

# Underwater Noise Modelling

## Construction of Steensby Port Facility– Marine Environment

JASCO Applied Sciences (Canada) Ltd

9 April 2025

**Submitted to:**

Phil Rouget

WSP Canada Inc.

WSP Project CA-GLD-20252228-13000.08 Task Order 001

**Authors:**

Melanie E. Austin

Mikhail M. Zykov

P001348-021

Document 03377

Version 1.0



## Suggested citation:

Austin, M.E. and M.M. Zykov. 2025. Underwater Noise Modelling: Construction of Steensby Port Facility–Marine Environment. Document 03377, Version 1.0. Technical report by JASCO Applied Sciences for WSP Canada.

## Report approved by:

<i>Version</i>	<i>Role</i>	<i>Name</i>	<i>Date</i>
1.0	Project Manager	Melanie Austin	January 8, 2025

*Disclaimer:* The results presented herein are relevant within the specific context described in this report. They could be misinterpreted if not considered in the light of all the information contained in this report. Accordingly, if information from this report is used in documents released to the public or to regulatory bodies, such documents must clearly cite the original report, which shall be made readily available to the recipients in integral and unedited form.

*Authorship statement:* Individual authors of this report may have only contributed to portions of the document and thus not be responsible for the entire content. This report may contain standardized (boilerplate) components that are common property of JASCO and are not directly attributed to their original authors/creators. The entire content of this report has been subject to senior scientific review by the qualified person listed in the front matter of the document.

# Contents

ᐅᐅᐅᐅ ᐅᐅᐅᐅ ᐅᐅᐅᐅ ᐅᐅᐅᐅ ᐅᐅᐅᐅ	1
Plain Language Summary	3
Executive Summary	5
1. Introduction	8
1.1. Modelled Scenarios	11
2. Underwater Noise Impact Criteria	13
3. Methods	15
3.1. Acoustic Sources	15
3.1.1. Drilling	15
3.1.2. Pile Driving	16
3.1.3. Onshore Rock Blasting	19
3.2. Acoustic Propagation Models	20
3.2.1. Drilling Modelling	20
3.2.2. Pile Driving Modelling	21
3.2.3. Blasting Modelling	22
3.2.4. Aggregate Scenarios	23
4. Results	24
4.1. Drilling	24
4.2. Impact Pile Driving	27
4.3. Vibratory Pile Driving	32
4.4. Onshore Rock Blasting	34
4.5. Aggregate Scenarios	39
5. Discussion and Conclusion	45
5.1. Individual Activity Scenarios	45
5.2. Aggregate Scenarios	47
Glossary of Acoustics Terms	50
Literature Cited	59
Appendix A. Underwater Acoustics Metrics	A-1
Appendix B. Impact Criteria	B-1
Appendix C. Modelling Methodology and Parameters	C-1

## Figures

Figure 1. Map of the Project area and the modelled locations.	10
Figure 2. Down-the-hole drilling: Modeled decidecade band energy source level (ESL) spectrum.	16
Figure 3. Impact pile driving of pipe piles: Modeled decidecade band energy source level (ESL) spectrum for (left) Scenario 2 (at combi-wall) and (right) Scenario 6 (at mooring point)	17
Figure 4. Impact pile driving of a sheet pile: Modelled decidecade band Energy Source Level (ESL) spectrum of a monopole effective source.	18
Figure 5. Vibratory pile driving of a sheet pile: Modelled decidecade band energy source level (ESL) spectrum of a monopole effective source.	19
Figure 6. Sound level contours for Scenario 1, drilling of pipe piles at combi-wall.	25
Figure 7. Sound level contours for Scenario 5, drilling of pipe piles at mooring point.	26
Figure 8. Sound level contours for Scenario 2, impact pile driving of pipe piles at combi-wall.	29
Figure 9. Sound level contours for Scenario 4, impact pile driving of sheet piles at combi-wall.	30
Figure 10. Sound level contours for Scenario 6, impact pile driving of pipe piles at mooring point.	31
Figure 11. Sound level contours for Scenario 3, vibratory pile driving of sheet piles at combi wall.	33
Figure 12. Sound level contours for aggregate Scenario 1 combining noise from drilling and impact pile driving required to drive 1.5 combi-wall pipe piles in one day.	40
Figure 13. Sound level contours for aggregate Scenario 2 combining noise from vibratory and impact pile driving required to drive 6 combi-wall sheet piles in one day.	41
Figure 14. Sound level contours for aggregate Scenario 3 combining noise from drilling and impact pile driving required to drive 1 mooring point pipe piles in one day.	42
Figure 15. Sound level contours for aggregate Scenario 4 combining noise from drilling, vibratory piling, and impact pile driving required to drive 1.5 combi-wall pipe piles and 6 combi-wall sheet piles in one day.	43
Figure 16. Sound level contours for aggregate Scenario 5 combining noise from blasting (100 detonations of 100 kg charges) with drilling and impact pile driving required to drive 1.5 combi-wall pipe piles in one day.	44
Figure A-1. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale	A-3
Figure B-1. Auditory weighting functions for the functional marine mammal hearing groups as recommended by NMFS (2018).	B-6
Figure C-1. Physical model geometry for impact driving of a cylindrical pile	C-1
Figure C-2. <i>ConWep attenuation factor tuning</i> : Modelled peak sound pressure level (maximum-over-depth) for the 1 kg TNT charge, compared to regression functions provided by Eagle River Flats measurements.	C-3
Figure C-3. Time-dependent pressure wave for underground detonations	C-3
Figure C-4. The $N \times 2$ -D and maximum-over-depth modeling approach.	C-4
Figure C-5. Example of synthetic pressure waveforms computed by FWRAM at multiple range offsets.	C-7
Figure C-6. Sample areas ensonified to an arbitrary sound level with $R_{\max}$ and $R_{95\%}$ ranges shown for two contrasting scenarios	C-8
Figure C-7. Bathymetry map for the modelling area.	C-9
Figure C-8. Bathymetry around proposed dock with in-fill in place.	C-10
Figure C-9. Monthly average sound speed profile in the water column for August	C-11

## Tables

Table 1. Summary of relevant acoustic terminology used in the modelling report.	10
Table 2. Location and description of modelled scenarios considered.	12
Table 3. <i>Impact pile driving</i> : Impulsive noise thresholds for temporary threshold shift (TTS) and permanent threshold shift (PTS) across five marine mammal hearing groups based on NMFS (2018), and for behavioural disturbance (all marine mammal species) based on NMFS (2013).	13
Table 4. <i>Drilling and vibratory pile driving</i> : Non-impulsive noise thresholds for permanent threshold shift (PTS), temporary threshold shift (TTS) and behavioural disturbance of marine mammals based on NMFS (2018) and (2013).	14
Table 5. <i>Blasting</i> : Impulsive noise thresholds for permanent threshold shift (PTS), temporary threshold shift (TTS) and behavioural disturbance of marine mammals based on Finneran et al. (2017).	14
Table 6. Noise exposure criteria for impact pile driving and blasting impacts on fish based on Popper et al. (2014).	14
Table 7. Specifications used for modelling drilling of pipe piles.	15
Table 8. Modelling parameters used in this work for impact pile driving operations for pipe piles.	17
Table 9. Modelling parameters for impact and vibratory pile driving of sheet piles.	18
Table 10. Specifications of the charge used for rock blasting.	19
Table 11. Parameters used for modelling 24 h SEL for drilling of pipe piles.	20
Table 12. Parameters used for modelling 24 h SEL for impact driving of pipe piles.	21
Table 13. Parameters used for calculating 24 h SEL for driving of sheet piles.	22
Table 14. Aggregate scenarios definition.	23
Table 15. <i>Drilling of pipe piles</i> : Distances (m) to $SEL_{w,24h}$ thresholds (NMFS 2018) for permanent threshold shift (PTS) and temporary threshold shift (TTS) for non-impulsive noise sources.	24
Table 16. <i>Drilling of pipe piles</i> : Distances (m) to NMFS (2013) 120 dB re 1 $\mu Pa^2$ SPL threshold for marine mammal behavioural disturbance for non-impulsive noise sources.	24
Table 17. <i>Impact pile driving</i> : Distances (m) to $SEL_{w,24h}$ thresholds (NMFS 2018) for permanent threshold shift (PTS) and temporary threshold shift (TTS).	27
Table 18. <i>Impact pile driving</i> : Distances (m) to PK thresholds (NMFS 2018) for permanent threshold shift (PTS) and temporary threshold shift (TTS).	27
Table 19. <i>Impact pile driving</i> : Distances (m) to NOAA Fisheries (2019) 160 dB re 1 $\mu Pa^2$ SPL threshold for marine mammal behavioural disturbance from impulsive noise sources.	28
Table 20. <i>Impact pile driving</i> : Distances (m) to fish mortality, potential mortal injury, and impairment $SEL_{w,24h}$ thresholds (Popper et al. 2014) due to impact pile driving.	28
Table 21. <i>Impact pile driving</i> : Distances (m) to fish mortality and potential mortal injury, and recoverable injury PK thresholds (Popper et al. 2014) due to impact pile driving.	28
Table 22. <i>Vibratory pile driving</i> : Distances (m) to $SEL_{w,24h}$ thresholds (NMFS 2018) for permanent threshold shift (PTS) and temporary threshold shift (TTS).	32
Table 23. <i>Vibratory pile driving</i> : Distances (m) to NMFS (2013) 120 dB re 1 $\mu Pa^2$ SPL threshold for marine mammal behavioural disturbance for non-impulsive noise sources.	32
Table 24. <i>Onshore rock blasting (at water edge)</i> : Distances (m) to $SEL_{w,24h}$ (NMFS 2018) for permanent threshold shift (PTS), temporary threshold shift (TTS) and behavioural disturbance thresholds for 100 detonations of charges with masses of 1, 10, 20, 30, 40, 50, and 100 kg TNT.	34

Table 25. Onshore rock <i>blasting (100 m from water)</i> : Distances (m) to $SEL_{w,24h}$ : (NMFS 2018) for permanent threshold shift (PTS), temporary threshold shift (TTS) and behavioural disturbance thresholds for 100 detonations of charges with masses of 1, 10, 20, 30, 40, 50, and 100 kg TNT.	35
Table 26. Onshore rock <i>blasting (at water edge)</i> : Distances (m) to PK thresholds (Finneran et al. 2017) for permanent threshold shift (PTS) and temporary threshold shift (TTS) for charges with masses of 1, 10, 20, 30, 40, 50, and 100 kg TNT.	36
Table 27. Onshore rock <i>blasting (100 m from water)</i> : Distances (m) to PK thresholds (Finneran et al. 2017) for permanent threshold shift (PTS) and temporary threshold shift (TTS) for charges with masses of 1, 10, 20, 30, 40, 50, and 100 kg TNT.	36
Table 28. Onshore rock <i>blasting (at water edge)</i> : Distances to fish mortality and potential mortal injury, and impairment $SEL_{w,24h}$ thresholds (Popper et al. 2014) for 100 detonations of charges with masses of 1, 10, 20, 30, 40, 50, and 100 kg TNT.	37
Table 29. Onshore rock <i>blasting (100 m from water)</i> : Distances to fish mortality and potential mortal injury, and impairment $SEL_{w,24h}$ thresholds (Popper et al. 2014) for 100 detonations of charges with masses of 1, 10, 20, 30, 40, 50, and 100 kg TNT.	37
Table 30. Onshore rock <i>blasting (at water edge)</i> : Distances (m) to fish mortality and potential mortal injury, and recoverable injury PK thresholds (Popper et al. 2014) for charges sizes of 1, 10, 20, 30, 40, 50, and 100 kg TNT.	38
Table 31. Onshore rock <i>blasting (100 m from water)</i> : Distances (m) to fish mortality and potential mortal injury, and recoverable injury PK thresholds (Popper et al. 2014) for charges sizes of 1, 10, 20, 30, 40, 50, and 100 kg TNT.	38
Table 32. Aggregate scenarios: Distances (m) to SEL (NMFS 2018) for permanent threshold shift (PTS) and temporary threshold shift (TTS) in marine mammals for the combined activity scenarios listed in Table 14.	39
Table 33. Aggregate scenarios: Distances (m) to fish mortality, potential mortal injury, and impairment $SEL_{w,24h}$ thresholds (Popper et al. 2014) for the combined activity scenarios listed in Table 14.	39
Table 34. Aggregate scenarios: Distances (m) to the NMFS (2013) 120 dB re 1 $\mu Pa^2$ SPL threshold for marine mammal behavioural disturbance for non-impulsive noise sources, for the combined activity scenarios listed in Table 14.	39
Table B-1. Sound pressure level (SPL; dB re 1 $\mu Pa$ ), peak sound pressure level (PK; dB re 1 $\mu Pa$ ), and sound exposure level (SEL; dB re 1 $\mu Pa^2 s$ ) thresholds for behavioural disturbance, auditory injury (PTS onset), and TTS onset for marine mammals for impulsive sounds, as proposed by NMFS (2013, 2018).	B-3
Table B-2. Fisheries Hydroacoustic Working Group (FHWG) mortality and impairment criteria for impact pile driving (Popper et al. 2014).	B-5
Table B-3. Parameters for the auditory weighting functions recommended by NMFS (2018).	B-6
Table C-1. Gaspin distance for modelled charge size.	C-3
Table C-2. Seabed geoacoustic properties for sites at combi-wall.	C-12
Table C-3. Seabed geoacoustic properties for on-land sites.	C-12

[illegible][illegible]

- ጋኒላቶችን (የፈጥሮአዊ ድክመት ጋኒላቶች ርዕስ)
- ልዩነቶችን ለማሳወቅ (የጋኒላቶች ማጠቃለያ)
- ጋኒላቶችን ድጋፍ ለማድረግ ለሚችሉ ልማቶች

[illegible]
$$C_{n\Delta} \geq \Delta^{\frac{1}{2}}$$

- [illegible]

 $\Delta^{\text{f}} \rightarrow \Delta^{\text{c}}$ 

- [illegible]

[illegible]

- [illegible]

[illegible][illegible]

- ተገዳሪዎች ለጥያቄው ሂሳብ ማረጋገጫ ማቅረብ ይገባቸዋል።
- የጥያቄው ሂሳብ ለጥያቄው ማረጋገጫ ማቅረብ ይገባቸዋል።
- ተገዳሪዎች ለጥያቄው ሂሳብ ማረጋገጫ ማቅረብ ይገባቸዋል።

[illegible]



## Plain Language Summary

Baffinland Iron Mines Corporation (Baffinland) is the owner and operator of the Mary River Project, an operating open pit iron ore mine located in the Qikiqtani Region of Baffin Island in Nunavut (the Project). The Nunavut Impact Review Board (NIRB) issued Project Certificate No. 005 on 28 December 2012, authorizing Baffinland to mine and transport iron ore from Deposit No. 1 by rail to a port site in Steensby Inlet (Steensby Port) for year-round shipping along the Southern Shipping Route (via Foxe Basin and Hudson Strait). Baffinland is now proceeding with construction of the approved Steensby Railway and Steensby Port. Construction activities such as blasting and pile driving during port construction will create underwater noise, which could potentially harm marine mammals and fish or disturb their behavior. To address this, JASCO Applied Sciences (JASCO) was commissioned by WSP, on behalf of Baffinland Iron Mines Corporation, to model how underwater sound from construction would travel and where the sound might affect marine animals and fish. JASCO estimated how far noise levels might exceed safe thresholds for:

- Hearing loss (temporary or permanent)
- Behavioural disturbance (such as swimming away from the noise)
- Injury or mortality for fish

## Key Findings

### Marine Mammals

- Noise from pile driving and blasting can temporarily disturb species like whales and seals up to several kilometers away.
- Hearing loss is unlikely for most marine mammals, except for low-frequency cetaceans (e.g., bowhead whales) near construction sites. Permanent hearing loss could be possible within 200 meters of drilling or within 80 meters of pile driving; temporary hearing loss could be possible within 3.2 kilometers from drilling or within at most 1 kilometer from pile driving.
- Noise from impact pile driving could cause hearing loss in low-frequency cetaceans at longer distances (as far as 1.6 km) if drilling occurs in the same area earlier in the day.
- Behavioral changes could occur as far as 13 kilometers from drilling and several kilometers (less than 5 kilometers) from other activities, depending on the noise source.

### Fish

- Noise from pile driving could cause temporary hearing loss to fish close to construction (up to 76 meters in some cases).
- No fish were expected to be killed or injured by noise from drilling or pile driving under normal construction conditions.

### Blasting Noise

- For marine mammals, blasting at the water's edge may disturb low-frequency cetaceans within 60 meters of the blast but is not expected to cause hearing loss (either permanent or temporary).

- Fish are not expected to be injured or killed by noise from on-shore blasting occurring 20 meters or more from the water's edge.

## Mitigation and Monitoring

The study results will guide noise reduction strategies and monitoring plans, which Baffinland will implement as part of a Marine Mammal Management Plan (MMMP) that will be included in the Construction Environmental Management Plan (CEMP). These plans aim to protect marine mammals, fish, and their habitats through measures like:

- Adjusting construction methods to minimize noise
- Monitoring underwater noise levels and wildlife responses
- Refining strategies over time based on new data and input from Inuit organizations and regulators

These measures will evolve as more data is collected and engagement continues with regulators and Inuit. By using this study's findings, Baffinland aims to limit impacts on marine wildlife during construction.

## Executive Summary

Baffinland Iron Mines Corporation (Baffinland) is the owner and operator of the Mary River Project, an operating open pit iron ore mine located in the Qikiqtani Region of Baffin Island in Nunavut (the Project). The Nunavut Impact Review Board (NIRB) issued Project Certificate No. 005 on 28 December 2012, authorizing Baffinland to mine and transport iron ore from Deposit No. 1 by rail to a port site in Steensby Inlet (Steensby Port) for year-round shipping along the Southern Shipping Route (via Foxe Basin and Hudson Strait). Baffinland is now proceeding with construction of the approved Steensby Railway and Steensby Port with construction planned to begin in late 2025.

During construction of the Steensby Port facility, underwater noise generated by construction activities has the potential to change the behaviour of marine mammals and fish in the local environment. If unmitigated, auditory injuries may occur due to underwater noise produced during blasting and pile driving. Blasting can also result in physical injury or direct mortality to marine mammals.

JASCO Applied Sciences (JASCO), on behalf of WSP Canada Inc., conducted a modelling study to predict underwater sound propagation and calculate noise footprints associated with port construction activities, including drilling, pile driving, and onshore blasting. The model results were interpreted to estimate distances over which underwater sound levels would exceed established acoustic injury and disturbance thresholds for marine mammals and fish. The relevant thresholds pertain to the onset of permanent threshold shift (PTS), temporary threshold shift (TTS), and the onset of behavioural disturbance. Separate thresholds were considered for fish (including fish eggs and larvae) and for five marine mammal functional hearing groups: low-frequency (LF) cetaceans, mid-frequency (MF) cetaceans, high-frequency (HF) cetaceans, and phocid (PW) and otariid (OW) pinnipeds in water. PTS and TTS thresholds are expressed using two different sound metrics, the peak instantaneous sound level (PK) and the frequency-weighted sound exposure level (SEL), weighted to account for the varying hearing sensitivities of the different marine mammal functional hearing groups. The reported distances to potential acoustic effects correspond to the metric with the longest exceedance distance. The model considered the total sound exposure for individual construction activities over a 24 hour period, as well as for aggregate (i.e., combined) construction activities over a 24 hour period.

Modelling results presented in this report will be used to inform mitigation and monitoring requirements that will be implemented during construction of the Steensby Port facility, which will be outlined in a Marine Mammal Management Plan (MMMP) in Baffinland's Construction Environmental Management Plan (CEMP). The purpose of these management plans is to outline commitments, mitigation measures and monitoring programs that Baffinland will implement during port construction to reduce potential Project-related adverse impacts on marine mammals and fish resulting from underwater noise caused by pile installation, blasting and other marine construction activities, in addition to impacts from Project-related vessels. The MMMP will address all marine mammal species that could be directly or indirectly affected by routine Project activities within the Regional Study Area (RSA) boundaries, including walrus, ringed seal, bearded seal, beluga, narwhal, bowhead whale, polar bear, and their related habitats. Mitigation measures may be refined over the course of the construction project, as a result of information learned through ongoing underwater noise and wildlife monitoring undertaken as part of the MMMP and CEMP, and through discussions with regulators and Inuit organizations.

Modelling results are presented in this report by activity type: drilling (Section 4.1), impact pile driving (Section 4.2), vibratory pile driving (Section 4.3), and rock blasting (Section 4.4). Results for the aggregate scenarios, which include more than one activity type, are presented in Section 4.5. A summary of results follows.

The threshold exceedance distances associated with PTS were longest for the LF cetacean marine mammal hearing group. The sound levels for individual construction activities exceeded the LF cetacean PTS thresholds out to the following distances:

- 200 and 85 m for drilling of combi-wall pipe piles and mooring point piles, respectively;
- 80 and 21 m for impact pile driving of combi-wall sheet piles and combi-wall pipe piles, respectively (the PTS threshold was not exceeded in water for impact pile driving of mooring point piles); and
- 20 m for vibratory driving of combi-wall sheet piles.

The threshold exceedance distances associated with PTS were shorter for the HF cetacean and PW pinniped marine mammal hearing groups, when the threshold was exceeded at all. The PTS threshold was not exceeded for the MF cetacean or OW pinniped hearing groups for any of the individual construction activities.

The threshold exceedance distances associated with TTS were also longest for the LF cetacean marine mammal hearing group. The sound levels for individual construction activities exceeded the LF cetacean TTS thresholds out to the following distances:

- 3.2 km and 1.7 km for drilling of combi-wall pipe piles and mooring point piles, respectively;
- 330, 970 and 25 m for impact pile driving of combi-wall sheet piles, combi-wall pipe piles, and mooring point piles, respectively; and
- 240 m for vibratory driving of combi-wall sheet piles.

The threshold exceedance distances associated with TTS were shorter for the HF cetacean and PW pinniped marine mammal hearing groups, when the threshold was exceeded at all. The TTS threshold was not exceeded for the MF cetacean or OW pinniped hearing groups for any of the individual construction activities.

The threshold exceedance distances associated with behavioural disturbance (applicable to all species) reached the following maximum values :

- 13.2 and 13.4 km ( $R_{95\%} = 11$  and 11.8 km) for drilling of combi-wall and mooring point pipe piles, respectively;
- 2.2 km, 800 m, and 95 m for impact pile driving of combi-wall pipe piles, combi-wall sheet piles, and mooring point piles, respectively (1.8 km, 662 m, and 85 m, respectively, based on  $R_{95\%}$ ); and
- 5.2 km ( $R_{95\%} = 4.3$  km) during vibratory pile driving of combi-wall sheet piles.

No thresholds for mortality, potential mortal injury, or recoverable injury for fish were exceeded within the water for impact pile driving of the combi-wall pipe piles, combi-wall sheet piles, or the mooring point piles. For the impact pile driving scenarios for the combi-wall (but not for other scenarios), the TTS threshold for fish was exceeded up to the following distances:

- 25 m for impact pile driving of the combi-wall pipe piles; and
- 76 m for impact pile driving the combi-wall sheet piles.

For aggregate scenarios, combining the total sound exposure from multiple activities occurring in the same day, the exceedance distances for PTS for impulsive sounds increased to the following maximum ranges for the LF cetacean hearing group:

- 1.6 km for combi-wall pipe pile installation involving drilling and impact pile driving;
- 187 m for combi-wall sheet pile installation involving impact and vibratory pile driving;
- 790 m for mooring pile installation involving drilling and impact pile driving; and
- 1.6 km when combi-wall pipe piles and sheet piles are installed on the same day.

Noise from the aggregate scenarios exceeded the LF cetacean thresholds for TTS from impulsive sounds at the following maximum ranges:

- 11.3 km ( $R_{95\%} = 9.5$  km) for combi-wall pipe pile installation involving drilling and impact pile driving;
- 1.9 km ( $R_{95\%} = 1.6$  km) for combi-wall sheet pile installation involving impact and vibratory pile driving;
- 7.0 km ( $R_{95\%} = 6.0$  km) for mooring pile installation involving drilling and impact pile driving; and
- 11.3 km ( $R_{95\%} = 9.5$  km) when combi-wall pipe piles and sheet piles are installed on the same day.

For these aggregate scenarios, the maximum TTS exceedance distance for any other hearing group was 1.3 km for PW pinnipeds when combi-wall pipe piles and sheet piles are installed on the same day.

The additional noise from rock blasting during these activities did not change the threshold exceedance distances. These distances are computed relative to the more precautionary thresholds for impulsive sounds and are most representative of the exceedance distances for the impact pile driving activities on those days, accounting for prior exposure to drilling noise on the same day. These exceedance distances are overly conservative for non-impulsive activities, i.e. drilling and vibratory pile driving.

When considered in combination with prior exposure to drilling noise during the installation of combi-wall pipe piles, sound levels resulting from impact pile driving exceeded thresholds for potential impacts to fish at the following distances:

- Sound levels exceeded the threshold for mortality or potential mortal injury at maximum ranges of 67 and 41 m for fish with a swim bladder involved with hearing and fish without a swim bladder involved with hearing, respectively;
- The threshold for recoverable injury was exceeded at a maximum range of 181 m for fish with a swim bladder;
- There was no risk for mortality, potential mortal injury, or recoverable injury for fish with no swim bladder; and
- The threshold for TTS in fish was exceeded at a maximum distance of 1.7 km ( $R_{95\%} = 1.4$  km).

No thresholds for PTS or TTS for marine mammals were reached in the water for up to 100 detonations per day for any of the modelled charge sizes. The behavioural disturbance threshold for LF cetaceans was exceeded in water at ranges between 28 m for a 1 kg charge to 60 m for a 100 kg charge (for charges detonated 20 m from the water's edge). The behavioural disturbance threshold was not exceeded for any of the other hearing groups, nor was it exceeded for any hearing group or modelled charge size for detonations occurring at least 100 m from the water. No thresholds for mortality, potential mortal injury, recoverable injury, or TTS in fish were exceeded for any of the modelled blasting scenarios

# 1. Introduction

Baffinland Iron Mines Corporation (Baffinland) is the owner and operator of the Mary River Project, an operating open pit iron ore mine located in the Qikiqtani Region of Baffin Island in Nunavut (the Project). The Nunavut Impact Review Board (NIRB) issued Project Certificate No. 005 on 28 December 2012, authorizing Baffinland to mine and transport iron ore from Deposit No. 1 by rail to a port site in Steensby Inlet (Steensby Port) for year-round shipping along the Southern Shipping Route (via Foxe Basin and Hudson Strait). Baffinland is now proceeding with construction of the approved Steensby Railway and Steensby Port with the earliest anticipated start of construction in late 2025.

JASCO Applied Sciences (Canada) Ltd. (JASCO) was commissioned by WSP Canada Inc. to perform an underwater acoustic modelling study to predict underwater sound propagation and calculate noise footprints associated with construction activities for Steensby Port, including drilling, pile driving, and onshore blasting. Modelling results have been interpreted to estimate distances over which underwater sound levels would exceed established acoustic injury and disturbance thresholds for marine mammals and fish.

Modelling results presented in this report will be used to inform mitigation and monitoring requirements that will be implemented during construction of the Steensby Port facility, which will be outlined in a Marine Mammal Management Plan (MMMP) within Baffinland's Construction Environmental Management Plan (CEMP). The purpose of these management plans is to outline commitments, mitigation measures and monitoring programs that Baffinland will implement during port construction to reduce potential Project-related adverse impacts on marine mammals and fish resulting from underwater noise caused by pile installation, blasting and other marine construction activities, in addition to impacts from Project-related vessels. The MMMP will address all marine mammal species that could be directly or indirectly affected by routine Project activities within the Regional Study Area (RSA) boundaries, including walrus, ringed seal, bearded seal, beluga, narwhal, bowhead whale, polar bear, and their related habitats. Mitigation measures may be refined over the course of the construction project, as the result of information learned through ongoing underwater noise and wildlife monitoring undertaken as part of the MMMP and CEMP, and through discussions with regulators and Inuit organizations.

The present report is focused exclusively on underwater noise modelling in the marine environment of Steensby Inlet. JASCO also modelled in-air sound levels associated with the port construction activities, for consideration of potential impacts to receptors in the marine environment that can occur on land, ice, or at the sea surface (e.g., seals, walrus, and polar bears). The in-air noise modelling results are presented in a separate report (Quijano and Austin 2024). JASCO also modeled underwater sound levels in the freshwater environment associated with the Steensby Port and Railway construction footprints (as a result of onshore blasting activities). Underwater noise modelling results for the freshwater environment are presented in a separate report (Kanu 2023).

Following is a list of construction activities that were modelled in the present report:

- Combi-wall pipe pile installation, including drilling and impact pile driving;
- Combi-wall sheet pile installation, including impact and vibratory pile driving;
- Mooring point pipe pile installation, including drilling and impact pile driving; and
- Rock blasting for site preparations.

JASCO applied its specialized source models for impact pile driving and blasting, along with empirical acoustic source data for drilling and sheet pile installation, in combination with JASCO's underwater sound propagation models to predict the maximum distances at which specified noise thresholds (see Section 2) could be exceeded in the water.

In general, sound propagation in the marine environment depends on water depth, bathymetry, sound speed in the water, and geoacoustic characteristics of the seabed sediment, all of which are accounted for in the noise propagation models. In addition, noise production depends on the type of operation. For pile driving, noise production depends on the hammer and pile characteristics, as well as the soil properties, which determine the penetration rate of the pile into the sediment. For blasting, noise production depends on the type and size of the charges being detonated and their location relative to the water. For drilling, noise production depends on the size of the drill and how it interacts with the rock media being drilled. Source sound levels were derived considering all of these influencing factors.

The modelled scenarios are intended to be conservatively representative of the activities emitting noise into the marine environment. The five model locations shown in Figure 1 were considered, representing the locations anticipated to result in the worst-case condition in terms of sound propagation (e.g., pile locations in the deepest water). Where uncertainties in operating conditions existed, the models were parametrized to yield conservative yet realistic noise levels. The following conservative assumptions were applied to the methods used in this study so that the results are unlikely to underestimate potential effects on marine life:

- Because marine mammals inhabit a wide range of depths, the distances to thresholds for underwater auditory effects represent the maximum sound levels over all depths.
- The underwater model incorporated bathymetry adjusted for high tide, which yielded the most conservative computation for acoustic propagation. In addition, modelled locations were selected at the deepest water for each of the locations considered in this study.
- For pile driving, cumulative metrics were computed using a conservative estimate of the maximum number of strikes (for impact) or maximum duration (for vibratory and drilling) required to drive a pile, based on feedback the client provided to JASCO.
- Underwater sound propagation was modelled for the most conservative season after assessing the sound speed profile for multiple months.

The selected modelling parameters are expected to provide an upper bound of the expected noise levels. However, substantial deviation from these parameters (e.g., using larger piling equipment, relocating the pile locations to deeper waters, changing the maximum number of piles driven per day, increasing the amount of explosives in the blasting operation) would require additional modelling.



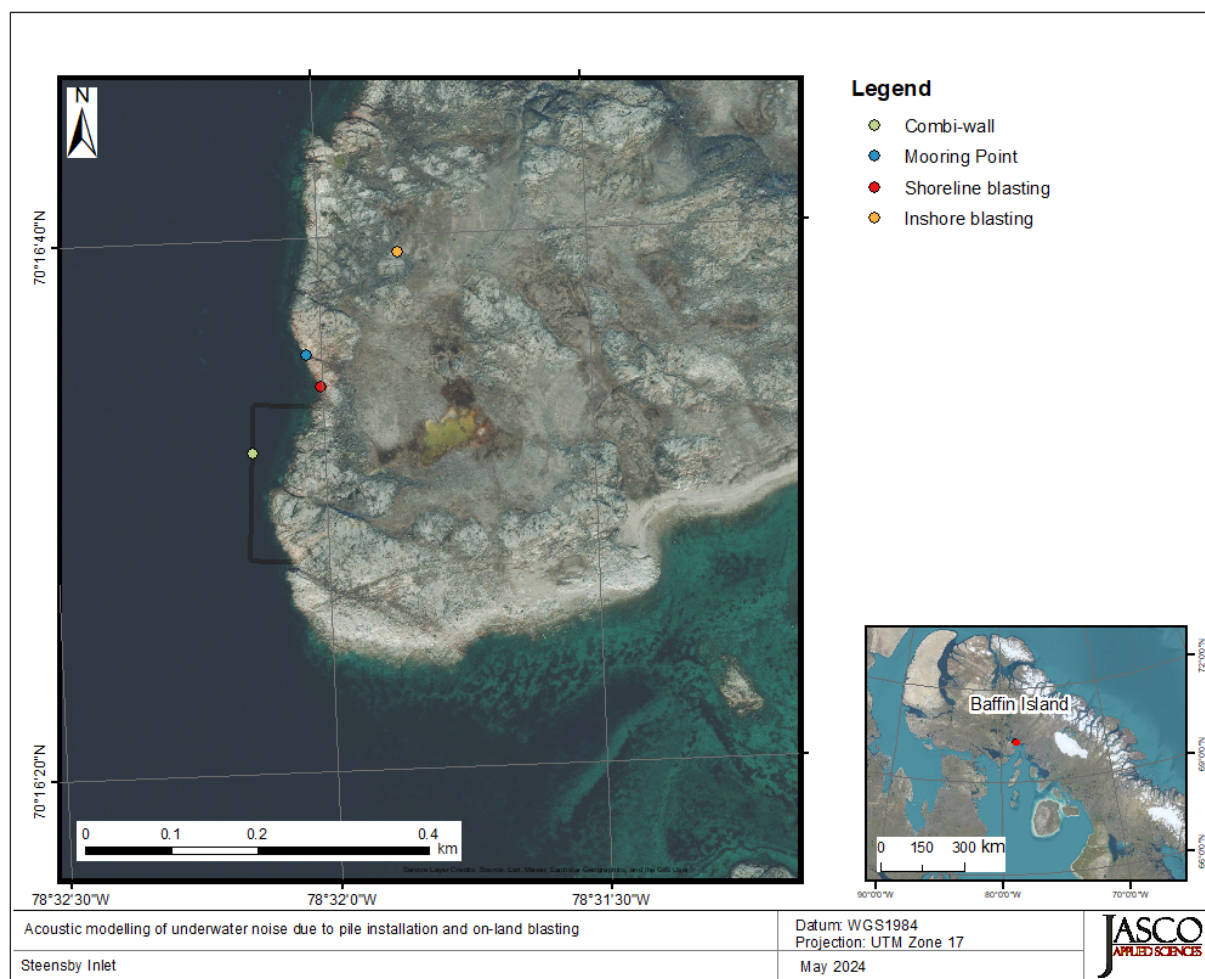


Figure 1. Map of the Project area and the modelled locations.

This acoustic modelling estimates the peak sound pressure (PK), sound exposure level (SEL), and sound pressure level (SPL) for the sources (pile driving, drilling, and blasting) planned to be used at each location. The estimated metrics—PK, SPL, SEL—are defined in Appendix A. We follow the definitions and conventions of ISO (2017) except where stated otherwise in Table 1.

Table 1. Summary of relevant acoustic terminology used in the modelling report.

Metric	Main text <sup>a</sup>	Equations/tables <sup>a</sup>
Sound pressure level	SPL	$L_{p,w}$ <sup>b</sup>
Peak pressure level	PK	$L_{pk}$
Cumulative sound exposure level	SEL	$L_{E,w,T}$ <sup>c</sup>

<sup>a</sup> Following (ISO 2017) with modifications described in the footnotes.

<sup>b</sup>  $w$  in  $L_{p,w}$  and  $L_{E,w,T}$  describes frequency-weighting function, if used.

<sup>c</sup>  $T$  in  $L_{E,w,T}$  describes the time window used to calculate SEL.



## 1.1. Modelled Scenarios

The underwater acoustic modelling considered the following activities, with details shown in Table 2:

- **Combi-wall (Scenarios 1–4):** The construction of the combi-wall forming the face of the ore dock involves installing pipe piles and sheet piles. Prior to the combi-wall being built, gravel will be placed to create the ore dock surface. The combi-wall pipe and sheet piles will be installed through the gravel in-fill; no pile driving will occur directly within the water. The pipe piles will be installed primarily by drilling through the gravel and the bedrock, and an impact hammer will be used at the end of the pile installation to ensure the pile has reached refusal at its final penetration depth. Sheet piles will be installed through the infill by means of a vibratory hammer, and then driven to refusal with an impact hammer. The pipe piles to be installed will be 1.2 m in diameter, 50 m long, with a 3.5 cm wall thickness. They will be installed through the infill (23 m of infill at the modelled location) and sediment, and down to a 1.5 m depth into the bedrock. The sheet piles will be 1.4 m wide and 1.6 cm thick. They will be installed through the depth of the infill (23 m at the modelled location). To assess total noise accumulation throughout a day, it was assumed that 1.5 pipe piles and 6 sheet piles could be installed per day. Each pipe pile is anticipated to require 5 hours of drilling followed by 5 impact hammer impulses for installation. For sheet piles, installation was assumed to require 30 minutes of vibratory pile driving followed by 50 impact hammer impulses.
- **Mooring anchors (Scenarios 5–6):** Pipe piles will be installed at four locations as mooring anchor points to secure ore carriers while alongside the ore dock. The piles will be installed by drilling into bedrock, followed by impact piling to ensure the pile has reached refusal at its final penetration depth. The installed pipe piles will be 0.914 m in diameter, 10 m long, with a 2.5 cm wall thickness. They will be installed to a 4 m depth into bedrock, requiring 1 hour of drilling followed by 5 impact hammer strikes at final penetration.
- **Rock blasting (Scenarios 7–8):** Areas of Steensby Island will be cleared for site preparation using rock blasting. Since the blasting plan for the Project has not yet been defined, the modelling considered a range of charge sizes that might be used, up to 100 kg TNT equivalent weight as a maximum. Two locations were selected for this modelling, one near the shore (20 m from the water) and one 100 m inland from shore, providing a range of options for blasting with in-land locations differentiated from blasting as close as 20 m to the water.

In addition to consideration of the individual activities, the following set of aggregate scenarios were modelled to consider the combined noise footprint of all activities that could occur within the same 24 hour period:

- **Scenario A1:** Combi-wall pipe pile installation involving drilling and impact pile driving within the same day (1.5 piles)
- **Scenario A2:** Combi-wall sheet pile installation involving vibratory and impact pile driving within the same day (6 piles)
- **Scenario A3:** Mooring point pipe pile installation involving drilling and impact pile driving within the same day (1.5 piles)
- **Scenario A4:** Simultaneous installation of combi-wall sheet piles and pipe piles within the same day (A1 + A2)
- **Scenario A5:** Simultaneous blasting at water edge and installation of combi-wall pipe piles (100 × 100 kg charges + A1)

The total accumulated SEL for these aggregate scenarios were compared with thresholds for marine mammal impacts based on the  $SEL_{w,24h}$  metric.

Table 2. Location and description of modelled scenarios considered.

Scenario	Location	Activity	Latitude	Longitude	UTM Coordinates, Zone 17N	
					Easting (m)	Northing (m)
1	Combi-wall pipe pile	Drilling	70.27556°N	78.53561°W	592804	7798482
2	Combi-wall pipe pile	Impact piling	70.27556°N	78.53561°W	592804	7798482
3	Combi-wall sheet pile	Vibratory piling	70.27556°N	78.53561°W	592804	7798482
4	Combi-wall sheet pile	Impact piling	70.27556°N	78.53561°W	592804	7798482
5	Mooring pile	Drilling	70.27655°N	78.53381°W	592867	7798595
6	Mooring pile	Impact piling	70.27655°N	78.53381°W	592867	7798595
7	Water edge	Blasting	70.27623°N	78.53325°W	592889	7798561
8	In land (100 m from water)	Blasting	70.27759°N	78.53091°W	592971	7798716

Acoustic modelling results are presented for the relevant PK, SPL, and SEL metrics described in Section 2. Section 3 describes the methods used to predict source levels (representing the noise emissions) and acoustic underwater propagation. Section 4 presents results as tables of distances to effects thresholds and as maps of contours at criteria thresholds. Section 5 contains the discussion and concluding remarks.

## 2. Underwater Noise Impact Criteria

Noise can affect marine fauna in several ways, including eliciting various behavioural responses or causing temporary or permanent hearing threshold shifts. For this study, JASCO modelled underwater sound propagation from activities that will occur during construction of the Steensby Port facility. The modelled activities include drilling, piling, and onshore rock blasting, which can all generate underwater sound levels high enough to disturb or injure marine fauna.

The distances to established acoustic thresholds for impacts on marine mammals and fish (including fish eggs and larvae) were predicted based on available sets of criteria for the onset of noise-induced injuries and behavioural disturbance. For noise induced injury, separate thresholds are considered for five different marine mammal functional hearing groups (explained further in Appendix B.3). The criteria used for this analysis are discussed further in Appendix B and are listed as follows::

- Acoustic injury (onset of permanent threshold shift, PTS), onset of temporary threshold shift (TTS), and behavioural disturbance thresholds for marine mammals for impact pile driving (Table 3) and vibratory pile driving (Table 4) based on NMFS (2018) and (2013).
- Acoustic injury (onset of PTS), TTS, and behavioural disturbance thresholds (Table 4) for marine mammals for drilling noise based on NMFS (2018) and (2013).
- Acoustic injury (onset of PTS), onset of TTS, and behavioural disturbance thresholds for marine mammals for blasting (Table 5) based on Finneran et al. (2017).
- Injury thresholds for fish, eggs, and larvae due to impact piling and blasting based on Popper et al. (2014) (Table 6). Also, DFO has requested that this project implement a threshold of PK = 50 kPa (214 dB re 1  $\mu$ Pa) for impacts to fish from blasting (DFO 2012).

Adhering to conservative approach principles, the aggregate scenarios that involve vibratory pile driving or drilling (non-impulsive sound sources) and impact pile driving (impulsive sound source) were assessed using criteria for impulsive sound (Table 3) as having lower threshold levels compared to criteria threshold levels defined for non-impulsive sound.

Table 3. *Impact pile driving*: Impulsive noise thresholds for temporary threshold shift (TTS) and permanent threshold shift (PTS) across five marine mammal hearing groups based on NMFS (2018), and for behavioural disturbance (all marine mammal species) based on NMFS (2013).

Hearing group	PTS thresholds		TTS thresholds		Disturbance threshold
	$L_{E,w,24h}$ (dB re 1 $\mu$ Pa <sup>2</sup> ·s)	$L_{pk}$ (dB re 1 $\mu$ Pa)	$L_{E,w,24h}$ (dB re 1 $\mu$ Pa <sup>2</sup> ·s)	$L_{pk}$ (dB re 1 $\mu$ Pa)	$L_p$ (dB re 1 $\mu$ Pa <sup>2</sup> )
LF cetaceans	183	219	168	213	160
MF cetaceans	185	230	170	224	
HF cetaceans	155	202	140	196	
Phocids in water	185	218	170	212	
Otariids in water	203	232	188	226	

LF: low-frequency; MF: mid-frequency; HF: high-frequency

Table 4. *Drilling and vibratory pile driving*: Non-impulsive noise thresholds for permanent threshold shift (PTS), temporary threshold shift (TTS) and behavioural disturbance of marine mammals based on NMFS (2018) and (2013).

Hearing group	PTS threshold $L_{E,w,24h}$ (dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ )	TTS threshold $L_{E,w,24h}$ (dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ )	Disturbance threshold $L_p$ (dB re 1 $\mu\text{Pa}^2$ )
LF cetaceans	199	179	120
MF cetaceans	198	178	
HF cetaceans	173	153	
Phocids in water	201	181	
Otariid pinnipeds in water	219	199	

LF: low-frequency; MF: mid-frequency; HF: high-frequency

Table 5. *Blasting*: Impulsive noise thresholds for permanent threshold shift (PTS), temporary threshold shift (TTS) and behavioural disturbance of marine mammals based on Finneran et al. (2017).

Hearing group	PTS thresholds		TTS thresholds		Disturbance thresholds $L_{E,w,24h}$ (dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ )
	$L_{E,w,24h}$ (dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ )	$L_{pk}$ (dB re 1 $\mu\text{Pa}$ )	$L_{E,w,24h}$ (dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ )	$L_{pk}$ (dB re 1 $\mu\text{Pa}$ )	
LF cetaceans	183	219	168	213	163
MF cetaceans	185	230	170	224	165
HF cetaceans	155	202	140	196	135
Phocids in water	185	218	170	212	165
Otariid pinnipeds in water	203	232	188	226	183

LF: low-frequency; MF: mid-frequency; HF: high-frequency

Table 6. Noise exposure criteria for impact pile driving and blasting impacts on fish based on Popper et al. (2014).

Faunal group	Mortality and Potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: No swim bladder (particle motion detection)	> 219 dB $L_{E,w,24h}$ or > 213 dB $L_{pk}$	> 216 dB $L_{E,w,24h}$ or > 213 dB $L_{pk}$	>> 186 dB $L_{E,w,24h}$	(N) Moderate (I, F) Low	(N) High (I) Moderate (F) Low
Fish: Swim bladder not involved in hearing (particle motion detection)	210 dB $L_{E,w,24h}$ or > 207 dB $L_{pk}$	203 dB $L_{E,w,24h}$ or > 207 dB $L_{pk}$	>> 186 dB $L_{E,w,24h}$	(N) Moderate (I, F) Low	(N) High (I) Moderate (F) Low
Fish: Swim bladder involved in hearing (primarily pressure detection)	207 dB $L_{E,w,24h}$ or > 207 dB $L_{pk}$	203 dB $L_{E,w,24h}$ or > 207 dB $L_{pk}$	186 dB $L_{E,w,24h}$	(N, I) High (F) Moderate	(N, I) High (F) Moderate
Fish eggs and fish larvae	> 210 dB $L_{E,w,24h}$ or > 207 dB $L_{pk}$	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I, F) Low	(N) Moderate (I, F) Low

$L_{pk}$  dB re 1  $\mu\text{Pa}$ ;  $L_{E,w,24h}$  dB re 1  $\mu\text{Pa}^2\cdot\text{s}$ .

All criteria are presented as sound pressure even for fish without swim bladders since no data for particle motion exist.

### 3. Methods

The following steps describe the general approach applied in this study to model sounds in the marine environment and to estimate distances to the relevant acoustic thresholds listed in Section 2:

1. The modelled operations are characterized as sound-radiating sources, and the source pressure functions are predicted. This characterization is done using a proxy (source level spectra derived from measurements 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 through the water, as a function of range, depth, and azimuthal direction.
3. The propagated sound field is used to compute received sound levels over a large regular grid from which distances to effect criteria thresholds are calculated and contour maps are generated. Two distances for each threshold are presented in this work:  $R_{\max}$ , the maximum distance from the source at which given sound level is predicted to occur, and  $R_{95\%}$ , the distance to a given sound level after the 5% farthest points were excluded (see Appendix C.4).

The output of these steps produces PK and SEL per blasting detonation, per impact piling strike or per second of drilling or vibratory piling at each considered location. Since the SEL criteria mentioned in Section 2 are cumulative (denoted as  $SEL_{24h}$ ), the accumulation of noise exposure within a 24 h period is accounted for by adding a factor of  $10\log(N_{24h})$  to the single-event SEL, where  $N_{24h}$  represents the maximum number of events per day. As mentioned in Section 1, we have computed  $SEL_{24h}$  for the individual noise sources, as well as for aggregate scenarios involving multiple sources likely to emit noise within the same day.

#### 3.1. Acoustic Sources

##### 3.1.1. Drilling

Drilling will be required for advancing the pipe piles through the infill and into the bedrock. Table 7 provides the parameters of the drilling operations considered in the present modelling study.

Table 7. Specifications used for modelling drilling of pipe piles.

Scenario	Location	Pile diameter (m)	Penetration depth (m)
1	Combi-wall	1.2	33
5	Mooring Point	0.9	4

Source levels for this activity were derived from available empirical measurements from a dock construction project at a ferry terminal at Kodiak, Alaska (Denes et al. 2016). These data provide the best reference of frequency-dependent source levels currently available. Measurements were conducted using three recording stations of a Numa Patriot 180 hydro-hammer driving several 24-inch (0.6 m) diameter piles into bedrock. The distances of the recording points to the piles were from 10 to 70 m. The representative SPL source levels were derived from the measured levels using 15.2 back propagation coefficient:  $15.2\log(r)$ . The value of the backpropagation coefficient was derived from inversion

modelling. The source level was defined in decidecade bands from 10 Hz to 31.5 kHz with the broadband Energy Source Level (ESL) of 195.4 dB re 1  $\mu\text{Pa}^2\text{s}$ .

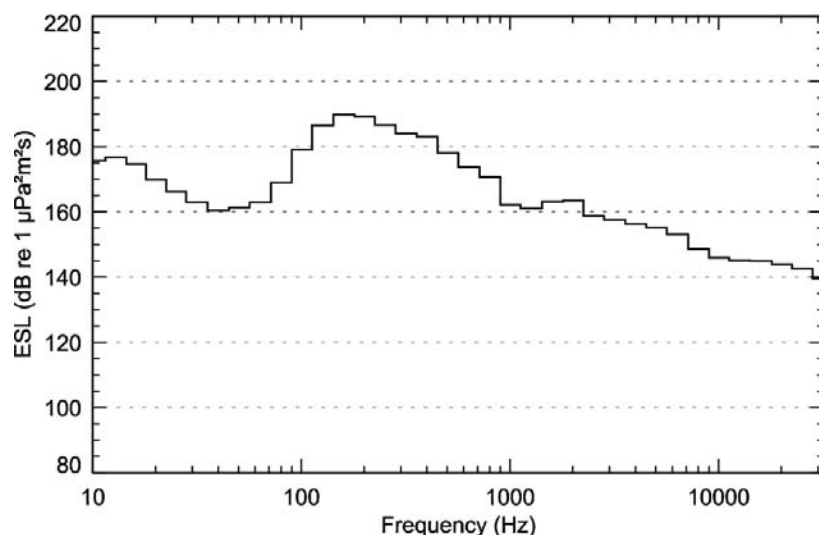


Figure 2. Down-the-hole drilling: Modeled decidecade band energy source level (ESL) spectrum.

### 3.1.2. Pile Driving

The pile driving scenarios included impact driving of pipe piles at two locations as well as impact and vibratory driving of sheet piles at one location. Additional scenario details relevant to the source level determinations are provided in the following subsections.

#### 3.1.2.1. Pipe piles

For the purpose of modelling underwater sound propagation from a pipe pile, the pile is represented as a distributed acoustic source to accurately characterize vertical directivity effects in the near-field zone. The source modeling was performed for the last stage of pile driving with the pile toe nearing the designed penetration into the bedrock layer.

The source functions for the steel pipe piles were predicted using JASCO's Pile Driving Source Model (PDSM) model. PDSM estimates an equivalent acoustic source represented by a linear array of monopoles evenly distributed along the pile (MacGillivray 2014). The model accounts for several parameters that describe the operation (the type, material, size, and length of piles), the pile driving equipment, and approximate pile penetration depth. Appendix C.1 provides more details about the model. Table 8 lists the parameters of the pile and pile driver accounted for by PDSM, as provided to JASCO by Baffinland.

Table 8. Modelling parameters used in this work for impact pile driving operations for pipe piles.

Scenario	Location	Pile driver parameters		Pile dimensions			Pile sediment penetration parameters	
		Model	Energy (kJ)	Length (m)	Diameter (m)	Wall thickness (mm)	Penetration rate (mm/strike)	Modelled penetration depth (m)
2	Combi-wall	IHC S280	280	50	1.2	35	2.5	33
6	Mooring Point	IHC S280	280	10	0.914	25	2.5	4

The pressure wave signatures of the monopole sources were modeled in the 9–2239 Hz (10–2000 Hz decade bands) frequency range and extrapolated up to 32,000 Hz band using a roll-off factor of 2 dB per decade band. Figure 3 shows the modeled decade band energy source levels for impact driving of pipe piles at the combi-wall and mooring point locations. The pile was represented by 66 discrete point sources, evenly distributed over the length of the pile with a 0.5 m vertical separation in Scenario 2 and by 16 discrete point sources with 0.25 m vertical separation in Scenario 6. The broadband ESL is 202.2 dB re 1  $\mu\text{Pa}^2\text{s}$  for pile driving at the combi-wall location and 197.7 dB re 1  $\mu\text{Pa}^2\text{s}$  at the mooring point location.

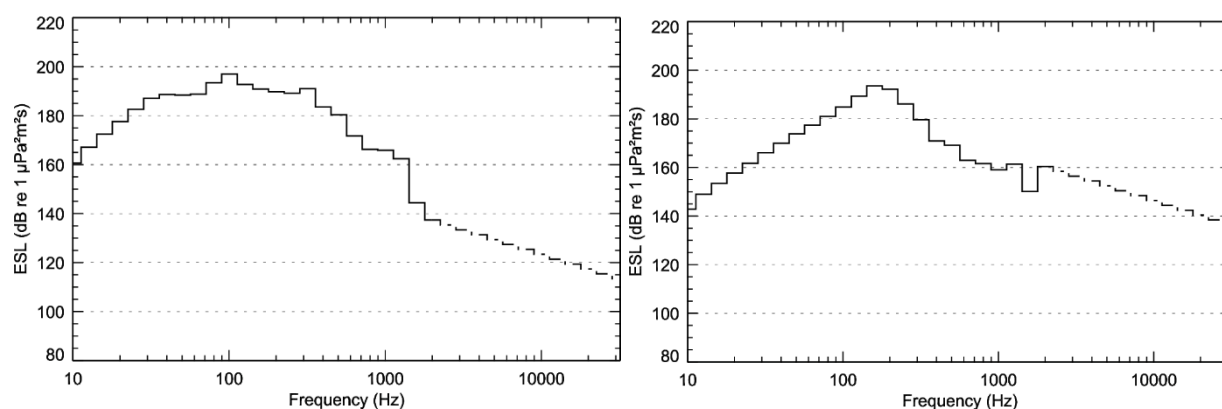


Figure 3. Impact pile driving of pipe piles: Modeled decade band energy source level (ESL) spectrum for (left) Scenario 2 (at combi-wall) and (right) Scenario 6 (at mooring point) calculated as a sum of individual monopole signatures in the far field without considering the environment effect. Dashed line indicates extrapolated section of the spectrum function.

### 3.1.2.2. Sheet piles

For sheet piles, source levels for impact and vibratory pile driving were obtained from measurements of similar activities available in the literature. Table 9 lists the parameters of the piles and pile drivers considered for estimating the source level. For the purpose of the sound propagation modelling, the pile was represented by a monopole acoustic source.

Table 9. Modelling parameters for impact and vibratory pile driving of sheet piles.

Scenario	Location	Pile driver parameters			Pile dimensions			Modelled penetration depth (m)
		Type	Model	Centrifugal force (kN) or Energy (kJ)	Length (m)	Diameter (m)	Wall thickness (mm)	
3	Combi-wall	Vibratory	APE-200-6	2,135	33	1.4	16	28
4	Combi-wall	Impact	IHC S280	280	33	1.4	16	28

The source level for impact driving of a sheet pile was derived based on measurements reported in Illingworth & Rodkin (2007). The measurements were conducted on a sheet pile driven by an ICE-60S impact pile driver with an impact energy of 81.4 kJ at a distance of 10 m from the pile. The reported band spectrum function was backpropagated to 1 m using  $20\log(r)$ , where  $r$  is measurement distance, to get the source level. The source level was also adjusted for the difference in impact energy between the measured pile driver and the pile driver being used in this project (IHCS-280 with 280 kJ impact energy) using  $10\log(E/E_0)$ , where  $E_0$  is the reference impact energy of the measured pile driver and  $E$  is the impact energy of the pile driver the source level is being derived for. Figure 4 shows the decidecade band Energy Source Level (ESL) with the broad band level of 203.4 dB re 1  $\mu\text{Pa}^2\text{s}$ .

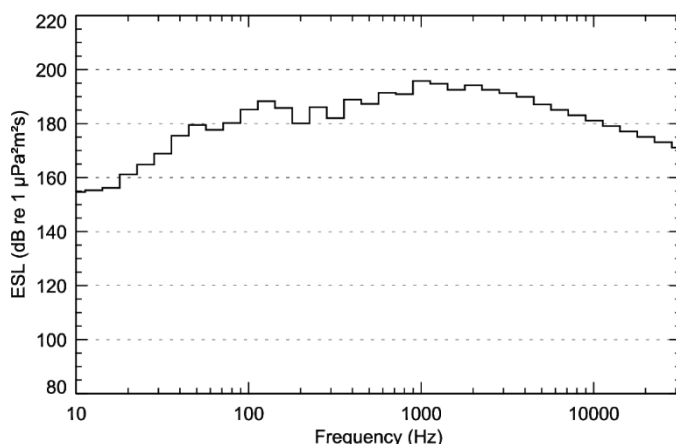


Figure 4. Impact pile driving of a sheet pile: Modelled decidecade band Energy Source Level (ESL) spectrum of a monopole effective source.

The source levels for vibratory driving of a sheet pile were derived based on measurements reported in Illingworth and Rodkin (2017). Eleven individual measurements were conducted on sheet piles driven by an ICE-416 vibratory pile driver with centrifugal force of 886 kN at a distance of 9 to 11 m from the piles. The reported measured received levels were backpropagated to 1 m using  $12.9\log(r)$ , where  $r$  is measurement distance. The back propagation coefficient of 12.9 was derived by Illingworth and Rodkin (2017) and averaged. The measured source levels were averaged to get an average source level. The source level was also adjusted for the difference in the centrifugal force between the measured pile driver



and the pile driver being used in this project (APE 200-6 with 2135 kN centrifugal force) using  $10\log(F/F_0)$ , where  $F_0$  is the reference centrifugal force of the measured pile driver and  $F$  is the centrifugal force of the pile driver the source level is being derived for. The band spectrum function (Figure 5) was also provided by Illingworth and Rodkin (2017). Figure 5 shows the decidecade band Energy Source Level (ESL) with the broad band level of 189.1 dB re 1  $\mu\text{Pa}^2\text{s}$ .

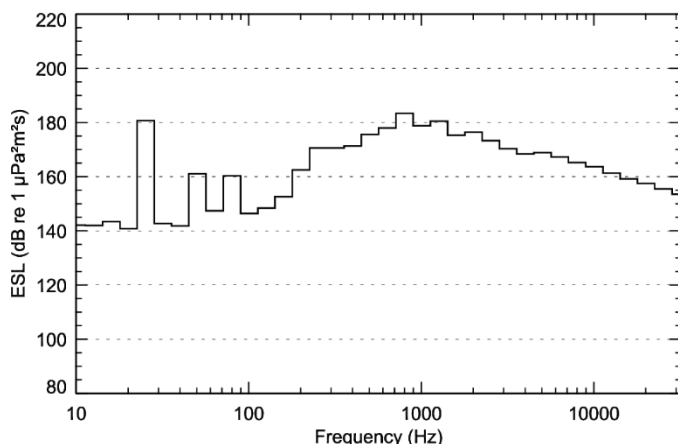


Figure 5. Vibratory pile driving of a sheet pile: Modelled decidecade band energy source level (ESL) spectrum of a monopole effective source.

### 3.1.3. Onshore Rock Blasting

Underground detonation of explosives 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 detonating explosives within boreholes drilled in rock was modelled using ConWep's Shockwave module (Hyde 1988, 1992). ConWep (see Appendix C.2.1) 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 a range of charge sizes with TNT equivalent weights from 1 to 100 kg (Table 10). The model was calibrated to reported measurements available in the literature (see Appendix C.2.1).

Table 10. Specifications of the charge used for rock blasting.

Explosive type	Explosive TNT mass (kg)	Deployment depth (m)	Backfill material
Bare High Explosive	1, 10, 20, 30, 40, 50, 100	3	Sediment (Granitoid/Gneiss)

## 3.2. Acoustic Propagation Models

Regardless of the sound propagation modelling approach or the sound source type, the following are applicable to all modelling scenarios:

- The acoustic field in three dimensions was generated through acoustic propagation modeling in two-dimensional (2-D) vertical planes equally spaced by azimuth in a 360° swath around the source ( $N \times 2$ -D approach, see Appendix C.3). The azimuthal spacing was scenario specific;
- The horizontal spacing between receivers was 5 m;
- The received levels were calculated at the following depths: 1 m, 2 m, every 5 m between 5 and 40 m, every 10 m between 50 and 100 m (the deepest depth within modelling area was less than 100 m);
- Composite broadband received SEL was computed by summing the received decidecade band levels across frequency (see Appendix C.3.1.2) and taking the maximum-over-depth. For weighted SEL, appropriate weighting factor (see Appendix B.3) was applied to each band level prior to summing; and
- The 24 h SEL was calculated using modelled  $SEL_{1 \text{ sec/per event}}$  adjusted for the total duration of activity within 24 h period: number of seconds the source is active for non-impulsive sources or number of sound emission events (strikes/blasts) for impulsive sources.

### 3.2.1. Drilling Modelling

The drill was represented by a single monopole source (see Section 3.1.1). The point source was placed within a sediment layer at a depth of 11 m below sea level (half-thickness of the in-fill layer) for the combi-wall pile installation scenario and at 3 m below sea level for the mooring point installation scenario. The sound propagation was performed using energy propagation loss in decidecade band approach (see Appendix C.3.1). The energy propagation loss was calculated using JASCO's Marine Operations Noise Model (MONM; Appendix C.3.1) in the 10 Hz to 10 kHz frequency range with MONM-RAM variant exclusively.

The modelling radials were azimuthally spaced at 3° in a 360° swath around the source for the total of 120 modelled radials. The maximum modelling range was 25 km.

Drilling emits sound that is considered to be non-impulsive. For non-impulsive sources, SPL is equal to  $SEL_{1 \text{ sec}}$  and PK is not calculated, since the impact criteria for non-impulsive sources does not include the PK metric.

Table 11 provides the parameters used for calculating 24 h SEL.

Table 11. Parameters used for modelling 24 h SEL for drilling of pipe piles.

Scenario	Location	Drilling duration per pile (s)	Piles per day	Drilling duration per 24 h (s)
1	Combi-wall	18000	1.5	27,000
5	Mooring Point	3600	1.5	5,400

## 3.2.2. Pile Driving Modelling

### 3.2.2.1. Pipe piles

The impact driving of pipe piles was defined as a distributed source with an array of monopole sources. Each monopole source was assigned individually calculated pressure signature time series (see Section 3.1.2.1). The monopoles were placed along the entire length of the pile within the in-fill (23 m).

The sound propagation was performed using a full-waveform modelling approach (see Appendix C.3.2) that outputs synthetic pressure waveforms. Synthetic pressure waveforms were modeled over the 9–2239 Hz frequency range (10–2000 Hz decidecade bands) inside a 1-second window. Extrapolation to higher frequencies (up to 32 kHz) was conducted with –2 dB per deci-decade band roll-off coefficient based on the received level of the last modelled band (2 kHz).

The modelling radials were azimuthally spaced at 5° in a 360° swath around the source for the total of 72 modelled radials. The maximum modelling range was 9 km.

The PK and SPL metric of the acoustic signal were calculated directly from the synthetic pressure waveforms (see Equations A-1 and A-3).

Parameters used for calculating 24 h SEL are provided in Table 12.

Table 12. Parameters used for modelling 24 h SEL for impact driving of pipe piles.

Scenario	Location	Strikes per pile	Piles per day	Strikes per 24 h
2	Combi-wall	5	1.5	7.5
6	Mooring Point	5	1.5	7.5

### 3.2.2.2. Sheet piles

The impact and vibratory driving of sheet piles were represented by a single monopole source (see Section 3.1.2.2). The point source was placed within a sediment layer at a depth of 11 m below sea level (half-thickness of the in-fill layer) for the combi-wall pile installation scenario. The sound propagation was performed using energy propagation loss in decidecade band approach (see Appendix C.3.1). The energy propagation loss was calculated using JASCO's Marine Operations Noise Model (MONM) in the 10 Hz to 10 kHz frequency range with MONM-RAM variant exclusively.

The modelling radials were azimuthally spaced at 3° in a 360° swath around the source for the total of 120 modelled radials. The maximum modelling range was 9 km.

Vibratory pile driving emits sound that is considered to be non-impulsive. For non-impulsive sources, SPL is equal to  $SEL_{1\text{ sec}}$  and PK is not calculated, since the impact criteria for non-impulsive sources does not include the PK metric.

Impact pile driving emits sound that is considered to be impulsive. The PK and SPL signal metrics were estimated from the modelled  $SEL_{1\text{ sec}}$  by applying SEL-to-SPL (13 dB) and SEL-to-PK (28 dB) conversion coefficients, defined based on the level difference of the measured metrics in Illingworth & Rodkin (2007).

Table 13 provides the parameters used for calculating 24 h SEL.

Table 13. Parameters used for calculating 24 h SEL for driving of sheet piles.

Scenario	Location	Driving type	Strikes or duration per pile <sup>a</sup>	Piles per day	Strikes or duration per 24 h <sup>a</sup>
3	Combi-wall	Impact	1800	6	10800
4	Combi-wall	Vibratory	50	6	300

<sup>a</sup> Strike count for impact driving, time duration in seconds for vibratory driving.

### 3.2.3. Blasting Modelling

An in-ground blast was defined as a monopole source with calculated pressure signature time series (see Section 3.1.3). The point source was placed at 3 m below sea level .

The sound propagation was performed using a full-waveform modelling approach (see Appendix C.3.2) that outputs synthetic pressure waveforms. Synthetic pressure waveforms were modeled over the 9–2239 Hz frequency range (10–2000 Hz decade bands), inside a 1-second window. Extrapolation to higher frequencies (up to 32 kHz) was conducted with –2 dB per deci-decade band roll-off coefficient based on the received level of the last modelled band (2 kHz).

The modelling radials were azimuthally spaced at 5° in a 360° swath around the source for the total of 72 modelled radials. The maximum modelling range was 9 km.

The PK and SPL metric of the acoustic signal were calculated directly from the synthetic pressure waveforms (see Equations A-1 and A-3).

The 24 h SEL was calculated assuming 100 charges per blast and single blast per 24 h period.

### 3.2.4. Aggregate Scenarios

The five aggregate scenarios shown in Table 14 were modelled to account for the combined acoustic field from multiple acoustic sources that are likely to occur within the same 24 h period. For the purpose of calculating the combined field from multiple sources, the fields from individual sources were summed up preserving the actual position of each source. The ranges were calculated based on the dominant source: the range for each grid cell was calculated towards the source that provided the maximum contribution to the received level in that cell.

Table 14. Aggregate scenarios definition. Single source scenario ID is provided as per Table 2.

Scenario	Description	Single source scenarios		
		Scenario ID	Description	Strikes or duration (s) per 24 h
A1	Combi-wall king pile Installation	1	Drilling-Pipe	27000
		2	Impact piling-Pipe	7.5
A2	Combi-wall sheet pile Installation	3	Vibratory piling-Sheet	10800
		4	Impact piling-Sheet	300
A3	Single mooring pile Installed	5	Drilling-Pipe	5400
		6	Impact piling-Pipe	7.5
A4	Combi-wall sheet pile Installation + combi wall pipe pile installation (A1 + A2)	1	Drilling-Pipe	27000
		2	Impact piling-Pipe	7.5
		3	Vibratory piling-Sheet	10800
		4	Impact piling-Sheet	300
A5	Blasting + combi-wall king pile installation (A1 + blasting)	1	Drilling-Pipe	27000
		2	Impact piling-Pipe	7.5
		3	Blasting of 100 kg charges at water edge	100

## 4. Results

Results are presented as tables of distances ( $R_{\max}$  and  $R_{95\%}$ ; a description of these measures, that are derived from the sound level contours shown in the maps, is provided in Appendix C.4) to the sound level thresholds listed in Section 3.1, and as sound level contour maps (for distances large enough to be displayed on a regional map). Results are presented by activity type: drilling (Section 4.1), impact pile driving (Section 4.2), vibratory pile driving (Section 4.3), and rock blasting (Section 4.4). Results for the aggregate scenarios, which include more than one activity type, are presented in Section 4.5.

For all scenarios other than blasting, the sources originated within 10 m of the water. For those scenarios, distances < 10 m presented in the tables represent sound levels in the ground as the corresponding thresholds were not reached in water. For the blasting scenarios, the same is true for distances < 20 m or 100 m for the near-shore and inland scenarios, respectively.

### 4.1. Drilling

Table 15. *Drilling of pipe piles*: Distances (m) to  $SEL_{w,24h}$  thresholds (NMFS 2018) for permanent threshold shift (PTS) and temporary threshold shift (TTS) for non-impulsive noise sources.

Type of effect	Hearing group	$L_{E,w,24h}$ threshold (dB re 1 $\mu Pa^2s$ )	Scenario 1		Scenario 5	
			$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$
PTS	LF cetaceans	199	199	190	85	81
	MF cetaceans	198	<10	-	<10	-
	HF cetaceans	173	<10	-	<10	-
	Phocids in water	201	<10	-	<10	-
	Otariids in water	219	<10	-	<10	-
TTS	LF cetaceans	179	3190	2600	1730	1460
	MF cetaceans	178	<10	-	<10	-
	HF cetaceans	153	32	32	28	28
	Phocids in water	181	228	209	117	108
	Otariids in water	199	<10	-	<10	-

LF: low-frequency; MF: mid-frequency; HF: high-frequency

A dash (-) indicates that the range to the threshold was not defined.

Scenario 1: Combi-wall location

Scenario 5: Mooring point location

Table 16. *Drilling of pipe piles*: Distances (m) to NMFS (2013) 120 dB re 1  $\mu Pa^2$  SPL threshold for marine mammal behavioural disturbance for non-impulsive noise sources.

$L_p$ threshold (dB re 1 $\mu Pa^2$ )	Scenario 1		Scenario 5	
	$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$
120	13,200	11,000	13,400	11,800

Scenario 1: Combi-wall location

Scenario 5: Mooring point location

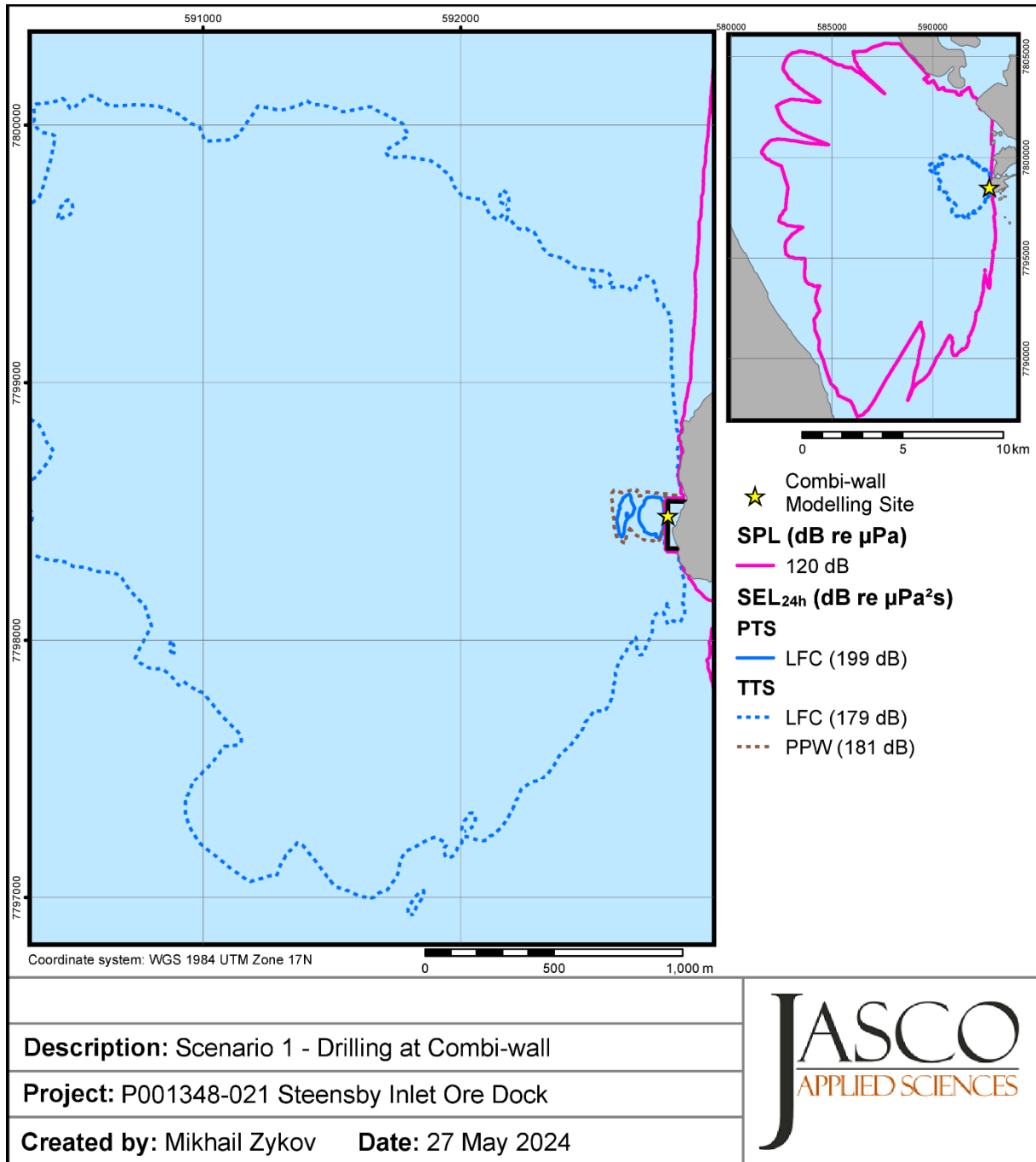


Figure 6. Sound level contours for Scenario 1, drilling of pipe piles at Combi-wall.

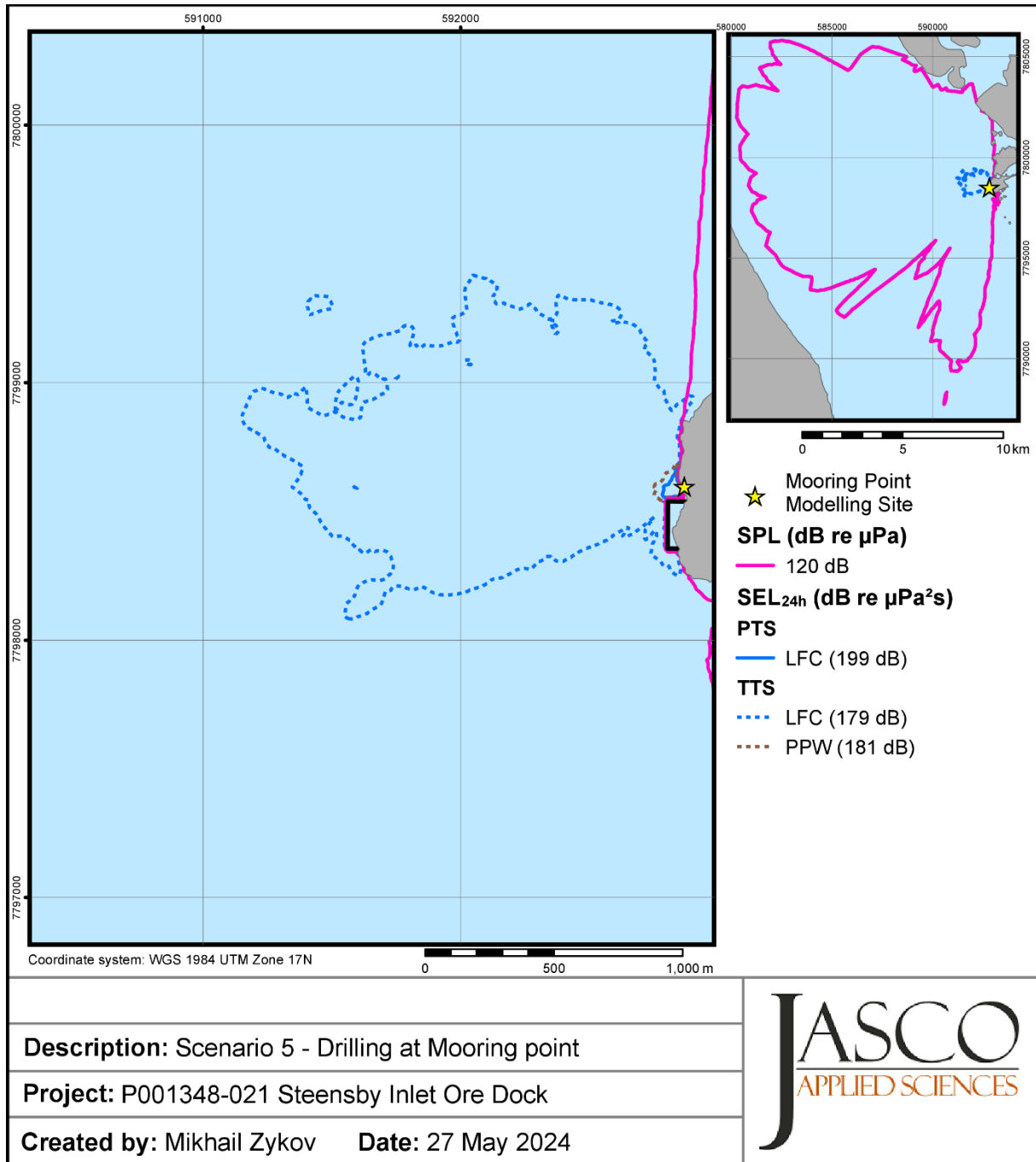


Figure 7. Sound level contours for Scenario 5, drilling of pipe piles at mooring point.



## 4.2. Impact Pile Driving

Table 17. *Impact pile driving*: Distances (m) to  $SEL_{w, 24h}$  thresholds (NMFS 2018) for permanent threshold shift (PTS) and temporary threshold shift (TTS).

Type of effect	Hearing group	$L_{E,w,24h}$ threshold (dB re 1 $\mu Pa^2s$ )	Scenario 2		Scenario 4		Scenario 6	
			$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$
PTS	LF cetaceans	183	21	21	80	73	<10	-
	MF cetaceans	185	<10	-	<10	-	<10	-
	HF cetaceans	155	<10	-	<10	-	<10	-
	Phocids in water	185	<10	-	22	22	<10	-
	Otariids in water	203	<10	-	<10	-	<10	-
TTS	LF cetaceans	168	334	280	973	869	25	21
	MF cetaceans	170	<10	-	<10	-	<10	-
	HF cetaceans	140	<10	-	91	82	<10	-
	Phocids in water	170	<10	-	173	160	<10	-
	Otariids in water	188	<10	-	<10	-	<10	-

LF: low-frequency; MF: mid-frequency; HF: high-frequency

A dash (-) indicates that the range to the threshold was not defined.

Scenario 2: Combi-wall pipe pile, impact pile driving

Scenario 4: Combi-wall sheet pile, impact pile driving

Scenario 6: Mooring pile, impact pile driving

Table 18. *Impact pile driving*: Distances (m) to PK thresholds (NMFS 2018) for permanent threshold shift (PTS) and temporary threshold shift (TTS).

Type of effect	Hearing group	$L_{pk}$ threshold (dB re 1 $\mu Pa$ )	Scenario 2		Scenario 4		Scenario 6	
			$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$
PTS	LF cetaceans	219	<10	-	<10	-	<10	-
	MF cetaceans	230	<10	-	<10	-	<10	-
	HF cetaceans	202	25	25	<10	-	<10	-
	Phocids in water	218	<10	-	<10	-	<10	-
	Otariids in water	232	<10	-	<10	-	<10	-
TTS	LF cetaceans	213	<10	-	<10	-	<10	-
	MF cetaceans	224	<10	-	<10	-	<10	-
	HF cetaceans	196	184	120	36	36	10	10
	Phocids in water	212	<10	-	<10	-	<10	-
	Otariids in water	226	<10	-	<10	-	<10	-

LF: low-frequency; MF: mid-frequency; HF: high-frequency

A dash (-) indicates that the range to the threshold was not defined.

Scenario 2: Combi-wall pipe pile, impact pile driving

Scenario 4: Combi-wall sheet pile, impact pile driving

Scenario 6: Mooring pile, impact pile driving

Table 19. *Impact pile driving*: Distances (m) to NOAA Fisheries (2019) 160 dB re 1  $\mu\text{Pa}^2$  SPL threshold for marine mammal behavioural disturbance from impulsive noise sources.

$L_p$ threshold (dB re 1 $\mu\text{Pa}^2$ )	Scenario 2		Scenario 4		Scenario 6	
	$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{\max}$	$R_{\max}$	$R_{\max}$
160	2200	1750	801	662	95	85

Scenario 2: Combi-wall pipe pile, impact pile driving

Scenario 4: Combi-wall sheet pile, impact pile driving

Scenario 6: Mooring pile, impact pile driving

Table 20. *Impact pile driving*: Distances (m) to fish mortality, potential mortal injury, and impairment  $SEL_{w,24h}$  thresholds (Popper et al. 2014) due to impact pile driving.

Type of effect	Faunal group	$L_{E,24h}$ threshold (dB re 1 $\mu\text{Pa}^2\text{s}$ )	Scenario 2		Scenario 4		Scenario 6	
			$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$
Mortality and potential mortal injury	Fish with no swim bladder	219	<10	-	<10	-	<10	-
	Fish with swim bladder not involved in hearing	210	<10	-	<10	-	<10	-
	Fish with swim bladder involved in hearing	207	<10	-	<10	-	<10	-
Recoverable injury	Fish with no swim bladder	216	<10	-	<10	-	<10	-
	Fish with swim bladder	203	<10	-	<10	-	<10	-
TTS	All fish	186	25	25	76	73	<10	-

A dash (-) indicates that the range to the threshold was not defined.

Scenario 2: Combi-wall pipe pile, impact pile driving

Scenario 4: Combi-wall sheet pile, impact pile driving

Scenario 6: Mooring pile, impact pile driving

Table 21. *Impact pile driving*: Distances (m) to fish mortality and potential mortal injury, and recoverable injury PK thresholds (Popper et al. 2014) due to impact pile driving.

Faunal group	$L_{pk}$ threshold (dB re 1 $\mu\text{Pa}$ )	Scenario 2		Scenario 4		Scenario 6	
		$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$
Fish with no swim bladder	213	<10	-	<10	-	<10	-
Fish with swim bladder	207	<10	-	<10	-	<10	-

A dash (-) indicates that the range to the threshold was not defined.

Scenario 2: Combi-wall pipe pile, impact pile driving

Scenario 4: Combi-wall sheet pile, impact pile driving

Scenario 6: Mooring pile, impact pile driving

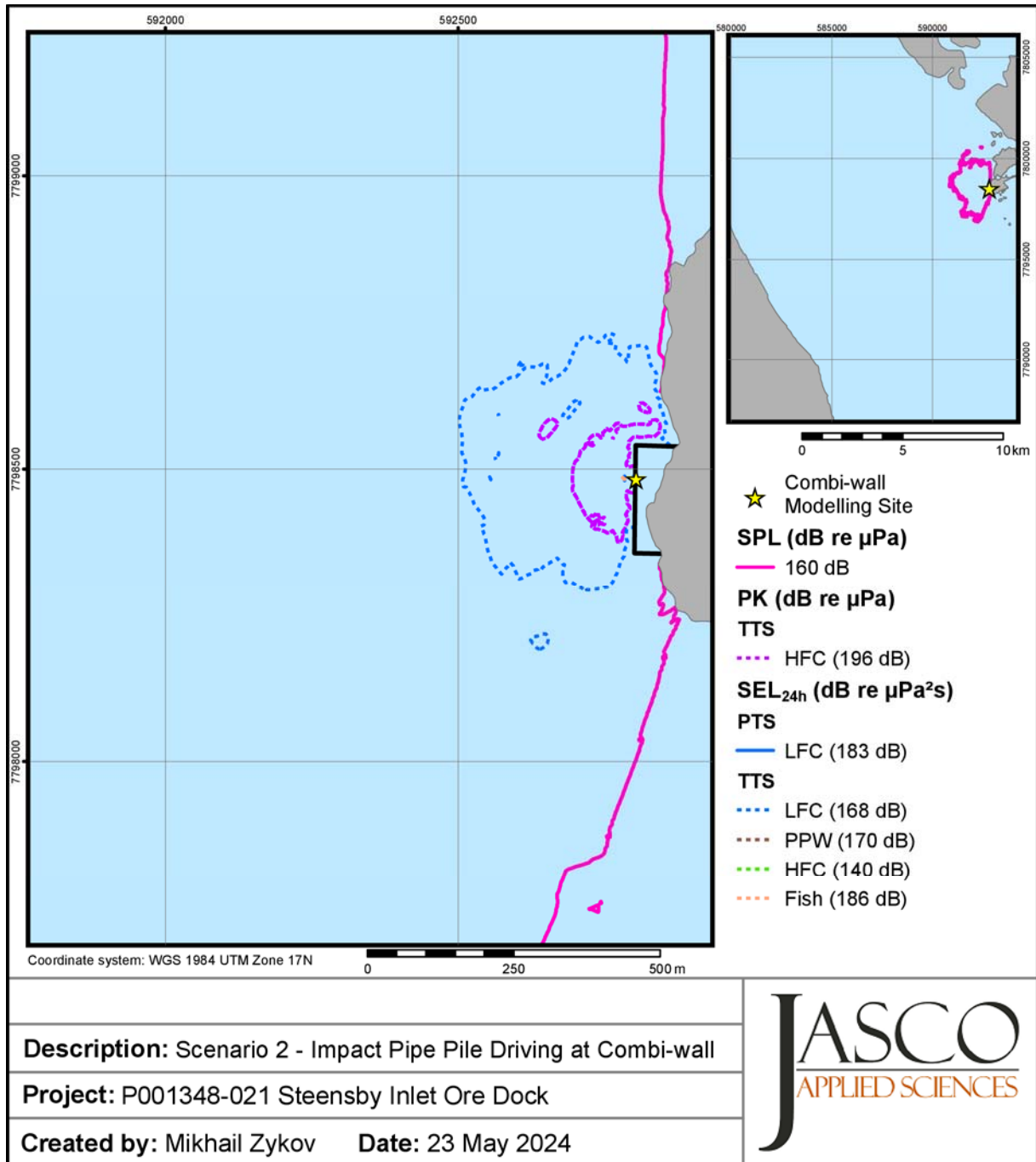


Figure 8. Sound level contours for Scenario 2, impact pile driving of pipe piles at combi-wall.

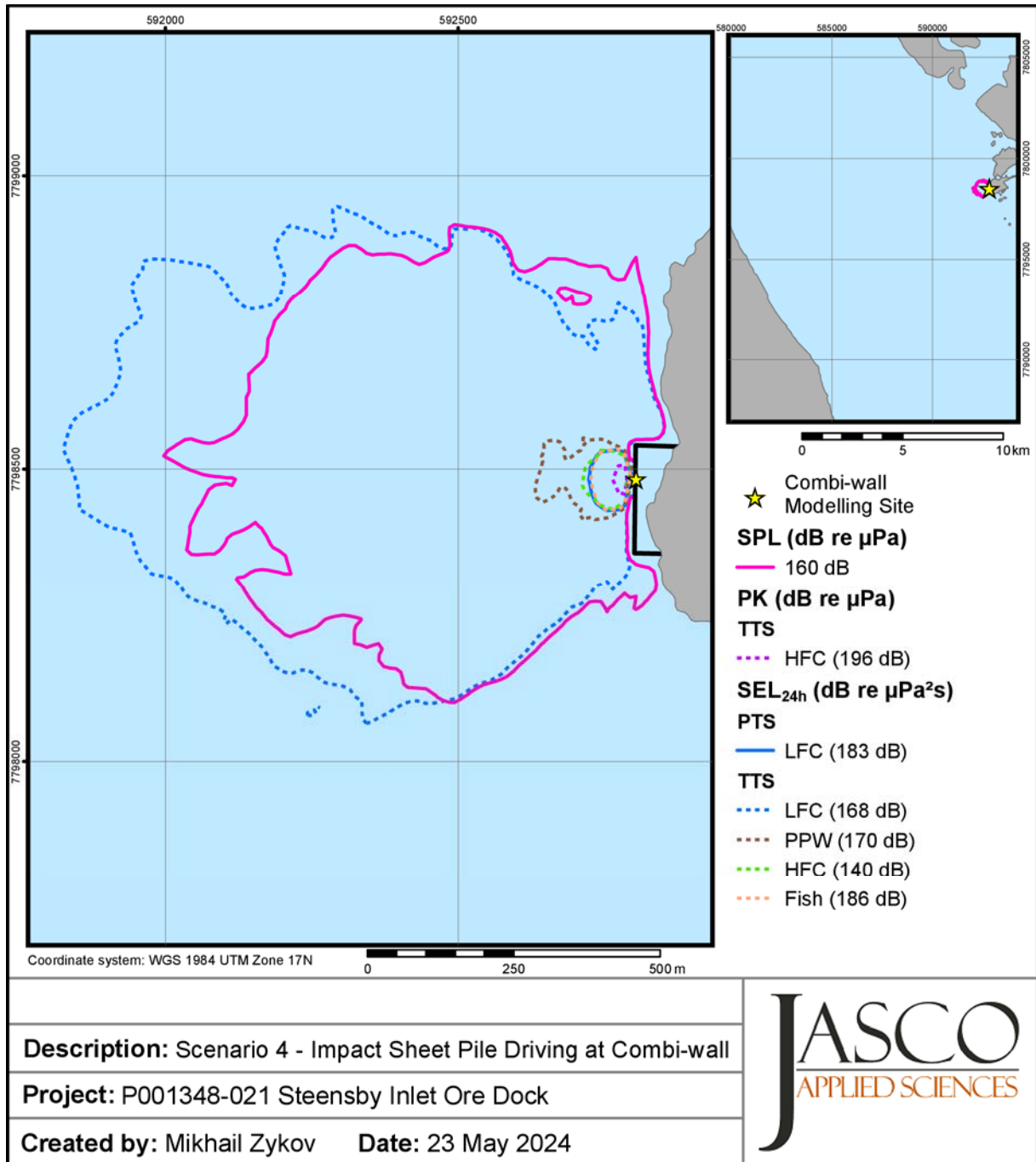


Figure 9. Sound level contours for Scenario 4, impact pile driving of sheet piles at combi-wall.

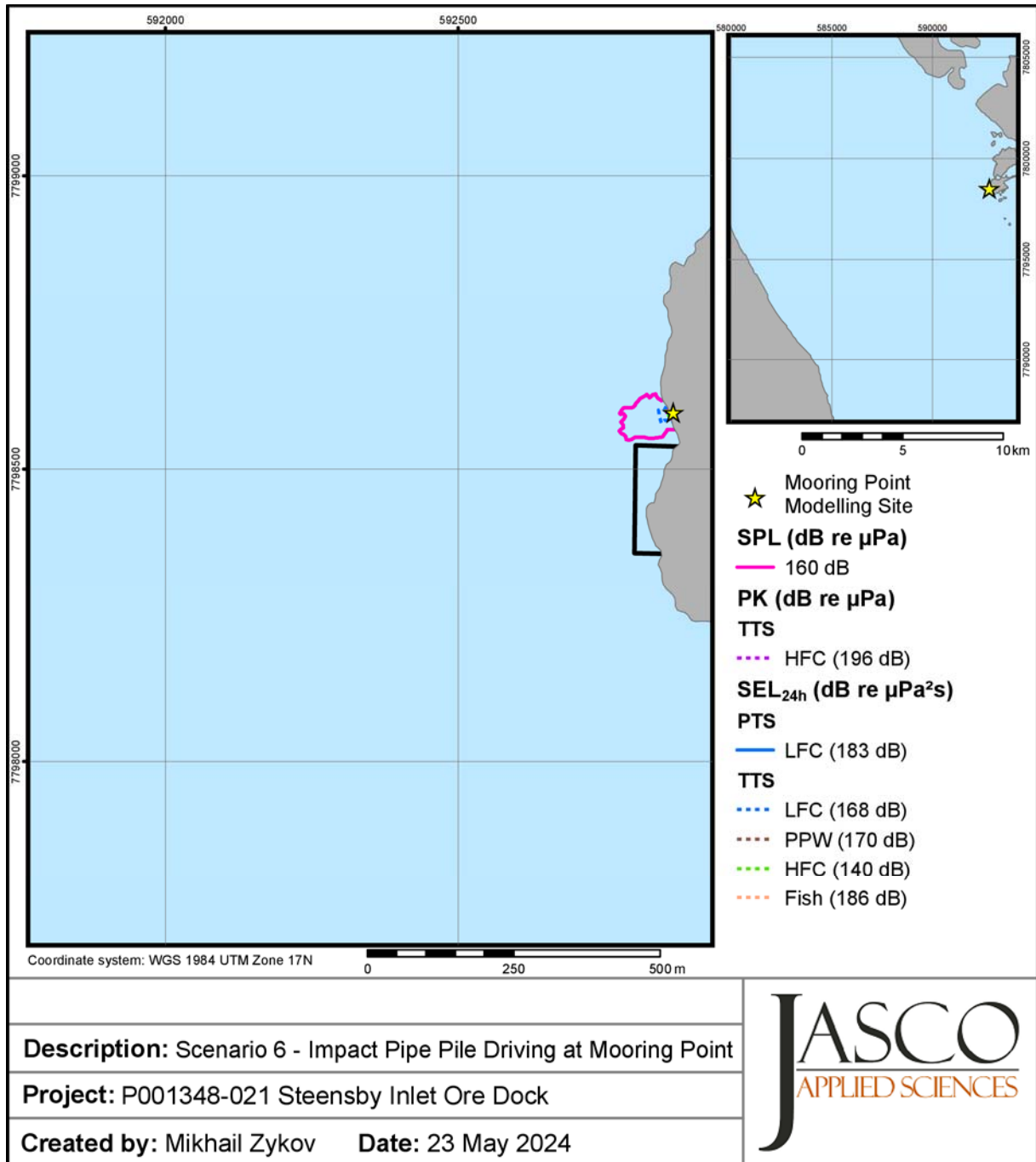


Figure 10. Sound level contours for Scenario 6, impact pile driving of pipe piles at mooring point.

### 4.3. Vibratory Pile Driving

Table 22. *Vibratory pile driving*: Distances (m) to  $SEL_{w,24h}$  thresholds (NMFS 2018) for permanent threshold shift (PTS) and temporary threshold shift (TTS).

Type of effect	Hearing group	$L_{E,w,24h}$ threshold (dB re 1 $\mu Pa^2s$ )	Scenario 3	
			$R_{max}$	$R_{95\%}$
PTS	LF cetaceans	199	20	20
	MF cetaceans	198	<10	-
	HF cetaceans	173	<10	-
	Phocids in water	201	<10	-
	Otariids in water	219	<10	-
TTS	LF cetaceans	179	242	200
	MF cetaceans	178	<10	-
	HF cetaceans	153	32	32
	Phocids in water	181	51	51
	Otariids in water	199	<10	-

LF: low-frequency; MF: mid-frequency; HF: high-frequency

A dash (-) indicates that the range to the threshold was not reached.

Scenario 3: Combi-wall sheet pile, vibratory pile driving

Table 23. *Vibratory pile driving*: Distances (m) to NMFS (2013) 120 dB re 1  $\mu Pa^2$  SPL threshold for marine mammal behavioural disturbance for non-impulsive noise sources.

$L_p$ threshold (dB re 1 $\mu Pa^2$ )	Scenario 3	
	$R_{max}$	$R_{95\%}$
120	5230	4340

Scenario 3: Combi-wall sheet pile, vibratory pile driving

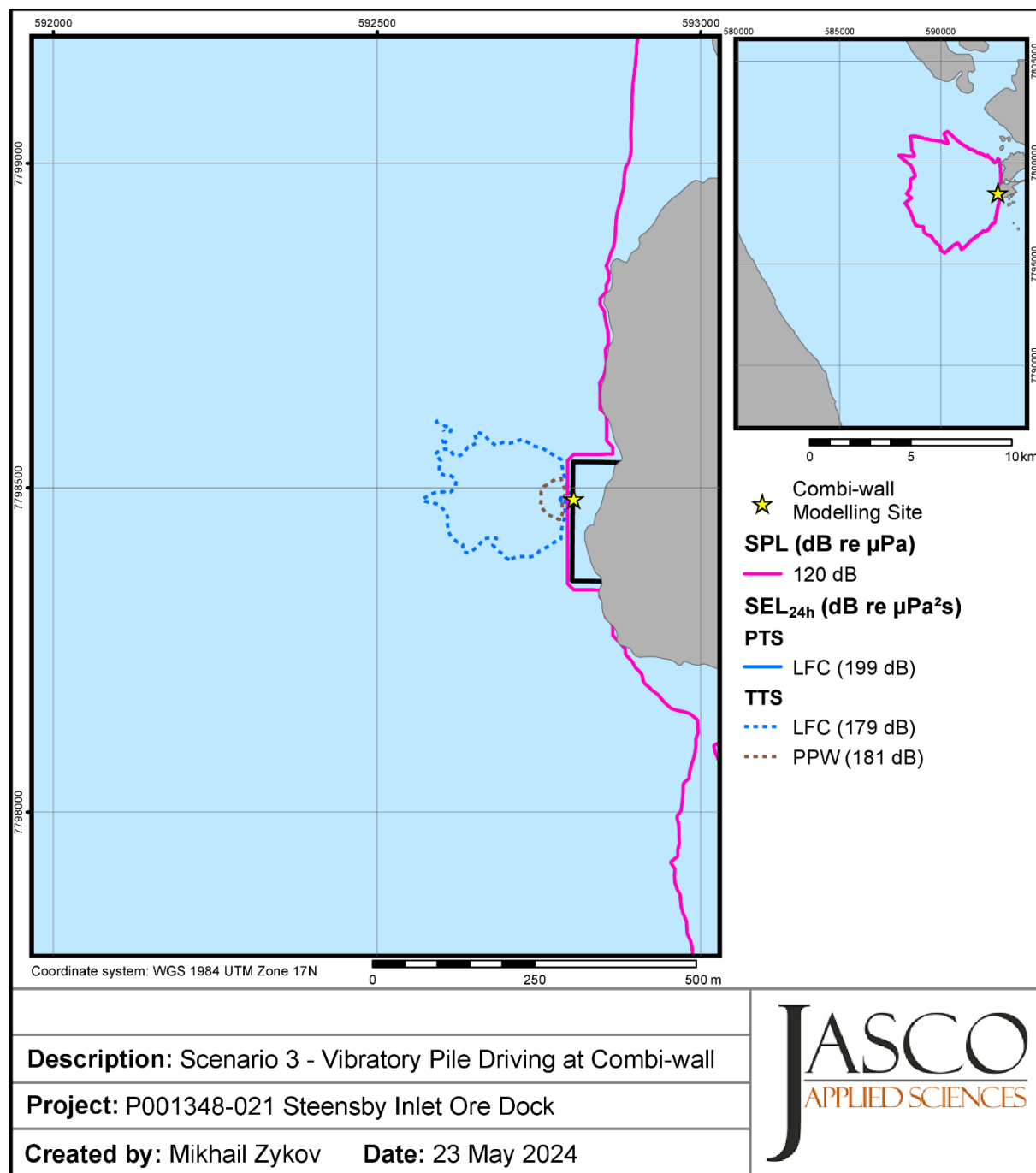


Figure 11. Sound level contours for Scenario 3, vibratory pile driving of sheet piles at combi wall.

## 4.4. Onshore Rock Blasting

Table 24. Onshore rock blasting (at water edge): Distances (m) to  $SEL_{w,24h}$  (NMFS 2018) for permanent threshold shift (PTS), temporary threshold shift (TTS) and behavioural disturbance thresholds for 100 detonations of charges with masses of 1, 10, 20, 30, 40, 50, and 100 kg TNT.

Type of effect	Hearing group	$L_{E,w,24h}$ threshold (dB re 1 $\mu Pa^2s$ )	1 kg		10 kg		20 kg		30 kg		40 kg		50 kg		100 kg	
			$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$
PTS	LF cetaceans	183	<10	-	<10	-	10	10	11	11	10	10	11	11	10	10
	MF cetaceans	185	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	HF cetaceans	155	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Phocids in water	185	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Otariids in water	203	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
TTS	LF cetaceans	168	18	18	28	27	40	35	40	36	40	34	40	35	40	32
	MF cetaceans	170	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	HF cetaceans	140	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Phocids in water	170	<10	-	10	10	11	11	11	11	11	11	11	11	11	11
	Otariids in water	188	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
Behaviour	LF cetaceans	163	28	27	43	40	60	50	60	51	60	47	60	51	60	46
	MF cetaceans	165	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	HF cetaceans	135	<10	-	<10	-	11	11	11	11	11	11	11	11	<10	-
	Phocids in water	165	10	10	16	16	21	21	21	21	18	18	20	20	18	18
	Otariids in water	183	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-

LF: low-frequency; MF: mid-frequency; HF: high-frequency

A dash (-) indicates that the range to the threshold was not reached.



Table 25. Onshore rock blasting (100 m from water): Distances (m) to  $SEL_{w,24h}$ : (NMFS 2018) for permanent threshold shift (PTS), temporary threshold shift (TTS) and behavioural disturbance thresholds for 100 detonations of charges with masses of 1, 10, 20, 30, 40, 50, and 100 kg TNT.

Type of effect	Hearing group	$L_{E,w,24h}$ threshold (dB re 1 $\mu Pa^2 \cdot s$ )	1 kg		10 kg		20 kg		30 kg		40 kg		50 kg		100 kg	
			$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$
PTS	LF cetaceans	183	<10	-	<10	-	10	10	11	11	10	10	11	11	10	10
	MF cetaceans	185	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	HF cetaceans	155	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Phocids in water	185	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Otariids in water	203	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
TTS	LF cetaceans	168	18	18	27	27	35	35	36	35	34	34	35	35	32	32
	MF cetaceans	170	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	HF cetaceans	140	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Phocids in water	170	<10	-	10	10	11	11	11	11	11	11	11	11	11	11
	Otariids in water	188	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
Behaviour	LF cetaceans	163	27	27	41	40	51	50	52	51	49	47	51	50	45	45
	MF cetaceans	165	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	HF cetaceans	135	<10	-	<10	-	11	11	11	11	11	11	11	11	<10	-
	Phocids in water	165	10	10	16	16	21	21	21	21	18	18	20	20	18	18
	Otariids in water	183	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-

LF: low-frequency; MF: mid-frequency; HF: high-frequency

A dash (-) indicates that the threshold was not reached.

Table 26. Onshore *rock blasting (at water edge)*: Distances (m) to PK thresholds (Finneran et al. 2017) for permanent threshold shift (PTS) and temporary threshold shift (TTS) for charges with masses of 1, 10, 20, 30, 40, 50, and 100 kg TNT.

Type of effect	Hearing group	$L_{pk}$ threshold (dB re 1 $\mu$ Pa)	1 kg		10 kg		20 kg		30 kg		40 kg		50 kg		100 kg	
			$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$
PTS	LF cetaceans	219	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	MF cetaceans	230	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	HF cetaceans	202	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Phocids in water	218	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Otariids in water	232	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
TTS	LF cetaceans	213	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	MF cetaceans	224	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	HF cetaceans	196	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Phocids in water	212	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Otariids in water	226	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-

LF: low-frequency; MF: mid-frequency; HF: high-frequency

A dash (-) indicates that the range to the threshold was not reached.

Table 27. Onshore *rock blasting (100 m from water)*: Distances (m) to PK thresholds (Finneran et al. 2017) for permanent threshold shift (PTS) and temporary threshold shift (TTS) for charges with masses of 1, 10, 20, 30, 40, 50, and 100 kg TNT.

Type of effect	Hearing group	$L_{pk}$ threshold (dB re 1 $\mu$ Pa)	1 kg		10 kg		20 kg		30 kg		40 kg		50 kg		100 kg	
			$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$
PTS	LF cetaceans	219	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	MF cetaceans	230	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	HF cetaceans	202	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Phocids in water	218	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Otariids in water	232	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
TTS	LF cetaceans	213	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	MF cetaceans	224	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	HF cetaceans	196	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Phocids in water	212	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Otariids in water	226	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-

LF: low-frequency; MF: mid-frequency; HF: high-frequency

A dash (-) indicates that the range to the threshold was not reached.

Table 28. Onshore *rock blasting (at water edge)*: Distances to fish mortality and potential mortal injury, and impairment  $SEL_{w,24h}$  thresholds (Popper et al. 2014) for 100 detonations of charges with masses of 1, 10, 20, 30, 40, 50, and 100 kg TNT.

Type of effect	Faunal group	$L_{E,24h}$ threshold (dB re 1 $\mu Pa^2s$ )	1 kg		10 kg		20 kg		30 kg		40 kg		50 kg		100 kg	
			$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$
Mortality and potential mortal injury	Fish with no swim bladder	219	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Fish with swim bladder not involved in hearing	210	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Fish with swim bladder involved in hearing	207	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
Recoverable injury	Fish with no swim bladder	216	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Fish with swim bladder	203	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
TTS	All fish	186	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-

A dash (-) indicates that the threshold was not reached.

Table 29. Onshore *rock blasting (100 m from water)*: Distances to fish mortality and potential mortal injury, and impairment  $SEL_{w,24h}$  thresholds (Popper et al. 2014) for 100 detonations of charges with masses of 1, 10, 20, 30, 40, 50, and 100 kg TNT.

Type of effect	Faunal group	$L_{E,24h}$ threshold (dB re 1 $\mu Pa^2s$ )	1 kg		10 kg		20 kg		30 kg		40 kg		50 kg		100 kg	
			$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$
Mortality and potential mortal injury	Fish with no swim bladder	219	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Fish with swim bladder not involved in hearing	210	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Fish with swim bladder involved in hearing	207	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
Recoverable injury	Fish with no swim bladder	216	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
	Fish with swim bladder	203	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
TTS	All fish	186	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-

A dash (-) indicates that the threshold was not reached.

Table 30. Onshore *rock blasting (at water edge)*: Distances (m) to fish mortality and potential mortal injury, and recoverable injury PK thresholds (Popper et al. 2014) for charges sizes of 1, 10, 20, 30, 40, 50, and 100 kg TNT.

Faunal group	$L_{pk}$ threshold (dB re 1 $\mu$ Pa)	1 kg		10 kg		20 kg		30 kg		40 kg		50 kg		100 kg	
		$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$
Fish with no swim bladder	213	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
Fish with swim bladder	207	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
All fish groups, single detonation	229	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
All fish groups, DFO overpressure limit	214 (50 kPa)	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-

A dash (-) indicates that the threshold was not reached.

Table 31. Onshore *rock blasting (100 m from water)*: Distances (m) to fish mortality and potential mortal injury, and recoverable injury PK thresholds (Popper et al. 2014) for charges sizes of 1, 10, 20, 30, 40, 50, and 100 kg TNT.

Faunal group	$L_{pk}$ threshold (dB re 1 $\mu$ Pa)	1 kg		10 kg		20 kg		30 kg		40 kg		50 kg		100 kg	
		$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$	$R_{max}$	$R_{95\%}$
Fish with no swim bladder	213	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
Fish with swim bladder	207	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
All fish groups, single detonation	229	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-
All fish groups, DFO overpressure limit	214 (50 kPa)	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-

A dash (-) indicates that the threshold was not reached.

## 4.5. Aggregate Scenarios

Table 32. Aggregate scenarios: Distances (m) to SEL (NMFS 2018) for permanent threshold shift (PTS) and temporary threshold shift (TTS) in marine mammals for the combined activity scenarios listed in Table 14.

Type of effect	Hearing group	$L_{E,w,24h}$ threshold (dB re 1 $\mu\text{Pa}^2\text{s}$ )	A1		A2		A3		A4		A5	
			$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$
PTS	LF cetaceans	183	1620	1320	187	173	790	651	1640	1360	1620	1320
	MF cetaceans	185	<10	-	<10	-	<10	-	<10	-	<10	-
	HF cetaceans	155	22	22	32	32	22	22	40	40	22	22
	Phocids in water	185	100	91	41	41	81	73	150	102	100	91
	Otariids in water	203	<10	-	<10	-	<10	-	<10	-	<10	-
TTS	LF cetaceans	168	11300	9520	1860	1620	6990	5980	11300	9510	11300	9520
	MF cetaceans	170	<10	-	<10	-	<10	-	20	20	<10	-
	HF cetaceans	140	228	194	190	180	112	103	273	241	228	194
	Phocids in water	170	1070	930	278	250	546	490	1270	1020	1070	930
	Otariids in water	188	32	32	32	32	36	36	41	41	32	32

LF: low-frequency; MF: mid-frequency; HF: high-frequency

A dash (-) indicates that the range to the threshold was not defined.

Table 33 Aggregate scenarios: Distances (m) to fish mortality, potential mortal injury, and impairment  $SEL_{w,24h}$  thresholds (Popper et al. 2014) for the combined activity scenarios listed in Table 14.

Type of effect	Faunal group	$L_{E,24h}$ threshold (dB re 1 $\mu\text{Pa}^2\text{s}$ )	A1		A2		A3		A4		A5	
			$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$	$R_{\max}$	$R_{95\%}$
Mortality and potential mortal injury	Fish with no swim bladder	219	<10	-	<10	-	<10	-	<10	-	<10	-
	Fish with swim bladder not involved in hearing	210	41	41	<10	-	28	28	41	41	41	41
	Fish with swim bladder involved in hearing	207	67	63	<10	-	42	36	67	63	67	63
Recoverable injury	Fish with no swim bladder	216	22	22	<10	-	<10	-	22	22	22	22
	Fish with swim bladder	203	181	171	<10	-	71	67	191	180	181	171
TTS	All fish	186	1650	1400	199	175	770	590	1670	1440	1650	1400

A dash (-) indicates that the range to the threshold was not defined.

Table 34. Aggregate scenarios: Distances (m) to the NMFS (2013) 120 dB re 1  $\mu\text{Pa}^2$  SPL threshold for marine mammal behavioural disturbance for non-impulsive noise sources, for the combined activity scenarios listed in Table 14.

$L_p$ threshold (dB re 1 $\mu\text{Pa}^2$ )	A4	
	$R_{\max}$	$R_{95\%}$
120	13,400	11,400

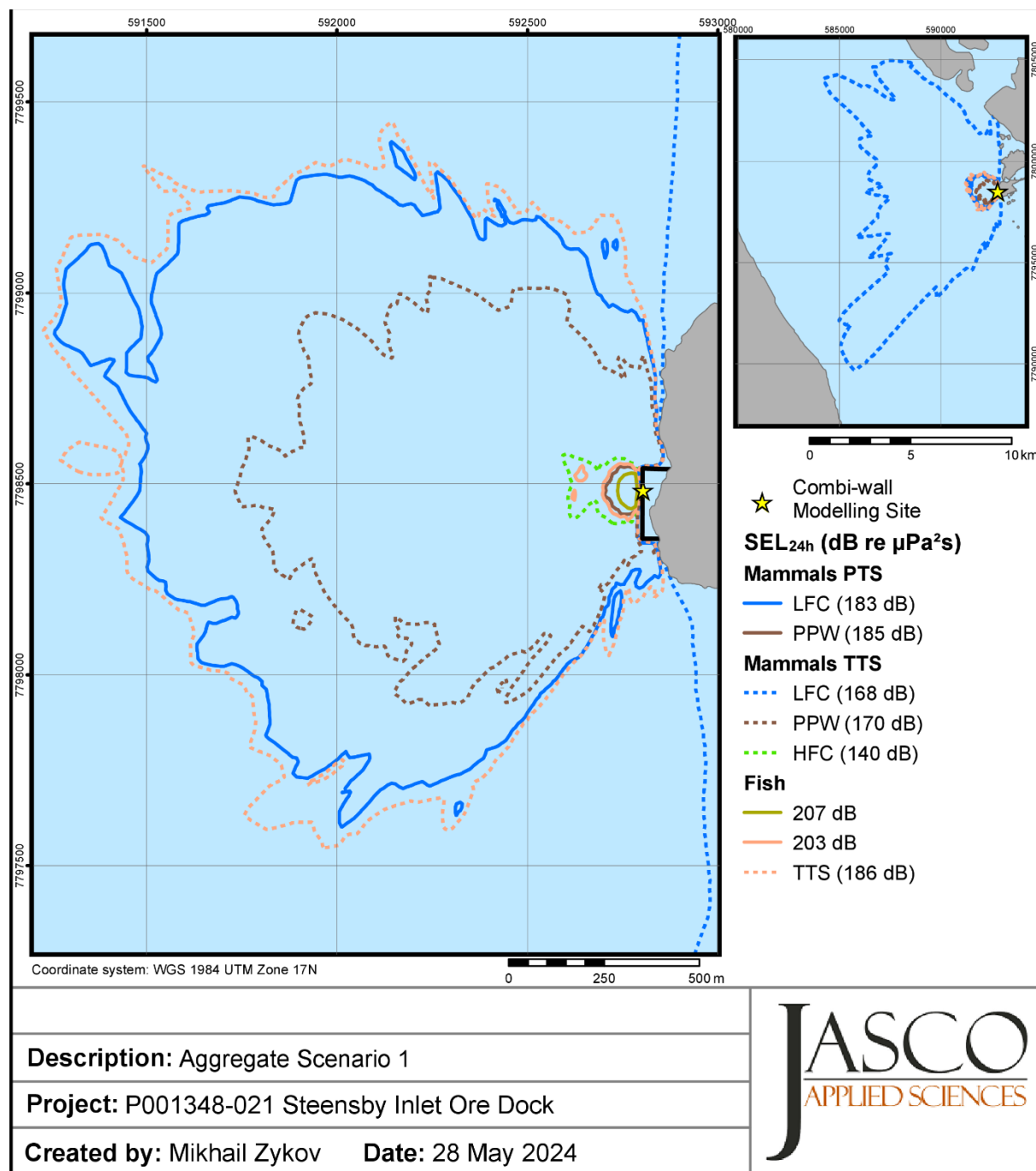


Figure 12. Sound level contours for aggregate Scenario 1 combining noise from drilling and impact pile driving required to drive 1.5 combi-wall pipe piles in one day.

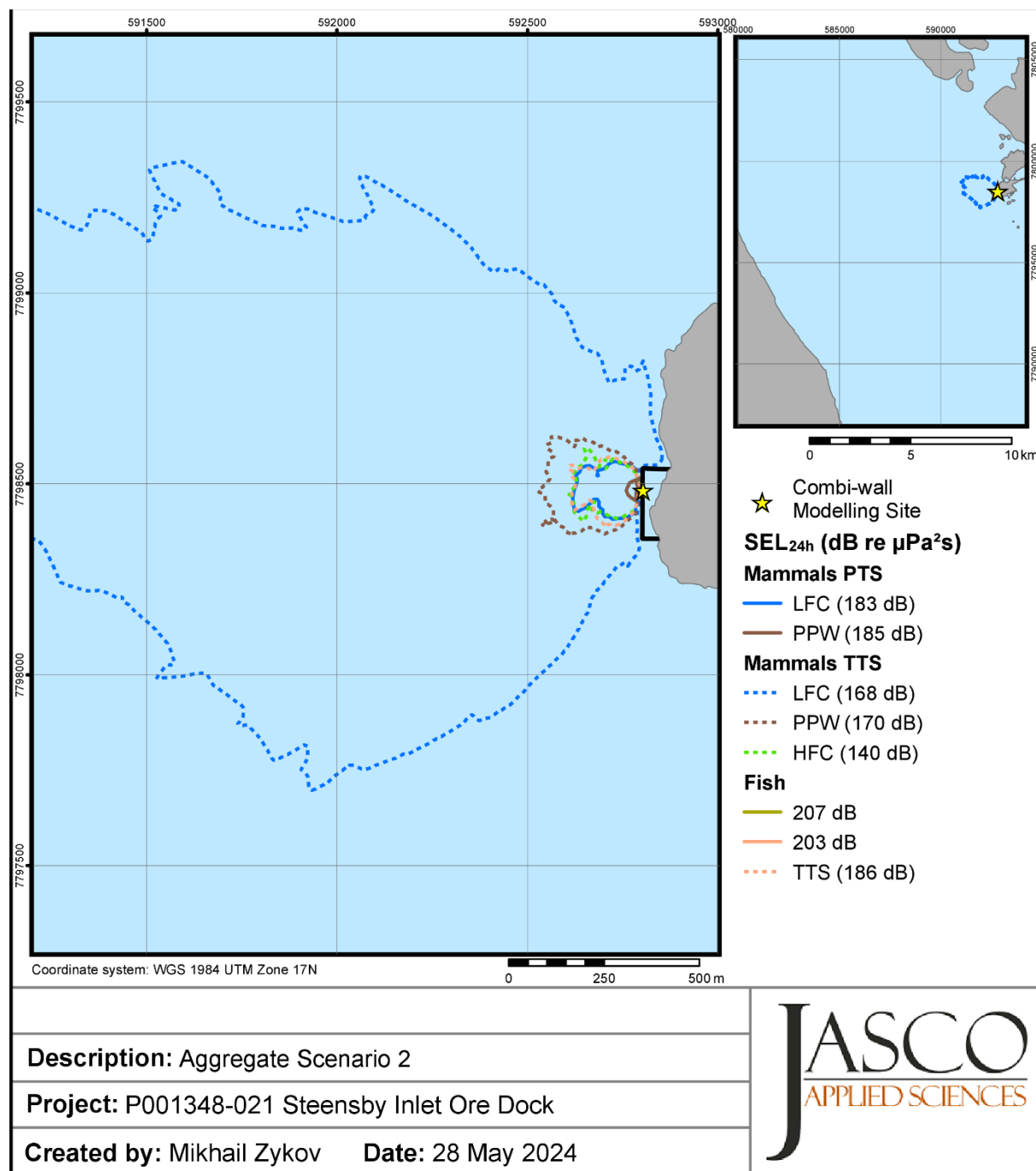


Figure 13. Sound level contours for aggregate Scenario 2 combining noise from vibratory and impact pile driving required to drive 6 combi-wall sheet piles in one day.

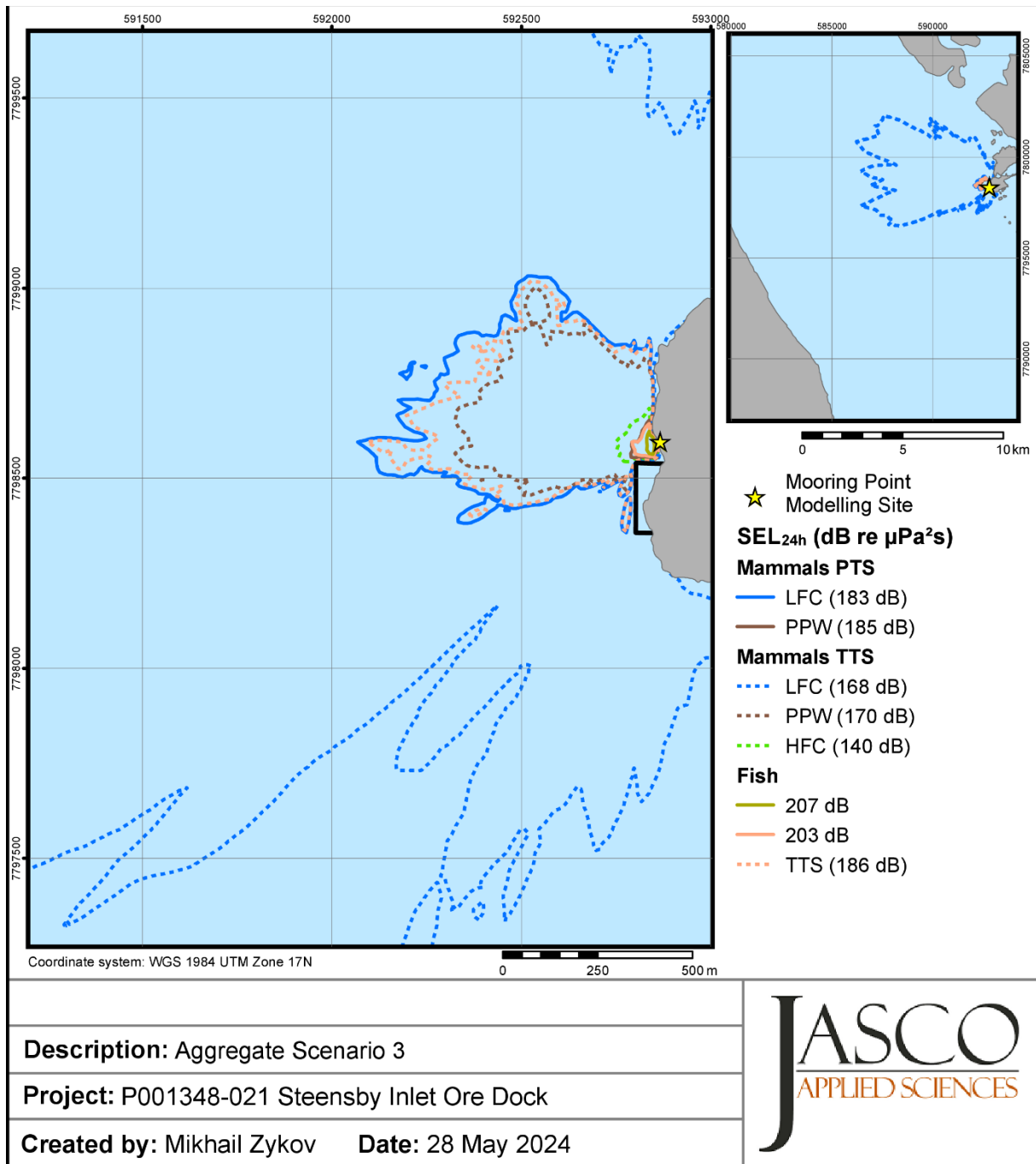


Figure 14. Sound level contours for aggregate Scenario 3 combining noise from drilling and impact pile driving required to drive 1 mooring point pipe piles in one day.



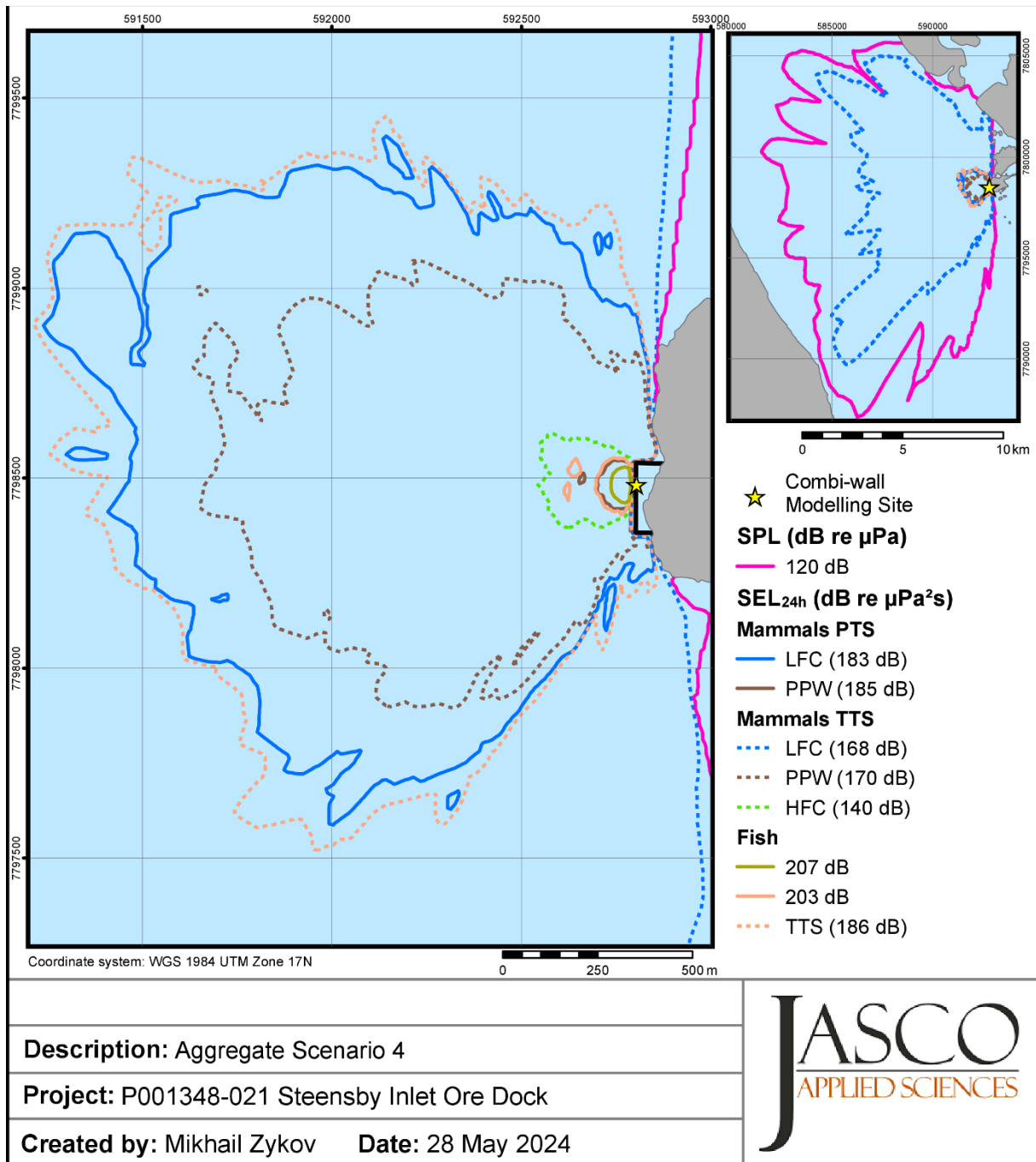


Figure 15. Sound level contours for aggregate Scenario 4 combining noise from drilling, vibratory piling, and impact pile driving required to drive 1.5 combi-wall pipe piles and 6 combi-wall sheet piles in one day.

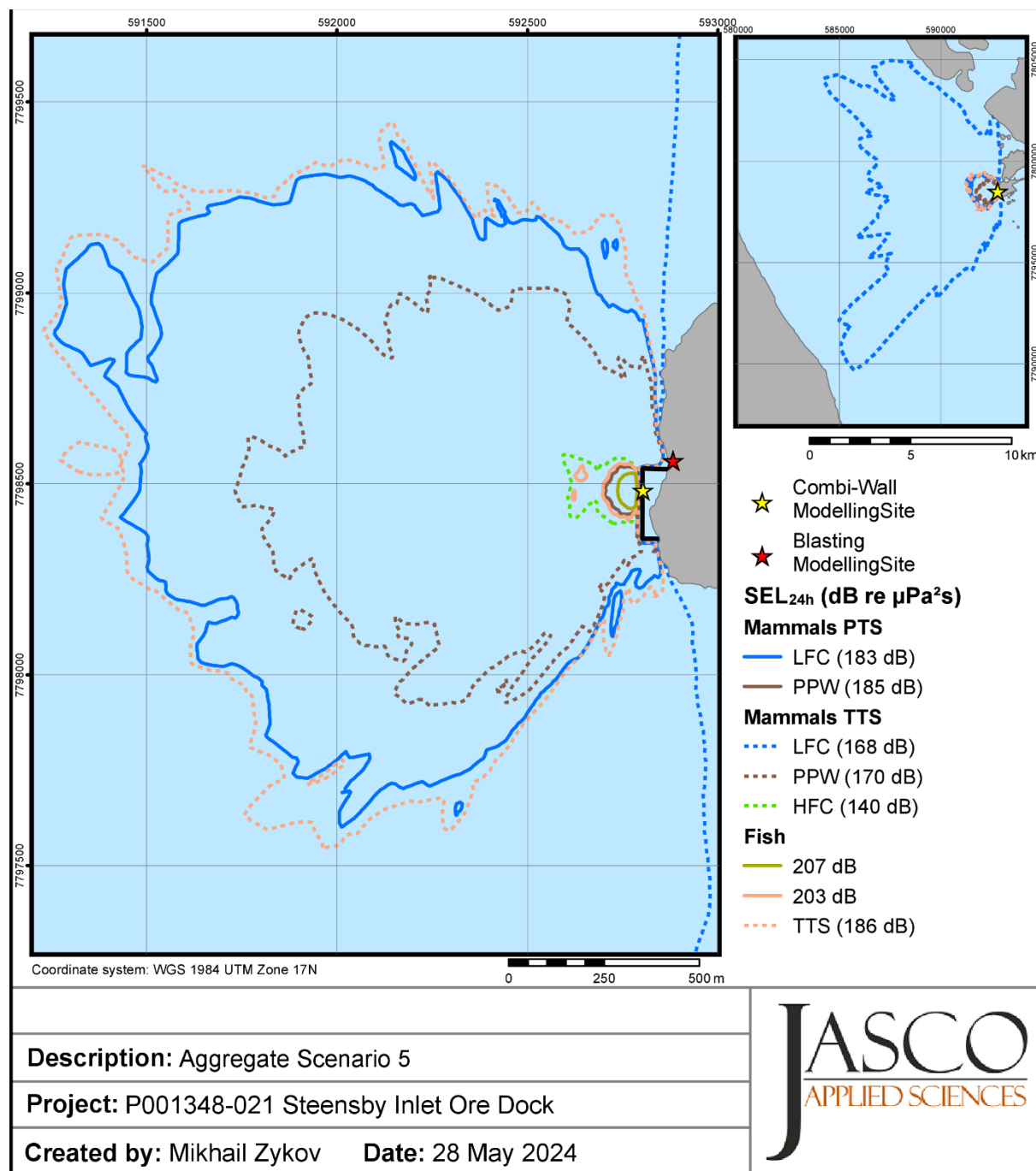


Figure 16. Sound level contours for aggregate Scenario 5 combining noise from blasting (100 detonations of 100 kg charges) with drilling and impact pile driving required to drive 1.5 combi-wall pipe piles in one day.

## 5. Discussion and Conclusion

Acoustic propagation modelling was conducted to estimate underwater sound levels at Steensby Inlet produced by noise sources associated with the construction of the Steensby Port facility. Model scenarios considered underwater noise from drilling, impact pile driving, and vibratory pile driving required to install pipe and sheet piles for the ore dock combi-wall and for mooring piles on shore, as well as for onshore rock blasting as part of site grading activities. Underwater sound footprints were modelled for individual noise sources as well as for five aggregate scenarios in which the combined noise was accumulated for all noise sources that could occur within the same day. Where uncertainties in operating conditions existed, the models were parametrized to yield realistically conservative noise levels.

### 5.1. Individual Activity Scenarios

The results of the modelling for individual construction activities are summarized as follows:

#### Drilling (Scenarios 1 and 5)

- *Marine mammals* – Underwater noise generated from drilling of the combi-wall pipe piles (Scenario 1) exceeded the PTS threshold for LF cetaceans at distances up to 199 m but did not exceed the PTS threshold for any of the other marine mammal hearing groups. For drilling of the mooring point piles, the PTS injury threshold was exceeded at a slightly shorter distance (85 m) for LF cetaceans (Scenario 5), with no exceedances of the PTS threshold predicted for the other hearing groups. For drilling of the combi-wall pipe piles, the TTS threshold was exceeded at distances up to at least 32 m (for HF cetaceans) and up to at most 3.2 km (for LF cetaceans). The maximum distances where noise exceeded the TTS thresholds for PW pinnipeds was 228 m and the TTS threshold was not exceeded for the MF cetacean or OW pinniped hearing groups (Table 15). For drilling of the mooring point piles, the TTS threshold was exceeded at distances up to at least 28 m (for HF cetaceans) and up to at most 1.7 km (for LF cetaceans). The maximum distances where noise exceeded the threshold for PW pinnipeds was 117 m and the TTS threshold was not exceeded for the MF cetacean or OW pinniped hearing groups (Table 15). Underwater noise from drilling exceeded the 120 dB re 1  $\mu$ Pa SPL behavioural disturbance threshold for marine mammals (all species) up to distances of 13.2 km ( $R_{95\%} = 11$  km) for the combi-wall pipe piles and up to 13.4 km ( $R_{95\%} = 11.8$  km) for the mooring point piles.

#### Impact pile driving (Scenarios 2, 4, and 6)

- *Marine mammals* – Underwater noise generated from impact pile driving for the combi-wall pipe piles (Scenario 2) exceeded the PTS threshold for LF cetaceans at distances up to 21 m, based on the  $SEL_{w,24h}$  threshold. The PTS thresholds were not exceeded in the water for any other hearing groups. Noise from impact pile driving of the combi-wall sheet piles (Scenario 4), exceeded the PTS threshold at distances up to 80 m for LF cetaceans, and 22 m for PW pinnipeds. The threshold was not exceeded in the water for any other hearing groups for this activity. Noise from impact pile driving for the mooring piles (Scenario 6) did not exceed the PTS threshold for any hearing groups. Underwater sound levels exceeded the TTS threshold out to a maximum distance of 330 m for LF cetaceans (the TTS threshold was not exceeded in the water for any other hearing groups) for impact pile driving of the combi-wall pipe piles, and for impact pile driving of combi-wall sheet piles, the noise exceeded the TTS threshold out to a distances of at least 91 m (for HF cetaceans) and at most 970 m (for LF cetaceans). The threshold was exceeded out to 173 m distance for PW pinnipeds and was not

exceeded in the water for the other hearing groups (Table 17). Noise from impact pile driving of the mooring piles exceeded the TTS threshold for LF cetaceans out to a maximum distance of 25 m. The noise did not exceed the TTS threshold for any other hearing groups for this scenario. The only PK threshold for PTS that was exceeded was that for HF cetaceans, out to a maximum distance of 25 m for impact piling of combi-wall pipe piles (Scenario 2). The PK threshold for TTS was also exceeded for HF cetaceans out to distances of 184 and 36 m for impact pile driving for the combi-wall pipe piles and combi-wall sheet piles, respectively (not reached for impact pile driving of the mooring point piles). Sounds from impact pile driving for the combi-wall pipe piles, combi-wall sheet piles, and the mooring point piles exceeded the 160 dB re 1  $\mu$ Pa threshold for behavioural disturbance from impulsive sound (for all species) out to maximum distances of 2.2 km, 800 m, and 95 m, respectively (1.8 km, 662 m, and 85 m, respectively, based on  $R_{95\%}$ ).

- *Fish* – No thresholds for mortality, potential mortal injury, or recoverable injury for fish were exceeded in the water for impact pile driving of the combi-wall pipe piles, combi-wall sheet piles, or the mooring point piles. The noise of impact pile driving of the combi-wall pipe piles and the combi-wall sheet piles exceeded the TTS threshold for fish out to distances of 25 m and 76 m, respectively; noise from impact pile driving of the mooring point piles did not exceed the TTS threshold for fish in the water.

### Vibratory pile driving (Scenario 3)

- *Marine mammals* – Noise from vibratory pile driving of the combi-wall sheet piles (Scenario 3) exceeded the threshold for PTS for LF cetaceans out to a distance of 20 m; the noise did not exceed the PTS thresholds for any other hearing groups. Noise from vibratory pile driving of sheet piles exceeded the thresholds for TTS out to a maximum range of 242 m for LF cetaceans, 51 m for PW pinnipeds, and 32 m for HF cetaceans but did not exceed the thresholds for the remaining hearing groups within the water. Vibratory pile driving noise exceeded the 120 dB re 1  $\mu$ Pa threshold for behavioural disturbance (for all species) out to a maximum distance of 5.2 km (4.3 km based on  $R_{95\%}$ ).

### Blasting (Scenarios 7 and 8)

- *Marine mammals* – None of the modelled scenarios for onshore blasting (i.e. up to 100 detonations of any considered charge size) generated noise that exceeded any of the thresholds for PTS or TTS in the water. Noise from onshore blasting did exceed the threshold for behavioural disturbance for LF cetaceans out to a distance of at least 28 m from a 1 kg charge and of at most 60 m from a 100 kg charge, for charges detonated 20 m from the water's edge. The behavioural threshold was not exceeded for any other hearing groups, nor was it exceeded for any hearing group or considered charge size for detonations occurring at least 100 m from the water.
- *Fish* – None of the modelled onshore blasting scenarios generated noise that exceeded any of the thresholds for mortality, potential mortal injury, recoverable injury, or TTS for fish.

## 5.2. Aggregate Scenarios

The results for aggregate model scenarios are summarized as follows:

**Scenario A1** (combi-wall pipe pile installation involving drilling and impact pile driving within the same day):

- **Marine mammals** – The total daily sound exposure accounting for noise from drilling and impact pile driving during the installation of combi-wall pipe piles resulted in an accumulated SEL that exceeded the threshold for PTS out to a maximum range of at most 1.6 km (for LF cetaceans,  $R_{95\%} = 1.3$  km) and at least 22 m (for HF cetaceans); the maximum distance where noise exceeded the threshold for PW pinnipeds was 100 m and the threshold was not reached in the water for OW pinnipeds and MF cetaceans (Table 32). Noise for Scenario A1 exceeded the thresholds for TTS out to maximum distances of at least 32 m (for OW pinnipeds) and at most 11.3 km (for LF cetaceans,  $R_{95\%} = 9.5$  km). The maximum distances where noise exceeded the thresholds for the other hearing groups were in between these values, though the threshold was not reached in the water for MF cetaceans (Table 32).
- **Fish** – Sound levels exceeded the threshold for mortality or potential mortal injury out to a maximum range of 67 or 41 m for fish with and without a swim bladder involved with hearing, respectively. The threshold for recoverable injury was exceeded at a maximum range of 181 m for fish with a swim bladder. There is no risk for mortality, potential mortal injury, or recoverable injury for fish with no swim bladder. The threshold for TTS in fish was exceeded to a distance of 1.7 km ( $R_{95\%} = 1.4$  km).

**Scenario A2** (combi-wall sheet pile installation involving vibratory and impact pile driving within the same day):

- **Marine mammals** – The total daily sound exposure accounting for noise from both vibratory and impact pile driving during the installation of combi-wall sheet piles results in an accumulated SEL that exceeded thresholds for PTS at a maximum range of at least 32 m (for HF cetaceans) and at most 187 m (for LF cetaceans). The maximum distance where noise exceeded the threshold for PW pinnipeds was 41 m and the threshold was not reached in the water for OW pinnipeds and MF cetaceans (Table 32). Thresholds for TTS were exceeded at ranges of at least 32 m (for OW pinnipeds) and at most 1.9 km (for LF cetaceans); the maximum distances where noise exceeded the thresholds for the other hearing groups were in between these values, though the threshold was not exceeded for MF cetaceans (Table 32).
- **Fish** – No thresholds for mortality, potential mortal injury, or recoverable injury for fish were exceeded for this scenario. The thresholds for TTS for fish was exceeded at a maximum distance of 200 m.

**Scenario A3** (mooring pile installation involving drilling and impact pile driving within the same day):

- **Marine mammals** – The total daily sound exposure accounting for noise from both drilling and impact pile driving during the installation of the mooring piles resulted in an accumulated SEL that exceeded the threshold for PTS at a maximum range of at least 22 m (for HF cetaceans) and at most 790 m (for LF cetaceans); the maximum distance where noise exceeded the threshold for PW pinnipeds was 81 m and the threshold was not exceeded in the water for OW pinnipeds and MF cetaceans (Table 32). The thresholds for TTS were exceeded out to a maximum distance of at least 36 m (for OW pinnipeds) and at most 7.0 km (for LF cetaceans  $R_{95\%} = 6.0$  km); the maximum distances where noise exceeded the thresholds for the other hearing groups were in between these values, though the threshold was not exceeded in the water for MF cetaceans (Table 32).

- **Fish** – Sound levels exceeded the threshold for mortality or potential mortal injury at a maximum range of 42 m or 28 m for fish with and without a swim bladder involved with hearing, respectively. The threshold for recoverable injury was exceeded at a maximum range of 71 m for fish with a swim bladder. There is no risk for mortality, potential mortal injury, or recoverable injury for fish with no swim bladder. The threshold for TTS in fish was exceeded to a distance of 790 m ( $R_{95\%} = 590$  m).

**Scenario A4** (combi-wall pipe pile and sheet pile installation within the same day):

- **Marine mammals** – The total daily sound exposure accounting for noise from the installation of both pipe piles and sheet piles at the combi-wall resulted in an accumulated SEL that exceeded the threshold for PTS at a maximum range of at least 40 m (for HF cetaceans) and at most 1.6 km (or LF cetaceans  $R_{95\%} = 1.3$  km) ; the maximum distance where noise exceeded the threshold for PW pinnipeds was 150 m and the threshold was not exceeded in the water for OW pinnipeds and MF cetaceans (Table 32). The thresholds for TTS were exceeded at maximum distances of at least 20 m (for MF cetaceans) and at most 11.3 km (for LF cetaceans,  $R_{95\%} = 9.5$  km) (Table 32). The maximum distances where noise exceeded the thresholds for the other hearing groups were in between these values.
- **Fish** – Sound levels exceeded the threshold for mortality or potential mortal injury at a maximum range of 67 m or 41 m for fish with and without a swim bladder involved with hearing, respectively. The threshold for recoverable injury was exceeded at a maximum range of 191 m for fish with a swim bladder. There is no risk for mortality, potential mortal injury, or recoverable injury for fish with no swim bladder. The threshold for TTS in fish was exceeded to a distance of 1.7 km ( $R_{95\%} = 1.4$  km).

**Scenario A5** (combi-wall pipe pile installation and blasting (100 detonations of 100 kg TNT charges) within the same day):

- **Marine mammals** – The total daily sound exposure accounting for noise from both drilling and impact pile driving during the installation of combi-wall pipe piles combined with blasting involving 100 detonations of 100 kg TNT charges resulted in an accumulated SEL that exceeded the threshold for PTS at a maximum range of at least 22 m (for HF cetaceans) and at most 1.6 km (for LF cetaceans,  $R_{95\%} = 1.3$  km); the maximum distance at which the threshold was exceeded for PW pinnipeds was 100 m and the threshold was not exceeded in the water for OW pinnipeds and MF cetaceans (Table 32). The thresholds for TTS were exceeded at a maximum distance of at least 32 m (for OW pinnipeds) and at most 11.3 km (for LF cetaceans,  $R_{95\%} = 9.5$  km) ; the maximum distances where noise exceeded the thresholds for the other hearing groups were in between these values though the threshold was not exceeded in the water for MF cetaceans (Table 32). These results are consistent with Scenario A1 (combi-wall pipe pile installation), indicating that the underwater noise from blasting does not increase the sound field associated with installation of the combi-wall pipe piles.
- **Fish** – Sound levels exceeded the threshold for mortality or potential mortal injury at a maximum range of 67 or 43 m for fish with and without a swim bladder involved with hearing, respectively. The threshold for recoverable injury was exceeded at a maximum range of 181 m for fish with a swim bladder. There is no risk for mortality, potential mortal injury, or recoverable injury for fish with no swim bladder. The threshold for TTS in fish was exceeded to a distance of 1.3 km ( $R_{95\%} = 1.1$  km). These results are consistent with Scenario A1 (combi-wall pipe pile installation), indicating that the underwater noise from blasting does not increase the sound field associated with installation of the combi-wall pipe piles.

The aggregate scenarios present the most precautionary assessment of potential noise impacts as they are based on the total noise exposure a marine mammal or fish would experience if it remained in the same location throughout the day's activities. These distances are computed relative to the more

precautionary thresholds for impulsive noise, although the scenarios include noise from both impulsive and non-impulsive sources. Because the duration of drilling is much longer than that for impact pile driving in the combi-wall pipe pile Scenario A1, for example, the drilling noise dominates the aggregate sound levels in that case. As such, the exposure distances for drilling of the combi-wall pipe piles are more reasonably represented by the results for model Scenario 1, assessed relative to the thresholds for non-impulsive noise, while the aggregate result for Scenario A1 is more directly applicable to the impact pile driving portion of that scenario. Similarly, results for vibratory pile driving of sheet piles are more reasonably represented by the results for Scenario 3, and those for drilling of mooring point piles are more reasonably represented by the results for Scenario 5. The results of the aggregate scenarios are more directly applicable to the impact pile driving activities.



## Glossary of Acoustics Terms

Unless otherwise stated in an entry, these definitions are consistent with ISO 18405 (2017).

Light blue text indicates related terms that might be in this glossary. Dark blue text indicates clickable links to related terms in this glossary

### absorption

The conversion of [sound](#) energy to heat energy. Specifically, the reduction of [sound pressure](#) amplitude due to particle motion energy converting to heat in the propagation medium.

### acoustic impedance

The ratio of the [sound pressure](#) in a medium to the volume flow rate of the medium through a specified surface due to the [sound](#) wave. It is a measure of how well sound propagates through a particular medium.

### acoustic noise

[Sound](#) that interferes with an acoustic process.

### acoustic self-noise

[Sound](#) at a receiver caused by the deployment, operation, or recovery of a specified receiver and its associated platform (ISO 18405:2017).

### attenuation

The gradual loss of acoustic energy from [absorption](#) and scattering as [sound](#) propagates through a medium. Attenuation depends on [frequency](#)—higher frequency sounds are attenuated faster than lower frequency sounds.

### audiogram

A graph or table of [hearing threshold](#) as a function of [frequency](#) that describes the hearing sensitivity of an animal over its hearing range.

### auditory frequency weighting

The process of applying an [auditory frequency-weighting function](#). An example for marine mammals are the auditory frequency-weighting functions published by Southall et al. (2007).

### auditory frequency-weighting function

[Frequency-weighting function](#) describing a compensatory approach accounting for a species' (or functional hearing group's) [frequency](#)-specific hearing sensitivity.

### azimuth

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

### background noise

Combination of [ambient sound](#), [acoustic self-noise](#), and, where applicable, sonar reverberation (ISO 18405:2017) that is detected, measured, or recorded with a signal.



**bandwidth**

A range within a continuous band of frequencies. Unit: [hertz \(Hz\)](#).

**broadband level**

The total [level](#) measured over a specified [frequency](#) range. If the frequency range is unspecified, the term refers to the entire measured frequency range.

**cetacean**

Member of the order Cetacea. Cetaceans are aquatic 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 a longitudinal wave. In seismology/geophysics, it's called a primary wave or P-wave. [Shear waves](#) in the seabed can be converted to compressional waves in water at the water-seabed interface.

**confined explosives**

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

**continuous sound**

A [sound](#) whose [sound pressure level](#) remains above the [background noise](#) during the observation period and may gradually vary in intensity with time, e.g., sound from a marine vessel.

**decade**

Logarithmic [frequency](#) interval whose upper bound is ten times larger than its lower bound (ISO 80000-3:2006). For example, one decade up from 1000 Hz is 10,000 Hz, and one decade down is 100 Hz.

**decibel (dB)**

Unit of [level](#) used to express the ratio of one value of a power quantity to another on a logarithmic scale. Especially suited to quantify variables with a large dynamic range.

**decidecade**

One tenth of a [decade](#). Approximately equal to one third of an octave ( $1 \text{ ddec} \approx 0.3322 \text{ oct}$ ), and for this reason sometimes referred to as a [1/3-octave](#).

**decidecade band**

[Frequency](#) band whose [bandwidth](#) is one [decidecade](#). The bandwidth of a decidecade band increases with increasing centre frequency.

**energy source level**

A property of a [sound](#) source equal to the [sound exposure level](#) measured in the [far field](#) plus the [propagation loss](#) from the acoustic centre of the source to the receiver position. Unit: [decibel \(dB\)](#).  
[Reference value](#):  $1 \mu\text{Pa}^2 \text{ m}^2 \text{ s}$ .

### energy spectral density

Ratio of energy (time-integrated square of a specified field variable) to **bandwidth** in a specified **frequency** band from  $f_1$  to  $f_2$ . In equation form, the energy spectral density  $E_f$  is given by:

$$E_f = 2 \int_{f_1}^{f_2} |X(f)|^2 df / (f_2 - f_1) \quad \text{where } X(f) \text{ is the Fourier transform of the field variable } x(t):$$

$$X(f) = \int_{-\infty}^{+\infty} x(t) \exp(-2\pi i f t) dt.$$

The field variable  $x(t)$  is a scalar quantity, such as **sound pressure**. It can also be the magnitude or a specified component of a vector quantity such as sound particle displacement, velocity, or acceleration. The unit of energy spectral density depends on the nature of  $x$ , as follows:

- If  $x$  = sound pressure:  $\text{Pa}^2 \text{ s/Hz}$
- If  $x$  = sound particle displacement:  $\text{m}^2 \text{ s/Hz}$
- If  $x$  = sound particle velocity:  $(\text{m/s})^2 \text{ s/Hz}$
- If  $x$  = sound particle acceleration:  $(\text{m/s}^2)^2 \text{ s/Hz}$

The factor of two on the right side of the equation for  $E_f$  is needed to express a **spectrum** that is symmetric about  $f = 0$ , in terms of positive frequencies only. See entry 3.1.3.9 of ISO 18405 (2017).

### energy spectral density level

The **level** ( $L_{E_f}$ ) of the **energy spectral density** ( $E_f$ ) in a stated **frequency** band and time window. Defined as:  $L_{E_f} = 10 \log_{10}(E_f/E_{f,0})$ . Unit: **decibel (dB)**. As with energy spectral density, energy spectral density level can be expressed in terms of various field variables (e.g., **sound pressure**, **sound particle displacement**). The **reference value** ( $E_{f,0}$ ) for energy spectral density level depends on the nature of the field variable.

### energy spectral density source level

A property of a **sound** source equal to the **energy spectral density level** of the **sound pressure** measured in the **far field** plus the **propagation loss** from the acoustic centre of the source to the receiver position. Unit: **decibel (dB)**. **Reference value**:  $1 \mu\text{Pa}^2 \text{ m}^2 \text{ s/Hz}$ .

### ensonified

Exposed to **sound**.

### far field

The zone where, to an observer, **sound** originating from an array of sources (or a spatially distributed source) appears to radiate from a single point.

### Fourier transform, Fourier synthesis

A mathematical technique which, although it has varied applications, is referenced in a physical data acquisition context as a method used in the process of deriving a spectrum estimate from time-series data (or the reverse process, termed the inverse Fourier transform). A computationally efficient numerical algorithm for computing the Fourier transform is known as the fast Fourier transform (FFT).

### 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.

### frequency weighting

The process of applying a [frequency-weighting function](#).

### frequency-weighting function

The squared magnitude of the [sound pressure](#) transfer function (ISO 18405:2017). For [sound](#) of a given [frequency](#), the frequency-weighting function is the ratio of output power to input power of a specified filter, sometimes expressed in decibels. Examples include the following:

- *Auditory frequency-weighting function*: compensatory frequency-weighting function accounting for a species' (or [functional hearing group's](#)) frequency-specific hearing sensitivity.
- *System frequency-weighting function*: frequency-weighting function describing the sensitivity of an acoustic recording system, which typically consists of a [hydrophone](#), one or more amplifiers, and an analog-to-digital converter.

### functional hearing group

Category of animal species when classified according to their hearing sensitivity, hearing anatomy, and susceptibility to [sound](#). For marine mammals, initial groupings were proposed by Southall et al. (2007), and revised groupings are developed as new research/data becomes available. Revised groupings proposed by Southall et al. (2019) include low-frequency cetaceans, high-frequency cetaceans, very high-frequency cetaceans, phocid carnivores in water, other carnivores in water, and sirenians. Example hearing groups for fish include species for which the swim bladder is involved in hearing, species for which the swim bladder is not involved in hearing, and species without a swim bladder (Popper et al. 2014). See also [auditory frequency-weighting functions](#), which are often applied to these groups.

### geoacoustic

Relating to the acoustic properties of the seabed.

### hearing threshold

For a given species or [functional hearing group](#), the [sound level](#) for a given signal that is barely audible (i.e., that would be barely audible for a given individual in the presence of specified [background noise](#) during a specific percentage of experimental trials).

### hertz (Hz)

Unit of [frequency](#) defined as one cycle per second. Often expressed in multiples such as kilohertz (1 kHz = 1000 Hz).

### high-frequency (HF) cetaceans

See [functional hearing group](#). The mid- and high-frequency cetaceans groups proposed by Southall et al. (2007) were renamed high- and very-high-frequency cetaceans, respectively, by Southall et al. (2019).

### hydrostatic pressure

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).

### impulsive sound

Qualitative term meaning [sounds](#) that are typically transient, brief (less than 1 s), broadband, with rapid rise time and rapid decay. They can occur in repetition or as a single event. Sources of impulsive sound include, among others, explosives, seismic airguns, and impact pile drivers.

**isopleth**

A line drawn on a map through all points having the same value of some specified quantity (e.g., sound pressure level isopleth).

**level**

A measure of a quantity expressed as the logarithm of the ratio of the quantity to a specified [reference value](#) of that quantity. For example, a value of [sound pressure level](#) with reference to  $1 \mu\text{Pa}^2$  can be written in the form  $x \text{ dB re } 1 \mu\text{Pa}^2$ .

**low-frequency (LF) cetaceans**

See [functional hearing group](#).

**mid-frequency (MF) cetaceans**

See [functional hearing group](#). The mid-frequency cetaceans group proposed by Southall et al. (2007) was renamed high-frequency cetaceans by Southall et al. (2019).

**mysticete**

Member of the Mysticeti, a suborder of [cetaceans](#). Also known as baleen whales, mysticetes have baleen plates (rather than teeth) that they use to filter food from water (or from sediment as for grey whales). This group includes rorquals (Balaenopteridae, such as blue, fin, humpback, and minke whales), right and bowhead whales (Balaenidae), and grey whales (*Eschrichtius robustus*).

**non-impulsive sound**

[Sound](#) that is not an [impulsive sound](#). Not necessarily a [continuous sound](#).

**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**

Member of Odontoceti, a suborder of [cetaceans](#). These whales, dolphins, and porpoises have teeth (rather than baleen plates). Their skulls are mostly asymmetric, an adaptation for their echolocation. This group includes sperm whales, killer whales, belugas, narwhals, dolphins, and porpoises.

**otariid**

Member of the family Otariidae, one of the three groupings of [pinnipeds](#) (along with [phocids](#) and walrus). These eared seals, commonly called fur seals and sea lions, are adapted to semi-aquatic life; they use their large fore flippers for propulsion underwater and can walk on all four limbs on land.

**otariid pinnipeds underwater (OW)**

See [functional hearing group](#).

**other marine carnivores in water (OCW)**

See [functional hearing group](#).

### parabolic equation method

A computationally efficient solution to the acoustic wave equation that is used to model [propagation loss](#). The parabolic equation approximation omits effects of backscattered [sound](#) (which are negligible for most ocean-acoustic propagation problems), simplifying the computation of propagation loss.

### peak sound pressure level (PK), zero-to-peak sound pressure level

The [level](#) ( $L_{pk}$ ) of the squared maximum magnitude of the [sound pressure](#) ( $p_{pk}^2$ ) in a stated [frequency](#) band and time window. Defined as  $L_{pk} = 10\log_{10}(p_{pk}^2/p_0^2) = 20\log_{10}(p_{pk}/p_0)$ . Unit: [decibel \(dB\)](#). [Reference value](#) ( $p_0^2$ ) for [sound](#) in water:  $1 \mu\text{Pa}^2$ .

### peak-to-peak sound pressure

The difference between the maximum and minimum [sound pressure](#) over a specified [frequency](#) band and time window. Unit: pascal (Pa).

### permanent threshold shift (PTS)

An irreversible loss of hearing sensitivity caused by excessive noise exposure. Considered auditory injury. Compare with [temporary threshold shift](#).

### phocid

Member of the family Phocidae, one of the three groupings of [pinnipeds](#) (along with [otariids](#) and walrus). 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 underwater.

### phocid pinnipeds underwater (PW), phocid carnivores in water (PCW)

See [functional hearing group](#).

### pinniped

Member of the superfamily Pinnipedia, which is composed of [phocids](#) (true seals or earless seals), [otariids](#) (eared seals or fur seals and sea lions), and walrus.

### power spectral density

Generic term, formally defined as power in a unit [frequency](#) band. Unit: watt per hertz (W/Hz). The term is sometimes loosely used to refer to the spectral density of other parameters such as squared [sound pressure](#). Ratio of [energy spectral density](#),  $E_f$  to time duration,  $\Delta t$ , in a specified temporal observation window. In equation form, the power spectral density  $P_f$  is given by  $P_f = E_f/\Delta t$ . Power spectral density can be expressed in terms of various field variables (e.g., sound pressure, [sound particle displacement](#)).

### power spectral density level

The [level](#) ( $L_{P_f}$ ) of the [power spectral density](#) ( $P_f$ ) in a stated [frequency](#) band and time window. Defined as:  $L_{P_f} = 10\log_{10}(P_f/P_{f0})$ . Unit: [decibel \(dB\)](#).

As with [power spectral density](#), power spectral density level can be expressed in terms of various field variables (e.g., [sound pressure](#), [sound particle displacement](#)). The [reference value](#) ( $P_{f0}$ ) for power spectral density level depends on the nature of the field variable.

### power spectral density source level

A property of a sound source equal to the **power spectral density level** of the **sound pressure** measured in the **far field** plus the **propagation loss** from the acoustic centre of the source to the receiver position.

Unit: **decibel (dB)**. **Reference value**:  $1 \mu\text{Pa}^2 \text{ m}^2/\text{Hz}$ .

### propagation loss (PL)

Difference between a **source level** (SL) and the level at a specified location,  $\text{PL}(x) = \text{SL} - L(x)$ .

Unit: **decibel (dB)**. See also **transmission loss**.

### received level

The **level** of a given field variable measured (or that would be measured) at a given location.

### reference value

Standard value of a quantity used for calculating underwater **sound level**. The reference value depends on the quantity for which the level is being calculated:

Quantity	Reference value
Sound pressure	$p_0^2 = 1 \mu\text{Pa}^2$ or $p_0 = 1 \mu\text{Pa}$
Sound exposure	$E_0 = 1 \mu\text{Pa}^2 \text{ s}$
Sound particle displacement	$\delta_0^2 = 1 \text{ pm}^2$
Sound particle velocity	$u_0^2 = 1 \text{ nm}^2/\text{s}^2$
Sound particle acceleration	$a_0^2 = 1 \mu\text{m}^2/\text{s}^4$

### shear wave

A mechanical vibration wave in which the direction of particle motion is perpendicular to the direction of propagation. Also called a 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.

### sound

A time-varying disturbance in the pressure, stress, or material displacement of a medium propagated by local compression and expansion of the medium. In common meaning, a form of energy that propagates through media (e.g., water, air, ground) as pressure waves.

### sound exposure

Time integral of squared **sound pressure** over a stated time interval in a stated **frequency** band. The time interval can be a specified time duration (e.g., 24 h) or from start to end of a specified event (e.g., a pile strike, an airgun pulse, a construction operation). Unit: pascal squared second ( $\text{Pa}^2 \text{ s}$ ). Symbol:  $E$ .

### sound exposure level (SEL)

The **level** ( $L_E$ ) of the **sound exposure** ( $E$ ) in a stated **frequency** band and time window:  $L_E = 10\log_{10}(E/E_0)$  (ISO 18405:2017). Unit: **decibel (dB)**. **Reference value** ( $E_0$ ) for **sound** in water:  $1 \mu\text{Pa}^2 \text{ s}$ .

**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** (ISO 18405:2017). Unit: pascal squared second per hertz ( $\text{Pa}^2 \text{s/Hz}$ ).

**sound field**

Region containing **sound** waves.

**sound intensity**

Product of the **sound pressure** and the **sound particle velocity** (ISO 18405:2017). The magnitude of the sound intensity is the **sound** energy flowing through a unit area perpendicular to the direction of propagation per unit time. Unit: watt per meter squared ( $\text{W/m}^2$ ). Symbol:  $I$ .

**sound pressure**

The contribution to total pressure caused by the action of **sound** (ISO 18405:2017). Unit: pascal (Pa). Symbol:  $p$ .

**sound pressure level (SPL), rms sound pressure level**

The **level** ( $L_p$ ) of the time-mean-square **sound pressure** ( $p_{\text{rms}}^2$ ) in a stated **frequency** band and time window:  $L_p = 10\log_{10}(p_{\text{rms}}^2/p_0^2) = 20\log_{10}(p_{\text{rms}}/p_0)$ , where rms is the abbreviation for root-mean-square. Unit: **decibel (dB)**. **Reference value** ( $p_0^2$ ) for **sound** in water:  $1 \mu\text{Pa}^2$ . SPL can also be expressed in terms of the root-mean-square (rms) with a **reference value** of  $p_0 = 1 \mu\text{Pa}$ . The two definitions are equivalent.

**sound speed profile**

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

**soundscape**

The characterization of the **ambient sound** in terms of its spatial, temporal, and **frequency** attributes, and the types of sources contributing to the **sound** field (ISO 18405:2017).

**source level (SL)**

A property of a **sound** source equal to the **sound pressure level** measured in the **far field** plus the **propagation loss** from the acoustic centre of the source to the receiver position. Unit: **decibel (dB)**. **Reference value**:  $1 \mu\text{Pa}^2 \text{m}^2$ .

**spectrogram**

A visual representation of acoustic amplitude over time and frequency. A spectrogram's resolution in the time and frequency domains should generally be stated as it determines the information content of the representation.

**spectrum**

Distribution of acoustic signal content over **frequency**, where the signal's content is represented by its power, energy, mean-square **sound pressure**, or **sound exposure**.

**temporary threshold shift (TTS)**

Reversible loss of hearing sensitivity caused by noise exposure. Compare with **permanent threshold shift**.

**thermocline**

A depth interval near the ocean surface that experiences larger temperature gradients than the layers above and below it due to warming or cooling by heat conduction from the atmosphere and by warming from the sun.

**transmission loss (TL)**

The difference between a specified level at one location and that at a different location:  $TL(x_1, x_2) = L(x_1) - L(x_2)$  (ISO 18405:2017). Unit: [decibel \(dB\)](#). See also [propagation loss](#).

**unweighted**

Term indicating that no [frequency-weighting function](#) is applied.

**very high-frequency (VHF) cetaceans**

See [functional hearing group](#).

**wavelength**

Distance over which a wave completes one cycle of oscillation. Unit: meter (m). Symbol:  $\lambda$ .



## Literature Cited

- [ANSI] American National Standards Institute and [ASA] Acoustical Society of America. S1.1-2013. *American National Standard: Acoustical Terminology*. New York. <https://webstore.ansi.org/Standards/ASA/ANSIASAS12013>.
- [BCMPDCA] BC Marine and Pile Driving Contractors Association and [DFO] Fisheries and Oceans Canada. 2003. *Best Management Practices for Pile Driving and Related Operations*. 7 p. <https://projects.eao.gov.bc.ca/api/document/5887e34fad20ac134d916367/fetch>.
- [DFO] Fisheries and Oceans Canada. 2012. *Final Intervention Comments to the Nunavut Impact Review Board (NIRB). Mary River Project. Baffinland Iron Mines*. 30 May 2012.
- [DoC] Department of Commerce (US) and [NOAA] National Oceanic and Atmospheric Administration (US). 2018. 83 FR 63268: Takes of Marine Mammals Incidental to Specified Activities; Taking Marine Mammals Incidental to Geophysical Surveys in the Atlantic Ocean. *Federal Register* 83(235): 63268–63270. <https://www.federalregister.gov/d/2018-26460>.
- [FHWG] Fisheries Hydroacoustic Working Group. 2008. *Agreement in Principle for Interim Criteria for Injury to Fish from Pile Driving Activities*. 12 Jun 2008 edition. <https://dot.ca.gov/-/media/dot-media/programs/environmental-analysis/documents/ser/bio-fhwg-criteria-agree-a11y.pdf>.
- [HESS] High Energy Seismic Survey. 1999. *High Energy Seismic Survey Review Process and Interim Operational Guidelines for Marine Surveys Offshore Southern California*. Prepared for the California State Lands Commission and the United States Minerals Management Service Pacific Outer Continental Shelf Region by the High Energy Seismic Survey Team, Camarillo, CA, USA. 98 p. <https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/PB2001100103.xhtml>.
- [IOC] Intergovernmental Oceanographic Commission, [IHO] International Hydrographic Organization, and [BODC] British Oceanographic Data Centre. 2003. *General Bathymetric Chart of the Oceans (GEBCO) Digital Atlas. Centenary Edition* (data set). [https://www.bodc.ac.uk/resources/products/data/bodc\\_products/gebco/](https://www.bodc.ac.uk/resources/products/data/bodc_products/gebco/).
- [ISO] International Organization for Standardization. 2006. ISO 80000-3:2006. *Quantities and units — Part 3: Space and time*. <https://www.iso.org/standard/31888.html>.
- [ISO] International Organization for Standardization. 2017. ISO 18405:2017. *Underwater acoustics — Terminology*. Geneva. <https://www.iso.org/obp/ui/en/#iso:std:62406:en>.
- [NMFS] National Marine Fisheries Service (US). 1998. *Acoustic Criteria Workshop*. Co-Chairs: Dr. Roger Gentry and Dr. Jeanette Thomas. 9-11 Sep 1998.
- [NMFS] National Marine Fisheries Service (US). 2013. *Marine Mammals: Interim Sound Threshold Guidance* (web page). National Marine Fisheries Service, National Oceanic and Atmospheric Administration, US Department of Commerce. [http://www.westcoast.fisheries.noaa.gov/protected\\_species/marine\\_mammals/threshold\\_guidance.html](http://www.westcoast.fisheries.noaa.gov/protected_species/marine_mammals/threshold_guidance.html).
- [NMFS] National Marine Fisheries Service (US). 2016. *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts*. US Department of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-55. 178 p.
- [NMFS] National Marine Fisheries Service (US). 2018. *2018 Revision to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts*. US Department of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-59. 167 p. [https://media.fisheries.noaa.gov/dam-migration/tech\\_memo\\_acoustic\\_guidance\\_\(20\)\\_pdf\\_508.pdf](https://media.fisheries.noaa.gov/dam-migration/tech_memo_acoustic_guidance_(20)_pdf_508.pdf).
- [NOAA] National Oceanic and Atmospheric Administration (US). 2013. *Draft guidance for assessing the effects of anthropogenic sound on marine mammals: Acoustic threshold levels for onset of permanent and temporary threshold shifts*. National Oceanic and Atmospheric Administration, US Department of Commerce, and NMFS Office of Protected Resources, Silver Spring, MD, USA. 76 p.
- [NOAA] National Oceanic and Atmospheric Administration (US). 2015. *Draft guidance for assessing the effects of anthropogenic sound on marine mammal hearing: Underwater acoustic threshold levels for onset of permanent and temporary threshold shifts*. NMFS Office of Protected Resources, Silver Spring, MD, USA. 180 p.
- [NOAA] National Oceanic and Atmospheric Administration (US). 2016. *Document Containing Proposed Changes to the NOAA Draft Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Threshold Levels for Onset of Permanent and Temporary Threshold Shifts*. National Oceanic and Atmospheric Administration and US Department of Commerce. 24 p.
- [ONR] Office of Naval Research. 1998. *Workshop on the Effect of Anthropogenic Noise in the Marine Environment. ONR Workshop*, 10–12 Feb 1998. <https://apps.dtic.mil/sti/tr/pdf/ADA640861.pdf>.

- Aerts, L.A.M., M. Bles, S.B. Blackwell, C.R. Greene, Jr., K.H. Kim, D.E. Hannay, and M.E. Austin. 2008. *Marine mammal monitoring and mitigation during BP Liberty OBC seismic survey in Foggy Island Bay, Beaufort Sea, July-August 2008: 90-day report*. Document P1011-1. Report by LGL Alaska Research Associates Inc., LGL Ltd., Greeneridge Sciences Inc., and JASCO Applied Sciences for BP Exploration Alaska. 199 p. [http://ftp.library.noaa.gov/noaa\\_documents.lib/NMFS/Auke%20Bay/AukeBayScans/Removable%20Disk/P1011-1.pdf](http://ftp.library.noaa.gov/noaa_documents.lib/NMFS/Auke%20Bay/AukeBayScans/Removable%20Disk/P1011-1.pdf).
- Babushina, Y.S., G.L. Zaslavskii, and L.I. Yurkevich. 1991. Air and underwater hearing characteristics of the northern fur seal: Audiograms, frequency and differential thresholds. *Biophysics* 36(5): 909–913.
- Bowman, V., E. Henderson, K. Jenkins, S. Kotecki, J. Shield, J. Mulsow, and B. Branstetter. 2019. *Underwater Measurements of Detonations at Eagle River Flats, Joint Base Elmendorf-Richardson, 18-19 July 2018*. Report by Bioacoustics Analysis and Applied Research Team, Space and Naval Warfare Systems Center, Pacific. <https://jber-pmart-eis.com/api/files/48766c82-a7c3-4d05-9815-08811104c298>.
- Buehler, D., R. Oestman, J.A. Reyff, K. Pommerenck, and B. Mitchell. 2015. *Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish*. Report CTHWANP-RT-15-306.01.01. Report by California Department of Transportation (CALTRANS), Division of Environmental Analysis. 532 p.
- Carnes, M.R. 2009. *Description and Evaluation of GDEM-V 3.0*. US Naval Research Laboratory, Stennis Space Center, MS. NRL Memorandum Report 7330-09-9165. 21 p. <https://apps.dtic.mil/dtic/tr/fulltext/u2/a494306.pdf>.
- Collins, M.D. 1993. A split-step Padé solution for the parabolic equation method. *Journal of the Acoustical Society of America* 93(4): 1736–1742. <https://doi.org/10.1121/1.406739>.
- Collins, M.D., R.J. Cederberg, D.B. King, and S. Chin-Bing. 1996. Comparison of algorithms for solving parabolic wave equations. *Journal of the Acoustical Society of America* 100(1): 178–182. <https://doi.org/10.1121/1.415921>.
- Coppens, A.B. 1981. Simple equations for the speed of sound in Neptunian waters. *Journal of the Acoustical Society of America* 69(3): 862–863. <https://doi.org/10.1121/1.382038>.
- Denes, S.L., G.A. Warner, M.E. Austin, and A.O. MacGillivray. 2016. *Hydroacoustic Pile Driving Noise Study – Comprehensive Report*. Document 001285, Version 2.0. Technical report by JASCO Applied Sciences for Alaska Department of Transportation & Public Facilities. <https://dot.alaska.gov/stwddes/research/assets/pdf/4000-135.pdf>.
- Ellison, W.T. and P.J. Stein. 1999. *SURTASS LFA High Frequency Marine Mammal Monitoring (HF/M3) Sonar: System Description and Test & Evaluation*. Under US Navy Contract N66604-98-D-5725. <http://www.surtass-lfa-eis.com/wp-content/uploads/2018/02/HF-M3-Ellison-Report-2-4a.pdf>.
- Fay, R.R. 1984. The goldfish ear codes the axis of acoustic particle motion in three dimensions. *Science* 225(4665): 951–954. <https://doi.org/10.1126/science.6474161>.
- Fay, R.R. 1988. *Hearing in Vertebrates: A Psychophysics Databook*. Hill-Fay Associates, Winnetka, IL, USA.
- Finneran, J.J. and C.E. Schlundt. 2010. Frequency-dependent and longitudinal changes in noise-induced hearing loss in a bottlenose dolphin (*Tursiops truncatus*). *Journal of the Acoustical Society of America* 128(2): 567–570. <https://doi.org/10.1121/1.3458814>.
- Finneran, J.J. and A.K. Jenkins. 2012. *Criteria and thresholds for U.S. Navy acoustic and explosive effects analysis*. SPAWAR Systems Center Pacific, San Diego, CA, USA. 64 p.
- Finneran, J.J. 2015. *Auditory weighting functions and TTS/PTS exposure functions for cetaceans and marine carnivores*. Technical report by SSC Pacific, San Diego, CA, USA.
- Finneran, J.J. 2016. *Auditory weighting functions and TTS/PTS exposure functions for marine mammals exposed to underwater noise*. Technical Report for Space and Naval Warfare Systems Center Pacific, San Diego, CA, USA. 49 p. <https://apps.dtic.mil/dtic/tr/fulltext/u2/1026445.pdf>.
- Finneran, J.J., E.E. Henderson, D.S. Houser, K. Jenkins, S. Kotecki, and J.L. Mulsow. 2017. *Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase III)*. Technical report by Space and Naval Warfare Systems Center Pacific (SSC Pacific). 183 p. [https://nwtteis.com/portals/nwtteis/files/technical\\_reports/Criteria\\_and\\_Thresholds\\_for\\_U.S. Navy Acoustic and Explosive Effects Analysis June2017.pdf](https://nwtteis.com/portals/nwtteis/files/technical_reports/Criteria_and_Thresholds_for_U.S._Navy_Acoustic_and_Explosive_Effects_Analysis_June2017.pdf).
- Fisher, F.H. and V.P. Simmons. 1977. Sound absorption in sea water. *Journal of the Acoustical Society of America* 62(3): 558–564. <https://doi.org/10.1121/1.381574>.
- Funk, D.W., D.E. Hannay, D.S. Ireland, R. Rodrigues, and W.R. Koski. 2008. *Marine mammal monitoring and mitigation during open water seismic exploration by Shell Offshore Inc. in the Chukchi and Beaufort Seas, July–November 2007: 90-day report*. LGL Report P969-1. Report by LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Research Ltd. for Shell Offshore Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. 218 p. [http://www-static.shell.com/static/usa/downloads/alaska/shell2007\\_90-d\\_final.pdf](http://www-static.shell.com/static/usa/downloads/alaska/shell2007_90-d_final.pdf).
- Hannay, D.E. and R. Racca. 2005. *Acoustic Model Validation*. Document 0000-S-90-04-T-7006-00-E, Revision 02, Version 1.3. Technical report by JASCO Research Ltd. for Sakhalin Energy Investment Company Ltd. 34 p.
- Harrison, C.H. and J.A. Harrison. 1995. A simple relationship between frequency and range averages for broadband sonar. *Journal of the Acoustical Society of America* 97(2): 1314–1317. <https://doi.org/10.1121/1.412172>.

- Hastings, M.C. and A.N. Popper. 2005. *Effects of Sound on Fish*. Volume Report by Jones & Stokes under California Department of Transportation Contract No. 43A0139, Task Order 1, Sacramento, CA, USA. 82 p.
- Hyde, D.W. 1988. *Microcomputer Programs CONWEP and FUNPRO, Applications of TM 5-855-1, 'Fundamentals of Protective Design for Conventional Weapons' (User's Guide)*. <https://apps.dtic.mil/sti/pdfs/ADA195867.pdf>.
- Hyde, D.W. 1992. *Conventional weapons effect computer program, US Waterways Experiment Station*. Document Instructional Report SL-88-1. US Army Corps of Engineers.
- Illingworth & Rodkin, Inc. 2007. Appendix I. Compendium of pile driving sound data. In *Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish*. Illingworth & Rodkin, Inc. for the California Department of Transportation, Sacramento, CA. p. 129. [www.dot.ca.gov/hq/env/bio/files/pile\\_driving\\_snd\\_comp9\\_27\\_07.pdf](http://www.dot.ca.gov/hq/env/bio/files/pile_driving_snd_comp9_27_07.pdf).
- Illingworth & Rodkin, Inc. 2013. *Naval Base Kitsap at Bangor Trident Support Facilities Explosive Handling Wharf (EHW-2) Project: Acoustic Monitoring Report*. Report by Illingworth & Rodkin, Inc. under contract with Hart Crowder for Navy Strategic Systems Programs, Bangor, USA. 165 p. [https://tethys.pnnl.gov/sites/default/files/publications/Reyff\\_Bangor\\_Pile\\_Driving\\_Sound\\_Monitoring\\_2013.pdf](https://tethys.pnnl.gov/sites/default/files/publications/Reyff_Bangor_Pile_Driving_Sound_Monitoring_2013.pdf).
- Illingworth & Rodkin, Inc. 2017. *Pile-Driving Noise Measurements at Atlantic Fleet Naval Installations: 28 May 2013–28 April 2016*. Final report by Illingworth & Rodkin, Inc. under contract with HDR Environmental for Naval Facilities Engineering Command Atlantic. 152 p. [https://www.navy.mariesthespeciesmonitoring.us/files/4814/9089/8563/Pile-driving\\_Noise\\_Measurements\\_Final\\_Report\\_12Jan2017.pdf](https://www.navy.mariesthespeciesmonitoring.us/files/4814/9089/8563/Pile-driving_Noise_Measurements_Final_Report_12Jan2017.pdf).
- Ireland, D.S., R. Rodrigues, D.W. Funk, W.R. Koski, and D.E. Hannay. 2009. *Marine mammal monitoring and mitigation during open water seismic exploration by Shell Offshore Inc. in the Chukchi and Beaufort Seas, July–October 2008: 90-Day Report*. Document P1049-1. 277 p.
- Kanu, C.O. 2023. *Construction of the Steensby Inlet Dock Railway Underwater Noise Modelling Report: Freshwater Locations. Document 03250, Version 2.0* Technical Report by JASCO Applied Sciences for WSP.
- Kastak, D. and R.J. Schusterman. 1998. Low-frequency amphibious hearing in pinnipeds: Methods, measurements, noise, and ecology. *Journal of the Acoustical Society of America* 103(4): 2216–2228. <https://doi.org/10.1121/1.421367>.
- Kastelein, R.A., R. van Schie, W.C. Verboom, and D. de Haan. 2005. Underwater hearing sensitivity of a male and a female Steller sea lion (*Eumetopias jubatus*). *Journal of the Acoustical Society of America* 118(3): 1820–1829. <https://doi.org/10.1121/1.1992650>.
- Ladich, F. and A.N. Popper. 2004. Parallel evolution in fish hearing organs. In Manley, G.A., A.N. Popper, and R.R. Fay (eds.). *Evolution of the Vertebrate Auditory System*. Volume 22. Springer-Verlag, New York. pp. 95–127. [https://doi.org/10.1007/978-1-4419-8957-4\\_4](https://doi.org/10.1007/978-1-4419-8957-4_4).
- Lucke, K., U. Siebert, P.A. Lepper, and M.-A. Blanchet. 2009. Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. *Journal of the Acoustical Society of America* 125(6): 4060–4070. <https://doi.org/10.1121/1.3117443>.
- MacGillivray, A.O. and N.R. Chapman. 2012. Modeling underwater sound propagation from an airgun array using the parabolic equation method. *Canadian Acoustics* 40(1): 19–25. <https://jcaa.caa-aca.ca/index.php/jcaa/article/view/2502/2251>.
- MacGillivray, A.O. 2014. A model for underwater sound levels generated by marine impact pile driving. *Proceedings of Meetings on Acoustics* 20(1). <https://doi.org/10.1121/2.0000030>.
- Malme, C.I., P.R. Miles, C.W. Clark, P.L. Tyack, and J.E. Bird. 1983. *Investigations of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Migrating Gray Whale Behavior. Final Report for the Period of 7 June 1982 - 31 July 1983*. Report 5366. Report by Bolt Beranek and Newman Inc. for the US Department of the Interior and Minerals Management Service (Alaska OCS Office), Cambridge, MA, USA. <https://www.boem.gov/sites/default/files/boem-newsroom/Library/Publications/1983/rpt5366.pdf>.
- Malme, C.I., P.R. Miles, C.W. Clark, P.L. Tyack, and J.E. Bird. 1984. *Investigations of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Migrating Gray Whale Behavior. Phase II: January 1984 Migration*. Report 5586. Report by Bolt Beranek and Newman Inc. for the US Department of the Interior and Minerals Management Service (Alaska OCS Office), Cambridge, MA, USA. <https://www.boem.gov/sites/default/files/boem-newsroom/Library/Publications/1983/rpt5586.pdf>.
- Malme, C.I., B. Würsig, J.E. Bird, and P.L. Tyack. 1986. *Behavioral responses of gray whales to industrial noise: Feeding observations and predictive modeling*. Document 56. NOAA Outer Continental Shelf Environmental Assessment Program. Final Reports of Principal Investigators. 393–600 p.
- Moore, P.W.B. and R.J. Schusterman. 1987. Audiometric assessment of northern fur seals, *Callorhinus ursinus*. *Marine Mammal Science* 3(1): 31–53. <https://doi.org/10.1111/j.1748-7692.1987.tb00150.x>.



- Mueller-Blenkle, C., P.K. McGregor, A.B. Gill, M.H. Andersson, J. Metcalfe, V. Bendall, P. Sigray, D.T. Wood, and F. Thomsen. 2010. *Effects of Pile-driving Noise on the Behaviour of Marine Fish*. COWRIE Ref: Fish 06-08; Cefas Ref: C3371. 62 p. <https://dspace.lib.cranfield.ac.uk/handle/1826/8235>.
- Mulsow, J.L. and C.J. Reichmuth. 2007. Electrophysiological assessment of temporal resolution in pinnipeds. *Aquatic Mammals* 33(1): 122–131. <https://doi.org/10.1578/AM.33.1.2007.122>.
- Mulsow, J.L., J.J. Finneran, and D.S. Houser. 2011a. California sea lion (*Zalophus californianus*) aerial hearing sensitivity measured using auditory steady-state response and psychophysical methods. *Journal of the Acoustical Society of America* 129(4): 2298–2306. <https://doi.org/10.1121/1.3552882>.
- Mulsow, J.L., C.J. Reichmuth, F.M.D. Gulland, D.A.S. Rosen, and J.J. Finneran. 2011b. Aerial audiograms of several California sea lions (*Zalophus californianus*) and Steller sea lions (*Eumetopias jubatus*) measured using single and multiple simultaneous auditory steady-state response methods. *Journal of Experimental Biology* 214: 1138–1147. <https://doi.org/10.1242/jeb.052837>.
- Nedwell, J.R. and A.W.H. Turnpenny. 1998. The use of a generic frequency weighting scale in estimating environmental effect. *Workshop on Seismics and Marine Mammals*. 23–25 Jun 1998, London, UK.
- Nedwell, J.R., A.W.H. Turnpenny, J. Lovell, S.J. Parvin, R. Workman, J.A.L. Spinks, and D. Howell. 2007. *A validation of the dB<sub>ht</sub> as a measure of the behavioural and auditory effects of underwater noise*. Document 534R1231 Report by Subacoustech Ltd. for Chevron Ltd, TotalFinaElf Exploration UK PLC, Department of Business, Enterprise and Regulatory Reform, Shell UK Exploration and Production Ltd, The Industry Technology Facilitator, Joint Nature Conservation Committee, and The UK Ministry of Defence. 74 p. <https://tethys.pnnl.gov/sites/default/files/publications/Nedwell-et-al-2007.pdf>.
- NOAA Fisheries. 2019. *Marine Mammal Acoustic Thresholds* (web page). [https://archive.fisheries.noaa.gov/wcr/protected\\_species/marine\\_mammals/threshold\\_guidance.html](https://archive.fisheries.noaa.gov/wcr/protected_species/marine_mammals/threshold_guidance.html).
- NOAA Fisheries. 2024. *ESA Section 7 Consultation Tools for Marine Mammals on the West Coast* (web page), 30 Jan 2024. <https://www.fisheries.noaa.gov/west-coast/endangered-species-conservation/esa-section-7-consultation-tools-marine-mammals-west>.
- O'Neill, C., D. Leary, and A. McCrodon. 2010. Sound Source Verification. (Chapter 3) In Blees, M.K., K.G. Hartin, D.S. Ireland, and D.E. Hannay (eds.). *Marine mammal monitoring and mitigation during open water seismic exploration by Statoil USA E&P Inc. in the Chukchi Sea, August-October 2010: 90-day report*. LGL Report P1112-1. Technical report by LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Applied Sciences Ltd. for Statoil USA E&P Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. pp. 1–34.
- Payne, R. and D. Webb. 1971. Orientation by means of long range acoustic signaling in baleen whales. *Annals of the New York Academy of Sciences* 188: 110–141. <https://doi.org/10.1111/j.1749-6632.1971.tb13093.x>.
- Pile Dynamics, Inc. 2010. GRLWEAP. <https://www.pile.com/>.
- Popper, A.N. 2003. Effects of Anthropogenic Sounds on Fishes. *Fisheries Magazine* 28(10): 24–31. [https://doi.org/10.1577/1548-8446\(2003\)28\[24:EOASOF\]2.0.CO;2](https://doi.org/10.1577/1548-8446(2003)28[24:EOASOF]2.0.CO;2).
- Popper, A.N., R.R. Fay, C. Platt, and O. Sand. 2003. Sound detection mechanisms and capabilities of teleost fishes. In Collin, S.P. and N.J. Marshall (eds.). *Sensory Processing in Aquatic Environments*. Springer-Verlag, New York. pp. 3–38. [https://doi.org/10.1007/978-0-387-22628-6\\_1](https://doi.org/10.1007/978-0-387-22628-6_1).
- Popper, A.N., A.D. Hawkins, R.R. Fay, D.A. Mann, S. Bartol, T.J. Carlson, S. Coombs, W.T. Ellison, R.L. Gentry, et al. 2014. *Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI*. ASA S3/SC1.4 TR-2014. SpringerBriefs in Oceanography. ASA Press and Springer. <https://doi.org/10.1007/978-3-319-06659-2>.
- Porter, M.B. and Y.C. Liu. 1994. Finite-element ray tracing. In: Lee, D. and M.H. Schultz (eds.). *International Conference on Theoretical and Computational Acoustics*. Volume 2. World Scientific Publishing Co. pp. 947–956.
- Quijano, J.E. and M.E. Austin. 2024. *Baffinland Acoustic Modelling for Construction of Steensby Inlet Dock; Airborne Noise for Piling and Blasting*. Document 03389, Version 1.0. Technical report by JASCO Applied Sciences for WSP.
- Richardson, W.J., C.R. Greene, Jr., W.R. Koski, C.I. Malme, G.W. Miller, and M.A. Smultea. 1990. *Acoustic effects of oil production activities on bowhead and white whales visible during spring migration near Pt. Barrow, Alaska—1989 phase*. OCS Study MMS 90-0017, NTIS PB91-105486. Report by LGL Ltd, Herndon, VA. 284 p.
- Schusterman, R.J., R.F. Balliet, and J. Nixon. 1972. Underwater audiogram of the California sea lion by the conditioned vocalization technique. *Journal of the Experimental Analysis of Behavior* 17(3): 339–350. <https://doi.org/10.1901/jeab.1972.17-339>.
- Siderius, M. and M.B. Porter. 2006. Modeling techniques for marine-mammal risk assessment. *IEEE Journal of Oceanic Engineering* 31(1): 49–60. <https://doi.org/10.1109/JOE.2006.872211>.

- Southall, B.L., A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Greene, Jr., D. Kastak, D.R. Ketten, J.H. Miller, et al. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. *Aquatic Mammals* 33(4): 411–521. <https://doi.org/10.1578/AM.33.4.2007.411>.
- Southall, B.L., J.J. Finneran, C.J. Reichmuth, P.E. Nachtigall, D.R. Ketten, A.E. Bowles, W.T. Ellison, D.P. Nowacek, and P.L. Tyack. 2019. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. *Aquatic Mammals* 45(2): 125–232. <https://doi.org/10.1578/AM.45.2.2019.125>.
- Teague, W.J., M.J. Carron, and P.J. Hogan. 1990. A comparison between the Generalized Digital Environmental Model and Levitus climatologies. *Journal of Geophysical Research* 95(C5): 7167–7183. <https://doi.org/10.1029/JC095iC05p07167>.
- Warner, G.A., C. Erbe, and D.E. Hannay. 2010. Underwater Sound Measurements. (Chapter 3) In Reiser, C.M., D.W. Funk, R. Rodrigues, and D.E. Hannay (eds.). *Marine Mammal Monitoring and Mitigation during Open Water Shallow Hazards and Site Clearance Surveys by Shell Offshore Inc. in the Alaskan Chukchi Sea, July-October 2009: 90-Day Report*. LGL Report P1112-1. Report by LGL Alaska Research Associates Inc. and JASCO Applied Sciences for Shell Offshore Inc., National Marine Fisheries Service (US), and Fish and Wildlife Service (US). pp. 1–54.
- Wood, J.D., B.L. Southall, and D.J. Tollit. 2012. *PG&E offshore 3-D Seismic Survey Project Environmental Impact Report—Marine Mammal Technical Draft Report*. Report by SMRU Ltd. 121 p. <https://www.coastal.ca.gov/energy/seismic/mm-technical-report-EIR.pdf>.
- Zhang, Z.Y. and C.T. Tindle. 1995. Improved equivalent fluid approximations for a low shear speed ocean bottom. *Journal of the Acoustical Society of America* 98(6): 3391–3396. <https://doi.org/10.1121/1.413789>.

## Appendix A. Underwater Acoustics Metrics

Underwater sound pressure amplitude is quantified in decibels (dB) relative to a fixed reference pressure of  $p_0 = 1 \mu\text{Pa}$ . 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 commonly used to evaluate sound and its effects on marine life. Here we provide specific definitions of relevant metrics used in the accompanying report. Where possible, we follow International Organization for Standardization definitions and symbols for sound metrics (e.g., ISO 18405:2017, ANSI S1.1-2013).

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

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

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 sound pressure level (SPL or  $L_p$ ; dB re  $1 \mu\text{Pa}$ ) is the root-mean-square (rms) pressure level in a stated frequency band over a specified time window ( $T$ ; s):

$$L_p = 10 \log_{10} \frac{p_{rms}^2}{p_0^2} = 10 \log_{10} \left( \frac{1}{T} \int_T p^2(t) dt / p_0^2 \right). \quad (\text{A-2})$$

It is important to note that SPL always refers to an rms pressure level (i.e., a quadratic mean over a time interval) and therefore not instantaneous pressure at a fixed point in time. The SPL can also be defined as the *mean-square* pressure level, given in decibels relative to a reference value of  $1 \mu\text{Pa}^2$  (i.e., in dB re  $1 \mu\text{Pa}^2$ ). The two definitions of SPL are numerically equivalent, differing only in reference value.

The SPL can also be calculated using a time weighting function,  $g(t)$ :

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

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 (e.g., from pile driving or seismic airguns), 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 ( $L_{p,90}$ ).

The sound exposure level (SEL or  $L_E$ ; dB re  $1 \mu\text{Pa}^2 \text{ s}$ ) is the time-integral of the squared acoustic pressure over a duration ( $T$ ):

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

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, the SEL can be computed by summing (in linear units) the SEL of the  $N$  individual events:

$$L_{E,N} = 10 \log_{10} \left( \sum_{i=1}^N 10^{\frac{L_{E,i}}{10}} \right) . \quad (\text{A-5})$$

Because the SPL and SEL are both computed from the integral of square pressure, these metrics are related numerically by the following expression, which depends only on the duration of the time window  $T$ :

$$L_p = L_E - 10 \log_{10}(T) . \quad (\text{A-6})$$

Likewise, the SPL( $T_{90}$ ) and SEL metrics are related by:

$$L_{p,90} = L_E - 10 \log_{10}(T_{90}) - 0.458 , \quad (\text{A-7})$$

where the 0.458 dB factor accounts for the 10 % of pulse SEL missing from the SPL( $T_{90}$ ) integration time window.

If applied, the frequency weighting of an acoustic event is always specified, as in the case of weighted SEL (e.g.,  $L_{E,LF,24h}$ ; see Appendix B.3) or auditory-weighted SPL ( $L_{p,ht}$ ).

Underwater sound amplitude is generally measured in decibels (dB) relative to a fixed reference pressure of  $p_0 = 1 \mu\text{Pa}$ . Underwater sound from blasting operations, however, is commonly characterized by the peak pressure expressed in kilopascals (kPa) or peak particle velocity (m/s). The peak pressure ( $p_{pk}$ ) is the maximum instantaneous sound pressure measured over the length of the waveform that results from an acoustic event:

$$p_{pk} = \max|p(t)| , \quad (\text{A-8})$$

where  $p(t)$  is the instantaneous sound pressure as a function of time.

## 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 1 Hz width, however, does not represent how animals perceive sound.

Animals perceive exponential increases in frequency rather than linear increases, so 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 one tenth of 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 of 10 in sound frequency; each octave represents a factor of 2 in sound frequency. The center frequency of the  $i$ th decidecade band,  $f_c(i)$ , is defined as:

$$f_c(i) = (1 \text{ kHz})10^{\frac{i}{10}} \quad (1)$$

and the low ( $f_{lo}$ ) and high ( $f_{hi}$ ) frequency limits of the  $i$ th band are defined as:

$$f_{lo,i} = 10^{\frac{-1}{20}} f_c(i) \quad \text{and} \quad f_{hi,i} = 10^{\frac{1}{20}} f_c(i) \quad (2)$$

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure A-1).

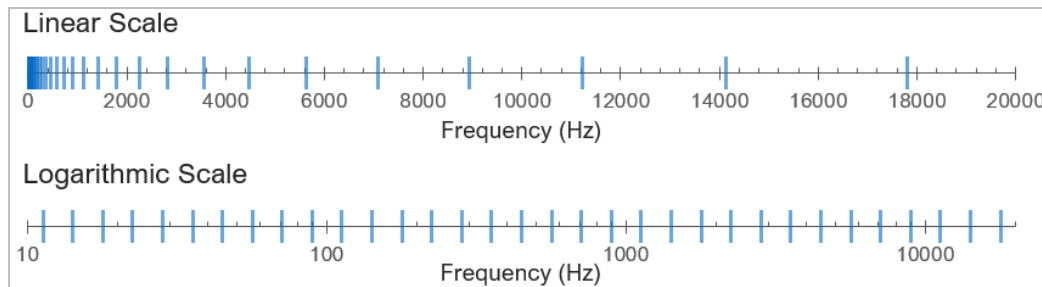


Figure A-1. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale



## Appendix B. Impact Criteria

### B.1. 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 auditory injury (Appendix B.1.1) and disturbance (Appendix B.1.2). The following sections summarize the development of the current thresholds relevant to this study; this remains an active research topic, however.

#### B.1.1. Auditory Injury Criteria

The NMFS SPL criteria for auditory 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 auditory injury thresholds of 190 dB re 1  $\mu$ Pa SPL for pinnipeds and 180 dB re 1  $\mu$ Pa SPL for cetaceans, for all types of sound sources except tactical sonar and explosives (NMFS 2018). These auditory 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)<sup>1</sup>  $L_{eq}$ ). 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 auditory 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 auditory injury criteria for impulsive sounds that included peak pressure level thresholds and SEL<sub>24h</sub> thresholds, where the subscripted 24h refers to the accumulation period for calculating SEL. The peak pressure level criterion is not frequency weighted, whereas SEL<sub>24h</sub> 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 (PW)<sup>2</sup>. Southall et al. (2007) referred to these weighting functions as M-weighting filters (analogous to the A-weighting filter for

---

<sup>1</sup> The “A” refers to a specific frequency-dependent filter shaped according to a human equal loudness contour.

<sup>2</sup> Pinnipeds in air were also included but are not applicable here.

humans; see Appendix B.3). 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 values for LF cetaceans and HF cetaceans while retaining the filter shapes (see Appendix B.3). 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 cetaceans of 179 dB re 1  $\mu Pa^2$  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  $\mu Pa^2$  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<sup>3</sup> to update weighting functions and auditory 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).

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 auditory 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- and high-frequency cetaceans groups from NMFS (2018) were renamed high- and very high-frequency cetaceans, respectively, in Southall et al. (2019). This report uses the hearing group names from NMFS (2018) for consistency with other projects. Table B-1 provides the recommended thresholds.

---

<sup>3</sup> An equal-loudness contour is the measured sound pressure level (dB re 1  $\mu Pa$  for underwater sounds) over frequency, for which a listener perceives a constant loudness when exposed to pure tones.

Table B-1. Sound pressure level (SPL; dB re 1  $\mu$ Pa), peak sound pressure level (PK; dB re 1  $\mu$ Pa), and sound exposure level (SEL; dB re 1  $\mu$ Pa<sup>2</sup>s) thresholds for behavioural disturbance, auditory injury (PTS onset), and TTS onset for marine mammals for impulsive sounds, as proposed by NMFS (2013, 2018).

Hearing group	Behaviour <sup>1</sup>	Auditory injury <sup>2</sup> (PTS)		TTS <sup>2</sup>	
	SPL	Weighted SEL <sub>24h</sub>	PK	Weighted SEL <sub>24h</sub>	PK
Low-frequency cetaceans	160	183	219	168	213
Mid-frequency cetaceans		185	230	170	224
High-frequency cetaceans		155	202	140	196
Sirenians		190	226	175	220
Otariid pinnipeds in water		203	232	188	226
Phocid pinnipeds in water		185	218	170	212

<sup>1</sup> NMFS (2013), <sup>2</sup> NMFS (2018)

### B.1.2. Disturbance Criteria

For non-impulsive sound, the US National Marine Fisheries Service (NMFS) currently uses a step function (all-or-none) threshold of 120 dB re 1  $\mu$ Pa SPL<sup>4</sup> (i.e., a sound pressure-based metric) to assess and regulate noise-induced behavioural impacts of non-impulsive underwater sounds on marine mammals (NOAA 2024). The 120 dB re 1  $\mu$ Pa SPL threshold for non-impulsive sounds was derived from studies by Malme et al. (1983, 1984, 1986) examining behavioural responses of migrating grey whales (*Eschrichtius robustus*) to drilling and dredging noise (NOAA 2018). Malme et al. (1984) determined that measurable reactions usually consisted of rather subtle short-term changes in speed and/or heading of the whale(s) under observation. Malme et al. (1986) found that playback of drillship noise did not produce clear evidence of disturbance or avoidance for levels below 110 dB re 1  $\mu$ Pa (SPL); avoidance possibly occurred for exposure levels approaching 119 dB re 1  $\mu$ Pa (SPL). A later study by Richardson et al. (1990) on migrating bowhead whales (*Balaena mysticetus*) generally supports their findings.

For impulsive noise, NMFS currently uses step function thresholds of 160 dB re 1  $\mu$ Pa SPL (unweighted) to assess and regulate noise-induced behavioural impacts for marine mammals (NMFS 2018, NOAA 2024). The threshold for impulsive sound is derived from the High-Energy Seismic Survey (HESS) panel (HESS 1999) report that, in turn, is based on the responses of migrating mysticete whales to airgun sounds (Malme et al. 1984). The HESS team recognized that behavioural responses to sound may occur at lower levels, but significant responses were only likely to occur above an SPL of 140 dB re 1  $\mu$ Pa. Southall et al. (2007) found varying responses for most marine mammals between an SPL of 140 and 180 dB re 1  $\mu$ Pa, consistent with the HESS (1999) report, but lack of convergence in the data prevented them from suggesting explicit step functions.

Because of the complexity and variability of marine mammal behavioural responses to acoustic exposure, NMFS has not yet released technical guidance on behaviour thresholds for use in calculating animal exposures (NMFS 2018).

<sup>4</sup> Unweighted; different auditory frequency weighting functions are applied to auditory impact thresholds to represent the differences in hearing sensitivities between different functional hearing groups (see NMFS 2018).

## B.2. Fish

Fish have all of the basic acoustic processing capabilities of other vertebrates (see review by Popper et al. 2003, Ladich and Popper 2004). Fish can discriminate between sounds of different magnitudes or frequencies, detect specific sounds when other signals are present, and determine the direction of a sound source. Their auditory systems differ, however, from those of marine mammals.

The pressure component of sound is represented by sound waves, which are characterized by the medium compressing and expanding as sound energy moves through it. At the same time, the particles that form the medium move back and forth (particle motion). All fish directly sense the particle motion component of sound (Fay 1984), although relatively few fish sense both the particle and pressure components (Popper et al. 2003). The ears of all fish consist of otolith- (or otoconia-) containing end organs that function as inertial accelerometers. Fish that sense pressure have additional morphological adaptations that allow them to detect acoustic pressure (e.g., Popper et al. 2003). In these fish, gas-filled bladders such as the swim bladder, which is near the ear, or mechanical connections such as Weberian ossicles, which are between the gas-filled bladder and the ear, convey sound pressure from the water to the ear when pressure deforms the bladder.

Most fish detect only particle motion, not pressure, and their hearing frequency range is typically limited to frequencies below 1 kHz. Pressure-sensing fish tend to have extended hearing bandwidth and lower detection thresholds. They are often capable of detecting signals up to 3–4 kHz, with thresholds that may be 20 dB or more lower than for fish that are not sensitive to pressure (Hastings and Popper 2005). Several fish taxonomic groups contain fish that can sense pressure, but this feature is not used to allocate fish into groups. Hearing abilities have been determined for relatively few (~100) of the more than 27,000 extant fish species (see Fay 1988, Popper et al. 2003). Hearing capabilities between different species, especially those that are taxonomically or geographically distant, must be extrapolated with caution.

### B.2.1. Injury Criteria

In 2008, the Fisheries Hydroacoustic Working Group (FHWG), sponsored by NOAA, developed (dual) criteria for onset of injury to fish from impact hammering noise (FHWG 2008, Buehler et al. 2015). These dual criteria specify a peak pressure level threshold of 206 dB re 1  $\mu\text{Pa}$  and a size-dependent  $\text{SEL}_{24\text{h}}$  threshold. For fish weighing 2 g or more, the threshold is 187 dB re 1  $\mu\text{Pa}^2\text{s}$ , whereas for fish under 2 g it is 183 dB re 1  $\mu\text{Pa}^2\text{s}$ . The FHWG did not establish criteria for fish injury caused by vibratory pile driving or other types of sources.

An ANSI-accredited standards committee on the effects of sound on fish and turtles, sponsored by the Acoustical Society of America (Popper et al. 2014), was formed in 2006 to develop noise exposure criteria for fish and sea turtles based on work started by the FHWG (a NOAA panel). Similar to the FHWG criteria, the ANSI guidelines also recommend peak pressure level and SEL thresholds, both without frequency weighting. They specify that SEL be integrated over 24 h or the duration of the activity, whichever is less.

Popper et al. (2014) categorized fish into three groups based on their hearing capabilities<sup>5</sup>, which are determined by whether a swim bladder is present and is directly involved in hearing. The categories are: (i) fish without a swim bladder, (ii) fish with a swim bladder not involved in hearing, and (iii) fish with a

---

<sup>5</sup> The classification of fish into 'hearing specialist' or 'hearing generalist' refers to their hearing sensitivity. Thresholds to impact criteria were not developed on this system of classification. Bony fish with specializations that enhance their hearing sensitivity are called 'hearing specialists' whereas those that lack such capabilities are called 'hearing generalists' (non-specialists; Popper 2003, Ladich and Popper 2004). These specializations are not criteria for assigning fish to specific taxa; hearing specialists and generalists are distributed over many taxa.

swim bladder involved in hearing. Their report provides received sound levels based on the best available science that are suitable as provisional guidelines for assessing onset of injury to fish from various sources (Table B-2).

The best management practices for pile driving and related operations in British Columbia also requires that a 30 kPa threshold, equivalent to 210 dB re 1 µPa peak pressure level, be assessed (BCMPDCA and DFO 2003).

Table B-2. Fisheries Hydroacoustic Working Group (FHWG) mortality and impairment criteria for impact pile driving (Popper et al. 2014).

Fish group		Mortality and potential mortal injury		Impairment		
				Recoverable injury		Temporary threshold shift
		SEL (24 h) (dB re 1 µPa <sup>2</sup> s)	PK (dB re 1 µPa)	SEL (24 h) (dB re 1 µPa <sup>2</sup> s)	PK (dB re 1 µPa)	SEL (24 h) (dB re 1 µPa <sup>2</sup> s)
i	No swim bladder (particle motion detection)	>219	>213	>216	>213	>>186
ii	Swim bladder not involved in hearing (particle motion detection)	210	>207	203	>207	>>186
iii	Swim bladder involved in hearing (primary pressure detection)	207	>207	203	>207	186

## B.2.2. Disturbance Criteria

Fish disturbance thresholds are not well documented. NOAA advises using a 150 dB re 1 µPa (SPL) criterion to predict fish behavioural responses to impulsive sounds (Mueller-Blenkle et al. 2010, NMFS 2013, Illingworth & Rodkin 2013); however, the rationale for using this criterion is unclear (Popper et al. 2014).

## B.3. Marine Mammal Auditory Frequency Weighting

The potential for noise to affect animals of a certain species depends on how well the animals can hear it. Noises are less likely to disturb or injure an animal if they are at frequencies that the animal cannot hear well. An exception occurs when the sound pressure is so high that it can physically injure an animal by non-auditory means (i.e., barotrauma). For sound levels below such extremes, the importance of sound components at particular frequencies can be scaled by frequency weighting relevant to an animal's sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

In 2015, a US Navy technical report by Finneran (2015) recommended auditory weighting functions for marine mammals that are applied in a similar way as A-weighting for noise level assessments for humans in air. The 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). The 2016 updates did not affect the content related to either the definitions of the weighting functions or the threshold values. Table B-3 lists the frequency-weighting parameters for each hearing group. Figure B-1 shows the resulting frequency-weighting curves.

Table B-3. Parameters for the auditory weighting functions recommended by NMFS (2018).

Functional hearing group	$a$	$b$	$f_1$ (Hz)	$f_2$ (Hz)	$K^1$ (dB)
Low-frequency cetaceans	1.0	2	200	19,000	0.13
Mid-frequency cetaceans	1.6	2	8,800	110,000	1.20
High-frequency cetaceans	1.8	2	12,000	140,000	1.36
Phocid pinnipeds in water	1.0	2	1,900	30,000	0.75
Otariid pinnipeds in water	2.0	2	940	25,000	0.64

<sup>1</sup> In NMFS (2018), this constant is symbolized by  $C$ .

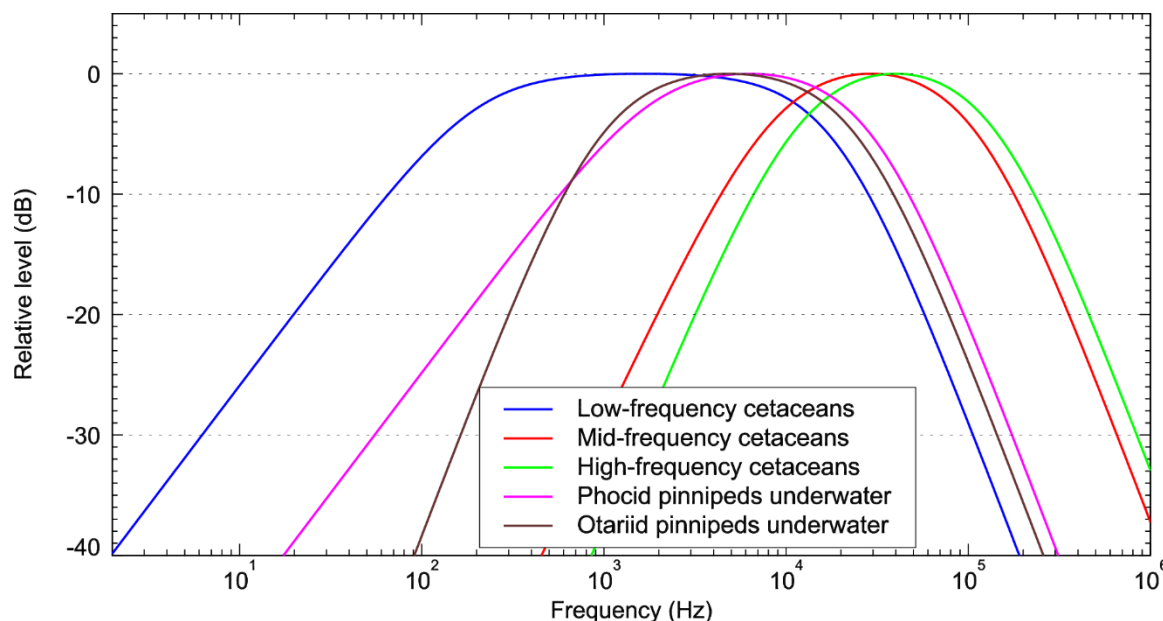


Figure B-1. Auditory weighting functions for the functional marine mammal hearing groups as recommended by NMFS (2018).

## Appendix C. Modelling Methodology and Parameters

### C.1. Pile Driving Source Model

A physical model of pile vibration and near-field sound radiation is used to calculate source levels of piles. The physical model employed in this study computes the underwater vibration and sound radiation of a pile by solving the theoretical equations of motion for axial and radial vibrations of a cylindrical shell. These equations of motion are solved subject to boundary conditions, which describe the forcing function of the hammer at the top of the pile and the soil resistance at the base of the pile (Figure C-1). Damping of the pile vibration due to radiation loading is computed for Mach waves emanating from the pile wall. The equations of motion are discretised using the finite difference (FD) method and are solved on a discrete time and depth mesh.

To model the sound emissions from the piles, the force of the pile driving hammers also had to be modelled. The force at the top of each pile was computed using the GRLWEAP 2010 wave equation model (GRLWEAP, Pile Dynamics 2010), which includes a large database of simulated hammers—both impact and vibratory—based on the manufacturer’s specifications. The forcing functions from GRLWEAP were used as inputs to the FD model to compute the resulting pile vibrations.

The sound radiating from the pile itself is simulated using a vertical array of discrete point sources. The point sources are centred on the pile axis. Their amplitudes are derived using an inverse technique, such that their collective particle velocity, calculated using a near-field wave-number integration model, matches the particle velocity in the water at the pile wall. The sound field propagating away from the vertical source array is then calculated using a time-domain acoustic propagation model (see Appendix C.3.2). MacGillivray (2014) describes the theory behind the physical model in more detail.

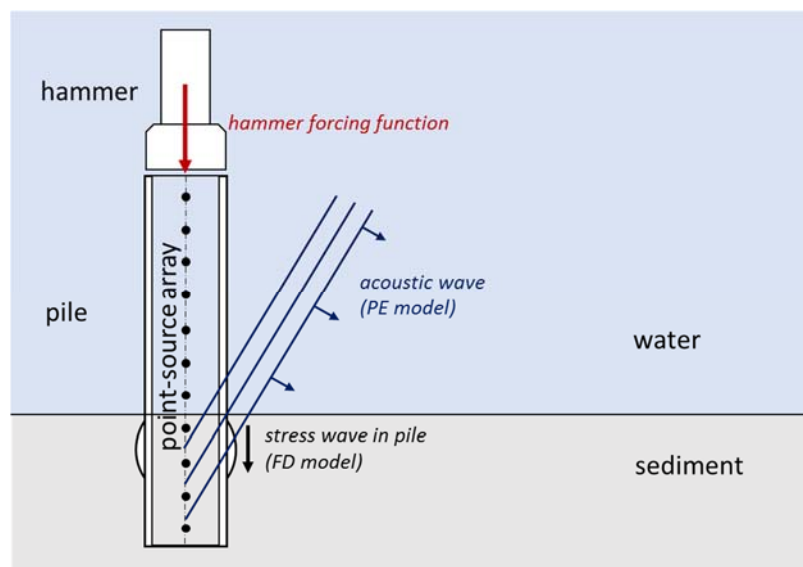


Figure C-1. Physical model geometry for impact driving of a cylindrical pile (vertical cross-section). The hammer forcing function is used with the finite difference (FD) model to compute the stress wave vibration in the pile. A vertical array of point sources is used with the parabolic equation (PE) model to compute the acoustic waves that the pile wall radiates.



## C.2. Blasting Source Model

Modelling detonation (shock) waves is challenging because the theory governing wave propagation close to a blast is non-linear because of the high pressures. Most modelling solutions use linear approximations of pressure wave propagation and consequently have limited accuracy close to the detonation. Still, these models can be accurate beyond a few metres from a confined blast, so they are suitable for biological effects assessments. Several empirical and numerical models can also be applied to predict sound pressure decay with distance from blasts. ConWep, a model based on empirical data, was used in this modelling to determine representative source levels for blasting that were appropriate to use as input to the FWRAM propagation model (Appendix C.3.2).

### C.2.1. Conventional Weapons Effects (ConWep) Model

The pressure wave from an explosive charge buried in a substrate, such as rock, can be modelled with Conventional Weapons Effects (ConWep; Hyde 1988, Hyde 1992). ConWep uses empirical equations and curves to model the effects from various conventional explosive weapons, including explosives detonated in bedrock. ConWep includes a database of the yield and detonation rates for several explosive compounds. In ground-shock mode, ConWep predicts the peak pressure and peak particle velocity at a chosen receiver range and depth in the substrate. The input parameters include the type of explosive, the charge weight, the geometry of the detonation (depth of the charge, distance to the receiver, and depth of the receiver in the substrate), and the geoacoustic parameters of the substrate (density, compressional-wave/P-wave speed, and attenuation coefficient). The model accommodates surface (unconfined), partially buried, and fully buried charges to accommodate source confinement. ConWep has more input parameters than the equations in Fisheries and Oceans Canada guidelines, and the model can be customized to a specific environment.

ConWep's Shockwave module was used to calculate the pressure wave that would be measured in-ground at distances specified by the Gaspin distance from the detonation point for each modelled charge size. These distances, as listed in Table C-1, were 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 was then 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.3.2). 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 calibrated by means of adjusting the attenuation factor to match received peak pressure levels at less than 500 m to lie along the empirical regression lines provided by measurements from Eagle River Flats, AK from the literature (Bowman et al. 2019). The Eagle River Flats measurements regression lines are derived from monitoring measurements of bedrock bottom blasting activity at distance of about 130 m from the Eagle River, with blasting buried at depths 3–6 m. Therefore, these measurements provide a suitable comparison for calibration. The value for the attenuation parameter in ConWep that provided the best match was 4.0 (see Figure C-2). 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.



Table C-1. Gaspin distance for modelled charge size.

Charge size (kg TNT)	Gaspin distance (m)
1	5
10	11
20	13
30	15
40	17
50	18
100	23

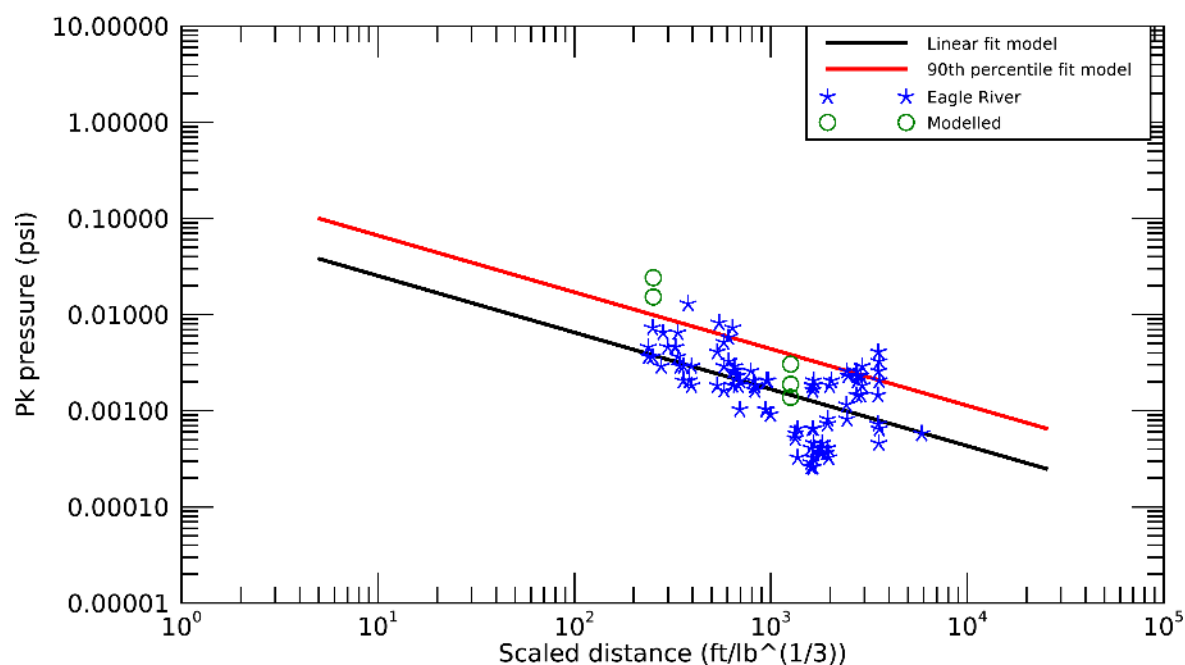


Figure C-2. *ConWep attenuation factor tuning*: Modelled peak sound pressure level (maximum-over-depth) for the 1 kg TNT charge, compared to regression functions provided by Eagle River Flats measurements. The attenuation factor value is 4.0.

Figure C-3 shows the source pressure waveforms for blasts of 1.0 kg and 100 kg TNT charges.

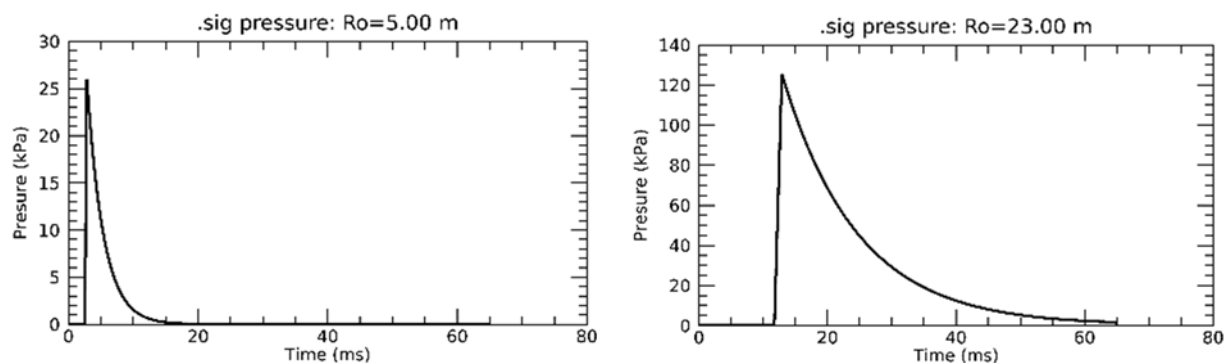


Figure C-3. Time-dependent pressure wave for underground detonations: (Left) 1 kg TNT charge and (right) 100 kg TNT charge.

### C.3. Sound Propagation Model

The sound field around a source can be estimated using two approaches: modeling in bands (Appendix C.3.1), usually in decidecade bands (Appendix A.1), and full waveform modeling (Appendix C.3.2). In the decidecade band modeling approach, the sound propagation modeling is performed only for the central frequencies of each band. Here, 35 individual frequency modeling runs are required for covering the frequency range from 10 Hz to 25 kHz. For the full waveform approach, the propagation modeling must be performed for individual frequencies with a small (e.g., 1 Hz) constant step across the entire modeled frequency range.

The sound propagation models employed for this project are two-dimensional (2-D) acoustic propagation models. The calculations of the acoustic fields in three dimensions are achieved by propagating the acoustic field within 2-D vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as  $N \times 2$ -D. These vertical radial planes are separated by an angular step size of  $\Delta\theta$ , yielding  $N = 360^\circ / \Delta\theta$  number of planes (Figure C-4).

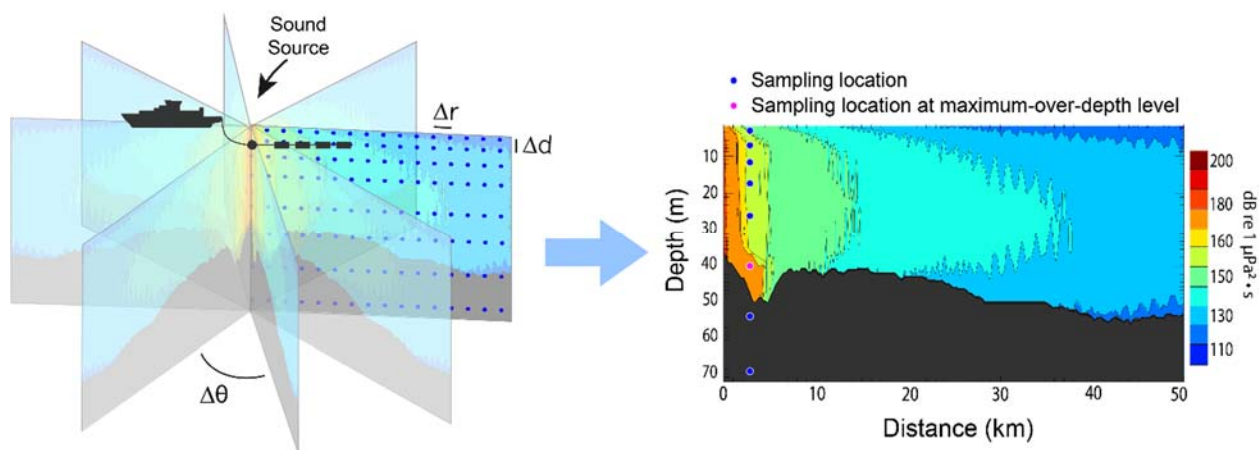


Figure C-4. The  $N \times 2$ -D and maximum-over-depth modeling approach.

The propagated sound field within each vertical radial plane is sampled at various ranges from the source, generally with a fixed radial step size ( $\Delta r$  in Figure C-4). At each sampling range along the surface, the sound field is sampled at various depths, with the step size between samples ( $\Delta d$  in Figure C-4) 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. The received acoustic levels 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 level. These maximum-over-depth acoustic levels are further used to calculate the ranges to specific thresholds and create acoustic field maps.

### C.3.1. Energy Propagation Loss Modeling using the Decidecade Band Approach

The propagation of sound through the environment can be modeled by predicting the acoustic propagation loss—a measure, in decibels, of the decrease in sound level between a source and a receiver some distance away. Geometric spreading of acoustic waves is the predominant way by which propagation loss occurs. Propagation loss also happens when the sound is absorbed and scattered by the seawater and absorbed, scattered, and reflected at the water surface and within the seabed. Propagation loss depends on the acoustic properties of the ocean and seabed; its value changes with frequency.

If the acoustic energy source level ( $L_{S,E}$ ), expressed in dB re 1  $\mu\text{Pa}^2\text{m}^2\text{s}$ , and energy propagation loss ( $N_{PL,E}$ ), in units of dB, at a given frequency are known, then the received level ( $L_{E,p}$ ) at a specific location can be calculated in dB re 1  $\mu\text{Pa}^2\text{s}$  by:

$$L_{E,p}(r) = L_{S,E} - N_{PL,E}(r), \quad (3)$$

where  $r$  is the range of the receiver from the source.

In the present study, JASCO's Marine Operations Noise Model (MONM) predicted propagation loss at decidecade band center frequencies from 10 to 25,000 Hz. MONM employs two underlying subroutines: MONM-RAM is used for propagating acoustic waves at low frequencies (e.g., up to 1600 Hz) and MONM-BELLHOP is used for high frequencies (e.g., above 1600 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 US 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 compressional wave attenuation 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 in addition to acoustic attenuation due to reflection at the medium boundaries and internal layers (Fisher and Simmons 1977). The former type of sound attenuation is 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, water column sound speed as a function of depth, as well as temperature and salinity for calculating the sound attenuation due to energy absorption, geoacoustic properties of the surficial sediments, and surface roughness (due to wind).

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).

### C.3.1.1. Range Averaging

The deficiency of the decidecade approach is the profound presence of spatial interference patterns in the propagation loss field specific to the single modeled frequency for the band. The propagation loss values calculated for each individual band are subject to range averaging that replaces frequency averaging (Harrison and Harrison 1995, Siderius and Porter 2006). The range averaging is performed by applying a Gaussian smoothing operator along the modelled radials at each depth slice separately. The Gaussian smoothing operator has variable width depending on the distance from the source. The width is calculated as a percentage of the range from the source, the “averaging coefficient”.

The range averaging technique compensates for the deficiencies of the band modeling approach and allows to achieve a better match of the propagation loss function calculated for single frequencies with the band average propagation loss calculated using 1-Hz step frequency propagation loss functions.

### C.3.1.2. Summing over Decidecade Bands

In a case where the source emits acoustic energy that spans across multiple frequency bands, such as with pile driving, the composite broadband received SEL can be computed by summing the received decidecade band levels (provided in dB units):

$$L_E = 10 \cdot \log_{10}(\sum_{i=1}^N 10^{L_{E,i}/(10\text{dB})}) \text{ dB} . \quad (4)$$

If frequency weighed SEL is required ( $L_{E,MW}$ ) for the impact assessment with criteria thresholds (see Appendix B), it can be obtained by adding the relative levels (MW) to the equation:

$$L_{E,MW} = 10 \cdot \log_{10}(\sum_{i=1}^N 10^{(L_{E,i}+MW_i)/(10\text{dB})}) \text{ dB} . \quad (5)$$

## C.3.2. Sound Propagation with FWRAM

In case a sound source can be defined using a time domain signature, a more comprehensive propagation modelling approach can be employed. For such sources JASCO uses Full-waveform modelling method (FWRAM), which is a time-domain acoustic model based on a wide-angle parabolic equation (PE).

FWRAM can handle a single source signature for a source represented by a monopole or more complex sources represented by multiple monopoles, each of which can have a unique source signature function. Examples of complex sources are multi-element seismic airgun array or a long pile defined as a distributed source.

FWRAM computes synthetic pressure waveforms versus range and depth for range-varying marine acoustic environments and takes environmental inputs (bathymetry, water sound speed profile, and seabed geoacoustic profile). computes pressure waveforms via Fourier synthesis of the modeled 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 are usually modeled over the frequency range from 10 to few kilohertz (typically 2 kHz), inside a 1 s window (e.g., Figure C-5.). The modelled synthetic pressure waveforms allow calculation of SEL as spectral density or in decidecade bands as well as direct calculation of SPL and  $L_{pk}$  signal metric versus range and depth from the source. If required, the acoustic field can be extrapolated to higher frequencies by applying a source specific decay rate estimated from acoustic measurements.

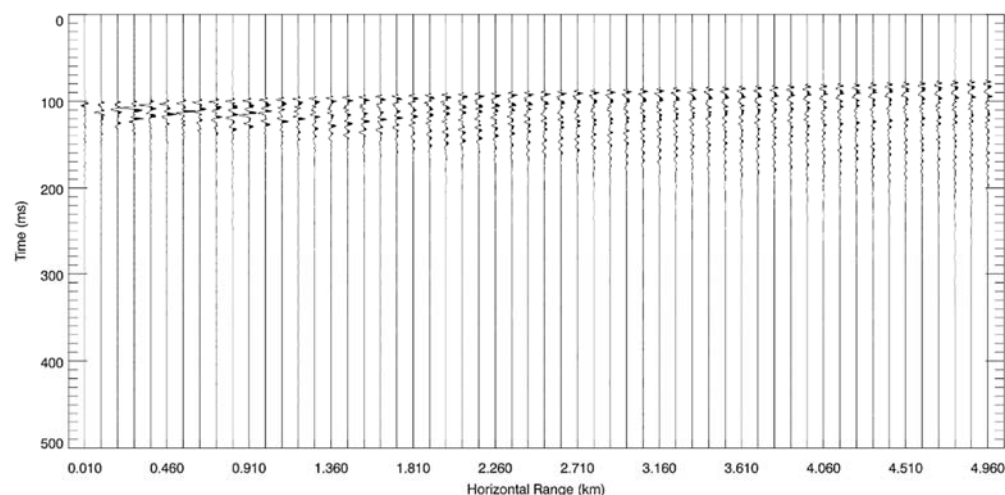


Figure C-5. Example of synthetic pressure waveforms computed by FWRAM at multiple range offsets. Receiver depth is 35 m and the amplitudes of the pressure traces have been normalized for display purposes.

## C.4. Estimating Ranges to Threshold Levels

Sound level contours were calculated based on the underwater sound fields predicted by the propagation models, sampled taking the maximum value over all modelled depths above the seafloor for each location in the modelled region. 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-6).

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-6a. 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 contrast, in strongly radially asymmetric cases such as shown in Figure C-6b,  $R_{95\%}$  neglects to account for substantial 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 that affect propagation. The difference between  $R_{\max}$  and  $R_{95\%}$  depends on the source directivity and the non-uniformity of the acoustic environment.

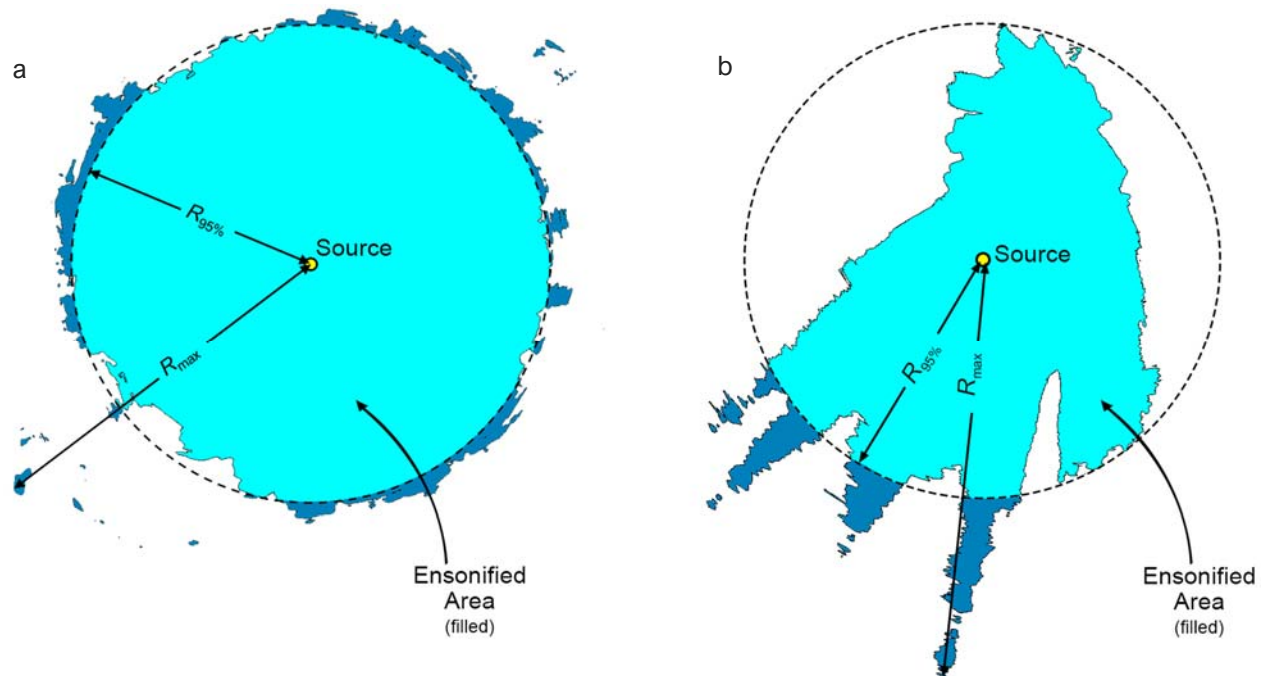


Figure C-6. Sample areas ensonified to an arbitrary sound level with  $R_{\max}$  and  $R_{95\%}$  ranges shown for two contrasting scenarios: (a) a largely radially symmetric sound level contour with small protrusions, for which  $R_{95\%}$  best represents the ensonified area; and (b) a strongly asymmetric sound level contour with long protrusions, for which  $R_{\max}$  best represents the ensonified areas in some directions. Light blue indicates the ensonified areas bounded by  $R_{95\%}$ ; darker blue indicates the ensonified areas beyond  $R_{95\%}$  that determine  $R_{\max}$ .

## C.1. Environmental Parameters

### C.1.1. Bathymetry

Bathymetry grid (Figure C-7) was compiled using client provided high-resolution sounding data with extension using GEBCO 2019 (IOC 2003) global grid data with nominal resolution of 15 arc seconds (~400–450 m).

The high-resolution data set coverage extended up to 9 km from the modelling site.

All construction activities considered in this modelling project are supposed to occur after the permanent and temporary in-fill is in place. The bathymetry grid was adjusted for the in-fill cone presence (Figure C-8) based on the in-fill footprint on the bottom (available from the engineering drawings) and the dock limits.



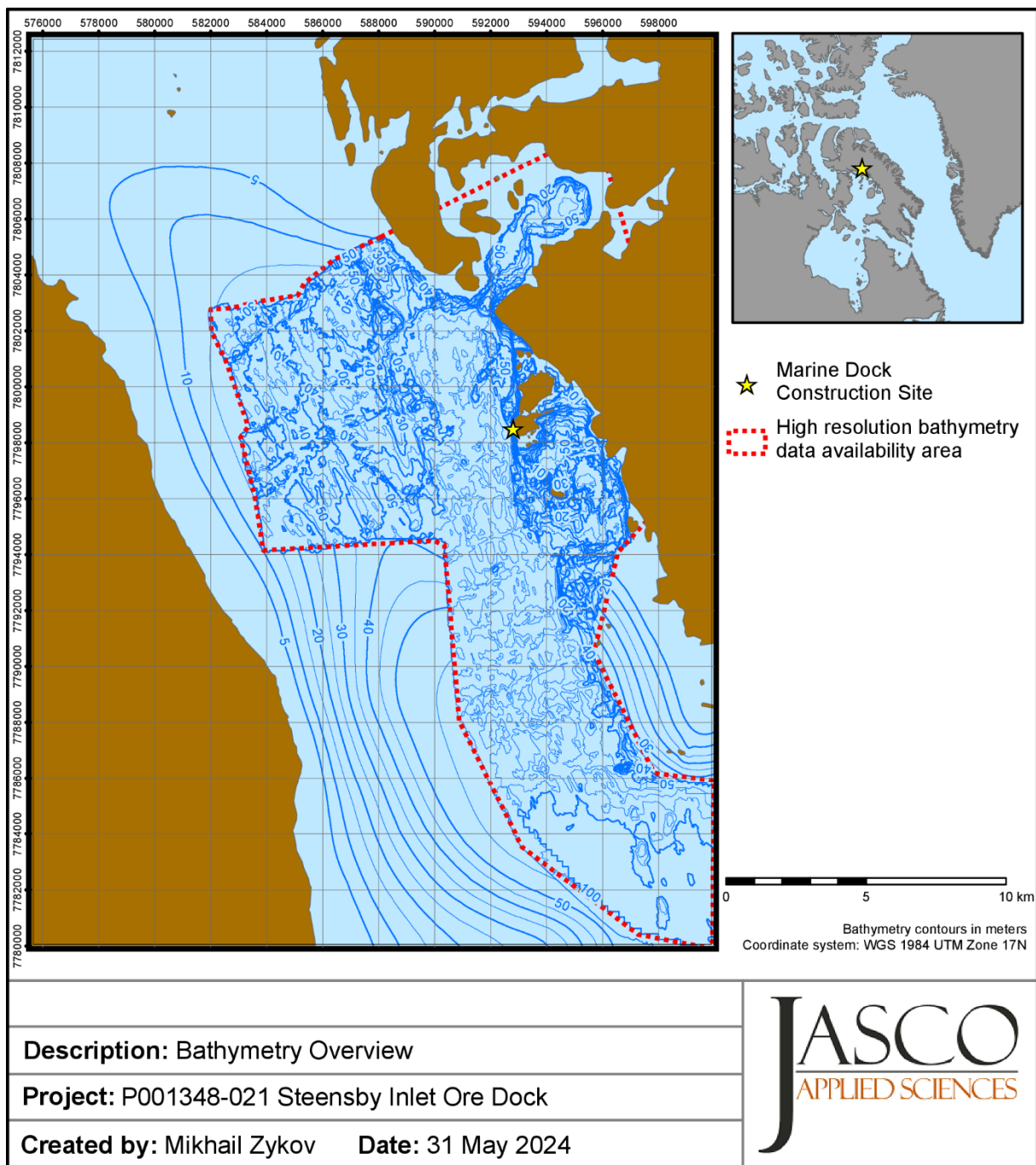


Figure C-7. Bathymetry map for the modelling area.

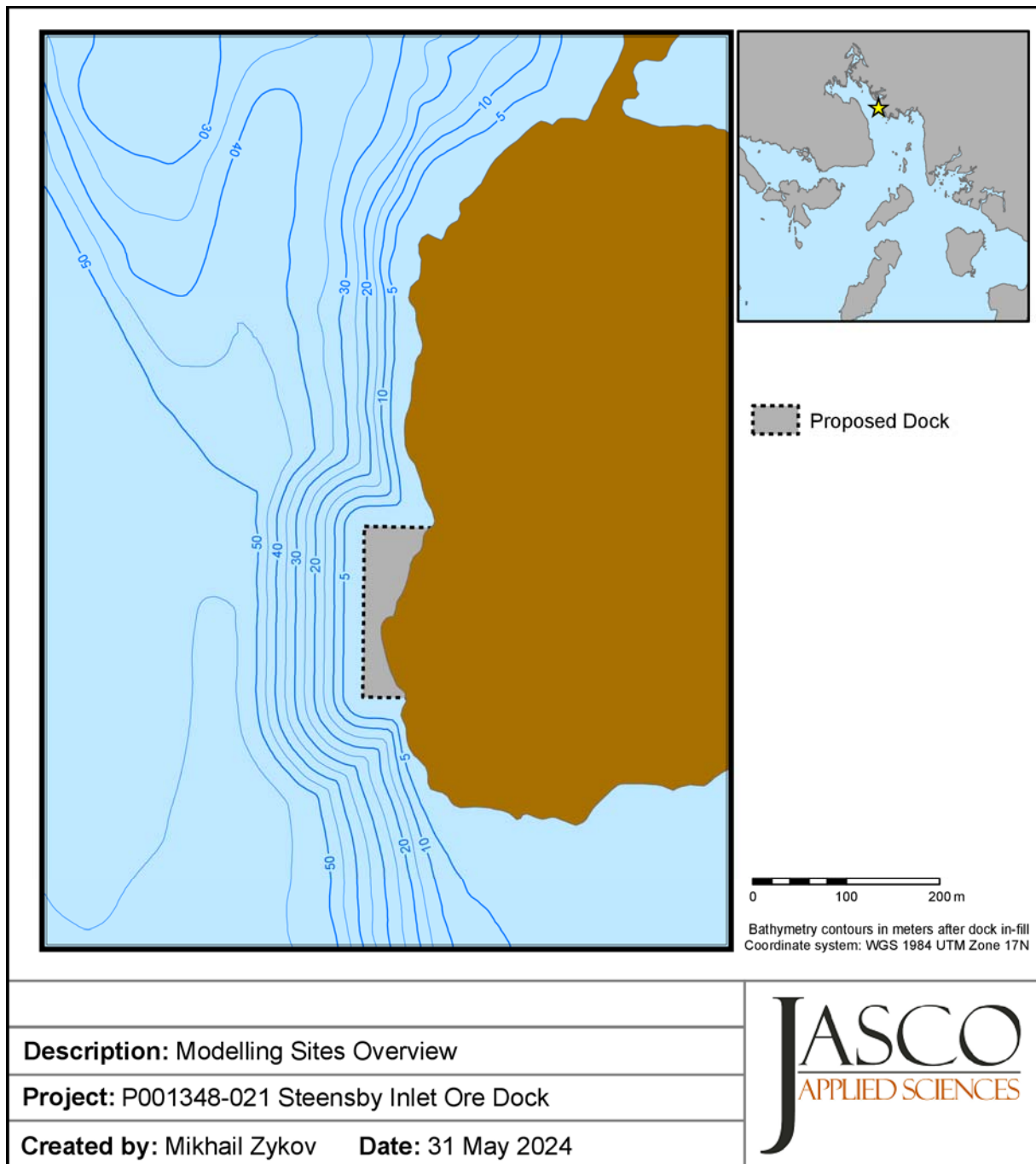


Figure C-8. Bathymetry around proposed dock with in-fill in place.



### C.1.2. Sound Speed Profiles

The sound speed profiles were derived using temperature and salinity profiles from the US 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 US 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).

Sensitivity analysis was completed to establish the most conservative month in terms of sound speed profile in the water column. It was found that the sound speed for August results in higher levels for the same distance, therefore the sound speed profile for August was used (Figure C-9).

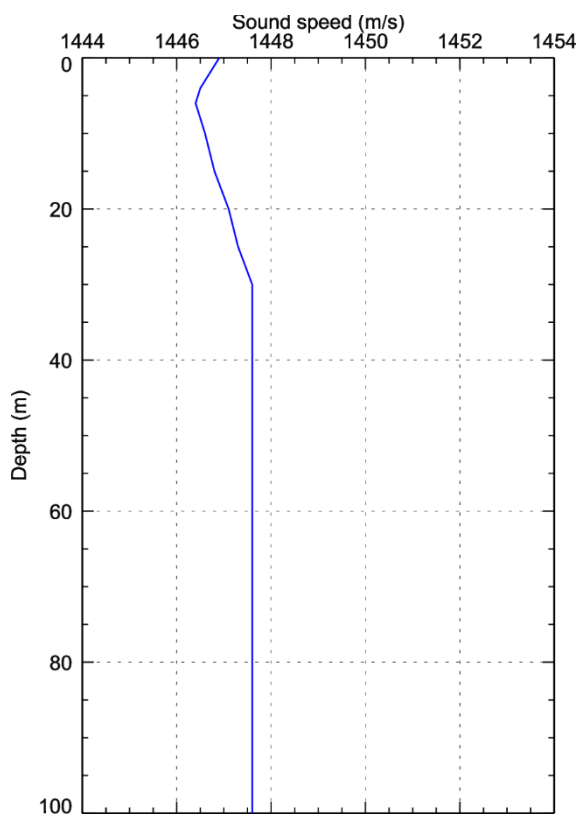


Figure C-9. Monthly average sound speed profile in the water column for August. Based on GDEM V 3.0 data at sampling location 69.5 °N 78.75 °W.

### C.1.3. Seabed Geoacoustic Profiles

The modelling sites were located either on top of the in-fill for the dock (Scenarios 1–4; Table 2) or on land (Scenarios 5–8; Table 2). Two geoacoustic profiles were designed, one for each group of scenarios.

The “combi-wall” geoacoustic profile (Table C-2) accounts for 23 m of the in-fill material (gravel) on top of the bedrock. The “on-land” geoacoustic profile (Table C-3) represents thin layer of a coarse unconsolidated sediment on top of the bedrock.

Table C-2. Seabed geoacoustic properties for sites at combi-wall. Within each depth range, each parameter varies linearly within the stated range. The compressional wave is the primary wave.

Depth below seafloor (m)	Material	Density (g/cm <sup>3</sup> )	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0–23	gravel (in-fill)	2.04–2.04	2100–2400	1.4–1.4	300	3.6
23–1000	bedrock	2.80–2.80	3300–4000	0.10–0.10		
>1000		2.8	4000	0.1		

Table C-3. Seabed geoacoustic properties for on-land sites. Within each depth range, each parameter varies linearly within the stated range. The compressional wave is the primary wave.

Depth below seafloor (m)	Material	Density (g/cm <sup>3</sup> )	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0–1	gravel (in-fill)	2.04–2.04	2100–2100	1.4–1.4	300	3.6
1–1000	bedrock	2.80–2.80	3300–4000	0.10–0.10		
>1000		2.8	4000	0.1		