound propagation modelling at project location

From an acoustic point of view, the source location area is shallow water, and low frequencies will thus be attenuated very quickly by the cut-off effect of the wave guide. Special consideration has to be given to the breakwaters enclosing the harbour. The breakwaters are depicted in Figure 3.4. As very dense and stiff structures, they can be assumed to effectively block direct transmission of sound waves through the water column. Sound may however be transmitted below the breakwaters through the seabed or be refracted horizontally around them. The latter effect is assumed to be of minor relevance as the acoustic wavelengths are very short compared to the geometrical dimensions of the breakwaters. As these effects cannot directly be considered using the Nx2D modelling approach, an empirical model was chosen where the breakwater geometry was removed from the model domain and replaced by an equivalent insertion loss. The resulting parameterization is provided in Appendix A.1.4.

Figure 3.4 **Map of the Peterhead harbour basin showing the breakwaters and noise source location used in this study (red star)**

The propagation characteristics are further influenced by the depth dependent sound speed and pH-, salinity and temperature profiles that define the attenuation as well as the geo-acoustic properties of the sea floor. These are provided in Appendix A.1.2 and Appendix A.1.3.

3.2.2 Source definition - pile driving

Impact pile driving may emit impulsive noise at very high levels. Both the broadband level as well as the spectral shape of the emitted signal depend on numerous factors, most notably pile diameter, ram energy, hammer type, and water depth.

The source spectrum was derived using a semi-empirical approach combining publicly available measurement data (Elmer *et al.* 2007; Jimenez-Arranz *et al.* 2020; Remmers and Bellmann 2022; von Pein *et al.* 2021) and the scaling laws for broadband (von Pein *et al.* 2022) and spectral data (von Pein *et al.* 2024). The assumed parameters for the definition of the source level and the obtained broadband values are given in Table 3.2, whereas the resulting spectrum is shown in Figure 3.5.

Table 3.2 Pile driving parameters and resulting broadband source level

Parameter	Unit	Value
Pile diameter	m	1.067
Water depth	m	~ 10
Pile driver energy	kJ	200
Ram mass	kg	14,000
Number of strikes to drive a single pile	-	3,000
SEL	dB re 1 µPa^2 s	206.8
SEL$_{cum}$	dB re 1 µPa^2 s	241.6
SPL$_{peak}$	dB re 1µPa	231.8
SPL$_{rms}$	dB re 1µPa	215.8

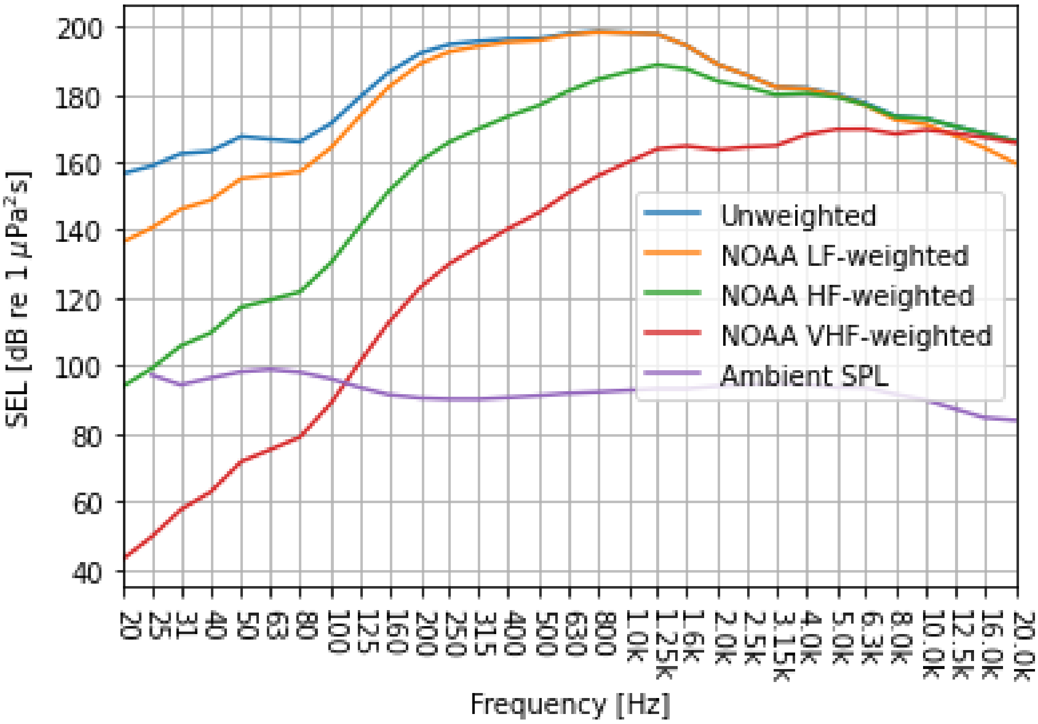

Figure 3.5 Source level for pile driving in 1/3 octave bands, weighted levels and ambient noise level

Accompanying activities such as drilling/boring are assumed to result in much lower impacts due to the generally lower source levels and the non-impulsive nature of the emitted noise.

3.2.3 Source definition - rock breaking

A range of different equipment is projected to be used during the construction work, including:

- Ripper;
- Diesel driven hydraulic power unit;
- Rock wheel;
- Rock breaker (e.g. *RAMMER 9033E*).

The ripper is essentially a different tool to be used with an excavator instead of the bucket. As a passive tool, it is assumed to have only little influence on the impact noise generated by hitting the substrate, and thus it is suggested to use the dredging noise defined in Section 3.2.4 as a proxy.

The hydraulic power unit is expected to have a little to no impact on underwater noise levels depending on its exact location. Airborne noise will not couple into the water due to the high impedance jump at the sea surface and only structural coupling paths into the water may contribute to underwater noise levels. Considering the capsuled design of the unit, it can be expected that no more noise will be introduced into the water than by a medium-sized vessel even if the unit is placed e.g. on a barge. The hydraulic power pack is thus deemed irrelevant regarding underwater noise emissions.

For the rock wheel, no detailed specifications were available. Due to similarities in the working principle, it may be expected that its source level is similar to or below that of a cutterhead suction dredge (CSD) which in turn has been shown to yield lower source levels than a backhoe dredge (Reine *et al.* 2012). It is thus suggested to consider the dredging noise defined in Section 3.2.4 as a proxy for the rock wheel as well.

The rock breaker *RAMMER 9033E* is a hydraulic hammer with a minimum weight of 7,400 kg, an input power of 138 kW and an impact rate of up to 645 beats per minute. It may operate completely submerged directly on the substrate. It may potentially emit considerable noise from its casing or via the substrate it is acting on, however, no measurements for underwater deployment are available. To effectively assess the environmental impact of the tool, down-the-hole (DTH) pile drilling was considered as a proxy. This technique is used to install piles in hard bedrock by combining rotational drilling with simultaneous percussive hammering on the drill bit. As impact rates and dimensions are comparable to the rock breaker investigated here, it is deemed a suitable proxy. As for DTH operations in general, it is difficult to classify the noise as either continuous or impulsive, following a precautionary principle, the source is considered impulsive. The single strike SEL source level shown in Figure 3.6 Figure 3was derived from measurements published by (Guan *et al.* 2022) for DTH drilling with a 0.84 m drill bit in Southeast Alaska. Specifically, the reported spectra for the initial 20 minutes of operation were considered. Resulting levels and underlying assumptions are given in Table .

Table 3.3 Rock breaking parameters and resulting broadband source levels

Parameter	Unit	Value
Assumed operational time per day	h	24
Impact rate	bpm	645
SEL	dB re 1 µPa^2 s	173.7
SEL$_{cum}$	dB re 1 µPa^2 s	233.4
SPL$_{peak}$	dB re 1µPa	193.7
SPL$_{rms}$	dB re 1µPa	185.7

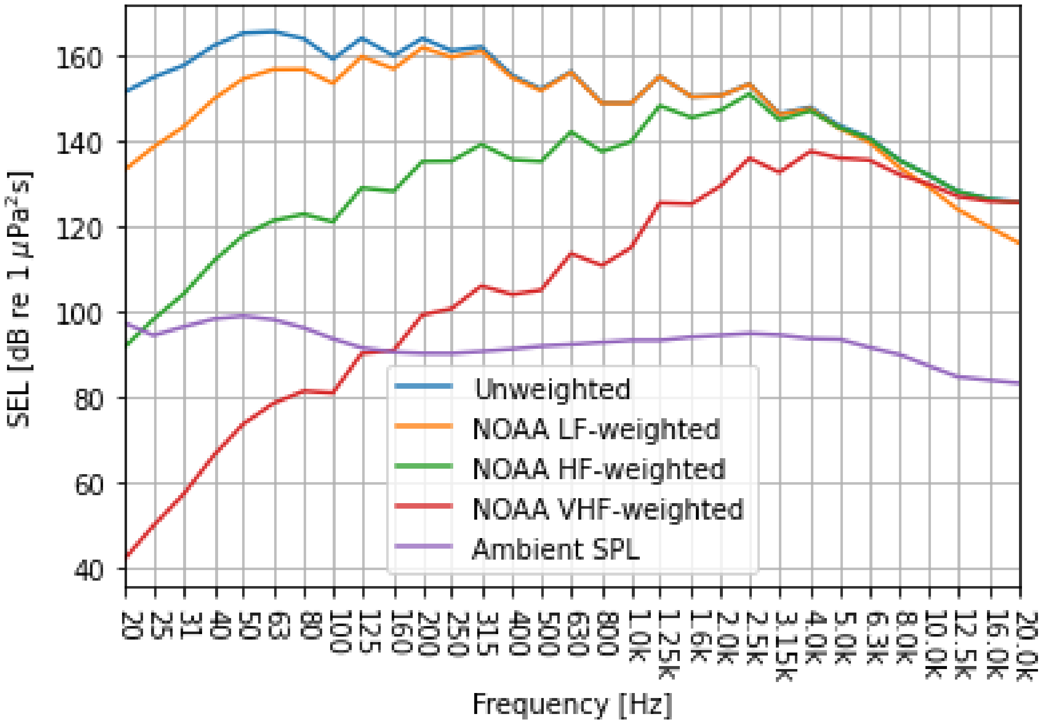

Figure 3.6 **Source level for DTH drilling used as proxy for rock breaking in 1/3 octave bands, weighted levels and ambient noise level**

3.2.4 Source definition - dredging

Dredging operations will be carried out using a backhoe dredge. This kind of operation results in continuous noise from several sources, the loudest of which is the bottom impact sound from the bucket with a reported source level of 179.4 dB re 1 µPa SPL (Reine *et al.* 2012). The source level was thus determined based on one-third octave band levels measured by Reine (Reine *et al.* 2012) for the impact sound during rock excavation in shallow waters of New York Harbour. The resulting spectrum is shown in Figure 3.7.

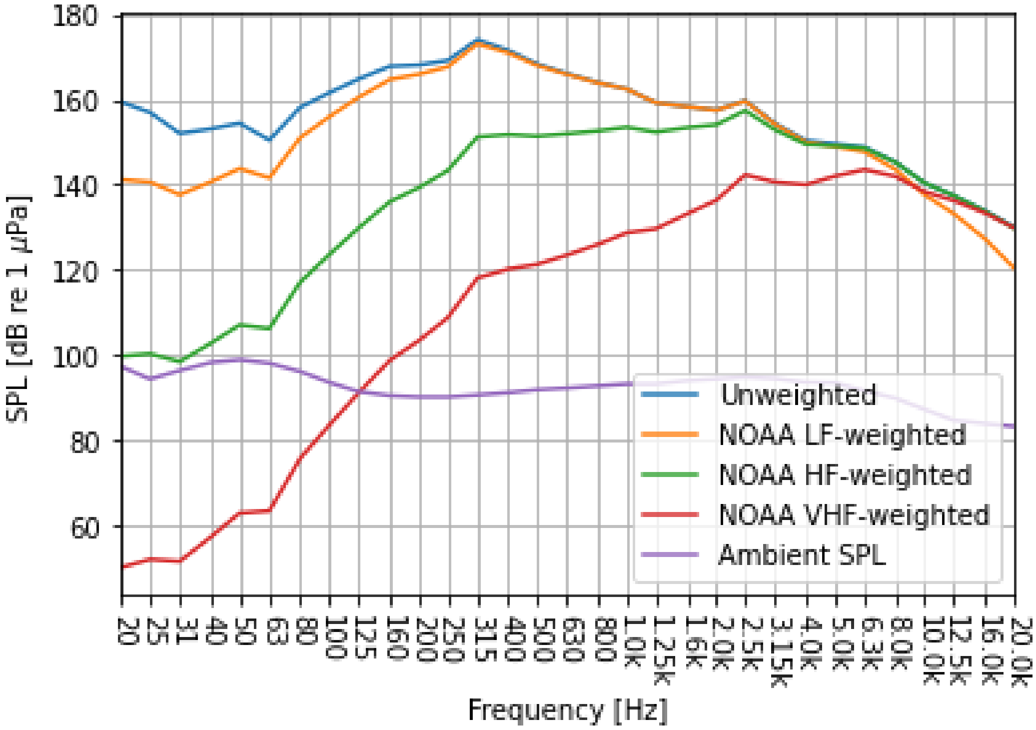

Figure 3.7 **Source level for backhoe dredging in 1/3 octave bands, weighted levels and ambient noise level**

3.2.5 Source definition - blasting

In case blasting is required to break rocks, a special non-explosive blasting technique will be applied. Instead of conventional explosives, a so-called Cardox system is used. It is designed to fracture materials by rapid discharging of carbon dioxide at high pressures into the material. The system and its application are described by Singh (Singh 1998). Acoustic measurements of underwater applications are currently not publicly available, but experimental analysis of the blast characteristics is reported by (Ke *et al.* 2019). Based on this, it can be concluded that a single Cardox blast releases the equivalent energy of approximately 0.030 kg TNT which was used to define the source level.

Blasting activities in general are from the acoustical point of view a highly non-linear transient phenomenon. To capture the characteristics of the blasting, attempts have been made to derive source levels that lead to realistic acoustical results in the far-field. The definition of the source level of the SEL is based on the approach developed by (Urick 1971; Urick 1983). The distribution of the sound exposure over the one-third octave bands is defined by this approach for the blasting of a single borehole. The following parameters have been considered for the derivation of the source levels:

- A TNT equivalent of 0.030 kg is assumed within every individual borehole. There is a time delay of 25 milliseconds between the blasting of the different boreholes.
- A total number of 20 boreholes is assumed for the evaluation of the SEL results.

The source level presented below is not accounting for the interaction of the blasting of several boreholes. However, the sound exposure level at the receiver position is derived by cumulating the SEL with the number of boreholes. Therefore, the plotted SEL results within maps and transect cuts are based on the blasting of one borehole. For the evaluation of the impact of the SEL, the SEL is adjusted to account for the number of boreholes blasted within the blasting procedure.

There are empirical approaches for the derivation of the peak sound pressure level. The one suggested by (Soloway and Dahl 2014) is used to derive the range dependent difference between the SEL and the

SPL$_{peak}$. The SPL$_{peak}$ is derived by adding the respective range dependent difference to the SEL. It is assumed that the time delay between the blasts of the different boreholes is long enough so the SPL$_{peak}$ is not affected by the number of boreholes subjected to blasting.

The respective source levels are:

- Sound Exposure Level (SEL) = 201.1 dB re 1 µPa^{2}s;
- Peak Sound Pressure Level (SPL$_{peak}$) = 254.7 dB re 1 µPa.

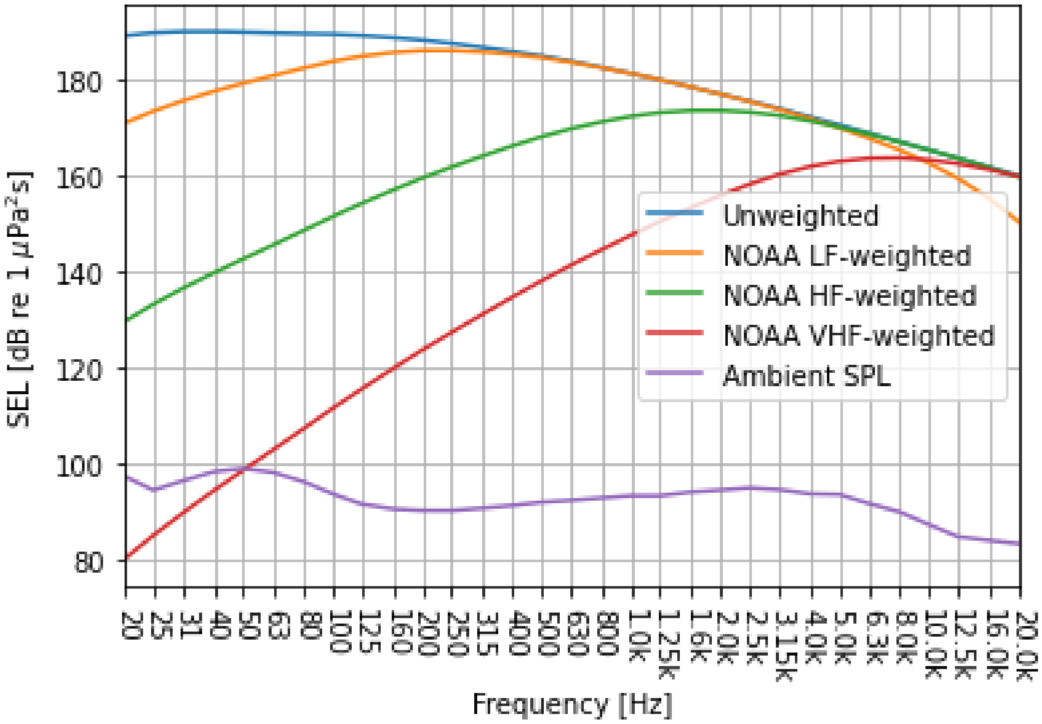

Figure 3.8 **Source level for blasting in 1/3 octave bands, weighted levels and ambient noise level**

3.3 Calculation of Biological Impact

According to the update of the NMFS guidelines for setting thresholds for the impacts of noise on marine organisms, the definition of the NMFS criteria has changed to prior modelling studies conducted by DHI.

The main differences are:

- Change in naming convention of the hearing groups. The harbour porpoise is grouped as a very high frequency cetacean (VHF);
- Change in the definition of the weighting curves;
- Changes in the definition of the thresholds;
- In case of cetaceans PTS is replaced by an Auditory Injury (AUD INJ).

The impacts were determined using thresholds that should not be exceeded in order to not cause harm to marine life. The criteria include effects in the form of hearing impairment, i.e. temporary threshold shift (TTS), auditory injury (for marine mammals) and recoverable injury (for fish), as well as changes in behaviour due to noise exposure. Acoustic thresholds for these effects were applied based on the international guidelines and recommendations (mainly (NMFS 2024) and (Popper *et al.* 2014)), as well as available studies ((Hawkins *et al.* 2014) and (Tougaard 2021)). Thresholds were grouped depending on the type of noise source, as following: impulsive noise (pile driving), continuous noise (dredging) and explosives (blasting). As in the study area, marine organisms with different hearing abilities occur, modelling was conducted for different hearing groups. Marine mammals were grouped based on (NMFS 2024) guidelines as: low-frequency (LF) cetaceans (minke whale), high-frequency (HF) cetaceans (bottlenose dolphin) and very high-frequency (VHF) cetaceans (harbour porpoise). For fish the grouping proposed by Popper et al. 2014 was applied, based on which, thresholds for fish with swim bladder were used. According to Popper et al. 2014 , these groups may be subdivided into fish with swim bladder involved in hearing and fish with swim bladder not involved in hearing (Atlantic salmon).

3.3.1 Threshold values used for pile driving and rock breaking noise

Marine mammals

For marine mammals, threshold values for modelling of the hearing impairment effects (TTS and Auditory injury) due to impulsive noise were based on NMFS, 2024 criteria. In the case of the behavioural reaction, NMFS criteria were applied for the low (LF) and high (HF) frequency cetacean groups. For the harbour porpoise, behavioural response threshold was based on the VHF criterion indicated in (Tougaard 2021).

The cumulative SEL was calculated including all strikes necessary for the installation of one pile. Although according to the work schedule up to four piles may be installed within 24h, these pile driving installations are deemed independent activities according to NMFS, 2024 which are not accumulated altogether.

A summary of the criteria values can be found in Table 3.4.

Table 3.4 Overview of the noise exposure criteria used for calculating impacts of piling and rock breaking noise on cetaceans

Source	Hearing group	Species representing the group	Effect	Sound type modelled	SEL (dB re. 1 µPa^{2}s)	SPL_{peak}/ SPL_{125ms}/ RMS (dB re 1 µPa)
NMFS 2024	Low-Frequency (LF) Cetaceans	Minke whale	AUD INJ	Cumulative	183 (LF-weighted SEL)	222 SPL_{peak}
			TTS	Cumulative	168 (LF-weighted SEL)	216 SPL_{peak}
	High-Frequency (HF) Cetaceans	Bottlenose dolphin	AUD INJ	Cumulative	193 (HF-weighted SEL)	230 SPL_{peak}
			TTS	Cumulative	178 (HF-weighted SEL)	224 SPL_{peak}
	Very High-Frequency (VHF) Cetaceans	Harbour porpoise	AUD INJ	Cumulative	159 (VHF-weighted SEL)	202 SPL_{peak}
			TTS	Cumulative	144 (VHF-weighted SEL)	196 SPL_{peak}
	Low-Frequency (LF) Cetaceans	Minke whale	Behavioural response	RMS	-	160 (RMS)
	High-Frequency (HF) Cetaceans	Bottlenose dolphin	Behavioural response	RMS	-	160 (RMS)
Tougaard 2021	Very High-Frequency (VHF) Cetaceans	Harbour porpoise	Behavioural response	Single strike	-	103 VHF-weighted SPL_{125ms}

Animal movement model (after Skjellerup et al. 2015)

For modelling of the impact of piling noise on VHF cetaceans, an animal movement model was used. According to the Skjellerup guidelines, marine mammals tend to escape radially from the sound source with a given escape speed (v =1.5 m s^{-1}). The received noise dose is then cumulated along the way of the escaping mammal, and due to the increasing distance from the source, it is smaller than for the static individual staying in one location while impacts accumulate. Moreover, the Skjellerup guidelines further assume an initial radius r_0 that is free of mammals. This radius should be chosen in such a way that mammals can escape without experiencing a hearing injury. In the conducted modelling, the behavioural threshold for VHF cetaceans in response to pile driving is included along with the animal movement / fleeing model.

Fish

In the case of fish, the noise exposure criteria for TTS and recoverable injury due to piling were taken from Popper *et al*. 2014. Modelling was conducted considering both groups of fish with a swim bladder (involved and not involved in hearing), as in the case of piling criteria indicated for hearing impairment are the same. Behavioural criterion was based on the investigation by Hawkins *et al*. 2014.

It should be noted that studies of fish indicate that these organisms can rebuild hair cells responsible for sound perception (e.g. Popper et al. 2014, Popper and Hawkins 2019). Therefore, hearing impairment is understood as a recoverable process.

Table 3.5 Overview of the noise exposure criteria used for calculating impacts of piling and rock breaking noise on fish with a swim bladder

Source	Group of fishes	Effect	Sound type modelled	SEL (unweighted)
Popper *et al*. 2014	Fish with swim bladder	Recoverable Injury	Cumulative	203 dB re. 1 µPa^{2}s
		TTS	Cumulative	186 dB re. 1 µPa^{2}s
Hawkins *et al*. 2014	Fish with swim bladder	Behavioural	Single strike	135 dB re. 1 µPa^{2}s

3.3.2 Threshold values used for continuous noise

Marine mammals

For marine mammals, to model the hearing impairment effects (TTS and auditory injury) due to continuous noise, the NMFS 2024 criteria were used. In case of the behavioural reaction of LF and HF cetaceans, also NMFS guidelines were applied. For the harbour porpoise, Southall et al. 2007 study was considered, based on which the criterion for adverse behavioural reaction (fleeing) was chosen.

Table 3.6 Overview of the noise exposure criteria used for calculating impacts of continuous noise on cetaceans

Source	Hearing group	Species	Effect	Threshold Level
NMFS 2024	Low-Frequency (LF) Cetaceans	Minke whale	AUD INJ	197 dB re. 1 µPa^{2}s (weighted SEL) -24 h
			TTS	177 dB re. 1 µPa^{2}s (weighted SEL) -24 h
	High-Frequency (HF) Cetaceans	Bottlenose dolphin	AUD INJ	201 dB re. 1 µPa^{2}s (weighted SEL) -24 h

			TTS	181 dB re. 1 µPa^{2}s (weighted SEL) -24 h
	Very High-Frequency (VHF) Cetaceans	Harbour porpoise	AUD INJ	181 dB re. 1 µPa^{2}s (weighted SEL) -24 h
			TTS	161 dB re. 1 µPa^2 s (weighted SEL)- 24 h
	Low-Frequency (LF) Cetaceans	Minke whale	Behavioural reaction	120 dB re 1 µPa (RMS)
	High-Frequency (HF) Cetaceans	Bottlenose dolphin	Behavioural reaction	
Southall et al. 2007	Very High-Frequency (VHF) Cetaceans	Harbour porpoise	Adverse behavioural reaction (fleeing)	140 dB re 1 µPa (RMS)

Fish

For fish, Popper et al. 2014 criteria were used to calculate impacts of continuous noise in the form of hearing impairment. Thresholds indicated for fish with swim bladder involved in hearing were applied, as the only available values. Behavioural impacts were not modelled.

Table 3.7 Overview of the noise exposure criteria used for calculating impacts of continuous on fish

Source	Hearing group	Effect	Threshold Level
Popper et al. 2014	Fish with swim bladder involved in hearing	TTS	158 dB re 1 µPa (RMS) – 12 h
		Recoverable injury	170 dB re 1 µPa (RMS) – 48 h

3.3.3 Threshold values used for explosive noise from blasting

As there are no separate thresholds for the type of blasting considered in the scope of the project, criteria described for the explosive sounds normally applied in case of blasting have been applied. Explosive sounds form a separate category of impulsive noise, characterised by a near-instantaneous pressure rise time and a very high peak pressure level, followed by a rapid pressure decay creating a shock wave (Dall'Osto et al. 2023). Due to such properties, emissions of explosive sounds can lead to severe effects on marine animals. Threshold values applied for the explosive sounds included in NMFS guidelines for cetaceans (NMFS 2024b), as well as FHWG 2008 and Popper et al. 2014 for fish (Table , Table).

Table 3.8 **Overview of the noise exposure criteria for calculating impacts of explosive sounds on cetaceans (NMFS 2024b)**

Hearing Group	Species	AUD INJ		TTS		Behavioural reaction
		SPL_{peak} (dB re 1 µPa)	SEL_{cum24h} (weighted) (dB re. 1 μPa^2s)	SPL_{peak} (dB re 1 µPa)	SEL_{cum24h} (weighted) (dB re. 1 μPa^2s)	$SEL_{cum\ 24\ h}$ (weighted) (dB re. 1 μPa^2s)
Low-Frequency (LF) Cetaceans	Minke whale	222	183	216	168	163
High-Frequency (HF) Cetaceans	Bottlenose dolphin	230	193	224	178	173
Very High-Frequency (VHF) Cetaceans	Harbour porpoise	202	159	196	144	139

Table 3.9 **Noise exposure criteria for calculating impacts of explosive sounds on fish (NMFS 2024c, FHWG 2008, Popper et al. 2014)**

Marine organism	Onset of Mortality (Received Level)	Onset of Physical Injury (Received Level)
Fish	L_{pk}: 229 dB	L_{pk}: 206 dB $L_{E,p,12h}$: 187 dB (≥ 2 g) $L_{E,p,12h}$: 183 dB (< 2 g)

3.3.4 Effective quiet – mammals

One important concept is the 'effective quiet' as defined by Finneran (Finneran 2015) as the highest SPL that would not produce a significant TTS or affect recovery from a TTS produced by a prior, higher-level exposure. Finneran (Finneran 2015) indicates that this value could be 124 dB re 1 µPa for the harbour porpoise and cites the study by (Kastelein 2002) in support of this conclusion. Kastelein *et al.* (Kastelein et al. 2002) did not investigate directly the 'effective quiet' but rather showed that very low sound exposures can lead to significant TTS in porpoises when the exposure duration is long. The 124 dB re 1 µPa is the lowest sound level so far measured, leading to TTS in harbour porpoises. It can, therefore, be viewed as a preliminary value until more solid data is available. In a similar way, (Finneran 2015) indicates that for dolphins and belugas the effective quiet would be in the range 150-160 dB and thus, 150 dB is indicated as a limit for HF-cetaceans.

Effective quiet is applied to the one-third octave bands. Whenever the unweighted SPL of a band is below 124 dB for VHF-cetaceans or below 150 dB for HF-cetaceans, it is neglected in the summation of the acoustical energy to the broadband SEL.

Effective quiet is applied to the acoustical results for impulsive and continuous noise in relation to cetaceans. In the case of impulsive noise, the SPL is estimated by adding a constant conversion factor to the SEL. Frequency weighting is conducted afterwards with the remaining bands.

4 Acoustics Results

4.1 Pile driving

LF cetaceans

Behavioural response of LF Cetaceans to pile driving is expected to occur mostly within the Peterhead harbour basin at the maximum extent of 1.16 km (Figure 4.1). Similarly, Auditory Injury is possible to occur at a maximum range of 1.16 km (Figure 4.2). Temporary threshold shift had the greatest range of all the pile driving impact modelling results for LF Cetaceans and reached up to 3.24 km, with more than five times larger impact area than the behavioural reaction (Figure 4.2, Table 4.1). However, thresholds indicated by NMFS (NMSF 2024) for behavioural impact are not species-specific thresholds and apply to all cetacean hearing groups in general.

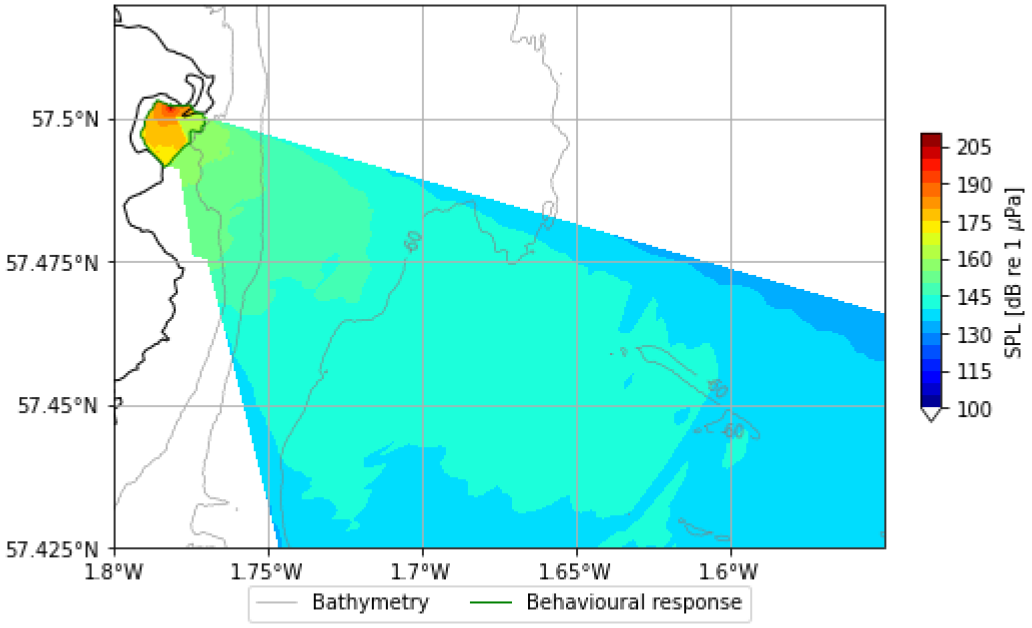

Figure 4.1 SPL levels and impact ranges for LF cetaceans predicted during piling works at the Peterhead harbour

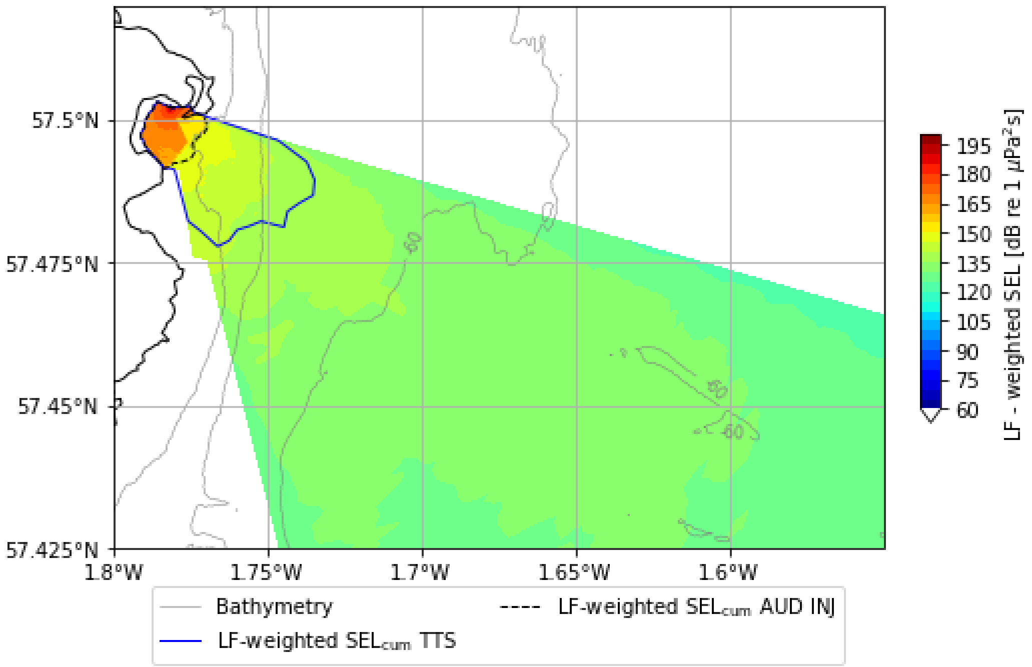

Figure 4.2 LF-weighted SEL levels and impact ranges for LF cetaceans predicted during piling works at the Peterhead harbour

Table 4.1 Impact ranges and areas predicted for LF cetaceans during piling works at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R_{min}	R_{mean}	R_{max}	
Low-Frequency (LF) Cetaceans	Behavioural	0.04	0.436	1.16	0.96
	TTS_{SEL}	0.04	0.842	3.24	5.49
	$TTS_{SPLpeak}$	0.02	0.02	0.02	0.001
	AUD INJ_{SEL}	0.04	0.464	1.16	1.1
	AUD $INJ_{SPLpeak}$	0.02	0.02	0.02	0.001

HF cetaceans

Based on the modelling results, the behavioural response impact for HF cetaceans is expected to have the same extent as for LF cetaceans, reaching at maximum 1.16 km and being mostly restricted to the Peterhead harbour basin area (Figure 4.3, Table 4.2). Auditory Injury for HF cetaceans is predicted to reach a similar but smaller mean range than in the case of the LF cetaceans. The maximum predicted ranges for Auditory Injury for LF and HF cetaceans both amounted to 1.16 km (Figure 4.4, Table 4.2). The areal extent of the Temporary Threshold Shift for HF cetaceans resulting from pile driving is almost five times smaller compared to LF cetaceans, mostly confined to the Peterhead harbour basin. In summary, all the considered impacts of pile driving sounds on HF cetaceans are expected to occur within approximately 1 km from the acoustic energy source (Table 4.2).

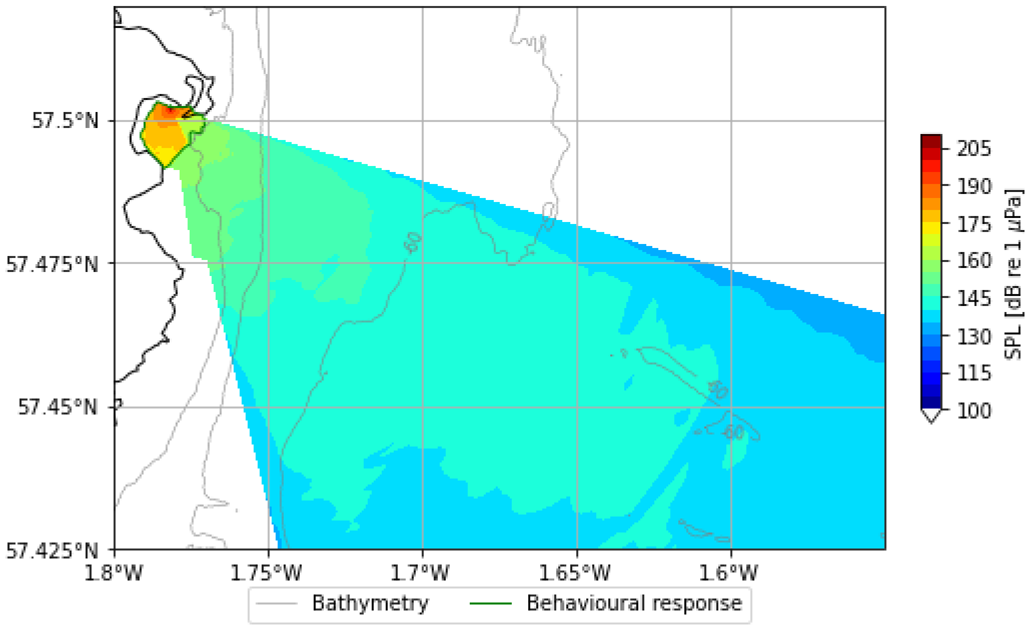

Figure 4.3 SPL levels and impact ranges for HF cetaceans predicted during piling works at the Peterhead harbour

.

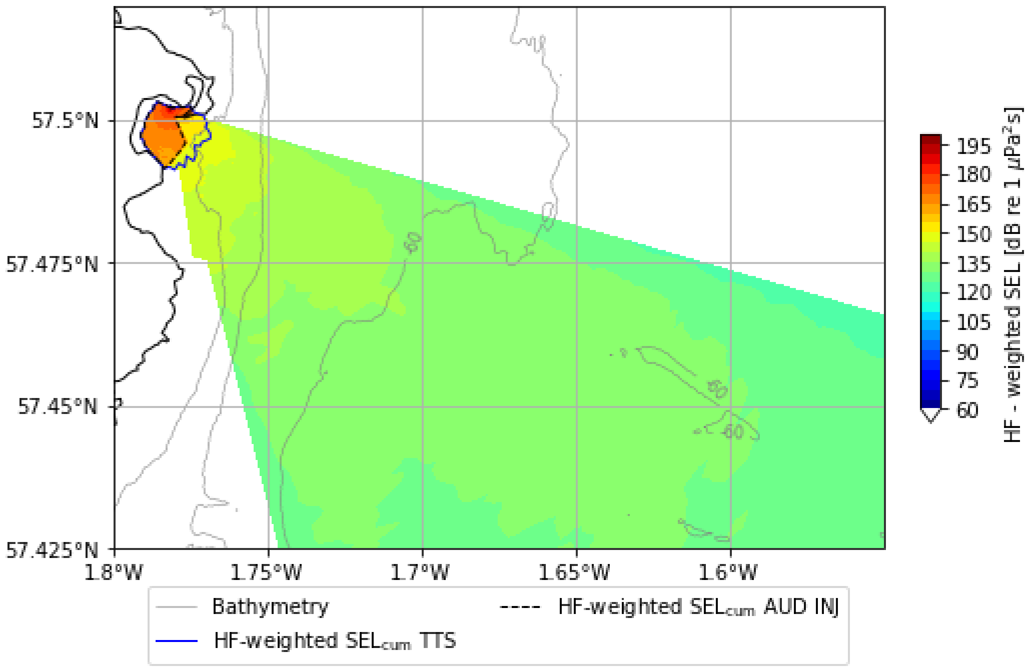

Figure 4.4 HF-weighted SEL levels and impact ranges for HF cetaceans predicted during piling works at the Peterhead harbour

Table 4.2 **Impact ranges and areas predicted for HF cetaceans during piling works at the Peterhead harbour**

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R_{min}	R_{mean}	R_{max}	
High-Frequency (HF) Cetaceans	Behavioural	0.04	0.436	1.16	0.96
	TTS$_{SEL}$	0.04	0.477	1.18	1.19
	TTS$_{SPLpeak}$	0.02	0.02	0.02	0.001
	AUD INJ$_{SEL}$	0.04	0.37	1.16	0.76
	AUD INJ$_{SPLpeak}$	0.02	0.02	0.02	0.001

VHF cetaceans

In case of the behavioural impact of piling on the VHF cetaceans, it is predicted to have the largest extent of all the considered effects predicted from piling for cetaceans (Figure 4.5). One should notice that the threshold applied for VHF cetaceans was species specific, not general as in the case of other hearing groups. The behavioural response of VHF cetaceans is expected to occur at a maximum distance of approximately 4.5 km from the pile driving site and cover the area of around 10km^2 (ten times larger area compared to LF and HF cetaceans) (Table 4.3). Auditory injury extent for this VHF cetaceans hearing group is around two times smaller than in case of HF cetaceans and is also contained in the harbour basin area (Figure 4.6). VHF cetaceans have the smallest impact area for Auditory Injury as a result of pile driving noise in comparison to the remaining cetaceans hearing groups (Table 4.3). It should be noted, thought that VHF cetaceans are the only hearing group for which the modelling includes a fleeing reaction as there is not enough reliable knowledge for the other hearing groups to predict the reaction.

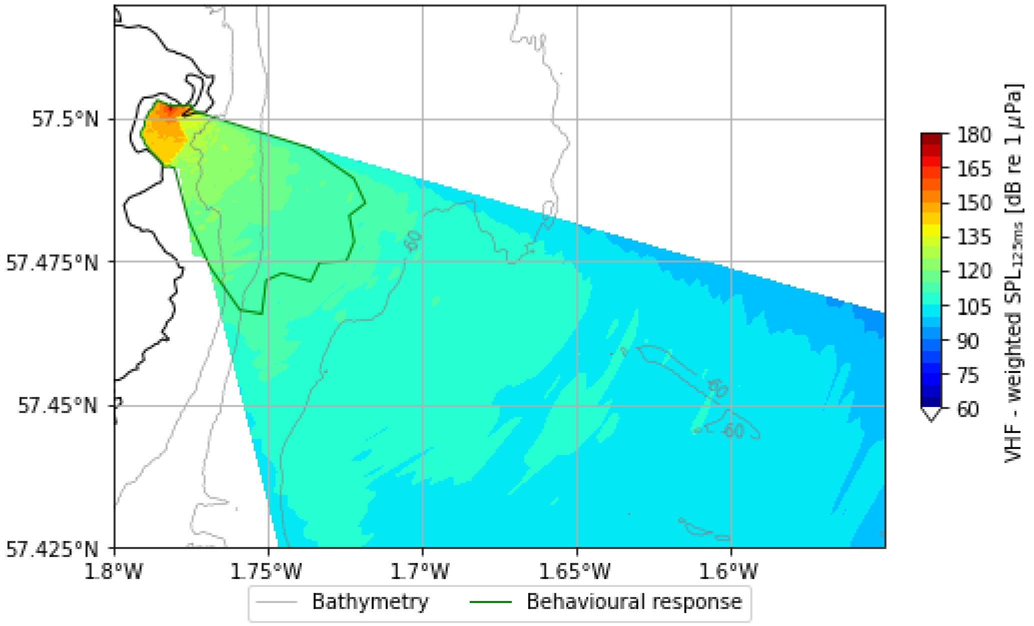

Figure 4.5 **VHF-weighted SPL$_{125rms}$ levels and impact ranges for VHF cetaceans predicted during piling works at the Peterhead harbour**

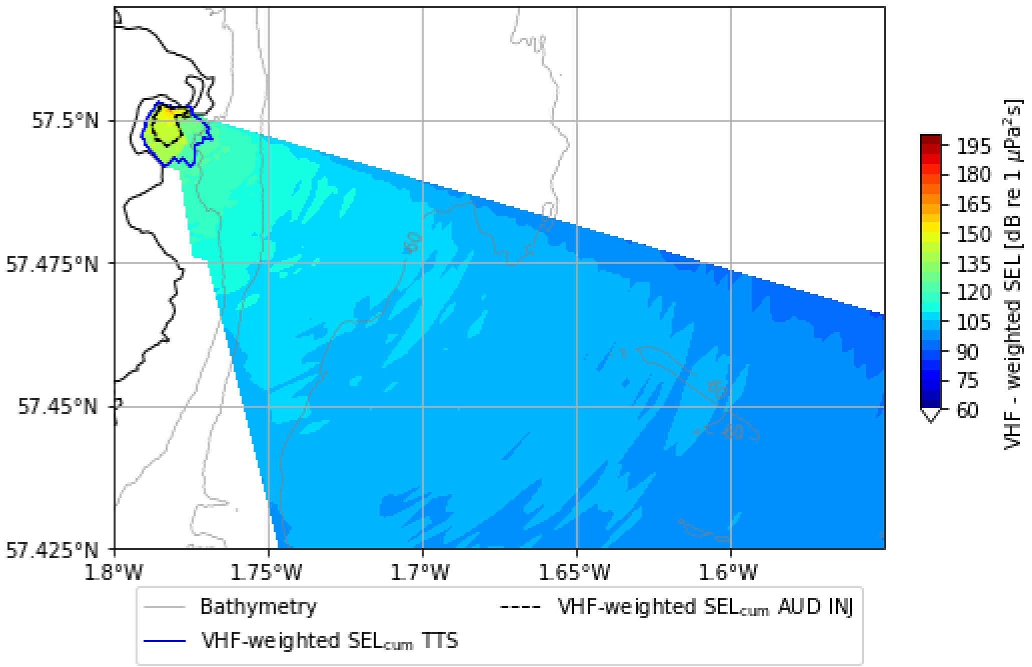

Figure 4.6 VHF-weighted SEL levels and impact ranges for VHF cetaceans predicted during piling works at the Peterhead harbour

Table 4.3 Impact ranges and areas predicted for VHF cetaceans during piling works at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R_{min}	R_{mean}	R_{max}	
Very High-Frequency (VHF) Cetaceans	Behavioural	0.04	1.049	4.54	10.02
	TTS_{SEL}	0.04	0.456	1.18	1.09
	$TTS_{SPLpeak}$	0.04	0.226	0.42	0.21
	AUD INJ_{SEL}	0.02	0.251	0.72	0.33
	AUD $INJ_{SPLpeak}$	0.04	0.109	0.16	0.04

Fish with a swim bladder

Fish having a swim bladder are expected to show behavioural reaction to the pile driving noise at a maximum distance of approximately 2.8 km from the sound source, within the area of 4.6 km^2 (Figure 4.7, Table 4.4). Recoverable injury and temporary threshold shift are expected to be mostly contained to the harbour basin area (Figure 4.7).

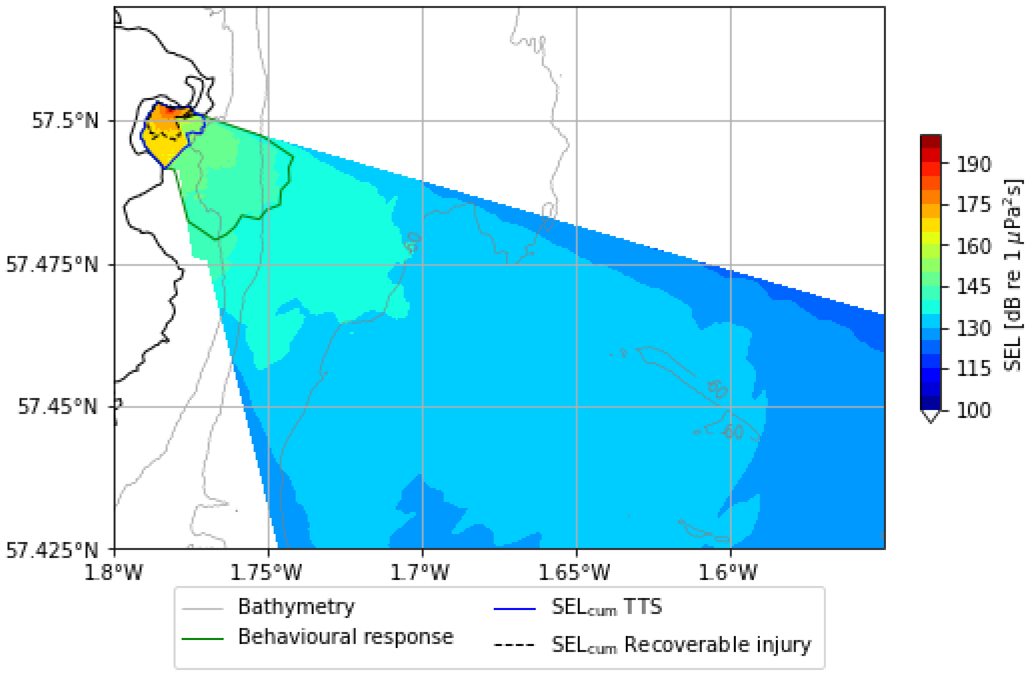

Figure 4.7 SEL levels and impact ranges for fish predicted during piling works at the Peterhead harbour

Table 4.4 Impact ranges and areas predicted for Fish with a swim bladder during piling works at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R_{min}	R_{mean}	R_{max}	
Fish with a swim bladder	Behavioural	0.04	0.793	2.82	4.65
	Recoverable Injury	0.04	0.287	0.66	0.38
	TTS_{SEL}	0.04	0.434	1.16	0.95

4.2 Rock breaking

LF cetaceans

Rock breaking noise is expected to result in the behavioural response of LF cetaceans only within the very short distance of 80 m from the sound source (Table 4.5). Auditory injury is predicted to not to occur outside of the harbour basin (Figure 4.8). However, temporary threshold shift can reach up to approximately 1.9 km^2 area range, spreading outside of the harbour area (Figure 4.9, Table 4.5). It is the largest impact extent for temporary threshold shift caused by noise from rock breaking of all the cetaceans hearing groups considered.

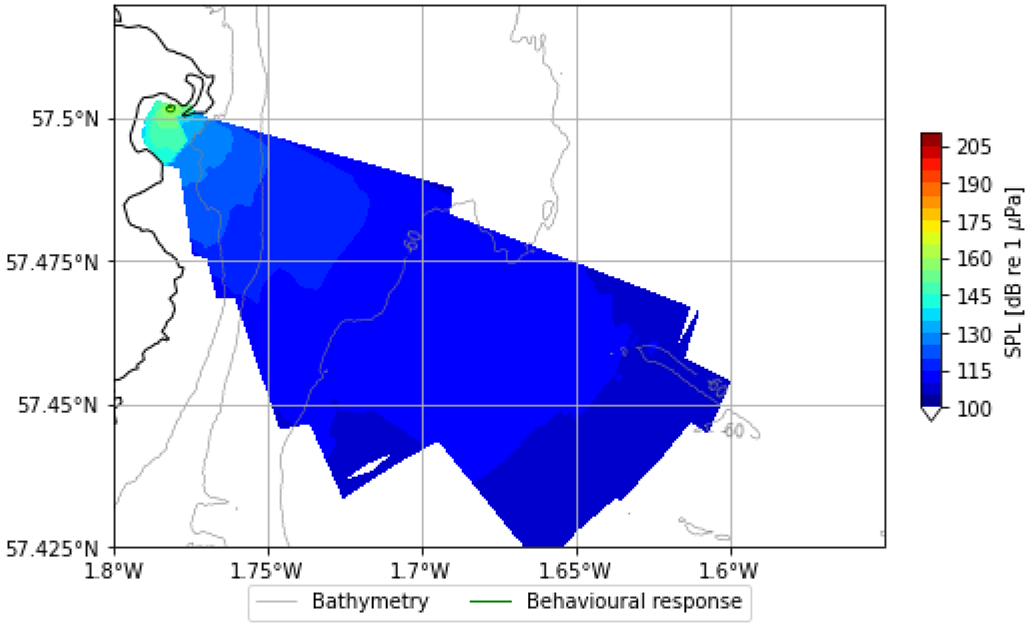

Figure 4.8 SPL levels and impact ranges for LF cetaceans predicted during rock breaking works at the Peterhead harbour

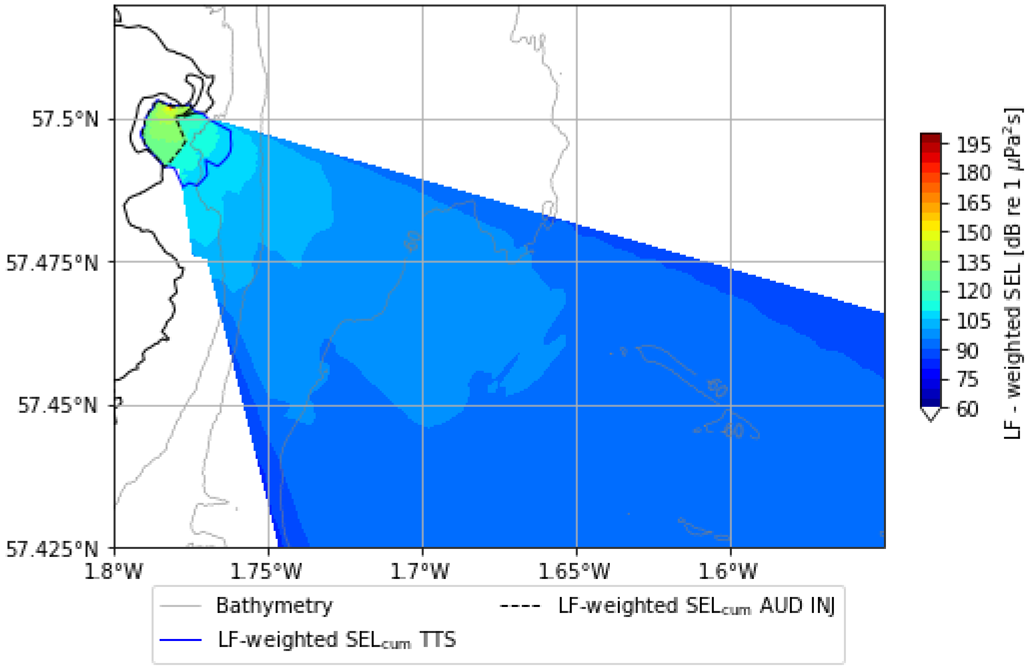

Figure 4.9 LF-weighted SEL levels and impact ranges for LF cetaceans predicted during rock breaking works at the Peterhead harbour

Table 4.5 Impact ranges and areas predicted for LF cetaceans during rock breaking works at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R_{min}	R_{mean}	R_{max}	
Low-Frequency (LF) Cetaceans	Behavioural	0.02	0.066	0.08	0.02
	TTS_{SEL}	0.04	0.568	1.6	1.86
	$TTS_{SPLpeak}$	0.02	0.02	0.02	0.001
	AUD INJ_{SEL}	0.04	0.369	1.16	0.75
	AUD $INJ_{SPLpeak}$	0.02	0.02	0.02	0.001

HF cetaceans

Based on the rock breaking sound modelling results for HF cetaceans, the potential effects of noise emission are contained within a small range of maximum 80 m, 40 m and 100 m, for behavioural response, auditory injury and temporary threshold shift respectively (Figure 4.10, Figure 4.11, Table 4.6).

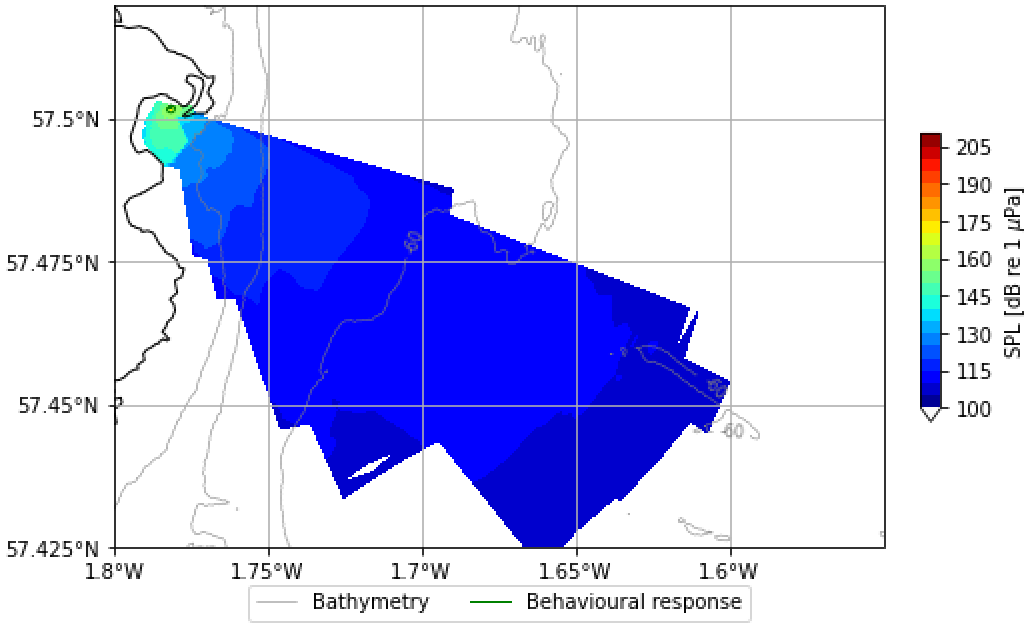

Figure 4.10 SPL levels and impact ranges for HF cetaceans predicted during rock breaking works at the Peterhead harbour

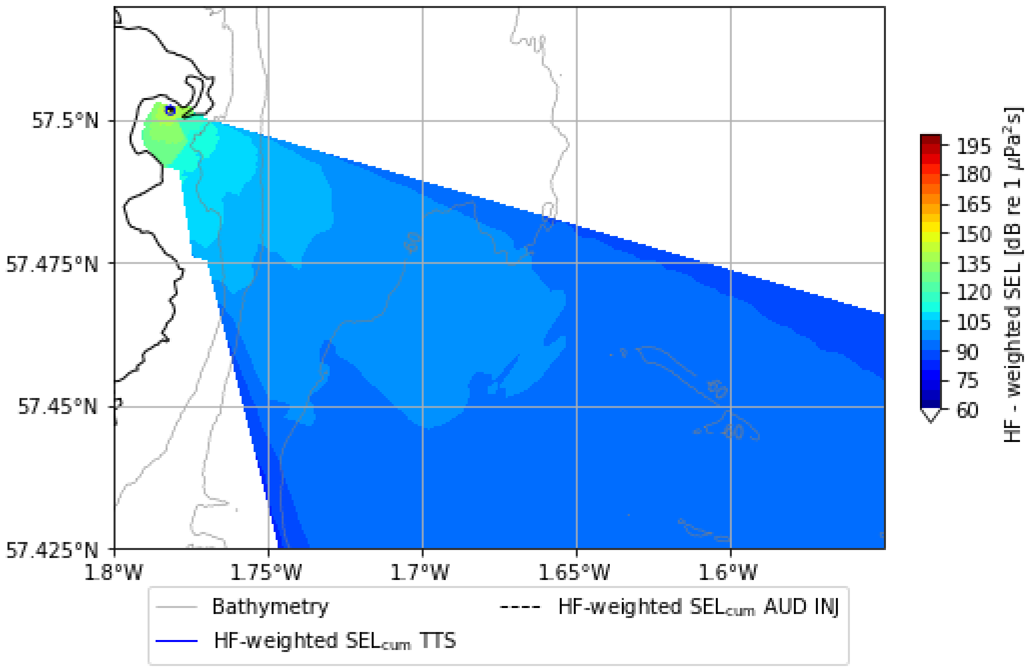

Figure 4.11 HF-weighted SEL levels and impact ranges for HF cetaceans predicted during rock breaking at the Peterhead harbour

Table 4.6 Impact ranges and areas predicted for HF cetaceans during rock breaking works at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km²)
		R_{min}	R_{mean}	R_{max}	
High-Frequency (HF) Cetaceans	Behavioural	0.02	0.066	0.08	0.02
	TTS_{SEL}	0.04	0.08	0.1	0.02
	$TTS_{SPLpeak}$	0.02	0.02	0.02	0.001
	AUD INJ_{SEL}	0.02	0.034	0.04	0.004
	AUD $INJ_{SPLpeak}$	0.02	0.02	0.02	0.001

VHF cetaceans

In the case of VHF cetaceans, the rock breaking sound is expected to result in the very similar and small ranges of auditory injury and temporary threshold shift as for HF cetaceans (Figure 4.13, Table 4.7). The behavioural response is expected to be of a larger range for VHF cetaceans than for LF and HF cetaceans, but it is going to be contained to the area of the harbour basin (Figure 4.12).

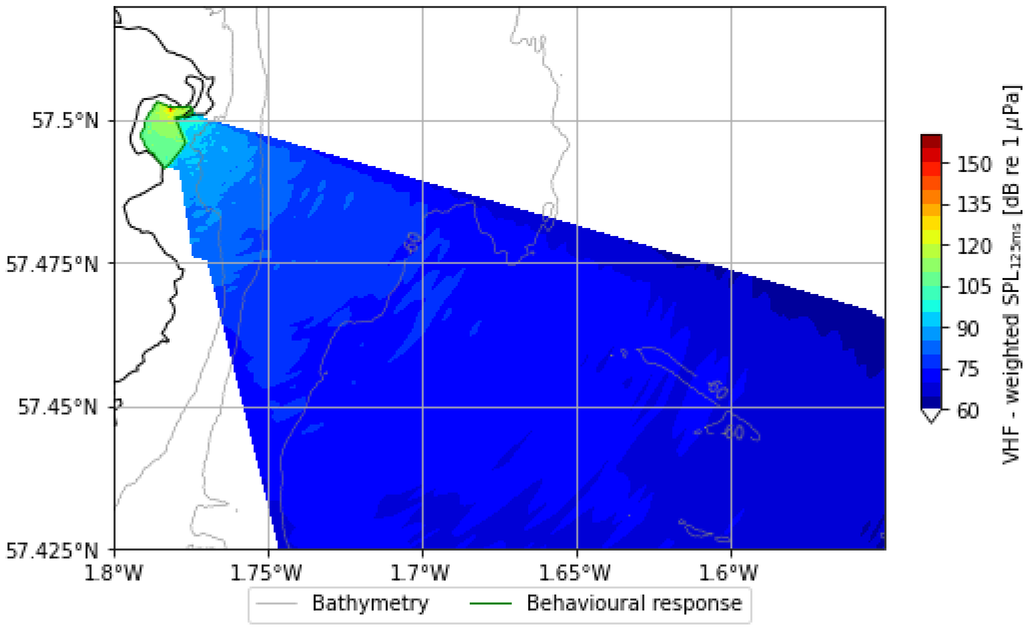

Figure 4.12 VHF-weighted SPL$_{125rms}$ levels and impact ranges for VHF cetaceans predicted during rock breaking at the Peterhead harbour

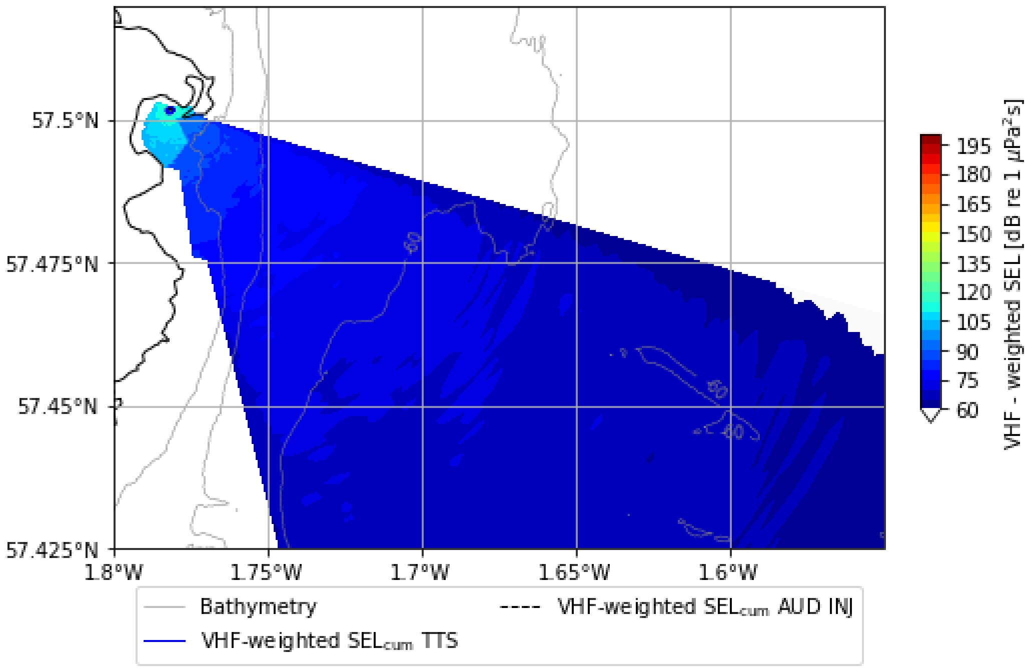

Figure 4.13 VHF-weighted SEL levels and impact ranges for VHF cetaceans predicted during rock breaking at the Peterhead harbour

Table 4.7 Impact ranges and areas predicted for VHF cetaceans during rock breaking works at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R_{min}	R_{mean}	R_{max}	
Very High-Frequency (VHF) Cetaceans	Behavioural	0.04	0.371	1.16	0.76
	TTS_{SEL}	0.02	0.055	0.1	0.01
	$\text{TTS}_{\text{SPLpeak}}$	0.02	0.02	0.02	0.001
	$\text{AUD INJ}_{\text{SEL}}$	0.02	0.02	0.02	0.001
	$\text{AUD INJ}_{\text{SPLpeak}}$	0.02	0.02	0.02	0.001

Fish with a swim bladder

The effects of rock breaking sound emission for fish are likely to occur at relatively small ranges of 640 m, 200 m and 1.16 km for behavioural response, recoverable injury and temporary threshold shift, respectively (Figure 4.14, Table 4.8). The impact with the largest predicted range is the temporary threshold shift.

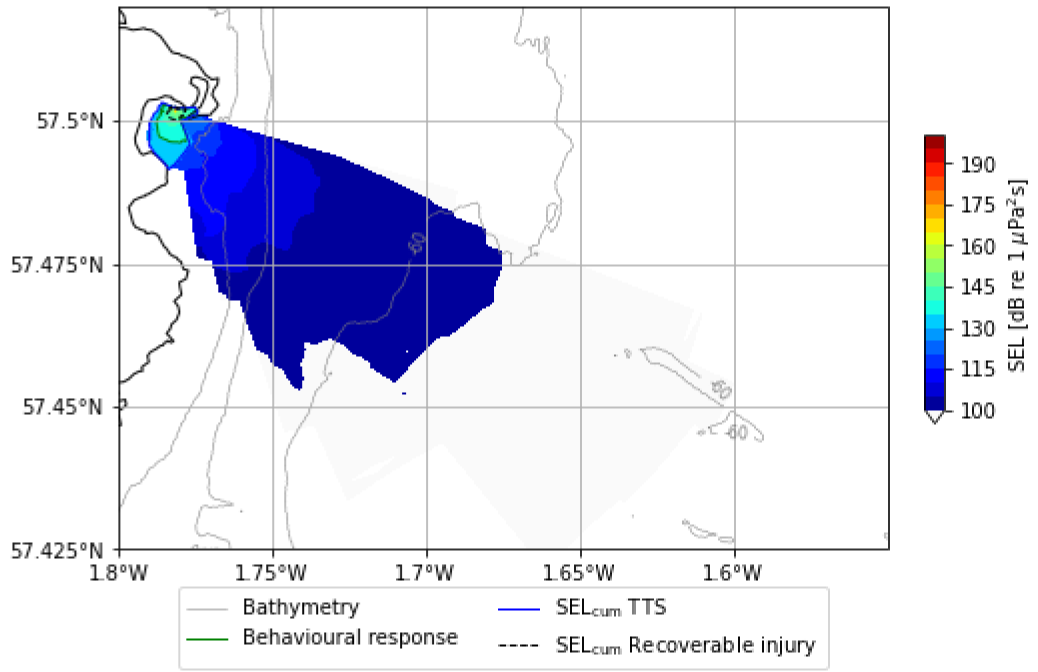

Figure 4.14 SEL levels and impact ranges predicted for fish with a swim bladder during rock breaking at the Peterhead harbour

Table 4.8 Impact ranges and areas predicted for fish with a swim bladder during rock breaking works at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R_{min}	R_{mean}	R_{max}	
Fish with a swim bladder	Behavioural	0.04	0.278	0.64	0.37
	Recoverable Injury	0.04	0.128	0.2	0.06
	TTS_{SEL}	0.04	0.372	1.16	0.75

4.3 Dredging

LF cetaceans

Emission of continuous sound from dredging is expected to result in behavioural response of LF cetaceans at a maximum distance of approximately 1.5 km from the sound source (Table 4.9, Figure 4.15). The effect of temporary threshold shift is predicted to be of smaller range compared to the behavioural response. Of all the considered effects of dredging sounds on LF cetaceans, auditory injury is expected to reach the smallest range of approximately 240 m from the sound source (Table 4.9, Figure 4.16).

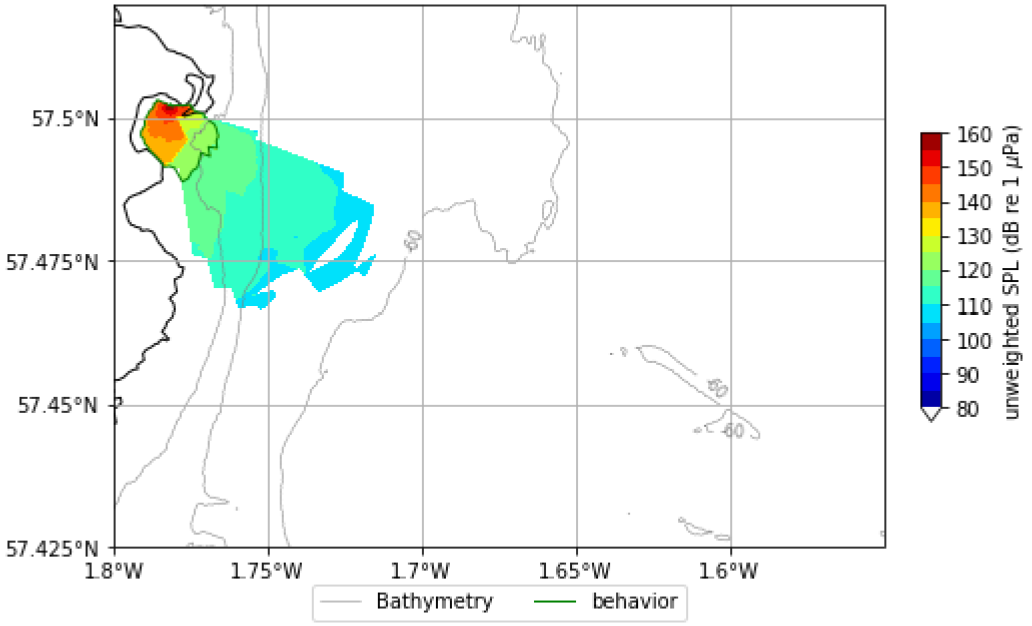

Figure 4.15 **Unweighted SPL levels and impact ranges predicted for LF cetaceans during dredging at the Peterhead harbour**

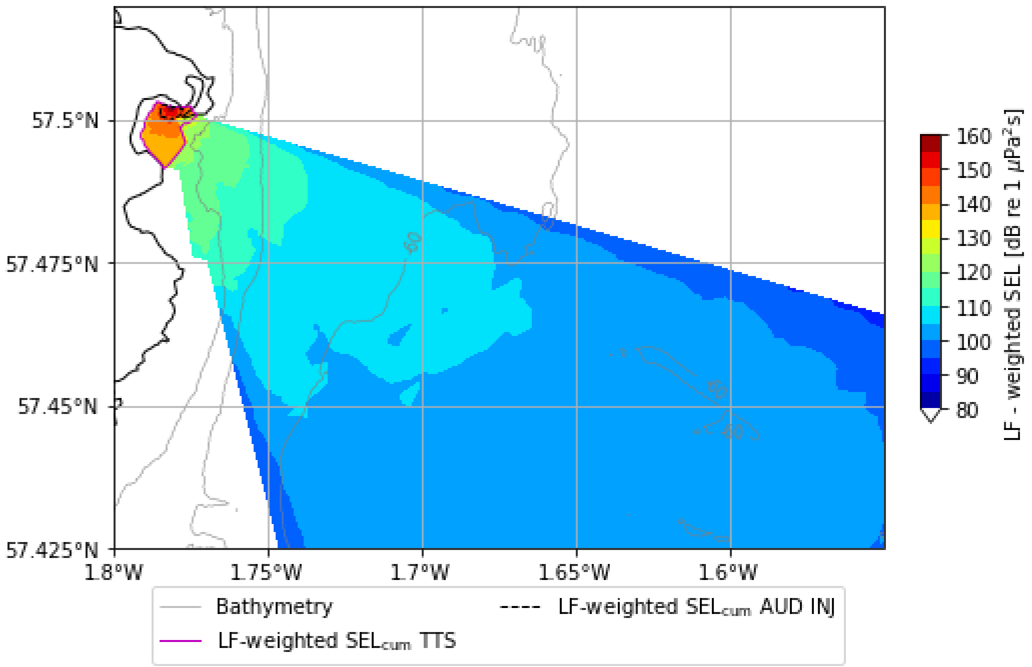

Figure 4.16 LF-weighted SEL levels and impact ranges predicted for LF cetaceans during dredging at the Peterhead harbour

Table 4.9 Impact ranges and areas predicted for LF cetaceans during dredging works at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R_{min}	R_{mean}	R_{max}	
Low-Frequency (LF) Cetaceans	Behavioural	0.04	0.52	1.46	1.47
	TTS_{SEL}	0.04	0.396	1.16	0.81
	AUD INJ_{SEL}	0.04	0.153	0.24	0.08

HF cetaceans

Modelling results of behavioural response for HF cetaceans are the same as in the case of LF cetaceans and indicate a maximum impact range of approximately 1.5 km (Table 4.10, Figure 4.17. The impact range of dredging for temporary threshold shift for HF cetaceans is significantly smaller than for LF cetaceans and is predicted to reach only 60 m from the sound source (1.16 km for LF cetaceans). The auditory injury effect range of dredging for HF cetaceans is minor and can reach up to 20 m (Table 4.10, Figure 4.18).

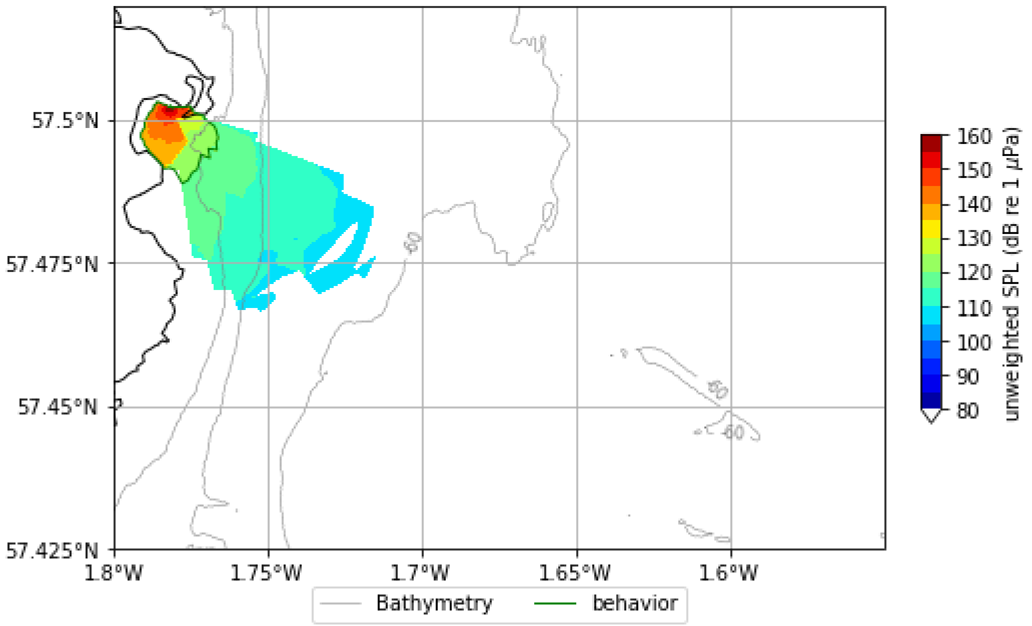

Figure 4.17 Unweighted SPL levels and impact ranges predicted for HF cetaceans during dredging at the Peterhead harbour

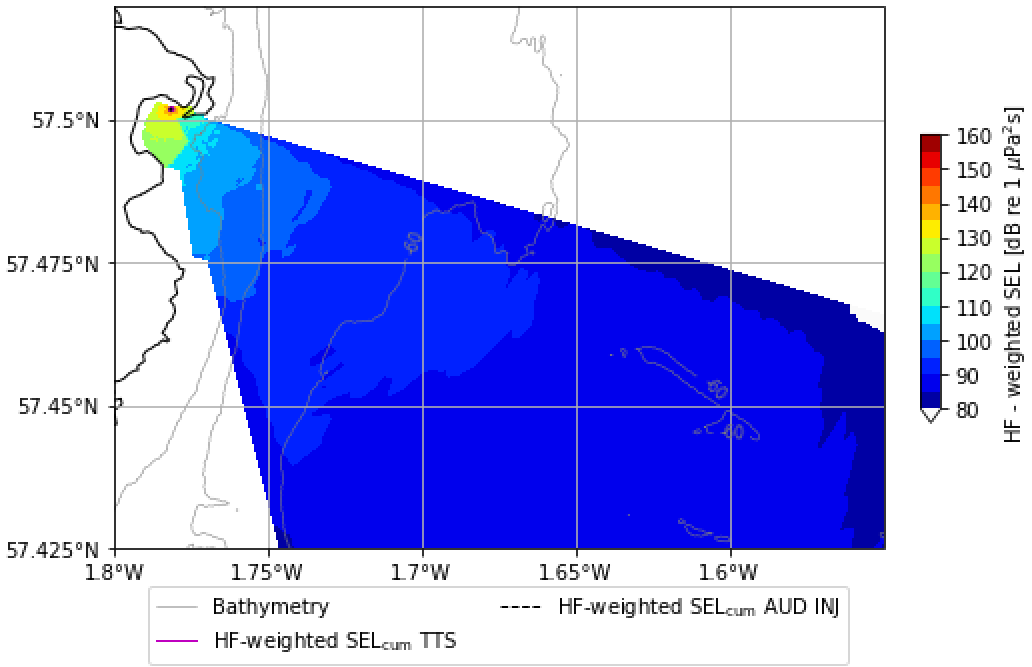

Figure 4.18 HF-weighted SEL levels and impact ranges predicted for HF cetaceans during dredging at the Peterhead harbour

Table 4.10 Impact ranges and areas predicted for HF cetaceans during dredging works at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R$_{min}$	R$_{mean}$	R$_{max}$	
High-Frequency (HF) Cetaceans	Behavioural	0.04	0.52	1.46	1.47
	TTS$_{SEL}$	0.02	0.039	0.06	0.005
	AUD INJ$_{SEL}$	0.02	0.02	0.02	0.001

VHF cetaceans

The behavioural effect of dredging in the case of the VHF cetaceans can reach up to 680 m and is smaller than for LF and HF cetaceans (Table 4.11, Figure 4.19). Temporary threshold shift is expected to reach 340 m and auditory injury can occur at a distance up to only 40 m (Table 4.11, Figure 4.20).

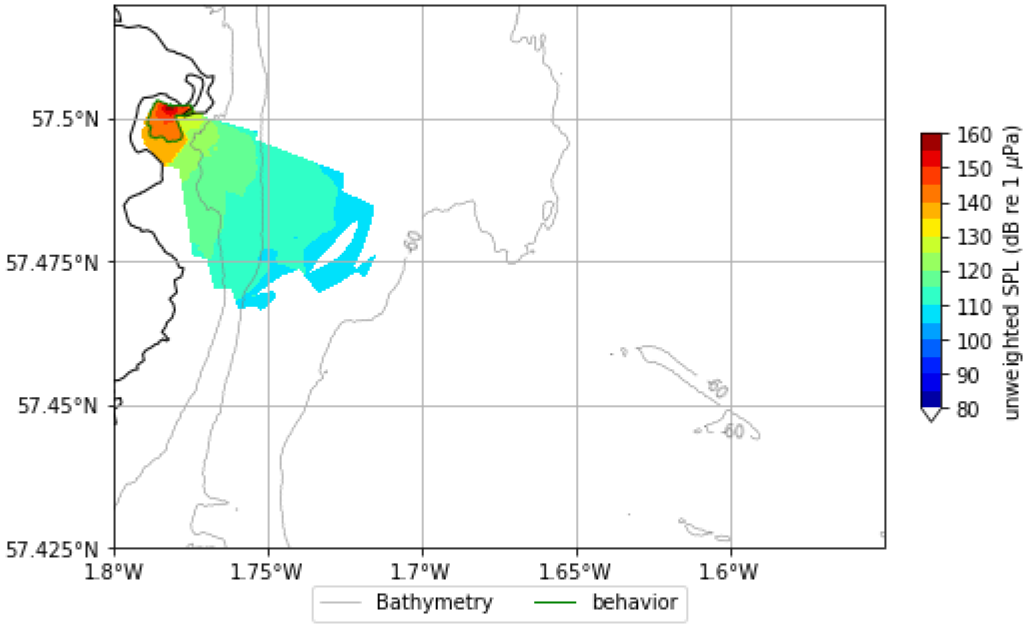

Figure 4.19 Unweighted SPL levels and impact ranges predicted for VHF cetaceans during dredging at the Peterhead harbour

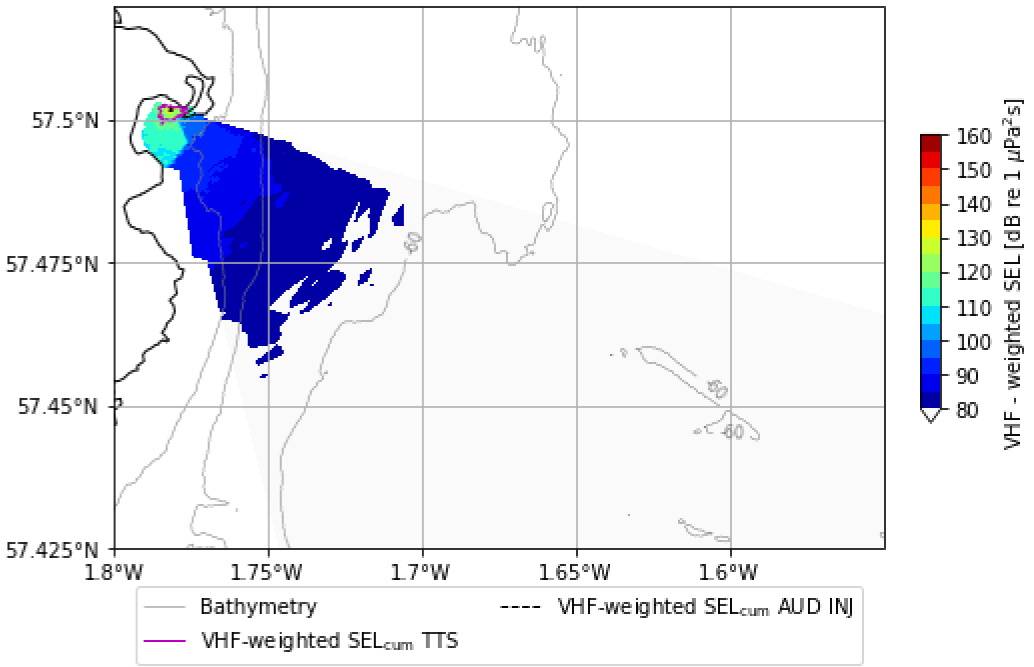

Figure 4.20 VHF-weighted SEL levels and impact ranges predicted for VHF cetaceans during dredging at the Peterhead harbour

Table 4.11 Impact ranges and areas predicted for VHF cetaceans during dredging works at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R_{min}	R_{mean}	R_{max}	
Very High-Frequency (VHF) Cetaceans	Behavioural	0.04	0.303	0.68	0.44
	TTS_{SEL}	0.04	0.168	0.34	0.11
	AUD INJ_{SEL}	0.02	0.021	0.04	0.001

Fish with a swim bladder

The modelling results of dredging sound indicate that recoverable injury can be expected to occur in fish with a swim bladder at a small range of 20 m. In case of the temporary threshold shift, the impact area is slightly larger than for the recoverable injury and can reach up to 40 m (Figure 4.21, Table 4.12).

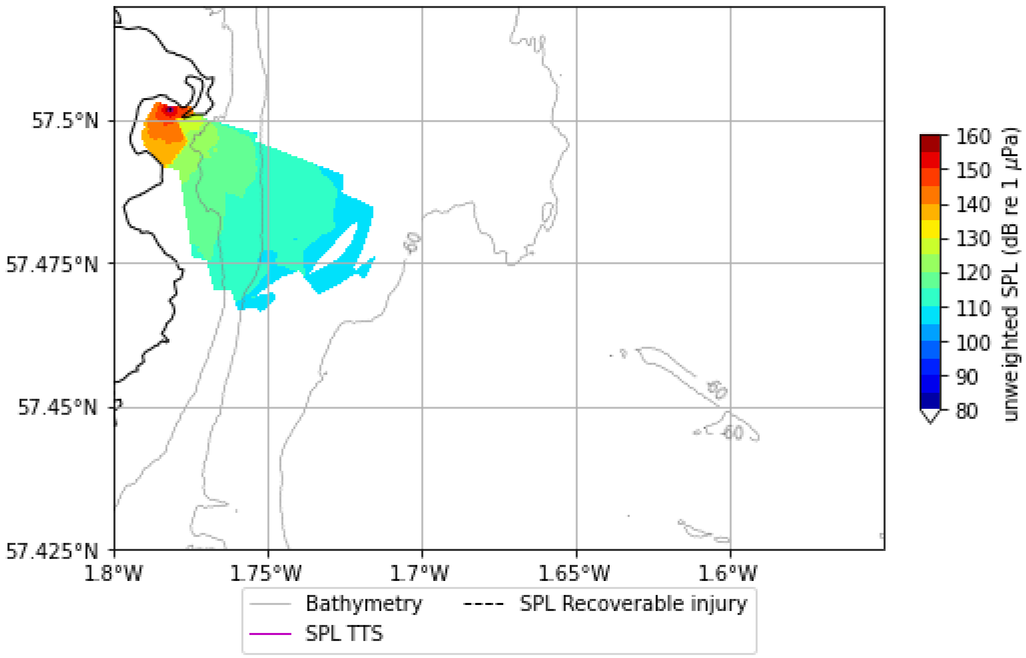

Figure 4.21 Unweighted SPL levels and impact ranges predicted for fish with a swim bladder during dredging at the Peterhead harbour

Table 4.12 Impact ranges and areas predicted for fish with swim bladder during dredging works at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R_{min}	R_{mean}	R_{max}	
	Recoverable Injury	0.02	0.02	0.02	0.001
	TTS_{SPL}	0.02	0.035	0.04	0.004

4.4 Blasting

LF cetaceans

Based on the modelling results, blasting sound can result in a behavioural response in case of LF cetaceans up to the range of approximately 1.2 km (Figure 4.22). The auditory injury and temporary threshold shift are expected to occur at maximum ranges of 80 m and 900 m respectively (Figure 4.23, Table 4.13).

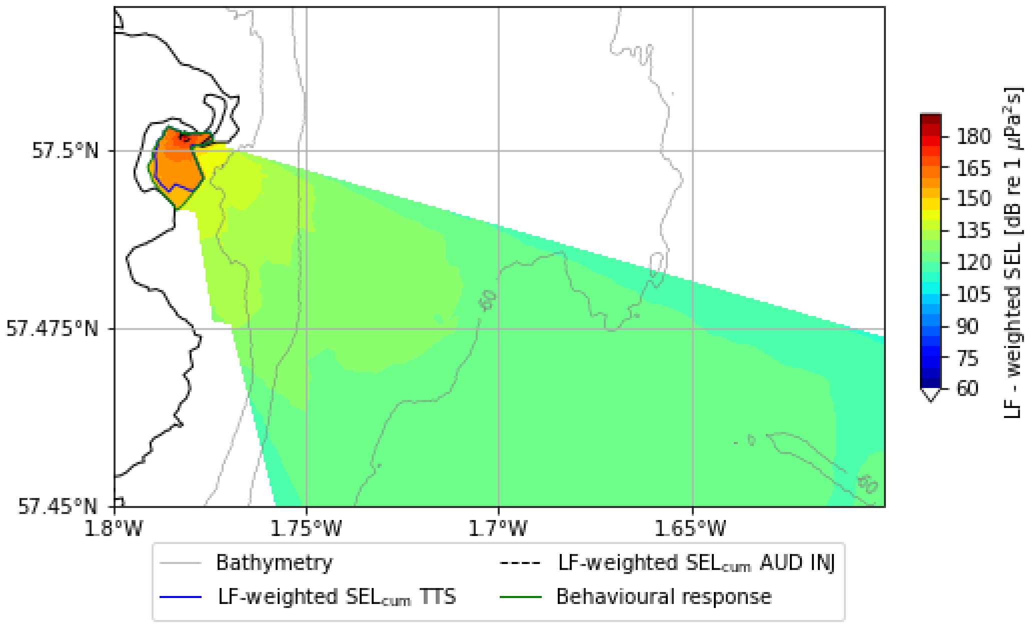

Figure 4.22 LF-weighted SEL levels and impact ranges predicted for LF cetaceans during blasting at the Peterhead harbour

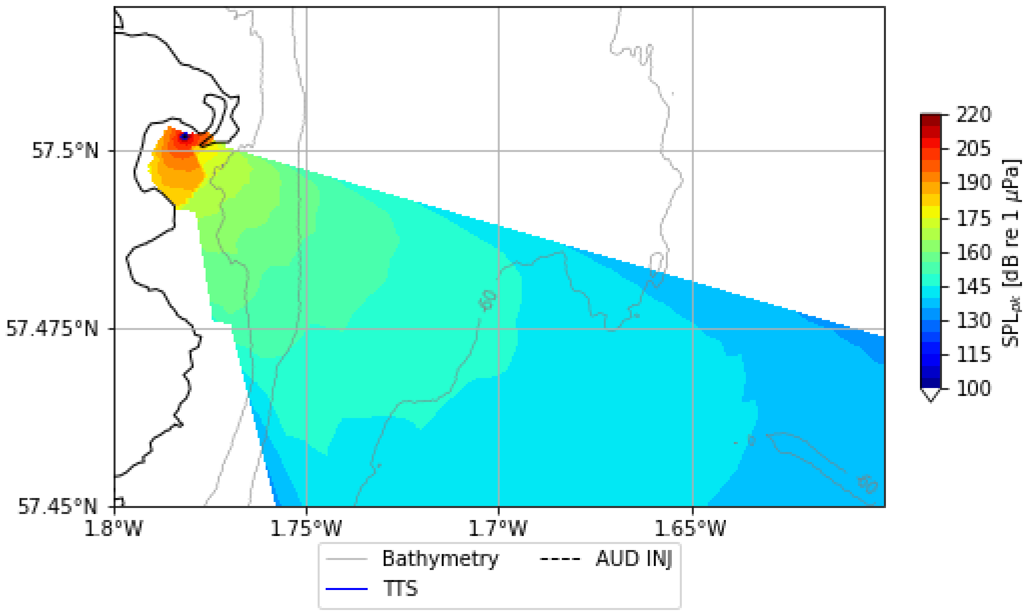

Figure 4.23 SPL$_{peak}$ levels and impact ranges predicted for LF cetaceans during blasting at the Peterhead harbour

Table 4.13 Impact ranges and areas predicted for LF cetaceans during blasting at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R_{min}	R_{mean}	R_{max}	
Low-Frequency (LF) Cetaceans	Behavioural	0.04	0.371	1.16	0.76
	TTS$_{SEL}$	0.04	0.339	0.9	0.597
	TTS$_{SPLpeak}$	0.02	0.039	0.06	0.005
	AUD INJ$_{SEL}$	0.02	0.07	0.08	0.016
	AUD INJ$_{SPLpeak}$	0.02	0.02	0.02	0.001

HF cetaceans

The modelled response ranges of HF cetaceans to blasting sound are expected to be small and confined to less than 200 m from the sound source (Table 4.14). The behavioural response, temporary threshold shift and auditory injury can reach the maximum impact range of 160 m, 80 m and 20 m respectively (Figure 4.24 HF-weighted SEL levels and impact ranges predicted for HF cetaceans during blasting at the Peterhead harbour

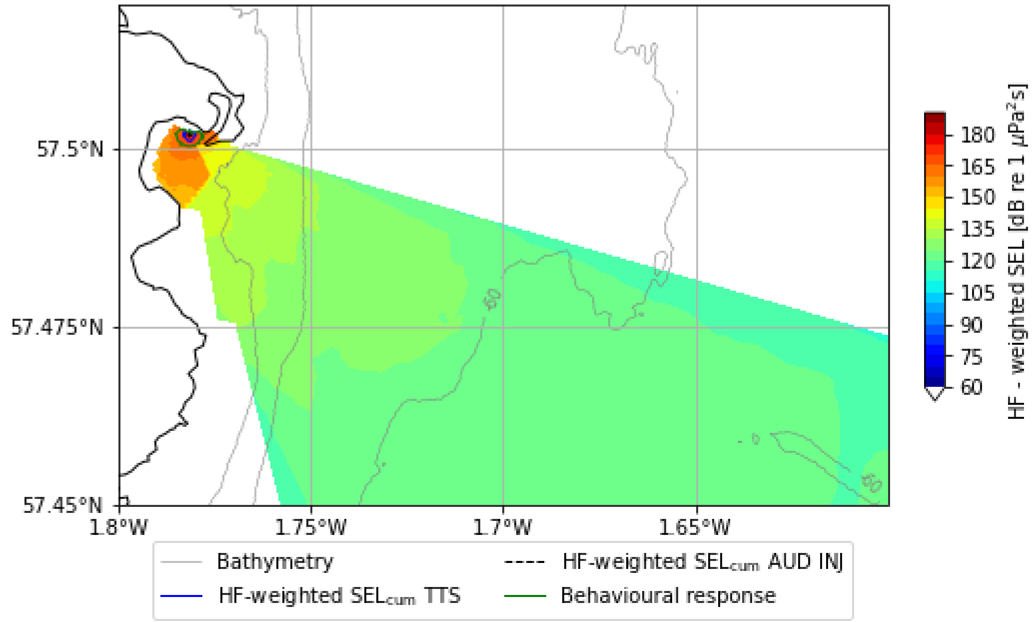

Figure 4.24 HF-weighted SEL levels and impact ranges predicted for HF cetaceans during blasting at the Peterhead harbour

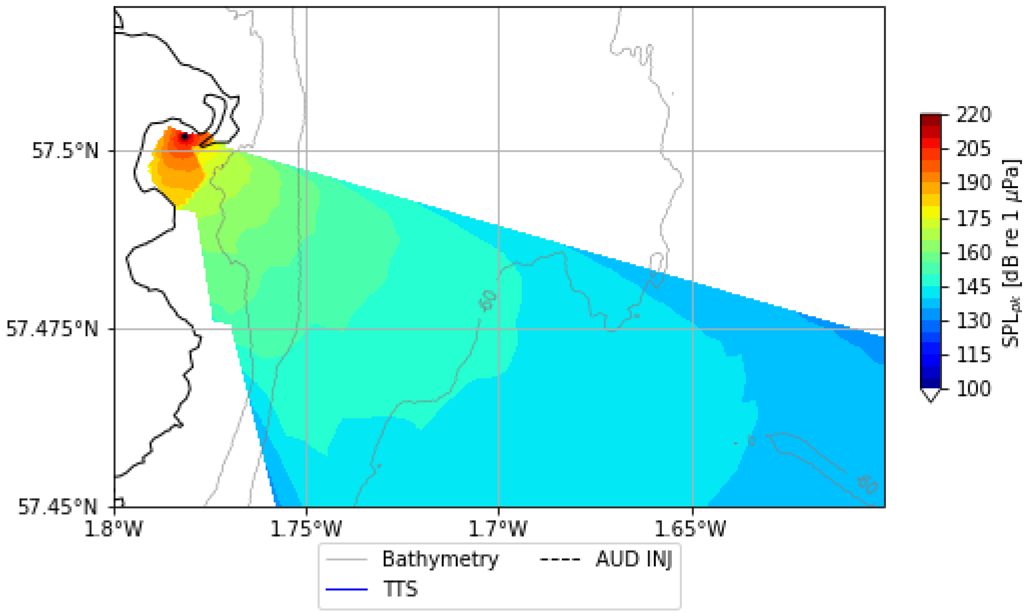

Figure 4.25 SPL$_{peak}$ levels and impact ranges predicted for HF cetaceans during blasting at the Peterhead harbour

Table 4.14 Impact ranges and areas predicted for HF cetaceans during blasting at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R$_{min}$	R$_{mean}$	R$_{max}$	
High-Frequency (HF) Cetaceans	Behavioural	0.04	0.106	0.16	0.04
	TTS$_{SEL}$	0.04	0.063	0.08	0.01
	TTS$_{SPLpeak}$	0.02	0.02	0.02	0.001
	AUD INJ$_{SEL}$	0.02	0.02	0.02	0.001
	AUD INJ$_{SPLpeak}$	0.02	0.02	0.02	0.001

VHF cetaceans

The effects of blasting noise on VHF cetaceans are expected to be mostly confined to the harbour basin area (Figure 4.26, Figure 4.27). The largest impact ranges are predicted for the behavioural response and the temporary threshold shift with ranges of 1.16 km and 1.1 km, accordingly. Auditory injury can occur within the maximum range of 200 m (Table 4.15).

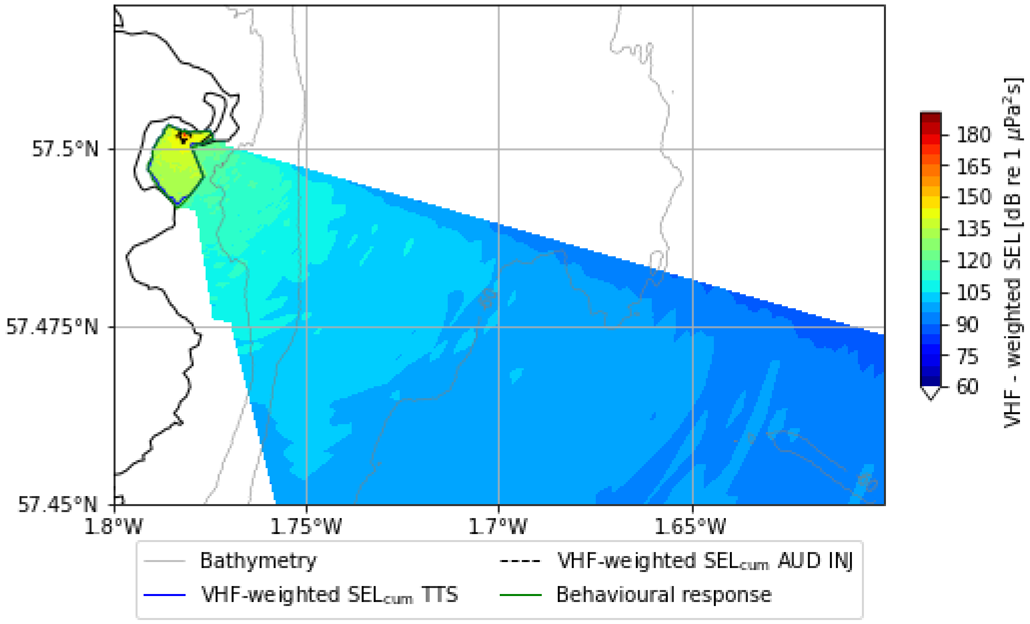

Figure 4.26 VHF-weighted SEL levels and impact ranges predicted for VHF cetaceans during blasting at the Peterhead harbour

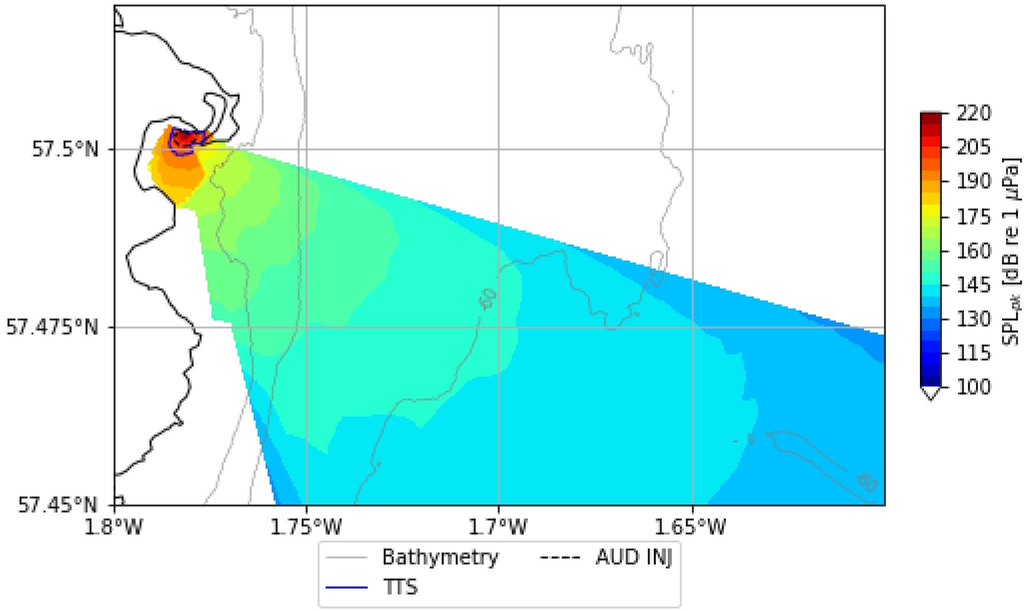

Figure 4.27 SPL_{peak} levels and impact ranges predicted for VHF cetaceans during blasting at the Peterhead harbour

Table 4.15 Impact ranges and areas predicted for VHF cetaceans during blasting at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R_{min}	R_{mean}	R_{max}	
Very High-Frequency (VHF) Cetaceans	Behavioural	0.04	0.373	1.16	0.76
	TTS_{SEL}	0.04	0.364	1.1	0.72
	$TTS_{SPLpeak}$	0.04	0.194	0.34	0.15
	AUD INJ_{SEL}	0.04	0.081	0.16	0.02
	AUD $INJ_{SPLpeak}$	0.04	0.133	0.2	0.06

Fish with swim bladder

The effects of blasting noise on fish are predicted to be confined to a relatively small range (Figure 4.28, Figure 4.29). Physical injury can reach 180 m at maximum, in case of fish weighing less than 2 g based on cumulative sound exposure, and 120 m for all fish based on peak sound pressure level. Mortality can be expected within a range of 20 m (Table 4.16).

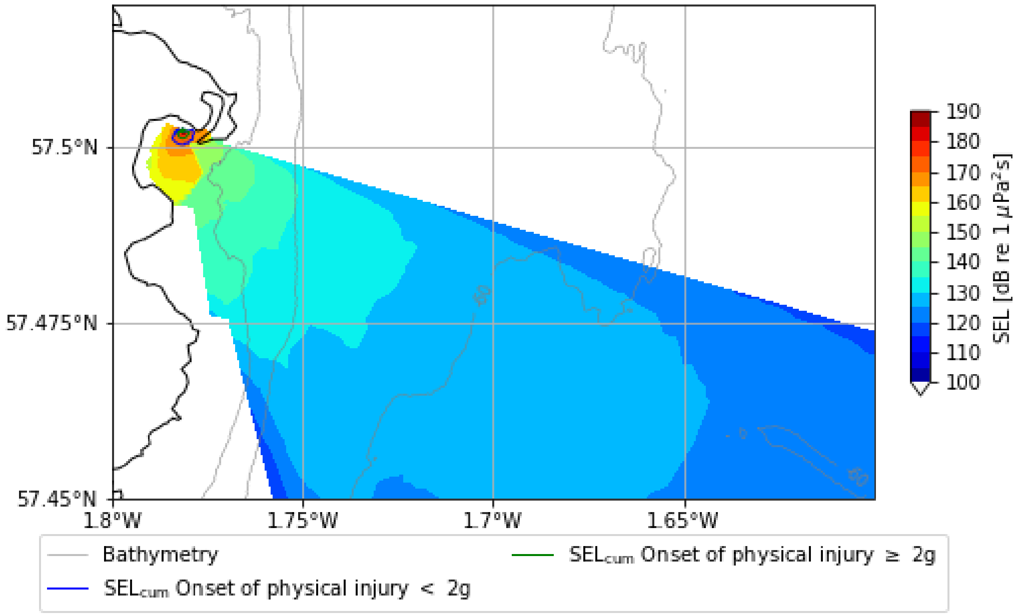

Figure 4.28 SEL levels and impact ranges predicted for fish during blasting at the Peterhead harbour

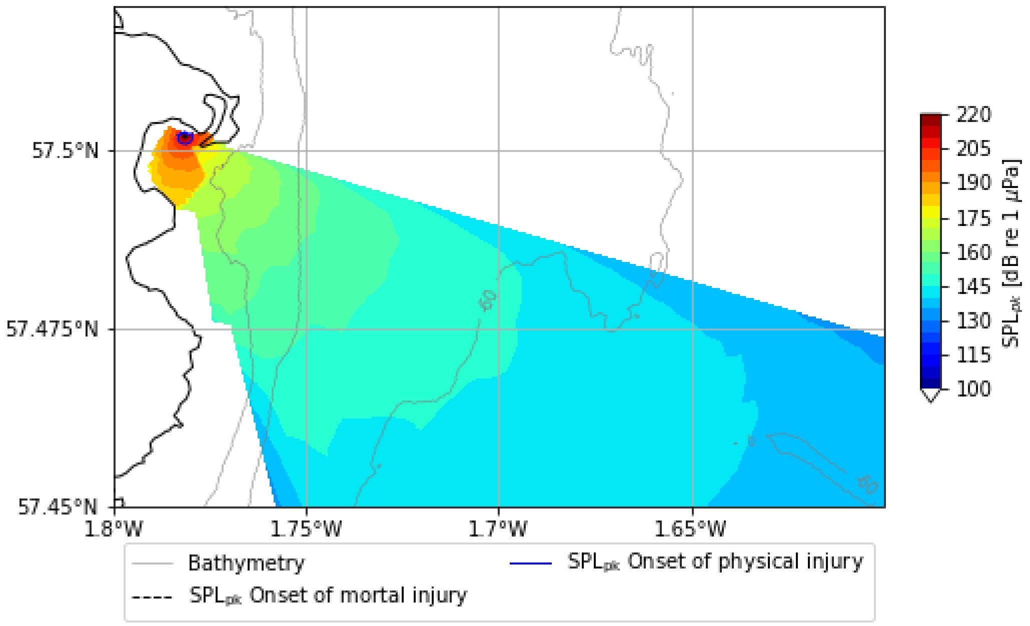

Figure 4.29 SPL$_{peak}$ levels and impact ranges predicted for fish during blasting at the Peterhead harbour

Table 4.16 Impact ranges and areas predicted for fish during blasting at the Peterhead harbour

Species Taxa	Effect	Impact Ranges (km)			Impact Area (km^2)
		R$_{min}$	R$_{mean}$	R$_{max}$	
Fish	Physical injury	0.04	0.095	0.12	0.031
	Physical injury (≥ 2 g)	0.02	0.069	0.1	0.016
	Physical injury (< 2 g)	0.04	0.126	0.18	0.059
	Mortal injury	0.02	0.02	0.02	0.001

5 Summary and Conclusions

This study for Peterhead Smith Quay Extension Noise Modelling, UK involved modelling the noise impacts for three hearing groups of cetaceans (LF, HF, VHF cetaceans) and for fishes with a swim bladder. The analysis included four types of noise expected to occur during construction work for the Peterhead harbour expansion - noise from pile driving, rock breaking, dredging and blasting.

The results show that noise generated by all the construction works in the bay is highly directional, thus limiting the potential impact on marine organisms.

For all marine fauna studied, the maximum impact ranges are estimated to be in the range of a few kilometres from the sound source. Furthermore, most impacts are predicted to occur within the harbour.

In the case of the pile driving noise, the results showed that it could cause auditory injury in LF and HF cetaceans within the harbour. The cumulative TTS impact was predicted for all cetacean groups within the harbour waters and for LF species also outside the bay. This result suggests that LF-cetaceans occurring in waters adjacent to Peterhead may be exposed to hearing impairment during construction activities. However, it should be noted that the model assumes the exposure to noise during the entire duration of one pile installation, which is highly unlikely. In terms of behavioural changes, the largest impact range was identified for the VHF cetaceans extending outside the harbour up to a distance of 4.5 km from the noise source. For the LF and HF species, a behavioural reaction was predicted only within the harbour basin. However, it should be noted that the threshold for behavioural reaction used for LF and HF cetacean groups was not species specific and had a relatively high value. Therefore, the impact ranges could have been underestimated to a certain extent. In fishes, the occurrence of TTS was predicted within the harbour, primarily affecting the noise-sensitive species. Behavioural responses of fishes could occur in the waters outside the harbour, up to a distance of about 3 km from the noise source. Since the behavioural threshold was based on the value given for clupeids, it is assumed that the effective range could be smaller for salmonid species, which are characterised by poorer hearing.

The impact of noise from rock breaking was assessed as negligible or low for all animal groups analysed. For LF cetaceans, auditory injury was predicted to occur within the harbour, while TTS was predicted to spread slightly outside the bay. Considering the modelled 24-hour noise exposure and a small impact area outside the harbour, the results can be considered of a low importance for LF cetaceans. In the case of fishes, the impact ranges identified were within the harbour basin, with the values indicating minor impacts on animals therein.

With regards to dredging, the predicted impact of noise was also negligible or low. In most cases, the estimated impact ranges for hearing damage were negligible. For LF cetaceans, the effect of TTS was predicted only for the harbour basin, which can be considered minor for the cetacean species. The same applies to the behavioural reaction of cetaceans, which were predicted to occur mainly in the harbour waters. It is worth noting that the behavioural reaction of fishes was not modelled due to lack of noise criteria.

Considering blasting, the modelling results did not reveal any serious impacts on the animal groups studied. Most of the predicted impact ranges were negligible. For the VHF species, the effect of TTS was found to be within the bay, which is considered to be of little concern. Similarly to dredging, no behavioural response was modelled for fish species.

In summary, the modelling study carried out did not identify any major impacts of any type of noise generated during the extension works. Based on the results obtained, the noise generated is not expected to significantly affect cetacean species outside Peterhead harbour. In the case of fish, no impact on Atlantic salmon migrating in the waters adjacent to the bay has been identified either. However, it should be pointed out that the conducted modelling does not consider any behavioural responses of fishes to the dredging and blasting noise due to lack of noise criteria. With regards to impacts within the harbour, the predicted impacts have considered scenarios of prolonged (up to 24 hours) noise exposure. It is therefore assumed that the animals of concern might be fish species that inhabit the harbour and are highly sensitive to noise.

6 References

Bellmann, M. A., Brinkmann, J., May, A., Wendt, T., Gerlach, S. & Remmers, P. 2020. Underwater noise during the impulse pile-driving procedure: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values. Supported by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU)), FKZ UM16 881500. Commissioned and managed by the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie (BSH)), Order No. 10036866. itap GmbH.

Collins, M. D. 1993. A split-step Padé solution for the parabolic equation method. *The Journal of the Acoustical Society of America.(93): 1736-1742*.

Dall'Osto, D. R., Dahl, P. H., & Chapman, N. R. (2023). The sound from underwater explosions. *Acoustics Today*. Retrieved February 20, 2025, from: https://acousticstoday.org/the-sound-from-underwater-explosions-david-r-dallosto-peter-h-dahl-and-n-ross-chapman/

DHI, 2023. UAS in MIKE, Underwater Acoustic Simulation Module, Scientific Documentation.

Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P. et al. 2021. The soundscape of the Anthropocene ocean. Science 371, eaba4658.DOI:10.1126/science.aba4658

Elmer, K. H., Betke, K. & Neumann, T. 2007. Standardverfahren zur Ermittlung und Bewertung der Belastung der Meeresumwelt durch Schallimmission von Offshore-Windenergieanlagen : Abschlussbericht zum BMU-Forschungsvorhaben 0329947.

European Commission. 2025. European Marine Observation and Data Network (EMODnet).

FHWG (Fisheries Hydroacoustic Working Group). 2008. Agreement in principle for interim criteria for injury to fish from pile driving activities. https://dot.ca.gov/-/media/dot-media/programs/environmental-analysis/documents/ser/bio-fhwg-criteria-agree-a11y.pdf

Finneran, J. J. 2015. Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. *The Journal of the Acoustical Society of America*, **138**, 1702-1726.

Francois, R. E. and G. R. Garrison 1982a. Sound absorption based on ocean measurements. Part I : Pure water and magnesium sulphate contributions. *Journal of the Acoustical Society of America,* **72**: 896-907.

Francois, R. E. and G. R. Garrison, 1982b. Sound absorption based on ocean measurements. Part II: Boric acid contribution and equation for total absorption. *Journal of the Acoustical Society of America,* **72**: 1879-1890.

Fofonoff, N. & Millard, R. 1983. Algorithms for Computation of Fundamental Properties of Seawater. *UNESCO Tech. Pap. Mar. Sci.*, **44**.

Gill, A. B., Bartlett, M. & Thomsen, F. 2012. Potential interactions between diadromous fishes of U.K. conservation importance and the electromagnetic fields and subsea noise from marine renewable energy developments. *Journal of Fish Biology*, **81**, 664-695.

Guan, S., Brookens, T. & Miner, R. 2022. Acoustic characteristics from an in-water down-the-hole pile drilling activity. *The Journal of the Acoustical Society of America*, **151**, 310-320.

Hawkins, A. D., Roberts, L. & Cheesman, S. 2014. Responses of free-living coastal pelagic fish to impulsive sounds. *J Acoust Soc Am*, **135**, 3101-3116.

Jimenez-Arranz, G., Banda, N., Cook, S. & Wyatt, R. 2020. Review on Existing Data on Underwater Sounds from Pile Driving Activities. Seiche Ltd.

Kastelein, R. A., Bunskoek, P., Hagedoorn, M., Au, W. W. L. 2002. Audiogram of a harbor porpoise (Phocoena phocoena) measured with narrow-band frequency modulated signals. *J. Acoust. Soc. Am. , 334-344.*

Ke, B., Zhou, K., Xu, C., Ren, G. & Jiang, T. 2019. Thermodynamic properties and explosion energy analysis of carbon dioxide blasting systems. *Mining Technology*, **128**, 39-50.

Locarnini, R. A., Mishonov, A. V., Baranova, O. K., Reagan, J. R., Boyer, T. P., Seidov, D., Wang, Z., Garcia, H. E., Bouchard, C., Cross, S. L., Paver, C. R. & Dukhovskoy, D. 2024. World Ocean Atlas 2023, Volume 1: Temperature.

NMFS. 2018. Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts." Technical Memorandum (No. NMFS-OPR-59): 167.

NMFS. 2024. Update to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 3.0). U.S. Dept. of Commer., NOAA, Silver Spring, MD.

NMFS. 2024b. Summary of Marine Mammal Protection Act Acoustic Thresholds. Retrieved on February 13, 2025 from: https://www.fisheries.noaa.gov/s3/2024-10/MM-Acoustic-Thresholds-OCT2024-508-secure-OPR1.pdf

NMFS. 2024c. Summary of Endangered Species Act Acoustic Thresholds (Fishes and Sea Turtles). Retrieved on February 12, 2025 from: https://www.fisheries.noaa.gov/s3/2024-10/ESA-AllSpeciesThresholdSummary-2024-508-OPR1.pdf

Popper, A.N, Hawkins, A. D. 2019. An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes. J Fish Biol. 94: 692–713. https://doi.org/10.1111/jfb.13948

Popper, A. N., Hawkins, A. D., Fay, R. R., Mann, D., Bartol, S., Carlson, T., Coombs, S., Ellison, W. T., Gentry, R., Halvorsen, M. B., Lokkeborg, S., Rogers, P., Southall, B. L., Zeddies, D. G. & Tavolga, W. N. 2014. *ASA S3/SC1.4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI*: Springer International Publishing.

Reagan, J. R., Seidov, D., Wang, Z., Dukhovskoy, D., Boyer, T. P., Locarnini, R. A., Baranova, O. K., Mishonov, A. V., Garcia, H. E., Bouchard, C., Cross, S. L. & Paver, C. R. 2024. World Ocean Atlas 2023, Volume 2: Salinity.

Reine, K. J., Clarke, D. G. & Dickerson, C. 2012. Characterization of Underwater Sounds Produced by a Backhoe Dredge Excavating Rock and Gravel - DOER Technical Notes Collection - ERDC TN-DOER-E36. Vicksburg, Mississippi, USA http://el.erdc.usace.army.mil/elpubs/pdf/doere36.pdf: US Army Engineer Research and Development Center

Remmers, P. & Bellmann, M. A. 2022. Messung der Hydroschallimmissionen beim Neubau LNG-Terminal am Bestandsbauwerk der UVG Brücke (Anleger 1) in Wilhelmshaven. itap GmbH.

Singh, S. P. 1998. Non-explosive applications of the PCF concept for underground excavation. *Tunnelling and Underground Space Technology*, **13**, 305-311.

Skjellerup, P., Maxon, C. M., Tarpgaard, E., Thomsen, F., Schack, H. B., Tougaard, J., Teilmann, J., Madsen, K. N., Mikaelsen, M. A. & Heilskov, N. F. 2015. Marine mammals and underwater noise in relation to pile driving – Working Group 2014. pp. 1-20: Energinet.dk.

Soloway, A. G. & Dahl, P. H. 2014. Peak sound pressure and sound exposure level from underwater explosions in shallow water. *The Journal of the Acoustical Society of America*, **136 3**, EL218.

Southall, B. L., Finneran, J. J., Reichmuth, C., Nachtigall, P. E., Ketten, D. R., Bowles, A. E., Ellison, W. T., Nowacek, D. P. & Tyack, P. L. 2019. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Effects *Aquatic Mammals*, **45**, 125-232.

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene, J. C. R., Kastak, D., Ketten, D. R., Miller, J. H., Nachtigall, P. E., Richardson, W. J., Thomas, J. A. & Tyack, P. 2007. Marine mammal noise exposure criteria: initial scientific recommendations. *Aquatic Mammals(33): 411-521*.

Thomsen, F., Mendes, S., Bertucci, F., Breitzke, M., C. E., Cresci, A., . . . dos Santos, M. E. 2021. Addressing underwater noise in Europe: Current state of knowledge and future priorities. *Future Science Brief 7 of the European Marine Board (Ed. by P. Kellett, R. van den Brand, B. Alexander, A. Muniz Piniella, A. Rodriguez Perez, J. van Elslander & J.*

Thomsen, F., Lüdemann, K., Kafemann, R., Werner, P., Thomsen, F., Lüdemann, K., Kafemann, R. & Werner, P. 2006. Effects of offshore wind farm noise on marine mammals and fishes, biola, Hamburg, Germany on behalf of COWRIE Ltd. Newbury, UK.

Tougaard, J. 2021. Thresholds for behavioural responses to noise in marine mammals. Background note to revision of guidelines from the Danish Energy. Aarhus University, DCE – Danish Centre for Environment and Energy.

UK Hydrographic Office. 2025. ADMIRALITY Marine Data Portal.

Urick, R. J. 1983. Principles of Underwater Sound: McGraw-Hill.

Urick, R. J. 1971. Handy Curves for Finding the Source Level of an Explosive Charge Fired at a Depth in the Sea. *The Journal of the Acoustical Society of America*, **49**, 935-936.

von Pein, J., Ram, M. & Thomsen, F. 2024. SCALING OFFSHORE PILE DRIVING NOISE: APPLICATION TO FREQUENCY WEIGHTED SOUND LEVELS. In: *ICUA 2024*. Bath, UK.

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

von Pein, J., Lippert, S. & von Estorff, O. 2021. Validation of a finite element modelling approach for mitigated and unmitigated pile driving noise prognosis. *The Journal of the Acoustical Society of America*, **149**.

Appendix A Noise modelling

Appendix A.1 Noise propagation modelling

Appendix A.1.1 Underwater acoustic simulator

The numerical noise modelling was performed using a parabolic equation and the in-house MIKE by DHI Underwater Acoustic Simulator (DHI 2023)

The model focuses on noise propagation in the far field. UAS uses the RAM code based on the sound propagation model developed by (Collins 1993). The detailed description of the underwater acoustic model, including the scientific bases and the assumptions of the model, is included in the technical documentation for UAS in MIKE (DHI 2023).

- Changes in sound speed and volume attenuation in the water column.
- Sound propagation in the seabed.
- Sound spectra at 1/3 octave bands with 20 Hz to 4 kHz centre frequencies. Higher frequencies of up to 20 kHz were based on the model results at 4 kHz but corrected in accordance with frequency dependant attenuation.

Sound propagation was calculated at discrete angular directions of the selected source location at 72 individual transects extending up to 150 km from the source. Previous investigations and literature data on the assumed sound spread from pile driving (Thomsen *et al.* 2006) indicate that sound impacts are negligible after this distance. Spatial maps were then derived by integrating the results across all transects.

Simulations were carried out considering the following simplified conditions and specific assumptions:

- The sea surface is treated as a simple, horizontal, perfectly reflecting boundary ignoring the sea states, where in addition to waves, the upper ocean will have an infusion of air bubbles which has a significant impact on the speed of sound in the surface part of the water column.
- The code is a 2D model ignoring 3D effects due to the horizontal refraction of sound rays reflected by a sloped sea bottom. E.g., when the sea floor is shoaling, as is the case for the ocean over a sloping beach and the continental slope, and around seamounts and islands, a ray travelling obliquely across the slope experiences the phenomenon of horizontal refraction.
- The impact of a hammer on a pile produces a sound source that moves down the pile and is partly reflected upwards by both the sea bottom and the end of the pile. In the present study, the noise source is modelled by a single point source at a depth of 5 m.
- Near-field effects are neglected in the present study, which is judged to have a minor effect on the far-field sound pressure level. At impact ranges of interest (e.g., > 100 m), the sound intensity effects and oblique radiated sound waves dominating the near field are diluted significantly.

Other assumptions and simplifications regarding the input data and impact assessment are described in the subsequent sections.

Sound source properties were fed into the propagation model to calculate the sound propagation in angular directions from the location of piling at 72 transects in 2D. Specific 1/3 octave bands with centre frequencies from 20 Hz to 4 kHz were modelled. For higher frequencies, the propagation losses at 4 kHz were applied in combination with a correction for the increasing volume attenuation with increasing frequency (Francois and Garrison, 1982a; 1982b). Based on the numerical model results, maps were developed presenting the sound exposure level as the function of distance from the sound source.

Appendix A.1.2 Sound speed profile

Sound propagation in seawater is influenced by several factors, including temperature, pressure, salinity, density and, to a lesser extent, acidity (pH value). Therefore, information on those properties is important for the model setup.

Data for pH was obtained from the World Ocean Database (WOD). The World Ocean Atlas (WOA) 2023 was selected for the analysis of temperature (Locarnini *et al.* 2024) and salinity (Reagan *et al.* 2024). The temperature and salinity data were converted into a sound velocity profile with a use of the UNESCO equation (Fofonoff and Millard 1983).

Pile driving, which is expected to be the most impactful activity is scheduled to take place during either two 17-week periods starting in spring and summer or one single 34-week period starting in spring. This means that in both cases the activities will extend well into autumn. Hence, three different sound speed profiles were derived, one each for spring, summer and autumn, these are shown in Figure A.1, Figure A.2 and Figure A.3. As only one season was modelled, the sound speed profile which favours the most effective sound propagation was selected from these three and as such the autumn sound speed profile was chosen.

The vertical sound speed profiles for spring and summer are shaped very similar with both profiles mainly having a negative gradient, i.e. sound speed decreases more or less monotonically as depth increases. This shape will result in refraction of sound waves towards the areas of lower sound speed – towards the seabed. Interaction with the seabed is however generally lossy and will result in additional attenuation.

In contrast to this, the autumn sound speed profile possesses an almost constant sound speed over the entire considered depth, meaning that no strong refraction effect will occur, resulting in less attenuation. Of the investigated profiles, the autumn sound speed profile thus constitutes a worst case scenario in terms of expected noise impacts.

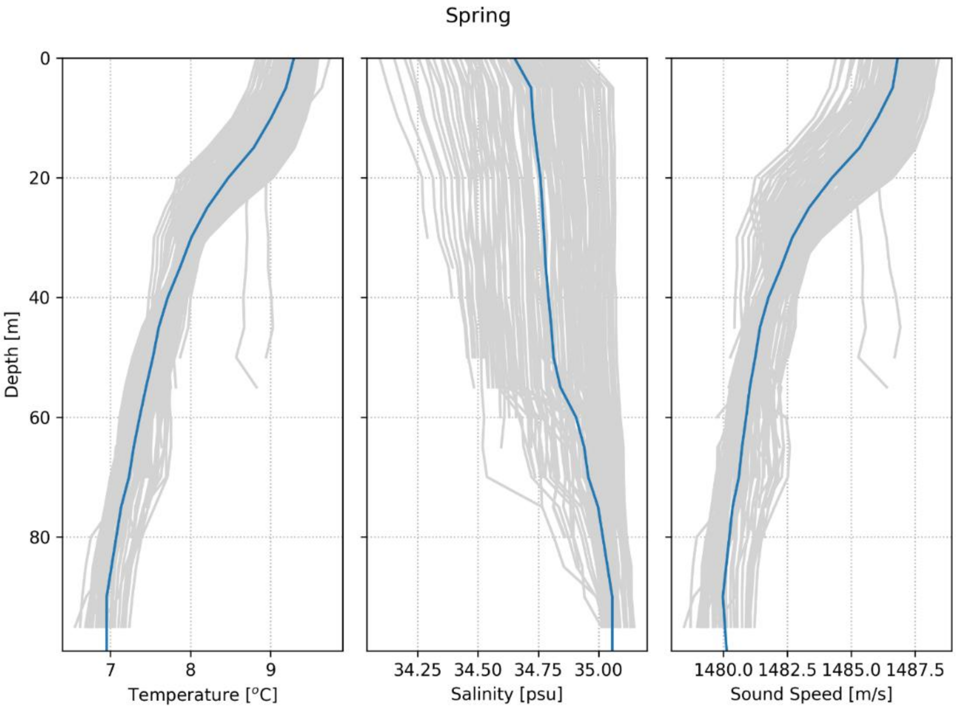

Figure A.1 Temperature, salinity and sound speed profile for the spring season

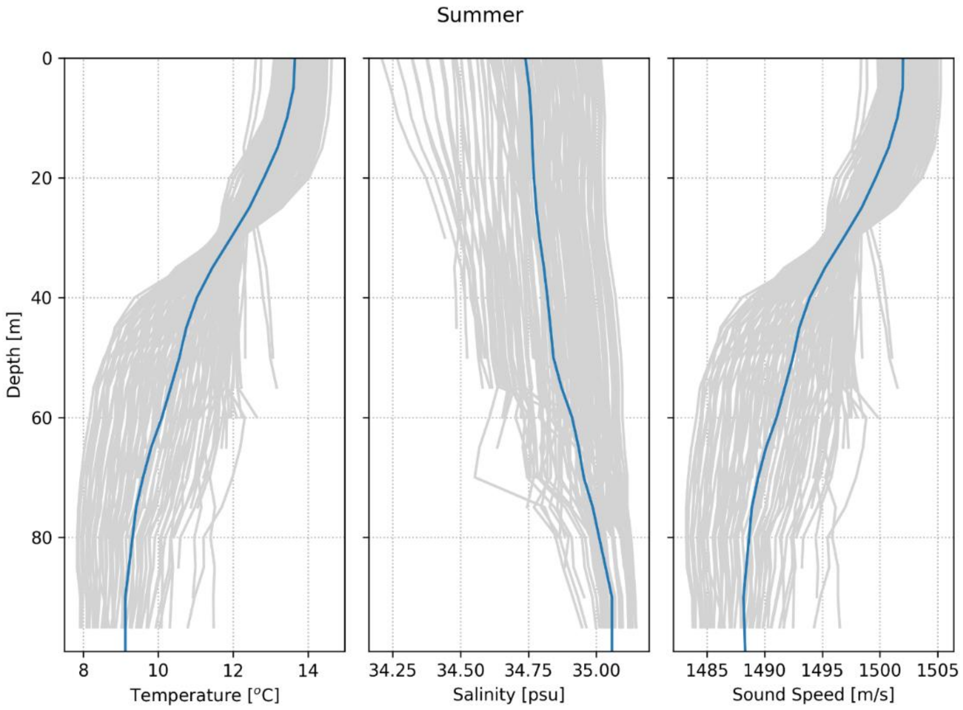

Figure A.2 Temperature, salinity and sound speed profile for the summer season

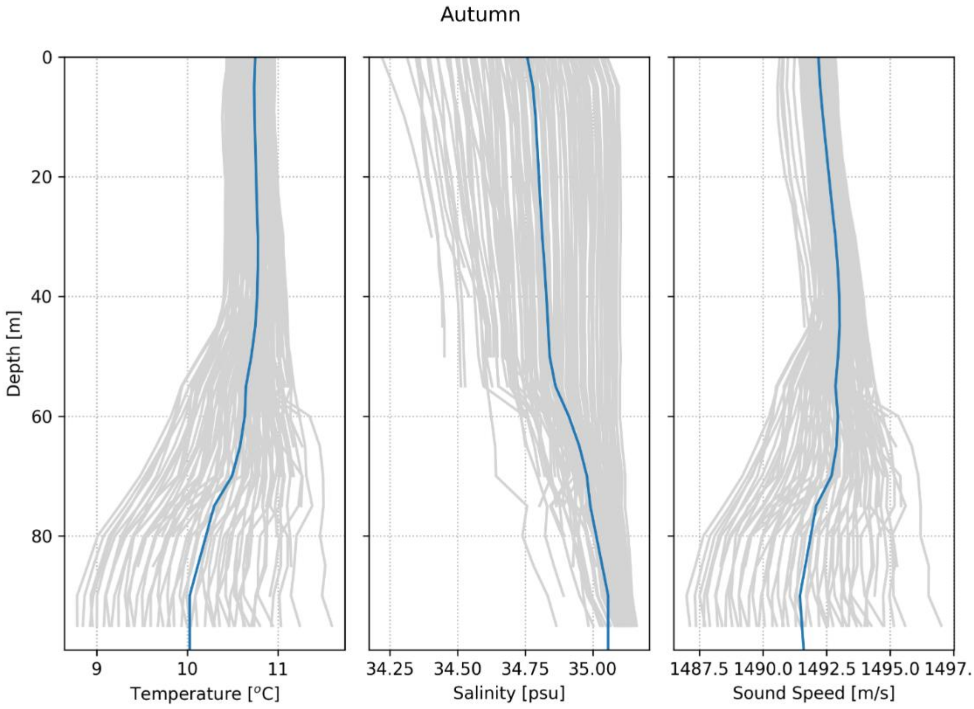

Figure A.3 Temperature, salinity and sound speed profile for the autumn season which was used for propagation modelling

Appendix A.1.3 Geo-acoustic profile

The seabed profile was based derived based on numerous borehole sections taken in the construction area which were supplied by the client as well as publicly available data of the seabed composition outside the harbour basin. The summary of the seabed profile and geo-acoustic properties of the layers for Peterhead harbour is presented in Figure A.4.

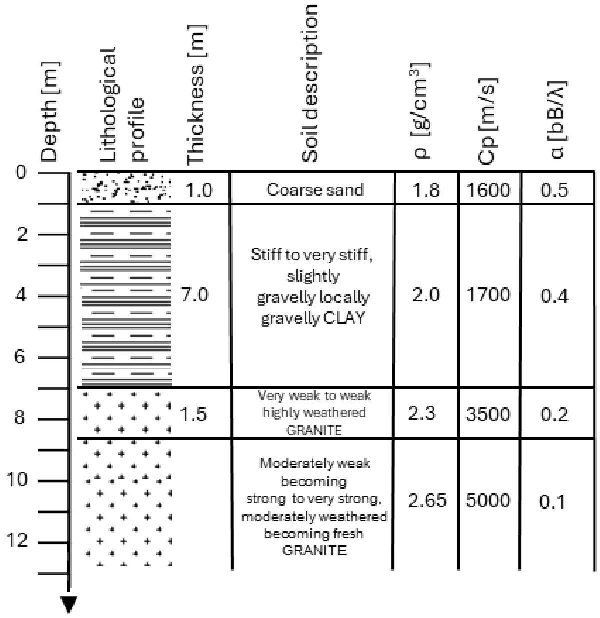

Figure A.4 The considered geo-acoustic profile for the Peterhead harbour

Appendix A.1.4 Insertion loss due to breakwater structures

The breakwaters are massive structures which can be considered as soundproof i.e. sound waves in the water will not be transmitted and transmission may only occur through the seabed or by horizontal refraction around them. From an acoustics point of view, the effect will be similar to the application of a close-range mitigation system such as IQIP-NMS. These systems have been shown to effectively fully absorb sound waves in the water column in the same manner as the breakwaters would (von Pein *et al.* 2021). The measured broadband insertion losses reported by (von Pein *et al.* 2021) are in the range of 12.5 dB to 14.5 dB. Similarly, (Bellmann *et al.* 2020) report a mean insertion loss of 15 dB and show a relatively uniform reduction over the entire frequency range which tends to even higher reductions at high frequencies.

Considering the above studies, a uniform insertion loss of **14 dB** due to the breakwater structures is assumed. It should be noted that due to the greater distance of the breakwaters to the source location the actual reduction might be even greater, as the transmission path through the seabed becomes less relevant with increasing range. Thus, the assumed insertion loss can be viewed as a conservative estimate.

Appendix B Acoustical Terminology

The underwater acoustic signal produced by an acoustical source is propagating to the receiver (e.g. marine mammals and fish) and is thereby attenuated because of geometric spreading, sound absorption, scattering, reflection and refraction. All of these propagation effects are highly frequency dependent with different mechanisms dominating different frequency ranges. Therefore, the propagation effects are site-specific, which is accounted for with the considered environmental parameters in the noise propagation modelling.

A very important differentiation in acoustics is the impulsiveness of the emitted noise. Therefore, different thresholds have been developed for impulsive and continuous noise. Typical examples for impulsive noise are pile driving or noise from the application of explosives. Vessel or operational noise are usually referred to as continuous.

In the following the acoustical terminology used in this study is described.

Appendix B.1 Sound levels of impulsive noise

Impulsive sound in the time domain is usually defined by a sharp increase in the acoustical pressure and a decay afterwards. A typical pile driving noise signal of unmitigated pile driving is displayed in Figure B.1. Therein, the part of the acoustical signal dominating the sound exposure level (SEL) is highlighted in red. The SEL is a measure for the acoustical energy of the signal. The SEL can be combined with the time duration of the red signal to derive the root mean squared sound pressure level often referred to as SPL_{rms}, SPL rms and in this report as SPL. The absolute maximum amplitude of the time signal defines the peak sound pressure level SPL_{peak}. The distribution of the acoustical energy can also be evaluated in one-third octave bands which is shown in the right plot. This allows the application of weighting functions and the combination with the frequency dependent propagation effects. Adding up the weighted and propagated SEL of all bands leads to the received SEL.

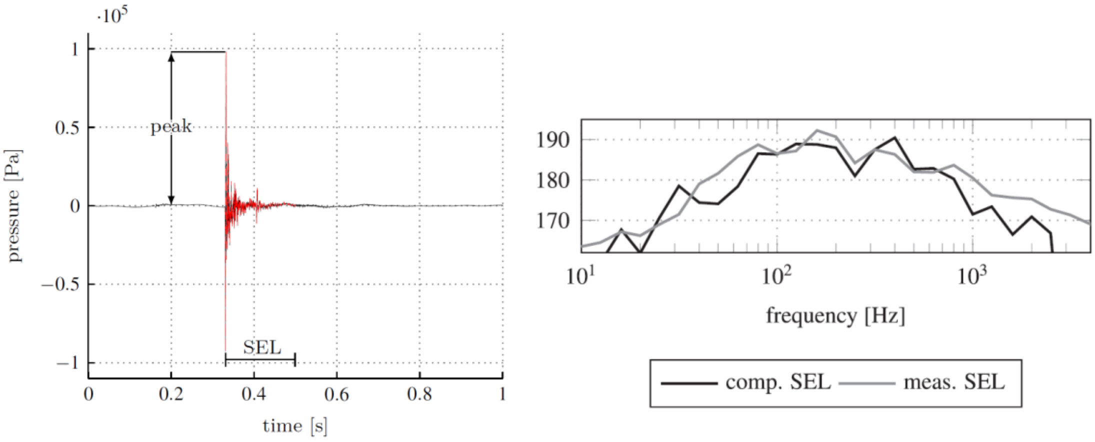

Figure B.1 Examples of the time domain pressure signal of a pile driving event (left side) and a representation of the SEL in the one-third octave band spectrum.

The SEL is defined with the sound exposure Ep, and the reference value E_{p0}=1 µPa^2 s over the whole duration of the impulsive event by:

$$\mathrm{SEL} = 10\log_{10}\left(\frac{E_p}{E_{p0}}\right) = 10\log_{10}\left(\int_{t_{\mathrm{start}}}^{t_{\mathrm{end}}} \frac{p^2(t)}{E_{p0}}\mathrm{d}t\right) \quad \text{with} \quad E_{p0} = 1\ \mu\mathrm{Pa}^2\mathrm{s} \qquad \text{Eq. B.1}$$

The SPL also considers the time duration $T_0 = t_{\mathrm{start}} - t_{end}$ of the signal duration by:

$$\mathrm{SPL_{rms}} \;=\; 10\log_{10}\left(\int_{t_{\mathrm{start}}}^{t_{\mathrm{end}}} \frac{p^2(t)}{T_0 p_0}\mathrm{d}t\right) \quad \text{with} \quad p_0 = 1\ \mu\mathrm{Pa} \qquad \textbf{Eq. B.2}$$

A special case is the SPL with a pre-defined time such as the $\mathrm{SPL}_{125\mathrm{ms}}$ which is derived with T_0=0.125 s.

The weighted SEL and SPL are derived by adding the weighting function *W(f)* to the spectral representation of the SEL by

$$\mathrm{SEL_{weighted}} = 10\log_{10}\left(\sum_f 10^{0.1\,\mathrm{SEL}(f) + 0.1\,W(f)}\right) \qquad \textbf{Eq. B.3}$$

and the SPL

$$\mathrm{SPL_{weighted}} = 10\log_{10}\left(\sum_f 10^{0.1\,\mathrm{SPL}\,(f) + 0.1\,W(f)}\right) \qquad \textbf{Eq. B.4}$$

The transmission loss is a measure of the accumulated decrease in acoustic intensity as the sound pressure wave propagates outwards from a source, hence the loss during the transmission from the source to the receiver. The influence of the sound propagation is usually described in terms of the transmission loss (TL) per 1/3 octave frequency band TL(f) with the frequency *f* and the pressure amplitude *p* the transmission loss is defined as

$$\mathrm{TL(f)} \quad = -10\log_{10}\left(\frac{p^2_{\mathrm{received}}}{p^2_{\mathrm{source}}}\right) \qquad \textbf{Eq. B.5}$$

Since both the source (SRC) sound levels and the transmission loss are frequency dependent, the total level is computed per 1/3 octave band. The range and depth dependent total sound exposure level is defined with the transmission loss and the weighting function *W(f)* defined in Appendix B.3 by:

$$\mathrm{SEL} = 10\log_{10}\left(\sum_f 10^{0.1\,\mathrm{SEL(f)^{SRC}} - 0.1\,\mathrm{TL(f)} + 0.1\,W(f)}\right) \qquad \textbf{Eq. B.6}$$

In case of the unweighted SEL, *W(f)* is equal to zero.

Exposure criteria require considering the strength of the impulsive noise and to evaluate the biological impact of a noise dose. The cumulative sound exposure level is the best analytical description of the acoustic dose from an activity because it covers the entire acoustic energy emitted. In principle, the acoustic events (e.g. construction noise) are added to one another to arrive at this dose. The term cumulative sound exposure level ($\mathrm{SEL}_{\mathrm{cum}}$) is used in underwater acoustics (Gill *et al.* 2012). It should not be confused with cumulative impacts usually used when impacts from several different locations (for example different projects) are analysed. If all the impulsive noise events (such as hammer strikes) are equal, the cumulative sound exposure levels are described by:

$$\mathrm{SEL_{cum}} = \mathrm{SEL} + 10\log_{10}(n) \qquad \textbf{Eq. B.7}$$

where the SEL of a single impulsive event is combined with is the number of impulsive noise events *n* (e.g. number of strikes). If the events vary in strength *n* is equal to the sum of the ratio of the acoustical energy of the SEL of a single impulsive event to the ones that are cumulated.

For moving receivers, the sound exposure levels are cumulated along the escape routes, e.g. along a straight line away from the sound source,

$$\mathrm{SEL}_c^{\text{moving}} = 10\log\sum_{i=1}^{N} 10^{\frac{(\mathrm{SEL}-\mathrm{TL}(r_0+vt_i))}{10}} \qquad \textbf{Eq. B.8}$$

where the calculation involves *N* impulsive sound events the SEL of a single impulsive event (such as a single hammer strike) after applying the frequency weighting, which is lined out in Appendix B.3. The transmission loss TL can be obtained from the numerical simulations at distance $r = r_0 + vt_i$ with initial distance of r_0, escape speed v and t_i the time since the beginning of the impulsive noise operations.

The $\mathrm{SPL}_{\mathrm{peak}}$ is defined with the maximum amplitude of the time domain signal *p(t)* as defined in Figure B.1.

$$\mathrm{SPL}_{\mathrm{peak}} = 10\log_{10}\left(\frac{\max\,(p^2(t))}{p_0^2}\right) \text{ with } p_0 = 1\,\mu\mathrm{Pa} \qquad \textbf{Eq. B.9}$$

The applied modelling framework assumes a constant difference between the $\mathrm{SPL}_{\mathrm{peak}}$ and the SEL. With the conversion factor $\Delta_{\mathrm{SPLpeak\text{-}SEL}}$ the $\mathrm{SPL}_{\mathrm{peak}}$ is derived by

$$\mathrm{SPL}_{\mathrm{peak}} = \mathrm{SEL} + \Delta_{\mathrm{SPL}_{\mathrm{peak}}-\mathrm{SEL}} \qquad \textbf{Eq. B.10}$$

which neglects the additional dispersion of the pulse in the time domain and thus leads to a conservative estimate of the $\mathrm{SPL}_{\mathrm{peak}}$ at the receiver location. The same assumptions apply for the estimation of the SPL with a different conversion factor $\Delta_{\mathrm{SEL\text{-}SPL}}$

$$\mathrm{SPL} = \mathrm{SEL} + \Delta_{\mathrm{SPL-SEL}} \qquad \textbf{Eq. B.11}$$

Appendix B.2 Sound levels of continuous noise

Continuous noise is generally described with the SPL. An important aspect in the evaluation of the SPL is the considered time window T_0. Usually, statistical evaluations of the measured SPL with the consideration of 1 s windows are provided in e.g. ambient noise studies. Within this study the maximum SPL is considered for the behavioural reaction of mammals and for the auditory injuries of fish.

$$\mathrm{SPL} = 10\log_{10}\left(\int_{t_{\text{start}}}^{t_{\text{end}}} \frac{p^2(t)}{T_0 E_{p0}}\mathrm{d}t\right) \text{ with } p_0 = 1\,\mu\mathrm{Pa} \qquad \textbf{Eq. B.12}$$

The cumulated sound exposure level once again represents the total acoustical dose received by the receiver. The measure for the total acoustical dose is the $\mathrm{SEL}_{\mathrm{cum}}$. The $\mathrm{SEL}_{\mathrm{cum}}$ is derived by cumulating the acoustic energy of the 1 s time window (SPL) over the time period (T_{cont} in seconds) the continuous noise is expected to last.

$$\mathrm{SEL}_{\mathrm{cum}} = \mathrm{SPL}_{\mathrm{rms}} + 10\log_{10}(T_{\mathrm{cont}}) \qquad \textbf{Eq. B.13}$$

The respective differences between the SPL and the $\mathrm{SEL_{cum}}$ are 49.4 dB for an exposure time of 24 hours, 46.4 dB for 12 hours, and 43.4 dB for 6 hours.

Appendix B.3 Weighting

Marine mammals are divided into functional hearing groups based on the way, in which they perceive sound. Different hearing characteristics related to the range of sounds, a particular group of animals perceives, were compared by the National Marine Fisheries Service (NMFS 2018, 2024; Southall *et al.* 2007) with the use of frequency weighting expressed as:

$$W(f) = C + 10\log_{10}\left(\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right) \quad \textbf{Eq. B.14}$$

where the parameters *a, b* and *C* and the frequencies f_1 and f_2 of the species of interest within this project are presented in Table B.1. The corresponding weighting curves are presented in Figure B.2. The hearing ranges are presented in Table B.1.

Table B.1 Functional hearing groups with the estimated audible frequency ranges (NMFS 2024; Southall *et al.* 2019)

Functional Hearing Groups	Estimated hearing range	a	b	f_1 [kHz]	f_2 [kHz]	C [dB]
Very high-frequency (VHF) cetaceans (Southall *et al.* 2019)	200 Hz – 165 kHz	1.8	2	12	140	1.36
Low-frequency (LF) cetaceans (NMFS, 2024)	7 Hz – 36 kHz	0.99	5	0.168	26.6	0.12
High-frequency (HF) cetaceans (NMFS, 2024)	150 Hz – 160 kHz	1.55	5	1.73	129	0.32
Very high-frequency (VHF) cetaceans (NMFS, 2024)	200 Hz – 165 kHz	2.23	5	5.93	186	0.91

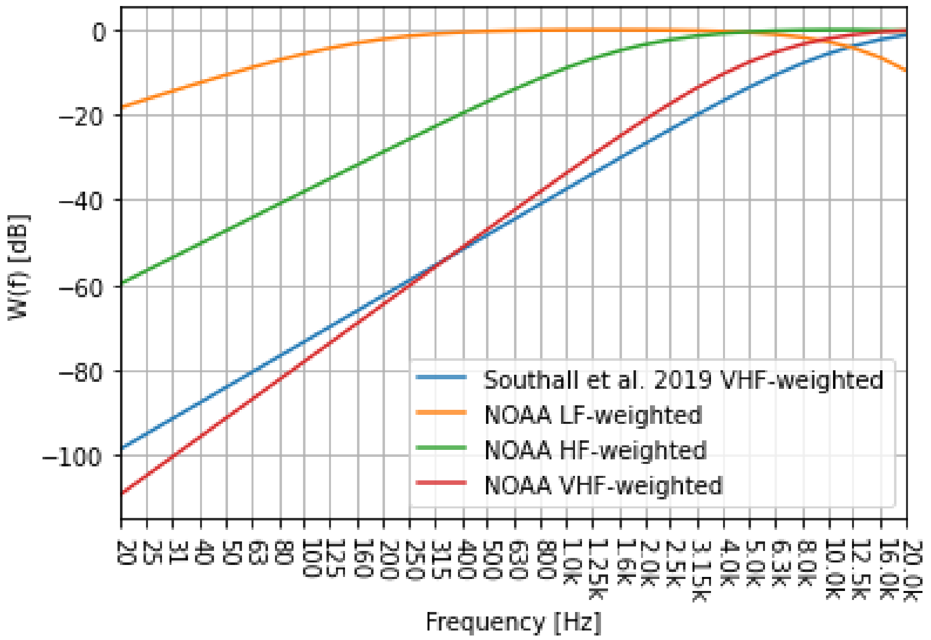

Figure B.2 Comparison of weighting functions for cetacean hearing groups

Appendix B.4 Impact ranges and areas

The impact range defines the confined area, in which specific animals are affected by the noise. This region was called the impact area A_{impact} and was calculated by adding all angular sectors with the radius r_i provided by the distance to the impact thresholds.

$$A_{impact} = \sum_{i=1}^{72} \pi r_i^2 \frac{d\alpha}{360°}$$

Angular resolution was used for the angular resolution $\alpha = 360°/72 = 5°$.