Aurora LNG Acoustic Study

Modelling of Underwater Sounds from Pile Driving, Rock Socket Drilling, and LNG Carrier Berthing and Transiting

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Executive Summary

In compliance with the requirements of the British Columbia Environmental Assessment Act (British Columbia Government 2002) and the Canadian Environmental Assessment Act 2012 (Government of Canada 2012), JASCO Applied Sciences Ltd. under contract to Stantec Consulting Ltd and Nexen Energy ULC (Nexen) performed an underwater acoustic modelling study for the Aurora LNG project located on the southeast corner of Digby Island near Prince Rupert, British Columbia. Sound propagation models were applied to assess underwater noise exposure of marine mammals and fish during marine terminal construction activities consisting of impact pile driving with confined bubble curtain and rock socket drilling for pile installation, as well as noise exposure from marine traffic activities of LNG carrier berthing and transiting. These models include JASCO's Full Waveform Range-dependent Acoustic Model (FWRAM) and Marine Operations Noise Model (MONM). Both models accept as input the activity-specific spectral source levels, bathymetry, water sound speed profiles, and seabed geoacoustic parameters. JASCO's physical model of pile vibration and near-field sound radiation was used to predict the acoustic emission characteristics of the impact pile driving. The source levels for rock socket drilling and vessel activities were derived from published measurements. M-weighting and audiogram frequency weighting were applied to the modelled sound fields to estimate received levels relative to hearing thresholds of four marine mammal hearing groups and key species.

The goal of this study was to predict the extent of ensonification from modelling scenarios as described below and to define zones of potential effects on marine fauna based on currently adopted sound level thresholds for auditory injury and behavioural disturbance. The threshold criteria and results are summarized below.

- Marine mammal injury: Thresholds were based on Wood et al. (2012), Southall et al. (2007), and NMFS (2016b).
    - Impact pile driving with confined bubble curtains at the materials offloading facility (MOF) at Casey Cove and the LNG jetty at south Digby Island: The maximum distances to marine mammal peak pressure level injury thresholds were less than 0.01 km; maximum distances to 24-hr M-weighted species-specific injury thresholds were 0.2 km to 9.8 km depending on the marine mammal group; and maximum distances to 190 and 180 dB re 1 µPa SPL (rms) were 0.1 km and 0.4 km, respectively.
    - Rock socket drilling at the LNG jetty: The maximum distances to marine mammal injury criteria did not exceed 0.01 km from the pile.
    - LNG carrier berthing assisted by four tugs at the LNG jetty and transiting escorted by two tugs: The maximum distances to marine mammal injury criteria did not exceed 0.03 km from the vessel locations.
- Marine mammal disturbance: Thresholds were based on NMFS (2016b) SPL (rms) criteria, and species-specific dB_{ht} thresholds proposed by McCauley et al. (2000), Bailey et al. (2010), MacGillivray et al. (2012), and Tougaard et al. (2015).
    - Impact pile driving with confined bubble curtains at MOF and the LNG jetty sites: The maximum distance to NMFS-recommended 160 dB re 1 µPa SPL (rms) was 7.2 km and 4.0 km, respectively. The maximum distances to species-specific behavioural thresholds were between 1.4 km and 26.8 km depending on the marine mammal species and modelling scenario.
    - Rock socket drilling at the LNG jetty: The maximum distance to NMFS-recommended 120 dB re 1 µPa SPL (rms) was 5.8 km. The maximum distances to species-specific behavioural thresholds were between 0.2 km and 4.7 km depending on the marine mammal species.
    - LNG carrier berthing assisted by four tugs at the LNG jetty and transiting escorted by two tugs: Depending on the operation and site considered, the maximum distance to NMFS-recommended 120 dB re 1 µPa SPL (rms) was between 21.4 km and 23.3 km. The maximum distances to species-specific behavioural thresholds were between 5.3 and 51.5 km depending on the marine mammal species.

- Fish injury due to impact pile driving: The thresholds were based on Popper et al. (2014) as well as the 30 kPa threshold from the Best Management Practices for Pile Driving and Related Operations in British Columbia (BC MPDCA and DFO 2003). The maximum distance to fish peak pressure level injury thresholds was 0.03 km; maximum distances to 24-hr SEL injury thresholds were between less than 0.01 km and 9.0 km depending on the injury types and fish species.
- Local Assessment Area (LAA) for marine mammals using 160 dB re 1µPa SPL (rms) threshold for all acoustic sources. DFO has advised Aurora LNG that for the assessment of the Project, the LAA should be set to encompass the area where any Project activity (construction, operations, decommissioning) will exceed 160 dB (BC EAO [British Columbia Environmental Assessment Office] 2015).
    - Impact pile driving with confined bubble curtains at MOF and the LNG jetty sites: The maximum distances to 160 dB re 1 µPa were 7.2 km and 4.0 km, respectively.
    - Rock socket drilling at the LNG jetty: The maximum distance to 160 dB re 1 µPa was less than 0.01 km.
    - LNG carrier berthing assisted by four tugs at the LNG jetty and transiting escorted by two tugs: The maximum distance to 160 dB re 1 µPa was less than 0.2 km.
- The zones of audibility (ZOA) were calculated as the region over which activity sound levels exceeded both the hearing threshold and ambient noise levels in the same frequency bands.
    - Impact pile driving with confined bubble curtains at MOF and the LNG jetty sites: The maximum range to the edge of ZOA for all marine mammals and fish was 29.7 km.
    - Rock socket drilling at the LNG jetty: The maximum range to the edge of ZOA was 26.3 km for all marine mammals and for herring. It was slightly smaller for salmon, with a maximum of 21.2 km.
    - LNG carrier berthing assisted by four tugs at the LNG jetty and transiting escorted by two tugs: The maximum range to the edge of ZOA for all marine mammals and for herring extended beyond the bounds of the modelled area (~40 and ~65 km from the source for the berthing and transiting scenarios respectively). The range was smaller for salmon, with a maximum of 47.3 km for vessels transiting south of Triple Island.

1. Introduction

Nexen Energy ULC (Nexen), for and on behalf of Aurora LNG, a joint venture between Nexen Energy ULC and INPEX Gas British Columbia Ltd. or their respective affiliates, is proposing to construct and operate the Aurora Liquefied Natural Gas (LNG) Project (the Project), an LNG facility and marine terminal on the southeast corner of Digby Island near Prince Rupert, British Columbia. Ocean-going LNG carriers will export natural gas overseas from the LNG jetty. Once complete, the marine terminal expects to receive LNG carriers of up to Q-Flex size. Additionally, Nexen plans to build an offloading facility (MOF) in Casey Cove, located on the east side of Digby Island. Terminal construction and increased marine traffic will generate underwater noise that has the potential to affect local marine mammals and fish.

JASCO Applied Sciences Ltd. (JASCO), under contract to Stantec Consulting Ltd. (Stantec), performed an underwater acoustic modelling study to predict the underwater sound levels generated by impact pile driving and rock socket drilling at the marine terminal and MOF locations, and by LNG carrier transiting and berthing. The goal of this study was to predict the extent of ensonification from these activities and to define zones of potential effects on marine fauna based on sound level thresholds for auditory injury and behavioural disturbance. The results are intended to support the assessment of potential effects on selected marine fauna for the Project's environmental assessment being developed by Stantec, as required by the British Columbia Environmental Assessment Act (BCEAA) (British Columbia Government 2002) and the Canadian Environmental Assessment Act (CEAA) 2012 (Government of Canada 2012).

Impact pile driving activities at the LNG jetty and the MOF were modelled with confined bubble curtain mitigation systems; rock socket drilling pile installation activities at the LNG jetty were modelled without a mitigation system since industry does not normally use one for this type of activity. The vessel transiting activities, involving an LNG carrier escorted by two tugs, were modelled at two locations along the planned shipping lane to the terminal. The berthing of an LNG carrier under the assistance of four tugs was modelled at the LNG jetty. JASCO's Full Waveform Range-dependent Acoustic Model (FWRAM) and Marine Operations Noise Model (MONM) were used to calculate sound propagation and received levels for each of the defined scenarios. Both models accept as input the activity-specific spectral source levels, bathymetry, water sound speed profiles, and seabed geoacoustic parameters. The models generate 2-D and 3-D sound level grids in several frequency bands that can be frequency weighted according to the audiometric sensitivity of the species of interest.

In addition to impact thresholds and criteria broadly applicable to all marine mammal (distinguished by hearing groups) and fish species, where species-specific thresholds were available they were considered for key species of interest (i.e., for humpback whales (*Megaptera novaeangliae*), killer whales (*Orcinus orca*), harbour seals (*Phoca vitulina*), harbour porpoises (*Phocoena phocoena*), Chinook salmon (*Oncorhynchus tshawytscha*), and Pacific herring (*Clupea pallasii*)). Modelled results are presented as tables of distances to the interim National Marine Fisheries Service (NMFS) sound pressure level criteria, marine mammal injury criteria based on Wood et al. (2012) and Southall et al. (2007), fish mortality and impairment criteria recommended by Popper et al. (2014), the recommended fish injury threshold based on the Best Management Practices for Pile Driving and Related Operations in British Columbia (BC MPDCA and DFO 2003), and zones of audibility and behavioural thresholds (where available) for key marine mammal and fish species. Results are also presented as sound field isopleth maps, which show the planar distribution of sound levels with range and azimuthal direction.

Section 1 of this report describes the modelled scenarios, introduces the acoustic metrics used in the study, and presents the impact criteria applied for assessing noise levels. Section 2 briefly outlines the methods for defining acoustic emission levels for the sources, the sound propagation models, and the mitigation system simulations. Section 3 describes the parameters used by the models to represent the acoustic environment, and discusses the assumed ambient noise conditions. Tables of distances to the various sound level thresholds for impact are provided in Section 4. Section 5 includes a discussion and interpretation of the results, and is followed by a glossary of acoustic terminology. Appendix A provides further details on the applied criteria, including a review of the recent published literature. Appendix B provides the modelled sound field isopleth maps.

1.1. Modelled Scenarios

Construction and operation of the MOF in Casey Cove and the LNG jetty on south Digby Island will generate underwater noise from a variety of sources. The scope of this modelling study is limited to analyzing underwater sound from pile installation activities at the MOF and at the LNG jetty, and vessel noise produced by LNG carriers and tugs transiting between Triple Island pilot station and the LNG jetty and berthing at the latter (Figure 1).

The following scenarios were modelled:

- Impact pile driving at the MOF: Two impact pile driving rigs simultaneously driving 60-inch steel pipe piles at the MOF in Casey Cove, Digby Island. The most eastern section of the MOF was chosen for impact pile driving providing conservative results, because this is where land would least likely obstruct sound and thus distances to sound level thresholds are larger. While the sound levels close to the piles (less than ~100 m) could be affected by the distance between the two rigs, sound levels received at ranges beyond 100 m would not be affected. Therefore, we assume that both rigs are at the same geographic location for modelling long-range sound levels. To determine the total number of minutes of pile driving operations within a 24-hr period, it was assumed that each pile takes 60 min of uninterrupted impact driving to be set into place, and 2 piles would be installed within one 10-hr shift, per set of equipment. Thus, assuming two 10-hr shifts per day and two sets of equipment, a total of 480 minutes of pile driving per day was postulated.
- Impact pile driving at the LNG jetty: Four impact pile driving rigs simultaneously driving 60-inch steel pipe piles at the LNG jetty on south Digby Island; two rigs were positioned at Berth 1 (northern berth) and two were positioned at Berth 2 (southern berth). While the sound levels close to the piles at one berth (less than ~100 m) could be affected by the distance between the two rigs, sound levels received at ranges beyond 100 m would not be affected. Therefore, we assume that the two rigs at each berth are at the same geographic location for modelling long-range sound levels. To determine the total number of minutes of pile driving operations within a 24-hr period, it was assumed that each pile takes 40 min of uninterrupted impact driving to be set into place, and 1 pile would be installed within one 10-hr shift, per set of equipment. Thus, assuming one 10-hr shift per day and 2 sets of equipment at each berth location, a total of 160 minutes of pile driving per day was postulated.
- Rock socket drilling at the LNG jetty: Four instances of rock socket pile installations for 60-inch steel pipe piles at the LNG jetty on south Digby Island; two drill rigs were positioned at Berth 1 (northern berth) and two drill rigs were positioned at Berth 2 (southern berth). While the sound levels close to the rigs at one berth (less than ~100 m) could be affected by the distance between the two rigs, sound levels at ranges beyond 100 m would not be affected. Therefore, we assume that the two rigs at each berth are at the same geographic location for modelling long-range sound levels. To determine the total time of rock socket drilling within a 24-hr period, it was assumed that each set of equipment carries out 360 minutes (6 hours) of active drilling within a 10-hr shift. Thus, assuming one 10-hr shift per day and 2 sets of equipment at each berth location, a total of 1,440 minutes of rock socket drilling per day was postulated.
- Vessel berthing at the LNG jetty: LNG carrier approaching the jetty, assisted by four tugs. The vessel speed used for source level estimation conformed to the proposed speed of 6 knots (kts) (11 km/h).
- Vessel transiting in south Chatham Sound: LNG carrier transiting along the ocean-bound shipping lane through south Chatham Sound, assisted by two tugs. The vessel speed used for source level estimation conformed to the proposed upper-end LNG carrier transit speed of 16 knots (kts) (30 km/h).
- Vessel transiting at Triple Island pilot station: Transiting of LNG carrier along the ocean-bound shipping route past the Triple Island pilot station, assisted by two tugs. The vessel speed used for source level estimation conformed to the proposed upper-end LNG carrier transit speed of 16 knots (kts) (30 km/h).

Figure 1 shows the modelled locations. Table 1 lists the modelled scenarios.

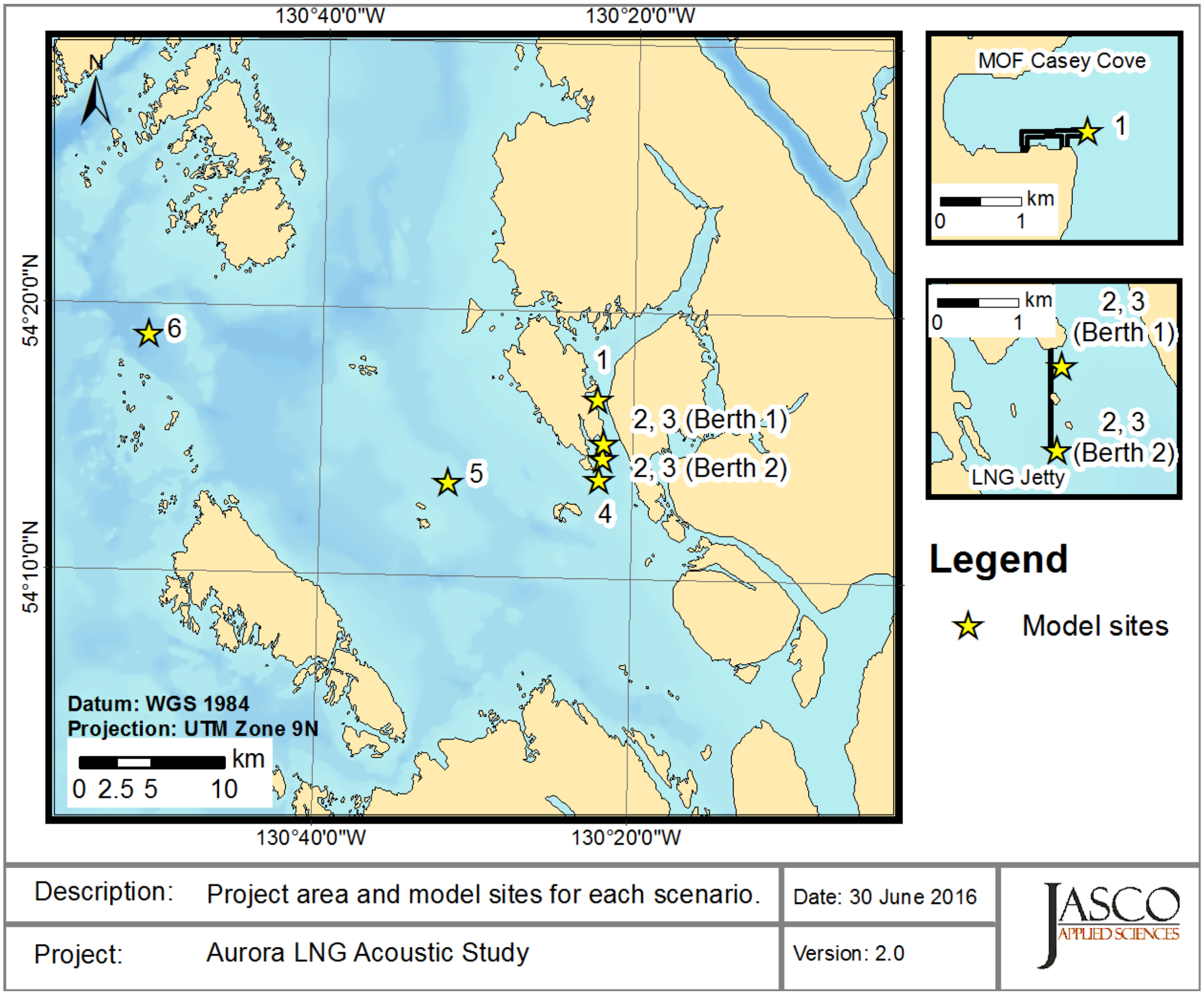

Figure 1. Map of the study area offshore of Prince Rupert, BC with modelled scenario numbers.

Table 1. Locations and water depth of modelled scenarios.

Scenario	Activity	Site Name	Site Location				Water Depth (m)
			Latitude	Longitude	UTM Coordinates; Zone 9		
					Easting	Northing	
1	Impact pile driving with confined bubble curtain	Casey Cove Materials Offloading Facility (MOF)	54.280°N	130.371°W	410740	6015512	22.6
2	Impact pile driving with confined bubble curtain	South Digby Island LNG jetty–Berth 1	54.252°N	130.364 W	411130	6012464	20.5
		South Digby Island LNG jetty–Berth 2	54.243°N	130.365°W	411073	6011425	15.3
3	Rock socket drilling	South Digby Island LNG jetty–Berth 1	54.252°N	130.364 W	411130	6012464	20.5

		South Digby Island LNG jetty–Berth 2	54.243°N	130.365°W	411073	6011425	15.3
4	LNG carrier and 4 support vessels–Berthing (6 kts)	Approach to south Digby Island LNG jetty	54.230°N	130.369°W	410772	6009969	36.6
5	LNG carrier and 2 support vessels–Transiting (16 kts)	South Chatham Sound	54.227°N	130.529°W	400330	6009834	49.6
6	LNG carrier and 2 support vessels–Transiting (16 kts)	Triple Island pilot station (West Chatham Sound)	54.31°N	130.847°W	379848	6020041	172.6

1.2. Acoustic Metrics

The properties of sound that can affect marine fauna are quantified using a variety of standard metrics. This report deals with sounds from vessels, impact pile driving, and rock socket drilling pile installation. Because the perceived loudness of sounds is not generally proportional to instantaneous acoustic pressure, evaluating sounds must also consider the temporal characteristics of individual pulses and the total duration over which sounds are received. This is particularly true for sounds from impulsive noise sources such as pile driving. Perceived loudness also depends partially on the frequency content of the sounds relative to the hearing acuity of the animals exposed.

The peak sound pressure level (SPL) is the maximum instantaneous sound pressure level in a stated frequency band attained by an acoustic pressure signal. It is expressed in dB re 1 µPa to indicate that it is measured relative to a fixed reference pressure. At high intensities, peak pressure level can be a valid criterion for assessing whether a sound is potentially injurious; however, because the peak pressure level does not account for the duration of a noise event, it is a poor indicator of perceived loudness.

The SPL (root-mean-square, rms) is a measure of the average or effective pressure over the duration of an acoustic event, such as the emission of one acoustic pulse, a marine mammal vocalization, or the passage of a vessel. It is also expressed in dB re 1 µPa. Events spread out in time have a lower SPL (rms) than short duration events with the same total acoustic energy density. For pulse events the 90% SPL (rms) is commonly used, in which the pulse width encompasses 90% of the total energy. However, for impulsive sounds, i.e., sound from impact pile driving, the frequency, duration, and repetition rate strongly influence the extent to which marine mammals in the vicinity perceive loudness of the sound. Like humans, auditory systems of marine mammals do not respond to instantaneous pressure. Rather, they integrate the pressure signal over a short time period, defined by a time constant (Plomp and Bouman 1959). To account for this, Tougaard et al. (2015) suggested a related “rms fast average” for underwater sound characterization. The rms fast average SPL (hereafter SPL (rms)) is a SPL metric that accounts for the perceived sound level of very brief sound (impulsive sound with very short pulse duration) for animals.

The SPL (rms) above hearing thresholds is the difference between the average sound pressure level and the sound pressure level that is barely audible for an individual when significant background noise is absent. Because it represents a comparison between two sound pressure levels, rather than being relative to a fixed reference pressure, it is expressed simply in dB and denoted as dB_{ht}(species).

The sound exposure level (SEL) is a measure of the total acoustic energy contained in one or more acoustic events. It represents a measure of the total sound energy to which an organism at that location would be exposed, and is expressed in dB re 1 µPa^2·s. SEL is a cumulative metric if it is calculated over a fixed time period that encompasses multiple acoustic events. In this study both the SEL per pulse and the SEL per 24 h are used in the estimations.

Appendix A.1 describes these metrics in detail and provides the relevant formulae; they are also defined in the Glossary.

1.3. Modelled Thresholds and Criteria

Underwater noise can affect marine fauna in several ways, and the criteria upon which impact assessments are based can be complex. At least three primary severity levels for how noise affects marine fauna should be considered in an environmental assessment: injury, disturbance, and chronic and cumulative effects. Regulatory conditions for marine industrial projects typically require and focus on evaluations that deal with the first two types, but agencies are increasingly requesting that chronic and cumulative effects also be appraised. Environmental assessments in Canada are governed by the Canadian Environmental Assessment Act (CEAA 2012) and require evaluating cumulative effects. There are different views among bioacousticians about the best method for estimating injury and disturbance effects on animals, and because evaluating chronic effects is even more complex and harder to quantify, there is little consensus at the moment on how to perform those assessments.

The assessment criteria we chose to apply in this study arose from several options. The question of which acoustic exposure levels might injure or disturb marine mammals is still an active research topic at the time of the present study. Since 2007, several expert groups have investigated an SEL-based assessment approach for injury, with a handful of key papers published on the topic. Likewise, the number of studies investigating the level of disturbance to marine animals by underwater noise has increased substantially. Those publications are reviewed, and the relative criteria discussed, in Appendix A.2 for marina mammals and in Appendix A.2.2 for fishes. In the present section we propose specific methods and thresholds to apply in the current study; we caution readers, however, that assessment criteria are likely to evolve in the near future as research progresses in this field.

Results of the modelling study will be presented in terms of the following noise criteria, which have been chosen to include standard thresholds and thresholds suggested by the best available science, as reviewed and discussed in Appendix A:

- Primary marine mammal auditory injury criteria: M-weighted sound exposure level (SEL) and peak pressure level thresholds for marine mammal injury based on Wood et al. (2012) and Southall et al. (2007), Wood et al. (2012), for all sound sources.
- Alternative marine mammal auditory injury criteria: SPL (rms) thresholds based on interim NMFS criteria (NMFS 2016b) for marine mammals of 190 and 180 dB re 1 µPa SPL (rms) (for pinnipeds in water and cetaceans, respectively) for all sound sources[1]. These are included primarily for comparisons with previous assessment of similar sources.
- Behavioural thresholds based on the current interim NMFS criteria (NMFS 2016b) for marine mammals of 120 and 160 dB re 1 µPa SPL (rms), for non-impulsive and impulsive sound sources respectively.
- SEL and peak pressure level thresholds for fish mortality and impairment based on sound exposure guidelines for fishes recommended by Popper et al. (2014), for impact pile driving only.
- The 30 kPa threshold based on the Best Management Practices for Pile Driving and Related Operations in British Columbia (BC MPDCA and DFO 2003) as an injury threshold for fish, for impact pile driving only.
- Behavioural thresholds above hearing thresholds for key species of interest, for all sound sources.
- Local Assessment Area (LAA) for marine mammals using 160 dB re 1µPa SPL (rms) threshold for all acoustic sources. DFO has advised Aurora LNG that for the assessment of the Project, the LAA

[1] As of August 2016, the interim NMFS injury criteria were superseded by NOAA's injury guidelines, which were not formally released when this study was conducted. The interim NMFS behavioural criteria remain in force.

should be set to encompass the area where any Project activity (construction, operations, decommissioning) will exceed 160 dB (BC EAO 2015).

- Zones of audibility for key species of interest, for all sound sources.

1.3.1. Marine mammals–Injury

The National Oceanic and Atmospheric Administration (NOAA) draft criteria for injury that were available when JASCO performed the modelling and analyses for this assessment included NOAA (2016) and its earlier iterations from 2013 and 2015. NOAA's draft injury criteria (2016) were scrutinized by the public, industrial proponents, and academics, but they were not formally peer reviewed. The latest peer-reviewed criteria that are most similar to the NOAA draft criteria (2016) were published by Wood et al. (2012), whose report reiterates the well-accepted criteria of Southall et al. (2007) updated with results for harbour porpoises from Lucke et al. (2009). JASCO's study, therefore, applied the methods and thresholds for injury summarized by Wood et al. (2012) and the peak pressure level criteria recommended by Southall et al. (2007). As mentioned earlier, we also included results based on the interim NMFS SPL (rms) injury criteria. All the marine mammal injury thresholds applied in this assessment are summarized in Table 2. After the completion of the analyses and just before we finalized this report, NOAA formally promulgated the 2016 draft injury criteria in a guidance document (NMFS/NOAA 2016a). The recently released criteria do not include peak pressure level thresholds for non-impulsive sounds.

Table 2. Marine mammal injury (PTS onset) thresholds based on Wood et al. (2012), Southall et al. (2007), and NMFS (2016b).

Functional hearing group	Impulsive Source			Non-impulsive Source	
	SPL (rms)* (dB re 1 µPa)	Peak pressure level† (dB re 1 µPa)	Weighted SEL (24 h)# (dB re 1 µPa²·s)	Peak pressure level† (dB re 1 µPa)	Weighted SEL (24 h)† (dB re 1 µPa²·s)
Low-frequency cetaceans	180	230	192	230	215
Mid-frequency cetaceans	180	230	198	230	215
High-frequency cetaceans	180	230	179	230	215
Pinnipeds in water	190	218	186	218	203

Sources: * NMFS (2016b); † Southall et al. (2007); # Wood et al. 2012.

1.3.2. Marine mammals–Disturbance

Unlike for injury thresholds, no recent guidance has been published on disturbance thresholds for marine mammals. In this assessment, we first applied the NMFS SPL (rms) criteria to be consistent with earlier studies. We also applied species-specific dB_{ht} thresholds for disturbance based on the literature (Appendix A.2.1.2). In the absence of published information supporting a different choice, we used the same dB_{ht} thresholds for both impulsive and non-impulsive sounds. The applied disturbance thresholds are presented in Table 3. We also calculated zones of audibility (Section 2.3.6) for individual species to determine the maximum extent over which animals are expected to detect the sound sources over background levels.

Table 3. Marine mammal disturbance thresholds.

Functional Hearing Group	Impulsive Source		Non-impulsive Source		Origin of dB_{ht} Thresholds
	SPL (rms)† (dB re 1 µPa)	dB_{ht} level	SPL (rms)† (dB re 1 µPa)	dB_{ht} level	
Humpback and other baleen whales	160	73	120	73	McCauley et al. (2000)
Killer whales	160	57/64*	120	57/64*	MacGillivray et al. (2012)
Harbour porpoise	160	45	120	45	Tougaard et al. (2015)
Harbour seal	160	64	120	64	Bailey et al. (2010)

* 57 dB_{ht} for subtle response and 64 dB_{ht} for overt response.
† Sources: NMFS (2016b)

1.3.3. Fishes–Injury and zones of audibility

In this study we applied the fish injury thresholds for impact pile driving recommended by Popper et al. (2014; Table 4) as well as the 30 kPa criterion based on the Best Management Practices for Pile Driving and Related Operations in British Columbia (BC MPDCA and DFO 2003). There is scarce knowledge on the behavioural impact of impulsive sounds on fishes, and very limited experimental data exist to account for the variability among fish species. Furthermore very few studies have been conducted in the wild, and wild fish show very different behavioural responses to stimuli than animals in tank experiments (Popper et al. 2014). In the present assessment we modelled the zone of audibility, which is the predicted maximum extent of detection of sound from a given source, as the outer boundary of any smaller region over which some reaction could potentially occur for each fish species considered.

Table 4. 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 µPa²·s)	Peak pressure level (dB re 1 µPa)	SEL (24 h) (dB re 1 µPa²·s)	Peak pressure level (dB re 1 µPa)	SEL (24 h) (dB re 1 µPa²·s)
I	No swim bladder (particle motion detection)	> 219	> 213	> 216	> 213	>> 186
II	Swim bladder is not involved in hearing (particle motion detection)	210	> 207	203	> 207	>> 186
III	Swim bladder is involved in hearing (primary pressure detection)	207	> 207	203	> 207	186

2. Modelling Methodology

2.1. Acoustic Sources

At the time of writing of this report, the specific equipment associated with pile driving and rock socket drilling activities had not yet been identified. The parameters required to model both types of activities were therefore based on reasonably precautionary assumptions. The actual source levels that will be generated may vary for a given activity, depending on the specific equipment used and its operation.

2.1.1. Impact pile driving

JASCO's physical model of pile vibration and near-field sound radiation (MacGillivray 2014) was used with the GRLWEAP 2010 wave equation model (GRLWEAP, Pile Dynamics 2010) to predict source levels associated with impact pile driving scenarios. The sound radiating from the pile itself was simulated using a vertical array of discrete point sources. The models account for several parameters that describe the operation, including pile type, material, pile dimensions (size and length), the pile driving equipment, and approximate pile penetration depth. The acoustic source models applied in this study are described in more detail in Appendix A.4.

Impact pile driving was modelled for steel cylindrical pipes of diameter 1.524 m (nominal 60 in), wall thickness of 0.0254 m (nominal 1 in), and lengths of 55 m and 45 m at the MOF and south Digby Island locations respectively. At the three modelled locations, at least 0.5 m of the pile length was assumed to remain above the water at all times. In terms of acoustics, this is equivalent to having a distributed source spanning the entire water column. The pile hammer Delmag D100-13, commonly used to drive piles more than 48 inches in diameter (ICF Jones & Stokes and Illingworth and Rodkin 2009), was selected in this study to model the force on top of the pile (i.e., the forcing function, Appendix A.4) resulting from a single hammer strike.

As illustrated in Figure A-4, sound emission from pile driving can be represented by an equivalent vertical line of acoustic sources along the pile axis. The spectral content of such sources can be modified to account for the mitigating impact of the confined bubble curtain (Section 2.2). FWRAM (Appendix A.5.2) was used to obtain time-domain acoustic signatures corresponding to a single hammer strike. By applying the back-propagation procedure described in Section 2.3.1, a single-source representation of the pile signature was obtained and used as an input into MONM, enabling efficient modelling of sound levels over large geographic areas. The modelling of pulses in FWRAM included contributions in the frequency range 10 Hz-2048 Hz. The source levels applied to MONM were extended to 8000 Hz by applying a decay trend of 31 dB/decade, which was obtained as the mean rate from several measurements of pile driving using confined bubble curtains (Caltrans 2009, ICF Jones & Stokes and Illingworth and Rodkin 2010, Caltrans 2001).

Source levels specific for each of the three modelled locations were obtained because geoacoustics and bathymetry features differed between the MOF site and south Digby Island.

2.1.2. Rock socket drilling

Source levels for rock socket drilling were derived from measurements rather than modelled. Because there are no documented source levels for rock socket drilling for pile installation specific to the proposed drill size of 1.524 m (nominal 60 in) and equipment, we approximated the source levels based on the technical coring drill measurements by Mann et al. (2009). Their study presents the power density spectrum levels of a small diameter (0.0635 m; nominal 2.5 in) coring drill at 5 m range (Figure 2). The spectral source levels were computed by back-propagating the measured received levels for the coring drill to 1 m range assuming spherical spreading, i.e., by adding $20*\log_{10}(d)$ to the received levels, where d is the distance in m of the measurement point from the source. The spectral source levels were then converted to 1/3-octave-band sound pressure levels (Appendix A.1.1). Since the size of the measured coring drill bit is different from the proposed bit size, the measured source levels were scaled by taking into account the ratio in frictional loss during drilling, which follows the assumptions that the weight applied to a drill-head is proportional to the cross sectional area of the pile. This scaling factor added $10*\log_{10}(r^2/r_0^2)$ = 27.6 dB to the measured source levels, where r and r_0 are the radii of the pile and of the coring drill bit (1.524 m and 0.0635 m respectively).

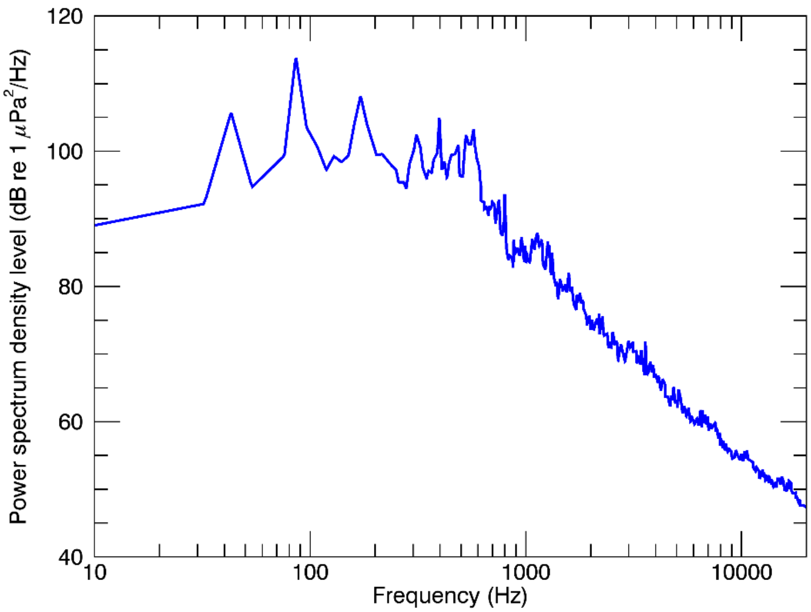

Figure 2. Power spectrum of the rock socket drilling acoustic pressure levels at 5 m (Figure 4 in Mann et al. 2009).

The rock socket drilling operation, like the technical coring, can emit sound both from the drill at the seabed and from the machinery on the barge. Since it is not possible to resolve the noise distribution within the water column from the published measurements, we assumed a mid-water column source depth. This assumption under most conditions estimates conservatively the sound field, i.e., results in longer ranges to sound level thresholds than would a source located closer to the seafloor or the surface.

2.1.3. Vessels

Source levels for the LNG carrier and the tugs were derived from measurements. Since source level measurements of the proposed vessels were not available, we used published measurements of vessels of similar type and size and adjusted them to the proposed vessel specifications (details in Appendix A.4.2). The LNG carriers proposed for this modelling study were based on a Q-Flex carrier (315 m length, 217 000 m^3 capacity). Measured source levels for Q-flex LNG carriers were not available at the time of this modelling study. Consequently, the source levels for an LNG carrier during transit were based on published measurements of three crude oil tankers (Table 5) operating under normal conditions (McKenna et al. 2012). These oil tankers transited at 13.5 kts on average; the mean spectral source levels based on measurements are presented in the cited reference in 1/3-octave-bands ranging from 20 to 800 Hz. We extrapolated 1/3-octave-band source levels to lower (10–20 Hz) and higher frequencies (800 Hz–16 kHz) based on measurements of the modern cargo ship M/V *Overseas Harriette* (Table 5) that transited at 8-16 kts (Arveson and Vendittis 2000).

The modelled transiting speed for the LNG carrier in Chatham Sound and at the Triple Island pilot station was 16 kts, which represents the estimated maximum speed expected in this area. The modelled LNG carrier source depth was 6 m, corresponding to the estimated depth of the cavitation bubbles (Leggat et al. 1981). The source depth assumes an 8-m propeller diameter and a loaded (maximum) draught of

12.5 m, which is a conservative assumption since sources farther from the sea surface radiate sound more efficiently (Brekhovskikh and Lysanov 2003).

The source levels for the escorting tugs were derived from acoustic measurements of a surrogate tug (Britoil 51; Hannay et al. 2004). The specifications of this surrogate tug are similar to the possible specifications provided by Nexen for the proposed tug type (Table 6). Source levels derived from measurements during pulling and pushing activities were used in Scenario 4 (vessels berthing); source levels derived from measurements during transit, adjusted to 16 kts, were applied in Scenarios 5 and 6. The modelled source depth for the escorting tugs was 3.1 m based on a draught of 6.1 m.

Table 5. Specifications of the target LNG carrier vessel class and of the surrogate vessels used to derive source levels for the acoustic model.

Vessel	Length (m)	Width (m)	Draught (m)	Speed (kts)
Q Flex (target class)	**315.0**	**50.0**	**12.0**	**16.0**
Singapore Voyager (McKenna et al. 2012)	241.0	42.0	14.0	12.6
NS Century (McKenna et al. 2012)	243.0	42.0	14.4	12.8
Chemtrans Sky (McKenna et al. 2012)	229.0	32.0	11.7	14.6
Overseas Harriette (Arveson and Vendittis 2000)	172.9	22.8	10.2	8–16

Table 6.Specifications of the target tug and of the surrogate tug used to derive source levels for the acoustic model.

Vessel	Length (m)	Width (m)	Draught (m)	Power (kW)	Speed (kts)
Tug (possible target specifications)	**34.0**	**14.5**	**6.1**	**2720.0**	**16.0**
Britoil 51 (Hannay et al. 2004).	45.0	11.8	5.6	4922.0	13.0

2.2. Mitigation Systems: Confined Bubble Curtains

Bubble curtain systems can reduce the sound energy propagating from pile driving operations. Noise mitigation is achieved by two mechanisms (Lucke et al. 2011): first, each bubble scatters sound because of the high acoustic impedance mismatch between the water and the injected air that forms the bubble; second, at certain wavelengths acoustic waves cause bubbles to resonate, resulting in a net acoustic energy loss. The broadband attenuation level achieved depends on environmental factors, the characteristics of the pile, and the penetration depth of the pile into the seabed substrate. The density of the bubbles rising through the water column from an unconfined bubble curtain is difficult to control, especially when currents are strong or in deep water. A higher attenuation level may be achieved using a confined bubble curtain, which traps the bubbles within a membrane and allows for better controls of the bubble density in the water. It is important that bubble curtains be appropriately designed for their specific environmental parameters to maximize their potential effectiveness; acoustic measurements of pile driving activities with confined bubble curtains have shown a range in achieved broadband sound level reductions, from 5 to 36 dB (Caltrans 2001, MacGillivray and Racca 2005, ICF Jones & Stokes and Illingworth and Rodkin 2009, MacGillivray et al. 2011, Martin et al. 2012).

Bubble curtains are less effective when a significant portion of sound travels unimpeded through the seabed substrate and enters the water column via the seafloor interface at a distance greater than the bubble curtain can contain (WSDOT 2010). Two factors can influence this indirect propagation: first, the length of pile already buried into the sediment, which radiates acoustic waves into the seabed; second, the ability of these ground-borne acoustic waves to couple into the water, which can result from upward-refracting sound speed profiles in the sediment as well as a reflective layering structure deflecting ground-borne waves up to the water-sediment interface. For the MOF and berth locations all the factors mentioned above are present, with pile sediment penetration of 20-30 m (i.e., a significant length of the pile is buried), a top upward-refracting clayey silt layer as seen in Tables 7 and 8, and an underlying layer of more consolidated sediment with higher acoustic impedance than the clayey silt layer.

To model the attenuation from a confined bubble curtain, the spectral content of the point sources representing the pile (Section 2.1.1 and Appendix A.4) was adjusted using a frequency-dependent attenuation coefficient. The attenuation coefficient was obtained by compiling measurements from multiple confined bubble curtain performance studies to determine an average attenuation across 1/3-octave-bands (measurements available at 63–6300 Hz; Caltrans 2001, MacGillivray and Racca 2005, ICF Jones & Stokes and Illingworth and Rodkin 2009, Martin et al. 2012). The attenuation coefficient was assumed to be 0 dB (no mitigation effect) below 63 Hz, which is consistent with measurements just above that frequency and justified by the attenuation mechanism of typical bubble curtains at low frequencies (MacGillivray et al. 2011). Based on assessment guidelines §2-25 (ICF Jones & Stokes and Illingworth and Rodkin 2009 §2-25, WSDOT 2010 §7.41), it was determined that for a typical confined bubble curtain system, a broadband sound level reduction by 10 dB is a realistic target assumption. This is especially true when little is known about the environment or for projects where multiple piles will be driven over a large area within which environmental conditions are likely to vary. Thus, the average attenuation coefficient was adjusted to give a reduction of broadband sound levels by 10 dB at 10 m from the pile. The confined bubble curtain used in this report is represented by the attenuation coefficient versus frequency band shown in Figure 3.

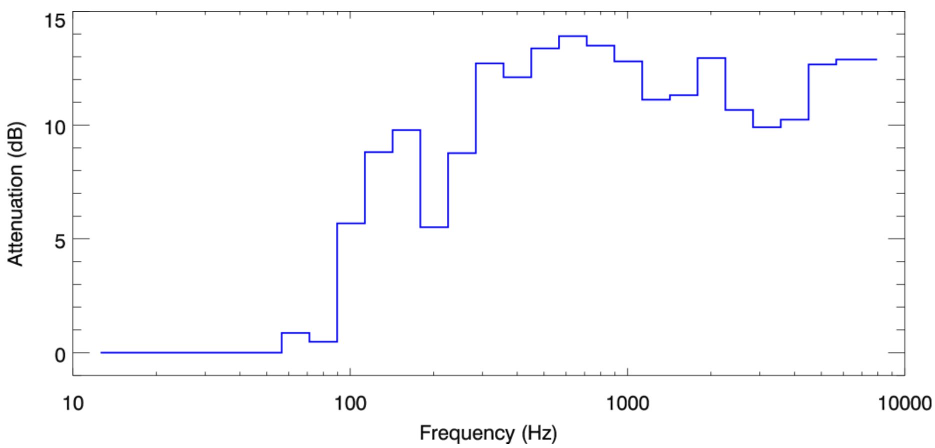

Figure 3. Averaged attenuation coefficient representing the mitigation effect from a confined bubble curtain.

2.3. Sound Propagation

2.3.1. Impact pile driving of cylindrical piles

JASCO's Marine Operations Noise Model (MONM; Appendix A.5.1) computes received per-pulse SEL for directional impulsive sources at a specified source depth. It is a far-field transmission loss model, which assumes that the separation between the source and receiver is sufficiently large that the physical dimensions of the source can be neglected. JASCO's time-domain Full Waveform Range-dependent model (FWRAM; Appendix A.5.2) on the other hand calculates sound propagation from physically distributed impulsive sources. FWRAM, while valid at all distances, becomes computationally inefficient at long ranges. In the present study, received sound levels were calculated using FWRAM along a single azimuth, and transmission loss was calculated using MONM on a long-range three-dimensional grid. A far-field point source representation of the acoustic signature from the pile was then determined by back-propagating the received sound levels generated with FWRAM using the transmission loss calculated with MONM. This point source representation accurately characterizes the vertical directivity of the pile-driving source with the advantage that it can be applied to MONM for computationally efficient long-range modelling.

2.3.2. Rock socket drilling and vessels

MONM directly computes received SPL (rms) for non-impulsive sources at a specified depth (Appendix A.5.1). This model was used in the present study to calculate the sound field associated with rock socket drilling and vessel activities on a long-range three-dimensional grid of receiver points.

2.3.3. M-weighted sound exposure level

MONM treats frequency dependence by computing acoustic transmission loss at the centre frequencies of 1/3-octave-bands (Appendix A.5.1). Auditory weighting functions for marine mammals, referred to as M-weighting functions (Appendix A.3.1) as proposed by Southall et al. (2007), were applied to the frequency-dependent band levels. Weighted broadband received SEL was computed by summing the weighted 1/3-octave-band levels.

The 24-hr SEL was calculated by adding the SEL of all sound sources that an animal could be exposed to over a 24-hour period. For repetitive sounds from pile driving, we computed the 24-hr SEL by summing the single pulse SEL values in decibels as

$$\text{24-hr SEL} = \text{per-pulse SEL} + 10\times\log10\text{N} \tag{1}$$

where per-pulse SEL is the level of a single strike, and *N* is the number of pile driving strikes within 24 hrs. Under the assumptions described in Section 1.1 and considering a strike rate of 40 strikes/min, the conversion $10\times\log_{10}N$ was computed as:

- Impact pile driving at the MOF: $10\times\log_{10}$(480 min×40 strikes/min) = 42.8 dB added to the single-strike SEL values for pile driving located at MOF.
- Impact pile driving at the LNG jetty: $10\times\log_{10}$(80 min×40 strikes/min) = 35.1 dB added to the single-strike SEL values for pile driving located at both Berth 1 and Berth 2.

For rock socket drilling at the LNG jetty, under the assumptions described in Section 1.1, a conversion factor of $10\times\log_{10}$(360 min × 60 s/min) = 43.3 dB was added to the SPL (rms) values for each drill rig (two drill rigs at each of the two berth locations) to obtain 24-hr SEL.

For berthing activities, since it cannot be expected that they would occur continuously during the whole 24-hr period, it was assumed in the absence of activity forecasts that an outside maximum of 4 berthing events per day (2 arrivals and 2 departures) could take place at one berth and each event took 60 min. This yields a factor of $10\times\log_{10}$(4 × 60 min × 60 s/min) = 41.6 dB, which was added to the SPL (rms) values to obtain the 24-hr SEL.

For vessels transiting at the waypoint, it was assumed very conservatively that the sound energy emitted from the vessel as it travelled a ~1km segment through the waypoint (2 min accumulation time based on 16 knots transit speed) would be concentrated at the waypoint. In this case, on the assumption that 2 vessels a day visited each of the 2 berths for a total of 8 passages, a factor of $10\times\log_{10}$(8 × 2 min × 60 s/min) = 29.8 dB was added to the SPL (rms) values to obtain the 24-hr SEL.

2.3.4. Peak pressure level and sound pressure level

To obtain peak pressure level for impulsive sources, FWRAM (Appendix A.5.2) was used to model synthetic time-domain pile driving pulses along one radial (azimuth) extending from each pile location. These radials were orientated toward areas where sound propagates the farthest. Distances to peak pressure level thresholds were calculated along these radials.

The SPL (rms) for impulsive sources is related to the SEL of a single pulse and the pulse length (Appendix A.1). For this reason, the SPL (rms) over a wide area can be estimated from the single-pulse

SEL values generated by MONM. The required conversion factor for SPL (rms) depends on the pulse length, which typically increases in duration as pulses propagate away from their source due to reverberation from seabed and sea-surface reflections as well as from in-water refractive effects. To investigate pulse length dependency on range and depth, FWRAM (Appendix A.5.2) was used to model synthetic pile driving pulses along a number of radials extending from each pile location. The synthetic pulses were analyzed to determine pulse length versus receiver depth and distance from the source. Conversion factors from single-pulse SEL to SPL (rms) were derived using two steps: first, the average pulse duration over depth at each modelled range was obtained by including only depth points with high SEL (i.e., within 3 dB from the largest SEL at each range); second, the depth-averaged pulse durations were averaged in range for 1 km radial steps. The resulting range-dependent conversion offset factors (Figure 4) were applied to the modelled SEL from MONM to calculate SPL (rms) values over a 360° area.

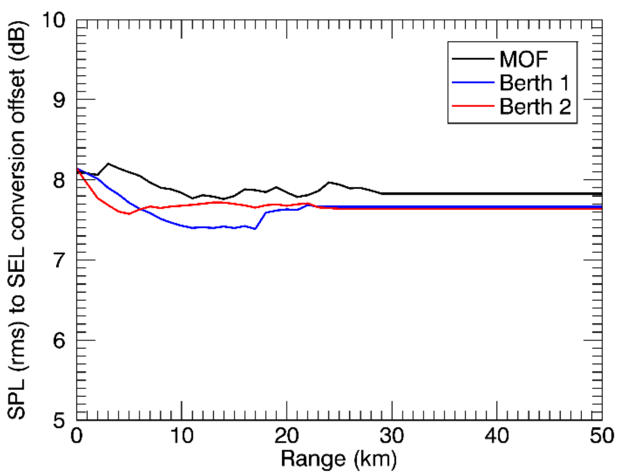

Figure 4. Range-dependent conversion offset factors for converting SEL to SPL (rms).

2.3.5. Sound pressure level above hearing threshold

Sound pressure level (SPL) above hearing threshold was calculated by subtracting species-specific audiograms from the received 1/3-octave-band sound pressure level (Appendix A-1). The audiogram-weighted 1/3-octave-band levels were summed to yield broadband sound levels relative to each species' hearing threshold. Audiogram-weighted levels are expressed in units of dB above hearing threshold (dB_{ht}(species)). Sound levels less than 0 dB_{ht}(species) are below the typical hearing threshold for the species, meaning that animals are unlikely to hear them.

In this study, audiogram weighting was applied to four marine mammal species and two groups of fishes by referring to results from published studies listed below. Appendix A.3.2 provides background information about audiograms and how the available data were extrapolated for this study.

Mammals:

- Humpback whales (*Megaptera novaeangliae*); Houser et al. (2001), Clark and Ellison (2004)
- Killer whales (*Orcinus orca*); Hall and Johnson (1972), Szymanski et al. (1999)
- Harbour seals (*Phoca vitulina*); Mohl (1968), Terhune (1988), Kastelein et al. (2009), Reichmuth et al. (2013)
- Harbour porpoises (*Phocoena phocoena*); Andersen (1970), Popov et al. (1986), Bibikov (1992), Kastelein et al. (2002), Kastelein et al. (2010)

Fishes:

- Chinook salmon (*Oncorhynchus tshawytscha*); Hawkins and Johnstone (1978), Oxman et al. (2007)
- Pacific herring (*Clupea pallasii*); Enger (1967), Mann et al. (2005)

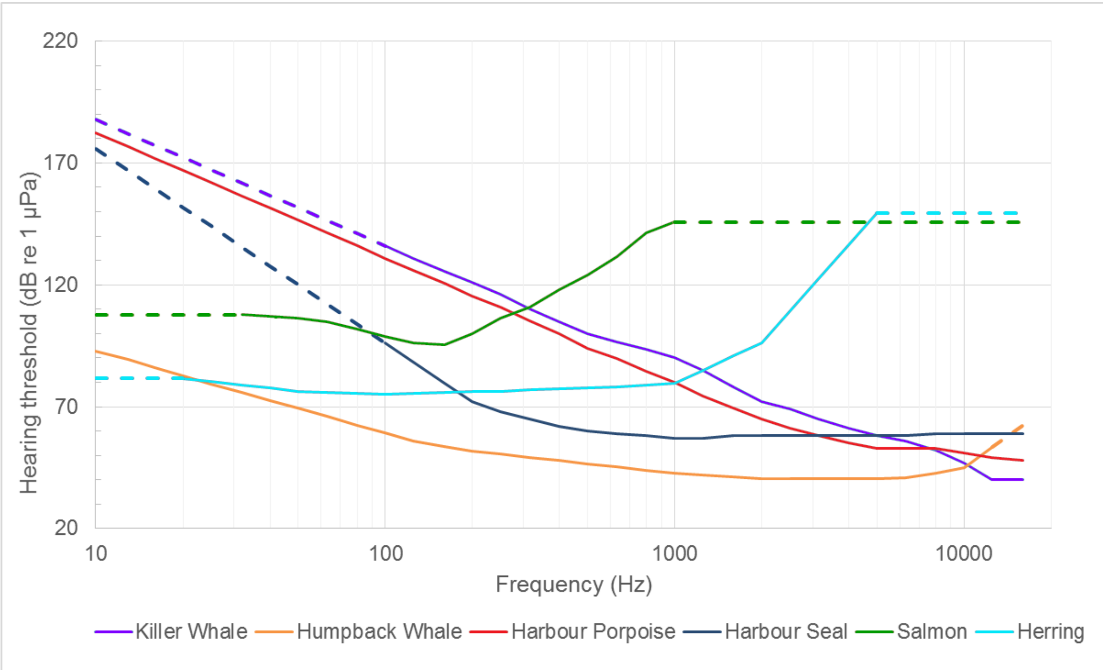

Figure 5. One-third-octave-band audiograms for humpback whale, killer whale, harbour porpoise, harbour seal, salmon, and herring. Dotted lines represent extrapolated hearing thresholds.

2.3.6. Zone of audibility

The areas of ensonification computed by the models do not necessarily represent areas over which animals will be able to detect the corresponding sounds; the levels may be below hearing threshold or below ambient noise levels that can mask the sounds. Regions where sound levels are both greater than ambient noise and above an animal's hearing threshold are referred to as zones of audibility (Richardson et al. 1995). For each activity, these zones were determined as the region where modelled levels were above hearing threshold and ambient noise levels in any 1/3-octave-band. Short duration impulsive signals might be less audible; the fast average SPL metric (Appendix A-1) was used to account for this effect. Ambient underwater noise levels around Digby Island and Triple Island were measured for this Project by JASCO in 2014 and reported in Frouin-Mouy et al. (2016). Median (50th percentile) ambient levels were used for this analysis and the SPL was maximized over all modelled depths (Section 3.2).

2.4. Computing Distances to Sound Thresholds

The underwater sound fields predicted by the propagation models were sampled so that the received sound level at each geographic location (horizontal plane) was set to the maximum value of all modelled depths at that location. Two distances from the source are reported for each sound level: (1) R_{max}, the maximum range over all azimuths (through 360°) at which the given sound level threshold was encountered, and (2) $R_{95\%}$, the maximum range at which the given sound level is encountered after the 5% farthest such points were excluded (Figure 6). The $R_{95\%}$ value is useful for non-circular noise footprints and when a few anomalously high amplitudes along a few azimuths skew results to be unrepresentative of the main ensonification zone. Regardless of the geometric shape of the maximum-over-depth footprint, $R_{95\%}$ is the predicted range encompassing at least 95% of the area (in the horizontal plane) that would be exposed to sound at or above that level. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the heterogeneity of the acoustic environment. The $R_{95\%}$ excludes ends of protruding areas or small isolated acoustic foci not representative of the nominal ensonification zone.

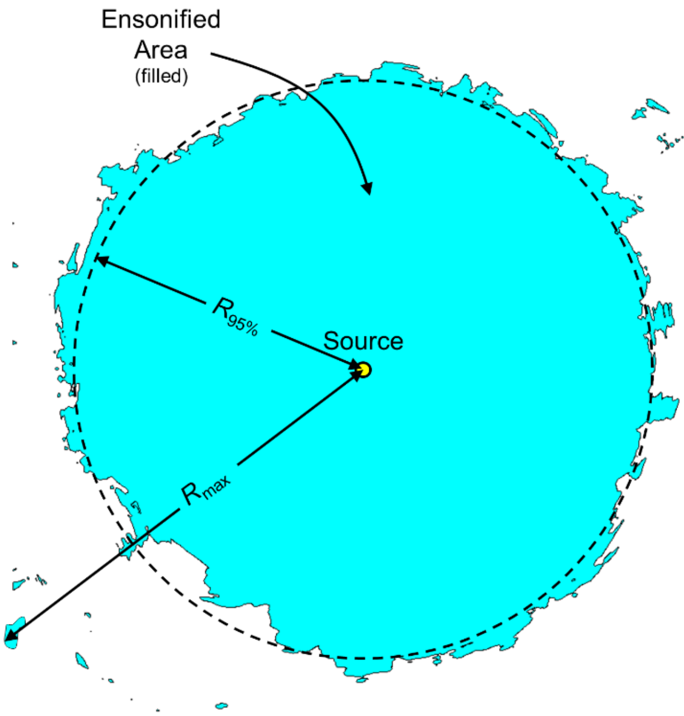

Figure 6. Example of an area ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ radii shown.

3. Model Parameters

3.1. Environmental Parameters

The underwater environment influences how far sound (energy) will travel away from the source generating the sound. The main factors are the speed of sound in water (related to water temperature, salinity, and pressure), the relief of the seafloor (bathymetry), and the composition of the sub-seafloor sediments.

3.1.1. Bathymetry

Water depths throughout the modelled area were extracted from three datasets:

- Nexen provided fine-grid (5 m) bathymetry data for the area proximal to the Casey Cove MOF and the South Digby Island LNG jetty.
- Navigational charts were used to extend the bathymetry data to ensure appropriate coverage of the waters through Chatham Sound to Triple Island.
- STRM30+ (v7.0) global bathymetry grid data, a 30 arc-second grid rendered for the entire globe (Rodríguez et al. 2005), were used to obtain values outside of Chatham Sound.

Bathymetry for a 137 × 175 km area was extracted from the three datasets and re-gridded, by minimum curvature gridding, onto a Universal Transverse Mercator (UTM) Zone 9 coordinate projection with a regular grid spacing of 10 × 10 m. The water depth at each location was calculated assuming high water level (i.e., datum plus 7.5 m).

3.1.2. Sound speed

Because sound speed in water depends mainly on temperature and salinity, variations in these factors affect sound propagation. For example, if the sound speed in deeper water is larger than near the surface, sound will refract upward and avoid interacting with the seabed. This situation leads to sound trapping that can lead to greater threshold distances. Refractive effects like these trapping sound are referred to as sound channels (i.e., they channel sound away from the bottom and/or surface, avoiding the greater energy losses incurred by reflections and scattering at those boundaries).

To assess monthly variations in refractive conditions, monthly sound speed profiles were derived from location-specific temperature and salinity profiles from the US Naval Oceanographic Office's Generalized Digital Environmental Model (GDEM) database (Teague et al. 1990, NAVO 2003, Carnes 2009). The GDEM database (version 3.0) provides average monthly profiles of ocean temperature and salinity on a latitude-longitude grid with 0.25° resolution. Profiles in GDEM are provided at 78 fixed depth points up to a maximum of 6,800 m. The profiles in GDEM are based on historical observations of global temperature and salinity from the US Navy's Master Oceanographic Observational Data Set (MOODS).

The GDEM temperature-salinity profiles at each location were converted to sound speed profiles according to Coppens (1981) equations:

$$\begin{aligned} c(z,T,S,\phi) &= 1449.05 + 45.7t - 5.21t^2 - 0.23t^3 \\ &\quad + (1.333 - 0.126t + 0.009t^2)(S-35) + \Delta \\ \Delta &= 16.3Z + 0.18Z^2 \\ Z &= (z/1000)(1 - 0.0026\cos(2\theta)) \\ t &= T/10 \end{aligned} \tag{2}$$

where z is water depth (m), T is water temperature (°C), S is salinity (psu), and θ is latitude (radians).

Figure 7 presents monthly averaged salinity, temperature, and sound speed profiles, taken from the GDEM data points closest to Scenario 1 (Casey Cove MOF; Figure 1). The December profile (olive green in Figure 7) is the most upward-refracting profile in the top 120 m. Because the GDEM profiles close to the modelled sites only range down to a depth of 180 m, profiles from the continental shelf area were selected to extrapolate to the maximum water depth of the modelled area (600 m) by splicing data points from neighbouring grid cells.

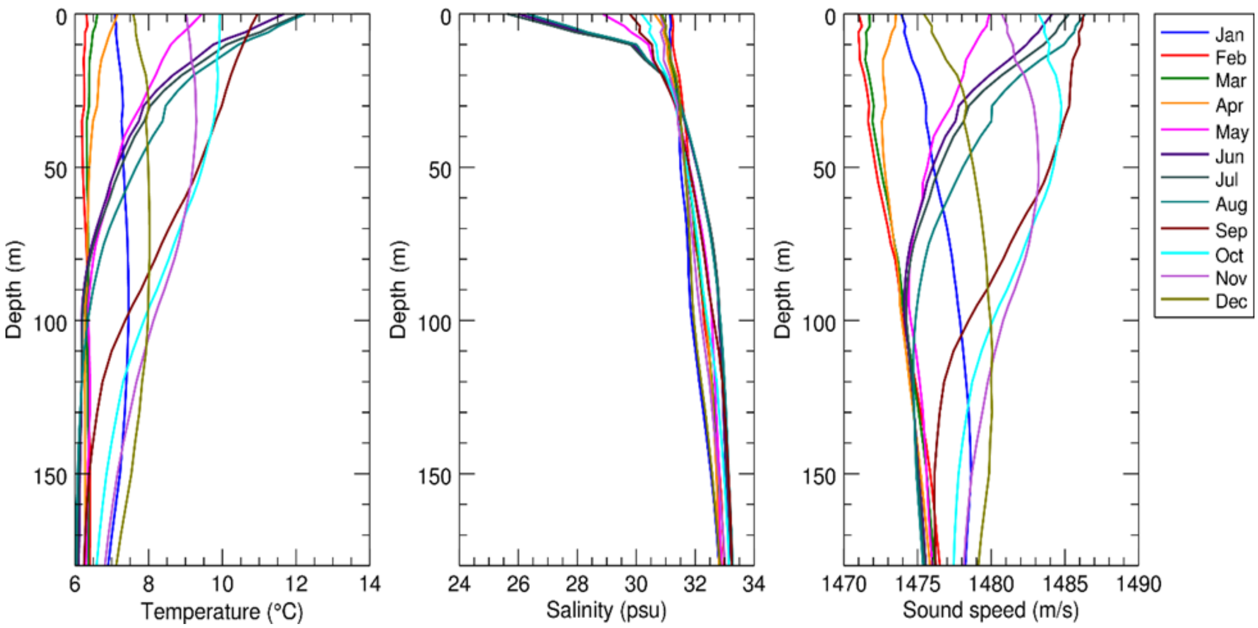

Figure 7. Monthly variation of temperature, salinity, and sound speed for the location closest to Casey Cove.

We applied only the December profile to all modelled scenarios to obtain conservative (longest threshold distance) results.

A seasonal comparison of sound speed profiles provided by Fisheries and Oceans Canada (DFO 2016) with the GDEM data at several locations throughout the modelled area showed little variation between the data sets. Because of the spatial and temporal variability among individual observations in the GDEM data set, the modelled profiles (in which these variations have been averaged) better represent typical conditions for a given location and time of year.

3.1.3. Geoacoustic profiles

Sound propagation is influenced by the geoacoustic properties that define the sediments and rocks in the sub-seafloor. The properties include sediment density, the sound speed within the sediments and rocks, and the attenuation of the sound energy in the seabed sediments. Softer sediments such as silt or clay absorb sound energy better than hard rocks such as granitic bedrock.

Since no information on the sediment type, grain size, or porosity was available, the geophysical properties of the seabed and of the sub-seafloor were obtained from a previous modelling study in the area (Matthews 2013) and are based on empirical formulae (Hamilton 1980, Buckingham 2005). Stantec provided sub-bottom profile depths for the MOF and LNG jetty locations. These data were applied to update the sediment layer thicknesses extracted from the earlier modelling study information. The parametrization of the geoacoustic layers that was used in this study follows the most recently accepted practices at JASCO based on a vetted process of revision in pace with our modelling framework. It might differ in some details (e.g. steepness of profiles) from the standards used in earlier work.

Because the modelled area is large, three simplified geoacoustic profiles were constructed to represent the major features of the sediment column at the modelled sites. The geoacoustic profile for Scenario 1 (Casey Cove MOF; Table 7) represents a bottom of a 45 m thick clayey silt and fine-grained sediment above granitic gneiss bedrock.

Table 7. Estimated geoacoustic profile for Scenario 1 (Casey Cove MOF), representing a bottom of fine-grained sediment above granitic gneiss bedrock.

Material	Depth Below Seafloor (m)	Density (g/cm³)	Compressional Sound Speed (m/s)	Compressional Attenuation (dB/λ)	Shear Sound Speed (m/s)	Shear Attenuation (dB/λ)
Clayey silt	0–45	1.8	1550–1770	0.3–1.1	190	0.1
Fine-grained sediment	45–200	2.1	1910–2150	1.1–1.7		
Bedrock	> 200	2.4	3500	0.4		

The geoacoustic profile for Scenarios 2-4 (LNG jetty; Table 8) represents the same clayey silt with a thickness of 20 m. The granitic gneiss bedrock follows beneath the fine-grained sediment, similar to Scenario 1.

Table 8. Estimated geoacoustic profile for Scenarios 2-4 (south Digby Island), representing a bottom of fine-grained sediment above granitic gneiss bedrock.

Material	Depth Below Seafloor (m)	Density (g/cm³)	Compressional Sound Speed (m/s)	Compressional Attenuation (dB/λ)	Shear Sound Speed (m/s)	Shear Attenuation (dB/λ)
Clayey silt	0–20	1.8	1550–1690	0.3–0.9	190	0.1
Fine-grained sediment	20–200	2.1	1820–2150	0.9–1.7		
Bedrock	> 200	2.4	3500	0.4		

In Chatham Sound, the seabed is generally covered with till and medium-grained harder sediments, as well as rocky outcrops (Table 9). Matthews (2013) estimated the thickness of that sediment layer as 200 m with granitic bedrock underneath the sediment layer. The geoacoustic properties were based on Philip et al. (2002).

Table 9. Estimated geoacoustic profile for Scenarios 5-6 (Chatham Sound), representing a bottom of till and medium-grained, hard sediments above granitic gneiss bedrock.

Material	Depth Below Seafloor (m)	Density (g/cm³)	Compressional Sound Speed (m/s)	Compressional Attenuation (dB/λ)	Shear Sound Speed (m/s)	Shear Attenuation (dB/λ)
Till/hard sediment	0–200	2.1	1750–2250	1.0–0.4	300	1.6
Bedrock	> 200	2.4	3500	0.4		

3.2. Ambient Noise

Ambient noise includes sound that is generated by wind and wave activities and human-made (anthropogenic) noise, such as ship traffic unrelated to the Project. Ambient underwater noise levels around Digby Island and Triple Island were measured for this Project by JASCO in 2014 and reported in Frouin-Mouy et al. (2016). Based on the analysis in this study, 50th percentile levels were used to determine the audibility zones for marine mammals and fishes (i.e., where sound levels are above both the threshold of hearing and ambient noise). The 50th percentile levels include the ambient noise contribution from all anthropogenic and natural sources that were present in the study area when measurements were taken, including wind, waves, and distant vessels. Because the 50th percentile levels, or median levels, exclude any outliers, these measurements conservatively estimate the zone of audibility. Measurements from the Digby Island station, with a broadband level of 98.6 dB re 1 µPa (Station 1; Figure 8), were used to assess the zone of audibility for Scenarios 1 to 4 (pile installations and vessels berthing). Measurements from the Triple Island station, with a broadband level of 100.0 dB re 1 µPa (Station 2; Figure 8) were applied to Scenarios 5 and 6 (vessels in transit).

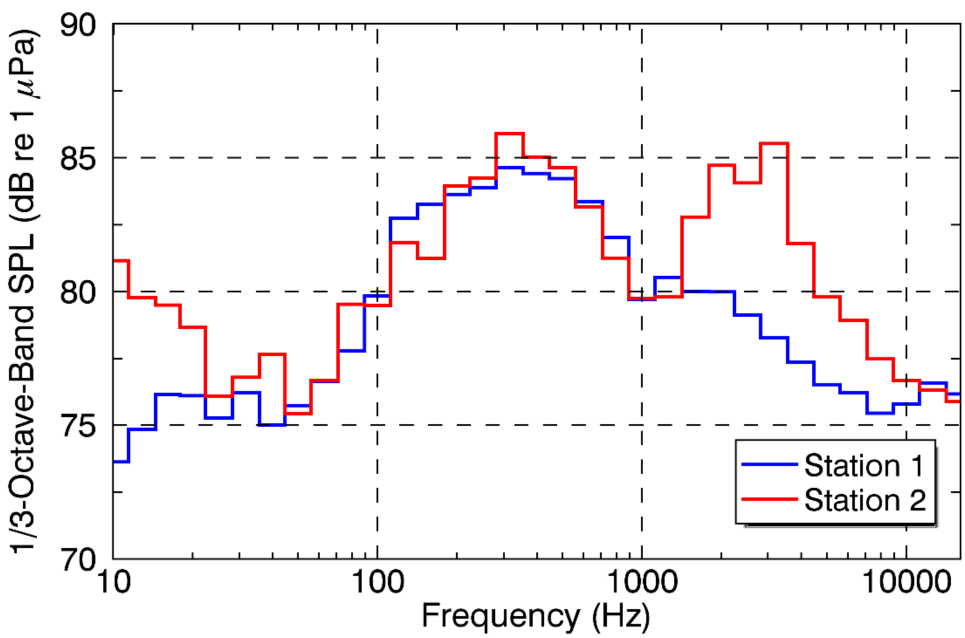

Figure 8. Ambient noise 1/3-octave-band SPL (50th percentile) for the Study Area. Station 1 was used for Scenarios 1 to 4; Station 2 was used for Scenarios 5 and 6.

4. Results

4.1. Acoustic Source Levels

The sections below detail the acoustic source levels for the sources modelled in this study.

4.1.1. Impact pile driving with confined bubble curtain

Figure 9 shows the 1/3-octave-band source levels (per-pulse SEL) used for far-field acoustic modelling of a Delmag D100-13 hammer driving cylindrical steel piles of 1.5 m diameter with a confined bubble curtain. The broadband (10 Hz–8 kHz) source levels at three modelled locations were 207.2 (MOF), 200.1 (Berth 1), and 201.0 (Berth 2) dB re 1 µPa²•s respectively. These equivalent source levels for MONM runs were obtained through FWRAM using the same hammer strike parameters for all three modelled locations. Variations between estimated source levels are therefore related to the different geoacoustics (Tables 7 and 8) and bathymetric features at each location. The most prominent difference between the estimated source levels at the MOF site and those at the berth sites at the LNG jetty is that the former shows markedly higher energy content in the frequency range of 400-1600 Hz.

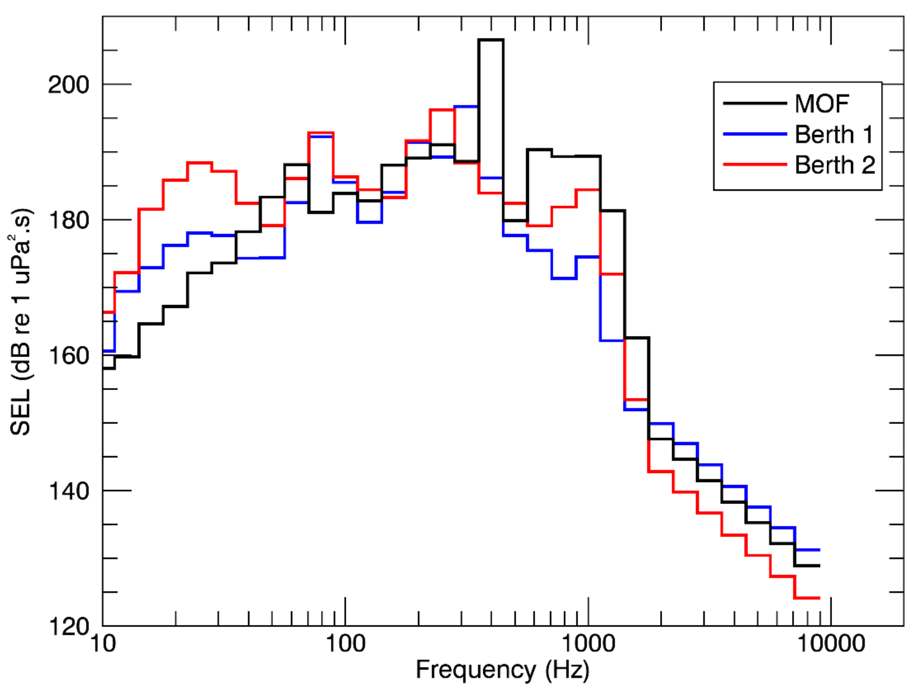

Figure 9. One-third octave-band source levels for impact pile driving with a confined bubble curtain at the three modelled locations.

4.1.2. Rock socket drilling

Source levels for rock socket drilling for pile installations were derived from published measurements (Mann et al. 2009). The spectral source levels were derived by back-propagating the measured received levels to a distance of 1 m from the source assuming spherical spreading, and adjusting for the pile diameter. Figure 10 shows the 1/3-octave-band source levels for rock socket drilling. The broadband (10 Hz–20 kHz) source level for rock socket drilling is 170.7 dB re 1 µPa.

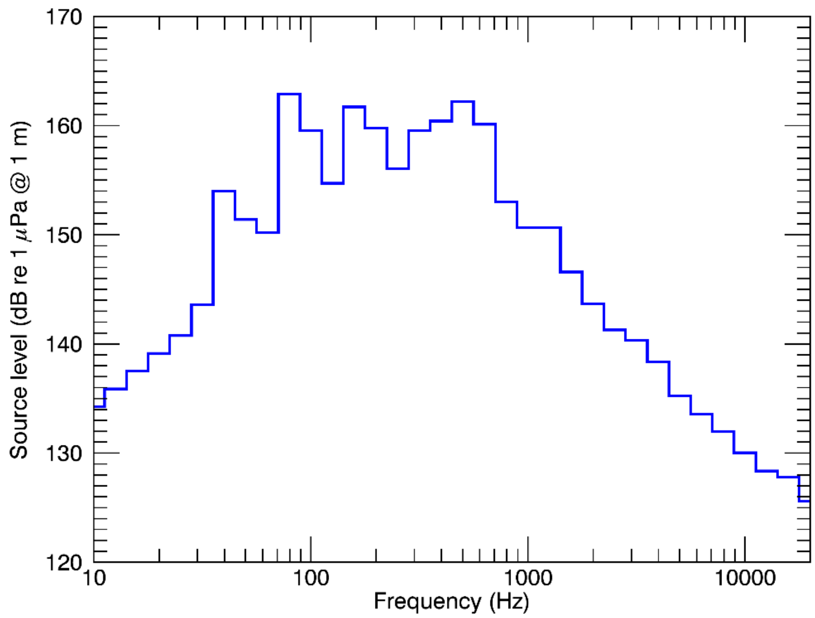

Figure 10. One-third octave-band source levels for the rock socket drilling scenario.

4.1.3. LNG carrier and tugs

Figure 11 shows the estimated 1/3-octave-band source levels for tugs and for the LNG carrier berthing and transiting. The broadband (10 Hz–16 kHz) source levels for tugs are 205.6 (transiting) and 202.6 (berthing) dB re 1 µPa; those for the LNG carrier are 186.0 (transiting) and 160.4 (berthing) dB re 1 µPa. The source level spectra for the tugs berthing and transiting differ only slightly, whereas the spectrum for the LNG carrier berthing is much lower than for the transiting scenario. While berthing, the LNG carrier's modelled speed drops from 16 kts to 6 kts, which substantially reduces its overall noise emissions. Tugs also reduce their average speed to 6 kts, but while berthing they engage in pushing and pulling the LNG carrier into its berth; this activity may require a varying amount of power (and thus result in different sound emission) depending on the wind and currents, but is intrinsically noisier. Based on the modelling assumptions, the expected source levels for individual tugs engaged in pushing/pulling operations won't be substantially different than when transiting at higher speeds.

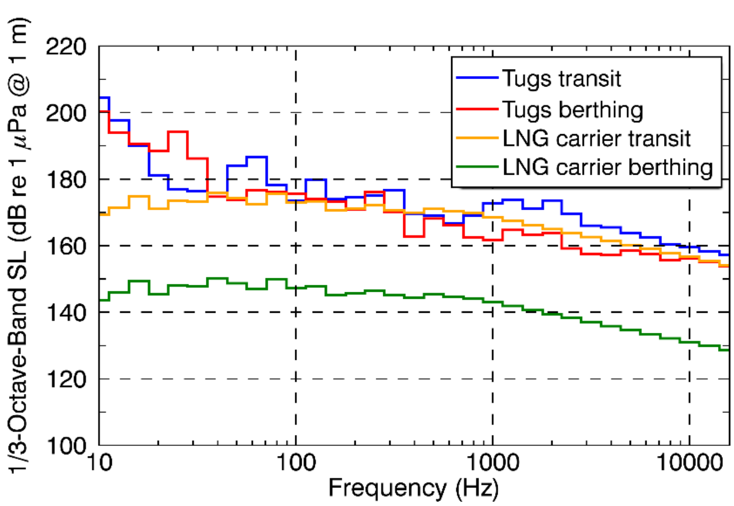

Figure 11. One-third octave-band source levels for the LNG carrier and tug scenarios.

4.2. Distances to Sound Level Thresholds

The sections below present the distances to sound level thresholds for each modelled scenario. Sound level contour maps, which show the directivity and range to various sound level isopleths, are presented in Appendix B. The reported radii for 24-hr SEL marine mammal injury thresholds by Wood et al. (2012) are based on the assumption that marine mammals are stationary during the entire period, which is very precautionary and in practical terms represents an unlikely worst-case scenario. This is discussed further in Section 5.

4.2.1. Impact pile driving with confined bubble curtain

This section includes the distances to marine mammal and fish injury thresholds, marine mammal behavioural thresholds, and edges of audibility for marine mammals and fish for Scenarios 1 and 2.

Table 10. Distances to marine mammal injury, sensory disturbance thresholds, zones of audibility, and behavioural disturbance thresholds for impact pile driving with a confined bubble curtain at the Casey Cove MOF and the south Digby Island LNG jetty.

Marine mammal group	Threshold	Reference	MOF		LNG jetty	
			R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Injury (Permanent threshold shift)						
Low-frequency cetaceans	230 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	< 0.01	N/C*	< 0.01	N/C*
Mid-frequency cetaceans	230 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	< 0.01	N/C*	< 0.01	N/C*
High-frequency cetaceans	230 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	< 0.01	N/C*	< 0.01	N/C*
Pinnipeds (in water)	218 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	< 0.01	N/C*	< 0.01	N/C*
Low-frequency cetaceans	192 re 1 µPa²·s (LFC SEL 24h)	Wood et al. (2012)	7.2	5.9	1.3	1.1
Mid-frequency cetaceans	198 re 1 µPa²·s (MFC SEL 24h)	Wood et al. (2012)	2.8	2.1	0.2	0.1
High-frequency cetaceans	179 re 1 µPa²·s (HFC SEL 24h)	Wood et al. (2012)	9.8	8.1	4.2	3.2
Pinnipeds (in water)	186 re 1 µPa²·s (PIN SEL 24h)	Wood et al. (2012)	8.8	6.9	3.1	1.8
Pinnipeds (in water)	190 re 1 µPa (SPL (rms))	NMFS (2016b)	0.1	0.1	0.02	0.02
Cetaceans	180 re 1 µPa (SPL (rms))	NMFS (2016b)	0.4	0.3	0.1	0.09
Marine mammal Local Assessment Area						
All species	160 dB re 1 µPa (SPL (rms))	DFO†	7.2	5.9	4.0	3.0
Zones of audibility						
Killer whale	above hearing threshold and ambient noise in any 1/3-octave-band	Richardson et al. (1995)	29.7	28.2	26.3	22.7

Marine mammal group	Threshold	Reference	MOF		LNG jetty	
			R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Humpback whale	above hearing threshold and ambient noise in any 1/3-octave-band	Richardson et al. (1995)	29.7	28.2	26.3	22.7
Harbour seal	above hearing threshold and ambient noise in any 1/3-octave-band	Richardson et al. (1995)	29.7	28.2	26.3	22.7
Harbour porpoise	above hearing threshold and ambient noise in any 1/3-octave-band	Richardson et al. (1995)	29.7	28.2	26.3	22.7
Behavioural disturbance thresholds						
All marine mammals	160 dB re 1 µPa (SPL (rms))	NMFS (2016b)	7.2	5.9	4.0	3.0
Killer whale	57 dBht(killer whale)	MacGillivray et al. (2012)	7.1	5.5	3.8	2.9
	64 dBht(killer whale)	MacGillivray et al. (2012)	2.7	2.1	1.4	1.1
Humpback whale	73 dBht(humpback whale)	McCauley et al. (2000)	26.8	25.5	26.3	22.6
Harbour seal	64 dBht(harbour seal)	MacGillivray et al. (2012)	26.8	21.3	26.3	22.5
Harbour porpoise	45 dBht(harbour porpoise)	Tougaard et al. (2015)	20.7	10.5	26.2	20.9

* Not computed because time domain pile driving signatures were modelled at a single radial from the pile.

† DFO has advised Aurora LNG that for the assessment of the Project, the LAA should be set to encompass the area where any Project activity (construction, operations, decommissioning) will exceed 160 dB (BC EAO 2015).

Table 11. Distances to fish injury thresholds for impact pile driving with a confined bubble curtain at the Casey Cove MOF and the south Digby Island LNG jetty. Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

Fish group	Threshold	Reference	MOF		LNG jetty	
			R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Mortality and potential mortal injury						
I	213 dB re 1 µPa (peak pressure level)	Popper et al. (2014)	< 0.02	N/C*	< 0.01	N/C*
II, III	207 dB re 1 µPa (peak pressure level)	Popper et al. (2014)	0.03	N/C*	< 0.02	N/C*
I	219 dB re 1 µPa²·s (SEL 24h)	Popper et al. (2014)	0.1	0.09	< 0.01	< 0.01
II	210 dB re 1 µPa²·s (SEL 24h)	Popper et al. (2014)	0.6	0.4	0.04	0.03
III	207 dB re 1 µPa²·s (SEL 24h)	Popper et al. (2014)	0.8	0.7	0.06	0.06
Recoverable injury						
I	213 dB re 1 µPa (peak pressure level)	Popper et al. (2014)	< 0.02	N/C*	< 0.01	N/C*
II, III	207 dB re 1 µPa (peak pressure level)	Popper et al. (2014)	0.03	N/C*	< 0.02	N/C*

Fish group	Threshold	Reference	MOF		LNG jetty	
			R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
I	216 dB re 1 µPa²·s (SEL 24h)	Popper et al. (2014)	0.2	0.1	0.01	0.01
II, III	203 dB re 1 µPa²·s (SEL 24h)	Popper et al. (2014)	1.8	1.1	0.1	0.1
Temporary threshold shift						
I, II, III	186 dB re 1 µPa²·s (SEL 24h)	Popper et al. (2014)	9.0	6.9	3.5	2.5
Best management practices for pile driving and related operations in British Columbia (30 kPa equivalent)						
All	210 dB re 1 µPa (peak pressure level)	BC MPDCA and DFO (2003)	0.02	N/C*	< 0.02	N/C*

* Not computed, since time domain pile driving signatures were modelled at a single radial from the pile.

Table 12. Distances to fish zone of audibility for impact pile driving with a confined bubble curtain at the Casey Cove MOF and the south Digby Island LNG jetty.

Fish group	MOF		LNG jetty	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Salmon	26.8	25.5	26.3	22.6
Herring	29.7	28.2	26.3	22.7

4.2.2. Rock socket drilling

This section includes the distances to marine mammal injury thresholds, marine mammal behavioural thresholds, and edges of audibility for marine mammals and fish for Scenario 3.

Table 13. Distances to marine mammal injury thresholds, sensory disturbance thresholds, zones of audibility, and behavioural disturbance thresholds for rock socket drilling at Berths 1 and 2 simultaneously in Scenario 3. A dash in table cells indicates that threshold was not reached.

Marine mammal group	Threshold	Reference	LNG jetty	
			R_{max} (km)	$R_{95\%}$ (km)
Injury (Permanent threshold shift)				
Low-frequency cetaceans	230 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	-	-
Mid-frequency cetaceans	230 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	-	-
High-frequency cetaceans	230 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	-	-
Pinnipeds (in water)	218 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	-	-
Low-frequency cetaceans	215 re 1 µPa²·s (LFC SEL 24 h)	Southall et al. (2007)	-	-

Marine mammal group	Threshold	Reference	LNG jetty	
			R_{max} (km)	$R_{95\%}$ (km)
Mid-frequency cetaceans	215 re 1 µPa²·s (MFC SEL 24 h)	Southall et al. (2007)	-	-
High-frequency cetaceans	215 re 1 µPa²·s (HFC SEL 24 h)	Southall et al. (2007)	-	-
Pinnipeds (in water)	203 re 1 µPa²·s (SEL 24 h)	Southall et al. (2007)	< 0.01	< 0.01
Pinnipeds (in water)	190 dB re 1 µPa (SPL (rms))	NMFS (2016b)	-	-
Cetaceans	180 dB re 1 µPa (SPL (rms))	NMFS (2016b)	-	-
Marine mammal Local Assessment Area				
All species	160 dB re 1 µPa (SPL (rms))	DFO†	< 0.01	< 0.01
Zones of audibility				
Killer whale	above hearing threshold and ambient noise in any 1/3-octave-band	Richardson et al. (1995)	26.3	21.8
Humpback whale	above hearing threshold and ambient noise in any 1/3-octave-band	Richardson et al. (1995)	26.3	22.7
Harbour seal	above hearing threshold and ambient noise in any 1/3-octave-band	Richardson et al. (1995)	26.3	22.7
Harbour porpoise	above hearing threshold and ambient noise in any 1/3-octave-band	Richardson et al. (1995)	26.3	22.5
Behavioural disturbance thresholds				
All marine mammals	120 dB re 1 µPa (SPL (rms))	NMFS (2016b)	5.8	3.9
Killer whale	57 dB_{ht}(killer whale)	MacGillivray et al. (2012)	0.7	0.5
	64 dB_{ht}(killer whale)	MacGillivray et al. (2012)	0.2	0.1
Humpback whale	73 dB_{ht}(humpback whale)	McCauley et al. (2000)	4.7	3.6
Harbour seal	64 dB_{ht}(harbour seal)	Bailey et al. (2010)	1.8	1.4
Harbour porpoise	45 dB_{ht}(harbour porpoise)	Tougaard et al. (2015)	2.2	1.7

-Threshold not reached.
† DFO has advised Aurora LNG that for the assessment of the Project, the LAA should be set to encompass the area where any Project activity (construction, operations, decommissioning) will exceed 160 dB (BC EAO 2015).

Table 14. Distances to fish zone of audibility for rock socket drilling at Berths 1 and 2 simultaneously in Scenario 3.

Fish group	LNG jetty	
	R_{max} (km)	$R_{95\%}$ (km)
Salmon	21.2	16.4
Herring	26.3	22.7

4.2.3. LNG carrier—Berthing

This section includes the distances to marine mammal injury and behavioural thresholds, and zones of audibility for marine mammals and fish for Scenario 4. In this scenario the edge of the zone of audibility exceeded the bounds of the modelled area (~39 km from the source) for all marine mammal species and for herring, so that only a lower bound can be given for R_{max} and the value of $R_{95\%}$ cannot be calculated.

Table 15. Distances to marine mammal sensory disturbance thresholds, zones of audibility, and behavioural disturbance thresholds for the LNG carrier berthing approach at the south Digby Island LNG jetty measured from the central point of all sources in Scenario 4. A dash in table cells indicates that threshold was not reached.

Marine mammal group	Threshold	Reference	LNG jetty	
			R_{max} (km)	$R_{95\%}$ (km)
Injury (Permanent threshold shift)				
Low-frequency cetaceans	230 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	-	-
Mid-frequency cetaceans	230 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	-	-
High-frequency cetaceans	230 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	-	-
Pinnipeds (in water)	218 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	-	-
Low-frequency cetaceans	215 re 1 µPa²·s (LFC SEL 24 h)	Southall et al. (2007)	0.02¤	0.02¤
Mid-frequency cetaceans	215 re 1 µPa²·s (MFC SEL 24 h)	Southall et al. (2007)	< 0.01¤	< 0.01¤
High-frequency cetaceans	215 re 1 µPa²·s (HFC SEL 24 h)	Southall et al. (2007)	< 0.01¤	< 0.01¤
Pinnipeds (in water)	203 re 1 µPa²·s (PIN SEL 24 h)	Southall et al. (2007)	0.03¤	0.03¤
Pinnipeds (in water)	190 dB re 1 µPa (SPL (rms))	NMFS (2016b)	< 0.01¤	< 0.01¤
Cetaceans	180 dB re 1 µPa (SPL (rms))	NMFS (2016b)	0.02¤	0.02¤
Marine mammal Local Assessment Area				
All species	160 dB re 1 µPa (SPL (rms))	DFO†	0.07	0.07
Zones of audibility				
All marine mammals	max(hearing threshold, ambient) in any 1/3-octave-band	Richardson et al. (1995)	> 38.9	N/C*
Behavioural disturbance thresholds				
All marine mammals	120 dB re 1 µPa (SPL (rms))	NMFS (2016b)	12.2	9.6
Killer whale	57 dB_{ht}(killer whale)	MacGillivray et al. (2012)	8.6	7.7
Killer whale	64 dB_{ht}(killer whale)	MacGillivray et al. (2012)	6.4	4.6
Humpback whale	73 dB_{ht}(humpback whale)	McCauley et al. (2000)	15.9	11.1
Harbour seal	64 dB_{ht}(harbour seal)	Bailey et al. (2010)	5.3	4.2
Harbour porpoise	45 dB_{ht}(harbour porpoise)	Tougaard et al. (2015)	28.3	22.5

-Threshold not reached.
¤ Maximum distance from individual vessel.
* Not computed.
† DFO has advised Aurora LNG that for the assessment of the Project, the LAA should be set to encompass the area where any Project activity (construction, operations, decommissioning) will exceed 160 dB (BC EAO 2015).

Table 16. Distances to fish zone of audibility for the LNG carrier berthing approach at the south Digby Island LNG jetty measured from the central point of all sources in Scenario 4.

Fish group	LNG jetty	
	R_{max} (km)	$R_{95\%}$ (km)
Salmon	25.5	20.4
Herring	> 38.8	N/C*

* Not computed.

4.2.4. LNG carrier—Transiting

This section includes the distances to marine mammal injury and behavioural thresholds, and zones of audibility for marine mammals and fishes for Scenarios 5 and 6. In this scenario the edge of the zone of audibility exceeded the bounds of the modelled area (~65 km from the source) for all marine mammal species and for herring, so that only a lower bound can be given for R_{max} and the value of $R_{95\%}$ cannot be calculated.

Table 17. Distances (km) to marine mammal sensory disturbance thresholds, zones of audibility, and behavioural disturbance thresholds for the LNG carrier transiting in south Chatham Sound and Triple Island pilot station measured from the central point of all sources in Scenarios 5 and 6. A dash in table cells indicates that threshold was not reached.

Marine mammal group	Threshold	Reference	South Chatham Sound		Triple Island pilot station	
			R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Injury (Permanent threshold shift)						
Low-frequency cetaceans	230 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	-	-	-	-
Mid-frequency cetaceans	230 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	-	-	-	-
High-frequency cetaceans	230 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	-	-	-	-
Pinnipeds (in water)	218 dB re 1 µPa (peak pressure level)	Southall et al. (2007)	-	-	-	-
Low-frequency cetaceans	215 re 1 µPa²·s (LFC SEL 24 h)	Southall et al. (2007)	< 0.01[¤]	< 0.01[¤]	< 0.01[¤]	< 0.01[¤]
Mid-frequency cetaceans	215 re 1 µPa²·s (MFC SEL 24 h)	Southall et al. (2007)	-	-	-	-
High-frequency cetaceans	215 re 1 µPa²·s (HFC SEL 24 h)	Southall et al. (2007)	-	-	-	-
Pinnipeds (in water)	203 re 1 µPa²·s (PIN SEL 24 h)	Southall et al. (2007)	< 0.01[¤]	< 0.01[¤]	< 0.01[¤]	< 0.01[¤]
Pinnipeds (in water)	190 dB re 1 µPa (SPL (rms))	NMFS (2016b)	< 0.01[¤]	< 0.01[¤]	< 0.01[¤]	< 0.01[¤]
Cetaceans	180 dB re 1 µPa (SPL (rms))	NMFS (2016b)	0.01[¤]	0.01[¤]	0.01[¤]	0.01[¤]

Marine mammal group	Threshold	Reference	South Chatham Sound		Triple Island pilot station	
			R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Marine mammal Local Assessment Area						
All species	160 dB re 1 µPa (SPL (rms))	DFO†	0.1	0.1	0.1	0.1
Zones of audibility						
All marine mammals	above hearing threshold and ambient noise in any 1/3-octave-band	Richardson et al. (1995)	> 64.9	N/C*	> 65.1	N/C*
Behavioural disturbance thresholds						
All marine mammals	120 dB re 1 µPa (SPL (rms))	NMFS (2016b)	23.3	15.0	21.4	12.6
Killer whale	57 dB_{ht}(killer whale)	MacGillivray et al. (2012)	12.8	9.5	10.7	9.6
Killer whale	64 dB_{ht}(killer whale)	MacGillivray et al. (2012)	5.9	5.7	6.5	5.6
Humpback whale	73 dB_{ht}(humpback whale)	McCauley et al. (2000)	29.5	23.7	35.7	27.2
Harbour seal	64 dB_{ht}(harbour seal)	Bailey et al. (2010)	16.9	10.4	14.3	8.5
Harbour porpoise	45 dB_{ht}(harbour porpoise)	Tougaard et al. (2015)	51.3	39.5	51.5	43.9

-Threshold not reached.
¤ Maximum distance from individual vessel.
* Not computed.
† DFO has advised Aurora LNG that for the assessment of the Project, the LAA should be set to encompass the area where any Project activity (construction, operations, decommissioning) will exceed 160 dB (BC EAO 2015).

Table 18. Distances (km) to fish zone of audibility for LNG transiting in south Chatham Sound and Triple Island pilot station measured from the central point of all sources in Scenarios 5 and 6.

Fish group	South Chatham Sound		Triple Island pilot station	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Salmon	33.7	24.0	47.3	26.4
Herring	> 64.8	N/C*	> 65.1	N/C*

* Not computed.

5. Discussion and Conclusions

The purpose of this study was to assess the extents over which marine mammal and fish species could be affected by noise from impact pile driving, rock socket drilling, and LNG carrier activities near the Project site. Acoustic models were used to predict noise levels from the Project activities and compare them with various effect metrics. In addition to impact thresholds and criteria broadly applicable to all marine mammal (distinguished by hearing groups) and fish species, where species-specific thresholds were available they were considered for key species of interest (humpback whale, killer whale, harbour porpoise, harbour seal, salmon, and herring).

Acoustic footprints were modelled by considering multiple sound sources for each operation to account for the noise emissions of all the relevant activities and equipment. The acoustic modelling was carried out using a combination of JASCO's Marine Operations Noise Model (MONM) and Full Waveform Range-dependent Acoustic Model (FWRAM). Model results were M-weighted to estimate effective received levels for four marine mammal hearing groups and audiogram weighted relative to several key species' hearing thresholds. Distances to all effect thresholds are presented in tables of maximum (R_{max}) ranges, the maximum distances at which thresholds are exceeded, and 95% ranges ($R_{95\%}$), the maximum range at which the given sound level was encountered after excluding 5% of the farthest such points to provide an estimate less affected by sound field outliers (see Tables 10–17).

Where uncertainties in operating conditions existed, the models were parametrized to yield realistically conservative noise levels. We applied several such conservative assumptions to the methods used in this study so the results would not underestimate potential effects on marine life:

- Because marine mammals may sample a wide depth range, all the distances to thresholds (R_{max}, $R_{95\%}$) and noise level contour maps represent the maximum sound levels over all depths.
- Because the Project schedule was not finalized at the time of modelling, and operations could occur throughout the year, we used the December sound speed profile which is upward-refracting and yields larger distances to sound level thresholds.
- The model location selected for impact pile driving at the MOF is where land was least likely to obstruct sound propagation. In addition, for the three modelled locations, we assumed a wall thickness for the piles that produced higher noise levels within realistic design parameters.
- Since sound levels generally increase with vessel speed, the LNG carrier and escort tugs were modelled at the maximum expected speed (16 knots) along the route between Triple Island pilot station and Digby Island.

Neither British Columbia nor Canada has prescribed sound level criteria for assessing injury or behavioural responses of marine animals to non-explosive noise sources. Previous assessments have generally deferred to the NMFS-recommended SPL (rms) criteria, which we have also done to facilitate cross-study comparisons. Additionally we computed results for criteria recommended by the BC MPDCA and DFO (2003), Southall et al. (2007), Wood et al. (2012), and Popper et al. (2014). Distances to marine mammal behavioural disturbance were calculated based on levels above hearing thresholds proposed by McCauley et al. (2000), Bailey et al. (2010), MacGillivray et al. (2012), and Tougaard et al. (2015). The zones of audibility were calculated as the region over which activity sound levels exceeded both the hearing threshold and ambient noise levels in the same frequency bands.

5.1. Potential Effects of Impact Pile Driving Noise on Marine Fauna

For impact pile driving, distances to marine mammal injury peak pressure level criteria were not reached beyond 10 m from the pile. The maximum distances to 190 dB re 1 µPa SPL were 0.1 km (MOF) and 0.02 km (LNG jetty); the maximum distances to 180 dB re 1 µPa SPL were 0.4 km (MOF) and 0.1 km (LNG jetty). The maximum distances to 24-hr M-weighted species-specific injury thresholds were 0.2 km to 9.8 km depending on the marine mammal group. Comparison of 24-hr SEL and peak pressure level injury thresholds radii requires understanding of the assumptions involved to obtain each metric. Peak pressure level thresholds reflect the potential range at which an animal could be injured by a single exposure to loud short-duration noise such as impact pile driving, and is usually limited to a short distance (i.e., within metres) from the pile. 24-hr SEL is a cumulative metric, reflecting the dosimetric impact of noise levels within a period of 24 hours under the assumption that an animal is consistently exposed to such noise levels at a fixed position. The corresponding radii are generally larger than those for peak pressure criteria but they represent an unlikely worst case scenario since, more realistically, marine mammals would not stay in the same location or at the same range for the whole 24-hr period. Therefore, a reported radius for 24-hr SEL criteria does not mean that any animal coming within this radius of the source will be injured, unless it were to remain within that range throughout the 24-hour period.

The maximum distance to the 160 dB re 1 µPa SPLNMFS threshold for behavioural disturbance due to pulsed noise (also DFO Local Assessment Area threshold) is 7.2 km (MOF) and 4.0 km (LNG jetty).

Based on published criteria (Section 1.3, Appendix A.2.1.2) we computed the following maximum distances to species-specific behavioural thresholds:

- 45 dB_{ht}(harbour porpoise): 20.7 km (MOF) and 26.2 km (LNG jetty)
- 57 dB_{ht}(killer whale, subtle response): 7.1 km (MOF) and 3.8 km (LNG jetty)
- 64 dB_{ht}(killer whale, overt response): 2.7 km (MOF) and 1.4 km (LNG jetty)
- 64 dB_{ht}(harbour seal): 26.8 km (MOF) and 26.3 km (LNG jetty)
- 73 dB_{ht}(humpback whale): 26.8 km (MOF) and 26.3 km (LNG jetty)

The maximum distances to peak pressure level for fish injury thresholds were 0.03 km (MOF) and less than 0.02 km (LNG jetty); maximum distances to 24-hr SEL fish injury thresholds were between less than 0.01 km and 9.0 km depending on the injury types and fish species.

For Scenario 2 (LNG jetty), in which concurrent piling operations are staged in separate locations at Berths 1 and 2, the effect radii for given thresholds had to be determined by visually inspecting pile driving noise contours maps. For thresholds which resulted in joined contours around both pilling locations, effect radii were measured from the center between Berths 1 and 2. For thresholds that yielded separate contours around each pilling site, effect radii were measured from the corresponding pile.

The following thresholds resulted in disjoined contours (Figure B-7 through Figure B-11):

- Marine mammal NMFS interim SPL (rms) injury thresholds, 190 and 180 dB re 1 µPa SPL (rms)
- Marine mammal MFC injury thresholds, 198 dB re 1 μPa^2.s (SEL 24 h)
- Fish mortality, potential mortal injury, and recoverable injury thresholds

Despite the proximity and similar pile driving conditions for Berths 1 and 2, noise emanating from Berth 2 propagated farther (Figure B-7 to Figure B-11). As can be seen from Figure 12 this effect results from local bathymetric features at Berth 1, such as the water depth decreasing from 22 m at the pile location to 10 m at 600 m range along the radial shown, that hindered the propagation properties of the waveguide.

The maximum range to the edge of the zone of audibility for all marine mammals and fish was 29.7 km.

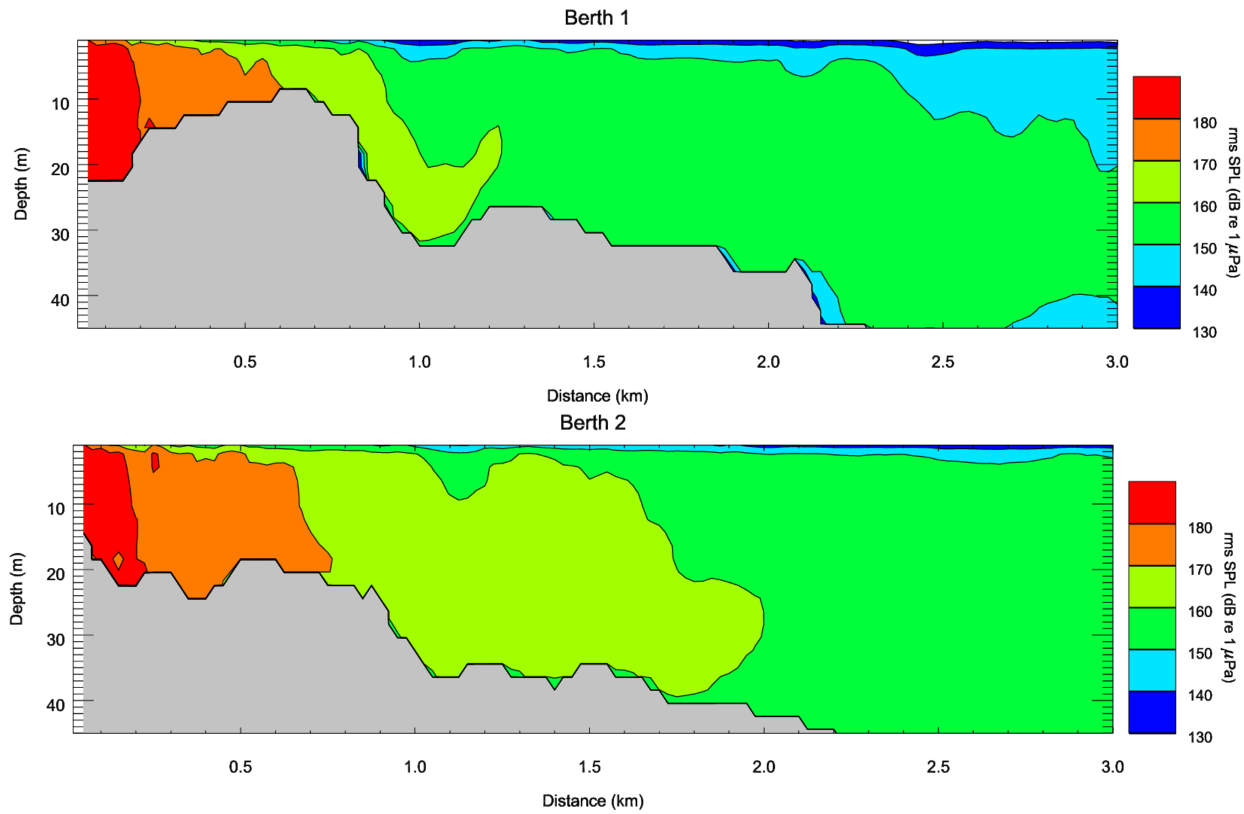

Figure 12. SPL (rms) at Berths 1 and 2 showing the effect of local bathymetric features on pile driving noise propagation. These results are from FWRAM runs along a radial pointing south from each site.

5.2. Potential Effects of Rock Socket Drilling Noise on Marine Fauna

Distances to marine mammal injury thresholds for rock socket drilling noise did not exceed 10 m from the pile location. The maximum distance to the 120 dB re 1 µPa (SPL (rms)) NMFS threshold for behavioural disturbance due to non-impulsive noise is 5.8 km.

Based on published criteria (Section 1.3, Appendix A.2.1.2) we computed the following maximum distances to species-specific behavioural thresholds:

- 45 dB_{ht}(harbour porpoise): 2.2 km
- 57 dB_{ht}(killer whale, subtle response): 0.7 km
- 64 dB_{ht}(killer whale, overt response): 0.2 km
- 64 dB_{ht}(harbour seal): 1.8 km
- 73 dB_{ht}(humpback whale): 4.7 km

The maximum distances to killer whale audiogram-weighted levels of 57 dB_{ht} and 64 dB_{ht} were computed from both drilling locations (Berths 1 and 2; Figure B-14). The maximum distances to other audiogram-weighted thresholds (Appendix A.2.1.2) were computed from the center between the two drilling locations because the ensonified areas from the two operations merged into a single footprint and the range to thresholds exceeded the distance between these two drilling locations.

The maximum distance to the DFO Local Assessment Area threshold of 160 dB re 1 µPa SPL was less than 0.01 km.

The maximum range to the edge of the zone of audibility was 26.3 km for all marine mammals and for herring; it was slightly smaller for salmon (21.2 km).

5.3. Potential Effects of LNG Carrier Noise on Marine Fauna

For LNG carrier activities, the ranges to marine mammal injury thresholds were smaller than each vessel's dimensions. The maximum distance to the 120 dB re 1 µPa (SPL (rms)) NMFS threshold for behavioural disturbance due to non-impulsive noise is between 12.2 km and 23.3 km, depending on the operational type (berthing or transiting) and the modelled site.

Based on published criteria (Section 1.3, Appendix A.2.1.2) we computed the following maximum distances to species-specific behavioural thresholds, depending on the modelled scenario and location:

- 45 dB_{ht}(harbour porpoise): 28.3 to 51.5 km
- 57 dB_{ht}(killer whale, subtle response): 8.6 to 12.8 km
- 64 dB_{ht}(killer whale, overt response): 5.9 to 6.5 km
- 64 dB_{ht}(harbour seal): 5.3 to 16.9 km
- 73 dB_{ht}(humpback whale): 15.9 to 35.7 km

The maximum distance to the DFO Local Assessment Area threshold of 160 dB re 1 µPa SPL was 0.1 km.

The maximum range to the edge of the zone of audibility for all marine mammals and for herring extended beyond the bounds of the modelled area (~40 and ~65 km from the source for the berthing and transiting scenarios respectively). The range was smaller for salmon, with a maximum of 30 km for vessels transiting in south Chatham Sound.

To calculate 24-hr SEL for vessel operations, some plausible operational schedules had to be assumed – which may or may not reflect the true level of activity once the terminal is in use. For berthing operations, it was assumed in the absence of activity forecasts that an outside maximum of 4 berthing events per day (2 arrivals and 2 departures) could take place at one berth and each event took 60 min. Our model shows that the thresholds to injury criteria (Southall et al. 2007) for cetaceans (215 dB re 1 $\mu Pa^2 \cdot s$) and for pinniped (203 dB re 1 $\mu Pa^2 \cdot s$) are not reached beyond the footprint of the vessel (radii are less than 30 m from the source location). For transiting at a waypoint, on the assumption that 2 vessels a day visited each of the 2 berths for a total of 8 passages, the model results show that the thresholds to injury criteria (Southall et al. 2007) for cetaceans (215 dB re 1 $\mu Pa^2 \cdot s$) and for pinniped (203 dB re 1 $\mu Pa^2 \cdot s$) are not reached beyond a distance of 10 m from the source.

The 180 and 190 dB re 1 µPa (SPL (rms)) NMFS injury thresholds are not reached beyond 0.02 km. The peak pressure level (218 and 230 dB re 1 µPa) from Southall et al. (2007) are not reached.

Glossary

1/3-octave-band
Non-overlapping passbands that are one-third of an octave wide (where an octave is a doubling of frequency). Three adjacent 1/3-octave-bands make up one octave. One-third-octave-bands become wider with increasing frequency. See also octave.

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

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

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

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

auditory weighting function (frequency-weighting function)
Auditory weighting functions account for marine mammal hearing sensitivity. They are applied to sound measurements to emphasise frequencies that an animal hears well and de-emphasise frequencies they hear less well or not at all (Southall et al. 2007, Finneran and Jenkins 2012, NOAA 2013).

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

bar
Unit of pressure equal to 100 kPa, which is approximately equal to the atmospheric pressure on Earth at sea level. 1 bar is equal to $10^{6\ \mathrm{Pa}}$ or $10^{11\ \mu\mathrm{Pa}}$.

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

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

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

fish injury
Direct physical injury (including permanent auditory threshold shift (PTS) and trauma in swim bladder) in fish exposed to underwater noise.

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.

functional hearing group
Grouping of marine mammal species with similar estimated hearing ranges. Southall et al. (2007) proposed the following functional hearing groups: low-, mid-, and high-frequency cetaceans, pinnipeds in water, and pinnipeds in air.

geoacoustic
Relating to the acoustic properties of the seabed.

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

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

high-frequency cetacean
The functional hearing group that represents odontocetes specialised for using high frequencies.

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

low-frequency cetacean
The functional hearing group that represents mysticetes (baleen whales).

marine mammal disturbance
Behavioural disruption in marine mammals exposed to underwater noise.

marine mammal injury
Direct physical injury (including permanent auditory threshold shift (PTS) and trauma in lungs) in marine mammals exposed to underwater noise.

masking
The process or the amount by which the threshold of hearing for one sound is raised by the presence of another (masking) sound, expressed in dB (ANSI/ASA S3.20-1995 R2008).

mid-frequency cetacean
The functional hearing group that represents some odontocetes (dolphins, toothed whales, beaked whales, and bottlenose whales).

M-weighting
The process of band-pass filtering loud sounds to reduce the importance of inaudible or less-audible frequencies for broad classes of marine mammals. “Generalized frequency weightings for various functional hearing groups of marine mammals, allowing for their functional bandwidths and appropriate in characterizing auditory effects of strong sounds” (Southall et al. 2007).

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

non-impulsive sound
Sound that is broadband, narrowband or tonal, brief or prolonged, continuous or intermittent, and typically does not have a high peak pressure with rapid rise time (typically only small fluctuations in decibel level) that impulsive signals have (ANSI/ASA S3.20-1995 R2008). Marine vessels, aircraft, machinery, construction, and vibratory pile driving are examples.

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

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

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

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

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

Phon
A unit of loudness that measures the intensity of a sound by the number of decibels (dB) above a reference tone having a frequency of 1000 hertz and a root-mean-square sound pressure of 20 micropascal (μPa).

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

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

power spectrum density
The acoustic signal power per unit frequency as measured at a single frequency. Unit: $\mu Pa^2/Hz$, or $\mu Pa^2 \cdot s$.

power spectrum density level
The decibel level ($10\log_{10}$) of the power spectrum density, usually presented in 1 Hz bins. Unit: dB re 1 $\mu Pa^2/Hz$.

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

received level
The sound level measured at a receiver.

rms
root-mean-square.

fast average sound pressure level
The average of the instantaneous sound pressure calculated with an exponentially-decreasing time window with a 125 ms decay constant. This metric is typically applied to characterize perceptive response of animals to impulsive noise events.

rms sound pressure level
The root-mean-square average of the instantaneous sound pressure as measured over some specified time interval. For continuous sound, the time interval is one second. Also see fast average sound pressure level and 90% SPL (rms).

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

signature
Pressure signal generated by a source.

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

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

sound exposure level (SEL)
A measure related to the sound energy in one or more pulses. Unit: dB re 1 $\mu Pa^2 \cdot s$.

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

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

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

$$\mathrm{SPL} = 10\log_{10}\left(p^2 / p_0^2\right) = 20\log_{10}\left(p / p_0\right)$$

Unless otherwise stated, SPL refers to the root-mean-square (rms) sound pressure level.

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

source level (SL)
The sound pressure level measured 1 meter from a theoretical point source that radiates the same total sound power as the actual source. Unit: dB re 1 μPa @ 1 m.

spectrum
An acoustic signal represented in terms of its power (or energy) distribution versus frequency.

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

time-average sound level (L_{eq})

A time-average sound level during a specified period. Equal to the corresponding sound exposure level according to L_{eq} = SEL − 10 log(T) where T is time in seconds; measured in units of dB re 1 μPa.

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

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

zone of audibility
The area within which the animal might hear a particular sound above local background.

zone of responsiveness
The region within which the animal may react behaviourally or physiologically to a particular sound.

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Appendix A. Underwater Acoustics

This section provides a detailed description of the acoustic metrics relevant to the modelling study and the modelling methodology.

A.1. Acoustic Metrics

Underwater sound amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa. Because the perceived loudness of sound, especially impulsive noise 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 noise and its effects on marine life.

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

$$\text{Peak pressure level} = 10\log_{10}\left[\frac{\max\left(\left|p^2(t)\right|\right)}{p_0^2}\right] \tag{A-1}$$

At high intensities, the peak pressure level can be a valid criterion for assessing whether a sound is potentially injurious; however, because the peak pressure level does not account for the duration of a noise event, it is a poor indicator of perceived loudness.

The root-mean-square (rms) SPL (dB re 1 μPa) is the rms pressure level in a stated frequency band over a time window (T, s) containing the acoustic event:

$$\text{SPL (rms)} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_0^2\right) \tag{A-2}$$

The SPL (rms) is a measure of the average pressure or of the effective pressure over the duration of an acoustic event, such as the emission of one acoustic pulse, a marine mammal vocalization, the passage of a vessel, or a fixed duration. Because the window length, T, is the divisor, events more spread out in time have a lower SPL (rms) for the same total acoustic energy density.

In studies of impulsive noise, T is often defined as the “90% energy pulse duration” (T_{90}): the interval over which the pulse energy curve rises from 5% to 95% of the total energy. The SPL computed over this T_{90} interval is commonly called the 90% SPL (rms) (dB re 1 μPa):

$$\text{90\% SPL (rms)} = 10\log_{10}\left(\frac{1}{T_{90}}\int_{T_{90}} p^2(t)dt \Big/ p_0^2\right) \tag{A-3}$$

The audibility of impulsive sounds is influenced by frequency content, signal duration, and repetition rate. A simple leaky integrator (Plomp and Bouman 1959) modelled human loudness perception of short duration sounds using an exponentially-decaying time window. This calculation is now implemented by most sound level meters used for monitoring impulsive or short-duration noise event exposures to humans. The fast average SPL setting of sound level meters uses an integration time constant τ of 125 ms. Tougaard et al. (2015) suggested a related “rms fast average” (SPL (rms), see Section 1.2) for underwater sound characterization which can be calculated from the rms-average over the duration of the pulse (L_{eq}) as:

$$\text{SPL (rms)} = L_{eq} + 10\times\log_{10}(1 - e^{-d/\tau}), \tag{A-4}$$

where d is the pulse duration in seconds and τ is 0.125 s. SPL (rms) is a sound pressure level (L_{eq}) of a 125 ms signal of constant amplitude having the same energy as a 125 ms window of the signal.

When pulse repetition rates become high so that more than a single pulse occurs within the integration time period, the equation from Tougaard et al. (2015) doesn't account for the additional sound energy of the other pulses. Plomp and Bouman (1959) had proposed a method for dealing with this, which we have included here. This was implemented by using the 90% energy pulse period (T_{90}) as the signal duration, and accounting for the inter-pulse period T in a modified form of Tougaard's expression:

$$\text{SPL (rms)} = L_{eq} + 10 \times \log_{10}\left(\frac{1 - e^{-T_{90}/\tau}}{1 - e^{-T/\tau}}\right). \tag{A-5}$$

The sound exposure level (SEL, dB re 1 μPa²·s) is a measure of the total acoustic energy contained in one or more acoustic events. The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (T_{100}):

$$\text{SEL} = 10\log_{10}\left(\int_{T_{100}} p^2(t)dt \Big/ T_0 p_0^2\right) \tag{A-6}$$

where T_0 is a reference time interval of 1 s. The SEL represents the total acoustic energy received at some location during an acoustic event; it measures the total sound energy to which an organism at that location would be exposed.

SEL is a cumulative metric if it is calculated over periods with multiple acoustic events or over fixed period. For multiple events, the cumulative SEL (dB re 1 μPa²·s) can be computed by summing (in linear units) the SEL values of the N individual events (A-6). For a fixed duration, the pressure is summed over the duration of interest (A-3).

$$\text{Cumulative SEL} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{\text{SEL}_i}{10}}\right) \tag{A-7}$$

To compute the SPL and SEL of acoustic events in the presence of high levels of background noise, Equations A-3 and A-6 are modified to subtract the background noise energy from the event energy:

$$\text{SPL (rms)} = 10\log_{10}\left(\frac{1}{T_{90}}\int_{T_{90}} (p^2(t) - \overline{n^2})dt \Big/ p_0^2\right) \tag{A-8}$$

$$\text{SEL} = 10\log_{10}\left(\int_{T_{100}} (p^2(t) - \overline{n^2})dt \Big/ T_0 p_0^2\right) \tag{A-9}$$

where $\overline{n^2}$ is the mean square pressure of the background noise generally computed by averaging the squared pressure of a nearby segment of the acoustic recording during which acoustic events are absent (e.g., between pulses).

A.1.1. 1/3-octave-band analysis

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

Because animals perceive exponential increases in frequency rather than linear increases, analyzing a sound spectrum with passbands that increase exponentially in size gives more meaningful data. In underwater acoustics, a spectrum is commonly split into 1/3-octave-bands, which are one-third of an octave wide; each octave represents a doubling in sound frequency. The center frequency of the ith 1/3-octave-band, $f_c(i)$, is defined as:

$$f_{\mathrm{c}}(i) = 10^{i/10}, \tag{A-10}$$

and the low (f_{lo}) and high (f_{hi}) frequency limits of the ith 1/3-octave-band are defined as:

$$f_{\mathrm{lo}} = 10^{-1/20} f_{\mathrm{c}}(i) \quad \text{and} \quad f_{\mathrm{hi}} = 10^{1/20} f_{\mathrm{c}}(i) \tag{A-11}$$

The 1/3-octave-bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure A-1). In this study, the acoustic modelling spans from band 10 ($f_c(10)$ = 10 Hz) to band 45 ($f_c(45)$ = 16000 kHz).

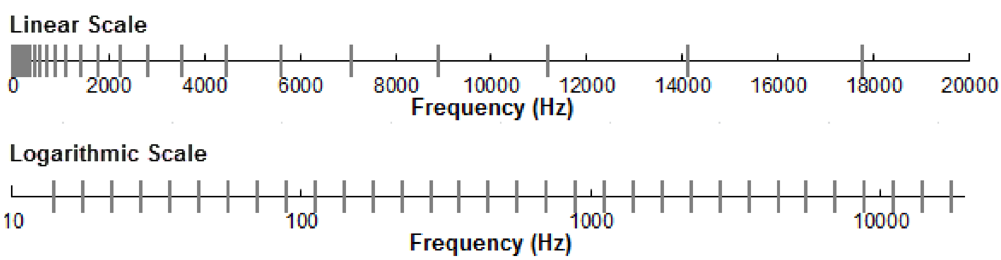


Figure A-1. One-third-octave-bands shown on a linear frequency scale and on a logarithmic scale.

The sound pressure level in the ith 1/3-octave-band $(L_b^{(i)})$ is computed from the power spectrum $S(f)$ between f_{lo} and f_{hi}:

$$L_{\mathrm{b}}^{(i)} = 10\log_{10}\left(\int_{f_{lo}}^{f_{hi}} S(f)df\right) \tag{A-12}$$

Summing the sound pressure level of all the 1/3-octave-bands yields the broadband sound pressure level:

$$\text{Broadband SPL} = 10\log_{10}\sum_i 10^{L_{\mathrm{b}}^{(i)}/10} \tag{A-13}$$

Figure A-2 shows an example of how the 1/3-octave-band sound pressure levels compare to the power spectrum of an ambient noise signal. Because the 1/3-octave-bands are wider with increasing frequency, the 1/3-octave-band SPL is higher than the power spectrum, especially at higher frequencies. Acoustic modelling of 1/3-octave-bands require less computation time than 1 Hz bands and still resolves the frequency-dependence of the sound source and the propagation environment.

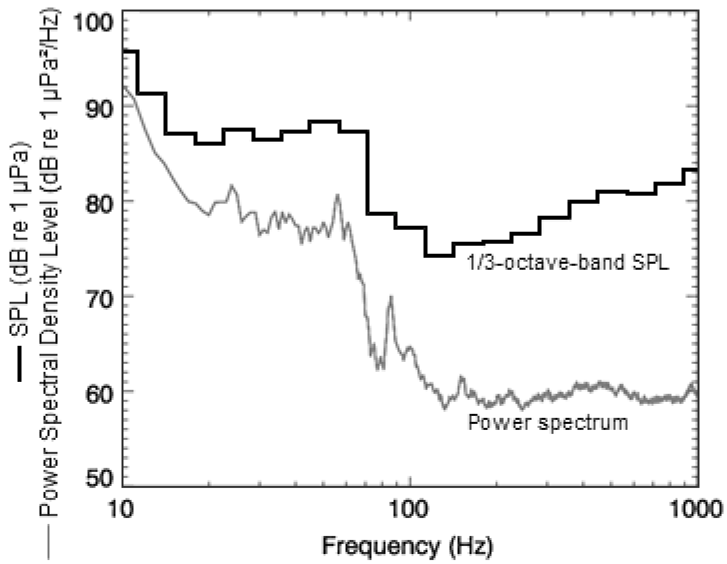


Figure A-2. A power spectrum and the corresponding 1/3-octave-band sound pressure levels of example ambient noise shown on a logarithmic frequency scale. The broadband (10–1000 Hz) SPL is 100.8 dB re 1 µPa.

A.2. Modelled Thresholds and Criteria

A.2.1. Marine mammals

It has been long recognized that marine mammals can be adversely affected by underwater anthropogenic noise. For example, Payne and Webb (1971) suggested 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, HESS Workshop 1998, Nedwell and Turnpenny 1998, Ellison and Stein 1999).

The U.S. National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service (NMFS) considered recommendations from these workshops and in 1998 adopted a set of interim thresholds for assessing injury and disturbance due to both impulsive and non-impulsive, or continuous, types of noise sources. We refer to these thresholds as the interim NMFS SPL (rms) criteria. Regulatory agencies in many countries have applied these criteria since the early 2000s, but recent advances in assessment approaches are starting to replace them. Note that the interim NMFS injury criteria were superseded as of August 2016 by NOAA's injury guidelines, which were not yet officially promulgated at the time this study was conducted. The interim NMFS behavioural criteria remain in force.

A.2.1.1. Injury

The NMFS SPL (rms) criteria for acoustic exposure injury to marine mammals were set according to recommendations for cautionary estimates of sound levels leading to onset of permanent hearing threshold shift (PTS). These criteria prescribe injury thresholds of 190 dB re 1 µPa SPL (rms) for pinnipeds and 180 dB re 1 µPa SPL (rms) for cetaceans (NMFS 2016b). A corresponding injury threshold was not defined for non-impulsive sounds at that time. NMFS indicates that the SPL (rms) criteria should be used for all sources including sonar and explosive (NMFS 2016b). These injury thresholds are applied to individual noise pulses and do not consider the overall duration of the noise or its acoustic frequency distribution.

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

In recognition of shortcomings of the SPL-only based injury criteria, in 2005 NMFS sponsored the Noise Criteria Group to review literature on marine mammal hearing to propose new noise exposure criteria (NMFS 2016b). Some members of this expert group published a landmark paper (Southall et al. 2007) that suggested assessment methods similar to those applied for humans. The resulting recommendations introduced dual acoustic injury criteria for impulsive sounds that included peak pressure level thresholds and cumulative SEL_{24h} thresholds, where the subscripted 24h refers to the accumulation period for calculating SEL. The peak pressure level criterion is not frequency weighted whereas the SEL_{24h} is frequency weighted according to one of four marine mammal species functional hearing groups: Low-, Mid- and High-Frequency Cetaceans (LFC, MFC, and HFC respectively) and Pinnipeds in Water (PINN). These weighting functions are referred to as M-weighting filters (analogous to the A-weighting filter for human; Appendix A.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 infers a 3 dB exchange rate). The recommended thresholds are provided in Table A-1.

Table A-1. Marine mammal injury (PTS onset) thresholds based on Southall et al. (2007).

Functional hearing group	Impulsive source		Non-impulsive source	
	Peak pressure level	Weighted SEL (24 h)	Peak pressure level	Weighted SEL (24 h)
Low-frequency cetaceans	230	198	230	215
Mid-frequency cetaceans	230	198	230	215
High-frequency cetaceans	230	198	230	215
Pinnipeds in water	218	186	218	203

Wood et al. (2012) refined Southall et al.'s (2007) thresholds, suggesting lower injury values for LFC and HFC while retaining the filter shapes (Appendix A.3.1). 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 HFC of 179 dB re 1 $\mu Pa^2 \cdot s$. Because there were no data available for baleen whales, Wood et al. (2012) based their recommendations for LFC on results obtained from MFC studies. In particular they referenced Finneran and Schlundt (2010) research, which found mid-frequency 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 LFC of 192 dB re 1 $\mu Pa^2 \cdot s$.

Also in 2012, the US Navy recommended a different set of criteria for assessing Navy operations (Finneran and Jenkins 2012). Their analysis incorporated new dolphin equal-loudness contours[3] to update weighting functions and injury thresholds for LFC, MFC, and HFC. They recommended separating the pinniped group into otariids (eared seals) and phocids (earless seals) and assigning adjusted

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

[3] An equal-loudness contour is the measured sound pressure level (dB re 1 µPa for underwater sounds) over frequency, for which a listener perceives a constant loudness when exposed to pure tones.

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).

There is consensus in the research community that an SEL-based approach is preferable, either alone or in conjunction with an SPL-based criterion, to assess the potential for injuries. NOAA's injury guidelines promulgated in August 2016 (after the present study was completed) are the culmination of a synthesis process based largely on the above-mentioned literature that went through two earlier draft versions (NOAA and US Dept of Commerce 2013, 2015) and was subjected to substantial public and expert input.

A.2.1.2. Disturbance

In 1998, NMFS also adopted the SPL (rms) threshold for behavioural response of 160 dB re 1 µPa for impulsive sounds and 120 dB re 1 µPa for non-impulsive sounds for all marine mammal species (NMFS 2016). As of 2016, NMFS applies these disturbance thresholds as a default, but makes exceptions on a species-specific and sub-population specific basis where warranted.

Nedwell et al. (2007) proposed an alternate method for assessing disturbance to marine mammals and fish by underwater noise. Their method considers the acoustic frequency content of the sounds relative to the frequency-dependent hearing acuity of the animals exposed to those sounds. The approach assumes the potential for an animal to be disturbed is related to how loud the animal perceives the sound (Nedwell and Turnpenny 1998, Nedwell et al. 2007). It applies methods similar to those used for assessing loudness of in-air sounds to humans, as discussed in Appendix A.2.1.1, with a slight difference. Whereas human weighting functions are derived from equal loudness contours at about 40 Phon, the audiogram is essentially the equal loudness contour for 0 Phon (just barely audible sounds) and has a steeper slope at high and low frequencies. This makes the audiogram slightly less cautionary than the higher equal loudness contour; i.e., audiogram-weighting filters out more energy from the signal than would normalized equal-loudness-contour-weighting. The Nedwell et al. approach de-emphasizes noise at frequencies the animal cannot hear well by weighting each frequency component of the noise according to the inverse of the animal's audiogram. The weighted frequency values are then summed to calculate an overall noise level, in decibels, relative to an animal's hearing threshold, expressed in dB re hearing threshold or dB_{ht}. The dB_{ht} units reference the species' audiogram, dB_{ht}(harbour porpoise) for example. Nedwell et al. (2007) further suggest that it is increasingly probable for an animal to exhibit a behavioural response as the audiogram-weighted levels increase from about 50 to 90 dB_{ht}. Following Nedwell's suggestion, an appropriate analysis of behavioural responses would be one that determines curves of probability of reaction by a percentage of the animal's population as a function of dB_{ht}, but most publications provide only a single value that corresponds to a behavioural response by some fraction of the population.

Ellison et al. (2012) suggest that disturbance assessments should also consider the context under which animals experience sounds. They suggest that an animal's response to sounds will also depend on the animals' behavioural state, their perception of whether or not the source of the sound might be dangerous, and their proximity to the source. Contextual parameters are relevant to assess the importance of the effect of a sound on an animal's well-being but do not influence effects such as masking, which occurs when a louder sound or background noise obscures a quieter sound in the same frequency band. Masking can limit the effectiveness of predator and prey detection, finding mates, and socializing.

In this report, disturbance thresholds for key species were estimated using the method proposed by Nedwell et al. (2007). Measured sound levels associated with behavioural response of animals are most often documented in term of SPL or SEL. These reported levels were converted to SPL above hearing thresholds by subtracting species-specific audiogram levels (Section 2.3.5) from a published disturbance level in the main frequency band of the measured source.

Killer Whale: Two studies documented Northern Resident killer whales' behavioural responses to vessels (MacGillivray et al. 2012). In both experiments, the authors noted that factors other than the noise itself (e.g., vessel proximity and speed) could have contributed to the whales' reactions. Applying audiogram weighting to the reported sound levels from the experiments showed that the killer whales overtly avoided received sound levels of approximately 64 dB_{ht}(killer whale). Subtle changes were observed at received levels of approximately 57 dB_{ht}(killer whale) (MacGillivray et al. 2012).

Humpback Whale: McCauley et al. (2000) showed that when migrating pods of humpback whale cows and their calves were exposed to levels equivalent to approximately 73 dB_{ht}(humpback whale), they exhibited detectable avoidance manoeuvres. The measured level associated with disturbance was higher, equivalent to approximately 95 dB_{ht}(humpback whale), for other southern migrating individuals. Dunlop et al. (2015) suggested that the behavioural thresholds for humpback whales, and possibly other mysticetes, could be higher than those noted in prior studies, which were based on observations of only a few individuals. Dunlop et al. (2015) observed that humpback whales in eastern Australia did not significantly alter their behaviour when they were exposed to noise from a small airgun array at approximately 51–102 dB_{ht}(humpback whale)[4]. When humpback whales are feeding or focused on other activities, they might not exhibit overt behavioural changes akin to those they exhibit otherwise (Ellison et al. 2012).

Harbour Porpoise: In light of new data from multiple recent studies of behavioural responses of harbour porpoises to impulsive sounds, including sounds from pile driving, Tougaard et al. (2015) suggested response thresholds as low as 45 dB_{ht}(harbour porpoise). While this threshold is lower than observed for other species, the Tougaard et al. results were derived from several different studies and may be more robust.

Harbour Seal: Most research on behavioural thresholds for harbour seals has considered high-frequency sources such as seal deterrents used near fish farms (Yurk and Trites 2000, Terhune et al. 2002), or studied a few captive individuals to determine detection thresholds compared to behavioural thresholds (Reichmuth et al. 2012). A behavioural threshold of 64 dB_{ht}(harbour seal) for low-frequency sounds from pile driving operations has been deduced from that for other seals (e.g. ringed, bearded, or spotted seals; Bailey et al. 2010).

The ability of an animal to detect signals of very short duration, such as pulses from pile driving or blasting, could depend on the signal duration. The ear operates as an integrating filter so that the loudness of a sound with constant rms pressure increases with the signal's duration up to a maximum duration, above which there is little further effect (Green et al. 1957, Johnson 1968, Kastelein et al. 2010). This maximum duration is referred to as the critical duration. Tougaard et al. (2015) recommended the same approach used for humans be applied to assess the effects of noise of short duration on marine mammals. It involves applying human fast-average time weighting using a 125 ms exponential time filter prior to calculating the SPL. This approach results in received levels that are lower than non-weighted SPL for signals that are shorter than the critical duration. The approach does not affect sounds longer than 1 s.

It is helpful to assess an animal's zone of audibility for marine construction noise; animals outside this zone are unlikely to be affected by noise because they cannot hear it. Still, masking effects can occur beyond the audibility zone boundary. The maximum distance at which an animal can hear sounds from a source is limited either by its hearing threshold or by ambient noise. The ear has the ability to perform frequency filtering when interfering noises are present. It can detect quiet signals even when interfering noise levels are higher than those of the signal of interest. This filtering requires, however, the signal and noise to be sufficiently separated in frequency. The zone of audibility must therefore be determined by considering the ambient noise spectral distribution relative to the sound source's noise spectra. Although the zone of responsiveness, the region within which the animal reacts behaviourally or physiologically, is often smaller than the zone of audibility, some species can detect certain signals slightly below ambient levels, i.e., outside the defined zone of audibility (Richardson et al. 1995). In most instances, however, the zone of audibility approximates the region outside of where noise effects are normally insignificant.

[4] Modal values of 74 dB_{ht}(humpback whale)

A.2.2. Fishes

Fishes have all of the basic acoustic processing capabilities of other vertebrates (see review by Popper et al. 2003, Ladich and Popper 2004). Fishes 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 motion (particle motion). All fish directly sense the particle motion component of sound (Fay 1984), while relatively few fish also sense the pressure component (Popper et al. 2003). The ears of all fish consist of otolith- (or otoconia-) containing end organs that function as inertial accelerometers. Pressure-sensing fish have additional morphological adaptations that allow them to detect acoustic pressure (e.g., Popper et al. 2003). In these fish, gas-filled bladders near the ear (such as the swim bladder) or mechanical connections between the gas-filled bladder and the ear (e.g., Weberian ossicles) convey sound pressure from the water to the ear when the bladder deforms with pressure.

The majority of fish do not have specializations for sensing pressure; they detect only particle motion 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 the pressure-insensitive fish (Hastings and Popper 2005). Pressure sensitivity is not strictly related to fish taxonomy as pressure sensing occurs in several fish taxonomic 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.

A.2.2.1. Injury

In 2008, the Fisheries Hydroacoustic Working Group (FHWG), sponsored by NOAA, developed interim 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 μPa and a size-dependent SEL_{24h} threshold. For fish weighing 2 g or more, the threshold is 187 dB re 1 $\mu Pa^2 \cdot s$ and for fish under 2 g it is 183 dB re 1 $\mu Pa^2 \cdot s$. The FHWG did not establish criteria for fish injury caused by vibratory pile driving or other source types.

An ANSI-accredited standard 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 fishes and sea turtles based on work already started by a NOAA panel (FHWG). Similar to the FHWG interim criteria, the ANSI guidelines also recommended peak pressure level and SEL thresholds, both without frequency weighting. They specified that SEL be integrated over 24 hours or the duration of the activity, whichever is less.

Popper et al. (2014) categorized fishes into three groups based on their hearing capabilities[5], which are determined by whether a swim bladder is present and is directly involved in hearing. The categories are (1) fishes without a swim bladder, (2) fishes with a swim bladder not involved in hearing, and (3) fishes with a swim bladder involved in hearing. Their report provides received sound levels based on the best

[5] The classification of fishes into "hearing specialist" or "hearing generalist" refers to their hearing sensitivity. Thresholds to impact criteria were not developed on this system of classification.

Bony fishes 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 fishes to specific taxa; hearing specialists and generalists are distributed over many taxa.

available science that are suitable as provisional guidelines for assessing onset of injury to fishes from various sources (Table A-2). Popper et al. (2014) define three categories of thresholds:

- Mortality and potential mortal injury. These levels are expected to results in immediate death from injuries, or delayed death resulting from reduced fitness that leads to predation or disease.
- Recoverable injury. Injuries not likely to results in mortality.
- Temporary threshold shift. A temporary reduction in hearing sensitivity, quantified as a change of ≥ 6 dB in hearing threshold.

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 (BC Marine and Pile Driving Contractors Association and Fisheries and Oceans Canada (DFO) 2003).

Table A-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 µPa²·s)	peak pressure level (dB re 1 µPa)	SEL (24 h) (dB re 1 µPa²·s)	peak pressure level (dB re 1 µPa)	SEL (24 h) (dB re 1 µPa²·s)
I	No swim bladder (particle motion detection)	> 219	> 213	> 216	> 213	> > 186
II	Swim bladder is not involved in hearing (particle motion detection)	210	> 207	203	> 207	> > 186
III	Swim bladder is involved in hearing (primary pressure detection)	207	> 207	203	> 207	186

A.2.2.2. Disturbance

Fish disturbance thresholds are not well documented. NOAA advises using a 150 dB re 1 µPa (SPL (rms)) criterion to predict fish behavioural responses to impulsive sources (Mueller-Blenkle et al. 2010, Illingworth & Rodkin 2013, NMFS 2016b); however the rationale for using this criterion is not clear (Popper et al. 2014).

A.3. Auditory Weighting Functions

The potential for noise to affect animals 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).

A.3.1. M-weighting based on Southall et al. 2007

Auditory weighting functions for marine mammals—called *M-weighting* functions—were proposed by Southall et al. (2007). Functions were defined for five functional hearing groups of marine mammals:

- Low-frequency cetaceans (LFCs)—mysticetes (baleen whales)
- Mid-frequency cetaceans (MFCs)—some odontocetes (toothed whales)
- High-frequency cetaceans (HFCs)—odontocetes specialized for using high-frequencies
- Pinnipeds in water—seals, sea lions, and walruses
- Pinnipeds in air (not addressed here)

The M-weighting functions have unity gain (0 dB) through the passband and their high and low frequency roll-offs are approximately –12 dB per octave. The amplitude response in the frequency domain of each M-weighting function is defined by:

$$G(f) = -20\log_{10}\left[\left(1+\frac{a^2}{f^2}\right)\left(1+\frac{f^2}{b^2}\right)\right] \tag{A-14}$$

where *G*(f) is the weighting function amplitude (in dB) at the frequency *f* (in Hz), and *a* and *b* are the estimated lower and upper hearing limits, respectively, which control the roll-off and passband of the weighting function. The parameters *a* and *b* are defined uniquely for each functional hearing group (Table A-3). The auditory weighting functions recommended by Southall et al. (2007) are shown in Figure A-3. In this study, we applied thresholds proposed by Wood et al. (2012), who retained Southall's filter functions but refined the thresholds (Section A.2.1.1).

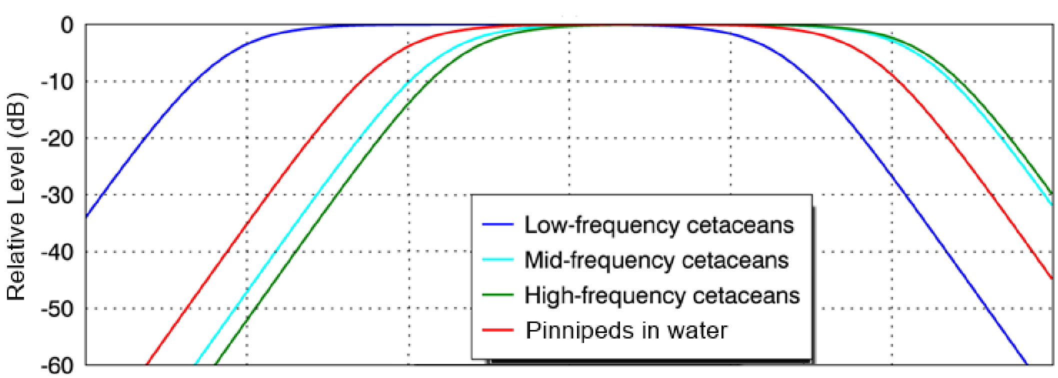


Figure A-3. Auditory weighting functions for functional marine mammal hearing groups as recommended by Southall et al. (2007).

Table A-3. Parameters for the auditory weighting functions recommended by Southall et al. (2007).

Functional hearing group	Southall et al. (2007)	
	a (Hz)	b (Hz)
Low-frequency cetaceans (LFC)	7	22,000
Mid-frequency cetaceans (MFC)	150	160,000
High-frequency cetaceans (HFC)	200	180,000
Pinnipeds in water (Pw)	75	75,000

A.3.2. Audiograms for marine mammals and fishes

Audiograms represent the hearing threshold for single-frequency sinusoidal signals as a function of frequency. These species-specific sensitivity curves are generally U-shaped, with higher hearing thresholds at very low and very high frequencies.

Noise levels above hearing threshold are calculated by subtracting species-specific audiograms from the received sound levels. The audiogram-weighted levels are summed to yield broadband sound levels relative to each species' hearing threshold. Audiogram-weighted levels are expressed in units of dB above hearing threshold (dB_{ht}). Sound levels less than 0 dB_{ht} are below the typical hearing threshold for a species and therefore it is likely the animal does not hear them.

Audiograms of marine species are obtained using either behavioural or physiological methods. Behavioural thresholds are obtained by training captive marine mammals to respond to auditory cues or observing behavioural responses in tanks. Data obtained from captive animals provide reliable sound level thresholds since these experiments are set up to minimize ambient noise levels. Results obtained using trained captives might not, however, be representative of wild populations. Studies conducted on animals in captivity are limited to a small subset of individuals, many of whom are older and thus may differ from wild populations with respect to their auditory sensitivity.

Physiological thresholds are obtained by measuring auditory evoked potentials (AEPs) from animals' nervous systems. Portable systems allow to collect data noninvasively using, for example, transducers embedded in suction cups to send modulated tones and surface electrodes to measure AEPs. Although thresholds can be measured on untrained (wild) animals, the measurements tend to provide higher thresholds than those obtained through behavioural experiments on captive animals (Szymanski et al. 1999, Wolski et al. 2003, Yuen et al. 2005, Houser and Finneran 2006, Schlundt et al. 2007, Mulsow and Reichmuth 2010, Erbe et al. 2015). Both types of thresholds are especially difficult to measure in two instances: at low frequencies (< 1 kHz) ambient noise levels are often too high to accurately measure received levels, and for larger animals, e.g. mysticetes s (Erbe et al. 2015), whose large size makes installing measurement apparatus challenging.

We reviewed existing literature to determine the best available information on audiograms of key species. In cases where available information was ambiguous or data were potentially unreliable, the most conservative value (i.e. lower level) was used. In cases where data were unavailable at frequencies between 10 Hz and 20 kHz, the audiogram was extrapolated to cover the entire modelled spectrum. Although not confirmed, marine mammals, like terrestrial mammals, have higher hearing thresholds at frequencies outside their hearing range, resulting in a U-shape audiogram curve. The terminal trend of the audiogram is, however, often at frequencies below measured audiogram frequencies. In this study, when data were unavailable, marine mammal audiograms were extrapolated to lower frequencies by following the trend of the measurement at the lower frequency end. Less is known about the auditory systems of fishes than mammals; the same roll-off trend on either end of their audiograms cannot be confirmed, especially at low frequencies where particle motion plays an important role in auditory sensitivity. We therefore used a more conservative approach: thresholds were extrapolated to the lower and upper modelled frequencies by extending the levels at the lowest and highest frequencies of audiogram measurements.

A.4. Acoustic Source Models

A.4.1. Pile driving source model

A physical model of pile vibration and near-field sound radiation was 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 A-4). Damping of the pile vibration due to radiation loading is computed for Mach waves emanating from the pile wall. The equations of motion are discretized using the finite difference (FD) method and are solved on a discrete time and depth mesh.

In order to model the sound emissions of the piles, it was also necessary to model the force of the pile driving hammers. 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 (Appendix A.5.2). MacGillivray (2014) describes the theory behind the physical model in more detail.

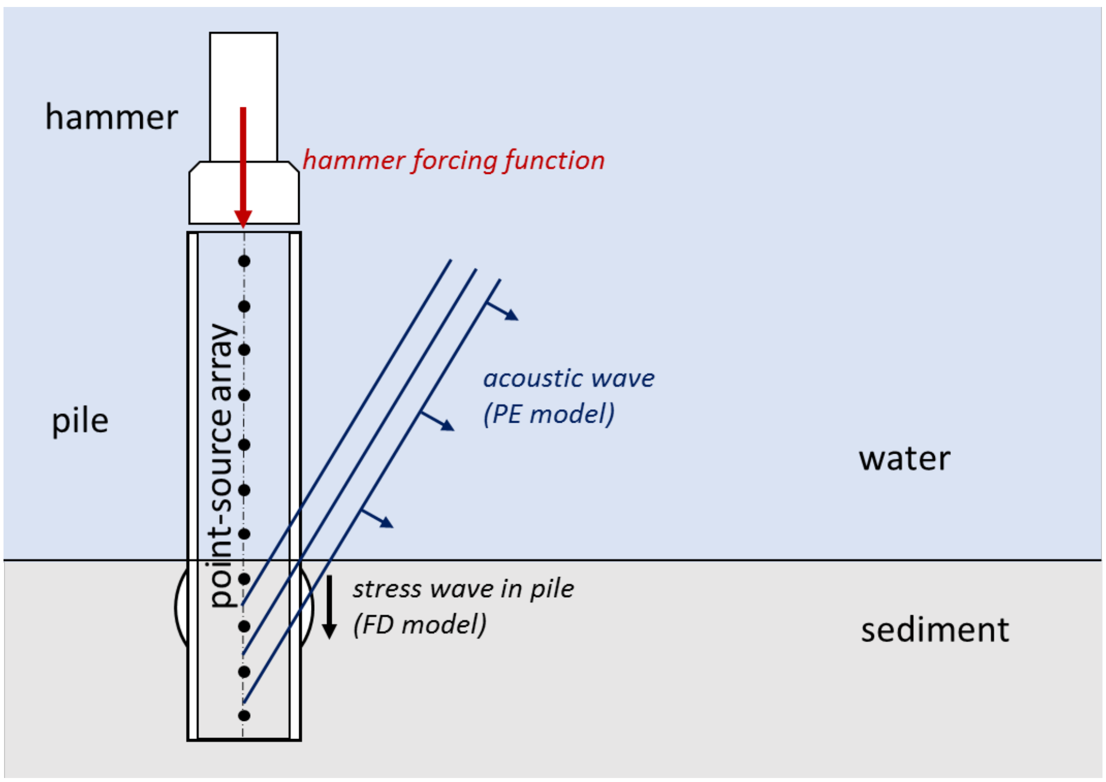


Figure A-4. Physical model geometry for impact driving of a cylindrical pile (vertical cross-section). The hammer forcing function is used with the finite difference (FD) model to compute the stress wave vibration in the pile. A vertical array of point sources is used with the parabolic equation (PE) model to compute the acoustic waves radiated by the pile wall.

A.4.2. Vessel source levels

Acoustic source emission levels for vessels used here are from measurements of ships similar to the tugs and LNG carriers expected to be used in the Project. The source levels from surrogate vessels for the LNG carrier, specified in 1/3-octave frequency bands, were adjusted for the difference in speed and length of the vessels using EquationA-17 from Ross (1976):

$$S(f,V,L) = S_0(f) + c_V 10\log\left(\frac{V}{V_0}\right) + c_L 10\log\left(\frac{L}{L_0}\right) \quad \text{(A-15)}$$

where *S*, *V*, and *L* are the source spectrum level, speed, and length of the modelled vessel, *f* is the frequency, S_0, V_0, and L_0 are the source level spectra, speed, and length for the surrogate vessel. Source levels based on published measurements depend less on vessel length than speed, and the maximum length for which a vessel can be adjusted is 150 m (based on Erbe et al. 2012); the source levels do not increase significantly for vessel lengths greater than 150 m.

Source level spectra from surrogate vessel were extrapolated to 16 kHz based on an empirical relationship that describes the typical high-frequency trend of source spectrum levels for surface vessels (Ross 1976):

$$S(f) \propto -20\log f \qquad f \geq 100\,\text{Hz} \quad \text{(A-16)}$$

where *S* is the source spectrum level (dB re 1 µPa^2/Hz @ 1 m) at frequencies above 100 Hz.

The source levels from a surrogate tug for the modelled escort tugs, specified in 1/3-octave frequency bands, were adjusted for the difference in speed and power of the vessels using Equation A-19, based on Ross (1976):

$$S(f,V,L) = S_0(f) + c_V 10\log\left(\frac{V}{V_0}\right) + 10\log\left(\frac{P}{P_0}\right) \quad \text{(A-17)}$$

where *S*, *V*, and P are the source spectrum level, speed, and power of the modelled tug, *f* is the frequency, S_0, V_0, and P_0 are the source level spectra, speed, and power for the surrogate tug.

Since the dominant source of underwater noise from shipping is generally propeller cavitation (Ross 1976, §8.6), we estimated vessel source depths from their propeller dimensions. The source of radiated noise was assumed to be at a point partway between the shaft and the top of the propeller disk, therefore we estimated the source depth, Z_s, of the modelled vessels with the following equation (Gray and Greeley 1980):

$$Z_s = D - 0.85 \times d \quad \text{(A-18)}$$

where *D* is the vessel draught and *d* is the propeller diameter.

A.5. Sound Propagation Models

A.5.1. Marine Operational Noise Model (MONM)

Underwater sound propagation (i.e., transmission loss) at frequencies of 10 Hz to 2 kHz was predicted with JASCO's Marine Operations Noise Model (MONM). MONM computes received per-pulse SEL for directional impulsive sources at a specified source depth.

MONM computes acoustic propagation via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid 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 accounts for the additional reflection loss at the seabed, which results from partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. MONM incorporates the following site-specific environmental properties: a bathymetric grid of the modelled area, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

MONM computes acoustic fields in three dimensions by modelling transmission loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as N×2-D. These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding N = 360°/$\Delta\theta$ number of planes (Figure A-5).

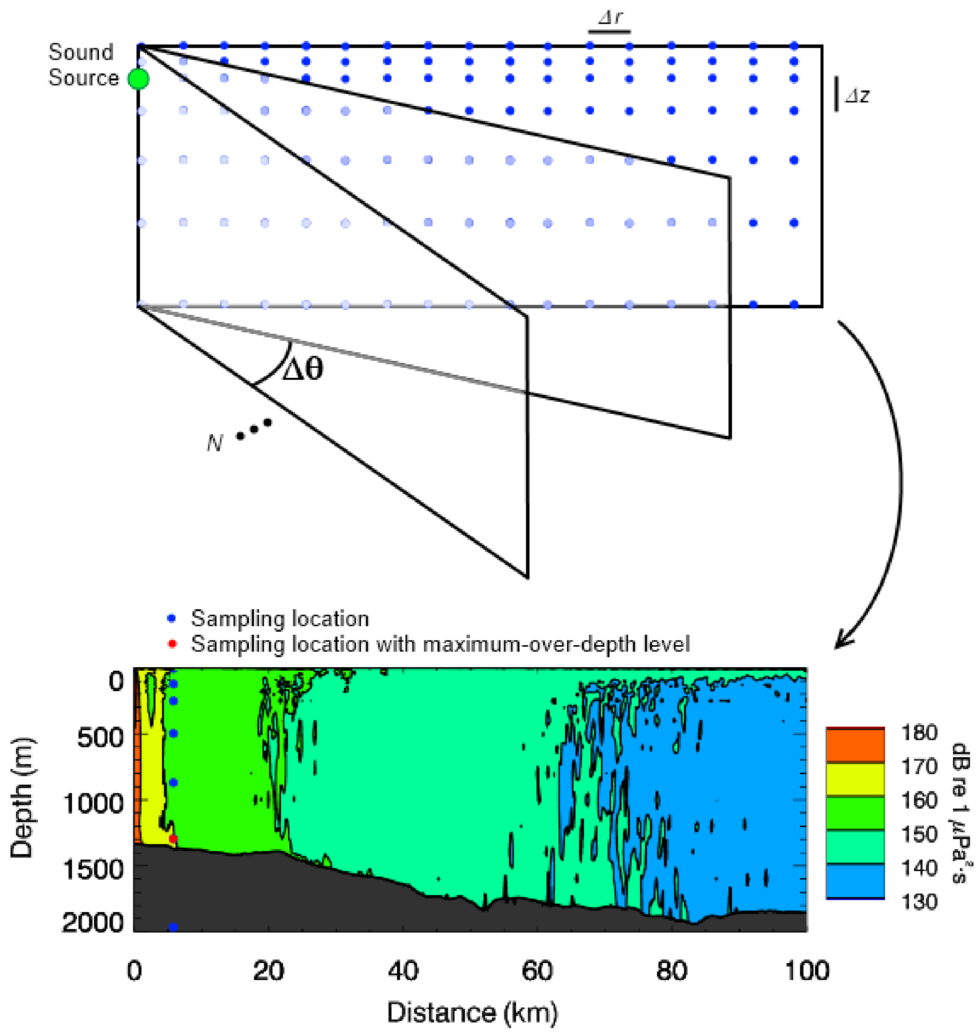


Figure A-5. The N×2-D and maximum-over-depth modelling approach used by MONM.

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

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

MONM's predictions have been validated against experimental data from several underwater acoustic measurement 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, Racca et al. 2012a, Racca et al. 2012b).

The transmission loss computed by MONM was further corrected to account for the attenuation of acoustic energy by molecular absorption in seawater. The volumetric sound absorption is quantified by an attenuation coefficient, expressed in units of decibels per kilometer (dB/km). The absorption coefficient depends on the temperature, salinity, and pressure of the water as well as the sound frequency. In general, the absorption coefficient increases with the square of frequency. The absorption of acoustic wave energy has a noticeable effect (> 0.05 dB/km) at frequencies above 1 kHz. At 10 kHz, the absorption loss over 10 km distance can exceed 10 dB. This coefficient for seawater can be computed according to the formulae of François and Garrison (1982b, 1982a), which consider the contribution of pure seawater, magnesium sulfate, and boric acid. The formulae apply to all oceanic conditions and frequencies from 200 Hz to 1 MHz.

In this study, the absorption coefficients were calculated based on water temperature at 7.4°C and salinity of 32.4 parts per thousand (ppt). Temperature and salinity were estimated from temperature and salinity profiles (Section 3.1.2) at a depth of 50 m, and averaged over all modelled locations that have similar values. The absorption coefficients were applied to the transmission loss for frequency greater than 1 kHz.

A.5.2. Full Waveform Range-dependent Acoustic Model (FWRAM)

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

Synthetic pressure waveforms were modelled over the frequency range 10–2048 Hz, inside a 1 s window (Figure A-6). The synthetic pressure waveforms were post-processed, after applying a travel time correction, to calculate standard SPL and SEL metrics versus range and depth from the source.

Besides providing direct calculations of the peak pressure level and SPL (rms), the synthetic waveforms from FWRAM can also be used to convert the SEL values from MONM to SPL (rms).

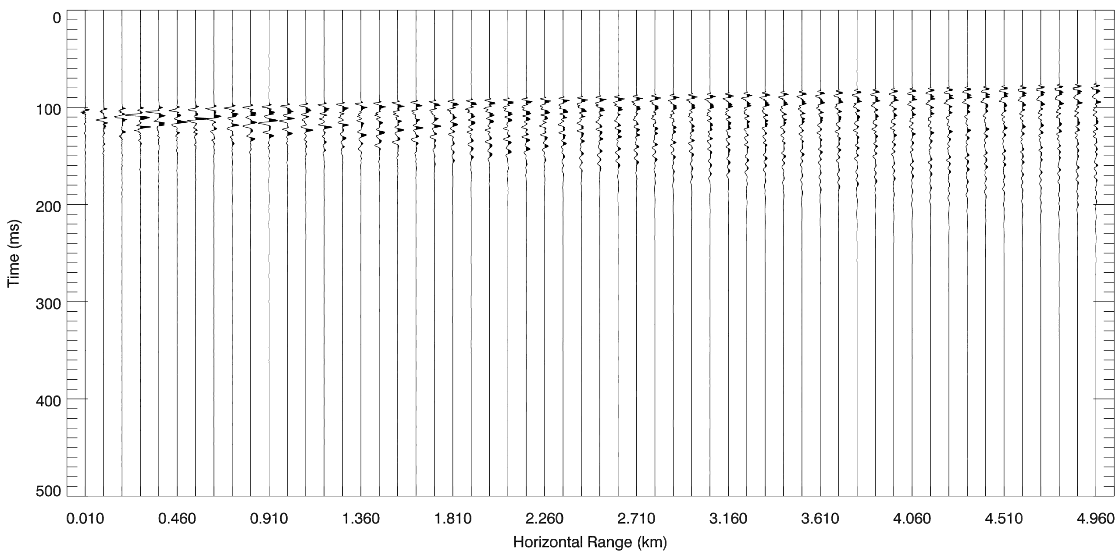


Figure A-6. Example of synthetic pressure waveforms computed by FWRAM at multiple range offsets for an unknown source. The pressure traces have been normalised for display purposes.

Appendix B. Modelled Sound Fields

B.1. Impact pile driving with confined bubble curtain

Figure B-1 and Figure B-7 show the maps of 24-hr SEL thresholds for impact pile driving with a confined bubble curtain operating at MOF and LNG jetty. The contours of 190 and 180 dB re 1 μPa SPL (interim NMFS criteria) are shown in the maps (Figure B-2 to-Figure B-5, and Figure B-8 to Figure B-11). The maximum distances to marine mammal injury peak pressure level criteria were not reached beyond 10 m from the pile (Table 10). The comparison of radii for these thresholds was discussed in detail in Section 5.1.

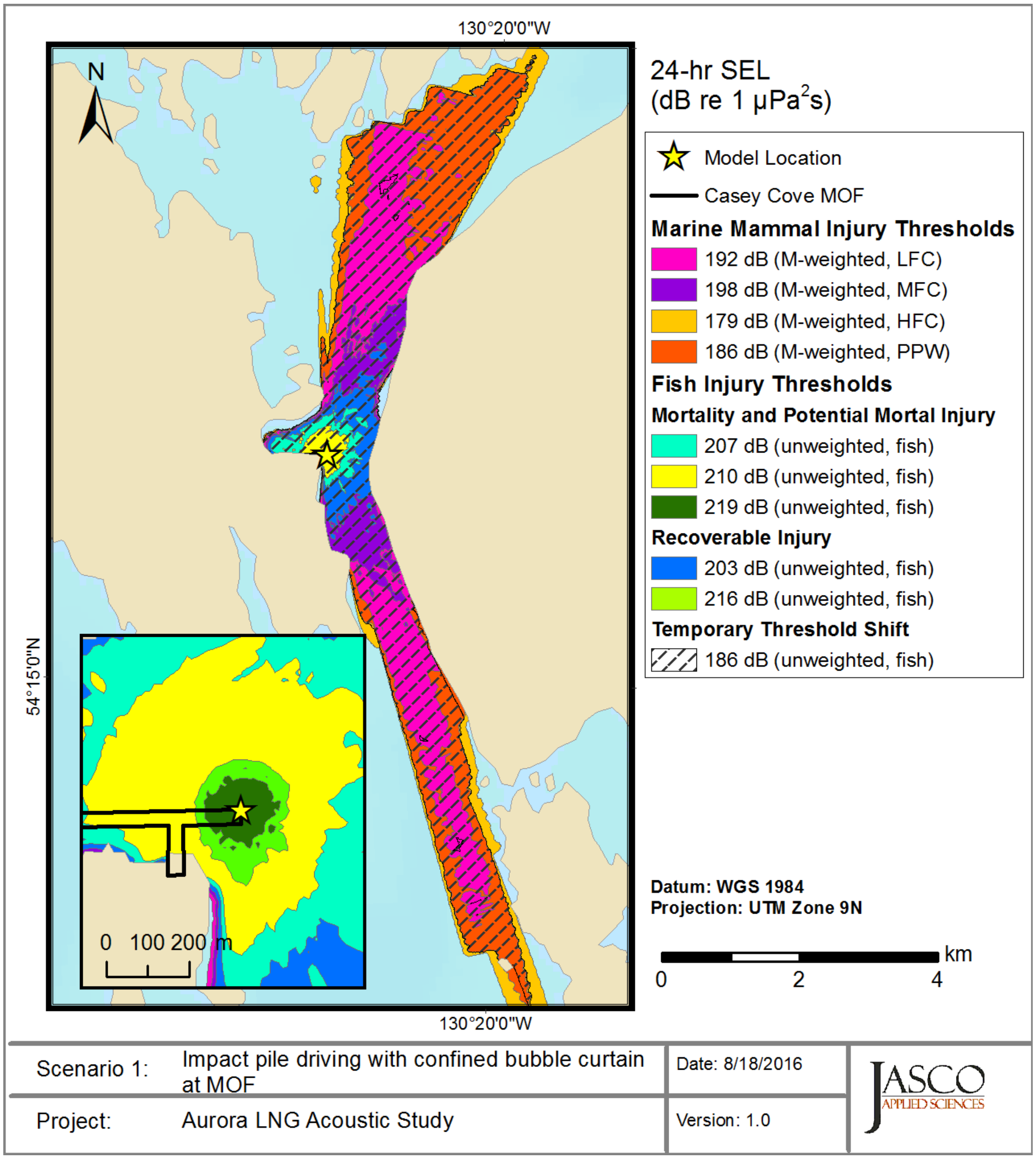
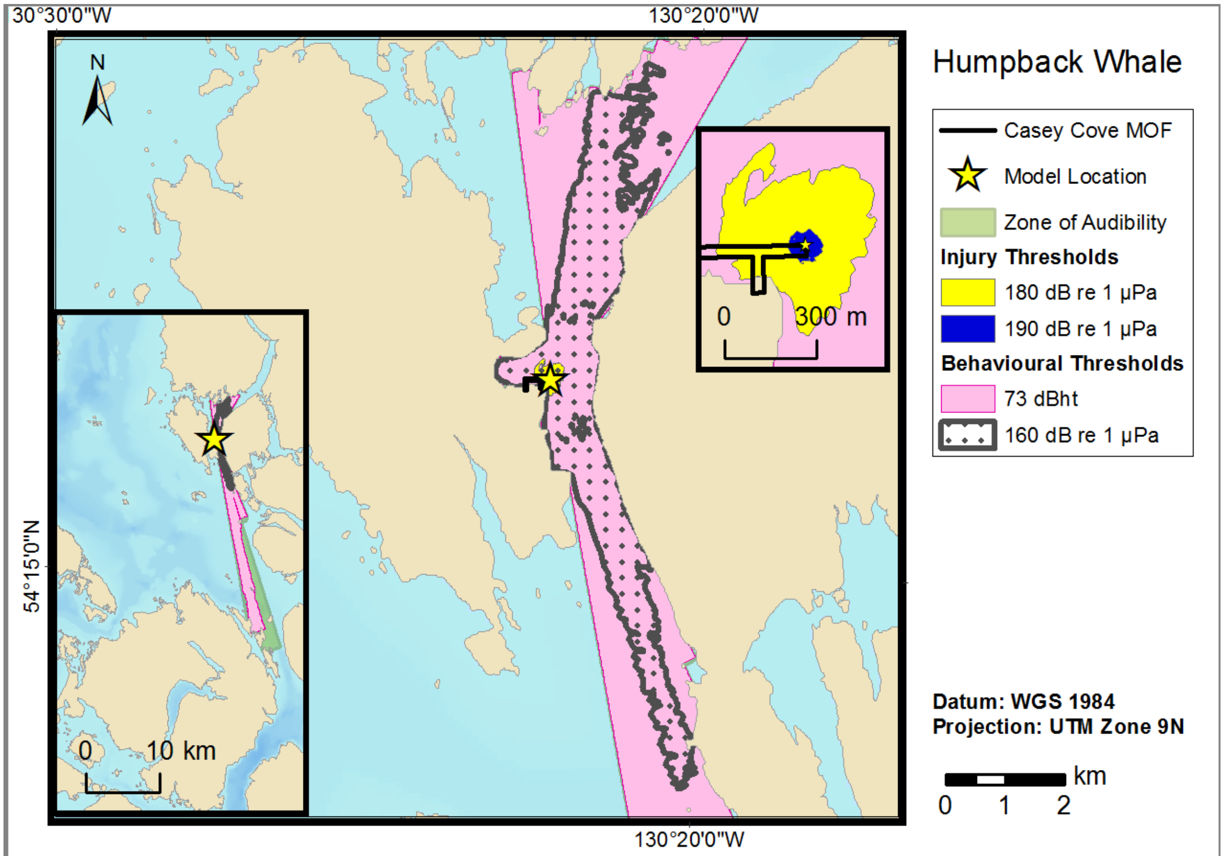


Figure B-1. 24-hr SEL–Scenario 1: Map of thresholds to selected impact criteria for impact pile driving with confined bubble curtain. The inset shows a close-up of the sound field around the source location.



Scenario 1:	Impact pile driving with confined bubble curtain at MOF	Date: 10/7/2016	JASCO APPLIED SCIENCES
Project:	Aurora LNG Acoustic Study	Version: 1.0	

Figure B-2. Humpback whale–Scenario 1: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for impact pile driving with confined bubble curtain. The lower inset shows the extent of the ZoA. The upper inset shows a close-up of the MOF. The 190, 180, and 160 dB re 1 µPa thresholds are SPL (rms). The 73 dBht threshold is humpback whale audiogram-weighted SPL.

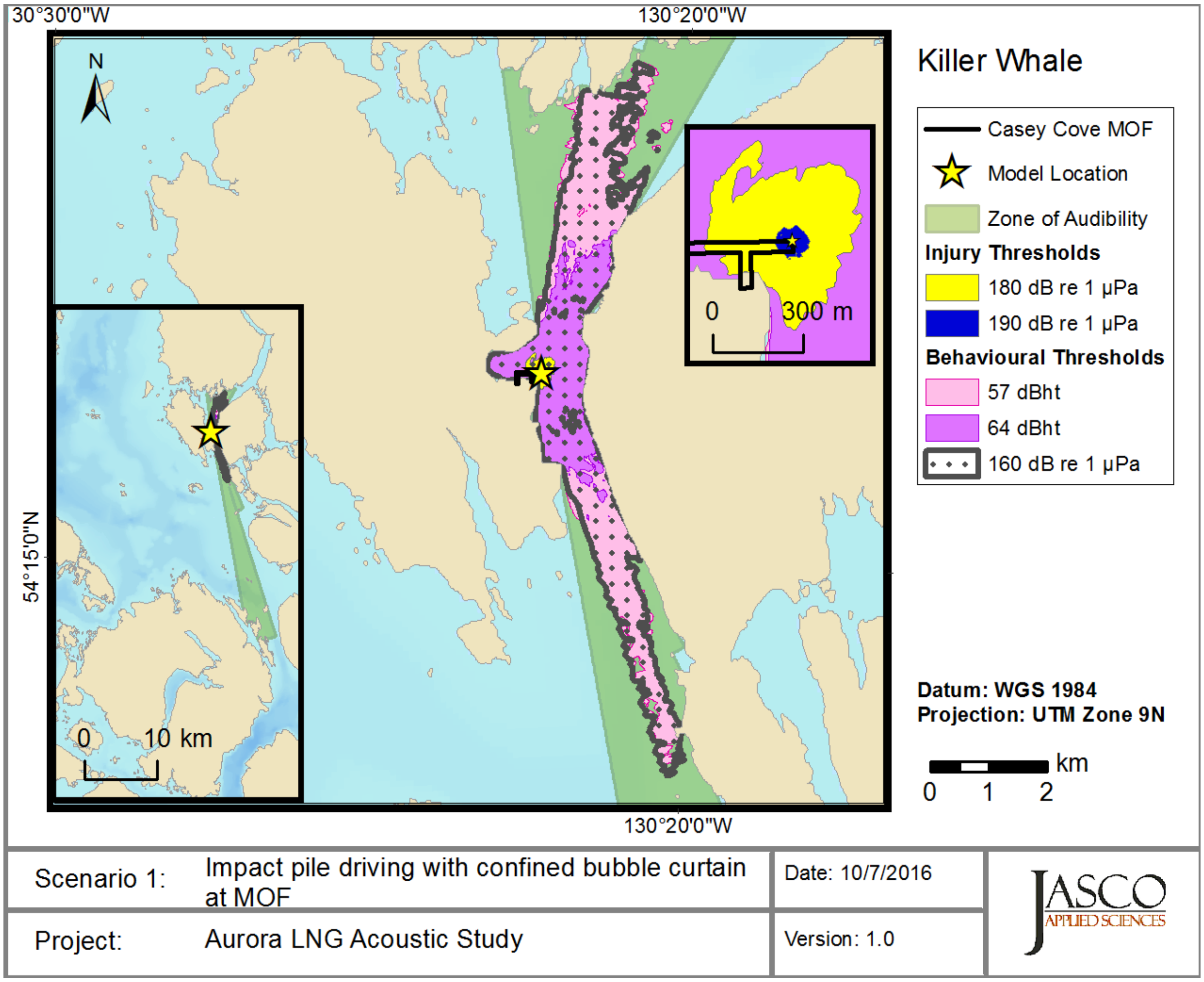
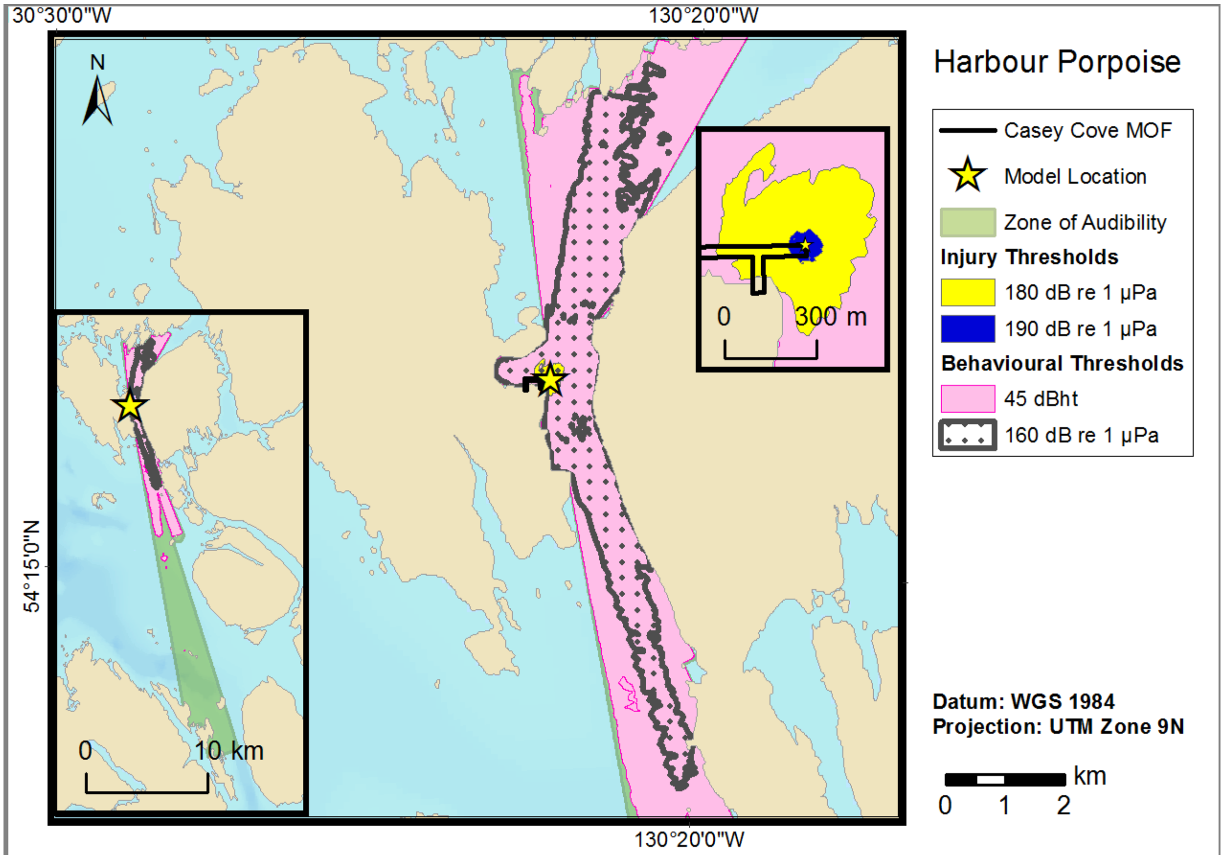


Figure B-3. Killer whale–Scenario 1: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for impact pile driving with confined bubble curtain. The lower inset shows the extent of the ZoA. The upper inset shows a close-up of the MOF. The 190, 180, and 160 dB re 1 µPa thresholds are SPL (rms). The 57 and 64 dBht threshold is killer whale audiogram-weighted SPL.



Scenario 1:	Impact pile driving with confined bubble curtain at MOF	Date: 10/7/2016	JASCO APPLIED SCIENCES
Project:	Aurora LNG Acoustic Study	Version: 1.0	

Figure B-4. Harbour porpoise–Scenario 1: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for impact pile driving with confined bubble curtain. The lower inset shows the extent of the ZoA. The upper inset shows a close-up of the MOF. The 190, 180, and 160 dB re 1 µPa thresholds are SPL (rms). The 45 dBht threshold is harbour porpoise audiogram-weighted SPL.

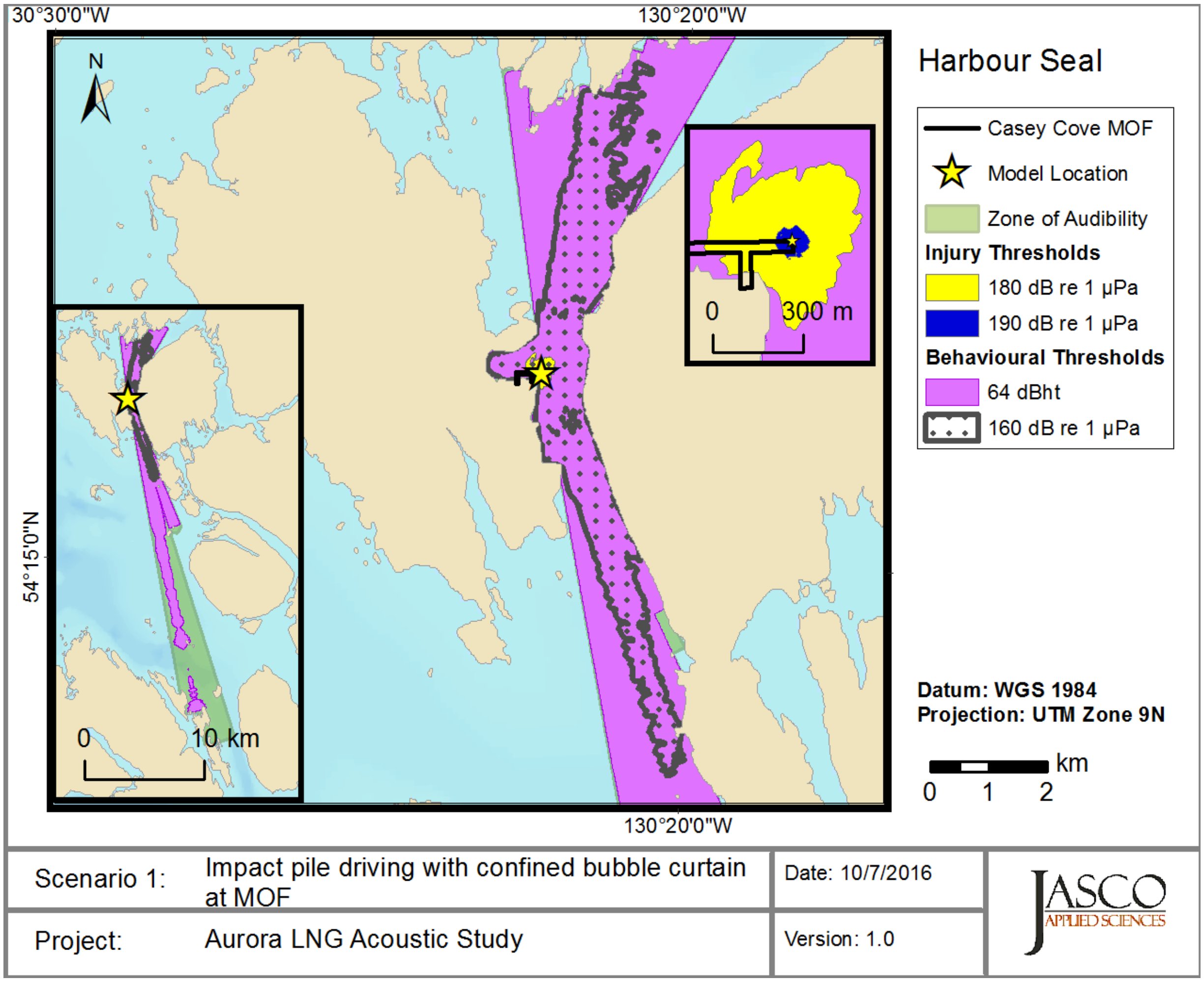


Figure B-5. Harbour seal–Scenario 1: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for impact pile driving with confined bubble curtain. The lower inset shows the extent of the ZoA. The upper inset shows a close-up of the MOF. The 190, 180, and 160 dB re 1 µPa thresholds are SPL (rms). The 64 dBht threshold is harbour seal audiogram-weighted SPL.

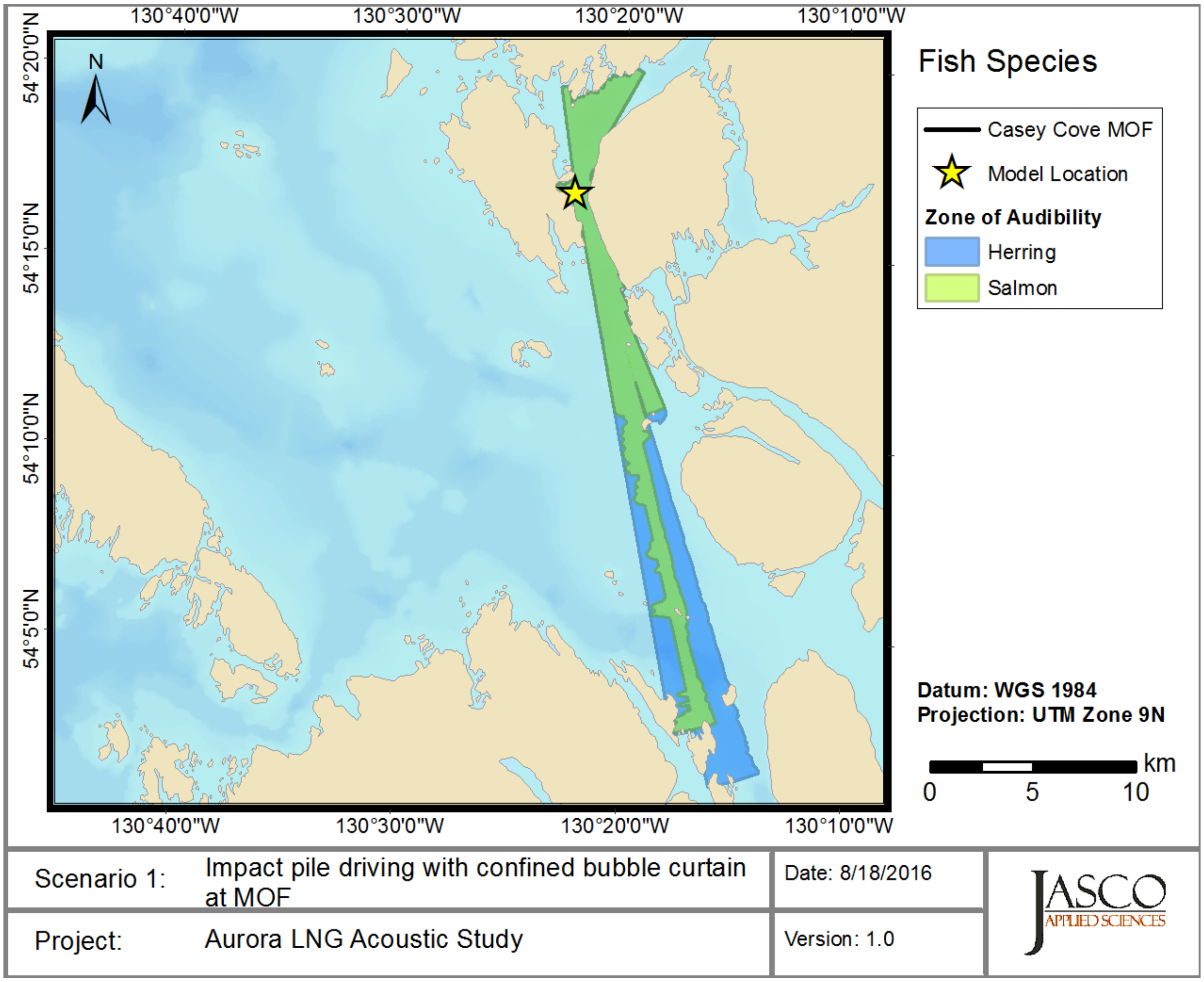


Figure B-6. Herring and salmon–Scenario 1: Map of zone of audibility (ZoA) for impact pile driving with confined bubble curtain.

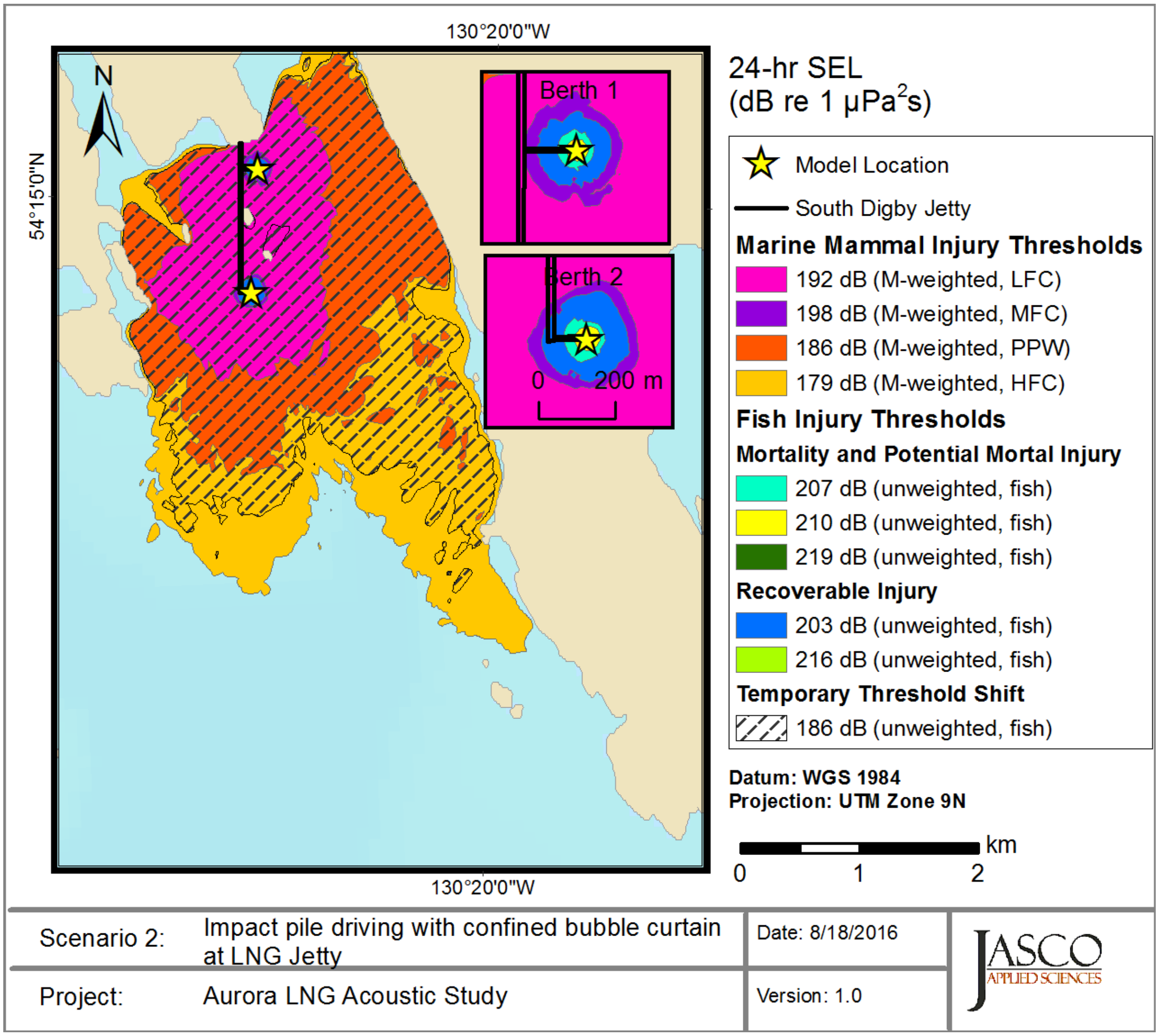
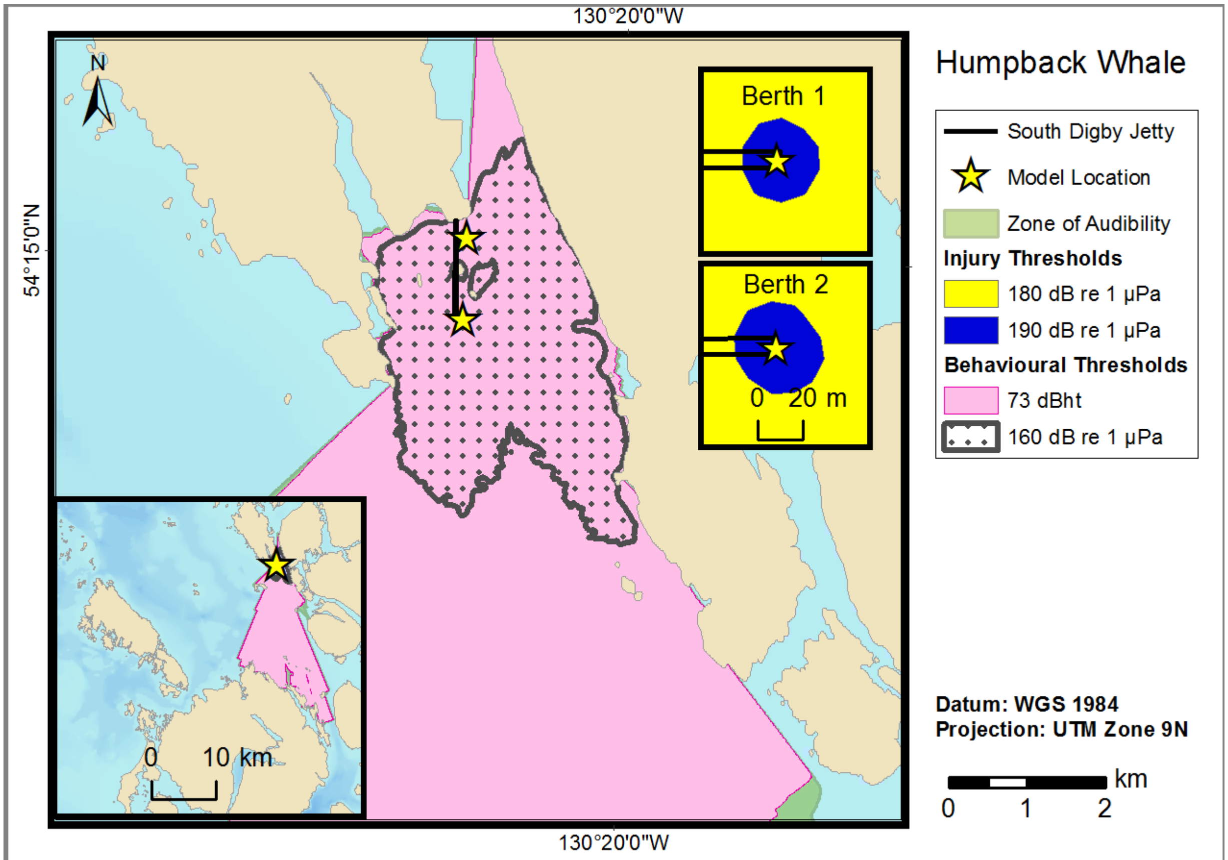


Figure B-7. 24-hr SEL–Scenario 2: Map of thresholds to selected impact criteria for impact pile driving with confined bubble curtain. The insets show close-ups of sound fields around each source location.



Scenario 2:	Impact pile driving with confined bubble curtain at LNG Jetty	Date: 10/7/2016	JASCO APPLIED SCIENCES
Project:	Aurora LNG Acoustic Study	Version: 1.0	

Figure B-8. Humpback whale–Scenario 2: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for impact pile driving with confined bubble curtain. The lower inset shows the extent of the ZoA. The upper insets show close-ups to the South Digby Island LNG jetty. The 190, 180, and 160 dB re 1 µPa thresholds are SPL (rms). The 73 dBht threshold is humpback whale audiogram-weighted SPL.

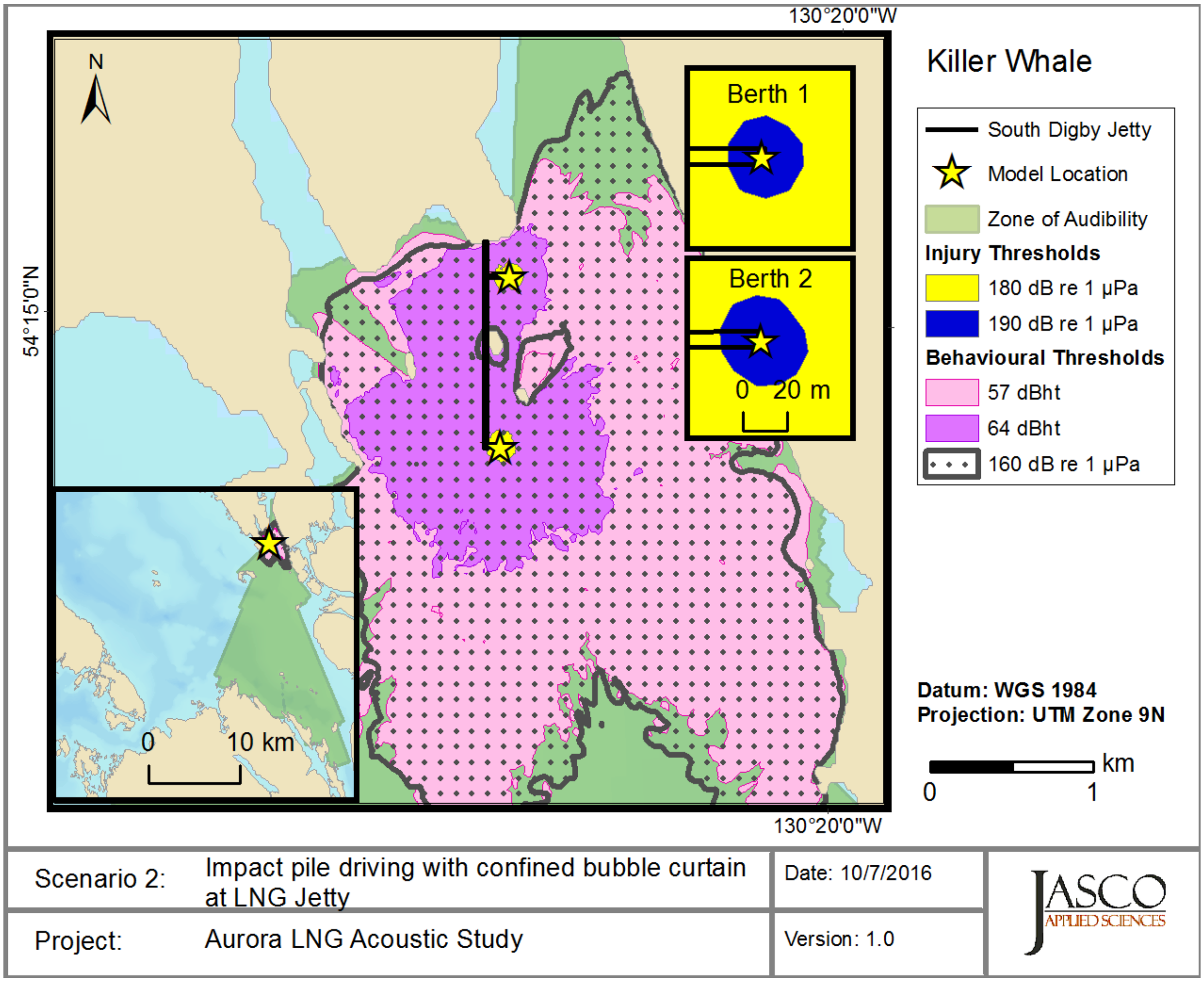
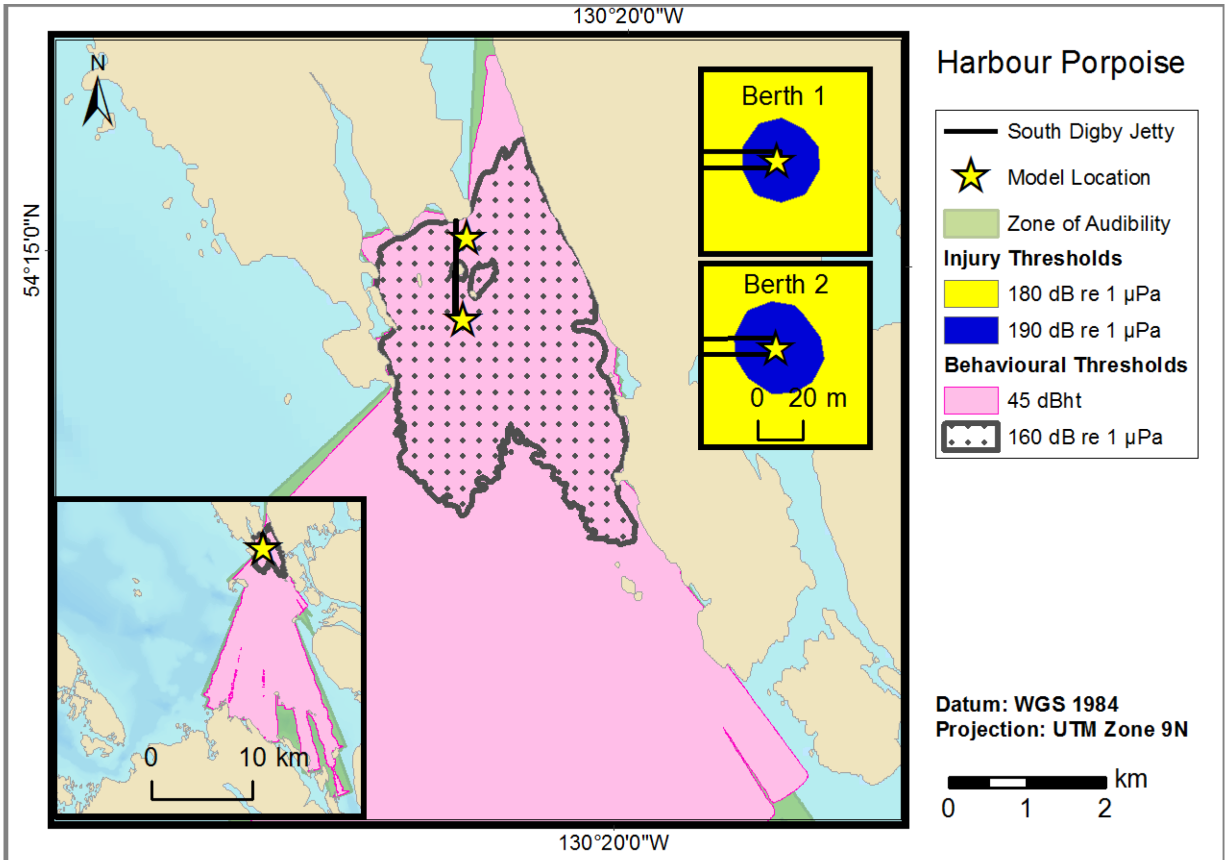
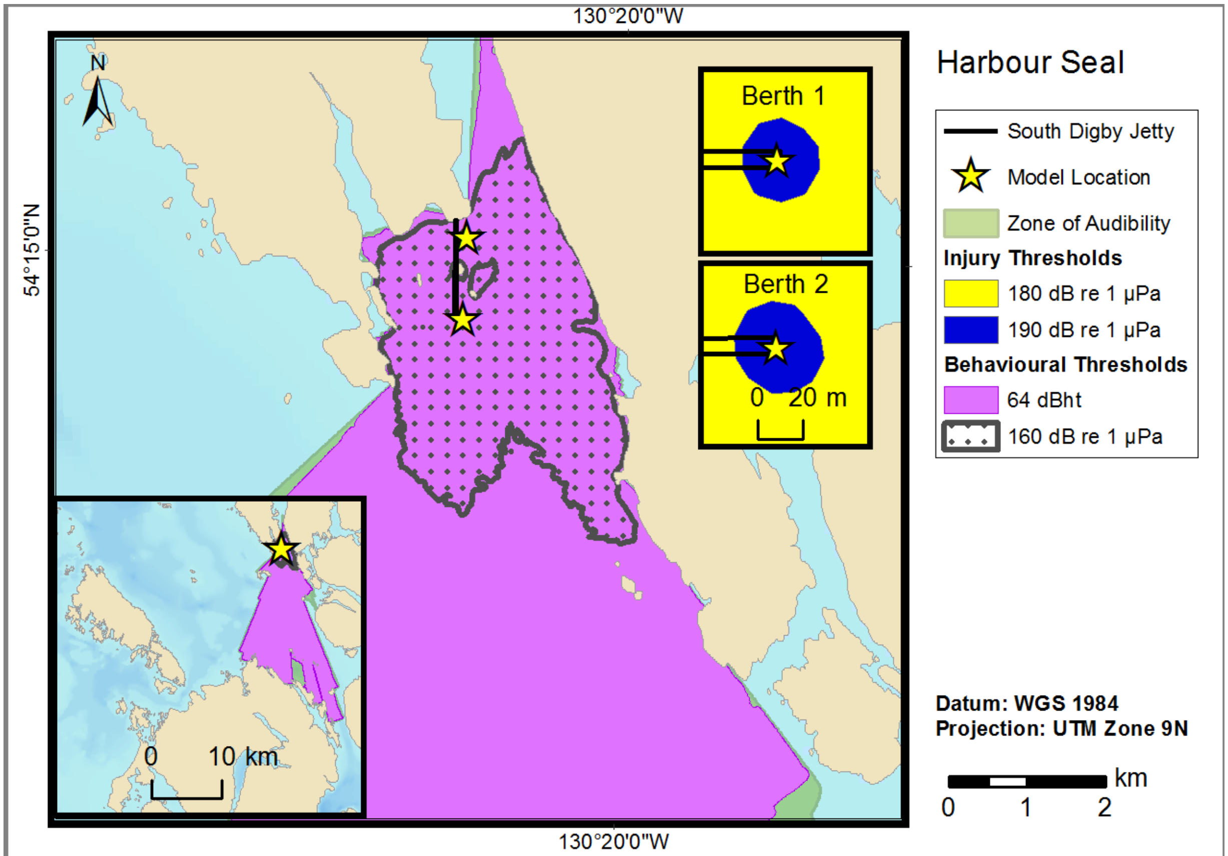


Figure B-9. Killer whale–Scenario 2: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for impact pile driving with confined bubble curtain. The lower inset shows the extent of the ZoA. The upper insets show close-ups to the South Digby Island LNG jetty. The 190, 180, and 160 dB re 1 µPa thresholds are SPL (rms). The 57 and 64 dBht threshold is killer whale audiogram-weighted SPL.



Scenario 2:	Impact pile driving with confined bubble curtain at LNG Jetty	Date: 10/7/2016	JASCO APPLIED SCIENCES
Project:	Aurora LNG Acoustic Study	Version: 1.0	

Figure B-10. Harbour porpoise–Scenario 2: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for impact pile driving with confined bubble curtain. The lower inset shows the extent of the ZoA. The upper insets show close-ups to the South Digby Island LNG jetty. The 190, 180, and 160 dB re 1 μPa thresholds are SPL (rms). The 45 dBht threshold is harbour porpoise audiogram-weighted SPL.



Scenario 2:	Impact pile driving with confined bubble curtain at LNG Jetty	Date: 10/7/2016	JASCO APPLIED SCIENCES
Project:	Aurora LNG Acoustic Study	Version: 1.0	

Figure B-11. Harbour seal–Scenario 2: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for impact pile driving with confined bubble curtain. The lower inset shows the extent of the ZoA. The upper insets show close-ups to the South Digby Island LNG jetty. The 190, 180, and 160 dB re 1 µPa thresholds are SPL (rms). The 64 dBht threshold is harbour seal audiogram-weighted SPL.

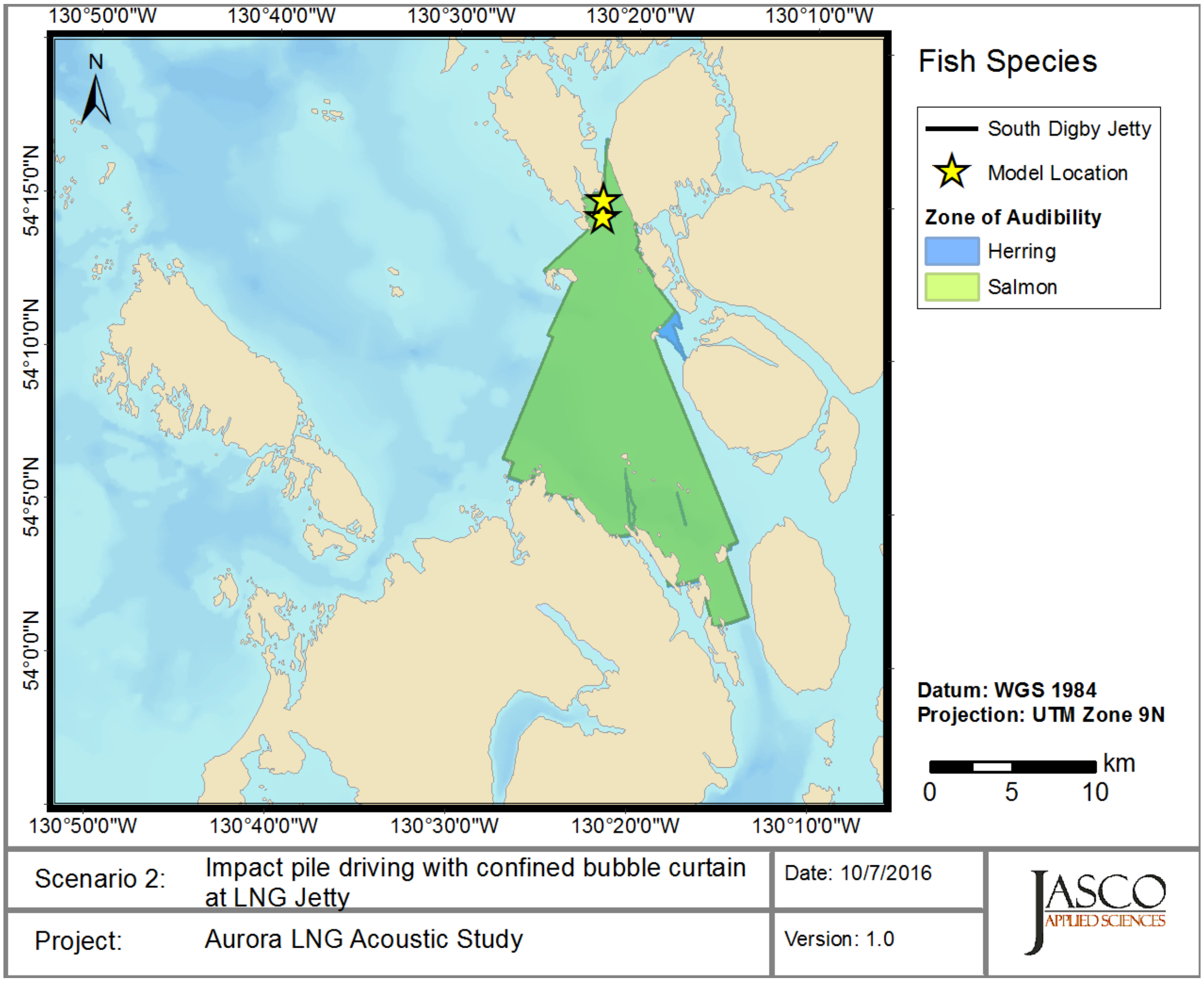


Figure B-12. Herring and salmon–Scenario 2: Map of thresholds to zone of audibility (ZoA) for impact pile driving with confined bubble curtain.

B.2. Rock socket drilling

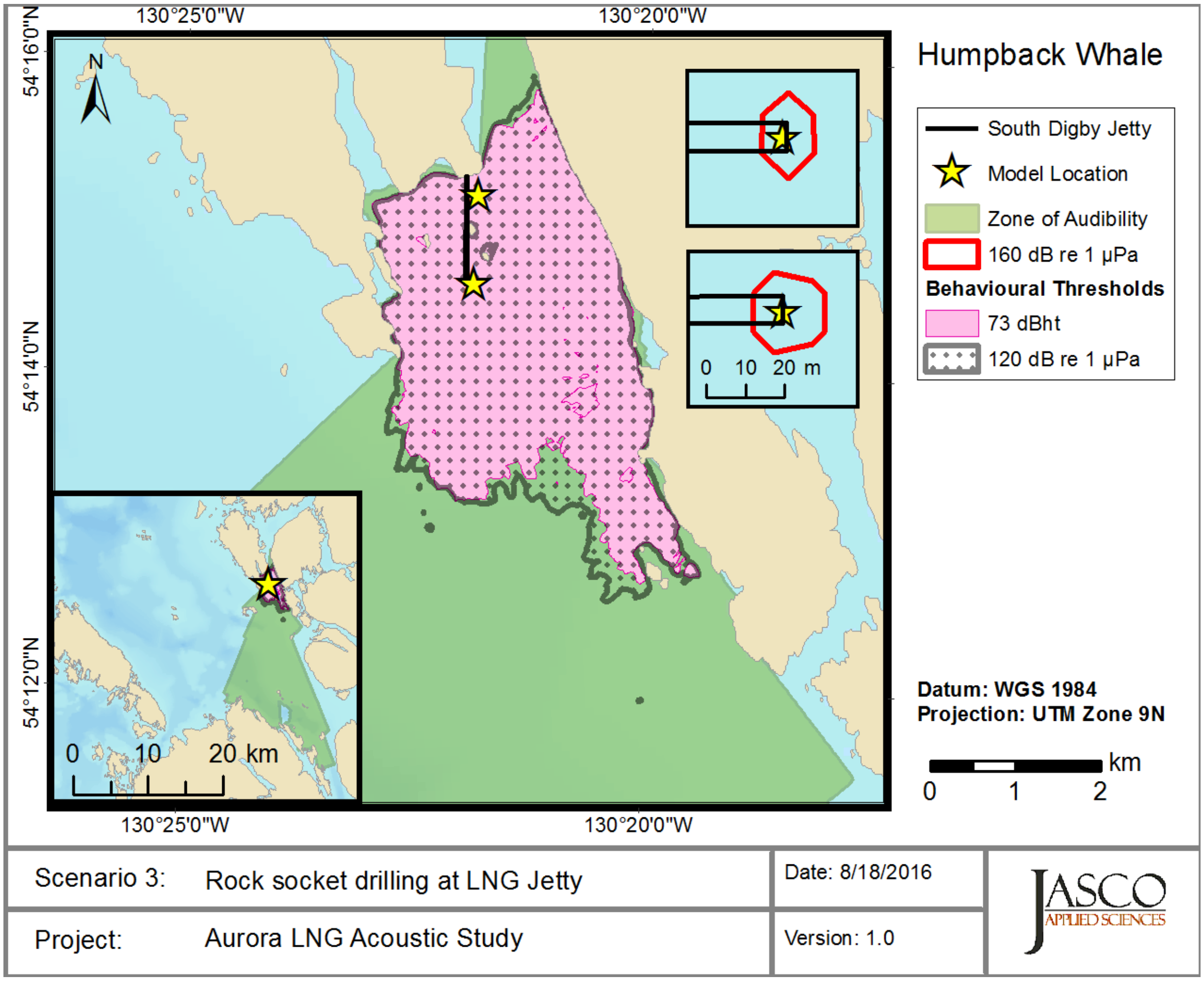
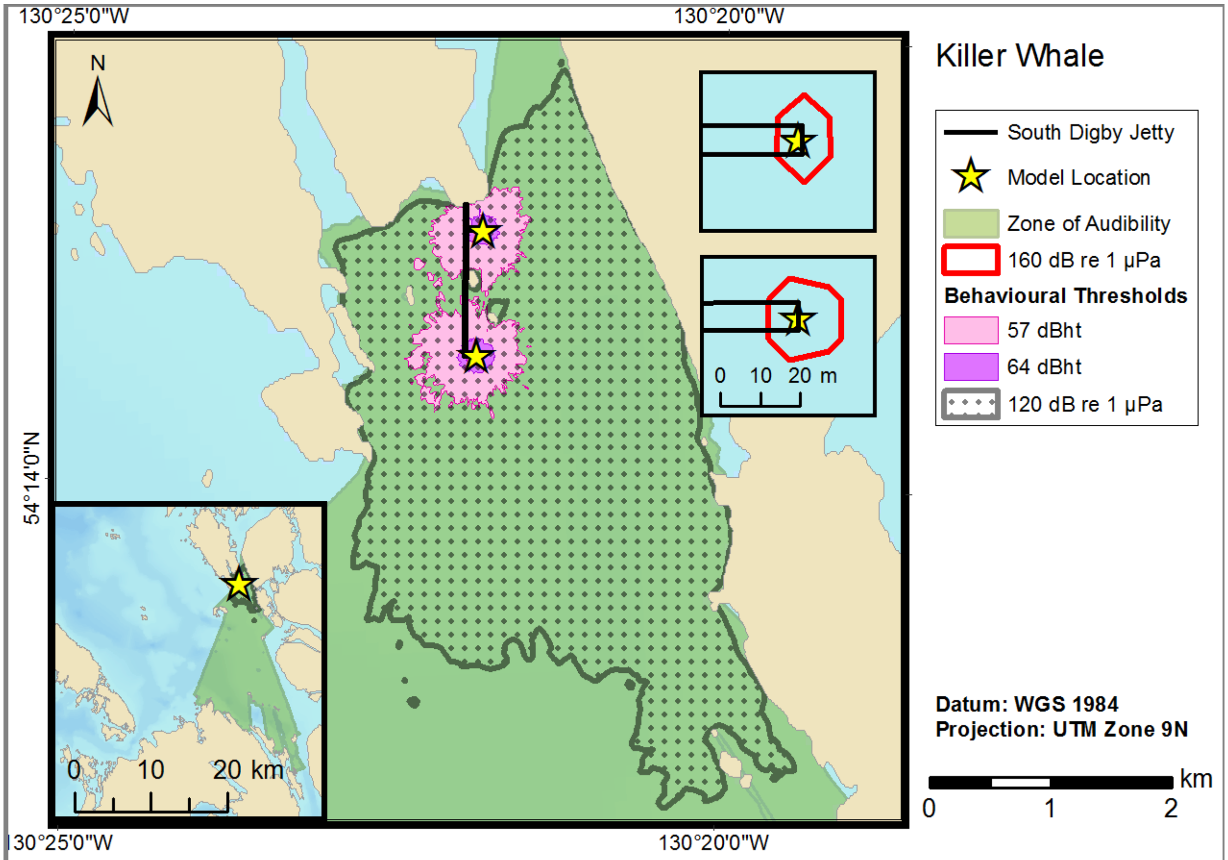
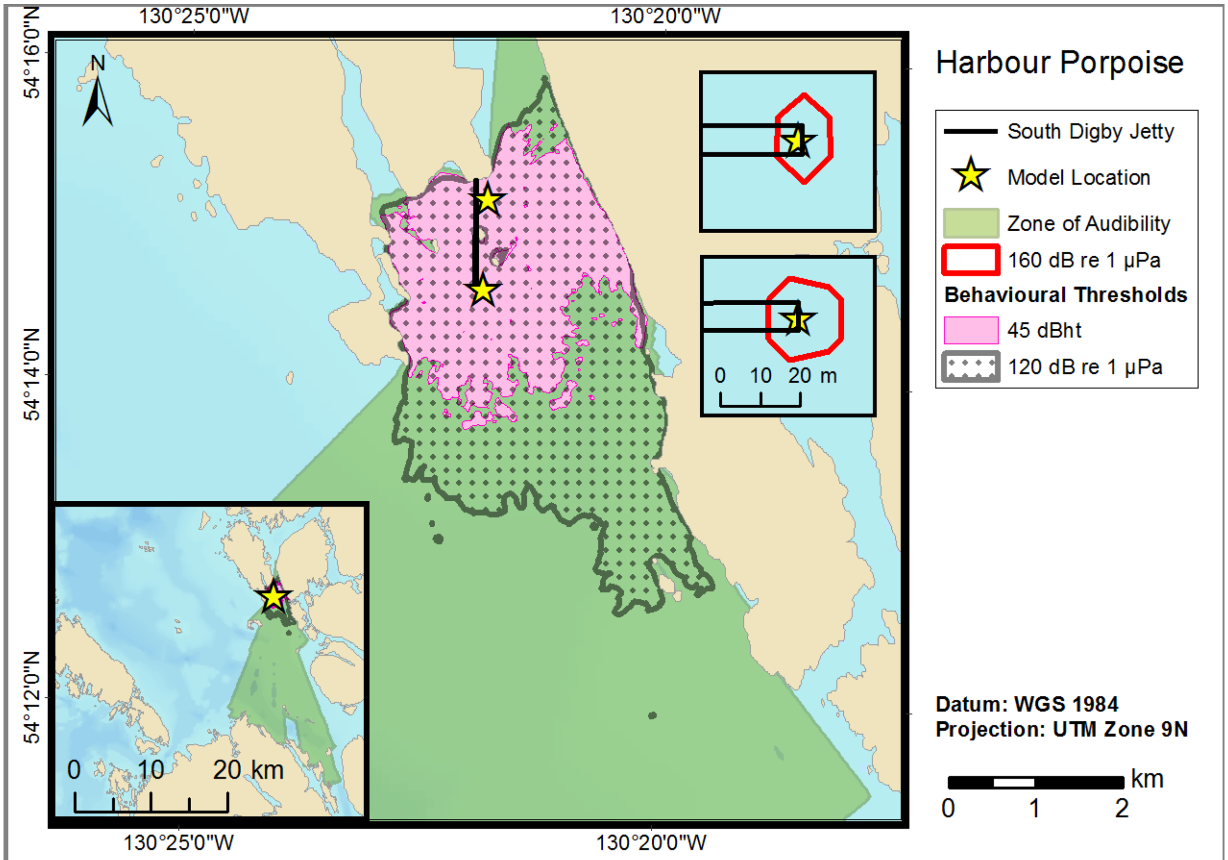


Figure B-13. Humpback whale–Scenario 3: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for rock socket drilling. The lower inset shows the extent of the ZoA. The upper insets show close-ups to the South Digby Island LNG jetty to show the extents of 160 dB re 1 µPa. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 73 dBht threshold is humpback whale audiogram-weighted SPL.



Scenario 3:	Rock socket drilling at LNG Jetty	Date: 8/18/2016	JASCO APPLIED SCIENCES
Project:	Aurora LNG Acoustic Study	Version: 1.0	

Figure B-14. Killer whale–Scenario 3: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for rock socket drilling. The lower inset shows the extent of the ZoA. The upper insets show close-ups to the South Digby Island LNG jetty to show the extents of 160 dB re 1 µPa. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 57 and 64 dBht threshold is killer whale audiogram-weighted SPL.



Scenario 3:	Rock socket drilling at LNG Jetty	Date: 8/18/2016	JASCO APPLIED SCIENCES
Project:	Aurora LNG Acoustic Study	Version: 1.0	

Figure B-15. Harbour porpoise–Scenario 3: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for rock socket drilling. The lower inset shows the extent of the ZoA. The upper insets show close-ups to the South Digby Island LNG jetty to show the extents of 160 dB re 1 µPa. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 45 dBht threshold is harbour porpoise audiogram-weighted SPL.

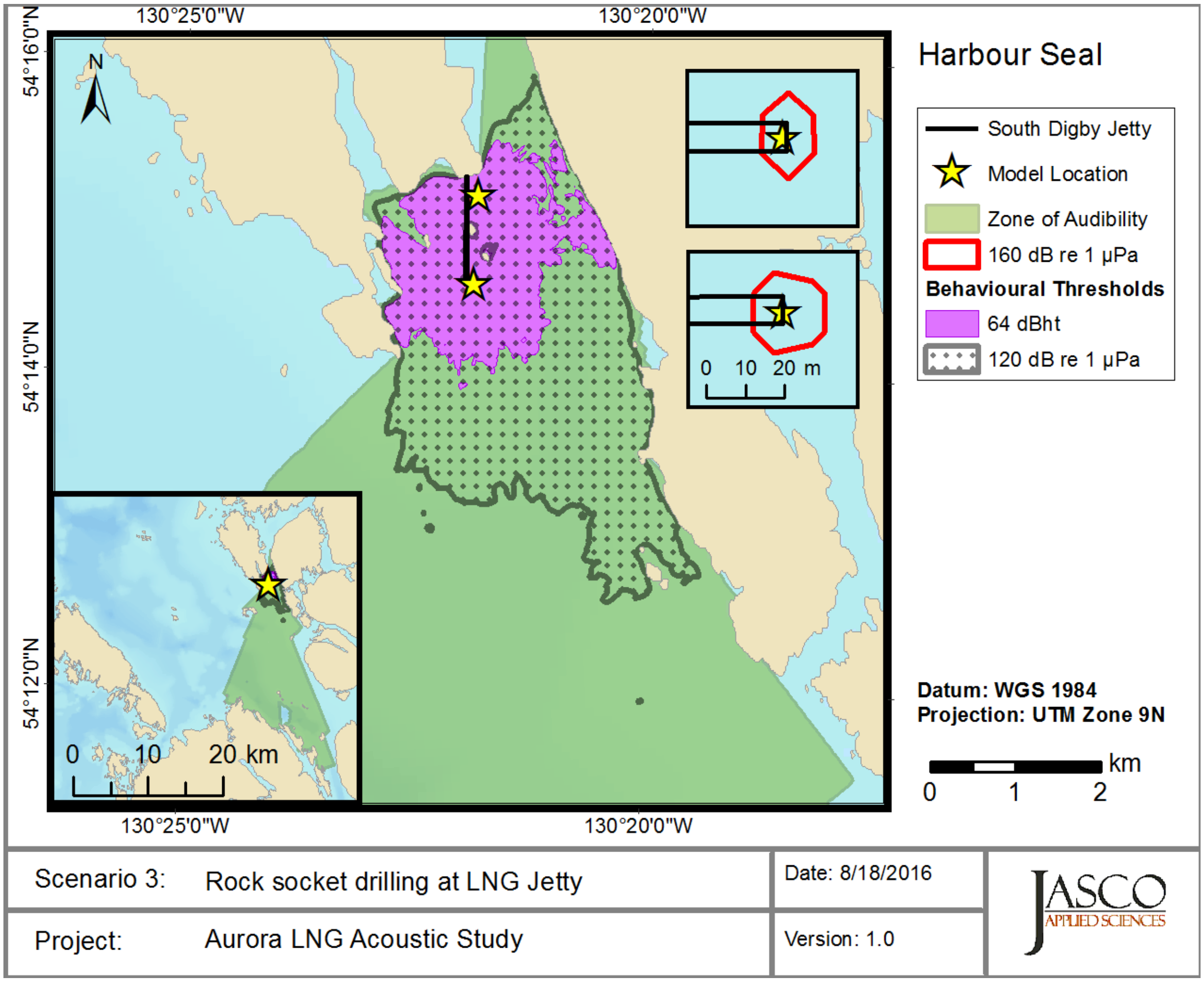


Figure B-16. Harbour seal–Scenario 3: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for rock socket drilling. The lower inset shows the extent of the ZoA. The upper insets show close-ups to the South Digby Island LNG jetty to show the extents of 160 dB re 1 µPa. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 64 dBht threshold is harbour seal audiogram-weighted SPL.

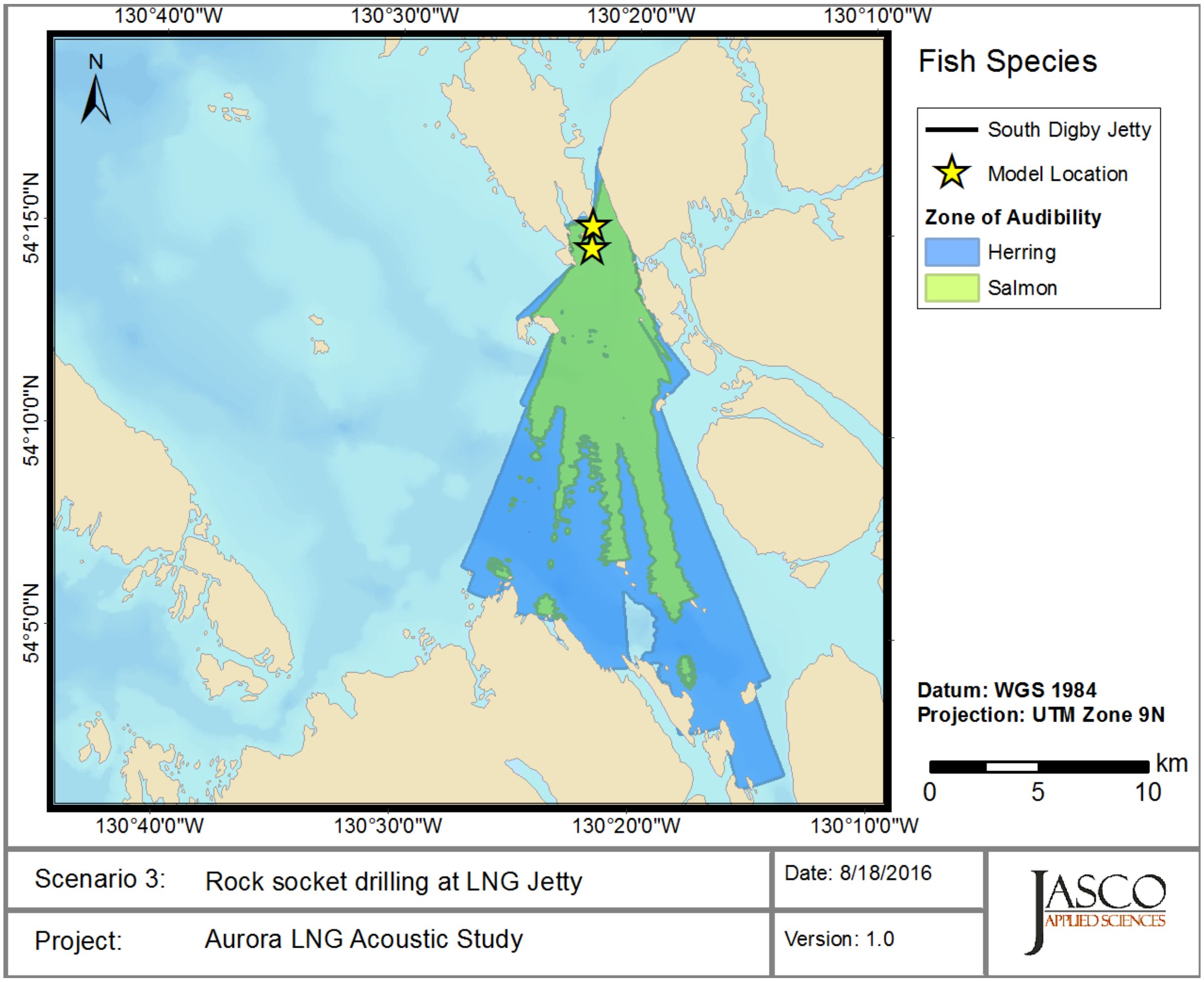


Figure B-17. Herring and salmon–Scenario 3: Map of thresholds to zone of audibility (ZoA) for rock socket drilling at the South Digby Island LNG jetty.

B.3. LNG carrier–Berthing

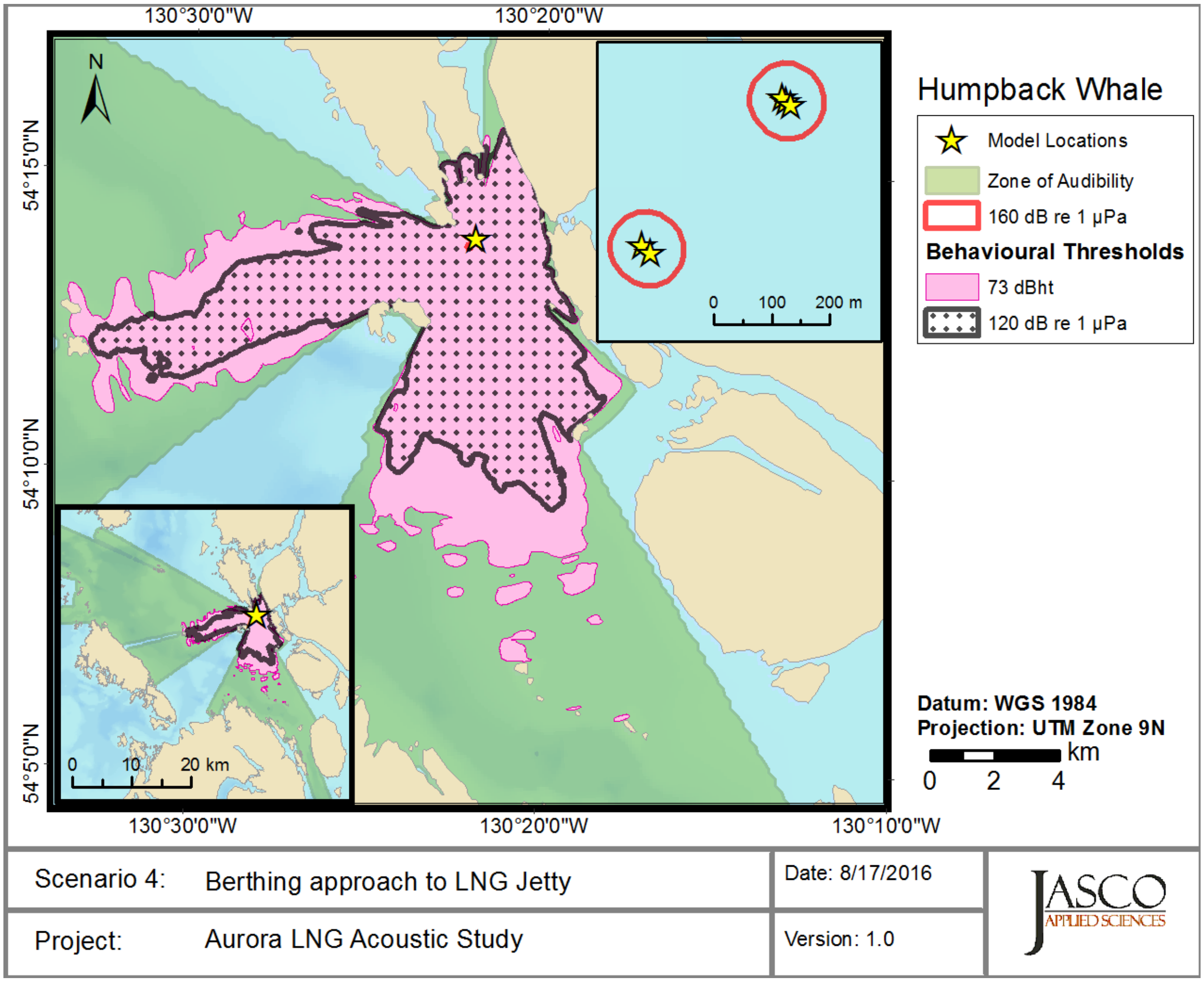


Figure B-18. Humpback whale–Scenario 4: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for LNG carrier approach. The lower inset shows the extent of the ZoA is greater than the modelled area. The upper inset shows a close-up of the vessel locations to show the extents of 160 dB re 1 µPa. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 64 dBht threshold is harbour seal audiogram-weighted SPL.

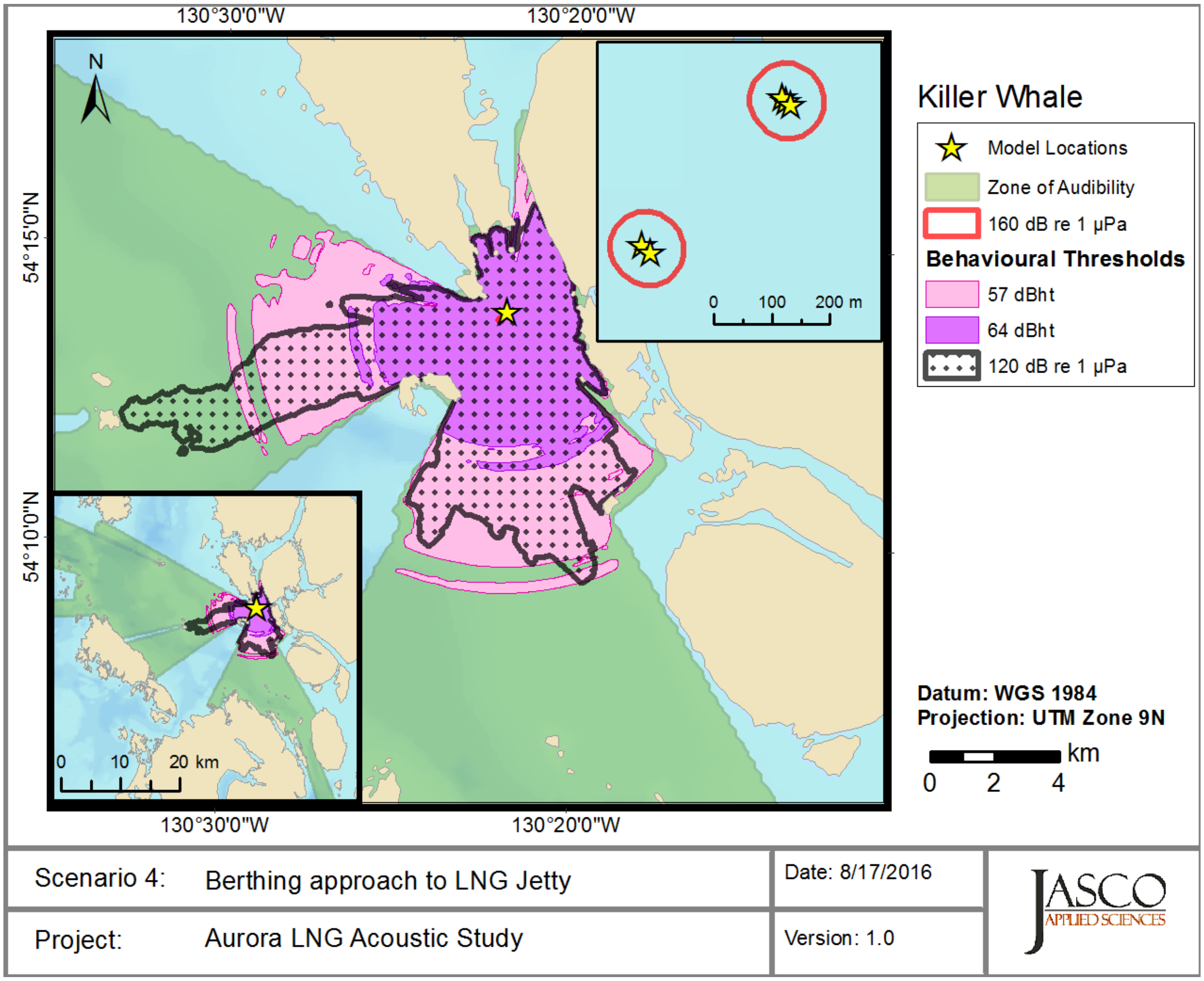


Figure B-19. Killer whale –Scenario 4: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for LNG carrier approach. The lower inset shows the extent of the ZoA is greater than the modelled area. The upper inset shows a close-up of the vessel locations to show the extents of 160 dB re 1 µPa. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 64 dBht threshold is harbour seal audiogram-weighted SPL.

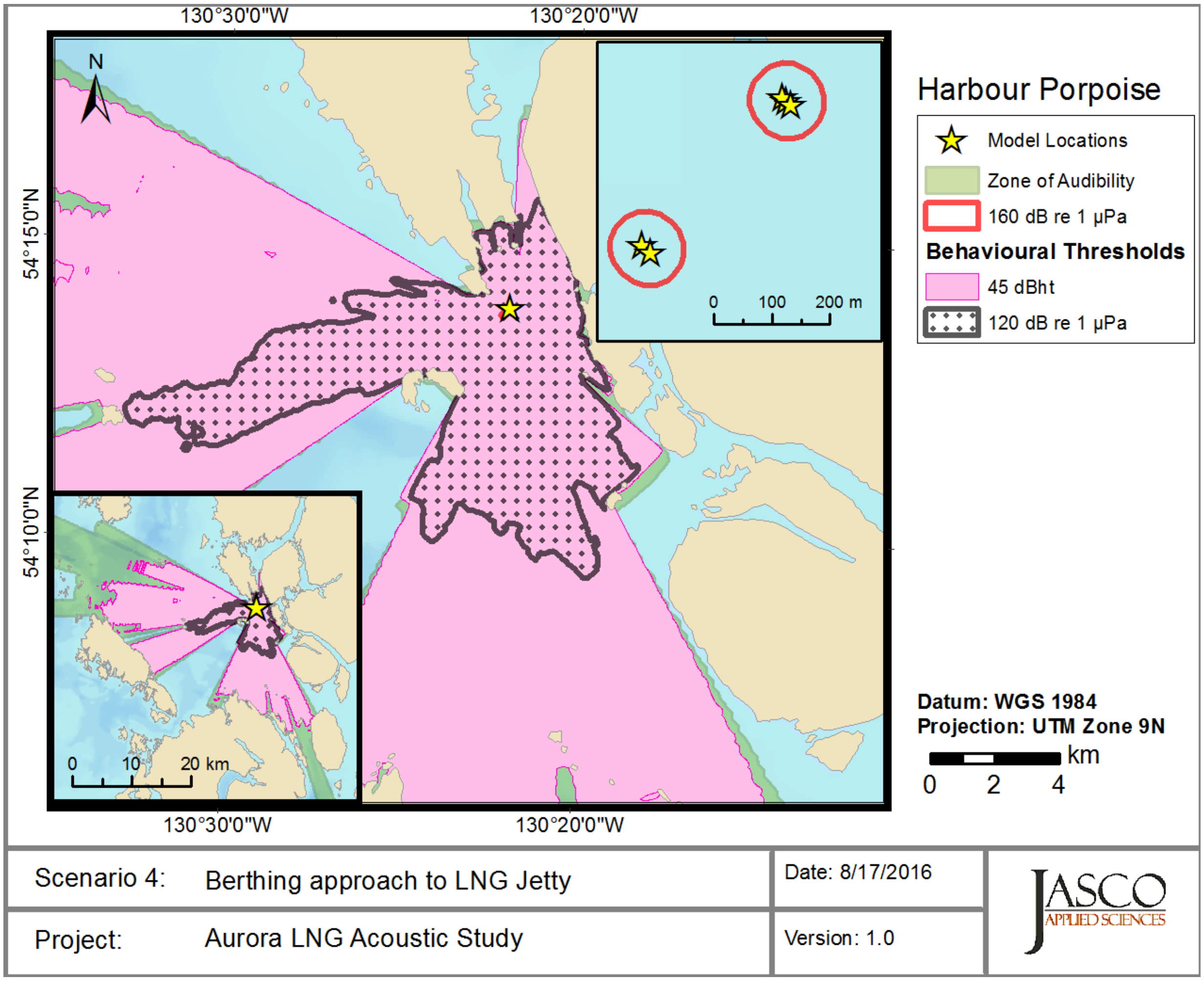
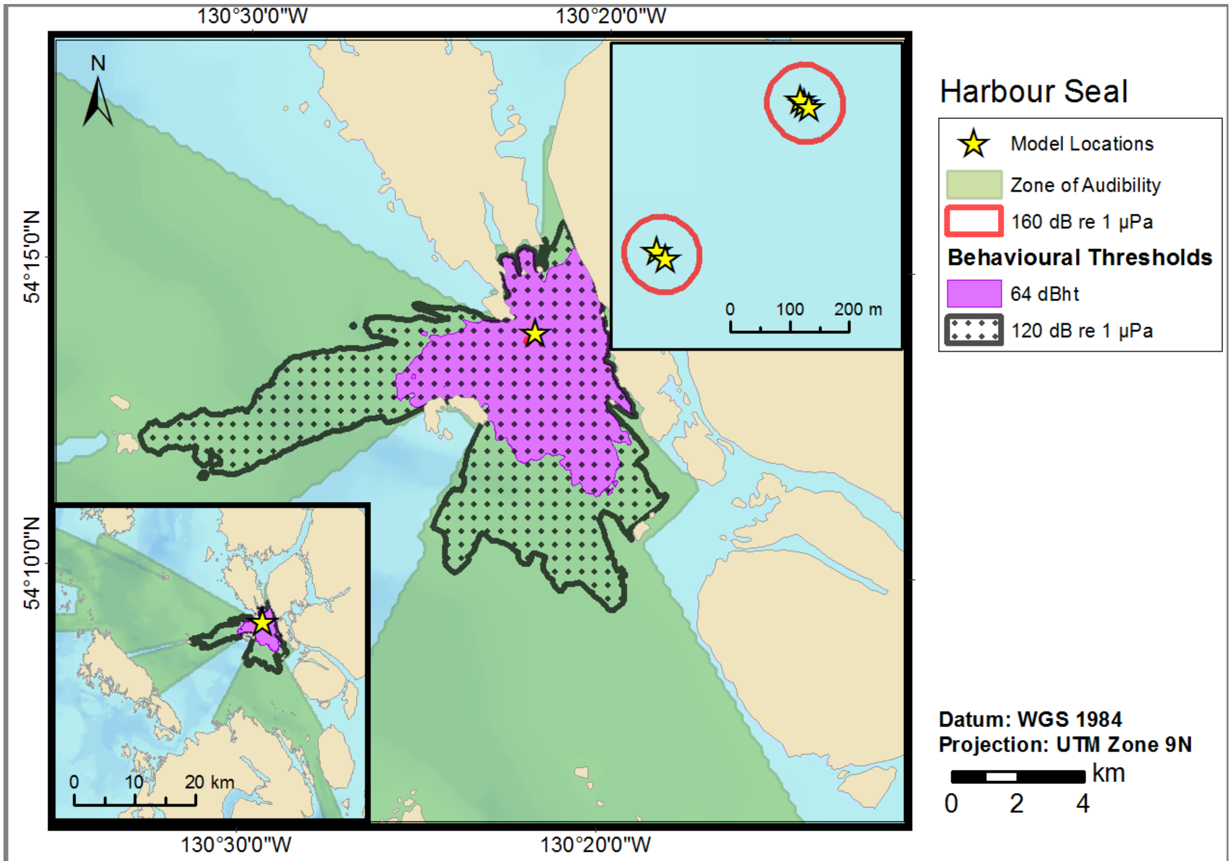


Figure B-20. Harbour porpoise–Scenario 4: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for LNG carrier approach. The lower inset shows the extent of the ZoA is greater than the modelled area. The upper inset shows a close-up of the vessel locations to show the extents of 160 dB re 1 µPa. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 64 dBht threshold is harbour seal audiogram-weighted SPL.



Scenario 4:	Berthing approach to LNG Jetty	Date: 8/17/2016	JASCO APPLIED SCIENCES
Project:	Aurora LNG Acoustic Study	Version: 1.0	

Figure B-21. Harbour seal–Scenario 4: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for LNG carrier approach. The lower inset shows the extent of the ZoA is greater than the modelled area. The upper inset shows a close-up of the vessel locations to show the extents of 160 dB re 1 µPa. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 64 dBht threshold is harbour seal audiogram-weighted SPL.

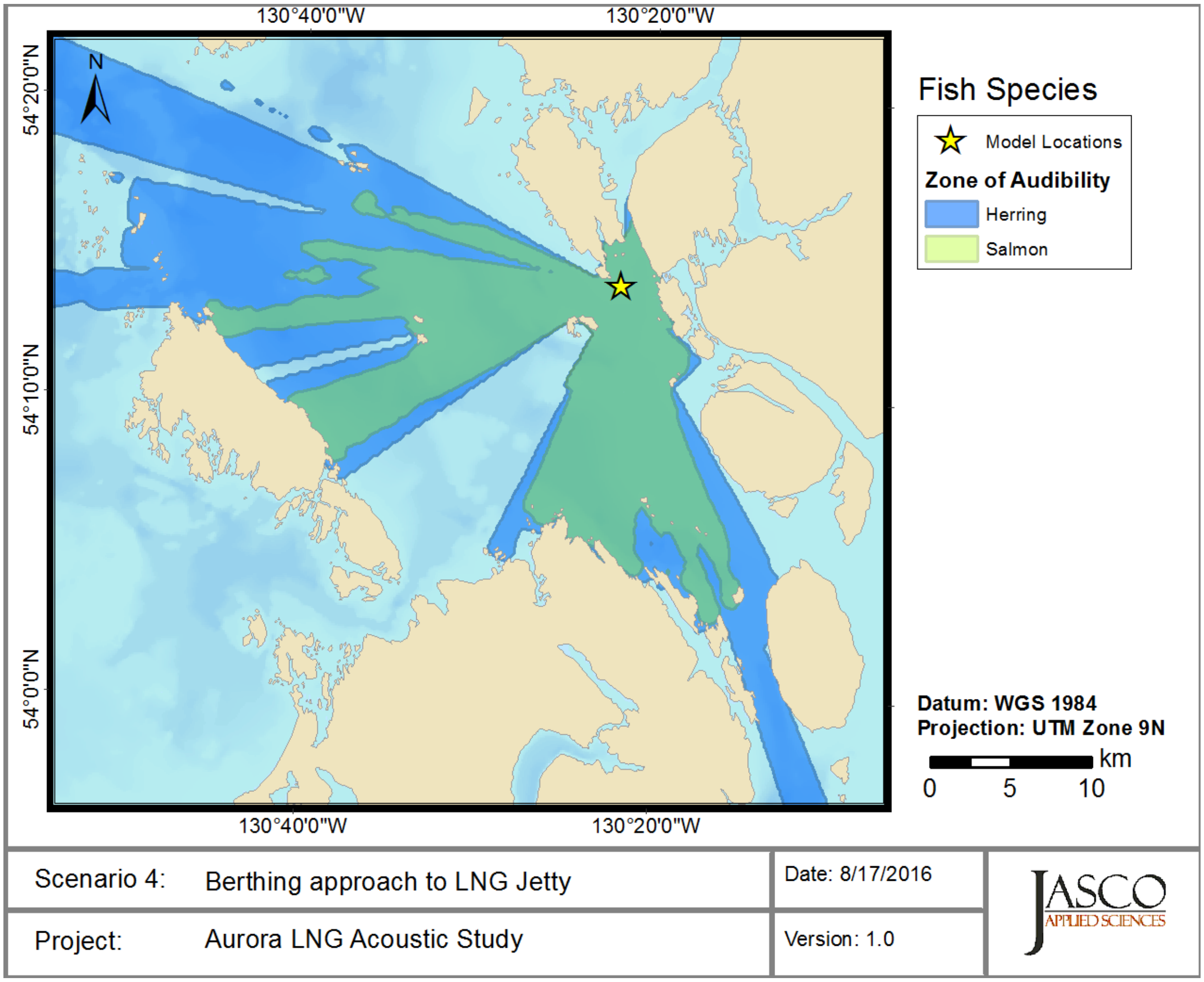


Figure B-22. Herring and salmon–Scenario 4: Map of thresholds to zone of audibility (ZoA) for the LNG carrier berthing approach

B.4. LNG carrier–Transiting

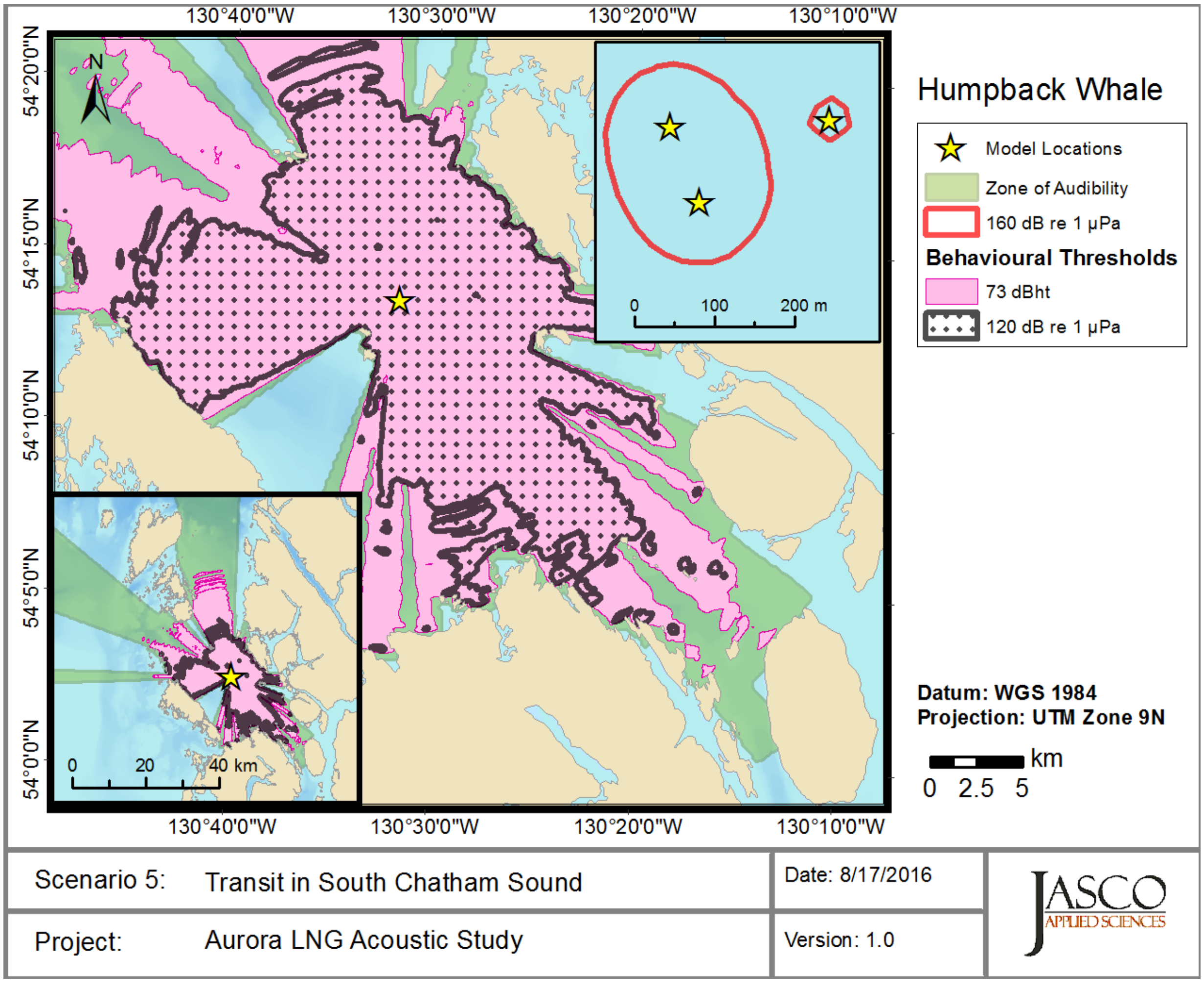
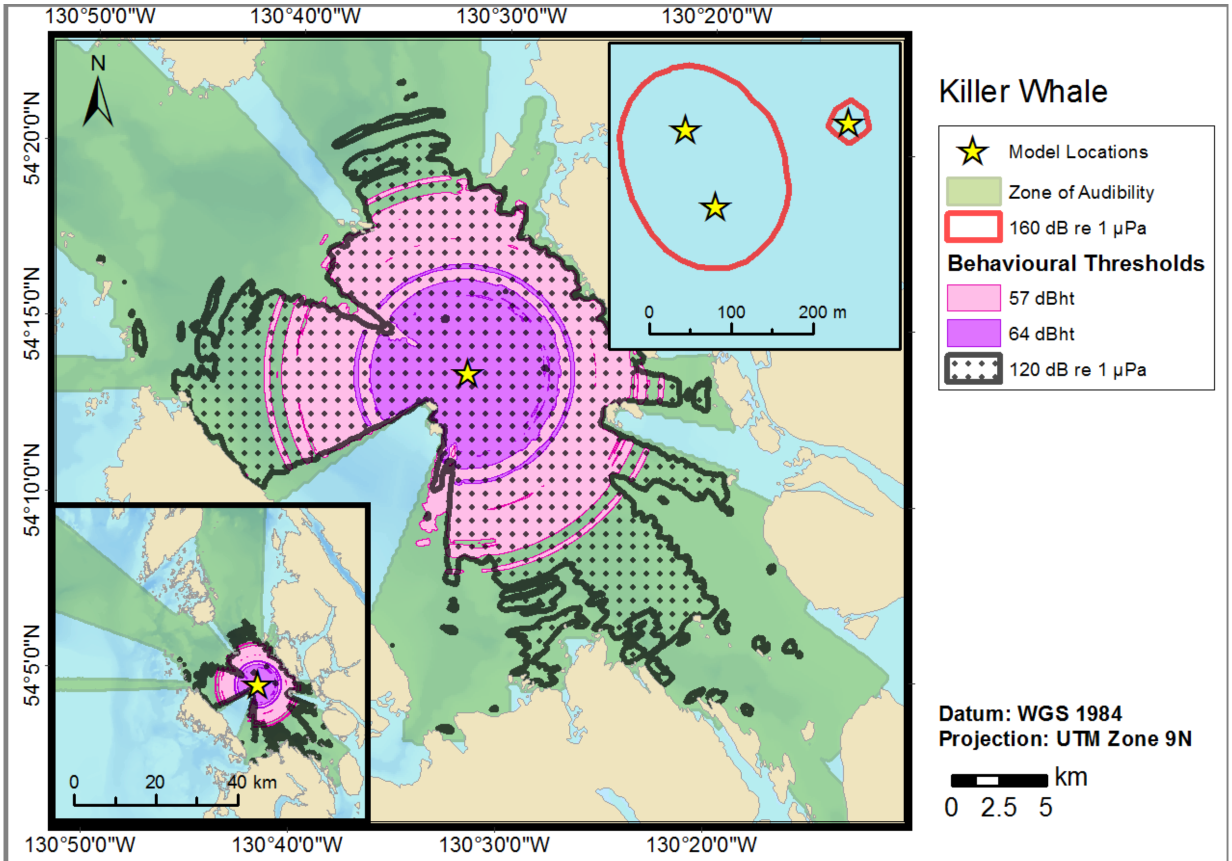
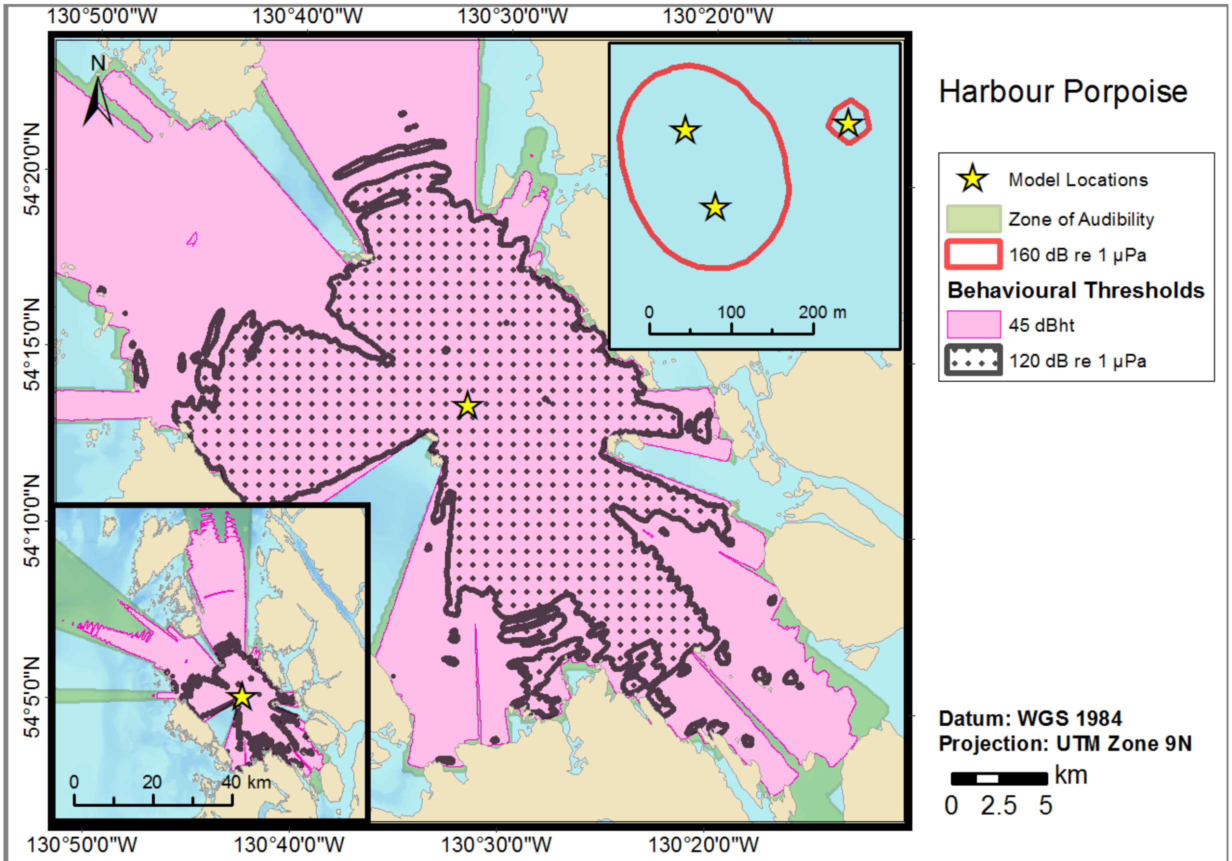


Figure B-23. Humpback whale–Scenario 5: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for LNG carrier transiting in South Chatham Sound. The lower inset shows the extent of the ZoA is greater than the modelled area. The upper inset shows a close-up of the vessel locations to show the extents of 160 dB re 1 µPa. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 73 dBht threshold is humpback whale audiogram-weighted SPL.



Scenario 5:	Transit in South Chatham Sound	Date: 8/17/2016	JASCO APPLIED SCIENCES
Project:	Aurora LNG Acoustic Study	Version: 1.0	

Figure B-24. Killer whale–Scenario 5: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for LNG carrier transiting in South Chatham Sound. The lower inset shows the extent of the ZoA is greater than the modelled area. The upper inset shows a close-up of the vessel locations to show the extents of 160 dB re 1 µPa. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 57 and 64 dBht threshold is killer whale audiogram-weighted SPL.



Scenario 5:	Transit in South Chatham Sound	Date: 8/17/2016	JASCO APPLIED SCIENCES
Project:	Aurora LNG Acoustic Study	Version: 1.0	

Figure B-25.Harbour porpoise–Scenario 5: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for LNG carrier transiting in South Chatham Sound. The lower inset shows the extent of the ZoA is greater than the modelled area. The upper inset shows a close-up of the vessel locations to show the extents of 160 dB re 1 µPa. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 45 dBht threshold is harbour porpoise audiogram-weighted SPL.

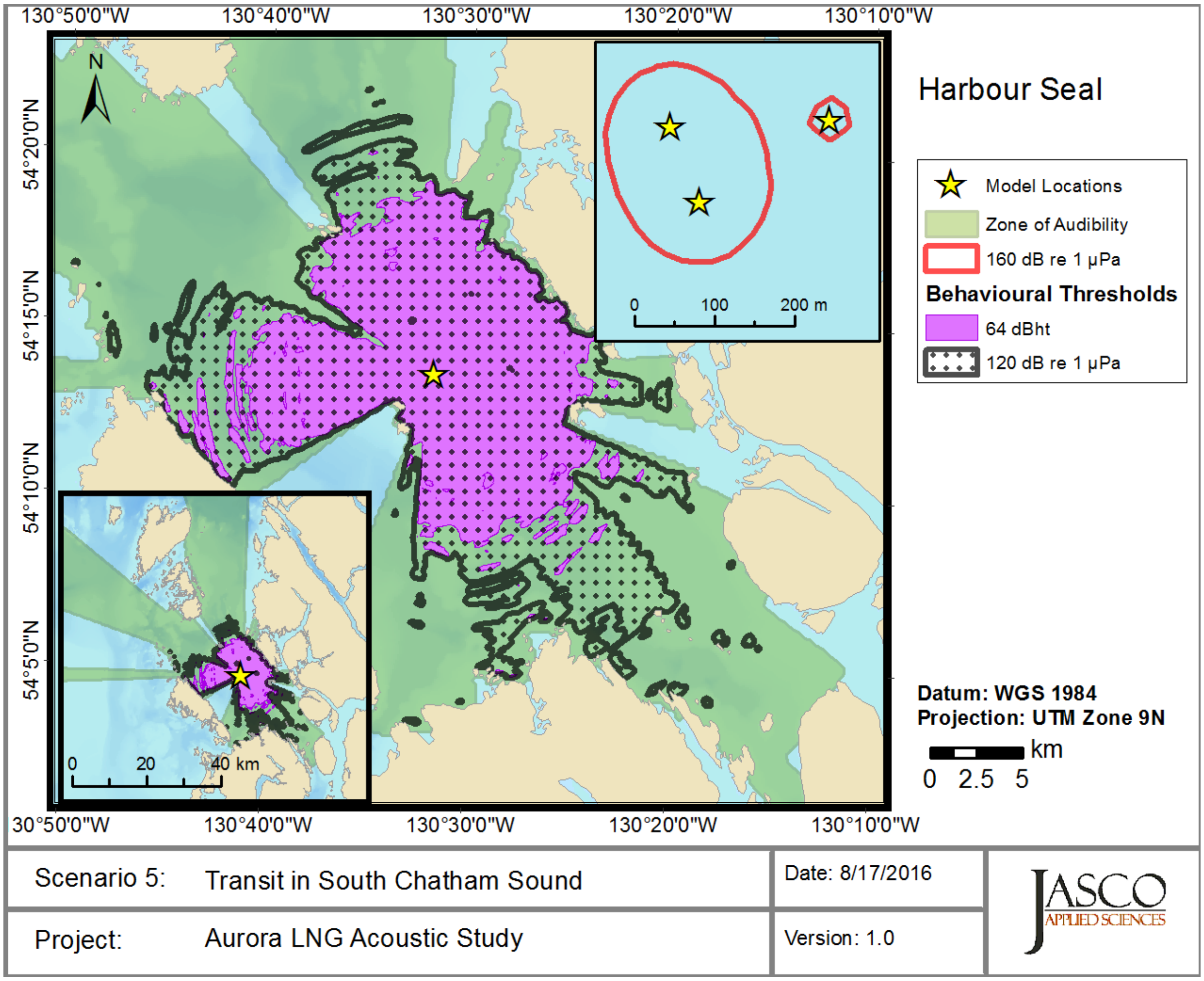
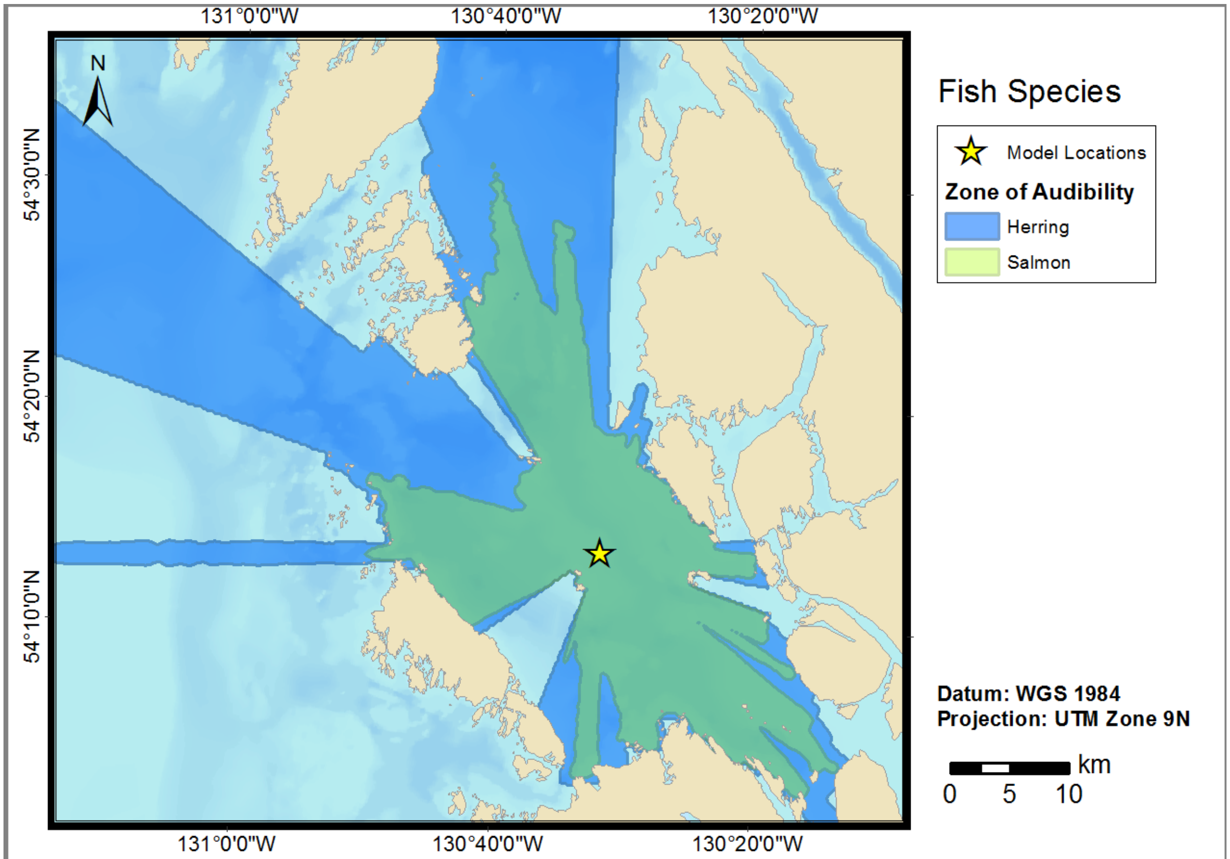


Figure B-26. Harbour seal–Scenario 5: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for LNG carrier transiting in South Chatham Sound. The lower inset shows the extent of the ZoA is greater than the modelled area. The upper inset shows a close-up of the vessel locations to show the extents of 160 dB re 1 µPa. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 64 dBht threshold is harbour seal audiogram-weighted SPL.



Scenario 5:	Transit in South Chatham Sound	Date: 8/19/2016	JASCO APPLIED SCIENCES
Project:	Aurora LNG Acoustic Study	Version: 1.0	

Figure B-27.Herring and salmon –Scenario 5: Map of thresholds to zone of audibility (ZoA) for the LNG carrier transiting in south Chatham Sound.

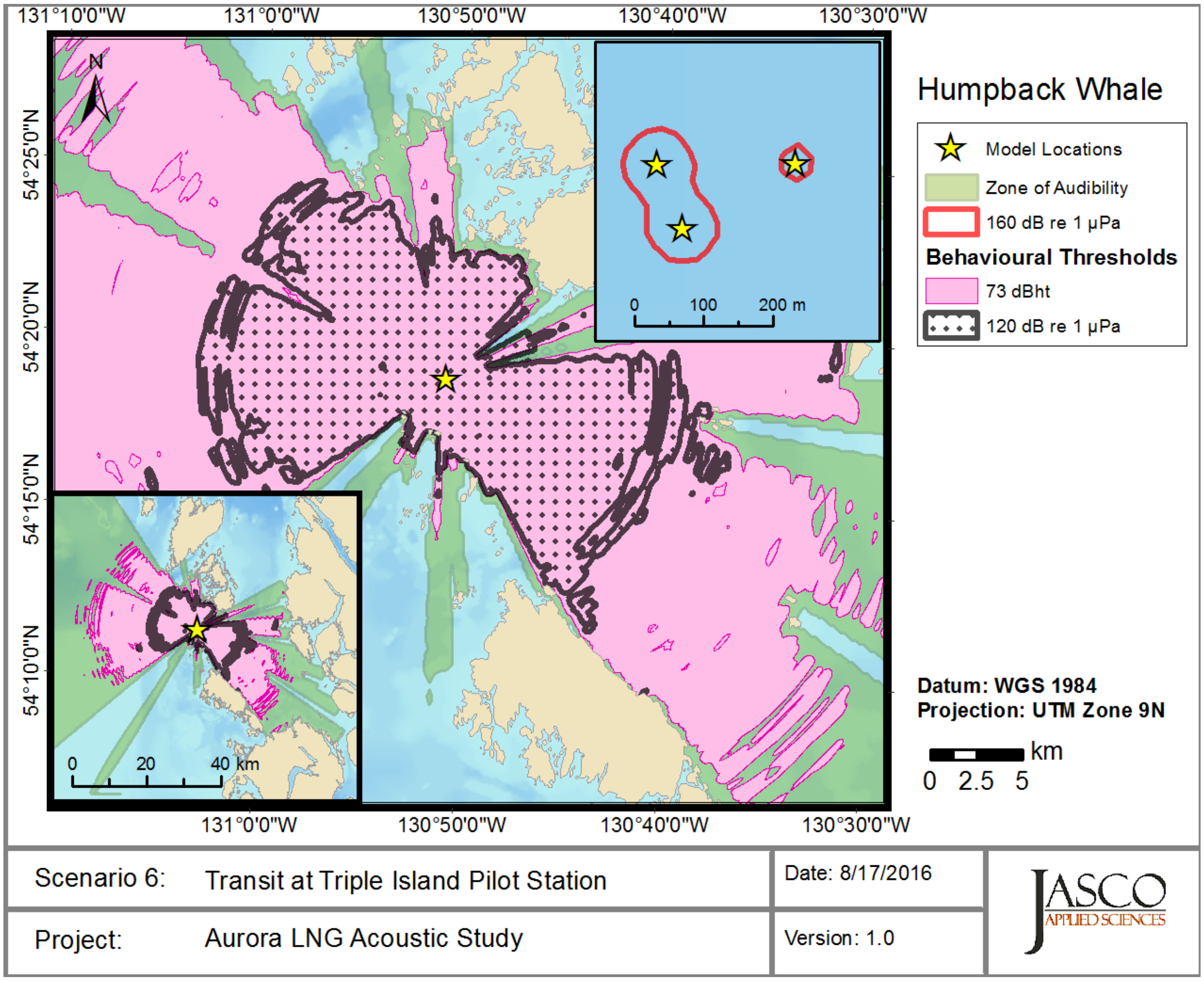


Figure B-28. Humpback whale–Scenario 6: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for LNG carrier transiting at the Triple Island Pilot Station in South Chatham Sound. The lower inset shows the extent of the ZoA is greater than the modelled area. The upper insets show a close-up of the vessel locations. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 73 dBht threshold is humpback whale audiogram-weighted SPL.

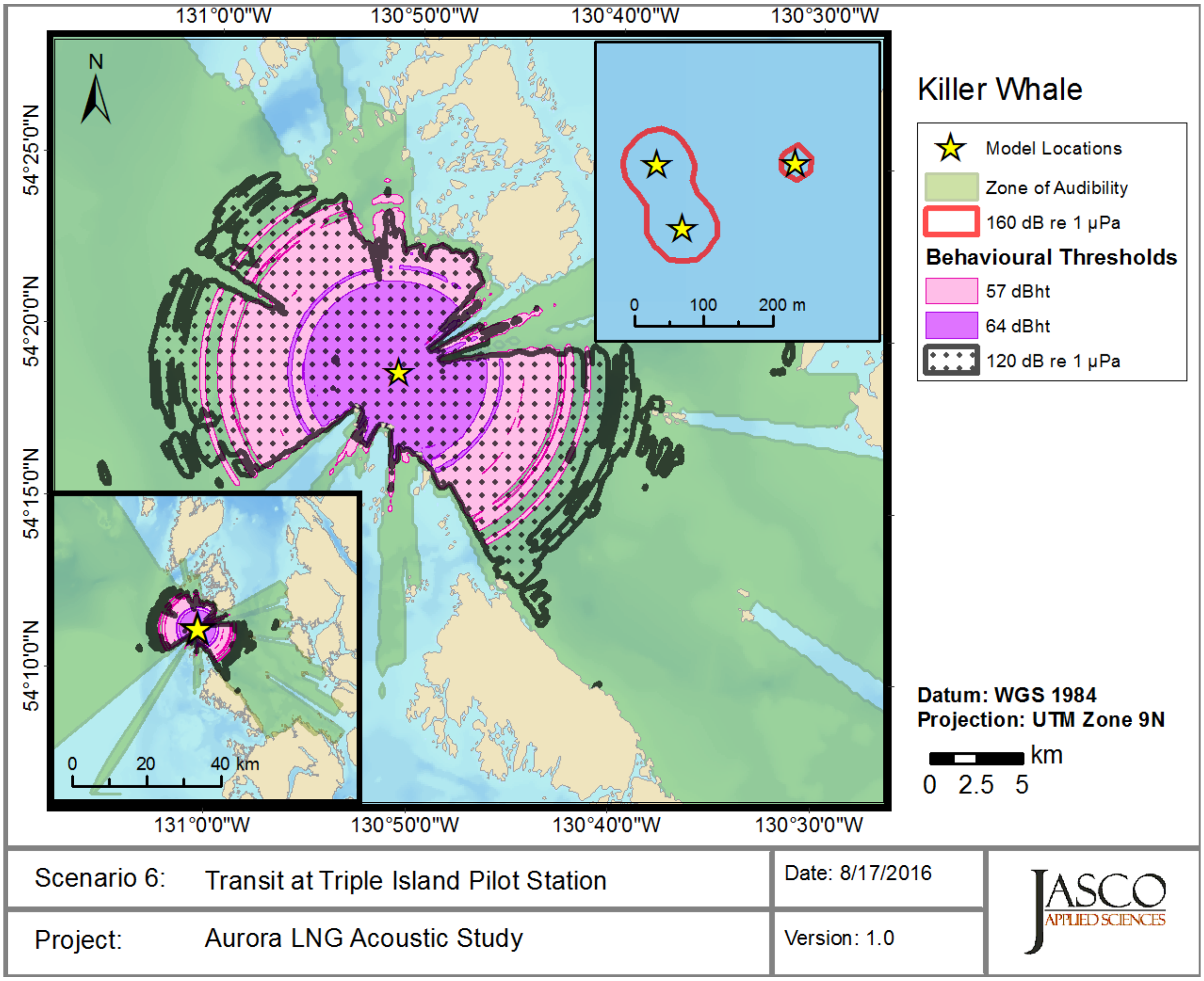


Figure B-29. Killer whale–Scenario 6: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for LNG carrier transiting at the Triple Island Pilot Station in South Chatham Sound. The lower inset shows the extent of the ZoA is greater than the modelled area. The upper insets show a close-up of the vessel locations. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 57 and 64 dBht threshold is killer whale audiogram-weighted SPL.

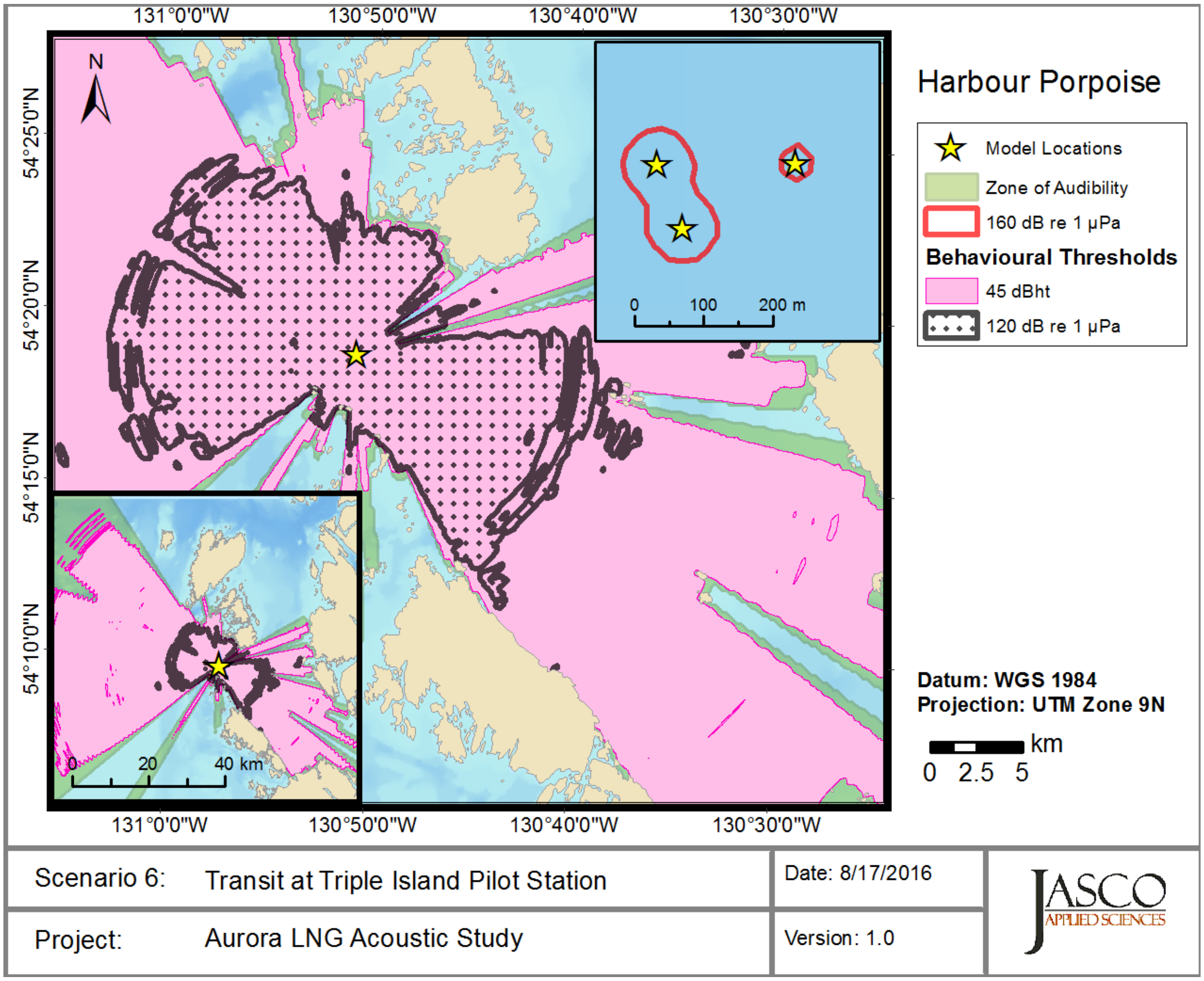


Figure B-30. Harbour porpoise –Scenario 6: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for LNG carrier transiting at the Triple Island Pilot Station in South Chatham Sound. The lower inset shows the extent of the ZoA is greater than the modelled area. The upper inset shows a close-up of the vessel locations. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 45 dBht threshold is harbour porpoise audiogram-weighted SPL.

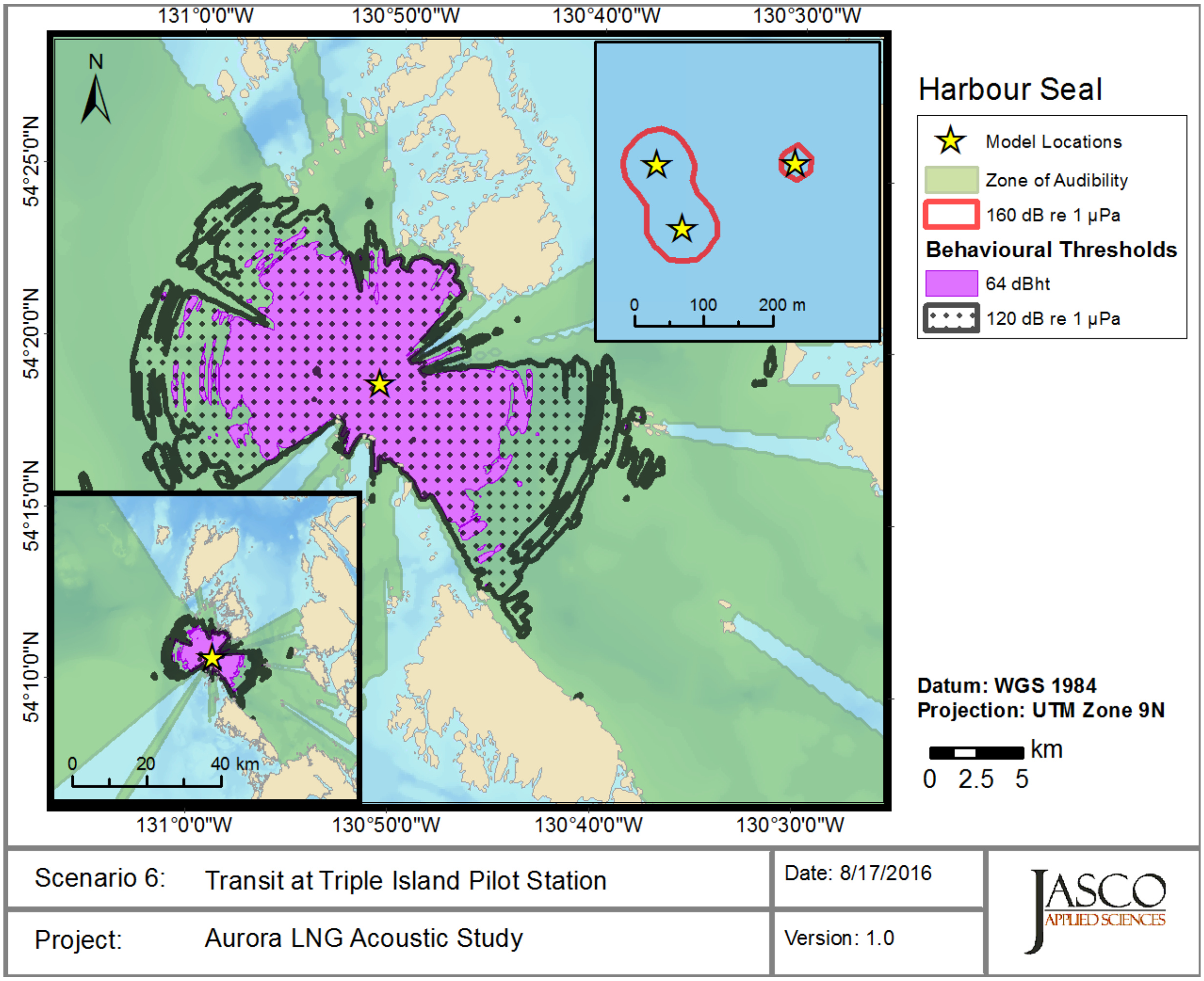


Figure B-31. Harbour seal –Scenario 6: Map of thresholds to selected impact criteria and zone of audibility (ZoA) for LNG carrier transiting at the Triple Island Pilot Station in South Chatham Sound. The lower inset shows the extent of the ZoA is greater than the modelled area. The upper inset shows a close-up of the vessel locations. The 120 and 160 dB re 1 µPa thresholds are SPL (rms). The 64 dBht threshold is harbour seal audiogram-weighted SPL.

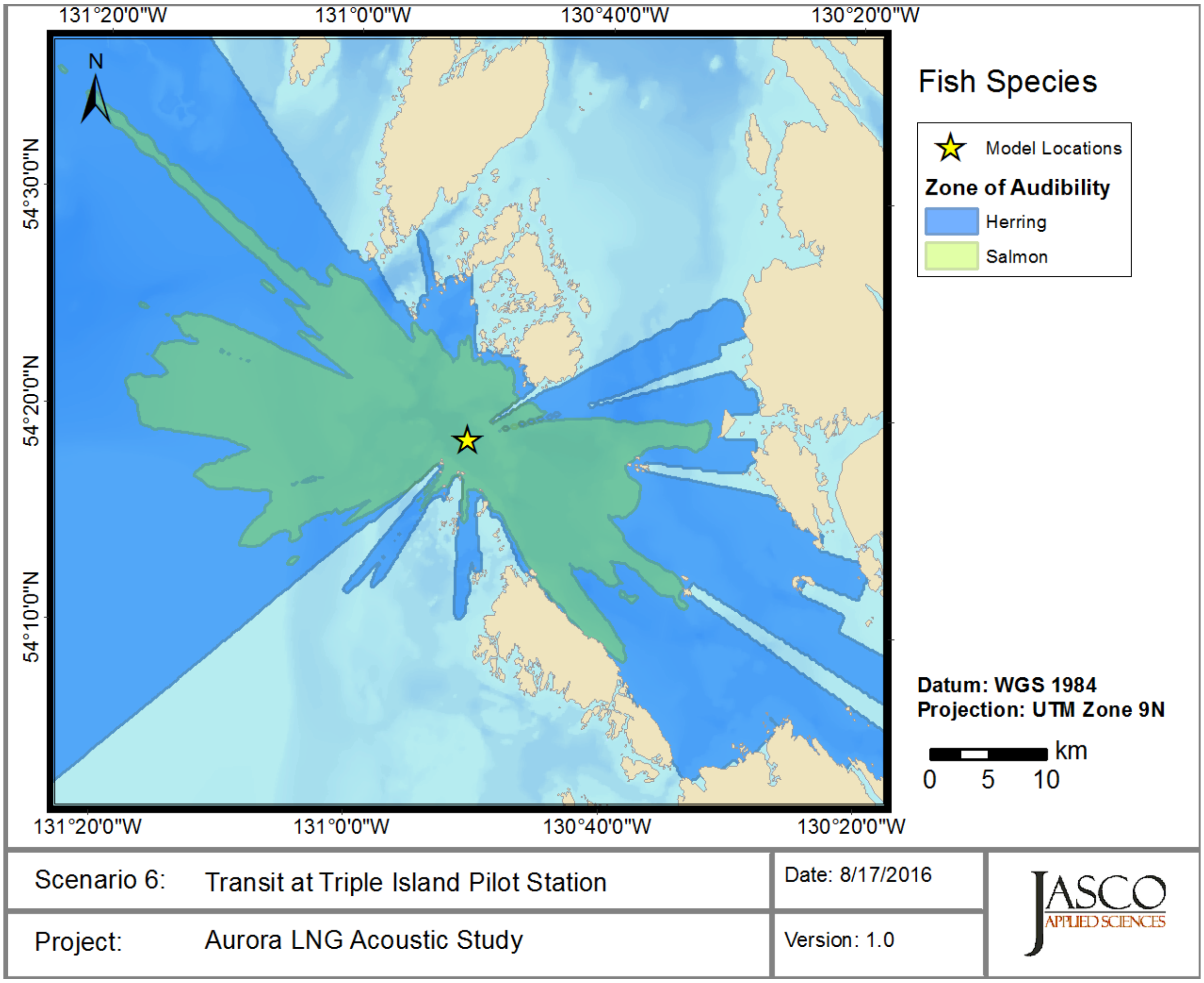


Figure B-32. Herring and salmon–Scenario 6: Map of thresholds to zone of audibility (ZoA) for the LNG carrier transiting in south Chatham Sound.