Assessment of Construction Noise for the Port Aux Basques Navigation Improvement Project

In-air and Underwater Acoustic Noise Modelling

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Contents

Figures

Tables

Executive Summary

JASCO Applied Sciences (JASCO) performed a modelling study of in-air and underwater sound levels associated with the proposed marine construction operations required for the Port aux Basques Navigation Improvement Project, located on the southwestern tip of Newfoundland. Numerical modelling for this assessment was carried out with model inputs selected to conservatively assess the extent of sound propagation due to underwater borehole drilling, rock blasting (with charges above and below the waterline), and dredging at Vardys Island and at Baldwin Rock.

The modelling methodology considered:

- The impact of environmental parameters, such as water sound speed profile, bathymetry, seabed geoacoustics, atmospheric conditions, and soil flow resistivity.
- The characteristics and placement of explosives in the blasting operations.
- The acoustic characteristics of drilling and dredging equipment.
- The cumulative effect of construction noise within a 24 h period.

Scenarios with a conservative maximum number of detonations per day (for rock blasting) and maximum operation duration per day (for drilling and dredging) were simulated to calculate the cumulative noise energy that could be emitted in a 24 h period (denoted SEL_{24h}). For blasting scenarios, single-detonation peak sound levels were also modelled.

For in-air sounds, distances to thresholds were computed for the following effects:

- Temporary threshold shift (TTS), permanent threshold shift (PTS), and behavioral impact for marine mammals in air.
- Injury for birds.

For underwater sounds, distances to thresholds were computed for the following effects:

- TTS, PTS, and behavioral impact for marine mammals.
- Injury for fish, invertebrates, eggs, larvae, and crustaceans.

For in-air propagation during rock blasting with charges above the water line, distances to PTS and TTS thresholds for marine mammals were <10 m from the detonation site in all cases. The distance to the PTS threshold for birds was also <10 m (Table 9) from the detonation site.

For underwater sound propagation out of two sites, maximum distances to thresholds occurred for operations at Baldwin Rock because this location has an unobstructed line of sight to the open sea. The following maximum distances to thresholds were estimated:

- Drilling operations: For marine mammals, the distance ($R_{95\%}$) to PTS is 350 m and to TTS is 2.9 km for Very High-frequency cetaceans. For fish, distances ($R_{95\%}$) to recoverable injury and TTS thresholds are 61 m and 360 m, respectively.
- Dredging operations: For marine mammals, the distance ($R_{95\%}$) to PTS is 44 m and to TTS is 640 m for Low-frequency cetaceans. For fish, distances to recoverable injury and TTS thresholds are <10 and 15 m, respectively.
- Underwater blasting operations without mitigation:
    - Marine mammals: The distance ($R_{95\%}$) to PTS is 3.15 km and to TTS >50 km for low-frequency cetaceans.
    - Fish: The distance ($R_{95\%}$) to mortality and potential mortal injury is 190 m.
    - Crustaceans: The distance ($R_{95\%}$) to mortality and potential mortal injury is 190 m, and to non-lethal injury is 1250 m.
    - Eggs and larvae: The distance to mortality and potential mortal injury is 113 m.

1. Introduction

JASCO Applied Sciences (JASCO) performed a modelling study of in-air and underwater noise levels associated with the proposed marine blasting and dredging operations required for the Port aux Basques Navigation Improvement Project. The project is located in southwestern Newfoundland. For this improvement project, a 150 m wide navigation channel will be cleared to a minimum depth of minus 10.0 m relative to Chart Datum (CD) and a turning basin at the head of the harbour will be added. This new channel alignment requires complete removal of Vardys Island, partial removal of Baldwin Rock, and deepening of two other minor areas located within the proposed turning basin (Figure 1). Channel deepening involves removing bedrock by blasting, using explosives placed in boreholes drilled in rock. Following detonations, the blast rock and debris will be removed by dredging. The blast pressure waves produced during the project will propagate into the surrounding underwater marine environment. In air pressure waves will propagate away as airborne noise.

Acoustic noise can affect marine fauna, birds, and humans in several ways. Moderate noise levels can elicit behavioural disturbances, while higher levels can cause temporary hearing threshold shift (TTS) or even permanent hearing threshold shifts (PTS). Here, 'hearing threshold shift' refers to a reduction in the hearing sensitivity of the exposed animals. PTS is a considered a direct auditory injury, but TTS can also lead to permanent injury if it occurs many times to the same animal. At the highest levels, noise pressures can cause severe physical injuries or death from barotrauma.

For this study, JASCO modelled in-air and underwater sound propagation to predict sound levels over regions surrounding each operation. These results were analyzed to extract the distances from the operations sites at which sound levels reached several thresholds associated with adverse effects to marine animals and birds. In total, seven scenarios were modelled (Table 1): in-air noise levels from detonating explosives were modelled at Vardys Island and underwater noise levels from drilling of boreholes, detonating explosives, and dredging were modelled at Vardys Island and Baldwin Rock.

The criteria for assessing the potential for injury and behavioural disturbance due to acoustic noise are summarized in Section 2. These criteria provide a list of noise thresholds associated with the onset of effects for marine mammals, fish, invertebrates, eggs, and larvae. The methodology used to assess the maximum distances to the listed noise thresholds is summarised in Section 3; the technical details are included in Appendices A, B, and C. The results are presented in Section 4 and discussed in Section 5. Some terms used in this report are defined in the Glossary; where possible, we follow International Organization for Standardization definitions and symbols for sound metrics (e.g., ISO 2017).

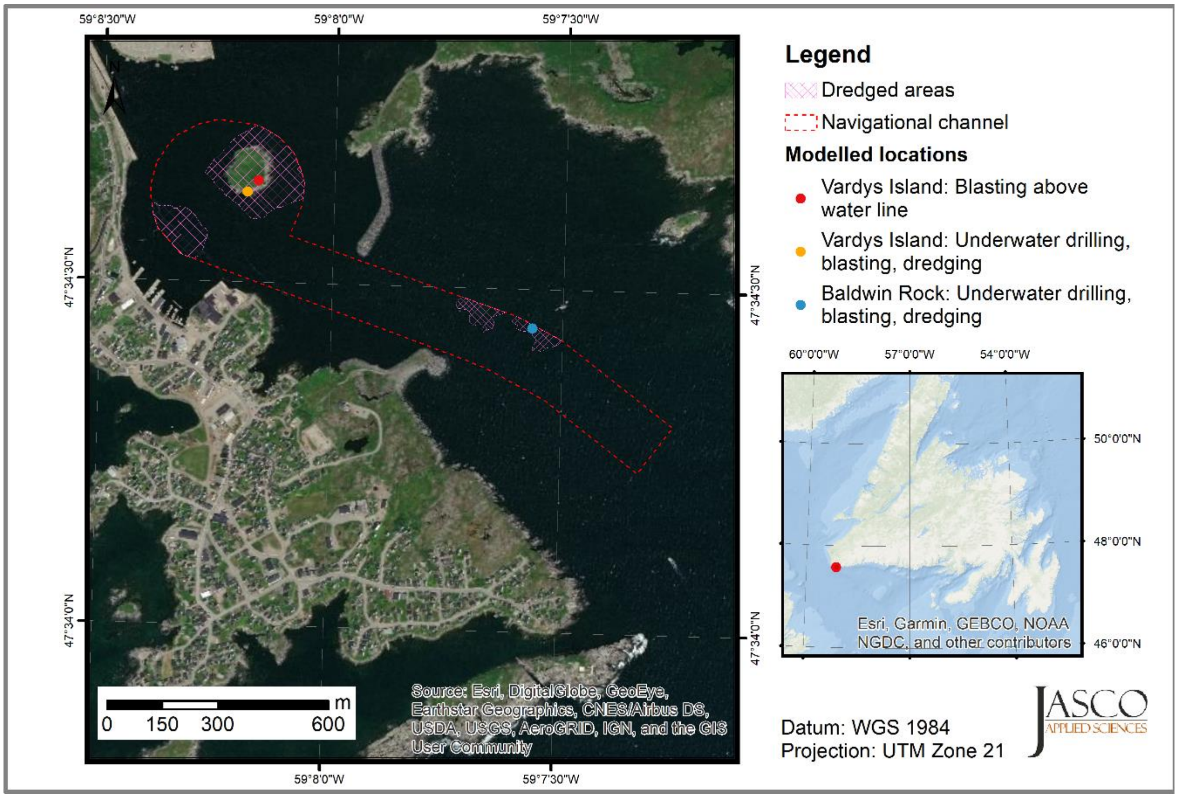


Figure 1. Map of the Project area, showing the locations where the modelled noise from rock drilling, detonating explosives, and dredging operations originated.

Table 1. Locations and descriptions of acoustic modelling scenarios.

Scenario	Site	Operation	Latitude (N)	Longitude (W)	UTM Zone 21N		Water depth (m)
					x (m)	*y* (m)	
1	Vardys Island	Blasting above water line	47° 34.651'	59° 08.157'	339375	5271555	n/a
2		Underwater drilling	47° 34.630'	59° 08.180'	339340	5271520	7.5
3		Underwater blasting	47° 34.626’	59° 08.180’	339345	5271510	0.1
4		Dredging	47° 34.630'	59° 08.180'	339340	5271520	12.5
5	Baldwin Rock	Underwater drilling	47° 34.446'	59° 07.561'	340110	5271150	9.6
6		Underwater blasting	47° 34.438’	59° 07.534’	340145	5271140	4.6
7		Dredging	47° 34.446'	59° 07.561'	340110	5271150	12.5

2. Noise Effects Criteria

Several sound level metrics, such as peak pressure level (PK), sound pressure level (SPL), and sound exposure level (SEL), are commonly used to evaluate noise and its effects on animals and humans (see Appendix A), although the choices of metrics and thresholds continue to evolve as associated research remains active.

We predicted distances to currently accepted thresholds for impacts to marine mammals, fish, fish eggs and larvae, birds, and humans, based on available sets of criteria for the onset of noise-induced injuries (including mortality (in fish), permanent threshold shift (PTS) and temporary threshold shift (TTS)), and for behavioural disturbance. These criteria, listed below, are discussed in more details in Appendix B; they include thresholds accepted by regulatory agencies and represent current best-available science.

For in-air noise due to detonating buried (i.e., capped) explosives, results are presented for the following criteria:

- Injury thresholds (onset of PTS and TTS; Table 2) for phocid carnivores in air (PCA) and other marine carnivores in air (OCA), based on Southall et al. (2019).
- Injury threshold for birds (125 dBA re 20 µPa), based on Dooling and Popper (2016).
- Behavioural thresholds for pinnipeds in air (Table 2), based on Southall et al. (2007).
- Regulation of construction noise in humans is subject to the Channel-Port aux Basques Noise and Nuisance Regulations (Channel-Port aux Basques Town Council 1992), which require approval by the Town Council for certain noise-generating activities but do not indicate noise level thresholds.

For underwater noise, results are presented for the following criteria:

- Injury (onsets of PTS and TTS) and behavioural disturbance thresholds (Table 3) to marine mammals due to detonation noise, based on Southall et al. (2019) and NOAA Fisheries (2019) for impulsive sources.
- Injury (onsets of PTS and TTS) and behavioural disturbance thresholds (Table 4) to marine mammals due to dredging and drilling noise, based on Southall et al. (2019) and NOAA Fisheries (2019) for non-impulsive sources.
- Injury thresholds for fish, invertebrates, eggs and larvae (Table 5), based on Popper et al. (2014).
- Injury threshold for crustaceans (Table 5), based on to Day et al. (2016a), Day et al. (2016b), and Day et al. (2019).

The PK criteria threshold is applied to maximum instantaneous value over the course of the operation. The SEL metric is the integral metric and the criteria threshold is applied to the combined exposure over a specific period, namely a 24-hour period, which is indicated as SEL_{24h}. The criteria thresholds are defined for each marine mammal functional hearing group individually and applied to frequency-weighted sound exposure level field ($SEL_{w,24h}$) using group specific auditory weighting curves.

Table 2. *Detonating explosives, in-air effects:* Injury and behavioural disturbance thresholds for phocid carnivores in air and other marine carnivores in air for impulsive sounds from Southall et al. (2007, 2019). SEL_{24h}: sound exposure level accumulated over 24 h; PK: peak sound pressure level.

Functional hearing group or species	PTS		TTS		Behavioural disturbance	
	$SEL_{w,24h}$ (dB re 20 µPa²·s)	PK (dB re 20 µPa)	$SEL_{w,24h}$ (dB re 20 µPa²·s)	PK (dB re 20 µPa)	$SEL_{w,24h}$ (dB re 20 µPa²·s)	PK (dB re 20 µPa)
Phocid carnivores in air	138*	161	123*	155	100‡	109
Other marine carnivores in air	161†	176	146†	170		

* Threshold values are frequency-weighted according to the curve for phocid carnivores in-air provided by Southall et al. (2019).
† Threshold values are frequency-weighted according to the curve for other carnivores in-air provided by Southall et al. (2019).
‡ Threshold values are frequency-weighted according to the curve for pinnipeds in-air provided by Southall et al. (2007).

Table 3. *Detonating explosives, underwater effects*: Thresholds for permanent threshold shift (PTS), temporary threshold shift (TTS) and behavioural disturbance for marine mammals underwater, based on Southall et al. (2019) and NOAA Fisheries (2019) for impulsive sources. LF: low-frequency; HF: high-frequency; VHF: very high-frequency; SEL_{24h}: sound exposure level accumulated over 24 h; PK: peak sound pressure level.

Functional hearing group or species	PTS		TTS		Behavioural disturbance
	$SEL_{w,24h}$* (dB re 1 µPa²·s)	PK (dB re 1 µPa)	$SEL_{w,24h}$* (dB re 1 µPa²·s)	PK (dB re 1 µPa)	SPL (dB re 1 µPa)
LF cetaceans	183	219	168	213	160
HF cetaceans	185	230	170	224	
VHF cetaceans	155	202	140	196	
Phocid in water	185	218	170	212	
Otariids, mustelids in water	203	232	188	226	

* $SEL_{w,24h}$ values are frequency-weighted according to the curve for each functional hearing group provided by Southall et al. (2019).

Table 4. *Drilling and dredging, underwater effects*: Thresholds for permanent threshold shift (PTS), temporary threshold shift (TTS) and behavioural disturbance for marine mammals underwater based on Southall et al. (2019) and NOAA Fisheries (2019). LF: low-frequency; HF: high-frequency; VHF: very high-frequency; SEL_{24h}: sound exposure level accumulated over 24 h; SPL: root-mean-square sound pressure level.

Functional hearing group or species	PTS	TTS	Behavioural disturbance
	$SEL_{w,24h}$* (dB re 1 µPa²·s)	$SEL_{w,24h}$* (dB re 1 µPa²·s)	SPL (dB re 1 µPa)
LF cetaceans	199	179	120
HF cetaceans	198	178	
VHF cetaceans	173	153	
Phocid carnivores in water	201	181	
Other carnivores in water	219	199	

* $SEL_{w,24h}$ values are frequency-weighted according to the curve for each functional hearing group provided by Southall et al. (2019).

Table 5. Thresholds for injury to fish, invertebrates, eggs, and larvae. n/a: no threshold is available. PK: peak sound pressure level; PK-PK: peak-to-peak sound pressure level; SPL: root-mean-square sound pressure level.

Species or group	Detonating explosives		Drilling and dredging	
	Mortality and potential mortal injury	Non-lethal injury	Recoverable Injury	Temporary threshold shift
No swim bladder (particle motion detection)	220 dB re 1 μPa (PK)*	n/a	n/a	n/a
Swim bladder not involved in hearing (particle motion detection)		n/a	n/a	n/a
Swim bladder involved in hearing (primary pressure detection)		n/a	170 dB re 1 μPa (SPL)†	158 dB re 1 μPa (SPL)†
Invertebrates (crustaceans)		209 dB re 1 μPa (PK-PK) ‡	n/a	n/a
Eggs and larvae	13 mm/s † (peak particle velocity)	n/a	n/a	n/a

* Based on Wright and Hopky (1998).
† Based on Popper et al. (2014).
‡ Based on Day et al. (2016a), Day et al. (2016b), and Day et al. (2019).

3. Methods

The operations considered in this study will occur in the harbour of Port-aux-Basques, where water depths are less than 40 m. Because the harbour does not freeze in winter, activities may occur year round. Atmospheric properties (i.e., pressure, temperature, relative humidity, and wind as a function of elevation) representative of April were used to model conditions leading to longest in-air propagation (see Appendix C.4.1). Properties of the water (i.e., temperature, salinity, and sound speed) representative of the month leading to the longest underwater acoustic propagation (February) were used for underwater modelling (see Appendix C.4.3). In the Project area, the bottom predominantly features exposed bedrock. The bedrock will be exposed at the modelled sites as the dredging operation progresses. More details are provided in Appendix C.4.4.

The following steps describe the general approach applied in this study to model sounds and estimate distances to the effect criteria thresholds (listed in Section 2):

1. The modelled operations are characterized as sound-radiating sources, and the source pressure functions are predicted in the nearfield, typically within a few tens of metres. This characterization is done using a proxy (source level spectra derived from measurement of similar operations) or by using theoretical models (see details in Section 3.1).
2. Computational propagation modelling is applied to predict how sound propagates from the sound sources into the air or the water column, as a function of range, elevation/depth, and azimuthal direction. To maximize the accuracy of estimation, different sound propagation models are used, depending on the characteristics of the sound source (see Section 3.2 and Appendices C.1 and C.2).
3. The propagated sound field is used to compute maximum-over-depth/maximum-over-elevation (for underwater and in-air noise modelling respectively) received levels over a large regular grid from which distances to effect criteria thresholds are calculated and contour maps are generated (see details in Appendix C.3). Two distances for each threshold are presented in this work: the maximum distance from the source at which given sound level is predicted to occur, (R_{max}), and the distance to a given sound level after the 5% farthest points were excluded, ($R_{95\%}$) (see Appendix C.3).

The following subsections describe the methods and parameters used to characterize the sound sources for drilling, detonating explosives and dredging, the acoustic propagation models, the frequency range and the accumulation periods considered in computing the sound fields in terms of SEL_{24h}.

3.1. Acoustic Sources

3.1.1. Noise due to Drilling Operations

The charges will be installed into boreholes drilled within the bedrock (gneiss). The source level spectra derived from recordings of Down-The-Hole (DTH) hydro-hammering were used as a proxy of the proposed drilling operations. DTH hydro-hammering is a percussive rotating drilling technique appropriate for hard rock formations. The proxy DTH levels correspond to a Numa Patriot 180 hammer, used to install 0.6 m diameter piles[1] at a ferry terminal at Kodiak, AK, USA (Denes et al. 2016). The acoustic monitoring of this activity was performed using hydrophones placed at 10 to 30 m from the borehole. The measured sound levels were backpropagated using sound propagation modelling and the site-specific environmental parameters to derive source level spectra in decidecade bands.

Statistical analysis of the recorded data for DTH hydro-hammering was performed to determine percentile values. A percentile is a measure used in statistics indicating the value below which a given percentage of observations in a group of observations falls. Specifically, 95th and 50th percentiles were used in this study. The 95th percentile is conservative measure and gives values close to maximum detected. It was

[1] For a given DTH model, the source levels are unaffected by pile diameter because there is no interaction between the drill and the actual pile.

used as the source level for the purpose of calculating the SPL exposure (Figure 2) with 197.2 dB re 1 µPa^{2}m²s broad band level. The 50th percentile is an average level over the course of the operation and was used for the purpose of calculating SEL_{24h} (Figure 2) with 191.6 dB re 1 µPa^{2}m²s broad band level.

The sound from drilling operations emanates mainly close to the seafloor, but some sound also originates from distributed sources along the drill shaft and through the hull of the vessel holding the equipment. Since the exact design and equipment for the drilling operations are unknown, drilling operations were simulated as a point source in the middle of the water column, as conservative but realistic assumption for estimating distances to sound level thresholds.

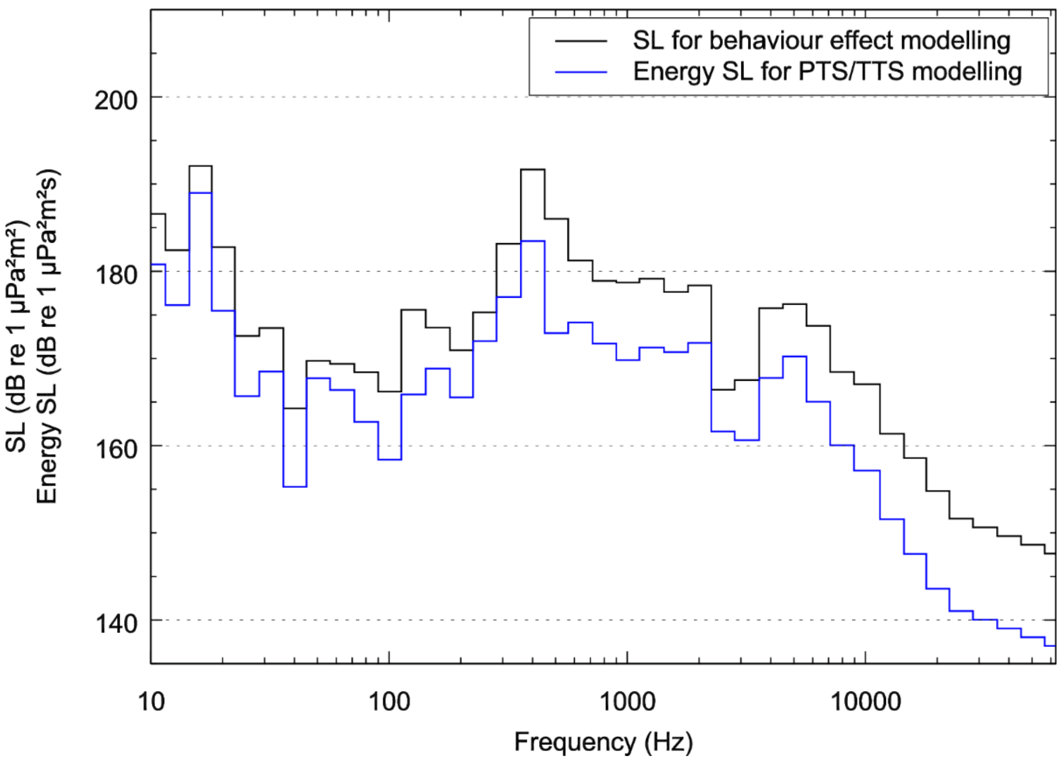


Figure 2. Decidecade-band source level spectra for drilling operation: Source Level (dB re 1 µPa^{2}m²) for modelling SPL field (used in behavioural disturbance assessment) and Energy Source Level (dB re 1 µPa^{2}m²s) for modelling SEL_{24h} field (used for PTS/TTS assessment).

In this study, we modelled three drills operating simultaneously. Each drill was assumed to operate for 766 min within a 24 h period for a total drilling time per day of 2298 min (or 137,880 s). Sound exposure level (SEL) thresholds commonly apply over each 24 h period. SEL is a dose-like metric calculated from the product of the mean-square pressure and time in seconds. In decibels, this is equivalent to adding the operation's SPL and its decibel duration. The decibel duration is calculated as ten times the logarithm of the total number of seconds the operation occurs within a day (N_{24h}). As per above, N_{24h} = 137,880 s. Therefore, the drilling operation SEL was computed by adding 10 log(N_{24h}) = 51.4 dB re s to the predicted drill noise SPL in dB re 1 µPa^2 (see Equation A-10, Appendix A).

3.1.2. Noise due to Bedrock Blasting Operations

Post-detonation compressive waves from underground detonation of explosive charges (underwater or in air) have the potential to cause physical injury and/or behavioural disturbance to marine mammals, fish, birds, and humans. This type of operation generates a series of very high amplitude but brief acoustic events. There is a zone in the immediate vicinity of the blast (typically within a few tens of meters) that is dominated by non-elastic strain, fracture, and bulk material transport within the medium (the shock wave zone). Outside this zone, the vibrational energy quickly transforms to linear acoustic signals that can be modelled using conventional in-air and underwater sound propagation models.

In this study, the noise generated by detonation of explosives placed within boreholes drilled in rock was modelled using ConWep (Hyde 1988, Hyde 1992). ConWep generates time-dependent waveforms of the detonation and accounts for scenario-specific input parameters, such as the type and size of explosive, the charge depth below ground and the characteristics of backfill material. Blasting was modelled assuming the following charge sizes:

- In-air blasting: Distances to PK and SPL thresholds were obtained for 48 kg NEW charges (i.e., the largest charges to be installed in the upper deck boreholes). Distances to SEL_{24h} thresholds were obtained for the average upper deck charge size of 37 kg NEW, for a maximum of 84 upper deck boreholes detonated per day in Vardys Island.
- Underwater blasting: 48 kg NEW charges for each lower deck borehole and maximum 84 lower deck boreholes detonated per day at Vardy's Island, and 56 kg NEW charge for each borehole and maximum 56 boreholes detonated per day at Baldwin Rock (Table 6).

Table 6. Specifications of the charge used for rock blasting. Charge masses are provided as Net Explosives Weight (NEW), where 1 NEW is equivalent to 1 kg of TNT.

Parameter	Value
Explosive	Blastex® TX packaged emulsion explosive
Explosive mass	• 48 kg NEW charge at Vardys Island. For in-air modelling related to SEL_{24h} metrics, the average charge size of 37 kg NEW was used instead. • 56 kg NEW charge at Baldwin Rock.
Deployment depth	In-air acoustic modelling: • Charges placed at 0–7.4 m elevation above waterline • Source signature modelled for charges buried 1.1 m depth
	Underwater acoustic modelling: • Charges placed at 8.5 m depth below the sea bottom at Vardys Island • Charge placed at 6 m depth below the sea bottom at Baldwin Rock
Backfill material	Angular gravel with particle size of approximately 1/12th the diameter of the borehole
Backfill thickness	0.6 m for submerged boreholes; 1.5 m for boreholes at Vardys Island

For in-air SEL modelling of detonation noise, ConWep's Shockwave module was used to obtain the pressure wave that would be measured in the bedrock at a distance of 6 m from the detonation point (i.e., the burial depth of the top largest charge). This pressure wave represents blast energy in the bedrock, and therefore it requires application of a bedrock-to-air coupling factor for in-air modelling. Mathematical description of this factor is complex, requiring accurate knowledge of the media surrounding the explosive and its dynamic behavior during the explosion. To overcome this complexity, this study applies a coupling (scaling) factor based on field measurements of rock blasting in quarries (Siskind et al. 1980), leading to the source levels shown in Figure 3 for in-air SEL modelling.

In-air SPL was modelled for the maximum 48 kg NEW charge, by increasing the single-detonation SEL (Figure 3, left) by 9 dB, corresponding to an integration time of 0.125 s. In-air SEL over 24 h was computed by applying a 10 log(N_{24h}) decibel shift to the single-detonation SEL (Figure 3, right), where N_{24h} = 84 is the total number of detonations that would occur above the water line in a single day. Terrain elevation at Vardys Island ranges from 0–7.4 m, such that the length of an upper deck borehole (and the amount of explosive within the borehole) varies: areas with the highest elevation require longer boreholes and more explosive. For the purpose of SEL24h modelling, JASCO used the average charge size of 37 kg NEW assuming preliminary blast design parameters.

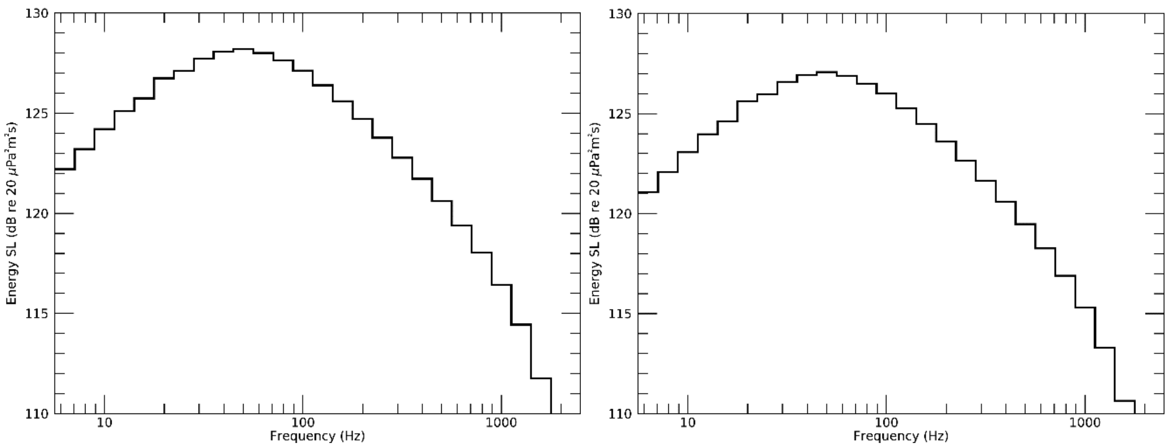


Figure 3. Frequency-dependent energy source levels in decidecade frequency-bands, corresponding to underground detonation of (left) 48 kg NEW and (right) 37 kg NEW. These spectra were used for modelling in-air SEL and SPL.

To model in-air PK levels, this study applies the measured-based model proposed by Siskind et al. (1980), which estimates in-air PK levels at a scaled distance from the detonation as:

$$\mathrm{P}_{Siskind} = 1117.0\left(\frac{3.28R}{(2.2W)^{1/3}}\right)^{-0.794} \tag{1}$$

where $\mathrm{P}_{Siskind}$ is the PK pressure in Pa, R is the distance in m from the detonation, W is the charge weight in kg of TNT.

For underwater modelling of detonation noise, ConWep's Shockwave module was used to obtain the pressure wave that would be measured in-ground at a distance of 18 m from the detonation point. That distance was chosen as sufficient for the blast pressure wave to have decayed to linear propagation; at very close distances the pressure wave shape evolves with distance due to non-linear effects that are not treated properly by linear propagation models. The ConWep pressure wave at 18 m was backpropagated assuming linear spherical spreading to obtain an equivalent point source, suitable for linear propagation modelling. The linear propagation model addresses underground propagation from rock to water, and accounts for the rock-to-water transmission (Appendix C.2.2). ConWep considers physical properties of the rock and/or sediment that surrounds the charge. This material is described in the model by its density, compressional sound speed, and absorption (or attenuation) coefficient. The model was fine-tuned by means of adjusting the attenuation factor to match received peak pressure levels at less than 300 m to lie between the regression lines provided by Hempen et al. (2007) and Oriard (2002). The Hempen et al. (2007) and Oriard (2002) regression lines are derived from monitoring measurements of bedrock bottom blasting operation. The value for the attenuation that provided the best match was 2.035 (see Figure 4). This approach maintains the pressure wave shape predicted by ConWep and simultaneously ensures the peak pressures are consistent with the empirical blasting peak pressure models.

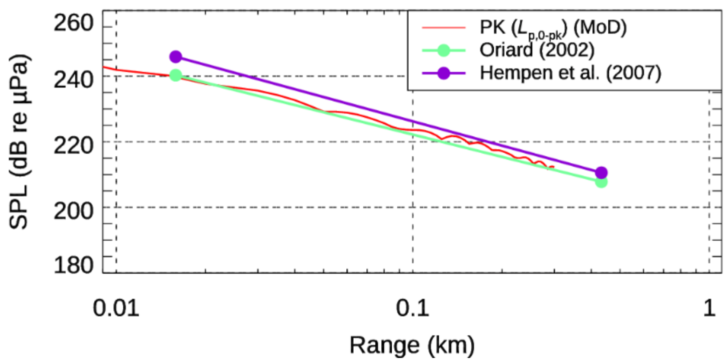


Figure 4 ConWep attenuation factor tuning: Modelled peak sound pressure level (maximum-over-depth) compared to regression functions provided by Hempen et al. (2007) and Oriard (2002). The attenuation factor value is 2.035.

The source pressure waveforms and corresponding energy source levels in decidecade bands for blasts of 56 kg and 48 kg charges are shown on Figures 5 and 6.

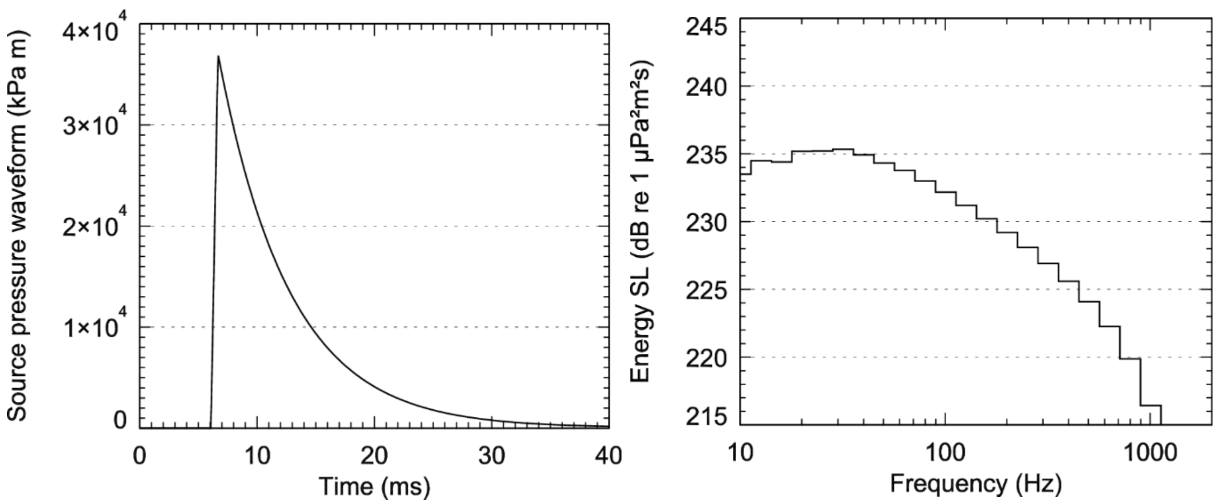


Figure 5. Blast source level modelling, Baldwin Rock site: (left) Time-dependent pressure wave for underground detonation of 56 kg TNT. (Right) Corresponding frequency-dependent energy source levels in decidecade frequency-bands.

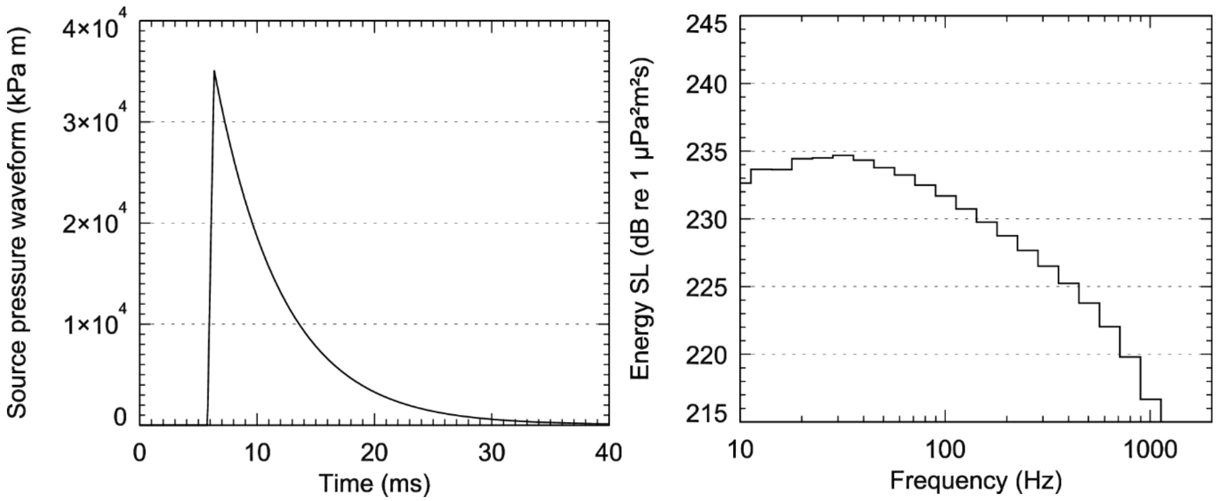


Figure 6. Blast source level modelling, Vardys Island site: (left) Time-dependent pressure wave for underground detonation of 48 kg TNT. (Right) Corresponding frequency-dependent energy source levels in decidecade frequency-bands.

Underwater SEL over 24 h for detonating multiple charges was computed by applying a 10 log(N_{24h}) decibel adjustment to the single-detonation SEL, where N_{24h} is the total number of detonations that would take place below the water line, over the period. This approach is based on a simple sum of acoustic energy of all blasts performed over the day.

According to the construction plan, the maximum number of charges in a 24 h period is 84 for the Vardys Island site and 56 for Baldwin Rock site. Hence, the adjustment to derive SEL_{24h} for blasting operation based on $SEL_{per\ charge}$ field was 19.2 dB for Vardys Island and 17.5 dB for Baldwin Rock.

3.1.3. Noise due to Dredging Operations

A mechanical dredge is expected to be used for removing material from the navigation channel. Because the exact type of mechanical dredge was unknown at the time of this study, a clamshell bucket dredge was used as a proxy. This type of dredge is efficient in shallow water (<50 m).

In this study two available measured spectra were analyzed: for the clamshell dredges *Viking*, reported by Dickerson et al. (2001), and *Argilopotes*, reported by Miles et al. (1987).The spectrum for the dredge *Viking* was based on recordings of the dredge operations in Cook Inlet (Alaska), at a distance of 158 m where the average water depth was 10 m. The reported received levels were backpropagated to the source location assuming spherical spreading for the first 20 m from the source and cylindrical spreading thereafter. The spectrum for *Argilopotes* was based on published levels measured at a distance of 1 km and backpropagated using environment-based transmission loss modelling.

For this study, the final spectrum was estimated using the maximum decidecade frequency-band levels from the *Viking* and *Argilopotes* dredge spectra. The frequency range of the measured spectra was 31.5 to 31,500 Hz. The extrapolation for the lower frequencies (down to 10 Hz) was done by keeping the value from the last available band constant. The extrapolation for the higher frequencies (up to 63,000 Hz) was done by using a 10 dB per decade (1 dB per decidecade band) roll-off. The decidecade band source level spectrum used for modelling the acoustic field from the dredging operation is provided in Figure 7.

In the case of bucket dredges, the primary source of noise is the machinery installed on the barge. For the purpose of modelling, the point source was placed at the depth equivalent to the draft of the dredging barge: 3 m.

SEL over 24 h for dredging operations was computed by applying a 10 log(N) decibel shift to the 1 s SEL estimates, corresponding to the total operational time at one location, within 24 h (N_{24h}, in seconds; Equation A-10, Appendix A). The dredge would move relatively little within a 24 h period. To provide conservative estimates of distances to effect thresholds, it was assumed that the dredge was stationary and continuously operating for 24 hours; here, N_{24h} = 86,400 s.

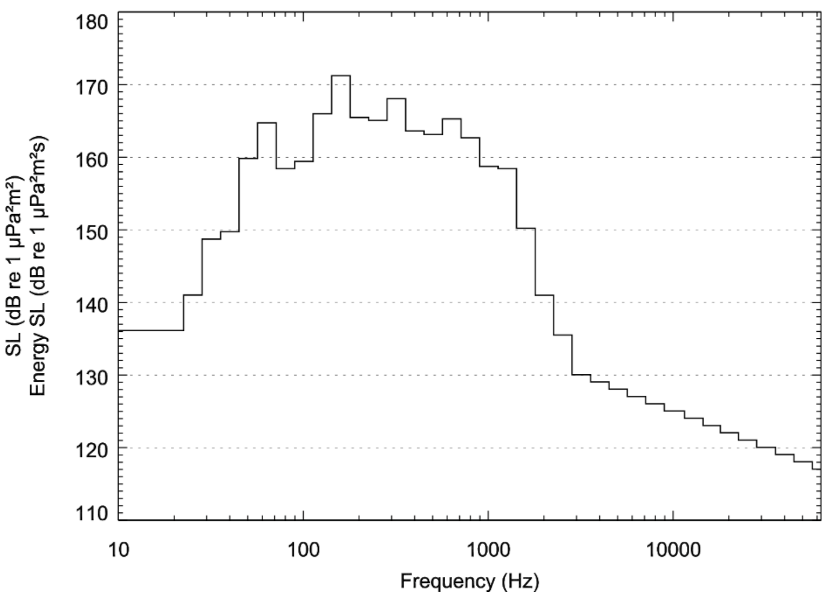


Figure 7. Decidecade-band source level spectra for drilling operation: Source Level (dB re 1 µPa^{2}m²) for modelling SPL field and Energy Source Level (dB re µPa^{2}m²s) for modelling SEL field. For continuous noise sources SPL and SEL have equivalent value.

3.2. Sound Propagation Models

3.2.1. In-air Sound Modelling

For in-air sound propagation, the loss in acoustic level depends on the sound speed as a function of elevation above the ground and the water, which is determined by atmospheric conditions. Sound ducts forming in the atmosphere can trap sound, leading to propagation over long distances from the source. To estimate distances to SEL and SPL thresholds, JASCO's Impulse Noise Propagation Model (INPM) was used with the source levels in Figure 3 to determine the sound levels that would be received by marine mammals and birds with their head above the water or the land's surface (see Appendix C.1). We assumed that an animal's ears were 0–15 cm above the water or the land and extracted modelled sound levels for a receiver at that elevation. Conservative modelling was implemented by selecting the seasonal input parameters (i.e., atmospheric profiles) that yielded the longest in-air sound propagation.

3.2.2. Modelling Impulsive Sound (Blasting)

The time-domain Full Waveform Range-dependent model (FWRAM; Appendix C.2.2) was used to model underwater sound propagating away from the detonation of explosives along multiple vertical planes leading radially away from and extending up to 50 km from the blast site, or terminating at shorelines. There were 86 vertical radial planes originating from the Vardys Island site with variable azimuthal steps of 2° to 5° to provide even density and adequate coverage of the narrow opening to open waters. Similarly, 72 radial planes were defined originating from the Baldwin Rock site with a constant 5° azimuthal step. The horizontal (radial) modeling step was 10 m and receiver (sampling) depths spanned the entire water column observed along the modelled radials (up to 440 m deep), with step size increasing with depth. The modelling frequency range was from 9 to 1122 Hz (the low limit of 10 Hz band and high limit of the 1000 Hz band). SEL source levels from 1200 to 25,000 Hz were obtained by adjusting the level of the 1000 Hz decidecade frequency band by −2 dB per decidecade. This approach led to the 10,000 Hz decidecade band SEL being 20 dB below that of the 1000 Hz band. For extrapolated high frequencies the propagation loss due to volumetric absorption and sea surface roughness was accounted for via range dependent functions derived for each frequency. The surface roughness was equivalent to wind speeds of 10 knots.

3.2.3. Modelling Continuous Sound (Dredging and Drilling)

JASCO's Marine Operations Noise Model (MONM; described in Appendix C.2.1), a combined implementation of parabolic-equation and ray-tracing propagation models, was used to model the sound field for drilling and dredging operations within a frequency range of 10 Hz to 25 kHz. The modelling was performed along a fan of radial planes with 1° and 2° steps at Site 1 and 2 respectively. The profiles extended from the source either to the shoreline or to a maximum of 50 km toward deep water. Receiver (sampling) depths were chosen to span the entire water column over the modelled area (to a maximum of 440 m depth), with step sizes that increased with depth. For high frequencies the propagation loss due to volumetric absorption and sea surface roughness was accounted for. The surface roughness was equivalent to wind speeds of 10 knots.

4. Results

Sound propagation modelling results using the most conservative input parameters are provided in the following formats:

- Sound propagation in air:
  - For phocid carnivores in air (PCA) and other marine carnivores in air (OCA), we provide tables of distances to $SEL_{w,24h}$ and PK thresholds for PTS and TTS.
  - For pinnipeds in air (PA), we provide tables of distances to $SEL_{w,24h}$ and PK thresholds for behavioral disturbance.
  - For birds, a table of distances to injury threshold is provided.
  - PK and A-weighted SPL levels at the northeast corner of the St. Christopher Hotel.
- Sound propagation underwater:
  - For marine mammals underwater, we provide tables of distances to $SEL_{w,24h}$ and PK thresholds for PTS and TTS and tables of distances to SPL thresholds for behavioral disturbance due to detonation noise.
  - We provide tables of distances to SEL_{24h} thresholds for PTS and TTS and tables of distances to SPL thresholds for behavioral disturbance for marine mammals underwater due to dredging and drilling noise.
  - For fish, invertebrates, eggs and larvae, we provide tables of distances to mortality, potential mortal injury and non-lethal injury.

Contour maps for sound propagation in air and underwater, indicating the corresponding thresholds of these criteria, are provided in this section.

4.1. Vardys Island Site

4.1.1. Blasting above the Water Line (Scenario 1)

4.1.1.1. Distances to In-air Thresholds and Maps

In this section, R_{max} and $R_{95\%}$ distances to criteria for marine mammals in air are presented as tables, followed by maps showing the directivity and distance to various in air sound levels.

Table 7. *Marine carnivores in air, $SEL_{w,24h}$ thresholds*: Distances to thresholds for permanent threshold shift (PTS) and temporary threshold shift (TTS) due to the detonation of 84 charges of 37 kg TNT (Southall et al. 2019).

Functional hearing group or species	PTS			TTS		
	$SEL_{w,24h}$ threshold ($L_{E,24h}$; dB re 20 μPa²·s)	R_{max} (m)	$R_{95\%}$ (m)	$SEL_{w,24h}$ threshold ($L_{E,24h}$; dB re 20 μPa²·s)	R_{max} (m)	$R_{95\%}$ (m)
Phocid carnivores in air	138	<10	<10	123	<10	<10
Other marine carnivores in air	161	<1	<1	146	<1	<1

Table 8. *Marine carnivores in air, PK thresholds*: Distances to thresholds for permanent threshold shift (PTS) and temporary threshold shift (TTS) due to the detonation of any number of charges of 48 kg TNT (Southall et al. 2019).

Functional hearing group or species	**PTS**		**TTS**	
	PK threshold (L_{pk}; dB re 20 µPa)	R_{max} (m)	PK threshold (L_{pk}; dB re 20 µPa)	R_{max} (m)
Phocid carnivores in air	161	-	155	-
Other marine carnivores in air	176	-	170	-

A dash indicates that the threshold was not reached at a distance greater than 2 m from the source.

Table 9. *Birds*: Distances to permanent threshold shift (PTS) due to the detonation of any number of charges of 48 kg TNT (Dooling and Popper 2016).

PTS SPL (dBA re 20 µPa)	R_{max} **(m)**	$R_{95\%}$ **(m)**	**Area (m²)**
125	<10	<10	<314

Table 10. *Pinnipeds in air, PK and PA-weighted thresholds*: Distances to thresholds for behavioural disturbance (Southall et al. (2007)).

Threshold	R_{max} **(m)**	$R_{95\%}$ **(m)**
$SEL_{PA,24h}$:100 dB re 20 µPa²·s*	472	424
PK: 109 dB re 20 µPa	1127	Not estimated

* Threshold values are frequency-weighted according to the curve for pinnipeds in-air (PA) provided by Southall et al. (2007).

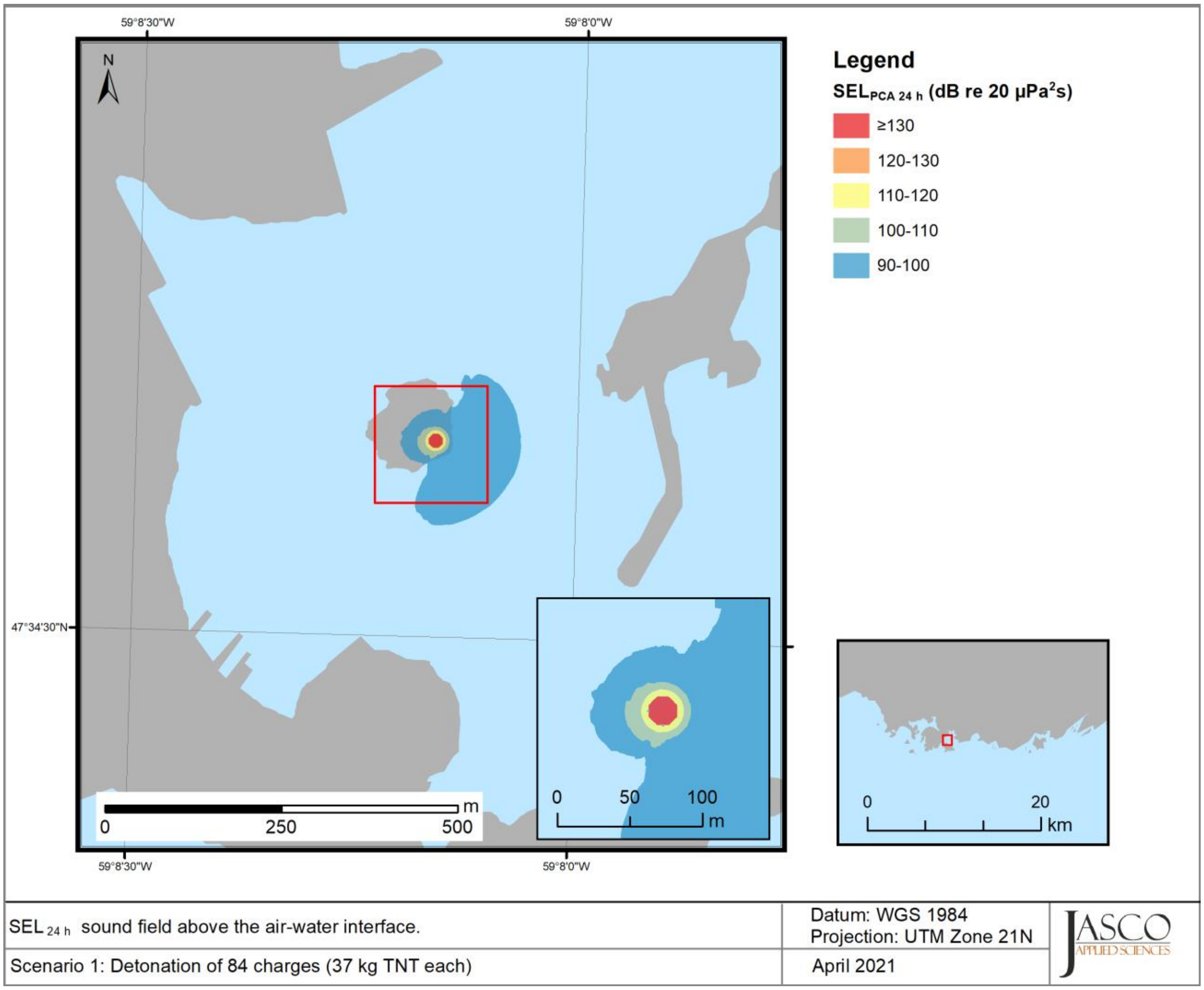


Figure 8. Scenario 1, Phocid carnivores in air hearing group: SEL_{24h} sound field due to detonation of 84 charges of 37 kg TNT, showing contours to the TTS SEL_{24h} threshold.

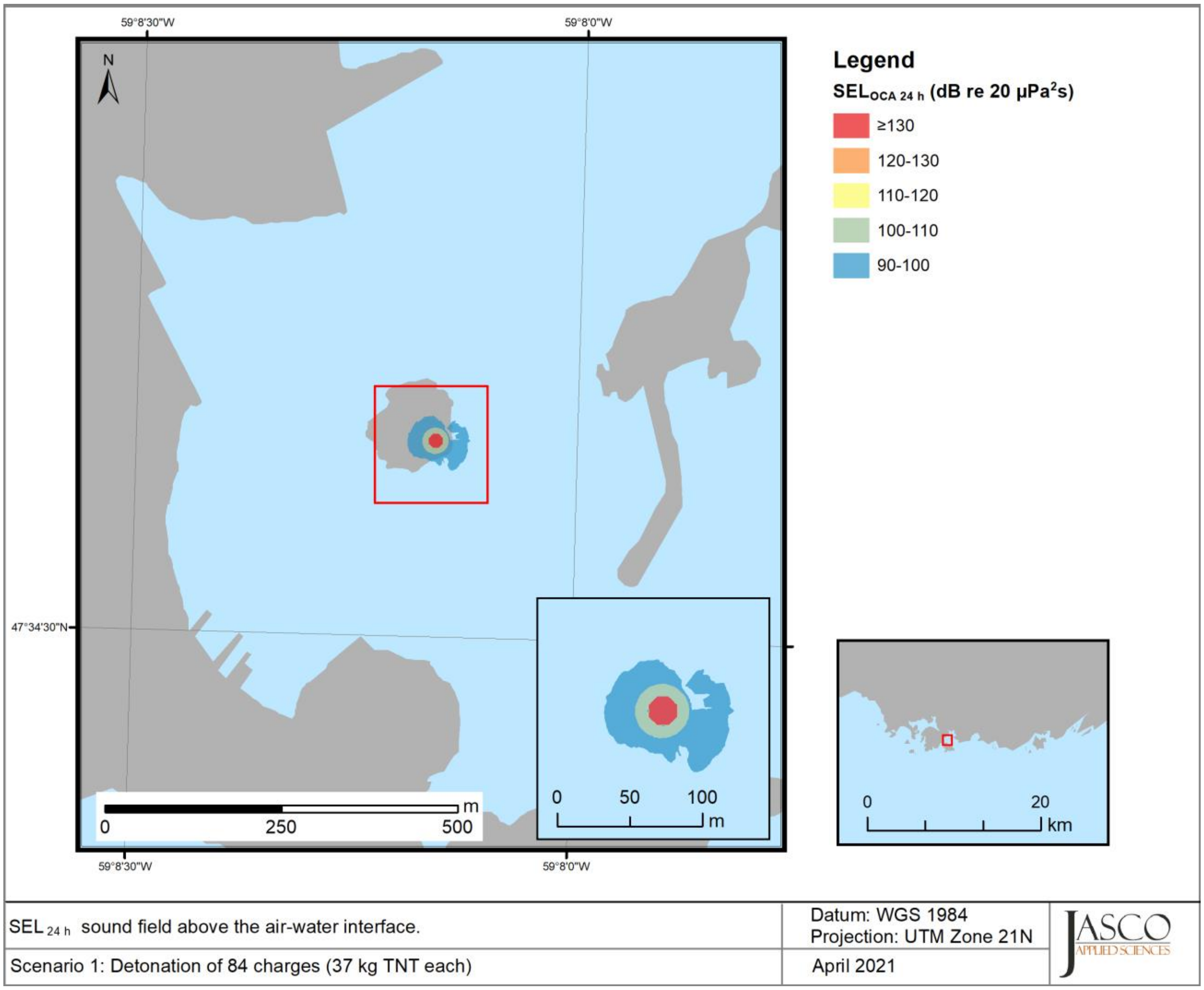


Figure 9. Scenario 1, Other marine carnivores in air hearing group: SEL_{24h} sound field due to detonation of 84 charges of 37 kg TNT. PTS and TTS SEL_{24h} thresholds were not reached for ranges >10 m.

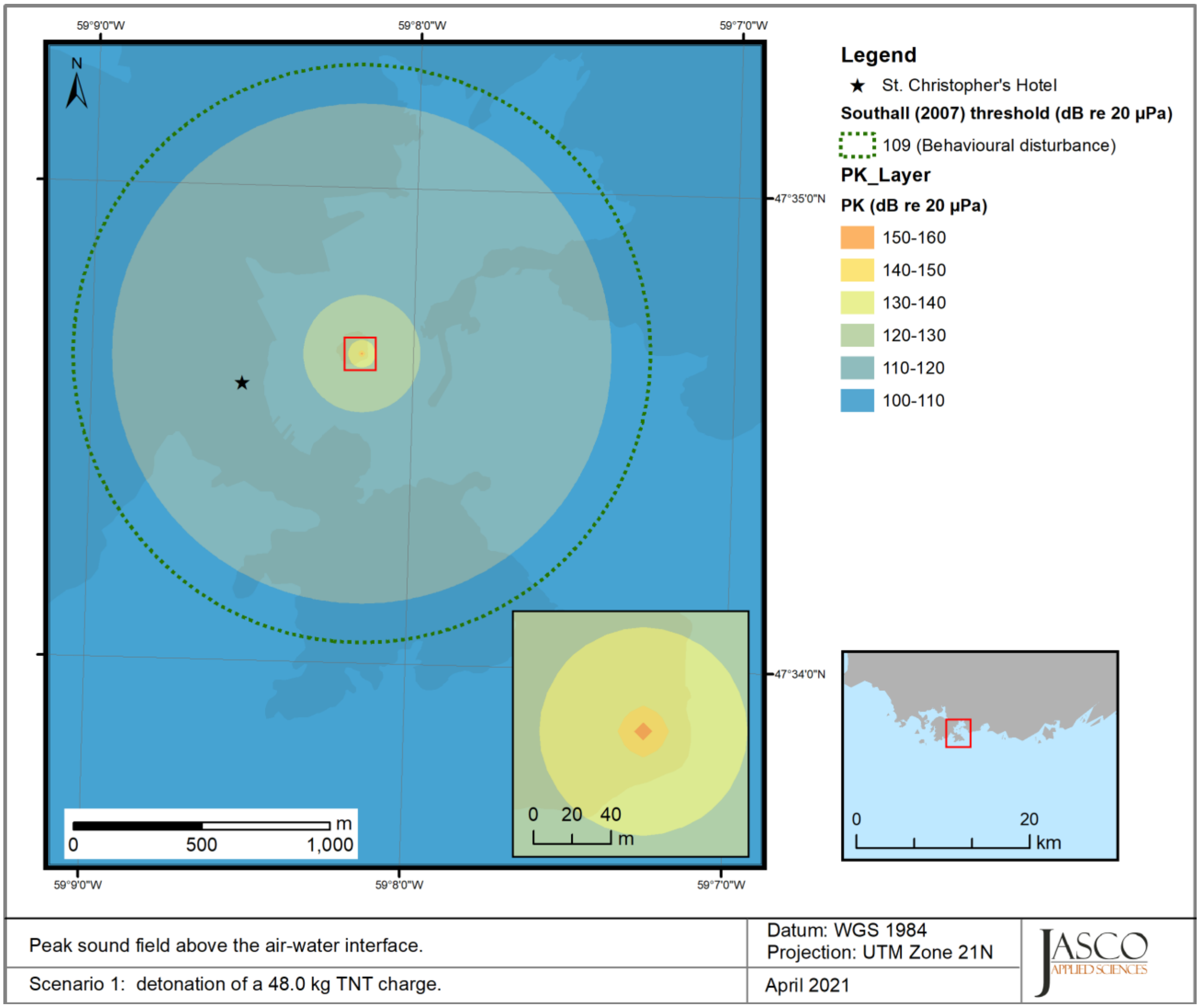


Figure 10. Scenario 1, Phocid carnivores and Other marine carnivores in air hearing groups: PK sound field due to detonation of a single charge of 48 kg TNT, showing the contour to the behavioural disturbance PK threshold. Thresholds to the PTS and TTS PK thresholds were not reached for ranges >10 m and are therefore not shown.

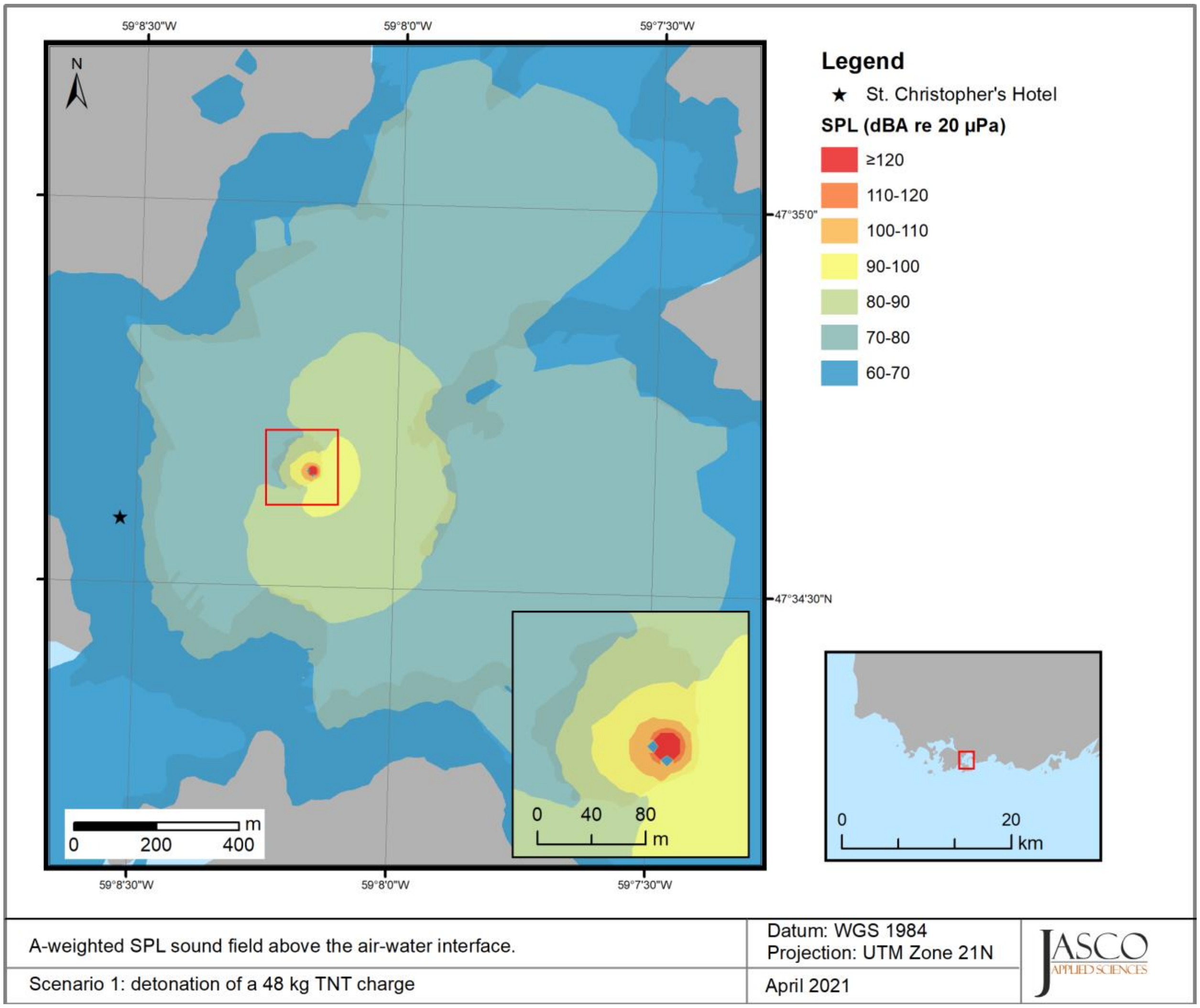


Figure 11. Scenario 1, birds: A-weighted SPL sound field due to detonation of a single charge of 48 kg TNT. The PTS threshold was not reached for ranges >10 m.

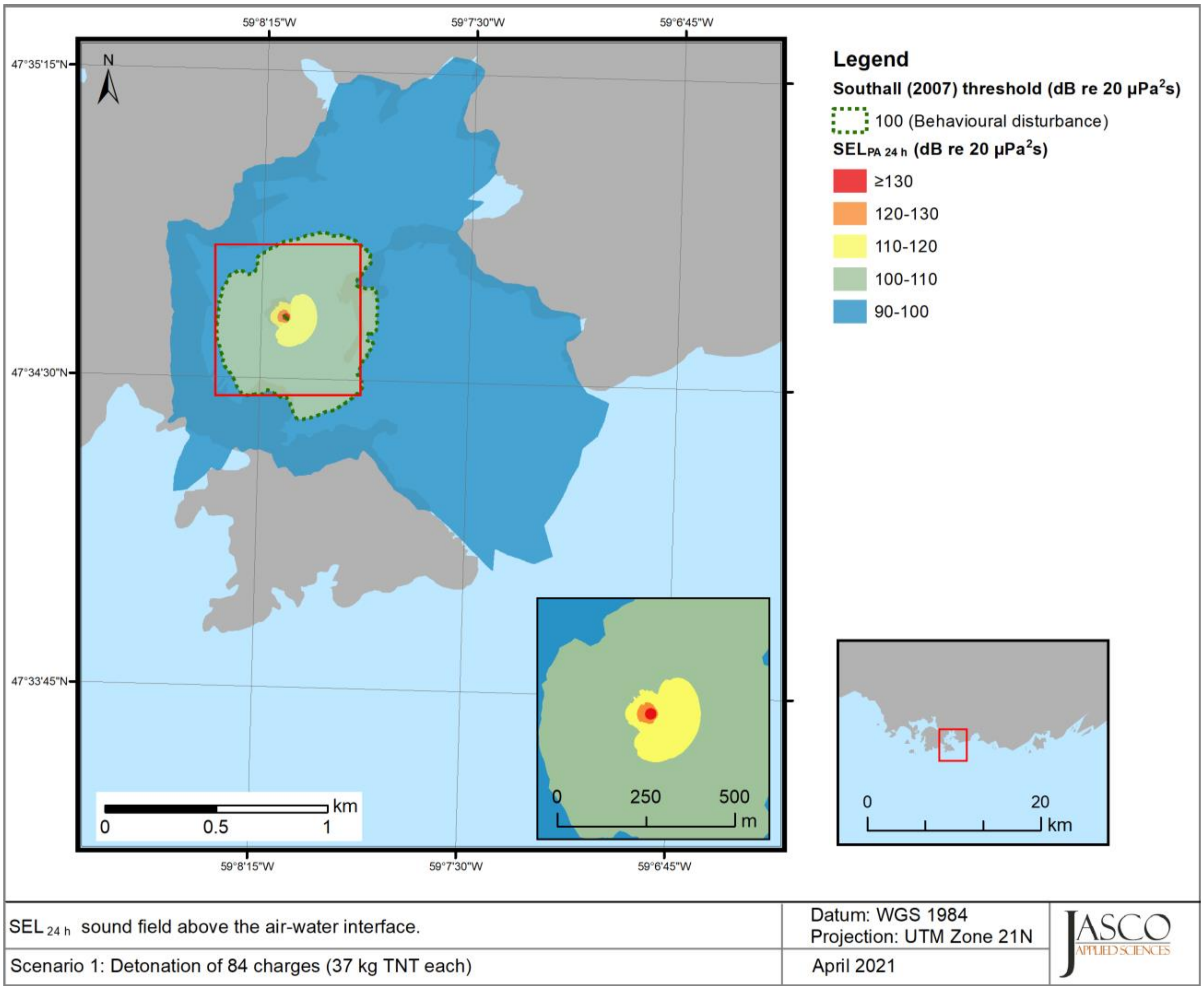


Figure 12. Scenario 1, pinnipeds in air hearing group: SEL_{24h} sound field due to detonation of 84 charges of 37 kg TNT, showing contours to the behavioural disturbance SEL_{24h} threshold.

4.1.1.2. Sound levels at St. Christopher's Hotel

In air sound levels at the northeast corner of the St. Christopher's Hotel (latitude 47° 34.584' N/longitude 59° 8.525' W) due to the detonation of a 48 kg TNT charge at the highest point at Vardys Island were modelled. The hotel is located 480 m from the detonation site and at an elevation of 13 m above sea level. The A-weighted SPL is shown in Figure 13 (left) as a slice plot in range and elevation. The elevation dependency of the A-weighted SPL at the hotel is shown in Figure 13 (right): levels vary between 67–76.6 dBA re 20 µPa for elevations 13–100 m, respectively. Peak levels reached 114.9 dB re 20 µPa. For context, air blast peak levels 110–117 dB re 20 µPa can cause glass window panes and mid-walls to rattle, while peak levels 140 dB re 20 µPa may cause some large windows to break (OSMRE 2008),

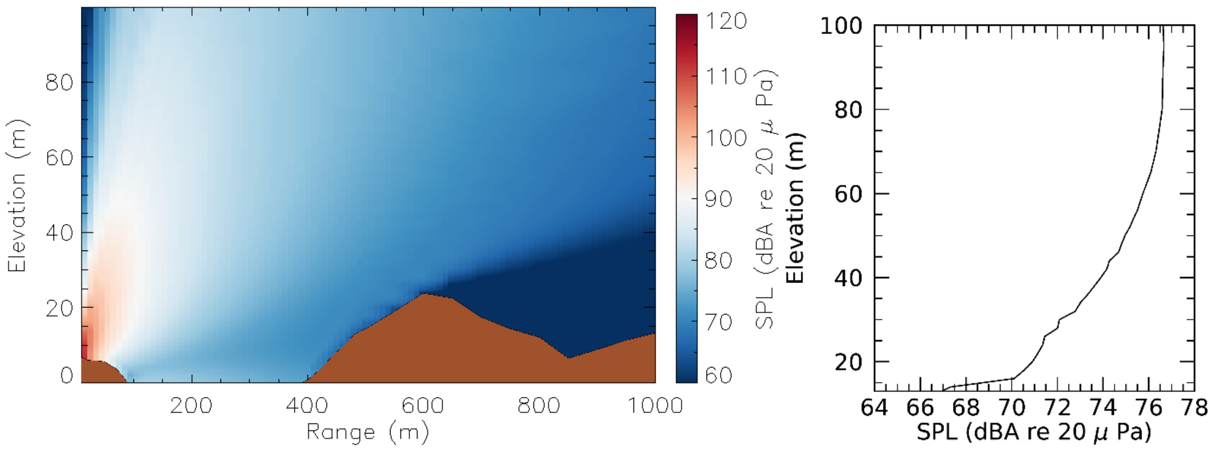


Figure 13. (left) Vertical slice plot showing range and elevation dependency of A-weighted SPL due to detonation of a single charge of 48 kg TNT at the highest point at Vardys Island. (right) A-weighted SPL versus elevation above sea level at the St. Christopher's Hotel.The St. Christopher's Hotel is located at range 480 m and elevation 13 m above sea level.

4.1.2. Drilling (Scenario 2)

Table 11. *Marine mammals, $SEL_{w,24h}$ thresholds*: Distances (m) to thresholds for permanent threshold shift (PTS), temporary threshold shift (TTS), and behavioural disturbance. LF: low-frequency; HF: high-frequency; VHF: very high-frequency.

Functional hearing group or species	PTS*			TTS*			Behavioural†		
	$SEL_{w,24h}$ threshold ($L_{E,24h}$; dB re 1 µPa²·s)	R_{max} (m)	$R_{95\%}$ (m)	$SEL_{w,24h}$ threshold ($L_{E,24h}$; dB re 1 µPa²·s)	R_{max} (m)	$R_{95\%}$ (m)	SPL threshold (L_p; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
LF cetaceans	199	602	399	179	3049	2280	120	21 700	16 200
HF cetaceans	198	15	15	178	375	279			
VHF cetaceans	173	375	280	153	2918	2497			
Phocid carnivores in water	201	103	94	181	1155	912			
Other carnivores in water	219	<10	<10	199	145	135			

* Thresholds, functional hearing group and frequency filters according to Southall et al. (2019).
† Threshold according to NOAA Fisheries (2019), no frequency filter applied.

Table 12. *Fish*: Distances to thresholds for recoverable injury and TTS based on Popper et al. (2014).

Functional hearing group or species	Recoverable Injury			TTS		
	SPL threshold (L_p; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)	SPL threshold (L_p; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
Fish – Swim bladder involved in hearing	170	91	89	158	530	340

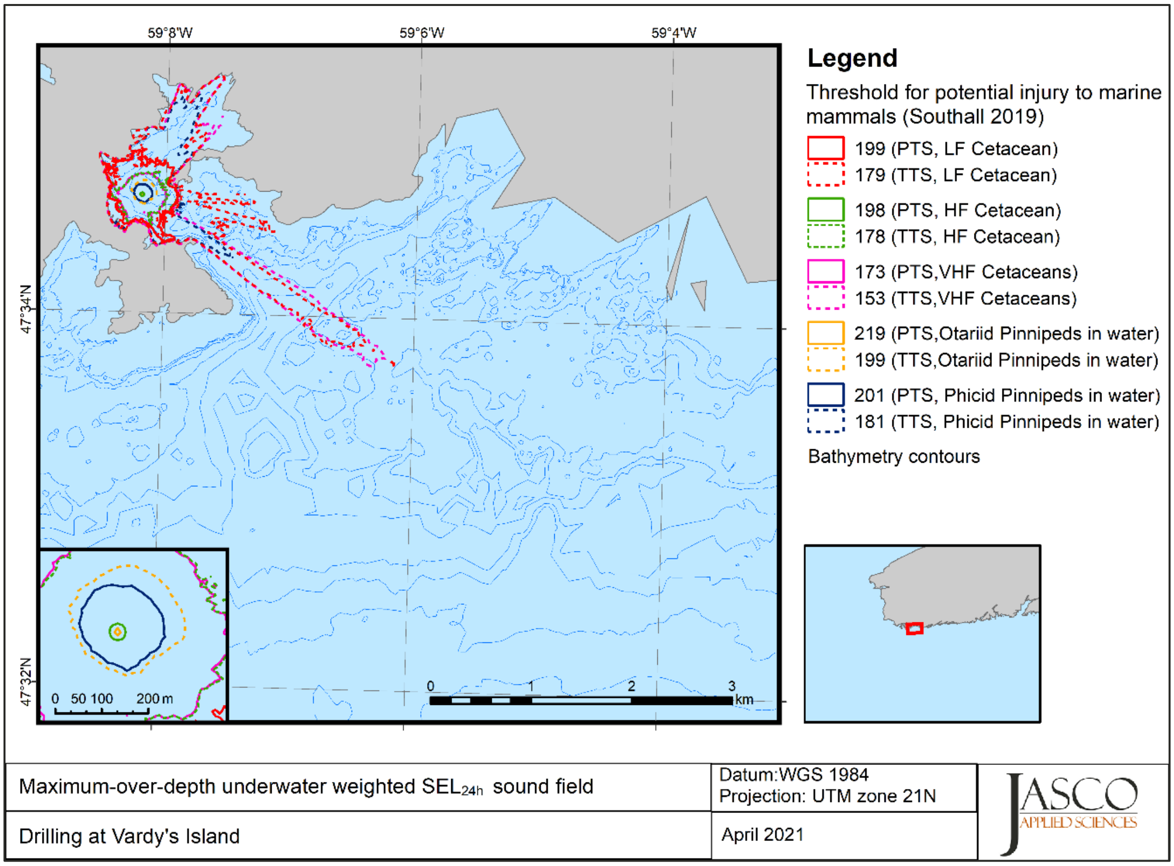
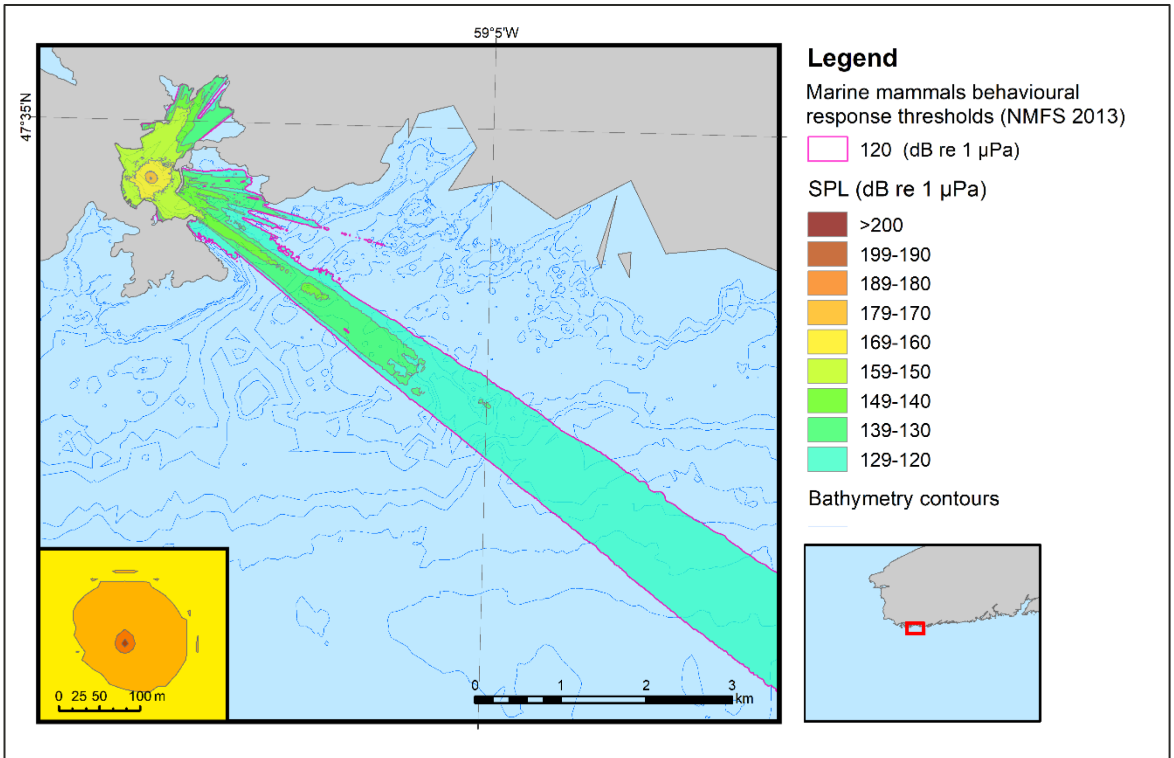


Figure 14. Scenario 2, marine mammals injury thresholds: 24 h frequency-weighted sound exposure level ($SEL_{w,24h}$) threshold contours due to drilling at Vardys Island.



Maximum-over-depth underwater SPL sound field	Datum:WGS 1984 Projection: UTM zone 21N	JASCO APPLIED SCIENCES
Drilling at Vardy's Island	April 2021	

Figure 15. Scenario 2, fish injury thresholds and marine mammal behavioural threshold: SPL sound field and threshold contours due to drilling at Vardys Island.

4.1.3. Underwater Blasting (Scenario 3)

Table 13. *Marine mammals $SEL_{w,24h}$ thresholds*: Distances (m) to thresholds for permanent threshold shift (PTS) and temporary threshold shift (TTS) due to the detonation of 84 charges. LF: low-frequency; HF: high-frequency; VHF: very high-frequency.

Functional hearing group or species	**PTS***			**TTS***		
	$SEL_{w,24h}$ threshold ($L_{E,24h}$; dB re 1 µPa²·s)	R_{max} (m)	$R_{95\%}$ (m)	$SEL_{w,24h}$ threshold ($L_{E,24h}$; dB re 1 µPa²·s)	R_{max} (m)	$R_{95\%}$ (m)
LF cetaceans	183	2500	2240	168	6160	5120
HF cetaceans	185	<10	<10	170	72	72
VHF cetaceans	155	227	177	140	753	572
Phocid in water	185	620	493	170	2470	1530
Otariids, mustelids in water	203	34	31	188	262	239

* Thresholds, functional hearing group and frequency filters according to Southall et al. (2019).

Table 14. Distances (m) to the NOAA Fisheries (2019) marine mammal behavioral disturbance threshold for impulsive noise, due to detonation of a single charge.

SPL threshold (L_p; dB re 1 µPa)	**R_{max} (m)**	**$R_{95\%}$ (m)**
160	6300	5270

Table 15. *Marine mammals PK thresholds*: Distances (m) to thresholds for permanent threshold shift (PTS) and temporary threshold shift (TTS) based on Southall et al. (2019) due to the detonation of a single charge. LF: low-frequency; HF: high-frequency; VHF: very high-frequency.

Functional hearing group or species	**PTS**			**TTS**		
	PK threshold ($L_{p,pk}$; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)	PK threshold ($L_{p,pk}$; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
LF cetaceans	219	290	244	213	600	395
HF cetaceans	230	66	66	224	169	150
VHF cetaceans	202	921	596	196	2180	909
Phocid in water	218	331	258	212	613	455
Otariids, mustelids in water	232	52	52	226	123	116

Table 16. Fish, Invertebrates, Eggs, and Larvae: Distances to PK and PK-PK thresholds for mortality, potential mortal injury, and non-lethal injury due to the detonation of explosives.

Functional hearing group or species	**Mortality and potential mortal injury**			**Non-lethal injury**		
	PK threshold ($L_{p,pk}$; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)	PK-PK threshold ($L_{p,pk-pk}$; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
Fish – all types	220*	253	231	n/a	n/a	n/a
Invertebrates (crustaceans)	220*	253	231	209‡	771	587
Eggs and larvae	13 mm/s (peak particle velocity)*†	105*	n/a	n/a	n/a	n/a

* Based on Wright and Hopky (1998).
† Based on Popper et al. (2014).
‡ Based on Day et al. (2016a), Day et al. (2016b), and Day et al. (2019).

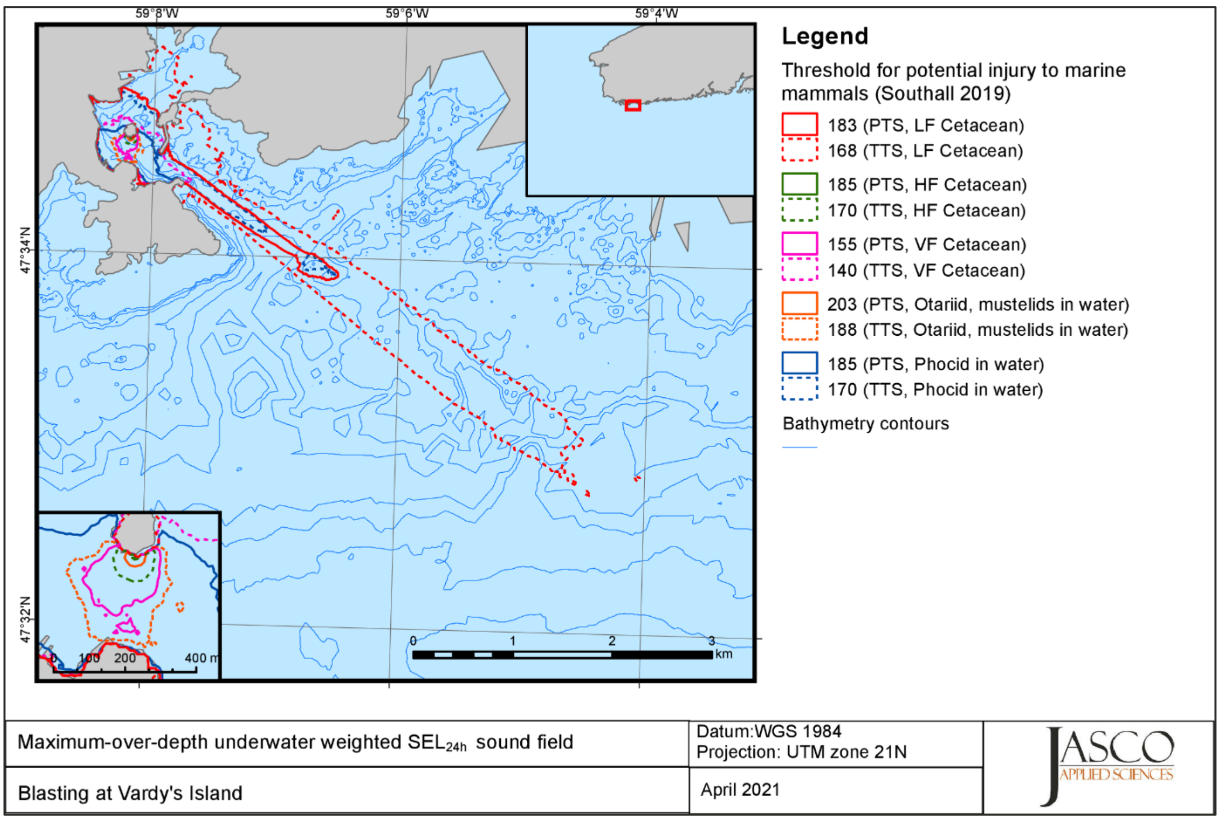


Figure 16. Scenario 3, marine mammals injury thresholds: 24 h frequency-weighted sound exposure level ($SEL_{w,24h}$) threshold contours due to the detonation of 84 charges at Vardys Island.

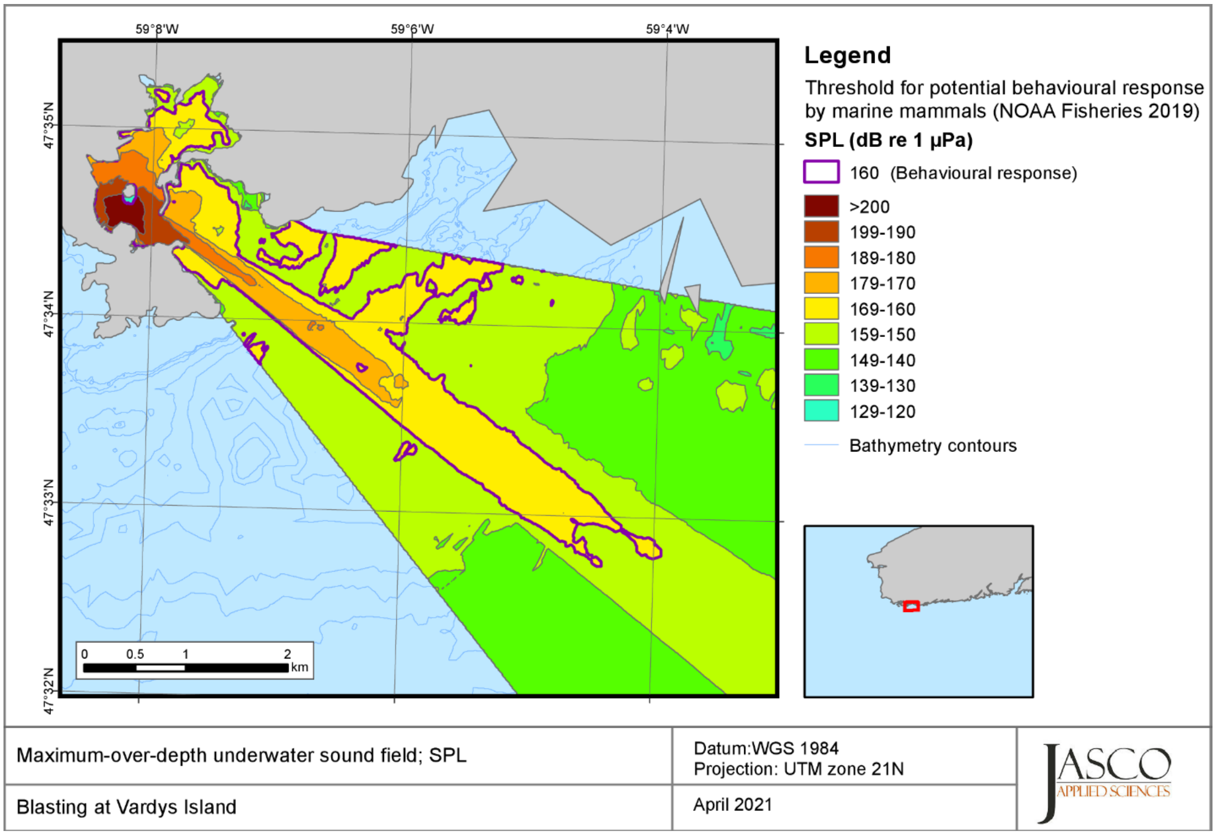


Figure 17. Scenario 3, marine mammal behavioural threshold: SPL sound field and threshold contour due to the detonation of charges at Vardys Island.

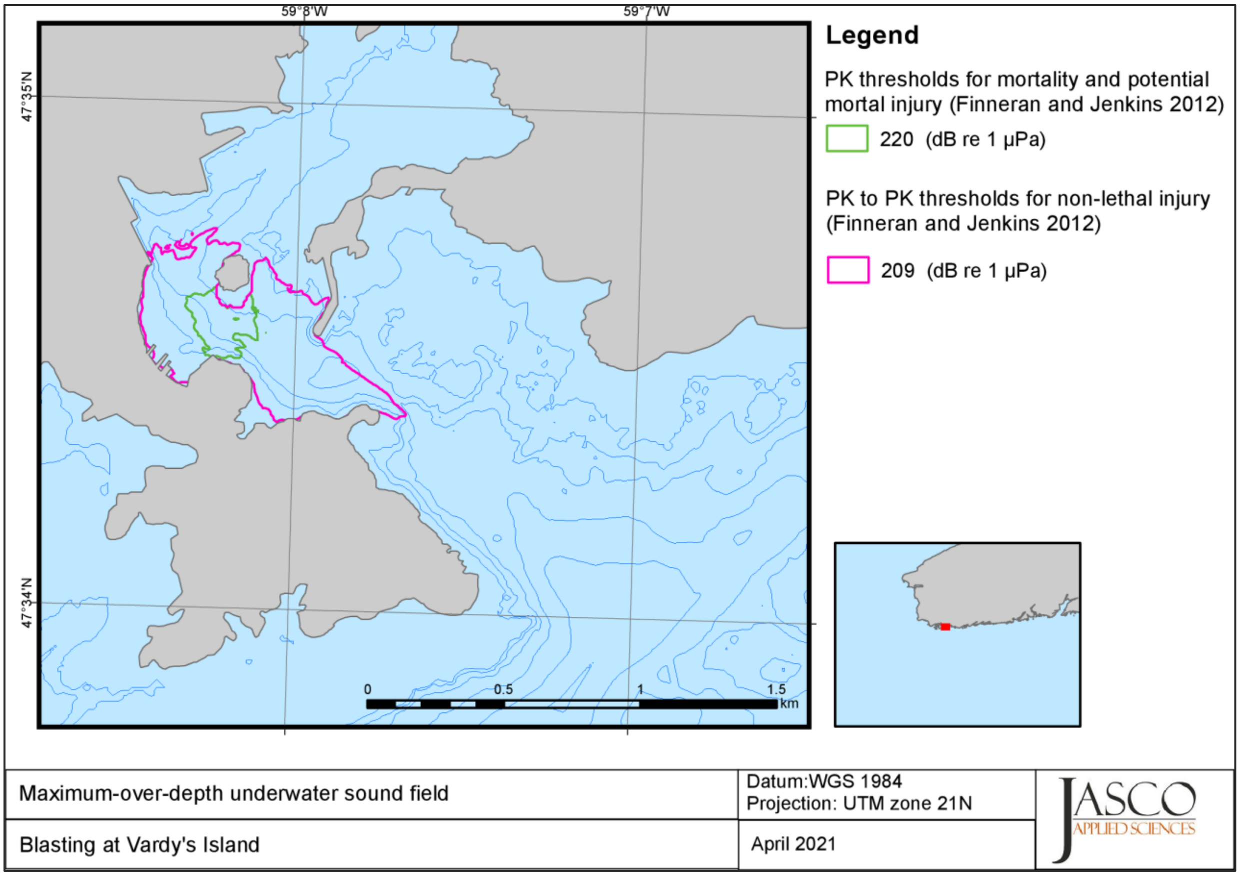


Figure 18. Scenario 3, fish and invertebrates injury thresholds: Zero to peak and peak-to-peak threshold contours due to the detonation of charges at Vardys Island.

4.1.4. Dredging (Scenario 4)

Table 17. *Marine mammals, $SEL_{w,24h}$ thresholds*: Distances (m) to thresholds for permanent threshold shift (PTS), temporary threshold shift (TTS), and behavioural disturbance. LF: low-frequency; HF: high-frequency; VHF: very high-frequency.

Functional hearing group or species	**PTS***			**TTS***			**Behavioural†**		
	$SEL_{w,24h}$ threshold ($L_{E,24h}$; dB re 1 µPa²·s)	R_{max} (m)	$R_{95\%}$ (m)	$SEL_{w,24h}$ threshold ($L_{E,24h}$; dB re 1 µPa²·s)	R_{max} (m)	$R_{95\%}$ (m)	SPL threshold (L_p; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
LF cetaceans	199	46	45	179	781	585	120	2493	2121
HF cetaceans	198	<10	<10	178	<10	<10			
VHF cetaceans	173	<10	<10	153	131	113			
Phocid carnivores in water	201	<10	<10	181	160	134			
Other carnivores in water	219	<10	<10	199	<10	<10			

* Thresholds, functional hearing group and frequency filters according to Southall et al. (2019).
† Threshold according to NOAA Fisheries (2019), no frequency filter applied.

Table 18. *Fish*: Distances to thresholds for recoverable injury and TTS based on Popper et al. (2014).

Functional hearing group or species	**Recoverable injury**			**TTS**		
	SPL threshold (L_p; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)	SPL threshold (L_p; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
Fish – Swim bladder involved in hearing	170	<10	<10	158	19	19

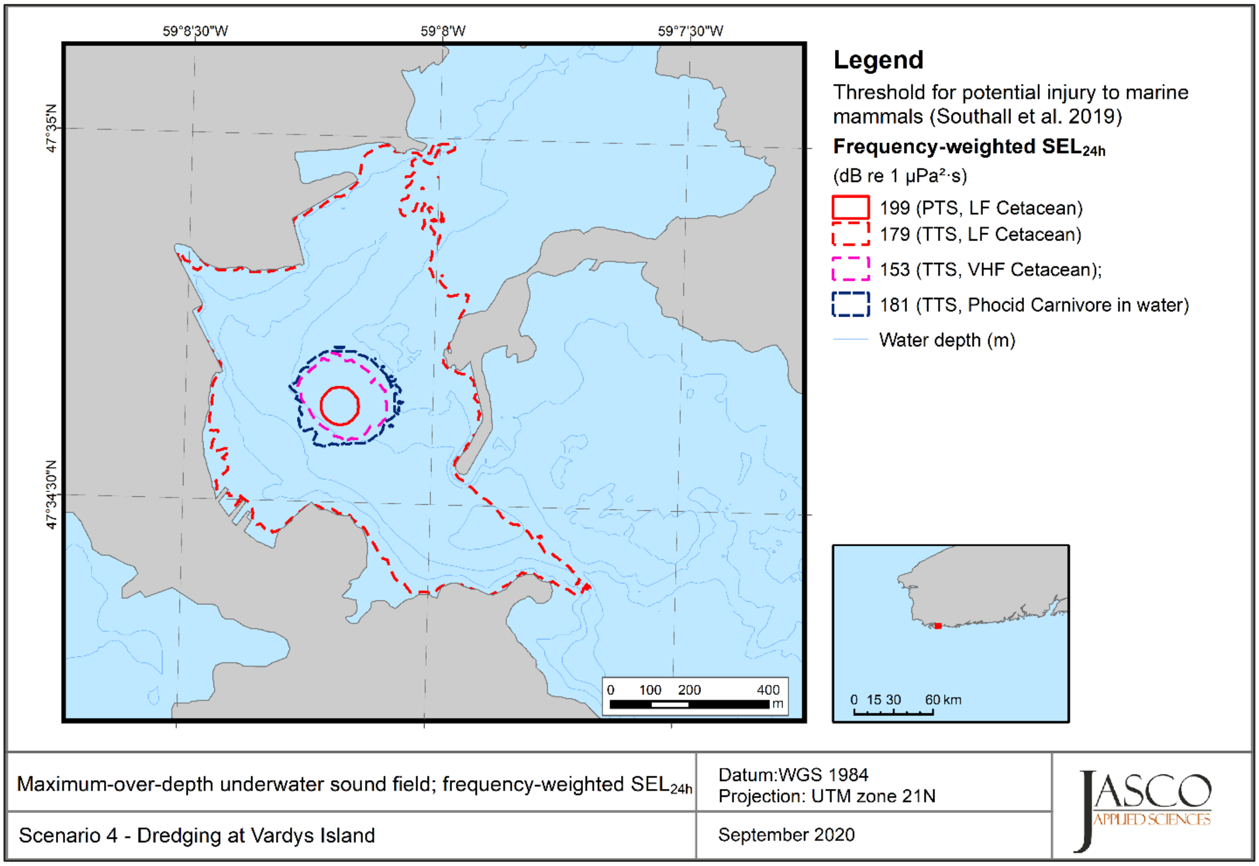


Figure 19. Scenario 4, marine mammals injury thresholds: 24 h frequency-weighted sound exposure level ($SEL_{w,24h}$) threshold contours due to dredging at Vardys Island.

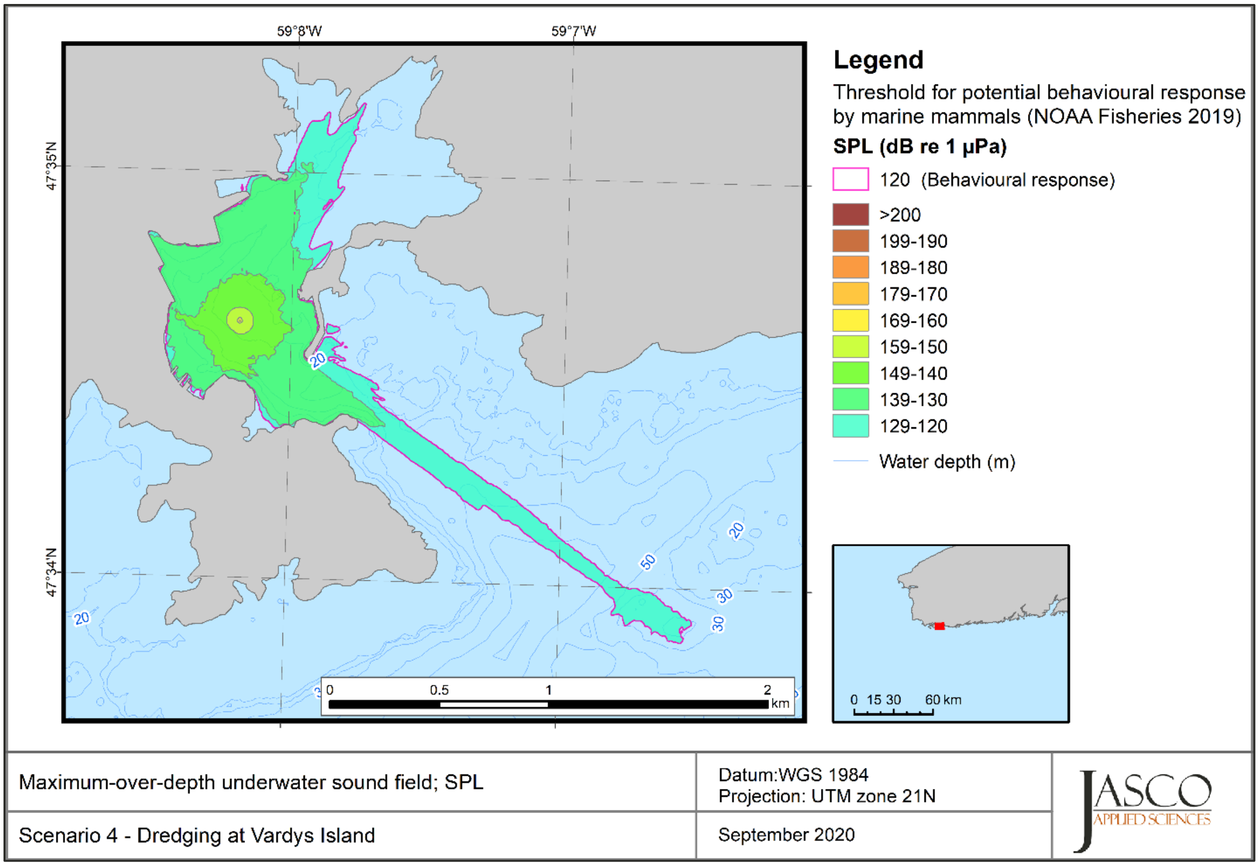


Figure 20. Scenario 4, marine mammal behavioural threshold: SPL sound field and threshold contour due to dredging at Vardys Island. Distances to fish injury thresholds are too short to be represented on a map.

4.2. Baldwin Rock Site

4.2.1. Drilling (Scenario 5)

Table 19. *Marine mammals, $SEL_{w,24h}$ thresholds*: Distances (m) to thresholds for permanent threshold shift (PTS), temporary threshold shift (TTS), and behavioural disturbance. LF: low-frequency; HF: high-frequency; VHF: very high-frequency.

Functional hearing group or species	PTS*			TTS*			Behavioural†		
	$SEL_{w,24h}$ threshold ($L_{E,24h}$; dB re 1 µPa²·s)	R_{max} (m)	$R_{95\%}$ (m)	$SEL_{w,24h}$ threshold ($L_{E,24h}$; dB re 1 µPa²·s)	R_{max} (m)	$R_{95\%}$ (m)	SPL Threshold (L_p; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
LF cetaceans	199	630	474	179	8400	7000	120	>50,000	-
HF cetaceans	198	15	15	178	433	333			
VHF cetaceans	173	430	350	153	3250	2900			
Phocid carnivores in water	201	94	80	181	1680	1065			
Other carnivores in water	219	<10	<10	199	133	133			

* Thresholds, functional hearing group and frequency filters according to Southall et al. (2019).
† Threshold according to NOAA Fisheries (2019), no frequency filter applied.

Table 20. *Fish*: Distances to thresholds for recoverable injury and TTS based on Popper et al. (2014).

Functional hearing group or species	Recoverable Injury			TTS		
	SPL threshold (L_p; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)	SPL threshold (L_p; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
Fish – Swim bladder involved in hearing	170	64	61	158	590	357

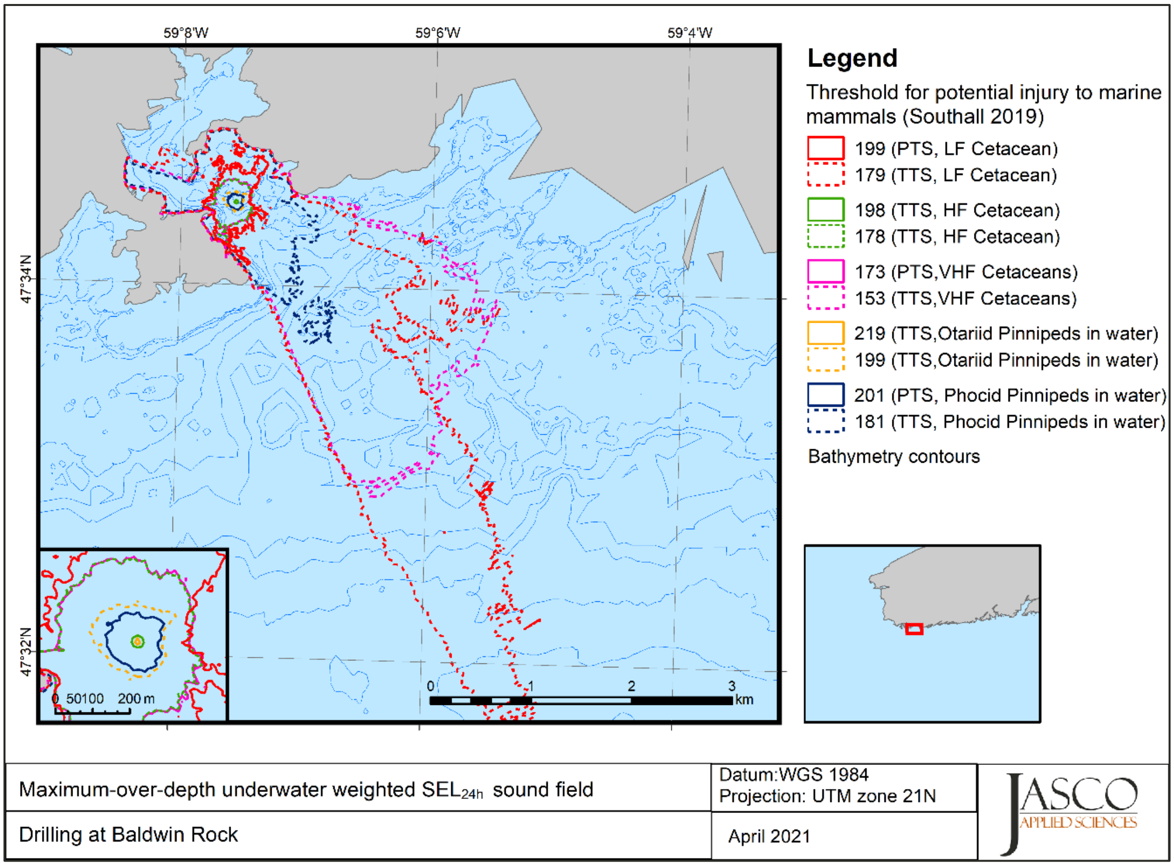


Figure 21. Scenario 5, marine mammals injury thresholds: 24 h frequency-weighted sound exposure level ($SEL_{w,24h}$) threshold contours due to drilling at Baldwin Rock.

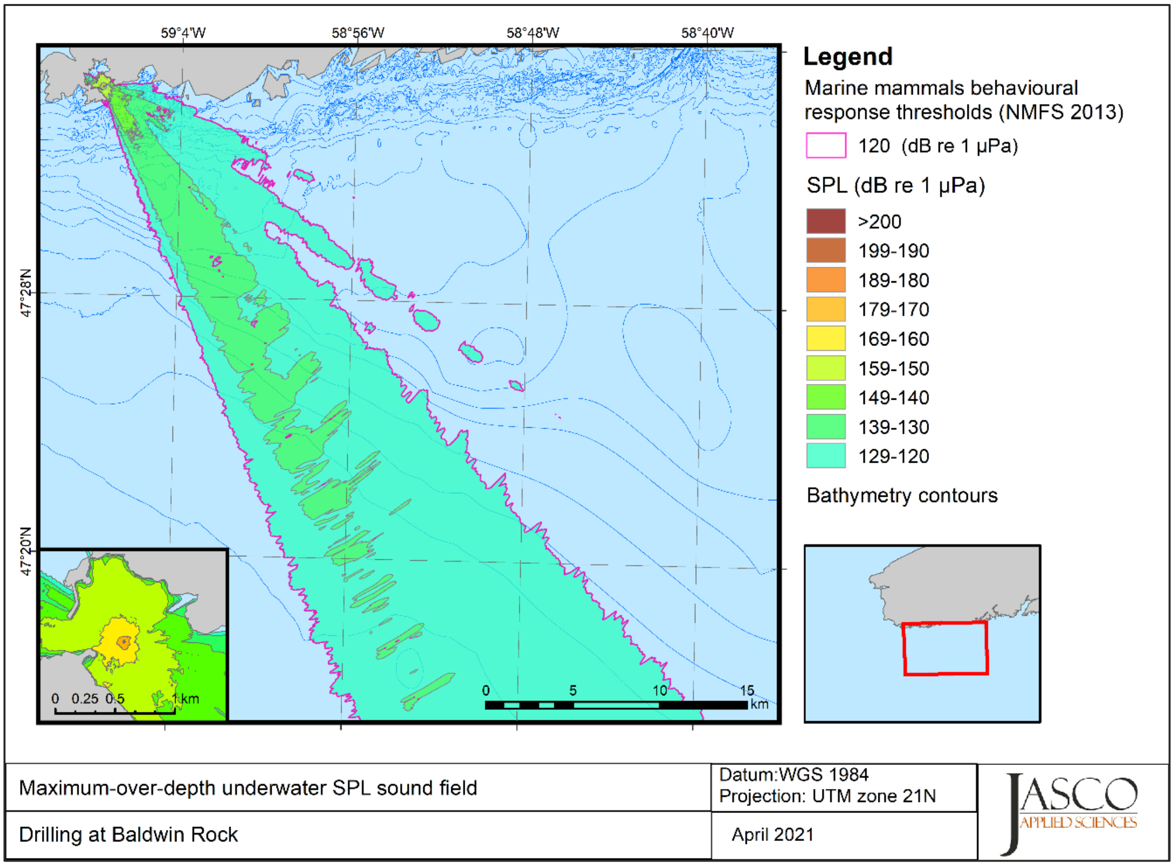


Figure 22. Scenario 5, fish injury thresholds and marine mammal behavioural threshold: SPL sound field and threshold contours due to drilling at Baldwin Rock.

4.2.2. Underwater Blasting (Scenario 6)

Table 21. *Marine mammals $SEL_{w,24h}$ thresholds*: Distances (m) to thresholds for permanent threshold shift (PTS) and temporary threshold shift (TTS) due to the detonation of 84 charges. LF: low-frequency; HF: high-frequency; VHF: very high-frequency.

Functional hearing group or species	PTS*			TTS*		
	$SEL_{w,24h}$ threshold ($L_{E,24h}$; dB re 1 µPa²·s)	R_{max} (m)	$R_{95\%}$ (m)	$SEL_{w,24h}$ threshold ($L_{E,24h}$; dB re 1 µPa²·s)	R_{max} (m)	$R_{95\%}$ (m)
LF cetaceans	183	3542	3146	168	>50000†	>50000
HF cetaceans	185	<10	<10	170	66	66
VHF cetaceans	155	114	98	140	817	593
Phocid in water	185	572	400	170	2700	2350
Otariids, mustelids in water	203	24	23	188	154	130

* Thresholds, functional hearing group and frequency filters according to Southall et al. (2019).
† The prediction at large ranges is not reliable due to environmental factors (such as complex scattering, and surface and ocean inhomogeneities) that the model does not account for. These factors can significantly increase propagation loss over large distance and decrease the range to the threshold.

Table 22. Distances (m) to the NOAA Fisheries (2019) marine mammal behavioral disturbance threshold for impulsive noise, due to detonation of a single charge.

SPL threshold (L_p; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
160	>50,000†	>50,000

† The prediction at large ranges is not reliable due to environmental factors (such as complex scattering, and surface and ocean inhomogeneities) that the model does not account for. These factors can significantly increase propagation loss over large distance and decrease the range to the threshold.

Table 23. *Marine mammals PK thresholds*: Distances (m) to thresholds for permanent threshold shift (PTS) and temporary threshold shift (TTS) based on Southall et al. (2019) due to the detonation of a single charge. LF: low-frequency; HF: high-frequency; VHF: very high-frequency.

Functional hearing group or species	PTS			TTS		
	PK threshold ($L_{p,pk}$; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)	PK threshold ($L_{p,pk}$; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
LF cetaceans	219	287	210	213	647	511
HF cetaceans	230	64	64	224	155	123
VHF cetaceans	202	1693	1422	196	3020	2324
Phocid in water	218	294	244	212	681	541
Otariids, mustelids in water	232	10	10	226	123	100

Table 24. Fish, Invertebrates, Eggs, and Larvae: Distances to PK and PK-PK thresholds for mortality, potential mortal injury, and non-lethal injury due to the detonation of explosives.

Functional hearing group or species	Mortality and potential mortal injury			Non-lethal injury		
	PK threshold ($L_{p,pk}$; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)	PK-PK threshold ($L_{p,pk\text{-}pk}$; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
Fish – all types	220*	280	187	n/a	n/a	n/a
Invertebrates (crustaceans)	220*	280	187	209‡	1524	1248
Eggs and larvae	13 mm/s (peak particle velocity)*†	113*	n/a	n/a	n/a	n/a

* Based on Wright and Hopky (1998).
† Based on Popper et al. (2014).
‡ Based on Day et al. (2016a), Day et al. (2016b), and Day et al. (2019).

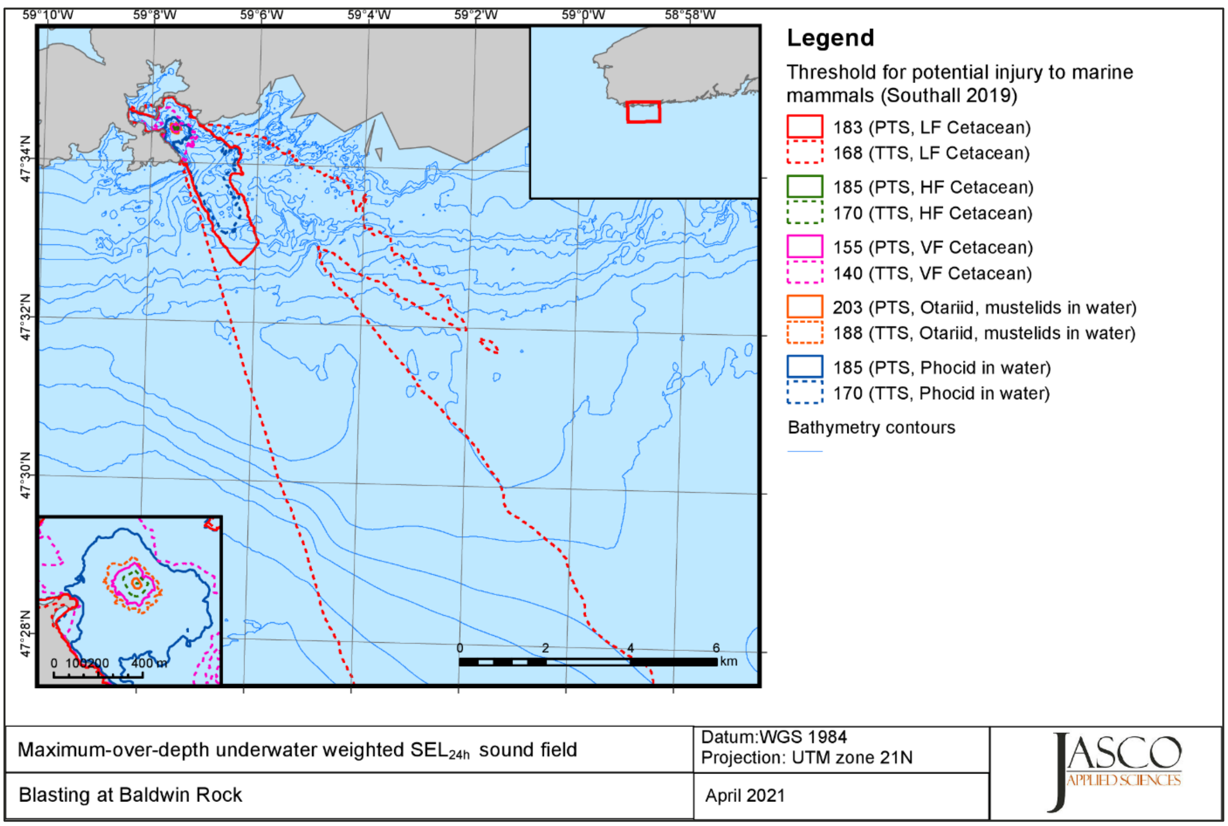


Figure 23. Scenario 6, marine mammals injury thresholds: 24 h frequency-weighted sound exposure level ($SEL_{w,24h}$) threshold contours due to the detonation of 56 charges at Baldwin Rock.

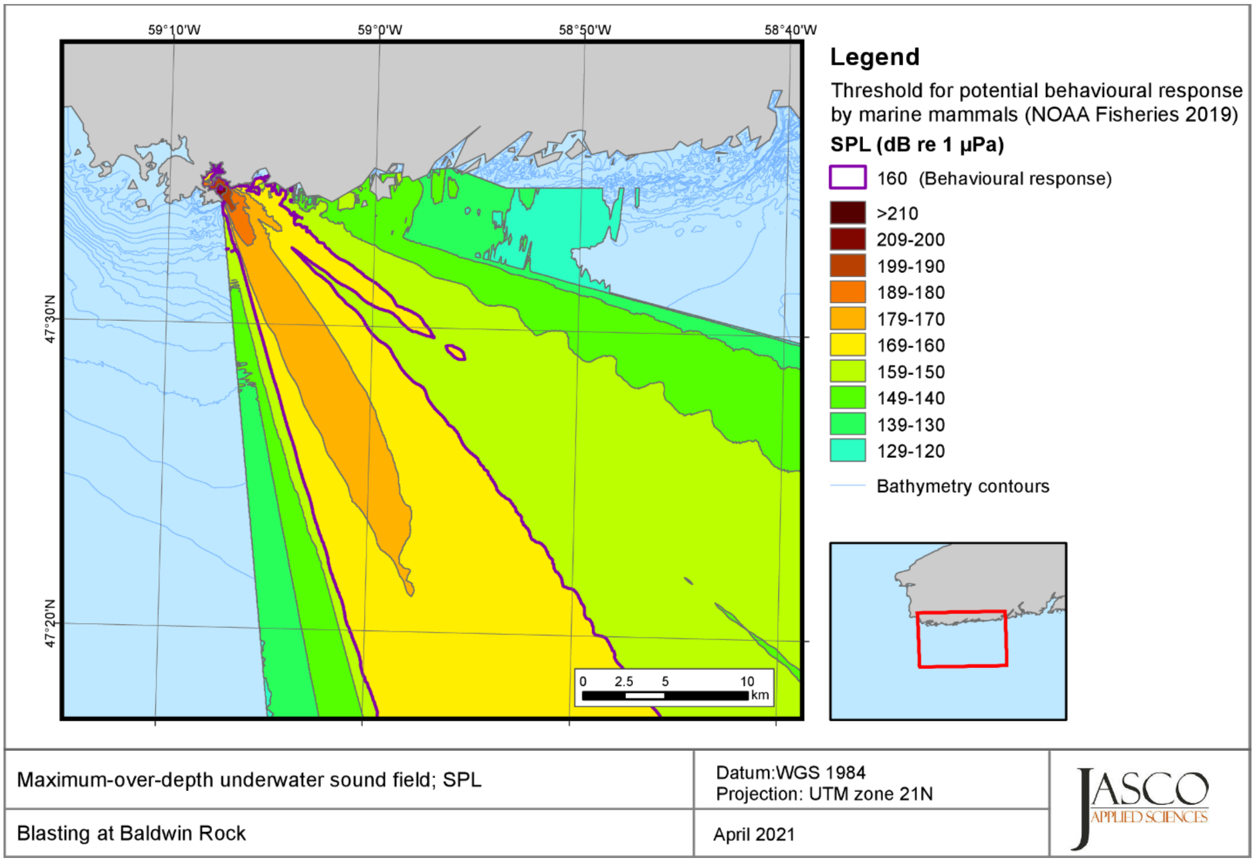


Figure 24. Scenario 6, marine mammal behavioural threshold: SPL sound field and threshold contour due to the detonation of charges at Baldwin Rock.

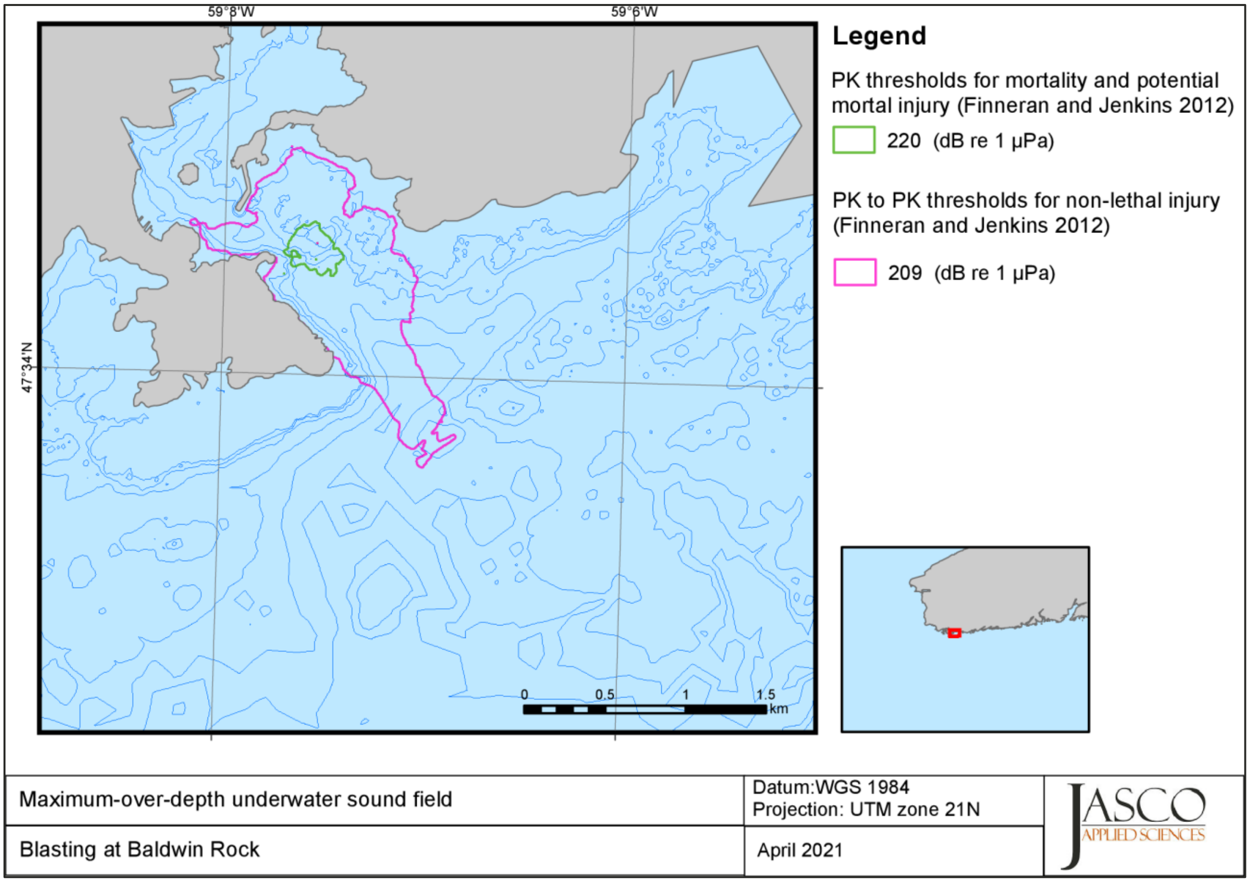


Figure 25. Scenario 6 fish and invertebrates injury thresholds: Zero to peak and peak-to-peak threshold contours due to the detonation of each charge at Baldwin Rock.

4.2.3. Dredging (Scenario 7)

Table 25. *Marine mammals, SEL$_{w,24h}$ thresholds*: Distances (m) to thresholds for permanent threshold shift (PTS), temporary threshold shift (TTS), and behavioural disturbance. LF: low-frequency; HF: high-frequency; VHF: very high-frequency.

Functional hearing group or species	PTS*			TTS*			Behavioural†		
	SEL$_{w,24h}$ threshold ($L_{E,24h}$; dB re 1 µPa²·s)	R_{max} (m)	$R_{95\%}$ (m)	SEL$_{w,24h}$ threshold ($L_{E,24h}$; dB re 1 µPa²·s)	R_{max} (m)	$R_{95\%}$ (m)	SPL threshold (L_p; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
LF cetaceans	199	51	44	179	945	642	120	3700	3075
HF cetaceans	198	<10	<10	178	<10	<10			
VHF cetaceans	173	<10	<10	153	121	104			
Phocid carnivores in water	201	<10	<10	181	158	121			
Other carnivores in water	219	<10	<10	199	<10	<10			

* Thresholds, functional hearing group and frequency filters according to Southall et al. (2019).
† Threshold according to NOAA Fisheries (2019), no frequency filter applied.

Table 26. *Fish*: Distances to thresholds for recoverable injury and TTS based on Popper et al. (2014).

Functional hearing group or species	Recoverable injury			TTS		
	SPL threshold (L_p; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)	SPL threshold (L_p; dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
Fish – Swim bladder involved in hearing	170	<10	<10	158	15	15

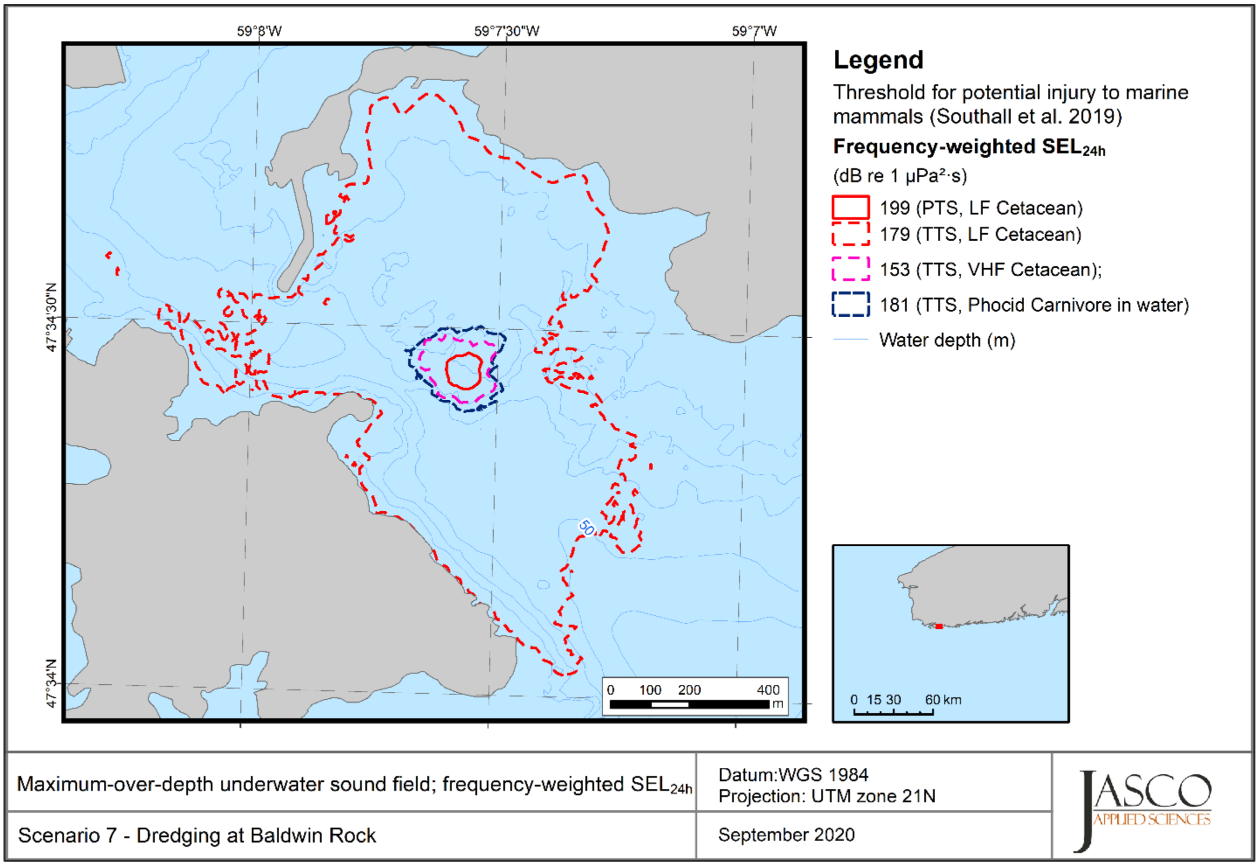


Figure 26. Scenario 7, marine mammals injury thresholds: 24 h frequency-weighted sound exposure level ($SEL_{w,24h}$) threshold contours due to dredging at Baldwin Rock.

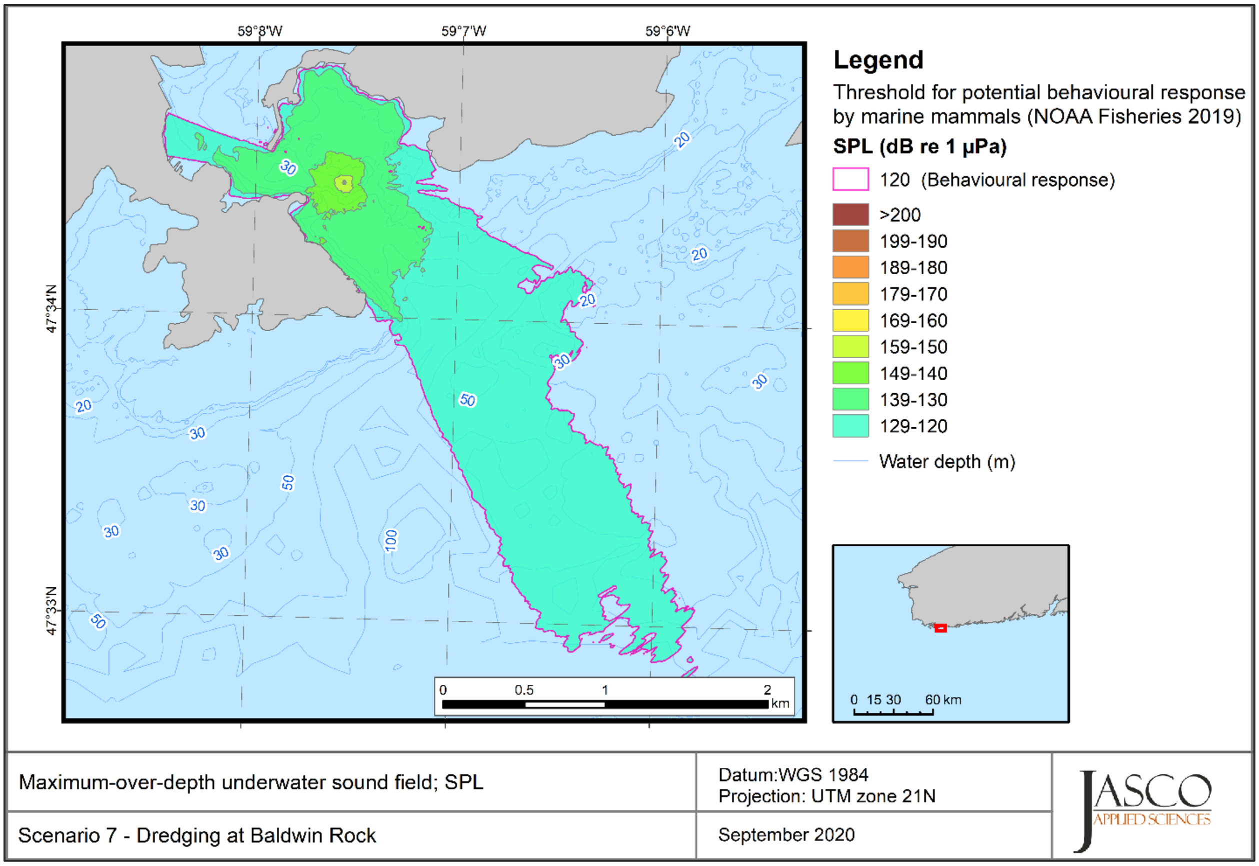


Figure 27. Scenario 7, marine mammal behavioural threshold: SPL sound field and threshold contour due to dredging at Baldwin Rock. Distances to fish injury thresholds are too short to be represented on a map.

5. Summary and Conclusions

JASCO performed acoustic modelling for the construction activities associated with the improvement project of Port aux Basques, NL. Modelled construction activities included rock blasting above the water line, underwater drilling, blasting, and dredging. The modelling was completed at two sites: in the limits of Vardys Island (to be removed completely) and at Baldwin Rock. Vardys Island is located behind the breakwater structure which limits underwater sound propagation towards open sea. Baldwin Rock is located outside of the sheltered harbour where underwater sound propagation is less restricted by land.

5.1. In-air Sound Modelling

In-air sound propagation was modelled only at the Vardys Island location. A gridded terrain elevation model was created and environmental properties representative of the month of April were used for conservative modelling as they resulted in the longest in-air propagation distances. Modelling to estimate distances to $SEL_{w,24h}$ thresholds was carried out assuming detonation of 84 charges (37 kg TNT per charge) placed within boreholes drilled in the island in a 2.5 x 2.5 m grid. Modelling to estimate distances to PK and SPL metrics was carried out assuming detonation of a single 48 kg TNT charge. Source levels for in-air charge detonation were estimated using ConWep software and measurements of in-air blasting. Distances to PTS and TTS thresholds for phocid carnivores in air (PCA) and other carnivores in air (OCA), as well as distances to the PTS threshold for birds based on (Dooling and Popper 2016)) were determined to be <10 m (Table 9) from the detonation site.

5.2. Underwater Sound Modelling

For underwater sound propagation modelling, a high resolution and accurate bathymetrical grid was created using data from multiple datasets: multi-beam bathymetry data provided by the client, navigational chart data, and the NOAA 3-sec bathymetrical grid. Two variants of the grid were created to reflect the state of the bottom relief at different stages of the construction project (Appendix C.4.2). The construction activities will be carried out year-round, so the month with the most favourable sound propagation conditions (February) was used for modelling.

The source levels for drilling and dredging operations were compiled using measurements of similar activities. The source signature for a TNT charge detonation below the water line was modelled using ConWep software with calibration to empirical regression curves.

The exposure assessment was performed in terms of ranges to specific sound level thresholds. The sound field from dredging and drilling operations was assessed using Southall et al. (2019) PTS/TTS criteria for non-impulsive sounds. The underwater sound field from underwater blasting operations was assessed using Southall et al. (2019) dual criteria defined for impulsive sounds.

The Baldwin Rock scenarios resulted in larger threshold ranges than corresponding operations at Vardys Island. This is because Baldwin Rock is located closer to the open sea and in deeper water. It is also worth noting that it is unlikely that a marine mammal would remain in the relatively narrow portion of the 24 h SEL field that escapes the inner harbour in the case of the Vardys Island scenarios (e.g., Figure 14 – TTS for VHF cetaceans).

For the drilling scenarios, we modelled total of 38.3 hours of drilling in 24 h period shared between three drills for the SEL_{24h} calculations. The longest distances to the marine mammal PTS and TTS thresholds are 630 m and 8.4 km, respectively, corresponding to the LF cetaceans hearing group. For fish, distances to recoverable injury and TTS thresholds are 64 m and 590 m, respectively.

Dredging was modelled using a time period of 24 hours per day to simulate continuous operation. Modelling results showed dredging produces the least noise of the three modelled construction activities. Out of all marine mammal hearing groups considered, the LF cetaceans hearing group had the longest range to PTS (51 m) and TTS (945 m). For fish, distances to recoverable injury and TTS thresholds are <10 m and 15 m, respectively.

The blasting operation was modelled using 84 boreholes with 48 kg of TNT-equivalent explosive at Vardys Island site and 56 boreholes with 56 kg of TNT-equivalent explosive at Baldwin Rock site detonated per 24 h period. Underwater rock blasting yielded the greatest acoustic impact due to the properties of the source (high amplitude, with PK source level of 271.3 dB re 1 µPa m and energy source level of 246.5 dB re 1 µPa²m²s for 56 kg TNT-equivalent charge), and the favourable underwater sound propagation path consisting of a highly reflective bottom and the presence of a strong surface channel during winter months.

A summary of ranges to specific PTS and TTS thresholds based on Southall et al. (2019) dual criteria are provided in Table 27. The ranges reported in this summary represent the maximum of the $SEL_{w,24h}$ and PK criteria per group.

The largest ranges (R_{max}) at which PTS may occur are for LF cetaceans at 3.5 km for blasting at Baldwin Rock, and 2.5 km at Vardys Island ($SEL_{w,24\,h}$-based criteria). VHF cetaceans may encounter PTS at ranges of 1.7 km from the blast site at Baldwin Rock and 920 m at Vardys Island (PK-based criteria). For Phocid pinnipeds, the PTS range is 570 m from Baldwin Rock and 620 m Vardys Island ($SEL_{w,24\,h}$-based criteria). The distance to the PTS threshold for HF cetaceans and Otariids was less than 65 m at both sites ($SEL_{w,24\,h}$-based criteria).

Table 27. Summary table for dual-criteria ranges to PTS- and TTS-onset thresholds (Southall et al. 2019) for underwater blasting. Maximum of R_{max} (m) are shown for $SEL_{w,24h}$ and PK fields at Vardys Island (84 charges of 48 kg) and Baldwin Rock (56 charges of 56 kg).

Functional hearing group or species	PTS	TTS
Vardys Island (Scenario 3)		
LF cetaceans	2500*	6160*
HF cetaceans	66†	169†
VHF cetaceans	921†	2180†
Phocid in water	620*	2470*
Otariids, mustelids in water	52†	262*
Baldwin Rock (Scenario 6)		
LF cetaceans	3542*	>50,000*‡
HF cetaceans	64†	155†
VHF cetaceans	1693†	3020†
Phocid in water	570*	2700*
Otariids, mustelids in water	24*	154*

* The range is based on criteria for $SEL_{w,24h}$

† The range is based on criteria for PK

‡ The prediction at large ranges is not reliable due to environmental factors (such as complex scattering, and surface and ocean inhomogeneities) that the model does not account for. These factors can significantly increase propagation loss over large distance and decrease the range to the threshold.

Glossary

1/3-octave
One third of an octave. Note: A one-third octave is approximately equal to one decidecade (1/3 oct ≈ 1.003 ddec; ISO 2017).

1/3-octave-band
Frequency band whose bandwidth is one one-third octave. Note: The bandwidth of a one-third octave-band increases with increasing centre frequency.

90%-energy time window
The time interval over which the cumulative energy rises from 5 to 95% of the total pulse energy. This interval contains 90% of the total pulse energy. Symbol: T_{90}.

90% sound pressure level (90% SPL)
The root-mean-square sound pressure levels calculated over the 90%-energy time window of a pulse. Used only for pulsed sounds.

A-weighting
Frequency-selective weighting for human hearing in air that is derived from the inverse of the idealized 40-phon equal loudness hearing function across frequencies.

absorption
The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

acoustic impedance
The ratio of the sound pressure in a medium to the rate of alternating flow of the medium through a specified surface due to the sound wave.

ambient noise
All-encompassing sound at a given place, usually a composite of sound from many sources near and far (ANSI S1.1-1994 (R2004)), e.g., shipping vessels, seismic activity, precipitation, sea ice movement, wave action, and biological activity.

attenuation
The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium.

audiogram
A graph of hearing threshold level (sound pressure levels) as a function of frequency, which describes the hearing sensitivity of an animal over its hearing range.

audiogram weighting
The process of applying an animal's audiogram to sound pressure levels to determine the sound level relative to the animal's hearing threshold (HT). Unit: dB re HT.

Auditory frequency weighting (auditory weighting function, frequency-weighting function)
The process of band-pass filtering sounds to reduce the importance of inaudible or less-audible frequencies for individual species or groups of species of aquatic mammals (ISO 2017). One example is M-weighting introduced by Southall et al. (2007) to describe "Generalized frequency weightings for various functional hearing groups of marine mammals, allowing for their functional bandwidths and appropriate in characterizing auditory effects of strong sounds".

azimuth
A horizontal angle relative to a reference direction, which is often magnetic north or the direction of travel. In navigation it is also called bearing.

background noise
Total of all sources of interference in a system used for the production, detection, measurement, or recording of a signal, independent of the presence of the signal (ANSI S1.1-1994 (R2004)). Ambient noise detected, measured, or recorded with a signal is part of the background noise.

bandwidth
The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., seismic airguns, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI/ASA S1.13-2005 (R2010)).

bar
Unit of pressure equal to 100 kPa, which is approximately equal to the atmospheric pressure on Earth at sea level. 1 bar is equal to 10^5 Pa or 10^{11} µPa.

boxcar averaging
A signal smoothing technique that returns the averages of consecutive segments of a specified width.

broadband sound level
The total sound pressure level measured over a specified frequency range. If the frequency range is unspecified, it refers to the entire measured frequency range.

cetacean
Any animal in the order Cetacea. These are aquatic, mostly marine mammals and include whales, dolphins, and porpoises.

compressional wave
A mechanical vibration wave in which the direction of particle motion is parallel to the direction of propagation. Also called primary wave or P-wave.

confined explosives
Explosives detonated within a substrate, including ice, as opposed to unconfined explosives that are detonated in open water, not within a substrate.

continuous sound
A sound whose sound pressure level remains above ambient sound during the observation period (ANSI/ASA S1.13-2005 (R2010)). A sound that gradually varies in intensity with time, for example, sound from a marine vessel.

decade
Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 2006).

decidecade
One tenth of a decade (ISO 2017). Note: An alternative name for decidecade (symbol ddec) is “one-tenth decade”. A decidecade is approximately equal to one third of an octave (1 ddec ≈ 0.3322 oct) and for this reason is sometimes referred to as a “one-third octave”.

decidecade band
Frequency band whose bandwidth is one decidecade. Note: The bandwidth of a decidecade band increases with increasing centre frequency.

decibel (dB)
One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power ([ANSI] American National Standards Institute S1.1-1994 (R2004)).

delphinid
Family of oceanic dolphins, or Delphinidae, composed of approximately thirty extant species, including dolphins, porpoises, and killer whales.

ensonified
Exposed to sound.

equal-loudness contour
A curve or curves that show, as a function of frequency, the sound pressure level required to cause a given loudness for a listener having normal hearing, listening to a specified kind of sound in a specified manner (ANSI S1.1-1994 (R2004)).

far-field
The zone where, to an observer, sound originating from an array of sources (or a spatially distributed source) appears t o radiate from a single point. The distance to the acoustic far-field increases with frequency.

fast-average sound pressure level
The time-averaged sound pressure levels calculated over the duration of a pulse (e.g., 90%-energy time window), using the leaky time integrator from Plomp and Bouman (1959) and a time constant of 125 ms. Typically used only for pulsed sounds.

fast Fourier transform (FFT)
A computationally efficiently algorithm for computing the discrete Fourier transform.

frequency
The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: *f*. 1 Hz is equal to 1 cycle per second.

hearing group
Groups of marine mammal species with similar hearing ranges. Commonly defined functional hearing groups include low-, mid-, and high-frequency cetaceans, pinnipeds in water, and pinnipeds in air.

geoacoustic
Relating to the acoustic properties of the seabed.

hearing threshold
The sound pressure level for any frequency of the hearing group that is barely audible for a given individual in the absence of significant background noise during a specific percentage of experimental trials.

hertz (Hz)
A unit of frequency defined as one cycle per second.

impulsive sound
Sound that is typically brief and intermittent with rapid (within a few seconds) rise time and decay back to ambient levels (NOAA 2013, ANSI S12.7-1986 (R2006)). For example, seismic airguns and impact pile driving.

masking
Obscuring of sounds of interest by sounds at similar frequencies.

mean-square sound pressure spectral density
Distribution as a function of frequency of the mean-square sound pressure per unit bandwidth (usually 1 Hz) of a sound having a continuous spectrum (ANSI S1.1-1994 (R2004)). Unit: $\mu Pa^2/Hz$.

median
The 50th percentile of a statistical distribution.

mysticete
Mysticeti, a suborder of cetaceans, use their baleen plates, rather than teeth, to filter food from water. They are not known to echolocate, but they use sound for communication. Members of this group include rorquals (Balaenopteridae), right whales (Balaenidae), and grey whales (*Eschrichtius robustus*).

non-impulsive sound
Sound that is broadband, narrowband or tonal, brief or prolonged, continuous or intermittent, and typically does not have a high peak pressure with rapid rise time (typically only small fluctuations in decibel level) that impulsive signals have (ANSI/ASA [ANSI] American National Standards Institute and [ASA] Acoustical Society of America S3.20-1995 (R2008)). For example, marine vessels, aircraft, machinery, construction, and vibratory pile driving (NIOSH 1998, NOAA 2015).

octave
The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

odontocete
The presence of teeth, rather than baleen, characterizes these whales. Members of the Odontoceti are a suborder of cetaceans, a group comprised of whales, dolphins, and porpoises. The skulls of toothed whales are mostly asymmetric, an adaptation for their echolocation. This group includes sperm whales, killer whales, belugas, narwhals, dolphins, and porpoises.

otariid
A common term used to describe members of the Otariidae, eared seals, commonly called sea lions and fur seals. Otariids are adapted to a semi-aquatic life; they use their large fore flippers for propulsion. Their ears distinguish them from phocids. Otariids are one of the three main groups in the superfamily Pinnipedia; the other two groups are phocids and walrus.

parabolic equation method
A computationally efficient solution to the acoustic wave equation that is used to model transmission loss. The parabolic equation approximation omits effects of back-scattered sound, simplifying the computation of transmission loss. The effect of back-scattered sound is negligible for most ocean-acoustic propagation problems.

peak pressure level (PK)
The maximum instantaneous sound pressure level, in a stated frequency band, within a stated period. Also called zero-to-peak pressure level. Unit: decibel (dB).

peak-to-peak pressure level (PK-PK)
The difference between the maximum and minimum instantaneous pressure levels. Unit: decibel (dB).

permanent threshold shift (PTS)
A permanent loss of hearing sensitivity caused by excessive noise exposure. PTS is considered auditory injury.

phocid
A common term used to describe all members of the family Phocidae. These true/earless seals are more adapted to in-water life than are otariids, which have more terrestrial adaptations. Phocids use their hind flippers to propel themselves. Phocids are one of the three main groups in the superfamily Pinnipedia; the other two groups are otariids and walrus.

pinniped
A common term used to describe all three groups that form the superfamily Pinnipedia: phocids (true seals or earless seals), otariids (eared seals or fur seals and sea lions), and walrus.

point source
A source that radiates sound as if from a single point (ANSI S1.1-1994 (R2004)).

power spectrum density
Generic term, formally defined as power in W/Hz, but sometimes loosely used to refer to the spectral density of other parameters such as square pressure or time-integrated square pressure.

pressure, acoustic
The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: p.

pressure, hydrostatic
The pressure at any given depth in a static liquid that is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid. Unit: pascal (Pa).

received level (RL)
The sound level measured (or that would be measured) at a defined location.

rms
root-mean-square.

shear wave
A mechanical vibration wave in which the direction of particle motion is perpendicular to the direction of propagation. Also called secondary wave or S-wave. Shear waves propagate only in solid media, such as sediments or rock. Shear waves in the seabed can be converted to compressional waves in water at the water-seabed interface.

signature
Pressure signal generated by a source.

sound
A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

sound exposure
Time integral of squared, instantaneous frequency-weighted sound pressure over a stated time interval or event. Unit: pascal-squared second ($Pa^2 \cdot s$) (ANSI S1.1-1994 (R2004)).

sound exposure level (SEL)
A cumulative measure related to the sound energy in one or more pulses. Unit: dB re 1 $\mu Pa^2 \cdot s$. SEL is expressed over the summation period (e.g., per-pulse SEL [for airguns], single-strike SEL [for pile drivers], 24-hour SEL).

sound exposure spectral density
Distribution as a function of frequency of the time-integrated squared sound pressure per unit bandwidth of a sound having a continuous spectrum (ANSI S1.1-1994 (R2004)). Unit: $\mu Pa^2 \cdot s/Hz$.

sound field
Region containing sound waves (ANSI S1.1-1994 (R2004)).

sound intensity
Sound energy flowing through a unit area perpendicular to the direction of propagation per unit time.

sound pressure level (SPL)
The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 (R2004)).

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 µPa) and the unit for SPL is dB re 1 μPa^2:

$$L_p = 10\log_{10}(p^2/p_0^2) = 20\log_{10}(p/p_0)$$

Unless otherwise stated, SPL refers to the root-mean-square (rms) pressure level. See also 90% sound pressure level and fast-average sound pressure level. Non-rectangular time window functions may be applied during calculation of the rms value, in which case the SPL unit should identify the window type.

sound speed profile
The speed of sound in the water column as a function of depth below the water surface.

source level (SL)
The sound level measured in the far-field and scaled back to a standard reference distance of 1 metre from the acoustic centre of the source. Unit: dB re 1 µPa·m (pressure level) or dB re 1 $\mu Pa^2 \cdot s \cdot m^2$ (exposure level).

spectral density level
The decibel level ($10 \cdot \log_{10}$) of the spectral density of a given parameter such as SPL or SEL, for which the units are dB re 1 $\mu Pa^2/Hz$ and dB re 1 $\mu Pa^2 \cdot s/Hz$, respectively.

spectrogram
A visual representation of acoustic amplitude compared with time and frequency.

spectrum
An acoustic signal represented in terms of its power, energy, mean-square sound pressure, or sound exposure distribution with frequency.

temporary threshold shift (TTS)
Temporary loss of hearing sensitivity caused by excessive noise exposure.

transmission loss (TL)
The decibel reduction in sound level between two stated points that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also referred to as propagation loss.

wavelength
Distance over which a wave completes one cycle of oscillation. Unit: metre (m). Symbol: λ.

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Appendix A. Acoustic Metrics

Because the perceived loudness of sound, especially pulsed sound such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are used to evaluate sound and its effects on marine life. Three metrics are commonly used: peak pressure level (PK), sound pressure level (SPL), and sound exposure level (SEL). Where possible, we follow International Organization for Standardization definitions and symbols for sound metrics (e.g., ISO 2017).

Figure A-1 shows a representation of a sinusoidal (single frequency) pressure wave to illustrate the various metrics. The amplitude of the pressure is shown along the vertical axis, and time is shown along the horizontal axis. The pressure of the wave fluctuates around the neutral point. The peak pressure is the absolute value of the maximum variation from the neutral position of a wave oscillation; therefore, it can result from either a compression or a rarefaction. The peak-to-peak sound pressure is the difference between the maximum and minimum pressures. The average amplitude is the average of absolute value of pressure over the period of interest.

The rms amplitude is a type of average determined by squaring all of the amplitudes over the period of interest, determining the mean of the squared values, and then taking the square root of this mean. The rms amplitude of an impulsive signal will vary significantly depending on the length of the period of interest.

SEL is a metric related to the sound energy per area received over time, though it does not have energy units; it is proportional to the square of the sound pressure and the time over which a sound is received.

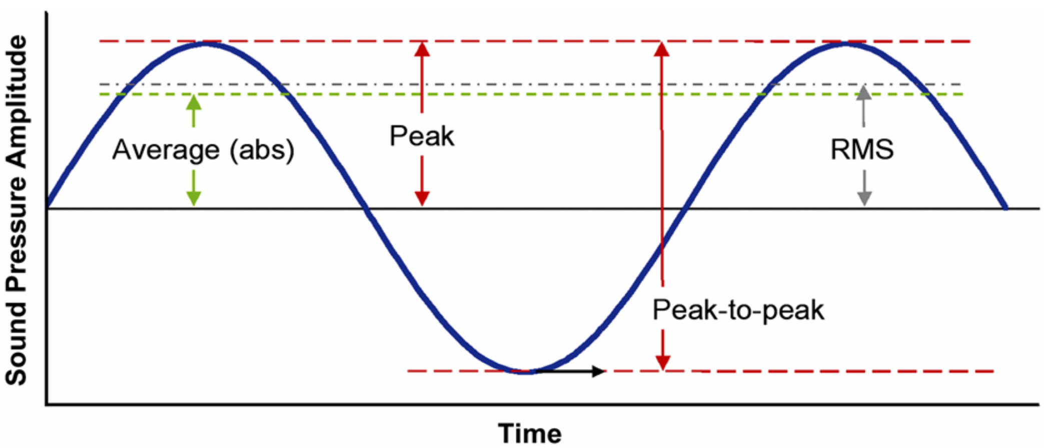

Figure A-1. Sound level metrics.

The US National Marine Fisheries Service (NMFS) issued a Technical Guidance document (NMFS 2018) is using a slightly different notation than ISO for the acoustic metrics (Table A-1) including a peak unweighted (or flat) sound pressure level metric PK (L_{pk}) and a cumulative sound exposure level SEL_{cum} (i.e., SEL_{24h}) metric with frequency weighting. The acoustic metric terminology used in Southall et al. (2019) is equivalent to this guidance. Following the ISO standard, the L_{pk} as used by NMFS and Southall et al. (2019) is here denoted as PK. The SEL_{cum} metric as used by NMFS and Southall et al. (2019) describes the sound energy received by a receptor over 24 h. Accordingly, following the ISO (2017) standard, this is denoted as SEL_{24h} in this report.

Table A-1. Acoustic metrics used in this underwater noise propagation modelling report, compared to other publications.

Metric	NMFS (2018) and Southall et al. (2019)	Current report (as per ISO 2017)		Unit
		Abbreviation in main text	Symbol in equations/tables	
Sound pressure level	n/a	SPL	L_p	decibel (dB) re 1 micropascal (µPa)
Peak sound pressure level	PK	PK	L_{pk}	dB re 1 µPa
Sound exposure level (per pulse)	n/a	Per-pulse SEL	L_E	dB re 1 µPa²·s
Sound exposure level (accumulated over time), $SEL_{time\text{-}period}$	SEL_{cum}	SEL_{24h}	$L_{E,24h}$	dB re 1 µPa²·s
Source level	SL	SL	$L_{S,pk}$ $L_{S,p}$ $L_{S,E}$	dB re 1 µPa·m (Peak or SPL source level) or dB 1 µPa²m²s (Per-pulse energy source level)

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 µPa. Here we provide specific definitions of the metrics mentioned above.

The zero-to-peak sound pressure level, or peak sound pressure (PK or $L_{p,pk}$; dB re 1 µPa), is the decibel level of the maximum instantaneous acoustic pressure in a stated frequency band attained by an acoustic pressure signal, $p(t)$:

$$L_{p,\mathrm{pk}} = 10\log_{10}\frac{\max|p^2(t)|}{p_0^2} = 20\log_{10}\frac{\max|p(t)|}{p_0} \quad \text{(A-1)}$$

PK is often included as a criterion for assessing whether a sound is potentially injurious; however, because it does not account for the duration of an acoustic event, it is generally a poor indicator of perceived loudness.

The peak-to-peak sound pressure (PK-PK or $L_{p,pk\text{-}pk}$; dB re 1 µPa) is the difference between the maximum and minimum instantaneous sound pressure, possibly filtered in a stated frequency band, attained by an impulsive sound, $p(t)$:

$$L_{p,\mathrm{pk\text{-}pk}} = 10\log_{10}\frac{[\max(p(t)) - \min(p(t))]^2}{p_0^2} \quad \text{(A-2)}$$

The sound pressure level (SPL or L_p; dB re 1 µPa) is the root-mean-square (rms) pressure level in a stated frequency band over a specified time window (T; s). It is important to note that SPL always refers to a rms pressure level and therefore not instantaneous pressure:

$$L_p = 10\log_{10}\left(\frac{1}{T}\int_T g(t)\,p^2(t)\,dt \Big/ p_0^2\right)\ \mathrm{dB} \quad \text{(A-3)}$$

where $g(t)$ is an optional time weighting function. In many cases, the start time of the integration is marched forward in small time steps to produce a time-varying SPL function. For short acoustic events, such as sonar pulses and marine mammal vocalizations, it is important to choose an appropriate time window that matches the duration of the signal. For in-air studies, when evaluating the perceived loudness of sounds with rapid amplitude variations in time, the time weighting function $g(t)$ is often set to a decaying exponential function that emphasizes more recent pressure signals. This function mimics the leaky integration nature of mammalian hearing. For example, human-based fast time-weighted SPL

($L_{p,fast}$) applies an exponential function with time constant 125 ms. A related simpler approach used in underwater acoustics sets $g(t)$ to a boxcar (unity amplitude) function of width 125 ms; the results can be referred to as $L_{p,boxcar\ 125ms}$. Another approach, historically used to evaluate SPL of impulsive signals underwater, defines $g(t)$ as a boxcar function with edges set to the times corresponding to 5% and 95% of the cumulative square pressure function encompassing the duration of an impulsive acoustic event. This calculation is applied individually to each impulse signal, and the results have been referred to as 90% SPL ($L_{p,90\%}$).

In the present report, SPL for impact pile driving operations were calculated using a boxcar function of width 125 ms, i.e., $L_{p,boxcar\ 125ms}$.

The sound exposure level (SEL or L_E; dB re 1 µPa^2·s) is the time-integral of the squared acoustic pressure over a duration (T):

$$L_E = 10 \log_{10}\left(\int_T p^2(t)\, dt \Big/ T_0 p_0^2 \right) \text{dB} \tag{A-4}$$

where T_0 is a reference time interval of 1 s. SEL continues to increase with time when non-zero pressure signals are present. It is a dose-type measurement, so the integration time applied must be carefully considered for its relevance to impact to the exposed recipients.

SEL can be calculated over a fixed duration, such as the time of a single event or a period with multiple acoustic events. When applied to pulsed sounds, SEL can be calculated by summing the SEL of the N individual pulses. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, may it be seconds, strikes, or multiple sources, the SEL can be computed by summing (in linear units) the SEL of the N individual events:

$$L_{E,N} = 10 \log_{10} \sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}} \text{dB} \tag{A-5}$$

If the SEL of the N individual event is identical, we can simply write:

$$L_{E,N} = L_{E,1} + 10 \log_{10}(N) \text{ dB} \tag{A-6}$$

A.1. Decidecade Band Analysis

The distribution of a sound's power with frequency is described by the sound's spectrum. The sound spectrum can be split into a series of adjacent frequency bands. Splitting a spectrum into 1 Hz wide bands, called passbands, yields the power spectral density of the sound. This splitting of the spectrum into passbands of a constant width of 1 Hz, however, does not represent how animals perceive sound.

Because animals perceive exponential increases in frequency rather than linear increases, analyzing a sound spectrum with passbands that increase exponentially in size better approximates real-world scenarios. In underwater acoustics, a spectrum is commonly split into decidecade bands, which are approximately one tenth a decade wide. A decidecade is sometimes referred to as a "1/3-octave" because one tenth of a decade is approximately equal to one third of an octave. Each decade represents a factor 10 in sound frequency. Each octave represents a factor 2 in sound frequency. The centre frequency of the ith band, $f_c(i)$, is defined as:

$$f_c(i) = 10^{\frac{i}{10}} \text{ kHz} \tag{A-7}$$

and the low (f_{lo}) and high (f_{hi}) frequency limits of the ith decade band are defined as:

$$f_{\mathrm{lo},i} = 10^{\frac{-1}{20}} f_{\mathrm{c}}(i) \quad \text{and} \quad f_{\mathrm{hi},i} = 10^{\frac{1}{20}} f_{\mathrm{c}}(i) \tag{A-8}$$

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure A-2). The acoustic modelling spans from band 10 (f_c (10) = 10 Hz) to band 44 ($f_{\mathrm{c}}(44)$ = 25 kHz).

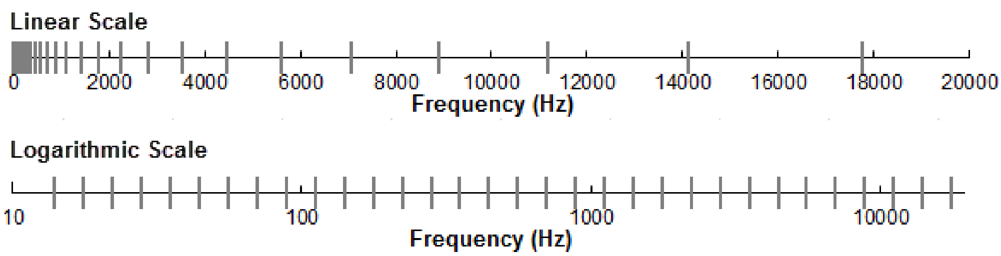

Figure A-2. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale.

The sound pressure level in the ith band ($L_{p,i}$) is computed from the spectrum $S(f)$ between $f_{\mathrm{lo},i}$ and $f_{\mathrm{hi},i}$:

$$L_{p,i} = 10 \log_{10} \int_{f_{\mathrm{lo},i}}^{f_{\mathrm{hi},i}} S(f)\, df \tag{A-9}$$

Summing the sound pressure level of all the bands yields the broadband sound pressure level:

$$\text{Broadband SPL} = 10 \log_{10} \sum_i 10^{\frac{L_{p,i}}{10}} \tag{A-10}$$

Figure A-3 shows an example of how the decidecade band sound pressure levels compare to the sound pressure spectral density levels of an ambient noise signal. Because the decidecade bands are wider with increasing frequency, the decidecade band SPL is higher than the spectral levels at higher frequencies. Acoustic modelling of decidecade bands requires less computation time than 1 Hz bands and still resolves the frequency-dependence of the sound source and the propagation environment.

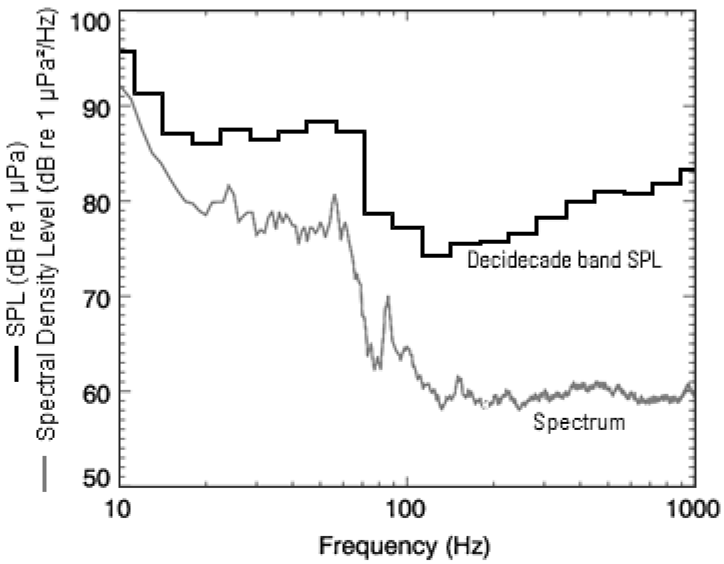

Figure A-3. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient noise shown on a logarithmic frequency scale.

Appendix B. Impact Criteria

B.1. Marine Mammal Hearing Groups

To better reflect the auditory similarities between phylogenetically closely related species, but also significant differences between species groups among the marine mammals, Southall et al. (2007) assigned the extant marine mammal species to functional hearing groups based on their hearing capabilities and sound production. This division into broad categories was intended to provide a realistic number of categories for which individual noise exposure criteria were developed. These groups were revised by NMFS (2018), but the categorisation as such has proven to be a scientifically justified and useful approach in developing auditory weighting functions and deriving noise exposure criteria for marine mammals. The division proposed by Southall et al. (2007) was updated in 2018 by the NMFS using more recent best available science.

Southall et al. (2019) published an updated set of criteria for onset of TTS and PTS in marine mammals (Tables 2-4). While the authors propose a new nomenclature and classification for the marine mammal functional hearing groups, the proposed thresholds and weighting functions for exposure to underwater sound do not differ in effect from those proposed by NOAA (2018), with exception of the addition of thresholds for hearing groups in air. The hearing groups proposed by Southall et al. (2019) used in this report are:

- Low-frequency (LF) cetaceans (mysticetes or baleen whales)
- High-frequency (HF) cetaceans (odontocetes: delphinids, beaked whales, sperm whales)
- Very high-frequency (VHF) cetaceans (other odontocetes)
- Phocid carnivores in water (PCW) (‘true’ seals, including e.g., harbor and gray seals)
- Other marine carnivores in water (OCW) (‘eared’ seals (fur seals and sea lions), walruses, sea otters, and polar bears).
- Phocid carnivores in air (PCA)
- Other marine carnivores in air (OCA)

B.2. Marine Mammal Auditory Weighting Functions

The potential for anthropogenic sounds to impact marine mammals is largely dependent on whether the sound occurs at frequencies that an animal can hear well (Appendix B.1), unless the sound pressure level is so high that it can cause physical tissue damage regardless of frequency. Auditory (frequency) weighting functions reflect an animal’s ability to hear a sound. Sound spectra are weighted at particular frequencies in a manner that reflects an animal’s sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007). Auditory weighting functions have been proposed for marine mammals, specifically associated with thresholds for onset of TTS and PTS. They are expressed in metrics that consider what is known about marine mammal hearing (e.g., SEL) (Southall et al. 2007, Erbe et al. 2016, Finneran 2016).

The application of marine mammal auditory weighting functions emphasizes the importance of making measurements and characterizing sound sources in terms of their overlap with biologically-important frequencies (e.g., frequencies used for environmental awareness, communication or the detection of predators or prey), and not only the frequencies of interest or concern for the completion of the sound-producing activity (i.e., context of sound source; NMFS 2018).This section describes the auditory weighting functions used in this work.

In 2015, a US Navy technical report by Finneran (2015) recommended new auditory weighting functions. The auditory weighting functions for marine mammals are applied in a similar way as A-weighting for noise level assessments for humans. The new frequency-weighting functions are expressed as:

$$G(f) = K + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a[1+(f/f_2)^2]^b}\right\} \quad \text{(B-1)}$$

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively), phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA's technical guidance that assesses acoustic impacts on marine mammals (NMFS 2018), as well as in Southall et al. (2019) criteria. Table B-1 lists the frequency-weighting parameters for each hearing group according to Southall et al. (2019). Figures B-1 and B-2 show the resulting frequency-weighting curves.

Table B-1. Parameters for the auditory weighting functions recommended by Southall et al. (2019).

Functional hearing group	a	b	f_1 (Hz)	f_2 (Hz)	K (dB)
Low-frequency cetaceans	1.0	2	200	19,000	0.13
High-frequency cetaceans	1.6	2	8,800	110,000	1.20
Very high-frequency cetaceans	1.8	2	12,000	140,000	1.36
Phocid carnivores in water	1.0	2	1,900	30,000	0.75
Other marine carnivores in water	2.0	2	940	25,000	0.64
Phocid carnivores in air	2	2	0.75	8.3	1.5
Other marine carnivores in air	1.4	2	2.0	20	1.39

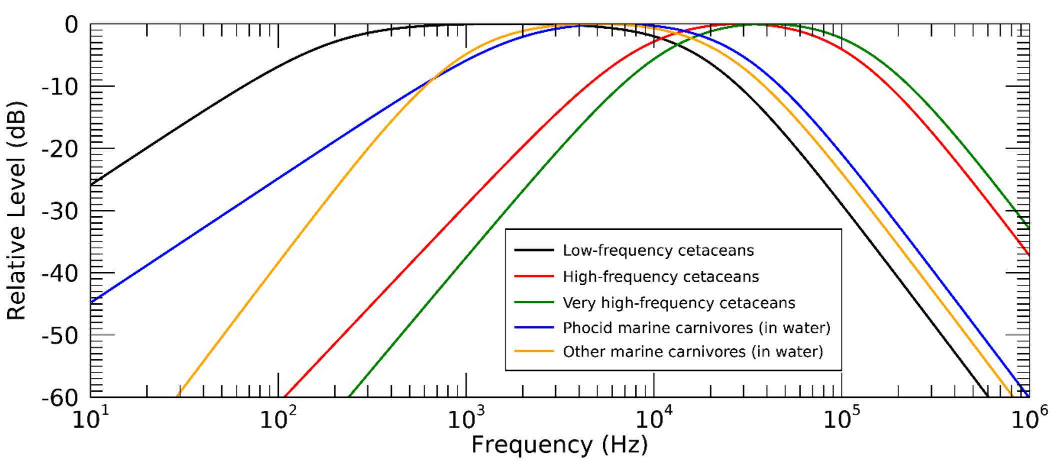

Figure B-1. Auditory weighting functions for underwater hearing sensitivity for functional marine mammal hearing groups as recommended by Southall et al. (2019).

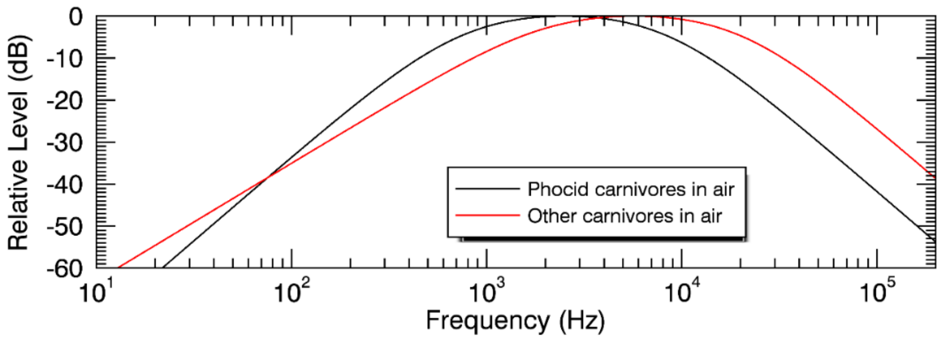

Figure B-2. Auditory weighting functions for in-air hearing sensitivity for pinnipeds hearing groups as recommended by Southall et al. (2019).

B.3. Marine Mammals

It has been long recognized that marine mammals can be adversely affected by underwater anthropogenic noise. For example, Payne and Webb (1971) suggest that communication distances of fin whales are reduced by shipping sounds. Subsequently, similar concerns arose regarding effects of other underwater noise sources and the possibility that impulsive sources—primarily airguns used in seismic surveys—could cause auditory injury. This led to a series of workshops held in the late 1990s, conducted to address acoustic mitigation requirements for seismic surveys and other underwater noise sources (NMFS 1998, ONR 1998, Nedwell and Turnpenny 1998, HESS 1999, Ellison and Stein 1999). In the years since these early workshops, a variety of thresholds have been proposed for both injury (Appendix B.3.1.1) and disturbance (Appendix B.3.1.2). The following sections summarize the development of the current thresholds relevant to this study; this remains an active research topic, however.

B.3.1.1. Injury Criteria

The NMFS SPL criteria for injury to marine mammals from acoustic exposure were set according to recommendations for cautionary estimates of sound levels leading to onset of permanent hearing threshold shift (PTS). These criteria prescribed injury thresholds of 190 dB re 1 µPa SPL for pinnipeds and 180 dB re 1 µPa SPL for cetaceans, for all types of sound sources except tactical sonar and explosives (NMFS 2018). These injury thresholds are applied to individual noise pulses or instantaneous sound levels and do not consider the overall duration of the noise or its acoustic frequency distribution.

Criteria that do not account for exposure duration or noise spectra are generally insufficient on their own for assessing hearing injury. Human workplace noise assessment metrics consider the SPL as well as the duration of exposure and sound spectral characteristics. For example, the International Institute of Noise Control Engineering (I-INCE) and the Occupational Safety and Health Administration (OSHA) suggests thresholds in C-weighted peak pressure level and A-weighted time-average sound level (dB(A)[2] L_{eq}). They also suggest exchange rates that increase the allowable thresholds for each halving or doubling of exposure time. This approach assumes that hearing damage depends on the relative loudness perceived by the human ear, and that the ear might partially recover from past exposures, particularly if there are periods of quiet during the overall exposure.

In recognition of shortcomings of the SPL-only based injury criteria, in 2005 NMFS sponsored the Noise Criteria Group to review literature on marine mammal hearing to propose new noise exposure criteria. Some members of this expert group published a landmark paper (Southall et al. 2007) that suggested assessment methods similar to those applied for humans. The resulting recommendations introduced dual acoustic injury criteria for impulsive sounds that included peak pressure level thresholds and SEL_{24h} thresholds, where the subscripted 24h refers to the accumulation period for calculating SEL. The peak

[2] The “A” refers to a specific frequency-dependent filter shaped according to a human equal loudness contour.

pressure level criterion is not frequency weighted, whereas SEL_{24h} is frequency weighted according to one of four marine mammal species hearing groups: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively) and pinnipeds in water (Pws)[3]. These weighting functions are referred to as M-weighting filters (analogous to the A-weighting filter for humans). The SEL_{24h} thresholds were obtained by extrapolating measurements of onset levels of Temporary Threshold Shift (TTS) in belugas by the amount of TTS required to produce Permanent Threshold Shift (PTS) in chinchillas. The Southall et al. (2007) recommendations do not specify an exchange rate, which suggests that the thresholds are the same regardless of the duration of exposure (i.e., it implies a 3 dB exchange rate).

Wood et al. (2012) refined Southall et al.'s (2007) thresholds, suggesting lower injury values for LF cetaceans and HF cetaceans while retaining the filter shapes. Their revised thresholds were based on TTS-onset levels in harbour porpoises from Lucke et al. (2009), which led to a revised impulsive sound PTS threshold for HF of 179 dB re 1 $\mu Pa^2 \cdot s$. Because no data were available for baleen whales, Wood et al. (2012) based their recommendations for LF cetaceans on results from MF cetacean studies. In particular they referenced Finneran and Schlundt's (2010) research, which found MF cetaceans are more sensitive to non-impulsive sound exposure than Southall et al. (2007) assumed. Wood et al. (2012) thus recommended a more conservative TTS-onset level for LF cetaceans of 192 dB re 1 $\mu Pa^2 \cdot s$.

Also in 2012, the US Navy recommended a different set of criteria for assessing Navy operations (Finneran and Jenkins 2012). Their analysis incorporated new dolphin equal-loudness contours[4] to update weighting functions and injury thresholds for LF, MF, and HF cetaceans. They recommended separating the pinniped group into otariids (eared seals) and phocids (earless seals) and assigning adjusted frequency thresholds to the former based on several sensitivity studies (Schusterman et al. 1972, Moore and Schusterman 1987, Babushina et al. 1991, Kastak and Schusterman 1998, Kastelein et al. 2005, Mulsow and Reichmuth 2007, Mulsow et al. 2011a, Mulsow et al. 2011b).

As of 2017, a definitive approach is still not apparent. There is consensus in the research community that an SEL-based method is preferable, either separately or in addition to an SPL-based approach, to assess the potential for injuries. In August 2016, after substantial public and expert input into three draft versions and based largely on the above-mentioned literature (NOAA 2013, 2015, 2016), NMFS finalized technical guidance for assessing the effect of anthropogenic sound on marine mammal hearing (NMFS 2016, NMFS 2018). The guidance describes injury criteria with new thresholds and frequency weighting functions for the five hearing groups described by Finneran and Jenkins (2012). The latest revision to this work was published in 2018 (NMFS 2018). Southall et al. (2019) revisited the interim criteria published in 2007. All noise exposure criteria in NMFS (2018) and Southall et al. (2019) are identical (for impulsive and non-impulsive sounds); however the mid-frequency cetaceans from NMFS (2018) are classified as high-frequency cetaceans in Southall et al. (2019), and high-frequency cetaceans from NMFS (2018) are classified as very-high-frequency cetaceans in Southall et al. (2019). In addition, Southall et al. (2019) defines frequency weighting functions for Phocid carnivores in air (PCA) and Other carnivores in air (OCA) hearing groups.

B.3.1.2. Disturbance Criteria

The NMFS currently uses SPL thresholds for behavioural disturbance of 160 dB re 1 µPa for impulsive sounds and 120 dB re 1 µPa for non-impulsive sounds for all marine mammal species (NMFS 2018), based on observations of mysticetes (Malme et al. 1983, 1984, Richardson et al. 1986, 1990). As of 2016, NMFS applies disturbance threshold as a default, but makes exceptions on a species-specific and sub-population specific basis where warranted.

[3] Pinnipeds in air were also included but are not applicable here.
[4] An equal-loudness contour is the measured sound pressure level (dB re 1 µPa for underwater sounds) over frequency, for which a listener perceives a constant loudness when exposed to pure tones.

B.4. Fish, Invertebrates, Eggs, and Larvae

In 2006, the Working Group on the Effects of Sound on Fish and Turtles was formed to continue developing noise exposure criteria for fish and turtles, work begun by a NOAA panel two years earlier. The resulting guidelines include specific thresholds for different levels of effects and for different groups of species (Popper et al. 2014). These guidelines defined quantitative thresholds for three types of immediate effects:

- Mortality, including injury leading to death.
- Recoverable injury, including injuries unlikely to result in mortality (such as hair cell damage and minor haematoma).
- TTS.

Masking and behavioural effects are assessed qualitatively, by assessing relative risk rather than by specific sound level thresholds. These effects are not assessed in this report. Because the presence or absence of a swim bladder has a role in hearing, a fish's susceptibility to injury from noise exposure varies depending on the species and the presence and possible role of a swim bladder in hearing. Thus, different thresholds were proposed for i) fish without a swim bladder (also appropriate for sharks and applied to whale sharks in the absence of other information), ii) fish with a swim bladder not used for hearing, and iii) fish that use their swim bladders for hearing.

For continuous noise generated by activities such as shipping, drilling, and dredging, there is no evidence of mortality or potential mortal injury to fish. For explosions, mortality and potential mortal injury can occur for peak levels 229–234 dB re µPa for all types of fish according to (Popper et al. 2014). In this work, however, mortality and potential mortal injury was assessed using the more conservative peak threshold of 220 dB re µPa from Wright and Hopky (1998).

Mortality and potential mortal injury in eggs and larvae was assessed in this work by considering a peak particle velocity of 13 mm/s, since it has been suggested that eggs and larvae may be vulnerable to the substrate vibration associated to impulsive noises such as those generated by pile driving or seismic airguns.

Appendix C. Modelling Methodology and Parameters

This section provides a detailed description of the modelling methodology report.

C.1. In-air Noise Propagation with Impulse Noise Propagation Model (INPM)

INPM uses a split-step Padé solution (Collins 1993) for the parabolic form of the wave equation to determine frequency-dependent transmission losses as a function of range away from a point source. The split-step Padé solution is computationally faster than the finite-difference solution of the Parabolic Equation (PE) by approximately two orders of magnitude and is more accurate than the split-step Fourier solution for wide angle propagation. This approach is also superior to standard ray tracing models that can yield unrealistically large received sound level values due to caustics, which are computationally intensive to remove (Salomons 2001). The model uses a two-dimensional (2-D) implementation of the PE method that accounts for diffraction, air turbulence, and sound interaction with the terrain. INPM has been verified by comparing model outputs against a set of benchmarks available in the open literature. The model shows nearly perfect agreement to the published results (Racca et al. 2006).

INPM can output the complete sound level field in range and height along a radial from the source. This can be rendered as an image plot (Figure C-1), which shows noise propagation for the detonation of a buried 6.77 kg TNT charge, using the April atmospheric profile, selected as the most conservative.

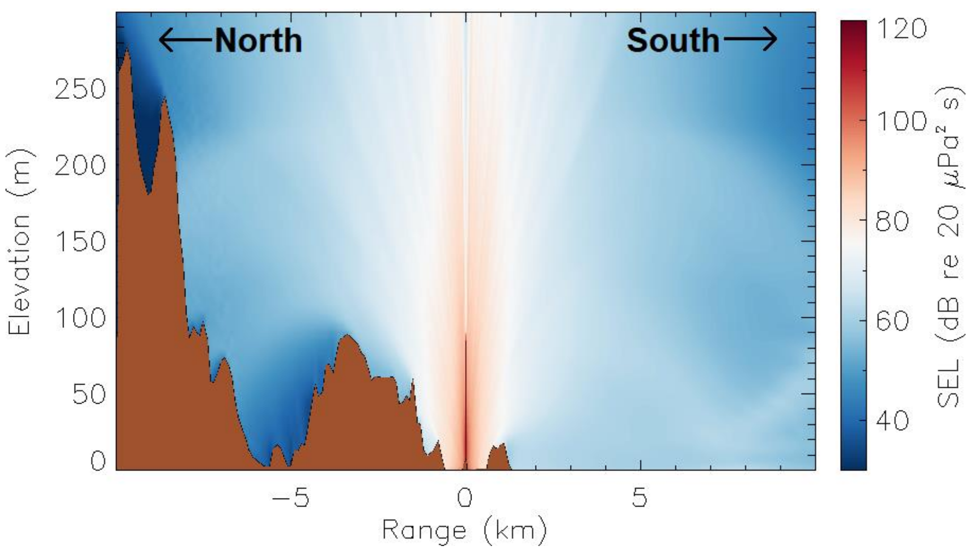

Figure C-1. Example of in-air unweighted broadband received sound level vertical radial plot from Impulse Noise Propagation Model (INPM), corresponding to underground detonation of a 6.77 kg TNT charge, using the most conservative atmospheric profile, corresponding to April. Vardys Island is located at 0 m range, while the topography toward north and south from the island can be observed along negative and positive ranges, respectively.

C.2. Underwater Noise Propagation

C.2.1. Marine Operations Noise Model (MONM)

Long-range sound fields were computed using JASCO's Marine Operations Noise Model (MONM). While other models may be more accurate for steep-angle propagation in high-shear environment, MONM is well suited for effective longer-range estimation.

MONM employs two underlaying subroutines: MONM-RAM is used for propagating acoustic waves at low frequencies (e.g., up to 2000 Hz) and MONM-BELLHOP is used for high frequencies (e.g., above 2000 Hz).

MONM-RAM computes acoustic propagation via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for an elastic seabed (Zhang and Tindle 1995). The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). MONM-RAM accounts for the additional reflection loss at the seabed due to partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. MONM-RAM incorporates the following site-specific environmental properties: a modeled area bathymetric grid, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

MONM-BELLHOP employs Gaussian beam acoustic ray-trace model (Porter and Liu 1994). This version of MONM accounts for sound attenuation due to energy absorption through ion relaxation and viscosity of water (Fisher and Simmons 1977) and propagation loss due to sea surface roughness. Both types of sound attenuation are significant for frequencies higher than 5 kHz and cannot be neglected without noticeably affecting the model results. MONM-BELLHOP incorporates the following site-specific environmental properties: a modeled area bathymetric grid, underwater sound speed as a function of depth, average temperature and salinity in the water column for calculating the sound attenuation due to energy absorption, and geoacoustic properties of the surficial sediments.

The accuracy of MONM's predictions have been validated against experimental data from several sound source verification programs conducted by JASCO (Hannay and Racca 2005, Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010). MONM computes acoustic fields in three dimensions by modelling transmission loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as N×2-D. These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding N = 360°/$\Delta\theta$ number of planes (Figure C-2).

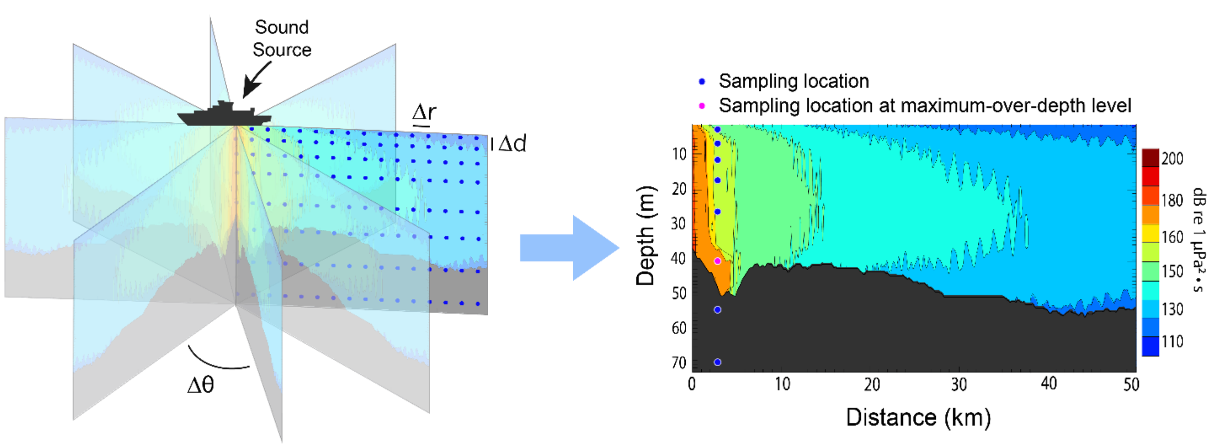

Figure C-2. The N×2-D and maximum-over-depth modelling approach used by MONM.

MONM treats frequency dependence by computing acoustic transmission loss at the centre frequencies of 1/3-octave-bands. Sufficiently many 1/3-octave-bands, starting at 10 Hz, are modelled to include most of the acoustic energy emitted by the source. At each centre frequency, the transmission loss is modelled within each of the N vertical planes as a function of depth and range from the source. The 1/3-octave-band received per-pulse SEL are computed by subtracting the band transmission loss values from the directional source level in that frequency band. Composite broadband received per-pulse SEL are then computed by summing the received 1/3-octave-band levels.

The received per-second SEL sound field (e.g., for dredging and drilling operations) within each vertical radial plane is sampled at various ranges from the source, generally with a fixed radial step size. At each sampling range along the surface, the sound field is sampled at various depths, with the step size between samples increasing with depth below the surface. The step sizes are chosen to provide increased coverage near the depth of the source and at depths of interest in terms of the sound speed profile. For areas with deep water, sampling is not performed at depths beyond those reachable by marine mammals. The received per-pulse or per-second SEL at a surface sampling location is taken as the maximum value that occurs over all samples within the water column, i.e., the maximum-over-depth received per-pulse SEL. These maximum-over-depth per-pulse SEL are presented as colour contours around the source.

C.2.2. Full Waveform Range-dependent Model (FWRAM)

For impulsive sounds from underwater blasting, time-domain representations of the pressure waves generated in the water are required for calculating SPL and peak pressure level. Furthermore, the pile must be represented as a distributed source to accurately characterize vertical directivity effects in the near-field zone. For this study, synthetic pressure waveforms were computed using FWRAM, which is a time-domain acoustic model based on the same wide-angle parabolic equation (PE) algorithm as MONM. FWRAM computes synthetic pressure waveforms versus range and depth for range-varying marine acoustic environments, and it takes the same environmental inputs as MONM (bathymetry, water sound speed profile, and seabed geoacoustic profile). Unlike MONM, FWRAM computes pressure waveforms via Fourier synthesis of the modelled acoustic transfer function in closely spaced frequency bands. FWRAM employs the array starter method to accurately model sound propagation from a spatially distributed source (MacGillivray and Chapman 2012).

Synthetic pressure waveforms were modelled over the frequency range 10–1024 Hz, inside a 1 s window (Figure C-3). The synthetic pressure waveforms were post-processed, after applying a travel time correction, to calculate standard SPL and SEL metrics versus range and depth from the source.

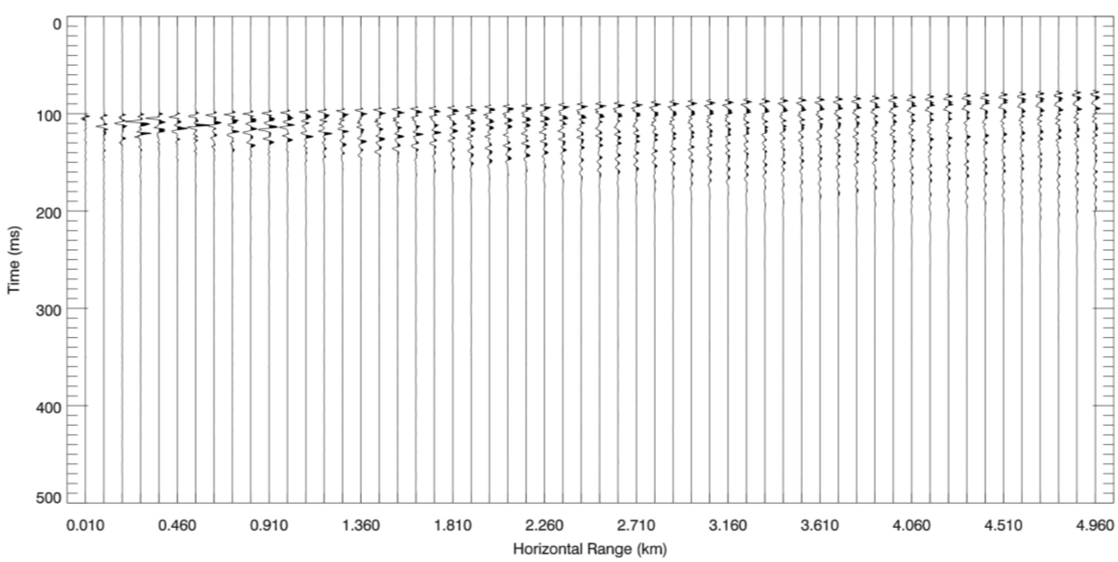

Figure C-3. Example of synthetic pressure waveforms computed by FWRAM for Pile 2 at multiple range offsets. Receiver depth is 35 m and the amplitudes of the pressure traces have been normalised for display purposes.

C.2.3. Model Validation Information

Predictions from JASCO's propagation models (MONM, FWRAM) have been validated against experimental data from a number of underwater acoustic measurement programs conducted by JASCO globally, including the United States and Canadian Artic, Canadian and southern United States waters, Greenland, Russia and Australia (Hannay and Racca 2005, Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010, Racca et al. 2012a, Racca et al. 2012b, Matthews and MacGillivray 2013, Martin et al. 2015, Racca et al. 2015, Martin et al. 2017a, Martin et al. 2017b, Warner et al. 2017, MacGillivray 2018, McPherson et al. 2018, McPherson and Martin 2018).

In addition, JASCO has conducted measurement programs associated with a significant number of anthropogenic activities which have included internal validation of the modelling (including McCrodan et al. 2011, Austin and Warner 2012, McPherson and Warner 2012, Austin and Bailey 2013, Austin et al. 2013, Zykov and MacDonnell 2013, Austin 2014, Austin et al. 2015, Austin and Li 2016, Martin and Popper 2016).

C.3. Estimating Ranges to Threshold Levels

For underwater modelling, sound level contours were calculated based on the sound fields predicted by the propagation models, sampled by taking the maximum value over all modelled depths above the sea floor for each location in the modelled region. For in-air modelling, sound level contours were calculated based on the sound field 0–15 cm above the water or the ground. The predicted distances to specific levels were computed from these contours. Two distances relative to the source are reported for each sound level: 1) R_{max}, the maximum range to the given sound level over all azimuths, and 2) $R_{95\%}$, the range to the given sound level after the 5% farthest points were excluded (see examples in Figure C-4).

The $R_{95\%}$ is used because sound field footprints are often irregular in shape. In some cases, a sound level contour might have small protrusions or anomalous isolated fringes. This is demonstrated in the image in Figure C-4(a). In cases such as this, where relatively few points are excluded in any given direction, R_{max} can misrepresent the area of the region exposed to such effects, and $R_{95\%}$ is considered more representative. In strongly asymmetric cases such as shown in Figure C-4(b), on the other hand, $R_{95\%}$ neglects to account for significant protrusions in the footprint. In such cases R_{max} might better represent the region of effect in specific directions. Cases such as this are usually associated with bathymetric features affecting propagation. The difference between R_{max} and $R_{95\%}$ depends on the source directivity (all sources in this study have uniform source directivity) and the non-uniformity of the acoustic environment.

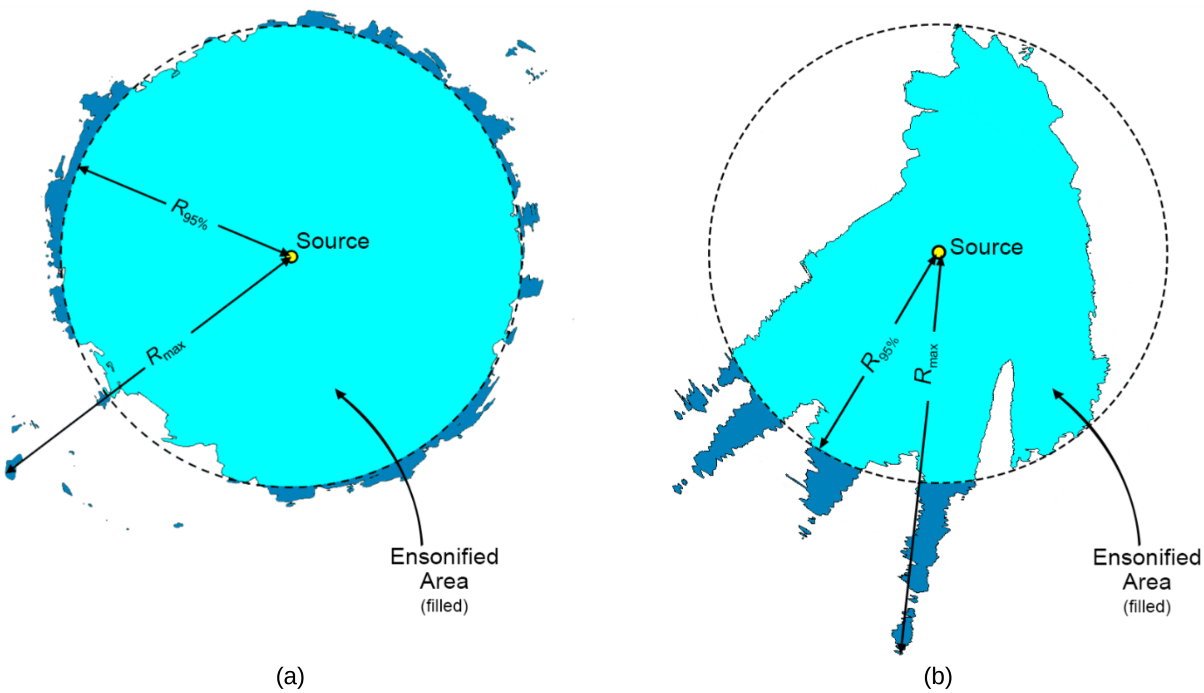

Figure C-4. Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ ranges shown for two different scenarios. (a) Largely symmetric sound level contour with small protrusions. (b) Strongly asymmetric sound level contour with long protrusions. Light blue indicates the ensonified areas bounded by $R_{95\%}$; darker blue indicates the areas outside this boundary which determine R_{max}.

C.4. Environmental Parameters

C.4.1. In-air Acoustic Environment

This section describes the terrain topography, terrain impedance, and atmospheric profiles, which are input to INPM for this study.

For the terrain topography, two data sets were used to generate an elevation grid of 25 × 25 km centered around Vardys Island:

- At Vardys Island, high-resolution terrain elevation was provided by the client.
- For the surrounding area, terrain elevations with 20 × 30 m resolution were obtained from the United States Geological Survey (USGS) 3-D Elevation Program (USGS 2020).

The two datasets were combined, adjusted to 0 m elevation at the water level mark corresponding to large tide, and grided to 10 × 10 m resolution for INPM acoustic modelling (Figure C-5).

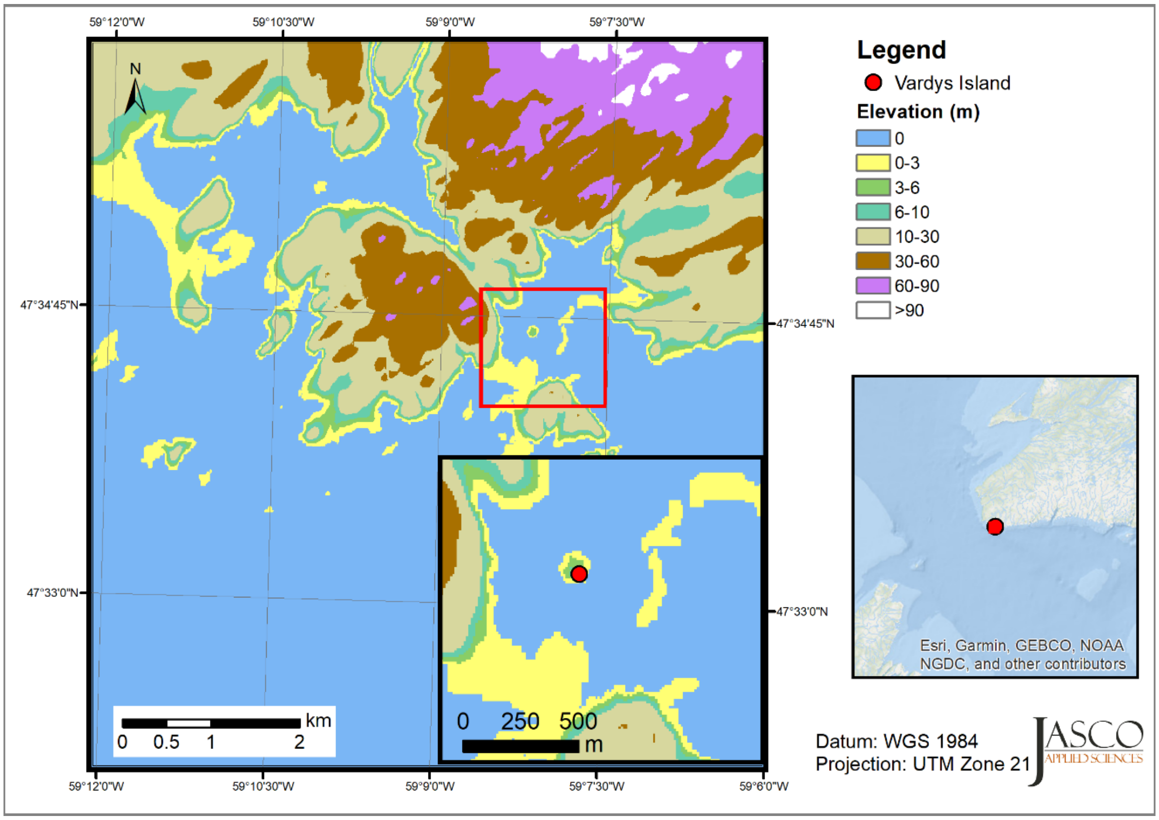

Figure C-5. Terrain elevation within the modelled area.

Interaction of sound with the terrain is accounted for in INPM by considering the relationship between acoustic impedance of the ground or the water and the air. This relationship dictates a ratio of sound energy that is reflected into the atmosphere and the sound energy that is absorbed into the ground or the water. The parameter that describes this absorption of energy is called the flow resistivity (Delany and Bazley 1970). In this study, multiple regions around the Vardys Island (Figure C-6) were selected to have a specific flow resistivity value, based on the type of material predominant at the surface (as determined by visual inspection of arial imagery). For snow-free seasons (May-October), land areas were classified either as rock/vegetation or urban areas. For snow seasons (November-April), all land areas were modelled with a flow resistivity corresponding to soft packed snow. For both seasons, waterbodies were assumed to be ice- and snow-free. The flow resistivity for each type of terrain is shown in Table C-1.

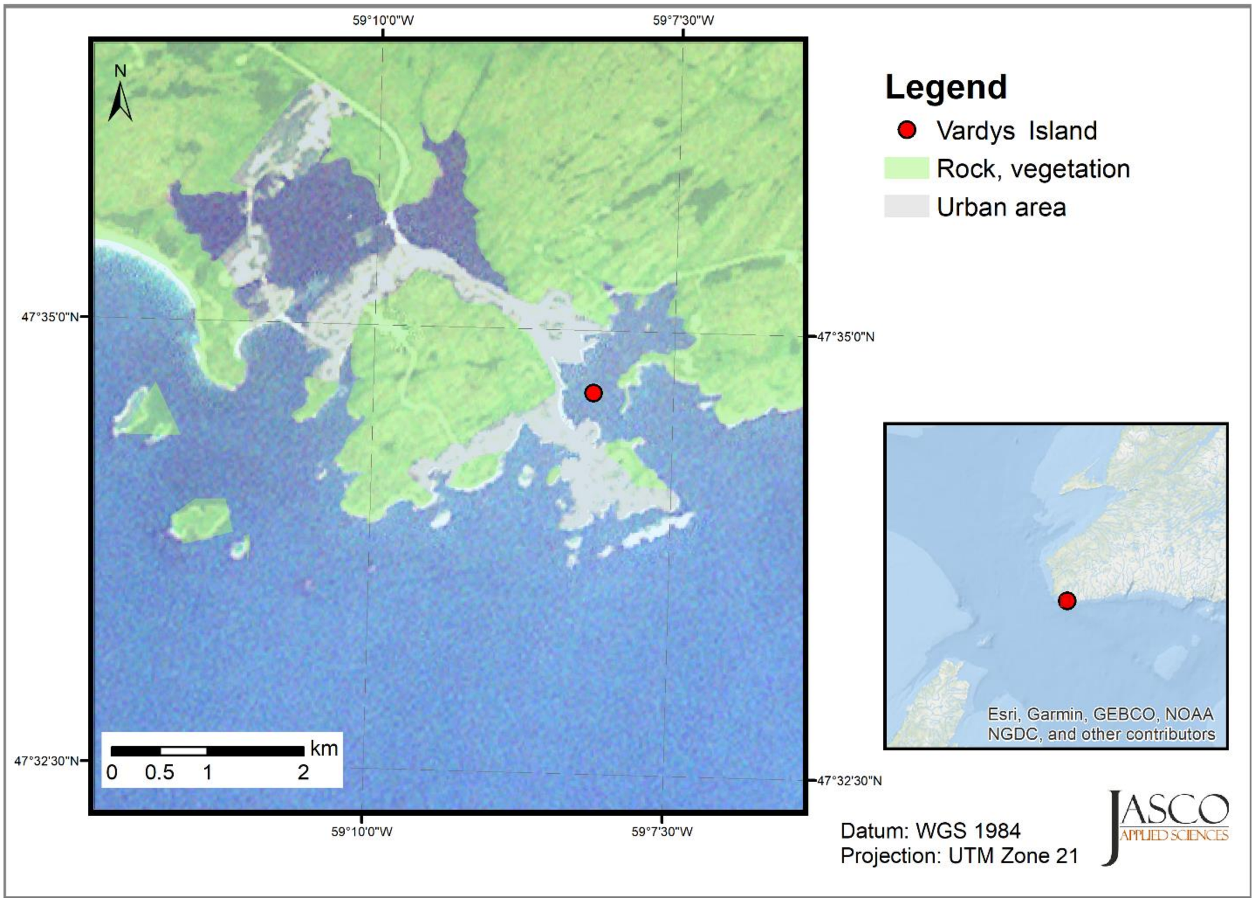

Figure C-6. Flow resistivity regions within the modelled area. Values can be seen in Table C-1.

Table C-1. Flow resistivity values assosiated with regions close to Vardys Island.

Region	Flow resistivity (kNs/m^4)
Rock/vegetation	100
Urban area	630
Soft packed snow	40
Water	2000

The atmospheric profiles used in this investigation were calculated from twice-daily weather balloon launches from the nearest data station at Stephenville, NL, during 2019. For each month, weather data consists of elevation-dependent profiles of pressure, temperature, and dew point. Relative humidity was then calculated from temperature and dew point using the equation from Alduchov and Eskridge (1996). All the data were averaged in 50 m bins, interpolated from 0 and 3 km elevation, and smoothed using a moving average. Pressure, temperature, dew point, and relative humidity at elevations less than 50 m were assumed to be constant because the lowest measurements at Anchorage were made at 50 m. Preliminary modelling of broadband unweighted SEL levels was carried out to determine the atmospheric profile that is likely to yield the most precautionary distances to thresholds. The April profile used in this study (Figure C-7) yielded the most conservative results among all profiles.

Wind velocity, unlike the other atmospheric profile parameters used in INPM, is a vector quantity. INPM uses a scalar wind speed profile that is the wind velocity projected along the modelled sound propagation radial. We used a wind velocity of zero in our model so as not to bias the sound propagation in any direction, given that there are no prevailing winds at this location.

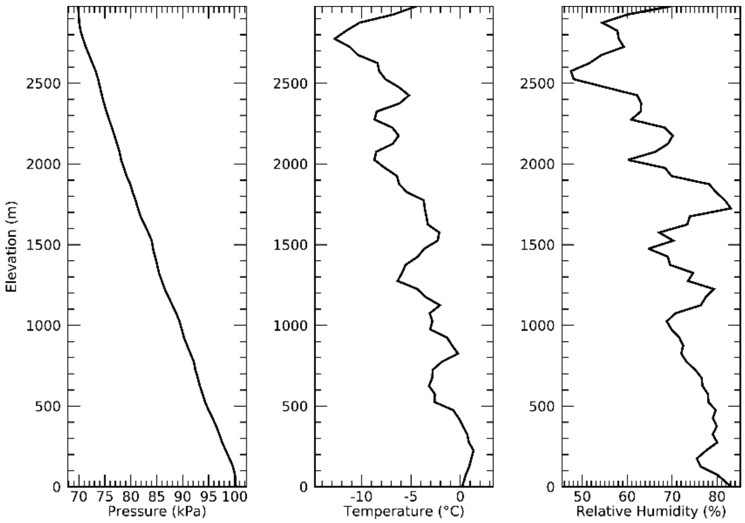

Figure C-7. April: Atmospheric pressure, temperature, and relative humidity profiles used to model sound propagation from buried explosive detonations.

C.4.2. Bathymetry

For underwater acoustic propagation modelling bathymetry gird was created using data from multiple datasets (Figure C-8). The available data for the project area included:

- Point data from the client covering the navigational channel and adjacent areas (~1 m spatial resolution),
- Features from Navigational chart CHS4641 (isobath contour lines, individual soundings, and shoreline) covering Part aux Basque and extending ~2 km into the open sea, and
- Eastern Canada 3 arc-second Bathymetric Digital Elevation Model compiled by NOAA (USA) (grid resolution ~60×90 m).

Two bathymetrical grids were produced to represent different stages of the construction: Stage 1 (Figure C-10) with present day bathymetry for modelling blasting operation and Stage 2 (Figure C-10) represented the final stage of dredging. The target depth for rock removal was 10.5 m below the sea surface within the navigational channel. Stage 2 grid represented the final stage of bedrock removal at which the target depth was reached. This grid was used to model acoustic field from dredging operation.

The original water depth data had “lowest normal tide” datum. The bathymetrical grid for the acoustic modelling was converted to “highest normal tide” datum by adding 2 m to the water depths. Hence, the target depth in the “highest normal tide” was 12.5 m.

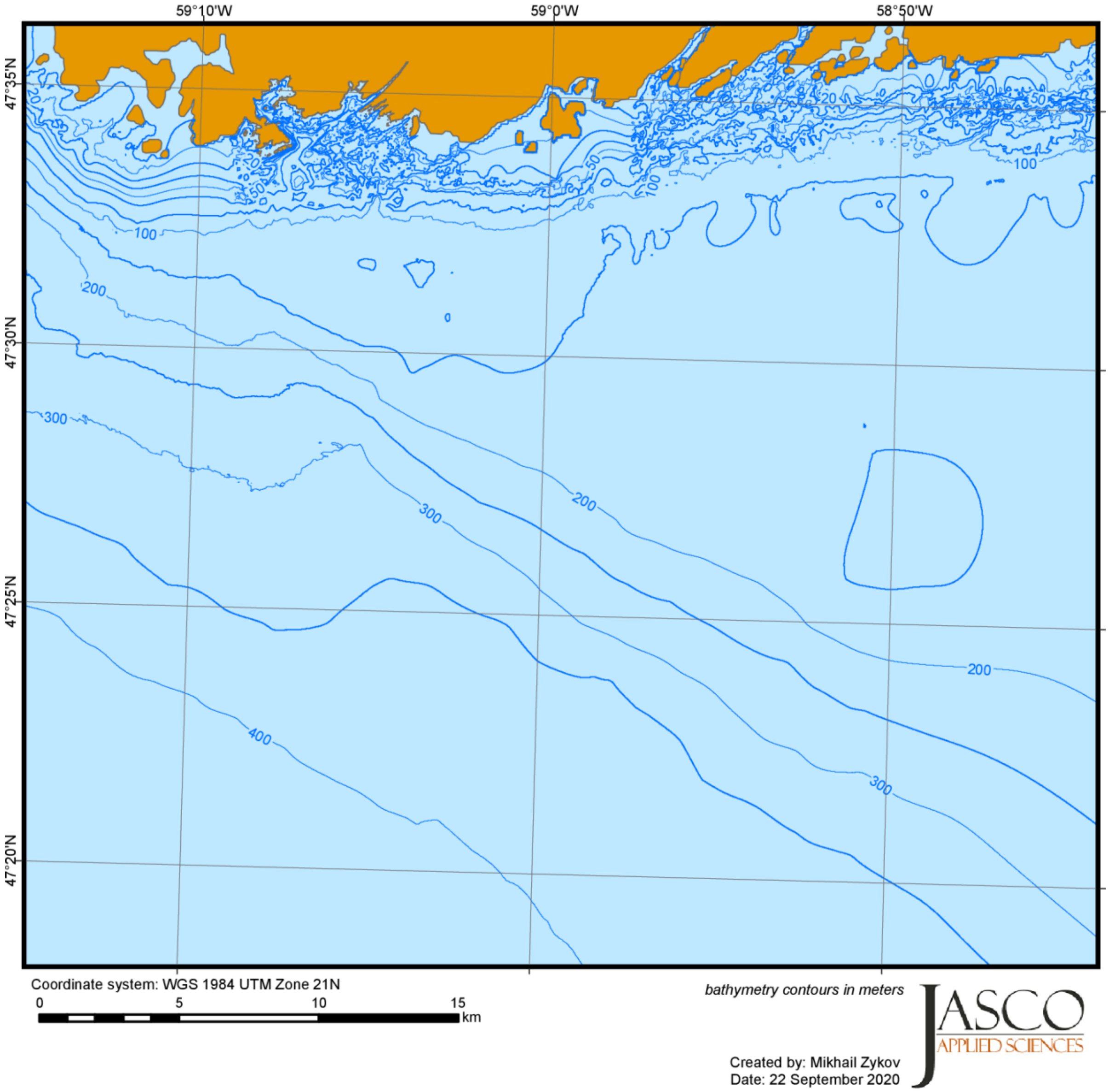

Figure C-8. Bathymetry map for the modelling area

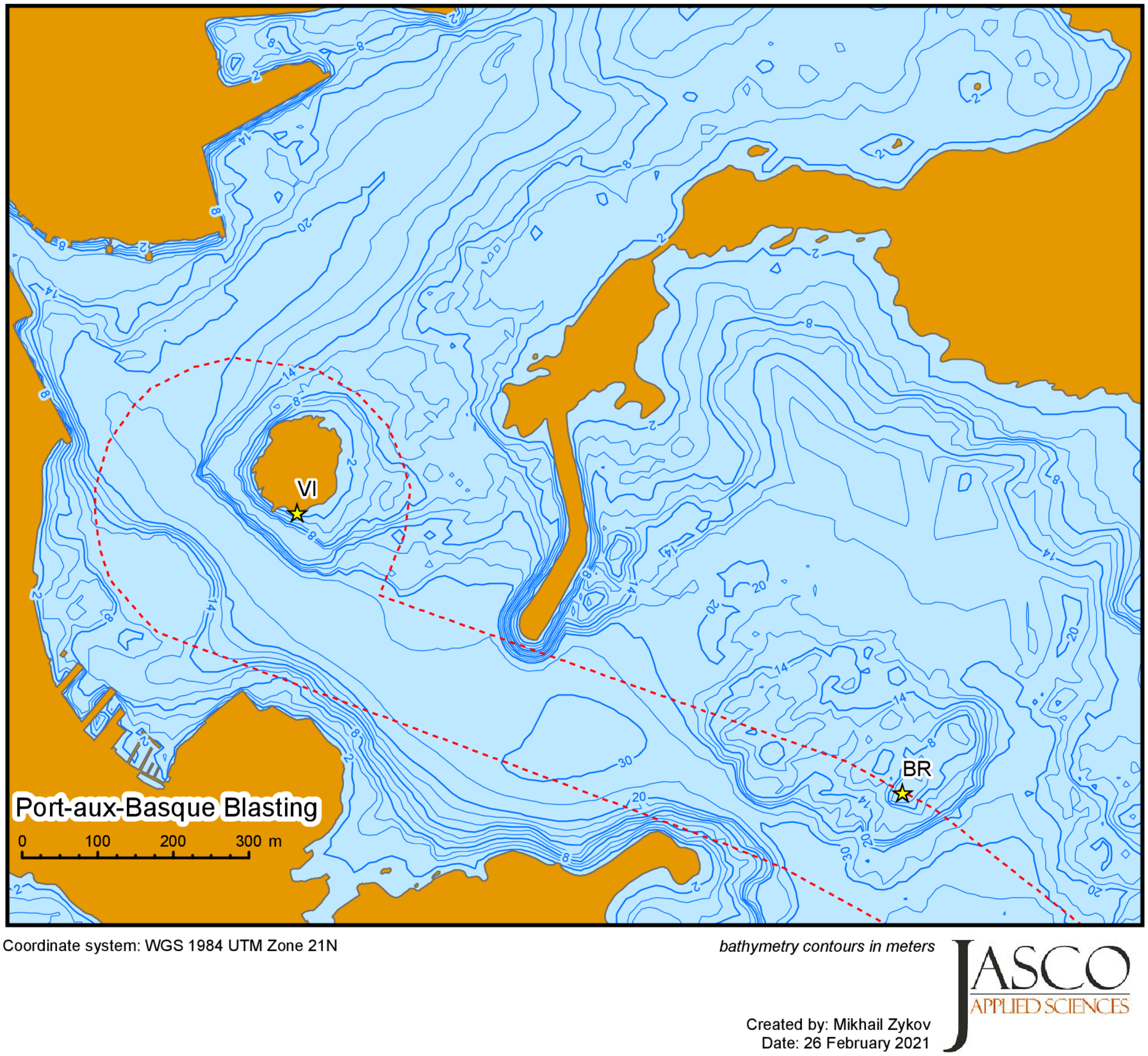
Port-aux-Basque Blasting
VI
BR
0 100 200 300 m
Coordinate system: WGS 1984 UTM Zone 21N
bathymetry contours in meters
Created by: Mikhail Zykov
Date: 26 February 2021
JASCO APPLIED SCIENCES

Figure C-9. Blasting specific bathymetry within Port-aux-Basque. Modelling locations: VI-Vardys Island; BR-Baldwin Rock

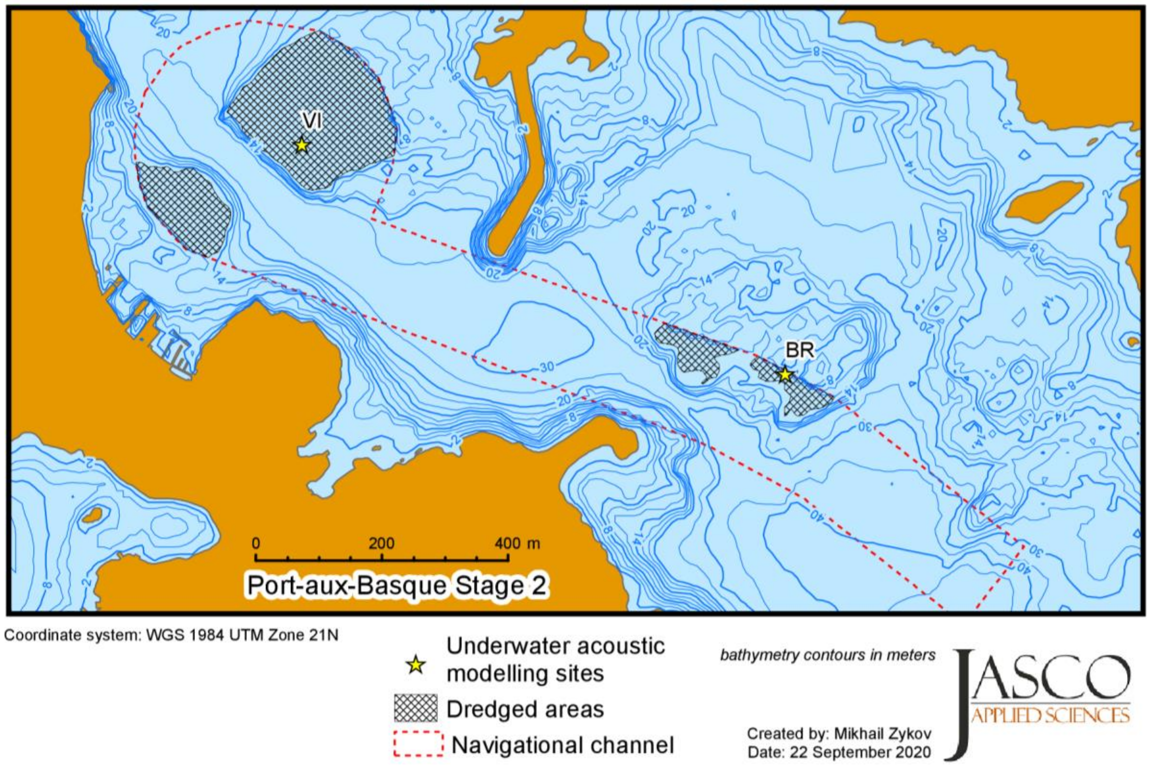

Figure C-10. Dredging stage specific bathymetry within Port-aux-Basque. Modelling locations: VI-Vardys Island; BR-Baldwin Rock

C.4.3. Underwater Sound Speed Profiles

The construction project is planned to be carried on year-round, so all twelve months were considered while selecting the sound speed profile for the propagation modelling.

The sound speed profiles were derived using temperature and salinity profiles from the U.S. Naval Oceanographic Office's *Generalized Digital Environmental Model V 3.0* (GDEM; Teague et al. 1990, Carnes 2009). GDEM provides an ocean climatology of temperature and salinity for the world's oceans on a latitude-longitude grid with 0.25° resolution, with a temporal resolution of one month, based on global historical observations from the U.S. Navy's Master Oceanographic Observational Data Set (MOODS). The climatology profiles include 78 fixed depth points to a maximum depth of 6800 m (where the ocean is that deep), including 55 standard depths between 0 and 2000 m. The GDEM temperature-salinity profiles were converted to sound speed profiles according to Coppens (1981).

The hydrology dataset was sampled at 47.5°N 59.25°W. The sound speed profiles for each of the twelve months are shown in Figure C-11 (left). The sound speed profile shows significant variation through the year featuring well developed surficial channel during winter months. The sound speed profile calculated for February (Figure C-11, right) was selected for modelling all propagation scenarios.

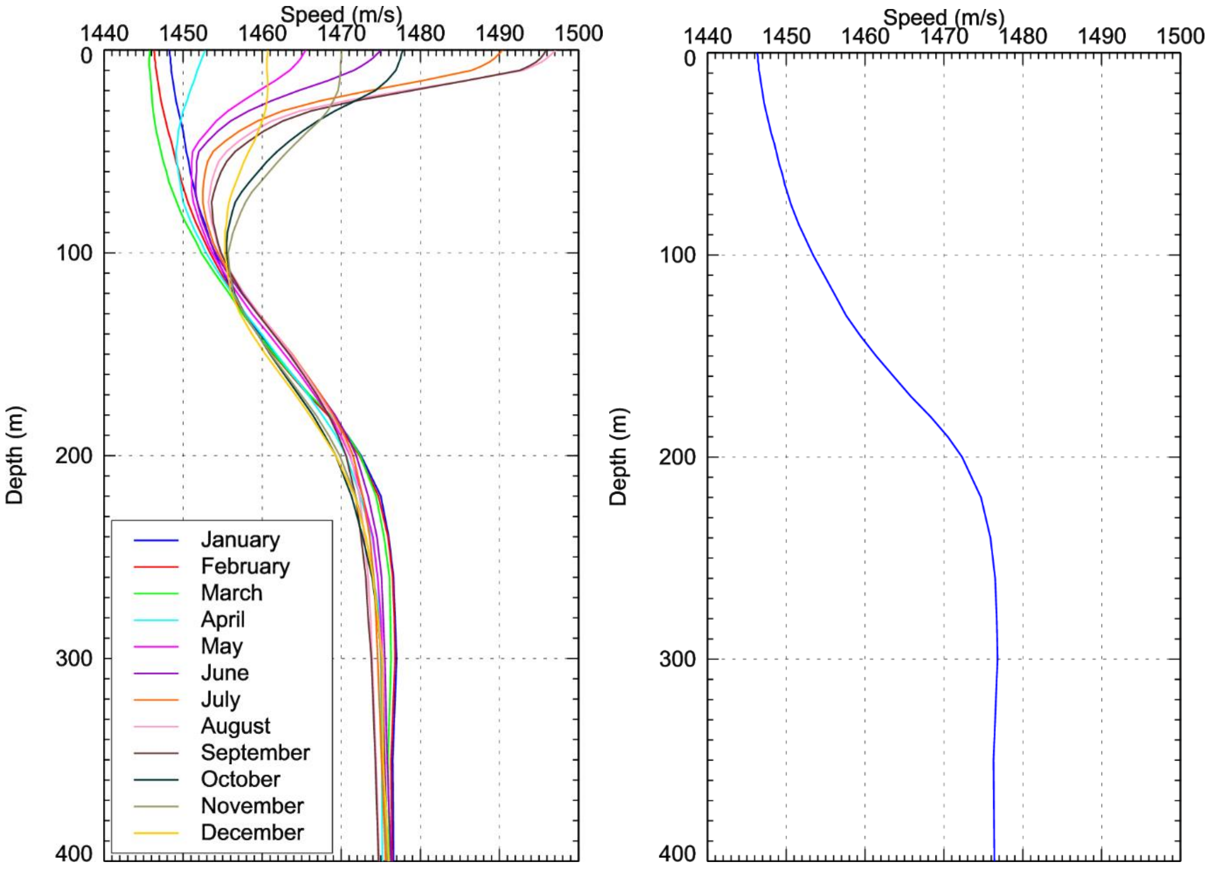

Figure C-11. Monthly average sound speed profile in the water column for all months of interest (left) and sound speed profile selected for propagation modelling (February; right). Based on GDEM V 3.0 data at sampling location 47.5°N 59.25°W.

C.4.4. Seabed Geoacoustic Profiles

The sea bottom in the project area is represented by bedrock with intermittent presence of a thin layer of uncompacted large grain size (gravel/coarse sand) sediments. The sound field predictions are to be provided for the project state at which at least a few metres of the sediment/bedrock layer is removed at the test site.

For the purpose of the acoustic propagation the bottom is considered to be a layer of bedrock. The geotechnical drilling on Vardys Island reported presence of amphibolite and gneiss. Typical geoacoustic properties for these types of rock were taken. The geoacoustic model used for underwater sound propagation is presented in Table C-2 (same for both sites).

Table C-2. Geoacoustic model for Port-aux-Basque Within each depth range, each parameter varies linearly within the stated range. The compressional wave is the primary wave. The shear wave is the secondary wave.

Depth below seafloor (m)	Material	Density (g/cm^3)	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0–1000	Amphibolite/ gneiss	2.7	3000–3500	0.1	500	0.2
>1000			3500			